Recent results on charmonia- and bottomonia-like particles at Belle

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Belle experiment

Introduction

B \to Y(4260) K
B \to h_c K
X(3872), X(3915) \to \chi_c \pi^0
B^0 \to X(3872) \gamma
ee^+ e^- \to \gamma X_c J
ee^+ e^- \to \Upsilon(nS) \pi^+ \pi^-

Summary

Backup

The Belle experiment

2nd generation Belle II has started.

Physics runs

Major part of the data was taken at the Upsilon(4S), in addition, a smaller sample at the nearby continuum, and at the "narrow-resonances" (Upsilon(1S,2S,3S))

Integrated luminosity of B factories

> 1 ab^{-1}
On resonance:
Y(5S): 121 fb^{-1}
Y(4S): 711 fb^{-1}
Y(3S): 3 fb^{-1}
Y(2S): 25 fb^{-1}
Y(1S): 6 fb^{-1}
Off res./scan: ~100 fb^{-1}

~ 550 fb^{-1}
On resonance:
Y(4S): 433 fb^{-1}
Y(3S): 30 fb^{-1}
Y(2S): 14 fb^{-1}
Off resonance: ~54 fb^{-1}
Introduction

- The first exotic state (charmonium-like $X(3872)$) was found in 2003 by Belle.
- Some new conventional quarkonium states + more than a dozen of exotic quarkonium-like states were discovered.
- Candidates of the exotic states: tetraquark, diquarkonium, meson molecules... etc.
Charmonium and Bottomonium States

Charmonium(-like) states

Bottomonium(-like) states
Charmonium(-like) states

- $B \rightarrow Y(4260)K$
- $B \rightarrow h_c K$
- $X(3872), X(3915) \rightarrow \chi_{c1} \pi^0$
- $B^0 \rightarrow X(3872)\gamma$
- $e^+ e^- \rightarrow \gamma \chi_{cJ}$

Bottomonium(-like) states

- $e^+ e^- \rightarrow \Upsilon(nS) \pi^+ \pi^-$
**Motivation**

- $Y(4260)$ was first observed in ISR by BaBar [1].
- $\mathcal{B}(B^+ \to Y(4260)K^+) \times \mathcal{B}(Y(4260) \to J/\psi \pi^+ \pi^-)$ is in range $3.0 \times 10^{-8} \sim 1.8 \times 10^{-6}$ by QCD sum rules, assuming $Y(4260)$ is a charmonium-tetraquark admixture [2].
- BaBar observed $128 \pm 42$ signal events ($3.1\sigma$) using $211 \text{ fb}^{-1}$, and set a 95% U.L. on $\mathcal{B}(B^+ \to Y(4260)K^+) \times \mathcal{B}(Y(4260) \to J/\psi \pi^+ \pi^-) < 2.9 \times 10^{-5}$ [3].
- $e^+e^-$ direct production observed by BESIII [4].
Analysis features

- Considered both $B^\pm$ and $B^0$, $Y(4260) \rightarrow J/\psi \pi^+ \pi^-$, $J/\psi \rightarrow \ell^+ \ell^-$ ($\ell \in \{e, \mu\}$).
- Control samples: $B \rightarrow \psi(2S)K$ and $B \rightarrow X(3872)K$.
- UML fit of $\Delta E$, signal yield from weighted $M_{J/\psi \pi \pi}$ by $sPlot$.

Upper limits

| Decay | $\epsilon$ (%) | $N_S$ | $\Sigma(\sigma)$ | U.L. |
|-------|----------------|-------|-------------------|-------|
| $B^+ \rightarrow Y(4260)K^+$, $Y(4260) \rightarrow J/\psi \pi^+ \pi^-$ | 19.8 | $179 \pm 53^{+55}_{-41}$ | 2.1 | $1.4 \times 10^{-5}$ |
| $B^0 \rightarrow Y(4260)K^0$, $Y(4260) \rightarrow J/\psi \pi^+ \pi^-$ | 10.6 | $39 \pm 28^{+7}_{-31}$ | 0.9 | $1.7 \times 10^{-5}$ |

$B^+$ decay: Consistent with BaBar, but more stringent.
$B^0$ decay: Given for the first time.

c.f. theoretical predictions: $3.0 \times 10^{-8} \sim 1.8 \times 10^{-6}$. 
\[ B \rightarrow h_c K \] (arXiv: 1903.06414 (to appear in PRD))

**Motivation**

- Both \( B^+ \rightarrow h_c K^+ \) and \( B^+ \rightarrow \chi_{c0} K^+ \) are suppressed by factorization [1,2].
- \( \mathcal{B}(B^+ \rightarrow \chi_{c0} K^+) = (1.49^{+0.15}_{-0.14}) \times 10^{-4} \), not strongly suppressed.
  - Factorization-allowed process \( \mathcal{B}(B^+ \rightarrow \chi_{c1} K^+) = (4.84 \pm 0.23) \times 10^{-4} \).
  - \( \mathcal{B}(B^+ \rightarrow h_c K^+) \) was expected to be of the same order, but not observed.
- Best upper limits:
  - Belle: \( \mathcal{B}(B^+ \rightarrow h_c K^+) < 3.8 \times 10^{-5} \) (90% C.L.) [3].
  - LHCb: \( \mathcal{B}(B^+ \rightarrow h_c K^+) \times \mathcal{B}(h_c \rightarrow pp) < 6.4 \times 10^{-8} \) (95% C.L.) [4].
- Theoretical predictions:
  - QCD factorization: \( 2.7 \times 10^{-5} \) [5].
  - Perturbative QCD: \( 3.6 \times 10^{-5} \) [6].

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[1] ZPC 34 103 (1987) [2] PRD 66 037503 (2002) [3] PRD 74 012007 (2006)
[4] EPJ C73 2462 (2013) [5] hep-ph/0607221 (2006) [6] PRD 74 114029 (2006)
$B \rightarrow h_c K$ (arXiv: 1903.06414 (to appear in PRD))

Analysis features

- Considered both $B^\pm$ and $B^0$, $h_c \rightarrow \eta_c \gamma$ and $pp\pi^+\pi^-$ (recently observed by BESIII [5]).

- $\eta_c$ candidates are reconstructed in 10 different decay channels:
  $\eta_c \rightarrow K^+ K_0^0 \pi^-, K^+ K^- \pi^0, K_0^0 K_0^0 \pi^0, K^+ K^- \eta, K^+ K^- K^+ K^-, \eta' (\rightarrow \eta \pi^+ \pi^-)\pi^+ \pi^- , pp, pp\pi^0, pp\pi^+ \pi^-, \text{and } \Lambda \Lambda$.

- MVA is used for each channel to separate signal from bkg.

- The decays of other charmonium states to $pp\pi^+\pi^-$ are also studied.

