# New $e^+e^-$ to hadronic results from Belle

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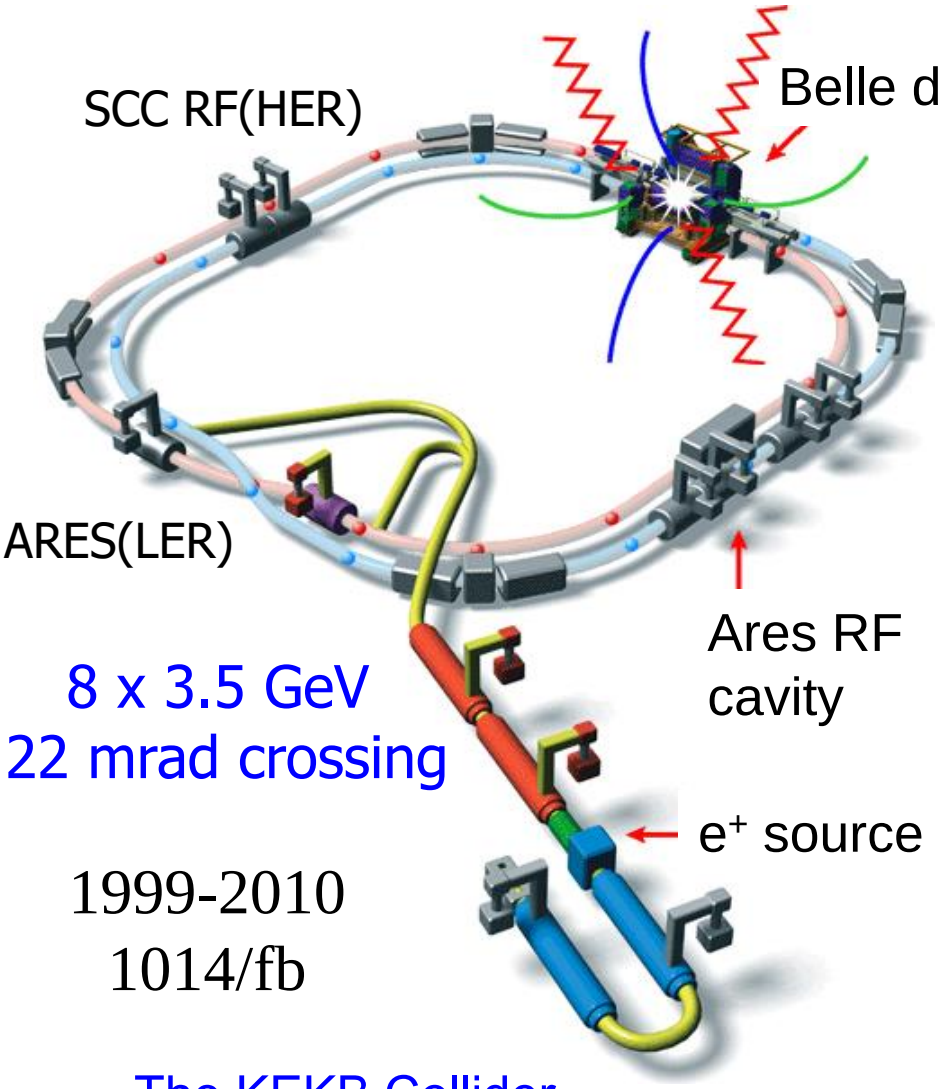
# Outline

- Introduction
- Updated $e^+e^- \to \pi^+\pi^-\psi(2S)$
- Updated $e^+e^- \to K^+K^-J/\psi$
- Measurement of $e^+e^- \to \gamma\, \chi_{cJ}$
- $e^+e^- \to \pi^+\pi^-\pi^0\, \chi_{bJ}$ at 10.867 GeV
- $e^+e^- \to b\bar{b}$
- $e^+e^- \to \pi^+\pi^- h_b(nP)$
- Summary

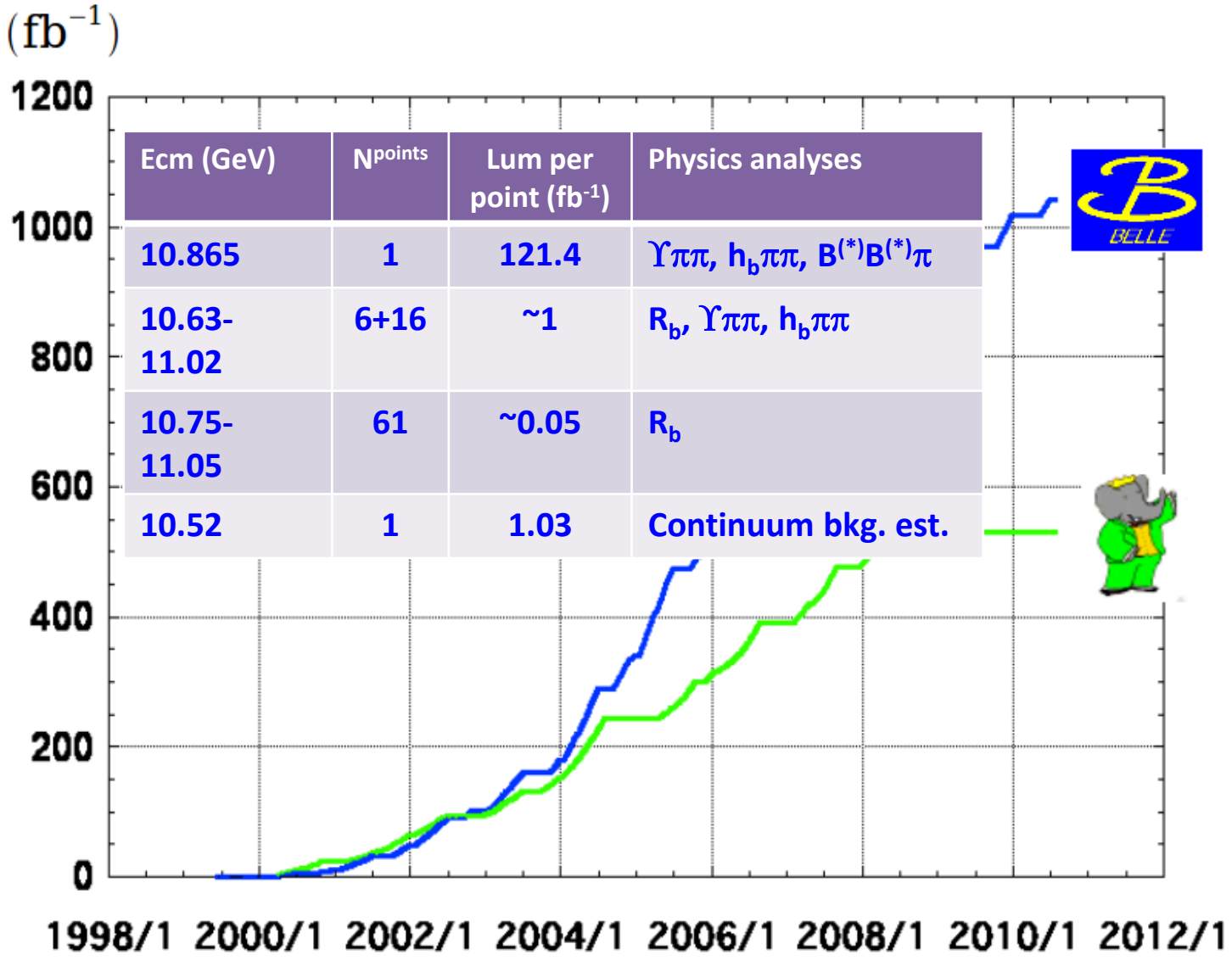
# The Belle experiment




World record:

**$L = 2.1 \times 10^{34}/cm^2/sec$**

# Integrated luminosity of B factories




| Ecm (GeV) | $N^{points}$ | Lum per point ($fb^{-1}$) | Physics analyses |
|---|---|---|---|
| 10.865 | 1 | 121.4 | $\Upsilon\pi\pi$, $h_b\pi\pi$, $B^{(*)}B^{(*)}\pi$ |
| 10.63-11.02 | 6+16 | ~1 | $R_b$, $\Upsilon\pi\pi$, $h_b\pi\pi$ |
| 10.75-11.05 | 61 | ~0.05 | $R_b$ |
| 10.52 | 1 | 1.03 | Continuum bkg. est. |

