Charmonium at e^+e^- colliders

XiaoLong Wang

VirginiaTech

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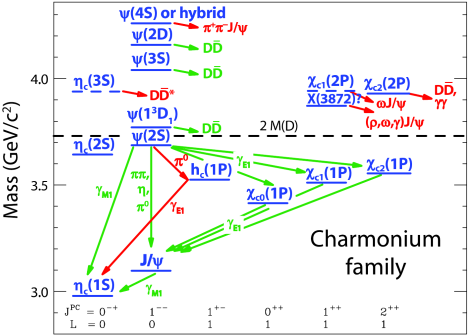
Introduction to charmonium

- Below $D\bar{D}$ – Very good agreement between theory and experiment.
- Above $D\bar{D}$ – Many charmonium(-like) states found in the past ten years.
- XYZ particles – Exotic properties! Their nature unclear.
  (QWG, Eur. Phy. J. C71, 1534(2011))



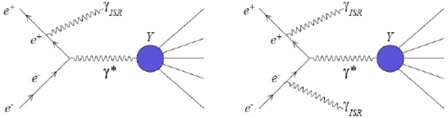
Eichten *et al.*, Rev. Mod. Phys.80,1161(2008)

State	m (MeV)	Γ (MeV)	J^{PC}	Modes	Interpretation
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$\pi^+\pi^- J/\psi$	$D^{*0}\bar{D}^0$ molecule (bound)
				$D^{*0}\bar{D}^0$	$D^{*0}\bar{D}^0$ unbound
				$\gamma J/\psi$, $\gamma\psi(2S)$	if 1^{++}, $\chi_{c2}(2P)$
				$\omega J/\psi$	if 2^{-+}, $\eta_{c2}(1D)$
					charmonium + mesonic-molecule mixture
					QCDSR: $[cq]_{\bar{3}}[\bar{c}\bar{q}]_3$ (S + A)
					QCDSR: $[c\bar{q}]_1[\bar{c}q]_1$ (P + V)
					QCDSR: $[c\bar{c}]_1$(A) + $[c\bar{q}]_1[\bar{c}q]_1$ (P + V)
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0,\ 2^{?+}$	$\omega J/\psi$	$D^{*+}D^{*-} + D^{*0}\bar{D}^{*0}$
$Z(3930)$	3927.2 ± 2.6	24.1 ± 6.1	2^{++}	$D\bar{D}$	$\chi_{c2}(2P)$ (i.e., $2^3P_2\ c\bar{c}$)
					$1^3F_2\ c\bar{c}$
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$D\bar{D}^*$	
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$D\bar{D}$	Coupled-channel effect
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$\pi^+\pi^- J/\psi$	
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$\pi^+\chi_{c1}(1P)$	hadrocharmonium
$Y(4140)$	4143.0 ± 3.1	$11.7^{+9.1}_{-6.2}$	$?^{?+}$	$\phi J/\psi$	QCDSR: $[c\bar{q}]_1[\bar{c}q]_1$ (V + V)
					QCDSR: $[c\bar{s}]_1[\bar{c}s]_1$ (V + V)
					$D_s^{*+}D_s^{*-}$
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$D\bar{D}^*$	
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$\pi^+\chi_{c1}(1P)$	hadrocharmonium
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$\pi^+\pi^- J/\psi$	charmonium hybrid
				$\pi^0\pi^0 J/\psi$	$J/\psi f_0(980)$ bound state
					$D_0\bar{D}^*$ molecular state
					$[cs][\bar{c}\bar{s}]$ tetraquark state
					hadrocharmonium
					QCDSR: $[c\bar{q}]_1[\bar{c}q]_1$ (S + V)
					QCDSR: $[c\bar{q}]_1[\bar{c}q]_1$ (P + A)
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	(see $Y(4140)$)
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,\ 2^{++}$	$\phi J/\psi$	
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$\pi^+\pi^-\psi(2S)$	hadrocharmonium
					crypto-exotic hybrid

QWG, Eur. Phy. J. C71, 1534(2011)

Processes at e^+e^- colliders

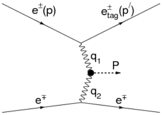
1. ISR: a new e^+e^- collider at wide $\sqrt{s'}$ region.



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

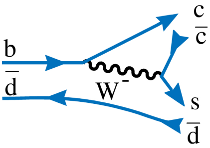
ψ’, ψ’’, Υ…

2. Two photon process: a $\gamma\gamma$ collider.



$C = +$

3. B decay:

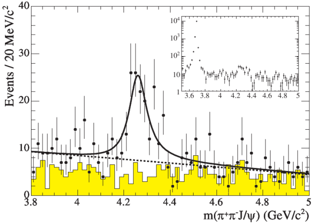


Outline

1. Update on $e^+e^- \to \pi^+\pi^- J/\psi$ via initial state radiation (ISR).
   BaBar, Lees *et al.*, Phys. Rev. D **86** (2012) 051102(R); Belle, Liu *et al.*, arXiv:1304.0121
2. Update on $e^+e^- \to \pi^+\pi^- \psi(2S)$ via ISR.
   BaBar, Lees *et al.*, arXiv:1211.6271
3. $e^+e^- \to \eta J/\psi$ via ISR.
   Belle, Wang *et al.*, Phys. Rev. D **87** (2013) 051101(R)
4. $\psi_2(1D)$ in $B \to (\chi_{c1}\gamma)K$.
   Belle, Bhardwaj *et al.*, arXiv:1304.3975
5. $X(3915)$ in $\gamma\gamma \to J/\psi\omega$
   Belle, Uehara *et al.*, PRL104,092001(2010); BaBar, Lees *et al.*, Phys. Rev. D **86** (2012) 072002
6. $\gamma\gamma \to \eta_c\pi^+\pi^-$
   BaBar, Lees *et al.*, Phys. Rev. D **86** (2012) 092005

