SEARCH FOR $B \rightarrow \psi(2S)\pi$ DECAY WITH BELLE DETECTOR AT KEK $B$-FACTORY

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Abstract

The study performed in the present thesis, uses the data collected with the Belle detector, at the KEKB $e^+ e^-$ asymmetric collider having $e^-$ and $e^+$ circulating with the energy of 8 GeV and 3.5 GeV, respectively. This whole experimental setup is situated at KEK (Japan). Data used for this analysis is collected at the $\Upsilon(4S)$ resonance, which immediately decays into $B \bar{B}$ pairs and this makes it a suitable place for performing the analysis related to $B$ Physics, which is the topic of this thesis. Study of $B^\pm \rightarrow \psi(2S)\pi^\pm$, $B^\pm \rightarrow \psi(2S)K^\pm$, $B^{\pm,0} \rightarrow \chi_{c1}K^{\pm,0}$, $B^{\pm,0} \rightarrow \chi_{c2}K^{\pm,0}$ and $B^{\pm,0} \rightarrow X(3872)K^{\pm,0}$ decays is presented in this thesis.

In the study of $B^\pm \rightarrow \psi(2S)\pi^\pm$ and $B^\pm \rightarrow \psi(2S)K^\pm$, 604 fb$^{-1}$ data is used. We observed $B^\pm \rightarrow \psi(2S)\pi^\pm$ (which is a Cabibbo- and color-suppressed) decay mode for the first time in the world and its branching fraction is measured to be $(2.44 \pm 0.22({\text{stat}}.) \pm 0.20({\text{syst}}.)) \times 10^{-5}$. Search for the direct $CP$ violation in the $B^\pm \rightarrow \psi(2S)\pi^\pm$ decay is also performed and in this search we measure its charge asymmetry, $A_{CP}^{B^\pm \rightarrow \psi(2S)\pi^\pm}$, to be $0.022 \pm 0.085({\text{stat}}.) \pm 0.016({\text{syst}}.)$. In addition to this, branching fraction measurement of $B^\pm \rightarrow \psi(2S)K^\pm$ decay mode is also done and is measured as $(6.12 \pm 0.09 ({\text{stat}}.) \pm 0.53({\text{syst}}.)) \times 10^{-4}$, which is consistent with the world average. We compute the ratio of the branching fractions of $B^\pm \rightarrow \psi(2S)\pi^\pm$ and $B^\pm \rightarrow \psi(2S)K^\pm$ as $\frac{\mathcal{B}(B^\pm \rightarrow \psi(2S)\pi^\pm)}{\mathcal{B}(B^\pm \rightarrow \psi(2S)K^\pm)} = (3.99 \pm 0.36({\text{stat}}.) \pm 0.17({\text{syst}}.))\%$, which extends support to the factorization hypothesis.

In our study of $B^{\pm,0} \rightarrow \chi_{c1}K^{\pm,0}$, $B^{\pm,0} \rightarrow \chi_{c2}K^{\pm,0}$ and $B^{\pm,0} \rightarrow X(3872)K^{\pm,0}$ decays, where $\chi_{c1,2,3} \rightarrow J/\psi \gamma$ while $X(3872)$ can either decays to $J/\psi \gamma$ or $\psi(2S)\gamma$ decays. This analysis is performed using 703 fb$^{-1}$ of the Belle data. The branching fractions $\mathcal{B}(B^{\pm} \rightarrow \chi_{c1}K^{\pm})$ and $\mathcal{B}(B^{0} \rightarrow \chi_{c1}K^{0})$ are measured as $(4.94 \pm 0.11({\text{stat}}.) \pm 0.33({\text{syst}}.) \times 10^{-4}$ and $(3.78_{-0.16}^{+0.17}({\text{stat}}.) \pm 0.33({\text{syst}}.) \times 10^{-4}$, respectively. For the first time an evidence has been found for the $B^{\pm} \rightarrow \chi_{c2}K^{\pm}$ decay (with a significance of $3.6\sigma$) and its branching fraction $\mathcal{B}(B^{\pm} \rightarrow \chi_{c2}K^{\pm})$ is measured as $(1.11_{-0.34}^{+0.36}({\text{stat}}.) \pm 0.09({\text{syst}}.) \times 10^{-5}$. While in the neutral mode, $B^{0} \rightarrow \chi_{c2}K^{0}$, no significant signal is seen and upper limit (U.L.) @90% confidence limit (C.L.) is derived for the
branching fraction as $< 1.5 \times 10^{-5}$. Measured branching fractions of $B^\pm \to \chi_{c2}K^\pm$ and $B^\pm \to \chi_{c1}K^\pm$ decays are compared, $\frac{B(B^\pm \to \chi_{c2}K^\pm)}{B(B^\pm \to \chi_{c1}K^\pm)}$, and this ratio is found to be $(2.25 \pm 0.71(\text{stat.}) \pm 0.16(\text{syst.}))\%$ which is useful for the theoretical modeling of the non-leptonic decay modes. We have observed first time (earlier only evidence was found) the $B^\pm \to X(3872)K^\pm$ decay where $X(3872) \to J/\psi\gamma$ (with a $4.9\sigma$ significance) and measured its branching fraction, $\mathcal{B}(B^\pm \to X(3872)K^\pm) \times \mathcal{B}(X(3872) \to J/\psi\gamma)$, as $(1.78^{+0.48}_{-0.44}(\text{stat.}) \pm 0.12(\text{syst.})) \times 10^{-6}$. While for the $X(3872) \to J/\psi\gamma$ decay in the neutral $B^0 \to X(3872)K^0$ decay channel, U.L. (@90% C.L.) for the branching fraction $\mathcal{B}(B^0 \to X(3872)K^0) \times \mathcal{B}(X(3872) \to J/\psi\gamma)$ is derived as $< 2.43 \times 10^{-6}$.

From our observation of $X(3872) \to J/\psi\gamma$ decay, we can now say that this decay mode is now a well established decay mode and we confirm the positive $C$-parity of the $X(3872)$.

In our search for $X(3872) \to \psi(2S)\gamma$ decay in the $B \to X(3872)K$ decay mode, no signal is seen in the charged as well as the neutral decay modes. We obtain the Upper Limit (@ 90% C.L.) for $\mathcal{B}(B^\pm \to X(3872)K^\pm) \times \mathcal{B}(X(3872) \to \psi(2S)\gamma)$ and $\mathcal{B}(B^0 \to X(3872)K^0) \times \mathcal{B}(X(3872) \to \psi(2S)\gamma)$ decay modes as $< 3.45 \times 10^{-6}$ and $< 6.62 \times 10^{-6}$, respectively. The results for the present analysis of $X(3872) \to \psi(2S)\gamma$ decay disagrees with the measurements performed earlier by the BaBar experiment (details can be found in the last Chapter). The results of $X(3872) \to \psi(2S)\gamma$ and $X(3872) \to J/\psi\gamma$ decays are compared for their charged decay modes i.e. $B^\pm \to X(3872)K^\pm$ and the Upper Limit (@ 90% C.L.) on the ratio of $\frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)}$ is obtained as $< 2.1$. 
No © on knowledge...
Just spread the knowledge...😊
Behold, we know not anything.
I can but trust that good shall fall
At last - far off - at last, to all.
And every winter change to spring.
So runs my dream: but what am I?
An infant crying in the night:
An infant crying for light:
And with no language but a cry.

- Tennyson, In Memoriam
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If I say this thesis is solely my work, this will be totally wrong. This thesis is the most beautiful gift wrapped in the “Golden Foil”, gifted to me by few persons who made this thesis alive. I want to decorate few pages of my thesis by inscribing their names (who have inscribed their charming and helping nature in my heart for ever). Although simple thanks will not be sufficient but finding suitable words is impossible, as they are out of the reach of any dictionary written till now.

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From the unknown era of the human evolution, questions have puzzled the human race and kept them busy. Thirst for knowledge keep on increasing, with the addition of more knowledge. Questions, like what we are and why we are, have puzzled everyone from the day one of their existence. Many known and unknown people spent their whole life, just to get these answers. Thanks to these intellectuals we are at a stage of unfolding few mysteries and have started getting lots of another questions. Study of Nature and it’s rule, and trying to produce the same results under similar circumstances has evolved into the branch of Science. As per the oxford dictionary, Physics is defined as “branch of science concerned with the nature and properties of matter and energy. The subject matter of physics includes mechanics, heat, light and other radiation, sound, electricity, magnetism, and the structure of atoms’. High Energy Physics (HEP) is the search of elementary particles and the basic laws of Nature. In HEP, current knowledge of the matter (universe) is subjected to rigorous tests whose sensitivity is limited by the available technology/knowledge (also funding). Parallel to this hunt is carried out for any unexplained phenomenon (which are not explained by the current knowledge/literature). During my Ph.D., I got a chance to work in the beautiful field of HEP. In this thesis I will try to summarize work performed during my Ph.D. In this chapter, I will try to pen down the relevant literature (including motivation) sufficient to justify (or explain) work carried out by me.
1.1 The Standard Model

At our present level of understanding of the elementary particles and their interactions, Leptons and Quarks are the basic building blocks of matter i.e. they are seen as “elementary particles”. Interaction between them are mediated by bosons. All known particle physics phenomena are extremely well described within the Standard Model (SM) of elementary particles and their fundamental interactions.

The SM consists of elementary particles grouped into two classes: bosons (with spin either 0, 1 or 2) and fermions (with spin 1/2). Fermions make up the matter while bosons transmit forces within the matter. The fermions are classified into leptons and quarks. The known leptons and quarks are grouped into three generations. The known leptons are: electron ($e^−$), muon ($\mu^−$) and tau ($\tau^−$) having electric charge $Q = −1$ and the corresponding neutrinos $\nu_e$, $\nu_\mu$ and $\nu_\tau$ with electric charge $Q = 0$. The quarks are of six different flavors: $u$, $d$, $s$, $c$, $b$ and $t$; and have fractional charge $Q = \frac{2}{3}, -\frac{1}{3}, -\frac{1}{3}, \frac{2}{3}, -\frac{1}{3}$ and $\frac{2}{3}$ respectively. Quarks also carry an additional number, color charge (which is of three types and denoted as $q_i$, $i = 1, 2, 3$). Quarks interact via the strong interaction. A phenomenon called color confinement results in being perpetually bound to one another, forming color-neutral composite particles (hadrons) containing either a quark and an antiquark (mesons) or three quarks (baryons). SM has successfully passed very precise tests which at present are at 0.1% [1].

The building blocks of matter interact through the Gravitational (not included in SM at present), Strong, Electromagnetic (EM), and Weak forces. These forces are mediated by bosons. Gravitational interaction is believed to be mediated by a massless spin-2 particles known as graviton (not confirmed at present). Strong interaction (between color charged particles, quarks) is mediated through gluons (eight in number). Gluons are massless. Due to their effective color charge, they can interact among themselves. The gluons and their interactions are described by the theory of quantum chromodynamics. The strong interaction is generally much more complicated than the electromagnetic interaction, since the color charges of the gluons allow them to interact with each other even in the absence of quarks. This is the
reason due to which isolated quarks and gluons are difficult to be observed directly in experiments, even at the highest energy accelerators. Electromagnetic force (between charged particles) is mediated by photon (which is a massless particle) and is well-described by the theory of quantum electrodynamics. The coupling of the photon is proportional to the electric charge of the quark or lepton. Weak interactions between particles of different flavors (quarks and leptons) is mediated by massive $W^+$, $W^-$ and $Z$ gauge bosons. The weak interaction involving $W^\pm$ act on exclusively left-handed particles and right-handed antiparticles and carry electric charge of +1 and -1 and couple to the EM interactions. While the neutral $Z$ boson interacts with both left-handed particles and antiparticles. These three gauge bosons along with the photons are grouped together and mediate the electroweak interactions [2].

Table 1.1: Three generation of fermions in the SM.

<table>
<thead>
<tr>
<th>Generation</th>
<th>Known as</th>
<th>Charge ($Q$)</th>
<th>Mass [$c^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Quark</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>up ($u$)</td>
<td>$+2/3$</td>
<td>1.5-3.3 MeV/$c^2$</td>
</tr>
<tr>
<td>I</td>
<td>down ($d$)</td>
<td>$-1/3$</td>
<td>3.5-6.0 MeV/$c^2$</td>
</tr>
<tr>
<td>II</td>
<td>charm ($c$)</td>
<td>$+2/3$</td>
<td>$1.27^{+0.07}_{-0.11}$ GeV/$c^2$</td>
</tr>
<tr>
<td>II</td>
<td>strange ($s$)</td>
<td>$-1/3$</td>
<td>$105^{+25}_{-35}$ MeV/$c^2$</td>
</tr>
<tr>
<td>III</td>
<td>top ($t$)</td>
<td>$+2/3$</td>
<td>171.3 ± 1.6 GeV/$c^2$</td>
</tr>
<tr>
<td>III</td>
<td>bottom ($b$)</td>
<td>$-1/3$</td>
<td>$4.20^{+0.17}_{-0.07}$ GeV/$c^2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lepton</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>electron ($e$)</td>
<td>-1</td>
<td>0.511 MeV/$c^2$</td>
</tr>
<tr>
<td>I</td>
<td>$\nu_e$</td>
<td>0</td>
<td>&lt; 0.46 MeV/$c^2$</td>
</tr>
<tr>
<td>II</td>
<td>muon ($\mu$)</td>
<td>-1</td>
<td>105.66 MeV/$c^2$</td>
</tr>
<tr>
<td>II</td>
<td>$\nu_\mu$</td>
<td>0</td>
<td>&lt; 0.19 MeV/$c^2$</td>
</tr>
<tr>
<td>III</td>
<td>tau ($\tau$)</td>
<td>-1</td>
<td>1.77 GeV/$c^2$</td>
</tr>
<tr>
<td>III</td>
<td>$\nu_\tau$</td>
<td>0</td>
<td>&lt; 18.2 MeV/$c^2$</td>
</tr>
</tbody>
</table>
### CHAPTER 1. INTRODUCTION

<table>
<thead>
<tr>
<th>Interaction Type</th>
<th>Charge-Flavor</th>
<th>Strength $(\alpha)$</th>
<th>Range $(R)$</th>
<th>Non-relativistic Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q, \ell$</td>
<td>$\mathcal{SU}(2)_{L}$ part of</td>
<td>$S = 1^-$</td>
<td>$\alpha \simeq 4.3\alpha_e \simeq 0.034Q^2 \sim 10^{-16}$ cm</td>
<td>$(V-V)$ term + $\delta(Q, \alpha_e) \times$ $\sigma_1 \cdot \sigma_2$ (AA)</td>
</tr>
<tr>
<td>Boson</td>
<td>fermion</td>
<td>$M_W^2$</td>
<td>$R \sim M_W^2 \sim 10^{-13}$ cm</td>
<td>$\Lambda_{QCD} \sim 150$ GeV</td>
</tr>
<tr>
<td>interaction</td>
<td>(chiral)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boson</td>
<td>$(W^\pm, Z^0)$</td>
<td>$QF: (V-A)$</td>
<td>$QF: (V-A)$</td>
<td></td>
</tr>
<tr>
<td>interaction</td>
<td>massless</td>
<td>$\alpha_s = 0.20$</td>
<td>$R \sim 10^{-13}$ cm</td>
<td>$V(r) \sim \frac{\alpha_s}{r} + kr$</td>
</tr>
<tr>
<td>(non-chiral)</td>
<td>$QCD: V$ quark</td>
<td>$Q^2 \sim 2$ GeV$^2$</td>
<td>$R \sim 10^{-13}$ cm</td>
<td>$V = -\frac{4}{3} \frac{\alpha_s}{r} + kr$</td>
</tr>
<tr>
<td>Boson</td>
<td>massless</td>
<td>$Km_N^2 \sim 10^{-39}$</td>
<td>$q - \bar{q}$ system</td>
<td>$\sigma \cdot p/m_f$ (VA)</td>
</tr>
<tr>
<td>interaction</td>
<td>gluons</td>
<td>$(K$ is)</td>
<td>$(\text{GeV})^2$ for</td>
<td>$q - \bar{q}$ system</td>
</tr>
<tr>
<td>(non-chiral)</td>
<td></td>
<td>gravitational</td>
<td>$q - \bar{q}$ system</td>
<td>$m_f$ is</td>
</tr>
</tbody>
</table>

Table 1.2: Types of forces in Nature [4].
1.2 Mesons

Mesons are the subatomic particles composed of one quark and one antiquark. They are part of the hadrons (particle made of quarks). The other members of the hadron family are the baryons - subatomic particles composed of three quarks. The main difference between mesons and baryons is that mesons are bosons while baryons are fermions. Mesons are explained here as they are relevant to this thesis work.

Mesons are composed of quarks due to which they can participate in both weak and the strong interactions. Mesons with electric charge can also participate in the EM interaction. They are classified according to their quark content, total angular momentum, parity, and various other properties such as $C$-parity. Mesons are less massive than the most of the baryons, meaning that they are more easily produced in experiments, and will exhibits higher energy phenomena sooner than baryons would. For example, the charm quark was first seen in the $J/\psi$ meson in 1974 [5], and the bottom quark in the $\Upsilon$ meson in 1977 [6].

1.2.1 Spin, Orbital Angular Momentum and Total Angular Momentum

Spin ($S$) represents the “intrinsic” angular momentum of a particle. It comes in increments of $\hbar/2$. Two quarks can have their spins aligned, the spin vectors add to make a vector of length $S = 1$ and three spin projections ($S_z = +1$, $S_z = 0$ and $S_z = -1$) called the spin-1 triplet. If two quarks have unaligned spins, the spin vectors add up to make up a vector of length $S = 0$ and has only one spin projection ($S_z = 0$), called spin-0 singlet. Since mesons are made of one quark and one antiquark, they can be found in triplet and singlet spin states.

There is another quantity of quantized angular momentum, called the orbital angular momentum ($L$), comes in increments of $\hbar$ and it represents the angular momentum due to the quarks orbiting each other. The total angular momentum ($J$) of a particle is a combination of $S$ and $L$ and can take any value from $|L - S|$ to $|L + S|$. 

\[ J = \sqrt{L(L+1)} \]

where $L$ is the orbital angular momentum and $S$ is the spin of the particle. The total angular momentum $J$ can be used to calculate the magnetic dipole moment $\mu_J$ of a particle, which is given by

\[ \mu_J = \frac{e \hbar}{2m} \]

where $e$ is the charge of the electron, $\hbar$ is the reduced Planck constant, and $m$ is the mass of the particle.

\[ \mu_J = \frac{e \hbar}{2m} \]

The magnetic dipole moment $\mu_J$ is a measure of the magnetic moment of a particle and it is related to the spin and orbital angular momentum of the particle. The magnetic dipole moment of a particle is given by

\[ \mu_J = e \hbar \frac{S_z}{L_z} \]

where $S_z$ is the projection of the spin on the z-axis and $L_z$ is the projection of the orbital angular momentum on the z-axis.

\[ \mu_J = e \hbar \frac{S_z}{L_z} \]

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\[ \mu_J = e \hbar \frac{S_z}{L_z} \]
in increments of 1.

1.2.2 Parity

If the Universe is reflected in a mirror, most of the laws of physics will be identical (i.e. things would behave the same way regardless of left/right). The concept of mirror reflection is called parity ($P$). In other words if the quantum field for each particle type is mirror-reversed, then the new set of wavefunction will satisfy the laws of physics. All forces except weak interactions obeys $P$ conservation.

For mesons, the $P$ is related to the orbital $L$ by relation $P = (-1)^{L+1}$. The “+1” in the exponent comes from the fact that, according to the Dirac equation, a quark and an antiquark have opposite intrinsic parities.

1.2.3 $C$-parity

$C$-parity is only defined for mesons these are their own antiparticles (i.e. neutral mesons). It represents whether or not the wavefunction of the meson remains the same under the interchange of their quark with their antiquark. If $|q\bar{q}> = |\bar{q}q>$ then, the meson is “$C$ even” ($C = +1$). On the other hand, if $|q\bar{q}> = - |\bar{q}q>$ then the meson is “$C$ odd” ($C = -1$). $C$-parity is rarely studied on its own, but the combination of $C$- and $P$-parity into $CP$-parity. $CP$-parity was thought to be conserved, but is found to be violated in weak interactions [7].

1.3 Weak Interactions

Weak interactions, the culprit responsible for radioactive decays. It affects all the left-handed leptons and quarks. Neutrinos feel only the weak interactions, which make them so difficult to study. The first attempt to construct a theory of the weak interaction was made by Fermi in 1932 [8]. In analogy to the EM interactions, Fermi proposed the following matrix elements

$$M = \frac{G_F}{\sqrt{2}}[\bar{u}_F\gamma^\mu u_N][\bar{u}_e\gamma^\nu u_\nu]$$ \hspace{1cm} (1.1)
1.3. WEAK INTERACTIONS

This term was not complete and a propagation term for the massive boson \( \frac{1}{M_{W,Z}^{\mu}} - q^2 \) was added to it.

In SM, the electroweak charged current interactions is given by the Lagrangian

\[
\mathcal{L}_{cc} = -\frac{G_F}{\sqrt{2}} \left\{ W^+_{\mu} (\bar{u} \bar{c} \bar{b}) \gamma^\mu (1 - \gamma_5) V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} + W^-_{\mu} (\bar{d} \bar{s} \bar{b}) \gamma^\mu (1 - \gamma_5) V'^{\dagger}_{CKM} \begin{pmatrix} u \\ c \\ t \end{pmatrix} \right\}
\]

Here \( W_{\mu} \) are the creation operators for the \( W \) bosons, \( G_F \) is overall coupling strength and \( (1 - \gamma_5) \) denotes the usual Dirac left-handed projections operator for the quark fields. \( V_{CKM} \) Cabibbo-Kobayashi-Maskawa (\( CKM \)) unitary matrix \[9]\]

\[
V_{CKM} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\]  

(1.3)

Off-diagonal elements of \( V_{CKM} \) are non-zero due to which the charged current induces transitions between different quark generations.

![Figure 1.1: Possible transitions between quarks.](image-url)
1.4 $B$ Decays (Non-Leptonic)

$B$ mesons are the bound state of a $b$ quark and a light anti-quark. $B$ mesons decaying via weak interaction plays important role in testing Kobayashi-Maskawa (KM) mechanism (which allows $CP$ violation in the SM) \cite{9} and also in exploration of physics beyond the SM (popularly known as New Physics (NP)). $B$ mesons help in studying strong-interaction physics related with the confinement of quarks and gluons into hadrons \cite{10}.

Charmless two-body nonleptonic $B$ decays are described by a tree-level spectator diagram or a one-loop penguin diagram. Such decays are usually divided into three types:

a) decays having only tree contribution,

b) decays having only penguin contribution,

c) decays having both tree and penguin (QCD and EW).

These decays can also have contribution from $W$-exchange, annihilation and vertical loop processes but their contributions are expected to be small \cite{11}.

![Feynman diagram](image)

Figure 1.2: Feynman diagram of $B$ decays, a) External spectator diagram and b) Internal spectator diagram.

In hadronic decays, the quark pair (produced via $W^-$ decays) makes one of the final state hadron while the $c$ quark pairs with the spectator anti-quark to form another hadron, shown in Figure 1.2 (External Spectator). The light quarks and the gluons surrounding the $b$ quark in the $B$ meson lead to significant correction that have to be taken into account. Spectator diagram is modified by hard gluon exchange.
between the initial and final quark and leads to the “color suppressed”, shown in Figure 1.2 (Internal Spectator), which has a different set of quark pairing. Two body hadronic decays of $B$ meson can be expressed as the product of two independent hadronic currents, one describing the formation of a charm meson and the other hadronization of the $\bar{u}d$ (or $\bar{c}s$) system from the virtual $W^{-}$ [12]. For a $B$ decay with a large energy release the $\bar{u}d$ pair, which is produced as a color singlet, travels fast enough to leave the interaction region without influencing the second hadron formed from the quark and the spectator antiquark. The assumption that the amplitude can be expressed as the product of two hadronic currents is called factorization.

The simple spectator diagram for two-body hadronic $B$ meson decays that occur through the CKM favored $b \rightarrow c$ transition is described by the Hamiltonian

$$H = \frac{G_F}{\sqrt{2}} V_{cb} \{ [\bar{d} \gamma_\mu (1 - \gamma_5) u + \bar{s} \gamma_\mu (1 - \gamma_5) c] \times \bar{c} \gamma_\mu (1 - \gamma_5) b \} \quad (1.4)$$

The spectator diagram is modified by hard gluon exchange between initial and final states. After including this into account the Equation (1.4) is modified as

$$H_{eff} = \frac{G_F}{\sqrt{2}} V_{cb} \{ (c_1(\mu_f) [\bar{d} \gamma_\mu (1 - \gamma_5) u + \bar{s} \gamma_\mu (1 - \gamma_5) c] \times \bar{c} \gamma_\mu (1 - \gamma_5) b)$$

$$+ c_2(\mu_f) [\bar{c} \gamma_\mu (1 - \gamma_5) u) (\bar{d} \gamma_\mu (1 - \gamma_5) b) + (\bar{c} \gamma_\mu (1 - \gamma_5) c) (\bar{s} \gamma_\mu (1 - \gamma_5) b)] \} \quad (1.5)$$

$c_1$ and $c_2$ are Wilson coefficient calculated from QCD. The calculation is inherently uncertain because it is unclear at what mass scale ($\mu_f$) these coefficients should be evaluated; $\mu_f = O(m_b)$ is considered to be the scale at which factorization is assumed to be relevant. The Wilson coefficients $c_i(\mu_f)$ takes into account the short-distance correction arising from the exchange of gluons with virtualities between $m_W$ and some hadronic scale $\mu_f$, chosen large enough for perturbation theory to be applicable. Without strong-interaction effects $c_1$ ($c_2$) is equal to 1 (0). Defining

$$c_\pm(\mu_f) = c_1(\mu_f) \pm c_2(\mu_f) \quad (1.6)$$

the leading-log approximation gives

$$c_\pm(\mu_f) = \left( \frac{\alpha_s(M_W^2)}{\alpha_s(\mu_f)} \right)^{-\delta_{\gamma_\mu}^{\pm}} \frac{1}{(13 - 2\beta_f)} \quad (1.7)$$
where $\gamma_- = -2\gamma_+ = 2$, and $n_f$ is the number of active flavors, which is taken to be five in this case. The additional term in the Hamiltonian in Equation (1.5) corresponds to the “color suppressed” diagram. The quark pairings in the diagram are different from those in the spectator diagram. In this $B$ decay, the $c$ quark from $b$ combines with a $\bar{c}$ quark from the virtual $W^-$ to form a charmonium diagram [12].

### 1.5 Factorization

In weak interactions, a meson can be directly generated by a quark current carrying the appropriate parity and flavor quantum numbers. The corresponding contribution to a decay amplitude factorizes into the product of two current matrix elements. In factorization amplitude is written according to the charge of the final states. On basis of which we can classify $B$ decays on three classes. Class I consists of decays where charged meson can be generated directly from a color-singlet current, for example $B^0 \to D^-\pi^+$ decay mode.

$$A_{B^0\to D^-\pi^+} = -\frac{G_F}{\sqrt{2}} V_{cb} V_{us}^* a_1 <\pi^-|(\bar{d}u)_{A}|0> <D^+|(\bar{c}b)_V|B^0>$$

For these processes, the relevant QCD coefficient is given by the combination

$$a_1 = c_1(\mu_f) + \zeta c_2(\mu_f) \quad \text{(class I)}$$

where $\zeta = 1/N_c$ ($N_c$ being the number of quark colors).

A second class of transitions consists of those decays where the mesons generated (directly from the current) are neutral, for example $B^0 \to J/\psi K^0$ decay mode. The corresponding decay amplitude,

$$A_{B^0\to J/\psi K^0} = -\frac{G_F}{\sqrt{2}} V_{cb} V_{us}^* a_2 <J/\psi|(\bar{c}c)_V|0> <K^0|(|\bar{s}b)_V|B^0>$$

is proportional to the QCD coefficient

$$a_2 = c_2(\mu_f) + \zeta c_1(\mu_f) \quad \text{(class II)}$$

For class I and class II two-body decay channel, the effective Hamiltonian can be rewritten in such a way that the quarks are paired according to the flavor quantum
1.5. FACTORIZATION

numbers of the final-state hadrons. The Hamiltonian for class I is written as

\[ H_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb} V_{ud}^\ast \left\{ \left( c_1(\mu_f) + \frac{c_2(\mu_f)}{N_c} \right) (d\bar{u})_{V-A}(\bar{c}b)_{V-A} + \frac{c_2(\mu_f)}{2} (d\bar{u}_a u)_{V-A}(\bar{c}t_a b)_{V-A} \right\} + ... \]  

1.12

The third class of transitions covers decays in which the \( a_1 \) and \( a_2 \) amplitudes interfere, such as in the \( B^- \rightarrow \psi(2S)\pi^- \) decay mode. Their final state contains a charged, as well as a neutral meson, both of them are generated from a current of one of the operators of the effective Hamiltonian. The corresponding amplitudes involves combination

\[ a_1 + x a_2 \quad \text{(class III)} \]  

1.13

where \( x = 1 \) in the formal limit of a flavor symmetry for the final-state mesons. Class III amplitudes are related to combinations of class I and class II amplitudes by isospin relations [12]. Before going further, it is reminded that there have been some phenomenological evidences that the \( \psi(2S) \) may not be a pure \( S \)-wave vector charmonium. Rather it may have some admixture of \( ^3D_1 \) component [13] so it should be written \( \psi' \) as:

\[ |\psi'\rangle = \cos \phi |2^3S_1\rangle - \sin \phi |1^3D_1\rangle \]

usually with \( \phi \) to be around \( 12^\circ \). As per this, it seems that \( \psi' \) should be used. In this thesis, \( \psi(2S) \) is used as commonly used in PDG to avoid any nomenclature confusion.

Naively speaking, on the basis of factorization we can break the amplitude into multiplication of two currents and can write matrix element for the \( B^- \rightarrow \psi(2S)\pi^- \) decay mode as

\[ < \pi \psi(2S)|(\bar{d}c)_{V-A}(\bar{c}b)_{V-A}|B > \approx < \pi |(db)_{V-A}|B > < \psi(2S)|(\bar{c}c)_{V-A}|0 > \]  

1.14

In this thesis, the following decays are discussed:

- \( B^\pm \rightarrow \psi(2S)\pi^\pm \) and \( B^\pm \rightarrow \psi(2S)K^\pm \) decays

The \( B^\pm \rightarrow \psi(2S)K^\pm \) is a color suppressed decay mode, which has been observed and its branching ratio is well known [14]. In this decay mode \( b \) quark decays
into $\bar{c}s$ via $W^-$ (Figure 1.3). This mode is a Cabibbo-favored decay mode. It is expected that there should be a Cabibbo-suppressed decay mode ($B^\pm \rightarrow \psi(2S)\pi^\pm$) corresponding to the $B^\pm \rightarrow \psi(2S)K^\pm$ decay mode. Measurement of Cabibbo-suppressed decay modes were not possible before the $B$-factories era, but thanks to the large data set (accumulated at the $B$-factories) we have access to Cabibbo- and Color-suppressed decay modes and can think of studying them in details [15,16]. In $B^\pm \rightarrow \psi(2S)\pi^\pm$, $b$ quark decays into $\bar{c}d$ and is expected to have branching fraction to the order of 0.05 to the Cabibbo-allowed decay, $B^\pm \rightarrow \psi(2S)K^\pm$ (on the basis of factorization) [12]. Our main motive behind this study is to search for this decay mode (as it has not been seen/measured yet) and to validate the factorization prediction. Both of these decay modes can also occur via penguin diagram (Figure 1.4) and it is expected that tree and penguin contribution may have different phases which can give rise to direct
1.5. FACTORIZATION

$CP$ violation of few percent. More details can be found in Section 1.6.

- $B^{0,\pm} \rightarrow \chi_{c1}K^{0,\pm}$ and $B^{0,\pm} \rightarrow \chi_{c2}K^{0,\pm}$

On the basis of factorization, $\chi_{c1}$ (vector $1^+$) couples to $V-A$ operator which results in a non-zero matrix element. $\chi_{c2}$ is a tensor $(2^+)$, so $\chi_{c2}$ does not couple to vector or axial-vector operator due to which $\langle \chi_{c2}|(\bar{c}c)_{V-A}|0 \rangle = 0$. Also, $\langle \chi_{c0}|(\bar{c}c)_{V-A}|0 \rangle = 0$ due to charge conjugation invariance ($\langle 0^{++}|(\bar{c}c)_{V-A}|0^{++} \rangle = 0$). From this it can be said that decay of $B \rightarrow \chi_{c1}K$ is allowed while $B \rightarrow \chi_{c0,2}K$ is not allowed. However, $B$ decay to $\chi_{c0,2}$ has been seen experimentally which contradicts the above derived statement [17]. Taking into account the next-to-leading order (NLO) corrections [18], re-scattering effects [19], $B \rightarrow \chi_{c0,2}K$ decays are allowed. $B \rightarrow \chi_{c2}K$ decay mode has not been seen yet, so the search for $B \rightarrow \chi_{c2}K$ will be a crucial verification of the mentioned theories [18–20].

- $B^{0,\pm} \rightarrow X(3872)K^{0,\pm}$

The $X(3872)$ particle has been discovered at Belle [21]. We have also search for its decays to charmonium and radiative decays in $B \rightarrow X(3872)K$ decay mode. More details are given in Section 1.11.

1.5.1 Decay Constants

The evaluations of factorized amplitudes requires the knowledge of meson decay constants and hadronic form factors of current matrix elements. For a pseudo-scalar meson $P = (q_1 \bar{q}_2)$, we define

$$<0|\bar{q}_2\gamma_\mu\gamma_5q_1|P(p)> = i f_P p_\mu$$  \hspace{1cm} (1.15)

The decay constant $f_V$ of a vector meson $P = (q_1 \bar{q}_2)$ is defined by

$$<0|\bar{q}_2\gamma_\mu q_1|V(\varepsilon)> = \varepsilon_\mu m_V f_V$$  \hspace{1cm} (1.16)

The experimental values of the decay constants of the charged pion and kaon, as obtained from their leptonic decays $P^+ \rightarrow \ell^+\nu_\ell(\gamma)$, are

$$f_\pi = (130.7 \pm 0.37)\text{MeV}$$
\[ f_K = (159.8 \pm 1.47) \text{MeV} \]  

1.6 \textit{CP} Violation

The very existence of the universe tells us about the existence of \textit{CP} violation. \textit{CP} violation in the SM is established, and is described by the phenomena in the quark sector described by the Kobayashi-Maskawa theory [22]. Kobayashi and Maskawa found that if there are three (or more than three) generation of the quarks (at that time only two were known) than a irreducible phase come into picture through which the \textit{CP} violation can be included in the SM. Quark eigenstates for the strong and weak interactions are not the same, but are related by a mixing matrix, \( V_{\text{CKM}} \).

\[
\begin{pmatrix}
    d' \\
    s' \\
    b'
\end{pmatrix} = V_{\text{CKM}} \begin{pmatrix}
    d \\
    s \\
    b
\end{pmatrix}
\]  

From the Equation (1.18) within SM, it was concluded that an irreducible complex phase (which give rise to \textit{CP} violation) is present in Kobayashi-Maskawa matrix if there are three or more generations of the quarks. Applying the \textit{CP} operators to \( \mathcal{L}_{cc} \) (Equation 1.2)

\[
(CP)\mathcal{L}_{cc}(CP)^{-1} = -\frac{G_F}{\sqrt{2}} \begin{pmatrix}
    W^-_\mu (\bar{d} \bar{s} \bar{b})\gamma^\mu (1 - \gamma_5) V_{\text{CKM}} \\
    u \\
    c \\
    t
\end{pmatrix} +
\]

\[
W^+_\mu (\bar{u} \bar{c} \bar{t})\gamma^\mu (1 - \gamma_5) V_{\text{CKM}}^* \begin{pmatrix}
    d \\
    s \\
    b
\end{pmatrix}
\]

\textit{CP} operator exchanges the two terms in Equation 1.2 while \( V_{\text{CKM}} \) and \( V_{\text{CKM}}^* \) remain unchanged. \( V_{\text{CKM}} \neq V_{\text{CKM}}^* \) for \textit{CP} violation to be present which can only happen if \( V_{\text{CKM}} \) has an irreducible complex phase (value not equal to 0 or \( \pi \)).
1.6. CP VIOLATION

1.6.1 Direct CP Violation in $\bar{B}^- \rightarrow \psi(2S)\pi^-$

$CP$ violation can be observed and measured in $B$ decays [23] through three different ways:

- Direct $CP$ violation - This kind of $CP$ violation can occur in both charged as well as neutral $B$ mesons decays. It occurs when the amplitudes for a decay and its $CP$ conjugate process have different magnitudes. This results from interference between the various terms in the amplitude.

- Indirect $CP$ violation - It occurs only in neutral $B$ mesons. It results from the mass eigenstates being different from the $CP$ eigenstates. In this one measures the difference between decays of time-evolving neutral $B$ mesons identified at time zero as pure $\bar{B}^0$'s or $B^0$'s, the only source of $CP$ violation is $B^0 - \bar{B}^0$ mixing. This type of $CP$ violation, called $CP$ violation in mixing or indirect $CP$ violation.

- $CP$ violation from interference between decays with ($B^0 \rightarrow \bar{B}^0 \rightarrow f$) and without ($B^0 \rightarrow f$) mixing. This can occur in decays where the final states are common to both $B^0$ and $\bar{B}^0$. It can occur both with and without the other two types of $CP$ violation. This form of $CP$ violation, called time-dependent $CP$ asymmetry, can for example be observed in decays to final states which are $CP$ eigenstates ($f_{CP}$).

In $B^- \rightarrow \psi(2S)\pi^-$ decay, amplitude phase consists of two types, first one is the complex phases which enter with the opposite signs in $A$ and $\bar{A}$ (these phases enter through CKM matrix in SM and are known as weak phases) while the second contribution is due to the strong interaction from the re-scattering process (popularly called final-state interaction effects) which enters with the same sign (and are known as strong phases).

We can divide an amplitude into three parts, magnitude ($A$), weak phase ($e^{i\phi}$) and strong phase ($e^{i\delta}$). If there are more then one process than amplitude can be
written as
\[ A = \Sigma_k A_k e^{i(\delta_k + \phi_k)} \]  \hspace{1cm} (1.20)

Using this we can write the ratio of \( B^+ \) and \( B^- \) as
\[ \frac{\bar{A}}{A} = \frac{\Sigma_k A_k e^{i(\delta_k - \phi_k)}}{\Sigma_k A_k e^{i(\delta_k + \phi_k)}} \]  \hspace{1cm} (1.21)

If we have only one process behind the decay then we can not find any information about the weak phase as
\[ \frac{|\bar{A}|}{|A|} = \left| \frac{e^{-i\phi}}{e^{i\phi}} \right| = 1 \]  \hspace{1cm} (1.22)
and no \( CP \) violation is present. But if there are more than one process and they have different weak and strong phases then we can expect \( CP \) violation to be present as
\[ |A|^2 - |\bar{A}|^2 = -2\Sigma_{k,l} A_k A_l \sin(\delta_k - \delta_l) \sin(\phi_k - \phi_l) \]  \hspace{1cm} (1.23)
which leads to \( \frac{|\bar{A}|}{|A|} \neq 1 \). \( CP \) violation can be measured in the charged \( B \) decays \((B^- \rightarrow \psi(2S)\pi^-)\) by measuring the difference between the charge conjugate decay modes.
\[ A_{CP} = \frac{\Gamma(B^- \rightarrow \psi(2S)\pi^-) - \Gamma(B^+ \rightarrow \psi(2S)\pi^+)}{\Gamma(B^- \rightarrow \psi(2S)\pi^-) + \Gamma(B^+ \rightarrow \psi(2S)\pi^+)} \]  \hspace{1cm} (1.24)
Amplitude can be written for \( B \rightarrow \psi(2S)\pi \) using the Feynman diagram (Figure 1.3 and Figure 1.4).
\[ A = <\psi(2S)\pi^-|H_T|B^-> + <\psi(2S)\pi^-|H_P|B^-> \]  \hspace{1cm} (1.25)
\[ \bar{A} = <\psi(2S)\pi^+|H_T|B^+> + <\psi(2S)\pi^+|H_P|B^+> \]  \hspace{1cm} (1.26)
where \( H_T \) and \( H_P \) are Hamiltonian for the tree and penguin operators, respectively. These equations can be written in the form of phases.
\[ A = <\psi(2S)\pi^-|H_T|B^-> (1 + r \exp^{i\Delta} \exp^{i\Delta_\phi}) \]  \hspace{1cm} (1.27)
\[ \bar{A} = <\psi(2S)\pi^+|H_T|B^+> (1 + r \exp^{i\Delta} \exp^{-i\Delta_\phi}) \]  \hspace{1cm} (1.28)
Here, \( \Delta \delta \) and \( \Delta \phi \) are the strong and weak phase difference between the tree and penguin decay amplitude, respectively and \( r \) is the absolute value of the ratio of tree and penguin amplitudes
\[ r = \left| \frac{<\psi(2S)\pi^-|H_P|B^->}{<\psi(2S)\pi^-|H_T|B^->} \right| \]  \hspace{1cm} (1.29)
Using these amplitudes, we can write asymmetry $A_{CP}$ as

$$A_{CP} = \frac{-2r \sin \Delta \delta \sin \Delta \phi}{1 + 2r \cos \Delta \delta \cos \Delta \phi + r^2}$$

(1.30)

From the Equation (1.30), we can vaguely say that if $\Delta \phi$, $\Delta \delta$ and $r$ are non-zero than we can expect $A_{CP}$ to be non-zero. Therefore, if there is phase difference between penguin and tree contribution of the decay mode under study, we can expect a non zero $A_{CP}$ and if we get large $A_{CP}$ it can give hint of New Physics (i.e. beyond SM).

### 1.7 Charmonium

Bound system of a quark and antiquark is known as quarkonium. The quarkonium model is applicable to the charmonium (bound system of $c\bar{c}$). The charmonium family have a net charm of zero. As charmonium is made from fermion (spin 1/2); the total spin $S = 0$ or 1 and $S_z = 0, \pm 1$. The charge conjugation $C$-parity and parity $P$ is defined as

$$C = (-1)^{L+s}$$

(1.31)

$$P = (-1)^{L+1}$$

(1.32)

For $L = 0, 1, 2, \ldots$, the spectroscopic notation $^{2S+1}L_J$ is used for a state.

