

# Recent Results on Charmonium from BaBar

Richard Kass for the BaBar Collaboration

## Outline of Talk

Introduction

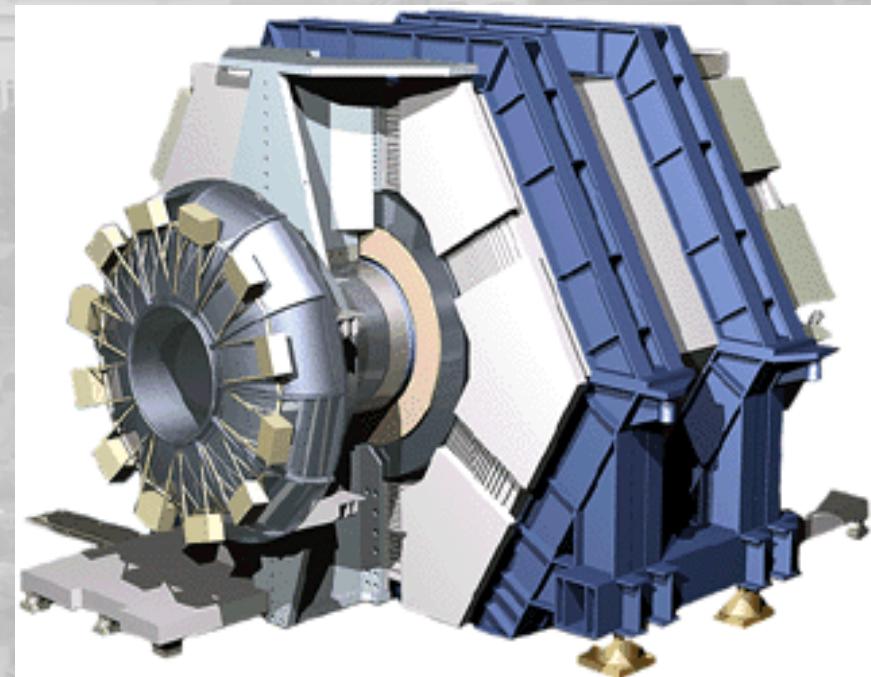
Study of  $e^+e^- \rightarrow \gamma_{ISR} J/\Psi \pi^+\pi^-$

Study of  $e^+e^- \rightarrow \gamma_{ISR} \Psi(2S) \pi^+\pi^-$

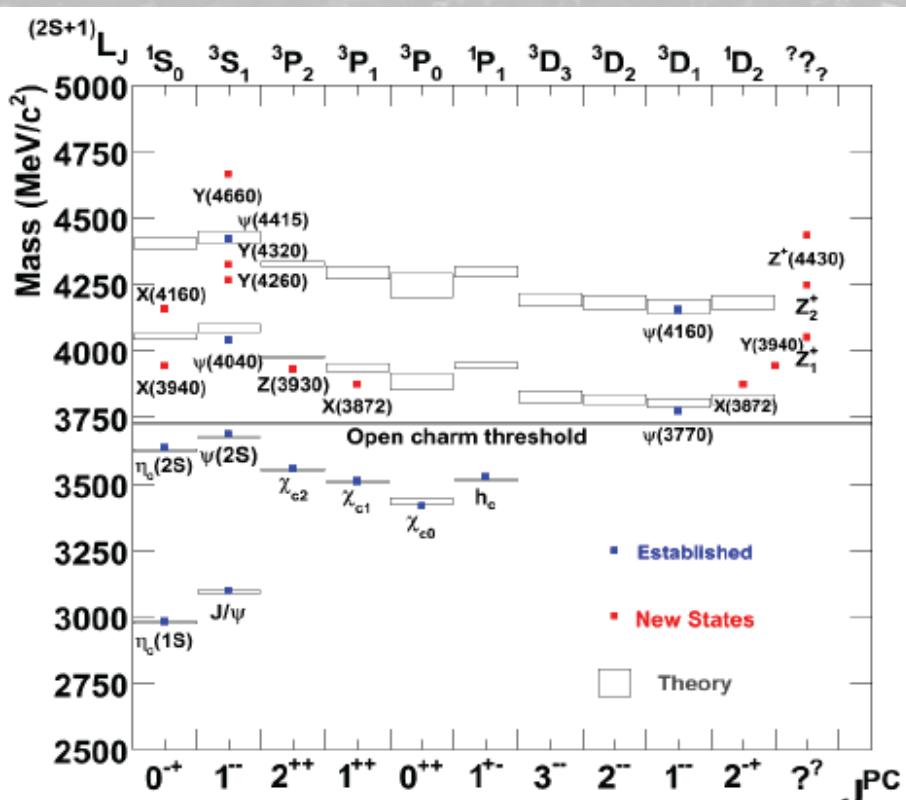
Study of  $\gamma\gamma \rightarrow X \rightarrow \eta_c(1S) \pi^+\pi^-$

Study of  $\gamma\gamma \rightarrow X(3915) \rightarrow J/\Psi \omega$

Summary



# Charmonium Spectrum



Charmonium properties are well understood up to  $\psi(3770)$   
(i.e. about the  $D\bar{D}$  threshold)

Many unexpected states above the  $D\bar{D}$  threshold. Several exotic hypotheses on their nature e.g. tetraquarks, hadronic molecules, hybrids..

To identify exotics:

- Measure  $J^{PC}$  that is forbidden for charmonium:  $0^{+-}, 1^{-+}, 2^{+-}$
- Observe a narrow width state above  $D\bar{D}$  threshold.
- Observe a  $c\bar{c}$ -like state with charge and/or strangeness

# Exotic Charmonium?

Conventional: Bound state of charm-anti-charm quarks.

Meng & KT Chao PRD 75, 114002 (2007), W Dunwoodie & V Ziegler PRL 100 062006 (2008)  
 O Zhang, C Meng & HQ Zheng arXiv:0901.1553, +++

Many predictions of new states,  
 Some with exotic quantum numbers

Molecule: Loosely bound state of a pair of mesons

The dominant binding mechanism should be pion exchange.  
 Being weakly bound, mesons decay as if free.

NATornqvist PLB 590, 209 (2004), ES Swanson PLB 598,197 (2004),  
 E Braaten & T Kusunoki PRD 69 074005 (2004), CY Wong PRC 69, 055202 (2004),  
 MB Voloshin PLB 579, 316 (2004) F Close & P Page PLB 578,119 (2004), +++++

Tetraquark: Bound state of 4 quarks, i.e., diquark-anti-diquark.

