Charmonium production in e^+e^- and $\gamma\gamma$ collisions at BABAR

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BaBar Collaboration

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on Meson Production,
Properties and Interaction
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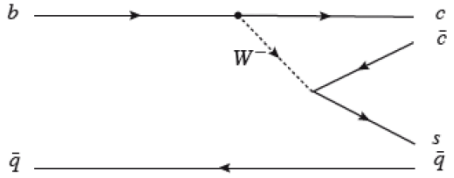
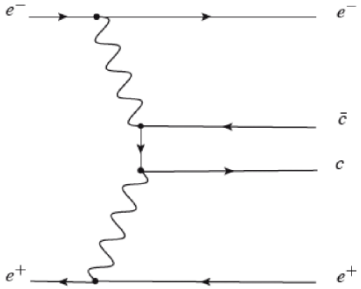
New charmonium states observed at B-factories

New charmonium-like states above DD threshold observed at B-factories from PDG2011:

- X(3872) B → KX, X → J/ψ $\pi^+\pi^-$ 2003
- X(3915) B→KX, γγ→ X, X→J/ψω 2005
- χ_{c2}(2P) γγ→DD 2006
- X(3940) e^+e^-→J/ψX 2007
- $X^{\pm}$(4050) B→KX, $X^{\pm}$ → $\pi^{\pm}$ χ_{c1} 2008
- X(4160) e^+e^-→J/ψX 2008
- $X^{\pm}$(4250) B→KX, $X^{\pm}$ → $\pi^{\pm}$ χ_{c1} 2008
- X(4260) e^+e^-→γ_{ISR} J/ψ $\pi^+\pi^-$ 2005
- X(4350) γγ→X, X→J/ψφ 2009
- X(4360) e^+e^-→γ_{ISR} ψ(2S) $\pi^+\pi^-$ 2007
- $X^{\pm}$(4430) B→KX, $X^{\pm}$ → $\pi^{\pm}$ ψ(2S) 2008
- X(4660) e^+e^-→γ_{ISR} ψ(2S) $\pi^+\pi^-$ 2007

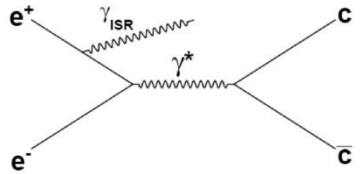
B decays

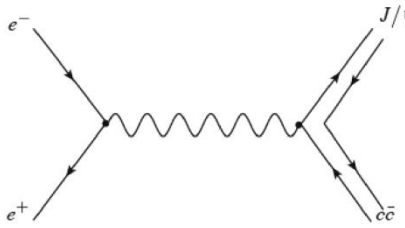




γγ collisions

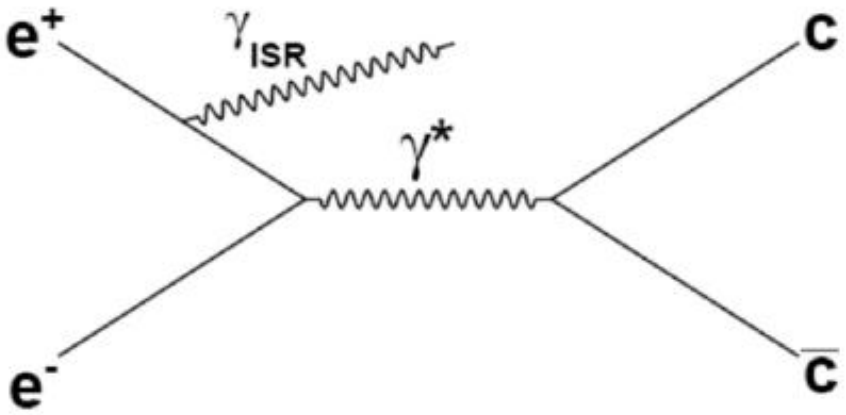
ISR





Double charmonium production

ISR production

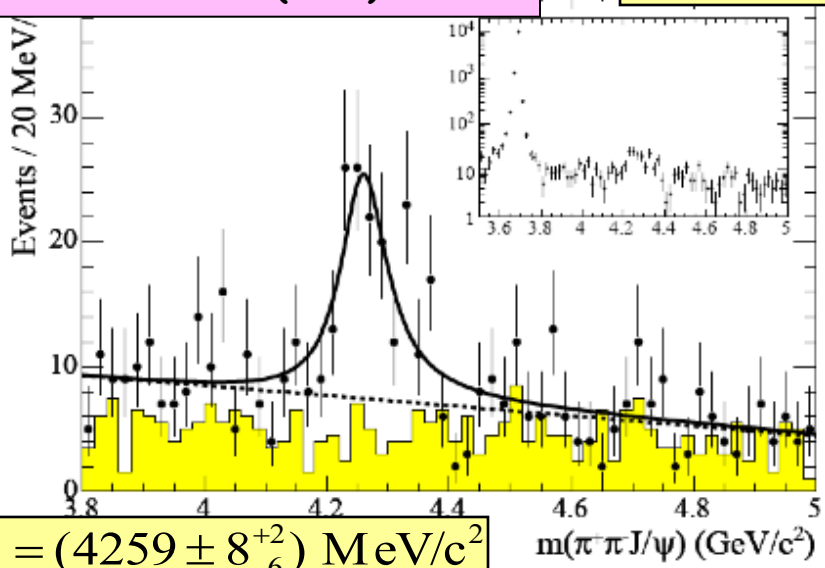


Existing data on Y(4260)

Y(4260) was observed by BaBar in 2005 in $J/\psi\pi^+\pi^-$ final state ising ISR technique (233 fb^{-1})

Phys. Rev. Lett. 95 (2005) 142001

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

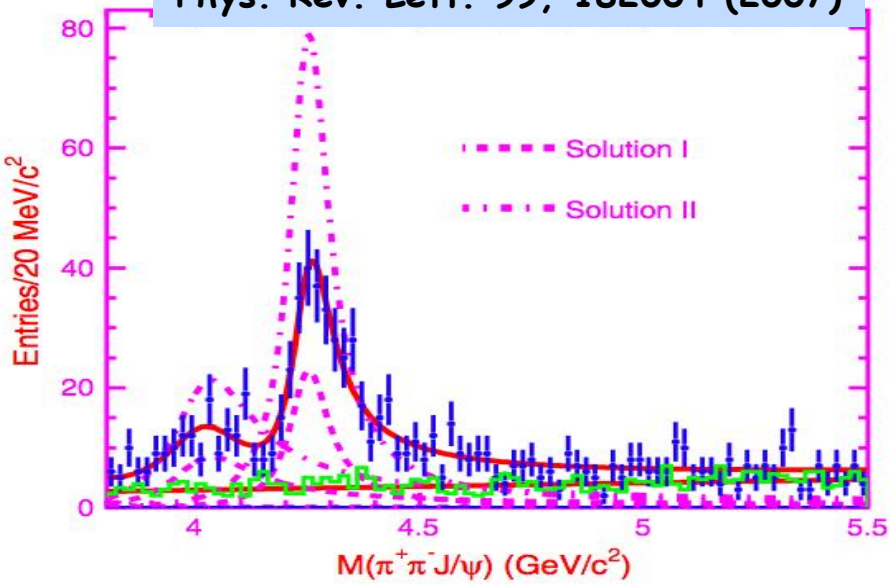


$m_Y = (4259 \pm 8^{+2}_{-6})\ \mathrm{MeV/c^2}$

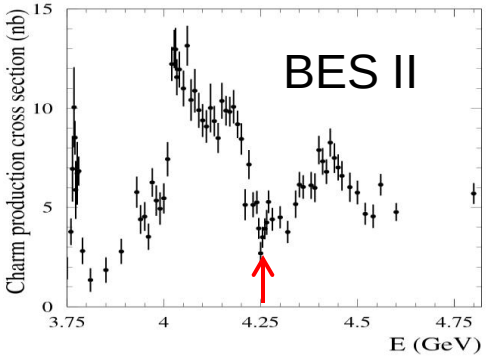
$\Gamma_Y = (88 \pm 23^{+6}_{-4})\ \mathrm{MeV}$

Confirmed by CLEO and Belle. Belle used the same method and same final state (548 fb^{-1})

Phys. Rev. Lett. 99, 182004 (2007)



The measured peak cross section is about 50 pb. There is no a clear Y(4260) signal in the charm cross section. $\Gamma(X\to J/\psi\pi\pi) > 1$ MeV, too large for conventional charmonium.



