



CHARM 2012

The 5<sup>th</sup> International Workshop on Charm Physics  
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*Recent Charmonium Results*



GEFÖRDERT VOM



Bundesministerium  
für Bildung  
und Forschung

*from*

*BaBar*



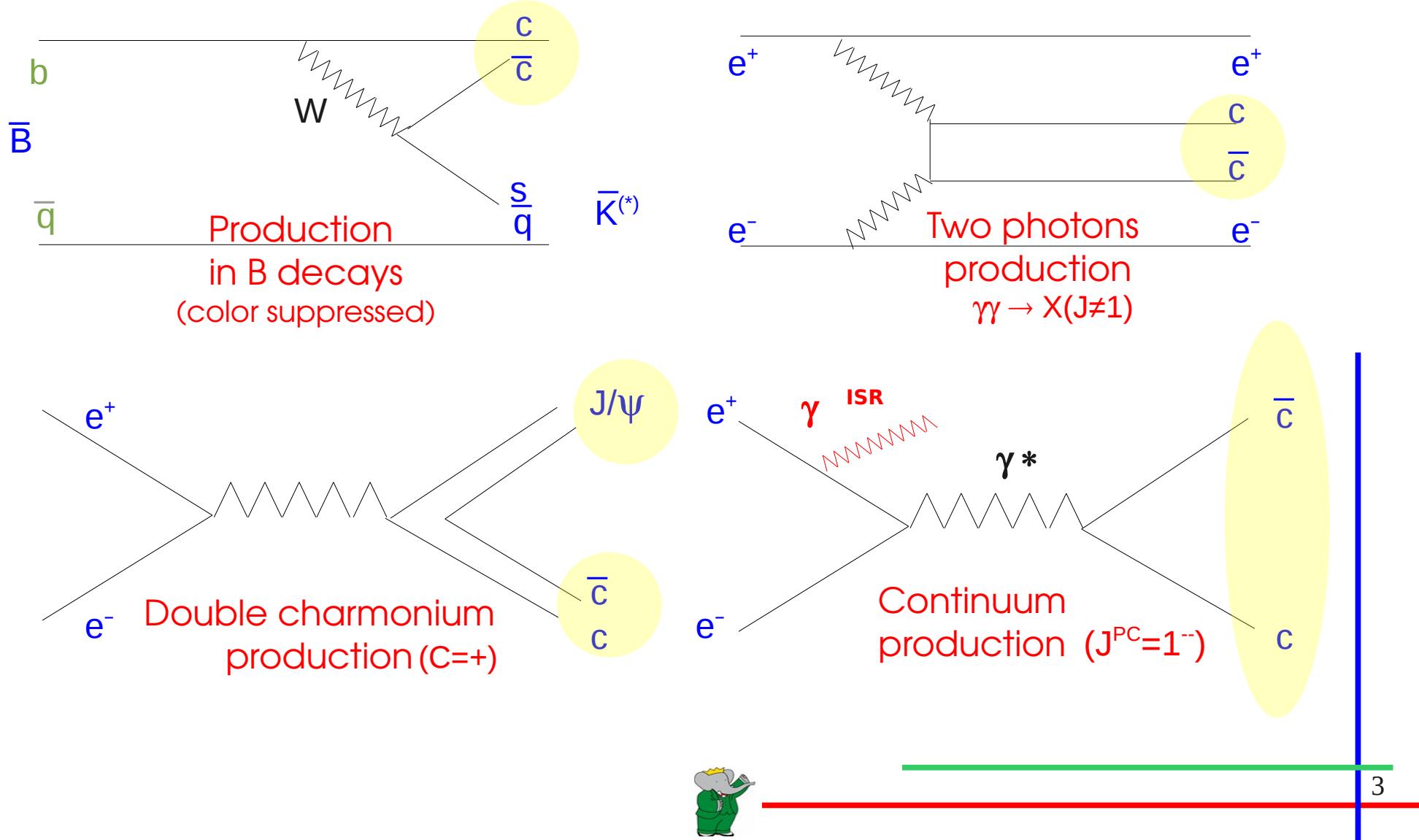
E. Prencipe on behalf of the BaBar Collaboration

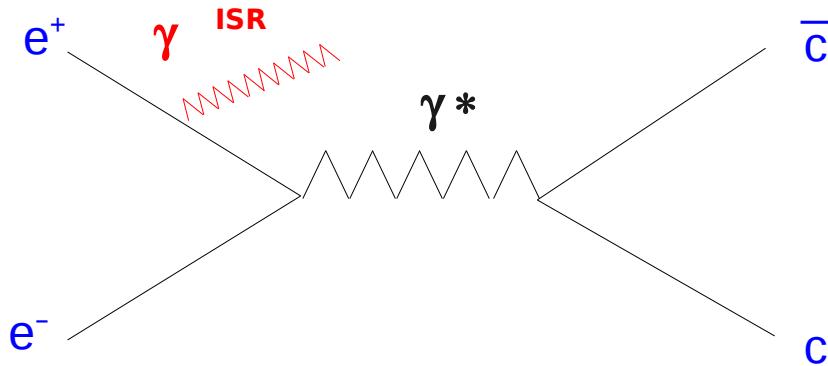
# Outline

- Introduction
- Motivation
- $e^+e^- \rightarrow \gamma_{\text{ISR}} J/\psi \pi^+\pi^-$
- $e^+e^- \rightarrow \gamma_{\text{ISR}} \psi(2S) \pi^+\pi^-$
- $\gamma\gamma \rightarrow \eta_c \pi^+\pi^-$
- $\gamma\gamma \rightarrow J/\psi\omega$
- Conclusions



