BABAR /Belle Heavy hadron production and decays, including Y(4260), Y(4350) and Y(4660) states

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On behalf of the *BABAR* Collaboration

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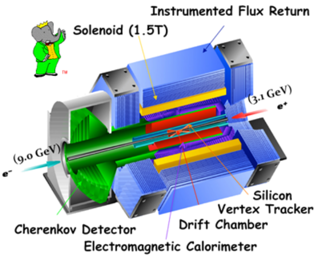
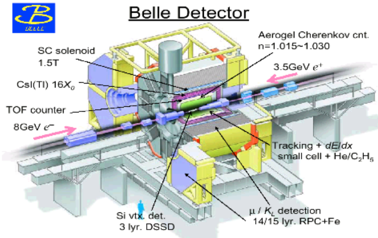
Outline

- *BABAR* and Belle experiments
- Charmonium spectrum
- Study of the $J/\psi\ \omega$ final state in two-photon collisions
  PRD 86, 072002 (2012) *BABAR* Collaboration
- Y(4260) *BABAR* and Belle; new results from BES III
- Y(4350) - Y(4660) *BABAR* and Belle
- Search for C-odd partner of X(3872) Preliminary - Belle Collaboration
- $e^+e^- \to J/\psi\eta$ via ISR arXiv: 1210.7550 Belle Collaboration
- Conclusion

The *BABAR* and Belle experiments





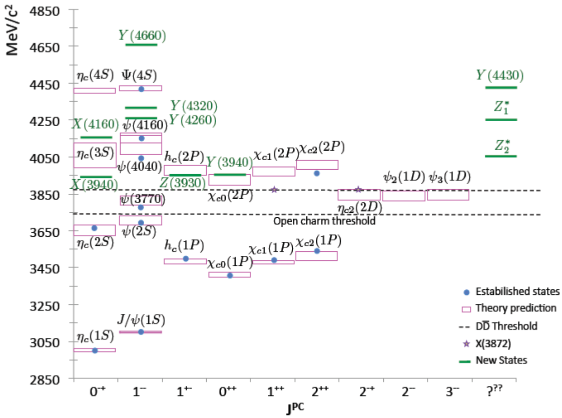
Features

- Very large samples of $\Upsilon(nS)$ and B mesons.
- Very large samples of charm mesons and charmonium
- $\sigma(e^+e^- \to c\bar{c}) \sim 1.3$ nb
- charmonium in B meson decays, ISR production, double charmonium and $\gamma\gamma$ production.
- Low multiplicity, can reconstruct complete events.

	Belle	*BABAR*
$\Upsilon(5S)$	121 fb^{-1}	-
$\Upsilon(4S)$	711 fb^{-1}	433 fb^{-1}
$\Upsilon(3S)$	3.0 fb^{-1}	30 fb^{-1}
$\Upsilon(2S)$	24 fb^{-1}	14 fb^{-1}
$\Upsilon(1S)$	5.7 fb^{-1}	-
Off-Res	87 fb^{-1}	54 fb^{-1}
Scan	68 fb^{-1}	3.9 fb^{-1}[1]
Total	1020 fb^{-1}	535 fb^{-1}

[1] PRL 102, 012001(2009)

Charmonium spectrum



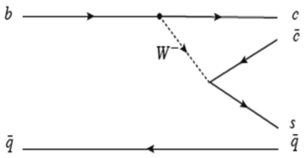
- Below the $D\bar{D}$ threshold, all expected states have been observed, with properties in good agreement with theory; there are no additional states.

- Many unexpected states have been reported above the $D\bar{D}$ threshold, seemingly too many with $J^{PC} = 1^{--}$.
Several exotic hypotheses about their nature: tetraquarks, hadronic molecules, hybrids, glueballs, hadro-quarkonia.

- These result mainly from Belle and *BABAR* , with significant contributions also from CDF, D0, CLEO, LHCb, ATLAS, CMS and BES

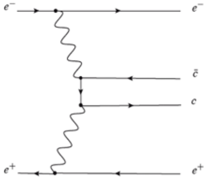
Experimental methods for charmonium production at the B-factories

B meson decays



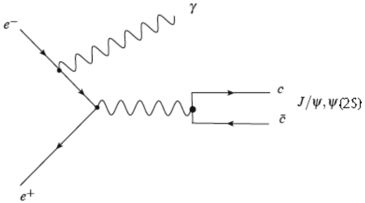
States of any quantum numbers can be produced