$e^+e^- \to \pi^+\pi^- J/\psi$ via ISR: Background

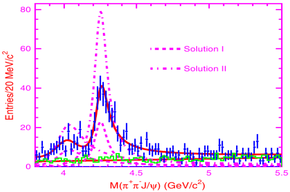
BaBar: First scan on charmonium, first observation of $Y(4260)$



125 $\pm$ 23 events,
$M = 4259 \pm 8(stat)^{+2}_{-6}(syst)\mathrm{MeV}/c^2$,
$\Gamma = 88 \pm 23(stat)^{+6}_{-4}(syst)$ MeV.

BaBar: PRL95, 142001(2005).

Belle: First confirm on $Y(4260)$, asymmetric line shape; enhancement around 4.0 GeV$/c^2$. $Y(4008)$???



Parameters	Solution I	Solution II
$M(R1)$	$4008 \pm 40^{+114}_{-28}$	
$\Gamma_{tot}(R1)$	$226 \pm 44 \pm 87$	
$\mathcal{B}\Gamma_{e^+e^-}(R1)$	$5.0 \pm 1.4^{+6.1}_{-0.9}$	$12.4 \pm 2.4^{+14.8}_{-1.1}$
$M(R2)$	$4247 \pm 12^{+17}_{-32}$	
$\Gamma_{tot}(R2)$	$108 \pm 19 \pm 10$	
$\mathcal{B}\Gamma_{e^+e^-}(R2)$	$6.0 \pm 1.2^{+4.7}_{-0.5}$	$20.6 \pm 2.3^{+9.1}_{-1.7}$
ϕ	$12 \pm 29^{+7}_{-98}$	$-111 \pm 7^{+28}_{-31}$

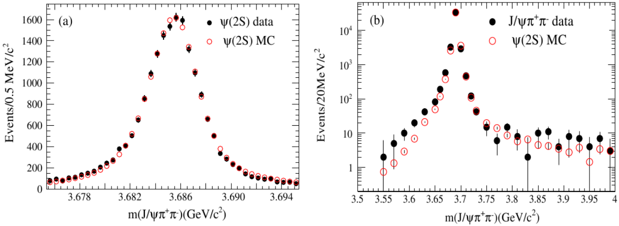
Belle: PRL99, 182004(2007).

Both BaBar and Belle have finished the update with their full data samples.

$\psi(2S)$ reference sample at BaBar

Pure $\psi(2S)$ sample for reference; $M_{\pi^+\pi^- J/\psi}$ need to be corrected.

- $M_{\pi^+\pi^- J/\psi}$:
  $M_{data} = 3685.32 \pm 0.02$ MeV$/c^2$, and $M_{MC} = 3685.43 \pm 0.01$ MeV$/c^2$; while PDG12: 3686.09 ± 0.04 MeV$/c^2$.
- $\sigma(M_{\pi^+\pi^- J/\psi})$ also corrected.



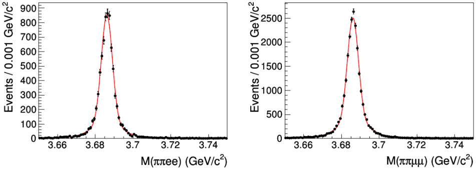
- Results of $\psi(2S)$: $N^{\rm sig} = 20893 \pm 145$.
  $\Gamma(\psi(2S) \to e^+e^-) = 2.31 \pm 0.05(stat)$ keV
  $(\Gamma^{\rm PDG}(\psi(2S) \to e^+e^-) = 2.35 \pm 0.04$ keV).

The high-mass tail to 4.0 GeV$/c^2$: good description to data.
But: 4.0 GeV$/c^2$ is 1000 full-widths beyond $m_{\psi(2S)}$.

BaBar, Lees *et al.*, Phys. Rev. D **86** (2012) 051102(R)

$\psi(2S)$ and $\psi(3770)$ at Belle

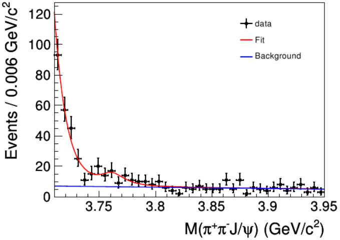
Pure $\psi(2S)$ samples in both e^+e^- and $\mu^+\mu^-$ modes.



