Update on $e^+e^- \to \pi^+\pi^-\psi(2S)$ via initial state radiation at Belle

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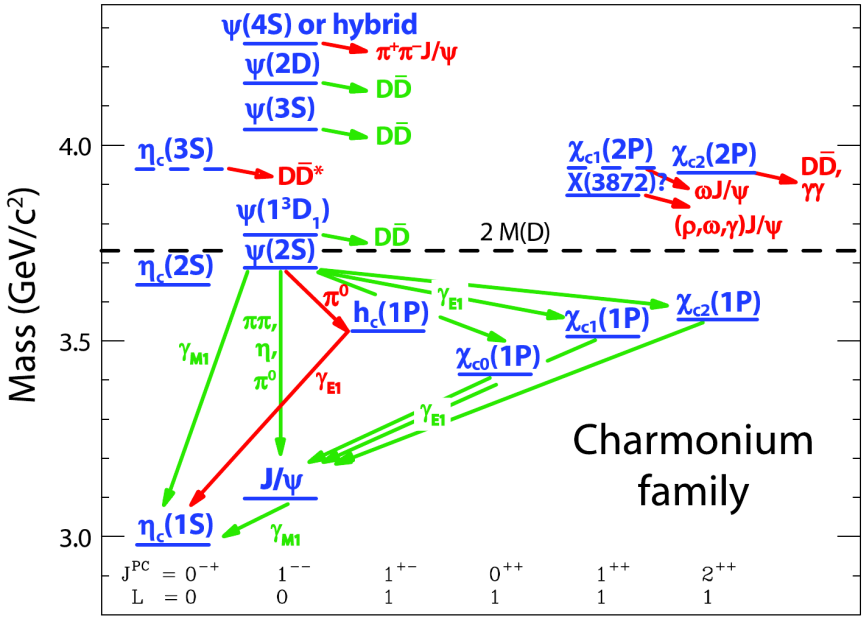
Introduction

- Potential model works very well for charmonium states below $D\bar{D}$ threshold.
- A lot of charmonum(-like) states above $D\bar{D}$ threshold were observed in the past decade.
- XYZ particles – Quarkonium-like states with many exotic properties! What is their nature? (QWG, Eur. Phy. J. C71, 1534(2011))



Eichten et al, Rev. Mod. Phys.80,1161(2008)

Example potential from Barnes, Godfrey, Swanson:

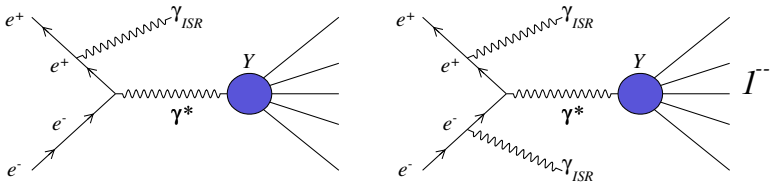
$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c\cdot\vec{S}_{\bar{c}}$$

(Coulomb + Confinement + Contact)

$$V_{\text{spin-dep}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

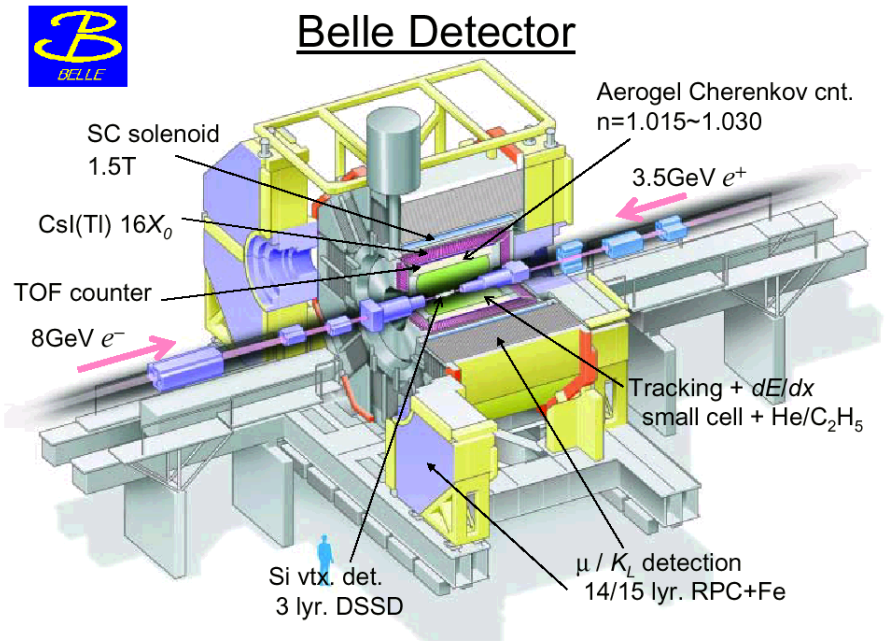
(Spin-Orbit + Tensor)

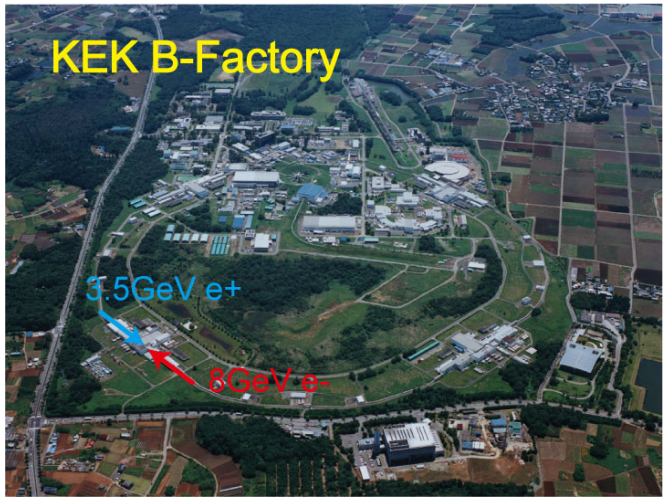
PRD72, 054026 (2005)



The charmonium(-like) states observed via ISR: $Y(4008)$, $Y(4260)$, $Y(4360)$, $Y(4660)$, $X(4630)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$, ...

KEKB and Belle





Physics targets:

CP Violation,
Spectroscopy,
τ Physics,
New Physics beyond Stand Model,
...

Belle data samples:

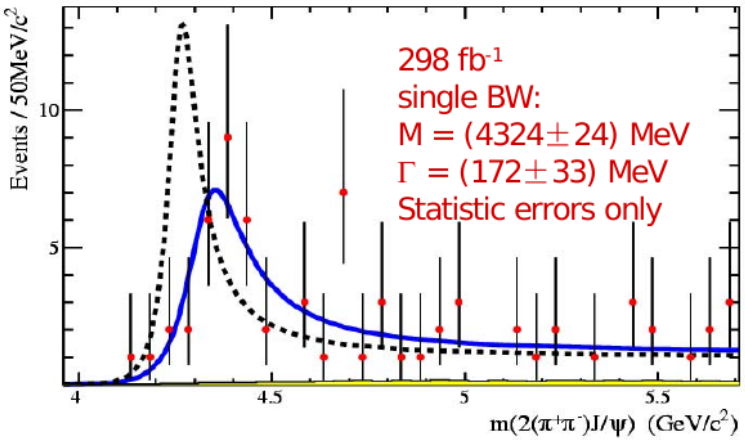
On resonances:

