# Charmonium and exotics from Belle

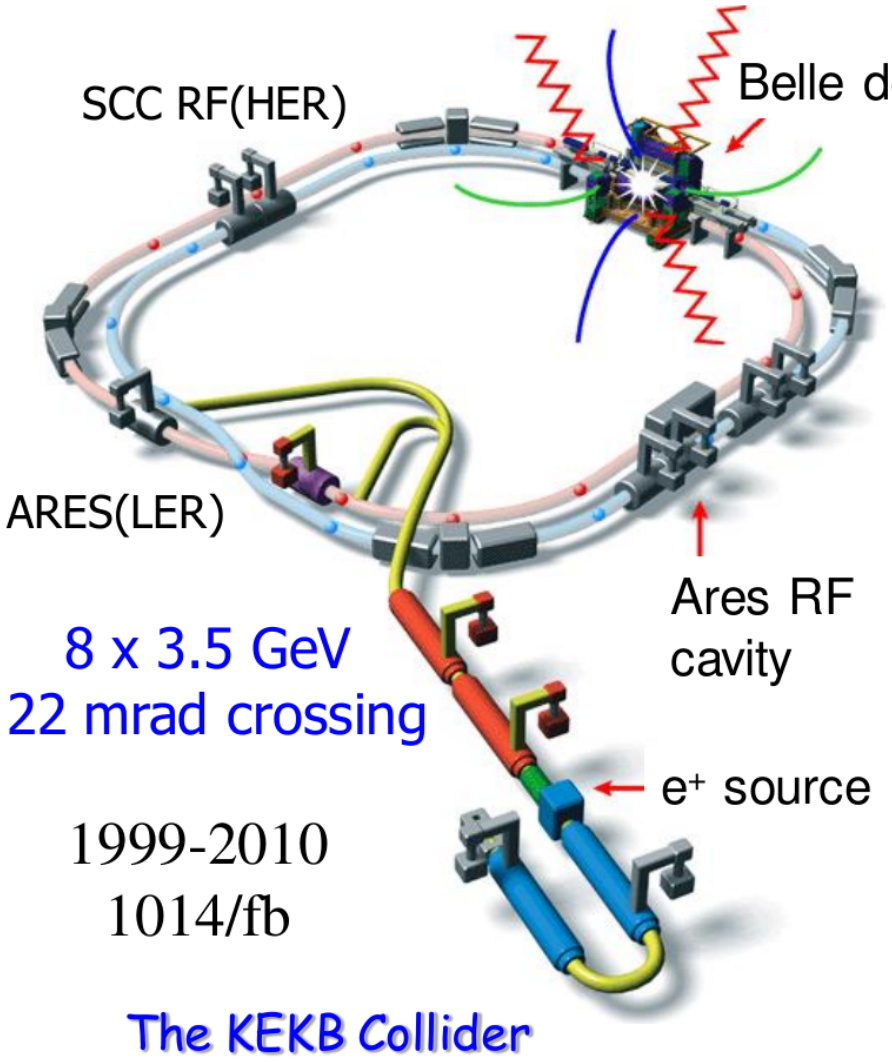
XiaoLong Wang

(for Belle Collaboration)

Virginia Tech

7th International Workshop on Charm Physics
Wayne State University
Detroit, US, May 18, 2015

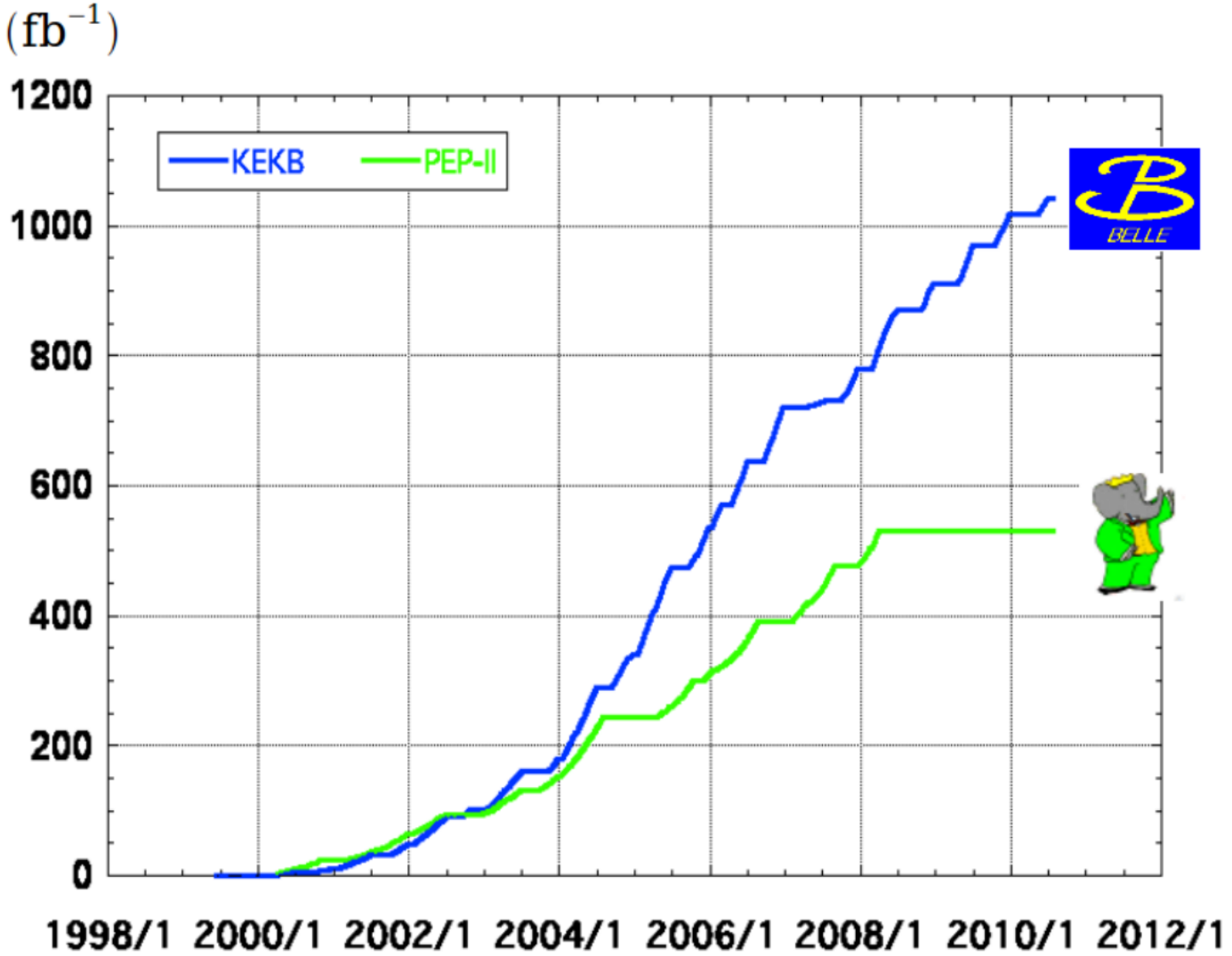
# The Belle Experiment




World record:

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

# Integrated Luminosities of B-factories




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

**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:**

$\sim 100$ $fb^{-1}$

**$\sim 550\ fb^{-1}$**

**On resonance:**

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

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

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

**Off resonance:**

$\sim 54$ $fb^{-1}$

# Outline

1. $X$-like states decaying to $\eta_c$ modes
2. Update on $e^+e^- \to \pi^+\pi^-\psi(2S)$ via ISR
3. Update on $e^+e^- \to K^+K^-J/\psi$ via ISR
4. $X(3872)$ in $B \to K\pi + J/\psi\pi^+\pi^-$ (Briefly)

# $X$-like states decaying to $\eta_c$ modes

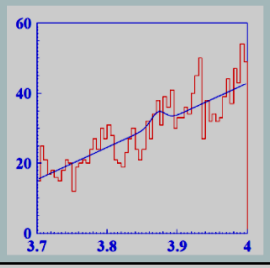
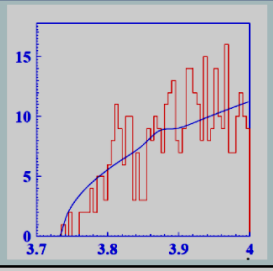
- Motivation:
  - $X(3872)$: observed by Belle in $B \to K(J/\psi\pi^+\pi^-)$; $J^{PC} = 1^{++}$ determined by LHCb from angular analysis.
  - If $X(3872)$ is a $D^0\bar{D}^{*0}$ molecule, there may be other "$X$-like" particles.

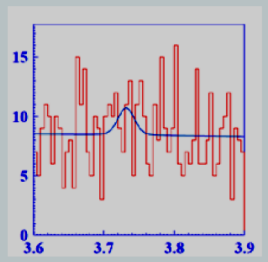
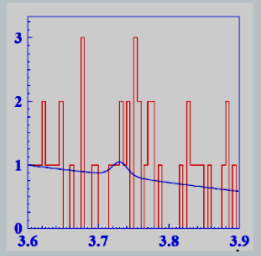
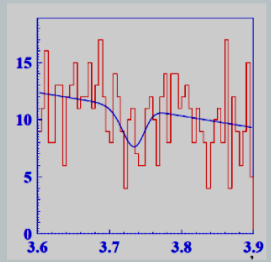
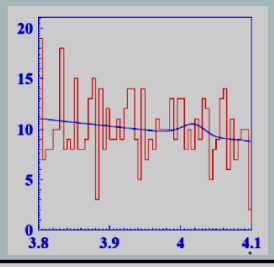
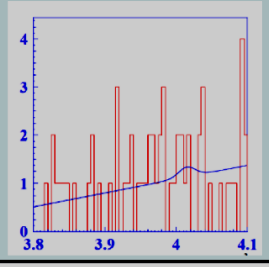
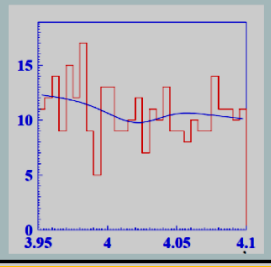
- Assumption:

| Candidate | Combination | Quantum number $J^{PC}$ | Decay modes |
|---|---|---|---|
| $X_1(3872)$ | $D^0\bar{D}^{*0} - \bar{D}^0 D^{*0}$ | $1^{+-}$ | $\eta_c\omega$, $\eta_c\rho$ |
| $X(3730)$ | $D^0\bar{D}^0 + \bar{D}^0 D^0$ | $0^{++}$ | $\eta_c\eta$, $\eta_c\pi^0$ |
| $X(4014)$ | $D^{*0}\bar{D}^{*0} + \bar{D}^{*0} D^{*0}$ | $0^{++}$ | $\eta_c\eta$, $\eta_c\pi^0$ |

- Analysis features:
  - $B^\pm \to K^\pm X$ with $\eta_c \to K_s K\pi$, $K_s \to \pi^+\pi^-$
  - Combined fit of $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$
  - Test mode: $B^\pm \to K^\pm\psi(2S)(\to J/\psi\pi^+\pi^-)$, consistent with PDG.
  - The same final states without intermediate $X$ are studied.

# $X$-like states decaying to $\eta_c$ modes

| | $X \to \eta_c \pi^+\pi^-$ | $X \to \eta_c \omega$ |
|---|---|---|
| $X_1(3872)$ |  |  |

| | $X \to \eta_c \eta$ | | $X \to \eta_c \pi^0$ |
|---|---|---|---|
| | $\eta \to \gamma\gamma$ | $\eta \to \pi^+\pi^-\pi^0$ | |
| $X(3730)$ |  |  |  |
| $X(4014)$ |  |  |  |

X: M(X) GeV/$c^2$ - Y: N events

**arXiv:1501.06351**

# $X$-like states decaying to $\eta_c$ modes

No signal was observed in any of the studied decay channels. The upper limits of their productions are determined at 90% C.L..