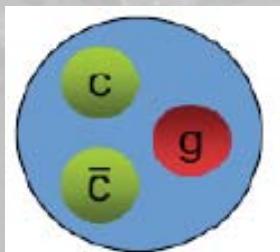
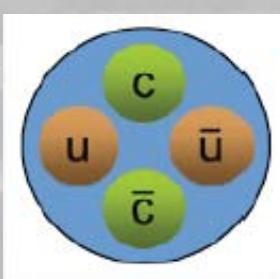
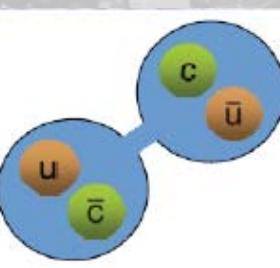
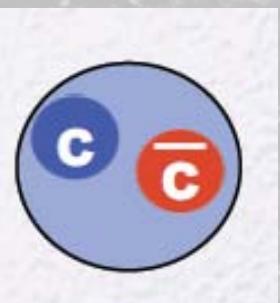
Strong decays proceed by re-arrangement processes.

L Maiani et al PRD 71,014028 (2005), T-W Chiu & TH Hsieh PRD 73, 111503 (2006),  
 D Ebert et al PLB 634, 214 (2006)

Hybrid: States with excited gluonic degree(s) of freedom.

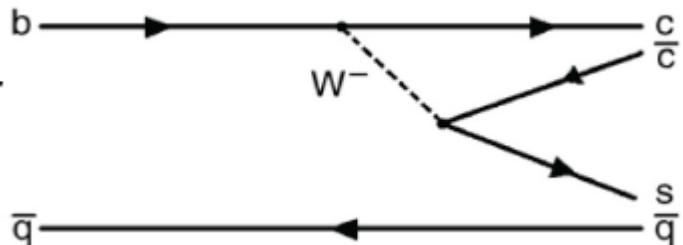
Lattice and model predictions for lowest lying hybrid~4.2 GeV

P Lacock et al (UKQCD) PLB 401, 308 (1997), SL Zhu PLB 625, 212 (2005),  
 FE Close, PR Page PLB 628, 215 (2005) E Kou, O Pene PLB 631, 164 (2005), ++



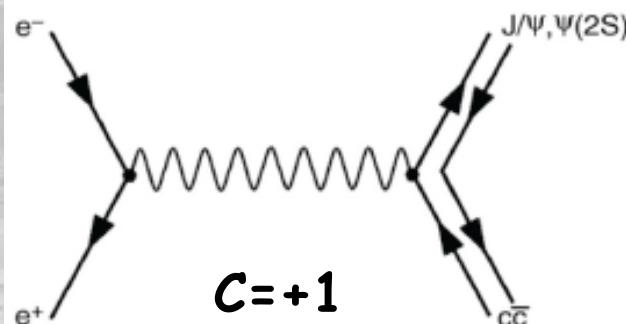
# Charmonium @ B-Factories

B meson decay

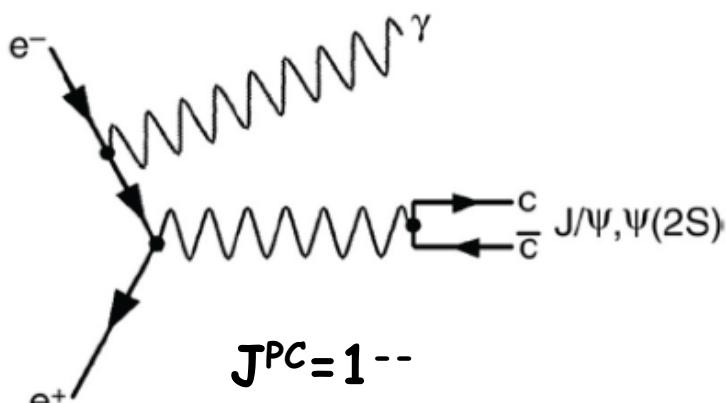


no restriction on quantum numbers

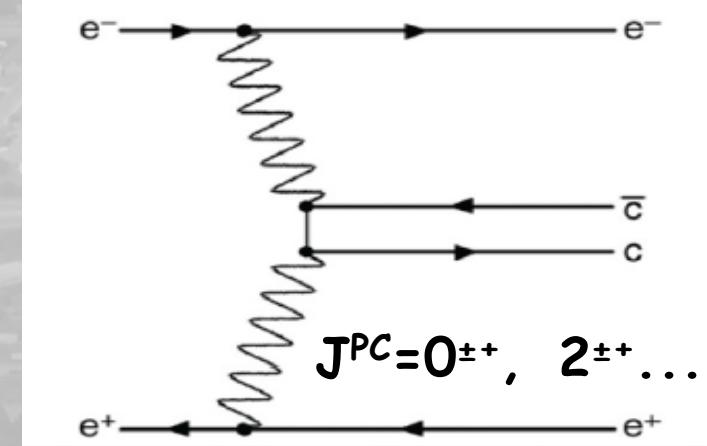
double Charmonium



Initial State Radiation

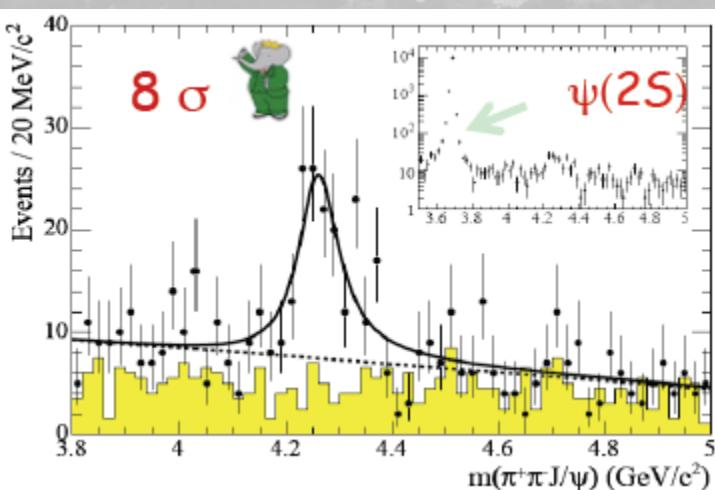


2-photon ( $\gamma\gamma$ )



$$e^+e^- \rightarrow \gamma_{\text{isr}} J/\Psi \pi^+\pi^-$$

$\Upsilon(4260)$  History: Discovered by BaBar using  $e^+e^- \rightarrow \gamma_{\text{isr}} J/\Psi \pi^+\pi^-$



PRL 95 (2005) 142001

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

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

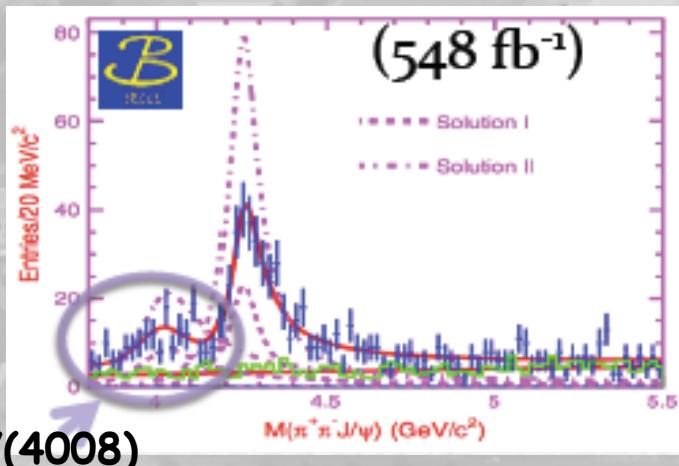
$$\Gamma_Y = (88 \pm 23^{+6}_{-4}) \text{ MeV}$$

Confirmed by CLEO-c, CLEO-III, Belle,  
but some spread in resonance parameters.