In the most simplest assumption (in conjunction with the QED), the bound state is considered to be a non-relativistic system with a spin-independent central potential (known as Cornell potential) [24]. This potential has two terms, one for asymptotic freedom and one for confinement

$$V(r) = -\frac{4\alpha_s}{3r} + kr$$

(1.33)

where first term is due to the single gluon exchange and the second term represents confinement. Here $\alpha_s$ and $k$ are determined from the fit to data. Using the said potential, spectrum is quite well reproduced (predicted $\psi''$ state). The non-relativistic treatment only describe feature of charmonium levels (without resolving the fine splitting between the states with the same $L$ and $S$ and different $J$, and the hyperfine splitting between the spin-triplet and spin-singlet states).
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The potential description extended to spin-dependent interaction results in three types of interaction terms that are to be added to the Equation (1.33) (non-relativistic interaction)

\[
V(r) = V_{LS}(r)(\vec{L} \cdot \vec{S}) + V_T(r) \left[ S(S+1) - \frac{3(\vec{S} \cdot \vec{r})(\vec{S} \cdot \vec{r})}{r^2} \right] + V_{SS}(r) \left[ S(S+1) - \frac{3}{2} \right]
\]

The spin-orbit \( V_{LS} \) and the tensor \( V_T \) terms describe the fine structure of the states, while the spin-spin terms \( V_{SS} \) which is proportional to \( 2(\vec{S}_q \cdot \vec{S}_q) = S(S+1) - \frac{3}{2} \) gives the spin-singlet splitting.

The minimal non-relativistic potential model uses the standard color Coulomb plus linear scalar form and also include a Gaussian-smeared contact hyperfine interaction in the zeroth-order potential \[25\]. The central potential is

\[
V(r) = -\frac{4\alpha_s}{3r} + kr + \frac{32\pi\alpha_s}{9m_e^2} \tilde{\delta}_s(r) \frac{L}{r} \cdot \vec{S} + \frac{4\alpha_s}{r^3} \frac{L}{r} \cdot \vec{S}
\]

where \( \tilde{\delta}_s(r) = (\sigma/\sqrt{\pi})^3 e^{-\sigma^2 r^2} \), The four parameters \( (\alpha_s, k, m_e, \sigma) \) are determined by fitting the spectrum \[25\].

The spin-spin contact hyperfine interaction is one of the spin-dependent terms predicted by one gluon exchange forces. Other spin-dependent terms are treated as mass shifts using the leading-order perturbation theory. These are the one gluon exchange spin-orbit and tensor interactions and a longer range inverted spin-orbit term, which arises from the assumed Lorentz scalar confinement. These are explicitly

\[
V_{\text{spin-dep}} = \frac{1}{m_e^2} \left[ \left( \frac{2\alpha_s}{r^3} - \frac{k}{2r} \right) \vec{L} \cdot \vec{S} + \frac{4\alpha_s}{r^3} \vec{T} \right]
\]

The spin-orbit operator is diagonal in a \( |J, L, S > \) basis, with the matrix elements

\[
\langle J, L, S | \vec{L} \cdot \vec{S} | J', L, S > = [J(J+1) - (L(L+1) - S(S+1))/2].\]

The tensor operator \( T \) has non-zero diagonal matrix elements between \( L > 0 \) spin-triplet states, which are:

\[
<^3L_J | T | ^3L_J > = \begin{cases} 
\frac{-L}{6(|2L+3|)}, & J=L+1 \\
0, & J=L \\
\frac{(L+1)}{6(|2L-1|)}, & J=L-1 
\end{cases}
\]
1.7. CHARMONIUM

Figure 1.5: Experimental (red color line) and theory (green color box) agreement of the charmonium spectrum. Blue color indicated new states (not well established).

The Godfrey-Isgur model is a “relativized” extension of the non-relativistic model, and it assumes a relativistic dispersion relation for the quark kinetic energy, a QCD-motivated running coupling $\alpha_s(r)$, a flavor-dependent potential smearing parameter $\sigma$, and replaces factors of quark mass with quark kinetic energy [26]. The Hamiltonian consists of a relativistic kinetic term and a generalized quark-antiquark potential

$$H = H_0 + V_{q\bar{q}}(\vec{p}, \vec{r})$$  \hspace{1cm} (1.38)$$

here $V_{q\bar{q}}(\vec{p}, \vec{r})$ incorporates the Lorentz scalar linear confining interaction. This model gives reasonably accurate results of the spectrum and matrix elements of quarkonia for all $u, d, s, c, b$ quark flavors, whereas the non-relativistic model works well for the $c\bar{c}$ system.
1.8 Charmonium Production

Charmonium can be produced in many ways, in this thesis only the processes (important ones) through which charmonium are produced at the $B$-factories are explained. These processes can be classified into four processes:

- $B$ meson decay
  
  Charge states are produced with a good fraction of $B$ meson (15%) decaying into charmonium and $K$ mesons. The large data sample available at the $B$ factories make this a promising approach for the study of known states and new resonances (popularly known as exotica). The decays of the $B$ meson provide a clean production environment for charmonium. As spatial as well as charge parities are broken in weak decays, charmonium with any quantum number can be produced in the two-body decays of $B$ meson. Decay mode studied

[Diagram of $B$ meson decay and double charmonium production]

Figure 1.6: Artistic illustration of processes leading to the production of charmonium at the “$B$-factories”.
1.8. CHARMONIUM PRODUCTION

in this thesis are produced through this mechanism. Details have already been described in Section 1.4 and Section 1.5.

- Two-photon production
  Electron-positron annihilation at higher energies can produce the $J$-even (0$^+$, 0$^{++}$, 2$^+$ and 2$^{++}$) charmonium states through two virtual photons via the process

  $$e^+e^- \rightarrow e^+e^- + (c\bar{c})$$

  Photon-photon collisions are produced when both an incoming particles $e^-$ and $e^+$ radiate photons that subsequently interact with each other. A charmonium state appearing in the two-photon collision has positive $C$-parity. The total cross section of two-photon production of a resonance $R$ with mass $m$ and spin $J$ is proportional to $(2J+1)\Gamma(R \rightarrow \gamma\gamma) \log^3(E_{CM})/m^3$, where $E_{CM}$ is the energy of $e^+e^-$ beam in the center-of-mass (CM) system [27].

- Initial-state radiation
  In this process either the electron or the positron radiates a photon before the annihilation, thereby lowering the effective CM energy. Only $J^{PC} = 1^{--}$ states can be produced in ISR. This process allows a large mass range to be explored and is very useful for the measurement of $R$,

  $$R = \frac{\sigma(e^-e^+ \rightarrow \text{hadrons})}{\sigma(e^-e^+ \rightarrow \mu^+\mu^-)} \quad (1.39)$$

- Double Charmonium
  The production of double charmonium states in $e^+e^-$ annihilation was discovered by the Belle collaboration from a sample of data collected near the $\Upsilon(4S)$ resonance at a CM energy $\sqrt{s} = 10.6$ GeV, by studying the recoil momentum spectrum of the $J/\psi\eta_c$ [28]. The collaboration also found evidence for $J/\psi\chi_{c0}$ and $J/\psi\eta_c^*$ production. In recent Belle work [29], the $e^+e^- \rightarrow J/\psi c\bar{c}$ cross section measured in a model independent way comes out to be $(0.74 \pm 0.08 \pm 0.09)$ pb. For the second charmonium with the mass below the open charm threshold, this fraction is $(16 \pm 3)\%$ [29]. Despite the small cross section value, these studies
CHAPTER 1. INTRODUCTION

are possible, thanks to the high luminosity B-factories era. We can reconstruct one of the two charmonium (for example, \( J/\psi \)), to observe the process of pair production. The second state can be seen in the spectrum of masses recoiling against the reconstructed ones, \( M_{\text{rec}}(J/\psi) = [(E_{\text{CM}} - E^*_{J/\psi})^2 - p^*_{J/\psi}^2]^{1/2} \), where \( E^*_{J/\psi} \) and \( p^*_{J/\psi} \) are the energy and momentum of \( J/\psi \). In the process of pair charmonium production in \( e^+e^- \) annihilation, the final charmonium states have opposite charge parities. It was experimentally found that either scalar mesons with the quantum numbers \( J^{PC} = 0^{++} \) (\( \chi_{c0} \)) or pseudo-scalar mesons with \( J^{PC} = 0^{-+} \) (\( \eta_c(2S) \)) are produced together with \( J/\psi \). The \( J^{PC} = 1^{++} \) \( \chi_{c1} \) and \( J^{PC} = 2^{++} \) \( \chi_{c2} \) are not seen. This could indicate that this process favors the production of \( J = 0 \) states over those with \( J = 1 \) and higher [30].

1.9 Charmonium Decays

There are in principle four different ways in which charmonium can change its state or decay, which are:

(a) A change of excitation level via photon emission (EM) e.g. \( \chi_{c1}(1^3P_1) \rightarrow J/\psi(1^3S_1)\gamma \)
(b) Quark-antiquark annihilation into real or virtual photons or gluons (EM or strong) e.g. \( \eta_c(1^1S_0) \rightarrow 2\gamma \),
\( J/\psi(1^3S_1) \rightarrow ggg \rightarrow \text{hadrons} \),
\( J/\psi(1^3S_1) \rightarrow \text{virtual } \gamma \rightarrow \text{hadrons} \),
\( J/\psi(1^3S_1) \rightarrow \text{virtual } \gamma \rightarrow \text{leptons} \)
(c) Creation of one or more light \( q\bar{q} \) pairs from vacuum to form light mesons (strong interactions).
(d) Weak decays of one or both heavy quarks, e.g. \( J/\psi \rightarrow D^- \bar{s} e^+ \nu_e \).

Weak decays are not so frequent, as strong and EM decays proceed more quickly. The strong decay is more likely (in principle) but this can only take place above a certain threshold (production of a pair of \( D \) mesons \( \sim 3.72 \text{ GeV} \) since the light \( q\bar{q} \) needs to be created from the quarkonia binding energy. (a) and (b) are the only option available to quarkonia above this threshold.
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The EM processes like de-excitation via photon emission are relatively slow. Although hadronization via the annihilation into gluons is a strong process but such decays are suppressed (according to the Zweig rule) relative to those decays where initial quarks still exists in the final state.

1.9.1 Radiative Transition

Since there is one photon emission between the two charmonium, and the $J^{PC}$ of photon is $1^{--}$, the radiative transition only occurs between the two $C$-parity different states. The transitions could be either electric multipole or magnetic multipole transitions depends on the spin and parities of the initial and final states. Assuming the spins of the initial (final) state is $S_i\ (S_f)$, the total angular momentum carried by the photon ($J_i$) can be any integer between $|S_i - S_f|$ and $|S_i + S_f|$. If the product of parities of the initial state ($\pi_i$) and final state ($\pi_f$) equals $(-1)^{J_f}$, the transition is $EJ$ transition; otherwise if $\pi_i \cdot \pi_f = (-1)^{J_f+1}$, it is an $MJ$ transition. It is obvious that the electric multipole transitions keep the quark spins, while the magnetic multipole transitions are accompanied by quark-flip. In this thesis, charmonium states ($/exotic$ $\chi_{c1}, \chi_{c2}$ and $X(3872)$ are expected to decay by radiative transition via $E1$ transition, whose partial width can be calculated [31] using:

$$\Gamma_{E1}(n^{2S+1}L,J \rightarrow n^{2S+1}L',J') = \frac{4}{3}C_{fi}\delta_{SS'}\epsilon_{\gamma}^2 |<\psi_f| \pi_f >|^2 \times E_{\gamma}^2 \frac{E_{f}^{(ce)}}{M_{i}^{(ce)}}$$

where $\epsilon_{\gamma} = 2/3$ is the charge of the $c$ quark, $\alpha_{e}$ is the fine-structure constant, $E_{\gamma}$ is the final photon energy, $E_{f}^{(ce)}$ is the total energy of the total energy of the final $c\bar{c}$ state, $M_{i}^{(ce)}$ is the mass of the initial $c\bar{c}$ state, the spatial matrix element $<\psi_f| r|\psi_i >$ involves the initial and final radial wave functions, and the angular matrix element $C_{fi}$ is

$$C_{fi} = \max(L,L')(2J' + 1) \left\{ \begin{array}{ll} L' & J' \ \ S \\ J & L \ \ 1 \end{array} \right\}^2 \quad (1.40)$$
1.10 Charmonium Like Exotic States

In recent years, particles have been found (like $X(3872)$, etc.) who resemble like charmonium but seem to have properties different than the conventional charmonium (like quark content or decay modes). They fall in the category of charmonium like or exotic states. These exotic states can be broadly classified into three models:

1.10.1 Multiquark

People can say why we have only two quarks (one quark and another anti-quark) or three quarks (different colors) to make up the matter. There are more combinations possible. Multiquark model supports such hypothesis. In 1970s, the idea of such a particle known as tetra-quark was considered to explain the properties of light scalar mesons ($f_0(600)$, $f_0(980)$, and $a_0(980)$) as their properties were not well explained by the existing quark model [32]. Two types of multiquark states have been considered. The first is a molecular state (also known as deuson) which comprises of two charmed mesons bound together to form a molecule. Molecular states are loosely bound and are expected to bind through two mechanism: quark/color exchange interactions at short distance and pion exchange at large distance (expected to dominate). Mesons inside the molecule are weakly bound, so they decay as if they are free. Also, molecular states are not isospin eigenstates which result in distinctive decay patterns. The idea of molecular states was initially used to explain an excessively large $D^* D^*$ production cross section compared with the $D \bar{D}$ and $D^* \bar{D}^*$ production cross sections at the peak of $\psi(4040)$ in $e^- e^+$ annihilation. It was supposed that $\psi(4040)$ can be a $P$-wave molecular resonance in the $D^* \bar{D}^*$ system and was forgotten but was revived in 2003 after the discovery of the $X(3872)$ particle [21] (more details in Section 1.11).

Multiquark state can also exist in the form of a tightly bound four-quark state (known as tetra-quark) and they are expected to have properties different from those of a molecular state. Maiani et al. [33] suggested that the tetra-quark can be described as a diquark-diantiquark structures in which the quarks group into color-triplet scalar and vector clusters and the interactions are dominated by a simple spin-spin interac-
1.10. CHARMONIUM LIKE EXOTIC STATES

Figure 1.7: Artistic illustration of the charmonium-like or exotic states.

...tion. The strong decays are expected to proceed via rearrangement processes, followed by disassociation, that give rise to (for example decays such as $X \rightarrow \rho J/\psi \rightarrow \pi \pi J/\psi$ or $X \rightarrow D\bar{D}^* \rightarrow D\bar{D}\gamma$). A prediction that distinguishes multiquark states containing a $c\bar{c}$ pair from conventional charmonia is the possible existence if multiplets that include members with nonzero charge (e.g. $[cu\bar{c}d]$), strangeness (e.g. $[cd\bar{s}\bar{s}]$), or both (e.g. $[cu\bar{s}\bar{s}]$).

1.10.2 Charmonium Hybrid

Hybrid mesons are states which has an excited gluon degree of freedom. Such states come into existence in many different models and calculations schemes. In lattice QCD, the quarks are viewed as moving in adiabatic potentials (produced by gluons) in analogy to the atomic nuclei in molecules moving in the adiabatic potentials (produced by electrons). Conventional charmonium spectrum is produced by lowest adiabatic surfaces while excited adiabatic surfaces lead to an octet of the lightest hybrids. These excitations introduces an additional degree of freedom related to gluons and add the spin and the angular momentum [30, 34]. In the flux-tube model [35], the lowest excited adiabatic surfaces corresponds to transverse excitations of the flux tube and leads to a doubly degenerate octet of the lowest mass hybrids with quantum numbers...
\[ J^{PC} = 0^{-+}, 0^{+-}, 1^{+-}, 1^{--}, 2^{+-}, 2^{--}, 1^{++}, \text{ and } 1^{--}. \] Some of the octet component having quantum numbers \( 0^{+-}, 1^{-+}, \text{ and } 2^{--} \) are not possible for \( c\bar{c} \) bound states in the usual quark model. If these states are observed, they will confirm the existence of an unconventional states. Lattice QCD predicts the lowest charmonium hybrid state to be roughly 4200 MeV/\( c^2 \) in mass [36].

### 1.10.3 Structure due to Threshold Effects

In addition to these states, threshold can also give rise to the structures in cross sections and kinematics distributions. The possible thresholds include the \( D\bar{D}^* \), \( D^*D \), \( DD_1 \) and \( D^*D_1 \) at \( E_{\text{cm}} \sim 3872 \), 4020, 4287 and 4430 MeV, respectively. S-wave \( (L = 0) \) scattering dominates the cross section at the threshold, however in few cases higher waves also become important. States in a relative S-wave with little relative momentum (which lives long on the timescale of strong interactions) will have enough time to exchange pions and interact [37]. Molecular state is possible due to the binding which is possible (via an attractive \( \pi \) exchange which could occur through couplings such as \( D \leftrightarrow D^*\pi^0 \)). It should be noted that there could also be a repulsive interaction which arises due to some strong interaction effects and it can result in a virtual state above threshold. Thus, near the kinematical threshold there can be a structure in the cross section which may or may not be a resonance. In addition, if there are \( c\bar{c} \) states which are near a threshold, they can interact with the threshold and will result in a mass shifts of both the \( c\bar{c} \) resonance and the threshold-related enhancement. This effects could be quite significant in the observed cross section, particularly for the \( c\bar{c} \) states close to the thresholds [37, 38].

### 1.11 A,B,C of \( X(3872) \) State

In the year 2003, the Belle Collaboration discovered a narrow state \( X(3872) \) \( (\rightarrow J/\psi\pi^+\pi^-) \) having width less than 2.3 MeV/\( c^2 \) (90\% C.L.) and a mass of 3872.0 ± 0.6 ± 0.5 MeV/\( c^2 \) in the charged \( B \) decay \( (B^- \rightarrow X(3872)K^-) \) [21]. Later on it was confirmed by CDF [39], DO [40] and BaBar [41] Collaborations. At present the
world average mass of $X(3872)$ is $3871.50 \pm 0.19$ MeV/$c^2$, using $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ decay [40, 42–44].

Figure 1.8: Observation of $X(3872)$, in a) data narrow peak around 3.872 GeV/$c^2$ (around 0.78 GeV/$c^2$ in this plot of mass difference) can be clearly seen while in b) Monte Carlo (MC) no such peak is visible.

Since $X(3872)$ decays to $J/\psi \pi^+ \pi^-$, it is quite obvious to identify $X(3872)$ as the new charmonium state. The most likely charmonium candidates are 1D or 2P states, however 1D states tends to lie below 3872 MeV/$c^2$ while 2P states are somewhat above. The mass and narrow width of $X(3872)$ does not agree well with the quark model expectations [45]. Initially $\psi_3$ or $\psi_2$ states were the strong contender for $X(3872)$ but soon doors were shut down for them after finding no significant signal in $X(3872) \rightarrow \chi_{c1}\gamma$ (or $X(3872) \rightarrow \chi_{c2}\gamma$) [21, 46]. If $X(3872)$ is a conventional charmonium state than it may decay in the same fashion as $\psi(2S)$. The $\psi(2S)$ decays to $J/\psi \eta$ by a factor of 10 less than it decays to $J/\psi \pi^+ \pi^-$; but $X(3872) \rightarrow J/\psi \eta$ was not seen by BaBar [47], although the Upper Limit doesn’t rule out the theory. All these things, makes $X(3872)$ an unconventional $q\bar{q}$ meson state which can not be explained by the simple quark model.

Can $X(3872)$ be identified as a diquark-antidiquark meson? Mainai et al. [48] constructed a model of $X(3872)$ as a diquark-antidiquark structure having $J^{PC} = 1.11. A,B,C OF X(3872) STATE$
1+. Their model predicts $X(3872)$ mass eigenstates as $X_u = [cu][ar{c}u]$ and $X_d = [cd][ar{c}d]$. These two $X$ states can mix with an angle $\theta$ ($\sim 20^\circ$). Considering the higher ($h$) and lower ($l$) eigenvalues, they predict:

$$\Delta m = M(X_h) - M(X_l) = 2(m_d - m_u)/\cos(2\theta) = (7 \pm 2)/\cos(2\theta) \text{ MeV}/c^2$$

Due to the narrow width of $X(3872)$, only one particle can dominate the final state of $B^+$, either $X_u$ or $X_d$. The $\Delta I = 0$ rule of the weak transition implies that $B^0$ decay is dominated by the other states $X_d$ or $X_u$. The ratio of neutral to the charge production of $X(3872)$, $r \equiv B(B^0 \to X(3872)K^0)/B(B^- \to X(3872)K^-)$, is predicted to be unity. BaBar measured this ratio ($r$) as $0.41 \pm 0.24 \pm 0.05$ and gave the mass difference to be $\Delta m = (2.7 \pm 1.6 \pm 0.4) \text{ MeV}/c^2$ [42]. Recent result from Belle put the ratio ($r = 0.82 \pm 0.22 \pm 0.05$) close to the unity; but $\Delta m = (0.18 \pm 0.89 \pm 0.07 \text{ MeV}/c^2)$ value does not agree with the one predicted by tetraquark model [43]. CDF II search for two $X(3872)$ mass states, also gives negative result [44].

$X(3872)$ was also suggested to be a $c\bar{c}g$ hybrid meson [49] which decays predominantly via $X(3872) \to J/\psi gg \to J/\psi\pi\pi$. Current lattice computations [36] predict the lightest charmonium hybrid meson’s mass to be in the range of 4200-4400 MeV/$c^2$ which is far away than the mass of $X(3872)$. Seth [50] proposed $X(3872)$ to be a vector glueball with a small admixture of vector $c\bar{c}$ which is contradictory to the observation.

<table>
<thead>
<tr>
<th>Collaboration</th>
<th>Collider ($\sqrt{s}$)</th>
<th>Decay Mode</th>
<th>Mass (MeV/$c^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>World Average</td>
<td></td>
<td>$X(3872) \to J/\psi\pi\pi$</td>
<td>3871.50 $\pm$ 0.19</td>
</tr>
<tr>
<td>CDF II [44]</td>
<td>$p\bar{p}$ (1.96 TeV)</td>
<td>$p\bar{p} \to X(3872)$ any</td>
<td>3871.61 $\pm$ 0.16 $\pm$ 0.19</td>
</tr>
<tr>
<td>Belle [43]</td>
<td>$e^+e^-$ (10.58 GeV)</td>
<td>$B^{0,\pm} \to X(3872)K^{0,\pm}$</td>
<td>3871.5 $\pm$ 0.4 $\pm$ 0.1</td>
</tr>
<tr>
<td>BaBar [42]</td>
<td>$e^+e^-$ (10.58 GeV)</td>
<td>$B^- \to X(3872)K^-$</td>
<td>3871.4 $\pm$ 0.6 $\pm$ 0.1</td>
</tr>
<tr>
<td>D [40]</td>
<td>$p\bar{p}$ (1.96 TeV)</td>
<td>$p\bar{p} \to X(3872)$ any</td>
<td>3871.8 $\pm$ 3.1 $\pm$ 3.0</td>
</tr>
</tbody>
</table>
of $X(3872)$ decays into $J/\psi\omega$ and $J/\psi\gamma$ [46].

$X(3872) \rightarrow D^0\bar{D}^0\pi^0$ decay was observed in $B \rightarrow (D^0\bar{D}^0\pi^0)K$ mode by Belle Collaboration [51] having mass of $3875.2 \pm 0.7_{-1.6}^{+0.3} \pm 0.8$ MeV/$c^2$, here the last error is due to the uncertainty in the world average of $D^0$ mass. Soon, the difference between $X(3872)$ in $D^0\bar{D}^0\pi^0$ ($D^0\bar{D}\pi^0$) and $J/\psi\pi\pi$ channel, was confirmed by BaBar Collaboration [52], and they got the mass to be $3875.1^{+0.7}_{-0.5} \pm 0.5$ MeV/$c^2$. However, Belle recent result $D^0\bar{D}^{*0}$ ($D^{*0} \rightarrow D^0\pi^0$ and $D^{*0} \rightarrow D^0\gamma$) determine the mass to be $3872.6^{+0.5}_{-0.4} \pm 0.4$ MeV/$c^2$ [53]. The Belle recent result is with $\sim 1.5$ times more statistics, and unbinned fit using improved Breit-Wigner formula (the Flatte formula).

![Diagram](image)

Figure 1.9: Feynman diagram of radiative decays of $X(3872)$ where a) and b) is for LQA process while c) is for VMD.

The mass of $X(3872)$ lies quite close to the $D^{*0}\bar{D}^0$ threshold of 3871.8 MeV/$c^2$, due to which it can be assumed as $D\bar{D}^*$ resonance. Molecular model predicts, $X(3872) \rightarrow J/\psi\pi^+\pi^-\pi^0$ decay is roughly half of that to $B \rightarrow J/\psi\pi^+\pi^-$, as observed by Belle [46]. Also $X(3872) \rightarrow J/\psi\pi^0\pi^0$ decay has not been seen which give some weightage to the molecular model. Radiative decays of $X(3872)$ are important in understanding the nature of $X(3872)$. In the molecular model, radiative decays of $X(3872)$ occurs
CHAPTER 1. INTRODUCTION

![Graphs showing events for different decay modes]

(a) $X(3872) \rightarrow J/\psi \gamma$ seen at Belle 
(b) $X(3872) \rightarrow J/\psi \gamma$ confirmed by BaBar

(c) $X(3872) \rightarrow \psi(2S) \gamma$ seen at BaBar in (a) $B^- \rightarrow X(3872)K^-$ decay mode while in other decay modes (b) $B^0 \rightarrow X(3872)K^\circ$, (c) $B^- \rightarrow X(3872)K^{*-}$ and (d) $B^0 \rightarrow X(3872)K^{*0}$ Upper Limit is given.

Figure 1.10: Radiative decays of $X(3872)$

through vector meson dominance (VMD) and light quark annihilation (LQA) \[45\]. VMD process proceeds via the $J/\psi \rho$ and $J/\psi \omega$ components and thus contribute
1.12. CHAPTER IN A NUTSHELL

to $\Gamma(X(3872) \to J/\psi \gamma)$. The LQA proceeds via the $D^0\bar{D}^{0*}$ + c.c. and $D^-\bar{D}^{+*}$ + c.c. components. The final rate of $X(3872) \to J/\psi \gamma$ is dominated by VMD while for $X(3872) \to \psi(2S) \gamma$, it is mostly driven by LQA. Due to this, $X(3872) \to \psi(2S) \gamma$ decay is highly unfavored as compared to $X(3872) \to J/\psi \gamma$. But recent result by BaBar [54], $\mathcal{B}(X(3872) \to \psi(2S) \gamma)/\mathcal{B}(X(3872) \to J/\psi \gamma) = 3.4 \pm 1.4$, shows inconsistency in the pure $D^{*0}\bar{D}^0$ molecular model. The $X(3872)$ enhanced decay rate to $\psi(2S) \gamma$ can be explained by $c\bar{c} - D^{*0}\bar{D}^0$ mixing [45, 55]. At present Belle has the world’s largest accumulated luminosity data at $\Upsilon(4S)$, using which we should measure $\mathcal{B}(X(3872) \to J/\psi \gamma)$ and $\mathcal{B}(X(3872) \to \psi(2S) \gamma)$ more precisely, as this is necessary in order to understand $X(3872)$ properties.

Observation of $X(3872) \to J/\psi \gamma$ favors charge conjugation $C$ to be 1 [46]. Belle [56] and CDF [57, 58] angular studies favors $X(3872)$’s $J^{PC}$ to be $1^{++}$ or $2^{-+}$. In this analysis we will assume $X(3872)$ as $1^{++}$ for nominal fits.

Table 1.4: E1 decays of the $X(3872)$ [45].

<table>
<thead>
<tr>
<th>Mode</th>
<th>$m_f$(MeV)</th>
<th>$q$(MeV)</th>
<th>$\Gamma[cc]$(keV)</th>
<th>$\Gamma[cc']$(keV)</th>
<th>$\Gamma[cc']$(keV)</th>
<th>$\Gamma[cc']$(keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \gamma$</td>
<td>3097</td>
<td>697</td>
<td>11</td>
<td>71</td>
<td>139</td>
<td>8</td>
</tr>
<tr>
<td>$\psi' (2^{3} S_1) \gamma$</td>
<td>3686</td>
<td>182</td>
<td>64</td>
<td>95</td>
<td>94</td>
<td>0.03</td>
</tr>
<tr>
<td>$\psi'' (1^{3} D_1) \gamma$</td>
<td>3770</td>
<td>101</td>
<td>3.7</td>
<td>6.5</td>
<td>6.4</td>
<td>0</td>
</tr>
<tr>
<td>$\psi_2 (1^{3} D_1) \gamma$</td>
<td>3838</td>
<td>34</td>
<td>0.5</td>
<td>0.7</td>
<td>0.7</td>
<td>0</td>
</tr>
</tbody>
</table>

1.12 Chapter in a Nutshell

In this Chapter, introduction to work taken in this thesis is given. Following decay modes are studied in this thesis:

- $B^\pm \to \psi(2S)\pi^\pm$ and $B^\pm \to \psi(2S)K^\pm$
- $B^- \to \psi(2S)K^-$ is a color-suppressed (Cabibbo-favored) decay mode which has
been observed [14]. It is expected that there should be a Cabibbo-suppressed
decay mode \((B^\pm \rightarrow \psi(2S)\pi^\pm)\) corresponding to the \(B^\pm \rightarrow \psi(2S)K^\pm\) decay
mode. Our main motive behind this study is to search for this decay mode as
it has not been seen/measured yet and to validate factorization prediction. A
search for direct \(CP\) violation is performed for \(B^- \rightarrow \psi(2S)\pi^-\), if large direct
\(CP\) violation is found we may get some hint of New Physics (i.e. beyond the
SM).

- \(B^{0,\pm} \rightarrow \chi_{c1}K^{0,\pm}\) and \(B^{0,\pm} \rightarrow \chi_{c2}K^{0,\pm}\)

  We search for \(B \rightarrow \chi_{c2}K\) decay mode. Search for this decay mode has been
carried out earlier but not seen yet. With more data and better reconstruction
efficiency, we hope to see this decay mode and compare it with the decay mode
\(B \rightarrow \chi_{c1}K\), which also acts like control sample for our study. Using both of these
decay modes, we will try to compare with the theoretical prediction [18, 19].

- \(X(3872) \rightarrow J/\psi\gamma\) and \(X(3872) \rightarrow \psi(2S)\gamma\)

  We have taken up the search of the \(E1\) radiative decay modes of \(X(3872)\)
in \(B \rightarrow X(3872)K\) decay. Radiative decays of \(X(3872)\), \(X(3872) \rightarrow J/\psi\gamma\)
and \(X(3872) \rightarrow \psi(2S)\gamma\), are important for the theoretical understanding of
\(X(3872)\). Using ratio of \(\Gamma(X(3872) \rightarrow \psi(2S)\gamma)/\Gamma(X(3872) \rightarrow J/\psi\gamma)\), we can
test the model predictions and try to understand the nature of \(X(3872)\).
Isn’t it she cute?

Definitely. after all
it is beauty from Belle...

Experimental Setup

The data used to perform this analyses has been collected at KEKB asymmetric $e^+e^-$ collider using the Belle detector, at High Energy Accelerator Research Organization, KEK, Japan. In this chapter, KEKB accelerator and Belle detector components are explained. When the work for this thesis started, Belle detector was already fully operational. So, the author doesn’t have contribution in building the detector. Although he took many expert and non-expert shifts (for the successful running of the detector and data taking) during which he learned about the detector and the accelerator part. Belle has the largest $B$-physics data, which make it the best place to search for new $B$ decay modes and new phenomenology. Accelerator construction was completed in year 1998, and at present accelerator is sleeping (as it is being upgraded to Super KEKB [59] for the Belle II experiment [60]) from 30th, June 2010 (9:00 a.m.).

2.1 KEKB Collider

The KEKB is an asymmetric energy $e^+e^-$ collider with $e^-$ having energy 8 GeV and $e^+$ having energy 3.5 GeV, located at KEK (Kō Enerugi Kasokuki Kenkyū Kikō) laboratory in Tsukuba, Japan. The center-of-mass (CM) energy $\sqrt{s}$ is

$$\sqrt{s} = \sqrt{4E_{e^+}E_{e^-}} = 10.58 \text{ GeV} ;$$

(2.1)
which is equal to the mass of $\Upsilon(4S)$ resonance. The $\Upsilon(4S)$ is a bound state of $b\bar{b}$ with $J^{PC} = 1^{--}$ and having mass just above the threshold of $B\bar{B}$ production, where $B$ is bound state either of $bu$ or $bd$ quarks. The $\Upsilon(4S)$ mainly decays to $B^0\bar{B}^0$ or $B^+B^-$ in equal amount as measured ratio [3] indicate that:

$$\frac{\Gamma(\Upsilon(4S) \to B^+B^-)}{\Gamma(\Upsilon(4S) \to B^0\bar{B}^0)} = 1.065 \pm 0.026$$  \hspace{1cm} (2.2)

Since the energy of $e^+$ and $e^-$ is asymmetric so, the $B$ meson pairs are created with a Lorentz boost factor of

$$\beta\gamma = \frac{E_{e^-} - E_{e^+}}{\sqrt{s}} = 0.425$$  \hspace{1cm} (2.3)

Since the branching fractions of the $B$ decays are very small, so large number of $B$ mesons are necessary for the studies. The design luminosity of KEKB machine is $1 \times 10^{34}$ cm$^{-2}$s$^{-1}$ which corresponds to $10^{8}$ $B$ mesons per year.

### 2.2 KEKB Accelerator

The complete detailed description of the accelerator can be found in Ref. [61]. The accelerator is composed of two side-by-side rings in which the beam is sent through a linear accelerator (linac). The rings are installed in a 3 km long tunnel buried 10 m below the surface. In a first stage of the linac, electrons are accelerated to an energy of 4 GeV. Positrons are then produced by hitting a thin tungsten monocrystal target with some of these electrons, which will radiate photons. These photons create electron-positron pairs and the positrons are collected and accelerated to 3.5 GeV. The electron beam is then accelerated further, and both beams are directly injected into the rings at full energies: the high-energy ring (HER) contains electrons at 8.0 GeV energy and the low-energy ring (LER) contains positrons at 3.5 GeV. Figure 2.1 shows the artistic illustration of the KEKB accelerator.

These beams are made to collide at the interaction point, called Tsukuba, where they cross each other in the center of the Belle detector. At the interaction point (IP) the beams intersect at an angle of 22 mrad; this finite crossing-angle reduces beam-beam interactions away from the IP and removes the need of separation magnets.
within the detector volume. In other words, the non-zero crossing angle provides effective beam separation at the collision point, without high level of background. This also means that the electron and positron bunches do not collide head-on as would happen at zero crossing angle. This raises the effective beam cross-sectional area and causes a reduction in the specific luminosity of the collisions. To compensate for this, specialized RF cavities Crab Cavities’ are installed on the beam-line in January 2007. Crab cavities give each bunch a kick to effectively rotate it to face the colliding bunch directly. On 17th, June 2009 double luminosity was achieved (2.1083 × 10^{-34} cm^{-2}s^{-1}). Accelerator stopped working on 30 June 2010 for a major upgrade for super KEKB. In its whole life, it has delivered more than 1040.86 fb^{-1} data and belle has acquired data of \sim 1014 fb^{-1} which can be divided into data sets of Table 2.1. While Table 2.2 summarizes the design parameter of KEKB accelerator.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Luminosity (fb^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Υ(1S)</td>
<td>6</td>
</tr>
<tr>
<td>Υ(2S)</td>
<td>24</td>
</tr>
<tr>
<td>Υ(3S)</td>
<td>3</td>
</tr>
<tr>
<td>Υ(4S)</td>
<td>711</td>
</tr>
<tr>
<td>Υ(5S)</td>
<td>121</td>
</tr>
<tr>
<td>Off reson./scan</td>
<td>\sim 100</td>
</tr>
</tbody>
</table>
2.3 The Belle Detector

The Belle detector is designed and constructed to carry out quantitative study of $B$ meson decays and in particular rare $B$ decay modes with very small branching fractions. $B$ mesons are very short-lived particles and decay almost instantaneously into relatively long life time particles before they reach the innermost detector. The Belle detector detects these particles, namely $e^\pm$, $\mu^\pm$, $\pi^\pm$, $K^\pm$, $p$, $\bar{p}$, $\gamma$ and $K^0$. The neutron and anti-neutron cannot be detected although they are also produced. Table 2.3 gives the parameters and performance of each sub-detector of Belle detector.

The Belle detector is a large asymmetric magnetic spectrometer having a large solid-angle acceptance. It consist of concentric layers of sub-detectors designed to
2.3. THE BELLE DETECTOR

provide momentum and position information via magnetic spectroscopy, energy measurements via electromagnetic calorimeter, and particle identification discrimination through energy loss and penetration depth data. Figure 2.2 is the dissected diagram of the detector showing all sub-detectors, the solenoid which provides a 1.5 T magnetic field, and the electron and positron beam-lines.

- Silicon vertex detector (SVD)
- Central drift chamber (CDC)
- Aerogel Čerenkov counter (ACC)
- Time of flight scintillator (TOF)
- Electromagnetic calorimeter (ECL)
- Kaon and muon detector (KLM)
- Extreme forward calorimeter (EFC)

Figure 2.2: Schematic diagram of the Belle detector.
### Table 2.2: Design parameter of KEKB accelerator, † (‡) without (with) wigglers.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LER (e⁺)</th>
<th>HER (e⁻)</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (E)</td>
<td>3.5</td>
<td>8.0</td>
<td>GeV</td>
</tr>
<tr>
<td>Circumference (C)</td>
<td>3016.26</td>
<td></td>
<td>m</td>
</tr>
<tr>
<td>Luminosity (L)</td>
<td>1 × 10^{34}</td>
<td></td>
<td>cm⁻²s⁻¹</td>
</tr>
<tr>
<td>Crossing angle (θₓ)</td>
<td>±11</td>
<td></td>
<td>mrad</td>
</tr>
<tr>
<td>Tune shift (ξₓ/ξᵧ)</td>
<td>0.039/0.052</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beta function at the IP (βₓ⁺/βᵧ⁺)</td>
<td>33/1</td>
<td></td>
<td>cm</td>
</tr>
<tr>
<td>Beam Current (I)</td>
<td>2.6</td>
<td>1.1</td>
<td>A</td>
</tr>
<tr>
<td>Natural bunch length (σₓ)</td>
<td>0.4</td>
<td></td>
<td>cm</td>
</tr>
<tr>
<td>Energy spread (σₓ/E)</td>
<td>7.1 × 10⁻⁴</td>
<td>6.7 × 10⁻⁴</td>
<td></td>
</tr>
<tr>
<td>Number of bunches</td>
<td>~5000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunch spacing (Sᵦ)</td>
<td>0.59</td>
<td></td>
<td>m</td>
</tr>
<tr>
<td>Particles/bunch</td>
<td>3.3 × 10^{10}</td>
<td>1.4 × 10^{10}</td>
<td></td>
</tr>
<tr>
<td>Emittance (εₓ/εᵧ)</td>
<td>18/0.36</td>
<td></td>
<td>nm</td>
</tr>
<tr>
<td>Synchrotron tune (νₛ)</td>
<td>0.01 ~ 0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Betatron tune (νₓ/νᵧ)</td>
<td>45.52/45.08</td>
<td>47.52/43.08</td>
<td></td>
</tr>
<tr>
<td>Momentum compaction factor (αₚ)</td>
<td>1 × 10⁻⁴</td>
<td>~2 × 10⁻⁴</td>
<td></td>
</tr>
<tr>
<td>Energy loss/turn (U₀)</td>
<td>0.81†/1.5‡</td>
<td>4.8</td>
<td>MeV</td>
</tr>
<tr>
<td>Total RF voltage (V_c)</td>
<td>5 ~ 10</td>
<td>10 ~ 20</td>
<td>MV</td>
</tr>
<tr>
<td>RF frequency (fₚRF)</td>
<td>508.887</td>
<td></td>
<td>MHz</td>
</tr>
<tr>
<td>Harmonic number (h)</td>
<td>5120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal damping time (τₑ)</td>
<td>43†/23‡</td>
<td>23</td>
<td>ms</td>
</tr>
<tr>
<td>Total beam power (P_b)</td>
<td>2.7†/4.5‡</td>
<td>4.0</td>
<td>MW</td>
</tr>
<tr>
<td>Radiation power (PₚSR)</td>
<td>2.1†/4.0‡</td>
<td>3.8</td>
<td>MW</td>
</tr>
<tr>
<td>HOM power (PₚHOM)</td>
<td>0.57</td>
<td>0.15</td>
<td>MW</td>
</tr>
<tr>
<td>Bending Radius (ρ)</td>
<td>16.3</td>
<td>104.5</td>
<td>m</td>
</tr>
<tr>
<td>Length of bending magnet (L_b)</td>
<td>0.915</td>
<td>5.86</td>
<td>m</td>
</tr>
</tbody>
</table>
Table 2.3: Parameters and performance of the detector and subsystems. $p$ and $p_t$ in GeV/c, $E$ in GeV.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Type</th>
<th>Configuration</th>
<th>Readout</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam pipe(SVDI)</td>
<td>Beryllium double-wall</td>
<td>inner $r=20$ mm, $0.5$(Be)/2.5(He)/0.5(Be)mm inner $r=15$mm, $0.5$(Be)/2.5(PF200)/0.5(Be)mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SVDI</td>
<td>Double sided Si-strip</td>
<td>$300 \mu$m thick 3-layers $r=3.0 \sim 6.05$cm</td>
<td></td>
<td>$\phi : 40.96$ k $\theta : 40.99$ k $\sigma_{\Delta z} \sim 100\mu$m</td>
</tr>
<tr>
<td>SVDII</td>
<td>Double sided Si-strip</td>
<td>$300 \mu$m thick 4-layers $r=2.0 \sim 8.8$cm</td>
<td></td>
<td>$\phi : 55.296$ k $\theta : 55.296$ k $\sigma_{\Delta z} \sim 100\mu$m</td>
</tr>
<tr>
<td>CDC</td>
<td>Small-cell drift chamber</td>
<td>Anode: $\phi$0 layer Cathode: 3 layers $r=8.3 \sim 86.3$ cm</td>
<td></td>
<td>$A: 8.4$ k $\sigma_{r\phi} = 130$ $\mu$m/cm $\sigma_{p_t}/p_t = 0.3%\sqrt{p_t^2 + 1}$ $\sigma_{dE/dx} = 6%$</td>
</tr>
<tr>
<td>ACC</td>
<td>Threshold Čerenkov $n = 1.01 \sim 1.03$ silica aerogel</td>
<td>Barrel: $128 \times 64$ $r = 120$ cm</td>
<td>FM-PMT readout</td>
<td>$1788$ $K/\pi$ separation: $1.2 &lt; p &lt; 3.5$ GeV/c</td>
</tr>
<tr>
<td>TOF/TSC</td>
<td>Plastic scintillator</td>
<td>$r = 125 \sim 162$ cm End-cap: $z = -102/196$ cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECL</td>
<td>CsI(Tl) crystal</td>
<td>$14$ layers $\phi : 16$k $\theta : 16$k $1%$ hadron fake rate for muon $\Delta \phi = \Delta \theta = 30$ mrad for $K_L$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnet</td>
<td>Superconducting</td>
<td>inner radius 179 cm $B=1.5$ T</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KLM</td>
<td>Glass resistive plate counter</td>
<td>$32$ in $\phi$, $5$ in $\theta$ $160 \times 2$ $\sigma_E/E = (0.3 - 1)%/\sqrt{E}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EFC</td>
<td>BGO crystal</td>
<td>$14$ layers $\phi : 16$k $\theta : 16$k $1%$ hadron fake rate for muon $\Delta \phi = \Delta \theta = 30$ mrad for $K_L$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.3.1 Beam Pipe

Beam pipe is the inner-most piece of the detector and all the particles transverse through it before reaching the SVD. The material in the pipe must be kept to a minimum to avoid Coulomb scattering which effects the resolution of the SVD and also it should be such thick that it withstand the beam-induced heating which can be up to several hundred watts. For this purpose double-walled beryllium cylinder is used. The two 0.5 mm thick walls are separated by a 2.5 mm gap through which helium gas is circulated as a coolant. The beryllium is covered in a 20 $\mu$m thick layer of gold foil, which absorbs X-rays from synchrotron radiation. Figure 2.3 shows the cross-section of beam pipe at interaction point.