Upper limits of $\mathcal{B}(B^{\pm} \to K^{\pm} X(\to \eta_c h)) \ (\times 10^{-5})$

| | Decay mode | Yield | UL |
|---|---|---|---|
| $X_1(3872)$ | $\eta_c \pi^+ \pi^-$ | $17.9 \pm 16.5$ | 3.0 |
| | $\eta_c \omega$ | $6.0 \pm 12.5$ | 6.9 |
| $X(3730)$ | $\eta_c \eta(\gamma\gamma)$ | $13.8 \pm 9.9$ | 4.6 |
| | $\eta_c \eta(\pi^+ \pi^- \pi^0)$ | $1.4 \pm 1.0$ | |
| $X(3730)$ | $\eta_c \pi^0$ | $-25.6 \pm 10.4$ | 5.7 |
| $X(4014)$ | $\eta_c \eta(\gamma\gamma)$ | $8.9 \pm 11.0$ | 3.9 |
| | $\eta_c \eta(\pi^+ \pi^- \pi^0)$ | $1.3 \pm 1.6$ | |
| $X(4014)$ | $\eta_c \pi^0$ | $-8.1 \pm 13.2$ | 1.2 |

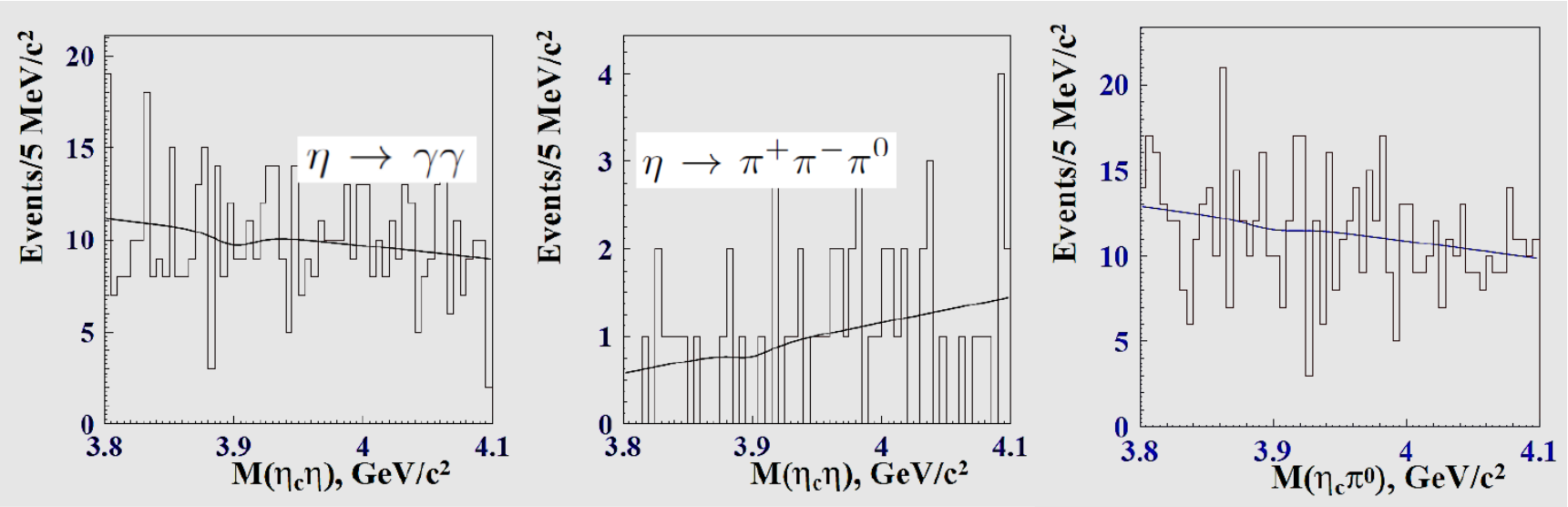
Upper limits of $\mathcal{B}(B^{\pm} \to K^{\pm} + \eta_c h) \ (\times 10^{-5})$ at 90% C.L.

| Mode | Yield | UL |
|---|---|---|
| $\eta_c \pi^+ \pi^-$ | $155 \pm 72$ | 3.9 |
| $\eta_c \omega$ | $-41 \pm 27$ | 5.3 |
| $\eta_c \eta(\gamma\gamma)$ | $-14.1 \pm 26.1$ | 2.2 |
| $\eta_c \eta(3\pi)$ | $-1.8 \pm 3.4$ | |
| $\eta_c \pi^0$ | $-1.9 \pm 12.1$ | 6.2 |

**arXiv:1501.06351**

# $Z(3900)^0/Z(4020)^0/X(3915) \to \eta_c$ modes

- $Z_c^{\pm}(3900)$ was observed in $\pi^{\pm}J/\psi$ final states and $Z_c^{\pm}(4020)$ was observed in $\pi^{\pm}h_c$ final states. Could they have neutral partners?
- $X(3915)$ was observed in $\gamma\gamma$ collisions.



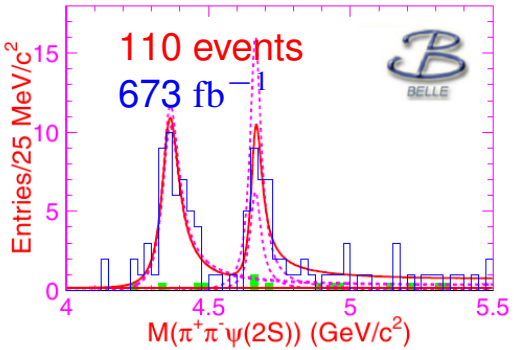

Upper limits of branching fractions at 90% C.L.

| Resonance | Decay mode | $\mathcal{B}(B \to K + R)$ |
|---|---|---|
| $Z^0(3900)$ | $\eta_c\pi^+\pi^-$ | $4.7 \times 10^{-5}$ |
| $Z^0(4020)$ | | $1.6 \times 10^{-5}$ |
| $X(3915)$ | $\eta_c\eta$ | $3.3 \times 10^{-5}$ |
| | $\eta_c\pi^0$ | $1.8 \times 10^{-5}$ |

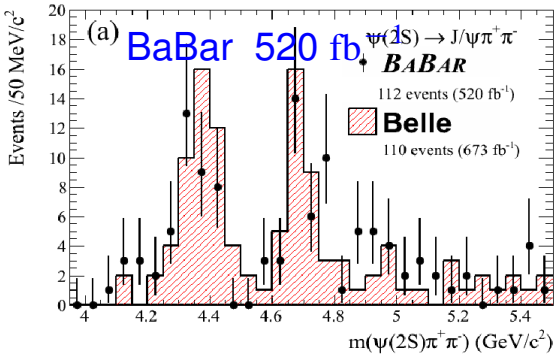
# Update on $e^+e^- \to \pi^+\pi^-\psi(2S)$ via ISR

- $Y(4360)$ was confirmed and $Y(4660)$ was discovered at Belle.
- $Y(4660)$ has been confirmed by BaBar:
  - The charmonium-like state with highest mass but narrowest width.
  - Are $Y(4660)$ and $Y(4630)$ the same?

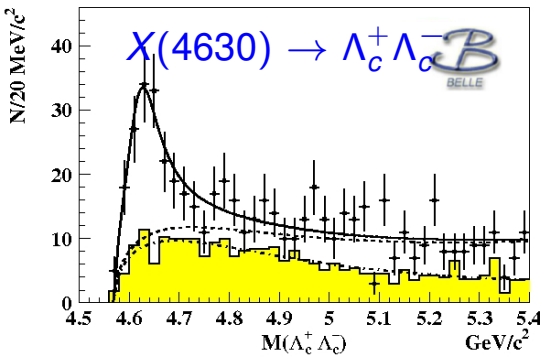
PRL99,142002(2007)




PRD89,111103(R)(2014)



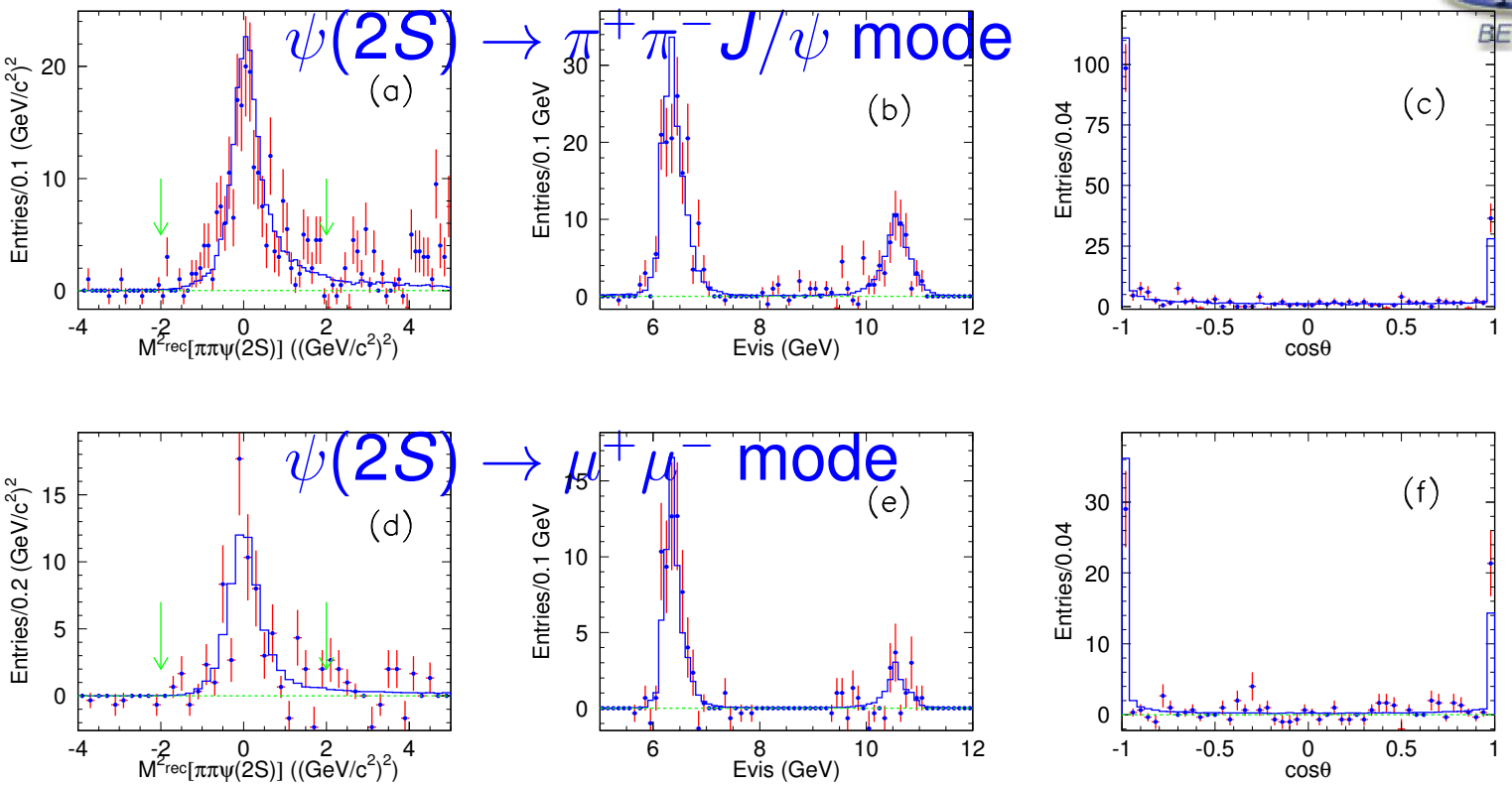

PRL101,172001(2008)




- Belle has about 1 $\mathrm{ab}^{-1}$ data after 2010, and efficiency increases after data reprocessed.
- Many more signal events are expected!
- Search for possible intermediate state(s) in $Y$ decays.