# B-factory: charmonium production processes





## ISR processes

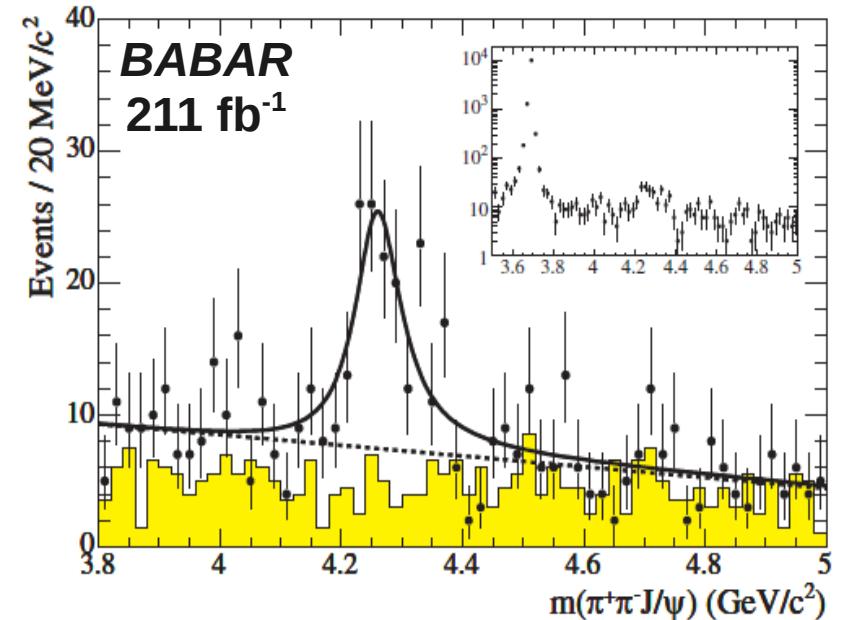
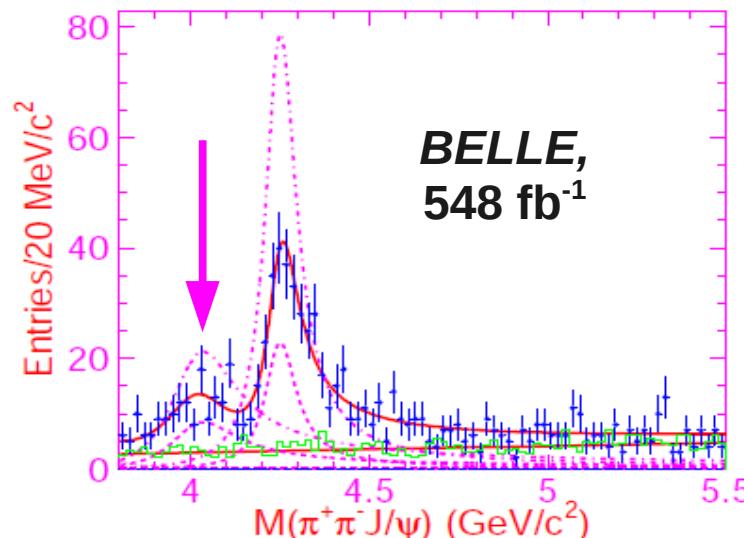
- $e^+e^- \rightarrow \gamma_{ISR} J/\psi \pi^+\pi^-$
- $e^+e^- \rightarrow \gamma_{ISR} \psi(2S) \pi^+\pi^-$



# Analysis $e^+ e^- \rightarrow \gamma_{ISR} J/\psi \pi^+ \pi^-$ : motivation

- Discovered by BaBar: PRL 95, 142001 (2005)  
Confirmed by CLEOc: PRL 96, 162003 (2006)  
CLEOIII: PRD74, 091104 (2006)  
BELLE: PRL 99, 182004 (2007)
- Produced in ISR of  $J/\psi \pi^+ \pi^- \Rightarrow J^{PC} = 1^{--}$

The existence of  $X(3872)$ , observed in  $B \rightarrow X K$ ,  $X \rightarrow J/\psi \pi^+ \pi^-$ , has suggested the idea to investigate further, even in ISR production of  $J/\psi \pi^+ \pi^-$

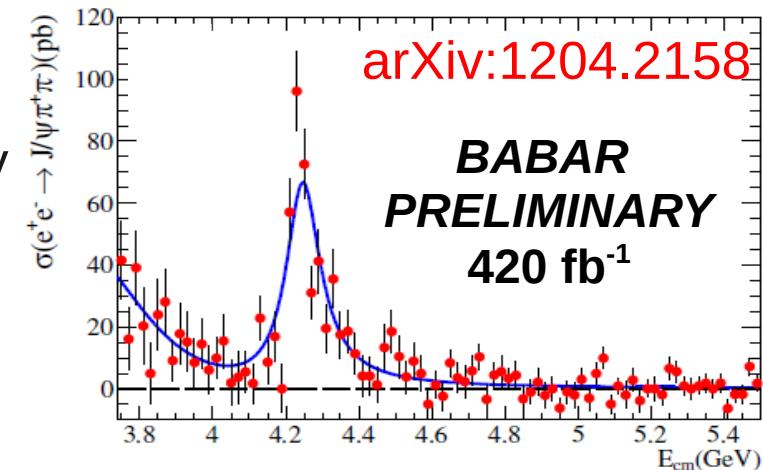
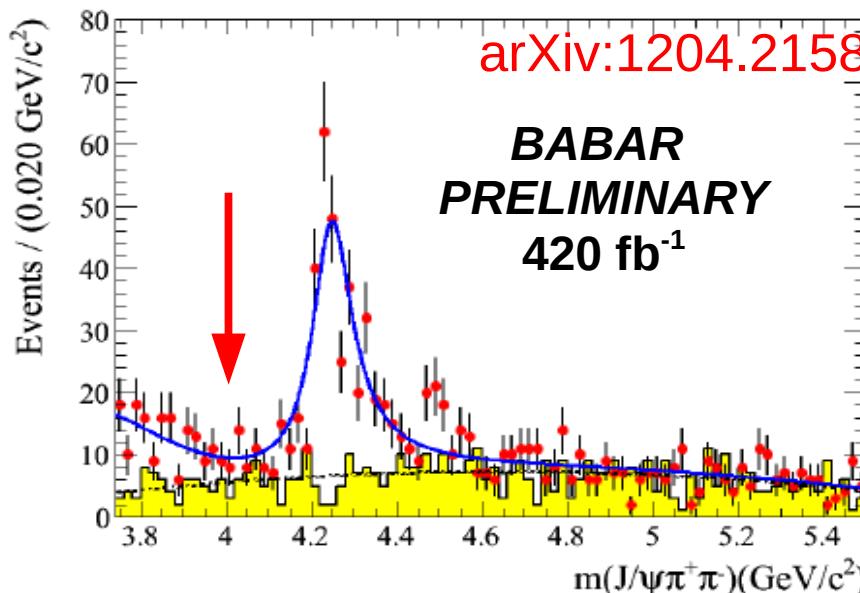


- All  $1^{--}$  slots in charmonium spectrum are filled: the nature of  $Y(4260)$  is still not clear
- BELLE suggested the existence of  $Y(4008)$  in ISR production of  $J/\psi \pi^+ \pi^-$ , too