![Cross section and side-view of the Belle beam-pipe.](image)

2.3.2 Silicon Vertex Detector (SVD)

The SVD provides precise measurement of the decay vertices of $B$ mesons, which is essential to study a time-dependent $CP$ asymmetry. The required $\Delta z$ resolution is $\lesssim 200 \, \mu m$ since the averaged separation of two $B$ meson vertices is $\sim 200\mu m$. The SVD is also useful for identifying and measuring the decay vertices of $D$ and $\tau$ particles and it also contributes to the track reconstruction of the charged particles.
and helps to improve the momentum resolution of the particle.

As most particles of interest in Belle have momenta less than 1 GeV/c the vertex resolution is dominated by the multiple Coulomb scattering. This imposes strict constraints on the design of the detector. In particular, the innermost layer of the vertex detector must be placed as close to the interaction point as possible. Also, the support structure must be low in mass; and the readout electronics must be placed outside of the tracking volume. Since the vertex resolution improves inversely with the distance to the first detection layer, the vertex detector has to be placed as close as possible to the interaction point and this to the beam pipe wall. Figure 2.4 shows the configuration of SVDI.

Figure 2.4: Configuration of SVDI.

The SVDI consists of three concentric cylindrical layers arranged in a barrel and covers a solid angle range $23^\circ < \theta < 139^\circ$, which corresponds to 86% of the full solid angle in the CMS. The three layers at radii of 30.0 mm, 45.5 mm and 60.5 mm surround the beam pipe. Three layers are constructed from eight, ten and fourteen independent ladders from inner to outer, respectively. Each ladder consists of double-sided silicon strip detectors (DSSDs) reinforced by boron-nitride support ribs. In
total, there are 32 ladders and 102 DSSDs. Each DSSD has 1280 sense strips and 640 readout pads on both side. Each DSSD size is $57.5 \times 33.5$ mm$^2$. The DSSDs are reverse-biased dipole strip detector. Signal from DSSDs are read out by 128 channel VA1 chips [62] placed on both sides of the ladder. Inside the VA1 chip, signals are amplified and sent to shaping circuits, where the shaping time is adjusted to about 1 $\mu$s. Then, the outputs of the shaper are held when the VA1 chips receive Level-0 (L0) trigger signal provided by TOF. This analog information is passed to fast analog-to-digital converters (FADC) in the electronic hut if a Level-1 (L1) trigger occurs. The total number of readout channels are 81920. VA1 has excellent noise performance and reasonably good radiation tolerance of 500 kRad.

For the $z$-coordinate measurement, the n-side strips are used and a double-metal structure running parallel to $z$ is employed to route the signals from orthogonal $z$-sense strips to the ends of the detector. Adjacent strips are connected to a single readout trace on the second metal layer which gives an effective strip pitch of 84 $\mu$m. A p-stop structure is employed to isolate the $z$-sense strips. A relatively large thermal noise ($\sim 600 e^-$) is observed due to the common-p-stop design. On the $\phi$ side only every other sense-strip is connected to a readout channel. Charged collected by the floating strips in between is read from adjacent strips by means of capacitive charge division.

The track-matching efficiency is defined as the probability that a CDC track within the SVD acceptance associates SVD hits in at least two layers, and in at least one layer with both the $r - \phi$ and $r - z$ information. Tracks from $K_S^0$ decays are excluded since these tracks do not necessarily go through the SVD. The averaged matching efficiency is better than 98.7%, although slight degradation is observed after one year operation as a result of the gain loss of VA1 from radiation damage [63].

The impact parameter resolution for reconstructed track is measured as a function of the track momentum $p$ (measured in GeV/$c$) and the polar angle $\theta$ to be

$$\sigma_{r\phi} = 19 + \frac{50}{p/\beta \sin^{3/2} \theta} \mu m \quad (2.4)$$

$$\sigma_z = 36 + \frac{42}{p/\beta \sin^{3/2} \theta} \mu m \quad (2.5)$$
here, $\oplus$ represents a quadratic sum.

Figure 2.5: SVDII detector

Figure 2.6: Side-view of SVDII.
CHAPTER 2. EXPERIMENTAL SETUP

SVD II

New SVD (SVD II) [64] has been installed in the summer of 2003. There are many improvement from SVD I. The geometrical configuration of SVDII is shown in Figure 2.5 and 2.6. The SVD II consists of four cylindrical layers whose the radii are 20.0 mm, 43.5 mm, 70.0 mm and 88.0 mm. The angular acceptance covers from 17° to 150°, which is same as CDC acceptance. The four layers are 6, 12, 18 and 18 ladders to cover all the φ region and in each ladder are consisted with 2, 3, 5 and 6 DSSDs. There are two kinds of DSSDs. One is used in 1st, 2nd and 3rd layers, the size is 28.4 × 79.6 mm², the strip pitch is 75 µm on p-side and 50 µm on n-side. The other one is used in 4th layer, the size is 34.9 × 76.4 mm², the strip pitch is 73 µm on p-side and 65 µm on n-side. The n-side DSSDs is used for measurement of the r − φ coordinate and the n-side is used for the measurement of the z-coordinate. The number of strip is 512 in the both n-side and p-side. The total number of DSSDs is 246. Therefore the total number of readout channel is 110592. As in SVD I each ladder is read out by four hybrids. Each hybrid employs four VAITA (VA1 with trigger functions) chips, each VAITA chips amplifies the signals from 128 strips, whose pulse heights are held and sent out serially. To minimize the readout deadtime the four chips on each hybrid are readin parallel, in contrast to SVD I where the chips were read sequentially. This represents a significant reduction in the overall deadtime of the Belle DAQ system. The VAI1TA also incorporated a fast shaper and discriminator that provide digital signal use in the trigger. The signals are demultiplexed in the FADC boards housed in the electronics hut.

2.3.3 Central Drift Chamber (CDC)

The primary role of CDC is the determination of three dimensional trajectories of charged particles and the precise measurement of their momenta. The 1.5 T magnetic field of superconducting solenoid bends the charged particle according to their momenta. The physics goal of the experiment require a momentum resolution of

$$\frac{\sigma_p}{p_t} \sim \sigma_{MS} \oplus \sigma_r \sim 0.5 \oplus 0.5 p_t \%$$  \hspace{1cm} (2.6)

for all charged particles with $p_t \geq 0.1 \text{ GeV}/c$ in the polar angle region $17^\circ \leq \theta \leq 150^\circ$. Here $\sigma_{MS}$ denotes the error which comes from the multiple Coulomb scattering and shows constant contribution in above $p_t$ region, and $\sigma_r$ denotes the error proportional to $p_t$, which arises from the position measurement. One can calculate $p_t$ from the radius of curvature $r$ as

$$p_t = 0.3 Br \tag{2.7}$$

where $p_t$ is in units of $\text{GeV}/c$, $B$ is the magnetic field in Tesla, and $r$ is in meter.

CDC provide good momentum and position resolution for charged tracks. It is essential to reduce the amount of the material in the tracking volume in order to obtain good momentum resolution since the effects of multiple Coulomb scattering on the resolution are dominant for the charged particles below 1.0 GeV/c where our target events decay into. In addition, the CDC is used to measure the energy loss ($dE/dx$) of charged particles for their particle identification. The amount of $dE/dx$ depends on $\beta = v/c$ of the charged particle (Bethe-Bloch formula). Another important role of the CDC is to provide an important information regarding trigger system in the $r - \phi$ and $z$ dimensions.

Structure of CDC is shown in Figure 2.7. It is a cylindrical wire drift chamber.
Figure 2.8: Cell structure of the CDC. Cathode sector configuration is also shown in the right figure.

having 50 layers (32 axial and 18 small angle stereo layers) of anode wires and three cathode strip layers. The CDC is asymmetric in z-direction, the axial wires are configured parallel to z-axis while the stereo wires are slanted approximately ±50 mrad. The stereo layers combined with axial layers provide z information of tracks. The cathode strips improve the z-measurement as well as produce a highly efficient fast z-trigger. An anode wire (sense wire) and field wires that surround the anode wire form a drift cell. The CDC has a total of 8400 drift cells and each drift cell has a maximum drift distance between 8 mm to 10 mm. The sense wires are gold-plated tungsten wires of 30 μm diameter while the field wires are of unplated aluminum of 126 μm diameter. Three z-coordinate measurements at the inner-most radii are provided by cathode strips as shown in Figure 2.8. The cathode strip having width of 7.4 mm is divided into eight segments in the φ-direction and has an 8.2 mm pitch in the z-direction. The total number of cathode channels are 1792.

Low-Z gas (50% helium (He) and 50% ethane) [65] is chosen in order to minimize
2.3. THE BELLE DETECTOR

Figure 2.9: Spatial resolution as a function of the drift distance.

multiple Coulomb scattering contribution to the momentum resolution. This mixture has a long radiation length (640 m) and a drift velocity that saturates at 4 cm/μs at a relatively low electric field.

Signals from the chamber are amplified by pre-amplifiers and sent to Shaper/Discriminator/ QTC modules in the electronics hut via ≈ 30 m long twisted pair of cables. These modules receive shaped and discriminated signals and perform a charge (Q) -to-time (T) conversion (QTC) [66]. The modules internally generate the logic level output where the leading edge corresponds to the drift time and width is proportional to the input pulse height. The output signals are read by time-to-digital converters (TDC). The input pulse height is used to measure $dE/dx$.

Figure 2.9 shows the spatial resolution as a function of the drift distance. The spatial resolution is approximately $\sigma_{r\phi} = 130 \, \mu m$. Charged particle tracking is done by Kalman filtering method [67], taking into account the effect of multiple Coulomb scattering, energy loss, and non-uniformity of the magnetic field.

The mean rate of energy loss ($dE/dx$) of a charged particle is given by the Bethe-Bloch equation,

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 Z \frac{Z}{A} \left( \frac{z}{\beta} \right) \left[ \log \left( \frac{2m_e c^2 \beta^2 \gamma^2}{I} \right) - \beta^2 - \delta \right]$$  \hspace{1cm} (2.8)

where $N_A$ is the Avogadro’s number, $r_e$ is the classical electron radius, $m_e$ is the mass of electron, $Z$ and $A$ are the atomic number and mass number of the atoms of the
Figure 2.10: Scatter plot for momentum vs $dE/dx$. Expected relation for $\pi$, $K$, $p$ and $e$ are shown by the solid curves. The momenta are given in units of GeV/c.

medium, $z$ and $v$ are the charge (in units of $e$) and velocity of the particle, $\beta = v/c$, $\gamma = 1/\sqrt{1 - \beta^2}$, $I \simeq 167Z^{0.89}$ eV is the mean excitation energy of the medium, and $x$ is the path length in the medium, measured in gcm$^{-2}$. Equation (2.8) shows that the $dE/dx$ is independent of the mass of the particle and depends on $\beta$. Therefore we can estimate $\beta$ from a measurement of $dE/dx$. The measurement of $\beta$ can provide a useful method for estimating the rest mass and thus differentiating particle species in conjunction with the momentum measurement.

Track parameters are improved by combining the SVD and CDC information. The combined performance is

$$\sigma_{xy} = 19 \oplus \frac{50}{p\beta\sin^{3/2}\theta}\mu$m
$$

$$\sigma_z = 36 \oplus \frac{42}{p\beta\sin^{5/2}\theta}\mu$m
$$

$$\frac{\sigma_{pt}}{p_t} = (0.34 \oplus 0.19 p_t)\%$$

where momentum ($p$) and transverse momentum ($p_t$) are in GeV/c, $\beta$ is the particle speed and $\theta$ its polar angle.

The CDC is involved in the particle identification for the tracks with $p < 0.8$ GeV/c and $p > 2.0$ GeV/c measuring $dE/dx$. Figure 2.10 shows the scatter plot of
the measured $dE/dx$ and the particle momentum. Expected relation for $\pi$, $K$, $p$ and $e$ are shown by the solid curves in Figure 2.10. The $dE/dx$ resolution is measured to be 6.9% for minimum-ionizing pions.

2.3.4 Aerogel Čerenkov Counter (ACC)

Particle identification, specifically the identification of $\pi^\pm$ and $K^\pm$, plays an important role in the study of $CP$ violation in the $B$ mesons system. In the momentum region below 1 GeV/$c$, the $K/\pi$ separations have been performed by $dE/dx$ measurement from CDC and time of flight measurements. The ACC provides the $K/\pi$ separation in momentum range of $1.2 < p < 3.5$ GeV/$c$ by detection of the Čerenkov light from particle penetrating through silica aerogel radiator. Čerenkov light is emitted if the velocity of the charged particle, $\beta$ satisfies

$$\beta = \frac{p}{\sqrt{p^2 + m^2}} > 1/n$$

(2.10)

where $n$ is the refractive index of the matter, $m$ and $p$ are the mass and momentum of the charged particle, respectively. Therefore there is a momentum region where pions emit Čerenkov light while kaons do not, depending on the refractive index of the matter. For example, pions with momentum 2 GeV/$c$ emit Čerenkov light in the matter if $n > 1.002$, while $n > 1.030$ is necessary for kaons with the same momentum.

The configuration of ACC is shown in Figure 2.11. The ACC consists of 960 counter modules segmented into 60 cells in the $\phi$-direction for the barrel part and 228 modules arranged in 5 concentric layers for the forward endcap part of the detector. All the counters are arranged in a semi-tower geometry, pointing to the interaction point. The possible momentum range of charged particles from $B$ decays depends on the polar angle at Belle due to the asymmetric beam energy, that is, higher momentum particles could come into forward endcap part. In order to obtain good $K/\pi$ separation for the momentum range from 1.2 GeV/$c$ to 3.5 GeV/$c$, the refractive indices of aerogels are selected between 1.01 and 1.028, depending on their polar angle region. A typical single ACC module is shown in Figure 2.12 for barrel and endcap ACC respectively. The Čerenkov light generated in the silica aerogel is fed into one
or two fine mesh photomultipliers (FMPMT) attached to the aerogel radiator modules which are operated in the 1.5 T magnetic field [68]. The total number of PMTs readout channels are 1560 in barrel ACC and 228 in the endcap ACC.

Figure 2.13 shows the measured pulse height distribution for the barrel ACC for $e^{\pm}$ tracks in Bhabha events and $K^{\pm}$ candidates in hadronic events, which are selected by TOF and $dE/dx$ measurements [69].

### 2.3.5 Time of Flight (TOF)

A time of flight (TOF) detector system [70] provides particle information for momentum below 1.2 GeV/c with time resolution 100 ps. It also provides fast timing signals for the trigger system to generate gate signals for ADCs and stop signals for TDCs. The trigger modules attached to the TOF are called Trigger Scintillation Counters (TSC). The counters measure the elapsed time between a collision at interaction point and the time when the particle hits the TOF layer. For the measured flight time ($T$) from TOF, and measured flight length and momentum by CDC track fit, one can estimate mass of each track in an event.
Figure 2.12: Schematic drawing of typical ACC module. (a) barrel and (b) endcap modules.

Figure 2.14 shows the TOF/TSC module. One 5 mm thick TSC layer and one 4 cm thick TOF counter layer with a gap of 1.5 cm are arrayed cylindrically at the position (L) 1.2 m in radius from the interaction point (IP). The scintillators are wrapped with 45 μm thick polyvinyl film for light tightness and surface protection. A total number of 128 TOF counters are placed in φ-sectors and each counter is viewed by the FM-PMT at both ends. One FM-PMT is glued to each TSC at backward end. The total number of TSC counters are 64. The total number of readout channels are 256 for the TOF and 64 for the TSC.

Output pulse from the TOF pass the time-stretcher circuit, which expands the time difference of the TOF pulse and the 64 MHz reference clock by a factor of 20 with readout by the TDCs as shown in Figure 2.15 [71]. By this scheme the timing of the TOF pulse with 25 ps precision using the common TDCs (whose timing precision is 500 ns) can be measured.

Figure 2.16 shows the mass distribution for each track in hadron events, calculated by using the equation

\[ m^2 = \left( \frac{1}{\beta^2} - 1 \right) p^2 = \left( \frac{cT_{\text{obs}}}{L_{\text{path}}} - 1 \right) p^2 \]

where \( m \) is mass of the particle, \( p \) is the momentum and \( L_{\text{path}} \) is the path length of the particle determined from CDC track fit assuming the muon mass. From Figure 2.15
CHAPTER 2. EXPERIMENTAL SETUP

![Graph showing pulse height spectrum for electrons and kaons](image)

Figure 2.13: Pulse height spectrum for electrons and kaons in units of photo electrons (p.e.) observed by the barrel ACC. Kaon candidates are obtained by $dE/dx$ and TOF measurements. The MC expectation are superimposed.

clear peaks corresponding to $\pi^\pm$, $K^\pm$ and protons (p) are seen. The data points are in good agreement with the Monte Carlo prediction (histogram) obtained by assuming $\sigma_{TOF} = 100$ ps.

2.3.6 Electromagnetic Calorimeter (ECL)

When a high-energy electron or photon is incident on a thick absorber, it initiates an electromagnetic cascade as pair production and bremsstrahlung which generate more electrons and photons with lower energy. The longitudinal development of the electromagnetic shower scales with the radiation length $X_0$ of the matter, which is defined as the mean distance over which a high-energy electron loses all but 1/e of its energy by bremsstrahlung. The main purpose of Electromagnetic Calorimeter (ECL) [72] is the detection of photons with high efficiency and good resolutions in energy and position. It also plays a primary role in the electron identification in Belle. Most of these photons are end products of cascade decays and have relatively low
Figure 2.14: Configuration of a TOF module made of two TOF counters and one TSC.
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Figure 2.15: Scheme for the time stretcher for the TOF.

![Diagram of time stretcher for TOF](image)

Figure 2.16: Mass distribution from TOF measurements for particles with momentum below 1.2 GeV/c. Points and histogram show the data and MC distributions respectively.
energies, and thus have good performance below 500 MeV is especially important. Few decay modes also produces photon energies upto 4 GeV, so high resolution is needed to reduce background for these modes. High momentum $\pi^0$ detection requires the separation of two nearby photons and a precise determination of their opening angle. This requires a fine-grained segmentation in the calorimeter.

The overall configuration of ECL is shown in Figure 2.17. It consists of a 8735 Thallium-doped Cesium Iodide scintillating crystal towers. The crystals are typically 30 cm in length, equivalent to 16.2 radiation for photons and electrons. They have inner faces $5.5 \text{ cm}^2 \times 5.5 \text{ cm}^2$ in area; this is a compromise between highly segmented array for precision spacial information and the energy resolution of a single crystal detector. Incident photons pair-produce via interaction with crystal nuclei. The subsequent electron and positron radiate bremsstrahlung photons which then also pair-produce, inducing an EM particle shower within crystals. Coulomb scattering creates a lateral shower spread. The shower proceeds to create more particles until
CHAPTER 2. EXPERIMENTAL SETUP

Table 2.4: Geometrical parameters of ECL.

<table>
<thead>
<tr>
<th>Item</th>
<th>$\theta$ coverage</th>
<th>$\theta$ seg.</th>
<th>$\phi$ seg.</th>
<th>No. of crystals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward endcap</td>
<td>$12.4^\circ - 31.4^\circ$</td>
<td>13</td>
<td>48–144</td>
<td>1152</td>
</tr>
<tr>
<td>Barrel</td>
<td>$32.2^\circ - 128.7^\circ$</td>
<td>46</td>
<td>144</td>
<td>6624</td>
</tr>
<tr>
<td>Backward endcap</td>
<td>$130.7^\circ - 155.1^\circ$</td>
<td>10</td>
<td>64 –144</td>
<td>960</td>
</tr>
</tbody>
</table>

Eventually all the energy is in the form of ionization or excitation photons, which are read out by a pair of silicon PIN photo-diodes couple to the rear of every crystal.

The towers all point to face the PI to minimize the possibility of photons being lost in the dead material between the crystals. The ECL barrel contains 6624 crystals in $12.4^\circ < \theta < 31.4^\circ$, and the backward end-cap 960 and covers $130.7^\circ < \theta < 155.1^\circ$. The total number of readout channels of ECL are 17472.

The other charged particles will also deposit some energy within ECL via ionization. Only photons and $e^\pm$ will interact strongly with the detector material and initiate large showers. The energy resolution of ECL measured as a function of incident photon energy with $3 \times 3$ ECL matrices [72] is given by

$$\frac{\sigma_E}{E} = \frac{0.0066}{E} \oplus \frac{1.53}{E^{1/4}} \oplus 1.18\%,$$

where $E$ is in GeV. Here, the first term is due to the contribution from electronic noise, and second and a part of the third term comes from the shower leakage fluctuations. The third term also induces systematic effects such as the uncertainty of the calibration on crystals. The spatial resolution measured by the photon beams is given by

$$\sigma_X (mm) = 0.27 + \frac{3.4}{E^{1/2}} + \frac{1.8}{E^{1/4}}$$

where $E$ is measured in the units of GeV.

In addition to the measurement of energy of photons and electrons, the ECL plays an important role for the electron identification [73]. The electron identification is
Figure 2.18: (a) $E/p$ and (b) $E_9/E_{25}$ distributions for electrons (solid) and charged pions (dashed). In (a), particle momenta limited to $0.5 < p < 3.0$ GeV/c.

performed by combining the following information:

- Matching between the position of the charged track measured by the CDC and that of the energy cluster measured by the ECL.

- $E/p$, i.e. the ratio of energy measured by the ECL to momentum measured by the CDC.

- $E_9/E_{25}$ at the ECL, i.e. the ratio of ECL shower energy in an array of 3 × 3 crystals to the energy in an array of 5×5 crystals.

- $dE/dx$ in CDC.

- Light yield in the ACC.

The probability density functions (PDFs) for above parameters have been made and then a likelihood ratio for every track has been calculated. Figure 2.18 shows the data distributions for $E/p$ and $E_9/E_{25}$ for the electrons and charged pions. The distributions for electrons are obtained from radiative Bhabha events ($e^+e^- \rightarrow e^+e^- \gamma$) and
those for pions are obtained from $K_S^0 \rightarrow \pi^+\pi^-$ decays. From the MC, the typical electron identification efficiency is estimated to be $92\%$ with the pion mis-identification rate of $0.25\%$ for electrons between 1 GeV/$c$ and 3 GeV/$c$ in the lab frame. The ECL also provides the trigger information and online luminosity information [74].

2.3.7 Solenoid Magnetic Field

A charged particle with a momentum vector at an angle $\lambda$ with respect to the magnetic field direction, will have a trajectory which is described by a helix. The magnitude of the momentum can be determined from the measured radius of curvature of the helix using the relation

$$p = 0.3 \times \frac{qBR}{\cos \lambda},$$

where $q = \pm 1$ is the charge of the particle, $B$ is magnetic field, $R$ is radius of curvature and $p$ is the momentum of particle. To measure particle momentum in the CDC, 1.5 T magnetic field is applied parallel to the beam pipe. The superconducting coil consists of a single layer of a niobium-titanium-copper alloy embedded in a high purity aluminum stabilizer. It is wound around the inner surface of an aluminum support cylinder with 3.4 m in diameter and 4.4 m length. The iron structure also works as an absorber material for the KLM and a support for all of the detector components. The configuration of superconducting magnetic coil is shown in Figure 2.19.

2.3.8 $K_L/\mu$ Detector (KLM)

The $K_L^0/\mu$ detector [75] is designed to detect $K_L^0$ mesons and identify muons. It is constructed from alternating 4.7 cm thick iron plates and 3.7 cm thick active KLM detector plates. The iron provides most of the 3.9 radiation lengths seen by $K_L^0$ mesons, while the detector plates register the passage of ionizing particles. The detector plates consist of two glass-electrode resistive-plate counters (RPC) sandwiched between layers of read-out strips in the $\theta$ and $\phi$ directions. An RPC has an active gaseous region between two highly resistive glass parallel plate electrodes. Charged
2.3. THE BELLE DETECTOR

Figure 2.19: Configuration of the superconducting magnetic coil.

particles ionize a streamer in the gas which results in a local discharge of the resistive plates, including a signal in the read-out strips.

Figure 2.20: KLM detector plate diagram for a) Barrel RPC and b) Endcap RPC.

To identify $K_L^0$'s and muons with high efficiency and low fake rate over a broad momentum range above 600 MeV/c, the $K_L/\mu$ Detector (KLM) is designed. It is the only detector which is outside the solenoid magnetic field. It has two major parts, namely barrel KLM and endcaps (backward and forward) KLM. The barrel shaped region around the interaction point covers an angular range $45^\circ$ - $125^\circ$ in the polar
angle and endcaps in the forward and backward directions extend this range to 20° - 155°. The KLM consists of alternating layers of resistive plate counters (RPCs) and 4.7 cm thick iron plates. There are 15 super layers in barrel and 14 super layers in both forward and backward endcaps. $K^0_L$ particles live long enough to travel beyond the ECL and interact primarily via the strong force. They are detected by the hadronic showers of ionizing particles they induce. Showers initiated in the ECL will continue into the KLM; $K^0_L$ will deposit most of their energy within the iron of the KLM proper. The detector provides position information for the $K^0_L$ but no useful energy information is gained as a significant proportion of the shower will generally not be within the KLM.

Muons on the hand will not interact via the strong force but do have an electromagnetic cross-section; they will lose energy mostly through ionization process. They penetrate the ECL easily and will continue through most of all the KLM. KLM tracks that are able to be matched with a track in the CDC are identified as muons.
2.3.9 Extreme Forward Calorimeter (EFC)

In order to improve the experimental sensitivity to physics processes, the extreme forward calorimeter (EFC) is needed to extend the polar angle coverage by ECL, $17^\circ < \theta < 150^\circ$. The EFC covers angular range from $6.4^\circ < \theta < 11.5^\circ$ in the forward direction and $163.3^\circ < \theta < 171.2^\circ$ in the backward direction. The EFC is attached to front faces of cryostats of the KEKB accelerator compensation solenoid magnets surrounding the beam pipe. The EFC is also required as a beam mask to reduce backgrounds for CDC. In addition, the EFC is used for a beam monitor in the KEKB control and a luminosity monitor for Belle experiment.

The view of EFC is shown in Figure 2.22. Since the EFC is placed in the very high radiation level area around the beam pipe near the interaction point, so it is required to be radiation hard. So, the Bi$_4$Ge$_3$O$_{12}$ (BGO) crystal has been adopted which has the property of radiation hardness at megarad level and has excellent $e/\gamma$ energy resolution of $(0.3 - 1.0)%/\sqrt{E}$ GeV [76]. Both forward and backward EFC
consist of BGO crystals segmented into 5 regions in \( \theta \)-direction and 32 regions in the \( \phi \)-direction in order to provide better position resolution. Typical cross-section of a crystal is about \( 2 \times 2 \) cm\(^2\) with 12\(X_0\) for the forward and 10.5\(X_0\) in backward region, where \( X_0 \) is the radiation length.

### 2.4 The Trigger

The trigger system in Belle experiment records or discards the hit signals on each sub-detector. Since at higher luminosity, the physics events including \( B \bar{B} \) events are produced at a very high rate, but also expect a large beam background due to the high beam current. Therefore, the trigger system which selects useful events from many unnecessary events in the online level plays an important role.

Figure 2.23 shows a schematic view of the Belle Level 1 trigger system which is composed of the sub-trigger system and the central trigger system called the Global
2.4. THE TRIGGER

Decision Logic (GDL) [77]. The sub-trigger system is based on two categories, track triggers and energy triggers. The CDC and TOF/TSC provide the trigger signals from charged particles, while the ECL trigger system provides triggers based on total energy deposit and cluster counting of crystal hits. The KLM and EFC trigger systems provide additional trigger information and the EFC triggers are used for tagging two-photon events as well as Bhabha events. The sub-triggers process event signals in parallel and provide trigger information to the GDL, where all information are combined to distinguish physics and background events and to characterize an physics event type. Information from the SVD is not implemented in the present trigger arrangement. The trigger system provides the trigger signal with the fixed time of 2.2 $\mu$s after the event occurrence, which used to be restricted by buffer size of the obsolete SVD module. Since process time of GDL is 350 ns, the sub-triggers are required to issue the signal within 1.85 $\mu$s of the event occurrence. The Belle trigger system, including the sub-trigger system, is operated in a pipelined manner with clocks synchronized to the KEKB accelerator RF signal. Fig 2.23 shows a schematic view of the GDL, which consists of Input Trigger Delay (ITD), Final Trigger Decision Logic (FTDL) and TiMing Decision Logic (TDL) modules. Timing of the sub-trigger signals is adjusted to overlap each other, by the ITD module, which therefore assigns larger delay to faster signal. Using thus adjusted signals the FTDL judges event occurrence or the type of the physics event with 32 MHz frequency. Pre-Scaled aNd Mask (PSNM) modules to prescale or mask the input signals are used. 40 logics are define which express physics events, for example if CDC nearly back-to-back tracks and KLM hits signals are detected at the same time, the FTDL identifies $e^+e^- \rightarrow \mu^+\mu^-$ event occurrence and send a signal to the next stage. Each of the multitrack, total energy, and isolated cluster counting trigger provides more than 95% efficiency for multi-hadronic data sample. As a result the combined efficiency is more than 99.5%. In summary Belle has two trigger levels: Level-1 (implemented in hardware) and Level-3 (implemented in software).
CHAPTER 2. EXPERIMENTAL SETUP

2.4.1 Level-1 Trigger

This is based on the information in the form of track triggers and energy triggers from the following detectors:

- **CDC**: main trigger in the trigger system and is divided into an \( r - \phi \) trigger and a \( z \) trigger. The \( r - \phi \) trigger identify the tracks originating from the IP along with discriminating the track transverse momentum \( p_t \) and on the direction and number of tracks. The \( z \) trigger estimates the \( z \) position of the tracks to suppress tracks from beam-gas events, from interactions with material around the beam pipe or from cosmic rays.

- **TOF**: provides timing signals with a time jitter less than 10 ns and information on event multiplicity and topology.

- **ECL**: on neutral and charged tracks using a total energy trigger and a cluster count trigger.

- **KLM**: saves many events containing muon tracks as possible.

- **EFC**: provides Bhabha scattering and \( \gamma \gamma \) event samples used to monitor the luminosity.

2.4.2 Level-3 Trigger

The level-3 trigger reduces the number of events to be stored on the disk for further analysis. It reduces the event rate by about 50% by selecting events with at least one track with \( z \) impact parameter less than 5 cm and at least 3 GeV energy deposition in the ECL. It reduces the overall data rate by 50-60% while retaining 99% of interesting physics events.
2.5 Data Acquisition System (DAQ)

The distributed-parallel system is devised for the Belle Data Acquisition System [78] in order to satisfy the requirements so that it works at 500 Hz with a deadtime fraction of less than 10%. The global scheme of the system is shown in Figure 2.24. The entire system is segmented into seven subsystems running in parallel, each handling the data from a sub-detector. Data from each subsystem are combined into a single event record by an event builder, which converts “detector-by-detector” parallel data streams to an “event-by-event” data river. The event builder output is transferred to an online computer farm, where another level of event filtering is done after the fast event reconstruction. The data are then sent to a mass storage system located at the computer center via optical fibers. A typical data size of a hadronic event by $B\bar{B}$ or $q\bar{q}$ production is measure to be about 30kB, which corresponds to the maximum data transfer rate of 15 MB/s.
2.6 Chapter in a Nutshell

In this Chapter introduction to Belle experiment is provided along with detailed description of the KEKB accelerator and Belle detector. KEKB accelerator is an asymmetric energy $e^+e^-$ collider with $e^-$ having energy 8 GeV and $e^+$ having energy 3.5 GeV. The center-of-mass (CM) energy $\sqrt{s}$ is $\sqrt{4E_{e^+}E_{e^-}} = 10.58$ GeV, which is equal to the mass of $\Upsilon(4S)$ resonance. $\Upsilon(4S)$ decays into $B\bar{B}$ pairs, which further decays into daughter particles, and these particles are detected by the Belle detector.

The Belle detector detects fairly stable particles, namely $e^\pm$, $\mu^\pm$, $K^\pm$, $p$, $\bar{p}$, $\gamma$ and $K_L$. Belle detector consists of sub-detectors: Silicon Vertex Detector (SVD), Central Drift Chamber (CDC), Aerogel Cerenkov Counter (ACC), Time-of-Flight (TOF), Electromagnetic Calorimeter (ECL) and $K_L$ and Muons (KLM) detector. The detector covers the $\theta$ region extending from $17^\circ - 150^\circ$. The part of the uncovered small angle region is instrumented with Extreme Forward Calorimeter (EFC). Table 2.5 summarizes the detection of various particle in the Belle detector components.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Energy</th>
<th>Momentum</th>
<th>Position</th>
<th>Particle Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+(e^-)$</td>
<td>ECL</td>
<td>CDC</td>
<td>SVD, CDC</td>
<td>ECL, ACC, TOF, CDC</td>
</tr>
<tr>
<td>$\mu^-(\mu^+)$</td>
<td>CDC</td>
<td>CDC</td>
<td>SVD, CDC</td>
<td>KLM, ACC, TOF, CDC</td>
</tr>
<tr>
<td>$\pi^-(\pi^+)$</td>
<td>CDC</td>
<td>CDC</td>
<td>SVD, CDC</td>
<td>ACC, TOF, CDC</td>
</tr>
<tr>
<td>$K^-(K^+)$</td>
<td>CDC</td>
<td>CDC</td>
<td>SVD, CDC</td>
<td>ACC, TOF, CDC</td>
</tr>
<tr>
<td>$p(\bar{p})$</td>
<td>CDC</td>
<td>CDC</td>
<td>SVD, CDC</td>
<td>ACC, TOF, CDC</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>ECL</td>
<td>ECL</td>
<td>ECL, CDC</td>
<td></td>
</tr>
<tr>
<td>$K_L$</td>
<td>KLM</td>
<td>KLM</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3
Analysis Tools

We have carried analysis of $B^\pm \rightarrow \psi(2S)\pi^\pm$, $B^\pm \rightarrow \psi(2S)K^\pm$, $B \rightarrow \chi_cK$, $B \rightarrow \chi_cK$ and $B \rightarrow X(3872)K$ decay modes. Some of the strategy (or techniques used) are common to these analyses, and are build up in this Chapter. This Chapter will act as base for the next Chapters. In this Chapter, identification and reconstruction of the particles which are used in this thesis are explained.

3.1 Blind Analysis

Blind analysis strategies, designed to minimize the possibility of bias in experimental results, have become increasingly popular for high energy physics analyses in the recent years [79]. A blind analysis is a measurement which is performed without looking at the answer, and the optimal way to reduce or eliminate the experimenter’s unintended bias [80]. This is done in order to avoid the unintended influence on a measurement toward prior results or theoretical expectations. As we known that the measurement depends (within the statistical uncertainty) upon the value of cut, and to measure a quantity (e.g., first time like evidence or observation), we may tune our cuts on data such that we get the needed significance (which is obviously a bias).

All the analysis carried out in this thesis are performed by blinding the signal region in data. Which means signal box (in data) is not seen until all the cuts/criteria are optimized and also, it is demonstrated that the procedure in the study is sensitive
and robust enough to search for the signal. We validate our measurements by checking our results in number of ways which will be unblinded at the appropriate time in this thesis.

3.2 Analysis Procedure

Procedure carried out for both of the analyses can be summarized using the following flowchart (which is over simplified):
3.3 Event selection

The Belle data consists of a large number of events which not only come from $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ but also from several other processes such as $\tau$ pair, Bhabha, continuum events $e^+e^- \rightarrow q\bar{q}$ (where $q$ stands for $u$, $d$, $s$ and $c$), two-photon, and beam gas interactions, which occurs with similar or large cross sections than $BB$ production.

In this study, we need only events coming from $B\bar{B}$. So, we will use the psi-skim data based on HadronBJ event selection [81]. Events with $B$ mesons candidates are selected by first applying general hadronic events selection criteria which include the following requirements :-

- At least three charged tracks originating from an event vertex consistent with the interaction region.

- Sum of charged track’s momenta and the sum of cluster energy (total visible energy in the rest frame, $E_{vis}$) to be greater than $0.2\sqrt{s}$ (where $\sqrt{s}$ is total CM energy).

- Absolute value of $z$-component sum for charged track momentum and cluster energy in the rest frame, $|p_z| \leq 0.5\sqrt{s}/c$.

- Total ECL energy between $0.025\sqrt{s}$ and $0.9\sqrt{s}$.

- Invariant mass of oppositely charged tracks with momentum $> 0.8 \text{ GeV}/c$, in the range of 2.5 - 4.0 GeV/$c^2$, is counted as a $\psi$ candidate. Here $\psi$ refers to $J/\psi$ or $\psi(2S)$. Number of such $\psi$ candidates should be $\geq 1$.

- All selected charged tracks are required to satisfy impact parameter cuts: distance of closest approach to the interaction point (IP) along the beam direction $|dz| < 5 \text{ cm}$ and in the transverse plane ($xy$-plane) $|dr| < 2.5 \text{ cm}$. 
Figure 3.1: $dr$ and $dz$ of the tracks (normalized to unity), with arrows showing the
cuts used in the analyses.

3.4 Data sample

Analyses of $B^\pm \to \psi(2S)\pi^\pm$, $B^\pm \to \psi(2S)K^\pm$, $B \to \chi_{c1}K$, $B \to \chi_{c2}K$ and $B \to X(3872)K$ decay modes were carried out at separate time, data sample used for them
are not same (as we use full Belle data set available at that time):

- $B^\pm \to \psi(2S)\pi^\pm$ and $B^\pm \to \psi(2S)K^\pm$: 604 $fb^{-1}$ ($657 \times 10^6$ $B\bar{B}$ pairs)
- $B \to \chi_{c1,2}K$ and $B \to X(3872)K$: 703 $fb^{-1}$ ($773 \times 10^6$ $B\bar{B}$ pairs)

The number of $B\bar{B}$ events in hadronic data sample are calculated as,

$$N_{BB} = N_{on} - \frac{\epsilon_{on}}{\epsilon_{off}} \cdot \frac{L_{on}}{L_{off}} N_{off}$$  \hspace{1cm} (3.1)

where, $N_{on}(N_{off})$, $\epsilon_{on}(\epsilon_{off})$ and $L_{on}(L_{off})$ are the number of events, $q\bar{q}$ continuum
events detection efficiency and the luminosity in the on-resonance (off-resonance)
data.

The 151.96 Million $B\bar{B}$ pairs have been accumulated using 3 layers SVD configuration and the rest accumulated with a 4-layers SVD configuration (Section 2.3.2). Due
to this, we have to be careful while the calculation of efficiency and the background estimation is performed, as difference in particle identification will lead to different efficiency and background source. This difference is studied for both of the studies, while it is elaborately performed for $B^- \rightarrow \psi(2S)\pi^-$ analysis.

3.5 Event generation

For Monte Carlo (MC) study, the EvtGen [82] as an event generator is used. These generated events are made to pass through the full detector simulation performed using GEANT package [83] (which accommodate the geometry of each detector components). Also, background (determined in data taking run) is added in these generated (simulated) events, which comes from the beam and electronic noise in the detector components. This procedure is followed for all the analysis. Decay files are written for each analysis separately (to generate the decay mode using the decay channel taken for the study of the particular decay channel) using the appropriate package available in the EvtGen. In cases where proper generation packages are not available, possible difference is taken care by adding it to the systematic.

3.6 Particle Identification

$B$ meson reconstruction is done from the decay particles (daughters and granddaughters) depending upon their stability (lifetime) and identification (in the detector) as they are more stable and can be easily identified in the detector. The particles used to reconstruct $B$ meson in the analyses undertaken are: $e$, $\mu$, $K^-$, $\pi^-$, $\pi^0$, $K_S^0$ and $\gamma$.

3.6.1 $\pi/K$ Selection

Charged $\pi/K$ selection is based on the information from ACC (number of Cerenkov photons), TOF (time of flight measurement) and CDC ($dE/dx$ measurement) detectors. The pion (kaon) identification is based upon the likelihood ratio (which is
defined as: $\mathcal{R}(\pi(K)) = \mathcal{L}_{\pi(K)}/(\mathcal{L}_{\pi} + \mathcal{L}_{K})$ calculated from the mentioned sub-detectors measurement.

In our analysis of $B^- \to \psi(2S)\pi^- \to \psi(2S)K^-$ decay, charged tracks with $\mathcal{R}_\pi > 0.85$ ($\mathcal{R}_K > 0.85$) are identified as $\pi^- (K^-)$. This requirement is 88.0% (82.6%) efficient for $\pi$ ($K$) with a $K$ ($\pi$) fake rate of 6.0% (3.7%). While, in our analysis of $B^- \to \chi_{c1,2}K^-$ and $B^- \to X(3872)K^-$ decays, kaon candidates are separated from the pions by cut made on the kaon likelihood ratio, $\mathcal{R}_K > 0.6$ which is 88% efficient for kaon, with a pion fake rate of 10%.

Charged pions identified by requiring the $\mathcal{R}_\pi > 0.4$ are used for the reconstruction of $\psi(2S)$.

![Graph showing $\mathcal{R}_K$ distribution in data (normalized to unity), arrows showing the cuts used in the analyses.]

3.6.2 $\mu$, $e$ Identification

Muons are identified on the basis of track penetration depth and hit scatter pattern in the KLM system. The track is identified as muon if the criteria of $\mathcal{L}_\mu > 0.1$ is
3.6. PARTICLE IDENTIFICATION

satisfied. While electrons are identified on the basis of $L_e > 0.01$; which uses $dE/dx$
in CDC, $E/p$ ratio ($E$ is the energy deposited in the ECL and $p$ is the momentum
measured in the CDC and SVD), shower shape in the ECL and Čerenkov photon in
the ACC.