# ISR characteristics

Improvements: selection criteria; $\psi(2S) \to \mu^+\mu^-$ mode include

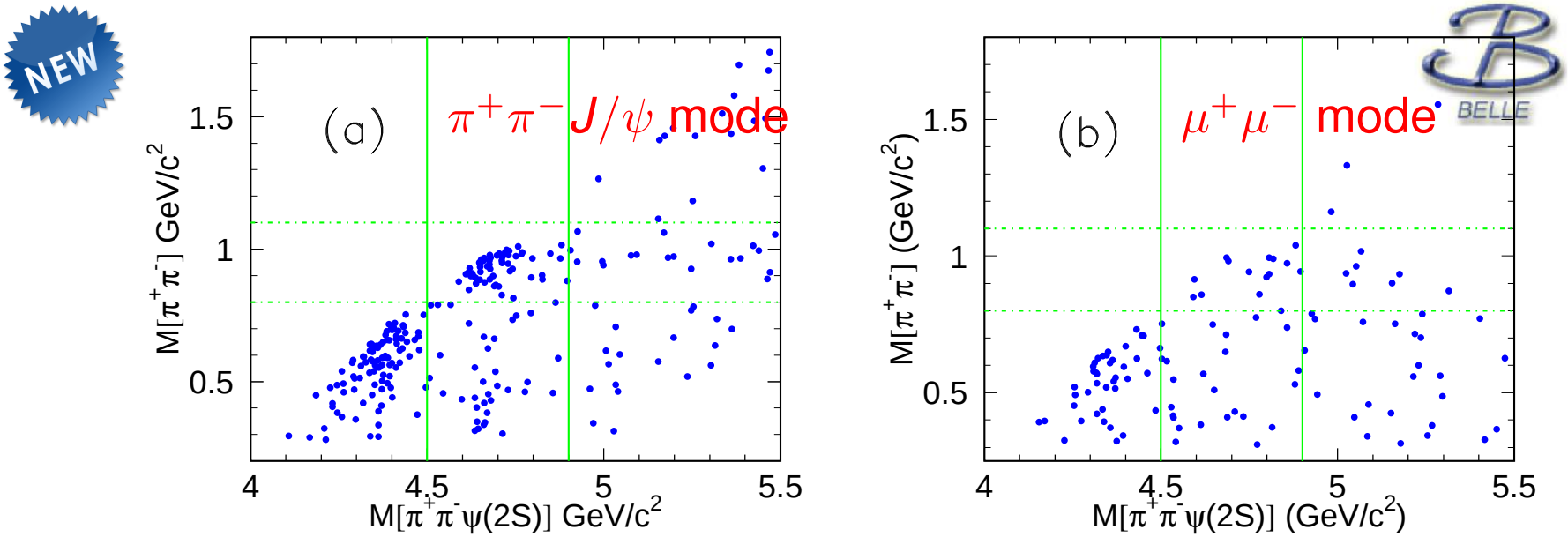



- **Missing mass:** signal of $\gamma_{\rm ISR}$. $-2 < M^2_{\rm rec}(\pi^+\pi^-\psi(2S)) < 2$ (GeV/$c^2$)$^2$ is required.
- **Visible energy:** $\gamma_{\rm ISR}$ is detected roughly 20% of the time.
- **Angular distribution:** $\gamma_{\rm ISR}$ highly forward/backward.

**arXiv:1410.7641, submitted to PRD.**

# $M_{\pi^+\pi^-}$ vs. $M_{\pi^+\pi^-\psi(2S)}$

After the selection criteria, we get pure $\pi^+\pi^- \psi(2S)$ events.




- **Clear clusters!**
- **Purity:** 245 candidate events with a purity of 96% from $\pi^+\pi^- J/\psi$ mode, and 118 events with a purity of 60% from $\mu^+\mu^-$ mode.
- $M_{\pi^+\pi^-}$**:** tends to the phase space boundary; $f_0(980)$ belts.

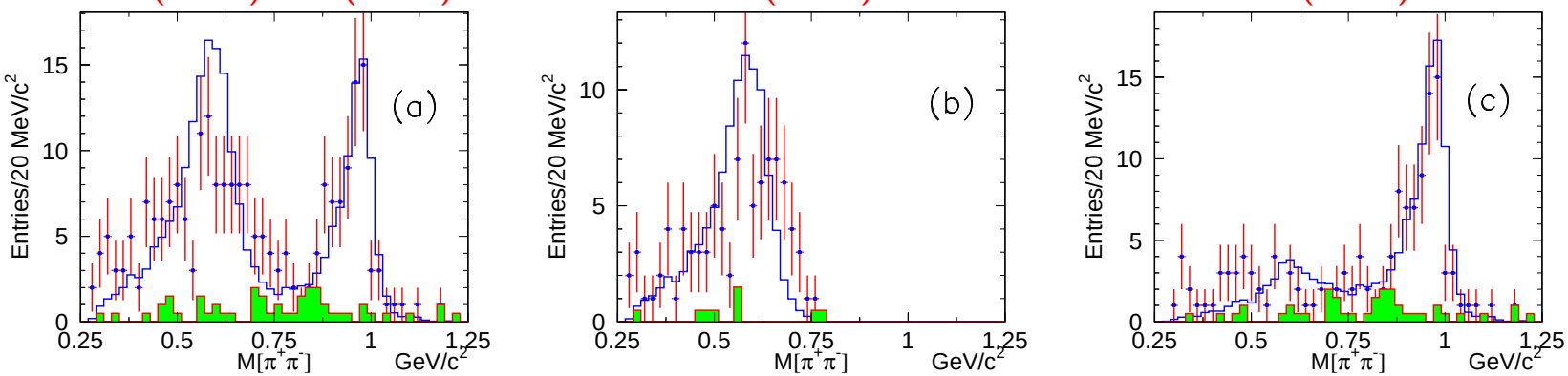
**arXiv:1410.7641**

# $M_{\pi^+\pi^-}$ projections in $\pi^+\pi^- J/\psi$

It's not so clean in $\mu^+\mu^-$ mode, due to the width of sidebands:

Mass resolution: $\sigma_{\pi^+\pi^- J/\psi} = 2.7 \pm 0.2$ MeV/$c^2$, $\sigma_{\mu^+\mu^-} = 13.8 \pm 2.1$ MeV/$c^2$.

$Y(4360) + Y(4660)$ $Y(4360)$ $Y(4660)$



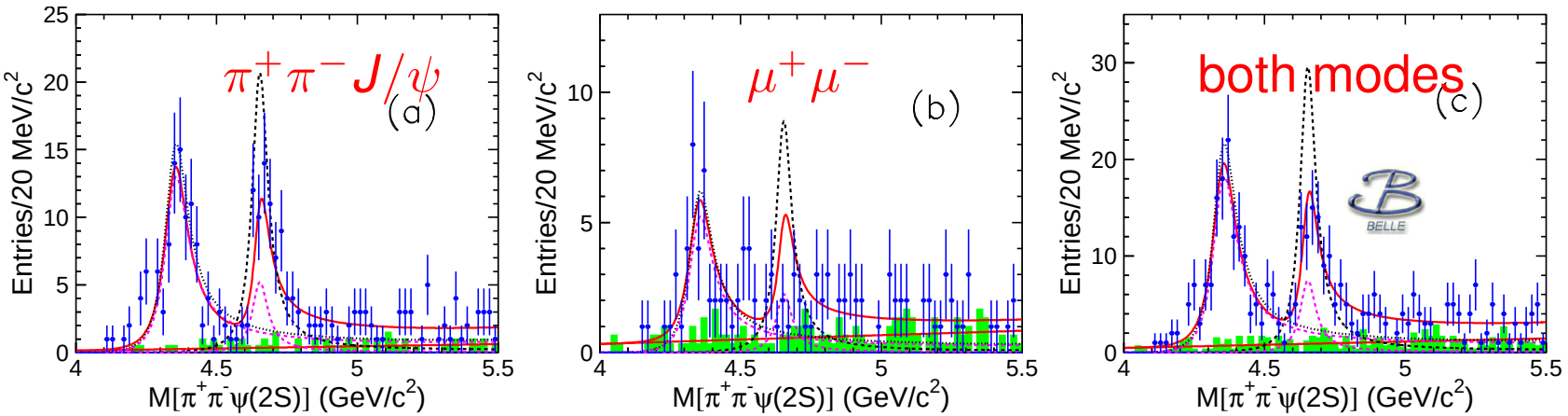

- `Dots`: data; `Blank hist`: MC simulations; `Shaded hist`: bkg from $\psi(2S)$ sidebands.
- **(a)** with $4.0 < M_{\pi^+\pi^-\psi(2S)} < 5.5$ GeV/$c^2$.
- $Y(4360)$: $4.0 < M_{\pi^+\pi^-\psi(2S)} < 4.5$ GeV/$c^2$, looks like $f_0(500)$
- $Y(4660)$: $4.5 < M_{\pi^+\pi^-\psi(2S)} < 4.9$ GeV/$c^2$, $f_0(980)$ determined by BaBar.

MC simulation with an incoherent sum of the $f_0(500)$ and $f_0(980)$.

# Fit of $M_{\pi^+\pi^-\psi(2S)}$ spectrum with two resonances

NEW

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) | $2.0 \pm 0.3 \pm 0.2$ | $8.1 \pm 1.1 \pm 1.0$ |
| $\phi$ (°) | $32 \pm 18 \pm 20$ | $272 \pm 8 \pm 7$ |

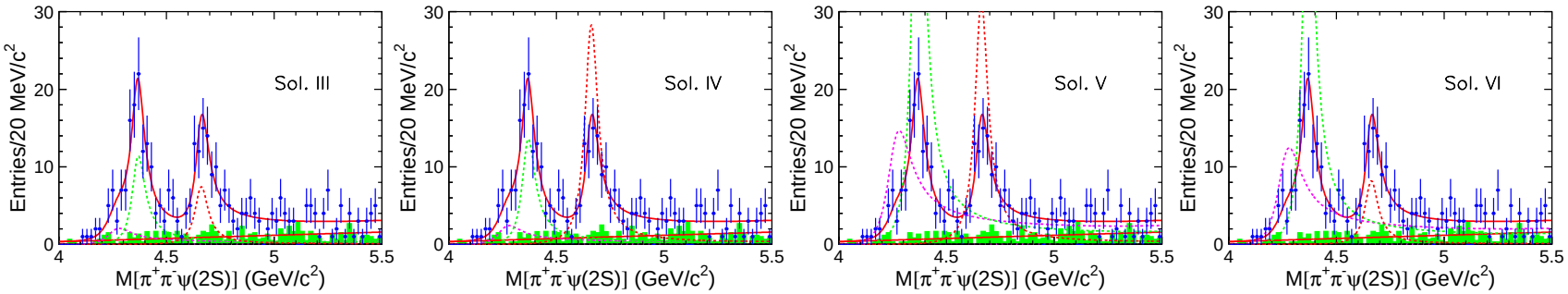
$\chi^2/ndf = 18.7/21$ .

- 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, ...

