Study of $B^0 \rightarrow X(3872) \ K^+ \ \pi^-$ decay mode at Belle

Anu Bala
Panjab University Chandigarh
(On behalf of the Belle Collaboration)
Hadron 2013
4-8 November, 2013
Outline

- Motivation
- Illustration with the large $B^0 \rightarrow \psi' K^+ \pi^-$ sample.
- Observation of $B^0 \rightarrow X(3872) K^+ \pi^-$ decay mode
- Branching Ratio measurement
- $M(K\pi)$ study
- Summary
KEKB and Belle

- Belle started in 1999
  - Experiment designed for CP Violation measurement in $B^0 \rightarrow J/\psi K^0$ (Golden Mode).
  - Data taking ended in June, 2010
- Belle recorded $\sim 772 \text{ M } B\bar{B}$ pairs as the final sample at $\Upsilon(4S)$ resonance.

KEKB B-Factory

Integrated luminosity of B factories

KEKB peak luminosity has world record in $e^+e^-$ collider $2.11 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

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Discovery mode of X(3872)

- X(3872) was first observed in Belle in exclusive decay $B^\pm \rightarrow (J/\psi\pi\pi) K^\pm$
- Confirmed by other experiments like CDF, D0, BaBar, LHCb and CMS

$\psi'$

$X(3872)$

$\Gamma < 1.2 \text{ MeV}$

$M = (3871.68 \pm 0.17) \text{ MeV}/c^2$

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Radiative and exotic decay(s) of $X(3872)$

Belle found evidence for $X(3872) \rightarrow J/\psi \gamma$ in $B^+ \rightarrow X(3872) K^+$

Also seen by BaBar $BR(B^+ \rightarrow XK^+) \cdot BR(X \rightarrow J/\psi \gamma) = (2.8 \pm 0.8 \pm 0.1) \times 10^{-6}$

BaBar find signal in $X(3872) \rightarrow \psi' \gamma$

$BR(X(3872) \rightarrow \psi' \gamma) / BR(X(3872) \rightarrow J/\psi \gamma) = 3.5 \pm 1.4$

Update from Belle, established $X(3872) \rightarrow J/\psi \gamma$ with $5.5\sigma$ observation*

$BR(B^+ \rightarrow XK^+) \times BR(X \rightarrow J/\psi \gamma) = (1.78 \pm 0.46 \pm 0.12) \times 10^{-6}$

No Belle evidence for $X(3872) \rightarrow \psi' \gamma$

$X(3872) \rightarrow D^{*0} \bar{D}^0$

$X(3872)$ loosely bound molecule $\rightarrow$ enhancement in $D^{*0} \bar{D}^0$ invariant mass near Threshold

Belle and BaBar both observed $X(3872) \rightarrow D^0 \bar{D}^{*0}$

Difficult to assign it to a conventional charmonium state because of its narrow width.

Recent study by LHCb favours $1^{++}$, & rules out $2^{-}$ with $8.4\sigma$

* combining $B^+ \rightarrow X K^+ & B^0 \rightarrow XK^0$

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Belle observed $B^0 \rightarrow X(3872)K^+\pi^-$ with smaller data sample (605 fb$^{-1}$)

$$\text{BR}(B^0 \rightarrow X(K^+\pi^-)_{\text{non-res}}) \times \text{BR}(X \rightarrow J/\psi\pi^+\pi^-) = (8.1 \pm 2.0^{+1.1}_{-1.4}) \times 10^{-6}$$

dominates! Unlike $B \rightarrow (c\bar{c})K\pi$.

$\text{BR}(B^0 \rightarrow XK^{*0}) \times \text{BR}(X \rightarrow J/\psi\pi^+\pi^-) < 3.4 \times 10^{-6}$ 90% CL

With full data sample (711 fb$^{-1}$) and reprocessed data, one expect more sensitivity to this decay mode. It’s crucial to investigate further the $X(3872)$'s properties by adding more $B$ decay modes involving $X(3872)$ like $X(3872)K^+\pi^-$, $X(3872)K_S\pi^+$ and $X(3872)K^+\pi^0$, and taking advantage of a $B$-factory environment.
Selection criteria

B⁰ → ψ’(K⁺π⁻) and B⁰ → X(3872) (K⁺π⁻) selection criteria

- Beam constraint mass

\[ M_{bc} = \sqrt{E_{beam}^\ast - \sum_i P_i^\ast} \geq 5.27 \text{ GeV/c}^2 \]

To avoid combinatorial background from π⁺π⁻

- \[ M_{\pi^+\pi^-} > (M_{\pi^+\pi^- J/\psi} - (m_{J/\psi} + 0.2 \text{ GeV/c}^2)) \]