Signal yields

- $B^+ \rightarrow h_c K^+ : 32.6 \pm 8.0 \ (4.8 \sigma) \rightarrow \textbf{Evidence!} \ (BF: \ (3.7^{+1.0+0.8}_{-0.9-0.8}) \times 10^{-5})$.
  - Consistent with the existing UL and agrees with the theoretical predictions ($(2.7 \sim 3.6) \times 10^{-5}$).

- $B^0 \rightarrow h_c K_0^0 : 3.1 \pm 3.7 \ (0.7 \sigma) \rightarrow \textbf{Upper limit is set at} \ 1.4 \times 10^{-5} \ \textbf{at 90\% C.L.}$
  - UL given first time.

[5] PRD 99, 072008 (2019)
$B \rightarrow h_c K$  (arXiv: 1903.06414 (to appear in PRD))

Simultaneous UML fit to $h_c \rightarrow \eta_c \gamma$ signal and $h_c \rightarrow pp\pi^+\pi^-$ background & signal
B → h_c K \quad \text{(arXiv: 1903.06414 (to appear in PRD))}

A closer look at h_c → pp\pi^+\pi^- signal in \chi_{cJ} region:

| Parameter | B^+ → h_cK^+ | B^0 → h_cK_S^0 |
|-----------|---------------|-----------------|
| N_{\eta_c} | 229 ± 18 | 96 ± 11 |
| \varphi_{\eta_c} | -1.12 ± 0.09 | -1.47 ± 0.14 |
| N_{J/\psi} | 345 ± 19 | 128 ± 12 |
| N_{\chi_{c0}} | 25.5 ± 7.1 | 0.9 ± 1.6 |
| \varphi_{\chi_{c0}} | -1.51 ± 0.23 | -2.05 ± 1.20 |
| N_{\chi_{c1}} | 34.5 ± 8.8 | 21.2 ± 6.1 |
| N_{\eta_c} | 32.6 ± 8.0 | 3.1 ± 3.8 |
| N_{\chi_{c2}} | -1.6 ± 6.3 | 11.6 ± 5.5 |
| N_{\eta_c(2S)} | 86.1 ± 11.9 | 24.0 ± 6.8 |
| \varphi_{\eta_c(2S)} | -1.41 ± 0.14 | -1.90 ± 0.23 |
| N_{\psi(2S)} | 36.9 ± 8.8 | 13.0 ± 5.6 |

- Observation of the new \eta_c(2S) decay channel: \eta_c(2S) → pp\pi^+\pi^-.
- Other charmonium signals are consistent with PDG.
$X(3872), X(3915) \rightarrow \chi_{c1} \pi^0$ (arXiv: 1904.07015 (to appear in PRD))

Motivation for $X(3872)$ mode

- $X(3872) \rightarrow \chi_{c1} \pi^0$ recently observed by BESIII [1].
- $\chi_{c1}(2P)$ interpretation of the $X(3872)$ suggests such decay should be very small due to isospin breaking [2].
- However, $\frac{\mathcal{B}(X(3872) \rightarrow \chi_{c1} \pi^0)}{\mathcal{B}(X(3872) \rightarrow J/\psi \pi^+ \pi^-)} = 0.88^{+0.33}_{-0.27} \pm 0.10$ is large compared to $\frac{\mathcal{B}(\psi(2S) \rightarrow J/\psi \pi^0)}{\mathcal{B}(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)} = 3.66 \times 10^{-3}$.

Motivation for $X(3915)$ mode

- $X(3915)$ was first observed by Belle in $B \rightarrow X(3915)K$ [3].
- Too narrow and too large for $c\bar{c}$ scenario (expect $> 100$ MeV/$c^2$ [4], measured $(20\pm5)$ MeV/$c^2$ [5]; suppressed in the $c\bar{c}$ scenario by OZI rule [6]).
- If $X(3915)$ is a non-conventional state, single pion transitions may be enhanced.

[1] arXiv: 1901.03992 (2019) [2] PRD 77 014013 (2008) [3] PRL 94 182002 (2005) [4] PRD 86 091501 (R) (2012) [5] PRD 98 030001 (2018) [6] PRD 91 057501 (2015)
**Analysis features**

- $B^+ \rightarrow X(3872)K^+, B^+ \rightarrow X(3915)K^+$.
- $\chi_{c1} \rightarrow J/\psi\gamma, J/\psi \rightarrow \ell^+\ell^-(\ell \in \{e, \mu\})$.
- $\gamma$ selections: $E_\gamma > 100$ MeV, $E_9/E_{25} > 0.85$, $\pi^0$ veto.
- $B^+ \rightarrow \chi_{c1}K^{*+}$ veto: $791.8$ MeV < $M_{K\pi^0} < 991.8$ MeV.

**Results**

- UML fit to $\Delta E$ gives $(806 \pm 69)$ signal events (consistent with similar previous Belle study of $B^+ \rightarrow \chi_{c1}\pi^+\pi^-K^+$ [5]).

**Signal yields:**
- $X(3872): 2.7 \pm 5.5$ (0.3$\sigma$), $X(3915): 42 \pm 14$ (2.3$\sigma$).

**Upper limits (90% C.L.):**

- $B(B^+ \rightarrow X(3872)K^+, ) \times B(X(3872) \rightarrow \chi_{c1}\pi^0) < 8.1 \times 10^{-6}$
  - $\rightarrow$ Compatible with $D^0 D^{*0} + \chi_{c1}(2P)$ admixture scenario.
- $B(B^+ \rightarrow X(3915)K^+) \times B(X(3915) \rightarrow \chi_{c1}\pi^0) < 3.8 \times 10^{-5}$
- $\frac{B(X(3872) \rightarrow \chi_{c1}\pi^0)}{B(X(3872) \rightarrow J/\psi\pi^+\pi^-)} < 0.97 \rightarrow$ No contradiction with BESIII result.

[5] PRD 93 052016 (2016)
Motivation

- Predictions of branching fractions of $B^0 \rightarrow c\bar{c}\gamma$ depend on the factorization approach of QCD interactions.

  - In the case of $B^0 \rightarrow J/\psi\gamma$,
    - $7.65 \times 10^{-9}$ using QCD factorization [1].
    - $4.5 \times 10^{-7}$ using pQCD approach [2].
    - $< 1.5 \times 10^{-6}$ (90% C.L.) from LHCb [3].

- Possible new physics enhancements: right-handed currents [1] or non-spectator intrinsic charm in $B^0$ [4].

- $X(3872)$ may contain components other than $c\bar{c}$: $B^0 \rightarrow X(3872)\gamma$ should have smaller branching fraction than that of $B^0 \rightarrow J/\psi\gamma$.