$M_{Y4260} = 4247 \pm 12\ ^{+17}_{-32}$

$\Gamma_{Y4260} = 108 \pm 19 \pm 10$

$M_{Y4008} = 4008 \pm 40\ ^{+114}_{-28}$

$\Gamma_{Y4008} = 226 \pm 44 \pm 87$

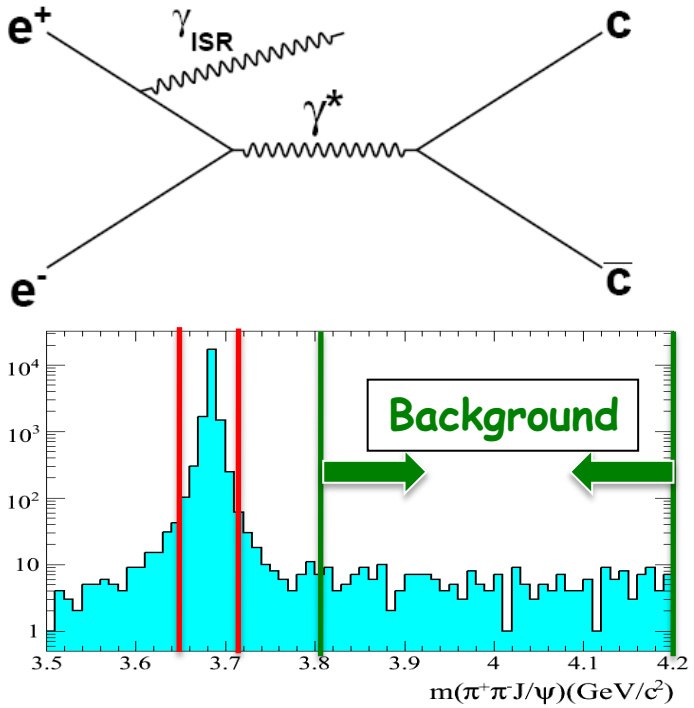
New Babar analysis

arXiv:1204.2158

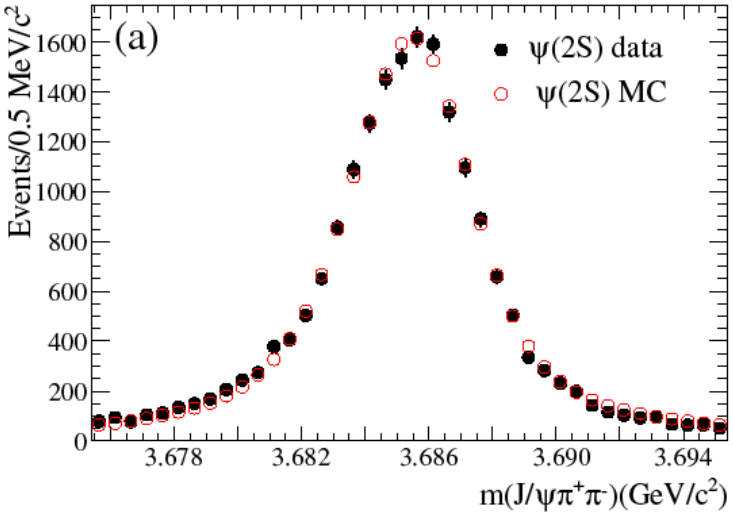
- Use full BaBar data (454 fb-1)
- Investigate the J/ψ $\pi^+\pi^-$ mass spectrum in a wider region, from threshold to 5.5 GeV/c2
- Study the mass and angular distributions of the $\pi^+\pi^-$ system

Event selection

- γ_{ISR} detection is not required
- Small mass recoiling against the final J/psi $\pi^+\pi^-$ state
- Low missing transverse momentum
- A candidate J/ψ is reconstructed via its decay to $\mu^+\mu^-$ or to e^+e^-
- J/ψ sideband is used to estimate background

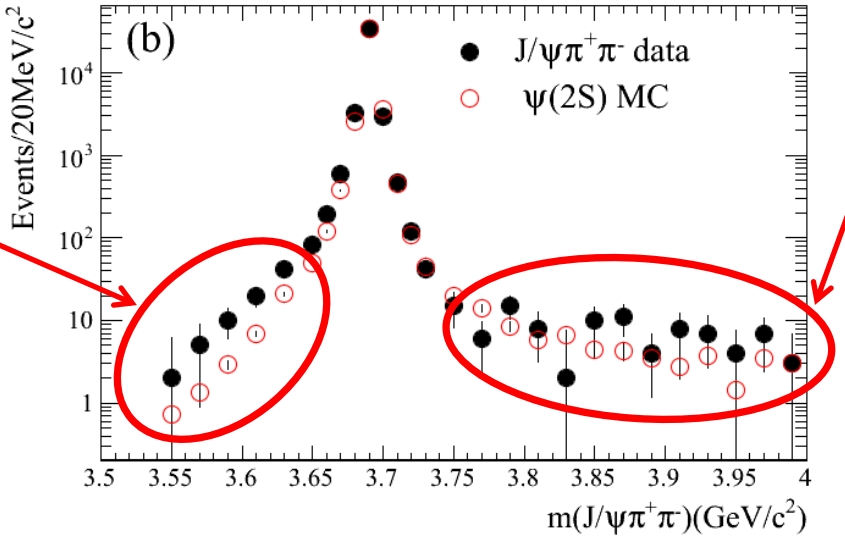


$\psi(2S)$ signal



To describe $\psi(2S)$ line shape we tune MC simulation introducing a mass shift and a resolution smearing.
From the number of $\psi(2S)$ events we determine $\Gamma(\psi(2S) \rightarrow e^+e^-)$ =
2.31±0.05 keV PDG: 2.35±0.04 keV

Evidence of non-resonant $J/\psi\ \pi^+\pi^-$ production

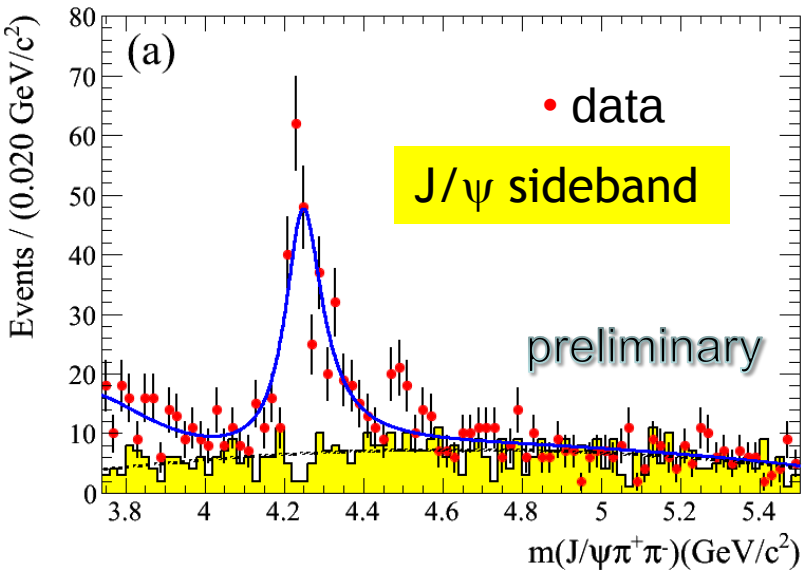


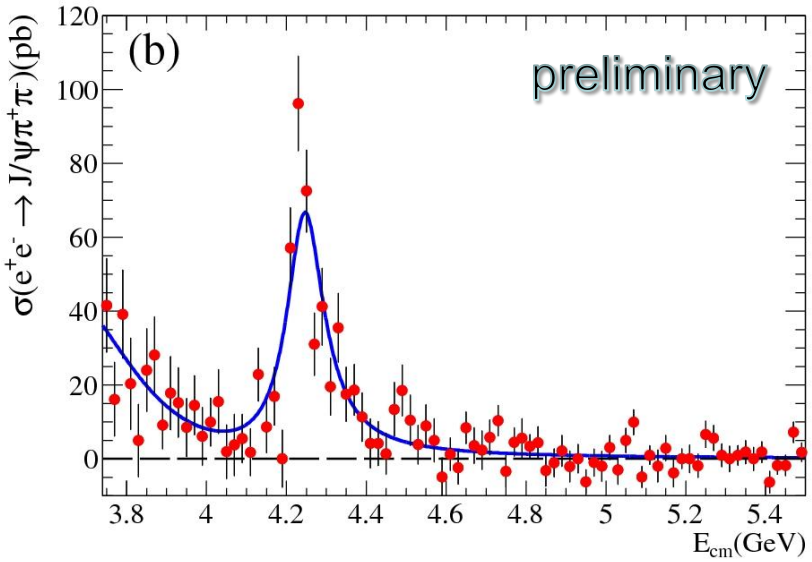
$\psi(2S)$ tail + possible non-resonant contribution