- $M(\psi(2S)) = 3686.1 \pm 0.2$ MeV$/c^2$
  ($M^{\rm PDG} = 3686.09 \pm 0.04$ MeV$/c^2$)
- Mass resolution $\sigma = 4.8$ MeV$/c^2$.
- $\sigma(\psi(2S))$ at Belle data samples:

	e^+e^-	$\mu^+\mu^-$	QED
$\sigma(\Upsilon(4S))$	$(14.12 \pm 0.18 \pm 0.85)$ pb	$(15.09 \pm 0.11 \pm 0.79)$ pb	(14.25 ± 0.26) pb
$\sigma(\Upsilon(5S))$	$(13.79 \pm 0.44 \pm 0.83)$ pb	$(13.33 \pm 0.25 \pm 0.70)$ pb	(13.42 ± 0.25) pb
$\sigma(\Upsilon(2S))$	$(16.75 \pm 0.85 \pm 1.01)$ pb	$(16.63 \pm 0.54 \pm 0.87)$ pb	(16.03 ± 0.29) pb

High mass tail of $\psi(2S) \to \psi(3770)$

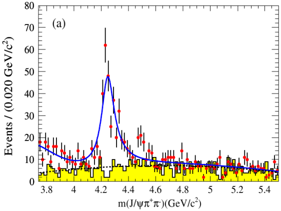


- $\psi(2S)$ tail: exponential function
- $\psi(3770)$: M and Γ fixed to PDG values
- backgrounds: a linear term
- $N(\psi(3770)) = 54 \pm 20, 2.8\sigma$.

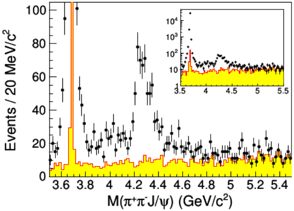
From 3.8 GeV$/c^2$ to 3.95 GeV$/c^2$, only low and flat backgrounds. The contributions from the tails of $\psi(2S)$ and $\psi(3770)$ are negligible. We will see it's an important difference between BaBar and Belle.

Belle: Liu *et al.*, arXiv:1304.0121

$M_{\pi^+\pi^- J/\psi}$ distributions



From BaBar



From Belle

Something similar:

- Asymmetric lineshape at $Y(4260)$
- J/ψ sidebands estimate backgrounds well at > 4.6 GeV$/c^2$.
- Signal candidate events well above sidebands from $\psi(2S)$ to $Y(4260)$

BUT, distributions at (3.8,4.1) GeV$/c^2$ are different.

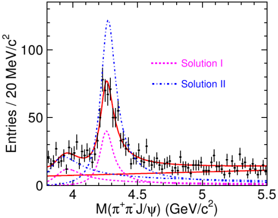
- BaBar: "...might result from the $\psi(2S)$ tail and a possible J/ψ continuum contribution"
- Belle: a broad structure $Y(4008)$ added to $Y(4260)$ is the best description to data.

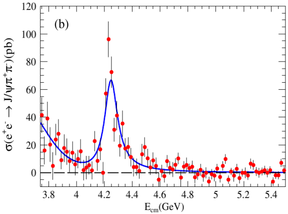
BaBar: PRD86,051102(R)(2012); Belle: arXiv:1304.0121

Fits on $M_{\pi^+\pi^- J/\psi}$

BaBar: $\sigma(M) = \sigma_{NY}(M) + \sigma_{BW}(M)$.

- σ_{BW} for $Y(4260)$.
- σ_{NY} for the low-statistics non-$Y(4260)$ contributions.
- Mass resolution (Gaussian) convolved.
- $M_Y = 4245 \pm 5(stat.) \pm 4(syst.)$ MeV$/c^2$, $\Gamma_Y = 114^{+16}_{-15}(stat.) \pm 7(syst.)$ MeV, $\mathcal{B}\Gamma_{e^+e^-} = 9.2 \pm 0.8(stat)$ eV





Belle: $Y(4008) + Y(4260)$.

- Two solutions of equal optimum fit quality, same mass, same width, different $\mathcal{B}\Gamma_{e^+e^-}$.
- $\chi^2/ndf = 101.6/84$.

Parameters	Solution I	Solution II
$M(R_1)$	$3890.8 \pm 40.5 \pm 11.5$	
$\Gamma_{\text{tot}}(R_1)$	$254.5 \pm 39.5 \pm 13.6$	
$\Gamma_{ee}\mathcal{B}(R_1 \to \pi^+\pi^- J/\psi)$	$(3.8 \pm 0.6 \pm 0.4)$	$(8.4 \pm 1.2 \pm 1.1)$
$M(R_2)$	$4258.6 \pm 8.3 \pm 12.1$	
$\Gamma_{\text{tot}}(R_2)$	$134.1 \pm 16.4 \pm 5.5$	
$\Gamma_{ee}\mathcal{B}(R_2 \to \pi^+\pi^- J/\psi)$	$(6.4 \pm 0.8 \pm 0.6)$	$(20.5 \pm 1.4 \pm 2.0)$
ϕ	$59 \pm 17 \pm 11$	$-116 \pm 6 \pm 11$

Large difference on $\mathcal{B}\Gamma_{e^+e^-}$: different fit treatments.

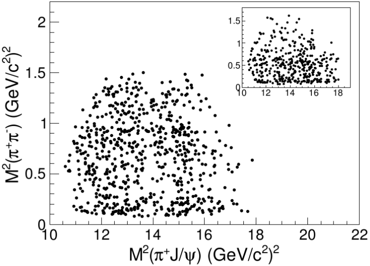
BaBar: PRD86,051102(R)(2012)