Note: all the  $1^{--}$  charmonium slots are already accounted for.

Where does  $\Upsilon(4260)$  fit in?

Belle result suggests a new state,  $\Upsilon(4008)$ : PRL 99, 182004 (2007)



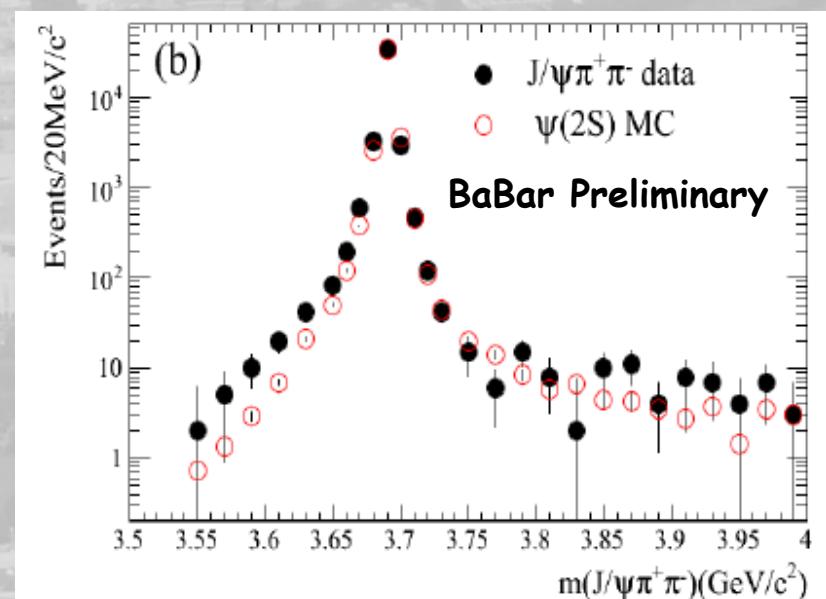
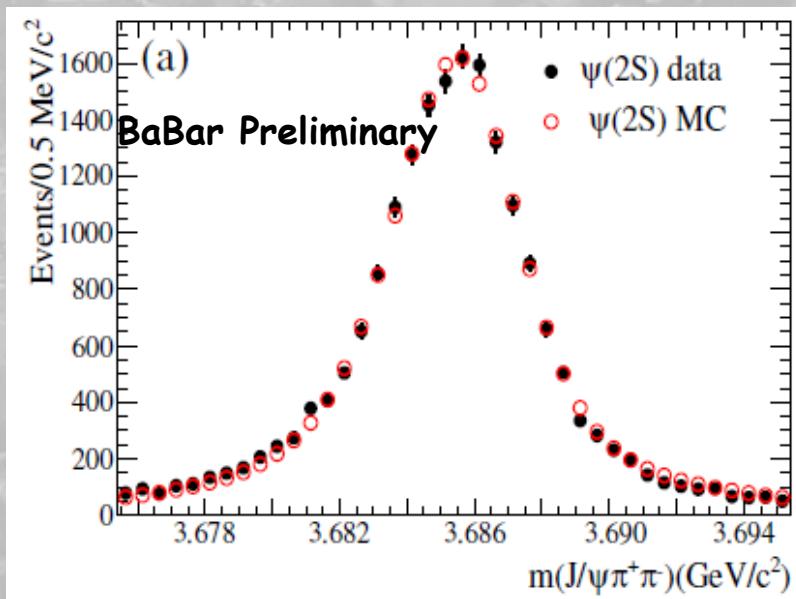
$$M_{Y(4008)} = 4008 \pm 40^{+114}_{-28} \text{ MeV}/c^2$$

$$\Gamma_{Y(4008)} = 226 \pm 44 \pm 87 \text{ MeV}$$

Updated BaBar analysis: arXiv: 1204.2158, submitted to PRD (RC)

Use  $454 \text{ fb}^{-1}$  of data, previous analysis used  $233 \text{ fb}^{-1}$

Very detailed study of the  $\Psi(2S)$  line shape in 3.5-4 GeV region



Possible sources of events above 3.74 GeV:

Tail of  $\Psi(2S)$

$J/\Psi\pi^+\pi^-$  from continuum

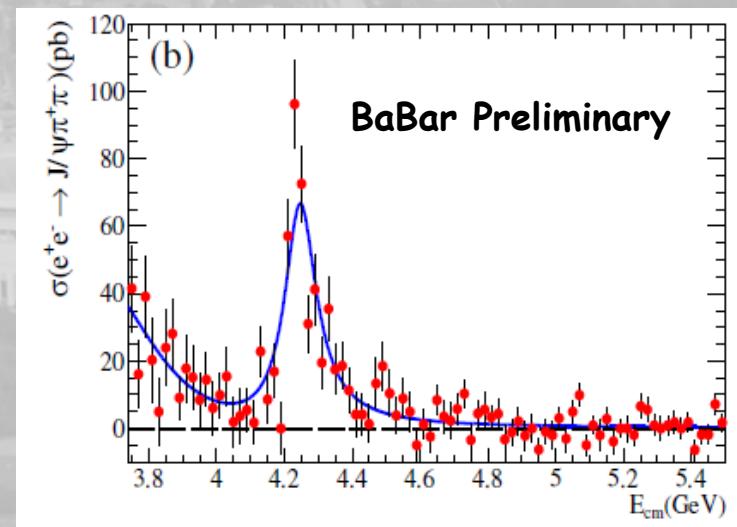
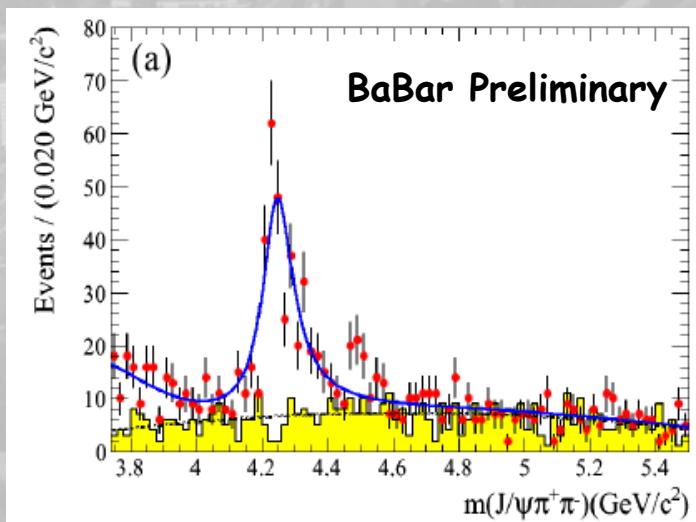
Decay of  $\Psi(3770)$  into non- $D\bar{D}$  states

(BES: PLB 605, 63 (2005), CLEO PRL 96, 082004 (2006))

$e^+e^- \rightarrow \gamma_{\text{isr}} J/\Psi \pi^+\pi^-$ 

# Detailed study in the $\Upsilon(4260)$ region

Perform an extended maximum likelihood fit in 3.74-5.5 GeV region  
The fit is corrected for efficiency.