# Fit of $M_{\pi^+\pi^-\psi(2S)}$ spectrum with three resonances

NEW

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) | $2.2 \pm 0.4 \pm 0.2$ | $8.4 \pm 0.9 \pm 0.9$ | $9.3 \pm 1.2 \pm 1.0$ | $2.4 \pm 0.5 \pm 0.3$ |
| $\phi_1$ ($^\circ$) | $304 \pm 24 \pm 21$ | $294 \pm 25 \pm 23$ | $130 \pm 4 \pm 2$ | $141 \pm 5 \pm 4$ |
| $\phi_2$ ($^\circ$) | $26 \pm 19 \pm 10$ | $238 \pm 14 \pm 21$ | $329 \pm 8 \pm 5$ | $117 \pm 23 \pm 25$ |

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

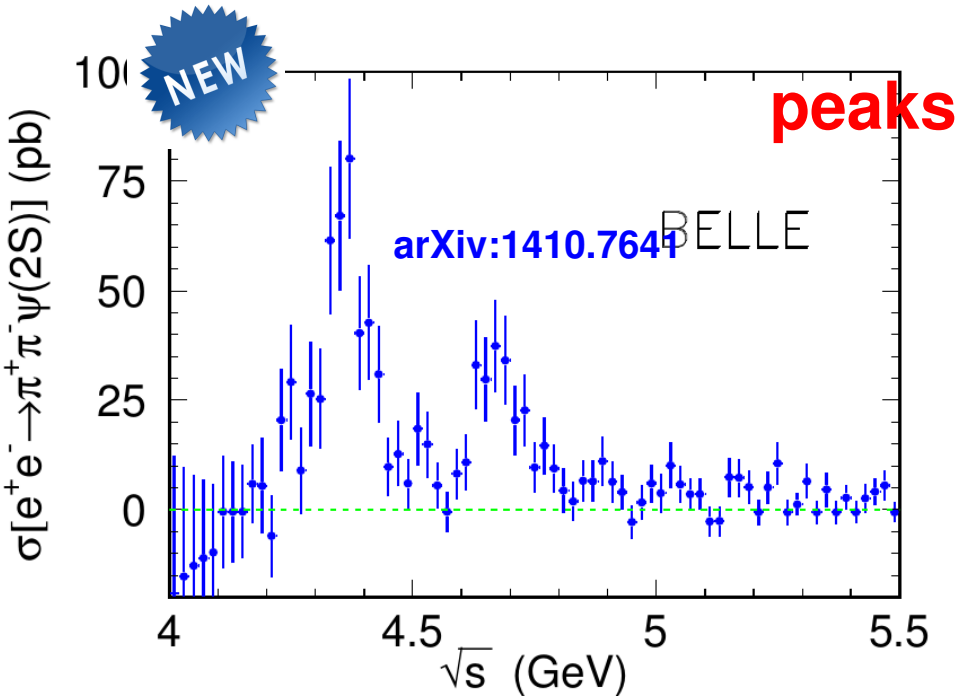
FOUR solutions with equally good fit quality, which is $\chi^2/ndf = 14.8/19$.

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

$e^+e^- \to \pi^+\pi^-\psi(2S)$ cross section is calculated with

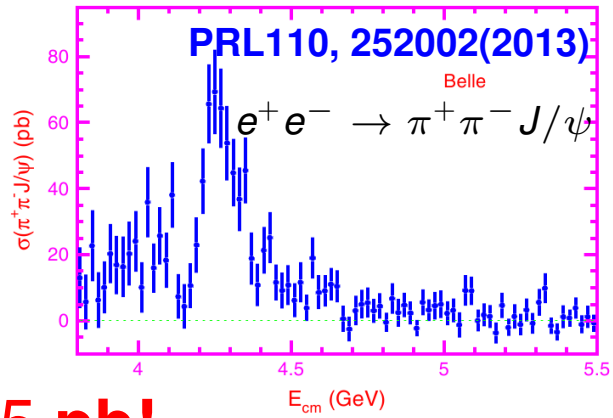
$$\sigma_i = \frac{n_i^{\rm obs} - n_i^{\rm bkg}}{\mathcal{L}_i \sum_{j=1}^{2} \varepsilon_{ij}\mathcal{B}_j},$$

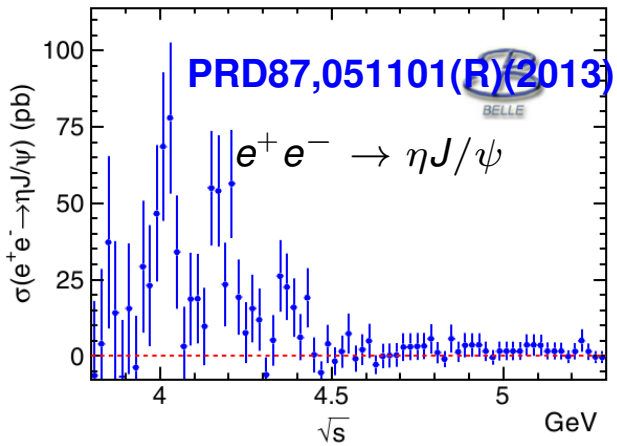
where $i$ indicates the mass bin and $j$ indicates the $\psi(2S)$ decay mode.




**peaks $\sim$ 75 pb!**

Other cross sections from ISR:



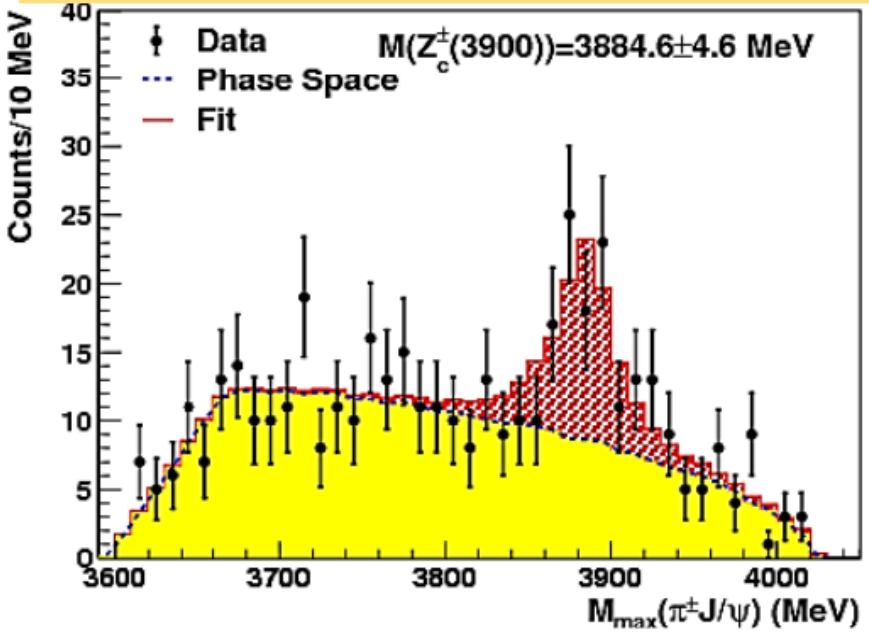

The $\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ at $Y(4260)$, $\sigma(e^+e^- \to \pi^+\pi^-\psi(2S))$ at $Y(4360)$ and $\sigma(e^+e^- \to \eta J/\psi)$ at $\psi(4040)$ are almost the same!!! WHY?

# Searh for $Z_c$

$Z_c(3900)$ observed in three experiments. Could it exist in $\pi^{\pm}\psi(2S)$ final states?

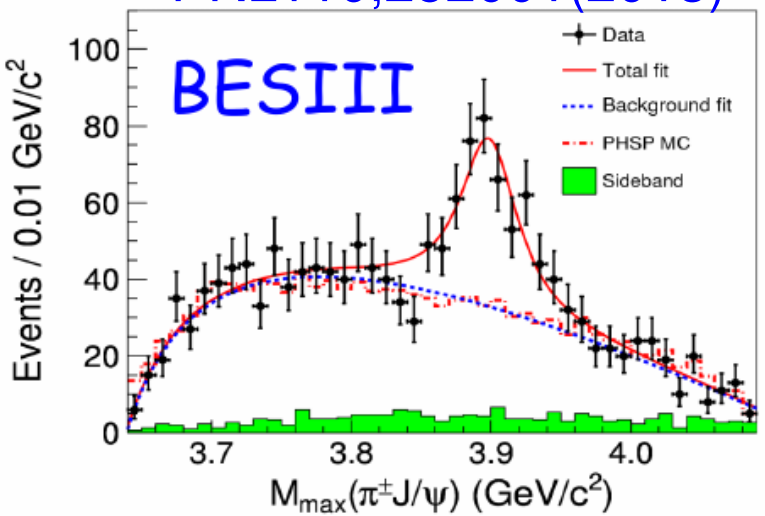
CLEOc data at 4.17 GeV:

arXiv:1304.3036, PLB727, 366 (2013)

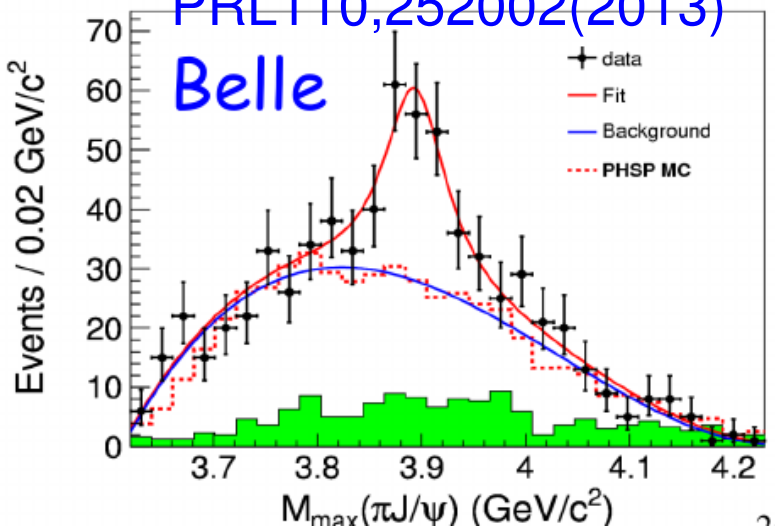



- M = 3885±5±1 MeV
- Γ = 34±12±4 MeV
- 81 ± 20 events 6.1σ

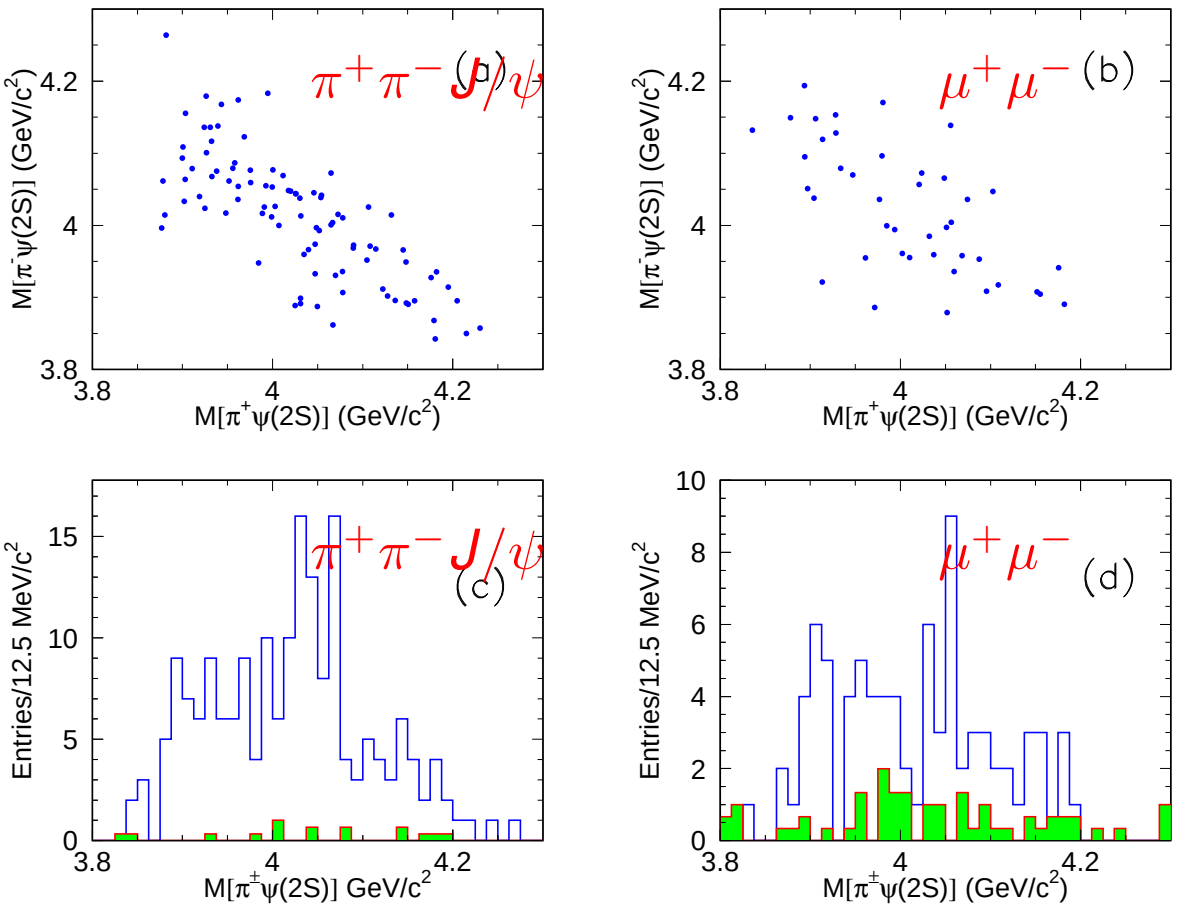
PRL110,252001(2013)