# Analysis $e^+ e^- \rightarrow \gamma_{ISR} J/\psi \pi^+ \pi^-$ : new results

- An extended-maximum-likelihood fit is performed in the signal region  $J/\psi \pi^+ \pi^-$  distribution and simultaneously to the background distribution in the region  $3.74\text{-}5.5 \text{ GeV}/c^2$
- The fit function incorporates the mass-dependence of efficiency and luminosity, and uses a relativistic BW for the  $Y(4260)$  fit, a 3<sup>rd</sup> order polynomial to describe the background from  $J/\psi$  sidebands, and an empirical exponential function describes the excess of events below 4  $\text{GeV}/c^2$ , which may result from  $\psi(2S)$  tail and a possible  $J/\psi \pi^+ \pi^-$  non-resonant contribution



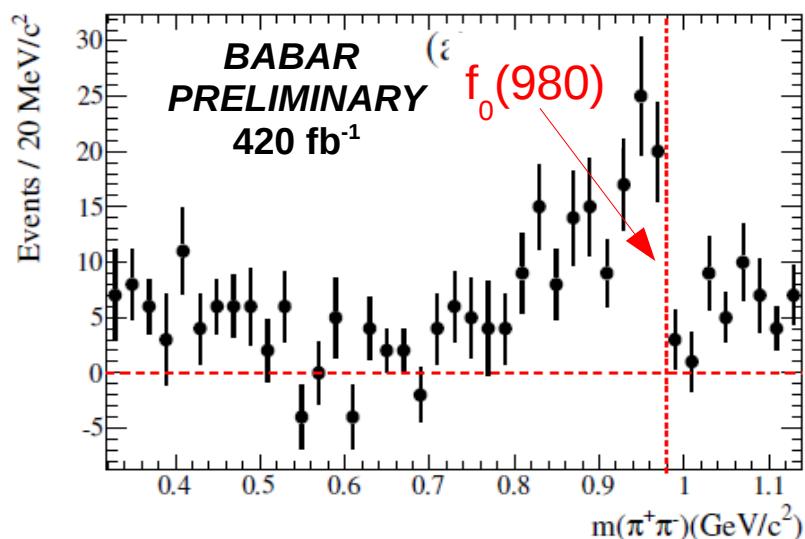
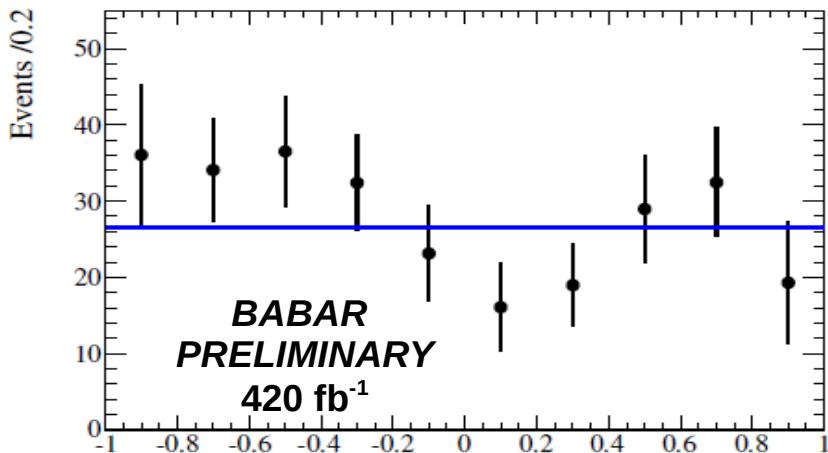
Mass ( $Y(4260)$ ) =  $4244^{+5 \pm 4} \text{ MeV}/c^2$   
 $\Gamma(Y(4260)) = 114^{+16}_{-15} \pm 7 \text{ MeV}$   
 $\Gamma_{e^+ e^-} \times B(J/\psi \pi^+ \pi^-) = 9.2 \pm 0.8 \pm 0.7 \text{ eV}$



NO evidence for  $Y(4008)$  is found

# Analysis $e^+e^- \rightarrow \gamma_{ISR} J/\psi \pi^+\pi^-$ : di-pion mass

- The di-pion mass distribution was investigated within  $4.15 < m(J/\psi\pi^+\pi^-) < 4.45$  GeV/c<sup>2</sup> : we define  $\theta_\pi$  as the angle between the  $\pi^+$  direction and that of the recoil  $J/\psi$ , both in the di-pion rest frame

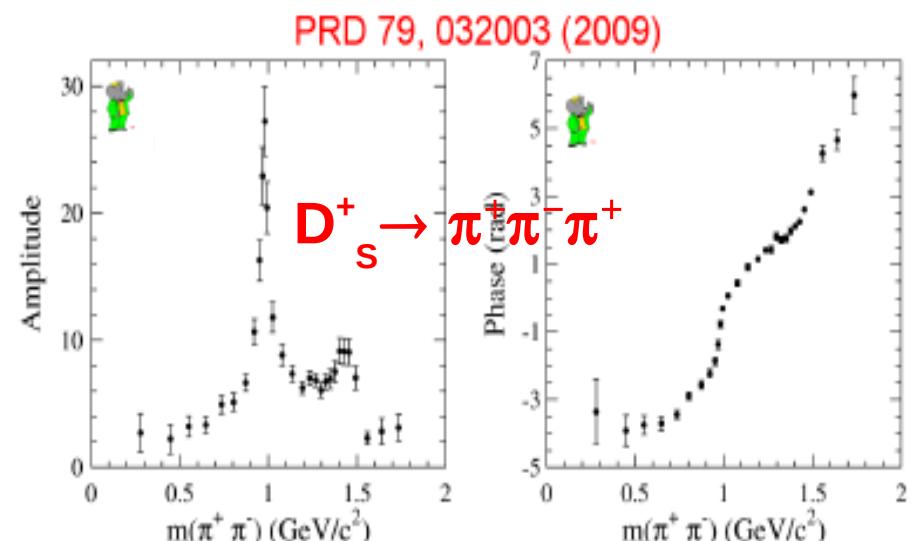
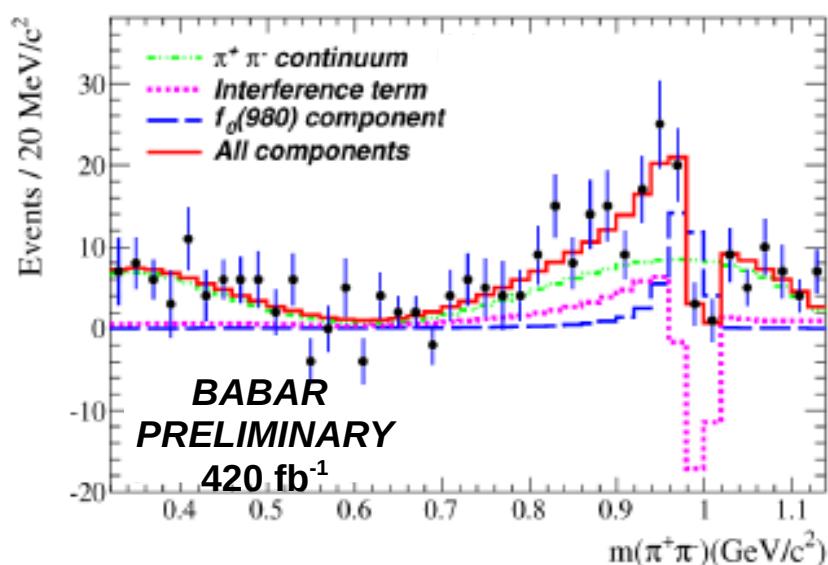