Two-photon production



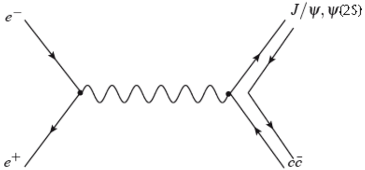
Only states with J^{PC} = $0^{\pm+}$, $2^{\pm+}$, $4^{\pm+}$,......, 3^{++}, 5^{++},....... can be produced

Initial State Radiation (ISR)

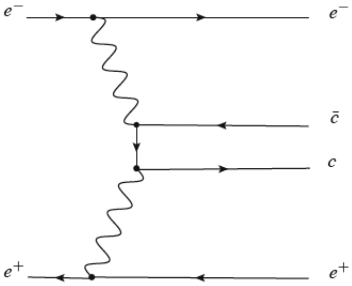


Only states with $J^{PC} = 1^{--}$ can be produced

Double charmonium production



Only charmonium states with C=+1 are allowed to be produced in association with the J/ψ or the ψ(2S)



Study of the $J/\psi\ \omega$ final state in two-photon collisions (519 fb^{-1})

PRD 86, 072002 (2012)

Confirm the X(3915) and search for the X(3872).

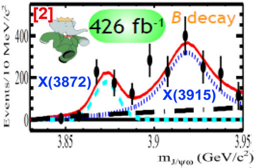
X(3915)

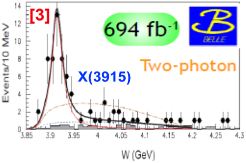
- The X(3915) was seen by both Belle [1] and *BABAR* [2] in $B \to X(3915)K$, with X(3915)$\to J/\psi\ \omega$
- Belle also observed the X(3915) in $\gamma\gamma \to X(3915) \to J/\psi\ \omega$ [3]
- Previous Belle and *BABAR* analyses of two-photon production in $D\bar{D}$ established the existence of a $J^{PC} = 2^{++}$ state in the 3.92-3.93 GeV region which is interpreted as the $\chi_{c2}(2P)$ state.

X(3872)

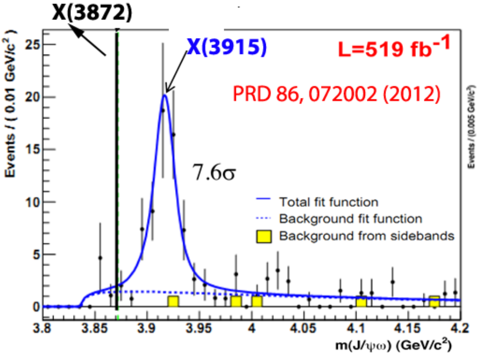
- The $X(3872) \to J/\psi\ \omega$ was seen in B decays by *BABAR* [2], and Belle [4]
- The possible X(3872) quantum numbers could be J^{PC}=1^{++} or J^{PC}=2^{-+} [5].
- Recent LHCb results seems to favor strongly J^{PC}=1^{++} [6].
- $\gamma\gamma \to X(3872)$ would imply $J^{PC} = 2^{-+}$
- $\gamma\gamma \to X(3872)$ is not seen in Belle's spectrum.

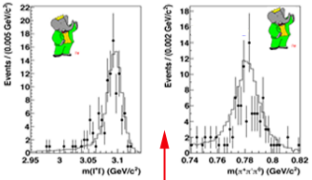
[1] Belle PRL 94,182002 (2005)
[2] *BABAR* PRD 82,011101(R) (2010)
[3] Belle PRL 104,092001 (2010)
[4] Belle arXiv:0505037
[5] CDF PRL 98, 132002 (2007)
[6] LHCb arXiv:1302.6269 (2013)





$\gamma\gamma \to J/\psi\ \omega$ - Results





After the event selection,
clear J/ψ and ω signal,
with negligible background

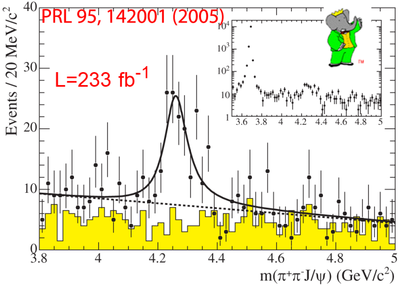
Results are consistent with Belle's:
(PRL 104, 092001 (2010))

	BABAR	Belle
Mass (MeV/c^2)	$3919.4 \pm 2.2 \pm 1.6$	$3915 \pm 3 \pm 2$
Width (MeV)	$13 \pm 6 \pm 3$	$17 \pm 10 \pm 3$
$\Gamma_{\gamma\gamma} \times \mathcal{B}$ (J=0) (eV)	$52 \pm 10 \pm 3$	$61 \pm 17 \pm 8$
$\Gamma_{\gamma\gamma} \times \mathcal{B}$ (J=2) (eV)	$10.5 \pm 1.9 \pm 0.6$	$18 \pm 5 \pm 2$