Very obvious  $\Upsilon(4260)$  signal  
No sign of a state at  $\sim 4$  GeV

excess of events above 3.74 GeV could result from tail of  $\psi(2S)$  and a possible  $J/\psi \pi^+ \pi^-$  continuum contribution.

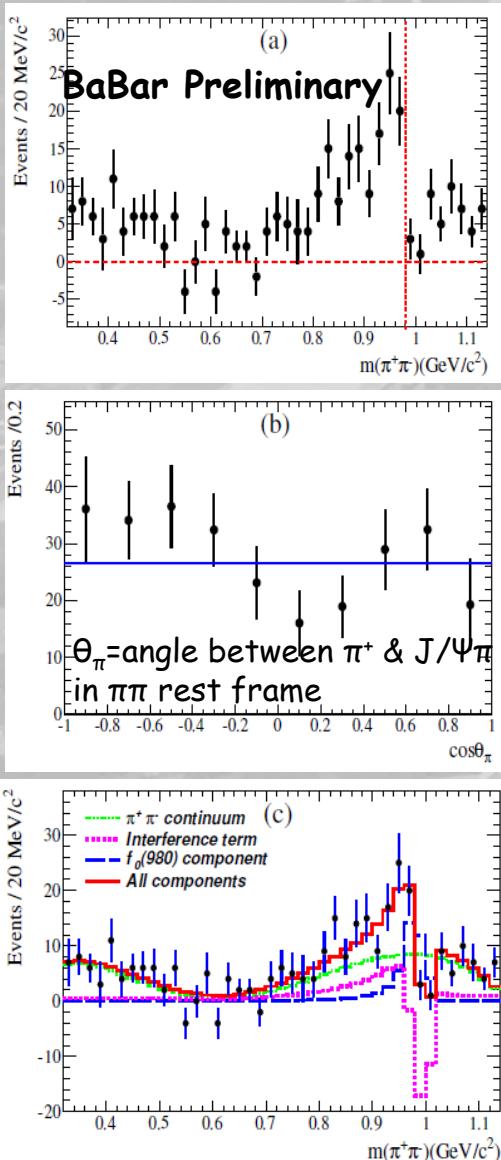
$\text{Mass } (\Upsilon(4260)) = 4244 \pm 5 \pm 4 \text{ MeV}/c^2$

$\Gamma(\Upsilon(4260)) = 114^{+16}_{-15} \pm 7 \text{ MeV}$

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

$$e^+e^- \rightarrow \gamma_{\text{isr}} J/\Psi \pi^+\pi^-$$

# Detailed study of the $\pi^+\pi^-$ invariant mass distribution



Study the region  $4.15 < m(J/\Psi\pi^+\pi^-) < 4.45 \text{ GeV}$   
 Mass distribution peaks near  $f_0(980)$ , but is displaced  
 $\cos\theta_\pi$  distribution consistent with S-wave  
 Fit the  $\pi^+\pi^-$  invariant mass distribution using:

$$f(m_{\pi\pi}) = |\sqrt{T(m_{\pi\pi})} + e^{i\phi} F_{f_0(980)}(m_{\pi\pi})|^2 \cdot p \cdot q ,$$

$T(m_{\pi\pi})$ =4<sup>th</sup> order polynomial

$F_{f_0(980)}$ =amplitude from BaBar  $D_s \rightarrow \pi\pi\pi$  analysis  
 PRD 79, 032003 (2009)

$p$ =  $\pi^+$  momentum in  $\pi^+\pi^-$  the rest frame

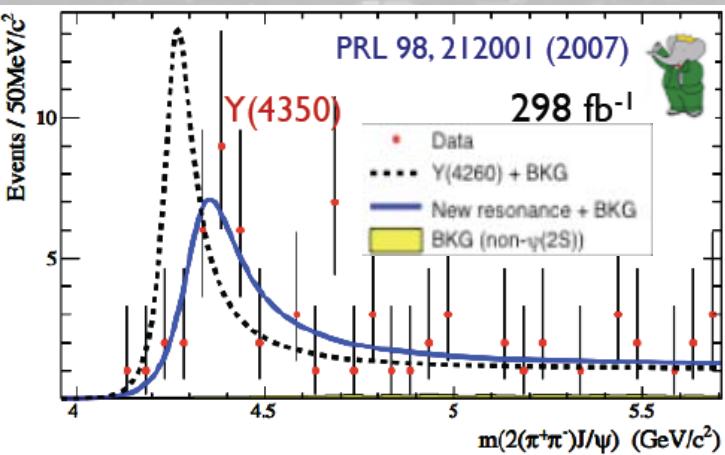
$q$ =  $J/\Psi$  momentum in the  $J/\Psi\pi^+\pi^-$  rest frame

$\phi$ = phase angle, determined by fit

Good fit to data,  $\chi^2/\text{dof}=33.6/35$

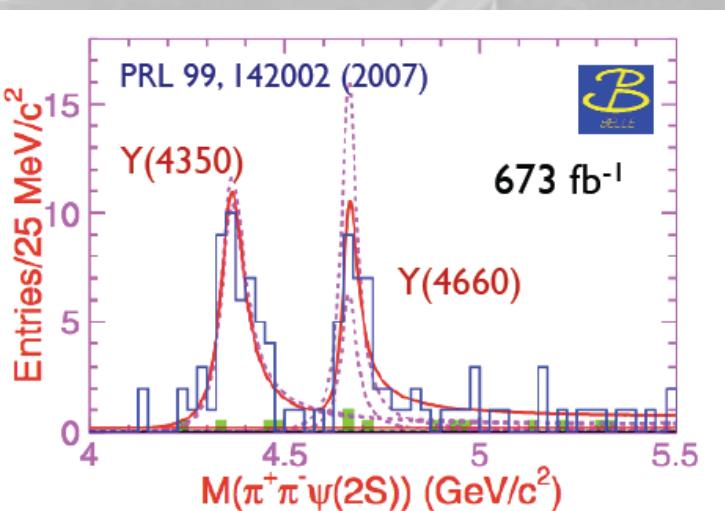
clear  $f_0(980)$  contribution, but not dominant