Y(4260) parameters

- The signal cross section is described by the incoherent sum $\sigma(m)=\sigma_{NR}(m)+\sigma_{BW}(m)$
  - $\sigma_{NR}(m)$ is an exponential function,
  - $\sigma_{BW}(m)$ is the S-wave Breit-Wigner function.
- The background is described by a third-order polynomial.

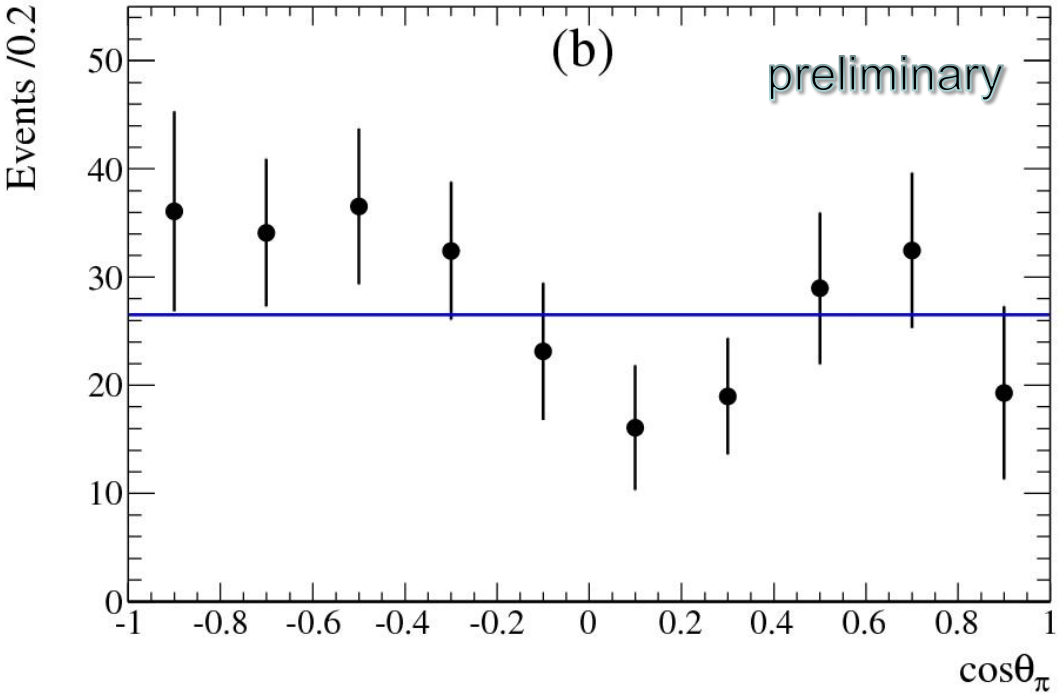
We do not confirm a broad structure at 4.01 GeV reported by Belle





	Our result	Old *BABAR*	Belle (548/fb)
Mass (MeV/c^2)	4243 ± 5	$4259 \pm 8^{+2}_{-6}$	4263 ± 6
Width (MeV)	118^{+16}_{-14}	$88 \pm 23^{+6}_{-4}$	126 ± 18
$\Gamma_{Y\to e^+e^-} \times \mathcal{B}_{Y\to\pi^+\pi^- J/\psi}(eV)$	9.3 ± 0.8	5.5 ± 1.0	9.7 ± 1.1

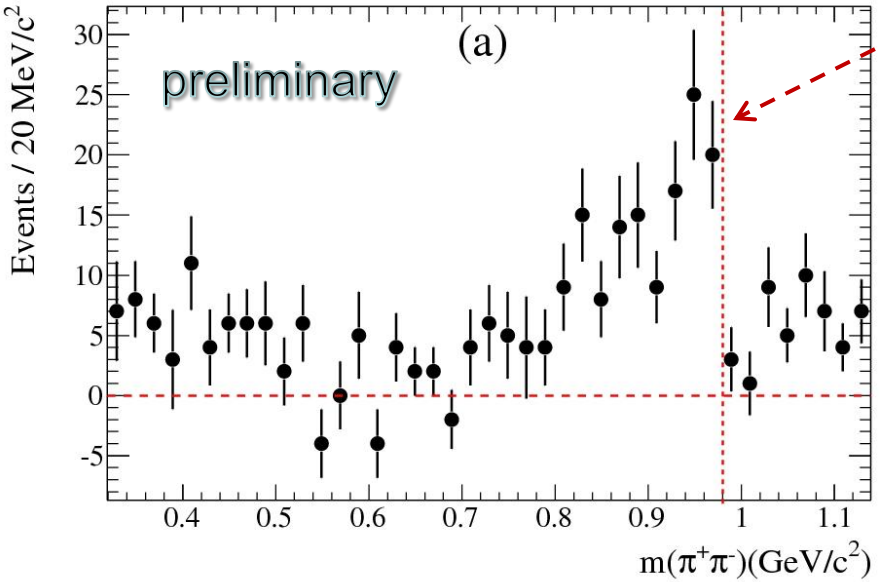
$\pi^+\pi^-$ system: angular distribution



We examine the dipion angular distribution using the cosine of the angle between the π^+ in the $\pi^+\pi^-$ rest frame and the dipion direction in the $J/\psi\pi^+\pi^-$ rest frame.

The straight line corresponding to S-wave dipion state describes data well (χ^2/NDF=12.3/9, probability ≈ 20%).

$\pi^+\pi^-$ mass distribution



$f_0(980)$ nominal mass

The shape of mass spectrum near 980 MeV/c² looks as interference.

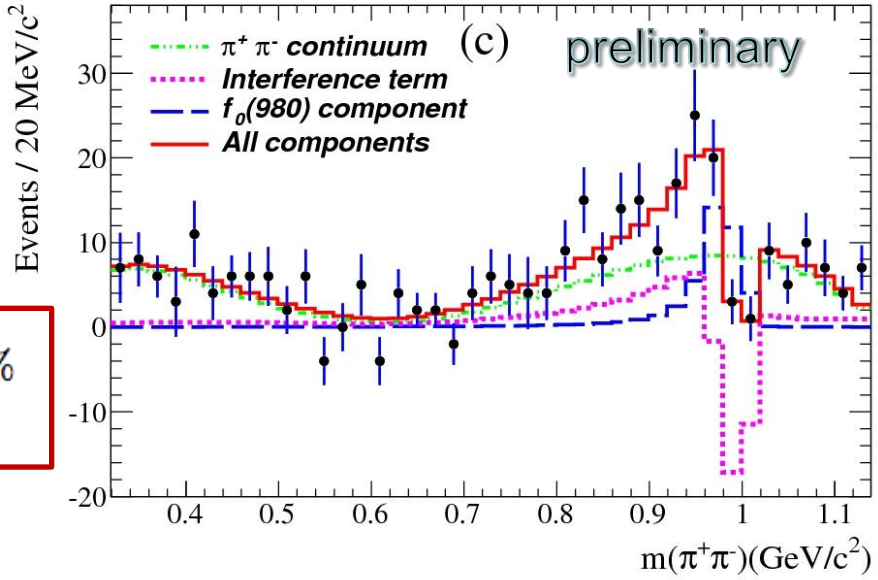
$$|\sqrt{pol} + e^{i\phi} F_{f_0(980)}|^2$$

pol is a 4th order polynomial, F_{f0} is the model independent f_0 shape taken from $D_s \to 3\pi$ analysis (Phys. Rev. D79, 032003 (2009)).