[1] EPJ C34 291 (2004) [2] PRD 74 097502 (2006) [3] PRD 98 030001 (2018) [4] PRD 65 054016 (2002)
\[ B^0 \rightarrow X(3872)\gamma \, \text{(arXiv: 1905.11718 (submitted to PRD))} \]

**Analysis features**

- \( X(3872) \rightarrow J/\psi \pi^+\pi^- \), \( J/\psi \rightarrow \ell^+\ell^- (\ell \in \{e, \mu\}) \).
- Selections on \( \Delta M = |M_{\ell\ell\pi\pi} - M_{\ell\ell}| \) to reduce combinatorial bkg and bkg from misidentified \( \gamma \) conversions.
- \( \gamma \) selections: \( E_\gamma > 600 \, \text{MeV}, \ E_9/E_{25} > 0.87, \ \pi^0 \) veto.
- MVA to suppress main bkg. from \( B \rightarrow J/\psi X \).
- Best candidate selection: Best \( \Delta M \) (choose the nearest one to the PDG value).
- Control samples: \( B^0 \rightarrow K_S^0\pi^+\pi^-\gamma \), \( B^0 \rightarrow J/\psi K_S^0 \), and \( B^0 \rightarrow \psi(2S)K_S^0 \).
$B^0 \rightarrow X(3872) \gamma$  (arXiv: 1905.11718 (submitted to PRD))

**Results**

- Using Feldman-Cousins counting method to get U.L.
- $\mathcal{B}(B^0 \rightarrow X(3872) \gamma) \times \mathcal{B}(X(3872) \rightarrow J/\psi \pi^+ \pi^-) < 5.1 \times 10^{-7}$ (90% C.L.)

| Channel | Dimuon | Dielectron | Total |
|---------|--------|------------|-------|
| Observed $N_{\text{evt}}$ | 9 | 9 | 18 |
| Expected $N_{\text{bkg}}$ | 9.3 | 12.1 | 21.4 |
| 90% U.L. | $9.2 \times 10^{-7}$ | $6.8 \times 10^{-7}$ | $5.1 \times 10^{-7}$ |
Motivation

- EM quarkonium production serves as a good testing ground for NRQCD factorization.
- BESIII measured cross sections of $e^+e^- \rightarrow \gamma \chi_{cJ}$ and $e^+e^- \rightarrow \gamma \eta_c$ at different energies, none of them $>3\sigma$ [1,2].
  - Combining data from all energy points: statistical significances for $\chi_{c1}$, $\chi_{c2}$, and $\eta_c$ are $3.0\sigma$, $3.4\sigma$, and $>3.6\sigma$, respectively.
- BESIII reported evidence for $e^+e^- \rightarrow X(3872)\gamma$ [3].
- Precise measurement of $e^+e^- \rightarrow \gamma \chi_{cJ}$ and $\gamma \eta_c$ is useful to understand C-even quarkonia and exotic XYZ states [4-6].

Analysis features

- $\chi_{cJ} \rightarrow J/\psi\gamma$, $J/\psi \rightarrow \mu^+\mu^-$. 
- $\eta_c \rightarrow K^+K^0\pi^-$, $\pi^+\pi^-K^+$, $\pi^+\pi^-\pi^+\pi^-$, $K^+K^-K^+K^-$, and $3(\pi^+\pi^-)$.
- $\sqrt{s} = 10.52, 10.68, 10.867$ GeV.
- ISR corrections: assuming $\sigma(e^+e^- \rightarrow \gamma \chi_{cJ}/\eta_c) \sim 1/s^n$.
  - $n = 1.4(\chi_{c0}), 2.1(\chi_{c1}), 2.4(\chi_{c2}), 1.3(\eta_c)$ [7,8].
- MVA is used to suppress background.
- Photon from $\chi_{cJ} \rightarrow J/\psi\gamma$ is the $2^{nd}$ highest energy one, requiring $E_\gamma > 300$ MeV to suppress backgrounds from fake photons.
\( e^+ e^- \rightarrow \gamma \chi_{cJ} \) (PRD 98, 092015 (2018))

- Significant \( \chi_{c1} \) signal (5.1\( \sigma \), systematics included) is observed at \( \sqrt{s} = 10.58 \) GeV.
- \( N_{\text{obs}} = 39.0^{+9.5}_{-8.8} \).
- For other modes and other c.m. energies, U.L.’s are given.
Measured Cross Sections

Born cross section for $\chi_{c1}$ signal at $\sqrt{s} = 10.58$ GeV: $17.3^{+4.2}_{-3.9} \pm 1.7$ fb.

Dependence of the cross section on energy (with BESIII data [1]): $1/s^{2.1^{+0.3}_{-0.4} \pm 0.3}$. 

$$e^+ e^- \rightarrow \gamma \chi_{cJ}$$ (PRD 98, 092015 (2018))
$e^+ e^- \rightarrow \Upsilon(nS)\pi^+\pi^-$

(arXiv: 1905.05521 (preliminary results, to be submitted to JHEP))

Motivation

- Above the $B\bar{B}$ threshold, $\Upsilon(4S)$, $\Upsilon(10860)$ and $\Upsilon(11020)$ have properties that are unexpected for pure $b\bar{b}$ bound states [1]. Possible explanations:
  - Contribution of hadron loops (equivalently, presence of a $B_s^{(*)} B_s^{(*)}$ admixture) [2-4].
  - Presence of other exotic states (e.g. compact tetraquarks [5] or hadrobottomonia [6]).
- $\Upsilon(3,4D)$ states are predicted in the region of the $\Upsilon(4,5,6S)$ levels [7,8].
- Recent study of $e^+ e^- \rightarrow \Upsilon(nS)\pi^+\pi^-$ in Belle show a small hint of new structure at $\sqrt{s} = 10.77$ GeV [9].

Analysis features

- $\Upsilon(nS) \rightarrow \ell^+\ell^-$ ($\ell \in \{\mu, e\}$).
- Signal yields are extracted via fitting to $M_{\text{recoil}}(\pi^+\pi^-)$ instead of counting.
- Using ISR process with the high stat. $\Upsilon(10860)$ on-resonance data to obtain additional information about the cross section shapes.
- Energy balance requirement:
  \[ |M_{\text{recoil}}(\pi^+\pi^-) - M(\ell^+\ell^-)| < 150 \text{ MeV}. \]
$e^+ e^- \rightarrow \Upsilon(nS)\pi^+ \pi^-$

(arXiv: 1905.05521 (preliminary results, to be submitted to JHEP))

**New structure**
- Global significance : 6.7\(\sigma\).
- Possible explanations :
  - Resonance : \(\Upsilon(3D)\), exotics,..
  - Non-resonant effect : complicated rescattering,..