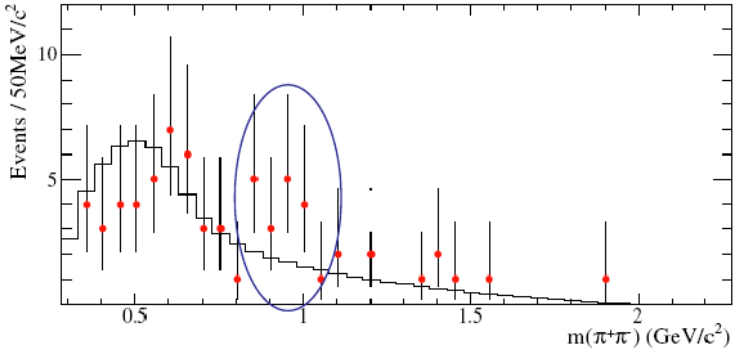
$\Upsilon(5S)$:	121 fb^{-1}
$\Upsilon(4S)$:	711 fb^{-1}
$\Upsilon(3S)$:	3 fb^{-1}
$\Upsilon(2S)$:	25 fb^{-1}
$\Upsilon(1S)$:	5.8 fb^{-1}

Off reson./scan:
100 fb^{-1}
Total: 984 fb^{-1}

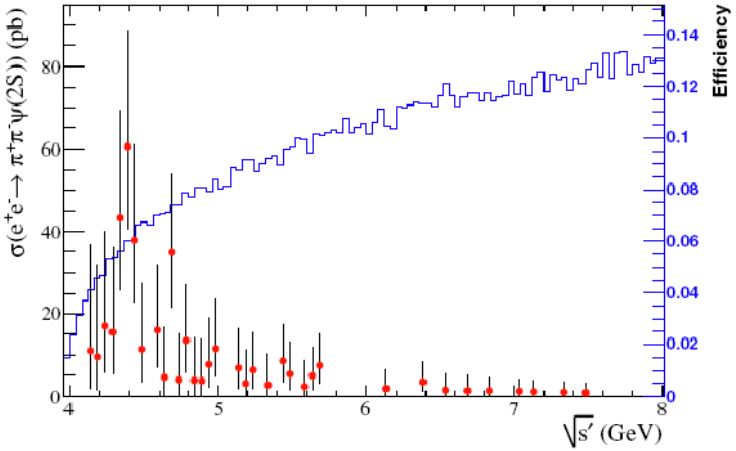
First $\pi^+\pi^-\psi(2S)$ scan at BaBar

BaBar searched for $Y(4260)$ in $\pi^+\pi^-\psi(2S)$ final states.





Significant enhancement but with a mass inconsistent with Y(4260).

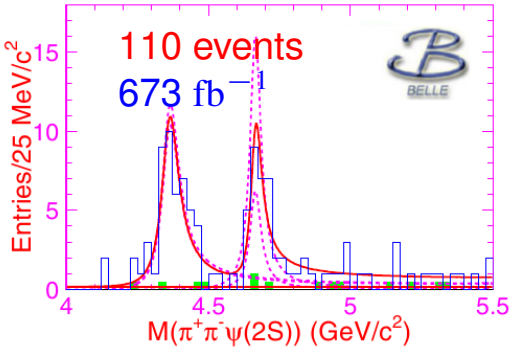


BaBar: B. Aubert *et al.*, PRL98, 212001(2007).

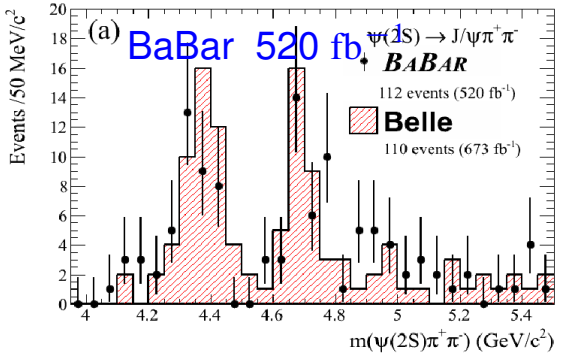
Update on $e^+e^- \to \pi^+\pi^-\psi(2S)$ via ISR

- $Y(4360)$ 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?

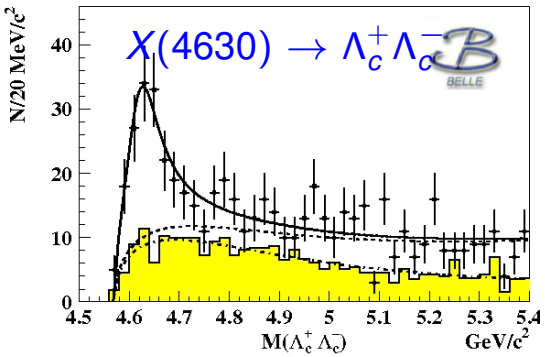
PRL99,142002(2007)



PRD89,111103(R)(2014)

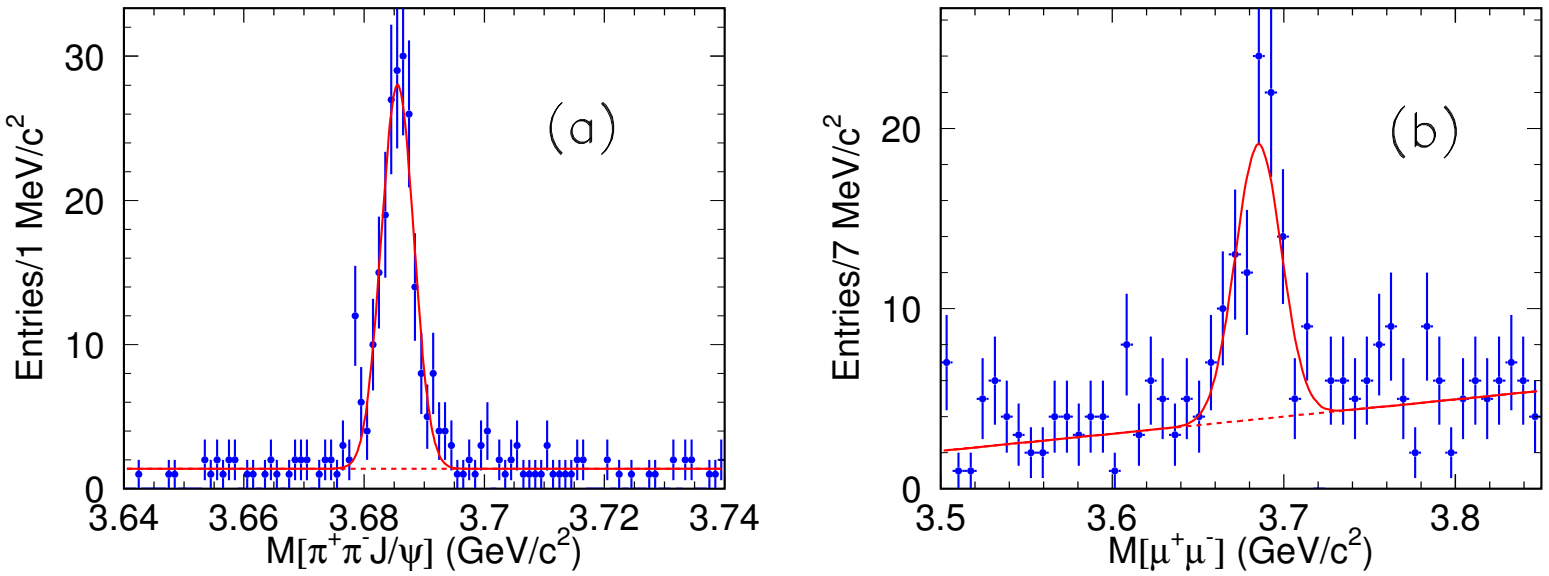


PRL101,172001(2008)