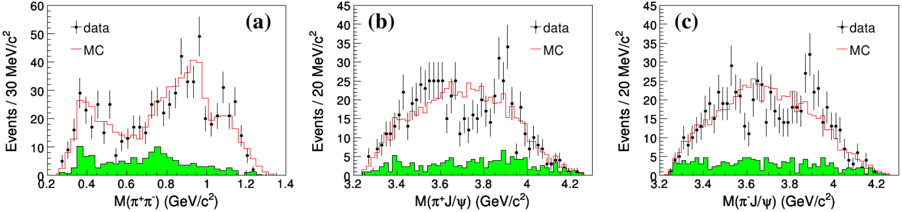
Belle: arXiv:1304.0121

Not only $Y(4260)$: $Z(3895)^{\pm}$

Belle: arXiv:1304.0121

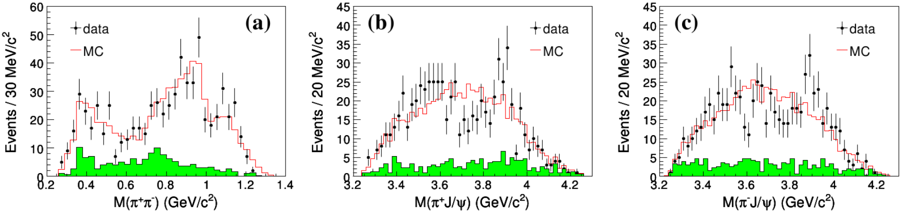
- Dalitz plot of $M^2(\pi^+\pi^-)$ vs $M^2(\pi^+ J/\psi)$ for $4.15 < M(\pi^+\pi^- J/\psi) < 4.45$ GeV$/c^2$.
- Inset: Background events in J/ψ sidebands.
- Structures both in $\pi^+\pi^-$ and $\pi^{\pm} J/\psi$ systems.
- MC simulation: open histograms, according to partial wave analysis with $f_0(500)$, $f_0(980)$, non-resonant S-wave, and $f_2(1270)$.





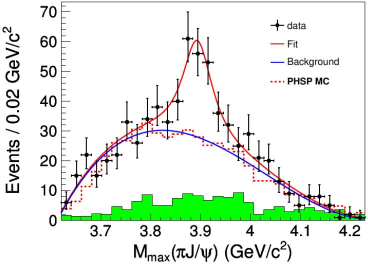
Is it a real signal?

- Is it due to $\pi^+\pi^-$ S-wave states, like $f_0(600)$, $f_0(980)$,...? No
- Is it due to $\pi^+\pi^-$ D-wave states, like $f_2(1270)$,...?
  There is no clear D-wave state contribution seen. No
- Are there two states, one at 3.4 GeV$/c^2$ and the other at 3.9 GeV$/c^2$? No
- Exist in both e^+e^- and $\mu^+\mu^-$ samples? Yes
- Exist in both $\pi^+\pi^-$ low mass and high mass samples? Yes
- Background fluctuation? (see next pages) No



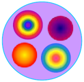
There are $f_0(600)$, $f_0(980)$ and non-resonant S-wave in $\pi^+\pi^-$. But they cannot reproduce the structure at 3.9 GeV$/c^2$ in $\pi^\pm J/\psi$ (histogram).

The $Z(3895)^{\pm}$ signal

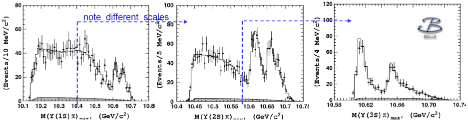


- S-wave Breit-Wigner convolved with a Gaussian (7.4 MeV$/c^2$).
- Significance: $> 5.2\sigma$
- Fit results:
  - $M = 3894.5 \pm 6.6 \pm 4.5$ MeV$/c^2$
  - $\Gamma = 63 \pm 24 \pm 26$ MeV
  - Fraction in $Y(4260)$ decays: $(29.0 \pm 8.9(stat.))\%$

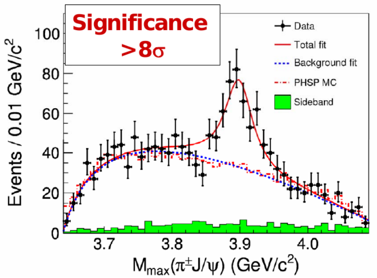
- Couples to $(c\bar{c})$.
- Has electric charge.
- At least 4 quarks.
- What's its nature?



- Similar to Z_b state observed in $\Upsilon(5S) \to \pi^{\mp} + \pi^{\pm}\Upsilon(nS)$?



$Z_c(3900)^{\pm}$ at BESIII



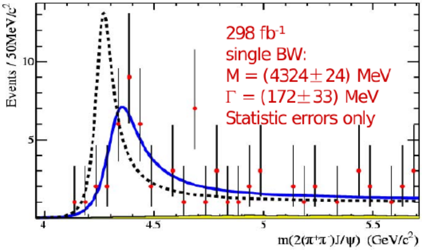
- Data at a fix energy point of $Y(4260)$.
- $M = 3899.0 \pm 3.6 \pm 4.9$ MeV$/c^2$
- $\Gamma = 46 \pm 10 \pm 20$ MeV
- Fraction $= (21.5 \pm 3.3 \pm 7.5)\%$
- First time of charged tetra-quark candidate observed outside Belle!

For more details, see Roy's talk.

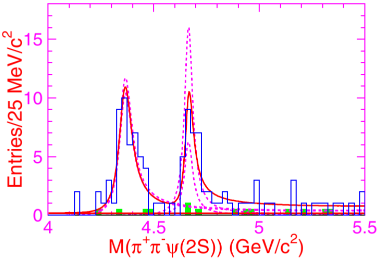
BESIII: arXiv: 1303.5949.

$\pi^+\pi^-\psi(2S)$ via ISR

BaBar searched for $Y(4260)$ in $e^+e^- \to \pi^+\pi^-\psi(2S)$, but instead, only $Y(4360)$ observed.