**> 1 $ab^{-1}$**

**On resonance:**

$\Upsilon(5S)$: 121 $fb^{-1}$

$\Upsilon(4S)$: 711 $fb^{-1}$

$\Upsilon(3S)$: 3 $fb^{-1}$

$\Upsilon(2S)$: 25 $fb^{-1}$

$\Upsilon(1S)$: 6 $fb^{-1}$

**Off reson./scan:**

~ 100 $fb^{-1}$

**~ 550 $fb^{-1}$**

**On resonance:**

$\Upsilon(4S)$: 433 $fb^{-1}$

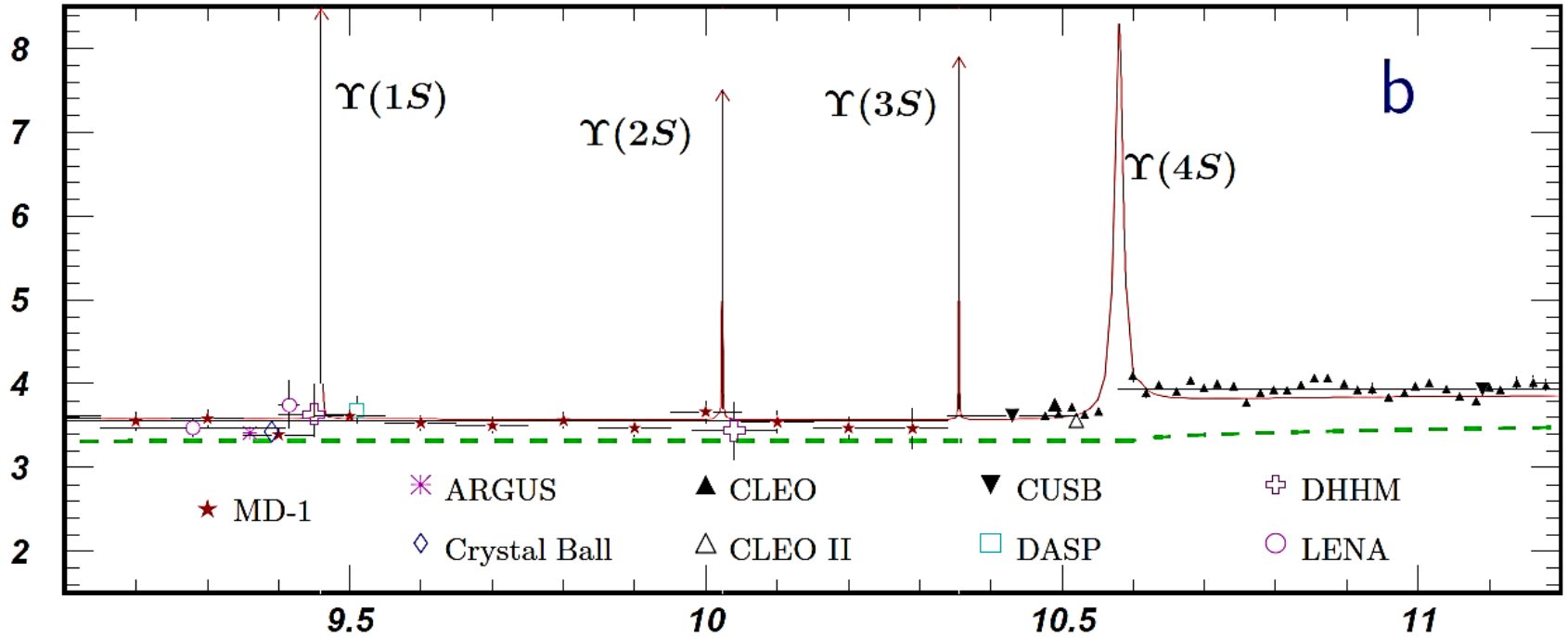
$\Upsilon(3S)$: 30 $fb^{-1}$

$\Upsilon(2S)$: 14 $fb^{-1}$

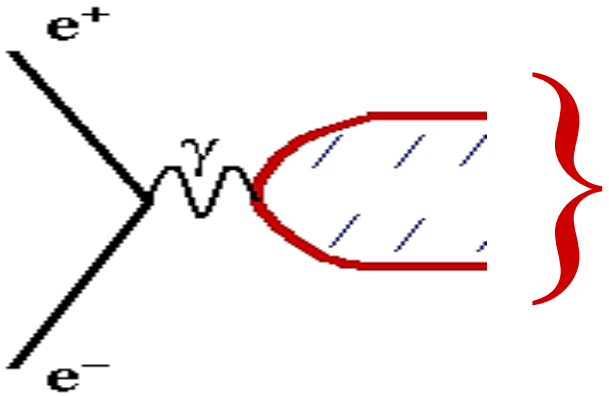
**Off resonance:**

~ 54 $fb^{-1}$

# $e^+e^-$ annihilation to vector bottomonia

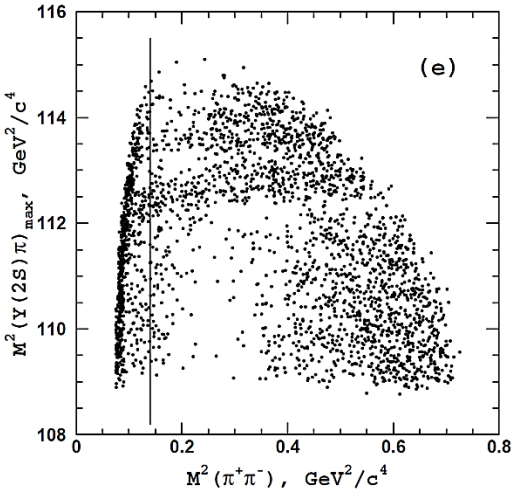



$\sqrt{s}$ [GeV]

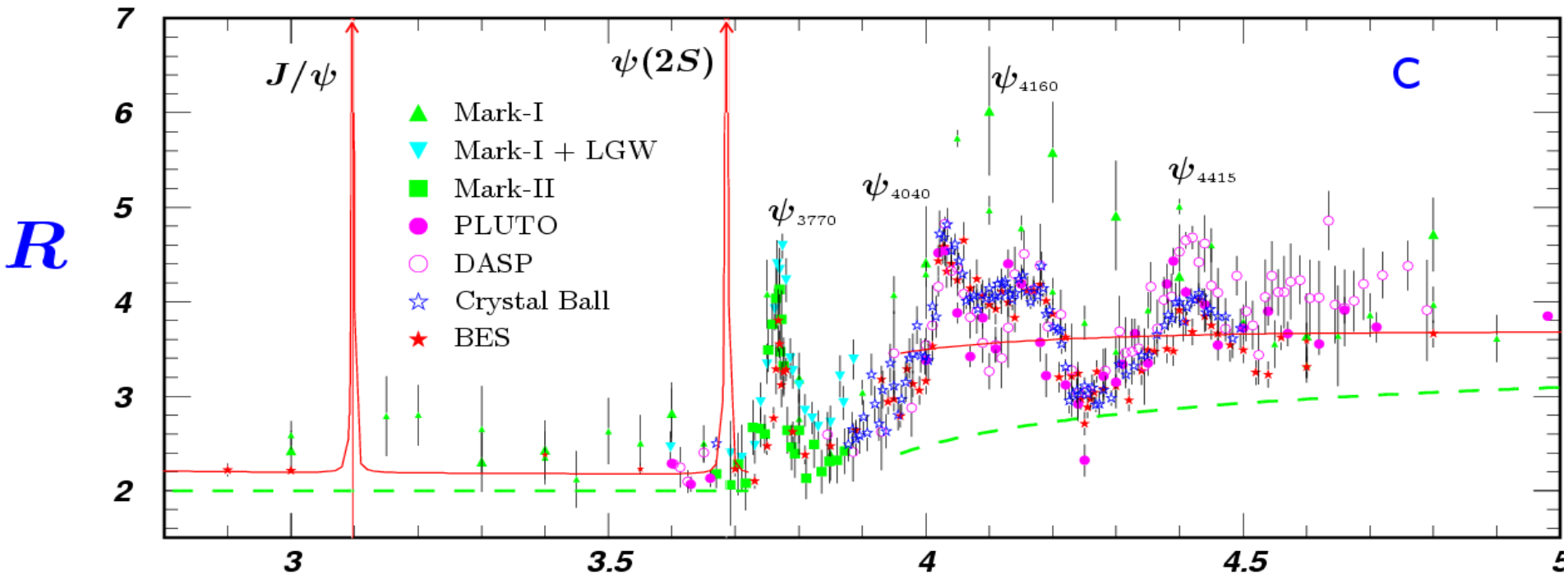


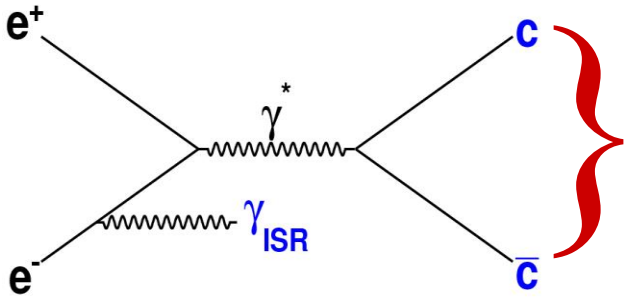

$J^{PC} = 1^{--}$

$\Upsilon(nS)$, $Y_b$…



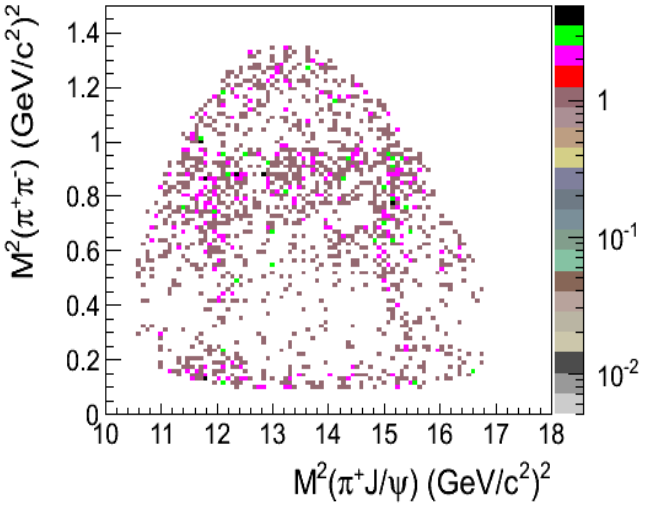
# ISR production of vector charmonia




$J^{PC} = 1^{--}$

ψ', ψ'', Υ…

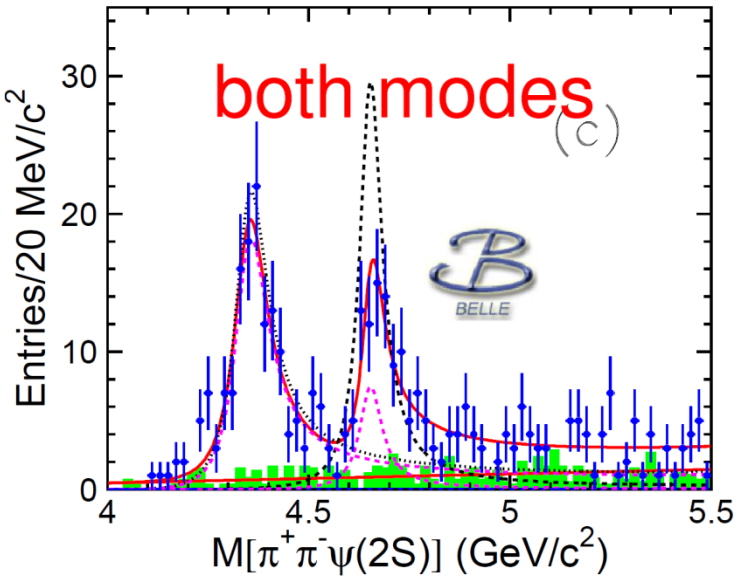


# Updated $e^+e^- \to \pi^+\pi^-\psi(2S)$

PRD 91, 112007 (2015)

Unbinned simultaneous maximum likelihood fit for $Y(4360)$ and $Y(4660)$.

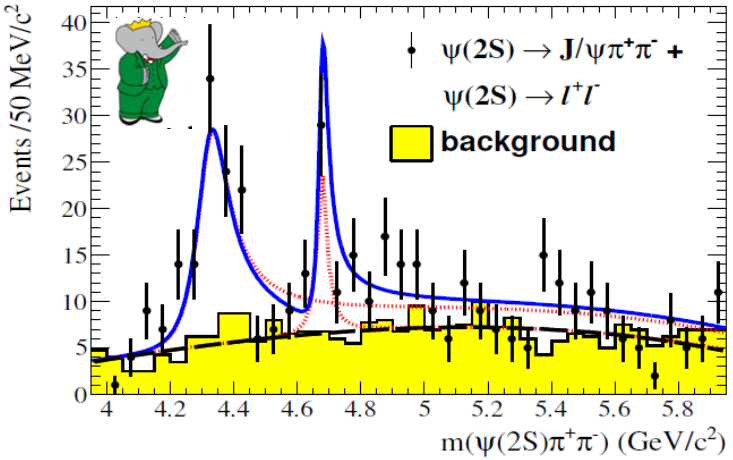
$Amp = BW_1 + e^{i\phi} \cdot BW_2$




| Parameters | Solution I | Solution II |
|---|---|---|
| $M_{Y(4360)}$ (MeV/$c^2$) | $4347 \pm 6 \pm 3$ | |
| $\Gamma_{Y(4360)}$ (MeV) | $103 \pm 9 \pm 5$ | |
| $\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4360)}$ (eV) | $9.2 \pm 0.6 \pm 0.6$ | $10.9 \pm 0.6 \pm 0.7$ |
| $M_{Y(4660)}$ (MeV/$c^2$) | $4652 \pm 10 \pm 11$ | |
| $\Gamma_{Y(4660)}$ (MeV) | $68 \pm 11 \pm 5$ | |
| $\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4660)}$ (eV) | $2.0 \pm 0.3 \pm 0.2$ | $8.1 \pm 1.1 \pm 1.0$ |
| $\phi$ (°) | $32 \pm 18 \pm 20$ | $272 \pm 8 \pm 7$ |

$\chi^2/ndf = 18.7/21$ .