New limit: $\Gamma_{\gamma\gamma}$(X(3872))x$B(X(3872) \to J/\psi\ \omega)(J=2)$<1.7 eV
X(3915) quantum number determination: $J^P = 0^+$ favored by *BABAR*

Y(4260)

Y(4260)



Y(4260) was discovered in the ISR process $e^+e^- \to Y(4260) \to J/\psi\pi^+\pi^-$ by *BABAR* PRL 95,142001 (2005).

$M(Y(4260)) = 4259 \pm 8^{+2}_{-6}$ MeV

$\Gamma(Y(4260)) = 88 \pm 23^{+6}_{-4}$ MeV

$\Gamma_{e^+e^-} \times B(\pi^+\pi^- J/\psi) = 5.5 \pm 1.0^{+0.8}_{-0.7}$ MeV

It was confirmed by Belle PRL 99,182004 (2007). They observed an additional structure the Y(4008)

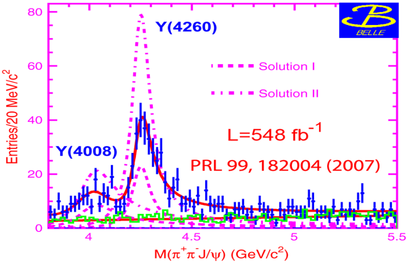
$M(Y(4260)) = 4263 \pm 6$ MeV

$\Gamma(Y(4260)) = 126 \pm 18$ MeV

$\Gamma_{e^+e^-} \times B(\pi^+\pi^- J/\psi) = 9.7 \pm 1.1$ MeV

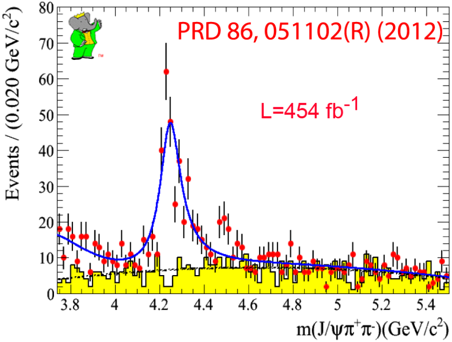
$M(Y(4008)) = 4008 \pm 40^{+114}_{-28}$ MeV

$\Gamma(Y(4008)) = 226 \pm 44 \pm 87$ MeV



Y(4260)

- New analysis from *BABAR* : more precise measurements of Y(4260) parameters in $J/\psi\pi^+\pi^-$ ISR production PRD 86, 051102(R) (2012)



An extendend-maximum-likelihood fit is performed to the signal region $J/\psi\pi^+\pi^-$ distribution and simultaneously to the background distribution in the region 3.74-5.5 GeV/c^2.

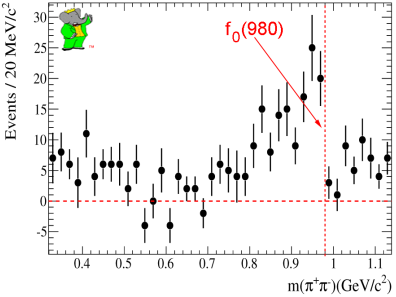
Mass (Y(4260)) = 4244±5±4 MeV/c^2

Γ(Y(4260))=$114^{+16}_{-15}\pm7$ MeV

$\Gamma_{e^+e^-} \times B(J/\psi\pi^+\pi^-)$=9.2±0.8±0.7 eV

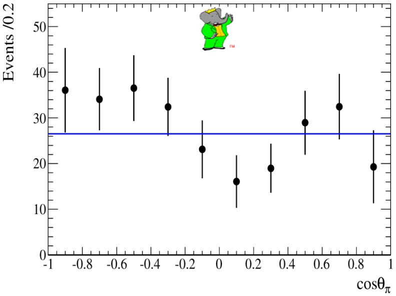
No evidence for the state at ∼4 GeV/c^2 reported by Belle.

$\pi^+\pi^-$ Invariant mass distribution in the Y(4260) decay (1)



- For $4.15 \leq m(J/\psi\pi^+\pi^-) \leq 4.45$ GeV/c^2
- The distribution seems to peak around the $f_0(980)$ mass; however the peak is displaced from the indicated $f_0(980)$ position.
- The fact that the peak is displaced suggests possible interference between the $f_0(980)$ and an $m(\pi^+\pi^-)$ contribution.