- The distribution of  $\pi^+\pi^-$ , which must be symmetric, is consistent with S-wave behaviour  $\chi^2/NDf = 12.3/9$ ; probability = 19.7%
- The  $\pi^+\pi^-$  system has **C=1<sup>+</sup>**
- The distribution looks peaking at  $f_0(980)$ , but it is displaced; this suggests the idea of an interference between  $f_0(980)$  and  $\pi^+\pi^-$  continuum



# Analysis $e^+e^- \rightarrow \gamma_{ISR} J/\psi \pi^+\pi^-$ : di-pion mass

- A simple model to describe the *di-pion mass* was used, namely the square of an amplitude consisting of the coherent sum of a non-resonant component, motivated by **QCD multipole expansion** and a  $f_0(980)$  **amplitude**; the relative strength and phase of these components are free to vary in the fit to the data
- Mass dependence of  $f_0(980)$  amplitude and phase is from the BaBar analysis  $D_s^+ \rightarrow \pi^+\pi^-\pi^+$  ⇒ there is **non-dominant  $f_0(980)$  contribution** to the  $\Upsilon(4260)$  decay to  $J/\psi\pi^+\pi^-$



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



# Analysis $e^+e^- \rightarrow \gamma_{ISR} \psi(2S) \pi^+\pi^-$ : motivation

## $\Upsilon(4360)$

- Discovered by BaBar: PRL 98, 212001 (2007)  
Confirmed by BELLE: PRL 99, 142002 (2007)

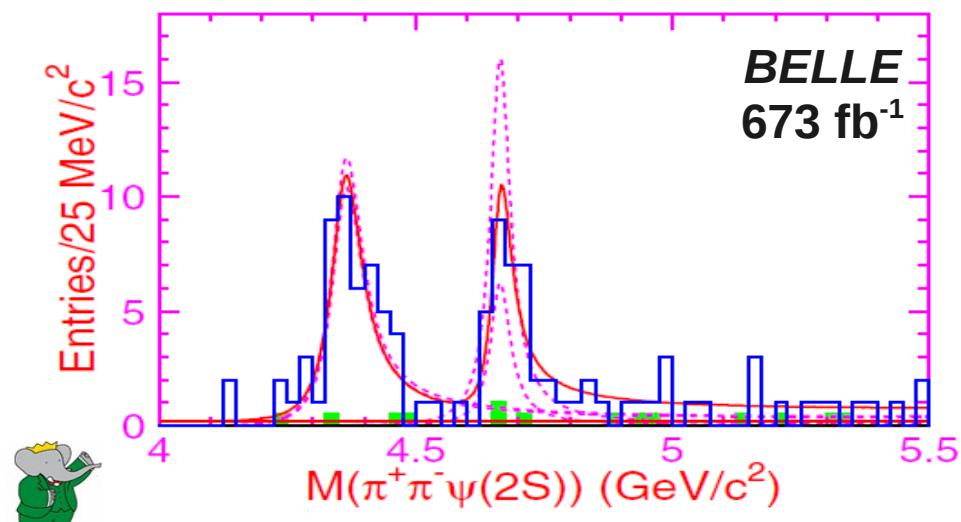
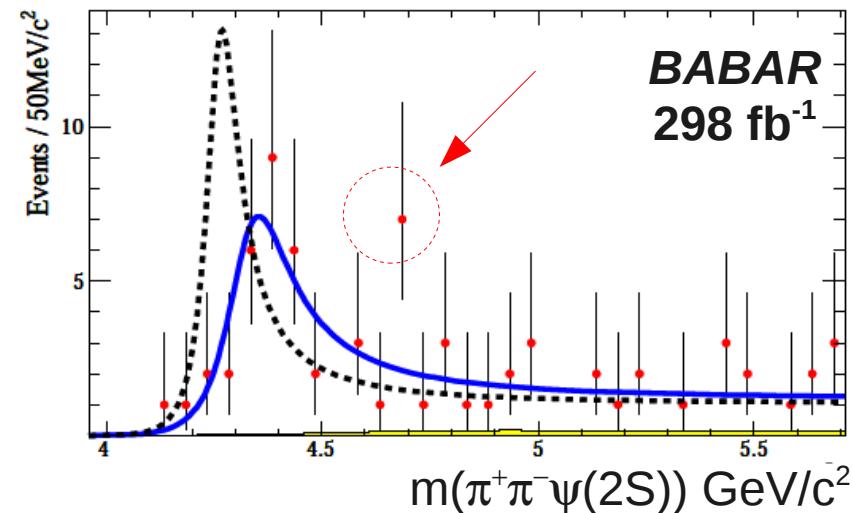
BELLE reported the observation of  $\Upsilon(4660)$