χ^2/NDF=33.6/35

ϕ=28°±24°

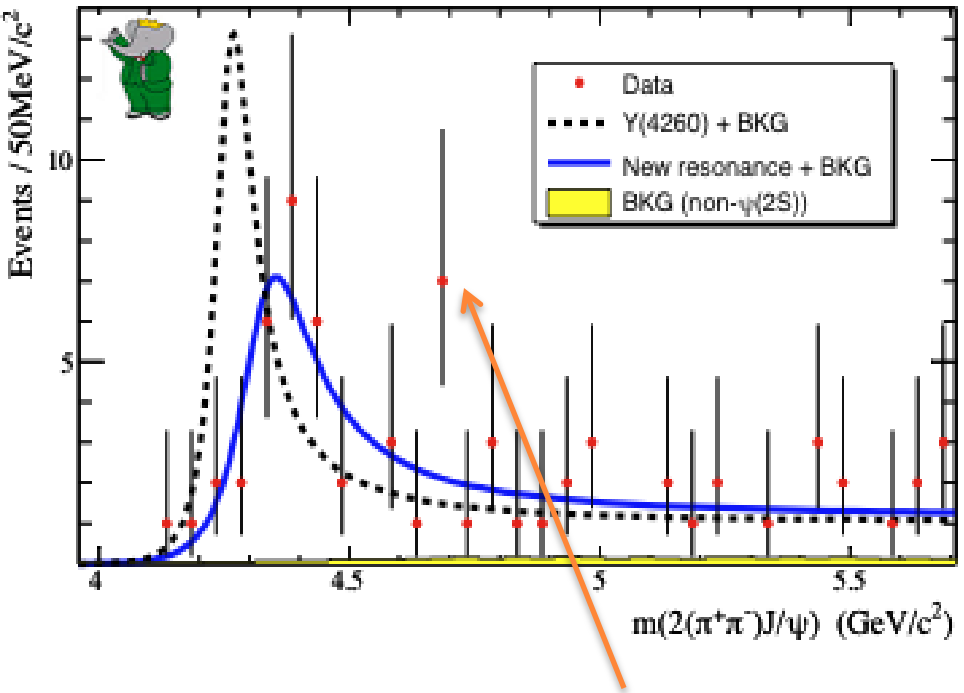
$$\frac{B(Y_{4260}\to J/\psi f_0(980),\ f_0(980)\to\pi^+\pi^-)}{\mathcal{B}(Y_{4260}\to J/\psi\pi^+\pi^-)} = (17 \pm 13)\%$$



Existing data on Y(4360) and Y(4660)

Phys. Rev. Lett. 98 (2007) 212001

298 fb^{-1}



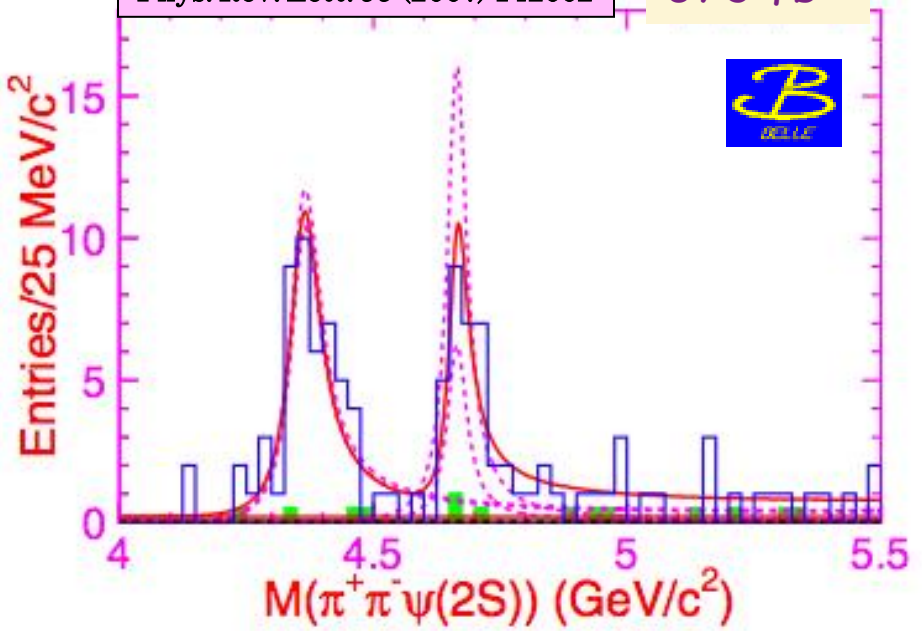
Excess of events at the Y(4660) mass

M_{Y4330} = 4324 ± 24 MeV/c2

Γ_{Y4330} = 172 ± 33 MeV

Phys. Rev. Lett. 99 (2007) 142002

673 fb^{-1}



M_{Y4360} = 4361 ± 9 ± 9 MeV/c2

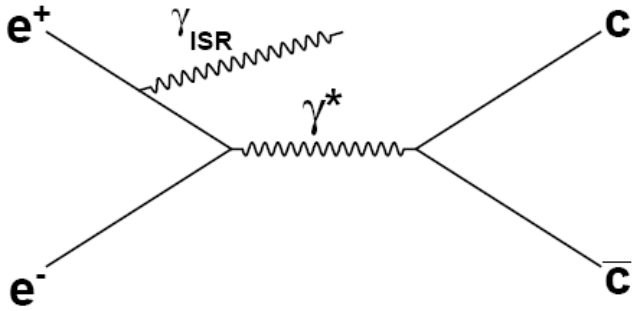
Γ_{Y4360} = 74 ± 15 ± 10 MeV

M_{Y4660} = 4664 ± 11 ± 5 MeV/c2

Γ_{Y4660} = 48 ± 15 ± 3 MeV

New Babar analysis

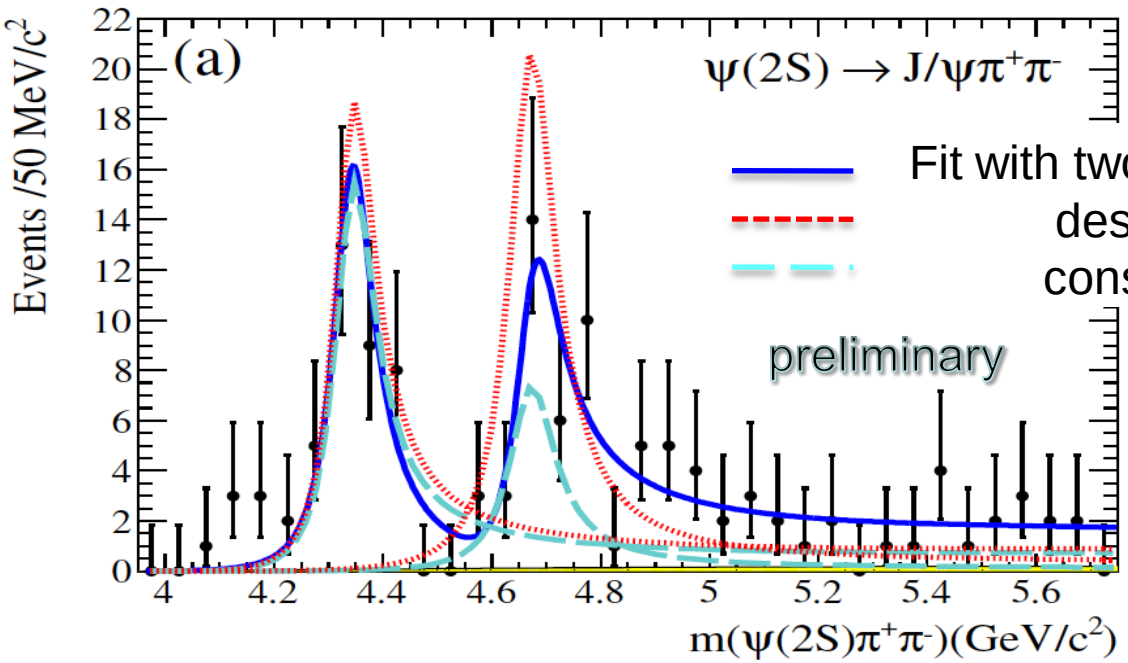
The full BaBar dataset, 520 fb^{-1}, is used for analysis