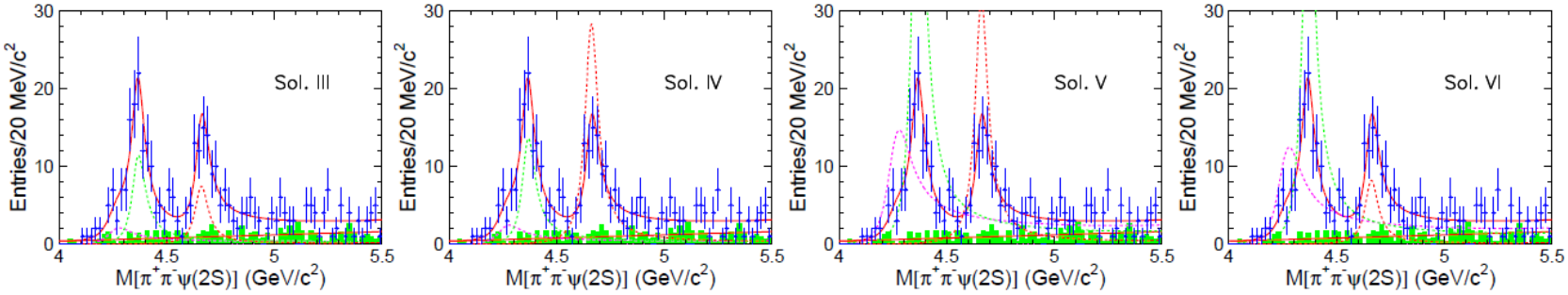
- Consistent with previous measurement
- No obvious signal above $Y(4660)$.
- Some events accumulate at $Y(4260)$, especially the $\pi^+\pi^- J/\psi$ mode.
- If $Y(4260)$ is included in the fit, ...




PRD89, 111103 (2014)

# M($\pi^+\pi^-\psi$(2S)) with Y(4260,4360,4660)

Unbinned simultaneous maximum likelihood fit for $Y(4260)$, $Y(4360)$ and $Y(4660)$. $Amp = BW_1 + e^{i\phi_1} \cdot BW_2 + e^{i\phi_2} \cdot BW_3$.




| Parameters | Solution I | Solution II | Solution III | Solution IV |
|---|---|---|---|---|
| $\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4260)}$ (eV) | $1.5 \pm 0.6 \pm 0.4$ | $1.7 \pm 0.7 \pm 0.5$ | $10.4 \pm 1.3 \pm 0.8$ | $8.9 \pm 1.2 \pm 0.8$ |
| $M_{Y(4360)}$ (MeV/$c^2$) | | $4365 \pm 7 \pm 4$ | | |
| $\Gamma_{Y(4360)}$ (MeV) | | $74 \pm 14 \pm 4$ | | |
| $\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4360)}$ (eV) | $4.1 \pm 1.0 \pm 0.6$ | $4.9 \pm 1.3 \pm 0.6$ | $21.1 \pm 3.5 \pm 1.4$ | $17.7 \pm 2.6 \pm 1.5$ |
| $M_{Y(4660)}$ (MeV/$c^2$) | | $4660 \pm 9 \pm 12$ | | |
| $\Gamma_{Y(4660)}$ (MeV) | | $74 \pm 12 \pm 4$ | | |
| $\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4660)}$ (eV) | $2.2 \pm 0.4 \pm 0.2$ | $8.4 \pm 0.9 \pm 0.9$ | $9.3 \pm 1.2 \pm 1.0$ | $2.4 \pm 0.5 \pm 0.3$ |
| $\phi_1$ (°) | $304 \pm 24 \pm 21$ | $294 \pm 25 \pm 23$ | $130 \pm 4 \pm 2$ | $141 \pm 5 \pm 4$ |
| $\phi_2$ (°) | $26 \pm 19 \pm 10$ | $238 \pm 14 \pm 21$ | $329 \pm 8 \pm 5$ | $117 \pm 23 \pm 25$ |

Significance of $Y(4260)$ is $2.4\sigma$—low, but affects $Y(4360)$ and $Y(4660)$ masses and widths.

FOUR solutions with equally good fit quality, which is $\chi^2/ndf = 14.8/19$.

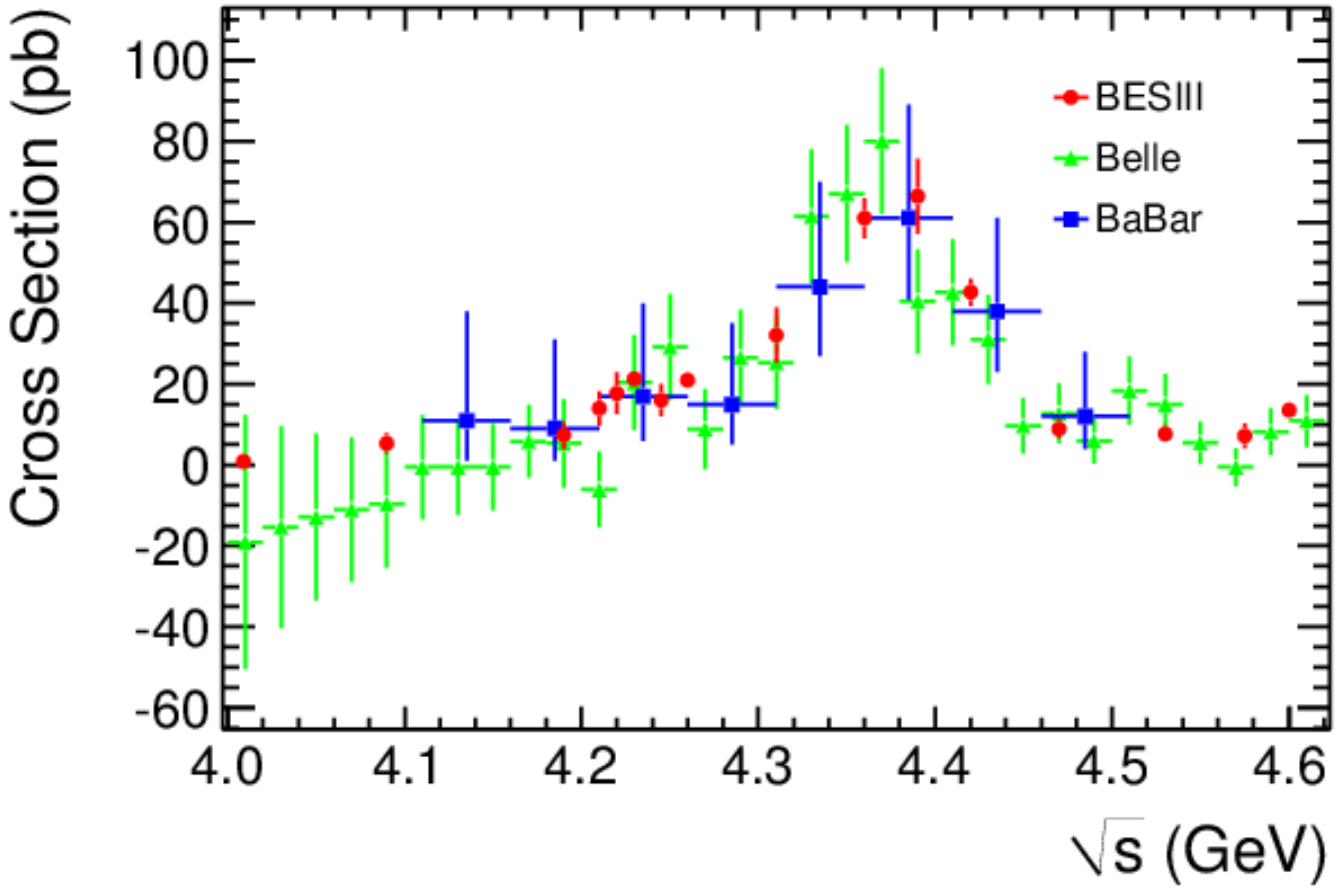
# Comparsion of $e^+e^-\rightarrow\pi^+\pi^-\psi(2S)$ cross section

**BESIII (16 energy points; $L_{tot}$=5.1fb$^{-1}$)**

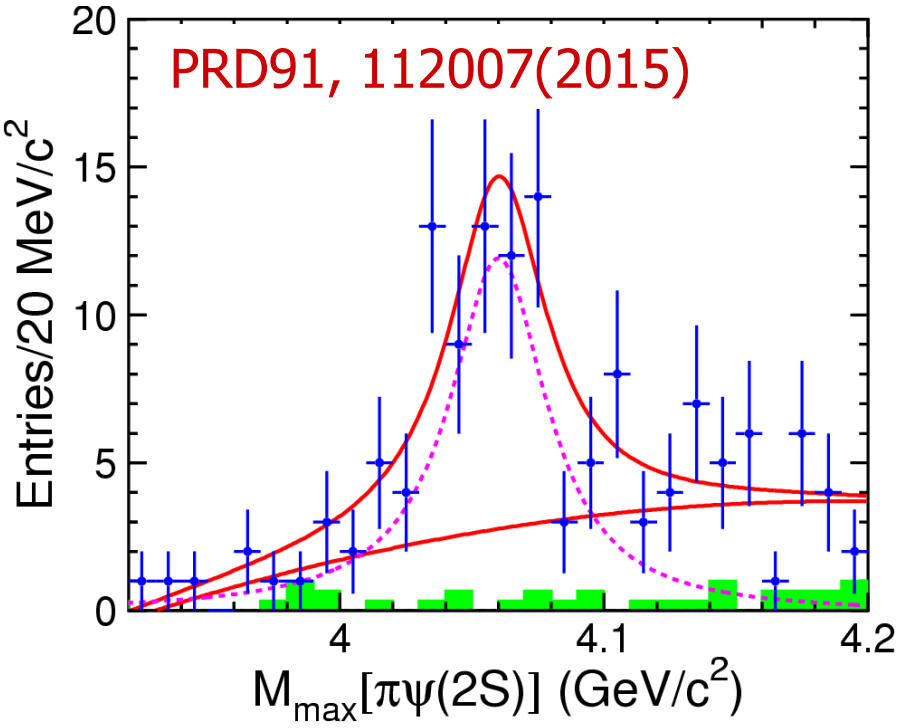
$\psi(2S)$ **Reconstructed modes:**

**Mode I:** $\Psi(3686)\rightarrow\pi^+\pi^- J/\psi$, $J/\psi\rightarrow l^+l^-$ ($l=e/\mu$)

**Mode II:** $\Psi(3686)\rightarrow$*neutrals*$+J/\psi$, *neutrals*$=(\pi^0\pi^0, \pi^0, \eta$ and $\gamma\gamma)$ $J/\psi\rightarrow l^+l^-$ ($l=e/\mu$)

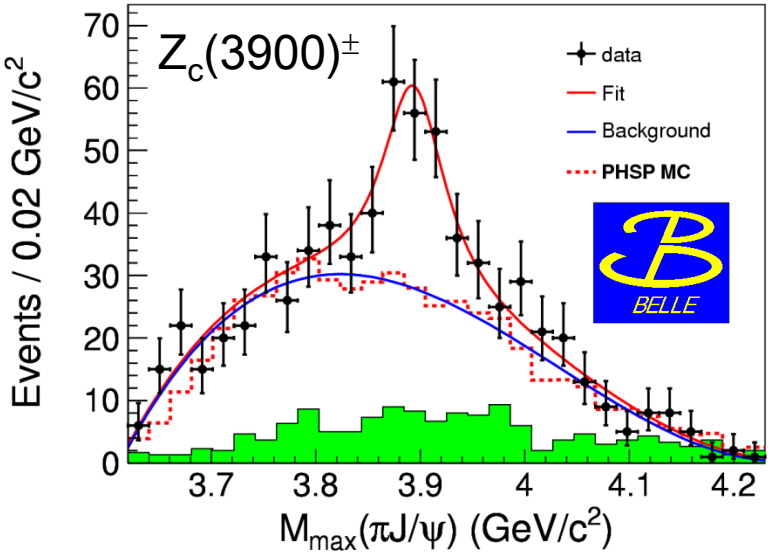


# $Z_c(4050)^{\pm} \rightarrow \pi^{\pm}\psi'$




- Y(4360) signal region
- $M(Z_c) = 4054 \pm 3 \pm 1$ MeV/$c^2$
- $\Gamma = 45 \pm 11 \pm 6$ MeV
- Significance: **>3.5σ**