Fit was performed in 2-D using \( \Delta E \) & \( M_{J/\psi\pi\pi} \)

- \( -0.1 \text{ GeV} < \Delta E = \sum_i E_{i}^\ast - E_{beam}^\ast < 0.1 \text{ GeV} \)

- \( M_{J/\psi\pi\pi} \{3.64, 3.74\} \text{ GeV/c}^2 \) for B⁰ → ψ’(K⁺π⁻)

- \&\{3.82, 3.92\} GeV/c² for B⁰ → X(3872) (K⁺π⁻)

Based upon above selection cuts, reconstruction efficiency from MC is:

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Signal Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B⁰ → ψ’(K⁺π⁻)</td>
<td>15.9</td>
</tr>
<tr>
<td>B⁰ → X(3872) (K⁺π⁻)</td>
<td>17.7</td>
</tr>
</tbody>
</table>

While reconstruction, we are getting multiple candidates/event with wrong combination 24.4% and 29.4% resp. for B⁰ → ψ’(K⁺π⁻) and B⁰ → X(3872)(K⁺π⁻). One candidate out of these multiple candidates can be selected using best candidate selection criteria.
Signal Extraction

For signal extraction, first step is to:

• Do a 2-D fit to $\Delta E \& M_{J/\psi\pi\pi}$ to observe $B^0 \rightarrow X(3872) (K^+\pi^-)$ decay mode.

• 2-D fit to $\Delta E \& M_{J/\psi\pi\pi}$ performed in bins of $M(K\pi)$ to obtain the signal-only $M(K\pi)$ distribution and extract the resonant ($K^*$) and non-resonant (PHSP) components by fit.

(50 MeV/c$^2$ wide for $\psi'$ and 100 MeV/c$^2$ wide for $X(3872)$).

The procedure is first test with $B^0 \rightarrow \psi' (K^+\pi^-)$ because of same final state than our target mode but with larger statistics (~2800 expected events).
2-D Fit ($\Delta E$ and $M_{J/\psi\pi\pi}$)

$B^0 \rightarrow \psi' K^+ \pi^-$ decay mode

Dimensions used for 2-D fitting: $\Delta E$ and $M_{J/\psi\pi\pi}$

**Signal PDF:** Product of Crujiff function (used for $\Delta E$) and sum of two Gaussian (used for $M_{J/\psi\pi\pi}$).
2-D Fit ($\Delta E$ and $M_{J/\psi \pi \pi}$)

$B^0 \rightarrow \psi' K^+ \pi^-$ decay mode

Dimensions used for 2-D fitting: $\Delta E$ and $M_{J/\psi \pi \pi}$

Peaking background in $M_{J/\psi \pi \pi}$ (flat in $\Delta E$) [e.g. all decay modes of the type $B \rightarrow \psi' X$ in their final state]: Product of sum of two Gaussian (used for $M_{J/\psi \pi \pi}$) and Chebychev polynomial of 2$^{nd}$ order (used for $\Delta E$).
2-D Fit ($\Delta E$ and $M_{J/\psi\pi\pi}$)

$B^0 \rightarrow \psi' K^+ \pi^-$ decay mode

Dimensions used for 2-D fitting: $\Delta E$ and $M_{J/\psi\pi\pi}$

Peaking background in $\Delta E$ (flat in $M_{J/\psi\pi\pi}$) [e.g. all decay modes of the type $B \rightarrow (J/\psi\pi\pi)(K\pi)$]: Product of Chebychev polynomial of 1$^{\text{st}}$ order (used for $M_{J/\psi\pi\pi}$) and Crujiff function (used for $\Delta E$)

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2-D Fit ($\Delta E$ and $M_{J/\psi\pi\pi}$)

$B^0 \rightarrow \psi' K^+ \pi^-$ decay mode

Dimensions used for 2-D fitting: $\Delta E$ and $M_{J/\psi\pi\pi}$

**Flat background:** Chebychev polynomial of 2$^{nd}$ order is used to parameterize background in $\Delta E$ and 1$^{st}$ order is used for $M_{J/\psi\pi\pi}$. 

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2-D Fit \((\Delta E \text{ and } M_{J/\psi\pi\pi})\)

**Signal PDF:** Product of Crujiff function (used for \(\Delta E\)) and sum of two Gaussian (used for \(M_{J/\psi\pi\pi}\)).

**Peaking background in \(M_{J/\psi\pi\pi}\) (flat in other dimension) [e.g. all decay modes of the type \(B \rightarrow \psi' X\) in their final state]:** Product of sum of two Gaussian (used for \(M_{J/\psi\pi\pi}\)) and Chebychev polynomial of 2\(^{nd}\) order (used for \(\Delta E\)).