**Fitting results**

| \(\Upsilon(10860)\) | \(\Upsilon(11020)\) | New structure |
|----------------------|----------------------|---------------|
| \(M\) (MeV/c\(^2\)) | 10885.3 \(\pm\) 1.5 \(\pm\) 2.2 \(\pm\) 2.9 | 11000.0 \(\pm\) 1.0 \(\pm\) 1.0 \(\pm\) 1.0 | 10752.7 \(\pm\) 5.9 \(\pm\) 7.7 |
| \(\Gamma\) (MeV)    | 36.6 \(\pm\) 1.5 \(\pm\) 0.5 \(\pm\) 0.9 \(\pm\) 1.1 | 23.8 \(\pm\) 1.3 \(\pm\) 0.8 \(\pm\) 1.3 \(\pm\) 1.5 | 35.5 \(\pm\) 17.6 \(\pm\) 3.3 |

| \(\Gamma_{ee} \times B\) (in eV) |
|----------------------|----------------------|----------------------|
| \(\Upsilon(1S)\pi^+ \pi^-\) | 0.75 – 1.43 | 0.38 – 0.54 \(\pm\) 0.12 – 0.47 |
| \(\Upsilon(2S)\pi^+ \pi^-\) | 1.35 – 3.80 | 0.13 – 1.16 | 0.53 – 1.22 |
| \(\Upsilon(3S)\pi^+ \pi^-\) | 0.43 – 1.03 | 0.17 – 0.49 | 0.21 – 0.26 |
\[ e^+ e^- \rightarrow \Upsilon(nS) \pi^+ \pi^- \]

(arXiv: 1905.05521 (preliminary results, to be submitted to JHEP))

**Continuum below \( \Upsilon(4S) \)**

- \( E_{c.m.} = 10.52 \) GeV.
- Required \( M(\pi^+ \pi^-) > 0.85 \) GeV.
- A clear signal for the \( \Upsilon(1S) \pi^+ \pi^- \) process is evident.
- \( \sigma[e^+ e^- \rightarrow \Upsilon(1S) \pi^+ \pi^-] = 42^{+17}_{-15} \) fb.
- Significance including syst.: > 3.5\( \sigma \).

\( \rightarrow \) Evidence for \( e^+ e^- \rightarrow \Upsilon(1S) \pi^+ \pi^- \) in continuum at \( E_{c.m.} = 10.52 \) GeV!
Summary

- $B \rightarrow Y(4260)K$
  - Upper limit on $\mathcal{B}(B^+ \rightarrow Y(4260)K^+) \times \mathcal{B}(Y(4260) \rightarrow J/\psi\pi^+\pi^-)$ is consistent with BaBar but more stringent.
  - Upper limit on $\mathcal{B}(B^0 \rightarrow Y(4260)K^0) \times \mathcal{B}(Y(4260) \rightarrow J/\psi\pi^+\pi^-)$ is given for the first time.

- $B \rightarrow h_cK$
  - Evidence of the decay $B^+ \rightarrow h_cK^+$ is found, and $\mathcal{B}(B^+ \rightarrow h_cK^+)$ is consistent with the existing limit and theoretical predictions.
  - Upper limit is set on $\mathcal{B}(B^0 \rightarrow h_cK^0_S)$ for the first time.
  - First observation of $\eta_c(2S) \rightarrow pp\pi^+\pi^-$ decay with 12.1σ significance.

- $X(3872), X(3915) \rightarrow \chi_{c1}\pi^0$
  - Upper limits are set on the product branching fractions $\mathcal{B}(B^+ \rightarrow X(3872)K^+) \times \mathcal{B}(X(3872) \rightarrow \chi_{c1}\pi^0)$ and $\mathcal{B}(B^+ \rightarrow X(3915)K^+) \times \mathcal{B}(X(3915) \rightarrow \chi_{c1}\pi^0)$. Compatible with the interpretation of $X(3872)$ as an admixture of $D^0 D^{*0}$ molecule and $\chi_{c1}(2P)$ charmonium state.
  - Branching ratio $\frac{\mathcal{B}(X(3872) \rightarrow \chi_{c1}\pi^0)}{\mathcal{B}(X(3872) \rightarrow J/\psi\pi^+\pi^-)} < 0.97$ (90% C.L.). No contradiction with BESIII result.
Summary (continued)

- $B^0 \rightarrow X(3872)\gamma$
  - Upper limit is set on $\mathcal{B}(B^0 \rightarrow X(3872)\gamma) \times \mathcal{B}(X(3872) \rightarrow J/\psi\pi^+\pi^-)$ for the first time.

- $e^+e^- \rightarrow \gamma\chi_{cJ}$
  - Significant $e^+e^- \rightarrow \gamma\chi_{c1}$ signal is first observed at $\sqrt{s} = 10.58$ GeV.
  - Upper limits are set for other remaining modes.
  - The energy dependency of $\sigma_B(e^+e^- \rightarrow \gamma\chi_{c1})$ is obtained.

- $e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-$
  - Observation of new structure $M = 10752.7 \pm 5.9^{+0.7}_{-0.4}$ MeV, $\Gamma = 35.5^{+17.6}_{-11.3} \pm 3.4$ MeV (6.7$\sigma$).
  - Evidence for $e^+e^- \rightarrow \Upsilon(1S)\pi^+\pi^-$ in continuum at $E_{c.m.} = 10.52$ GeV below the $B\bar{B}$ threshold.
**B → Y(4260)K**

The sample of inclusive $B$ decays with a $J/\psi(\ell^+ \ell^-)$ in the final state is studied; the sample corresponds to an integrated luminosity of 19.3 fb$^{-1}$. The branching fractions of the $B \to Y(4260)K$, $Y(4260) \to J/\psi \pi^+ \pi^-$ decays are obtained as $B = \frac{N_S}{\frac{1}{2} N_B \bar{N}_B \times \epsilon \times f_K \times B(Y(4260) \to J/\psi \pi^+ \pi^-) \times B(J/\psi \to \ell^+ \ell^-) K_0}$, where $N_S$ is the number of signal events, $N_B$ is the number of background events, $\epsilon$ is the reconstruction efficiency, $f_K$ is the $K$ polarization fraction, and $B(Y(4260) \to J/\psi \pi^+ \pi^-)$ and $B(J/\psi \to \ell^+ \ell^-)$ are the branching fractions for the $Y(4260)$ decay and the $J/\psi$ decay, respectively.

**FIG. 2.** Fit to the $\Delta E$ [(a) and (b)] and $M_{Y(4260)}$ [(c) and (d)] distributions for $B^+ \to \psi(2S) \to J/\psi \pi^+ \pi^- \to Y(4260) K$ decays (top) and $B^0 \to \psi(2S) \to J/\psi \pi^+ \pi^- \to Y(4260) K^0_S$ decays (bottom), respectively. Fit follows the same convention as Fig. 1.
Resolution

The resolution is parameterized by the function

\[
S(\Delta E, M_{bc}) = N_{CB} F_{CB}(x_1) G_a^{(12)}(y_1) + N_{G1} G_a^{(21)}(x_2) G_a^{(22)}(y_2) + N_{G2} G_a^{(31)}(x_3) G_a^{(32)}(y_3),
\]

(1)

where \( F_{CB} \) is an asymmetric Crystal Ball function, \( G_a^{(ij)} \) are asymmetric Gaussian functions, \( N_{CB}, N_{G1} \) and \( N_{G2} \) are normalizations and \( x_i \) and \( y_i \) (\( i = 1, 2, 3 \)) are rotated variables that are given by

\[
\begin{pmatrix}
    x_i \\
    y_i
\end{pmatrix} =
\begin{pmatrix}
    \cos \alpha_i & \sin \alpha_i \\
    -\sin \alpha_i & \cos \alpha_i
\end{pmatrix}
\begin{pmatrix}
    \Delta E - (\Delta E)_0 \\
    M_{bc} - (M_{bc})_0
\end{pmatrix}.
\]