Belle with ISR: PRL110, 252002



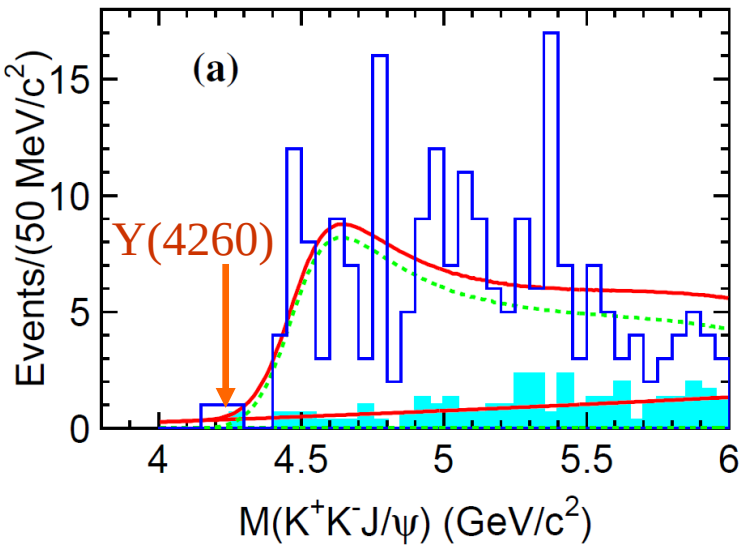

- $M = 3894.5 \pm 6.6 \pm 4.5$ MeV
- $\Gamma = 63 \pm 24 \pm 26$ MeV
- $159 \pm 49$ events
- $>5.2\sigma$

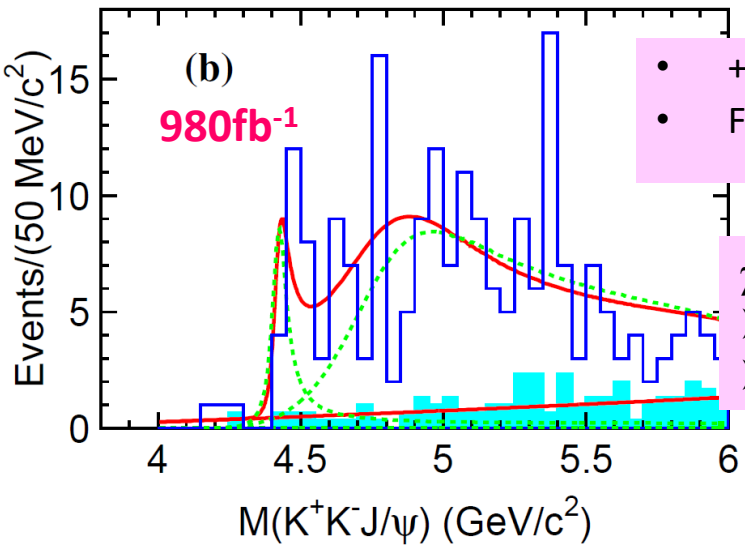
# Updated $e^+e^- \to K^+K^-J/\psi$

PRD 89,072015(2014)

**Event selections are almost the same as in Phys. Rev. D 77, 011105(R) (2008)**

Shaded hist.: J/ψ mass sidebands



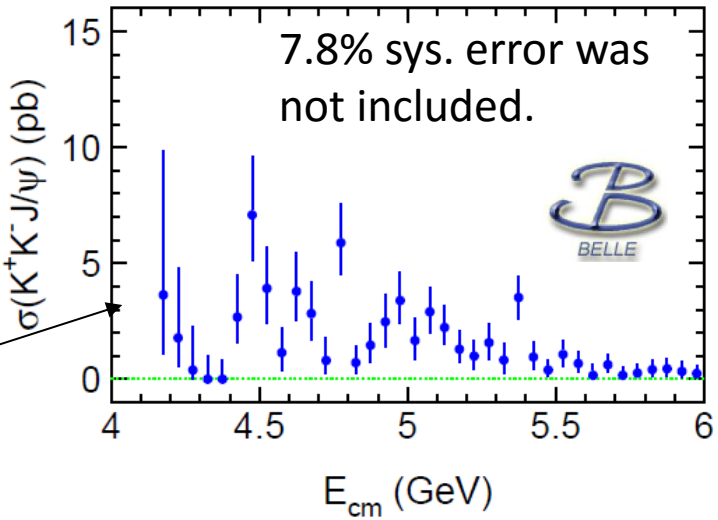




- +one resonance.
- Fit with ψ(4415)

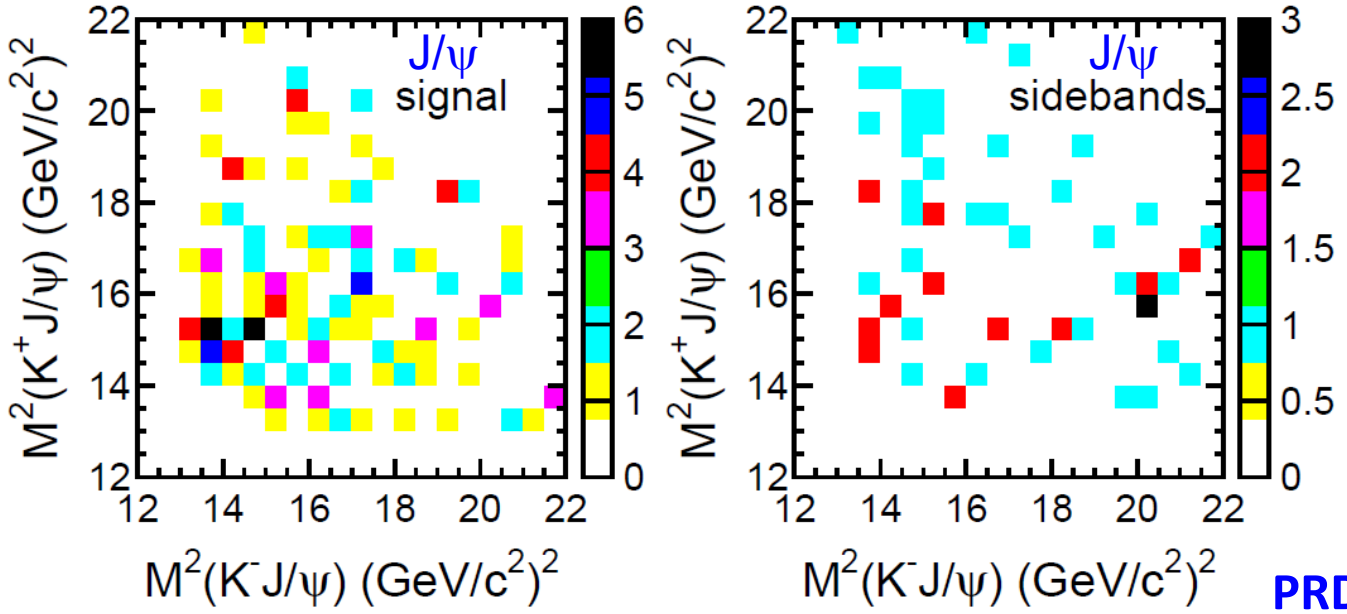
$\chi^2$/ndf=30/11
- M=4747±117MeV
- Γ=671±86 MeV

4-6 GeV: 213 events
35 bkg, 178±16 signal

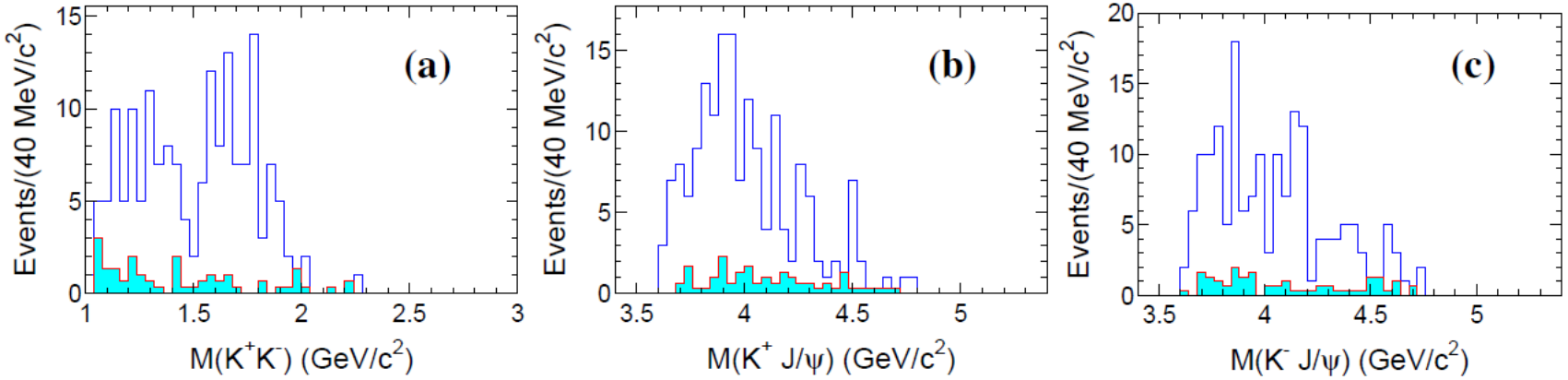
$$\sigma_i = \frac{n_i^{\rm obs} - f \times n_i^{\rm bkg}}{\mathcal{L}_i \cdot \epsilon_i \cdot \mathcal{B}(J/\psi \to \ell^+\ell^-)}$$



# Search for $Z_{cs}$→$KJ/\psi$ states




PRD 89,072015(2014)




No evident structure in $K^{+-}J/\psi$ mass distribution under current statistics

# Measurement of $e^+e^- \to \gamma\chi_{cJ}$ via ISR

- Y(4260),Y(4360) did not show in hadronic R inclusive scan
- Large dipion transitions rate than conventional charmonium.

It is important to investigate them using much larger data samples and new decay channels.

