Introduction

- Heavy Quarkonia are ideal tool for testing QCD
- Charmonium-like states found at B-factories
- Conventional cc_bar – states found
  - Spectra incomplete
- Possible indications for exotic states
  - X(3872) → J/ψ π π π
  - Y(3940) → J/ψ ω; Y(4260)
  - Z+(4430) → ψ' π+
- Bottomonium-like states
  - Z+ b
Belle

• Belle Measurements:
  • Exotic charmonium-like states
    - X, Y, Z
  • $e^+ e^- \rightarrow \eta \ J/\psi$ via Initial State Radiation (ISR)
  • $B \rightarrow \chi_{c1,2} \gamma K$
  • $B_0 \rightarrow J/\psi \ K^- \pi^+$
  • First evidence for $\eta_b(2S)$
  • Exotic bottomonia-like states
    - $Y(nS,) \ \pi^+\pi^- \ through \ Z^+$
    - $h \ (m_P) \pi^+ \pi^- \ through \ Z^+$
X, Y, Z Particles – exotic charmonium-like states

- X(3872): strong signal
  - Properties still under investigation
    - \( M(X(3872)) = 3871.67 \pm 0.17 \text{ MeV} \)
    - \( \Gamma(X(3872)) < 1.2 \text{ MeV} \)
    - \( C = +1 \)
    - \( C = -1 \) partner or charged partner so far not found
  - \( JPC = 1^{++} \) or \( 2^{--} \), no significant discrimination in fits so far
  - \( X(3872) \rightarrow J/\psi \pi^+ \pi^- \)
    - \( M \) just around \( D*D \)
- \( 1^3D_2 = \psi_2 \)
- Y-series — Y(4260), Y(4360), Y(4660), (etc?)
  - Belle 673 fb\(^{-1}\):
    - \( M(Y(4360)) = 4361 \pm 9 \pm 9 \)
    - \( \Gamma(Y(4360)) = 74 \pm 15 \pm 10 \)
    - \( M(Y(4660)) = 4664 \pm 11 \pm 5 \)
    - \( \Gamma(Y(4660)) = 48 \pm 15 \pm 3 \)
  - Charged Z states (Z(4430)+, Z(4050)+, Z(4250)+)
- New charmonia:
  - X(3915)
    - Two photon process, \( \gamma \gamma \rightarrow J/\psi \omega \), \( J = 0 \) or \( J = 2 \)
    - Angular analysis ongoing
    - \( M = 3915 \pm 3 \pm 2 \text{ MeV} \)
    - \( \Gamma = 17 \pm 10 \pm 3 \text{ MeV} \)
\(e^+ e^- \rightarrow J/\psi \eta \) via ISR

- **ISR:**
  - coloured and/or charged objects in the initial state
  - gluon and/or photon radiation → corrections
  - only states with 1-- produced
  - Y family states found in \(\psi \pi^+ \pi^-\) studied via ISR
- **ISR** \(\eta J/\psi\) measured, with \(\eta\) reconstructed from \(\pi^+ \pi^- \pi^0\) and \(\gamma \gamma\) final states
- full data sample taken at Belle: \(771.6 \pm 10.6\) million (final data set) \(B B\_\bar{B}\) events at \(\Upsilon(4S)\)

- fits to mass spectrum
  - unbinned maximum likelihood fit to \(\eta J/\psi\)
  - Breit-Wigner function of resonance decaying into final state
  - masses and widths in good agreement with \(\psi(4040)\) and \(\psi(4160)\)
  - \(B(\psi(4040) \rightarrow \eta J/\psi) = (0.62 \pm 0.17)\%\) → using \(\Gamma_{\psi(4040)} = (0.86 \pm 0.07)\) keV/c from PDG or \(B(\psi(4040) \rightarrow \eta \psi) = (1.22\pm0.26)\%\)
  - \(B(\psi(4160) \rightarrow \eta J/\psi) = (0.41 \pm 0.12)\%\) or \((1.42 \pm 0.28)\%\) → using PDG average
  - \(\Gamma_{\psi(4160)} = (0.83 \pm 0.07)\) keV/c^2
  - \(7.5\sigma\) and \(7.7\sigma\) → statistical significance of \(\psi(4040)\) and \(\psi(4160)\) respectively.
  - systematic Error: \(8.7\%\)
  - BRs imply widths of \(1\) MeV for J/psi eta transitions → quite large for charmonia above \(DD^*\_\bar{B}\) threshold

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$B^\pm \to \chi_{c1} \gamma K$ and $\chi_{c2} \gamma K$