Event selection

- γ_{ISR} detection is not required
- Small mass recoiling against the final $\psi(2S)\ \pi^+\pi^-$ state
- Low missing transverse momentum
- A candidate $\psi(2S)$ is reconstructed via its decay to
  - $J/\psi\ \pi^+\pi^-$, $J/\psi \to \mu^+\mu^-$ or to e^+e^-
  - $\psi(2S) \to \mu^+\mu^-$ or to e^+e^-
- $\psi(2S)$ sideband events is used to estimate background

$\psi(2S) \to J/\psi\,\pi^+\pi^-$ decay mode



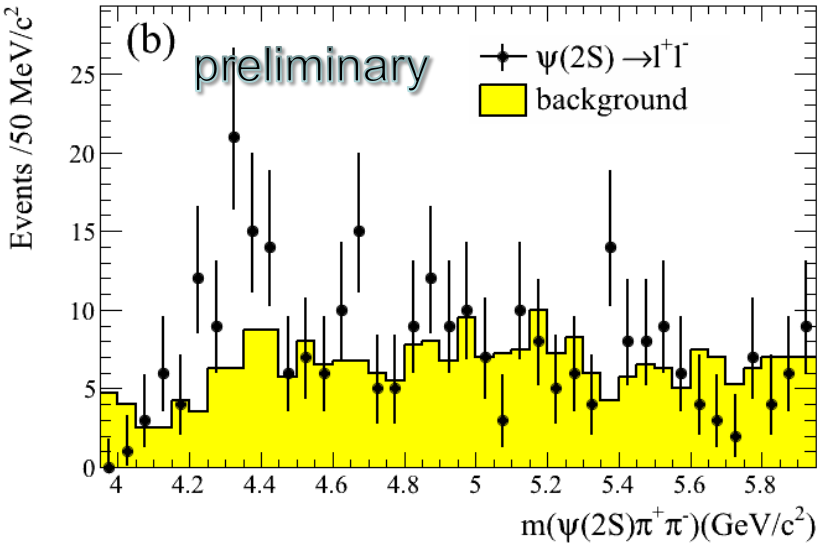
Fit with two coherent resonances
destructive solution
constructive solution

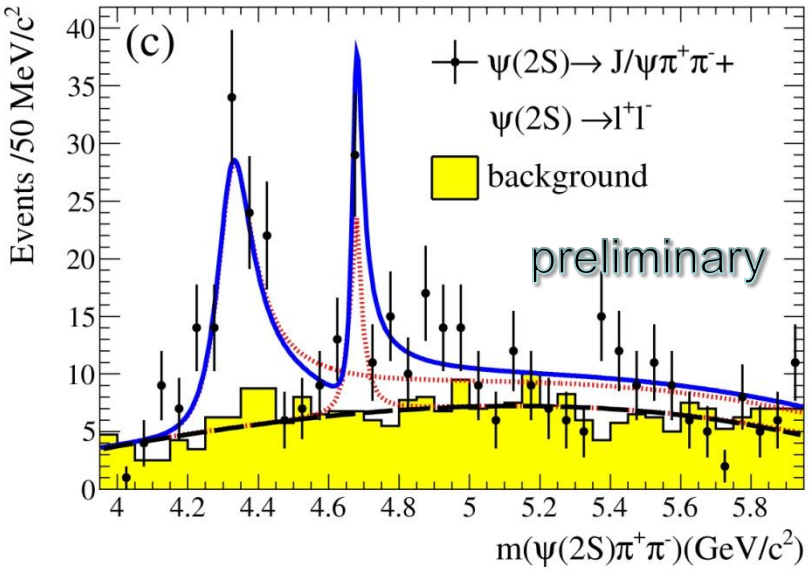
Parameters	First Solution [constructive interference]	Second Solution [destructive interference]
Mass Y(4360)(MeV/c^2)	$4340 \pm 16 \pm 9$	
Width Y(4360)(MeV)	$94 \pm 32 \pm 13$	
$\mathcal{B} \times \Gamma_{ee}(Y(4360))(eV)$	$6.0 \pm 1.0 \pm 0.5$	$7.2 \pm 1.0 \pm 0.6$
Mass Y(4660)(MeV/c^2)	$4669 \pm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

BELLE RESULT

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

$\psi(2S) \to l^+l^-$ decay mode



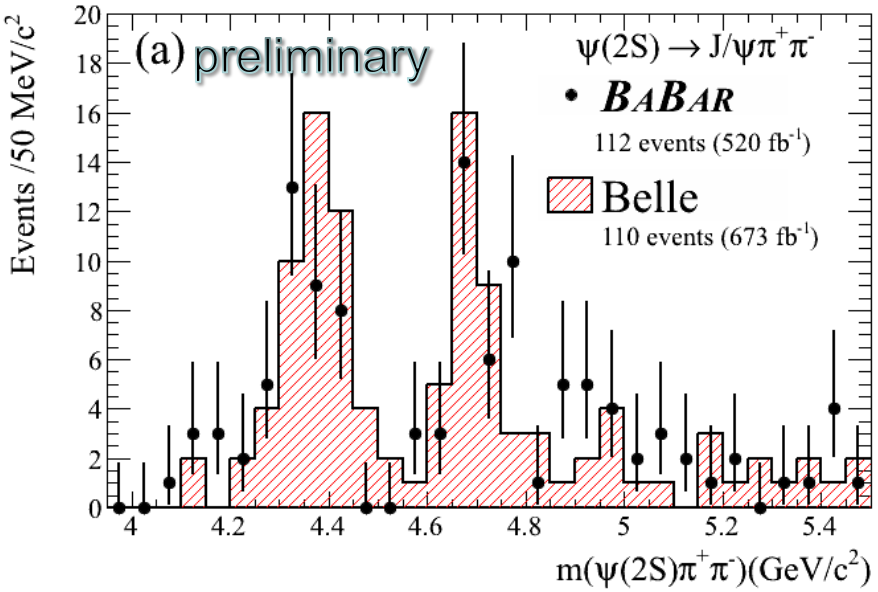


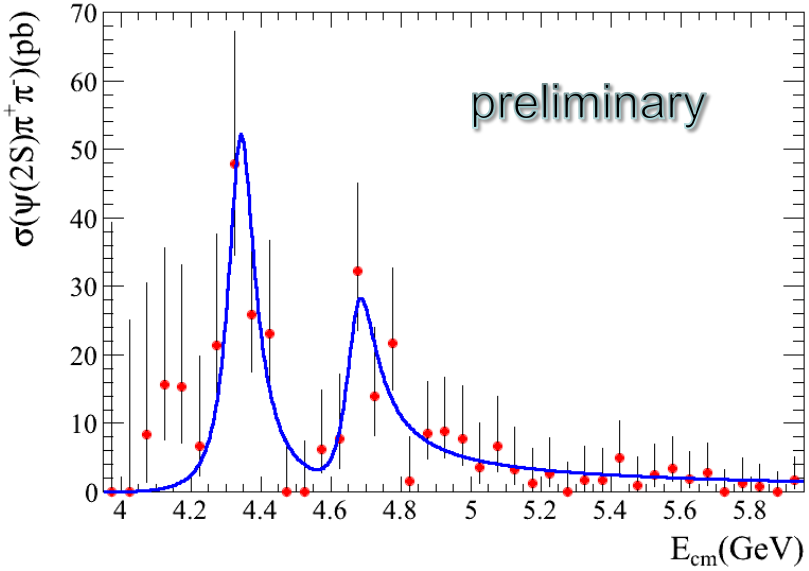
For the fit to the combined data distribution for both $\psi(2S)$ decay modes, the constructive and destructive interference solutions coalesce, only the constructive-interference solution remains.