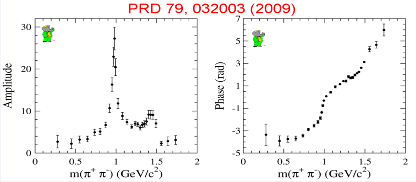
- The $\pi^+\pi^-$ system has C=+1 and hence even angular momentum.
- Define θ_π as the angle between the π^+ direction and that of the recoil J/ψ both in the dipion rest frame.
- The distribution, which must be symmetric, is consistent with S-wave behaviour (blue line) $\chi^2/NDF = 12.3/9$; probability=19.7%.

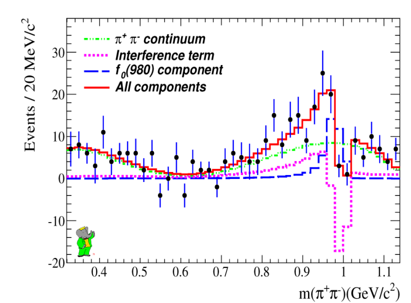


$\pi^+\pi^-$ Invariant mass distribution in the Y(4260) decay (2)

A simple model has been used to describe the $\pi^+\pi^-$ mass distribution, namely the square of an amplitude consisting of the coherent sum of a nonresonant component motivated by a QCD multipole expansion and an $f_0(980)$ amplitude; the relative strength and phase of these components are free to vary in the fit to the data.

The mass-dependence of the $f_0(980)$ amplitude and phase is from the *BABAR* analysis of the decay $D_s^+ \rightarrow \pi^+\pi^-\pi^+$





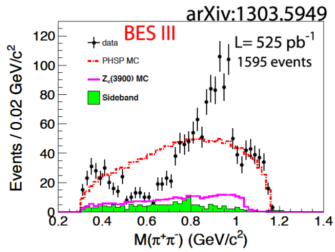
Using this simple model, a good description of the $\pi^+\pi^-$ mass distribution is obtained.

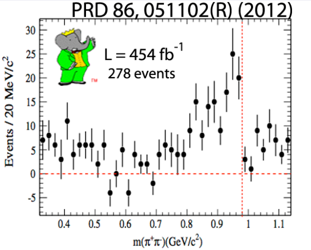
This indicates that there is an $f_0(980)$ contribution to the decay of the Y(4260) to $J/\psi\pi^+\pi^-$ but that contribution is not dominant.

$$\frac{B(Y_{4260} \to J/\psi f_0(980), f_0(980) \to \pi^+\pi^-)}{B(Y_{4260} \to J/\psi\pi^+\pi^-)} = (17 \pm 13)\%$$

New analysis coming from BES III: arXiv:1303.5949 (1)

They reported a study of the process $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s}$=4.260 GeV



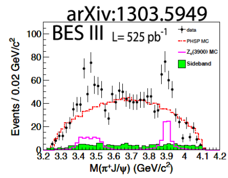


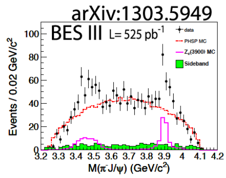
Their $\pi^+\pi^-$ invariant mass distribution is very similar to that obtained in the *BABAR* analysis PRD 86,051102(R) (2012) [but BES III $\sim$ 6$\times$ *BABAR* in statistics].

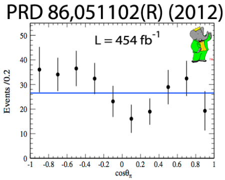
BES shows phase space MC projections on their plots although it is clear that the dipion mass distribution differs significantly from PS.

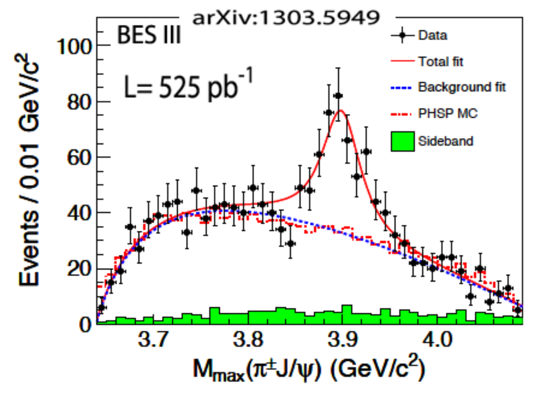
The BES $J/\psi\pi$ mass distributions imply structure in cosθ_π

The *BABAR* distribution may reflect this, but within the large uncertainties it is also consistent with being flat.