- Radiative transitions: $e^+e^- \to \gamma\chi_{cJ}$ via ISR, $\chi_{cJ} \to \gamma J/\psi$, $J/\psi \to \mu^+\mu^-$

Phys. Rev. D 92, 012011 (2015)

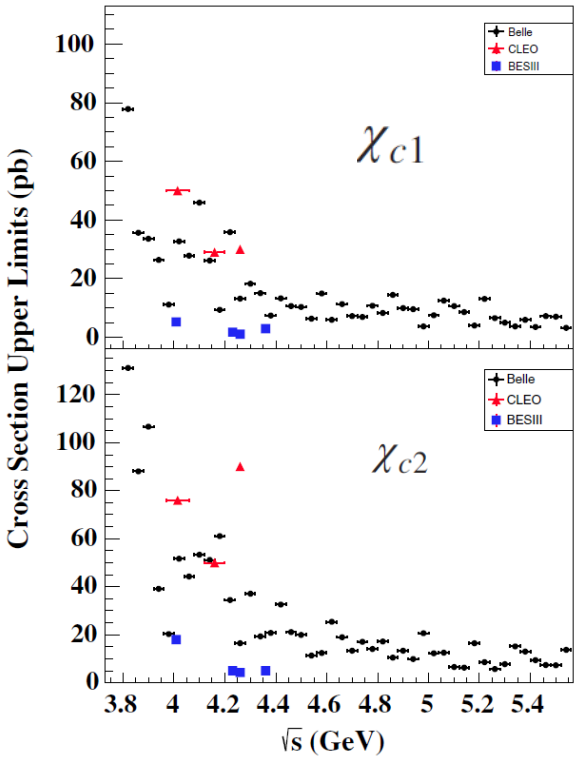
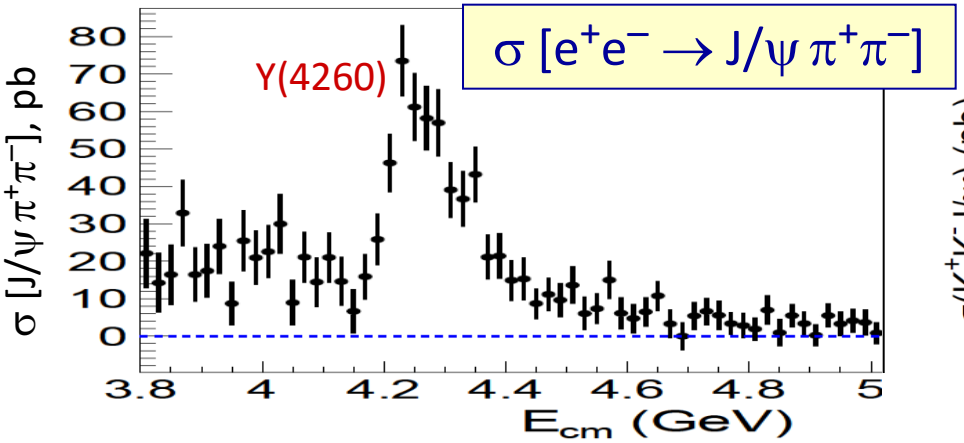


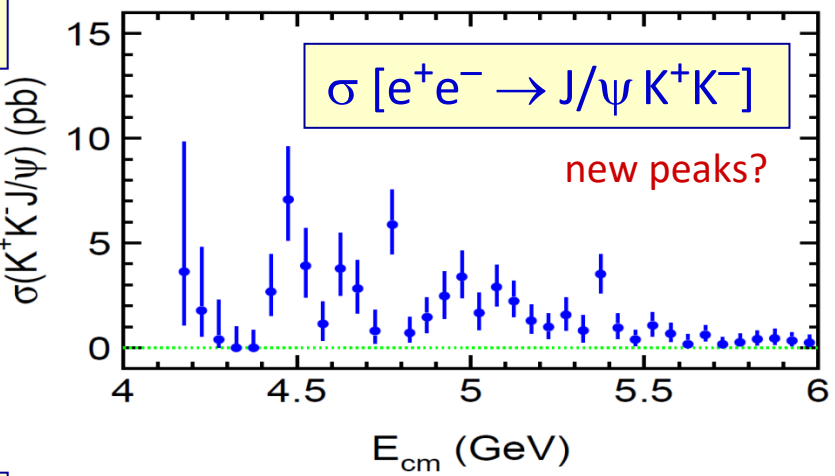

TABLE II. Upper limits on $\Gamma_{ee} \times \mathcal{B}$ at the 90% C.L.

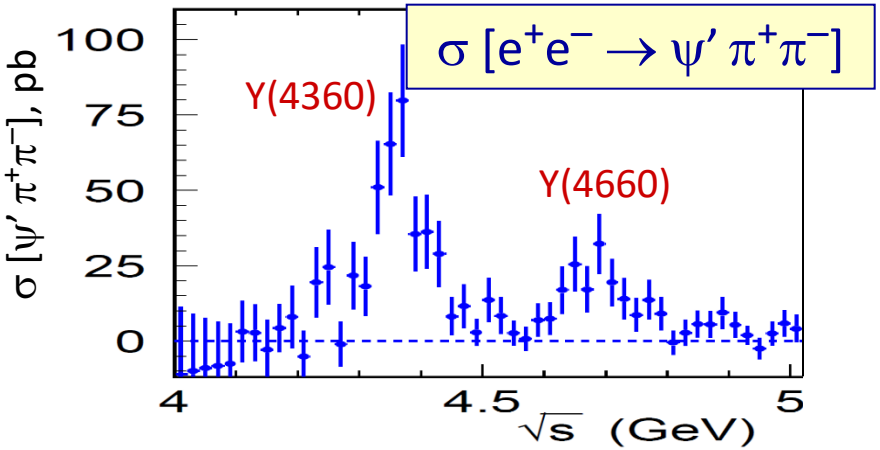
| | $\chi_{c1}$ (eV) | $\chi_{c2}$ (eV) |
|---|---|---|
| $\Gamma_{ee}[\psi(4040)] \times \mathcal{B}[\psi(4040) \to \gamma\chi_{cJ}]$ | 2.9 | 4.6 |
| $\Gamma_{ee}[\psi(4160)] \times \mathcal{B}[\psi(4160) \to \gamma\chi_{cJ}]$ | 2.2 | 6.1 |
| $\Gamma_{ee}[\psi(4415)] \times \mathcal{B}[\psi(4415) \to \gamma\chi_{cJ}]$ | 0.47 | 2.3 |
| $\Gamma_{ee}[Y(4260)] \times \mathcal{B}[Y(4260) \to \gamma\chi_{cJ}]$ | 1.4 | 4.0 |
| $\Gamma_{ee}[Y(4360)] \times \mathcal{B}[Y(4360) \to \gamma\chi_{cJ}]$ | 0.57 | 1.9 |
| $\Gamma_{ee}[Y(4660)] \times \mathcal{B}[Y(4660) \to \gamma\chi_{cJ}]$ | 0.45 | 2.1 |

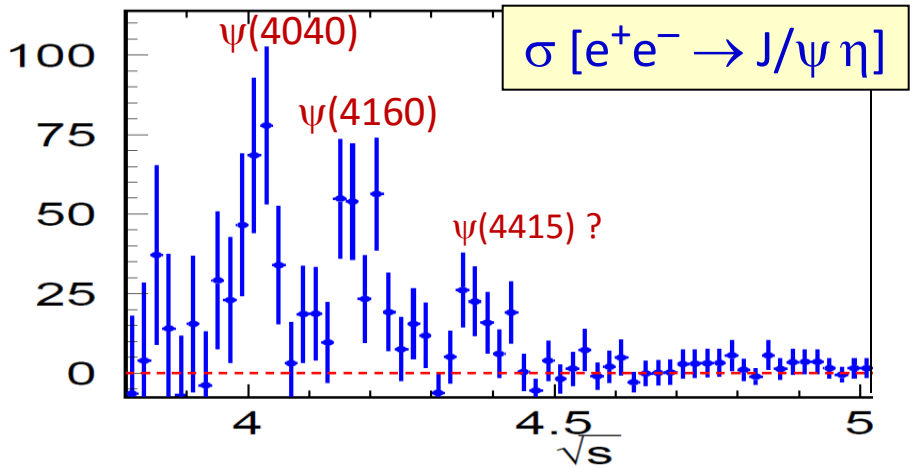
Table: Upper limits on branching fractions $\mathcal{B}(R \to \gamma\chi_{cJ})$ at the 90% C.L.

| Resonance | $\gamma\chi_{c1}$ $(10^{-3})$ | $\gamma\chi_{c2}$ $(10^{-3})$ |
|---|---|---|
| $\psi(4040)$ | 3.4 | 5.5 |
| $\psi(4160)$ | 6.1 | 16.2 |
| $\psi(4415)$ | 0.83 | 3.9 |



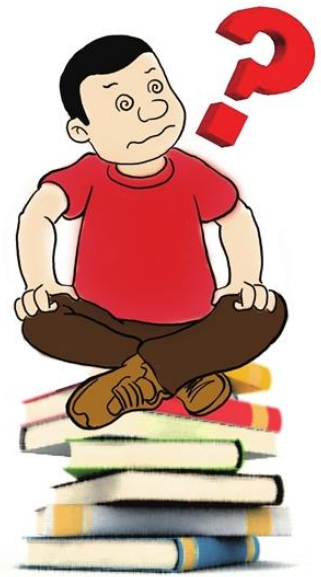




Different cross sections have different peaks.

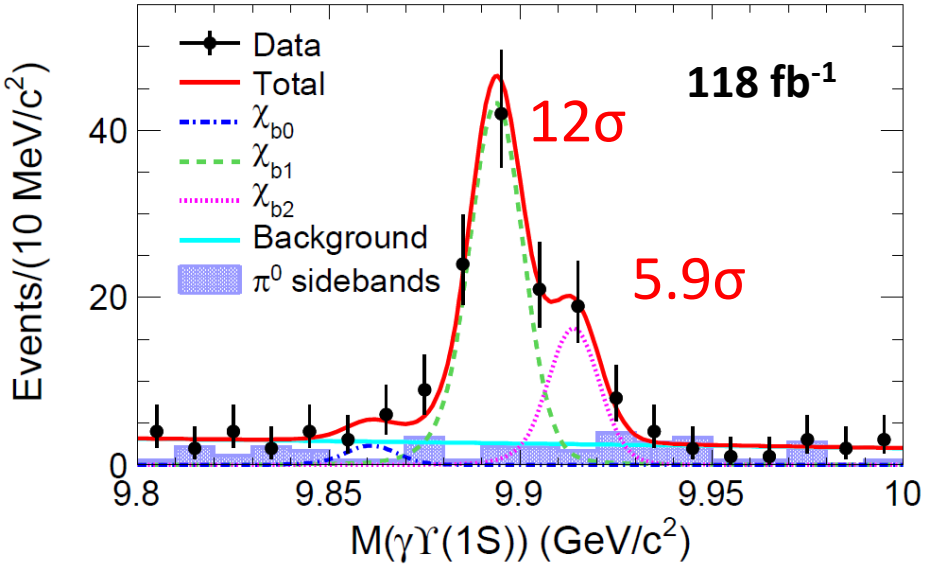
Each Y or ψ state decays to only one channel.



# $e^+e^- \to \pi^+\pi^-\pi^0 \chi_{bJ}$ at 10.867 GeV

PRL 113, 142001 (2014)

**Heavy quarkonia hadronic transition : QCD multipole expansion (QCDME) model**. [Y. P Kuang, Front Phys. China 1, 19 (2006)]



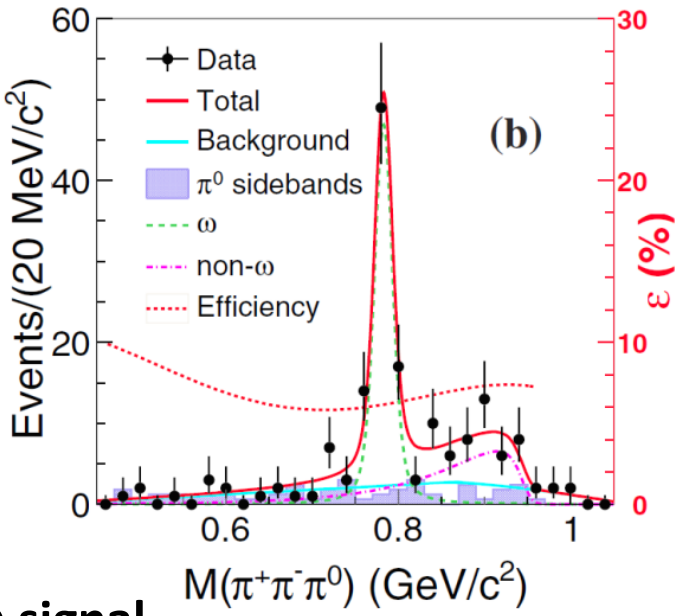

**For Υ(5S) resonance peak**:

- The anomalously large width :$e^+e^- \to \pi^+\pi^-\Upsilon(nS)$ [Belle PRL 100, 112001] and $e^+e^- \to \pi^+\pi^- h_b(nS)$ [PRL 108, 032001] .
- $Z_b(10610)^{\pm}$ and $Z_b(10650)^{\pm}$ [PRL 108, 122001].