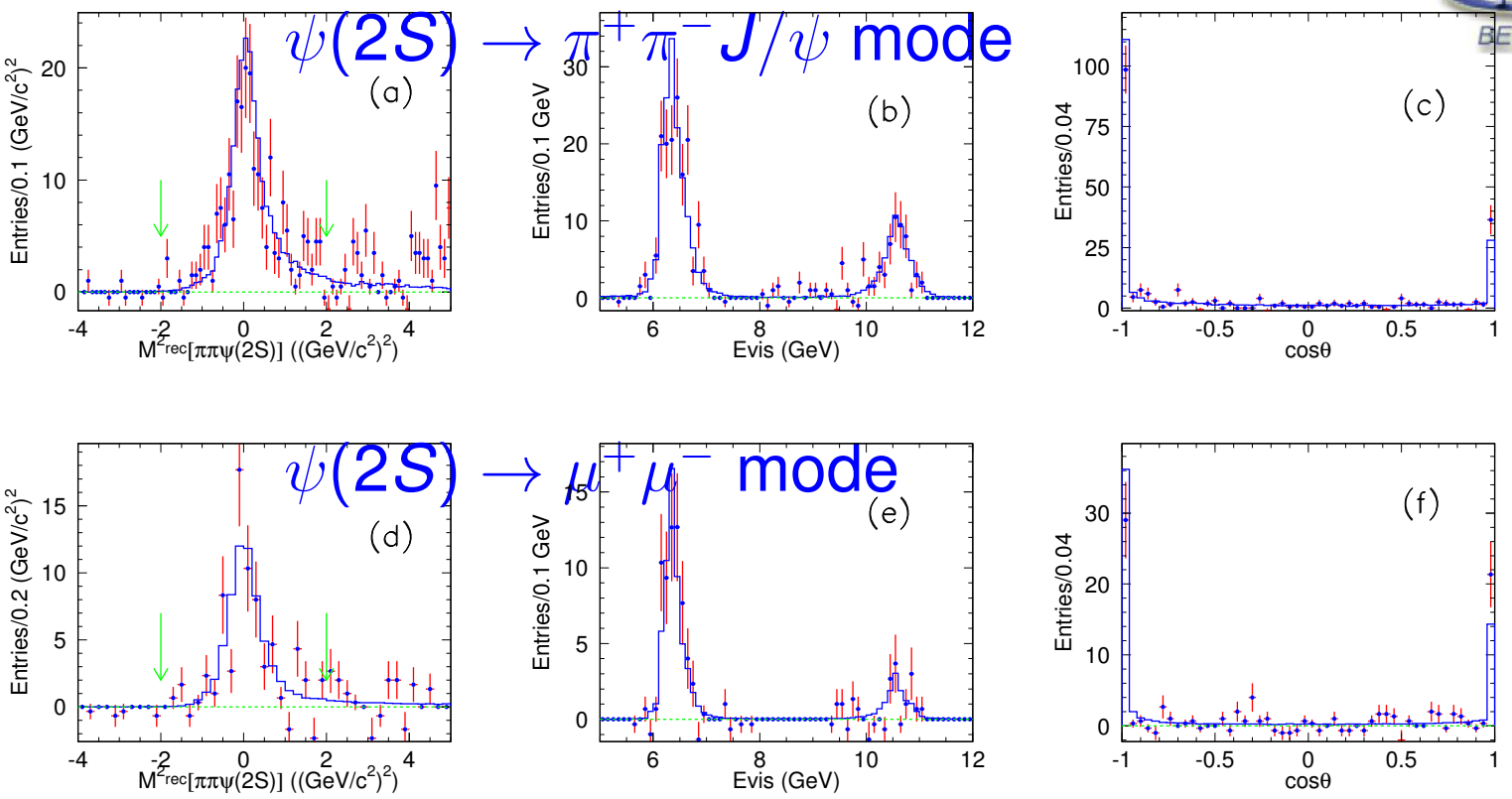
- Belle has about 1 ab^{-1} data after 2010, and efficiency increases after data reprocessed.
- Many more signal events are expected!
- Search for possible intermediate state(s) in Y decays.

$\psi(2S)$ signals



- $\psi(2S) \to \pi^+\pi^- J/\psi$ mode: selection criteria optimized.
  $M_{\psi(2S)} = M_{\pi^+\pi^-\ell^+\ell^-} - M_{\ell^+\ell^-} + m_{J/\psi}$
- $\psi(2S) \to \mu^+\mu^-$ mode: a new mode.
- $\psi(2S) \to e^+e^-$ mode is not used due to high background level.
- Mass resolution:
  $\sigma_{\pi^+\pi^- J/\psi} = 2.7 \pm 0.2$ MeV$/c^2$, $\sigma_{\mu^+\mu^-} = 13.8 \pm 2.1$ MeV$/c^2$.

ISR characteristics

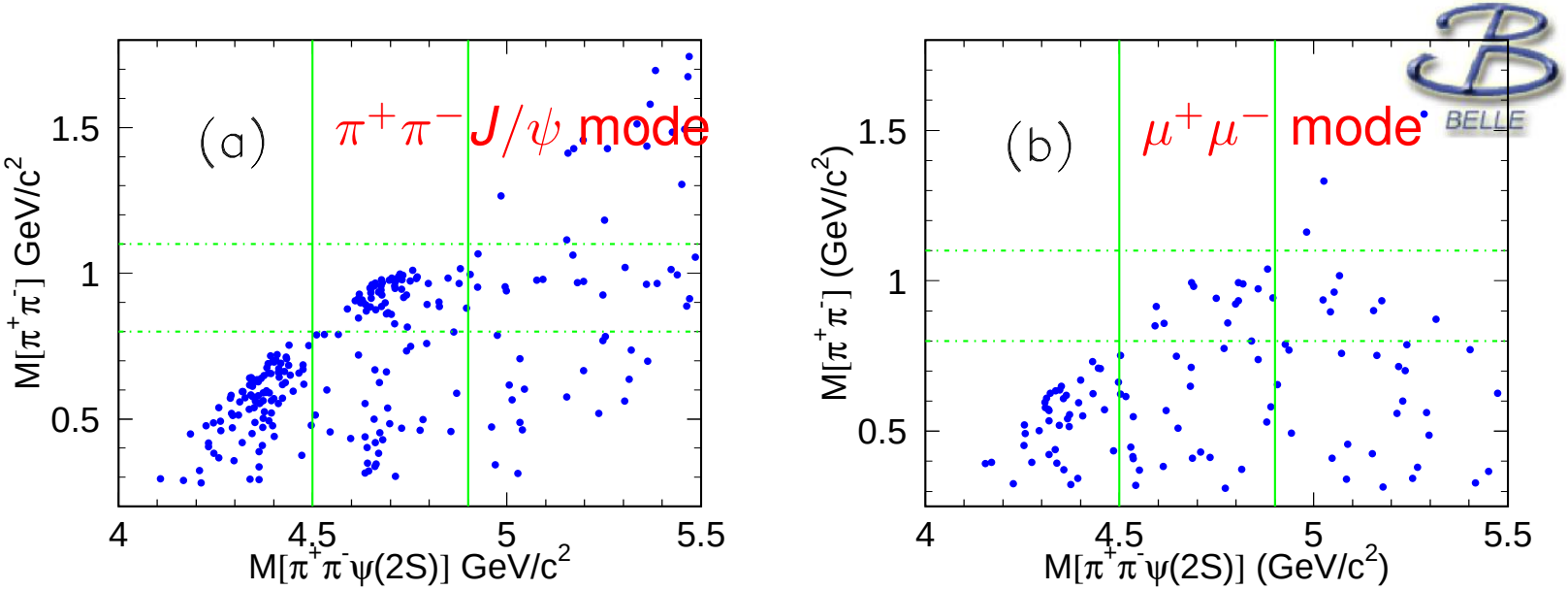


- **Missing mass:** signal of $\gamma_{\rm ISR}$. $-2 < M^2_{\rm rec}(\pi^+\pi^-\psi(2S)) < 2\ ({\rm GeV}/c^2)^2$ is required.
- **Visible energy:** Only 10-20% $\gamma_{\rm ISR}$ can be detected.
- **Angular distribution:** $\gamma_{\rm ISR}$ highly forward/backward.