(2)

Here, \((\Delta E)_0, (M_{bc})_0\) is the central point and \(\alpha_i\) are the rotation angles. Resolution for \(B^+ \to h_c K^+\) with \(\eta_c \to K^+ K^- \pi^0\):
Fit to the $(\Delta E, M_{bc})$ distribution

The $(\Delta E, M_{bc})$ distribution is fitted in order to estimate the expected number of the background events in the signal region. The distribution is fitted to the function

$$N_S S(\Delta E, M_{bc}) + B(\Delta E, M_{bc}),$$

where $N_S$ is the number of signal events and $B$ is the background density function that is given by

$$B(\Delta E, M_{bc}) = \sqrt{m_0 - M_{bc}} \exp[-a(m_0 - M_{bc})]P_3(\Delta E, M_{bc}),$$

where $m_0$ is the threshold mass, $a$ is a rate parameter and $P_3$ is a two-dimensional third-order polynomial. The region with $\Delta E < -0.12$ GeV is excluded for the channel $h_c \rightarrow p\bar{p}\pi^+\pi^-$ because of peaking backgrounds from partially reconstructed $B$ decays with an additional $\pi$ meson. Background for $B^+ \rightarrow h_c K^+$ with $\eta_c \rightarrow K^+ K^- \pi^0$ (with $M_{bc} > 5.272$ GeV/$c^2$ for the projection onto $\Delta E$ and $|\Delta E| < 20$ MeV for the projection onto $M_{bc}$):
A multivariate analysis is performed for each channel using the MLP from TMVA. Variables:

- All channels: thrust angles $B$ daughters - remaining particles in the event and all tracks - all photons, ratio of the Fox-Wolfram moments $F_2/F_0$, the $B$ production angle, vertex-fit quality.
- $h_c \rightarrow \eta_c \gamma$: the $h_c$ helicity angle, the $\eta_c$ mass, the numbers of $\pi^0$ candidates that have the $h_c$ daughter photon as one of their daughters.
- $\eta_c \rightarrow K^+K^0\pi^-$, $\eta_c \rightarrow K^+K^-\pi^0$ and $\eta_c \rightarrow K^0K^0\pi^0$: invariant masses of both $(K, \pi)$ combinations.
- Channels with the corresponding particles in the final state: $K$ and $p$ particle-identification likelihoods.
- Channels with a $\pi^0$ or $\eta$: the $\pi^0$ ($\eta$) mass, the minimal energy of its daughter photons in the laboratory frame, the numbers of $\pi^0$ candidates that have the $\pi^0$ ($\eta$) daughter photon as one of their daughters.
- Channels with $\eta \rightarrow \pi^+\pi^-\pi^0$ or $\eta' \rightarrow \eta\pi^+\pi^-$: the $\eta$ ($\eta'$) mass.
Optimization of the selection requirements

An elliptical channel-dependent signal region is selected: $$(\frac{\Delta E}{R_{\Delta E}^{(i)}})^2 + (\frac{M_{bc}}{R_{M_{bc}}^{(i)}})^2 < 1$$. The following variables are optimized for each decay channel: half-axes $R_{\Delta E}^{(i)}$, $R_{M_{bc}}^{(i)}$, and cutoff for MLP output ($v_0$). The value being maximized is $F_{\text{opt}} = (\sum_i N_{\text{sig}}^{(i)}) / (a/2 + \sqrt{\sum_i N_{\text{bg}}^{(i)}})$, where $a = 3$ is the target significance. The optimization is performed separately for all $\eta_c \gamma$ channels and $p\bar{p}\pi^+\pi^-$. Results ($B^+ \rightarrow h_c K^+$):

| Channel | Parameters | Efficiency |
|---------|------------|------------|
| $\eta_c(\rightarrow K^+K_0^0\pi^-)\gamma$ | $R_{\Delta E}^{(i)}$ | $R_{M_{bc}}^{(i)}$ | $v_0^{(i)}$ | $\epsilon_{\text{SR}}^{(i)}$ | $\epsilon_S^{(i)}(v_0^{(i)})$ | $\epsilon_B^{(i)}(v_0^{(i)})$ |
| $\eta_c(\rightarrow K^+K^-\pi^0)\gamma$ | 32.7 | 4.82 | 0.804 | 6.27% | 59.5% | 5.08% |
| $\eta_c(\rightarrow K^+K^0_0\pi^-)\gamma$ | 36.2 | 3.90 | 0.958 | 4.27% | 31.7% | 0.56% |
| $\eta_c(\rightarrow K^+K^0_0\pi^-)\gamma$ | 42.3 | 4.49 | 0.976 | 1.79% | 17.8% | 0.18% |
| $\eta_c(\rightarrow K^+K^0_0\pi^+)\gamma$ | 34.4 | 4.16 | 0.977 | 4.21% | 20.2% | 0.22% |
| $\eta_c(\rightarrow K^+K^-\eta_{2\gamma})\gamma$ | 24.9 | 3.59 | 0.978 | 1.75% | 29.7% | 0.23% |
| $\eta_c(\rightarrow K^+K^-\eta_{3\pi})\gamma$ | 25.3 | 4.13 | 0.770 | 4.89% | 53.2% | 6.69% |
| $\eta_c(\rightarrow K^+K^-K^+K^-)\gamma$ | 30.5 | 4.21 | 0.958 | 2.69% | 40.5% | 0.63% |
| $\eta_c(\rightarrow \eta'\rightarrow \eta_{2\gamma}\pi^+\pi^-)\pi^+\pi^-\gamma$ | 26.8 | 4.16 | 0.990 | 1.01% | 29.2% | 0.13% |
| $\eta_c(\rightarrow \eta'\rightarrow \eta_{3\pi}\pi^+\pi^-)\pi^+\pi^-\gamma$ | 38.9 | 5.48 | 0.654 | 17.70% | 75.7% | 10.66% |
| $\eta_c(\rightarrow p\bar{p}\pi^-)\gamma$ | 30.2 | 3.75 | 0.954 | 4.65% | 30.3% | 0.50% |
| $\eta_c(\rightarrow p\bar{p}\pi^+\pi^-)\gamma$ | 24.1 | 4.03 | 0.912 | 6.31% | 30.0% | 1.53% |
| $\eta_c(\rightarrow \Lambda\Lambda)\gamma$ | 40.4 | 5.66 | 0.727 | 4.04% | 70.6% | 6.79% |
| $p\bar{p}\pi^+\pi^-\gamma$ | 13.5 | 4.36 | 0.598 | 14.81% | 64.6% | 18.40% |

Efficiencies: $\epsilon_{\text{SR}}^{(i)}$ - reconstruction an signal region selection; $\epsilon_S^{(i)}(v_0^{(i)})$, $\epsilon_B^{(i)}(v_0^{(i)})$ - MLP for signal and background, respectively.
\[ B \rightarrow h_c K \]