| **Born cross section:** |
|---|
| **$\sigma(e^+e^- \to \pi^0\pi^+\pi^- \chi_{b0}) < 3.4$ (pb) at 90% C.L.** |
| **$\sigma(e^+e^- \to \pi^0\pi^+\pi^- \chi_{b1}) = 0.98 \pm 0.12 \pm 0.12$ (pb)** |
| **$\sigma(e^+e^- \to \pi^0\pi^+\pi^- \chi_{b2}) = 0.62 \pm 0.14 \pm 0.08$ (pb)** |

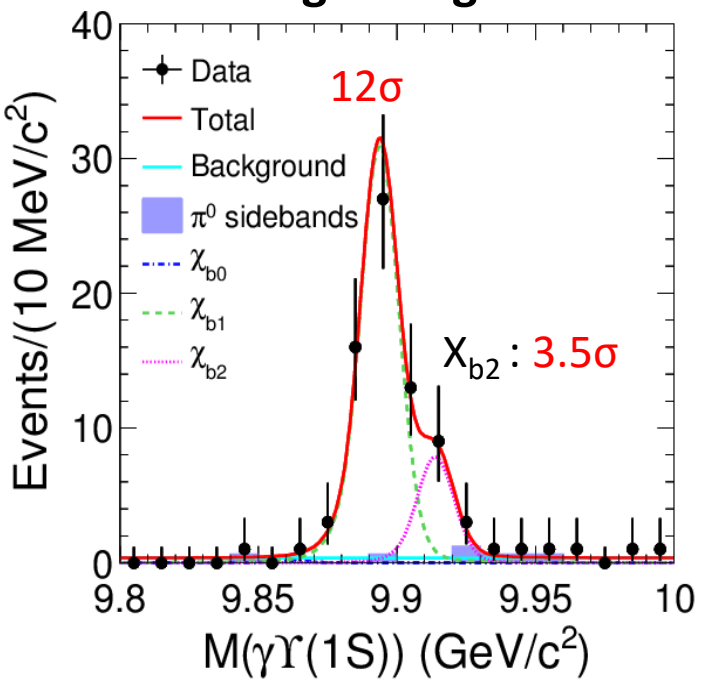
- **The same order as $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$.** [PRL 100, 112001].
- **Hadronic loop effect?** [arXiv:1406.6763]

# $e^+e^- \to \omega\chi_{bJ}$ at 10.867 GeV




- ω signal
- An enhancement in higher $M(\pi^+\pi^-\pi^0)$

**ω signal region.**




The $\frac{Br(\Upsilon(5S)\to\omega\chi_{b2})}{Br(\Upsilon(5S)\to\omega\chi_{b1})}$ higher than **expectation from quark symmetry**. [PLB 346, 129 (1995)].

→ **a molecular component in** ϒ(5S) [arXiv: 1406.0082]

→ **S- and D- wave mixing** [arXiv:1406.6543]

**Born cross section:**

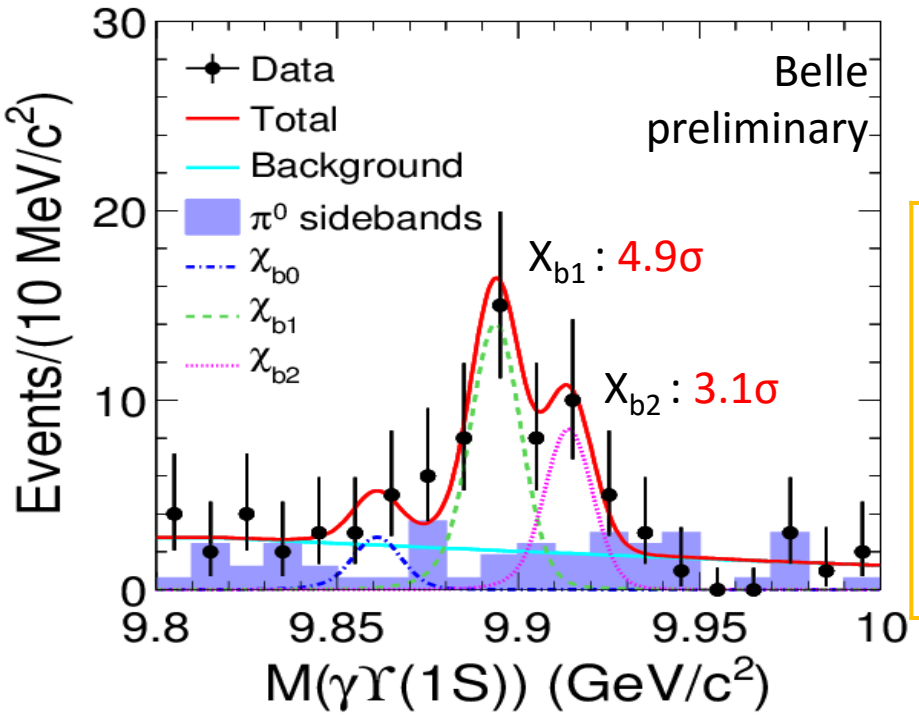
$\sigma(e^+e^-\to\omega\chi_{b0}) < 1.9$ (pb) at 90% C.L.

$\sigma(e^+e^-\to\omega\chi_{b1}) = 0.76 \pm 0.11 \pm 0.11$ (pb)

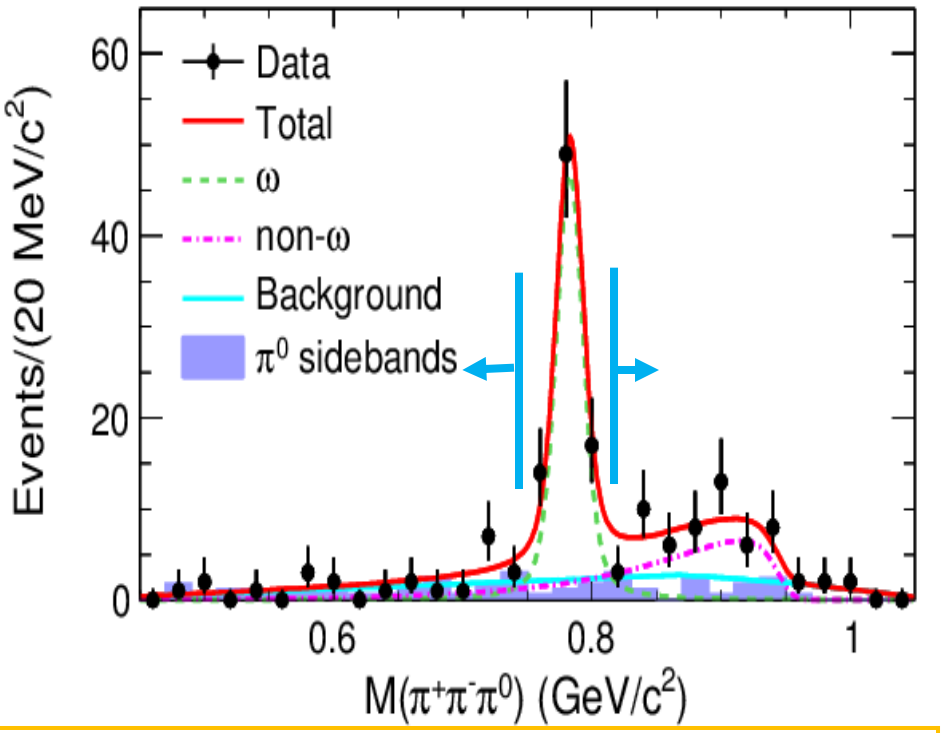
$\sigma(e^+e^-\to\omega\chi_{b2}) = 0.29 \pm 0.11 \pm 0.08$ (pb)

# $e^+e^- \to (\pi^+\pi^-\pi^0)_{non\text{-}\omega}\,\chi_{bJ}$

- The $\chi_{bJ}$ candidates out of ω signal region.
- Possible cascade decay from $\Upsilon(5S) \to \pi Z_b \to \pi\rho\chi_{bJ}$ [arXiv:1406.0082]
- **The interpretation is currently limited.**




PRL 113, 142001 (2014)




**Born cross section:**

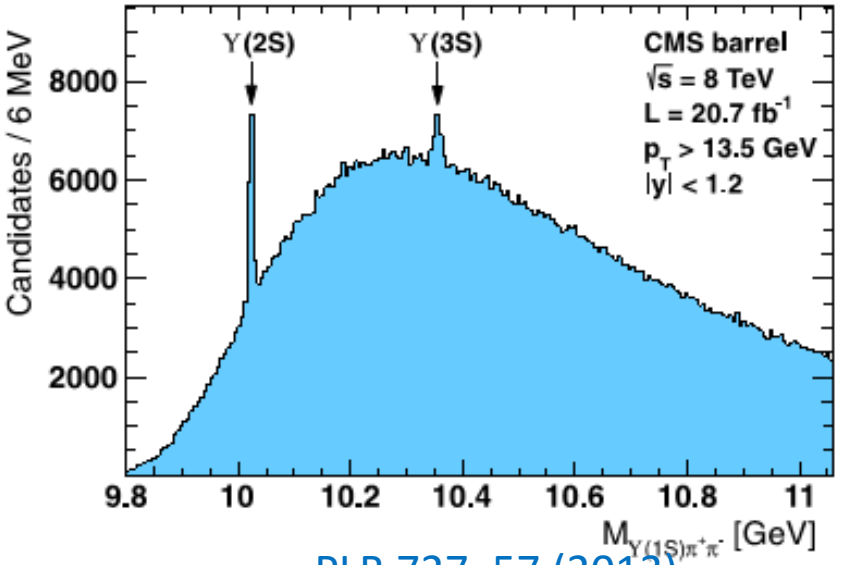
$\sigma(e^+e^- \to (\pi^+\pi^-\pi^0)_{non\text{-}\omega}\chi_{b0}) < 2.3$ (pb) at 90% C.L.

$\sigma(e^+e^- \to (\pi^+\pi^-\pi^0)_{non\text{-}\omega}\chi_{b1}) = 0.25 \pm 0.07 \pm 0.06$ (pb)

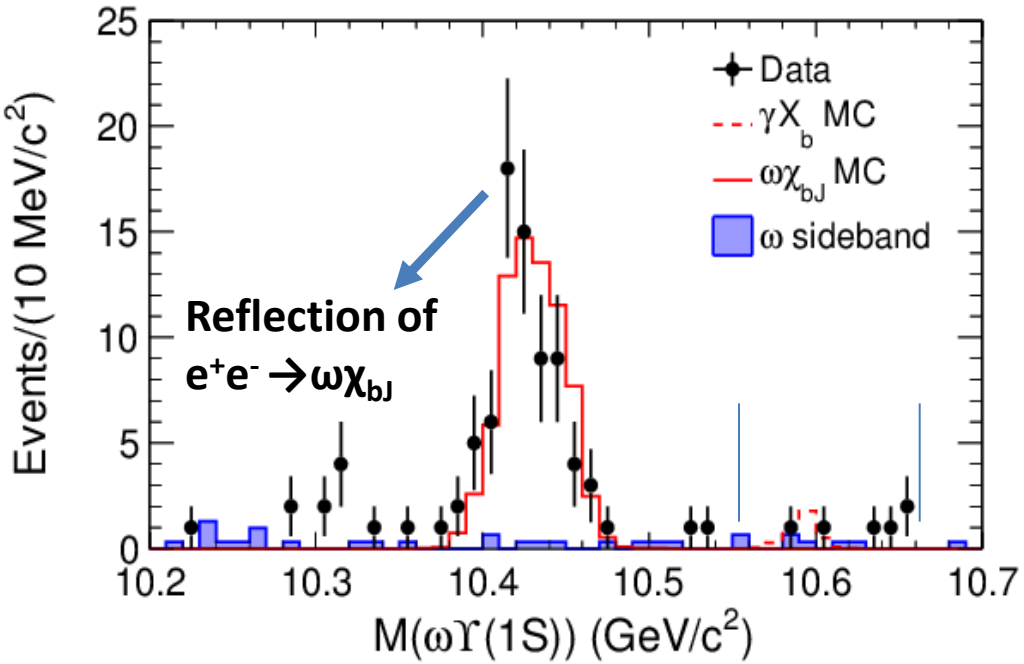
$\sigma(e^+e^- \to (\pi^+\pi^-\pi^0)_{non\text{-}\omega}\chi_{b2}) = 0.30 \pm 0.11 \pm 0.14$ (pb)

# $e^+e^- \rightarrow \gamma X_b \rightarrow \gamma\omega\Upsilon(1S)$

- **The X(3872) counterpart in the bottomonium sector $X_b$, NOT observed decay channel $\pi^+\pi^-\Upsilon(1S)$.**
- **As $X_b$ is above $\omega\chi_{bJ}$ threshold, this Isospin-conserving process should be a more promising decay mode.** [PRD88, 054007].