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



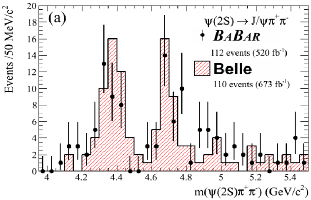
Belle confirmed $Y(4360)$, and observed a new structure $Y(4660)$, which decays to $f_0(980)\psi(2S)$ dominantly.

Belle: PRL99,142002(2007)

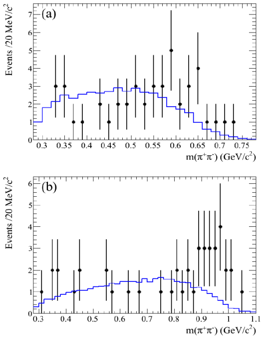
Update on $\pi^+\pi^-\psi(2S)$ via ISR

BaBar: Lees *et al.*, arXiv: 1211.6271

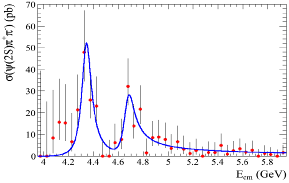
- The $Y(4660)$ is confirmed.
- All results from $\psi(2S) \to \pi^+\pi^- J/\psi$ mode are in consistent with Belle results.
- $\psi(2S) \to \ell^+\ell^-$ mode is studied, but it's a much worse sample with much high backgrounds.



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 (°)	$12 \pm 27 \pm 4$	$-78 \pm 12 \pm 3$



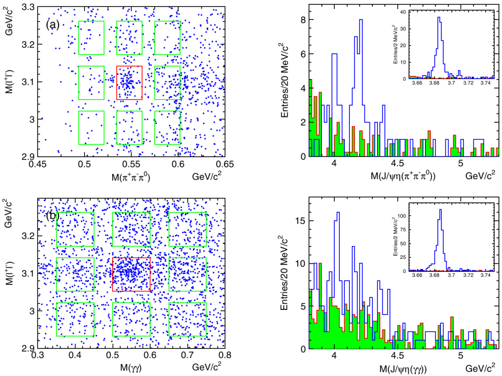
$M(\pi^+\pi^-)$: (a): $Y(4360)$ decays; (b): $Y(4660)$ decays.



The cross section $e^+e^- \to \pi^+\pi^-\psi(2S)$.

$\eta J/\psi$ via ISR

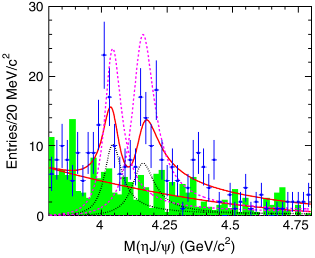
- Via emitting η should have large partial width of hadronic transition of charmonium.
- Belle searches for $e^+e^- \to \eta J/\psi$ via ISR for the first time.
- $\eta \to \gamma\gamma/\pi^+\pi^-\pi^0$, and $J/\psi \to e^+e^-$ or $\mu^+\mu^-$ in the reconstructions.



- $\sigma(\psi(2S)) = 13.9 \pm 1.4$ pb in $\eta \to \pi^+\pi^-\pi^0$ mode; $\sigma(\psi(2S)) = 14.0 \pm 0.8$ pb in $\eta \to \gamma\gamma$ mode. The expectation: $\sigma(\psi(2S)) = 14.7$ pb.
- Clear $\psi(4040)$ and $\psi(4160)$, but no Y state found! Really Y???

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

$\eta J/\psi$ via ISR

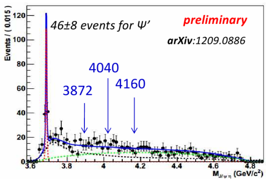


Parameters	Solution I	Solution II
$M_{\psi(4040)}$	4039 (fixed)	
$\Gamma_{\psi(4040)}$	80 (fixed)	
$\mathcal{B}\cdot\Gamma_{e^+e^-}^{\psi(4040)}$	$4.8 \pm 0.9 \pm 1.5$	$11.2 \pm 1.3 \pm 2.1$
$M_{\psi(4160)}$	4153 (fixed)	
$\Gamma_{\psi(4160)}$	103 (fixed)	
$\mathcal{B}\cdot\Gamma_{e^+e^-}^{\psi(4160)}$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

$\Gamma_{e^+e^-}(\psi(4040)) = (0.86 \pm 0.07)$ keV from PDG $\rightarrow$ $\mathcal{B}(\psi(4040) \rightarrow \eta J/\psi) = (0.56 \pm 0.10 \pm 0.18)\%$ or $(1.30 \pm 0.15 \pm 0.26)\%$.
$\Gamma_{e^+e^-}(\psi(4160)) = (0.83 \pm 0.07)$ keV from PDG $\rightarrow$ $\mathcal{B}(\psi(4160) \rightarrow \eta J/\psi) = (0.48 \pm 0.10 \pm 0.17)\%$ or $(1.66 \pm 0.16 \pm 0.29)\%$.
The $\Gamma(\psi \rightarrow \eta J/\psi)$ is about 1 MeV.

- 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 $\mathcal{B}(\psi \rightarrow \eta J/\psi)$!
  $\mathcal{B}(\psi(2S) \rightarrow \eta J/\psi) = (3.28 \pm 0.07)\%$
- Unlike $\pi^+\pi^-$ transition, no significant Y signal!!!
- Fit with parameters of $\psi(4040)$ and $\psi(4160)$ free, first time in an exclusive channel:
  - $\psi(4040)$: $M = 4012 \pm 5$ MeV$/c^2$, $\Gamma = 54 \pm 13$ MeV.
  - $\psi(4160)$: $M = 4157 \pm 10$ MeV$/c^2$, $\Gamma = 84 \pm 20$ MeV.