Parameters	Solution
Mass $\Upsilon(4360)$(MeV/c^2)	$4318^{+15}_{-19} \pm 3$
Width $\Upsilon(4360)$(MeV)	$123 \pm 20 \pm 13$
$\mathcal{B} \times \Gamma_{ee}(\Upsilon(4360))$(eV)	$7.4 \pm 0.9 \pm 0.7$
Mass $\Upsilon(4660)$(MeV/c^2)	$4667^{+6}_{-7} \pm 2$
Width $\Upsilon(4660)$(MeV)	36^{+32}_{-14}
$\mathcal{B} \times \Gamma_{ee}(\Upsilon(4660))$(eV)	$1.4 \pm 0.5 \pm 0.2$
$\phi(^\circ)$	$+25 \pm 21 \pm 2$

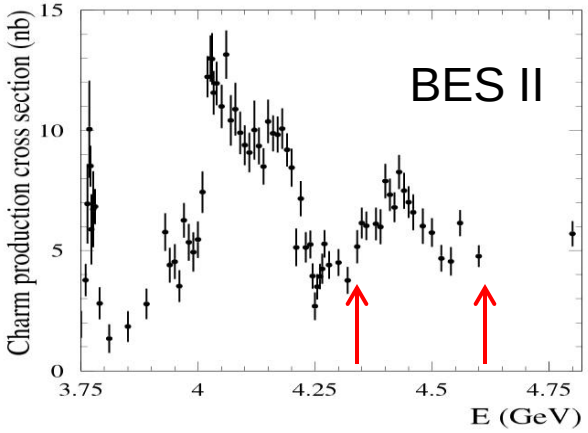
$\psi(2S) \to J/\psi\,\pi^+\pi^-$ decay mode

The distributions agree very well, and each shows evidence of two resonant signals in the mass distribution. There can be no doubt about the existence of two structures.

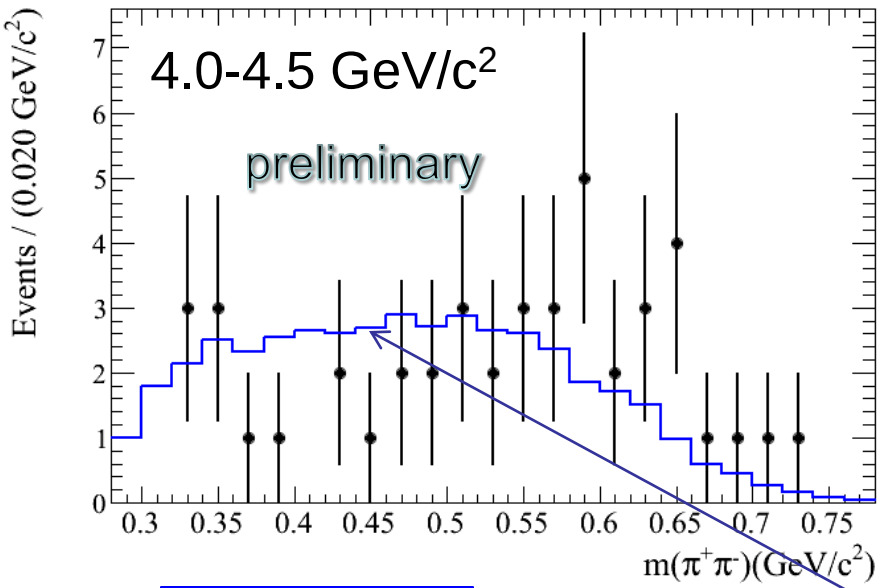


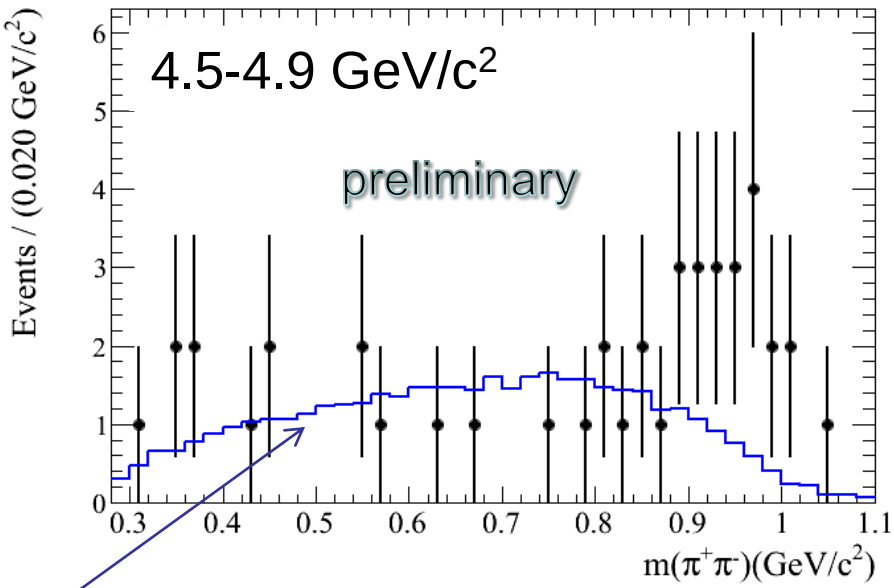


For conventional cc states we expect about 1000 times larger signal in D-mesons.



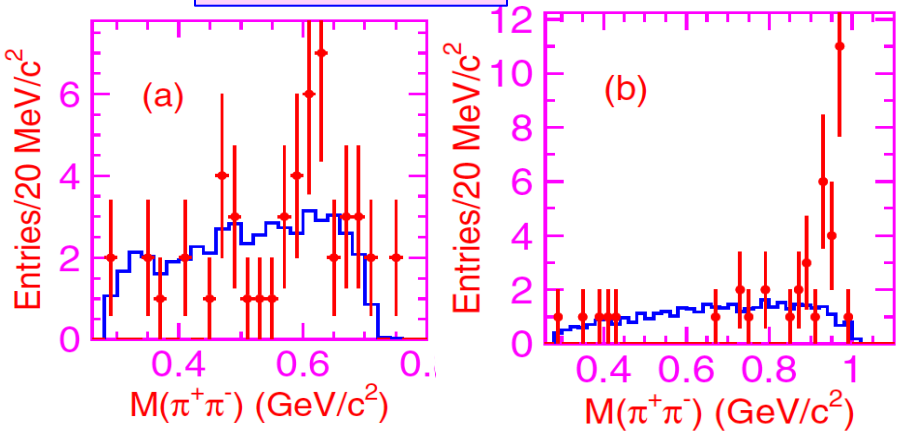
$\pi^+\pi^-$ mass distribution





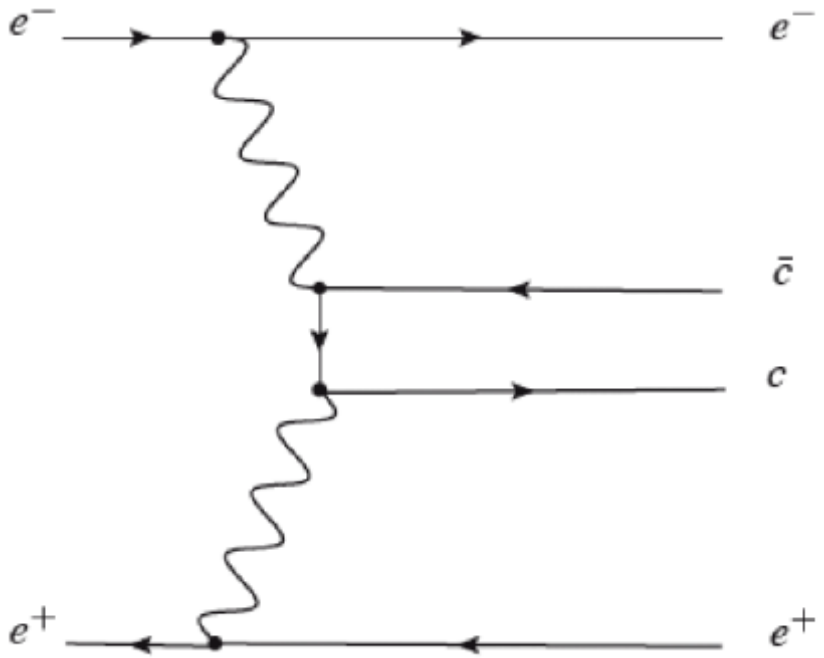
Phase space

BELLE RESULT



The $\pi^+\pi^-$ mass spectrum for Y(4660) is similar to that for Y(4260) $\rightarrow J/\psi\ \pi^+\pi^-$