- study of $B$ meson decay into $\chi_{c1} \gamma K$ and $\chi_{c2} \gamma K$
- search for $X(3872)$ partner with $C$-parity=-1 and/or missing D-wave charmonia expected $> 3.8$GeV
- Calculation of branching fractions for $B \to \psi^\prime (\to \chi_{c1} \gamma)K$ and $B \to \psi^\prime (\to \chi_{c2} \gamma)K$
- $771.6 \pm 10.6$ million (final Belle $\Upsilon(4S)$ data set) used
- Signal and BG studied using MC
- MC/Data difference in scale
- Resolution callibrated with $\psi^\prime$
- in addition to psi', evidence of $\psi_2 \to \chi_{c1} \gamma$ found
- no $X(3872)$ signal found
- fit was done in 2D $M(\chi_{c1,2} \gamma)-M_{bc}$

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$BR. (\times 10^{-4})$</th>
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<tbody>
<tr>
<td>$B^+ \to \psi^\prime (\to \chi_{c1} \gamma)K$</td>
<td>7.60 ± 0.75</td>
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<tr>
<td>$B^- \to \psi^\prime (\to \chi_{c2} \gamma)K^-$</td>
<td>5.55 ± 0.90</td>
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<tr>
<th>Resonance</th>
<th>Yield</th>
<th>Mass (MeV/c$^2$)</th>
<th>Width (MeV)</th>
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<tbody>
<tr>
<td>$\psi^\prime$</td>
<td>200 ± 19</td>
<td>3685.5 ± 0.7</td>
<td>0.304</td>
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<tr>
<td>$X(3820)$</td>
<td>38 ± 15</td>
<td>3823.5 ± 2.8</td>
<td>5.3 ± 8.2</td>
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Fig 1: Fit to $M(\chi_{c1} \gamma)$, red: red dashed for $B^\pm \psi^\prime (\to \chi_{c1} \gamma)K^\pm$, pink: $B^\pm \psi^\prime (\to \chi_{c2} \gamma)K^\pm$; purple dashed: BG components for $B^\pm \psi^\prime (\to \chi_{c1} \gamma)K^\pm$, cyan: rest of BG

$B^+ \to X(3820) (\to \chi_{c2} \gamma) K^+$
$B^- \to \psi^\prime (\to \chi_{c2} \gamma) K^-$

Combinatorial

$711 fb^{-1}$
\( \mathcal{B}^0 \rightarrow J/\psi \ K^- \ \pi^+ \)

- charged (exotic) \( Z^+ \) states observed by Belle in \( \psi' \ \pi^+ \), \( \chi_{c1} \ \pi^+ \)
- not confirmed by Babar
- search for \( Z^+\rightarrow J/\psi\pi\pi^+ \) via 4D amplitude analysis \( \mathcal{B}^0 \rightarrow J/\psi \ K^- \ \pi^+ \)
- all known \( K^* \rightarrow K\pi \) amplitudes included in signal fit; \( Z^+ \) contribution added
- analysis based on 711 fb\(^{-1}\) data sample collected by the Belle detector on the asymmetric \( e^+ e^- \) collider KEKB
- Gaussian signal and 3\(^{rd}\) order polynomial background distribution
- amplitude for the three-body decay \( \mathcal{B}^0 \rightarrow J/\psi \ K^- \ \pi^+ \) represented as sum of Breit-Wigner contributions for different intermediate two-body states
- angular independent part of the amplitude of \( \mathcal{B}^0 \rightarrow J/\psi \ K^- \ \pi^+ \) via two-body intermediate resonance \( R \)

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B^0 \rightarrow J/\psi K^- \pi^+

- background distribution divided into 3 parts:
  - Background sources
    - K*(892) meson and random J/ψ
    - BG from K → π+ π−
    - combinatorial background from other sources
  - background from first two: peaking
  - background from third: not peaking

- search for X^+ with arbitrary mass and width
- J^P = 0^−, 1^+, 1^−, 2^+, 2^− considered
- 0+ impossible due to the parity conservation in X^+ → J/ψ π^+
- Search for X^+
  - No significant signal of X^+ found
  - Upper limits for branching fractions set
    \( \mathcal{B}(B^0 \rightarrow X^+ K^-) \times \mathcal{B}(X^+ \rightarrow J/\psi \pi^+) < 6.5 \times 10^{-6} \) (90% CL),
    \( \mathcal{B}(B^0 \rightarrow X^+ K^-) \times \mathcal{B}(X^+ \rightarrow J/\psi \pi^+) < 7.3 \times 10^{-6} \) (95% CL).