PRL110,252002(2013)



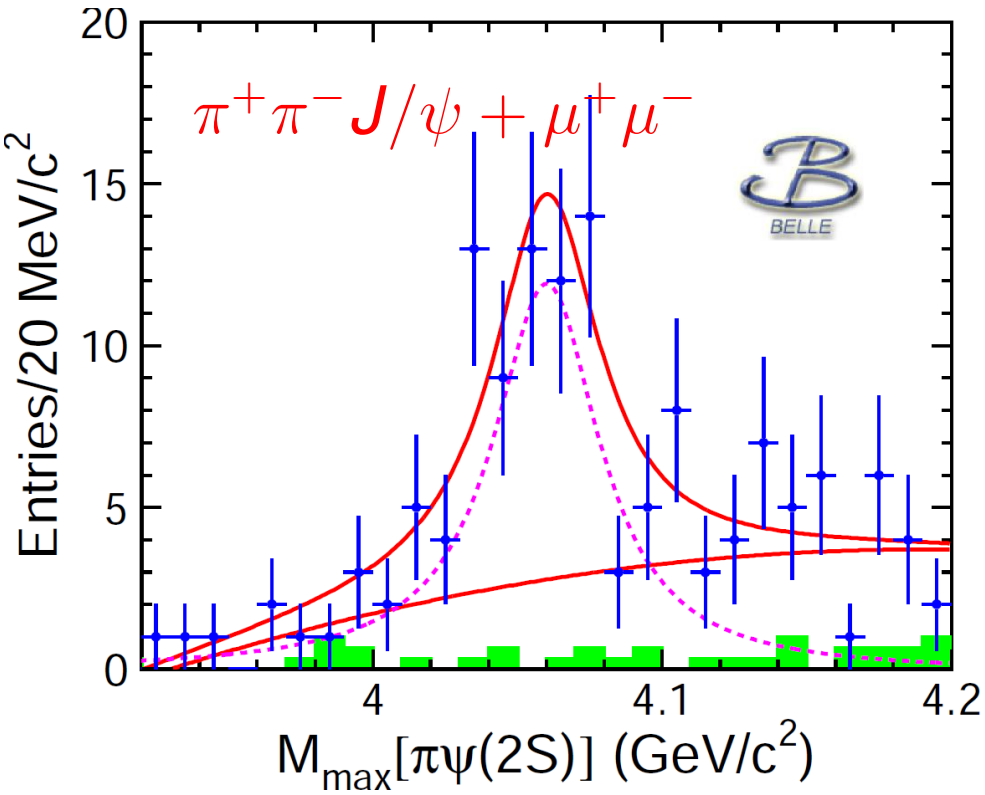
# Search for intermediate states in $Y(4360)$ decays




- An excess at both $\pi^+\pi^- J/\psi$ and $\mu^+\mu^-$ modes, and both $M_{\pi^+\psi(2S)}$ and $M_{\pi^-\psi(2S)}$! A new $Z_c$ at 4.05 GeV/$c^2$?
- $M_{\pi^\pm\psi(2S)}$: sum of the $M_{\pi^+\psi(2S)}$ and $M_{\pi^-\psi(2S)}$

# $Z_c(4050)$?

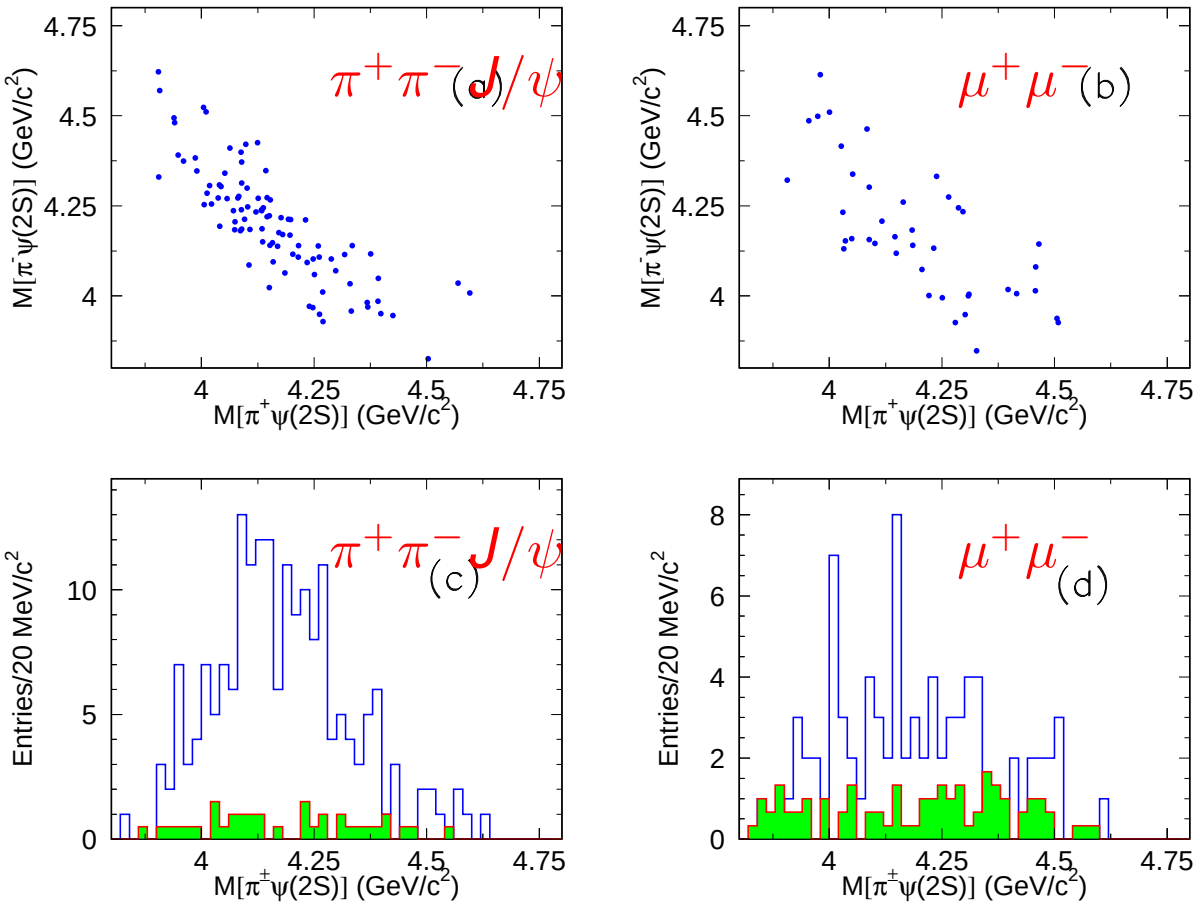
An unbinned maximum-likelihood fit is performed on the distribution of $M_{\max}(\pi^{\pm}\psi(2S))$, the maximum of $M(\pi^{+}\psi(2S))$ and $M(\pi^{-}\psi(2S))$, simultaneously with both modes.


- $M = (4054 \pm 3(\text{stat.}) \pm 1(\text{syst.}))$ MeV$/c^2$
- $\Gamma = (45 \pm 11(\text{stat.}) \pm 6(\text{syst.}))$ MeV
- The significance is $3.5\sigma$.

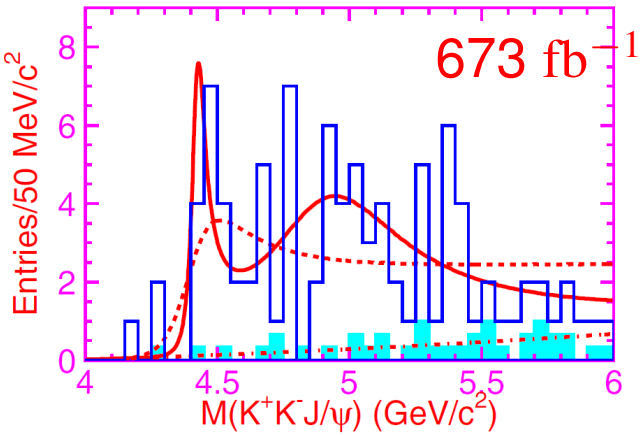
# Search for intermediate states in $Y(4660)$ decays

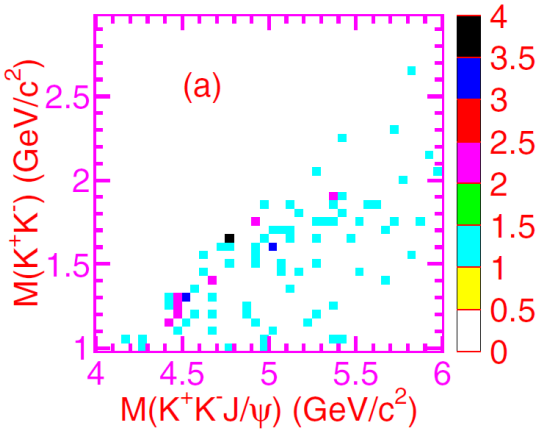
We search for intermediate states in $\pi^{\pm}\psi(2S)$ final states in $Y(4660)$ decays. No obvious excess found in the final states.

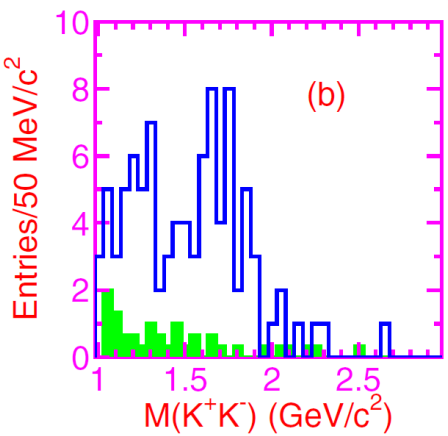


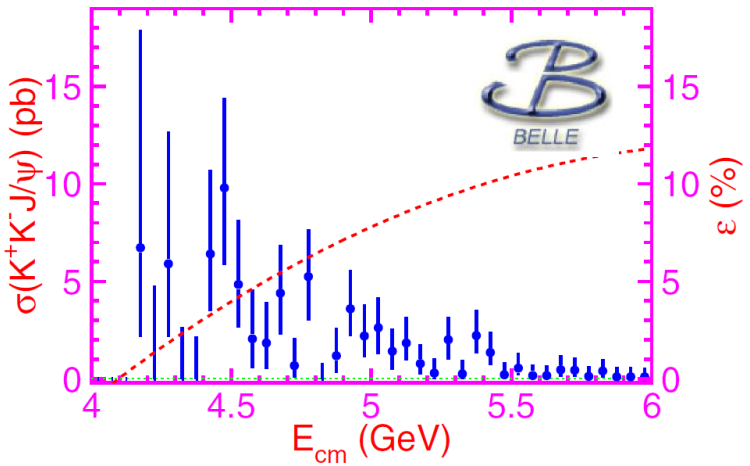

$f_0(980)\psi(2S)$ dominates in $Y(4660)$ decays.