## $\Upsilon(4360), \Upsilon(4660)$

- Produced in ISR of  $\psi(2S)\pi^+\pi^- \Rightarrow J^{PC} = 1^{--}$

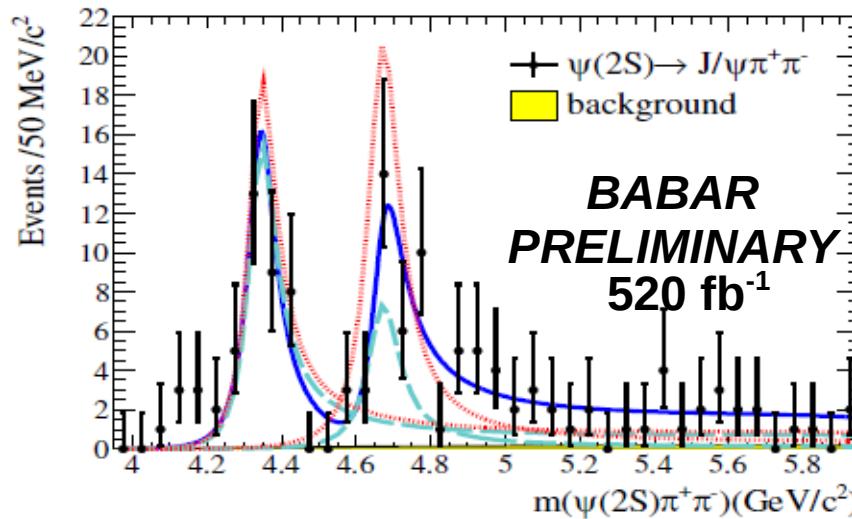
- Need to investigate the invariant mass  $\psi(2S)\pi^+\pi^-$ , as new structures have been shown in ISR production of Charmonium states

- This analysis has been performed in BaBar with the full data sample  $\Upsilon(nS)$ ,  $n=2,3,4$



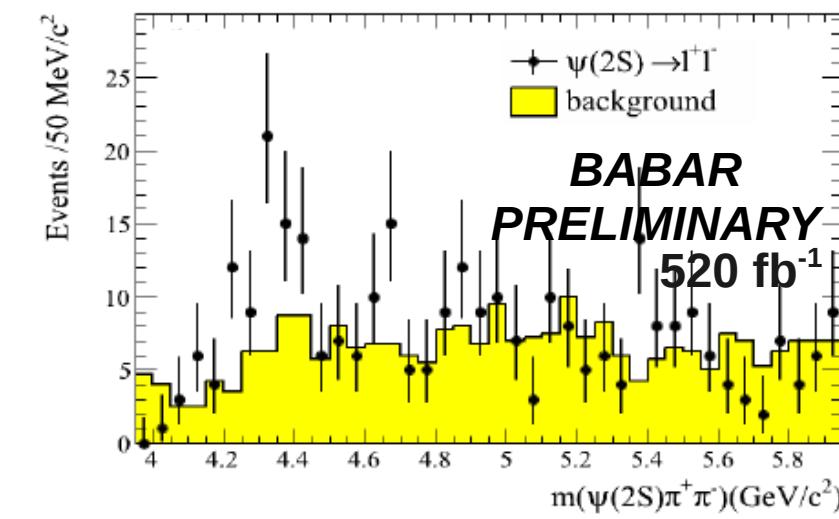
# Analysis $e^+e^- \rightarrow \gamma_{ISR} \psi(2S) \pi^+\pi^-$ : new results

- $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$  and  $\psi(2S) \rightarrow l^+l^-$  are investigated. Huge background contribution from  $\psi(2S) \rightarrow l^+l^-$  is seen
- An unbinned extended-maximum-likelihood fit is performed in the signal region and simultaneously to the background distribution: background is studied and selected from  $\psi(2S)$  sidebands



Mass(Y(4360)) =  $4340 \pm 16 \pm 9$  MeV/c<sup>2</sup>  
 $\Gamma(Y(4350)) = 94 \pm 32 \pm 13$  MeV

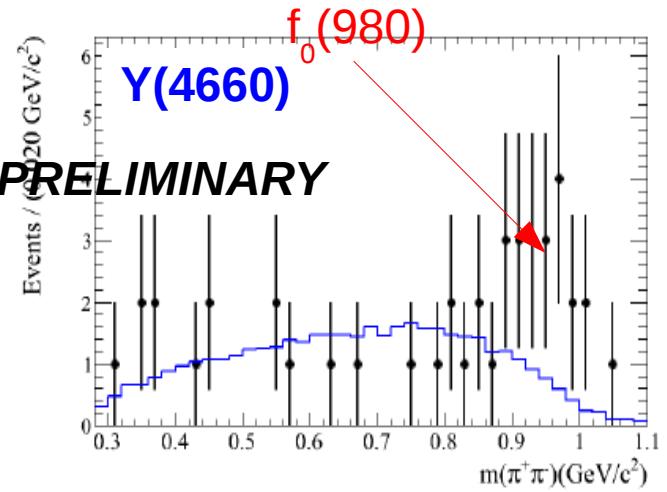
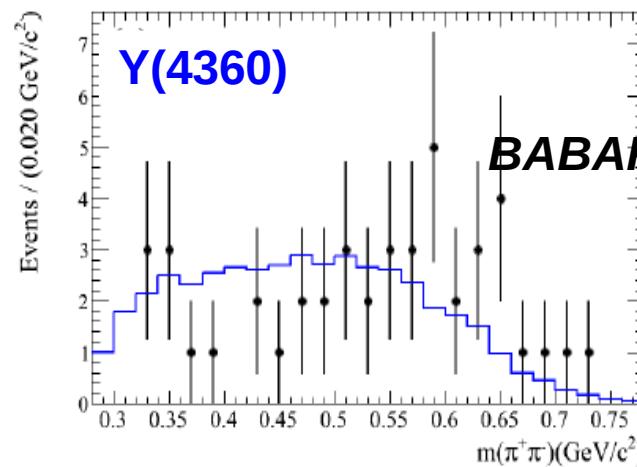
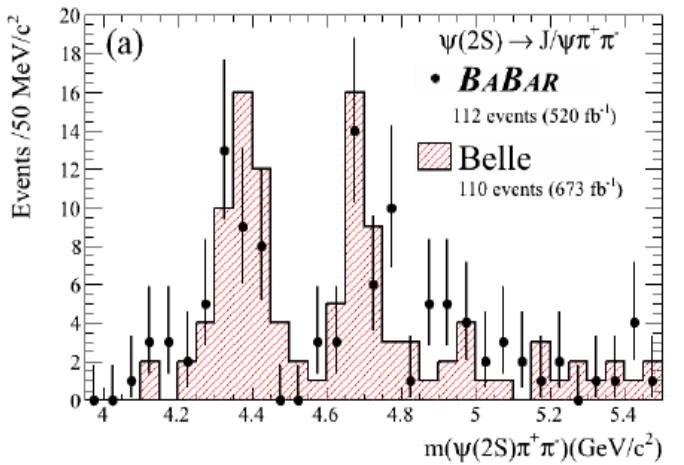
Mass(Y(4660)) =  $4669 \pm 21 \pm 3$  MeV/c<sup>2</sup>  
 $\Gamma(Y(4660)) = 104 \pm 48 \pm 10$  MeV