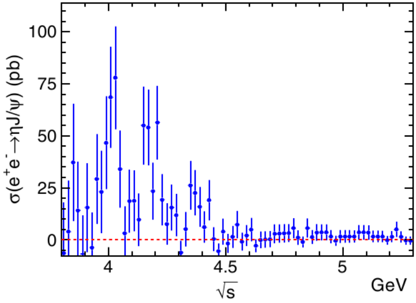
$B^+ \rightarrow J/\Psi \eta K^+$

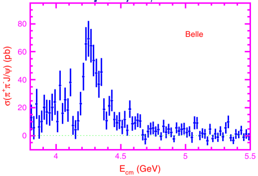


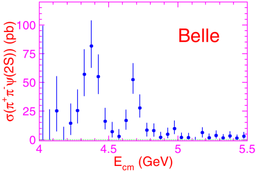
Meanwhile, no $\psi(4040)$ or $\psi(4160)$ in $\eta J/\psi$ seen in $B \rightarrow K + \eta J/\psi$.

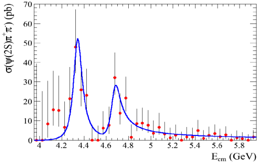
Cross section of $e^+e^- \to \eta J/\psi$

$$\sigma_i = \frac{n_i^{\mathrm{obs}} - n_i^{\mathrm{bkg}}}{\varepsilon_i \mathcal{L}_i \mathcal{B}(\eta \to \pi^+\pi^-\pi^0 + \gamma\gamma)\mathcal{B}(J/\psi \to \ell^+\ell^-)}$$









A systematic error of 8.0% to all data points is not shown.

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.

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

Y, why?

The current situation is amazing:

- Assume a $\psi^?$ above 4 GeV/c^2:
  $\mathcal{B}(\psi^? \to \pi^+\pi^-\psi(2S)) > \mathcal{B}(\psi^? \to \pi^+\pi^- J/\psi) >> \mathcal{B}(\psi^? \to \eta J/\psi)$, and
  $\sigma(e^+e^- \to f) = \sigma(e^+e^- \to \psi^?) \times \mathcal{B}(\psi^? \to f)$, so
  $\sigma(e^+e^- \to \pi^+\pi^-\psi(2S)) > \sigma(e^+e^- \to \pi^+\pi^- J/\psi) >> \sigma(e^+e^- \to \eta J/\psi)$. However, they are at SAME order! Why?
- Why no Y at $\eta J/\psi$? Why no $\psi(4040/4160/4415)$ at $\pi^+\pi^- J/\psi$ or $\pi^+\pi^-\psi(2S)$? Y states from interference?
- In $\pi^+\pi^- J/\psi$, state from $\pi^\mp Z(3895)^\pm$ is the same as state from $\pi^+\pi^- J/\psi$ (no $Z(3895)^\pm$ component)? Does it happen to be? Or not?
- Why $\mathcal{B}(\psi(4040/4160) \to \eta J/\psi)$ so large? Or it's only enhancement in $\eta J/\psi$?
- What is $Y(4660)$? Why $f_0(980)\psi(2S)$ dominates in $Y(4660)$ decay?
- Lineshapes of $\psi(4040)$ and $\psi(4160)$ different in inclusive decays and exclusive decays? Or not?
- Is $Z(3895)^\pm$ like charged Z_b?

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

- $\chi_{c1}\gamma$ and $\chi_{c2}\gamma$: suitable final state to look for either C-odd partner of $X(3872)$ or unseen charmonium.
- Theory predict $^3D_2$ $(c\bar{c})$ state to lie around $3810 - 3840$ MeV$/c^2$ mass and be narrow.

  $\Gamma(\psi_2 \to \chi_{c1}\gamma) = 260$ keV
- There should be $^3D_3$ $(c\bar{c})$ state lying around $3830 - 3880$ MeV$/c^2$ mass.

  $\Gamma(\psi_3 \to \chi_{c2}\gamma) = 286$ keV

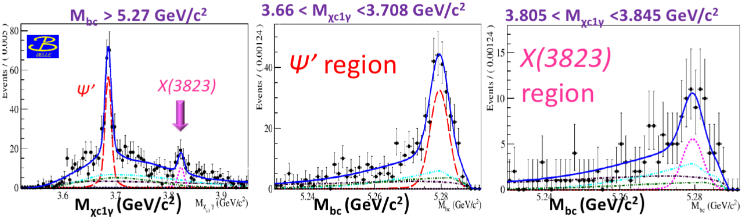
name	spect.	J^{PC}	M_{exp}	M_{model}[MeV]	dominant decay
η_{c2}	1^1D_2	2^{-+}	--	3780−3840	$\eta_c\pi\pi$
ψ''	1^3D_1	1^{--}	3772.9(4)	3785−3819	$D\bar{D}$
ψ_2	1^3D_2	2^{--}	--	3800−3840	$\chi_{c1,2}\gamma$
ψ_3	1^3D_3	3^{--}	--	3810−3850	$D\bar{D}^{(*)}$

S. Godfrey & N. Isgur, PRD32, 189(1985); E. Eichten *et al.*, PRL89,162002(2002), PRD69,094019(2004)

Belle: Bhardwaj *et al.*, arXiv: 1304.3975

$\psi_2 \to \gamma\chi_{c1}$

- No $X(3872)$ C-odd partner found.