**Data fitting procedure**

We perform a simultaneous extended unbinned likelihood fit to the \( h_c \rightarrow \eta_c \gamma \) signal, \( h_c \rightarrow p\bar{p}\pi^+\pi^- \) background and \( h_c \rightarrow p\bar{p}\pi^+\pi^- \) signal distributions. The signal PDF for the channel \( h_c \rightarrow \eta_c \gamma \) is given by

\[
S_{\eta_c \gamma}(M) = (N_{h_c} |A_{h_c}(M)|^2) \otimes R_{h_c}^{(\eta_c \gamma)}(\Delta M) + P_2(M),
\]

(5)

where \( N_{h_c} \) is the number of signal events, \( R_{h_c}^{(\eta_c \gamma)} \) is the \( h_c \) mass resolution, and \( P_2 \) is a second-order polynomial. The background PDF \( B_{p\bar{p}\pi^+\pi^-}(M) \) for the channel \( h_c \rightarrow p\bar{p}\pi^+\pi^- \) is a third-order polynomial. The signal PDF for the channel \( h_c \rightarrow p\bar{p}\pi^+\pi^- \) is given by

\[
S_{p\bar{p}\pi^+\pi^-}(M) = \left( |P_3(M) + \sum_{R=\eta_c,\chi_{c0},\eta_c(2S)} \sqrt{N_R} e^{i\varphi_R} A_R(M)|^2 \right) \otimes R_{h_c}(\Delta M),
\]

(6)

where \( P_3 \) is a third-order polynomial representing the noncharmonium signal. The wide states are added coherently to the signal PDF, while the states that are narrower than the resolution are added incoherently. The amplitudes are normalized in such a way that all the parameters \( N \) represent the yields of the corresponding states. The signal distribution is fitted to the function \( S_{p\bar{p}\pi^+\pi^-}(M) + wB_{p\bar{p}\pi^+\pi^-}(M) \), where \( w \) is the weight of the background events in the signal region that is calculated as the ratio of integrals of the background distribution in \((\Delta E, M_{bc})\) over the signal and background regions.
## B → h_c K

### Table IV. Model dependence of the $h_c$ and $\eta_c(2S) \rightarrow p\bar{p}\pi^+\pi^-$ significance.

| Model                                                                 | $h_c$ significance | $\eta_c(2S) \rightarrow p\bar{p}\pi^+\pi^-$ significance |
|-----------------------------------------------------------------------|--------------------|-----------------------------------------------------------|
| Default                                                               | $5.0\sigma$        | $12.3\sigma$                                              |
| Free masses and widths                                                | $5.0\sigma$        | $12.3\sigma$                                              |
| Polynomial order ($h_c \rightarrow \eta_c\gamma$)                    | $4.8\sigma$        | $12.3\sigma$                                              |
| Polynomial order ($h_c \rightarrow p\bar{p}\pi^+\pi^-$ background)  | $5.0\sigma$        | $12.3\sigma$                                              |
| Polynomial order ($h_c \rightarrow p\bar{p}\pi^+\pi^-$ signal)      | $5.0\sigma$        | $12.3\sigma$                                              |
| Fitting range variation ($h_c \rightarrow \eta_c\gamma$)             | $5.0\sigma$        | $12.3\sigma$                                              |
| Fitting range variation ($h_c \rightarrow p\bar{p}\pi^+\pi^-$)       | $5.0\sigma$        | $12.3\sigma$                                              |
| Scaled resolution                                                     | $5.0\sigma$        | $12.3\sigma$                                              |
| Fraction of $h_c \rightarrow \eta_c\gamma$ and $h_c \rightarrow p\bar{p}\pi^+\pi^-$ | $4.9\sigma$        | $12.3\sigma$                                              |

### Table VI. Relative systematic uncertainties of the branching fraction products.

| Channel                                                                 | Relative uncertainty (%) |
|------------------------------------------------------------------------|--------------------------|
| $B \rightarrow \psi(2S) K^+$                                           | $1.6 \pm 0.5$             |
| $B \rightarrow \eta_c(2S) K^+$                                         | $1.6 \pm 0.5$             |
| $B \rightarrow \chi_{c1}(1P) K^+$                                      | $1.6 \pm 0.5$             |
| $B \rightarrow \chi_{c1}(2S) K^+$                                      | $1.6 \pm 0.5$             |

### Branching fraction

| Branching fraction | Value or confidence interval (90 % C. L.) | World-average value |
|--------------------|------------------------------------------|---------------------|
| $B(B^+ \rightarrow h_c K^+)$                                      | $(3.7^{+1.0+1.2}_{-0.9-0.8}) \times 10^{-5}$ | $< 3.8 \times 10^{-5}$ |
| $B(B^+ \rightarrow \eta_c K^+ \times B(\eta_c \rightarrow p\bar{p}\pi^+\pi^-)$ | $(39.4^{+1.1+2.2}_{-3.9-1.8}) \times 10^{-7}$ | $(57.8 \pm 20.2) \times 10^{-7}$ |
| $B(B^+ \rightarrow J/\psi K^+ \times B(J/\psi \rightarrow p\bar{p}\pi^+\pi^-)$ | $(56.4^{+3.3+2.7}_{-3.2-2.5}) \times 10^{-7}$ | $(60.6 \pm 5.3) \times 10^{-7}$ |
| $B(B^+ \rightarrow \chi_{c0} K^+ \times B(\chi_{c0} \rightarrow p\bar{p}\pi^+\pi^-)$ | $(3.7^{+1.2+0.2}_{-1.0-0.3}) \times 10^{-7}$ | $(3.1 \pm 1.1) \times 10^{-7}$ |
| $B(B^+ \rightarrow \chi_{c1} K^+ \times B(\chi_{c1} \rightarrow p\bar{p}\pi^+\pi^-)$ | $(4.7^{+1.3+0.4}_{-1.0-0.3}) \times 10^{-7}$ | $(2.4 \pm 0.9) \times 10^{-7}$ |
| $B(B^+ \rightarrow \chi_{c2} K^+ \times B(\chi_{c2} \rightarrow p\bar{p}\pi^+\pi^-)$ | $< 1.9 \times 10^{-7}$ | $(0.15 \pm 0.06) \times 10^{-7}$ |
| $B(B^+ \rightarrow \eta_c(2S) K^+ \times B(\eta_c(2S) \rightarrow p\bar{p}\pi^+\pi^-)$ | $(11.2^{+1.8+0.5}_{-1.6-0.7}) \times 10^{-7}$ | not seen |
| $B(B^+ \rightarrow \psi(2S) K^+ \times B(\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-)$ | $[0.5, 3.5] \times 10^{-7}$ | $(3.7 \pm 0.3) \times 10^{-7}$ |
| $B(B^0 \rightarrow h_c K^0_S)$                                      | $< 1.4 \times 10^{-5}$ | not seen |
| $B(B^0 \rightarrow \eta_c K^0_S \times B(\eta_c \rightarrow p\bar{p}\pi^+\pi^-)$ | $(19.0^{+3.2+1.3}_{-2.9-4.7}) \times 10^{-7}$ | $(20.9 \pm 7.8) \times 10^{-7}$ |
| $B(B^0 \rightarrow J/\psi K^0_S \times B(J/\psi \rightarrow p\bar{p}\pi^+\pi^-)$ | $(24.3^{+2.3+1.2}_{-2.2-1.3}) \times 10^{-7}$ | $(26.2 \pm 2.4) \times 10^{-7}$ |
| $B(B^0 \rightarrow \chi_{c0} K^0_S \times B(\chi_{c0} \rightarrow p\bar{p}\pi^+\pi^-)$ | $< 1.3 \times 10^{-7}$ | $(1.5 \pm 0.6) \times 10^{-7}$ |
| $B(B^0 \rightarrow \chi_{c1} K^0_S \times B(\chi_{c1} \rightarrow p\bar{p}\pi^+\pi^-)$ | $(3.7^{+1.2+0.3}_{-1.0-0.2}) \times 10^{-7}$ | $(1.0 \pm 0.4) \times 10^{-7}$ |
| $B(B^0 \rightarrow \chi_{c2} K^0_S \times B(\chi_{c2} \rightarrow p\bar{p}\pi^+\pi^-)$ | $[0.7, 3.8] \times 10^{-7}$ | not seen |
| $B(B^0 \rightarrow \eta_c(2S) K^0_S \times B(\eta_c(2S) \rightarrow p\bar{p}\pi^+\pi^-)$ | $(4.2^{+1.4+0.3}_{-1.2-0.3}) \times 10^{-7}$ | not seen |
| $B(B^0 \rightarrow \psi(2S) K^0_S \times B(\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-)$ | $< 1.9 \times 10^{-7}$ | $(1.7 \pm 0.2) \times 10^{-7}$ |
TABLE VI. Relative systematic uncertainties of the branching fractions for the channel $B^0 \rightarrow (c\bar{c})K^+_S$ for the $h_c$ and $B^0 \rightarrow (c\bar{c})(\rightarrow p\bar{p}\pi^+\pi^-)K^+_S$ for all other charmonium states.