PRD91, 112007(2015)

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

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



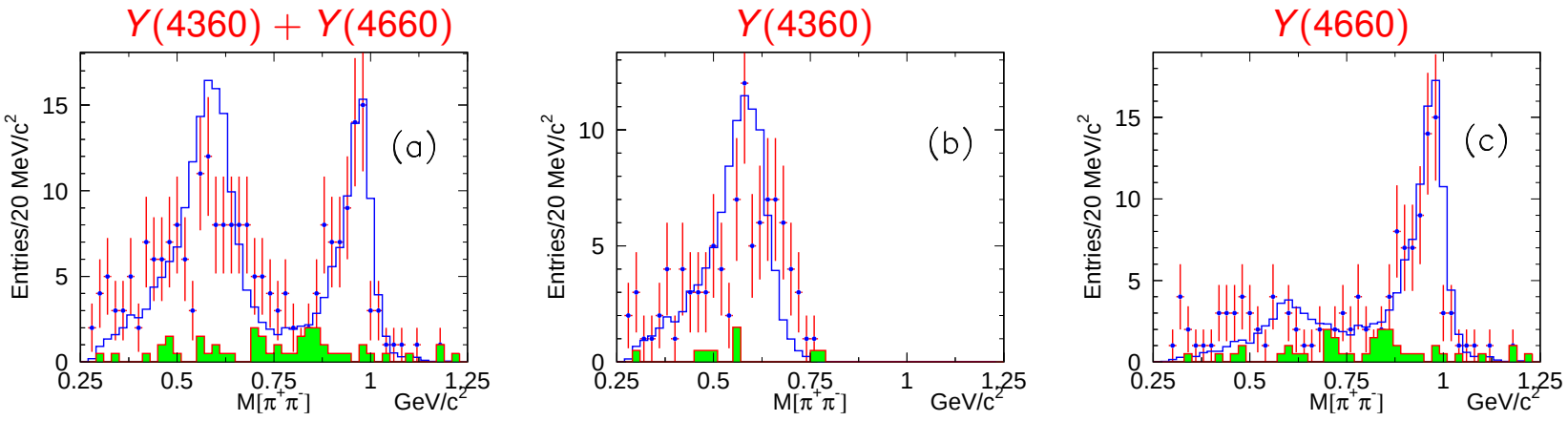
- **Clear clusters!**
- **Purity:** 245 candidate events with a purity of 96% from $\pi^+\pi^- J/\psi$ mode, and 118 events with a purity of 60% from $\mu^+\mu^-$ mode.
- $M_{\pi^+\pi^-}$**:** tends to the phase space boundary; $f_0(980)$ belts.

PRD91, 112007(2015)

$M_{\pi^+\pi^-}$ 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$/c^2$.

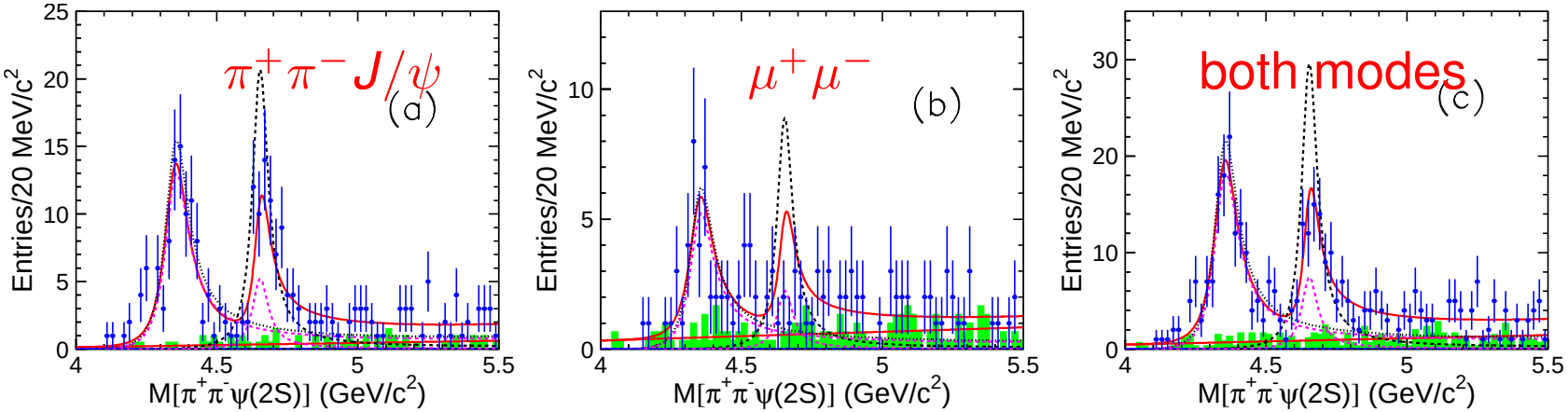


- `Dots`: data; `Blank hist`: MC simulations; `Shaded hist`: bkg from $\psi(2S)$ sidebands.
- **(a)** with $4.0 < M_{\pi^+\pi^-\psi(2S)} < 5.5$ GeV$/c^2$.
- $Y(4360)$**:** $4.0 < M_{\pi^+\pi^-\psi(2S)} < 4.5$ GeV$/c^2$, looks like $f_0(500)$
- $Y(4660)$**:** $4.5 < M_{\pi^+\pi^-\psi(2S)} < 4.9$ GeV$/c^2$,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

Unbinned simultaneous maximum likelihood fit for $Y(4360)$ and $Y(4660)$: $Amp = BW_1 + e^{i\phi} \cdot BW_2$.



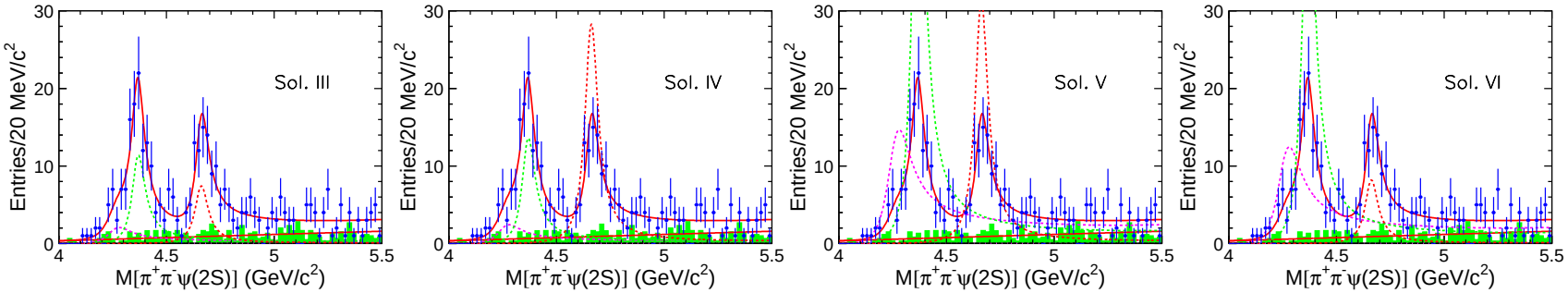
Parameters	Solution I	Solution II
$M_{Y(4360)}$ (MeV/c^2)	$4347 \pm 6 \pm 3$	
$\Gamma_{Y(4360)}$ (MeV)	$103 \pm 9 \pm 5$	
$\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4360)}$ (eV)	$9.2 \pm 0.6 \pm 0.6$	$10.9 \pm 0.6 \pm 0.7$
$M_{Y(4660)}$ (MeV/c^2)	$4652 \pm 10 \pm 11$	
$\Gamma_{Y(4660)}$ (MeV)	$68 \pm 11 \pm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

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

- 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

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)	$2.2 \pm 0.4 \pm 0.2$	$8.4 \pm 0.9 \pm 0.9$	$9.3 \pm 1.2 \pm 1.0$	$2.4 \pm 0.5 \pm 0.3$
ϕ_1 ($^\circ$)	$304 \pm 24 \pm 21$	$294 \pm 25 \pm 23$	$130 \pm 4 \pm 2$	$141 \pm 5 \pm 4$
ϕ_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 2.4σ—low, but affects $Y(4360)$ and $Y(4660)$ masses and widths.