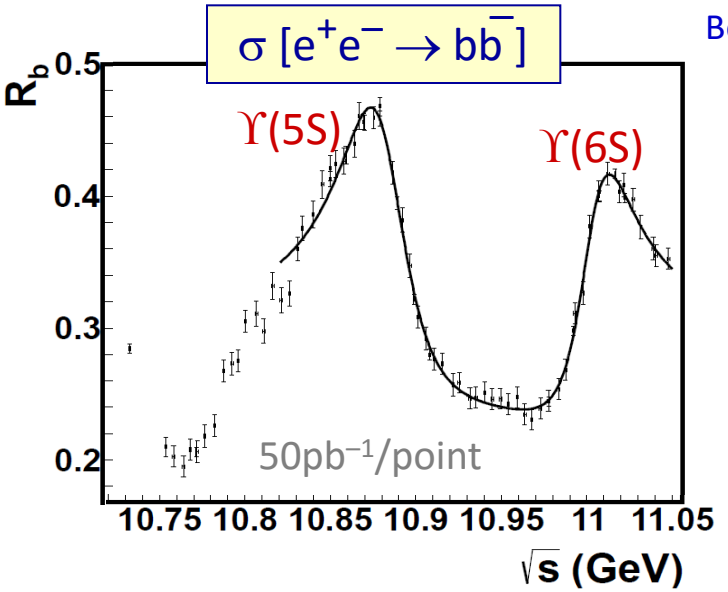



PLB 727, 57 (2013) .

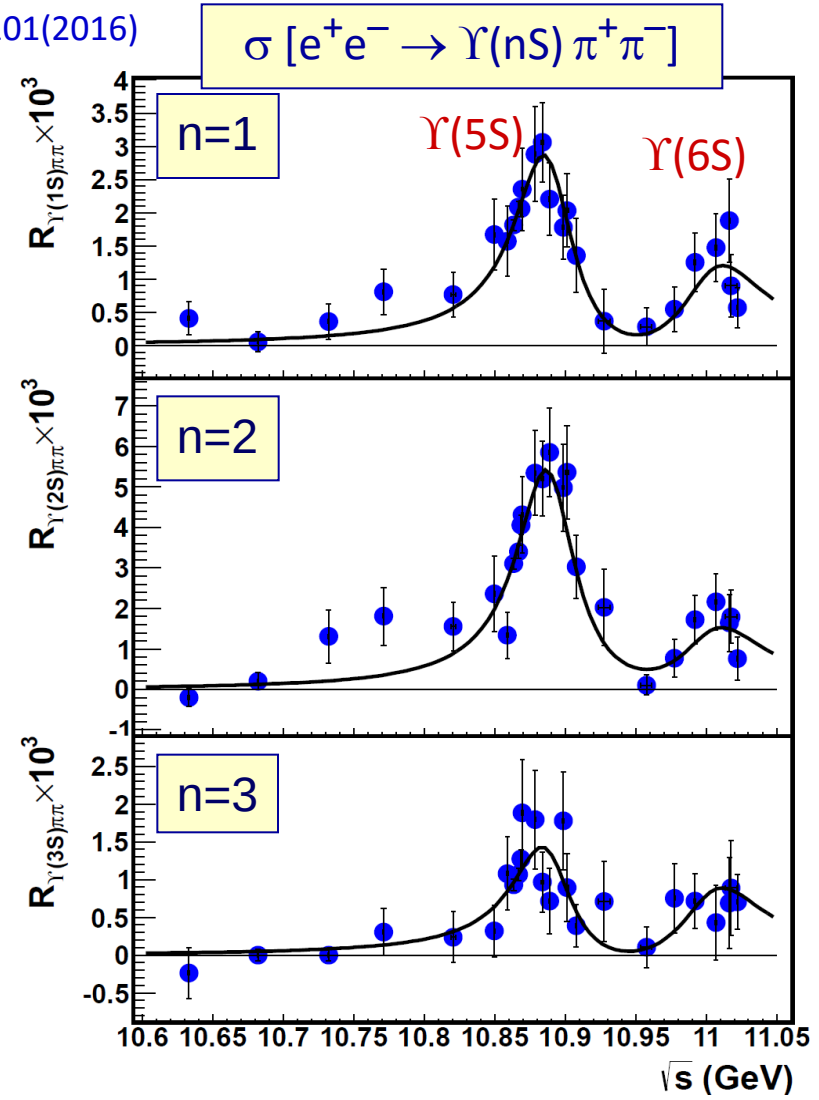



**Assuming $X_b$ is narrow**, the product branching fraction :

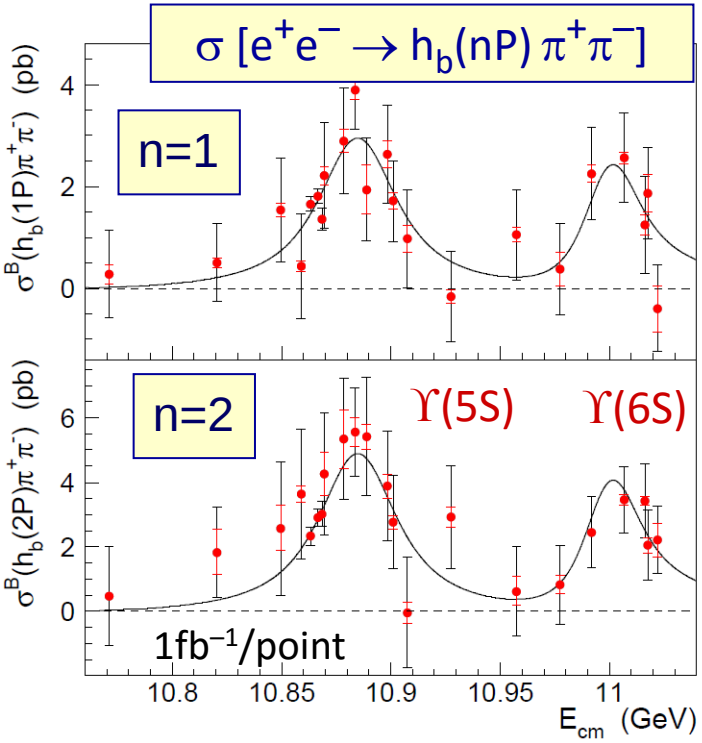
**$Br(\Upsilon(5S) \rightarrow \gamma X_b)\, Br(X_b \rightarrow \omega\chi_{bJ})$** varies from **$2.6 \times 10^{-5}$ to $3.8 \times 10^{-5}$ between 10.55 and 10.65 GeV/$c^2$**.




Belle PRD93,011101(2016)



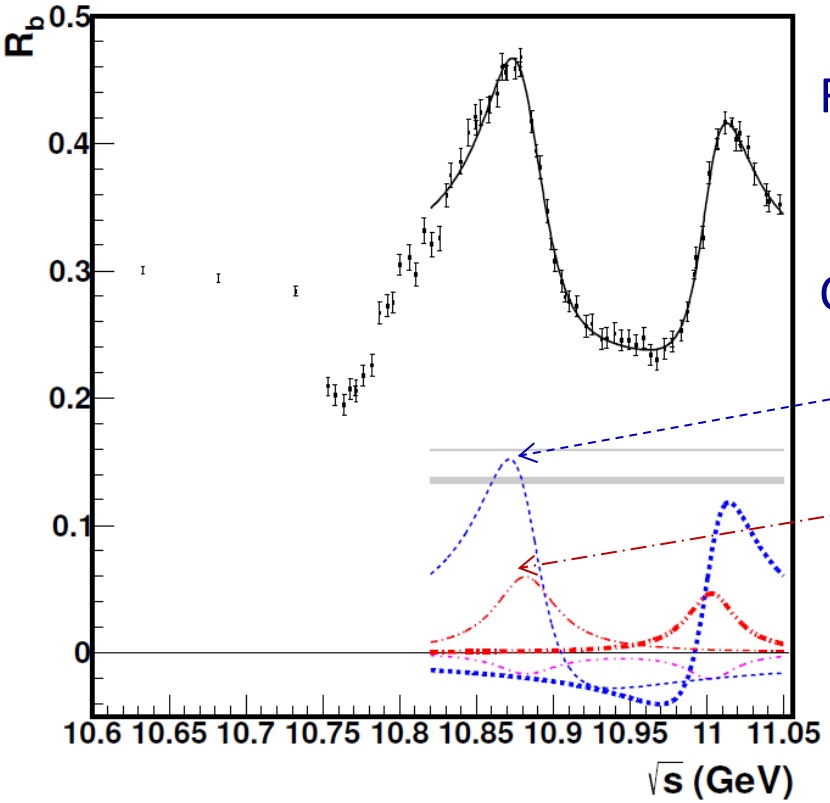

arXiv:1508.06562




Only $\Upsilon(5S)$ and $\Upsilon(6S)$ peaks in all cross sections.

Difference btw decay patterns of charmonium-like and bottomonium-like states is not understood.