Confirmation of the old Y(4360)  
and the new Y(4660)



# Analysis $e^+e^- \rightarrow \gamma_{ISR} \psi(2S) \pi^+\pi^-$ : cross section

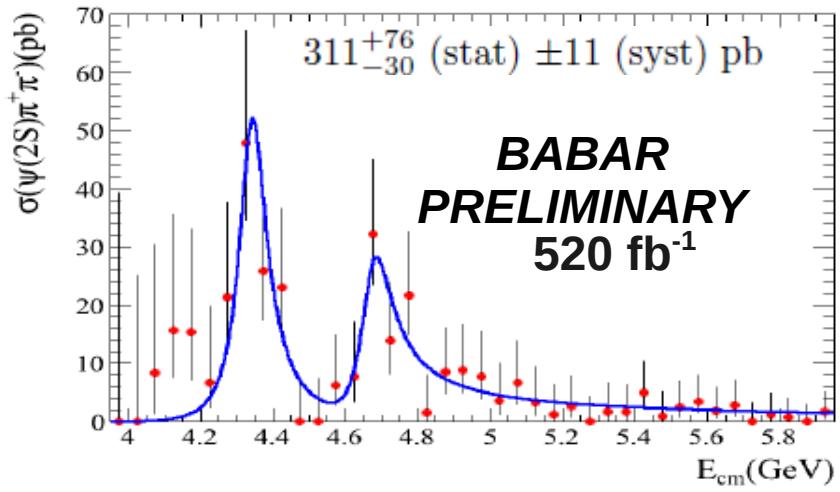


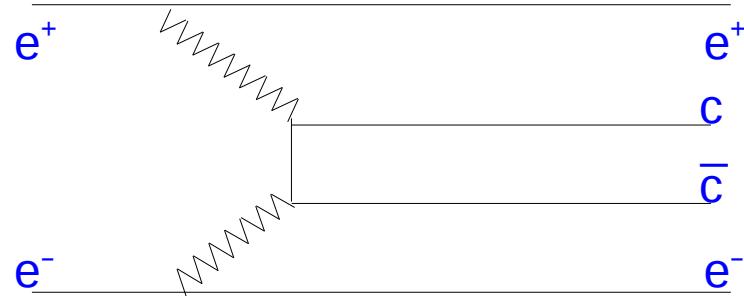
We cannot conclude anything on the di-pion mass distribution because of the low statistics!

$$\sigma(m) = \frac{12\pi C}{m^2} \cdot |A_1(BW)| \cdot \sqrt{\frac{PS(m)}{PS(m_1)}} + A_2(BW) \cdot \sqrt{\frac{PS(m)}{PS(m_2)}} \cdot e^{i\phi}|^2$$

$$\left. \begin{array}{l} C = 0.3894 \cdot 10^9 \text{ GeV}^2 \text{ pb} \\ PS(m) = \text{mass-dependence of } \psi(2S)\pi^+\pi^- \text{ phase space} \\ \phi = \text{relative phase between the amplitudes } A_1 \text{ and } A_2 \end{array} \right\}$$

$$A_j(BW) = \frac{m_j \sqrt{(\Gamma_{e^+e^-} \cdot \Gamma_{\psi(2S)\pi^+\pi^-})_j}}{m_j^2 - m^2 - im_j \Gamma_j}$$





## $\gamma\gamma$ interactions

- $\gamma\gamma \rightarrow \eta_c \pi^+ \pi^-$
- $\gamma\gamma \rightarrow J/\psi \omega$



# Analysis $\gamma \rightarrow \eta_c \pi^+ \pi^-$ : Strategy

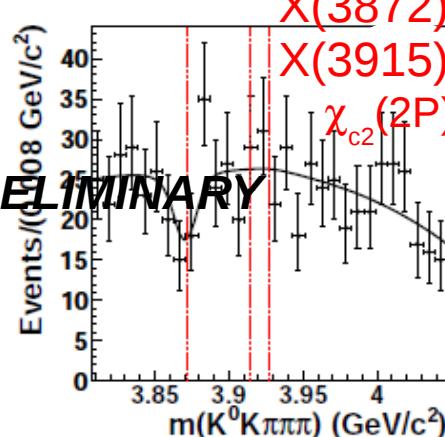
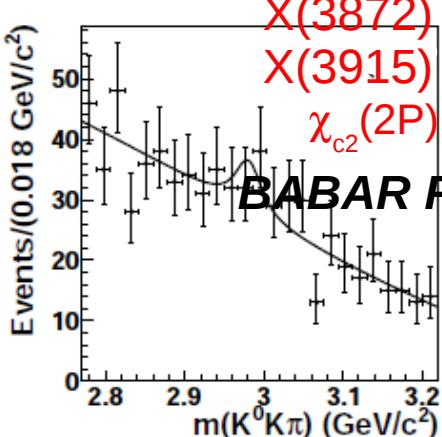
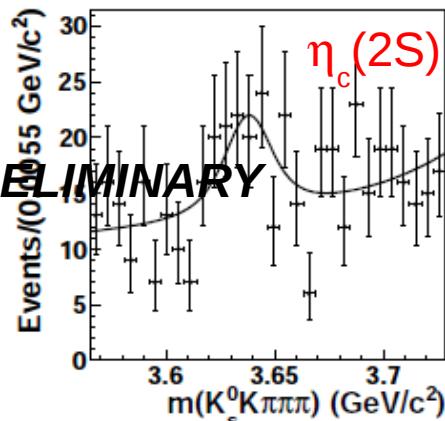
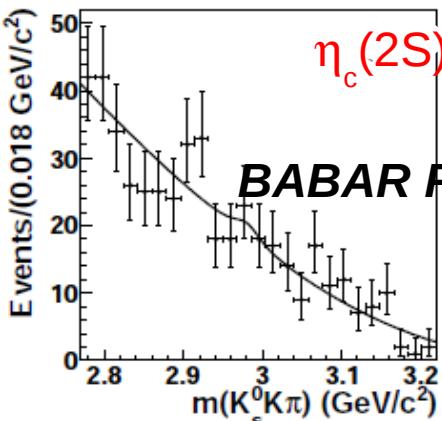
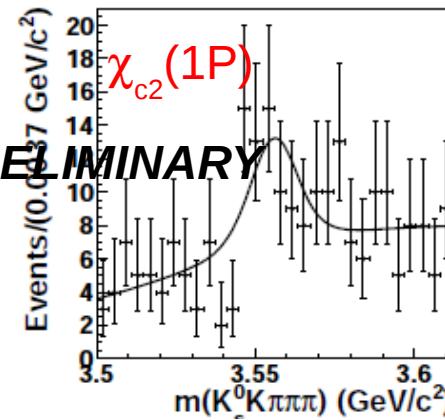
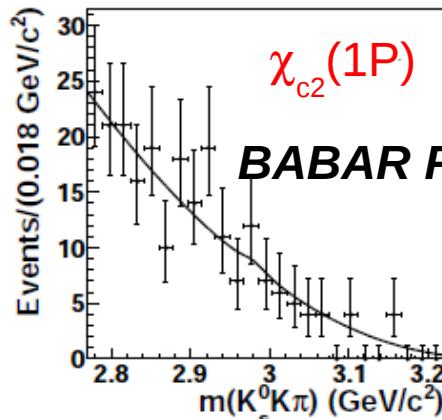
- The process under exam is the production of a X state, where  $\gamma \rightarrow X \rightarrow \eta_c \pi^+ \pi^-$   
 $X = \chi_{c2}(1P), \eta_c(2S), X(3872), \text{ or } \chi_{c2}(2P)$ 