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

$e^+e^- \rightarrow \gamma_{\text{isr}} \Psi(2S) \pi^+ \pi^-$ 


## New state!

Observed by BaBar @ 4350 MeV  
 Incompatible with (4415)  
 Poor fit to  $\Upsilon(4260)$

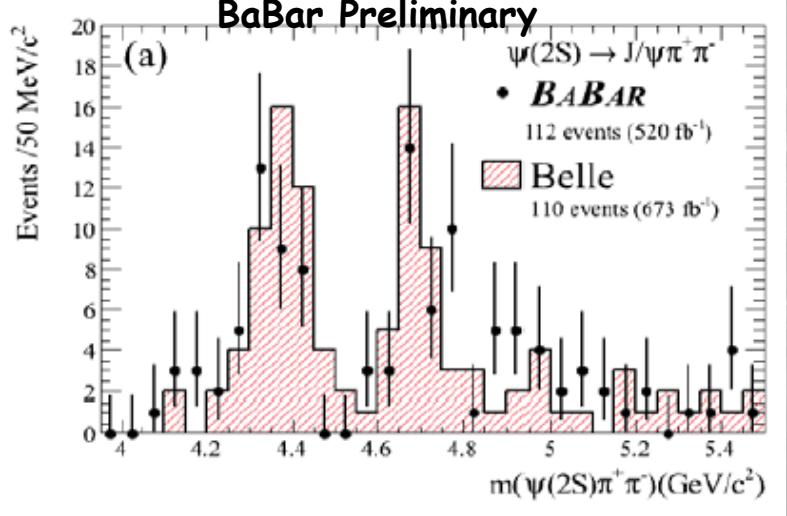
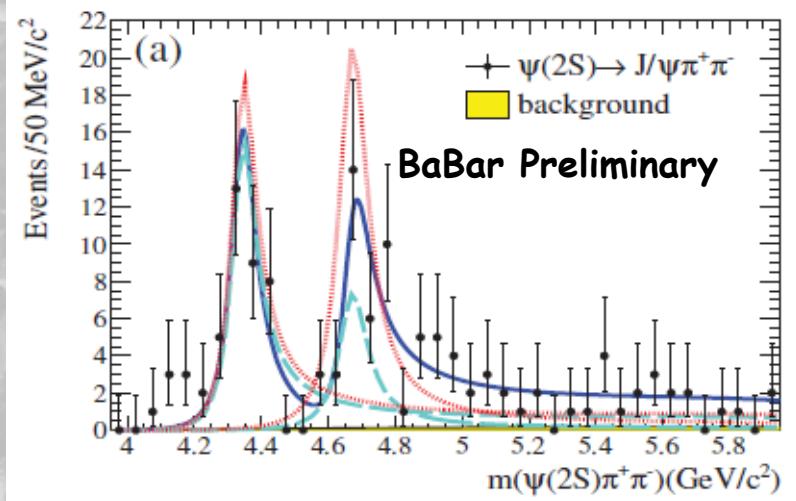


Belle confirmed the  $\Upsilon(4350)$   
 Observed a new state at 4660 MeV!

	State	$M (\text{MeV}/c^2)$	$\Gamma_{\text{tot.}}, \text{MeV}$
	$\Upsilon(4325)$	$4324 \pm 24$	$172 \pm 33 [1]$
	$\Upsilon(4325)$	$4361 \pm 9 \pm 9$	$74 \pm 15 \pm 10 [2]$
	$\Upsilon(4660)$	$4664 \pm 11 \pm 5$	$48 \pm 15 \pm 3 [2]$

- [1] BaBar: PRL 98, 212001 (2007)  
 [2] Belle: PRL 99, 142002 (2007)

# Updated analysis with full BaBar data set, 520 fb<sup>-1</sup>



$\Psi(2S) \rightarrow J/\Psi \pi^+ \pi^-$

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

Also analyse  $\Psi(2S) \rightarrow l^+l^-$  find similar results  
 Statistics too low to draw conclusions  
 from  $\pi^+\pi^-$  invariant mass distribution

New BaBar results are  
 consistent with Belle results  
 for  $Y(4360)$  &  $Y(4660)$

$$\gamma\gamma \rightarrow X \rightarrow \eta_c(1S)\pi^+\pi^-$$

arXiv:1206:2008v1

Study  $\gamma\gamma \rightarrow X \rightarrow \eta_c(1S)\pi^+\pi^-$  where  $X$  can be:

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

Use  $\eta_c(1S) \rightarrow K_s K^+ \pi^-$

Goal is to measure the BFs for  $X \rightarrow \eta_c(1S)\pi^+\pi^-$

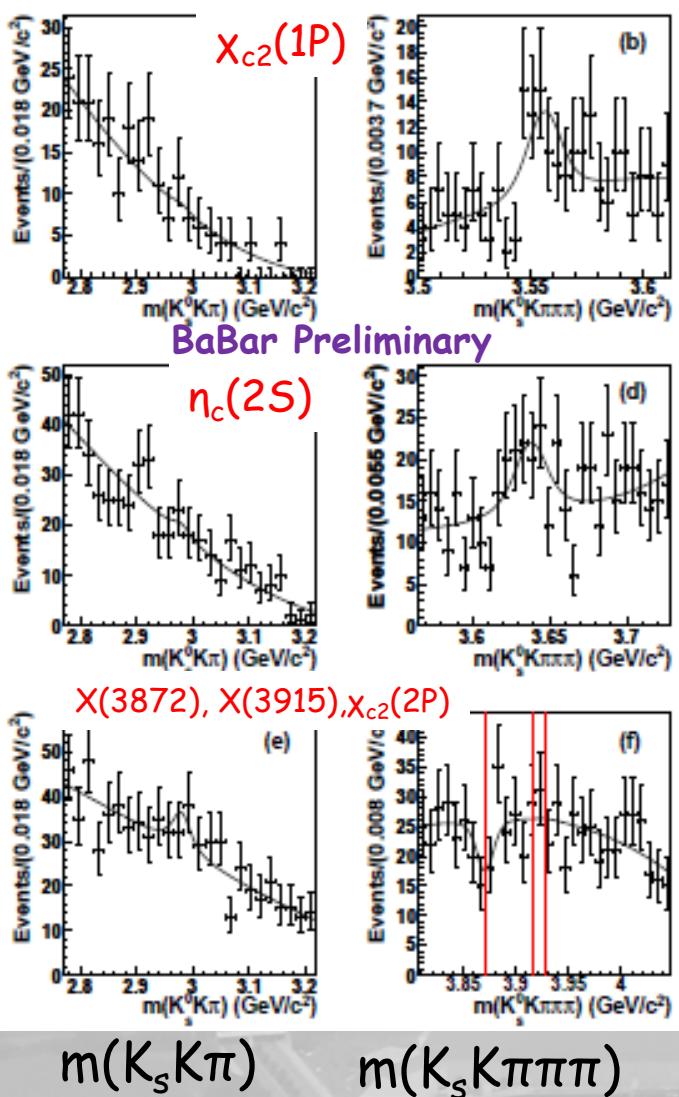
Many predictions for BFs:

$B(\eta_c(2S) \rightarrow \eta_c(1S)\pi^+\pi^-) \sim 2.2\%$  (M. B. Voloshin, Mod. Phys. Lett. A 17: 1533 (2002))  
from  $\Gamma(\eta_c(2S) \rightarrow \eta_c(1S)\pi^+\pi^-) / \Gamma(\Psi(2S) \rightarrow J/\Psi\pi^+\pi^-) \sim 2.9$

If  $X(3872)$  is the  $1D_1$  state the  $\eta_{c2}$  then the BF  $X(3872) \rightarrow \eta_c\pi^+\pi^-$   
could be significantly larger than  $B(X(3872) \rightarrow J/\Psi\pi^+\pi^-)$   
(S. L. Olsen, Int. J. Mod. Phys. A20, 240 (2005))

The quantum numbers  $J^{PC}=2^{-+}$  of the  $\eta_{c2}$  are consistent with CDF analysis  
of  $X(3872)$  which would allow it to be produced via  $\gamma\gamma$  process  
(PRL 98, 132002 (2007))

# $\gamma\gamma \rightarrow X \rightarrow n_c(1S)\pi^+\pi^-$ Results



2-step signal extraction procedure  
 1-D fit to  $m(K_s K^+ \pi^-)$  without restriction on  
 $m(K_s K^+ \pi^- \pi^- \pi^+)$  to determine combinatorial bkg  
 2-D fit to  $m(K_s K^+ \pi^-)$  &  $m(K_s K^+ \pi^- \pi^- \pi^+)$  for  
 each "X"

**No significant signals observed**  
 possible non-resonant signals in  $X_{c2}(1P)$  &  $n_c(2S)$

Resonance	$\Gamma_\gamma B(eV)$	UL @90% CL
$X_{c2}(1P)$	$7.2^{+5.5}_{-4.4} \pm 2.9$	15.7
$n_c(2S)$	$65^{+47}_{-44} \pm 18$	133
$X(3872)$	$-4.5^{+7.7}_{-6.7} \pm 2.9$	11.1
$X(3915)$	$-13^{+12}_{-12} \pm 8$	16
$X_{c2}(2P)$	$-16^{+15}_{-14} \pm 6$	19

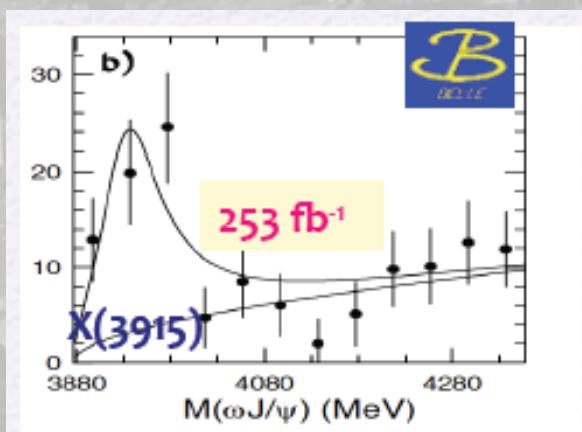
Using  $B(X_{c2}(1P) \rightarrow K_S K^\pm \pi^\mp)$  &  $B(n_c(2S) \rightarrow K_S K^\pm \pi^\mp)$   
 we obtain:

$B(X_{c2}(1P) \rightarrow n_c(1S) \pi\pi) < 2.2\% @ 90\% CL$   
 $B(n_{c2}(2S) \rightarrow n_c(1S) \pi\pi) < 7.4\% @ 90\% CL$

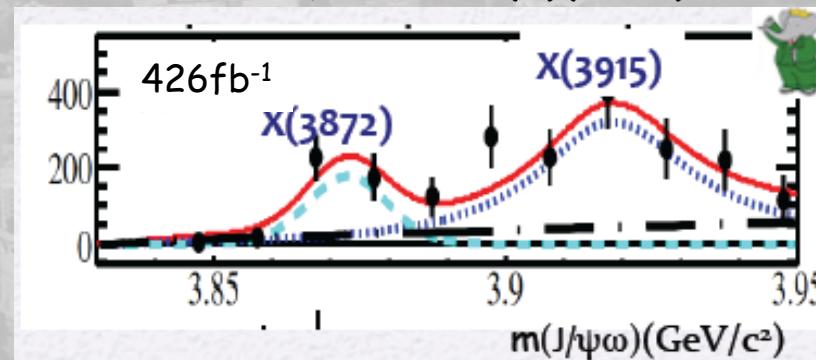
# $\gamma\gamma \rightarrow J/\Psi\omega$ and $X(3915)$

The  $X(3915)$  was discovered by Belle and confirmed by BaBar using  $B \rightarrow (3915)K$ ,  $X(3915) \rightarrow J/\Psi\omega$

PRL 94, 182002 (2005)

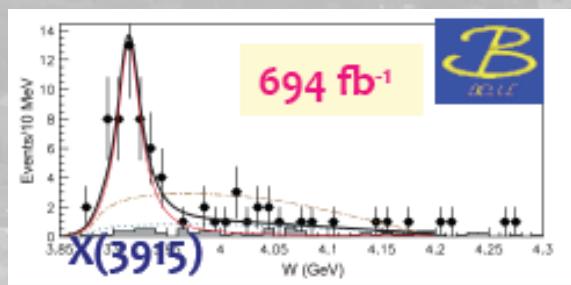


PRD 82, 011101 (R)(2010)



Belle also observed the  $X(3915)$  in the process  $\gamma\gamma \rightarrow X(3915) \rightarrow J/\Psi\omega$

PRL 104, 092001 (2010)



Interpretation of  $X(3915)$  as the  $X_{c0}(2P)$  or  $X_{c2}(2P)$  has been suggested.