| Error source | $h_c$ | $\eta_c$ | $J/\psi$ | $\chi_{c0}$ | $\chi_{c1}$ | $\chi_{c2}$ | $\eta_c(2S)$ | $\psi(2S)$ |
|--------------|-------|----------|----------|-------------|-------------|-------------|--------------|-----------|
| Model dependence | $(+9.99\%)$ | $(+1.14\%)$ | $(+1.96\%)$ | $(+5.59\%)$ | $(+7.10\%)$ | $(+21.13\%)$ | $(+1.75\%)$ | $(+1.74\%)$ |
| PID           | $3.99\%$     | $3.64\%$     | $3.62\%$     | $3.50\%$     | $3.50\%$     | $3.51\%$     | $3.52\%$     | $3.53\%$     |
| Overtraining  | $0.41\%$     |             | $0.14\%$     |             |             |             |             |             |
| Tracking      | $1.60\%$     |             | $1.75\%$     |             |             |             |             |             |
| MLP efficiency| $12.73\%$    |             | $0.25\%$     |             |             |             |             |             |
| Number of $\pi^0$ candidates | $11.60\%$ |             |             |             |             |             |             |             |
| $\eta_c$ mass and width | $0.99\%$ |             |             |             |             |             |             |             |
| $h_c$ branching fraction | $10.22\%$ |             |             |             |             |             |             |             |
| $B(\Upsilon(4S) \rightarrow B^+B^-)$ | $1.17\%$ |             |             |             |             |             |             |             |
| Number of $\Upsilon(4S)$ events | $1.37\%$ |             |             |             |             |             |             |             |
| Total         | $(+22.51\%)$ | $(+1.46\%)$ | $(+24.37\%)$ | $(+1.96\%)$ | $(+1.80\%)$ | $(+25.51\%)$ | $(+4.81\%)$ | $(+6.17\%)$ |

TABLE VI. Relative systematic uncertainties of the branching fractions for the channel $B^0 \rightarrow (c\bar{c})K^+_S$ for the $h_c$ and $B^0 \rightarrow (c\bar{c})(\rightarrow p\bar{p}\pi^+\pi^-)K^+_S$ for all other charmonium states.

| Error source | $h_c$ | $\eta_c$ | $J/\psi$ | $\chi_{c0}$ | $\chi_{c1}$ | $\chi_{c2}$ | $\eta_c(2S)$ | $\psi(2S)$ |
|--------------|-------|----------|----------|-------------|-------------|-------------|--------------|-----------|
| Model dependence | $(+30.94\%)$ | $(+4.91\%)$ | $(+1.45\%)$ | $(+34.01\%)$ | $(+6.79\%)$ | $(+8.63\%)$ | $(+5.11\%)$ | $(+10.89\%)$ |
| PID           | $4.86\%$     | $3.93\%$     | $3.93\%$     | $3.87\%$     | $3.87\%$     | $3.86\%$     | $3.83\%$     | $3.81\%$     |
| Overtraining  | $0.15\%$     |             |             | $0.19\%$     |             |             |             |             |
| Tracking      | $1.95\%$     |             |             | $2.10\%$     |             |             |             |             |
| MLP efficiency| $12.79\%$    |             |             | $0.25\%$     |             |             |             |             |
| Number of $\pi^0$ candidates | $11.66\%$ |             |             |             |             |             |             |             |
| $\eta_c$ mass and width | $0.96\%$ |             |             |             |             |             |             |             |
| $h_c$ branching fraction | $10.27\%$ |             |             |             |             |             |             |             |
| $B(\Upsilon(4S) \rightarrow B^0B^0)$ | $1.23\%$ |             |             |             |             |             |             |             |
| Number of $\Upsilon(4S)$ events | $1.37\%$ |             |             |             |             |             |             |             |
| Total         | $(+37.33\%)$ | $(+6.89\%)$ | $(+5.04\%)$ | $(+34.10\%)$ | $(+5.30\%)$ | $(+9.87\%)$ | $(+6.56\%)$ | $(+11.88\%)$ |
$X(3872), X(3915) \rightarrow \chi_{c1}\pi^0$