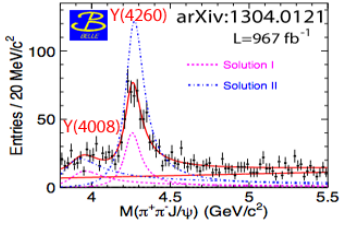
They observe a new structure around 3.9 GeV/c^2 in the $\pi^{\pm} J/\psi$ mass spectrum, which they refer to as the $Z_c(3900)$.

$$M(Z_c(3900)) = 3899.0 \pm 3.6 \pm 4.9 \text{ MeV}/c^2$$
$$\Gamma(Z_c(3900)) = 46 \pm 10 \pm 20 \text{ MeV}$$

For additional details see Yaqian Wang's talk. (10th April)

New analysis coming from Belle: arXiv:1304.0121 (1)

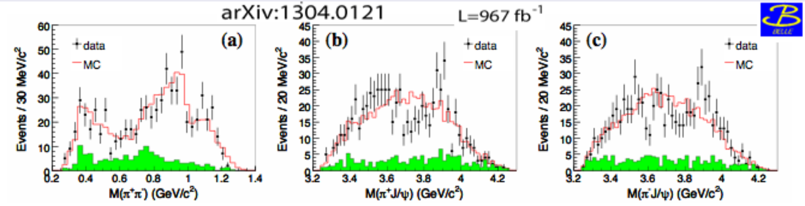
They reported a study of the process $e^+e^- \to \pi^+\pi^- J/\psi$ with 967 fb^{-1} collected at $\Upsilon(nS)$ (n=1,2,. . . .,5)



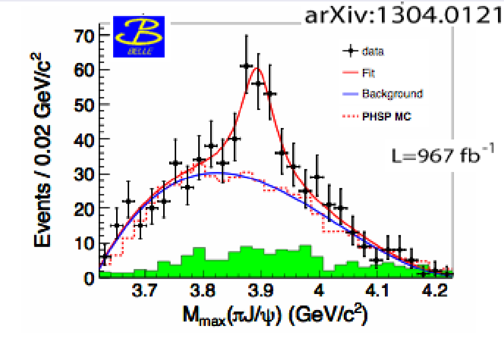
Parameters	Solution I	Solution II
$M(R_1)$	$3890.8 \pm 40.5 \pm 11.5$	
$\Gamma_{tot}(R_1)$	$254.5 \pm 39.5 \pm 13.6$	
$\Gamma_{ee}\mathcal{B}(R_1 \to \pi^+\pi^- J/\psi)$	$(3.8 \pm 0.6 \pm 0.4)$	$(8.4 \pm 1.2 \pm 1.1)$
$M(R_2)$	$4258.6 \pm 8.3 \pm 12.1$	
$\Gamma_{tot}(R_2)$	$134.1 \pm 16.4 \pm 5.5$	
$\Gamma_{ee}\mathcal{B}(R_2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

They confirm the Y(4260) and the Y(4008).

They show the $m(\pi^+\pi^-)$ and $m(\pi^\pm J/\psi)$ distributions which are consistent with the BES results (arXiv:1303.5949).



New analysis coming from Belle: arXiv:1304.0121 (2)



They observe a new structure around 3.9 GeV/c^2 in the $\pi^{\pm} J/\psi$ mass spectrum, which they refer to as the $Z_c(3895)$ with 5.2σ significance.

$$M(Z_c(3895)) = 3894.5 \pm 6.6 \pm 4.5 \text{ MeV}/c^2$$
$$\Gamma(Z_c(3895)) = 63 \pm 24 \pm 26 \text{ MeV}$$

The results are consistent with the BES analysis (arXiv:1303.5949).