**Peaking background in \(\Delta E\) (flat in other dimension) [e.g. all decay modes of the type \(B \rightarrow (J/\psi\pi\pi)(K\pi)\):** Product of Chebychev polynomial of 1\(^{st}\) order (used for \(M_{J/\psi\pi\pi}\)) and Crujiff function (used for \(\Delta E\)).

**Flat background:** Chebychev polynomial of 2\(^{nd}\) order is used to parameterize background in \(\Delta E\) and 1\(^{st}\) order is used for \(M_{J/\psi\pi\pi}\).
2-D ($\Delta E - M_{J/\psi\pi\pi}$) fit to data for $B^0 \rightarrow \psi' K^+ \pi^-$ decay mode

Projection in signal region of $|\Delta E| < 0.02$ GeV

Projection in signal region of $\psi'$, where $3.678 < M_{J/\psi\pi\pi} < 3.692$ in GeV/c$^2$

**BR (Data)** ($B^0 \rightarrow \psi' K^+ \pi^-$) = $(6.04 \pm 0.16) \times 10^{-4}$ ("Statistical error only")

**BR from Belle latest measurement:** $(5.80 \pm 0.16 \pm 0.32) \times 10^{-4}$

PRD 88, 074026 (2013) (This B.R. includes $\psi' \rightarrow J/\psi\pi\pi$ and $\psi' \rightarrow ll$) PRD result is full amplitude fit result.

Here interference as well as $Z(4430)^+ \rightarrow \psi'\pi$ component is not taken into account.

This is just an illustration for $B \rightarrow X(3872)K\pi$ study, as in $X(3872)$ mode we have much less statistics $\sim$ 100-150 signal events

$B^0 \rightarrow \psi' K\pi$ decay mode is used to calibrate our PDF resolutions.

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We are able to model properly the backgrounds

Signal PDF

Peaking background in $M_{J/\psi \pi \pi}$ (flat in other dimension)

Peaking background in $\Delta E$ (flat in other dimension)

Combinatorial background
Different components of $M(K\pi)$ system

BR (Data) ($B^0 \to \psi' K^+ \pi^-$) (Slide 14) = $(6.04 \pm 0.16) \times 10^{-4}$

This branching ratio includes all the possible components of $M(K\pi)$ system: $K^*(892)$, $K_2^*(1430)$ and $(K^+\pi^-)_{NR}$ etc.

Next step is to separate resonant and non-resonant components of this system. So a fit to $M(K\pi)$ is necessary.
Signal Extraction

For signal extraction, 2\textsuperscript{nd} step is:

- Do a 2-D fit to \( \Delta E & M_{J/\psi \pi \pi} \) to observe \( B^0 \rightarrow X(3872) (K^+ \pi^-) \) decay mode.

- 2-D fit to \( \Delta E & M_{J/\psi \pi \pi} \) performed in bins of \( M(K\pi) \) to obtain the signal-only \( M(K\pi) \) distribution and extract the resonant (K*) and non-resonant (PHSP) components by fit.

(50 MeV/c\(^2\) wide for \( \psi' \) and 100 MeV/c\(^2\) wide for \( X(3872) \)).

The benefit of this method is that we get background subtracted (K\pi) mass distribution.

The procedure is first test with \( B^0 \rightarrow \psi' (K^+ \pi^-) \) because of same final state than our target mode but with larger statistics (~2800 expected events).
Yields and Errors provided by 2-D fit in each bin of $M_{K\pi}$

Yield from 2-D fit with 50 MeV wide bins of $M_{K\pi}$
Fit results of data for $B^0 \rightarrow \psi' K^+ \pi^-$ for $M(K\pi)$ Study

$B^0 \rightarrow \psi' K^*(892)^0$ signal is fitted with Histogram from signal MC.

$B^0 \rightarrow \psi' K_2^*(1430)^0$ signal is fitted with Histogram from signal MC.

$B^0 \rightarrow \psi'(K\pi)_{NR}$ also fitted with Histogram from signal MC

$B \rightarrow \psi' K^*(892)$ dominate over other components

BR (Data) ($B^0 \rightarrow \psi' K^*(892)^0$) = $(6.11 \pm 0.19) \times 10^{-4}$ ("Statistical error only")

BR in PDG = $(6.1 \pm 0.5$ (including systematic also)) $ \times 10^{-4}$

Belle latest measurement = $(5.55 + 0.22 (-0.23) + 0.41 (-0.84)) \times 10^{-4}$

PRD 88, 074026 (2013)
$B^0 \rightarrow X(3872) \ K^+\pi^- \ decay \ mode \ study$
2-D ($\Delta E - M_{J/\psi\pi\pi}$) Fit to data for $B^0 \to X(3872) K^+\pi^-$ decay mode