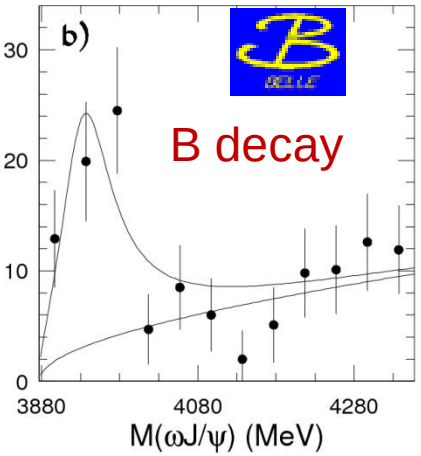
Two-photon production



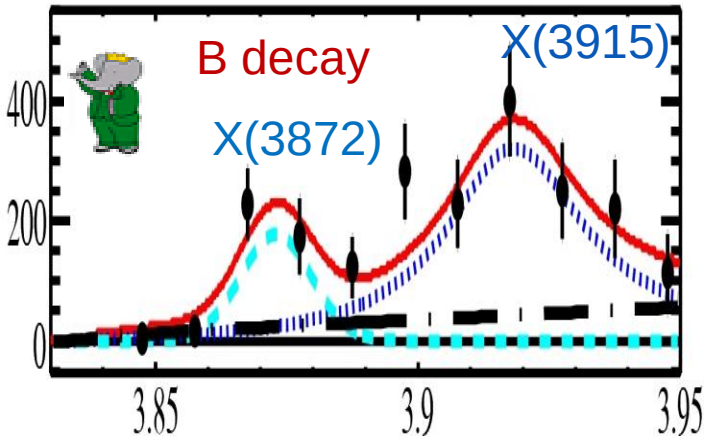
$\gamma\gamma \to J/\psi\omega$, motivation

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

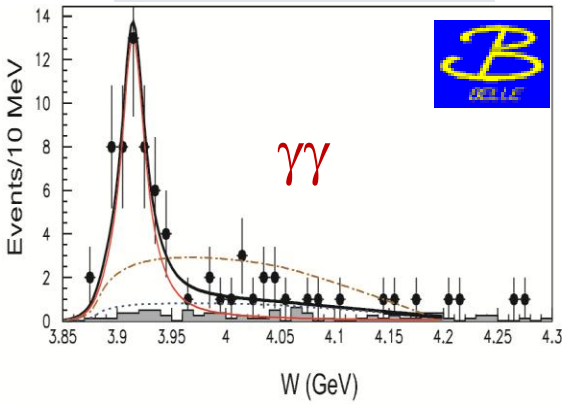
PRL 94 182002



PRD 82 011101(R)



PRL 104 092001



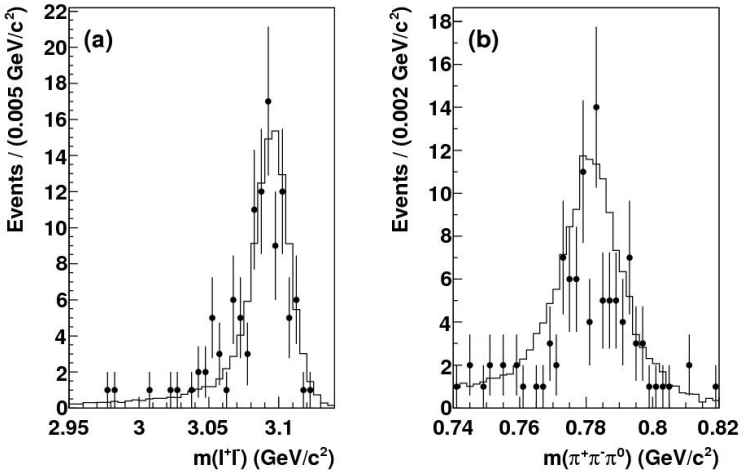
- Both Belle and BABAR observed X(3915) in $B \to XK$ decay with $X \to J/\psi\omega$.
- Belle also observed it in $\gamma\gamma \to J/\psi\omega$ channel.

- The X(3872) $\to J/\psi\omega$, was also seen in B decays.
- J^{PC} for X(3872) is 1^{++} or 2^{-+} (CDF: PRL 98 132002).
- Observation of $\gamma\gamma \to X(3872)$ would imply $J^{PC}=2^{-+}$.
- $\gamma\gamma \to X(3872)$ is not seen in Belle's spectrum

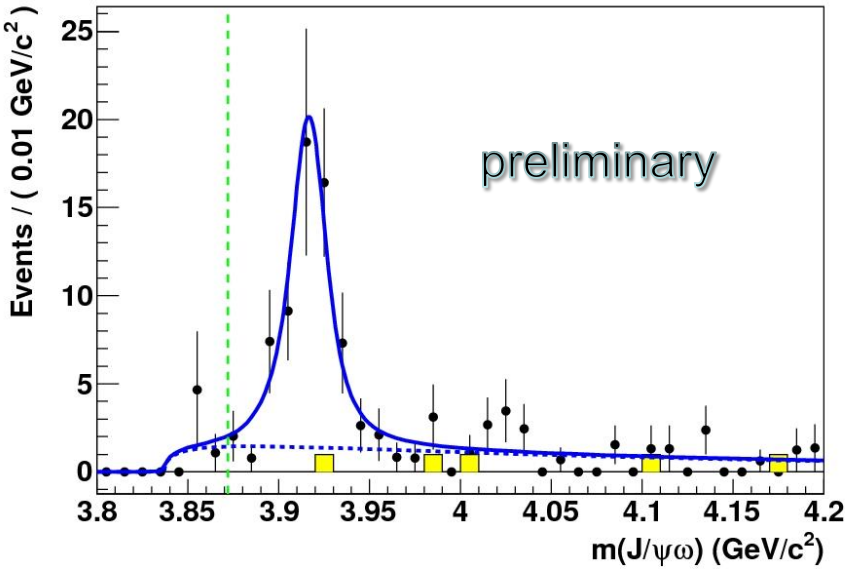
$\gamma\gamma \to J/\psi\omega$ result

Main selection:

- $J/\psi \to l^+l^-$, $\omega \to \pi^+\pi^-\pi^0$
- $p_T < 0.2$ GeV/c
- $M_{miss} > 2$ (GeV/c^2)



Clear J/ψ and ω signals with small background



	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)	$10.5 \pm 1.9 \pm 0.6$	$18 \pm 5 \pm 2$

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

✓Upper limit on X(3872) production:

$\Gamma\gamma\gamma B(X(3872) \to J/\psi\omega) < 1.7$ eV (J=2)

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

- Several new charmonium-like states were found in $J/\psi\pi^+\pi^-$, such as the Y(4260), X(3872), … .
- Interesting to look for new states in $\eta_c\pi^+\pi^-$ mode, due to different J^{PC} (0^{-+} for η_c, 1^{--} for J/ψ).
- Provide branching fractions for known states: $\chi_{c2}(1P)$, $\eta_c(2S)$, X(3872), X(3915) and $\chi_{c2}(2P)$.
  - Prediction for $B(\eta_c(2S) \to \eta_c\pi^+\pi^-) \approx 2.2\%$.
    M.B. Voloshin Mod.Phys.Lett. A 17,1533(2002)

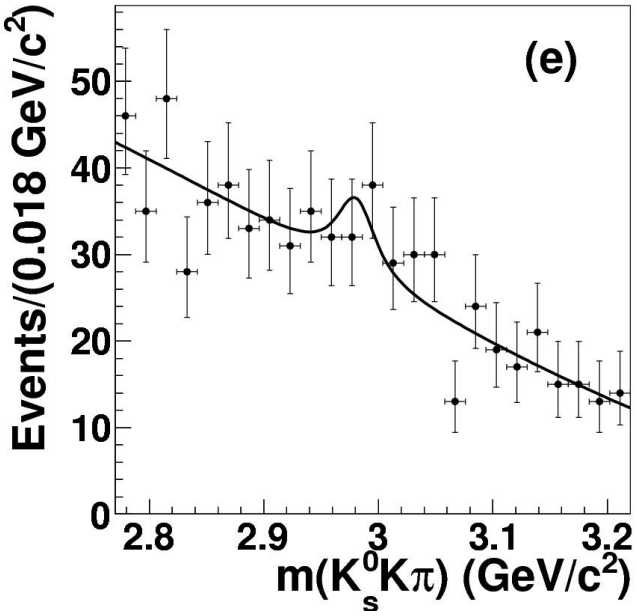
$\gamma\gamma \to \eta_c \pi^+ \pi^-$, event selection