3.6.3 Reconstruction of $K_S^0$

The $K_S^0$ reconstruction is done using two oppositely charged pions ($\pi^+$ and $\pi^−$). The
selection criteria of $K_S^0$ is based upon the four variables in three momentum ranges
of $K_S^0$ candidate [84].

Table 3.1: $K_S^0$ selection cuts in the three momentum ranges.

<table>
<thead>
<tr>
<th>Momentum (GeV/$c^2$)</th>
<th>$dr$ (cm)</th>
<th>$d\phi$ (radian)</th>
<th>$z$ dist. (cm)</th>
<th>$fl$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.5</td>
<td>&gt; 0.05</td>
<td>&lt; 0.3</td>
<td>&lt; 0.8</td>
<td>-</td>
</tr>
<tr>
<td>0.5 – 1.5</td>
<td>&gt; 0.03</td>
<td>&lt; 0.1</td>
<td>&lt; 1.8</td>
<td>&gt; 0.08</td>
</tr>
<tr>
<td>&gt; 1.5</td>
<td>&gt; 0.02</td>
<td>&lt; 0.03</td>
<td>&lt; 2.4</td>
<td>&gt; 0.22</td>
</tr>
</tbody>
</table>

- $dr$ : is smaller of $dr1$ and $dr2$, which are the smallest approach at the IP to the
two tracks in $x - y$ plane.

- $d\phi$: is the azimuthal angle between the momentum vector and the decay vertex
  vector of the $K_S^0$ candidate.

- $z$ dist: is the distance between the two daughter tracks at their interaction
  point.

- $fl$: is the flight length of $K_S^0$ candidate in $x - y$ plane.

The $K_S^0$ candidates within the mass range of $0.482$ GeV/$c^2$ < $M_{\pi\pi}$ < $0.514$ GeV/$c^2$
are kept for further use while rest are rejected.
Figure 3.3: Mass distribution of dipion (normalized to unity) identified as $K_S^0$, arrows shows the cuts used in the analysis.

### 3.6.4 $\gamma$ Selection

The $\gamma$ is a neutral candidate, hence they can not be identified directly. In Belle detector, the $\gamma$ candidate identification is based upon their EM interactions (inside the ECL by a shower production mechanism of $\gamma$). Selection criteria applied on the EM shower is $E_9/E_{25} > 0.85$, where $E_9$ ($E_{25}$) is energy deposited in the $3 \times 3$ ($5 \times 5$) crystals in the ECL. Figure 3.4 shows $E_\gamma$ distribution for the different signal MC samples.

### 3.6.5 $\pi^0$ Reconstruction

Neutral pions are reconstructed by combining the photon with another photon pair inside that event with a condition that their invariant mass should lie within $\pm 16$ MeV/$c^2$ of the nominal $\pi^0$ mass. The photon momenta are improved (as $\gamma$ momentum is difficult to calculate due to poor resolution) by applying a mass constraint. Also, the energy of the photons is taken to be greater than 60 MeV in the barrel and the end-cap region of the ECL.
3.7. RECONSTRUCTION OF PARTICLES

Figure 3.4: $E_\gamma$ distribution (normalized to unity) for $B^- \to X(3872)(\to \psi(2S)\gamma)K^-$ (blue), $B^- \to \chi_{c1}K^-$ (red), $B^- \to \chi_{c2}K^-$ (orange) and $B^- \to X(3872)(\to J/\psi\gamma)K^-$ (magenta). These distributions are from signal MC samples.

3.7 Reconstruction of $J/\psi$

Using the identified particles (defined in Previous Section), intermediate and final states can be reconstructed.

3.7.1 Reconstruction of $J/\psi$

The $J/\psi$ candidate is reconstructed via its decay mode $J/\psi \to \ell^+\ell^-$, where $\ell$ stands for $e$ or $\mu$. There is a loss of energy from electron, in the form of the emission of bremsstrahlung photons. The four momenta of the photons within 0.05 radian of $e^+$ or $e^-$ direction are included in the invariant mass calculation as a correction for the emission of bremsstrahlung photons. However, even after this correction, the $J/\psi(e^+e^-)$ signal shape is still skewed, this is taken into account by using an asymmetric invariant mass window 2.95 (3.03) GeV/$c^2 \leq M_{ee(\mu\mu)} \leq 3.13$ GeV/$c^2$ to define the $J/\psi$ candidate in the electron (muon) channel. The vertex fit and
Figure 3.5: Reconstruction of $\pi^0$ from two gammas, arrows shows the cuts used in the analyses. Plot is normalized to unity.

Figure 3.6: $J/\psi$ reconstructed from $e^+e^-$ and $\mu^+\mu^-$, arrows shows the cuts used in the analyses. Plots are normalized to unity.
a kinematic mass constrain is applied to the selected $J/\psi$ candidates in order to improve the momentum resolution.

![Graph with $M_{\mu\mu}$ and $M_{J/\psi\pi\pi}$ distributions](image)

Figure 3.7: $\psi(2S)$ reconstructed from $\ell^+\ell^-$ and $J/\psi\pi^+\pi^-$, arrows shows the cuts used in the analyses. Plots are normalized to unity.

### 3.7.2 Reconstruction of $\psi(2S)$

The $\psi(2S)$ is reconstructed using two of its decay modes: $\psi(2S) \to \ell^+\ell^-$ and $\psi(2S) \to J/\psi\pi^+\pi^-$. For $\psi(2S) \to \ell\ell$ selection, $3.55 \ (3.65) \ \text{GeV}/c^2 \leq M_{ee(\mu\mu)} \leq 3.75 \ \text{GeV}/c^2$, defines the $\psi(2S)$ candidate in the electron (muon) channel; criteria is same for $e$ and $\mu$ identification as for $J/\psi \to \ell\ell$. Reconstruction procedure of $\psi(2S) \ (\to \ell\ell)$ is identical to that of $J/\psi \ (\to \ell\ell)$.

For $\psi(2S) \to J/\psi\pi^+\pi^-$ decay, reconstruction is done by combining two oppositely charged pions with the reconstructed $J/\psi$. To reduce the combinatorial background coming from low momentum pions, dipion mass is taken to be greater than 0.4 GeV/$c^2$. Also, $J/\psi$ candidates are selected with momentum less than 2 GeV/$c^2$ to avoid $J/\psi$ coming from $B$ meson decays. A mass constrained fit is applied to the $\psi(2S)$ candidates in the mass window of $0.578 \ \text{GeV}/c^2 < \Delta M \equiv M_{J/\psi(\ell\ell)\pi\pi} - M_{J/\psi(\ell\ell)} < 0.598$
GeV/c^2.

3.7.3 Reconstruction of \( \chi_{c1}, \chi_{c2} \) and \( X(3872) \)

The \( \chi_{c1,c2} \) and \( X(3872) \) candidates are reconstructed by combining \( J/\psi \) with \( \gamma \) candidates. The \( X(3872) \) is also reconstructed by combining \( \psi(2S) \) and \( \gamma \) candidates. \( E_\gamma > 60 \text{ MeV} \) is used for reconstruction of \( \chi_{c1,c2} \) and \( X(3872) \) particle from \( J/\psi \) and \( \gamma \); while \( E_\gamma > 100 \text{ MeV} \) for \( X(3872) \) reconstructed from \( \psi(2S) \) and \( \gamma \). In case of \( X(3872) \rightarrow \psi(2S)\gamma \), tight cut on \( E_\gamma \) is used, as most of the background is due to low energy \( \gamma \). This cut applied on \( E_\gamma \) (this stage) is just for preselection, and will be optimized in the later part of the analysis.

To identify \( \chi_{c1,c2} \) or \( X(3872) \) we use \( M_{\psi\gamma} \equiv M_{\ell\ell\gamma} - M_{\ell\ell} + m_\psi \), where \( M_{\ell\ell\gamma} \) (\( M_{\ell\ell} \)) is the reconstructed mass of \( \psi\gamma \) (\( \psi \)) and \( m_\psi \) is the PDG mass of \( \psi \). Here \( \psi\gamma \) refers to \( \chi_{c1,c2} \) or \( X(3872) \) depending upon reconstruction of the particle. The \( \gamma \) scaling is used to improve the resolution of \( M_{\psi\gamma} \).

3.7.4 Reconstruction of \( B \)

The reconstruction of the \( B \) meson is done by combining the reconstructed daughters depending upon the analyses. For \( B^\pm \rightarrow \psi(2S)\pi^\pm \) (or \( B^\pm \rightarrow \psi(2S)K^\pm \)) decay, \( \psi(2S) \) is combined with \( \pi^- \) (or \( K^- \)). Similarly, for \( B \rightarrow \chi_{c1,c2}K \) (or \( B \rightarrow X(3872)K \)) decay, we combine \( \chi_{c1,c2} \) or \( X(3872) \) candidate with a charged \( K \) or a neutral \( K_S^0 \) candidate (based upon the study). These decays are two body and can be in general written as

\[
B \rightarrow D_1 + D_2
\]

where \( D_1 \) and \( D_2 \) are two daughters of \( B \) meson. Using this terminology, we can define the variables used to identify the \( B \) meson. The beam constrained mass; \( M_{bc} \) is defined as \( M_{bc} = \sqrt{E_{\text{beam}}^2 - (p_{D_1} + p_{D_2})^2} \). \( \Delta E \) is defined as \( \Delta E \equiv (E_{D_1} + E_{D_2}) - E_{\text{beam}} \), where \( E_{\text{beam}} \) is the beam energy in the center of mass (CM) frame and \( p_{D_1(D_2)} \), \( E_{D_1(D_2)} \) are momentum and energy of the \( D_1 \) (\( D_2 \)) candidate in the CM frame of \( \Upsilon(4S) \).

In an ideal case \( \Delta E \) should peak around zero which is described by the sum of two
3.8. ANALYSIS STRATEGY

Gaussians (as in the case of $B^- \to \psi(2S)K^-$, as we are able to reconstruct without any loss of energy). However, due to the radiative losses in the decay of $B \to \chi_{c1,2}K$ and $B \to X(3872)K$, there is a long tail at negative $\Delta E$ region and this shape can be well represented by a Crystal Ball line shape [85].

3.8 Analysis Strategy

Different strategies are used for the analyses based on the sensitivity and the need of the analysis.

3.8.1 The $B^- \to \psi(2S)\pi^-$ Decay

The $\Delta E$ distributions peaks around zero and represented by the sum of two Gaussians, while the $M_{bc}$ distribution with Gaussian shape peaking around the $B$ meson mass [3].

![Diagram showing MC illustration of extraction of the signal using $\Delta E$ projection in $M_{bc}$ signal window for the $B^- \to \psi(2S)\pi^-$ decay.](image)

The grand selection for the $B$ mesons candidates was taken as $-0.2 \text{ GeV} < \Delta E < \Delta E_{\text{cut}}$.
0.2 GeV and $M_{bc} > 5.20$ GeV/c$^2$ region. A valid signal window for $M_{bc}$ is defined as $5.27 \leq M_{bc} \leq 5.29$ GeV/c$^2$. For illustration of how signal looks like, please see Figure 3.8.

With all above selection criteria, a small fraction of $B^\pm \rightarrow \psi(2S)\pi^\pm$ decays produce multiple candidates. There are 7.1% (2.3%) multiple candidate in $B^- \rightarrow \psi(2S)(\rightarrow J/\psi\pi\pi)\pi^- (B^- \rightarrow \psi(2S)(\rightarrow \ell\ell)\pi^-)$. In order to select best $B$ out of the multiple $B$ candidates two choices are studied:
1. Closest pion track origination to the vertex of the $\psi(2S)$.
2. $M_{bc}$ closest to the nominal $B$ mass.

It is found out that we get $\sim 3\%$ more efficiency in case of $B \rightarrow \psi(2S)(\rightarrow J/\psi\pi\pi)\pi$ (while 0.5% more in case of $B \rightarrow \psi(2S)(\rightarrow \ell\ell)\pi$) when $M_{bc}$ is used as the best $B$ candidate selection criteria. As, 1d $\Delta E$ is used to extract the signal yield. Therefore $M_{bc}$ closest to nominal $B$ mass is used to select the best $B$ from the multiple candidates.

3.8.2 The $B \rightarrow \chi_{c1,2}K$ and $B \rightarrow X(3872)K$ Decay

In this analysis, $\chi_{c1} \rightarrow J/\psi\gamma$ is used as control sample due to the same final state as of $\chi_{c2}$ (or $X(3872)$). $M_{\psi\gamma}$ is used to extract the signal yield, for illustration of signal MC please see Figure 3.9.

The scaling of $\gamma$ energy (equivalent to the $\Delta E$ constraint) is used in order to improve the $\gamma$ resolution. This is based on the assumption that the reconstructed $B$ candidate has a true value of $\Delta E$ at zero while the spread in the distribution of the $\Delta E$ is due to the poor gamma energy resolution. The difference in the $\Delta E$ is then used to scale the energy of $\gamma$. For this, events in the $\Delta E$ window of $-60 \text{ MeV} < \Delta E < 40 \text{ MeV}$ are used (this window is optimized in the later part of analysis).

Figure 3.10 shows the mass distribution before and after applying the $\gamma$ scaling. As seen from the figure, there is a clear improvement in the resolution, earlier the shape is defined by a CB line shape (due to the poor $\gamma$ resolution) but after $\gamma$ scaling, the distribution can be modeled by a sum of two Gaussian.
3.9. BACKGROUND STUDY AND ITS REDUCTION

Figure 3.9: MC illustration of how signal will look like in $M_{J/\psi\gamma}$ variable in the $\Delta E$ and $M_{bc}$ signal window for the $B^- \rightarrow X(3872)(\rightarrow J\psi\gamma)K^-$ decay.

3.9 Background Study and it’s Reduction

From the cuts applied in Section 1.3, we have already reduce lot of events (which are irrelevant and can be a source of background for the analyses taken up in this thesis). To further suppress the background coming from the continuum (relative to $B\bar{B}$ events), ratio of second to zeroth Fox-Wolfram moments [86]

$$R_2 = \frac{H_2}{H_0}, \quad \text{where} \quad H_i = \frac{\sum_{ij} |\vec{p}_i||\vec{p}_j|P_i(\cos \theta_{ij})}{(\sum_i E_i)^2}$$

is used; which is 0 for a perfect spherical event. Here, $P_i$ is the Legendre Polynomial and $\vec{p}_i$ ($\vec{p}_j$) represents the four momentum of the particles while $\Sigma_i E_i$ represents the visible energy of the particles in the event. The $B\bar{B}$ mesons are produced almost at rest and their decay axis are uncorrelated. So, $B\bar{B}$ events are almost spherical in shape and can be distinguished from the jet like continuum events of $u$, $d$, $s$ or $c$. To reduce the continuum background $R_2$ parameter is chosen to be less than 0.5.

As we are dealing with $B$ meson whose final decay state has one $J/\psi$ or $\psi(2S)$, most of the background contribution is expected to come from decays where $J/\psi$
Figure 3.10: The mass distribution \( M_{J/\psi \gamma} \) of \( \chi_{c1} \rightarrow J/\psi \gamma \), shape before \( \gamma \) scaling (red) and after applying \( \gamma \) scaling (blue).

and \( \psi(2S) \) are present. To study these background, \( B \rightarrow J/\psi X \) and \( B \rightarrow \psi(2S)X \) inclusive MC samples are analyzed, which corresponds to \( 387.72 \times 10^8 \) \( B\bar{B} \) pairs. The \( B \rightarrow J/\psi X \) \( (B \rightarrow \psi(2S)X) \) inclusive MC samples includes all the possible/known decay modes of \( B \), which has \( J/\psi \) \( (\psi(2S)) \) meson in their final state. Background study and the reduction techniques used in the analyses will be explained at the appropriate time in the coming chapters for a better continuity.

3.10 Systematic Uncertainty

In statistical context, the term systematic uncertainty usually arises where the sizes and directions of possible errors are unknown. For our measurements we are using MC, particle identification techniques (which may not be 100% perfect) and other measurements. These error are taken into account by treating them as the systematic uncertainty in our measurements. In this Section, systematic uncertainty estimation (common to the analyses taken in this thesis) are explained. Possible systematic errors can come from the following sources:
3.10. SYSTEMATIC UNCERTAINTY

- **$K/\pi$ identification**
  Kaons and pions have uncertainty on their identification and to estimate it Belle official PID group estimation (based upon the $D^{*+} \to D^0(K^-\pi^+)\pi^+_\text{slow}$ study) is used [87]. Correction factor for the difference in kaon (pion) efficiency between data and MC is obtained. This correction is used to correct the efficiency while error on it is included as the systematic uncertainty coming from the $K/\pi$ identification.

- **Charged track systematic**
  Charged particle track reconstruction has an uncertainty of about $\sim 1\%$ per track, estimated on the basis of partially reconstructed $D^{*-} \to \bar{D}^0(K^0_S(\pi^-\pi^+)\pi^+\pi^-)$ study done by Belle’s official tracking group. Due to the correlation, the uncertainty due to each tracks are added linearly.

- **Secondary Branching Fraction ($B$)**
  Secondary branching ratio ($B$ measurements done by others or world average) are used for the calculation of the primary $B$. These secondary branching fractions have some uncertainty (due to the limited statistics and systematic uncertainty) in the used measurements and are taken as the systematics coming from the secondary $B$.

- **$\gamma$ systematic**
  2.0% systematic uncertainty is estimated (another study done at Belle based on $ee\gamma$ [88]) to be coming from $\gamma$.

- **$K^0_S$ reconstruction**
  4.5% is estimated to be the uncertainty on the reconstruction of $K^0_S$. This study (done at Belle [89]) is based upon $D^+ \to K^0_S\pi^+$ and $D^+ \to K^-\pi^-\pi^+$ sample.

- **Lepton identification**
  There can be a difference between lepton identification in data and MC, this difference is taken into account. To get this correction factor, $J/\psi \to \ell^+\ell^-$ sample are used (more details can be found in Appendix A).
• Efficiency
Due to the limited statistical sample of signal MC, there will be sizeable statistical uncertainty on the calculated efficiency and this uncertainty is taken into account in systematic uncertainty.

• $N_{B\bar{B}}$
This systematic is due to the uncertainty on $N_{B\bar{B}}$ value. Official number of $B\bar{B}$ pairs used is $771.6 \pm 10.6 \times 10^6$, which gives systematic uncertainty of 1.4%.

• Systematic due to PDF
Signal extraction is done by performing fits to the data. Signal yield depends upon the parameters fixed in the fit, due to which there will be a systematic uncertainty coming from the different components of the PDF. It will be different for each analyses depending upon the parametrization of the PDF.

In addition to these, there are also some other systematic uncertainties (depending upon the analysis) and are explained at the appropriate time in order to avoid any confusion.

### 3.11 Chapter in a Nutshell

In this Chapter introduction to the analysis tools used to perform the analysis in this thesis have been explained. We use the identified tracks of $e^\pm$, $\mu^\pm$, $K^\pm$, $\pi^\pm$ and $\gamma$ to reconstruct $J/\psi$, $\psi(2S)$, $K^0_S$, $\pi^0$, $\chi_{c1}$, $\chi_{c2}$ and $X(3872)$. We reconstruct $B$ meson from $\psi(2S)K^\pm$ using $\Delta E$ with $M_{bc} > 5.27$. In our analysis of $B \to \chi_{c1,2}(\to J/\psi\gamma)K$ and $B \to X(3872)(\to \psi\gamma)K$ (here $\psi$ can be $J/\psi$ and $\psi(2S)$), $M_{\psi\gamma}$ is used to identify the decay mode under study. For background study large sample of $B \to \psi X$ inclusive MC samples are used.
Analysis of \( B^{\pm} \rightarrow \psi(2S)\pi^{\pm} \) decay mode has been described in this Chapter. \( B^{\pm} \rightarrow (2S)\pi^{\pm} \) decay is a Cabibbo- and color-suppressed decay mode which has not been seen yet by any experiment. It is expected to have branching fraction of 5% to the that of \( B(B^{\pm} \rightarrow \psi(2S)K^{\pm}) \) \cite{12,15,16}. In this Chapter, the measurement of the branching fraction \( B(B^{\pm} \rightarrow \psi(2S)\pi^{\pm}) \) is explained (this measurement is carried out for the first time) and also we have searched for direct \( CP \) violation in this decay mode (which can provide some hint of New Physics). In addition to this analysis, \( B^{\pm} \rightarrow \psi(2S)K^{\pm} \) decay mode which is a control sample of the above decay is also presented in this Chapter.

### 4.1 Reconstruction

For the search of \( B^{\pm} \rightarrow \psi(2S)\pi^{\pm} \) decay, the \( B \) meson reconstruction is done by combining the reconstructed \( \psi(2S) \) meson with the track identified as \( \pi^{-} \) (or \( K^{-} \)), as explained in the previous Chapter (Section 3.8.1). The \( \psi(2S) \) reconstruction is done from the following two of it’s decay modes (as reconstruction is much cleaner):

- \( \psi(2S) \rightarrow \ell\ell \), here \( \ell \) stands for electrons and muons.
- \( \psi(2S) \rightarrow J/\psi\pi^{+}\pi^{-} \), here \( J/\psi \) is reconstructed using \( \ell\ell \) (explained in Section 3.7.2).

\[ B^{\pm} \rightarrow \psi(2S)\pi^{\pm} \]
CHAPTER 4. $B^\pm \rightarrow \psi(2S)\pi^\pm$ ANALYSIS

The reconstruction of $B$ meson is not 100% efficient due to the detector acceptance and the software reconstruction limitations. To study the reconstruction efficiency, Monte Carlo (MC) study is performed. For MC study, 50,000 signal events are generated for $B^\pm \rightarrow \psi(2S)(\rightarrow J/\psi(\rightarrow e^-e^+)\pi^+\pi^-)\pi^\pm$ decay. Same is done for $B^\pm \rightarrow \psi(2S)(\rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-)\pi^\pm$, $B^\pm \rightarrow \psi(2S)(\rightarrow e^+e^-)\pi^\pm$ and $B^\pm \rightarrow \psi(2S)(\rightarrow \mu^+\mu^-)\pi^\pm$ decays. The Belle data is accumulated with two detector configurations (Section 2.3.2) and is taken into account while generation of the events. The MC is not perfect as compared to data. In order to know its possible difference, the $B^\pm \rightarrow \psi(2S)K^\pm$ (Cabibbo-allowed) decay mode is used, which is a well established high statistics decay mode with a similar event topology (as of $B^\pm \rightarrow \psi(2S)\pi^\pm$). So, MC study is also performed for $B^\pm \rightarrow \psi(2S)K^\pm$ decay mode.

![Graph](image)

Figure 4.1: Fit to $\Delta E$ (GeV) and $M_{bc}$ (GeV/c$^2$) distribution of $B^- \rightarrow \psi(2S)(\rightarrow e^-e^-)\pi^-$ signal MC for data set I.

To identify the signal events $\Delta E$ and $M_{bc}$ variables are used (Section 3.8.1). The $\Delta E$ distribution for signal is described by sum of two Gaussians, while $M_{bc}$ distribution is described by a Gaussian. Background in the fits are described by chebyshev of 1st order polynomial for $\Delta E$ distribution while in $M_{bc}$ it is described by the Argus function [90]). To estimate the reconstruction efficiency ($\epsilon$), fits are performed to the $\Delta E$ as well as $M_{bc}$ distribution. As this distribution is for signal
4.1. RECONSTRUCTION

Table 4.1: Reconstruction efficiency, after performing the fit to generated MC sample.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Data set</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$M_{bc}$</td>
</tr>
<tr>
<td>$B^- \to \psi(2S)\pi^-$</td>
<td>$\psi(2S) \to e^- e^+$</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>$\psi(2S) \to \mu^- \mu^+$</td>
<td>II</td>
</tr>
<tr>
<td></td>
<td>$\psi(2S) \to J/\psi(\to e^- e^+)\pi^- \pi^+$</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>$\psi(2S) \to J/\psi(\to \mu^- \mu^+)\pi^- \pi^+$</td>
<td>II</td>
</tr>
<tr>
<td>$B^- \to \psi(2S)K^-$</td>
<td>$\psi(2S) \to e^- e^+$</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>$\psi(2S) \to \mu^- \mu^+$</td>
<td>II</td>
</tr>
<tr>
<td></td>
<td>$\psi(2S) \to J/\psi(\to e^- e^+)\pi^- \pi^+$</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>$\psi(2S) \to J/\psi(\to \mu^- \mu^+)\pi^- \pi^+$</td>
<td>II</td>
</tr>
</tbody>
</table>

MC sample (with no background generated), very small background (almost null) contribution is expected as visible from the fits. One example from the fits performed to MC is shown in Figure 4.1 while the calculated efficiencies are given in tabular form in Table 4.1. It should be noted that, these efficiencies are without any correction from the particle identification.

As shown, $M_{bc}$ distribution can also be used for the signal extraction. We expect significant signal in $B^\pm \to \psi(2S)\pi^\pm$ decay mode and $\Delta E$ is more reliable for the signal extraction. The 1D fit to $\Delta E$ is used to extract the signal yield after applying
a cut of $M_{bc} > 5.27$ GeV/c$^2$.

4.2 Background Study

To study the possible sources of the background in the $B^\pm \rightarrow \psi(2S)\pi^\pm$ decay under consideration, $B \rightarrow \psi(2S)X$ and $B \rightarrow J/\psi X$ inclusive MC samples are analyzed. This inclusive MC samples corresponds to $\sim 59$ times of the data used in this analysis.

4.2.1 The $B^\pm \rightarrow \psi(2S)(\rightarrow \ell^+\ell^-)\pi^\pm$ Decay

In order to estimate the background for the $B^\pm \rightarrow \psi(2S)(\rightarrow \ell^+\ell^-)\pi^\pm$ decay mode, $B \rightarrow \psi(2S)X$ inclusive MC sample is used. This sample is processed through analysis code and different sources of the background (different decay channels) are tagged using the MC truth match. The expected background is shown in Figure 4.2. From this figure it can be seen that the signal region, -25 MeV < $\Delta E$ < 25 MeV, is safe from any peaking structure in the $\Delta E$ distribution. While at $\Delta E \sim -70$ MeV there is a peaking structure. This prominent peaking at $\Delta E \sim -70$ MeV is due to the $B^\pm \rightarrow \psi(2S)K^\pm$ (Cabibbo-allowed) decay mode, here $K^\pm$ is misidentified as $\pi^\pm$ and due to poorly reconstructed energy $\Delta E$ is shifted by 70 MeV to the negative side. The good thing about the background is that this background peak is away from the signal region and can be easily modeled. In addition to $B^\pm \rightarrow \psi(2S)K^\pm$ peak, a peak around $\Delta E \sim -190$ MeV is also visible which can be attributed due to the $B^0 \rightarrow \psi(2S)K^0$ decay channel. The $B^0 \rightarrow \psi(2S)K^0$ decay mode contributes to the background in two ways: $K^0$ can get missed and a $\pi^\pm$ can combine with the $\psi(2S)$ meson and would form $B^\pm$ meson or a $\pi^\pm$ is missed from $K^0_S \rightarrow \pi^-\pi^+$. This creates a peak around $\Delta E \sim -190$ MeV and can be easily neglected while writing the probability density function (PDF) for the signal extraction. Rest background has a combinatorial nature and has no peaking structure which is modeled using a 2$^{nd}$ order chebyshev polynomial.

There can also be background coming from non-\$\psi(2S)$ sources in addition to the above said background (from $\psi(2S)$ source). To study the possible background
coming from non-$\psi(2S)$, data sideband of leptonic invariant mass ($M_{\ell\ell}$) is used. Two sidebands corresponding to [3.45, 3.55] GeV/c$^2$ and [3.8, 3.9] GeV/c$^2$ are used. As seen from the Figure 4.6 there is no peaking background in the $\Delta E$ (signal region).

Figure 4.2: Background estimation for $B^\pm \rightarrow \psi(2S)(\rightarrow \ell\ell)^\pm$ using $B \rightarrow \psi(2S)X$ MC sample, in $\Delta E$ (GeV) and $M_{bc}$ (GeV/c$^2$).

### 4.2.2 The $B^\pm \rightarrow \psi(2S)(\rightarrow J/\psi\pi\pi)^\pm$ Decay

For the $B^\pm \rightarrow \psi(2S)(\rightarrow J/\psi\pi\pi)^\pm$ decay channel, most of the background is expected to come from $B \rightarrow J/\psi X$ inclusive decays. To study the possible background sources, $B \rightarrow J/\psi X$ inclusive MC sample is used. Figure 4.3 shows the main sources of the background. As expected from the study (Section 4.2.1), background is mostly coming from the $B^{0,\pm} \rightarrow \psi(2S)(\rightarrow J/\psi\pi\pi)K^{0,\pm}$ decay modes. In addition to these backgrounds, $B^\pm \rightarrow J/\psi K^{*\pm}$ also contribute to the background as $K^{*\pm}$ can decay to $K_S^0(\rightarrow \pi^+\pi^-)^\pm$ which result in the final state as $J/\psi\pi^-\pi^+\pi^-$ (same as signal). Due to the same final state, reconstruction of $B^\pm$ meson will result in $\Delta E$ equal to zero and this is the reason for $B^\pm \rightarrow J/\psi K^{*\pm}$ to peak in the signal region (Figure 4.3). This background (due to $B^\pm \rightarrow J/\psi K^{*\pm}$) is due to the dipion coming from $K_S^0$ and getting combined with $J/\psi$ to make a $\psi(2S)$ (although not a real $\psi(2S)$). A cut is
Figure 4.3: Background estimation for $B^\pm \to \psi (2S)(\to J/\psi \pi \pi)\pi^\pm$ using $B \to J/\psi X$ MC sample, in $\Delta E$ (GeV) and $M_{bc}$ (GeV/$c^2$).

Figure 4.4: Background estimation for $B^\pm \to \psi (2S)(\to J/\psi \pi \pi)\pi^\pm$ using $B \to J/\psi X$ MC sample, in $\Delta E$ (GeV) and $M_{bc}$ (GeV/$c^2$) after applying $K_S^0$ veto.

applied to the dipion invariant mass ($M_{\pi\pi}$) in order to reduce the background coming from $B^\pm \to J/\psi K^{*\pm}$. If a pion combined with another oppositely charged pion (in
Figure 4.5: $\Delta E$ (GeV) plot for $\Delta M$ data sideband, a) without $K_S^0$ veto for data (red) and $B \to J/\psi X$ MC (blue), while b) shows the distribution with $K_S^0$ veto. After $K_S^0$ veto peaking background seems to disappear and the the distribution can now be fitted with linear fit.

the same event) has an invariant mass in between $\pm 12 \text{ MeV}/c^2$ of $K_S^0$ mass, $485.6 \text{ MeV}/c^2 < M_{\pi\pi} < 509.6 \text{ MeV}/c^2$, the pion is rejected (this cut is known as $K_S^0$ veto). Using the $K_S^0$ veto, peaking background is totally removed as shown in Figure 4.4 but at a cost of efficiency loss of 4.2%.

The effectiveness of the $K_S^0$ veto has been checked using $\Delta M$ sideband, also this provides a double check that there is no other possible peaking background. For this study $\Delta M$ sidebands, $0.49 \text{ GeV}/c^2 < \Delta M < 0.53 \text{ GeV}/c^2$ and $0.64 \text{ GeV}/c^2 < \Delta M < 0.68 \text{ GeV}/c^2$, are taken. Mass constrained to the central value is performed. Figure 4.5 shows the comparison of data (red) and $B \to J/\psi X$ inclusive MC (blue) without $K_S^0$ veto, a clear peak (of the background) is seen in the data while in $B \to J/\psi X$ inclusive MC it is small. After the application of $K_S^0$ veto, the prominent peak in data (in the signal region) disappear and the distribution is easily fitted with the 1$^{st}$ order chebyshev polynomial (shown in Figure 4.5). The $K_S^0$ veto is effective in removing the background but at the cost of efficiency reduction (can be accepted viewing the
higher significance expected for the signal).

To study the possible background coming from the non-$J/\psi$ component, data sideband of leptonic invariant mass ($M_{\ell\ell}$) is used (similar to non-$\psi(2S)$). Two data sidebands, $2.6 \text{ GeV}/c^2 < M_{J/\psi \rightarrow \mu^+\mu^-} < 2.9(2.8) \text{ GeV}/c^2$ and $3.2 \text{ GeV}/c^2 < M_{J/\psi \rightarrow \mu^+\mu^-} < 3.4 \text{ GeV}/c^2$, are used for this study. As can be seen from the Figure 4.6 there is no peaking background in the $\Delta E$ signal region.

![Graphs showing $\Delta E$ projection for $\psi(2S)$ decay modes](image)

Figure 4.6: $\Delta E$ projection of the $M_{\ell\ell}$ data sideband for $\psi(2S) \rightarrow e^+e^-$, $\psi(2S) \rightarrow \mu^+\mu^-$, $J/\psi \rightarrow e^+e^-$, $J/\psi \rightarrow \mu^+\mu^-$ and $J/\psi \rightarrow e^+e^-$ (clockwise from top left). In these figures, there is no peaking (in the signal region) as seen from the non-$\psi$ background component in case of $B^\pm \rightarrow \psi(2S)\pi^\pm$.

### 4.2.3 Continuum Background

As explained in Section 3.9, continuum background is suppressed using $R_2 < 0.5$ cut. In order to verify the background coming from continuum events, $59.45 \text{ fb}^{-1}$
4.3. $B^\pm \rightarrow \psi(2S)K^\pm$ CONTROL SAMPLE

off-resonance data is used. From the plots shown in Figures 4.7, it is clear that no peaking background (in the signal region) is present in both of the decay modes $(B^\pm \rightarrow \psi(2S)(\rightarrow \ell\ell)\pi^\pm$ and $B^\pm \rightarrow \psi(2S)(\rightarrow J/\psi\pi\pi)\pi^\pm$). From this it can be inferred that $R_2$ cut is reliable.

Figure 4.7: Off-resonance (59.45 fb$^{-1}$) data 2D scatter plot of $\Delta E$ (GeV) vs $M_{bc}$ (GeV/$c^2$), here blue box is the signal region. $\Delta E$ ($M_{bc}$) projection with $M_{bc}$ ($\Delta E$) cuts for a) $B^\pm \rightarrow \psi(2S)(\rightarrow J/\psi\pi\pi)\pi^\pm$ and b) $B^\pm \rightarrow \psi(2S)(\rightarrow \ell\ell)\pi^\pm$.

4.3 $B^\pm \rightarrow \psi(2S)K^\pm$ Control Sample

To get the difference between MC and data for $B^\pm \rightarrow \psi(2S)\pi^\pm$ decay mode, the $B^\pm \rightarrow \psi(2S)K^\pm$ (Cabibbo-allowed) decay mode is used due to its high statistics sample. Background study is also performed for this decay mode.

4.3.1 Background Study

No peaking background is found in the decay channel $B^\pm \rightarrow \psi(2S)(\rightarrow \ell\ell)\pi^\pm$ and can be easily fitted with 2nd order chebyshev polynomial. Whereas in the case of $B^\pm \rightarrow \psi(2S)(\rightarrow J/\psi\pi\pi)K^\pm$ there is a peaking background coming from $B \rightarrow$
CHAPTER 4. $B^\pm \rightarrow \psi(2S)\pi^\pm$ ANALYSIS

$J/\psi K_1(1270)$ and $B \rightarrow J/\psi \pi \pi K$ decay mode as seen from Figure 4.8. However the peaking background is not serious one and can be fixed while fitting the experimental data distribution, using the PDF for the peaking background obtained from $B \rightarrow J/\psi X$ inclusive MC sample. As, $B(B \rightarrow J/\psi K_1(1270))$ and $B(B \rightarrow J/\psi \pi \pi K)$ decays are not updated (with the PDG) in the $J/\psi$ inclusive MC sample ($B \rightarrow J/\psi X$) DECAY.DEC. To be independent of any branching fraction as input, the $\Delta M$ data sideband (as explained in Section 4.2.2) is used for the estimation of the background coming from these modes (as this background is due to non-$\psi(2S)$). Figure 4.9 shows the background estimated from $\Delta M$ data sideband for $B \rightarrow J/\psi X$ inclusive MC and data sample.

The peaking background is fitted with a Gaussian and 2$^{nd}$ order chebyshev polynomial. From the $B \rightarrow J/\psi X$ inclusive MC sample, parameters of the Gaussian PDF is estimated and is fixed for $\Delta M$ sideband in both samples (MC and data). The yield estimated in the fit of $\Delta M$ sidebands after proper scaling (based on the region of the sideband and the luminosity used) is summarized in Table 4.2. To check the effect of the $B^\pm \rightarrow \psi(2S)K^\pm$ signal feedback in the $B \rightarrow J/\psi X$ MC sideband, study is performed with exclusion and inclusion, of the signal $B^\pm \rightarrow \psi(2S)K^\pm$. The background estimated from data is fixed in the fit for extraction of the signal yield. To be on the safe side (as a conservative approach), difference between MC and data estimation is adjusted in the systematic.

Table 4.2: Estimated peaking background from $B \rightarrow J/\psi X$ MC and data, using $\Delta M$ sideband for $B^\pm \rightarrow \psi(2S)K^\pm$. Difference between MC and data estimation is adjusted in the systematic.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Sideband MC (without signal)</th>
<th>Sideband MC (with signal)</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \rightarrow \psi(2S)(\rightarrow J/\psi(\rightarrow ee)\pi\pi)K$</td>
<td>15.3 ± 0.4</td>
<td>13.8 ± 0.4</td>
<td>7.2 ± 2.7</td>
</tr>
<tr>
<td>$B \rightarrow \psi(2S)(\rightarrow J/\psi(\rightarrow \mu\mu)\pi\pi)K$</td>
<td>20.0 ± 0.4</td>
<td>17.8 ± 0.5</td>
<td>9.4 ± 2.7</td>
</tr>
</tbody>
</table>
4.3. $B^{\pm} \rightarrow \psi(2S)K^{\pm}$ CONTROL SAMPLE

Figure 4.8: These $\Delta E$ (GeV) plots shows the expected background for $\psi(2S)K$ mode, a) $B \rightarrow \psi(2S)(\rightarrow J/\psi(\rightarrow ee)\pi\pi)K$ and b) $B \rightarrow \psi(2S)(\rightarrow J/\psi(\rightarrow \mu\mu)\pi\pi)K$. This study uses $B \rightarrow J/\psi X$ MC sample.

Figure 4.9: $\Delta E$ (GeV) projection of $\Delta M$ sideband for a) $B \rightarrow J/\psi X$ sample and b) data in order to estimate peaking background component (explained in text) coming in $B \rightarrow \psi(2S)(\rightarrow J/\psi(\rightarrow ee)\pi\pi)K$ decay mode.

4.3.2 PDF Parametrization

Signal yield is extracted using 1D unbinned maximum likelihood fit to the $\Delta E$ distribution. PDF comprises of two parts:

- **Signal PDF**: Sum of two Gaussian with all the parameters floated.
• Background PDF: The 2nd order chebyshev polynomial is used to fit the combinatorial non-peaking background, while in the case of $B^\pm \to \psi(2S)(\to J/\psi \pi \pi)K^\pm$ a Gaussian PDF (with fixed yield and parameters estimated) is added to take into account the peaking background as explained above (Section 4.3.1).

Figure 4.10: Simultaneous fit performed to data (data set I and data set II) for $B \to \psi(2S)(\to J/\psi(\to ee)\pi \pi)K$ , $B \to \psi(2S)(\to J/\psi(\to \mu \mu)\pi \pi)K$, $B \to \psi(2S)(\to ee)K$ and $B \to \psi(2S)(\to \mu \mu)K$ (clockwise from top left).

Simultaneous fit with common $B$ is performed to the both data sets (I and II) and the four sub-decay modes of the $\psi(2S)$. In order to check the consistency of the result, each sub-decay mode of the $\psi(2S)$ is separately fit by performing a simultaneous fit (only to the data sets). Fits are performed to the data ($656 \times 10^6$ $B\bar{B}$ pairs) with the above explained PDF and are shown in Figure 4.10-4.11 while the results are summarized in Table 4.3. Statistical significance ($\Sigma$) is estimated as

$$\Sigma = \sqrt{-2\log(\mathcal{L}_0/\mathcal{L}_{\text{max}})}$$

(4.1)
4.3. \( B^\pm \to \psi(2S)K^\pm \) CONTROL SAMPLE

Figure 4.11: Simultaneous fit performed to the four sub-decay mode of \( \psi(2S) \); \( B^\pm \to \psi(2S)K^\pm \).

where \( \mathcal{L}_{\text{max}} (\mathcal{L}_0) \) denotes the maximum likelihood with normal yield (with signal yield fix at zero).

Table 4.3: Measurement of branching fraction for \( B^\pm \to \psi(2S)K^\pm \) (with PID, LID and \( \Delta M \) correction, Section 4.7).

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Branching Fraction ( (\times 10^{-4}) )</th>
<th>( \Sigma (\sigma) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B \to \psi(2S)(\to J/\psi(\to ee)\pi\pi)K )</td>
<td>6.37 ± 0.18</td>
<td>62</td>
</tr>
<tr>
<td>( B \to \psi(2S)(\to J/\psi(\to \mu\mu)\pi\pi)K )</td>
<td>5.53 ± 0.15</td>
<td>65</td>
</tr>
<tr>
<td>( B \to \psi(2S)(\to ee)K )</td>
<td>6.75 ± 0.22</td>
<td>59</td>
</tr>
<tr>
<td>( B \to \psi(2S)(\to \mu\mu)K )</td>
<td>6.21 ± 0.18</td>
<td>65</td>
</tr>
<tr>
<td>( B \to \psi(2S)K )</td>
<td>6.12 ± 0.09</td>
<td>125</td>
</tr>
</tbody>
</table>

The \( \mathcal{B}(B^- \to \psi(2S)K^-) \) comes out to be \( (6.12 \pm 0.09 \text{(stat.)} \pm 0.53 \text{(syst.)}) \times 10^{-4} \) (systematic estimation in Section 4.7) which is consistent with the world average [3,91], and gives credibility to the \( \Delta E \) variable for the signal yield extraction. In order to calculate the difference between MC and data, mass of the charged pion is assigned to the track of the charged kaon \( (\mathcal{R}_K > 0.6) \). In other words, for reconstruction of \( B^\pm \) meson from \( \psi(2S) \) and \( K^\pm \), kaon is forced to be misidentified as a pion. This result in the track energy getting scale down (becoming less) and a negative shift (from 0
Figure 4.12: $\Delta E$ distribution of $B^{\pm} \rightarrow \psi(2S)(\rightarrow J/\psi(\rightarrow \mu\mu)\pi\pi)K^{\pm}$ with $K$ misidentified as $\pi$, a) $B \rightarrow J/\psi X$ inclusive MC and b) data for data set I.

Figure 4.13: $\Delta E$ distribution of $B^{\pm} \rightarrow \psi(2S)(\rightarrow J/\psi(\rightarrow \mu\mu)\pi\pi)K^{\pm}$ with $K$ misidentified as $\pi$, a) $B \rightarrow J/\psi X$ inclusive MC and b) data for data set II.