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

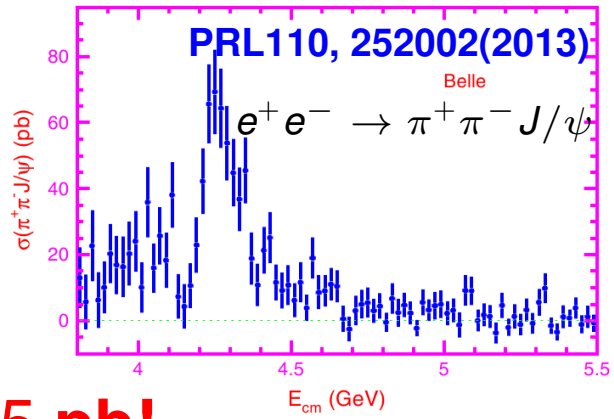
$\sigma(e^+e^- \to \pi^+\pi^-\psi(2S))$ measurement

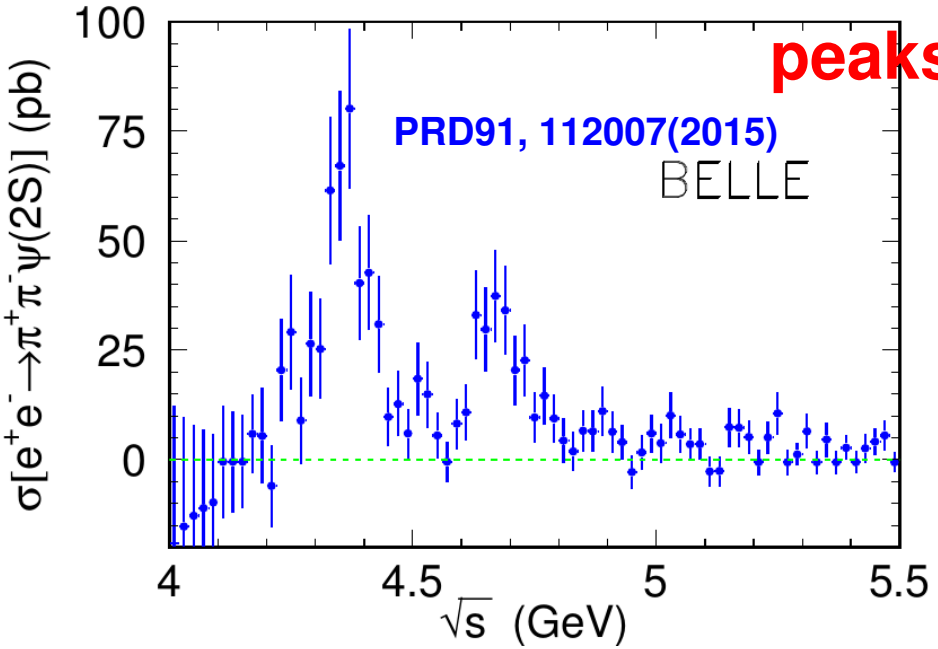
$e^+e^- \to \pi^+\pi^-\psi(2S)$ cross section is calculated with

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

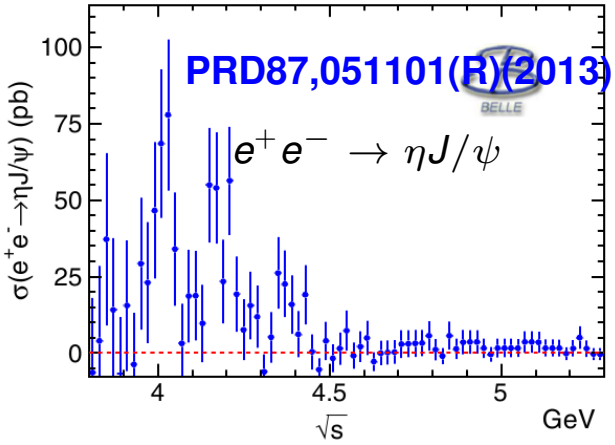
where i indicates the mass bin and j indicates the $\psi(2S)$ decay mode.

Other cross sections from ISR:





peaks $\sim$ 75 pb!

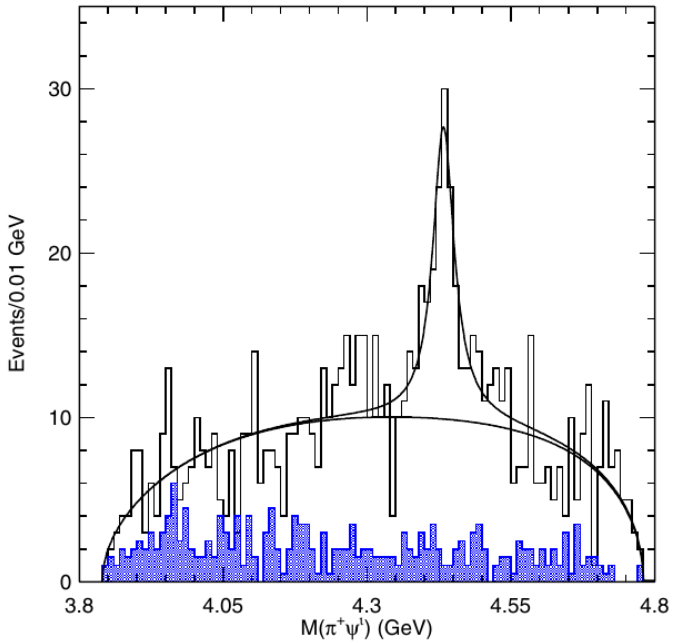


The $\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ at $Y(4260)$, $\sigma(e^+e^- \to \pi^+\pi^-\psi(2S))$ at $Y(4360)$ and $\sigma(e^+e^- \to \eta J/\psi)$ at $\psi(4040)$ are almost the same!!! WHY?

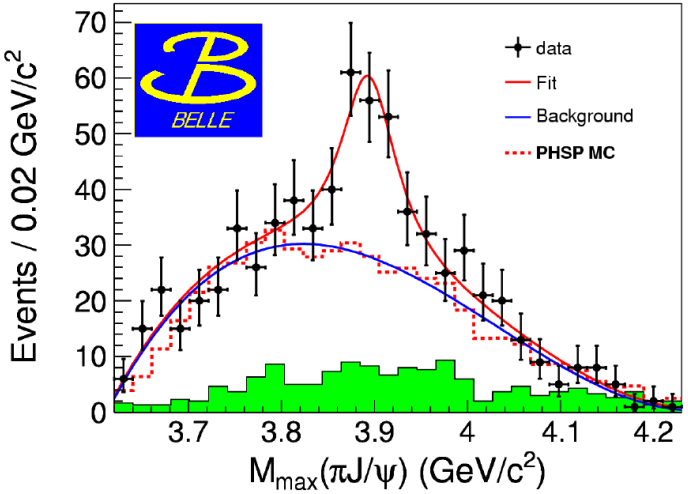
Tetra-quark state candidate: Z_c

- $Z(4430)^{\pm}$ observed in $\pi^{\pm}\psi(2S)$ final states.
- $Z_c(3900)$ observed in $Y(4260)$ decay.
- Both $Z(4430)$ and $Z_c(3900)$ are candidates of tetra-quark states.
- Here are two Ys, and $\pi^{\pm}\psi(2S)$ final states.
- What can we get in $Y(4360)/Y(4660)$ decays?