<table>
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<tr>
<th>TABLE VII: Fit results: X^+</th>
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<tr>
<td>J^P</td>
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<tr>
<td>X^+ \rightarrow J/ψ π^+</td>
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<tr>
<td>Mass, MeV</td>
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<td>Sign.</td>
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<th>B(B^0 \rightarrow X^+ K^-) \times \mathcal{B}(X^+ \rightarrow J/ψ \pi^+) limits</th>
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Evidence for $\eta_b$ (2S) & observation of $h_b$ (1P) $\rightarrow \eta_b$ (1S)$\gamma$ and $h_b$ (2P) $\rightarrow \eta_b$ (1S)$\gamma$.

- Data collected at Y(5S) used.
- First evidence for $\eta_b$ (2S) using $h_b$ (2P) $\rightarrow \eta_b$ (2S)$\gamma$.
- First observation of $h_b$ (1P) $\rightarrow \eta_b$ (1S)$\gamma$ and $h_b$ (2P) $\rightarrow \eta_b$ (1S)$\gamma$.
- Mass and width of $\eta_b$ (1S) and $\eta_b$ (2S) measured to be:
  - $m_{\eta_b}$ (1S) = 9402.4 ± 1.5 ± 1.8 MeV/$c^2$
  - $m_{\eta_b}$ (2S) = 9999.0 ± 3.5 +2.8 MeV/$c^2$
  - and $\Gamma_{\eta_b}$ (1S) = 10.8 + 4.0 + 4.5 MeV.
- Better agreement with theory and larger branching fractions than expected.
- $B_{h_b}$ (2P) $\rightarrow \eta_b$ (2S)$\gamma = (47.5 \pm 10.5 +6.8\%)$.
- Update to $h_b$ (1P) and $h_b$ (2P) mass measurements.
- 133.4 fb$^{-1}$ data sample, at energies near Y(5S) resonance from Belle detector at the KEKB used.
- Belle collected largest data set at Y(5S).
  - Clean source for bottomonium spectrum.

Fig: (a) $h_1$ (1P) yield vs $M^{(1)}_{\text{miss}}$(π+ π−γ); (b) $h_2$ (1S) yield vs $M^{(2)}_{\text{miss}}$(π+ π−γ) in the $\eta_b$ (1S) region; (c) $\eta_b$ (2S) region; solid / dashed: fit results for signal and BG respectively.
Y(5S) → Y(nS,) π⁺π⁻ through Z⁺_b

- Belle 121-1 fb
- Analysis of: Y(5S) → Y(nS) π⁺π⁻
  n = (1,2)
  - two horizontal bands in Yπ⁺ max fitted with:
    \[ A = A(Z^+ ) + A(Z^+ ) + A(f_0(980)) + \]
    \[ A(f_2(1270)) + A(NR) \]
- JP = 1⁺ assumed
- angular analysis performed
  - Possible interpretations for Z+:
    - Molecule, coupled channel resonance, tetraquark

Fig 1: Dalitz plots for Y(nS)π⁺π⁻ events in (a) Y(1S); (b) Y(2S); (c) Y(3S) signal regions

Fig 2: Comparison of fit results with data for Y(1S) (top), Y(2S) (middle), Y(3S) (bottom) signal regions.
Hatched histograms represent BG

Fig 3: Angular distributions for Z₁(10610) signal region: (top) Y(2S) π candidates; (bottom) Y(3S) π candidates, as a function of cosθ₂ (middle column); open histograms represent fit results for different J^P hypotheses: (black) 1⁺, (red) 1⁻, (green) 2⁺, (blue) 2⁻
Y(5S) → h_{b} (mP )π^{+} π^{-} through Z^{+}_{b}

- Belle 121-1 fb
- Analysis of: h_{b} (mP )π^{+} π^{-}
  \( M = (1,2) \)
- JP = 1+ assumed
- angular analysis performed
- same \( Z_{b}^{+} \) in \( h \) π and Y(nS) π

Fig2: points: h_{b}(1P) yield as a function of \( \cos\theta_{1} \) (left); \( \cos\theta_{2} \) (middle); \( \cos\theta_{ππ} \) (right); (top) \( Z_{b}(10610) \); (bottom) \( Z_{b}(10650) \); histograms represent different J^P hypotheses: (black) 1^+, (red) 1^−, (blue) 2^−

Fig1: Comparison of \( Z_{b}(10610) \) and \( Z_{b}(10650) \) parameters obtained from different decay channels. The vertical dotted lines indicate B * B thresholds.

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Summary

- Many new and exciting results
- Conventional quarkonia are being established
- unexpected exotic states, still only vaguely understood
- $\eta_b$ and $h_b$ finally found $\rightarrow$ completing bottomonium table
- More information obtained to understand $X,Y,Z$
- More and exciting results to be expected from Belle II