# Decomposition of $R_b$




Fit to $R_b$:

$$|A_{NR}|^2 + |A_R + A_{5S}\, e^{i\phi_{5S}}\, BW(M_{5S}, \Gamma_{5S}) + A_{6S} e^{i\phi_{6S}}\, BW(M_{6S}, \Gamma_{6S}))|^2$$

Conclusions:

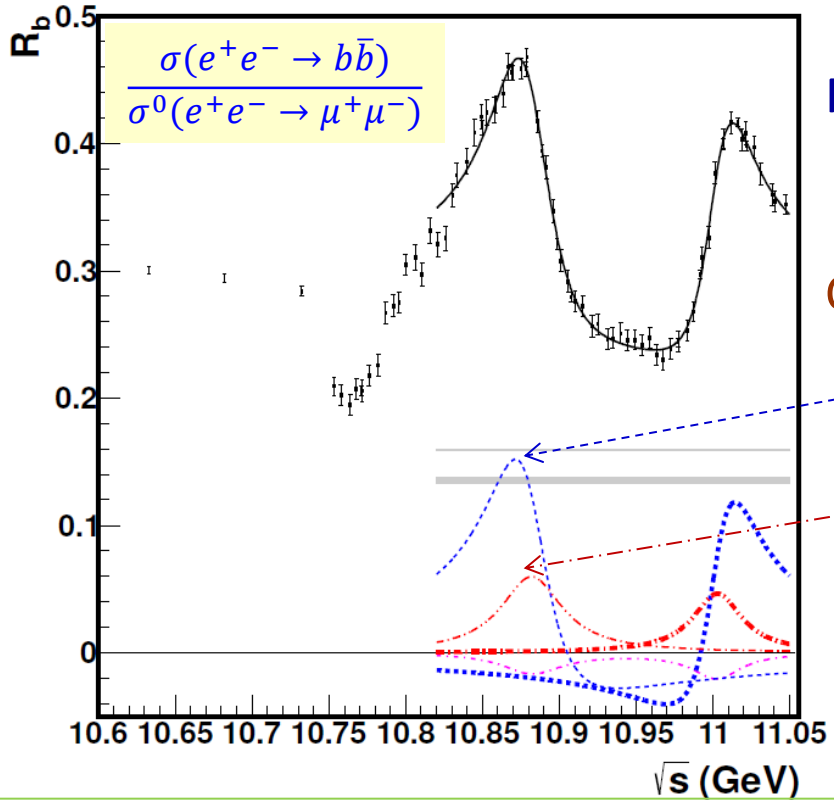
Strong interference btw $\Upsilon$(5S) & continuum

$\Upsilon$(5S) peak is saturated by

$B^{(*)}B^*\pi$, $\Upsilon(nS)\pi\pi$, $h_b(mP)\pi\pi$

BB/BB*/B*B* do not resonate $\Rightarrow$ continuum

# Decomposition of $R_b$

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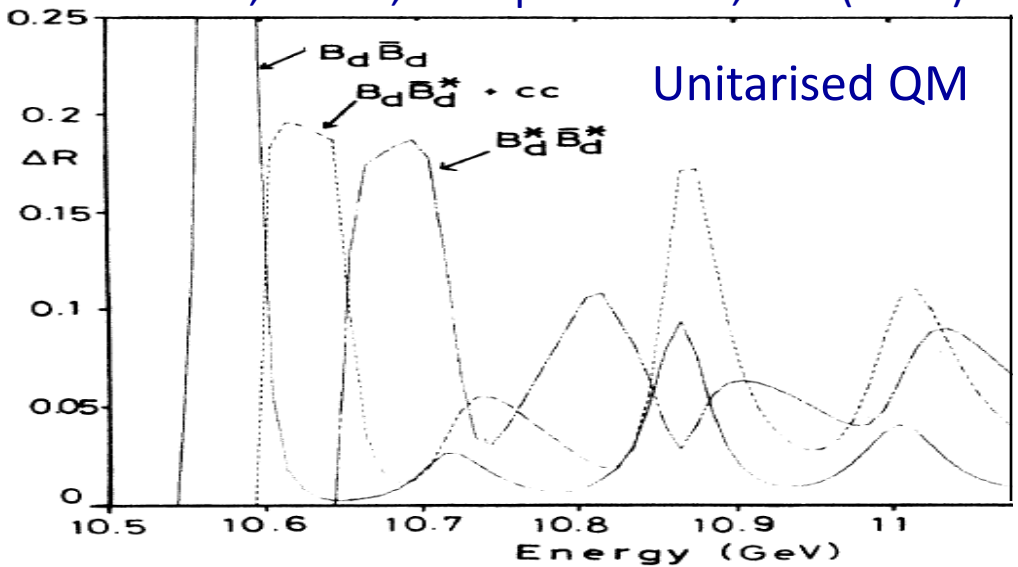
Simple fit model for $R_b$ should not be used.

Ono, Sanda, Tornqvist PRD34, 186 (1986)




Many peaks in BB/BB*/B*B* cross sections $\Rightarrow$ important information

Plan to measure at Belle.

# $e^+e^- \to \pi^+\pi^- h_b(nP)$

Simultaneous fit:

$$A_n\ \Phi_n(s)\ |F_{\rm BW}(s, M_5, \Gamma_5) + a\, e^{i\,\phi}\, F_{\rm BW}(s, M_6, \Gamma_6)|^2$$

$\Upsilon(5S)$:

Mass = $(10884.7 \pm^{3.6}_{3.4} \pm^{8.9}_{1.0})$ MeV

Width = $(40.6 \pm^{12.7}_{8.0} \pm^{1.1}_{19.1})$ MeV

$\Upsilon(6S)$:

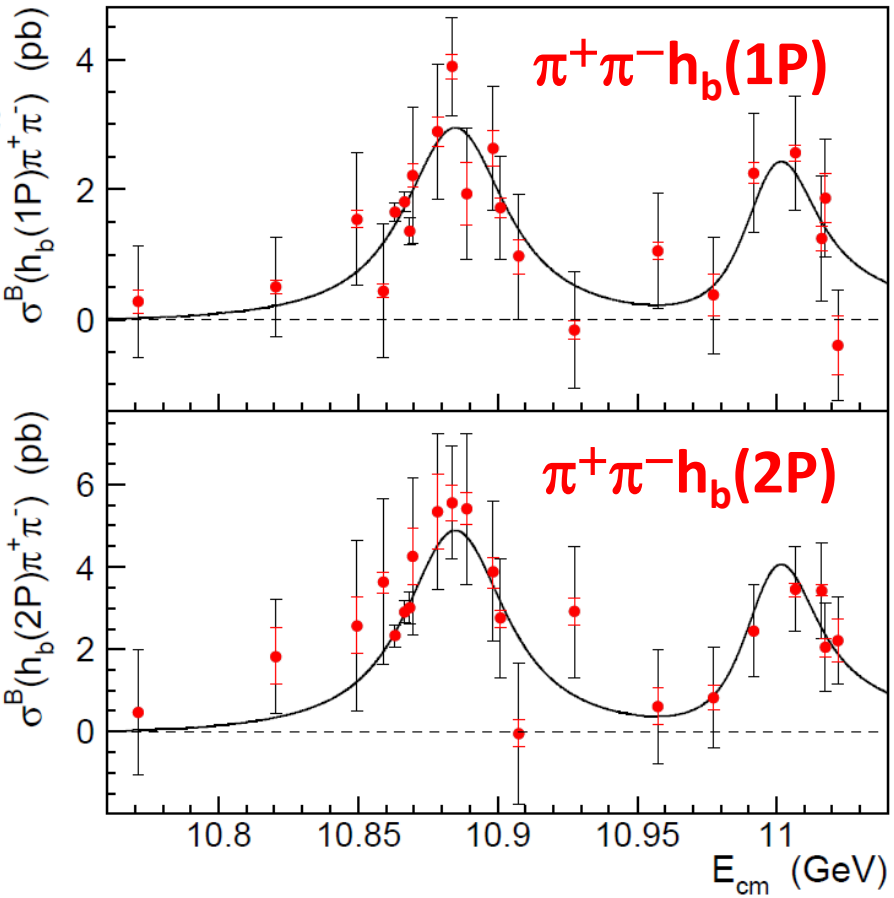
Mass = $(10999.0 \pm^{7.3}_{7.8} \pm^{16.7}_{1.0})$ MeV

Width = $(27 \pm^{27}_{11} \pm^{1}_{12})$ MeV

$\Delta\phi = 0.1 \pm^{0.4}_{0.8} \pm^{0.1}_{0.3}$ rad

- Resonant parameters agree with from $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$
- $e^+e^- \to \pi^+\pi^- h_b(nP)$ at the same level as $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$; similar shape.
- 1st obs. of $\Upsilon(6S) \to \pi^+\pi^- h_b(nP)$

  3.5σ for 1P, 5.3σ for 2P.




Ecm=10865.6 ±2.0 MeV

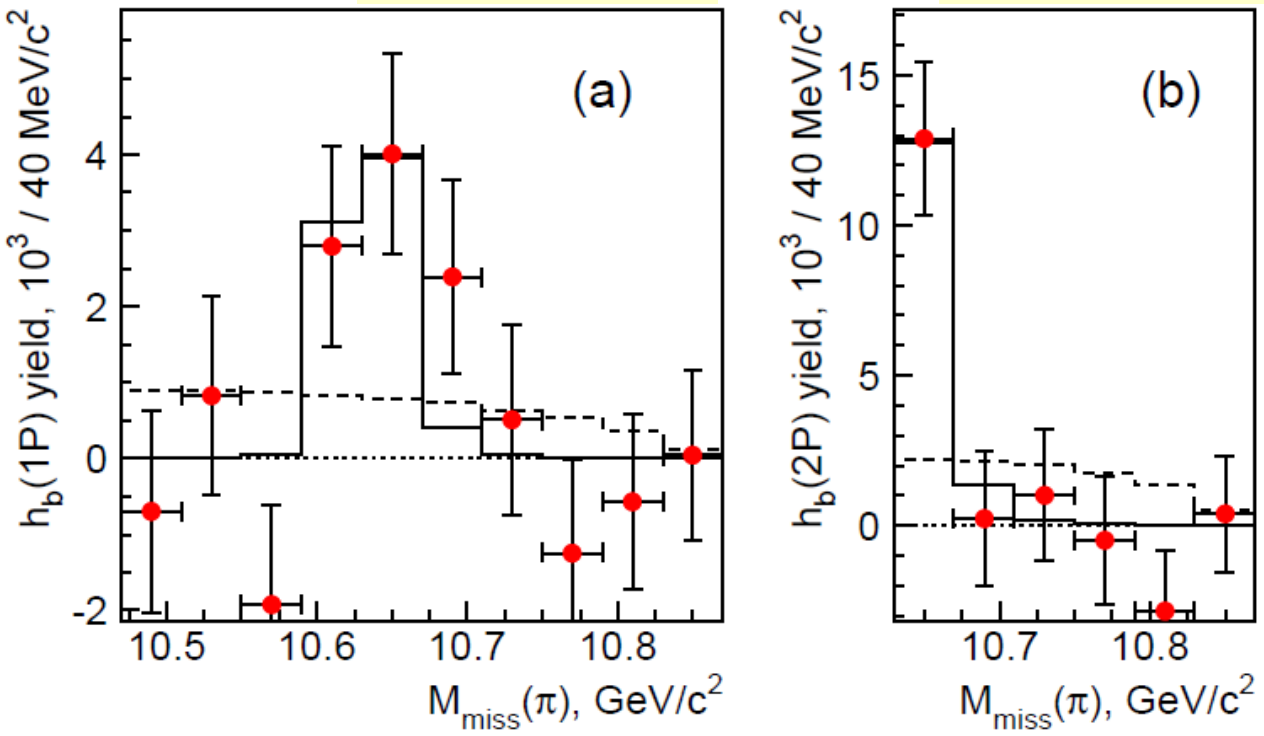
$$\sigma^B(e^+e^- \to h_b(1P)\pi^+\pi^-) = 1.66 \pm 0.09 \pm 0.10\,\text{pb},$$
$$\sigma^B(e^+e^- \to h_b(2P)\pi^+\pi^-) = 2.70 \pm 0.17 \pm 0.19\,\text{pb}.$$

arXiv:1508.06562
Accepted by PRL

# $Z_b$ in $\Upsilon(6S) \rightarrow \pi^+\pi^- h_b(nP)$

- Fit $\pi^+\pi^-$ missing in each $\pi$ missing mass spectra
- Events mainly from $Z_b$ intermediate states: not clear if only one $Z_b$ or both. Single $Z_b(10610)$ hypothesis is excluded at 3.3σ in $\pi^+\pi^- h_b(1P)$; Single $Z_b(10650)$ hypothesis cannot excluded.

**$\pi^+\pi^- h_b(1P)$** **$\pi^+\pi^- h_b(2P)$**




Belle: arXiv:1508.06562

# Summary & outlooks

- Some updated on e+e- to charmonium(like)
- More measurements on e+e- to bottomonium(like)
- Obviously there are many puzzles need to be solved with more statistics
- Very exciting time ahead for BelleII from 2018 !

thank you!