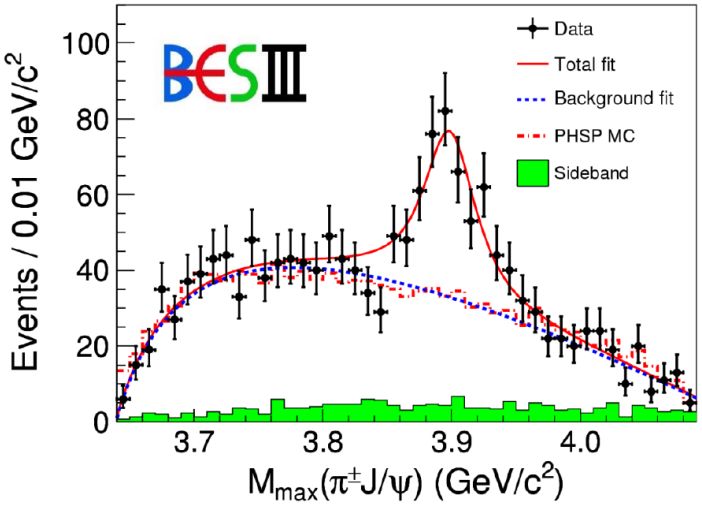
PRL100, 142001(2008)



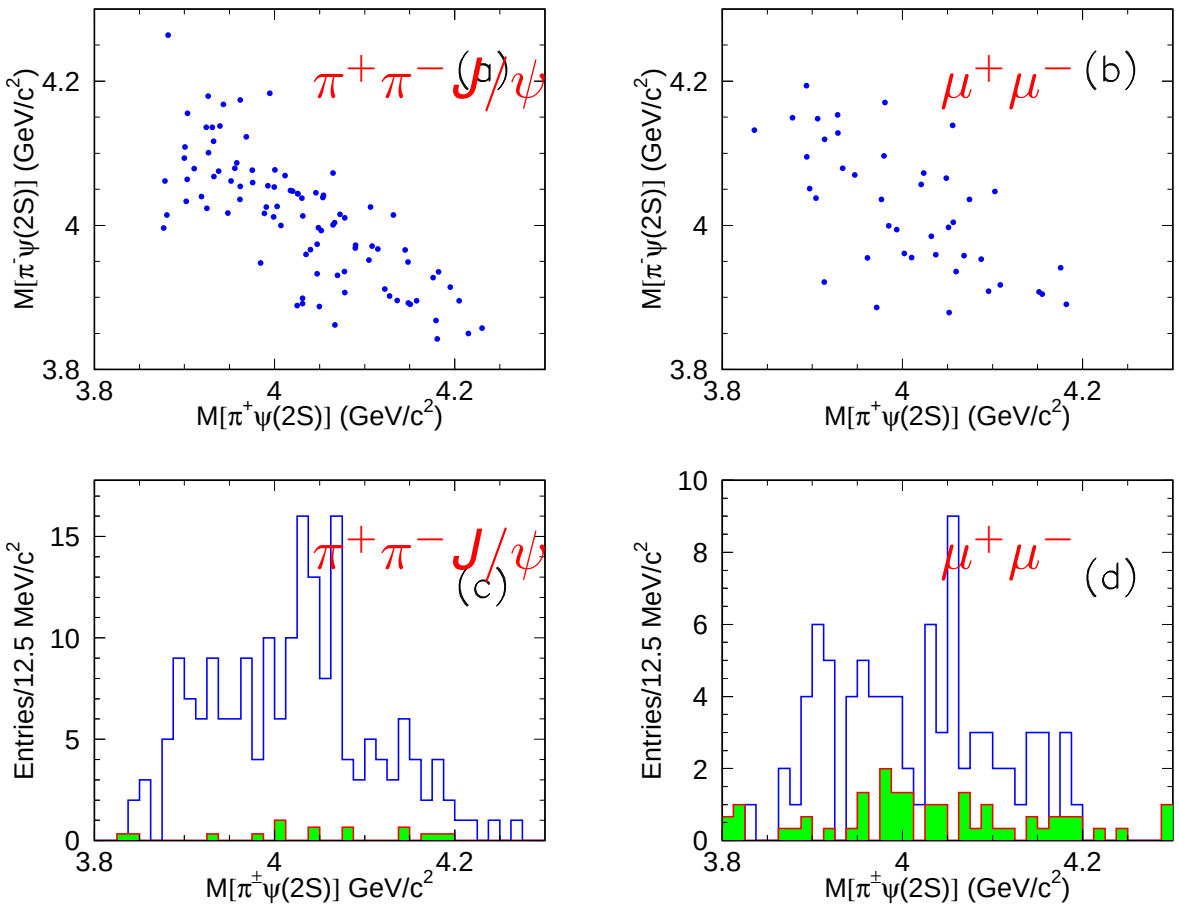
PRL110,252002(2013)



PRL110,252001(2013)



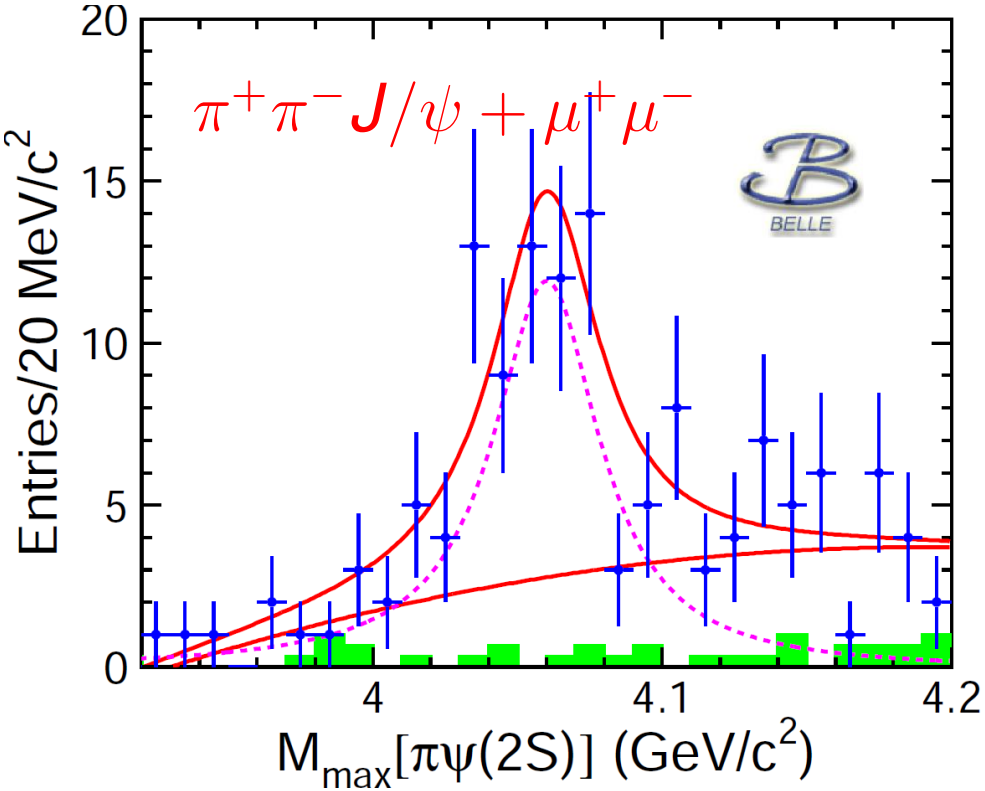
Search for intermediate states in $Y(4360)$ decays



- 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 $M_{\pi^-\psi(2S)}$

$Z_c(4050)$?