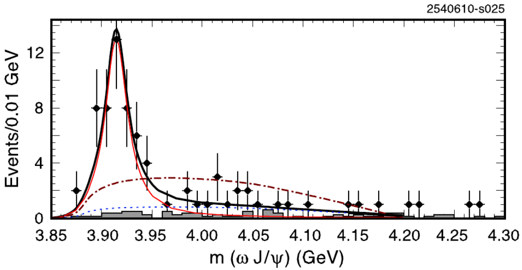
- $X(3823)$ significance $> 3.8\sigma$ w/syst. First evidence from Belle!!!
- $M = 3823.1 \pm 1.8(stat.) \pm 0.7(syst.)$ MeV$/c^2$.
- $\Gamma(\psi_2) = 1.7 \pm 5.5$ MeV$/c^2$ if fitted.
- $\frac{\mathcal{B}(X(3823)\to\chi_{c2}\gamma))}{\mathcal{B}(X(3823)\to\chi_{c1}\gamma))} < 0.41$ @90% C.L.

$X(3823)$ seems to be the missing ψ_2 from the charmonium spectrum.

No obvious signal found in $\chi_{c2}\gamma$, except $\psi(2S)$.

Belle: Bhardwaj *et al.*, arXiv: 1304.3975

Study of $\gamma\gamma \to \omega J/\psi$

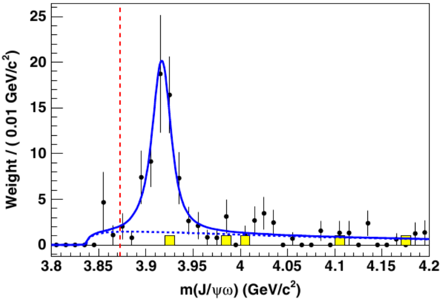


- $M(X(3915)) = 3914 \pm 3 \pm 2$ MeV$/c^2$.
- $\Gamma(X(3915)) = 23 \pm 10^{+2}_{-8}$ MeV$/c^2$.
- Significance is 7.8σ. $N^{sig} = 55 \pm 14^{+2}_{-14}$.
- No obvious $\gamma\gamma \to X(3872) \to \omega J/\psi$ found.

Belle: Uehara *et al.*, PRL104,092001(2010)

Study of $\gamma\gamma \to \omega J/\psi$

BaBar: Lees *et al.*, PRD86,072002(2012).



- Confirm Belle's measurement on $X(3915)$, using 519 fb^{-1} data.
- Significance: 7.6σ w/ syst.
- $M_{X(3915)} = (3919.4 \pm 2.2 \pm 1.6)$ MeV$/c^2$
- $\Gamma_{X(3915)} = (13 \pm 6 \pm 3)$ MeV
- No obvious $\gamma\gamma \to X(3872) \to \omega J/\psi$ found.

$J^{PC} = 2^{-+}$ has been ruled out for $X(3872)$ by LHCb (8.4σ), see Tomasz Skwarnicki's talk.

Study of $\gamma\gamma \to \eta_c\pi^+\pi^-$ at BaBar

Predictions :

- $\Gamma(\eta_c(2S) \to \eta_c\pi^+\pi^-)/\Gamma(\psi(2S) \to J/\psi\pi^+\pi^-) = 2.9$
  That is $\mathcal{B}(\eta_c(2S) \to \eta_c\pi^+\pi^-) = (2.2^{+1.6}_{-0.6})\%$

  Mod. Phys. Lett. A 17 (2002) 1533

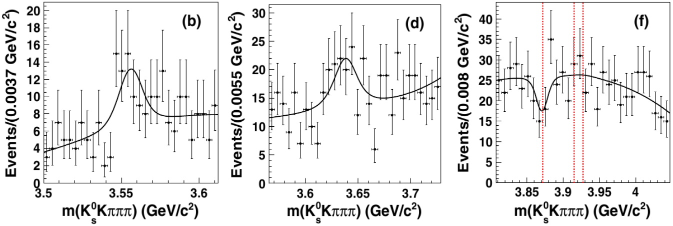
- Then
  - If $X(3872) \equiv \eta_{c2}$ $(1^1D_2,\ J^{PC} = 2^{-+})$,
  - then $\mathcal{B}(X(3872) \to \eta_c\pi^+\pi^-) > \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$

    (Int J. Mod. Phys A 20 240 (2005))

- $\Rightarrow$ what about $X \to \eta_c\pi^+\pi^-$?

Study of $\gamma\gamma \to \eta_c \pi^+ \pi^-$ (BaBar)

- $473.9\ \mathrm{fb}^{-1}$ data used, and $\eta_c \to K^0_S K^+ \pi^-$.
- No evidence for $\gamma\gamma$ production of $X(3872)$, $X(3915)$ nor $\chi_{c2}(2P)$.