Projection in signal region of $X(3872)$, where $3.863 < M_{J/\psi\pi\pi} < 3.878$ in GeV/$c^2$

Significance > 5 $\sigma$

Signal: $B \to X(3872)K\pi$

All decay modes of the type $B \to (J/\psi\pi\pi)(K\pi)$

Combinatorial backgrounds

Projection in signal region of $|\Delta E| < 0.02$ GeV

Yield: $135 \pm 20$

A clear signal peak is observed for $B^0 \to X(3872) K^+\pi^-$ decay mode

$BR(B^0 \to X(3872) K^+\pi^-) \times BR(X(3872) \to J/\psi\pi^+\pi^-) = (8.55 \pm 1.31 (+0.48-0.76)) \times 10^{-6}$
Projection plots for sidebands

3.826 GeV/c^2 < M_{J/ψππ} < 3.855 GeV/c^2

3.886 GeV/c^2 < M_{J/ψππ} < 3.915 GeV/c^2

Signal: B → X(3872)Kπ

All decay modes of the type B → (J/ψππ)(Kπ)

Combinatorial backgrounds

(-0.08 GeV < ΔE < -0.04 GeV)

(0.04 GeV < ΔE < 0.08 GeV)

We are able to model properly the backgrounds

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Fit results of data for $B^0 \rightarrow X(3872) K^+ \pi^-$ for M(K\pi) Study

B$^0 \rightarrow X(3872) K^*(892)^0$ signal is fitted with Histogram from signal MC
B$^0 \rightarrow X(3872) (K\pi)^{NR}$ is also fitted with Histogram from signal MC.

$\frac{K^*(892)}{(K^*(892) + (K\pi)^{NR})} = 0.29 \pm 0.08$

Upper bound on M(K\pi) due to the kinematics is 1.41GeV/c$^2$. In light of this, we excluded $K_2^*(1430)$ in this fit.

In contrast to $\psi'$ results, here non resonant component in M(K\pi) system seems to be more as compared to resonant one.

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✓ BR(B⁰ → ψ’ K⁺ π⁻) from 2-D is consistent with previous study.

✓ Clear observation of B⁰ → X(3872) K⁺ π⁻ decay mode with Belle full data sample.

✓ BR(B⁰ → X(3872)K⁺π⁻)×BR(X(3872) → J/ψπ⁺π⁻) =

\[ (8.55 \pm 1.31 \pm 0.48-0.76) \times 10^{-6} \]

✓ Non-resonant component of (Kπ) system in X(3872) dominates as compared to resonant one which is in contrast to other charmonium states.

✓ We are exploring other final states which includes B± → X(3872) K± π₀ and B± → X(3872) K_S π±.
Backup
Production of $c\bar{c}$ (-like) @ B-factories

A few % of B mesons decay into $c\bar{c}$ and $K^{(*)}$

- **B-decays**
  - From $b\bar{u}$ to $c\bar{c}$ via $W^-$
  - $J/\psi, \psi', \eta_c, \chi_c, ...$
  - Easy to study.
  - Low background.
  - $J^{PC}$ using angular studies.

- **Double Charmonium**
  - From $e^+e^-$ to $\gamma$
  - $C=+1$
  - Reconstruct $J/\psi$ and look at recoil mass

- **Annihilation at smaller energy**
  - $e^+e^-$ to $\gamma$
  - $J^{PC} = 1^{-}$
  - Initial state radiation

- **Two photon production**
  - $e^+e^- \rightarrow \gamma \gamma$
  - $C=+1$
  - $J$ even
  - $c\bar{c}$ states produced without additional hadrons.
Decay modes of $B^0 \rightarrow \psi' K^+ \pi^-$ and $B^0 \rightarrow X(3872) K^+ \pi^-$

$B^0 \rightarrow \psi'(\rightarrow J/\psi \pi \pi) K^+ \pi^-$ decay mode (Control Sample) includes:

- $B^0 \rightarrow \psi' \ K^*(892)^0 (\rightarrow K^+ \pi^-)$
- $B^0 \rightarrow \psi' (K^+ \pi^-)_{NR} \ (3 \ Body \ Phase \ Space)$
- $B^0 \rightarrow \psi' \ K_2^*(1430)^0 (\rightarrow K^+ \pi^-)$

$B^0 \rightarrow X(3872)(\rightarrow J/\psi \pi \pi) K^+ \pi^-$ decay mode includes:

- $B^0 \rightarrow X(3872) K^*(892)^0 (\rightarrow K^+ \pi^-)$
- $B^0 \rightarrow X(3872) (K^+ \pi^-)_{NR} \ (3 \ Body \ Phase \ Space)$