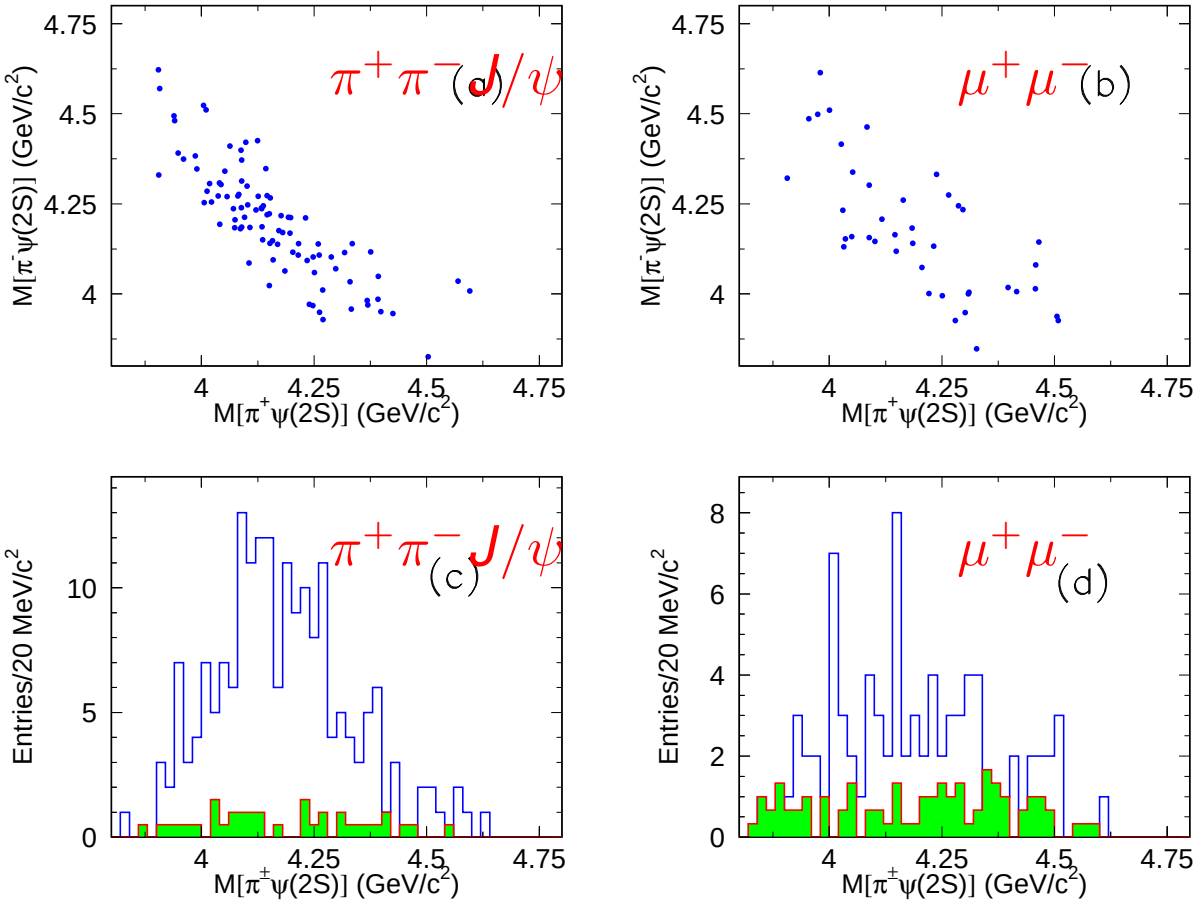
- An unbinned maximum-likelihood fit is performed simultaneously.
- $M_{\max}(\pi^{\pm}\psi(2S))$: the maximum of $M(\pi^{+}\psi(2S))$ and $M(\pi^{-}\psi(2S))$



- $M = (4054 \pm 3(\text{stat.}) \pm 1(\text{syst.}))$ MeV$/c^2$
- $\Gamma = (45 \pm 11(\text{stat.}) \pm 6(\text{syst.}))$ MeV
- The significance is 3.5σ.
- Bias between $M_{\max}[\pi\psi(2S)]$ and $M_{\pi^{\pm}\psi(2S)}$ is corrected according to MC simulation.

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.

Summary

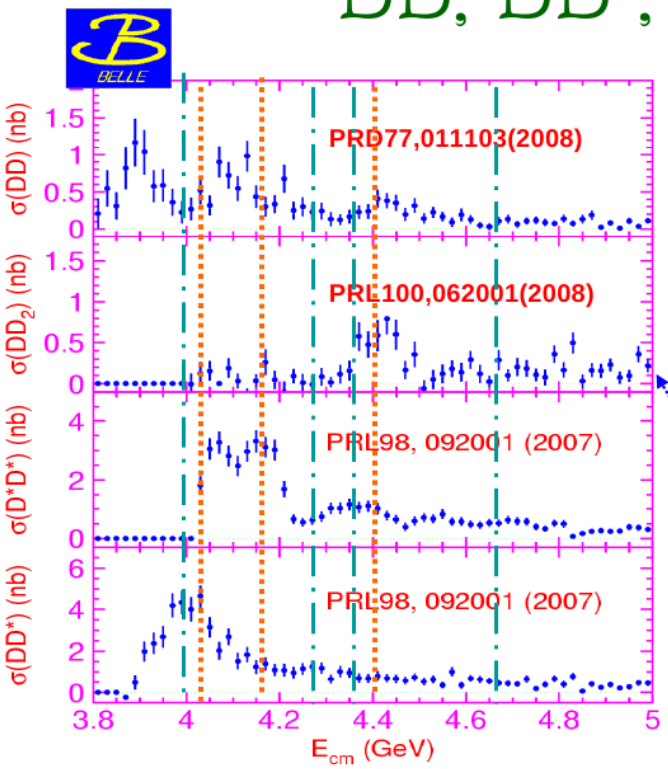
- Belle updates the measurement on $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^-\psi(2S)$ with 980 $\rm fb^{-1}$ data.
- Resonance parameters of $Y(4360)$ and $Y(4660)$ are updated.
- $Y(4260) \to \pi^+\pi^-\psi(2S)$ is studied. The significance of $Y(4260)$ is $< 3\sigma$, but it has significant affect on $Y(4360)$ and $Y(4660)$ parameters.
- Comparison between $Y(4660)$ and $X(4630)$:
  - $X(4630)$ from $\Lambda_c^+\Lambda_c^-$: $M = 4634^{+8+5}_{-7-8}$ MeV$/c^2$, $\Gamma = 92^{+40+10}_{-24-21}$ MeV.
  - $Y(4660)$ from 2R fit: $M = 4652 \pm 10 \pm 11$ MeV$/c^2$, $\Gamma = 68 \pm 11 \pm 5$ MeV.
  - $Y(4660)$ from 3R fit: $M = 4660 \pm 9 \pm 12$ MeV$/c^2$, $\Gamma = 74 \pm 12 \pm 4$ MeV.
- Evidence of a structure in $M_{max}(\pi^\pm\psi(2S))$ in $Y(4360)$ decays with significance of 3.5σ.

  $M = (4054 \pm 3(\rm stat.) \pm 1(\rm syst.))$ MeV$/c^2$; $\Gamma = (45 \pm 11(\rm stat.) \pm 6(\rm syst.))$ MeV

Thank you!