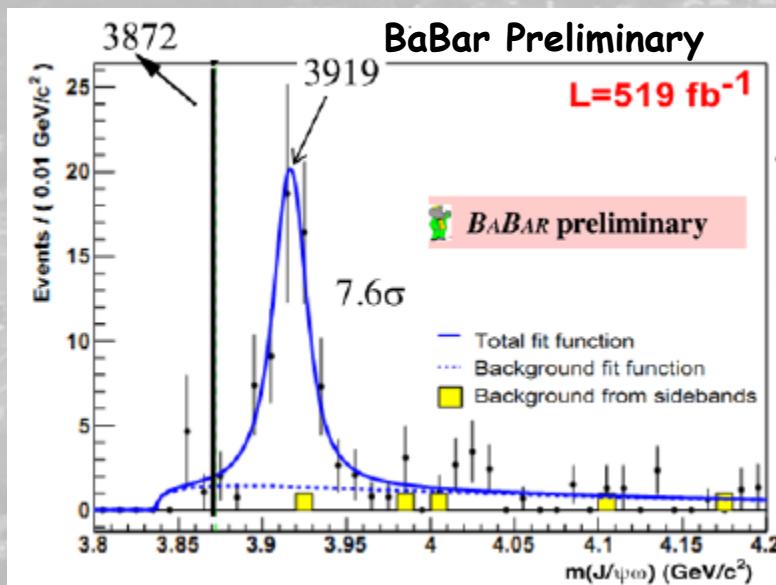
T. Branz et al., Phys. Rev. D 83, 114015 (2011)

But the  $\Gamma_{\gamma\gamma}(X(3915))B(X(3915) \rightarrow J/\Psi\omega)$  reported by Belle is unexpectedly large compared to other excited charmonia.

Molecular interpretation suggested. X. Liu et al., Eur. Phys. Jour. C 61, 411 (2009)

T. Branz et al., Phys. Rev. D 80, 054019 (2009) W. H. Liang et al., Eur. Phys. Jour. A 44, 479 (2010)

New BaBar result with  $519 \text{ fb}^{-1}$  confirms Belle results for  $\gamma\gamma \rightarrow X(3915) \rightarrow J/\Psi\omega$



arXiv:1207.2651v1

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

If  $\Gamma_{\gamma\gamma} \sim O(1 \text{ keV})$  (typical  $c\bar{c}$ ) then  $\mathcal{B}(J/\Psi\omega) > (1-6)\%$  which is relatively large compared to charmonium model predictions.

Detailed angular analysis finds  $J^P=0^\pm$  preferred over  $2^+$  and  $0^+$  preferred over  $0^-$  and this spin-parity assignment would identify the  $X(3915)$  as the  $X_{c0}(2P)$ . Details in backup slide.

The X(3872) was discovered by Belle in B decays PRL 94, 182002 (2005)

The X(3872) $\rightarrow$ J/ $\Psi\omega$  seen in B decays by BABAR PRD 82, 011101R (2010)

Quantum numbers of X(3872) still uncertain:

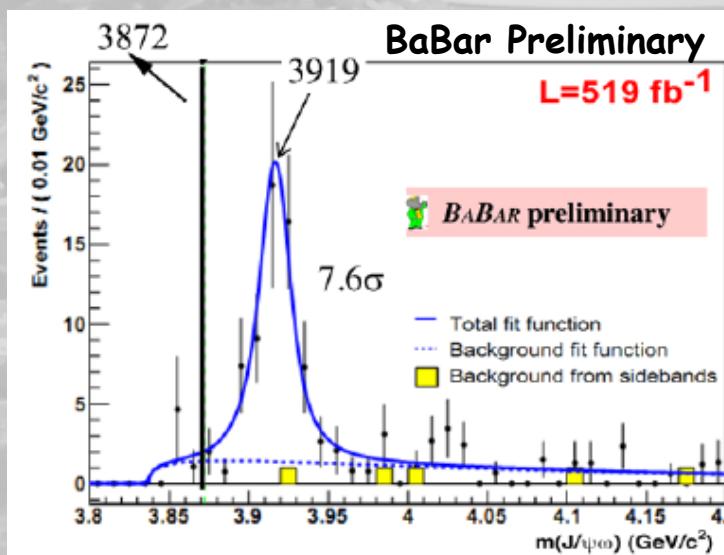
observation of X(3872) $\rightarrow$ J/ $\Psi\gamma$  implies C=+

BaBar favors  $J^{PC}=2^{-+}$  but  $1^{++}$  also possible

BaBar: PRL 102, 132001 (2009)

Belle: PRL 107, 091803 (2011)

**Observation of  $\gamma\gamma \rightarrow X(3872) \rightarrow J/\Psi\omega$  would imply  $J^{PC}=2^{-+}$**



No sign of  $\gamma\gamma \rightarrow X(3872) \rightarrow J/\Psi\omega$  signal in the data

$$\Gamma_{\gamma\gamma}(X(3872)) \times B(X(3872) \rightarrow J/\psi\omega) (J=2) < 1.7 \text{ eV}$$

Belle does not see a signal either in this production mode.

# Summary & Conclusions

## ISR production of Charmonium-like states

$e^+e^- \rightarrow \gamma_{ISR} J/\Psi \pi^+\pi^-$ :

arXiv:1204:2158

Improved precision on  $\Upsilon(4260)$  parameters

$\Upsilon(4008)$  not observed

$e^+e^- \rightarrow \gamma_{ISR} \Psi(2S) \pi^+\pi^-$ :

Confirmation of  $\Upsilon(4360)$  &  $\Upsilon(4660)$

## $\gamma\gamma$ production of Charmonium-like states

$\gamma\gamma \rightarrow X \rightarrow \eta_c(1S) \pi^+\pi^-$ :

arXiv:1206:2008

No significant signals for:

$X = X_{c2}(1P), \eta_c(2S), X(3872), X(3915), X_{c2}(2P)$

$\gamma\gamma \rightarrow J/\Psi \omega$ :

Observation of  $X(3915)$

arXiv:1207.2651v1

no sign of  $X(3872)$

## Charmonium spectroscopy remains interesting!



# Extra slides

asymmetric  $e^+e^-$  collider: 9 GeV ( $e^-$ )/3.1 GeV ( $e^+$ )  
PEP-II Peak Luminosity  $1.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