$$\eta_c(1S) \rightarrow K_S^0 K^\pm \pi^\mp$$

$$K_S^0 \rightarrow \pi^+ \pi^-$$
- The BF of the decay  $\chi_{c2}(1P), \eta_c(2S), X(3872), \text{ and } \chi_{c2}(2P)$  to  $\eta_c \pi^+ \pi^-$  is measured  
 Prediction for  $B(\eta_c(2S) \rightarrow \eta_c(1S) \pi^+ \pi^-) \sim 2.2\%$   
 obtained from  $\Gamma(\eta_c(2S) \rightarrow \eta_c(1S) \pi^+ \pi^-) / \Gamma(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-) \sim 2.9$   
 (M.B.Voloshin Mod.Phys.Lett A 17, 1533 (2002))
- The extraction of signal proceeds in 2 steps:
  - determine the values of  $m(K_S^0 K^\pm \pi^\mp)$  distribution parameters for the combinatorial background from **1-dim fit** to  $m(K_S^0 K^\pm \pi^\mp)$
  - perform **2-dim fit** in  $m(K_S^0 K^\pm \pi^\mp)$  and  $m(K_S^0 K^\pm \pi^\mp \pi^+ \pi^-)$  in a window around each resonance of interest



# Analysis $\gamma\gamma \rightarrow \eta_c \pi^+ \pi^-$ : results



Summary table of the results

Resonance	$M_X$ (MeV/ $c^2$ )	$\Gamma_X$ (MeV)	$\Gamma_{\gamma\gamma} \mathcal{B}$ (eV)	
			Central value	UL
$\chi_{c2}(1P)$	$3556.20 \pm 0.09$	$1.97 \pm 0.11$	$7.2^{+5.5}_{-4.4} \pm 2.9$	15.7
$\eta_c(2S)$	$3638.5 \pm 1.7$	$13.4 \pm 5.6$	$65^{+47}_{-44} \pm 18$	133
$X(3872)$	$3871.57 \pm 0.25$	$3.0 \pm 2.1$	$-4.5^{+7.7}_{-6.7} \pm 2.9$	11.1
$X(3915)$	$3915.0 \pm 3.6$	$17.0 \pm 10.4$	$-13^{+12}_{-12} \pm 8$	16
$\chi_{c2}(2P)$	$3927.2 \pm 2.6$	$24 \pm 6$	$-16^{+15}_{-14} \pm 6$	19

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

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

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



# Analysis $\gamma\gamma \rightarrow J/\psi\omega$ : motivation

## $Y(3940)$

- Discovered by BELLE in  $B \rightarrow J/\psi\omega K$  PRL 94, 182002 (2005)
- Confirmed by BaBar: PRD 82, 011101(R) 2010  
but lower mass and width were observed

$Y(3940)$	Mass (MeV/c <sup>2</sup> )	Width (MeV)
BABAR	$3914.6^{+3.8}_{-3.4} \pm 2.0$	$34^{+12}_{-8} \pm 5$
BELLE	$3943 \pm 11 \pm 13$	$87 \pm 22 \pm 26$

In this analysis also  $X(3872) \rightarrow J/\psi\omega$  was seen  
 $\text{Prob}(J^P=2^-)=62\%$ ;  $\text{Prob}(J^P=1^+)=7\%$

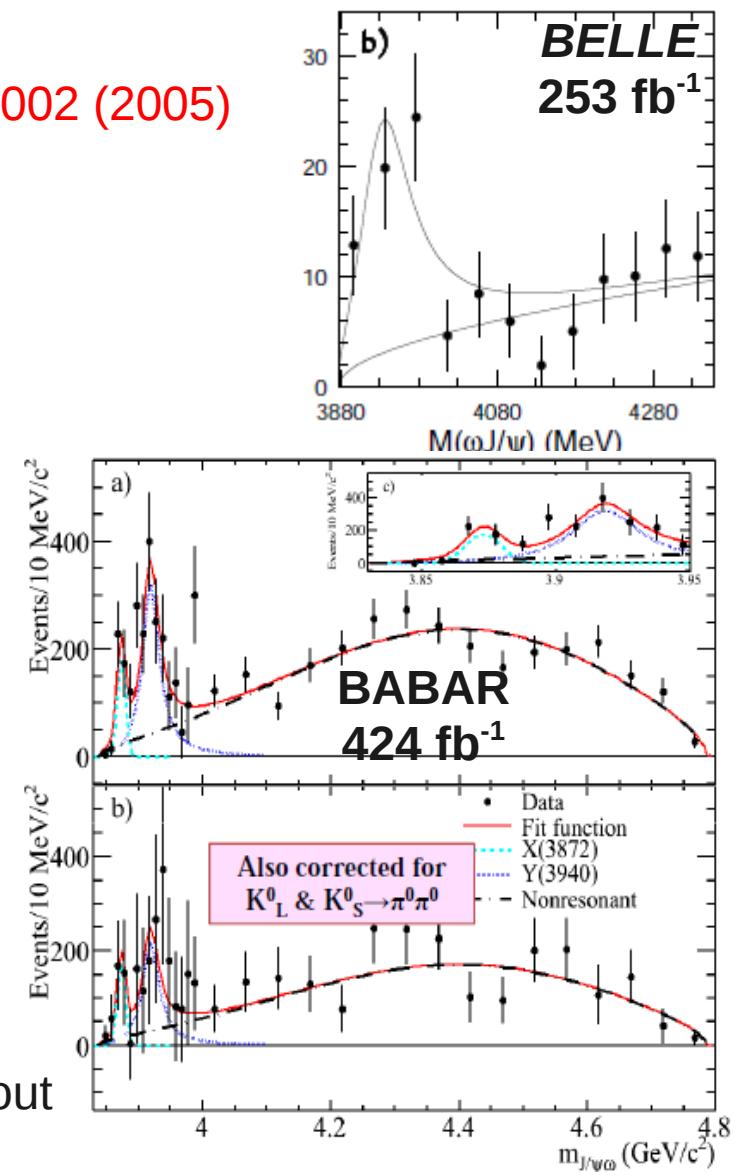
- Even more interesting:  $\gamma\gamma \rightarrow J/\psi\omega$  from BELLE  
PRL 104, 092001 (2010)  
New state observed:  $X(3915)$   
State not confirmed:  $X(3872)$