# History: $e^+e^- \to K^+K^-J/\psi$ via ISR at Belle



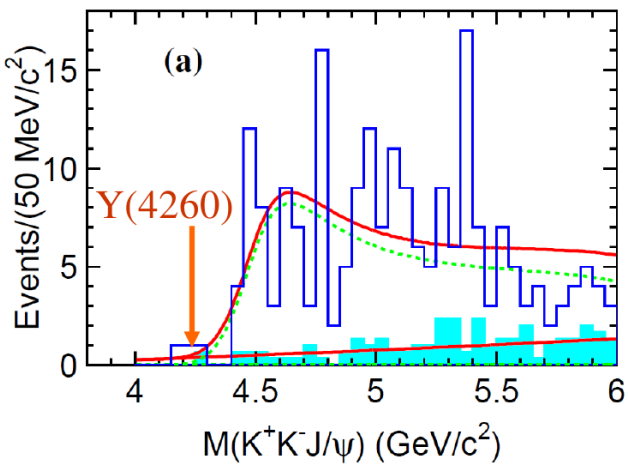



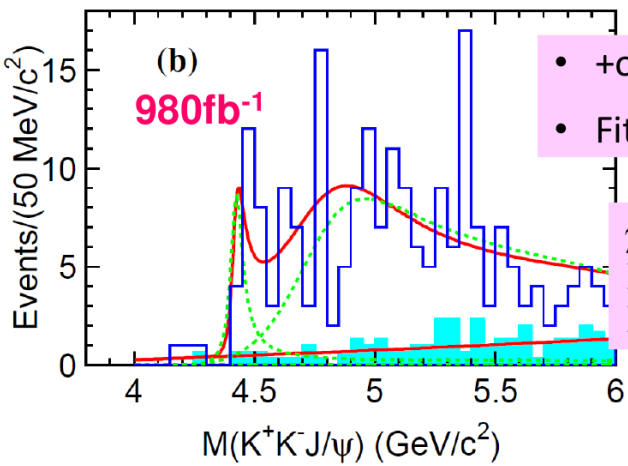




PRD77, 011105(R)(2008).

- Cross section was measured from 4 GeV to 6 GeV.
- There is one very broad structure.
- Two events near the $Y(4260)$ mass.
- Dalitz plot not shown in 2008 paper.

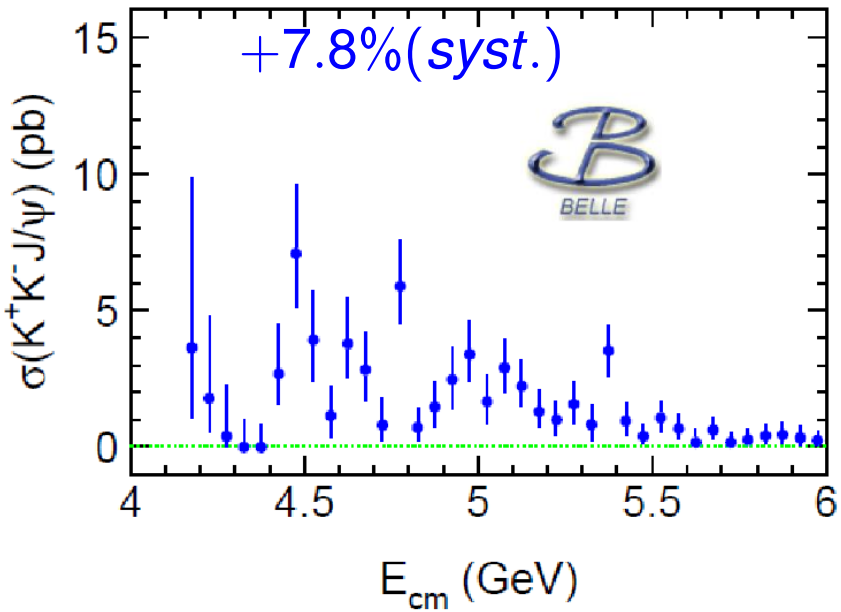
# Update on $e^+e^- \to K^+K^-J/\psi$ via ISR




- +one resonance.
- Fit with $\psi(4415)$

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

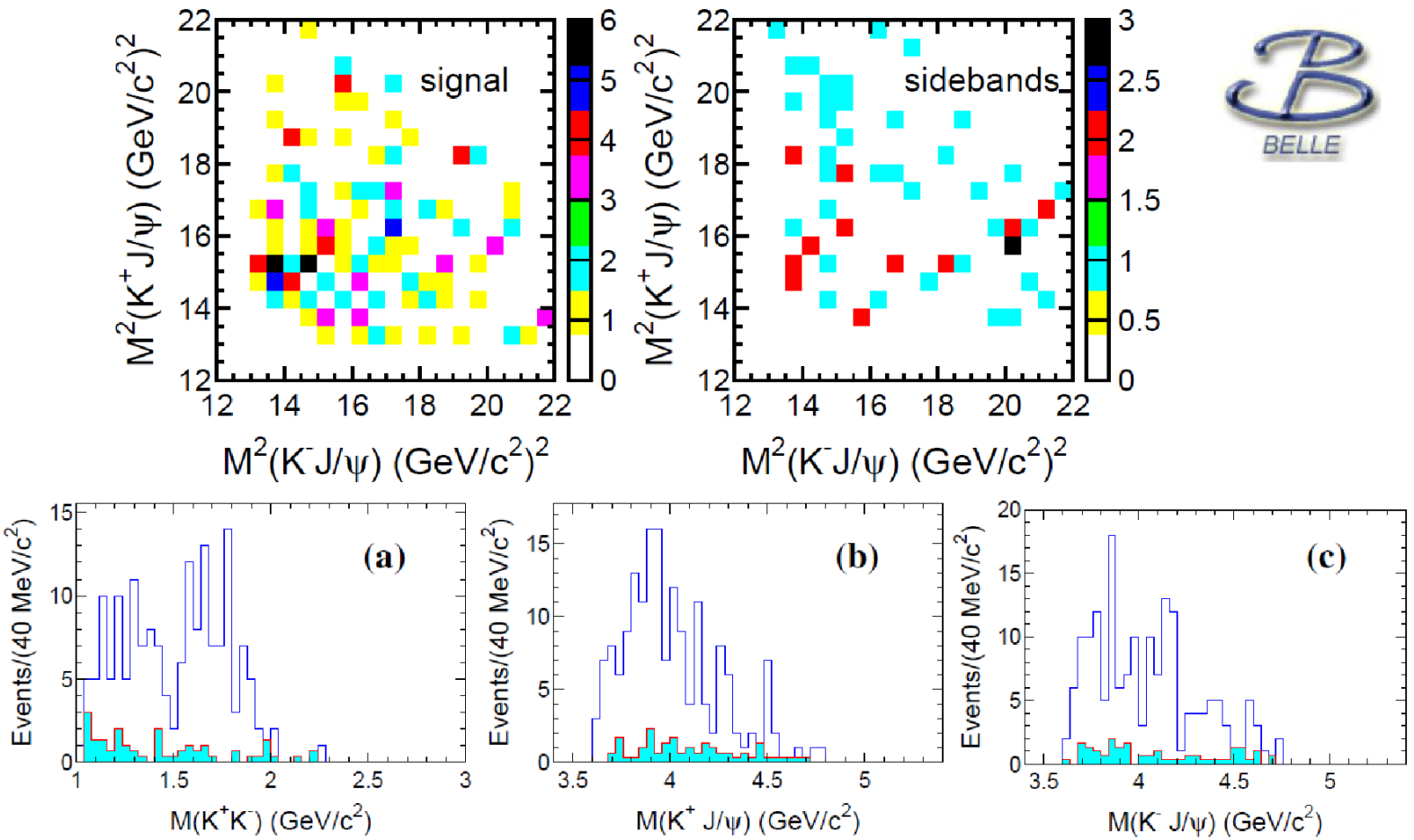



- Event selections almost same as in PRD77,011105(R)(2008).
- $4-6$ GeV, 213 events:
- $n^{\rm sig} = 178 \pm 16$, $n^{\rm bkg} = 35$.
- $\sigma_i = \frac{n_i^{\rm obs} - f \times n_i^{\rm bkg}}{\mathcal{L}_i \cdot \epsilon_i \cdot \mathcal{B}(J/\psi \to \ell^+\ell^-)}$
- Structures may be complicated!

Fit quality ($\chi^2/ndf = 30/11$) is not good, so the assumptions with structures may not match reality. Need larger data sample — Belle II.

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

Dalitz analysis performed.

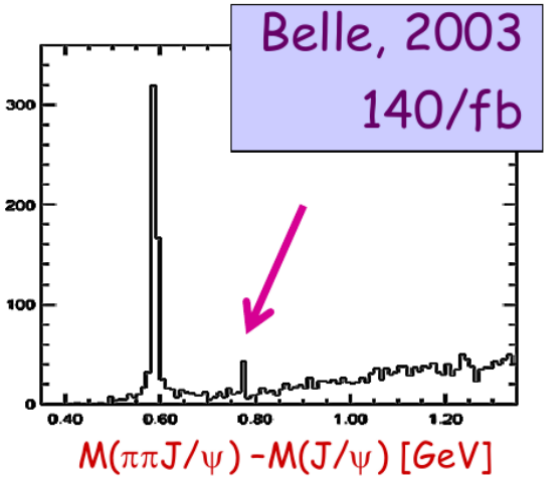



No evident structure in $K^{\pm}J/\psi$ mass distribution from current statistics.

**PRD89, 072015(2014)**

# Back to $X(3872)$

- **Mass:** Very close to $\bar{D}^0 D^{*0}$ threshold
- **Width:** Very narrow, $< 1.2$ MeV$/c^2$
- $J^{PC} = 1^{++}$
- **Production:**
  - In $p\bar{p}/pp$ – rate similar to charmonia
  - In $B$ decays – $KX/K^*X$ vs. charmonia
    - arXiv:0809.1224 (Never published!) with 605 $\text{fb}^{-1}$ Belle data
    - $\mathcal{B}(B^0 \to X(K\pi)_{NR}) \cdot \mathcal{B}(X \to J/\psi\pi^+\pi^-) = (8.1 \pm 2.0^{+1.1}_{-1.4}) \times 10^{-6}$
    - $\mathcal{B}(B^0 \to XK^*) \cdot \mathcal{B}(X \to J/\psi\pi^+\pi^-) < 3.4 \times 10^{-6}$ @90% C.L.
  - $Y(4260) \to \gamma + X(3872)$ [from BESIII]
- **Decay $\mathcal{B}$:** open charm $\sim 50\%$, charmonium $\sim O\%$
- **Nature:** (very exotic)
  - Loosely $\bar{D}^0 D^{*0}$ bound state (like deuteron?)?
  - Mixture of excited $\chi_{c1}$ and $\bar{D}^0 D^{*0}$ bound state?
  - Many other possibilities (if it's not $\chi'_{c1}$, then where is $\chi'_{c1}$?)