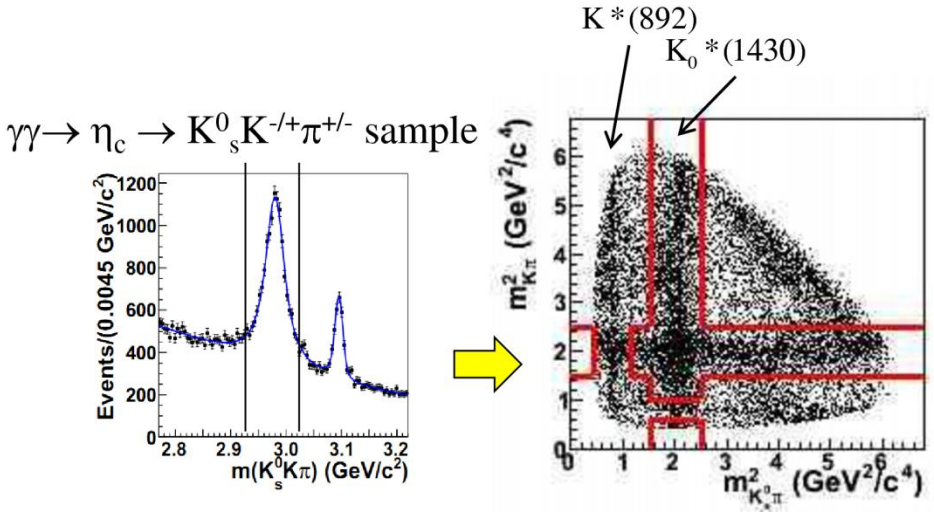
Main event selection:

- $\eta_c \to K_S K^+ \pi^-$
- $p_T < 1.5$ GeV/c
- $M^2_{miss} > 10$ GeV^2
- $E_{ex} < 0.8$ GeV
- Neural network (P_T,E_{ex},PID).
- η_c Dalitz plot

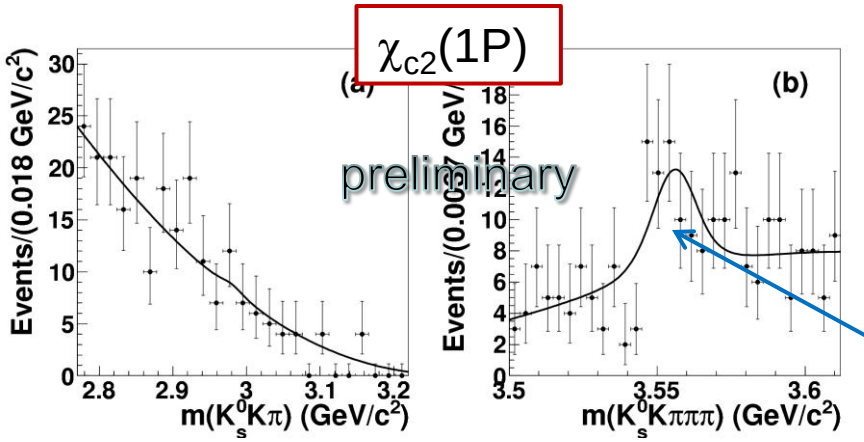
474 fb^{-1}

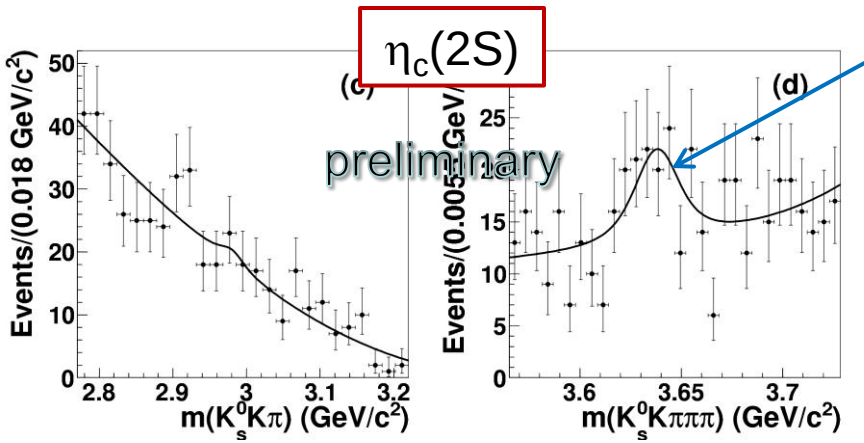
$N_{\eta_c} = 50 \pm 37$

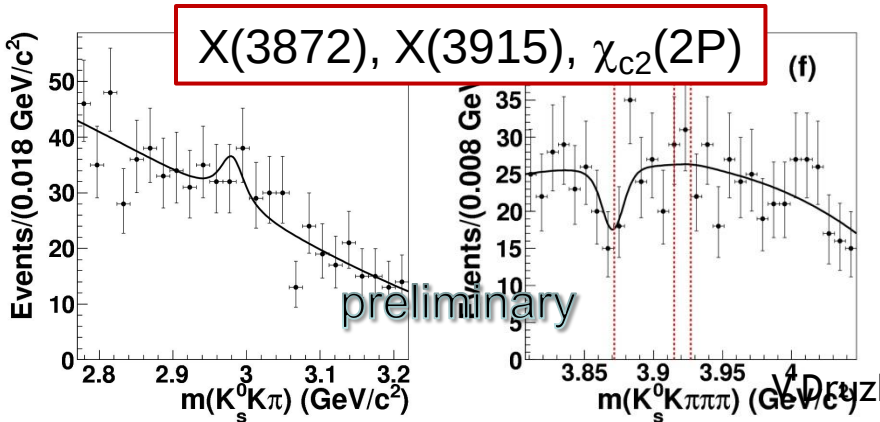




$\gamma\gamma \to \eta_c \pi^+ \pi^-$, results







The two-dimensional fit to the $m(K_S K^+\pi^-)$ and $m(K_S K^+\pi^-\pi^+\pi^-)$ spectra is carried out in the mass region of each state.

non-resonant decay to $K_S K^-\pi^+\pi^+\pi^-$

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

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

$$\mathrm{B}(\eta_c(2\mathrm{S}) \to \eta_c(1\mathrm{S})\pi\pi) < 7.4\% \ @\,90\,\mathrm{CL}$$

Summary

ISR processes:

- ✓Improved measurement of Y(4260) parameters has been performed in the reaction $e^+e^- \to \gamma_{ISR}\ J/\psi\ \pi^+\pi^-$
- ✓We do not confirm a structure at 4.01 GeV reported by Belle
- ✓The $f_0(980)$ signal has been observed in the $\pi^+\pi^-$ mass spectrum: $B(Y \to J/\psi f_0(980), f_0 \to \pi^+\pi^-)/ B(Y \to J/\psi\ \pi^+\pi^-)=0.17\pm0.13$
- ✓We confirm Belle observation of Y(4660) resonance in the reaction $e^+e^- \to \gamma_{ISR}\ \psi(2S)\ \pi^+\pi^-$
- ✓Parameters of Y(4360) and Y(4660) have been measured

Two-photon collisions:

- The Belle's observation of the X(3915) in $\gamma\gamma \to J/\psi\omega$ has been confirmed.
- $\Gamma\gamma\gamma B(X(3872) \to J/\psi\omega) < 1.7$ eV @ 90%CL for J=2
- New limits on $\chi_{c2}(1P)$, $\eta_c(2S)$, X(3872), X(3915) and $\chi_{c2}(2P)$ production in the reaction $\gamma\gamma \to \eta_c\pi^+\pi^-$ have been set.