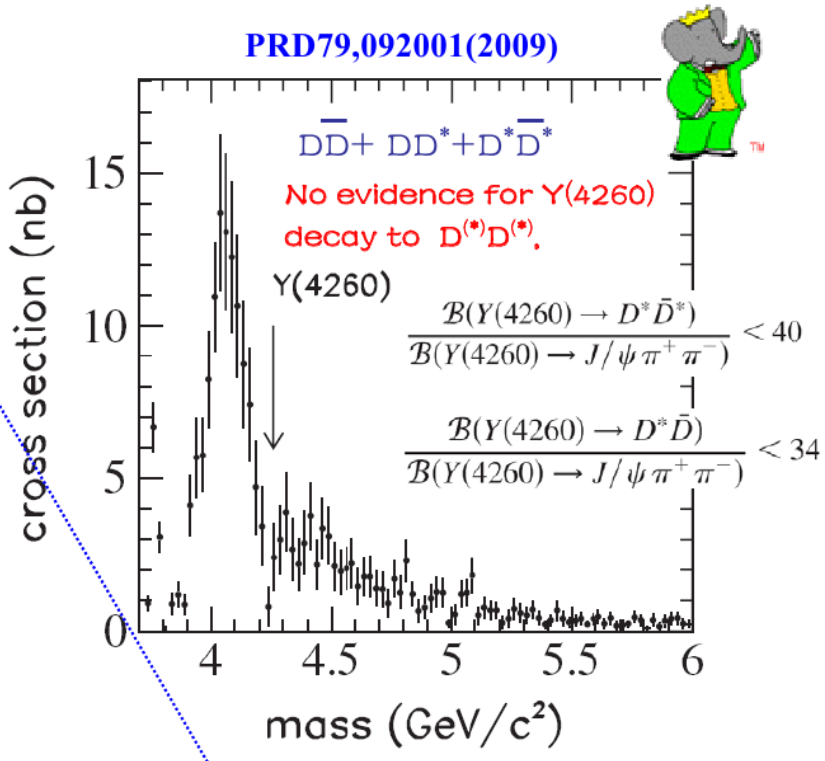
Back-up

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



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

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

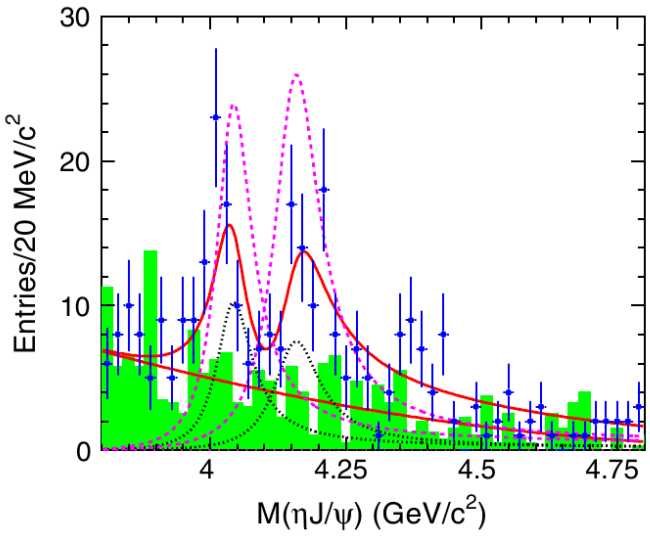


$D\bar{D}\pi$ is dominated by $DD_2(2460)$.

$e^+e^- \to D\bar{D}$ 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 η. ($\eta \to \gamma\gamma/\pi^+\pi^-\pi^0$)



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)	
$\mathcal{B}\cdot\Gamma^{\psi(4160)}_{e^+e^-}$	$4.0 \pm 0.8 \pm 1.4$	$13.8 \pm 1.3 \pm 2.1$
ϕ	$336 \pm 12 \pm 14$	$251 \pm 4 \pm 7$

- This is the first time to found ψ 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!!!

$\Gamma_{e^+e^-}(\psi(4040)) = (0.86 \pm 0.07)$ 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 $\mathcal{B}(\psi(4160) \to \eta J/\psi) = (1.66 \pm 0.16 \pm 0.29)\%$.

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

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

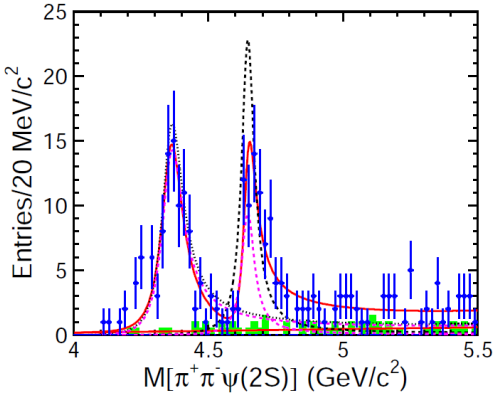
Published Belle results:

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

Current BaBar results:

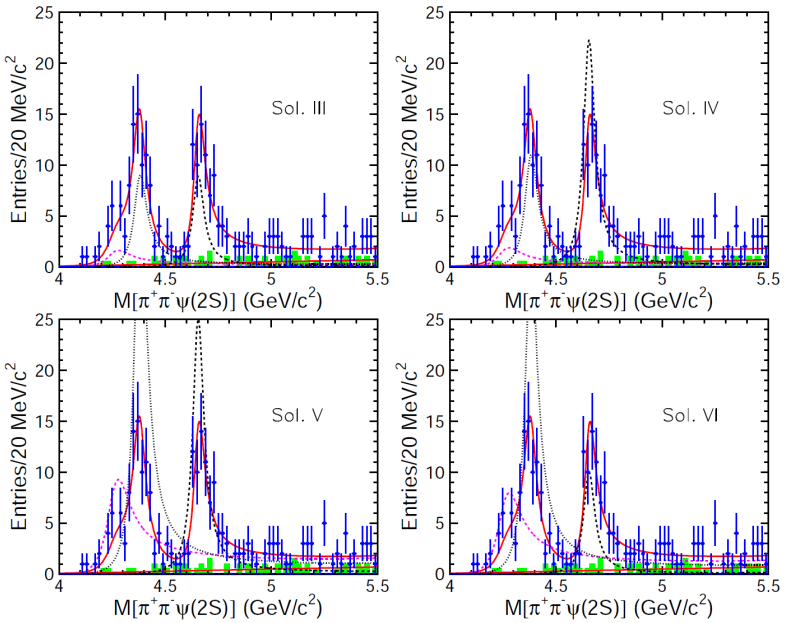
Parameters	First Solution (constructive interference)	Second Solution (destructive interference)
Mass Y(4360) (MeV/c^2)	$4340 \pm 16 \pm 9$	
Width Y(4360) (MeV)	$94 \pm 32 \pm 13$	
$\mathcal{B} \times \Gamma_{ee}(Y(4360))$ (eV)	$6.0 \pm 1.0 \pm 0.5$	$7.2 \pm 1.0 \pm 0.6$
Mass Y(4660) (MeV/c^2)	$4669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

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



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

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)		
$\mathcal{B}[Y(4260) \to \pi^+\pi^-\psi(2S)] \cdot \Gamma^{e^+e^-}_{Y(4260)}$	$1.6 \pm 0.6 \pm 0.4$	$1.8 \pm 0.8 \pm 0.6$	$9.1 \pm 1.2 \pm 0.7$	$7.8 \pm 1.1 \pm 0.8$
$M_{Y(4360)}$		$4378 \pm 9 \pm 6$		
$\Gamma_{Y(4360)}$		$74 \pm 14 \pm 3$		
$\mathcal{B}[Y(4360) \to \pi^+\pi^-\psi(2S)] \cdot \Gamma^{e^+e^-}_{Y(4360)}$	$4.5 \pm 1.0 \pm 0.4$	$5.5 \pm 1.4 \pm 0.6$	$19.1 \pm 2.8 \pm 1.1$	$15.7 \pm 2.3 \pm 1.6$
$M_{Y(4660)}$		$4654 \pm 7 \pm 6$		
$\Gamma_{Y(4660)}$		$65 \pm 10 \pm 3$		
$\mathcal{B}[Y(4660) \to \pi^+\pi^-\psi(2S)] \cdot \Gamma^{e^+e^-}_{Y(4660)}$	$3.3 \pm 0.6 \pm 0.3$	$8.3 \pm 1.0 \pm 0.9$	$9.3 \pm 1.2 \pm 1.2$	$3.7 \pm 0.7 \pm 0.5$
ϕ_1	$282 \pm 25 \pm 24$	$270 \pm 27 \pm 28$	$130 \pm 5 \pm 3$	$142 \pm 6 \pm 7$
ϕ_2	$359 \pm 19 \pm 3$	$243 \pm 17 \pm 20$	$337 \pm 10 \pm 7$	$93 \pm 25 \pm 17$