### Signal branching fraction uncertainties

| Source                  | $\mathcal{B}$ (%) | $R_{\chi_{c1}/\psi} \times 10^4$ (%) |
|-------------------------|-------------------|--------------------------------------|
|                         | $X(3915)$ | $X(3872)$ |                           |
| Lepton identification   | 2.3      | 2.2       | -                       |
| Kaon identification     | 1.0      | 1.0       | -                       |
| Efficiency              | 0.5      | 0.5       | 2.2                     |
| $B\bar{B}$ pairs       | 1.4      | 1.4       | -                       |
| Tracking                | 1.1      | 1.1       | 0.7                     |
| $\gamma$ identification | 2.0      | 2.0       | 2.0                     |
| $\pi^0$ veto            | 1.2      | 1.2       | 1.2                     |
| $\pi^0$ reconstruction  | 2.2      | 2.2       | 2.2                     |
| Signal extraction       | $+16.1$  | $+37.0$   | $+37.1$                 |
|                         | $-19.5$  | $-44.4$   | $-44.5$                 |
| Secondary $\mathcal{B}$ | 3.0      | 3.0       | 2.9                     |
| Total                   | $+17.0$  | $+37.4$   | $+37.4$                 |
|                         | $-20.2$  | $-44.7$   | $-44.8$                 |
$B^0 \rightarrow X(3872) \gamma$

**Signal branching fraction uncertainties**

| Source                           | Dimuon | Dielectron |
|---------------------------------|--------|------------|
| $N_{B\bar{B}}$                  | 1.4%   | 1.4%       |
| Tracking (4 tracks)             | 1.4%   | 1.4%       |
| $\mathcal{B}(J/\psi \rightarrow \ell^+\ell^-)$ | 0.6%   | 0.5%       |
| $\gamma$ detection             | 3.1%   | 3.1%       |
| MC gen. model                   | 1.1%   | 1.9%       |
| $\pi^\pm$ identification       | 1.3%   | 1.3%       |
| $\ell^\pm$ identification      | 2.1%   | 1.8%       |
| Bkg. suppression                | 2.3%   | 2.5%       |
| $\pi^0$ veto                    | 0.8%   | 0.8%       |
| Signal region fraction          | 3.5%   | 3.5%       |
| **Total**                       | 6.2%   | 6.4%       |

**Background uncertainties**

- Dimuon channel: 10.9%
- Dielectron channel: 17.3%
$e^+ e^- \rightarrow \gamma \chi_{cJ}$

## Uncertainties on the cross-section measurements

| Final state | $\gamma\chi_{c0}/\chi_{c1}/\chi_{c2}$ | $\gamma\eta_c$ |
|-------------|---------------------------------|----------------|
| C.M. energy (GeV) | 10.52 | 10.58 | 10.867 | 10.52 | 10.58 | 10.867 |
| Detection efficiency | 6.0 | 6.0 | 6.0 | 2.8 | 2.9 | 3.0 |
| MC sample size | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Trigger | 4.8 | 4.8 | 4.8 | 0.6 | 0.6 | 0.6 |
| Branching fractions | 4.8/3.7/3.8 | 4.8/3.7/3.8 | 4.8/3.7/3.8 | 7.5 | 7.6 | 7.7 |
| Resonance parameters | 1.7/0.3/0.7 | 2.0/0.2/0.1 | 0.9/0.4/2.1 | 0.6 | 1.7 | 2.0 |
| $\theta_f$ distribution | $\sim / \sim / 8.2$ | $\sim / \sim / 8.2$ | $\sim / \sim / 8.2$ | $\sim / \sim / 8.2$ | $\sim / \sim / 8.2$ | $\sim / \sim / 8.2$ |
| Fit uncertainty | 5.3/1.9/4.5 | 9.1/5.0/17.1 | 1.4/10.3/7.7 | 7.7 | 9.8 | 2.6 |
| Integrated luminosity | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 |
| Sum in quadrature | 10.7/8.9/12.8 | 13.1/10.0/20.9 | 9.4/13.4/14.4 | 11.3 | 13.0 | 9.1 |
Data samples

Scan data: 22 points ×1 fb⁻¹
Γ(5S) on-resonance data: 121 fb⁻¹ in 5 points, \( E_{\text{max}} - E_{\text{min}} = 3 \text{MeV} \)
Continuum data, 10.52GeV: 61 fb⁻¹

Selection requirements

PID, energy balance;
extra in \( e^+e^- \) channel: \( M_{\text{recoil}}(e^+e^-) > 350 \text{ MeV} \), \( \cos \theta_{e^-} < 0.82 \)

Background: QED production of 4 tracks
Signal shape in $M_{\text{recoil}}(\pi^+\pi^-)$

Calculation scheme

**Momentum resolution**
- includes effects of
  - FSR
  - decays-in-flight
  - secondary interactions

**ISR**
- Kuraev-Fadin radiator function
  - $\times \sigma(E_{\text{cm}})$
  - $\times \varepsilon (E_{\gamma\text{ISR}})$

**Ecm spread**
- Gaussian $\times \sigma(E_{\text{cm}})$
- $\times \varepsilon$ of energy balance requirement
  - soft cut-off at $\sim 200$ MeV

$\sigma(E_{\text{cm}})$ is being measured $\Rightarrow$ iterations

- compute signal shapes
- measure cross sections
- fit energy dependence of cross sections

Slide from R. Mizuk’s talk at QWG2019.
$e^+ e^- \rightarrow \Upsilon(nS) \pi^+ \pi^-$

Verification of signal shape

$\Upsilon(2S)$ data $24\text{ fb}^{-1}$

$\Upsilon(2S)$ is narrow $\Rightarrow$ no contributions of ISR and energy spread
Momentum resolution fudge factor $f = 1.160 \pm 0.003$
$e^+ e^- \rightarrow \Upsilon(nS) \pi^+ \pi^-$

**Fit to $M_{\text{recoil}}(\pi^+ \pi^-)$**

**Signal:**
- fix ratio of $ee/\mu\mu$ yields,
- float $\mu\mu$ yields and overall shift
  \[ \Rightarrow E_{\text{cm}} \text{ calibration} \]

**Non-peaking background:**
\[ B(x) = A (x - x_0)^P P_3(x) \]

**Peaking background:**
- e.g. $e^+ e^- \rightarrow \gamma^* \gamma^* \rightarrow \Upsilon(nS) \pi^+ \pi^- \rightarrow \mu^+ \mu^-$
- from MC, small contribution

Slide from R. Mizuk’s talk at QWG2019.
Fit to energy dependence of cross sections

Simultaneous fit to cross sections measured at different energies and $M_{\text{recoil}}(\pi^+\pi^-)$ distribution in the $\Upsilon(5S)$ on-resonance data (ISR tails).

Fit function

$$|BW_{\Upsilon(10860)}^{(n)} + e^{i\alpha_n} BW_{\Upsilon(11020)}^{(n)} + e^{i\beta_n} BW_{\text{new}}^{(n)} + e^{i\gamma_n} BW_{\Upsilon((n+1)S)}^{(n)}|^2 \otimes \text{Gaussian}$$

$$BW(s, M, \Gamma, \Gamma_{ee}^0 \times B_f) = \frac{\sqrt{12\pi \Gamma \Gamma_{ee}^0 \times B_f}}{s - M^2 + iM\Gamma} \sqrt{\frac{\Gamma_f(s)}{\Gamma_f(M^2)}}$$

$\Gamma_f(s)$ – numerical integration of Dalitz plot distribution at various energies
Data and QED background simulation. The simulation describes the shape and the normalization of the data quite well.