GeV to $\sim 0.07 \, (GeV)$ is seen in the $\Delta E$ distribution for the $B^{\pm} \rightarrow \psi(2S)K^{\pm}$. This
4.3. $B^{\pm} \rightarrow \psi(2S)K^{\pm}$ CONTROL SAMPLE

Figure 4.14: $\Delta E$ distribution of $B^{\pm} \rightarrow \psi(2S)(\mu\mu)K^{\pm}$ with $K$ misidentified as $\pi$, a) $B \rightarrow \psi(2S)X$ inclusive MC and b) data for data set I.

Figure 4.15: $\Delta E$ distribution of $B^{\pm} \rightarrow \psi(2S)(\rightarrow \mu\mu)K^{\pm}$ with $K$ misidentified as $\pi$, a) $B \rightarrow \psi(2S)X$ MC and b) data for data set II.

shifted distribution of $B^{\pm} \rightarrow \psi(2S)K^{\pm}$ is fitted with a sum of the two bifurcated
CHAPTER 4. \( B^\pm \rightarrow \psi(2S)\pi^\pm \) ANALYSIS

Gaussian. Shape of the PDF used for fitting is fixed (area, mean and \( \sigma_1 \) are floated) for data fitting using the fitted ones from the inclusive MC sample \( (B \rightarrow \psi(2S)X \) and \( B \rightarrow J/\psi X) \). The fits are performed to data and the inclusive MC samples \( (B \rightarrow \psi(2S)X \) and \( B \rightarrow J/\psi X) \); are shown in Figures 4.12-4.16.

From the above mentioned fits, fudge factors (F.F.) are calculated. The F.F. are basically the difference between MC and data, and are calculated as follows:

\[
F.F. = \text{Mean}_{\text{data}} - \text{Mean}_{\text{MC}} \tag{4.2}
\]

\[
F.F._\sigma = \frac{\sigma_{\text{data}}}{\sigma_{\text{MC}}} \tag{4.3}
\]

This is done for each four sub-decay modes of \( \psi(2S) \) (used for reconstruction of \( \psi(2S) \)) and also data sets (I and II).

Table 4.4: F.F. calculated, after performing fits to the MC sample and data.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Data set</th>
<th>F.F._\sigma</th>
<th>F.F. (MeV/e^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^- \rightarrow \psi(2S)K^- )</td>
<td>( \psi(2S) \rightarrow e^-e^+ )</td>
<td>I</td>
<td>1.03 ± 0.07</td>
</tr>
<tr>
<td></td>
<td>( \psi(2S) \rightarrow \mu^-\mu^+ )</td>
<td>I</td>
<td>0.97 ± 0.36</td>
</tr>
<tr>
<td></td>
<td>( \psi(2S) \rightarrow J/\psi(\rightarrow e^-e^+)\pi^-\pi^+ )</td>
<td>II</td>
<td>0.99 ± 0.14</td>
</tr>
<tr>
<td></td>
<td>( \psi(2S) \rightarrow J/\psi(\rightarrow \mu^-\mu^+)\pi^-\pi^+ )</td>
<td>I</td>
<td>1.01 ± 0.27</td>
</tr>
<tr>
<td></td>
<td>( \psi(2S) \rightarrow J/\psi(\rightarrow \mu^-\mu^+)\pi^-\pi^+ )</td>
<td>II</td>
<td>0.98 ± 0.21</td>
</tr>
</tbody>
</table>

4.4 Strategy for \( B^\pm \rightarrow \psi(2S)\pi^\pm \) Signal Extraction

From the background study and the control sample \( (B^\pm \rightarrow \psi(2S)K^\pm) \) study, it can be safely inferred that use of \( \Delta E \) distribution is safe for the signal extraction. After
4.4. STRATEGY FOR $B^\pm \rightarrow \psi(2S)\pi^\pm$ SIGNAL EXTRACTION

getting confidence (or experience) over the control sample and getting the correction factors between MC and data, next step is to parametrize the signal PDF. The PDF for signal extraction is divided into three parts:

- **Signal PDF**: described by the sum of two Gaussian whose parameters are fixed from the signal MC after applyig data/MC correction (which we got from the control sample study).

- **Peaking background**: coming from $B^\pm \rightarrow \psi(2S)K^\pm$ (explained in Section 4.2), is parametrized using a sum of two bifurcated Gaussian whose parameters are fixed from the inclusive MC ($B \rightarrow J/\psi X$ and $B \rightarrow \psi(2S)X$) study (Figure 4.16 as a one example) after applying correction factors (F.F.s and F.F.M from Table 4.9).

Figure 4.16: Shows the $\Delta E$ (GeV), a) $J/\psi$ inclusive MC distribution of $B^\pm \rightarrow \psi(2S)(\rightarrow J/\psi(\rightarrow ee)\pi\pi)K^\pm$ and b) $\psi(2S)$ inclusive MC distribution of $B^\pm \rightarrow \psi(2S)(\rightarrow ee)K^\pm$ (data set I). Similarly for data set II and for $\psi(2S) \rightarrow \mu\mu$ and $\psi(2S) \rightarrow J/\psi(\rightarrow \mu\mu)\pi\pi$.

- **Combinatorial background**: it is smooth with no peaking structure and is fitted using a 2nd order chebyshev polynomial, with parameters floated in order to take into account the possible difference between MC and data.
CHAPTER 4. $B^\pm \rightarrow \psi(2S)\pi^\pm$ ANALYSIS

In the present analysis, the $\psi(2S)$ reconstruction is done from the following four decay modes:

- $\psi(2S) \rightarrow J/\psi(e^-e^+)\pi^-\pi^+$
- $\psi(2S) \rightarrow J/\psi(\mu^-\mu^+)\pi^-\pi^+$
- $\psi(2S) \rightarrow e^-e^+$
- $\psi(2S) \rightarrow \mu^-\mu^+$

In addition to this, two data sets (I and II) are used which needs to be taken into account. This makes total eight samples which are used in this study while the reconstruction of $B$ meson. In order to fit the samples properly, simultaneous fit is performed to the data samples. The final fit is a grand simultaneous fit having a common $B$ for the eight samples (four $\psi(2S)$ sub-decay modes $\times$ two data samples) after applying efficiency correction (estimated in Section 4.7) and data/MC correction (which we get from $B^\pm \rightarrow \psi(2S)K^\pm$).

4.5 Fit Validation

Before looking at the signal region in data; methodology to be used for signal yield extraction needs to be verified and is done by performing a MC study. As in $B \rightarrow \psi(2S)X$ and $B \rightarrow J/\psi X$ inclusive MC sample, signal ($B^\pm \rightarrow \psi(2S)\pi^\pm$) decay mode is not present (as this decay has not been observed and its branching fraction has not been measured before this study). Signal events corresponding to 5% (Section 1.5) of $B(B^\pm \rightarrow \psi(2S)K^\pm)$ corresponding to $387.72 \times 10^8$ $B\bar{B}$ pairs are generated. PDG 2004 [92] value of $B(B^\pm \rightarrow \psi(2S)K^\pm)$ is used for this purpose, which results in $B(B^\pm \rightarrow \psi(2S)\pi^\pm)$ to be $3.4 \times 10^{-5}$. Reason for using the value of PDG 2004 is that in generation of the official MC samples ($B \rightarrow \psi(2S)X$ and $B \rightarrow J/\psi X$) branching fraction from PDG 2004 is used. Events are generated as:

- $B^\pm \rightarrow \psi(2S)(\rightarrow J/\psi \pi \pi)\pi^\pm$ decay: The generated events are 49353 which are further divided into 19343 for data set I and 30010 for data set II (depending
4.5. FIT VALIDATION

Figure 4.17: Shows the Signal ∆E distribution of $B^\pm \rightarrow \psi(2S) (\rightarrow J/\psi \pi \pi) \pi^\pm$ (left) from signal MC and $B^\pm \rightarrow \psi(2S) (\rightarrow J/\psi \pi \pi) \pi^\pm$ (right, as expected in data) from signal MC + Inclusive MC study.

upon the luminosity of the data sets).

- $B^\pm \rightarrow \psi(2S) (\rightarrow \ell\ell) \pi^\pm$ decay: The generated events are 19379 which are further divided into 7595 for data set I and 11784 for data set II.

The generated signal events are embedded in the inclusive MC sample ($B \rightarrow \psi(2S)X$ and $B \rightarrow J/\psi X$). This way signal embedded MC sample ($\sim 59 \times$ data sample) is produced. Fits are performed to $B^\pm \rightarrow \psi(2S) (\rightarrow J/\psi \pi \pi) \pi^\pm$ and $B^\pm \rightarrow \psi(2S) (\rightarrow \ell\ell) \pi^\pm$, separately. Simultaneous fit is not performed for this sample, as the main motive behind this study is to check how well our PDF (at simplest level) can extract the signal yield. If the PDF works well in this simplest case than, it is expected to work for the simultaneous fit also. Figures 4.17 shows the fits to the signal MC and signal embedded MC sample. Table 4.5 gives the comparison of yield from the fits performed and it can said that we are able to extract the signal within the statistical uncertainty, which justify the approach used for this analysis.
Fig. 4.18: Shows the Signal $\Delta E$ distribution of $B^\pm \rightarrow \psi(2S)(\to \ell\ell)\pi^\pm$ (left) from signal MC and $B^\pm \rightarrow \psi(2S)(\to \ell\ell)\pi^\pm$ (right, as expected in data) from signal MC + Inclusive MC study.

Table 4.5: Comparison of yield from fit to signal MC and signal embedded MC.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield from fit to signal MC</th>
<th>Yield from fit to signal embedded MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \rightarrow \psi(2S)(\to J/\psi\pi\pi)\pi^\pm$</td>
<td>8423.9±95.6</td>
<td>8401.4±226.1</td>
</tr>
<tr>
<td>$B^\pm \rightarrow \psi(2S)(\to \ell\ell)\pi^\pm$</td>
<td>7474.8±86.8</td>
<td>7356.0±99.1</td>
</tr>
</tbody>
</table>

4.6 Opening of Data Box

After the validation of the fit procedure, we went ahead and unblinded the signal region in the data ($657 \times 10^6 N_{BB}$ pairs). Fit used is explained in Section 4.4. Fitted plots are shown in Figure 4.19-4.20 and results are summarized in Table 4.6. In order to cross check the results, the four sub-decay modes of $\psi(2S)$ meson are fitted separately and same branching fraction $B$ (within statistical uncertainty) is measured for each sub-decay modes. In the fit, PID, LID and $\Delta M$ correction (Section 4.7) has
been applied. Systematic uncertainty is expected to be 8.4% (explained in Section 4.7).

$$B(B^\pm \to \psi(2S)\pi^\pm) = 2.44^{+0.23}_{-0.22}(\text{stat.}) \pm 0.20(\text{syst.}) \times 10^{-5}$$

Figure 4.19: $\Delta E$ distributions of the $B^\pm \to \psi(2S)\pi^\pm$ candidates, reconstructed in the following four sub-modes: (a) $B^\pm \to \psi(2S)(\to J/\psi(\to ee)\pi^+\pi^-)\pi^\pm$, (b) $B^\pm \to \psi(2S)(\to J/\psi(\to \mu\mu)\pi^+\pi^-)\pi^\pm$, (c) $B^\pm \to \psi(2S)(\to ee)\pi^\pm$ and (d) $B^\pm \to \psi(2S)(\to \mu\mu)\pi^\pm$. The curves show the signal (green dashed) and the background components (red dot-dashed for $B^\pm \to \psi(2S)K^\pm$, magenta dotted for combinatorial background) as well as the overall fit (blue solid).
Figure 4.20: Simultaneous fit performed to the four sub-decay modes of the $B^\pm \rightarrow \psi(2S)\pi^\pm$ on data.

Table 4.6: Summary of the results of the $B^\pm \rightarrow \psi(2S)\pi^\pm$ decay study. Efficiency ($\epsilon$), Yield ($Y$), measured branching fraction ($B$) and Significance ($\Sigma$) systematic uncertainty not included as total significance is high. For $B$, the first (second) uncertainty is statistical (systematic).

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$\epsilon$ (%)</th>
<th>$Y$</th>
<th>$B$, $10^{-5}$</th>
<th>$\Sigma$ ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \rightarrow \psi(2S)(\rightarrow J/\psi(\rightarrow e^+e^-)\pi^+\pi^-)\pi^\pm$</td>
<td>15.1</td>
<td>48.9±8.3</td>
<td>2.57±0.44</td>
<td>9.5</td>
</tr>
<tr>
<td>$B^\pm \rightarrow \psi(2S)(\rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-)\pi^\pm$</td>
<td>16.8</td>
<td>44.0±8.1</td>
<td>2.08±0.38</td>
<td>8.4</td>
</tr>
<tr>
<td>$B^\pm \rightarrow \psi(2S)(\rightarrow e^+e^-)\pi^\pm$</td>
<td>32.2</td>
<td>44.0±9.0</td>
<td>2.80±0.57</td>
<td>7.3</td>
</tr>
<tr>
<td>$B^\pm \rightarrow \psi(2S)(\rightarrow \mu^+\mu^-)\pi^\pm$</td>
<td>35.7</td>
<td>43.5±7.7</td>
<td>2.50±0.44</td>
<td>9.0</td>
</tr>
<tr>
<td>$B^\pm \rightarrow \psi(2S)\pi^\pm$ (simultaneous)</td>
<td></td>
<td></td>
<td>2.44±0.22±0.20</td>
<td>17</td>
</tr>
</tbody>
</table>

### 4.7 Systematic Uncertainty

In addition to the statistical uncertainty, there is also an uncertainty coming in the result from the systematic uncertainty. The main sources of the systematic uncertainty are identified as follows:
4.7. SYSTEMATIC UNCERTAINTY

4.7.1 $\Delta M$ Correction

The mass cut ($0.578 \text{ Mev}/c^2 < \Delta M < 0.598 \text{ Mev}/c^2$) on $\Delta M$ is applied in order to identify the $\psi(2S)$ meson. As this cut is optimized on MC, there may be a possible difference between MC and data distribution. In order to estimate this difference, the $B^\pm \rightarrow \psi(2S)K^\pm$ sample is used. This cut is relaxed ($0.57 \text{ Mev}/c^2 < \Delta M < 0.61 \text{ Mev}/c^2$) and possible difference between MC and data is calculated. Sum of two Gaussian is used to fit $\Delta M$ in both MC and the data, while yield is estimated in the mentioned cuts. Fit to MC and data is shown in Figure 4.21. From the fitted yield, $A$ ($B$) for $0.578 \text{ Mev}/c^2 < \Delta M < 0.598 \text{ Mev}/c^2$ ($0.57 \text{ Mev}/c^2 < \Delta M < 0.61 \text{ Mev}/c^2$), ratio ($A/B$) is obtained. For estimation of the uncertainty on this ratio ($A/B$), correlation between the parameters are taken into account by using external error matrix ($V$) obtained from the normal fit (MINUIT). Derivative vector ($DX$) is calculated by changing the parameter by $\pm 1\sigma$ while other parameters are fixed.

$$DX_i = \frac{A/B(+\sigma) - A/B(-\sigma)}{2\sigma}$$ \hfill (4.4)

$DX$ for MC and data are as follow:

$$DX(\text{MC}) = (0, -2.941, -49.250, -0.116, -0.014)$$

$$DX(\text{data}) = (0, -0.505, -52.190, -6.657 \times 10^{-2}, -4.439 \times 10^{-2})$$

As seen first element of $DX$ is zero, the first element stands for error on the area while other elements are of Mean, $\sigma_1$, Area2/Area and $\sigma_2/\sigma_1$ parameters in the fit. Area is floated in the fit due to which the first element of $DX$ is zero.

Error on the ratio of the yields ($A/B$) for MC (or data) is calculated as follows:

$$\sigma(A/B) = DX \cdot V \cdot DX^T$$ \hfill (4.5)

Using this procedure correction of 1.07 is estimated on $\Delta M$ cut and is used to correct the efficiency while uncertainty of $\sim 0.9\%$ is adjusted in the systematic.
Figure 4.21: Shows the ΔM distribution of a) $B^+ \rightarrow \psi(2S)(\rightarrow J/\psi \pi \pi) K^+ \pi^-$ MC and b) data.

### Table 4.7: ΔM correction.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>A/B</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC</td>
<td>3228.08±61.16</td>
<td>3359.38±63.64</td>
<td>0.9092±0.0034</td>
</tr>
<tr>
<td>Data</td>
<td>2426.28±55.27</td>
<td>2496.78±56.87</td>
<td>0.9718±0.0076</td>
</tr>
<tr>
<td>Data/MC</td>
<td>1.07±0.01</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 4.7.2 Pion - ID

Correction on the $R_\pi$ is estimated as explained in Section 3.10, while uncertainty on the correction is cover up in the systematic uncertainty. Table 4.8 summarizes the uncertainty.
### 4.7. SYSTEMATIC UNCERTAINTY

Table 4.8: Pid correction and systematic uncertainty.

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Data set</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
<td>II</td>
</tr>
<tr>
<td>$B^\pm \rightarrow \psi(2S)(\rightarrow J/\psi(\rightarrow ee)\pi^+\pi^-)\pi^\pm$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\pi^- (\psi(2S))$</td>
<td>0.9981</td>
<td>1.0019</td>
</tr>
<tr>
<td>$\pi^+ (\psi(2S))$</td>
<td>0.9980</td>
<td>1.0021</td>
</tr>
<tr>
<td>$\pi^\pm (B)$</td>
<td>0.9395</td>
<td>0.9189</td>
</tr>
<tr>
<td>$B^\pm \rightarrow \psi(2S)(\rightarrow J/\psi\pi^+\pi^-)\pi^\pm$ (total)</td>
<td>0.9358</td>
<td>0.9226</td>
</tr>
<tr>
<td>Systematic Uncertainty</td>
<td>1.95%</td>
<td>2.23%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^\pm \rightarrow \psi(2S)(\rightarrow J/\psi(\mu\mu)\pi^+\pi^-)\pi^\pm$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\pi^- (\psi(2S))$</td>
<td>0.9982</td>
<td>1.0083</td>
</tr>
<tr>
<td>$\pi^+ (\psi(2S))$</td>
<td>0.9980</td>
<td>1.0023</td>
</tr>
<tr>
<td>$\pi^\pm (B)$</td>
<td>0.9385</td>
<td>0.9224</td>
</tr>
<tr>
<td>$B^\pm \rightarrow \psi(2S)(\rightarrow J/\psi\pi^+\pi^-)\pi^\pm$ (total)</td>
<td>0.9349</td>
<td>0.9253</td>
</tr>
<tr>
<td>Systematic Uncertainty</td>
<td>1.91%</td>
<td>2.26%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^\pm \rightarrow \psi(2S)(\rightarrow ee)\pi^\pm$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\pi^\pm (B)$</td>
<td>0.9382</td>
<td>0.9185</td>
</tr>
<tr>
<td>$B^\pm \rightarrow \psi(2S)(\rightarrow \ell^+\ell^-)\pi^\pm$</td>
<td>0.9382</td>
<td>0.9185</td>
</tr>
<tr>
<td>Systematic Uncertainty</td>
<td>0.71%</td>
<td>0.62%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^\pm \rightarrow \psi(2S)(\rightarrow \ell^+\ell^-)\pi^\pm$</td>
<td>0.9381</td>
<td>0.9183</td>
</tr>
<tr>
<td>Systematic Uncertainty</td>
<td>0.71%</td>
<td>0.63%</td>
</tr>
</tbody>
</table>

#### 4.7.3 Tracking

Uncertainty on the identification of the tracks also contribute to the systematic and need to be taken into account. Its estimation is described in Section 3.10 while the systematic uncertainty is summarized in Table 4.9.
Table 4.9: Uncertainty on each tracks and the total uncertainty on each sub-modes.

<table>
<thead>
<tr>
<th>Source</th>
<th>Data set I</th>
<th>Data set II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \rightarrow \psi(2S)(\rightarrow J/\psi(\rightarrow ee)\pi^+\pi^-)\pi^\pm$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e^-(J/\psi)$</td>
<td>1.06</td>
<td>1.06</td>
</tr>
<tr>
<td>$e^+(J/\psi)$</td>
<td>1.06</td>
<td>1.06</td>
</tr>
<tr>
<td>$\pi^+(\psi(2S))$</td>
<td>1.54</td>
<td>1.52</td>
</tr>
<tr>
<td>$\pi^-(\psi(2S))$</td>
<td>1.53</td>
<td>1.52</td>
</tr>
<tr>
<td>$\pi^\pm(B^\pm)$</td>
<td>1.06</td>
<td>1.06</td>
</tr>
<tr>
<td>$B^\pm \rightarrow \psi(2S)(\rightarrow J/\psi(\rightarrow \mu\mu)\pi^+\pi^-)\pi^\pm$</td>
<td>6.2</td>
<td>6.2</td>
</tr>
<tr>
<td>$\mu^-(J/\psi)$</td>
<td>1.06</td>
<td>1.06</td>
</tr>
<tr>
<td>$\mu^+(J/\psi)$</td>
<td>1.06</td>
<td>1.06</td>
</tr>
<tr>
<td>$\pi^+(\psi(2S))$</td>
<td>1.53</td>
<td>1.52</td>
</tr>
<tr>
<td>$\pi^-(\psi(2S))$</td>
<td>1.50</td>
<td>1.50</td>
</tr>
<tr>
<td>$\pi^\pm(B^\pm)$</td>
<td>1.06</td>
<td>1.06</td>
</tr>
<tr>
<td>$B^\pm \rightarrow \psi(2S)(\rightarrow ee)\pi^\pm$</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>$e^+(\psi(2S))$</td>
<td>1.06</td>
<td>1.06</td>
</tr>
<tr>
<td>$e^-(\psi(2S))$</td>
<td>1.06</td>
<td>1.06</td>
</tr>
<tr>
<td>$\pi^\pm(B^\pm)$</td>
<td>1.06</td>
<td>1.06</td>
</tr>
<tr>
<td>$B^\pm \rightarrow \psi(2S)(\rightarrow \mu\mu)\pi^\pm$</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>$\mu^+(\psi(2S))$</td>
<td>1.06</td>
<td>1.06</td>
</tr>
<tr>
<td>$\mu^-(\psi(2S))$</td>
<td>1.06</td>
<td>1.06</td>
</tr>
<tr>
<td>$\pi^\pm(B^\pm)$</td>
<td>1.06</td>
<td>1.06</td>
</tr>
</tbody>
</table>

4.7.4 Lepton ID Correction

Leptons are identified on the basis of the likelihood cuts, which needs to be corrected. For correction, official LID group study ($e^+e^- \rightarrow e^+e^-\ell^+\ell^-$) study with correction from $J/\psi \rightarrow \ell\ell$ decay is used for $\mu$ identification while for $e$ identification, another study ($J/\psi \rightarrow \ell\ell$) [93] is used. Table 4.10 summarizes the lepton id correction. This correction is used to correct the efficiency while uncertainty on this correction is added.
to the systematic uncertainty.

For eik, correction is almost negligible and is included in the systematic uncertainty as 2.7%.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Data set I</th>
<th>Systematic</th>
<th>Data set II</th>
<th>Systematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$ from J/ψ</td>
<td>0.9511</td>
<td>4.7%</td>
<td>0.9173</td>
<td>6.3%</td>
</tr>
<tr>
<td>$\mu$ from ψ(2S)</td>
<td>0.9383</td>
<td>4.8%</td>
<td>0.9008</td>
<td>6.1%</td>
</tr>
</tbody>
</table>

4.7.5 Fitting Uncertainty

Parameters for the PDF are fixed using MC and control sample which may not be perfect. In order to estimate the uncertainty, each fixed parameter in the fit is changed by ±1σ one at a time and fit is performed. While for 2nd order chebyshev polynomial, fit is performed using 1st order chebyshev polynomial. This way uncertainty on the fit is estimated to be 2.5%.

4.7.6 Total Systematic Uncertainty

Table 4.11 summarizes the systematic uncertainties from all the possible sources (which are serious for this analysis). Taking proper care of the correlation and uncorrelation, systematic uncertainties are added. Total systematic uncertainty is estimated to be 8.4% for $B^{\pm} \to \psi(2S)\pi^{\pm}$. Same systematic study is repeated for the control sample ($B^{\pm} \to \psi(2S)K^{\pm}$) and uncertainty (summarized in Table 4.12) is estimated to be 8.7%

4.8 Search for Direct CP Violation

As explained in Section 1.6.1 CP violation may be present in $B^{-} \to \psi(2S)\pi^{-}$. A search has been carried out for the direct CP violation in $B^{-} \to \psi(2S)\pi^{-}$. Direct CP
### Table 4.11: Summary of systematic uncertainty in the $B^\rightarrow \psi(2S)\pi^-$ decay.

<table>
<thead>
<tr>
<th>Sources</th>
<th>$\psi(2S) \rightarrow ee$</th>
<th>$\psi(2S) \rightarrow \mu\mu$</th>
<th>$J/\psi \rightarrow ee$</th>
<th>$J/\psi \rightarrow \mu\mu$</th>
<th>$B^\rightarrow \psi(2S)\pi^-$ total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data set</td>
<td>I</td>
<td>II</td>
<td>I</td>
<td>II</td>
<td>I</td>
</tr>
<tr>
<td>$N_{BB}$</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Tracking</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
<td>6.2</td>
</tr>
<tr>
<td>$\pi$-id</td>
<td>0.7</td>
<td>0.6</td>
<td>0.7</td>
<td>0.6</td>
<td>1.9</td>
</tr>
<tr>
<td>$\mu$-id</td>
<td>-</td>
<td>-</td>
<td>4.8</td>
<td>6.1</td>
<td>-</td>
</tr>
<tr>
<td>$e$-id</td>
<td>5.4</td>
<td>5.4</td>
<td>-</td>
<td>-</td>
<td>5.4</td>
</tr>
<tr>
<td>MC</td>
<td>0.8</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>1.2</td>
</tr>
<tr>
<td>$\Delta M$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.9</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.5</td>
</tr>
</tbody>
</table>

The violation is measured in terms of the charge asymmetry which is defined in Equation (1.24) and can be further simplified in terms of yield as:

$$A_{CP} = \frac{N_{-} - N_{+}}{N_{-} + N_{+}}$$

Here $N_{-}$ ($N_{+}$) is the number of events in $B^\rightarrow \psi(2S)\pi^-$ ($B^+ \rightarrow \psi(2S)\pi^+$) decay mode. $N_{-}$ ($N_{+}$) are extracted using 1D UML simultaneous (yield as common parameter) fit to $\Delta E$ distribution (same as done for branching fraction) of $B^\rightarrow \psi(2S)\pi^-$ ($B^+ \rightarrow \psi(2S)\pi^+$). In this fit, parameters of 2$^{nd}$ chebyshev order polynomial (except normalization) are fixed while fitting the desired sample. To look for any
Table 4.12: Summary of systematic uncertainty in the $B^- \rightarrow \psi(2S)K^-$ decay.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{bb}$</td>
<td>1.4</td>
</tr>
<tr>
<td>Tracking</td>
<td>5.0</td>
</tr>
<tr>
<td>$\pi$ id</td>
<td>1.7</td>
</tr>
<tr>
<td>$\ell$ id</td>
<td>5.7</td>
</tr>
<tr>
<td>MC</td>
<td>0.9</td>
</tr>
<tr>
<td>Secondary $B$</td>
<td>3.5</td>
</tr>
<tr>
<td>$\Delta M$</td>
<td>0.5</td>
</tr>
<tr>
<td>Background estimation</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>8.7</strong></td>
</tr>
</tbody>
</table>

Figure 4.22: Charge Asymmetry Plots; $B^+ \rightarrow \psi(2S)\pi^+$ and $B^- \rightarrow \psi(2S)\pi^-$

difference in MC between positive and negative charge track, events are generated for $B^+ \rightarrow \psi(2S)\pi^+$ and $B^- \rightarrow \psi(2S)\pi^-$ decays. Difference calculated between negative and positive charge tracks from PID correction comes out to be $1.00 \pm 0.006$. This value is unity, therefore no correction is applied to the central value while the error (0.6%) is included in the systematic uncertainty. Uncertainty in the yield extraction is estimated to be 4.6% while the systematic uncertainty from the difference in shape parameters of $B^-$ and $B^+$ is estimated to be 5.3%. Possible detector bias is included in the systematic uncertainty as 0.0159 (value estimated from study of $B^- \rightarrow J/\psi K^-$ [94]). $N_-$ ($N_+$) comes out to be $93 \pm 11$ ($89 \pm 11$) and the calculated charge asymmetry
comes out to be

\[ \mathcal{A}_{CP}^{B^- \to \psi(2S)\pi^-} = 0.022 \pm 0.085 \pm 0.016. \]  

The charge asymmetry comes out to be consistent with the SM expectation. However, this search for \( \mathcal{A}_{CP} \) is limited by the statistics and with the increase in data one may be able to measure (or observe) the charge asymmetry. With this statistics, it will not be possible to jump on any conclusion at this stage.

4.9 Chapter in A Nutshell

In this Chapter, \( B^\pm \to \psi(2S)\pi^\pm \) decay has been described along with the analysis of \( B^\pm \to \psi(2S)K^\pm \) decay as the control sample. We measure \( \mathcal{B}(B^\pm \to \psi(2S)K^\pm) \) to be \((6.12 \pm 0.09\,\text{(stat.)} \pm 0.53\,\text{(syst.)}) \times 10^{-4}\) which is consistent with the world measurement \([3, 91] \). Also, we observe \( B^\pm \to \psi(2S)\pi^\pm \) decay at the Belle for the first time in the world. We measure its branching fraction \( \mathcal{B}(B^\pm \to \psi(2S)\pi^\pm) \) as \( 2.44^{+0.23}_{-0.22}(\text{stat.}) \pm 0.20(\text{syst.}) \times 10^{-5} \). Search for the direct \( CP \) violation has been carried out in the \( B^- \to \psi(2S)K^- \) decay mode in hope of finding hint of New Physics phenomenon. We measured \( \mathcal{A}_{CP}^{B^- \to \psi(2S)\pi^-} \) to be as \( 0.022 \pm 0.085 \pm 0.016 \), which is consistent with the SM.
That's not right.
That's not even wrong.
Wolfgang Pauli

\[ B \to \chi_{c1,c2}K \quad & \quad B \to X(3872)K \] Analysis

Analyses of \( B \to \chi_{c1}K \), \( B \to \chi_{c2}K \) and \( B \to X(3872)K \), where \( \chi_{c1,c2} \) and \( X(3872) \) decays to \( J/\psi \gamma \), have been described in this Chapter. The \( K \) stands for \( K^0 \) and \( K^\pm \) mesons unless stated otherwise. The \( B \to \chi_{c2}K \) decay mode has not been seen yet, although searches has already been carried out by Belle and BaBar \([17,54]\). If \( B \to \chi_{c2}K \) is seen than it will provide a nice test for the factorization hypothesis, explained in Section 1.5. The \( B^\pm \to \chi_{c1}K^\pm \) decay mode is used as control sample, in order to get the difference between MC and data, due to its high statistics sample with a plus point of having same events kinematics as modes under study (\( B \to \chi_{c2}K \) and \( B \to X(3872)K \) decay modes). The \( B \to X(3872)K \) study is also present here, evidence for which has already been found by Belle and BaBar \([46,54]\). However with the large data sample (\( \sim 2.7 \times \) last study done at Belle \([46]\)), there is an opportunity to observe (establish) this decay mode (till now only evidence has been seen) and provide the most precise measurement of this decay mode, which is necessary for the theoretical understanding of the \( X(3872) \) and charmonium production in the \( B \)-decays.

5.1 Reconstruction

\( B \) meson reconstruction is done by combining \( \chi_{c1,c2} \) or \( X(3872) \) with the \( K \) meson, as explained in Section 3.8.2. For Monte Carlo study, EvtGen is used as an event
CHAPTER 5. $B \to \chi_{c1,c2}K \& B \to X(3872)K$ ANALYSIS

generator. Events are generated as:

a) $B^\pm \to \chi_{c1}[\to J/\psi(\to \ell^+\ell^-)\gamma]K^\pm$.
b) $B^\pm \to \chi_{c2}[\to J/\psi(\to \ell^+\ell^-)\gamma]K^\pm$.
c) $B^\pm \to X(3872)K^\pm$, here $X(3872)$ decays to $J/\psi(\to \ell^+\ell^-)\gamma$.
d) $B^0 \to \chi_{c1}[\to J/\psi(\to \ell^+\ell^-)\gamma]K_S^0$.
e) $B^0 \to \chi_{c2}[\to J/\psi(\to \ell^+\ell^-)\gamma]K_S^0$.
f) $B^0 \to X(3872)K_S^0$, here $X(3872)$ decays to $J/\psi(\to \ell^+\ell^-)\gamma$.

Here $\ell$ stands for electrons and muons.

As signal events, 500,000 events are generated in equal number for the above said decay chain and detector difference between data set I and data set II has been taken into account while performing the simulation of the events. The $M_{J/\psi\gamma}$ is used to identify the particular decay channel and extract the yield. The 1D UML fit is performed for this purpose. Figure 5.1 shows the fit for the charge decay modes. Table 5.1 lists the efficiency for the generated samples.

Table 5.1: Efficiency of the generated samples, these efficiencies are going to change after the application of additional cuts (optimized) in order to improve the significance.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Variable</th>
<th>Efficiency(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^- \to \chi_{c1}K^-$</td>
<td>$M_{J/\psi\gamma}$</td>
<td>25.00 ± 0.07</td>
</tr>
<tr>
<td>$B^0 \to \chi_{c1}K_S^0$</td>
<td>$M_{J/\psi\gamma}$</td>
<td>22.07 ± 0.07</td>
</tr>
<tr>
<td>$B^- \to \chi_{c2}K^-$</td>
<td>$M_{J/\psi\gamma}$</td>
<td>25.66 ± 0.07</td>
</tr>
<tr>
<td>$B^0 \to \chi_{c2}K_S^0$</td>
<td>$M_{J/\psi\gamma}$</td>
<td>22.00 ± 0.07</td>
</tr>
<tr>
<td>$B^- \to X(3872)K^-$</td>
<td>$M_{J/\psi\gamma}$</td>
<td>26.33 ± 0.07</td>
</tr>
<tr>
<td>$B^0 \to X(3872)K_S^0$</td>
<td>$M_{J/\psi\gamma}$</td>
<td>20.69 ± 0.07</td>
</tr>
</tbody>
</table>
5.2. BACKGROUND STUDY

![Figure 5.1](image)

(b) $B^+ \rightarrow \chi_{c2} K^-$ mode

(c) $B^+ \rightarrow \chi_{c1} K^-$ mode

Figure 5.1: Fit to $M_{J/\psi\gamma}$ distributions using double Gaussian PDF (signal MC sample).

5.2 Background Study

To study the possible background sources, the $B \rightarrow J/\psi X$ inclusive MC samples, which is $\sim 50$ times the available data ($771.6 \times 10^6 N_{BB}$), are analyzed as most of the background is expected to come from the $J/\psi$ inclusive modes.

5.2.1 The $B^{\pm,0} \rightarrow \chi_{c1,2}(\rightarrow J/\psi \gamma)K^{\pm,0}$ Decay

For $B^{\pm} \rightarrow \chi_{c1,2}(\rightarrow J/\psi \gamma)K^{\pm}$ decay mode, the $B \rightarrow J/\psi X$ inclusive MC sample is used to understand the possible sources of the background as most of the background is expected from the $J/\psi$ inclusive modes and $J/\psi$ sideband (data) is used to study
Figure 5.2: $M_{J/\psi\gamma}$ (GeV/$c^2$) distribution (~50 x data), $B \to J/\psi X$ inclusive MC background study for a) $B^\pm \to \chi_{c1,2}K^\pm$ and b) $B^0 \to \chi_{c1,2}K_S^0$.

The possible background coming from non-$J/\psi$ contribution (explained in the later part of this Section). Expected background is shown in Figure 5.2a. As seen from the Figure, there is not much peaking background in the $M_{J/\psi\gamma}$ distribution, background is smooth in the signal region and the shape can easily be described with a 2nd order chebyshev polynomial. Major contribution to the background, comes from $B^{\pm,0} \to J/\psi K^*(892)^{\pm,0}$. The $K^*(892)^{\pm} \to K^{\pm}\pi^0$ decay can contribute to the total background in two ways. In one way, a $\gamma$ is missed from $\pi^0$ of $K^*$ and we get the final state as $J/\psi K^{\pm}\gamma$ (we call this $\gamma$ OK case) while in other way, $\pi$ of $K^*$ is missed and $\gamma$ comes from some other random sources (this one is called $\gamma$ not OK case). As it can be seen from Figure 5.2a there are two small peaks; the green peak at $\chi_{c0}$ mass is due to the $\sim 3.8$ times over-estimation of $B^{\pm} \to \chi_{c0}K^\pm$ branching fraction in the $B \to J/\psi X$ MC (DECAY.DEC) whereas the second (yellow one) is due to $\eta_c \to J/\psi\gamma$ (which has not been seen yet and also the mass of $\eta'_c$ is different than the current world average) included in the $B \to J/\psi X$ inclusive MC sample. Due to the smooth background and no peaking structure in the signal region, signal can be easily extracted.

In the same way, background study is performed for $B^0 \to \chi_{c1,2}K_S^0$ decay using the $B \to J/\psi X$ inclusive MC sample and we find that most of the background...
5.2. BACKGROUND STUDY

Figure 5.3: $M_{J/\psi\gamma}$ (GeV/$c^2$) distribution for $M_{\text{non}-J/\psi\gamma}$, non-$J/\psi$ background estimation (after proper scaling to the data) for $B^\pm \rightarrow \chi_{c1,c2}K^\pm$ and b) $B^0 \rightarrow \chi_{c1,c2}K^0_S$.

(not peaking in the signal region) is coming from $B^{\pm,0} \rightarrow J/\psi K^*(892)^{\pm,0}$ and can be described by 2nd order chebyshev polynomial. Figure 5.2b shows the background for $B^0 \rightarrow \chi_{c1,c2}K^0_S$. As observed from Figure 5.2b, $B^0 \rightarrow \chi_{c1,c2}K^0_S$ background components are same as the one for $B^{\pm} \rightarrow \chi_{c1,c2}K^{\pm}$ background, the only difference is that the charge of the components have changed. In the charged mode, $B^{\pm} \rightarrow J/\psi K^*(892)^{\pm}$ contributes to the background in two ways ($\gamma$ OK and $\gamma$ not OK case) while $B^0 \rightarrow J/\psi K^*(892)^0$ contributes mostly through $\gamma$ not OK case; whereas in the neutral mode, $B^{\pm} \rightarrow J/\psi K^*(892)^{\pm}$ contributes to the background mostly through $\gamma$ not OK case and $B^0 \rightarrow J/\psi K^*(892)^0$ contributes through two ways ($\gamma$ OK and $\gamma$ not OK case).

In order to study the background coming from non-$J/\psi$, three sidebands corresponding to $[3.2, 3.3]$, $[3.3, 3.4]$ and $[3.4, 3.5]$ GeV/$c^2$ of $M_{\ell\ell}$ are used. These bands (in sum) corresponds to 2.3 times the signal region. Mass constrained is performed to the center of each band. As it can be seen from Figure 5.3a there is no peaking background for the charge as well as the neutral mode. At present, background coming from non-$J/\psi$ is small as compared to the background coming from $B \rightarrow J/\psi X$ inclusive decays. But after the application of additional cuts (explained in Section 5.3), non-$J/\psi$ contribution becomes comparable to the $J/\psi$ inclusive background (see
Figure 5.4: $M_{J/\psi\gamma}$ (GeV/$c^2$) distribution ($\sim 50 \times$ data), $B \to J/\psi X$ inclusive MC background study for a) $B^\pm \to X(3872)K^\pm$ and b) $B^0 \to X(3872)K_S^0$.

5.2.2 The $B^\pm,0 \to X(3872)(\to J/\psi\gamma)K^{\pm,0}$ Decay

To study the possible sources of background in $B^\pm \to X(3872)(\to J/\psi\gamma)K^\pm$ mode, the $B \to J/\psi X$ inclusive MC sample is used. Figure 5.4a shows the expected background in the case of $B^\pm \to X(3872)(\to J/\psi\gamma)K^\pm$; background is smooth and mainly consists of $B^\pm \to \psi(2S)K^\pm$ and $B \to J/\psi K^*(892)$. In $B^\pm \to \psi(2S)K^\pm$ case, $\psi(2S) \to \chi_{c1,2}\gamma$, the $\gamma$ (either from $\chi_{c1,2}$ or the one coming from $\psi(2S)$) is missed and we get $J/\psi K\gamma$ in the final state (same as the signal). Similarly for $B \to J/\psi K^*(892)$, we get the final state as $J/\psi K\gamma$ after $\gamma$ is lost from $\pi^0$ of $K^*(892)$; or $\pi$ of $K^*(892)$ is lost and $\gamma$ from some other sources contribute to the final state. Background can be well described by the 1st order chebyshev polynomial.

In the same manner, background study is performed for $B^0 \to X(3872)(\to J/\psi\gamma)K_S^0$, using the $J/\psi$ inclusive MC. Background is smooth and most of it comes from $B \to J/\psi K^*(892)$, and can be modeled by 1st order chebyshev polynomial. Figure 5.4b shows the background for $B^0 \to X(3872)(\to J/\psi\gamma)K_S^0$.

To look for any non-$J/\psi$ contribution, three sidebands corresponding to [3.2, 3.3],
5.3. OPTIMIZATION OF CUTS

![Graphs showing distributions]

Figure 5.5: $M_{J/\psi\gamma}$ (GeV/$c^2$) distribution for $M_{\text{non-}J/\psi\gamma}$, non-$J/\psi$ background contribution for a) $B^\pm \rightarrow X(3872)K^\pm$ (left) and b) $B^0 \rightarrow X(3872)K^0_S$ (right).

[3.3, 3.4] and [3.4, 3.5] GeV/$c^2$ of $M_{\ell\ell}$ are used. These bands (in total) correspond to 2.3 times the signal region width. Mass constrained is performed to the center of each mass band. As it can be seen from Figure 5.5, there is no peaking background for the charge as well as neutral decay modes. At present, background coming from non-$J/\psi$ is small as compared to the background coming from $B \rightarrow J/\psi X$ inclusive. But after the application of additional cuts (explained in Section 5.3), non-$J/\psi$ contribution becomes comparable to the $J/\psi$ inclusive background (see Figure 5.19).