Implications on the quantum numbers of :

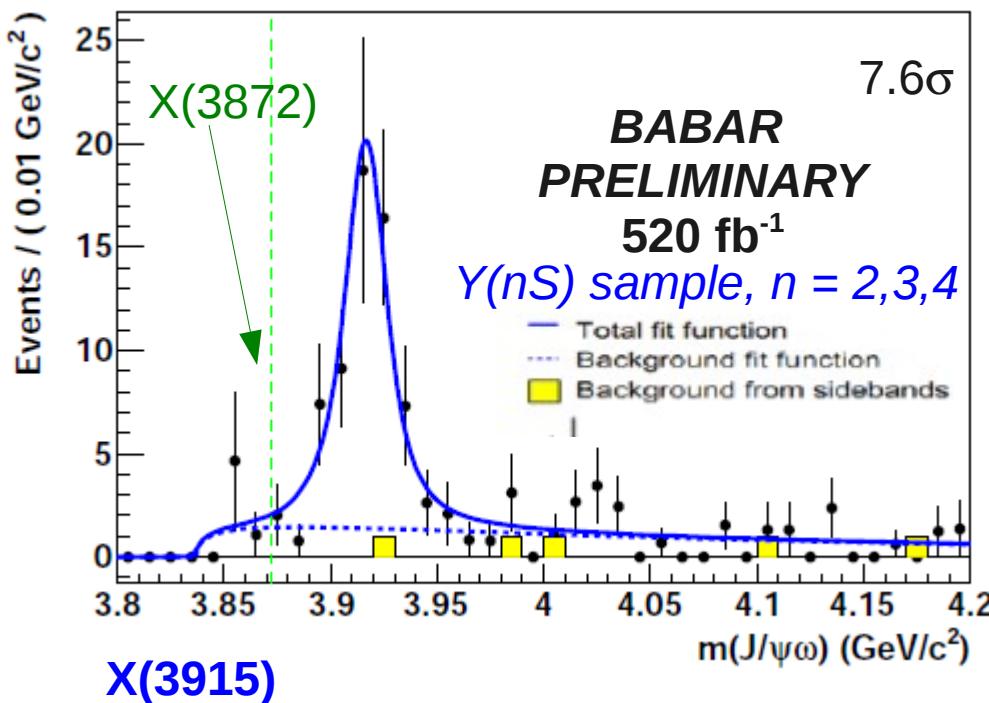
$X(3872)$ : BABAR in favor of  $J^P = 2^-$ , but  $1^+$  not ruled out

$X(3915)$ : interpretation in favor of  $\chi_{c0}(2P)$  or  $\chi_{c2}(2P)$

Are  $Y(3940)$  and  $X(3915)$  the same structure?



# Analysis $e^+ e^- \rightarrow J/\psi \omega$ : results

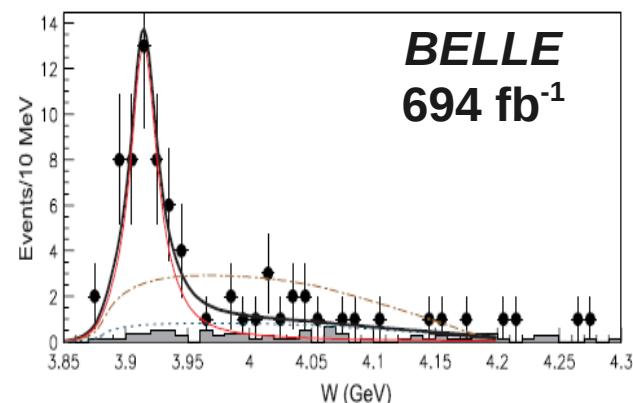


- No observation of  $X(3872)$
- New limit (under the hypothesis  $J=2$ ):  
 $\Gamma_{\gamma\gamma}[X(3872)] \times \mathcal{B}(X(3872) \rightarrow J/\psi \omega) < 1.7 \text{ eV}$
- Assignment of spin parity to  $X(3915)$ : the analysis is ongoing...

	BABAR	Belle
Mass ( $\text{MeV}/c^2$ )	$3919.4 \pm 2.2 \pm 1.6$	$3915 \pm 3 \pm 2$
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)	$10.5 \pm 1.9 \pm 0.6$	$18 \pm 5 \pm 2$

BABAR  
PRELIMINARY

BELLE  
PRL 104, 092001 (2010)



# Conclusions



- Several new charmonium analyses are going on in BaBar: interesting new preliminary results have been shown.

## **ISR production** (states with $J^{PC}=1^{--}$ )

- $e^+e^- \rightarrow \gamma_{\text{ISR}} J/\psi \pi^+\pi^-$ 
  - confirmation of **Y(4260)**, now known with higher precision
  - **Y(4008)** not confirmed
- $e^+e^- \rightarrow \gamma_{\text{ISR}} \psi(2S) \pi^+\pi^-$ 
  - confirmation of **Y(4360)**, now known with higher precision
  - confirmation of **Y(4660)**

## **$\gamma\gamma$ interactions** (states with $J \neq 1$ )

- $\gamma\gamma \rightarrow \eta_c \pi^+\pi^-$ 
  - upper limit for  $\chi_{c2}(1P) \rightarrow \eta_c(1S) \pi^+\pi^-$  and  $\eta_c(2S) \rightarrow \eta_c(1S) \pi^+\pi^-$  was set up
- $\gamma\gamma \rightarrow J/\psi \omega$ 
  - observation of **X(3915)**
  - **X(3872)** not observed

THANK YOU!

17