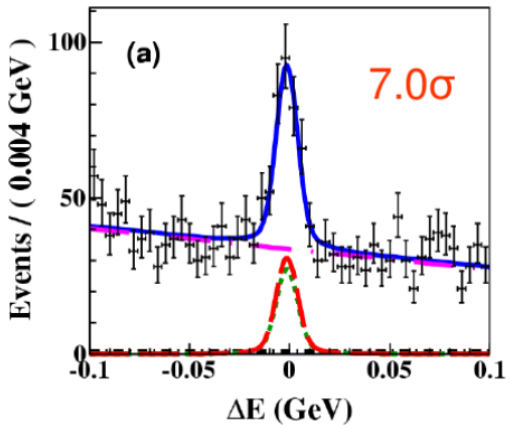


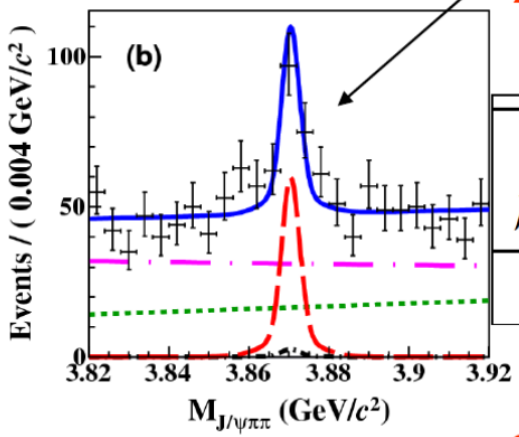

**Dr. Vishal Bhardwaj will talk on more details**

## 2D-fit to $\Delta E$ and $M(J/\psi\pi^+\pi^-)$

**PRD91,051101(R) (2015)**

### $B^0 \to X(3872)K^+\pi^-$

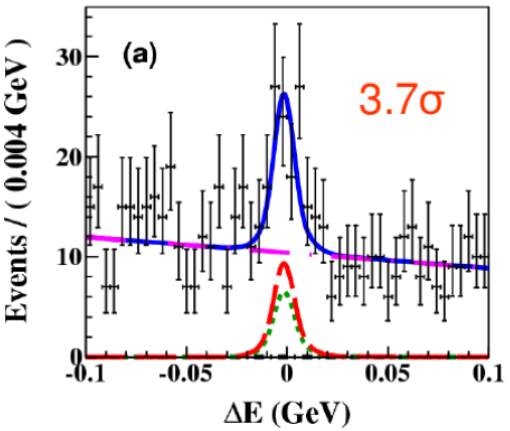


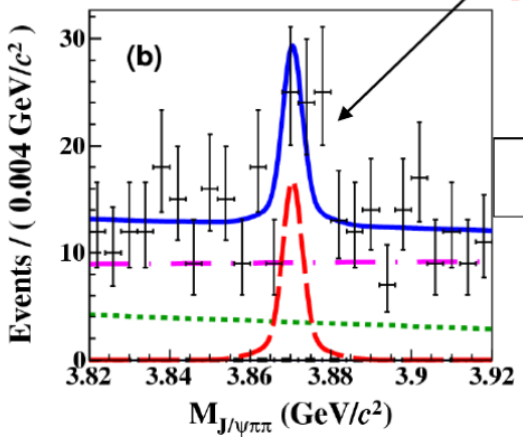




**116±19 X(3872)**

$$\mathcal{B}(B \to X(3872)K\pi) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (7.9 \pm 1.3 \pm 0.4) \times 10^{-6}$$

### $B^+ \to X(3872)K_S\pi^+$

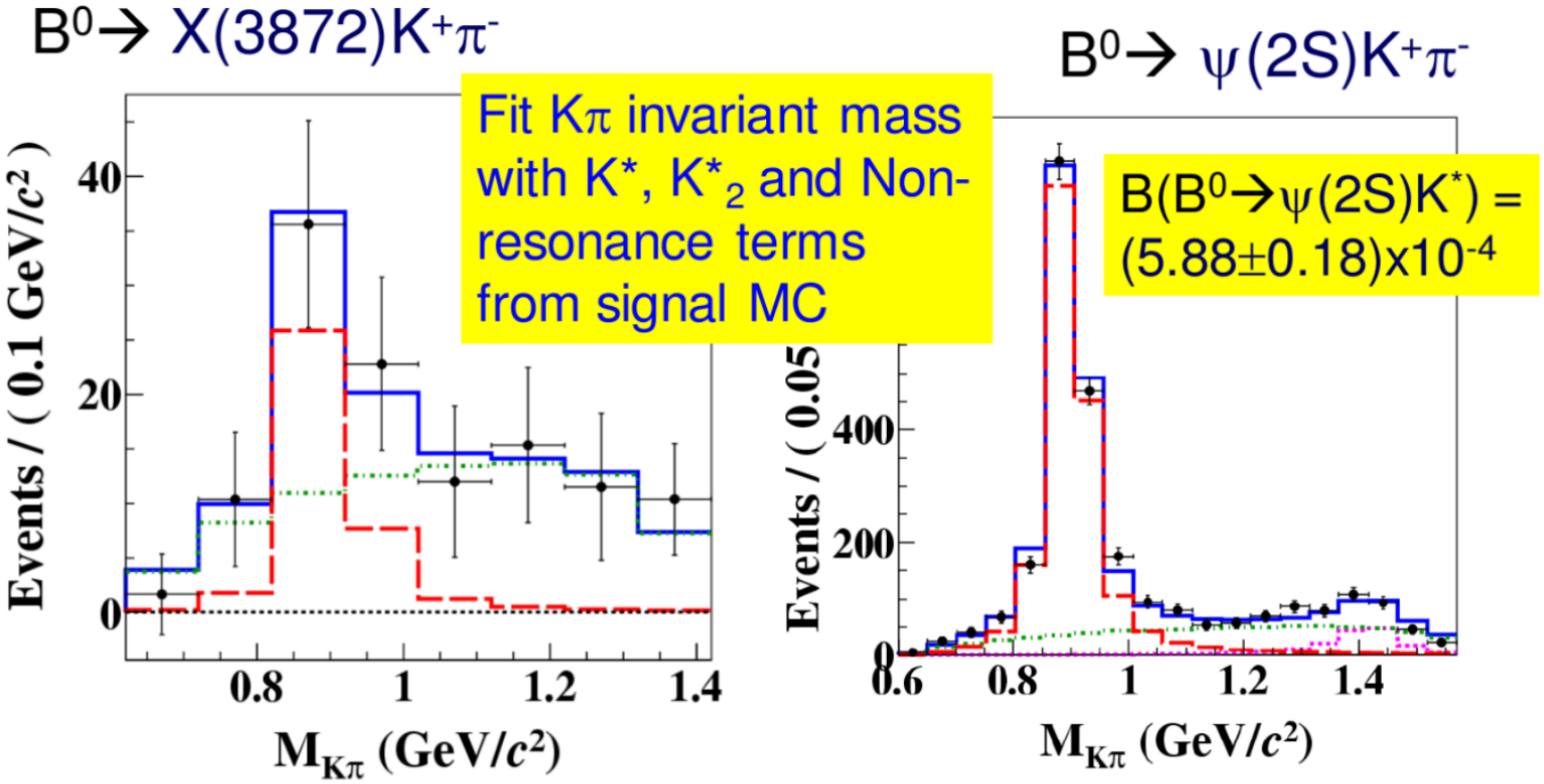



**35±10 X(3872)**

$$(10.6 \pm 3.0 \pm 0.9) \times 10^{-6}$$

# $B \to X(3872)K\pi$




$$\frac{\mathcal{B}(B^0 \to X(3872)K^*(892)^0) \times \mathcal{B}(K^*(892)^0 \to K^+\pi^-)}{\mathcal{B}(B^0 \to X(3872)K^+\pi^-)} = 0.34 \pm 0.09(stat.) \pm 0.02(syst.).$$

**PRD91, 051101(R)(2015)**

# Summary

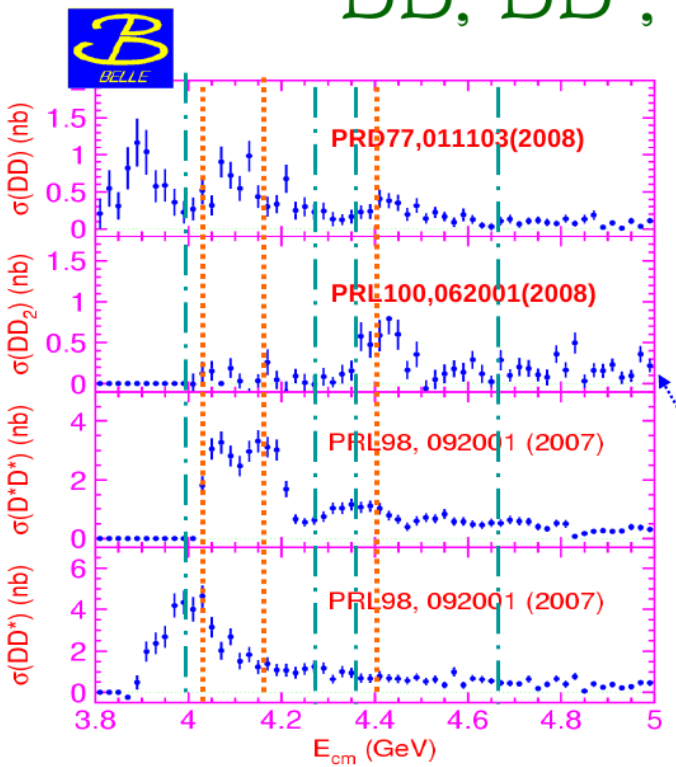
- $X$-like states are searched in $\eta_c$ modes.
- The update on $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^-\psi(2S)$ via ISR at Belle has been finished.
- The $Y(4260)$ is tried in the fit and we get four solutions. Its significance is $< 3\sigma$, but it has significant affect on $Y(4360)$ and $Y(4660)$ parameters.
- Does $Y(4660)$ agree with $X(4630)$?
  - $X(4630)$ from $\Lambda_c^+\Lambda_c^-$: $M = 4634^{+8+5}_{-7-8}$ MeV/$c^2$, $\Gamma = 92^{+40+10}_{-24-21}$ MeV/$c^2$.
  - $Y(4660)$ from 2R fit: $M = 4652 \pm 10 \pm 11$ MeV/$c^2$, $\Gamma = 68 \pm 11 \pm 5$ MeV/$c^2$.
  - $Y(4660)$ from 3R fit: $M = 4660 \pm 9 \pm 12$ MeV/$c^2$, $\Gamma = 74 \pm 12 \pm 4$ MeV/$c^2$.
- Evidence of a structure in $M_{max}(\pi^\pm\psi(2S))$ in $Y(4360)$ decays with significance of $3.5\sigma$. $Z(4050)$?

  $M = (4054 \pm 3(\text{stat.}) \pm 1(\text{syst.}))$ MeV/$c^2$; $\Gamma = (45 \pm 11(\text{stat.}) \pm 6(\text{syst.}))$ MeV
- The $e^+e^- \to K^+K^-J/\psi$ cross sections are updated. There are clear $K^+K^-J/\psi$ signal events.
- No clear $Z_{cs}$ structure is observed in $K^\pm J/\psi$ final states.
- $X(3872)$ is observed in $B \to K\pi + J/\psi\pi^+\pi^-$ decays. Non-resonant component is found to dominante the $K\pi$ final states.

# Thank you!

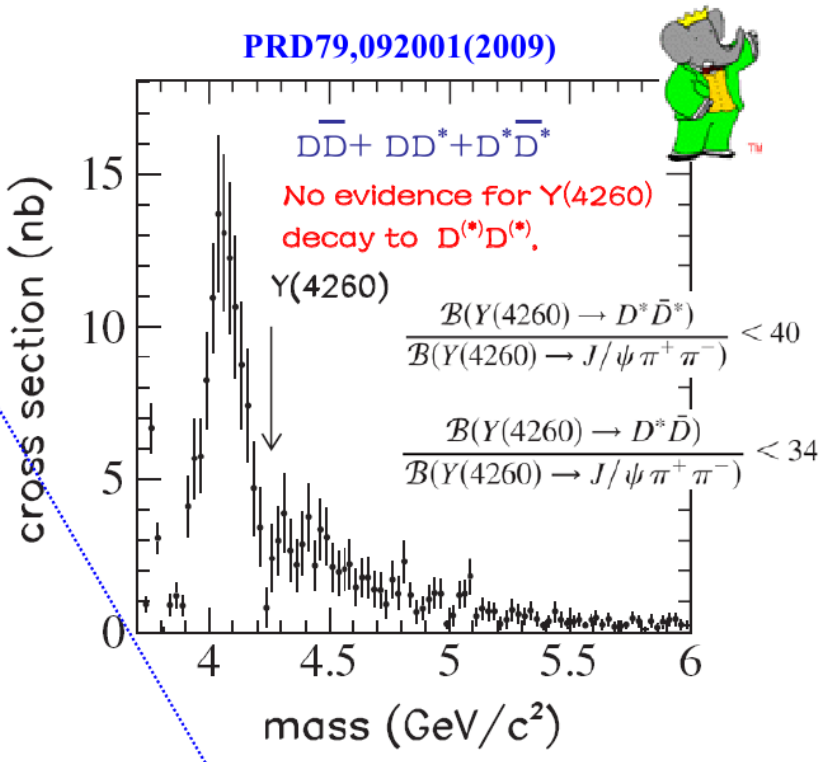
# Back-up

# $D\bar{D}$, $DD^*$, $D^*\bar{D}^*$, $D\bar{D}\pi$




: $\psi(4040)$, $\psi(4160)$, $\psi(4415)$ positions

: Y(4008), Y(4260), Y(4360),Y(4660) positions

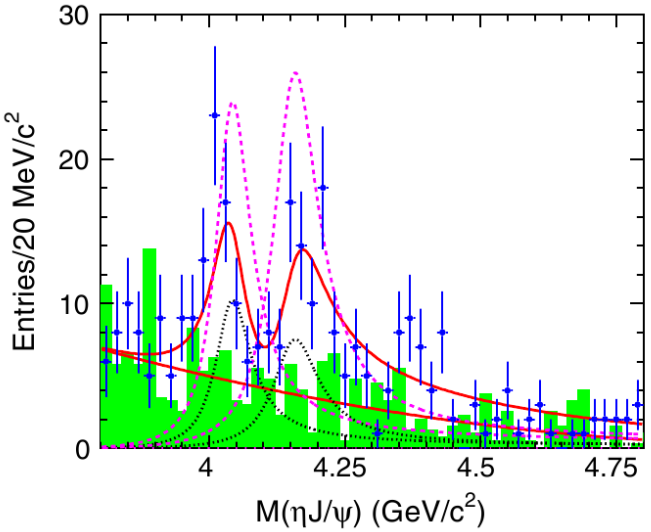



$D\bar{D}\pi$ is dominated by $DD_2(2460)$.