5.3 Optimization of Cuts

5.3.1 The $B \rightarrow \chi_{c1,2}(\rightarrow J/\psi\gamma)K$ decay

In order to reduce the background, we need to study the possible background sources; and how to discriminate between them and the signal. The following components are used for this purpose:

- $E_\gamma$ is the energy of $\gamma$ in the lab frame. Signal and background can be distinguished on the basis of their $\gamma$'s energy. Background have low energy $\gamma$s as compared to the signal (Figure 5.6a). By applying cut on $E_\gamma$, we can reduce lots of background.
Figure 5.6: These distributions (normalized to unity) are shown for different components; red is for $B^\pm \rightarrow \chi_{c1}K^\pm$, magenta is for $B^\pm \rightarrow \chi_{c2}K^\pm$, dark blue is for $B^\pm \rightarrow J/\psi K^*(892)^\pm$, sky blue for $B^0 \rightarrow J/\psi K^*(892)^0$ and black is for the rest of the background.

- $\pi^0$-veto, we use Koppenberg $\pi^0$ veto function package [95]. In this package, $\gamma$ is combined with other $\gamma$’s from that event and get an invariant mass of the two photons. Using this invariant mass, the lab energy and polar angle of the second photon; $\gamma$’s probability of being from a $\pi^0$ is estimated. From all the combinations of the $\gamma$ with all other $\gamma$’s in the event; we store the maximum $\pi^0$ probability. Most of the background comes from $\pi^0$, therefore by applying a cut on $\pi^0$ probability, we expect to reduce significantly the background. The
5.3. Optimization of Cuts

\( \pi^0 \) probability for \( \gamma \)s coming from signal is peaking at 0, whereas for the \( \gamma \)'s coming from other sources, it is near 1 (Figure 5.6b).

- \( \cos \theta_{\text{hel}} \), where \( \theta_{\text{hel}} \) is the angle between \( B \) direction and the \( \gamma \) direction (vector opposite to the \( \gamma \) original vector). Most of the background is dominated by \( B \to J/\psi K^* \). Angular polarization will be different for the \( \gamma \) coming from \( \chi_c1, \chi_c2, K^* \) and random sources; which can be exploited in order to reduce the background further. Figure 5.6c shows \( \cos \theta_{\text{hel}} \) distribution for the different components. \( B^\pm \to \chi_{c2} K^\pm \) (magenta) has a flat distribution as \( \chi_{c2} \) is made to decay using PHSP model in the absence of TVP model in EvtGen. Distribution of \( B^\pm \to J/\psi K^*(892)^\pm \) (dark blue) is different than the distribution of \( B^0 \to J/\psi K^*(892)^0 \) (sky blue) as the \( \gamma \) used in reconstruction of \( \chi_{c1, c2} \) comes from different sources. For \( K^{*\pm} \), gamma comes from two sources: random sources and from \( K^{*\pm} \)'s \( \pi^0 \), while in case of \( K^{*0} \), gamma comes from random sources only.

![FoM plots](image)

Figure 5.7: FoM plots of \( \Delta E \) for \( B^\pm \to \chi_{c2} K^\pm \) decay mode.

In order to reduce the background in an efficient manner, Figure of Merit (FoM) study is performed. FoM is defined as \( S/\sqrt{S+B} \), where \( S \) is the expected signal events, using the BaBar current result \( B(B^\pm \to \chi_{c2} K^\pm) = 1.8 \times 10^{-5} \) (U.L.) [34] and \( B \) is the expected background events from the \( B \to J/\psi X \) inclusive MC sample. FoM is calculated for these three cuts simultaneously and the cuts are selected where
CHAPETR 5. \( B \rightarrow \chi_{C1,C2}K \& B \rightarrow X(3872)K \) ANALYSIS

FoM is maximum. Cuts are coming out to be close for \( K^+ \) and \( K_S^0 \) mode; for \( K^+ \) mode we get the FoM maximize at \( E_\gamma > 290 \) MeV, \( \pi^0 \) probability < 0.52 and \( \cos \theta_{\text{hel}} < 0.76 \) whereas for \( K_S^0 \) mode FoM comes out to be at \( E_\gamma > 290 \) MeV, \( \pi^0 \) probability < 0.55 and \( \cos \theta_{\text{hel}} < 0.73 \); we select the cuts of the \( K^+ \). On the basis of 3D cut optimization, following cuts in the analysis are used:

- \( E_\gamma > 290 \) MeV
- \( \pi^0 \) probability < 0.52
- \( \cos \theta_{\text{hel}} < 0.76 \)

Until now, we are using the interval range of \( \Delta E \) as [−60, 40] MeV, this is not optimized. The optimization of \( \Delta E \) range gives [−25, 30] MeV (Figure 5.7).

Using these cuts, the background is reduced by 86.4% and the signal by 35.5% for \( B^\pm \rightarrow \chi_{C2}K^\pm \). For neutral mode, \( B^0 \rightarrow \chi_{C2}K_S^0 \), background is reduced by 87.0% and the signal by 34.7%.

Optimization of these cuts is based on MC study, there can be a difference between data and our MC understanding. This difference will be taken into account in the systematic uncertainty estimation (Please refer to Section 5.8.10 for more details).

Figure 5.8: After cut, \( M_{J/\psi} \) (GeV/c^2) (∼ 50 × data) plot of a) \( B^\pm \rightarrow \chi_{C1,C2}K^\pm \) b) \( B^0 \rightarrow \chi_{C1,C2}K_S^0 \) for \( B \rightarrow J/\psi X \) inclusive MC sample.
5.3. OPTIMIZATION OF CUTS

There is a clear improvement of the significance of $\chi_{c2}K^\pm$ after applying these cuts. The $B \to J/\psi X$ inclusive MC sample is fit by using two double Gaussian functions (one for each $\chi_{c1}$ and $\chi_{c2}$ components) while for the smooth background, 2nd order chebyshev polynomial is used. In the final fit, shown in Figure 5.10, shape and area of $\chi_{c0}$ is fixed from the separate fit performed to $\chi_{c0}$ (shown in Figure 5.9a). For $\chi_{c1}$ and $\chi_{c2}$, fraction is fixed from the signal MC study. Mean of $\chi_{c2}$ is parametrized as $M(\chi_{c2}) = M(\chi_{c1}) + \delta M$, where $M(\chi_{c1})$ is the free parameter of the $\chi_{c1}$ mass and $\delta M$ is a fixed value obtained from $m_{\chi_{c2}} - m_{\chi_{c1}}$ (PDG’09) $[96]$, which is $45.540 \pm 0.114$ MeV/$c^2$. Also, the width of $\chi_{c2}$ is expressed as $\text{width}(\chi_{c2}) = \text{width}(\chi_{c1}) \times \kappa_{\text{width}}$, where $\text{width}(\chi_{c1})$ is the free parameter of the $\chi_{c1}$ width and $\kappa_{\text{width}}$ is a fixed value obtained from $\text{width}_{\chi_{c2}}/\text{width}_{\chi_{c1}}$ (MC study).

![Graph Showing $\chi_{c0}$](image1.png)

![Graph Showing $\chi_{c1}$](image2.png)

![Graph Showing $\chi_{c2}$](image3.png)

Figure 5.9: $B \to J/\psi X$ inclusive MC study ($\sim 50 \times $ data) for $B^\pm \to \chi_{c1,2}K^\pm$. 
In order to study the significance and to check the fitter, an ensemble study check is performed. For this purpose, $B \to J/\psi X$ inclusive MC sample is divided into 50 different samples after removing $\chi_{c1}$ and $\chi_{c2}$ signal from it. These 50 samples are generated for $772 \times 10^6$ $N_{BB}$ events using the signal PDF ($B^\pm \to \chi_{c1,c2}K^\pm$) and the branching fraction corresponding to the BaBar’s recent $B(B^\pm \to \chi_{c1}K^\pm)$ ($B(B^\pm \to \chi_{c2}K^\pm)$) as $4.5 \times 10^{-4}$ ($1.8 \times 10^{-5}$, U.L.) [54]. For one sample, 2082 (53) events are generated for $B \to \chi_{c1}K^\pm$ ($B \to \chi_{c2}K^\pm$) with the Poisson fluctuations. These
generated samples (of $\chi_{c1}$ and $\chi_{c2}$ signals) are combined with the $B \to J/\psi X$ inclusive
MC sample; which gives us 50 different samples in total. Fit is performed to these
samples and the statistical significance is calculated. From this study, we may expect
about $6.3\sigma$ statistical significance for $\chi_{c2}K^\pm$ assuming $\mathcal{B}(B^\pm \to \chi_{c2}K^\pm) = 1.8 \times 10^{-5}$
(U.L.). Figure 5.10b and 5.10c shows the number of events and the significance. In
a similar manner we estimate the significance for $B \to \chi_{c2}K_S^0$ and it comes out to be
$4.9\sigma$, assuming $\mathcal{B}(B^0 \to \chi_{c2}K^0) = 2.8 \times 10^{-5}$ (U.L.).

5.3.2 The $B \to X(3872)(\to J/\psi \gamma)K$ decay

We used the parameters $E_\gamma$, $\pi^0$ probability and $\cos \theta_{\text{hel}}$ in order to reduce the background (mainly coming from $K^*(892)$). Figure 5.11 shows the different components separately.

To optimize the cuts, $\text{FoM}$ study is performed for these variables. $\text{FoM}$ is calculated for these three cuts simultaneously and the cuts with maximum $\text{FoM}$ value is selected. Cuts comes out to be similar for $K^+$ and $K_S^0$ mode; for $K^+$ mode the optimal cut come out to be $E_\gamma > 470$ MeV, $\pi^0$ probability $< 0.52$ and $\cos \theta_{\text{hel}} < 0.85$, whereas for $K_S^0$ mode the optimal cuts are $E_\gamma > 430$ MeV, $\pi^0$ probability $< 0.76$ and $\cos \theta_{\text{hel}} < 0.7$. Same cuts for $K_S^0$ are used, as the one optimized for the charged mode ($K^+$). Cuts for $K_S^0$ may look different but $\text{FoM}$ is almost same if $K^+$ optimal cuts on $K_S^0$ is applied; $2.77 \pm 0.03$ is the $\text{FoM}$ for the original $K_S^0$ cuts and $2.75 \pm 0.03$ if $K^+$ mode cuts are used for $K_S^0$ mode. On the basis of 3D cut optimization, following cuts are optimized:

- $E_\gamma > 470$ MeV
- $\pi^0$ probability $< 0.52$
- $\cos \theta_{\text{hel}} < 0.85$

Until now, the range of $\Delta E$ used is $[0.60, 40]$ MeV, which is not optimized. The optimized $\Delta E$ range, comes out to be $[-30, 35]$ MeV (Figure 5.12).
Figure 5.11: These distributions (normalized to unity) shows the different components; magenta is $B^\pm \rightarrow X(3872)K^\pm$, dark blue is for $B^\pm \rightarrow J/\psi K^*(892)^\pm$, sky blue for $B^0 \rightarrow J/\psi K^*(892)^0$ and black shows rest of the background.

Using these cuts, the background is reduced by 78.9% and the signal by 30.5% for $B^\pm \rightarrow X(3872)K^\pm$ decay. For neutral mode, $B^0 \rightarrow X(3872)K^0_S$ decay, background is reduced by 79.0% and the signal by 30.5%. Figure 5.13 shows the background for $B^{\pm,0} \rightarrow X(3872)K^{\pm,0}$ after applying the cuts.

We fit the ($M_{J/\psi\gamma}$) signal $X(3872)$, using a double Gaussian function and a 1st order chebyshev polynomial for the background shape. Mean and the width of $X(3872)$ is fixed using the signal MC study after applying correction from the $B^\pm \rightarrow \chi_{c1}K^\pm$ sample.
5.3. OPTIMIZATION OF CUTS

Figure 5.12: FoM plots for $\Delta E$ range of $X(3872)(\to J/\psi\gamma)K^{\pm}$.

Figure 5.13: After cut, $M_{J/\psi\gamma}$ (GeV/$c^2$) distribution ($\sim 50 \times$ data) plots of a) $B^{\pm} \to X(3872)K^{\pm}$ b) $B^0 \to X(3872)K_S^0$.

In order to study the significance and to check the fitter, we perform an ensemble check. In this, $B \to J/\psi X$ MC sample is divided into 50 different samples. These 50 samples are generated for $772 \times 10^6 N_{BB}$ events using the signal ($B^{\pm} \to X(3872)K^{\pm}$) PDF with BaBar’s recent $B(B^{\pm} \to X(3872)K^{\pm}) \times B(X(3872) \to J/\psi\gamma) = 2.8 \times 10^{-6}$ [54]. For one sample, we generate 47 events with the Poisson fluctuation. These generated samples ($X(3872)$) are combined with $B \to J/\psi X$ inclusive MC sample; which provide us with total 50 samples. Fit to $M_{J/\psi\gamma}$ distribution is performed, and the statistical significance ($\Sigma$) is calculated for each sample. From this study, we
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may expect about 7.7\( \sigma \) statistical significance for \( X(3872)K^\pm \). Figure 5.14 shows the number of events and the significance we get. In similar manner, we estimate the significance for \( B^0 \to X(3872)K^0_S \) mode to be 6\( \sigma \).

![Figure 5.14: a) Events and b) significance of \( B^\pm \to X(3872)(\to J/\psi\gamma)K^\pm \).](image)

### 5.4 Fit Strategy

The \( M_{J/\psi\gamma} \) distribution is used to extract the yield. The \( B \to \chi_{c1}K^\pm \) decay is used as the control sample to take into account the possible difference between MC and data, due to its high statistics and same final state. Fit is performed to \( M_{J/\psi\gamma} \) for \( \chi_{c1,c2} \) together. In this fit, we use two double Gaussian functions (one for \( \chi_{c1} \) and other for \( \chi_{c2} \)), while the background is parametrized by 2\textsuperscript{nd} order chebyshev polynomial. In the case of \( B^\pm \to \chi_{c1,c2}K^\pm \) decay, fraction for \( \chi_{c1} \) and \( \chi_{c2} \) is same and is fixed from the signal MC study. Mean of the distribution for \( \chi_{c2} \) is parametrized as \( M(\chi_{c2}) = M(\chi_{c1}) + \delta M \), the \( M(\chi_{c1}) \) (\( \chi_{c1} \) mass) is a free parameter and \( \delta M \) is fixed from \( m_{\chi_{c2}} - m_{\chi_{c1}} \) mass from PDG’09. The width of \( \chi_{c2} \) is expressed as \( \text{width}(\chi_{c2}) = \text{width}(\chi_{c1}) \times \kappa_{\text{width}} \), where \( \text{width}(\chi_{c1}) \) is a free parameter (\( \chi_{c1} \) width) and \( \kappa_{\text{width}} \) (which has a value of \( \approx 1.1 \)) is fixed from the \( \text{width}_{\chi_{c2}}/\text{width}_{\chi_{c1}} \) obtained in MC.

In the case of \( B^0 \to \chi_{c1,c2}K^0_S \) decay, we use the PDFs obtained from the \( B^\pm \to \)}
5.4. FIT STRATEGY

$\chi_{c1,c2} K^\pm$ decay, as $\chi_{c1,c2}$ in the neutral $B$ mode has the same shape as $\chi_{c1,c2}$ in the charged $B$ mode.

For $B \rightarrow X(3872)K^\pm$ mode, signal shape is defined by one double Gaussian and the background by the 1$^{st}$ order chebyshev polynomial. Double Gaussian parameters are fixed from the MC study after applying the correction (difference between data and MC seen in $B^\pm \rightarrow \chi_{c1} K^\pm$). Mean of $X(3872)$ is parametrized as $M(X(3872)) = m_{X(3872)w} + \delta(\equiv M(\chi_{c1}) - m_{\chi_{c1}})$, where $M(\chi_{c1})$ is the value we get for $\chi_{c1}$ from fit to data and $m_{X(3872)w}$ ($m_{\chi_{c1}}$) is the value obtained from the world average Table 1.3 (PDG’09). The value of $\delta$ comes out to be $0.72 \pm 0.17$ MeV/$c^2$ (the estimated uncertainty comes from the PDG $\chi_{c1}$ mass uncertainty and our stat. uncertainty on $\chi_{c1}$ mass). The $\sigma_1(X3872)$ is parametrized as $\sigma_1(X3872)_{MC} \times \kappa \sigma_{\chi_{c1}} (\kappa \sigma_{\chi_{c1}} \equiv \sigma_1(\chi_{c1})_{data}/\sigma_1(\chi_{c1})_{MC})$. In this case also, neutral mode ($B^0 \rightarrow X(3872)K^0$) shape is fixed from the charged $B^\pm \rightarrow X(3872)K^\pm$ mode. Table 5.2 and 5.3 summarizes the parameters used in the fit.

Table 5.2: Fit parameters of $B^{\pm,0} \rightarrow \chi_{c1,c2} K^{\pm,0}$ decay.

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<th>Parameter</th>
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<th>$K_S^0$</th>
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<td>$M(\chi_{c2})$</td>
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<td>$M(\chi_{c1}) + \delta M$</td>
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<td>$\delta M$</td>
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<td>chebyshev 2$^{nd}$ polynomial</td>
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Table 5.3: Fit parameters of $B^{\pm,0} \to X(3872)K^{\pm,0}$ decay.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
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<td>$M(X3872)$</td>
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<td>$\delta$</td>
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</table>

5.5 Fit Bias Study

To look for any bias in the fitter, toy MC study is performed. In this study, 1000 signal MC samples are generated with $\chi_{c1}$ PDF (from signal MC) using the BaBar branching fraction [54] and the $2^{nd}$ order chebyshev polynomial for the background (from $B \to J/\psi X$ inclusive MC study). There is no $\chi_{c2}$ signal in these samples. So, if a fit is performed to these samples using the explained fitter, no event for $\chi_{c2}$ is expected and its pull ($= (\text{Yield} - \text{Expected})/(\text{error on Yield})$) distribution sigma should be equal to 1. Fit is performed to each sample and the result from these fits are shown in Figures 5.15 and 5.16. Figure 5.15 a) shows one of the typical fit while b) shows the yield of $\chi_{c1}$, which comes out to be $2083.6 \pm 1.6$ events consistent with the generated events (2082 events) and c) shows the yield of $\chi_{c2}$ (which is consistent with zero, $-0.26 \pm 0.23$). Figure 5.16 a) shows the pull distribution for $\chi_{c1}$, and b) for $\chi_{c2}$. There is no significant bias in the fitter.

Similarly, for the neutral decay mode $B^0 \to \chi_{c1,c2}K^0_S$ toy MC study is performed. We generated 600 events with Poisson fluctuations (using BaBar’s branching fraction
5.5. FIT BIAS STUDY

(a) One of the typical fit from the 1000 fits performed

(b) Yield of $\chi_{c1}$, we get from the fits

(c) Yield of $\chi_{c2}$, we get from the fits

Figure 5.15: Fit bias study.

Figure 5.16: Fit bias study, pull distribution for a) $B^\pm \to \chi_{c1} K^\pm$ and b) $B^\pm \to \chi_{c2} K^\pm$.

[54]) for $B^0 \to \chi_{c1} K_S^0$ using the signal PDF, and the background using the 2nd order
chebyshev polynomial shape. Fit is performed to each sample. Yield for $\chi_{c1}$ comes out to be 600.1 ± 0.8 events while for $\chi_{c2}$, it is close to zero ($-0.23 ± 0.12$). Figure 5.7 a) shows the pull distribution for $B^0 \rightarrow \chi_{c1} K^0_S$ and b) for $B^0 \rightarrow \chi_{c2} K^0_S$. Bias seems to be insignificant in the fitter.

![Pull distribution](image1)

**Figure 5.17:** Fit bias study, pull distribution for a) $B^0 \rightarrow \chi_{c1} K^0_S$ and b) $B^0 \rightarrow \chi_{c2} K^0_S$.

![Pull distribution](image2)

**Figure 5.18:** $M_{J/\psi\gamma}$ (GeV/$c^2$) distribution, data sideband (red) overlapped with the sum of $B \rightarrow J/\psi X$ sideband + non-$J/\psi$ component (dark blue) for: a) $B^\pm \rightarrow \chi_{c1,2} K^\pm$ and b) $B^\pm \rightarrow X(3872) K^\pm$; sky blue is non-$J/\psi$ component estimated from data sidebands.
5.6 Data Sideband Study

To look for any difference between the data and MC, the $M_{J/\psi\gamma}$ distributions of data and MC (excluding the signal region $\pm 6\sigma$) is compared. Figures 5.18 and 5.19 show the agreement between red dots (data) and the blue line (MC + non-$J/\psi$ component estimated from the data sidebands). As it can be seen from figures, they agree very well with each other. However still there is a small mismatch between data and MC in $B^{\pm} \rightarrow X(3872)K^{\pm}$ (above 4.02 GeV/$c^2$); which is not a serious problem for this study, as this is flat and will be taken care by floating the 1$^{\text{st}}$ order chebyshev polynomial.

![Graphs showing $M_{J/\psi\gamma}$ distribution](image)

Figure 5.19: $M_{J/\psi\gamma}$ (GeV/$c^2$) distribution, data sideband (red) overlapped with the sum of $B \rightarrow J/\psi + X$ sideband + non-$J/\psi$ component (dark blue) for: a) $B^0 \rightarrow \chi_{c1,c2}K_S^0$ and b) $B^0 \rightarrow X(3872)K_S^0$; sky blue is non-$J/\psi$ component estimated from data sidebands.

5.7 Data Fitting

After conforming the reliability of understanding of the background and finding no bias in the fitter. We went ahead and open the data box. We used the whole data available at $\Upsilon(4S)$, $772 \times 10^6 N_{B\overline{B}}$. 
Figure 5.20: Fit to data ($772 \times 10^6 N_{D\bar{D}}$); for $B^\pm \rightarrow \chi_{c1, c2} K^\pm$, with zoom region showing peak of $\chi_{c2} K^\pm$. The curves show the signal (pink dot-dashed for $\chi_{c1}$ and red dashed for $\chi_{c2}$), and the background component (blue dotted) as well as overall fit (blue solid).

Figure 5.20 shows the fit performed for $B^\pm \rightarrow \chi_{c1, c2} K^\pm$ to data. From the fit, we get $2308.2^{+52.6}_{-51.8}$ events for $B^\pm \rightarrow \chi_{c1} K^\pm$ and $32.8^{+10.9}_{-10.2}$ events in case of $B^\pm \chi_{c2} K^\pm$ decay. With this analysis, significance for $B^\pm \rightarrow \chi_{c2} K^\pm$, comes out to be 3.56$\sigma$.

Fit to $B^0 \rightarrow \chi_{c1,c2} K^0_S$ decay is presented in Figure 5.21. From the fit, we get $542.0^{+24.4}_{-23.7}$ events as the yield for $B \rightarrow \chi_{c1} K^0_S$ which is as per the expectation, while for $B \rightarrow \chi_{c2} K^0_S$ we get the yield less than the expectation, $2.8^{+4.7}_{-3.9}$ events, with a significance of 0.69$\sigma$.

Using the PDF as explained in the Section 5.4, fit is performed to $M_{J/\psi \gamma}$ mass distribution of $B \rightarrow X(3872)K$ as shown in Figure 5.22. We obtained the yield of $30.05^{+8.17}_{-7.76}$ events for the charged mode ($B^\pm \rightarrow X(3872)K^\pm$) with 4.87$\sigma$ significance while in the case of neutral mode ($B^0 \rightarrow X(3872)K^0_S$) decay we get $5.66^{+3.51}_{-2.80}$ events as the yield and a significance of 2.39$\sigma$.

Table 5.4 summarizes the fitted results to the $M_{J/\psi \gamma}$ distribution in data.
5.7. DATA FITTING

Figure 5.21: Fit to data ($772 \times 10^6 N_{B\pi\pi}$); for $B^0 \rightarrow \chi_c1,2 K_S^0$, with zoom region showing peak of $\chi_c2 K_S^0$. The curves show the signal (pink dot-dashed for $\chi_c1$ and red dashed for $\chi_c2$), and the background component (blue dotted) as well as overall fit (blue solid).

Figure 5.22: Fit to data ($722 \times 10^6 N_{B\pi\pi}$); for a) $B^\pm \rightarrow X(3872) K^{\pm}$ and b) $B^0 \rightarrow X(3872) K_S^0$. The curves show the signal (red dashed for $X(3872)$), and the background component (blue dotted) as well as overall fit (blue solid).
Table 5.4: Summary of the results of the $B \to \chi_{c1}K$, $B \to \chi_{c2}K$ and $B \to X(3872)K$ decay study. Efficiency ($\epsilon$), Yield ($Y$), Significance ($\Sigma$) with systematic uncertainty included and measured branching fraction ($B$) comparing our results with the PDG [3] and BaBar [54]. For $B$, the first (second) uncertainty is statistical (systematic). Systematic uncertainty is included in the significance (explained in Appendix C). Upper limit (UL) is obtained at 90% confidence level (CL), more details in section 6.5. Here $B$ for $B \to X(3872)K$ is $B(B \to X(3872)K) \times B(X(3872) \to J/\psi\gamma)$.

<table>
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<th>Mode</th>
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<th>$\Sigma$($\sigma$)</th>
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<td>$B^\pm \to \chi_{c1}K^\pm$</td>
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<td>2308.2$^{+52.0}_{-51.8}$</td>
<td>79.2</td>
<td>4.94$^{+0.11}_{-0.33}$ ± 0.33</td>
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<tr>
<td>$B^0 \to \chi_{c1}K^0_S$</td>
<td>13.2</td>
<td>5420.0$^{+24.4}_{-23.7}$</td>
<td>36.8</td>
<td>3.78$^{+0.17}_{-0.16}$ ± 0.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$&lt; 1.8$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$&lt; 1.5$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\epsilon$ (%)</th>
<th>$Y$</th>
<th>$\Sigma$($\sigma$)</th>
<th>$B$, $\times 10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Present analysis</td>
</tr>
<tr>
<td>$B^\pm \to \chi_{c2}K^\pm$</td>
<td>16.6</td>
<td>32.8$^{+10.9}_{-10.2}$</td>
<td>3.6</td>
<td>1.11$^{+0.36}_{-0.34}$ ± 0.09</td>
</tr>
<tr>
<td>$B^0 \to \chi_{c2}K^0_S$</td>
<td>14.4</td>
<td>2.8$^{+4.7}_{-3.9}$</td>
<td>0.7</td>
<td>0.32$^{+0.53}_{-0.44}$ ± 0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$&lt; 2.43$</td>
</tr>
<tr>
<td>$B^\pm \to X(3872)K^\pm$</td>
<td>18.3</td>
<td>30.0$^{+8.2}_{-7.4}$</td>
<td>4.9</td>
<td>1.78$^{+0.48}_{-0.44}$ ± 0.12</td>
</tr>
<tr>
<td>$B^0 \to X(3872)K^0_S$</td>
<td>14.5</td>
<td>5.7$^{+3.5}_{-2.8}$</td>
<td>2.4</td>
<td>1.24$^{+0.76}_{-0.61}$ ± 0.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$&lt; 2.43$</td>
</tr>
</tbody>
</table>
5.8 Systematic Uncertainty Study

Main sources of the systematic uncertainty in this analysis are:

- Kaon identification.
- $K^0_S$ reconstruction.
- Lepton identification.
- $\gamma$ identification.
- Efficiency.
- Secondary branching fractions.
- $N_{B\pi}$.
- Charged track finding efficiency.
- Difference between data and MC in behavior to the $(E_\gamma, \cos \theta_{hel},$ Koppenberg's $\pi^0$-veto and $\Delta E$) cuts.
- $\cos \theta_{hel}$ distribution.
- Fit bias.

5.8.1 Kaon Identification.

In $B^\pm \rightarrow \chi_{c1,2}K^\pm$ and $B^\pm \rightarrow X(3872)K^\pm$ decays, kaons have uncertainty on their identification and this uncertainty is estimated as explained in Section 3.10. A correction for the difference in kaon efficiency (between data and MC) is then obtained. This correction is used to correct the efficiency while error on it is included as systematic error coming from kaon's identification. Table 5.5 summarizes the kaon’s systematic uncertainty.
Table 5.5: Kaon identification Systematic uncertainty for different modes under study.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Correction</th>
<th>Syst. uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \to \chi_{c1} K^\pm$</td>
<td>$1.010 \pm 0.006$</td>
<td>0.6</td>
</tr>
<tr>
<td>$B^\pm \to \chi_{c2} K^\pm$</td>
<td>$1.011 \pm 0.006$</td>
<td>0.6</td>
</tr>
<tr>
<td>$B^\pm \to X(3872) K^\pm$</td>
<td>$1.001 \pm 0.005$</td>
<td>0.5</td>
</tr>
</tbody>
</table>

5.8.2 $K_S^0$ Systematic Uncertainty

The $K_S^0$ systematic uncertainty is estimated to be $4.5\%$ (Section 3.10).

5.8.3 Lepton Identification Systematic Uncertainty

There can be a difference between lepton identification in data and MC. This difference can be estimated as explained in Appendix A. Combining the electron and muon identification give total correction factor of $0.9993 \pm 0.0109$ on the lepton identification from $J/\psi \to \ell\ell$ study. As the correction factor is near unity, instead of correcting the efficiency, the difference is included in the systematic uncertainty. The total systematic uncertainty comes out to be $1.1\%$ due to the lepton identification.

5.8.4 $\gamma$ Systematic Uncertainty

$2.0\%$ is used as the systematic uncertainty coming from $\gamma$ (Section 3.10).

5.8.5 Efficiency

Due to the limited statistical samples of signal MC ($500,000$ events generated for each mode), there will be sizable statistical uncertainty on the calculated efficiency and this uncertainty is taken into account as systematic uncertainty (Table 5.6).
5.8. SYSTEMATIC UNCERTAINTY STUDY

Table 5.6: Systematic Uncertainty due to the statistics of the MC samples.

<table>
<thead>
<tr>
<th>Eff. syst. (%)</th>
<th>$\chi_{c1}$</th>
<th>$\chi_{c2}$</th>
<th>$X(3872)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+$</td>
<td>0.34</td>
<td>0.36</td>
<td>0.33</td>
</tr>
<tr>
<td>$K_S^0$</td>
<td>0.38</td>
<td>0.35</td>
<td>0.34</td>
</tr>
</tbody>
</table>

5.8.6 Secondary Branching Fraction

We are using secondary branching fraction for the calculation of primary branching fraction. These secondary branching fractions have uncertainty, these uncertainties are included in the systematic uncertainty coming from the secondary branching fractions. Table 5.7 summarizes the systematics coming from the secondary branching fractions. We are using the branching ratios from PDG'09 [96].

Table 5.7: Secondary branching fraction systematic uncertainty.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Syst. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow \chi_{c1} K^\pm$</td>
<td>4.5</td>
</tr>
<tr>
<td>$B^\pm \rightarrow \chi_{c2} K^\pm$</td>
<td>4.1</td>
</tr>
<tr>
<td>$B^\pm \rightarrow X(3872) K^\pm$</td>
<td>0.7</td>
</tr>
<tr>
<td>$B^0 \rightarrow \chi_{c1} K_S^0$</td>
<td>4.5</td>
</tr>
<tr>
<td>$B^0 \rightarrow \chi_{c2} K_S^0$</td>
<td>4.2</td>
</tr>
<tr>
<td>$B^0 \rightarrow X(3872) K_S^0$</td>
<td>0.7</td>
</tr>
</tbody>
</table>

5.8.7 Systematic Uncertainty on $N_{B\bar{B}}$

The systematic uncertainty on the number of $B\bar{B}$ events with the Belle detector ($N_{B\bar{B}}$) is estimated to be 1.4%. 

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5.8.8 Systematic Uncertainty due to PDF

The signal yield is extracted by performing a fit to the experimental distribution. Signal yield depends upon the various parameters fixed in the fit. Due to this, there is systematic uncertainty coming from the modeling of the different components of the $\Delta M$ distribution (PDF). For this purpose the parameters of the PDFs are varied as explained below.

- $B^\pm \to \chi_{c1,c2}K^\pm$ decay
  
  $\rightarrow$ In order to take the difference coming from the fraction ($\text{Area}_{2}/\text{Area}$), we free this ratio in the fit and the difference in the yield (0.7% from $\chi_{c1}K^\pm$) is taken as the possible systematic uncertainty.

  $\rightarrow$ In order to take the difference due to the combinatorial background shape described by a 2$^{nd}$ order chebyshev polynomial. We change it to 3$^{rd}$ (and also to 1$^{st}$) order chebyshev polynomial and took the maximum possible difference, 0.13% (2.4%) as the Systematic uncertainty for $\chi_{c1}$ ($\chi_{c2}$).

  $\rightarrow$ To consider the systematic uncertainty on PDG mass of $\chi_{c1}$ and $\chi_{c2}$ into account, we shift the mass difference ($\delta M$) by $\pm 1\sigma$ and find negligible differences in the yield of $\chi_{c1}$ and $\chi_{c2}$.

  $\Rightarrow$ So, we get 0.7% (3.8%) Systematic Uncertainty on $B^\pm \to \chi_{c1}K^\pm$ ($B^\pm \to \chi_{c2}K^\pm$) yield, respectively.

- $B^0 \to \chi_{c1,c2}K_S^0$ decay

  We are fixing the shape for $B^0 \to \chi_{c1,c2}K_S^0$ using $B^\pm \to \chi_{c1,c2}K^\pm$ PDF as explained in Section 5.4. Due to this the systematic uncertainty coming from PDF will be same as that of $B^\pm \to \chi_{c1,c2}K^\pm$ which is 0.7% (3.8%) systematic uncertainty on $B^\pm \to \chi_{c1}K^\pm$ ($\chi_{c2}K^\pm$) with additional systematics coming from
5.8. SYSTEMATIC UNCERTAINTY STUDY

\(M(\chi_{c1}), \sigma_2/\sigma_1, \) and \(\sigma_1(\chi_{c1})\) parameters, as they are floated for \(B^\pm \rightarrow \chi_{c1,c2}K^\pm\) but are fixed in case of \(B^0 \rightarrow \chi_{c1,c2}K^0\).

\(\rightarrow\) We shift the mean of \(M(\chi_{c1})\) by \(\pm 1\sigma\) and find negligible difference in the yield of \(\chi_{c1}\) and \(\chi_{c2}\).

\(\rightarrow\) To take the difference into account, which may arise due to the uncertainty on the \(\sigma_2/\sigma_1\), we fit the distribution with \(\pm 1\sigma\) variation and find a difference of about \(0.7\% \ (0.2\%)\) in the yield of \(\chi_{c1} \ (\chi_{c2})\).

\(\rightarrow\) Also, we vary the \(\sigma_1(\chi_{c1})\) by \(\pm 1\sigma\) and the difference in the yield, which is 0.4\% (negligible) for \(\chi_{c1} \ (\chi_{c2})\), is taken as the possible Systematic Uncertainty.

\(\Rightarrow\) We get 1.1\% (3.8\%) Systematic Uncertainty on \(B^0 \rightarrow \chi_{c1}K_S^0 \ (B^0 \rightarrow \chi_{c2}K_S^0)\) yield.

• \(B \rightarrow X(3872)K\) Decay

We vary the parameters fixed in the fit by \(\pm 1\sigma\) to obtain the systematic uncertainty due to the PDF.

\(\rightarrow\) We shift the mean of \(X(3872)\) mass \((M(X3872))\) by \(\pm 1\sigma\) (uncertainty on the world average mass is also included) and we get 0.6\% as the possible difference in the yield one can expect.

\(\rightarrow\) The \(\sigma_1(X(3872))\) is also varied by \(\pm 1\sigma\) and we get 1.5\% uncertainty.

\(\rightarrow\) To check the difference on yield which may arise due to fixed value of \(\sigma_2/\sigma_1\), we vary it by \(\pm 1\sigma\) and get 0.1\% as the maximum possible deviation.

\(\rightarrow\) Similarly, for \textit{Area}_{2}/\textit{Area} we get the possible systematic uncertainty as 0.2\%.

\(\rightarrow\) In order to take the difference due to the combinatorial background shape described by 1\textsuperscript{st} order chebyshev polynomial. We change it to 2\textsuperscript{nd} order chebyshev polynomial and took the difference, 0.7\%, as the possible uncertainty on the yield.

\(\Rightarrow\) We get 1.8\% as the Systematic Uncertainty on \(B^\pm \rightarrow X(3872)K^\pm\). As \(B^0 \rightarrow X(3872)K_S^0\) has the same PDF as the charged mode, we assign same
systematic uncertainty (1.8%) for the $B^0 \rightarrow X(3872)K_S^0$ yield.

### 5.8.9 Charged Track Systematic

Charged particle track reconstruction has an uncertainty of about 1% per track which has been estimated (Section 3.10). For $B^\pm \rightarrow (J/\psi\gamma)K^\pm$ decay the uncertainty comes out to be 3.0% and for $B^0 \rightarrow (J/\psi\gamma)K^0_S$, it comes out to be 4.0%.

### 5.8.10 Difference due to cuts in MC & Data

Cuts are applied on variables $E_\gamma$, $\cos \theta_{\text{hel}}$, $\pi^0 - \text{veto}$ and $\Delta E$. These cuts are based on a MC study, but MC may not represent data quite well (100%). To take this difference in systematics uncertainty, effect of the cut is studied on $B^\pm \rightarrow \chi_{c1}K^\pm$ decay (MC and data, separately). Table 5.8 shows the effect of the cuts on MC and data. The difference between data and MC is $(1.74 \pm 1.28)\%$. The 3.0% is quoted as the maximum possible difference between MC and data.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Yield from the fit</th>
<th>Loss $(B-A) / B$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC</td>
<td>Before cuts (B)</td>
<td>After cuts (A)</td>
</tr>
<tr>
<td>data</td>
<td>240917 ± 643</td>
<td>145110 ± 384</td>
</tr>
<tr>
<td>Difference in MC and data</td>
<td>3723 ± 87</td>
<td>2307 ± 53</td>
</tr>
</tbody>
</table>

### 5.8.11 $\cos \theta_{\text{hel}}$ Distribution.

For $\chi_{c2}$ and $X(3872)$ charm particles, MC generation is not proper due to the unavailability of TVP generation model in the EvtGen. As we are applying cut on helicity we may expect some difference for $\chi_{c2}$ and $X(3872)$ in the efficiency, the one used and the one we may get after using the proper model for generation. This possible
5.8. SYSTEMATIC UNCERTAINTY STUDY

difference should be taken into account as the systematic uncertainty arising due to \( \cos \theta_{\text{hel}} \).

Table 5.9: Generation models.

<table>
<thead>
<tr>
<th>Mode ( (J^{PC}) )</th>
<th>Decay Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \chi_{c2}(1^{++}) \rightarrow J/\psi\gamma )</td>
<td>VVP</td>
</tr>
<tr>
<td>( \chi_{c2}(2^{++}) \rightarrow J/\psi\gamma )</td>
<td>PHSP</td>
</tr>
<tr>
<td>( X(3872)(1^{++}) \rightarrow J/\psi\gamma )</td>
<td>VVP</td>
</tr>
</tbody>
</table>

The \( \chi_{c2} \) is made to decay \( (\rightarrow J/\psi\gamma) \) using PHSP in EvtGen whereas it is a tensor \( 2^{++} \) while in the case of \( X(3872) \), it is not sure whether \( X(3872) \) is \( 1^{++} \) particle or \( 2^{+-} \); and we have used \( 1^{++} \) model. In the absence of TVP model in EvtGen, and to take the possible difference between the real situation and used MC generation model, we tried to get the possible difference by using different models for signal generation. We generated \( \chi_{c2} \) as scalar (SVP\_helamp) and vector (VVP) model while \( X(3872) \) is generated as scalar (SVP\_helamp) and PHSP model. As these are extreme cases, we quote the difference in the efficiency as the maximum possible difference between real situation and MC generation, which one can expect. We quote 3.8\% (4.2\%) as the maximum possible difference for \( \chi_{c2} \) \( (X(3872)) \) between real situation and MC and take this number as systematics coming due to helicity cut.

Table 5.10: Helicity cut systematic study.

<table>
<thead>
<tr>
<th>Mode ( \rightarrow )</th>
<th>( \chi_{c2} )</th>
<th>( X(3872) )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Eff. (%)</td>
<td>Diff. (%)</td>
</tr>
<tr>
<td>Scalar</td>
<td>16.43 ± 0.06</td>
<td>0.78 ± 0.51</td>
</tr>
<tr>
<td>Vector</td>
<td>15.93 ± 0.06</td>
<td>3.80 ± 0.50</td>
</tr>
<tr>
<td>Tensor</td>
<td>16.56 ± 0.06</td>
<td>ref.</td>
</tr>
<tr>
<td>Syst. (%) ( \rightarrow )</td>
<td>3.8</td>
<td>4.2</td>
</tr>
</tbody>
</table>
5.8.12 Fit Bias

The details about the fit bias has been presented in Appendix B. We get 0.54% (2.1%) bias in $B^\pm \rightarrow \chi_{c2}K^\pm$ ($B^0 \rightarrow \chi_{c2}K^0$) decay. In case of $B^0 \rightarrow \chi_{c2}K^0$ decay mode fit bias comes out to be 0.04%. While for $B^\pm \rightarrow X(3872)(J/\psi\gamma)K^\pm$ ($B^0 \rightarrow X(3872)(\rightarrow J/\psi\gamma)K^0$) fit bias is estimated to be 0.54% (0.24%).

Table 5.11: Systematic uncertainty of the $B \rightarrow \chi_{c1,2}K$ and $B \rightarrow X(3872)K$ decays.