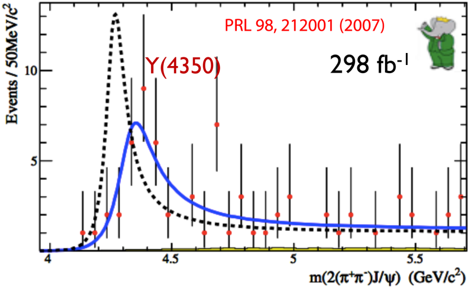
Summary of the Y(4260) properties

- $J^{PC} = 1^{--}$ because it is directly produced in the e^+e^- annihilation
- $Y(4260) \to J/\psi\pi^0\pi^0$ decay mode indicates I=0 PRL 96, 162003 (2006)
- Not observed in $Y(4260) \to \psi(2S)\pi^+\pi^-$ decays
- No observed decay to $D^*\bar{D}^*$ nor to $D_s^*\bar{D}_s^*$ so that its properties do not lend themselves to a simple charmonium interpretation
- BES III and Belle have reported the existence of a narrow resonant structure in the $J/\psi\pi$ sub-system at ∼3.9 GeV/c^2 which would correspond to an isovector four-quark state BES: arXiv:1303.5949; Belle: arXiv:1304.0121;
- Other interpretations:
  - four- quark state (PRD 72, 114016 (2005)). If the Y(4260) is a four-quark state it is expected to decay to $D_s^+\bar{D}_s^-$ but this has not been observed (PRD 82, 052004 (2010)).
  - baryonium state (J. Phyd. G 35, 075008 (2008))
  - hybrid state (PL B 625, 212 (2005)).

Y(4350) - Y(4660)

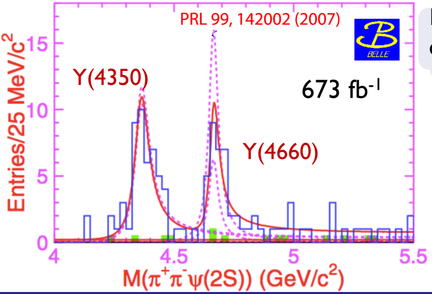
Y(4350) - Y(4660)

BABAR searched for the Y(4260) by the chain: $e^+e^- \rightarrow Y(4260) \rightarrow \psi(2S)\pi^+\pi^- \rightarrow J/\psi\pi^+\pi^-$ via ISR without finding evidence of signal PRL 98, 212001 (2007), but in the same final state discovered a new state, the Y(4350)



Mass (Y(4325)) $= 4324 \pm 24$ MeV/c^2

$\Gamma(Y(4325)) = 172 \pm 33$ MeV/c^2

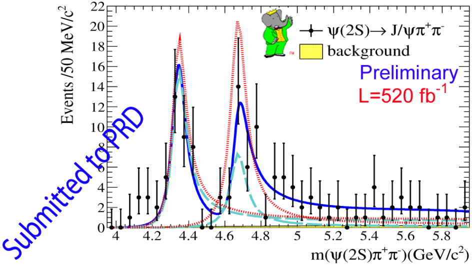


Belle confirmed the Y(4350) state and discovered the Y(4660) PRL 99, 142002 (2007)

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

Y(4350) - Y(4660)

- *BABAR* update arXiv:1211.6271 using the full dataset, including $\Upsilon(2S)$ and $\Upsilon(3S)$



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)	$2.7 \pm 1.3 \pm 0.5$	$7.5 \pm 1.7 \pm 0.7$
$\phi(^\circ)$	$12 \pm 27 \pm 4$	$-78 \pm 12 \pm 3$

Y(4350) - Y(4660)

arXiv:1211.6271

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PRL 99, 142002 (2007)

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ϕ	$39 \pm 30 \pm 22$	$-79 \pm 17 \pm 20$

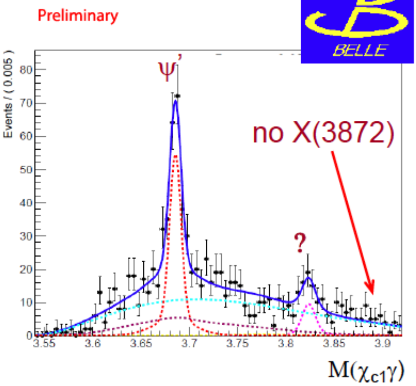
Summary of the Y(4350) - Y(4660) properties

- $J^{PC} = 1^{--}$ because they are directly produced in the e^+e^- annihilation
- They have been observed only in ISR $\psi(2S)\pi^+\pi^-$ production.
- Why are there states decaying into 2^3S_1 and not to 1^3S_1?
- One possible interpretation is hadro-charmonium states
  - M. B. Voloshin arXiv:0711.4556
  - Dubynsky & Voloshin PLB 671 (2009) 82

Search for C-odd partner of X(3872)
Preliminary results

Search for C-odd partner of X(3872)

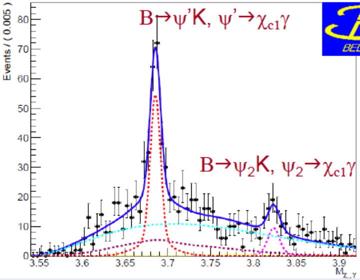
- Earlier search for tetraquark charged partner of the X(3872), but no signal was seen (PRD 84, 052004 (2011))
- If the X(3872) is a tetraquark, its C-odd partner can decay into $\chi_{c1,c2}\gamma$