$e^+e^- \to D\bar{D}$ scanned by both BaBar and Belle. The results are consistent. Clear $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$. But no evidence for $Y$ states in these channels.

# $\eta J/\psi$ via ISR

Belle: Search for hadronic transition via emitting $\eta$. ($\eta \to \gamma\gamma/\pi^+\pi^-\pi^0$)




- This is the first time to found $\psi$ states in charmonium transition. ($> 6.0\sigma$ for $\psi(4040)$; $> 6.5\sigma$ for $\psi(4160)$.)
- Large $\mathcal{B}(\psi \to \eta J/\psi)$!
  $\mathcal{B}(\psi(2S) \to \eta J/\psi) = (3.28 \pm 0.07)\%$
- Unlike $\pi^+\pi^-$ transition, no significant $Y$ signal!!!

Belle: X. L. Wang *et al.*, PRD87,051101(R)(2013).

| Parameters | Solution I | Solution II |
|---|---|---|
| $M_{\psi(4040)}$ | 4039 (fixed) | |
| $\Gamma_{\psi(4040)}$ | 80 (fixed) | |
| $\mathcal{B}\cdot\Gamma^{\psi(4040)}_{e^+e^-}$ | $4.8 \pm 0.9 \pm 1.5$ | $11.2 \pm 1.3 \pm 2.1$ |
| $M_{\psi(4160)}$ | 4153 (fixed) | |
| $\Gamma_{\psi(4160)}$ | 103 (fixed) | |
| $\mathcal{B}\cdot\Gamma^{\psi(4160)}_{e^+e^-}$ | $4.0 \pm 0.8 \pm 1.4$ | $13.8 \pm 1.3 \pm 2.1$ |
| $\phi$ | $336 \pm 12 \pm 14$ | $251 \pm 4 \pm 7$ |

$\Gamma_{e^+e^-}(\psi(4040)) = (0.86 \pm 0.07)$ keV from PDG $\to$
$\mathcal{B}(\psi(4040) \to \eta J/\psi) =$
$(0.56 \pm 0.10 \pm 0.18)\%$ or $\mathcal{B}(\psi(4040) \to \eta J/\psi) = (1.30 \pm 0.15 \pm 0.26)\%$.
$\Gamma_{e^+e^-}(\psi(4160)) = (0.83 \pm 0.07)$ keV from PDG $\to$
$\mathcal{B}(\psi(4160) \to \eta J/\psi) =$
$(0.48 \pm 0.10 \pm 0.17)\%$ or $\mathcal{B}(\psi(4160) \to \eta J/\psi) = (1.66 \pm 0.16 \pm 0.29)\%$.

# Other fit results on $M_{\pi^+\pi^-\psi(2S)}$

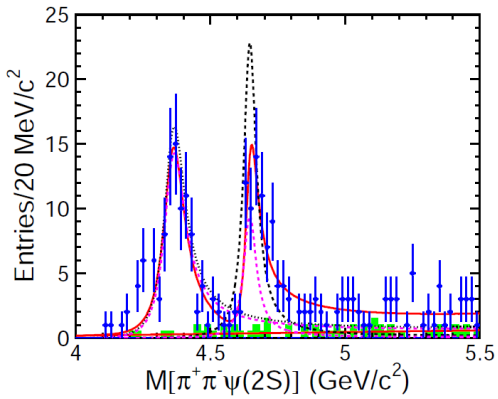
Published Belle results:

| Parameters | Solution I | Solution II |
|---|---|---|
| $M(Y(4360))$ | $4361 \pm 9 \pm 9$ | |
| $\Gamma_{\rm tot}(Y(4360))$ | $74 \pm 15 \pm 10$ | |
| $\mathcal{B}\Gamma_{e^+e^-}(Y(4360))$ | $10.4 \pm 1.7 \pm 1.5$ | $11.8 \pm 1.8 \pm 1.4$ |
| $M(Y(4660))$ | $4664 \pm 11 \pm 5$ | |
| $\Gamma_{\rm tot}(Y(4660))$ | $48 \pm 15 \pm 3$ | |
| $\mathcal{B}\Gamma_{e^+e^-}(Y(4660))$ | $3.0 \pm 0.9 \pm 0.3$ | $7.6 \pm 1.8 \pm 0.8$ |
| $\phi$ | $39 \pm 30 \pm 22$ | $-79 \pm 17 \pm 20$ |

Current BaBar results:

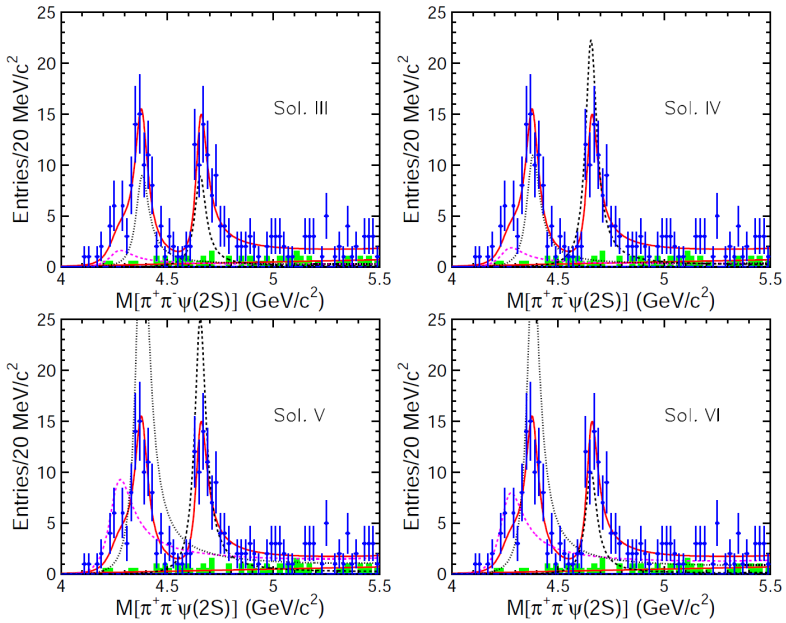
| Parameters | First Solution (constructive interference) | Second Solution (destructive interference) |
|---|---|---|
| Mass Y(4360) (MeV/c$^2$) | $4340 \pm 16 \pm 9$ | |
| Width Y(4360) (MeV) | $94 \pm 32 \pm 13$ | |
| $\mathcal{B} \times \Gamma_{ee}(Y(4360))$ (eV) | $6.0 \pm 1.0 \pm 0.5$ | $7.2 \pm 1.0 \pm 0.6$ |
| Mass Y(4660) (MeV/c$^2$) | $4669 \pm 21 \pm 3$ | |
| Width Y(4660) (MeV) | $104 \pm 48 \pm 10$ | |
| $\mathcal{B} \times \Gamma_{ee}(Y(4660))$ (eV) | $2.7 \pm 1.3 \pm 0.5$ | $7.5 \pm 1.7 \pm 0.7$ |
| $\phi$ ($^\circ$) | $12 \pm 27 \pm 4$ | $-78 \pm 12 \pm 3$ |

$\pi^+\pi^- J/\psi$ only:




| Parameters | Solution I | Solution II |
|---|---|---|
| $M_{Y(4360)}$ | $4358 \pm 6 \pm 2$ | |
| $\Gamma_{Y(4360)}$ | $96 \pm 10 \pm 6$ | |
| $\mathcal{B}[Y(4360) \to \pi^+\pi^-\psi(2S)] \cdot \Gamma^{e^+e^-}_{Y(4360)}$ | $9.4 \pm 0.8 \pm 0.7$ | $10.8 \pm 0.7 \pm 0.7$ |
| $M_{Y(4660)}$ | $4644 \pm 7 \pm 5$ | |
| $\Gamma_{Y(4660)}$ | $57 \pm 9 \pm 5$ | |
| $\mathcal{B}[Y(4660) \to \pi^+\pi^-\psi(2S)] \cdot \Gamma^{e^+e^-}_{Y(4660)}$ | $3.1 \pm 0.5 \pm 0.4$ | $7.6 \pm 1.3 \pm 0.9$ |
| $\phi$ | $10 \pm 17 \pm 12$ | $288 \pm 10 \pm 5$ |

# Fit with three resonance using $\pi^+\pi^- J/\psi$ mode




| Parameters | Solution III | Solution IV | Solution V | Solution VI |
|---|---|---|---|---|
| $M_{Y(4260)}$ | $4259$ (fixed) | | | |
| $\Gamma_{Y(4260)}$ | $134$ (fixed) | | | |
| $\mathcal{B}[Y(4260) \to \pi^+\pi^-\psi(2S)] \cdot \Gamma^{e^+e^-}_{Y(4260)}$ | $1.6 \pm 0.6 \pm 0.4$ | $1.8 \pm 0.8 \pm 0.6$ | $9.1 \pm 1.2 \pm 0.7$ | $7.8 \pm 1.1 \pm 0.8$ |
| $M_{Y(4360)}$ | $4378 \pm 9 \pm 6$ | | | |
| $\Gamma_{Y(4360)}$ | $74 \pm 14 \pm 3$ | | | |
| $\mathcal{B}[Y(4360) \to \pi^+\pi^-\psi(2S)] \cdot \Gamma^{e^+e^-}_{Y(4360)}$ | $4.5 \pm 1.0 \pm 0.4$ | $5.5 \pm 1.4 \pm 0.6$ | $19.1 \pm 2.8 \pm 1.1$ | $15.7 \pm 2.3 \pm 1.6$ |
| $M_{Y(4660)}$ | $4654 \pm 7 \pm 6$ | | | |
| $\Gamma_{Y(4660)}$ | $65 \pm 10 \pm 3$ | | | |
| $\mathcal{B}[Y(4660) \to \pi^+\pi^-\psi(2S)] \cdot \Gamma^{e^+e^-}_{Y(4660)}$ | $3.3 \pm 0.6 \pm 0.3$ | $8.3 \pm 1.0 \pm 0.9$ | $9.3 \pm 1.2 \pm 1.2$ | $3.7 \pm 0.7 \pm 0.5$ |
| $\phi_1$ | $282 \pm 25 \pm 24$ | $270 \pm 27 \pm 28$ | $130 \pm 5 \pm 3$ | $142 \pm 6 \pm 7$ |
| $\phi_2$ | $359 \pm 19 \pm 3$ | $243 \pm 17 \pm 20$ | $337 \pm 10 \pm 7$ | $93 \pm 25 \pm 17$ |