<table>
<thead>
<tr>
<th>Mode $\rightarrow$</th>
<th>$B \rightarrow \chi_{c1}K$</th>
<th>$B \rightarrow \chi_{c2}K$</th>
<th>$B \rightarrow X(3872)K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>$K^+$</td>
<td>$K_S^0$</td>
<td>$K^+$</td>
</tr>
<tr>
<td>$K$-id</td>
<td>0.6</td>
<td>-</td>
<td>0.6</td>
</tr>
<tr>
<td>$K_S^0$</td>
<td>-</td>
<td>4.5</td>
<td>-</td>
</tr>
<tr>
<td>$\ell$ id</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>$\gamma$-syst.</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>MC</td>
<td>0.3</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Sec. $B$</td>
<td>4.5</td>
<td>4.5</td>
<td>4.1</td>
</tr>
<tr>
<td>$N_{B,\Upsilon}$</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>PDF</td>
<td>0.7</td>
<td>1.1</td>
<td>3.8</td>
</tr>
<tr>
<td>Tracking</td>
<td>3.0</td>
<td>4.0</td>
<td>3.0</td>
</tr>
<tr>
<td>MC,data diff</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>$\cos \theta_{hel}$</td>
<td>-</td>
<td>-</td>
<td>3.8</td>
</tr>
<tr>
<td>Fit bias</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>Total</td>
<td>6.8</td>
<td>8.6</td>
<td>8.4</td>
</tr>
</tbody>
</table>

5.9 Chapter in a Nutshell

Detailed analyses of $B \rightarrow \chi_{c1,2}K$ and $B \rightarrow X(3872)K$ decay modes have been described in this Chapter. Here $\chi_{c1,2}$ and $X(3872)$ decays into $J/\psi\gamma$. Background
study is performed using $B \rightarrow J/\psi X$ inclusive MC sample and data sidebands. There is no peaking background in the signal region. Still in order to improve the significance of the result (in simple language to reduce the background) cuts are applied on physics variables $E_\gamma$, $\pi^0$-veto and $\cos \theta_{hel}$. The branching fractions $\mathcal{B}(B^- \rightarrow \chi_{c1} K^-)$ and $\mathcal{B}(B^0 \rightarrow \chi_{c1} K^0)$ are measured as $(4.94 \pm 0.11 \text{(stat.)} \pm 0.33 \text{(syst.)}) \times 10^{-4}$ and $(3.78^{+0.17}_{-0.16} \text{(stat.)} \pm 0.3 \text{(syst.)}) \times 10^{-4}$, respectively. These measurements are in agreement with the world average [3] and in addition to this, they are the most precise measurements till date. Thanks to the Belle large data sample, first evidence for $B^- \rightarrow \chi_{c2} K^-$ decay is also seen with a significance of $3.6\sigma$ and the branching fraction $\mathcal{B}(B^- \rightarrow \chi_{c2} K^-)$ is measured as $(1.11^{+0.36}_{-0.34} \text{(stat.)} \pm 0.09 \text{(syst.)}) \times 10^{-5}$. The upper limit (U.L.) @90\% confidence limit (C.L.) is also derived for the branching fraction of $B^0 \rightarrow \chi_{c2} K^0$ decay mode at $< 1.5 \times 10^{-5}$. The $X(3872) \rightarrow J/\psi \gamma$ decay mode is confirmed by observing this decay mode with a $4.9\sigma$ significance. The branching fraction $(B^- \rightarrow X(3872) K^-) \times \mathcal{B}(X(3872) \rightarrow J/\psi \gamma)$ is measured as $(1.78^{+0.48}_{-0.44} \text{(stat.)} \pm 0.12 \text{(syst.)}) \times 10^{-6}$. The U.L. (@90\% C.L.) for branching fraction $\mathcal{B}(B^0 \rightarrow X(3872) K^0) \times \mathcal{B}(X(3872) \rightarrow J/\psi \gamma)$ is derived as $< 2.43 \times 10^{-6}$. Now, with the present analysis the decay of $X(3872) \rightarrow J/\psi \gamma$ is a well established decay mode.
In this Chapter, analysis procedure of $B \rightarrow X(3872)K$ decay mode has been explained, where $X(3872)$ decays to $\psi(2S)\gamma$. Recently, BaBar has found an evidence for $X(3872) \rightarrow \psi(2S)\gamma$ decay mode and has measured the branching fraction $B(X(3872) \rightarrow \psi(2S)\gamma)$ to be 3.4 times to the that of $B(X(3872) \rightarrow J/\psi\gamma)$ [54]. The verification and improved measurement of this decay mode is awaited, as this decay mode is of great interest for the theoretical understanding of the newly discovered charmonium state $X(3872)$ (explained in Section 1.11). Using the large amount of Belle data set, which is about 1.5 times the size of data used by BaBar in their analysis, we have a chance of observing this decay mode. The $X(3872) \rightarrow J/\psi\gamma$ decay mode analysis has been already explained in the previous Chapter. Summary of the results from both Chapters (5 and 6) are presented in Chapter 7.

6.1 Reconstruction

The $B$ meson reconstruction is done by combining the $X(3872)$ (reconstructed from $\psi(2S)$ meson and $\gamma$) with the $K$ meson, as explained in Section 3.8.2. For MC study, signal events are generated using the EvtGen as an event generator and signal events generated are as follows:

a) $B^{\pm} \rightarrow X(3872)K^{\pm}$, here $X(3872)$ decays to $\psi(2S)(\rightarrow \ell^{+}\ell^{-})\gamma$.

b) $B^{\pm} \rightarrow X(3872)K^{\pm}$, here $X(3872)$ decays to $\psi(2S)(\rightarrow J/\psi(\rightarrow \ell^{+}\ell^{-})\pi^{-}\pi^{+})\gamma$. 

---

8

If we knew what it was we were doing, it would not be called research, would it?

Albert Einstein
c) $B^0 \to X(3872)K_0^*$, here $X(3872)$ decays to $\psi(2S)(\to \ell^+\ell^-)\gamma$.

d) $B^0 \to X(3872)K_0^*$, here $X(3872)$ decays to $\psi(2S)(\to J/\psi(\ell^+\ell^-)\pi^-\pi^+)\gamma$.

Here $\ell$ stands for electrons and muons.

Figure 6.1: Fit to $M_{\psi(2S)\gamma}$ (GeV/c$^2$) distributions using double Gaussian PDF for a) $B^\pm \to X(3872)[\to \psi(2S)(\to \ell\ell)\gamma] K^\pm$ decay mode and b) $B^\pm \to X(3872)[\to \psi(2S)(\to J/\psi\pi\pi)\gamma] K^\pm$ decay mode.

The 500,000 events are generated for the above said decay chain and the detector difference between data set I and data set II has been taken into account during the simulation of the events. The $M_{\psi(2S)\gamma}$ is used to identify the particular decay channel and extract the yield. The 1D UML fit is performed for this purpose.

Figure 6.1 shows the fit to $M_{\psi(2S)\gamma}$ distribution for the charge decay modes. Table 6.1 lists the efficiency for the generated samples.

### 6.2 Background Study

To study the possible sources of background, the $B \to \psi(2S)X$ inclusive MC sample is used for $B^{\pm,0} \to X(3872)[\to \psi(2S)(\to \ell\ell)\gamma] K^{\pm,0}$ while $B \to J/\psi X$ inclusive MC sample is used for $B^{\pm,0} \to X(3872)[\to \psi(2S)(\to J/\psi\pi^+\pi^-)\gamma] K^{\pm,0}$ decay mode.
Table 6.1: Efficiency of the generated samples, these efficiencies are going to change after the application of additional cuts (optimized) in order to improve the significance.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Efficiency(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^- \rightarrow X(3872)K^-$</td>
<td>$\psi(2S) \rightarrow \ell\ell$</td>
</tr>
<tr>
<td></td>
<td>$\psi(2S) \rightarrow J/\psi\pi\pi$</td>
</tr>
<tr>
<td>$B^0 \rightarrow X(3872)K^0$</td>
<td>$\psi(2S) \rightarrow \ell\ell$</td>
</tr>
<tr>
<td></td>
<td>$\psi(2S) \rightarrow J/\psi\pi\pi$</td>
</tr>
</tbody>
</table>

addition to this $M_{\ell\ell}$ data sidebands (explained in Section 5.2) are also used for the background study.

Figure 6.2: $M_{\psi(2S)\gamma}$ (GeV/c$^2$) distribution from $B \rightarrow \psi(2S)X$ inclusive MC sample (scaled to data) for a) $B^{\pm} \rightarrow X(3872)(\rightarrow \psi(2S)\gamma)K^{\pm}$ (left) and b) $B^0 \rightarrow X(3872)(\rightarrow \psi(2S)\gamma)K_S^0$ (right), decay modes here $\psi(2S)$ meson decays into $\ell^+\ell^-$. Figure 6.2 shows the expected background for $B^{\pm/0} \rightarrow X(3872)K^{\pm}/K^0$ decay mode where $X(3872) \rightarrow \psi(2S)\gamma$ and further $\psi(2S) \rightarrow \ell\ell$ decay channel, estimated from the $B \rightarrow \psi(2S)X$ inclusive MC sample. The background consists of a broad
peak lying in the signal region, most of which comes from $B \rightarrow \psi(2S)K^*(892)$ decay mode and a small contribution from $B \rightarrow \psi(2S)K$ decay mode. In the decay channel where $\psi(2S) \rightarrow J/\psi \pi \pi$ decay (Figure 6.3) background has a similar structure as for $\psi(2S) \rightarrow \ell \ell$ with an addition of non peaking background coming from $B \rightarrow \psi(2S)K \pi \pi$, $B \rightarrow J/\psi K \pi \pi$ and $B \rightarrow J/\psi K(1270)$ decay modes. It is also observed that the background coming from $\psi(2S)K$ decay mode is larger in the $\psi(2S) \rightarrow J/\psi \pi \pi$ decay channel as compared to the $\psi(2S) \rightarrow \ell \ell$ decay channel. This can be explained by the fact that in the $B \rightarrow \psi(2S)(\rightarrow \ell \ell)K$ decay mode, we need one random $\gamma$ to make the final state same as the signal state ($\psi(2S)\gamma K$) which has less chance of lying in the signal region (due to the $\gamma$ from some random sources). Whereas in the case of $B \rightarrow \psi(2S)(\rightarrow J/\psi \pi \pi)K$ decay mode, a $\gamma$ can come from some random source (just like $\psi(2S) \rightarrow \ell \ell$ case) and also we can miss one (or both) $\pi$ meson (which can be replaced by another $\pi$ meson from some random source), this increases the chance of the final state ($J/\psi \pi \pi \gamma K$) of lying in the signal region. Also we have $\psi(2S) \rightarrow \chi_{c1,2}\gamma$ decay modes, where $J/\psi \gamma K$ can combine with two $\pi$ mesons.

Figure 6.3: $M_{\psi(2S)\gamma}$ (GeV/$c^2$) distribution from $B \rightarrow J/\psi X$ inclusive MC sample (scaled to data) for a) $B^\pm \rightarrow X(3872)(\rightarrow \psi(2S)\gamma)K^\pm$ (left) and b) $B^0 \rightarrow X(3872)(\rightarrow \psi(2S)\gamma)K_S^0$ (right), decay mode here $\psi(2S)$ meson decays into $J/\psi \pi^+\pi^-$. 
6.2. BACKGROUND STUDY

(from some random sources) and can lead the final state \((J/\psi \pi \pi \gamma K)\) to lie in the signal region. This is the reason that \(B \to \psi(2S)K\) decay mode’s background is more in the \(B \to X(3872)[\to \psi(2S)(\to J/\psi \pi \pi \gamma)]K\) decay mode than in the \(X(3872)[\to \psi(2S)(\to \ell \ell \gamma)K]\) decay mode.

In the case of \(B \to X(3872)\rightarrow J/\psi \gamma K\), we were able to reduce the background using \(E_\gamma, \pi^0\) probability and \(\cos \theta_{\text{hel}}\) as explained in Section 5.3. In \(B \to X(3872)\rightarrow \psi(2S)\gamma K\) case, we find them ineffective to reduce the background (mostly from \(B \to \psi(2S)K^*\)). So, we tried to reduce the \(B \to \psi(2S)K^*\) contribution using a \(\psi(2S)K^*\)-veto. For this purpose, we add a \(\pi^\pm\) and \(\pi^0\) to the \(\psi(2S)\) and \(K\) of the \(B \to \psi(2S)\gamma K\) candidate signal events and form three variables, namely \(\Delta E_\psi^{\psi(2S)K^*} (\equiv E_\psi(2S) + E_{K^*} - E_{\text{beam}}\), \(M_{bc}^{\psi(2S)K^*} (\equiv \sqrt{E_{\text{beam}}^2 - (p_{\psi(2S)} + p_{K^*})^2}\) and the invariant mass of \(K\pi\) \((M_{K\pi})\). These variables are used to identify the \(B \to \psi(2S)K^*\). Here, \(E_\psi(2S)\)\((or\ K^*)\) and \(p_{\psi(2S)\(or\ K^*)}\) are the energy and the momentum of the \(\psi(2S)\) \((or\ K^*)\) candidate in the CM frame of the \(\Upsilon(4S)\). The \(\Delta E_\psi^{\psi(2S)K^*}\) is the \(\Delta E\) and \(M_{bc}^{\psi(2S)K^*}\) is the \(M_{bc}\) for the combination of \(\psi(2S)K\pi\) particles, hence the \(\Delta E\ (M_{bc})\) will peak around zero \((B\) nominal mass\) for the real \(\psi(2S)K^*\) while in \(M_{K\pi}\) distribution it will peak around \(K^*\) mass.

In Figure 6.4, it is clearly seen that the \(B \to \psi(2S)K^*\) decay mode’s background events peaks around zero in \(\Delta E_\psi^{\psi(2S)K^*}\) and in \(M_{K\pi}\) around the \(K^*\) mass. Background can be reduced if we apply cut on \(M_{K\pi}\) as \(817\ \text{MeV}/c^2 < M_{K\pi} < 967\ \text{MeV}/c^2\), and on \(\Delta E_\psi^{\psi(2S)K^*}\) cut as \(-20\ \text{MeV} < \Delta E_\psi^{\psi(2S)K^*} < 20\ \text{MeV}\) (Figure 6.4). Also, \(M_{bc}^{\psi(2S)K^*}\) is required to be greater than \(5.27\ \text{GeV}/c^2\).

By using these cuts, background is reduced by \(41\%\ (47\%)\) as compared to \(16.5\%\ (19\%)\) loss in the signal for the \(\psi(2S) \to \ell \ell \gamma\) decay channel and \(22\%\ (25\%)\) reduction in background as compared to \(18\%\ (17\%)\) loss in signal in case of \(\psi(2S) \to J/\psi \pi \pi\) decay channel, in the \(B \to \psi(2S)\gamma K^\pm(B \to \psi(2S)\gamma K^0_S)\) decay mode. The reduction of \(K^*\) background is more effective when there is a charged \(\pi\) in the final state of \(K^*\) meson as compared to \(\pi^0\) meson in the final state: we reduce by \(58\%\ (60\%)\) the background when we have a charged \(\pi\) meson in the final state of \(B \to \psi(2S)K^*\) decay mode as compared to \(27\%\ (32\%)\) loss for \(\pi^0\) meson in the final state, in
Figure 6.4: These distributions are for $B^\pm \to X(3872)(\to \psi(2S)\gamma)K^\pm$ decay mode using $B \to \psi(2S)X$ inclusive MC. Blue hatched events are the ones which fulfill the $\psi(2S)K^*$ veto conditions (see text) and red events survives the $\psi(2S)K^*$ veto.

$B^\pm \to (\psi(2S)(\to \ell\ell)\gamma)K^\pm$ ($B^0 \to (\psi(2S)(\to \ell\ell)\gamma)K_S^0$) decay mode.

Upto this stage, the interval range of $\Delta E$ as [-60, 40] MeV is being used which is not optimized (shown in Figure 6.5 with different background components). The optimization of $\Delta E$ range gives [-20, 20] MeV (Figure 6.6-6.9). There is a 59% reduction
6.2. BACKGROUND STUDY

Figure 6.5: $\Delta E$ distribution (scaled to data), $B \rightarrow \psi X$ inclusive MC background study for $B^{\pm} \rightarrow X(3872)[\rightarrow \psi(2S)\gamma]K^{\pm}$ decay mode where a) $\psi(2S) \rightarrow \ell\ell$ decay channel (left) and b) $\psi(2S) \rightarrow J/\psi\pi\pi$ decay channel (right).

Figure 6.6: FoM plots of $\Delta E$ for $B^{\pm} \rightarrow X(3872)[\rightarrow \psi(2S)(\rightarrow \ell\ell)\gamma]K^{\pm}$ decay mode. In the background as compared to 22% loss in the signal, for the $B \rightarrow X(3872)(\rightarrow \psi(2S)\gamma)K$ decay mode. Figures 6.10-6.11 shows the background estimated after applying the $\psi(2S)K^*$ veto (which is the removal of events suspected of coming from $B \rightarrow \psi(2S)K^*$, by the application of $\Delta E_{\psi(2S)K^*}$, $M_{bc\psi(2S)K^*}$ and $M_{K\pi}$ cuts).

Table 6.2 lists the efficiencies (after applying all the selection cuts) and the signal yield expected on the basis of BaBar recent branching fractions for $B^{\pm} \rightarrow X(3872)(\rightarrow$
Figure 6.7: $FoM$ plots of $\Delta E$ for $B^0 \rightarrow X(3872)[\rightarrow \psi(2S)(\rightarrow \ell\ell)\gamma]K_S^0$ decay mode.

Figure 6.8: $FoM$ plots of $\Delta E$ for $B^\pm \rightarrow X(3872)[\rightarrow \psi(2S)(\rightarrow J/\psi\pi\pi)\gamma]K_S^\pm$ decay mode.

Figure 6.9: $FoM$ plots of $\Delta E$ for $B^0 \rightarrow X(3872)[\psi(2S)(\rightarrow J/\psi\pi\pi)\gamma]K_S^0$ decay mode.
6.2. BACKGROUND STUDY

Figure 6.10: After applying cuts, \( M_{\psi(2S)\gamma} \) from \( \psi(2S) \) inclusive MC sample (scaled to data) for a) \( B^\pm \to X(3872)(\to \psi(2S)\gamma)K^\pm \) (left) and b) \( B^0 \to X(3872)(\to \psi(2S)\gamma)K_S^0 \) (right), here \( \psi(2S) \) decays into \( \ell^+\ell^- \).

Figure 6.11: After applying cuts, \( M_{\psi(2S)\gamma} \) from \( J/\psi \) inclusive MC sample (scaled to data) for a) \( B^\pm \to X(3872)(\to \psi(2S)\gamma)K^\pm \) (left) and b) \( B^0 \to X(3872)(\to \psi(2S)\gamma)K_S^0 \) (right), here \( \psi(2S) \) decays into \( J/\psi\pi^+\pi^- \).
CHAPTER 6.  $B \to X(3872)K$ ANALYSIS

$\psi(2S)\gamma K^\pm (B^0 \to X(3872)(\to \psi(2S)\gamma)K^0)$, as $9.5 \times 10^{-6} (11.4 \times 10^{-6})$ [54]. We expect more than 55 events in the charged decay mode of $B \to X(3872)(\to \psi(2S)\gamma)K$, while in neutral decay mode about 18 events are expected.

Table 6.2: Efficiencies and the expected yields after applying all selection cuts, for $B \to X(3872)(\to \psi(2S)\gamma)K$ decay mode.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Efficiency(%)</th>
<th>Expected yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\psi(2S) \to \ell\ell$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K^\pm$</td>
<td>21.57 ± 0.11</td>
<td>24.1 ± 6.8</td>
</tr>
<tr>
<td>$K_S^0$</td>
<td>16.31 ± 0.08</td>
<td>7.6 ± 3.6</td>
</tr>
<tr>
<td>$\psi(2S) \to J/\psi \pi^+\pi^-$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K^\pm$</td>
<td>12.08 ± 0.08</td>
<td>34.8 ± 9.9</td>
</tr>
<tr>
<td>$K_S^0$</td>
<td>8.69 ± 0.06</td>
<td>10.39 ± 5.0</td>
</tr>
</tbody>
</table>
6.3 $M_{\psi(2S)\gamma}$, Mass $\psi$ & $M_{bc}$ Data Sideband Study

Figure 6.12: $M_{\psi(2S)\gamma}$ (GeV/$c^2$), data sideband (black) overlapped with the sum of $B \to \psi(2S)X$ inclusive MC + $\psi(2S)$ data sideband component (green color) for: a) $B^\pm \to X(3872)[\to \psi(2S)(\to \ell\ell)\gamma]$ and b) $B^0 \to X(3872)[\to \psi(2S)(\to \ell\ell)\gamma]K_S^0$ decay mode.

To look for any difference between the data and MC, the data $M_{\psi(2S)\gamma}$, sideband distribution (excluding ±6σ signal region) is compared with the MC background distribution. Figures 6.12 and 6.13 shows the agreement between data (black points with error bars) and inclusive MC (+ the non $\psi$ component estimated from the data sidebands, green color). For $J/\psi$, four sidebands [2.5, 2.6], [3.2, 3.3], [3.3, 3.4] and [3.4, 3.5] GeV/$c^2$ which corresponds to ~3.1× signal region are used while for $\psi(2S)$, [3.35, 3.45], [3.8, 3.9] and [3.9, 4.0] GeV/$c^2$ corresponding to ~3.5× signal region are used. One can notice that the data $M_{\psi}$ sideband contribution to the total background is large in case of $\psi(2S) \to \ell\ell$ decay channel as compared to $\psi(2S) \to J/\psi \pi\pi$ decay channel. After the addition of $M_{\psi}$ data sideband contribution to the inclusive MC sample, the shape of $M_{\psi\gamma}$ data sideband matches quite well with the MC distribution.

Three $M_{bc}$ data sidebands ([5.2, 5.22], [5.22, 5.24] and [5.24, 5.26] GeV/$c^2$) are used to confirm our background understanding. In case of multiple candidates, the
Figure 6.13: \( M_{\psi(2S)\gamma} \) (GeV/c\(^2\)), data sideband (black) overlapped with the sum of 
\( B \rightarrow J/\psi X \) inclusive MC + \( J/\psi \) data sideband component (green color) for: a) \( B^\pm \rightarrow X(3872)[\rightarrow \psi(2S)(\rightarrow J/\psi\pi\pi)\gamma]K^\pm \) and b) \( B^0 \rightarrow X(3872)[\rightarrow \psi(2S)(\rightarrow J/\psi\pi\pi)\gamma]K_S^0 \) decay mode.

one having \( M_{bc} \) closest to the center of the sideband is selected. Figures 6.14 and 
6.15 show the data sideband overlaid on inclusive MC (+ non-\( \psi \) component estimated 
from data sidebands, green color). As observed from Figures 6.14 and 6.15 the non-\( \psi \) 
background contributes more in the lower \( M_{bc} \) region as compared to higher \( M_{bc} \) 
region. The \( M_{bc} \) sidebands are free from any kind of the unexpected peak. The 
\( B \rightarrow J/\psi X \) (and \( B \rightarrow \psi(2S)X \)) inclusive MC sample with the addition of the non-\( \psi \) 
background component (estimated from the data sideband, green color) is able to 
describe data sideband very well, as seen from the reduced \( \chi^2 \).

6.4 Fit Strategy

The signal is extracted from a fit to the \( M_{\psi(2S)\gamma} \) distribution. The signal is described 
by a double Gaussian whose parameters will be fixed using signal MC sample after 
applying the possible difference between MC and data. The difference is estimated 
from the \( B^\pm \rightarrow \chi_{c1}K^\pm \) decay mode.
6.4. FIT STRATEGY

Figure 6.14: $M_{\psi(2S)\gamma}$ (GeV/$c^2$) distribution for $M_{bc}$ sideband a) [5.2, 5.22] GeV/$c^2$, b) [5.22, 5.24] GeV/$c^2$ and c) [5.24, 5.26] GeV/$c^2$, comparison of data (black dots with error bar) with $B \rightarrow \psi(2S)X$ inclusive MC sample after addition of $\psi(2S)$ data sideband (green color) for $B^{\pm} \rightarrow X(3872)[\rightarrow \psi(2S)(\rightarrow \ell\ell)\gamma]K^{\pm}$ decay mode.

Figure 6.15: $M_{\psi(2S)\gamma}$ (GeV/$c^2$) distribution for $M_{bc}$ sideband a) [5.2, 5.22] GeV/$c^2$, b) [5.22, 5.24] GeV/$c^2$ and c) [5.24, 5.26] GeV/$c^2$, comparison of data (black dots with error bar) with $B \rightarrow J/\psi X$ inclusive MC sample after addition of $J/\psi$ data sideband (green color) for $B^{\pm} \rightarrow X(3872)[\rightarrow \psi(2S)(\rightarrow J/\psi\pi\pi)\gamma]K^{\pm}$ decay mode.

Background is divided into five different components:

- $B^{+} \rightarrow \psi(2S)K^{*+}$
- $B^{0} \rightarrow \psi(2S)K^{*0}$
- $B^{+} \rightarrow \psi(2S)K^{+}$
• $B^0 \to \psi(2S)K^0_S$

• rest (all combinatorial)

We generated large samples (10 to 15 million events) of $B \to \psi(2S)K^*$ using the polarization measured in Ref. [97]. We also generated large samples of events (5 to 10 million events) of $B \to \psi(2S)K$ decay mode.

![Figure 6.16](image1.png)  
**Figure 6.16:** Fit to generated a) $B^+ \to \psi(2S)K^*(892)^+$ and b) $B^0 \to \psi(2S)K^*(892)^0$, background for $\psi(2S)(\to \ell\ell)\gamma K^\pm$ decay mode.

![Figure 6.17](image2.png)  
**Figure 6.17:** Fit to generated a) $B^+ \to \psi(2S)K^+$ and b) $B^0 \to \psi(2S)K_S^0$, background for $\psi(2S)(\to \ell\ell)\gamma K^\pm$ decay mode.

Background coming from $B \to \psi(2S)K^*$ and $B \to \psi(2S)K$ decay modes is parametrized by using the sum of the bifurcated Gaussians and Gaussians, whose
parameters are floated in the MC, and is fixed in the final fit. Also in the final fit, the $B \rightarrow \psi(2S)K^*$ and $B \rightarrow \psi(2S)K$ fraction in the PDF is fixed using the branching fraction from the PDG. The fitted distribution of the generated samples are shown in Figures 6.16-6.19. The rest of the background (Figure 6.20) is not peaking and can be easily parametrized by a threshold function, as

$$(M_{\psi(2S)\gamma})^2 \times \exp(A \times (M_{\psi(2S)\gamma} - M_{\text{Th}}) + B \times (M_{\psi(2S)\gamma} - M_{\text{Th}})^2)$$

where $M_{\text{Th}} = 3.725$ GeV/$c^2$.

In the PDF, background is divided into two components. One component consist of $B \rightarrow \psi(2S)K^*$ and $B \rightarrow \psi(2S)K$ (fractions are fixed for each component, using the MC study). The second component consist of non-$\psi$ background (from $\psi$ data sideband) along with the remaining background from $B \rightarrow J/\psi X$ and $B \rightarrow \psi(2S)X$ inclusive MC sample after the removal of $B \rightarrow \psi(2S)K^*$ and $B \rightarrow \psi(2S)K$ decay component (shape described by a threshold function). Parameters for these two components are fixed and yields are floated. The yields are floated take into account the difference between data and MC, as shown in Figure 6.21 (which is a fit to the background expected using the $B \rightarrow \psi(2S)X$ and $B \rightarrow J/\psi X$ inclusive MC sample).

![Figure 6.18: Fit to generated a) $B^+ \rightarrow \psi(2S)K^*(892)^+$ and b) $B^0 \rightarrow \psi(2S)K^*(892)^0$, background for $X(3872)[\rightarrow \psi(2S)(\rightarrow J/\psi \pi \pi)\gamma]\, K^+$ decay mode.](image)

In order to extract the yield from $B \rightarrow X(3872)(\psi(2S)\gamma)K$ decay, we perform simultaneous fit to $M_{\psi(2S)\gamma}$ distribution of the two different $\psi(2S)$ sub-decay modes:
Figure 6.19: Fit to generated a) $B^+ \to \psi(2S)K^+$ and b) $B^0 \to \psi(2S)K_S^0$, background for $X(3872)\to \psi(2S)(\to J/\psi \pi \pi) \gamma K^\pm$ decay mode.

Figure 6.20: Fit to the rest of the $\psi$ inclusive MC (after removing $\psi(2S)K^*$ and $\psi(2S)K$ components from it) for a) $X(3872)\to \psi(2S)(\to \ell \ell) \gamma K^\pm$ and b) $X(3872)\to \psi(2S)(\to J/\psi \pi \pi) \gamma K^\pm$ decay mode.

$\psi(2S) \to \ell \ell$ and $\psi(2S) \to J/\psi \pi \pi$. The fit to the individual mode consist of three PDFs:

1) Two Gaussian describes the signal PDF, parameters for which are fixed from signal MC study and common branching fraction to both sub-modes of the $\psi(2S)$ is free in the fit.

2) The PDFs from the generated MC samples of $B \to \psi(2S)K^*$ and $B \to \psi(2S)K$
Figure 6.21: Fit to the expected $\psi$ background expected from $\psi$ inclusive MC in case of a) $X(3872)[\rightarrow \psi(2S)(\rightarrow \ell\ell)\gamma]K^\pm$ and b) $X(3872)[\rightarrow \psi(2S)(\rightarrow J/\psi\pi\pi)\gamma]K^\pm$ decay mode.

Figure 6.22: Shape (of non-$\psi$ data sideband, $\sim 3 \times$ data) used to generate non-$\psi$ background part for the pseudo-experiment sample (explained in the text) for a) $B^\pm \rightarrow X(3872)[\rightarrow \psi(2S)(\rightarrow \ell\ell)\gamma]K^\pm$ and b) $B^\pm \rightarrow X(3872)[\rightarrow \psi(2S)(\rightarrow J/\psi\pi\pi)\gamma]K^\pm$ decay mode.

3) Threshold function to describe combinatorial non-peaking background and non-$\psi$
Figure 6.23: Fit to the total combinatorial background expected from inclusive MC and non-\(\psi\) component for a) \(B^\pm \rightarrow X(3872)[\rightarrow \psi(2S)(\rightarrow \ell\ell)\gamma]K^\pm\) and b) \(B^\pm \rightarrow X(3872)[\rightarrow \psi(2S)(\rightarrow J/\psi\pi\pi)\gamma]K^\pm\) decay mode. Here, inclusive MC combinatorial background (~50 \times data) is scaled to the non-\(\psi\) data sideband (~3 \times data) and added to it.

Figure 6.24: Simultaneous fit to one of the pseudo-experiments (explained in text) a) \(B^\pm \rightarrow X(3872)[\rightarrow \psi(2S)(\rightarrow \ell\ell)\gamma]K^\pm\) and b) \(B^\pm \rightarrow X(3872)[\rightarrow \psi(2S)(\rightarrow J/\psi\pi\pi)\gamma]K^\pm\) decay mode.

background, its parameters are fixed and its area is floated in the fit (separately for each sub-modes of the \(\psi(2S)\))
Figure 6.25: From the fit performed to the 50 GSIM samples, we get a) pull to be consistent with zero within errors and b) the expected significance comes out to be 4.9 (after using the BaBar branching fraction). These plots are for \(B^\pm \rightarrow X(3872)(\rightarrow \psi(2S)\gamma)K^\pm\) decay mode.

In the final fit, parameters for the threshold function are used from the fit (Figure 6.23) performed to the combinatorial background expected from the inclusive MC and non-\(\psi\) component (expected from the data sideband of \(\psi\)). The total combinatorial background is the sum of combinatorial background from the \(B \rightarrow \psi(2S)X\) and \(B \rightarrow J/\psi X\) inclusive MC sample (scaled to non-\(\psi\) background) and the non-\(\psi\) data sideband.

To test the fitter, an ensemble study is performed using GSIM samples. \(B \rightarrow \psi(2S)X\) and \(B \rightarrow J/\psi X\) inclusive MC sample is divided into 50 samples and 50 samples of generated signal events (using Poisson fluctuations) are added, further to which 50 samples of the expected non-\(\psi\) background is added (after generating them using the PDF obtained from non-\(\psi\) data sideband study). This way 50 pseudo-experiments to test the fitter are obtained. Figure 6.24 shows an example of fit for one of these pseudo-experiments. Figure 6.25a shows the pull distribution and significance we get from the fits performed to all the 50 samples. As seen from the figure, mean value of pull is zero, so no significant bias in the fitter is observed. Assuming BaBar branching fraction [54] for this decay mode, a statistical significance of 4.9 standard deviation is expected using the data sample of 772 Million BB pairs.
(Figure 6.5b). Similarly for $B^0 \to X(3872)(\to \psi(2S)\gamma)K_S^0$ decay mode, pseudo GSIM study is performed, no significant bias is observed in the fitter as the pull comes out to be consistent with zero ($-0.15 \pm 0.16$) and the statistical significance is expected to be $3.07\sigma$.

Further more toy MC study has also been performed to test the fitter. The 1000 samples of expected signal and background are generated (with Poisson fluctuation) using the PDFs explained above and the fit is performed to each sample using the fitter. Pull and significance is calculated for the each fit. The BaBar branching fraction [54] is assumed for the generation of the signal. We also assume the case where branching fraction is considered to be one sigma less than the BaBar's branching fraction central value. Table 6.3 summarizes the results of the toy MC study. The $5\sigma$ ($3\sigma$) statistical significance for $B^\pm \to X(3872)(\to \psi(2S)\gamma)K^\pm$ ($B^0 \to X(3872)(\to \psi(2S)\gamma)K_S^0$) decay mode is expected from present data with this study.

Table 6.3: Toy MC study

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$\mathcal{B}$, $\times 10^{-6}$</th>
<th>Pull</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \to X(3872)K^+$</td>
<td>9.5</td>
<td>$-0.08 \pm 0.03$</td>
<td>$1.01 \pm 0.02$</td>
</tr>
<tr>
<td>$B \to X(3872)K_S^0$</td>
<td>6.8</td>
<td>$-0.03 \pm 0.03$</td>
<td>$0.99 \pm 0.02$</td>
</tr>
</tbody>
</table>

The $M_{bc}$ data sidebands (explained in Section 6.3) are also used to check the fitter. Figure 6.26-6.28 shows the fit to $M_{bc}$ data sideband. The PDF is able to describe $M_{bc}$ sideband. As we go towards higher $M_{bc}$ region, combinatorial background decreases and the $B \to \psi(2S)X$ inclusive background increases, as expected. Successful working of the fitter is demonstrated by the $M_{bc}$ data sidebands also.
Figure 6.26: Simultaneous fit performed to a) $\psi(2S) \rightarrow \ell\ell$ and b) $\psi(2S) \rightarrow J/\psi\pi\pi$ sub-decay modes of $B^\pm \rightarrow X(3872)(\rightarrow \psi(2S)\gamma)K^\pm$ using $M_{bc}$ data sideband region of $[5.20, 5.22]$ GeV/$c^2$.

Figure 6.27: Simultaneous fit performed to a) $\psi(2S) \rightarrow \ell\ell$ and b) $\psi(2S) \rightarrow J/\psi\pi\pi$ sub-decay modes of $B^\pm \rightarrow X(3872)(\rightarrow \psi(2S)\gamma)K^\pm$ using $M_{bc}$ data sideband region of $[5.22, 5.24]$ GeV/$c^2$.

6.5 Data Fitting

After confirming the reliability of our understanding of the background and the fitting procedure. We went ahead and unblinded the signal region of the data. We used the whole available belle data at $\Upsilon(4S)$ resonance which is $772 \times 10^6 N_{B\bar{B}}$. Figure 6.29 and
Figure 6.28: Simultaneous fit performed to a) $\psi(2S) \to \ell\ell$ and b) $\psi(2S) \to J/\psi \pi\pi$ sub-decay modes of $B^\pm \to X(3872)(\to \psi(2S)\gamma)K^\pm$ using $M_{bc}$ data sideband region of [5.24, 5.26] GeV/$c^2$.

6.30 show the fit performed to $B \to X(3872)(\to \psi(2S)\gamma)K$, we get a yield of $5 \pm 11$ events having 0.5σ Statistical Significance for the charged mode ($B^\pm \to X(3872)K^\pm$), and in the case of the neutral mode ($B^0 \to X(3872)K_S^0$) we get $2 \pm 4$ events as yield with a Statistical Significance of 0.4σ. Table 6.4 summarizes the fit results to the Belle data.

Upper limit (UL) on the yield at the 90% confidence level (CL) using Toy MC sample is estimated. For a given signal yield, 10000 sets of signal and background events are generated using the PDFs and fits are performed. The confidence level is obtained as the fraction of samples where yield is larger than data (5 for $K^+$ and 2 for $K_S^0$ mode). To include Systematic Uncertainty into account, we smear the distribution of the yield (which we get from toy MC) by Systematic Uncertainty (estimated in Section 6.6). After including the Systematic Uncertainty we obtain 20.8 (8.9) events as UL at 90% CL for the charged (neutral) mode.
Figure 6.29: Simultaneous fit performed to a) $\psi(2S) \rightarrow \ell\ell$ and b) $\psi(2S) \rightarrow J/\psi \pi \pi$ sub-decay modes of $B^{\pm} \rightarrow X(3872)(\rightarrow \psi(2S)\gamma)K^{\pm}$. 772 $\times 10^6$ $N_{B\bar{B}}$ is used for this fit. We get $5.0^{+11.9}_{-11.0}$ events as the signal yield. The curve shows the signal (red dashed for $X(3872)$) and the background component pink dot-dashed for background from $B \rightarrow \psi(2S)K^*$ and $B \rightarrow \psi(2S)K$ component, and blue dotted for combinatorial background as well as solid overall fit.

Table 6.4: Summary of the results of the $B \rightarrow X(3872)(\rightarrow \psi(2S)\gamma)K$ decay study. Yield ($Y$), Significance ($\Sigma$) with systematic uncertainty included and measured branching fraction ($B$) comparing our results with the BaBar measurement [54]. For $B$, the uncertainty is the statistical uncertainty. In the calculation of U.L. (@ 90% C.L.) systematic uncertainty has been taken into account. Here $B$ is $B(B \rightarrow X(3872)K)\times B(X(3872) \rightarrow \psi(2S)\gamma)$.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$Y$</th>
<th>$\Sigma$ ($\sigma$)</th>
<th>$B(\times 10^{-6}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^{\pm} \rightarrow X(3872)(\rightarrow \psi(2S)\gamma)K^{\pm}$</td>
<td>$5.00^{+11.89}_{-11.02}$</td>
<td>$0.4\sigma$</td>
<td>$&lt; 3.45$</td>
</tr>
<tr>
<td>$B^0 \rightarrow X(3872)(\rightarrow \psi(2S)\gamma)K^0_S$</td>
<td>$1.49^{+4.80}_{-3.89}$</td>
<td>$0.3\sigma$</td>
<td>$&lt; 6.62$</td>
</tr>
</tbody>
</table>
Figure 6.30: Simultaneous fit performed to a) $\psi(2S) \rightarrow \ell\ell$ and b) $\psi(2S) \rightarrow J/\psi \pi\pi$ sub-decay modes of $B^0 \rightarrow X(3872)(\rightarrow \psi(2S)\gamma)K^0_S$ decay mode. $772 \times 10^6 N_{BB}$ is used for this fit. We get $1.49^{+4.80}_{-3.89}$ events as the signal yield. The curve shows the signal (red dashed for $X(3872)$) and the background component pink dot-dashed for background from $B \rightarrow \psi(2S)K^*$ and $B \rightarrow \psi(2S)K$ component, and blue dotted for combinatorial background as well as solid overall fit.

Figure 6.31: Toy MC study to obtain UL on the yield at 90% CL for a) $B^\pm \rightarrow X(3872)(\rightarrow \psi(2S)\gamma)K^\pm$ and b) $B^0 \rightarrow X(3872)(\rightarrow \psi(2S)\gamma)K^0_S$ decay modes. Pink (red) color represents the CL estimated without (with) systematic. Green line gives the UL at 90% CL (with systematic taken into account). To include Systematic Uncertainty into account, we smear the distribution of the yield (which we get from toy MC) by Systematic Uncertainty (estimated in section 6.6).
6.6 Systematic Uncertainty Study

Main sources of the Systematic Uncertainty for $B \to X(3872)(\to \psi(2S)\gamma)K$ decay mode are almost same as of the $B \to X(3872)(\to J/\psi \gamma)K$ decay mode study (explained in Section 5.8) and are :-

6.6.1 Kaon/Pion-Identification.

To estimate the kaon/pion identification uncertainty, we use PID group estimation (described in Section 3.10). Table 6.5 (6.6) summarizes the kaon (pion) systematic study.

Table 6.5: Kaon identification systematic for $B^\pm \to X(3872)(\to \psi(2S)\gamma)K^\pm$ decay mode.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Correction</th>
<th>Syst. Uncertainty(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \to X(3872)(\to \psi(2S)\gamma)K^\pm$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\psi(2S) \to \ell\ell$</td>
<td>1.000 ± 0.009</td>
<td>0.9</td>
</tr>
<tr>
<td>$\psi(2S) \to J/\psi\pi\pi$</td>
<td>1.000 ± 0.009</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 6.6: Pion identification systematic for $\psi(2S) \to J/\psi\pi\pi$ sub-decay mode.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Correction</th>
<th>Syst. Uncertainty(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \to X(3872)(\to \psi(2S)\gamma)K^\pm$</td>
<td>0.992 ± 0.015</td>
<td>1.5</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>0.996 ± 0.011</td>
<td>1.1</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>0.996 ± 0.011</td>
<td>1.1</td>
</tr>
</tbody>
</table>

6.6.2 $K_S^0$ Identification Uncertainty

The Systematic uncertainty coming from $K_S^0$ is estimated as 4.5%.
6.6.3 Lepton identification Uncertainty

Systematic uncertainty coming from lepton identification is estimated to be 1.1%.

6.6.4 $\gamma$ systematic Uncertainty

The $\gamma$ coming from $X(3872) \rightarrow \psi(2S)\gamma$ decay is of low energy (around 200 MeV) as compared to $\gamma$ in the $B \rightarrow X(3872)(\rightarrow J/\psi\gamma)K$ decay mode. For this low energy $\gamma$ detection, 3.5% is estimated to be the uncertainty. This uncertainty is estimated using the $B \rightarrow \chi_{c1}K$ decay mode sample [89].

6.6.5 Efficiency Estimation Uncertainty

Due to the limited statistical samples of signal MC (500,000 events generated for each mode), there will be a sizeable statistical uncertainty on the calculated efficiency and this statistical uncertainty is taken into account (Table 6.7).

<table>
<thead>
<tr>
<th>Eff. syst. (%)</th>
<th>$\psi(2S) \rightarrow \ell\ell$</th>
<th>$\psi(2S) \rightarrow J/\psi\pi\pi$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+$</td>
<td>0.51</td>
<td>0.66</td>
<td>0.44</td>
</tr>
<tr>
<td>$K^0_S$</td>
<td>0.49</td>
<td>0.69</td>
<td>0.45</td>
</tr>
</tbody>
</table>

6.6.6 Secondary Branching Fraction Uncertainty

Table 6.8 summarizes the uncertainty coming from the secondary branching fraction used to calculate the signal branching fraction.

6.6.7 Systematic Uncertainty due to PDF

To get the systematic uncertainty coming from PDF, parameters fixed in the fit are varied by $\pm 1\sigma$ one at a time. For combinatorial non-peaking background, we fix
6.6. SYSTEMATIC UNCERTAINTY STUDY

Table 6.8: Secondary branching fraction systematic uncertainty.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$\psi(2S) \rightarrow \ell\ell$</th>
<th>$\psi(2S) \rightarrow J/\psi\pi\pi$</th>
<th>Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+$</td>
<td>5.4</td>
<td>1.7</td>
<td>2.4</td>
</tr>
<tr>
<td>$K_{S}^{0}$</td>
<td>5.4</td>
<td>1.7</td>
<td>2.4</td>
</tr>
</tbody>
</table>

the shape of the threshold function using the non-$\psi$ data sideband (section 6.4). To calculate the systematic uncertainty coming from this threshold function, we vary one parameter at a time by $\pm 1\sigma$ and get the rest parameters by performing a fit to the non-$\psi$ data sideband, and using these parameters we fix the shape of threshold function in the data and the difference in the signal yield is taken as the possible Systematic Uncertainty. We are also fixing the fraction of the $B \rightarrow \psi(2S)K^*$ decay mode and $B \rightarrow \psi(2S)K$ decay modes in the parametrization of the background shape. To estimate the possible Systematic Uncertainty coming due to this fixing of the background fraction, we vary the branching fraction $\mathcal{B}(B \rightarrow \psi(2S)K^*)$ and $\mathcal{B}(B \rightarrow \psi(2S)K)$ by $\pm 1\sigma$, and the difference is included in the possible Systematic Uncertainty. Using this method, we estimate the systematic uncertainty on the signal yield ($B^\pm \rightarrow X(3872)(\rightarrow \psi(2S)\gamma)K^\pm$) to be $^{+42.2}_{-50.2}$%. To be on the conservative side, we use $\pm 50.2\%$ as the systematic error coming from the PDF. For $B^0 \rightarrow X(3872)(\rightarrow \psi(2S)\gamma)K^0$, we quote the same error ($\pm 50.2\%$), as there is very small difference between the PDF of the charged and the neutral decay mode of $B \rightarrow X(3872)(\rightarrow \psi(2S)\gamma)K$.