- $B \to K + \gamma\chi_{c1}$: no X(3872) signal observed
  - $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X \to \gamma\chi_{c1})$ <2.0×10^{-6} @ 90% C.L.
  - $\mathcal{B}(X \to \gamma\chi_{c1}/\mathcal{B} \to J/\psi\pi^+\pi^-)$ <0.26@ 90% C.L.
- but, what is the peak at $M_{\gamma\chi_{c1}}$ ~3.82 GeV? A new charmonium state observed? This new state seems to be the missing ψ_2 from the charmonium spectrum

Evidence for $\psi_2 \rightarrow \chi_{c1}\gamma$

- $\psi_2 \rightarrow \chi_{c1}\gamma$ was predicted
- Godfrey & Isgur, PRD 32, 189 (1985): Prediction of a state $1^3D_2(3840)$ with $J^{PC} = 2^{--}$
- Eichten et al., PRL 89 162002 (2002) & PRD 69, 094019 (2004), prediction of a mass of 3831 MeV/c^2 and $\Gamma(\psi_2 \rightarrow \chi_{c1}\gamma) = 260$ keV
- No analysis defining I, J or P



Preliminary

	yield	Mass[MeV]	$BR(B^+ \rightarrow \psi(\rightarrow \chi_{c1}\gamma)K^+)$
ψ'	193 ± 18	3685.3 ± 0.6	$(7.7 \pm 0.8 \pm 0.9) \times 10^{-4}$
ψ_2	33 ± 9	3823.5 ± 2.8	$(9.7^{+2.8}_{-2.5} \pm 1.1) \times 10^{-6}$

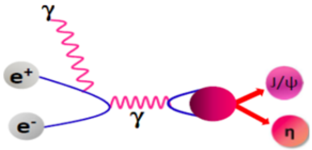
- First ψ_2 evidence
- ψ_2 significance is 4.2σ including systematics
- $\Gamma(\psi_2) = 4 \pm 6$ MeV from the fit

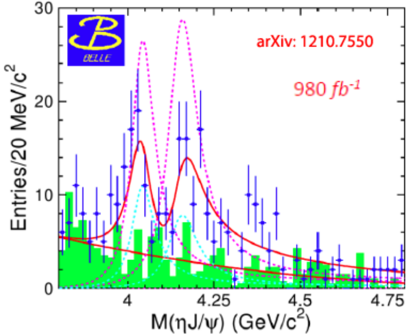
$e^+e^- \to J/\psi\eta$ via ISR

arXiv: 1210.7550

$e^+e^- \to J/\psi\eta$ via ISR

Previous measurements:
- CLEO Phys. Rev. Lett. 96, 162003 (2006) ($\mathcal{L}$=281 pb^{-1})
- BESIII Phys. Rev. D 86, 071101 (2012) ($\mathcal{L}$=478 pb^{-1}))





Parameters	Solution I	Solution II
$M_{\psi(4040)}$	4039 (fixed)	
$\Gamma_{\psi(4040)}$	80 (fixed)	
$\mathcal{B}\cdot\Gamma^{\psi(4040)}_{e^+e^-}$	$4.8 \pm 0.9 \pm 1.4$	$11.2 \pm 1.3 \pm 1.9$
$M_{\psi(4160)}$	4153 (fixed)	
$\Gamma_{\psi(4160)}$	103 (fixed)	
$\mathcal{B}\cdot\Gamma^{\psi(4040)}_{e^+e^-}$	$4.0 \pm 0.8 \pm 1.4$	$13.8 \pm 1.3 \pm 2.0$
ϕ	$336 \pm 12 \pm 14$	$251 \pm 4 \pm 7$

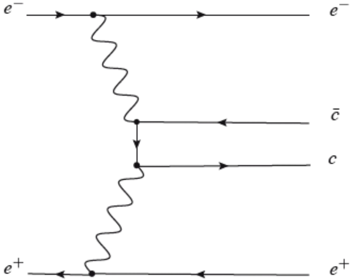
- First time $\psi(4040)$ and $\psi(4160)$ have been observed in final states not involving charm meson pair
- No signal from Y(4260), Y(4360), Y(4660)

Conclusion

- Quarkonium spectroscopy is a very interesting field, many new exotic states have been discovered in recent years;
- New exciting results are still coming from *BABAR* , Belle and also from BES III;
- Still many missing pieces need to be found to have the full picture.