$\chi_{c2}(1P)$ $\eta_c(2S)$ $X(3872)/X(3915)/\chi_{c2}(2P)$

- $\frac{\mathcal{B}(\chi_{c2}(1P)\to\eta_c\pi^+\pi^-)}{\mathcal{B}(\chi_{c2}(1P)\to K^0_S K^+\pi^- + c.c.)} = 14.5^{+10.9}_{-8.9} \pm 7.3 \pm 2.5$, $\mathcal{B}(\chi_{c2} \to \eta_c \pi^+\pi^-) < 2.2\%$
- $\frac{\eta_c(2S)\to\eta_c\pi^+\pi^-}{\eta_c(2S)\to K^0_S K^+\pi^- + c.c.} = 4.9^{+3.5}_{-3.3} \pm 1.3 \pm 0.8$, $\mathcal{B}(\eta_c(2S) \to \eta_c\pi^+\pi^-) < 7.4\%$
- $\Gamma_{\gamma\gamma}(X) \cdot \mathcal{B}(X \to \eta_c\pi^+\pi^-) < 11.1/16/19$ eV for $X(3872)/X(3915)/\chi_{c2}(2P)$

BaBar: Lees *et al.*, PRD86,092005(2012)

Summary

1. Update on $e^+e^- \to \pi^+\pi^- J/\psi$ via ISR at BaBar doesn't confirm $Y(4008)$.
2. In the same update, Belle observes a charged structure $Z(3895)^\pm$ in $M_{\pi^\pm J/\psi}$ in $Y(4260)$ decays. Same structure observed at BES III.
3. Update on $e^+e^- \to \pi^+\pi^-\psi(2S)$ via ISR at BaBar confirms the $Y(4660)$.
4. Scan on $e^+e^- \to \eta J/\psi$ via ISR at Belle shows obvious $\psi(4040)$ and $\psi(4160)$ signals in the final states. Not like in $\pi^+\pi^-$ transition, no $Y(4260/4360/4660)$ state seen.
5. $\mathcal{B}(\psi(4040/4160) \to \eta J/\psi$ are at 1% level, the partial widths are about 1 MeV.
6. $X(3823)$ observed in $B \to K + \chi_{cJ}\gamma$ by Belle, should be ψ_2 state.
7. $X(3915)$ observed at Belle in $\gamma\gamma \to \omega J/\psi$, and confirmed by BaBar. No $X(3872)$ found in the process.
8. $\gamma\gamma \to \eta_c\pi^+\pi^-$ scanned by BaBar, no evidence for production of $X(3872)$, $X(3915)$ nor $\chi_{c2}(2P)$.

Thank you!

Back-up

Selection criteria of $e^+e^- \to \pi^+\pi^- J/\psi$ via ISR

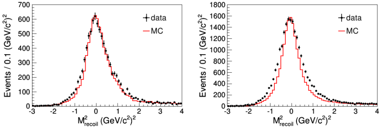
Both updates from BaBar and Belle finished. Here some comparisons are listed.

Selection criteria at BaBar:

- $N_{trk} = 4$, $Q_{net} = 0$.
- J/ψ reconstruction from e^+e^- and $\mu^+\mu^-$.
- Vertex fit to e^+e^- interaction region; kinematical constraint to $m_{J/\psi}$.
- For $\pi^+\pi^-$: $J/\psi + \pi^+\pi^-$ vertex fit again, at least one pion identified, and neither satisfy eID.
- Missing mass to consist with $\gamma_{\rm ISR}$: $-0.5 < M^2_{\rm rec}(\pi^+\pi^- J/\psi) < 0.75\ ({\rm GeV}/c^2)^2$
- γ-conversion bkg: $M_{e^+e^-} > 50\ {\rm MeV}/c^2$ for $\pi^+\pi^-$.
- Transverse component of missing momentum: $P_t^{miss}((\gamma_{\rm ISR})\pi^+\pi^- J/\psi) < 2.25\ {\rm GeV}/c$.

Selection criteria at Belle:

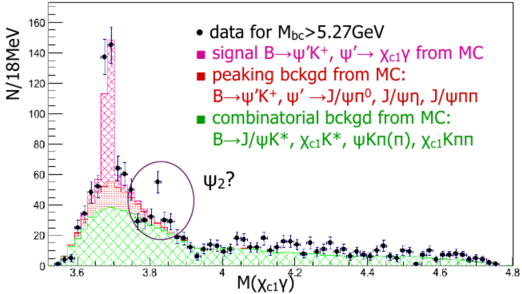
- $dr < 0.5cm$, $|dz| < 4.0cm$, $P_t > 0.1\ {\rm GeV}/c$ for good charged track. $N_{trk} = 4$ and $Q_{net} = 0$.
- e-ID and μ-ID, and J/ψ reconstructed from e^+e^- or $\mu^+\mu^-$.
- π-ID for both $\pi^+\pi^-$, and $\mathcal{R}e < 0.75$ and $M_{\pi^+\pi^-}$ to remove γ-conversion bkg.
- $-2 < M^2_{\rm rec}(\pi^+\pi^- J/\psi) < 2\ ({\rm GeV}/c^2)^2$ for $\gamma_{\rm ISR}$.



Differences: vertex fit, mass constrain, one pion ID, and P_T^{miss} at BaBar. Belle selection criteria are very simple.

Study of $\gamma\chi_{c1}$

- $B^+ \to \gamma\chi_{c1}K^+$ with $\chi_{c1} \to \gamma J/\psi$ using 772×10^6 $B\overline{B}$.
- Efficiency and resolution improve with increasing $M_{\gamma\chi_{c1}}$



- $M_{\gamma\chi_{c1}}$ in data agree with inclusive MC simulation, except for the peak at 3.82 GeV$/c^2$.
- Missing $\psi_2(1^3D_2)$ charmonium? Mass agrees with prediction.