6.6.8 Charged Track Systematic Uncertainty

Charged particle track reconstruction has an uncertainty of about 1% per track.

6.6.9 Fit Bias Uncertainty

Please refer to Appendix C for more detailed study. The 16% is the difference between the generated signal yield and the yield from the fit to the toy MC for the $B^\pm \rightarrow$
\textbf{CHAPTER 6.  \(B \rightarrow X(3872)K\) ANALYSIS}

\(X(3872) \rightarrow \psi(2S)\gamma)K^\pm\) decay mode and 6\% is the difference coming for the \(B^0 \rightarrow X(3872) \rightarrow \psi(2S)\gamma)K^0\) decay mode. We have included this difference as the possible uncertainty coming from fit bias.
Table 6.9: Summary of systematic uncertainty for \( B \to X(3872)(\to \psi(2S)\gamma)K \) decay mode.

<table>
<thead>
<tr>
<th>Source</th>
<th>( B^\pm \to X(3872)(\to \psi(2S)\gamma)K^\pm )</th>
<th>( B^0 \to X(3872)(\to \psi(2S)\gamma)K^0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \psi(2S) \to \ell \ell )</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>( \psi(2S) \to J/\psi\pi\pi )</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Combine</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( K^0 )</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>( \ell \text{ id} )</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>( \gamma\text{-syst.} )</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>MC</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>( N_{\delta B} )</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Tracking</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>PDF</td>
<td>50.2</td>
<td>50.2</td>
</tr>
<tr>
<td>Fit bias</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Total</td>
<td>53.0</td>
<td>51.2</td>
</tr>
</tbody>
</table>
6.7 Chapter in a Nutshell

Analysis of $B \to X(3872)(\to \psi(2S)\gamma)K$ decay mode has been carried out in this Chapter. Search for the $X(3872) \to \psi(2S)\gamma$ decay has been performed. Background study is performed using $B \to \psi(2S)X$ and $B \to J/\psi X$ inclusive MC sample and data sidebands. There is a broad peaking background mostly coming from $B \to \psi(2S)K^*$ decay and in order to reduce this background $\psi(2S)K^*$ veto (rejecting $B \to \psi(2S)K^*$ events) is used. In our search for $X(3872) \to \psi(2S)\gamma$, no signal is seen in the charged as well as in the neutral decays $B \to X(3872)K$. This result is opposite of what BaBar has found recently [54]. With this Upper Limit (at 90% C.L.) is given for $\mathcal{B}(B^- \to X(3872)K^-) \times \mathcal{B}(X(3872) \to \psi(2S)\gamma)$ as $< 3.45 \times 10^{-6}$ and $\mathcal{B}(B^0 \to X(3872)K^0) \times \mathcal{B}(X(3872) \to \psi(2S)\gamma)$ to be as $< 6.62 \times 10^{-6}$, respectively.
Don’t fear failure so much that you refuse to try new things. The saddest summary of a life contains three descriptions: could have, might have, and should have.

Louis E. Boone

Summary & Conclusions

This Chapter summarizes the results from the work taken up in this thesis, and also tries to show the power hidden in these numbers. Along with the numbers, a short summary and the conclusions of the analyses are also provided. In the present thesis, the $B^\pm \to \psi(2S)\pi^\pm$, $B \to \chi_{c1}K$, $B \to \chi_{c2}K$ and $B \to X(3872)K$ decay modes have been performed. Search for the direct $CP$ violation is taken up in the analysis of $B^\pm \to \psi(2S)\pi^\pm$ decay mode which may give a hint for New Physics (beyond the Standard Model). The search of $B \to \chi_{c2}K$ decay mode is taken up in order to test the theoretical understanding of the $B$ decays; along with a motive to give an improved measurement of the branching fraction of the $B \to \chi_{c1}K$ decay. The $X(3872)$ state’s radiative $E1$ decay modes: $X(3872) \to J/\psi\gamma$ and $X(3872) \to \psi(2S)\gamma$ are studied in order to understand the nature of the newly discovered exotic charmonium like $X(3872)$ state. In addition, the factorization hypothesis is also being tested here. Efforts have been carried out to provide the results in a model independent manner for the $X(3872)$ state.

7.1 The $B^- \to \psi(2S)\pi^-$ Decay Study

The procedure carried out for the study of Cabibbo- and color-suppressed decay $B^- \to \psi(2S)\pi^-$ can be summarized as follows:
CHAPTER 7. SUMMARY & CONCLUSIONS

- A Monte Carlo sample study is performed to calculate the reconstruction efficiency and to understand the background, \( B \rightarrow \psi X \) inclusive Monte Carlo sample has been used.

- In the \( B^- \rightarrow \psi(2S)(\rightarrow J/\psi \pi \pi)\pi^- \) decay, background study shows that the \( B \rightarrow J/\psi K^* \) decay peaks around the signal region (±25 MeV) in the \( \Delta E \) distribution. This peaking background is suppressed after applying the \( K_S^0 \) veto (i.e. ±12 MeV mass cut around the \( K_S^0 \) mass), though at the cost of a 4.2% loss in the signal reconstruction efficiency.

- The background knowledge is verified using the \( M_{J/\psi} \), \( M_{\psi(2S)} \) and \( \Delta M \) data sidebands, and no peaking background structure is seen in the signal region.

- The \( B^\pm \rightarrow \psi(2S)K^\pm \) decay mode has been used as a control sample to verify the signal extraction strategy for the \( B^\pm \rightarrow \psi(2S)\pi^\pm \) decay mode.

- The MC and data difference is estimated using \( B^\pm \rightarrow \psi(2S)K^\pm \) decay sample where \( K^\pm \) is assigned the mass of the \( \pi^\pm \). This results in a shift of \( \sim 70 \) MeV in the negative side of the \( \Delta E \) distribution for the \( B^\pm \rightarrow \psi(2S)K^\pm \) decay.

- The fitter used to extract the signal was validated on the Monte Carlo and results were found to be reliable.

- After validating our cuts, reconstruction procedure and the fitter used to extract the signal events in the Monte Carlo, we adopted the same strategy to look for the signal events in the data sample. Using these signal events the branching fraction \( \mathcal{B}(B^- \rightarrow \psi(2S)\pi^-) \) was measured.

- In addition to the branching fraction measurement, we also performed the search for the direct \( CP \) violation in the \( B^- \rightarrow \psi(2S)\pi^- \) decay mode by measuring it’s charge asymmetry (\( \mathcal{A}_{CP} \)).

Table 7.1 and 7.2 summarize the results for the branching fraction measurements for \( B^- \rightarrow \psi(2S)K^- \) and \( B^- \rightarrow \psi(2S)\pi^- \) decay modes, respectively. Figure 7.1 shows the graphical representation of these results (with systematic uncertainty included).
7.1. THE $B^- \to \psi(2S)\pi^-$ DECAY STUDY

While Table 7.3 summarizes the result of our search for the direct $CP$ violation in the $B^- \to \psi(2S)\pi^-$ decay mode.

Table 7.1: Summary of the results of $B^\pm \to \psi(2S)K^\pm$ decay study. Measured branching fraction ($\mathcal{B}$) and statistical significance ($\Sigma$). For $\mathcal{B}$, the first (second) error is statistical (systematic).

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>$\mathcal{B}$, $\times 10^{-4}$</th>
<th>$\Sigma$ ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \to \psi(2S)(\to J/\psi(\to ee)\pi\pi)K^\pm$</td>
<td>$6.37 \pm 0.18$</td>
<td>62</td>
</tr>
<tr>
<td>$B^\pm \to \psi(2S)(\to J/\psi(\to \mu\mu)\pi\pi)K^\pm$</td>
<td>$5.53 \pm 0.15$</td>
<td>65</td>
</tr>
<tr>
<td>$B^\pm \to \psi(2S)(\to ee)K^\pm$</td>
<td>$6.75 \pm 0.22$</td>
<td>59</td>
</tr>
<tr>
<td>$B^\pm \to \psi(2S)(\to \mu\mu)K^\pm$</td>
<td>$6.21 \pm 0.18$</td>
<td>65</td>
</tr>
<tr>
<td>$B^\pm \to \psi(2S)K^\pm$</td>
<td>$6.12 \pm 0.09 \pm 0.53$</td>
<td>126</td>
</tr>
</tbody>
</table>

Figure 7.1: The measured a) $\mathcal{B}(B^- \to \psi(2S)K^-)$ and b) $\mathcal{B}(B^- \to \psi(2S)\pi^-)$, point (with bar) show individual branching fraction measurement (with the uncertainty) performed for different sub-decay modes of $\psi(2S)$. Green solid line show the branching fraction measured after performing a simultaneous fit to the four sub-decay modes of $\psi(2S)$ and green dotted lines show the uncertainty on the measured value. Total uncertainty includes statistical as well as the systematic uncertainty.
Table 7.2: Summary of the results of $B^\pm \to \psi(2S)\pi^\pm$ decay study. Signal Yield ($Y$) from the fit, statistical significance ($\Sigma$), systematic uncertainty not included in the significance and measured branching fraction ($B$). For $B$, the first (second) error is statistical (systematic).

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>$Y$</th>
<th>$\Sigma$ ($\sigma$)</th>
<th>$B$, $\times 10^{-5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \to \psi(2S)(\to J/\psi(\to ee)\pi^+\pi^-)\pi^\pm$</td>
<td>$48.9 \pm 8.3$</td>
<td>9.5</td>
<td>$2.57 \pm 0.44$</td>
</tr>
<tr>
<td>$B^\pm \to \psi(2S)(\to J/\psi(\to \mu\mu)\pi^+\pi^-)\pi^\pm$</td>
<td>$44.0 \pm 8.1$</td>
<td>8.4</td>
<td>$2.08 \pm 0.38$</td>
</tr>
<tr>
<td>$B^\pm \to \psi(2S)(\to e^+e^-)\pi^\pm$</td>
<td>$44.0 \pm 9.0$</td>
<td>7.3</td>
<td>$2.80 \pm 0.57$</td>
</tr>
<tr>
<td>$B^\pm \to \psi(2S)(\to \mu^+\mu^-)\pi^\pm$</td>
<td>$43.5 \pm 7.7$</td>
<td>9.0</td>
<td>$2.50 \pm 0.44$</td>
</tr>
<tr>
<td>$B^\pm \to \psi(2S)\pi^\pm$</td>
<td></td>
<td>17.0</td>
<td>$2.44^{+0.23}_{-0.22} \pm 0.20$</td>
</tr>
</tbody>
</table>

Table 7.3: $A_{CP}$ measurement of the $B^- \to \psi(2S)\pi^-$ decay mode. For $A_{CP}$, the first (second) error is statistical (systematic).

<table>
<thead>
<tr>
<th>$B^- \to \psi(2S)\pi^-$</th>
<th>$B^+ \to \psi(2S)\pi^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>93±11</td>
</tr>
<tr>
<td>$A_{CP}$</td>
<td>0.022 ± 0.085 ± 0.016</td>
</tr>
</tbody>
</table>

7.1.1 Conclusions

The branching fraction $B(B^- \to \psi(2S)K^-)$ is measured to be $(6.12 \pm 0.09\text{(stat.)} \pm 0.53\text{(syst.)}) \times 10^{-4}$ which agrees well with the world average, $(6.46\pm0.33) \times 10^{-4}$ [3]. For the first time the $B^- \to \psi(2S)\pi^-$ decay mode is observed and its branching fraction is measured. The $B^\pm \to \psi(2S)\pi^\pm$ decay mode is a Cabibbo- and color-suppressed decay mode and we have observed this mode through the four decay processes of $\psi(2S)$ with a statistical significance greater than 7$\sigma$. However, the simultaneous fit to these four sub-decay modes of $\psi(2S)$ give the branching fraction, $B(B^- \to \psi(2S)\pi^-)$, as $(2.44^{+0.23}_{-0.22}\text{(stat.)} \pm 0.20\text{(syst.)}) \times 10^{-5}$ with a statistical significance of 17$\sigma$. We also compute the ratio of the branching fraction of $B^- \to \psi(2S)\pi^-$ and $B^- \to \psi(2S)K^-$.
#### 7.2. THE $\bar{B} \rightarrow \chi_{c1,c2}K \& \ B \rightarrow X(3872) (\rightarrow J/\psi\gamma)K$ DECAY STUDY

Decays as:

$$\frac{B(B^- \rightarrow \psi(2S)\pi^-)}{B(B^- \rightarrow \psi(2S)K^-)} = (3.99 \pm 0.36\text{ (stat.)} \pm 0.17\text{ (syst.)})\%$$  \hfill (7.1)

which is consistent with the factorization model [12]. According to this model, $B^- \rightarrow \psi(2S)\pi^-$ decay mode is expected to have a branching fraction of the order of $5\%$ to the Cabibbo-allowed decay, $B^- \rightarrow \psi(2S)K^-$. Therefore, this study provides support to the factorization model.

We have also performed the search for the direct CP violation in the decay mode of $B^- \rightarrow \psi(2S)\pi^-$. For this purpose, we have measured the charge asymmetry

$$A_{CP}^{B^-\rightarrow\psi(2S)\pi^-} = 0.022 \pm 0.085\text{ (stat.)} \pm 0.016\text{ (syst.)}$$  \hfill (7.2)

which is consistent with the expectation of the SM framework. As, in the $B \rightarrow d\bar{c}c$ transitions, the direct CP violation is expected to be of the order of $1\%$ [98]. Thus, with these results, no hint for the New Physics is found in our search. But, our results are limited by the statistics, more statistics is required for the search of the direct CP violation in the $B^- \rightarrow \psi(2S)\pi^-$ decay mode.

#### 7.2 The $B \rightarrow \chi_{c1,c2}K \& \ B \rightarrow X(3872) (\rightarrow J/\psi\gamma)K$ Decay Study

This study covers $B \rightarrow \chi_{c1}K$, $B \rightarrow \chi_{c2}K$ and $B \rightarrow X(3872)K$ decay modes. The procedure carried out for this study is summarized as follows:

- The signal Monte Carlo study is performed to get the reconstruction efficiency of $B \rightarrow \chi_{c1}K$, $B \rightarrow \chi_{c2}K$ and $B \rightarrow X(3872)K$ decay modes. For the background study $B \rightarrow J/\psi X$ inclusive MC sample has been used.

- No peaking structure due to the background is found in the $M_{J/\psi\gamma}$ distribution, however in order to improve the significance, we introduce three observables, namely $\cos \theta_{hel}$, $\pi^0$-veto and $E_{\gamma}$ to reduce the background further.
We also used $M_{\ell\ell}$ and $M_{J/\psi\gamma}$ data sidebands in order to look for any unexpected peaking background in the signal region. No peaking background is found in the signal region.

The fitter used to extract the signal yield is tested using a large number of signal embedded Monte Carlo ensemble and no significant bias is observed.

We looked at the signal region in the data to extract the yield and we calculated the branching fractions. The systematic uncertainty estimation is also performed.

Table 7.4 summarizes the results of the branching fraction measurements for the $B \to \chi_{c1}K$, $B \to \chi_{c2}K$ and $B \to X(3872)K$ decay modes. Figure 7.2 shows the graphical representation of these results (with systematic uncertainty included), and compares our results (red) with the world average, PDG (green) [3] and BaBar recent measurement (blue) [54]. The height of the box shows the uncertainty on the measurement. The Upper Limit (U.L.) estimated at 90% Confidence Level (C.L.) is shown in the figure by the box, the one reaching zero.

7.2.1 Conclusions

From Figure 7.2, the agreement between our measurements of the branching fraction $B(B \to \chi_{c1}K)$, $B(B \to \chi_{c2}K)$ and $B(B \to X(3872)K)$ with other experiments can be clearly seen. Our measurements of the branching fraction are the most precise measurements (till date). For the first time, an evidence has been found for the $B^- \to \chi_{c2}K^-$ decay (with a significance of $3.6\sigma$) and its measured branching fraction is compared with that of $B^- \to \chi_{c1}K^-$ decay as:

$$\frac{B(B^- \to \chi_{c2}K^-)}{B(B^- \to \chi_{c1}K^-)} = (2.25 \pm 0.71(\text{stat.}) \pm 0.16(\text{syst.}))\%.$$  

The branching fraction measurement of the $B^- \to \chi_{c2}K^-$ decay mode provides a nice test for the theoretical understanding of this decay mode [18–20]. For this decay mode, our measurement of the branching fraction, $B(B^- \to \chi_{c2}K^-)$ which is
7.2. THE B → χ_{c1c2}K & B → X(3872)(→ J/ψγ)K DECAY STUDY

Table 7.4: Summary of the results of the B → χ_{c1}K, B → χ_{c2}K and B → X(3872)K decay study. Significance Σ (with systematic uncertainty included) and measured branching fraction (B) comparing our results with the PDG [3] and BaBar [54]. For B, the first (second) uncertainty is statistical (systematic).

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Σ (σ)</th>
<th>( \mathcal{B}, \times10^{-4} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>B^{\pm} → χ_{c1} K^{\pm}</td>
<td>79.0</td>
<td>4.94 ± 0.11 ± 0.33 4.6 ± 0.4 4.5 ± 0.1 ± 0.3</td>
</tr>
<tr>
<td>B^{0} → χ_{c1} K^{0}_{S}</td>
<td>36.8</td>
<td>3.78^{+0.17}_{-0.16} ± 0.33 3.9 ± 0.3 4.2 ± 0.3 ± 0.3</td>
</tr>
<tr>
<td>B^{\pm} → χ_{c2} K^{\pm}</td>
<td>3.6</td>
<td>1.11^{+0.36}_{-0.34} ± 0.09 &lt; 1.8 &lt; 1.8</td>
</tr>
<tr>
<td>B^{0} → χ_{c2} K^{0}_{S}</td>
<td>0.7</td>
<td>0.32^{+0.53}_{-0.44} ± 0.03 &lt; 2.6 &lt; 2.8</td>
</tr>
</tbody>
</table>

| B(B → X(3872)K) x B(X(3872) → J/ψγ), \times10^{-6} |
|-------------------------------|-------|-------------------------------|
| B^{\pm} → X(3872) K^{\pm} | 4.9 | 1.78^{+0.48}_{-0.44} ± 0.12 2.8 ± 0.8 2.8 ± 0.8 ± 0.1 |
| B^{0} → X(3872) K^{0}_{S} | 2.4 | 1.24^{+0.76}_{-0.61} ± 0.11 < 4.9 < 4.9 |

(1.11^{+0.36}_{-0.34}(\text{stat.})± 0.09(\text{syst.})) \times 10^{-5}, is well within the predicted range (0.2−4)×10^{-4} [18-20].

We also observe the X(3872) → J/ψγ decay in the B^{−} → X(3872)K^{−} decay mode with a significance of 4.9σ. We measure the branching fraction, \( B(B^{−} → X(3872)K^{−}) \times B(X(3872) → J/ψγ) \) to be (1.78^{+0.48}_{-0.44}(\text{stat.}) ± 0.12(\text{syst.})) \times 10^{-6} which agrees well with the Belle’s previous measurement [46] and BaBar’s recent one [54]. The X(3872) → J/ψγ radiative decay mode is now a well established decay mode and our measurement of the branching fraction is the most precise measurement (till date). The charge conjugation (C)-parity of the J/ψ meson and the γ are both negative, which implies that C = + for the X(3872). The observation of X(3872) → J/ψγ decay mode confirms the positive C-parity of the X(3872) state.
Figure 7.2: The measured branching fraction of the $B \to \chi_{c1} K$, $B \to \chi_{c2} K$ and $B \to X(3872) K$ decay in comparison with the other measurements. This graph compares our results (red) with the world average, PDG (green) and the BaBar’s recent measurement (blue). The height of the box shows the uncertainty on the measurement. The Upper Limit (U.L.) estimated at 90\% Confidence Level (C.L.) is shown in the figure by the box, the one reaching zero.

7.3 The $B \to X(3872)(\to \psi(2S)\gamma)K$ Decay Study

We have performed the $B \to X(3872)K$ decay study where $X(3872) \to \psi(2S)\gamma$, and this study can be summarized as follows:

- The signal Monte Carlo study is performed to get the reconstruction efficiency of the $B \to X(3872)(\to \psi(2S)\gamma)K$ decay. To study the possible sources of the background for this mode, we have used $B \to \psi X$ inclusive Monte Carlo sample.

- A broad peaking structure of the background is observed lying in (and near) the signal region in the $M_{\psi(2S)\gamma}$ distribution. This structure mostly comes from
the $B \to \psi(2S)K^*$ and $B \to \psi(2S)K$ decay modes.

- The above mentioned peaking background can be modeled using the Monte Carlo study, as our signal has a narrow peak. Still in order to reduce the background coming from the $B \to \psi(2S)K^*$ decay mode, a procedure to veto this contribution was developed. We applied a $\psi(2S)K^*$ veto, in which events having $817 \text{ MeV}/c^2 < M_{K\pi} < 967 \text{ MeV}/c^2$, $-20 \text{ MeV} < \Delta E_{\psi(2S)K^*} < 20$ MeV and $M_{bc}^{\psi(2S)K^*} > 5.27 \text{ GeV}/c^2$ were rejected.

- To look for any unexpected peaking background in the signal region, the $M_{ll}$, $M_{bc}$ and $M_{\psi(2S)\gamma}$ data sidebands are used. From this study, no peaking structure in the signal region was found.

- We look at the signal region in the data and measure the branching fractions and estimated the possible systematic uncertainty.

Table 7.5: Summary of the results of the $B \to X(3872)(\to \psi(2S)\gamma)K$ decay study. Significance $\Sigma$ (with systematic uncertainty included) and measured branching fraction ($B$) comparing our results with the BaBar’s measurement [54]. For $B$, the uncertainty is the statistical uncertainty. In the calculation of Upper Limit(at 90% C.L.) systematic uncertainty has been taken into account.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$\Sigma$ (σ)</th>
<th>$B$, $\times 10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \to X(3872)(\to \psi(2S)\gamma)K^\pm$</td>
<td>0.4</td>
<td>&lt; 3.45</td>
</tr>
<tr>
<td>$B^0 \to X(3872)(\to \psi(2S)\gamma)K^0_S$</td>
<td>0.3</td>
<td>&lt; 6.62</td>
</tr>
</tbody>
</table>

Table 7.5 summarizes the result of the branching fraction measurements for the $B \to X(3872)(\to \psi(2S)\gamma)K$ modes. Figure 7.3 shows the graphical representation...
of these results (with the systematic uncertainty included), and compares our results (red) with the BaBar’s recent measurements (blue) [54]. The height of the box shows the uncertainty on the measurement. The Upper Limit (U.L.) estimated at 90% Confidence Level (C.L.) is shown in the figure by the box, the one reaching zero.

![Graph](image)

Figure 7.3: The measured branching fraction of the $B \to X(3872)(\to \psi(2S)\gamma) K$ decay mode comparison with the BaBar’s measurement. It compares our results (red) with the BaBar’s recent measurements (blue) [54]. The height of the box shows the uncertainty on the measurement. The Upper Limit (U.L.) estimated at 90% Confidence Level (C.L.) is shown in the figure by the box, the one reaching zero.

### 7.3.1 Conclusions

From Figure 7.3, a clear disagreement between our upper limit on the branching fraction $B(B \to X(3872) K) \times B(X(3872) \to \psi(2S)\gamma)$ and BaBar’s measurement [54] is seen. Our U.L. (@90% C.L.) is 2.2σ away from BaBar’s central value of the charged mode. And for the neutral mode, a significantly more constraining limit is obtained compared to the one obtained by BaBar. On the basis of BaBar’s measurements we
expected to have more than 5σ significance (having more than 50 events) in our data sample as summarized in the Table 6.2. However, no signal is observed in our search for $X(3872) \rightarrow \psi(2S)\gamma$ decay mode. So, we assign Upper Limit at 90% C.L. for the $B^\pm \rightarrow X(3872)K^\pm$ decay mode, $B(B^\pm \rightarrow X(3872)K^\pm) \times B(X(3872) \rightarrow \psi(2S)\gamma)$, as $< 3.45 \times 10^{-6}$. On the branching fraction measurement for the $B^0 \rightarrow X(3872)K^0$ decay mode, $B(B^0 \rightarrow X(3872)K^0) \times B(X(3872) \rightarrow \psi(2S)\gamma)$, upper limit of $< 6.62 \times 10^{-6}$ is given by us. We also searched for the possible signal events in the rejected events sample (rejected during the selection criteria) and found no signal event. An independent study was carried out at Belle by another group using 3D fit ($\Delta E$, $M_{bc}$ and $M_{\psi(2S)\gamma}$ variables are used for the fit), they found a result very consistent with ours. This provides independent cross check and confirmation to our search.

![Branching ratio graph](image)

Figure 7.4: The graphical representation of the E1 radiative studies of $X(3872)$ state in the $B^\pm \rightarrow X(3872)K^\pm$ decay mode and comparison of our result (red box) with the BaBar’s one (blue box). The Upper Limit (U.L.) estimated at 90% Confidence Level (C.L.) is shown in the figure by the box, the one reaching zero.
CHAPTER 7. SUMMARY & CONCLUSIONS

Both of these analyses performed (by us and BaBar) are using different analysis techniques. BaBar used $m_{miss}$ and $m_X$ variables to extract the signal. They used a Plot technique in order to extract the signal yield by fitting $m_{miss}$ in the bins of $m_X$ and fitting the projection in $m_X$. However, we have used much simpler 1D Unbinned Maximum Likelihood (UML) fit to the $M_{\psi(2S)\gamma}$ distribution. Both of these studies have passed the benchmark commonly used in the HEP community. Thus, we concentrate on the conclusion based on our results.

We compared the measurement of the branching fractions, $\mathcal{B}(X(3872) \rightarrow \psi(2S)\gamma)$ with the $\mathcal{B}(X(3872) \rightarrow J/\psi\gamma)$. Figure 7.4 shows our results in comparison with the BaBar’s one [54]. The $X(3872) \rightarrow J/\psi\gamma$ decay study agrees quite nicely. We derive the Upper Limit (@ 90% C.L.) on the ratio of $\mathcal{B}(X(3872) \rightarrow \psi(2S)\gamma)/\mathcal{B}(X(3872) \rightarrow J/\psi\gamma) < 2.1$. The upper limit determined by us, overlap (negligible) with BaBar’s measured value at the extreme but it should be noted that the upper bound is perhaps determined in an overly conservative manner. From this result, it can be inferred that the $X(3872)$ state may not have the large admixture of $c\bar{c}$ with $D\bar{D}^*$ as was expected on the basis of BaBar’s result [54].

We can also try to understand this result on the basis of $J^{PC}$ of the $X(3872)$ state. As explained in Section 1.9, the favorable $J^{PC}$ for $X(3872)$ are $1^{++}$ and $2^{-+}$. If it is $1^{++}$, than two possible natural assignments of the $X(3872)$ are: the molecular state or the traditional charmonium, $\chi_{c1}(2P)$ state. If the $X(3872)$ is a molecule, one would expect the ratio $\Gamma_{\psi(2S)\gamma}/\Gamma_{J/\psi\gamma} \sim 4 \times 10^{-3}$ [45], which is compatible with the 90% C.L. Upper Limit we obtain. However, this result disagrees with the BaBar’s result of $3.4 \pm 1.3$ [54]. If an admixture of $c\bar{c}$ component is taken into account for $D^0\bar{D}^0$ molecule, then the enhanced decay rate of $X(3872) \rightarrow \psi(2S)\gamma$ as seen by BaBar (but not seen by us) can be explained. A recent theoretical work [99] has considered $X(3872)$ to be $\chi_{c1}(2P)$ candidate and they get $\Gamma_{\psi(2S)\gamma}/\Gamma_{J/\psi\gamma}$ to be 4.4, consistent with the BaBar’s result, but twice larger than our 90% C.L. Upper Limit.

If $J^{PC} = 2^{-+}$ for $X(3872)$, a recent claim from BaBar on the basis of $B \rightarrow J/\psi\omega K$ decay mode analysis is that the $P$-wave orbital angular momentum for the $J/\psi\omega$ system is more favored than the $S$-wave, which implies that the $X(3872)$ may fa-
7.4. CONCLUSIONS IN A NUTSHELL

For the first time we have observed the Cabibbo- and color-suppressed $B^\pm \to \psi(2S)\pi^\pm$ decay mode and measured its branching fraction. We tested the factorization hypothesis, by comparing the measured branching fraction of the $B^\pm \to \psi(2S)\pi^\pm$ decay mode with the branching fraction of the $B^\pm \to \psi(2S)K^\pm$ decay. Our results support the factorization hypothesis. Along with this search, a direct $CP$ violation (charge asymmetry) search is also carried out for the $B^\pm \to \psi(2S)\pi^\pm$ decay and found the measured charge asymmetry to be consistent within the expectation of the Standard Model framework. However our search for the direct $CP$ violation is limited by the statistics.

First evidence for the $B^- \to \chi_{c2}K^-$ decay mode is found and its measured branching fraction is compared with the measured branching fraction of the $B^- \to \chi_{c1}K^-$ decay mode, which comes out to be consistent with the theoretical expectation. Along with this, we also observed the E1 radiative decay of $X(3872)$, where $X(3872) \to J/\psi\gamma$, in the charged decay mode of $B^\pm \to X(3872)K^\pm$. We confirm and establish
the $X(3872) \rightarrow J/\psi \gamma$ decay mode, along with the positive $C$-parity of the $X(3872)$ state.

However, in our search of the other $E1$ radiative decay of $X(3872)$, $X(3872) \rightarrow \psi(2S)\gamma$, no signal was seen in the charged decay mode. On the basis of this search, we may expect that the $X(3872)$ is either a pure molecular state or it has less $c\bar{c}$ admixture (not large as was previously expected on the basis of BaBar’s measurement [54]). The result of the $X(3872) \rightarrow \psi(2S)\gamma$ decay mode comes out to be consistent with the pure molecular model interpretation of the $X(3872)$. Although, it would not be a correct idea (at this stage) to say that the $X(3872)$ is a molecular state, as there is also an interpretation of the $X(3872)$ state having a $J^{PC}$ of $2^{-+}$ (discussed in Previous Section) due to which it may be a charmonium. An improved theoretical treatment is required to interpret the $X(3872)$'s nature based on this thesis result.

Search for the $X(3872) \rightarrow \psi(2S)\gamma$ decay mode is constrained due to the limited statistics. May be in future, we can access or rule out this decay mode with more precision. These precise studies of such decay modes will be possible at the upcoming experiments like the SuperB-factory. The $X(3872)$ has come out to be more interesting state than the author earlier visualized (before starting this analysis). Author has tried his best to project the results without getting influenced and biased from any theoretical aspects.
Leptonic Systematic

There can be a difference between lepton identification in data and MC. This difference needs to be estimated.

We are using $L_e > 0.01$ and this cut has not been studied by the PID group. To get the correction factor for our cut on the lepton identification, we use $J/\psi \rightarrow \ell^+\ell^-$ inclusive mode. The $B \rightarrow J/\psi X$ inclusive sample is used for MC sample and for data.

We reconstruct the $J/\psi$ by combining a tagged ($L_e > 0.9$) electron with the under study tagged id cut ($L_e > 0.01$) electron, called double tagged (DT); and the another $J/\psi$ using a tagged ($L_e > 0.9$) electron with a non tagged one, called single tagged (ST). Ratio of $(\text{Yield}_{\text{DT}} / \text{Yield}_{\text{ST}})$ is calculated for both (data and MC) [93, 103]. Using this ratio, correction for the difference between MC and data is obtained; and uncertainty on this correction is taken as systematic uncertainty coming from $\ell$-identification. This is performed in momentum ($p_\ell$) and angle ($\theta_\ell$) bins in the lab frame for lepton. We get correction for each bin for data set I and II, separately (Section 2.3.2). Correction is calculated using weightage, depending upon the population of signal in the bins of $p_\ell$ and $\theta_\ell$, and also on the basis of experiment.

Similarly, muon id correction study for $L_\mu > 0.1$ is obtained.

Table A.1 summarizes the electron identification systematic study and electron identification correction comes out to be $1.0007 \pm 0.0047$ and uncertainty on its value...
Figure A.1: Lepton id study.

Table A.1: Eid systematic study.

<table>
<thead>
<tr>
<th>Data/MC</th>
<th>$p_x$(GeV/c)</th>
<th>$\theta_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>[18, 60]</td>
</tr>
<tr>
<td>Data set I</td>
<td>[0.75, 1.5]</td>
<td>0.9791 ± 0.0443</td>
</tr>
<tr>
<td></td>
<td>[1.5, 5]</td>
<td>0.9961 ± 0.0124</td>
</tr>
<tr>
<td>Data set II</td>
<td>[0.75, 1.5]</td>
<td>0.9798 ± 0.0366</td>
</tr>
<tr>
<td></td>
<td>[1.5, 5]</td>
<td>1.0019 ± 0.0093</td>
</tr>
</tbody>
</table>

is taken as systematic uncertainty coming from $\epsilon$-id. Similarly, Table A.2 summarizes the muon identification systematic study.
Table A.2: Muid systematic study.

<table>
<thead>
<tr>
<th>Data/MC</th>
<th>$p_\mu$(GeV/c)</th>
<th>18, 60</th>
<th>60, 125</th>
<th>125, 151</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data set I</td>
<td>[0.75, 1.5]</td>
<td>1.0096 ± 0.0347</td>
<td>0.9988 ± 0.0101</td>
<td>0.9982 ± 0.0212</td>
</tr>
<tr>
<td></td>
<td>[1.5, 5]</td>
<td>1.0004 ± 0.0080</td>
<td>1.0001 ± 0.0084</td>
<td>0.9999 ± 0.0444</td>
</tr>
<tr>
<td>Data set II</td>
<td>[0.75, 1.5]</td>
<td>0.9966 ± 0.0273</td>
<td>0.9977 ± 0.0080</td>
<td>0.9891 ± 0.0169</td>
</tr>
<tr>
<td></td>
<td>[1.5, 5]</td>
<td>0.9971 ± 0.0065</td>
<td>0.9989 ± 0.0066</td>
<td>1.0042 ± 0.0337</td>
</tr>
</tbody>
</table>
To estimate the fit bias, 10,000 toys are generated for each decay mode using the PDF and the yield obtained from the fit to the data (after including Poisson fluctuation in the yield generation). Fit is performed to the each sample and we obtain average yield from these fits. Difference between the generated and the obtained yield is taken as the fit bias. Table B.1 summarizes the expected fit bias in the each decay mode.

<table>
<thead>
<tr>
<th>Mode</th>
<th>From fit</th>
<th>Generated</th>
<th>Fit bias (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \to \chi_c K^\pm$</td>
<td>2308.02 ± 0.52</td>
<td>2308</td>
<td>-</td>
</tr>
<tr>
<td>$B^\pm \to \chi_c K^0_S$</td>
<td>32.82 ± 0.10</td>
<td>33</td>
<td>0.54</td>
</tr>
<tr>
<td>$B^0 \to \chi_c K^0_S$</td>
<td>542.24 ± 0.24</td>
<td>542</td>
<td>0.04</td>
</tr>
<tr>
<td>$B^0 \to \chi_c K^0_S$</td>
<td>3.06 ± 0.04</td>
<td>3</td>
<td>2.10</td>
</tr>
</tbody>
</table>

Table B.1: Fit bias estimated for the decay modes under study.

\[ B_i \times 10^{-6} \]

$B^\pm \to X(3872)(\to J/\psi \gamma)K^\pm$ $1.77 \pm 0.01$ $1.78$ $0.54$

$B^0 \to X(3872)(\to J/\psi \gamma)K^0_S$ $1.30 \pm 0.01$ $1.31$ $0.24$

$B^\pm \to X(3872)(\to \psi(2S) \gamma)K^\pm$ $0.89 \pm 0.02$ $0.76$ $16.0$

$B^0 \to X(3872)(\to \psi(2S) \gamma)K^0_S$ $1.02 \pm 0.03$ $1.09$ $6.0$
Significance (Including Systematic)

We include the systematic error in the calculation of the signal significance using marginalization technique [89]. We only include the systematic coming from the PDF shape and the fit bias, as they are the one which can potentially affect the signal yield [89, 104]. First we get the maximum likelihood curve by fixing the signal yield (or branching fraction) from zero to the nominal value and obtain the negative log-likelihood minimization curve with the statistical uncertainties. This likelihood curve is then smeared with the probability distribution \( (p_y B) \),

\[
p_y(B) = \int_0^{\infty} \exp^{-B S} \frac{1}{\sqrt{2\pi \sigma_S^2}} \exp^{-\frac{(S-\hat{S})^2}{2\sigma_S^2}} dS \tag{C.1}
\]

where, \( \sigma_S \) is the systematic error on yield \( (y) \), and branching fraction \( (B) \) is given by \( B = y \hat{S} \) and \( S \) is the true value of sensitivity (combination of beam flux, detector acceptance, etc.).

This way we generate the effective likelihood, which now includes the effects of the systematic. Figure C.1 shows the log-likelihood curves before (blue in color) and after (red in color) inclusion of the systematic uncertainties for \( B^{\pm} \to X(3872)(\to J/\psi\gamma)K^{\pm} \).
Figure C.1: The Negative log-likelihood curve for $B^\pm \rightarrow X(3872)(\rightarrow J/\psi\gamma)K^\pm$. Blue (red) curve is before (after) the inclusion of the systematic uncertainty.
Cross check for $B^0 \to \chi_{c1} K^0_S$

We performed the cross check of our results using $B^0 \to \chi_{c1} K^0$ decay mode. Instead of the procedure explained for the extraction of yield. Another method is used to check whether we can get the same result or not.

The $\chi_{c1}$ meson is reconstructed by combining $J/\psi$ meson with $\gamma$ candidates having $E_\gamma > 60$ MeV. To identify $\chi_{c1}$ we use $M_{J/\psi\gamma} \equiv M_{\ell\ell\gamma} - M_{\ell\ell} + m_{J/\psi}$, where $M_{\ell\ell\gamma}$ ($M_{\ell\ell}$) is the reconstructed mass of $J/\psi\gamma$ ($J/\psi$) and $m_{J/\psi}$ is PDG mass [3] of $J/\psi$. The $\chi_{c1}$ candidates within 3.467 GeV/$c^2$ and 3.535 GeV/$c^2$ are kept and kinematic mass constrained is applied, in order to improve the momentum resolution.

The reconstruction of the $B$ meson is done by combining a $\chi_{c1}$ candidate with a neutral $K^0_S$ candidate. The beam constrained mass ($M_{bc}$) and $\Delta E$ is used to extract signal yield. The $M_{bc}$ is defined as $\sqrt{E_{\text{beam}}^2 - (p_{J/\psi\gamma} + p_K)^2}$, while $\Delta E$ is defined as $(E_{J/\psi\gamma} + E_K) - E_{\text{beam}}$, where $E_{\text{beam}}$ is the beam energy in CM frame and $p_{J/\psi\gamma (\text{or} K)}$, $E_{\chi_{c1} (\text{or} K)}$ are momentum and energy of the $\chi_{c1}$ (or $K$) candidate in the CM frame of $\Upsilon(4S)$. In case of multiple candidates, which is 12.3 % of the total events for $B^0 \to \chi_{c1} K^0_S$ candidates, one with the least $\chi^2$ is kept. The $\chi^2$ is calculated using independent $\chi$ information from $\chi_{c1}$, $J/\psi$ and $K^0_S$ which depends upon the reconstructed mass and the width. Efficiency of (24.37±0.07) % is estimated from signal MC study. For background study $B \to J/\psi X$ inclusive MC sample is used. After parametrization of the background, fit is performed to data. The 2D
UML fit is performed to $\Delta E$ and $M_{bc}$ distribution shown in Figure D.1. We get the branching fraction $\mathcal{B}(B \to \chi_{c1}K_S^0)$ to be $(3.8 \pm 0.1 \text{(stat.)}) \times 10^{-4}$ from the fit to data. This result agrees quite well with our measurement using 1D UML fit to $M_{J/\psi\gamma}$ of $(3.8 \pm 0.2 \text{(stat.)} \pm 0.3 \text{(syst.)}) \times 10^{-4}$. This validate the analysis technique used in $B \to (\psi\gamma)K$ decay study.

Figure D.1: 2D UML fit to $772 \times 10^6$ data sample for $B^0 \to \chi_{c1}K_S^0$. 
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Publication

Publication as first author:

1. Observation of $B^{\pm} \to \psi(2S)\pi^{\pm}$ and search for direct $CP$-violation.

2. Observation of $X(3872) \to J/\psi \gamma$ and search for $X(3872) \to \psi(2S)\gamma$ in the $B$ decays.
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Author’s name in the publications as a Belle collaborator:

1. Observation of $B^0 \to D^{*+}\tau^-\nu$ decay at Belle.

2. Production of new charmonium states in $e^+e^- \to J/\psi D^*D^*$ at $\sqrt{s}=10.6$ GeV.

3. Observation of $B_s^0 \to \phi \gamma$ and search for $B_s^0 \to \gamma \gamma$ at Belle.

4. Observation of anomalous $\pi^+\pi^-\Upsilon(1S)$ and $\pi^+\pi^-\Upsilon(2S)$ production at $\sqrt{s}\sim 10.87$ GeV.

5. Measurement of the ratio $B(D^0 \to \pi^+\pi^-\pi^0)/B(D^0 \to K^-\pi^+\pi^0)$ and the time-integrated $CP$ asymmetry in $D^0 \to \pi^+\pi^-\pi^0$.

6. Measurement of $B(D^+_s \to \mu^+\nu)$.
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8. Measurement of masses of $\Xi_c(2645)$ and $\Xi_c(2815)$ baryons and observation of $\Xi_c(2980) \to \Xi_c(2645)\pi$.

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12. Search for $B^0 \to J/\psi\phi$ decays.


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5. K. Trabelsi (KEK) “Hadron physics and spectroscopy"
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   (June 9 - 19, 2010, Zakopane, Poland)

6. S. Lange (Giessen) “Recent Results from Belle and BaBar (XYZ mesons etc.)"
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   of the Nucleon (MENU 2010)
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