THANKS FOR YOUR ATTENTION

BACKUP SLIDES



Search for resonances decaying into $\eta_c\pi^+\pi^-$ using two-photon interactions (474 fb^{-1})

PRD 86, 092005 (2012)

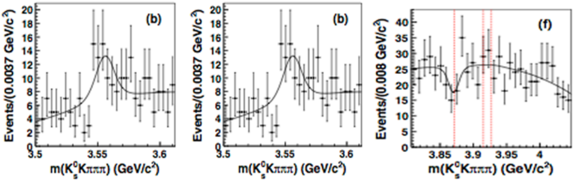
$\gamma\gamma \to \eta_c\pi^+\pi^-$ - Motivation

- Look for the process $\gamma\gamma \to X \to \eta_c(1S)\pi^+\pi^-$ where X stands for one of the resonances $\chi_{c2}(1P)$, $\eta_c(2S)$, X(3872), X(3915) or $\chi_{c2}(2P)$, where $\eta_c(1S) \to K^0_s K^\pm \pi^\mp$ and $K^0_s \to \pi^+\pi^-$

- Measure branching fractions for the decay of the states $\chi_{c2}(1P)$, $\eta_c(2S)$, X(3872), X(3915) and $\chi_{c2}(2P)$ to $\eta_c(1S)\pi^+\pi^-$

- Prediction for $B(\eta_c(2S) \to \eta_c(1S)\pi^+\pi^-)$ ~2.2%
obtained from $\Gamma(\eta_c(2S) \to \eta_c(1S)\pi^+\pi^-)/\Gamma(\psi(2S) \to J/\psi\pi^+\pi^-)$ ~2.9
(M.B.Voloshin Mod.Phys.Lett A 17, 1533 (2002))

- First measurement



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

Resonance	$\Gamma_{\gamma\gamma}\mathcal{B}$(eV)	
	Central value	UL
$\chi_{c2}(1P)$	$7.2^{+5.5}_{-4.4} \pm 2.9$	15.7
$\eta_c(2S)$	$65^{+47}_{-44} \pm 18$	133
$X(3872)$	$-4.5^{+7.7}_{-6.7} \pm 2.9$	11.1
$X(3915)$	$-13^{+12}_{-12} \pm 8$	16
$\chi_{c2}(2P)$	$-16^{+15}_{-14} \pm 6$	19

No resonant signal observed

PRD 86, 092005 (2012)

Using $B(\chi_{c2}(1P) \rightarrow K^0_s K^{\pm}\pi^{\mp})$ and $B(\eta_c(2S) \rightarrow K^0_s K^{\pm}\pi^{\mp})$ we obtain:

B($\chi_{c2}(1P) \rightarrow \eta_c(1S)\pi\pi$) <2.2% @90%CL

B($\eta_c(2S) \rightarrow \eta_c(1S)\pi\pi$) <7.4% @90%CL

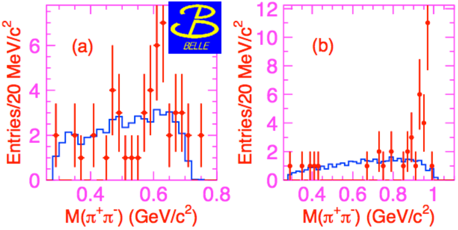


FIG. 4: $\pi^+\pi^-$ invariant mass distributions of events in different $\pi^+\pi^-\psi(2S)$ mass regions. (a): 4.0 GeV/c^2 $< m_{\pi^+\pi^-\psi(2S)} <$ 4.5 GeV/c^2, and (b): 4.5 GeV/c^2 $< m_{\pi^+\pi^-\psi(2S)} <$ 4.9 GeV/c^2. Points with error bars are data while the histograms are MC simulation with the phase-space distribution generated at $\sqrt{s} = 4.4$ GeV (a) and 4.7 GeV (b).

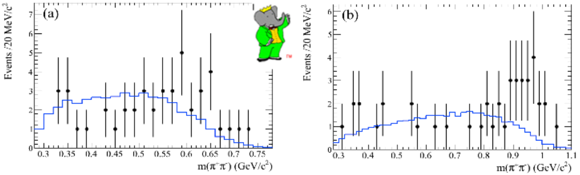


FIG. 4. The $\pi^+\pi^-$ invariant mass spectrum for the $\psi(2S) \to J/\psi\pi^+\pi^-$ channel in the $\psi(2S)\pi^+\pi^-$ mass region (a) 4.0–4.5 GeV/c^2, and (b) 4.5–4.9 GeV/c^2.