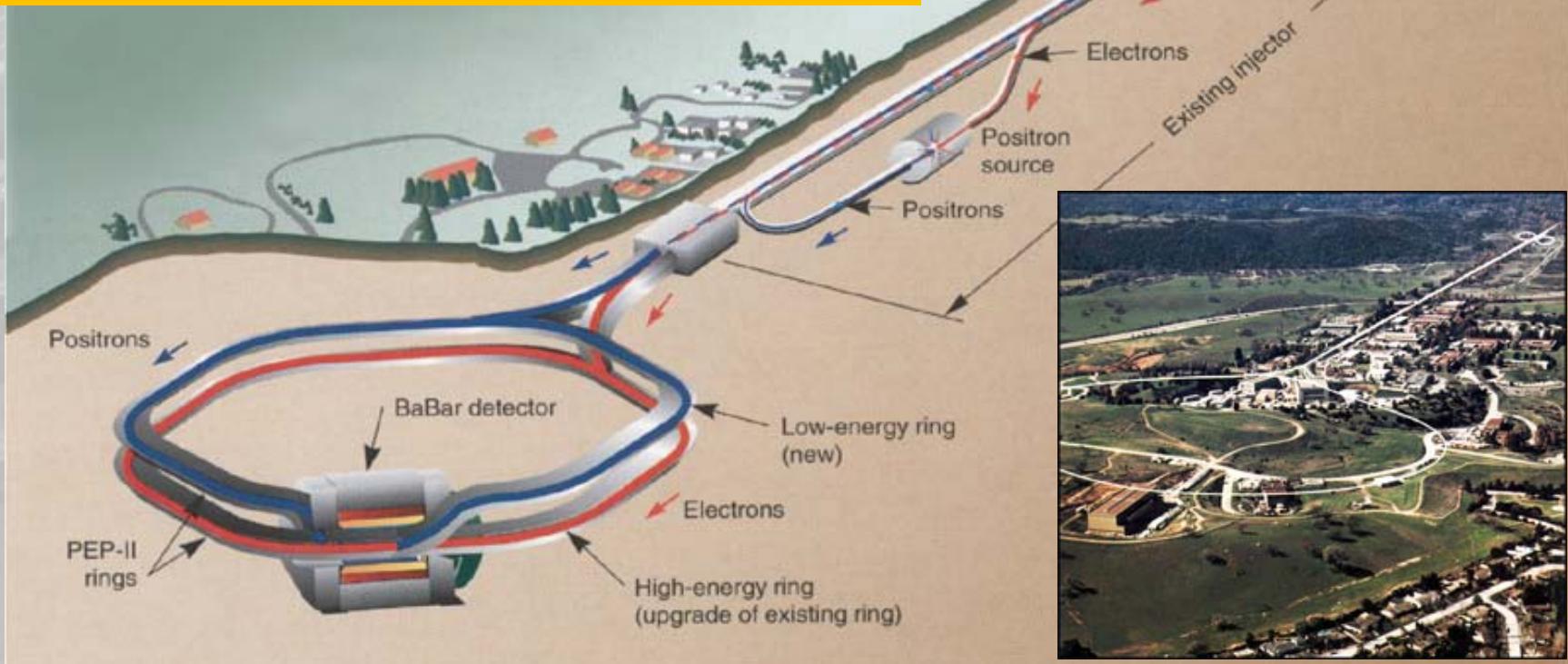
Took data 1999-2008

$\Upsilon(4S)$  [ $431\text{fb}^{-1}$ ] (On-Peak)

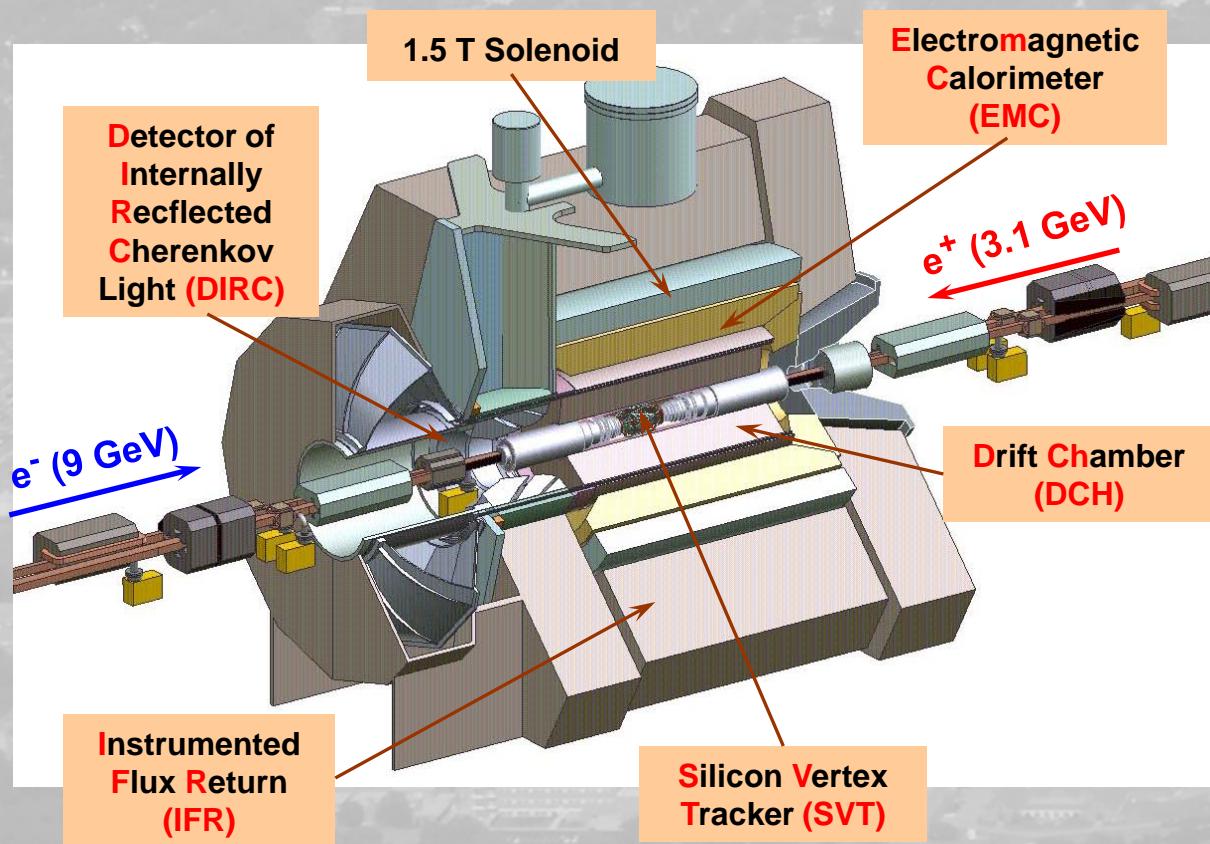
40MeV below  $\Upsilon(4S)$  [ $45\text{fb}^{-1}$ ] (Off-Peak)

$\Upsilon(3S)$  [ $30\text{fb}^{-1}$ ]

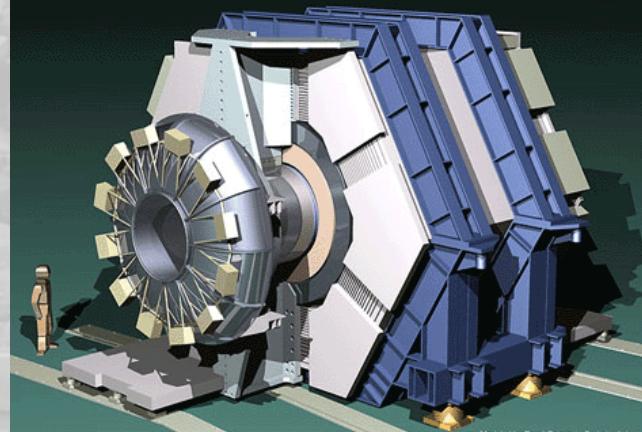
$\Upsilon(2S)$  [ $14\text{fb}^{-1}$ ]



# BaBar Detector



BABAR DETECTOR FOR THE PEP-II B FACTORY

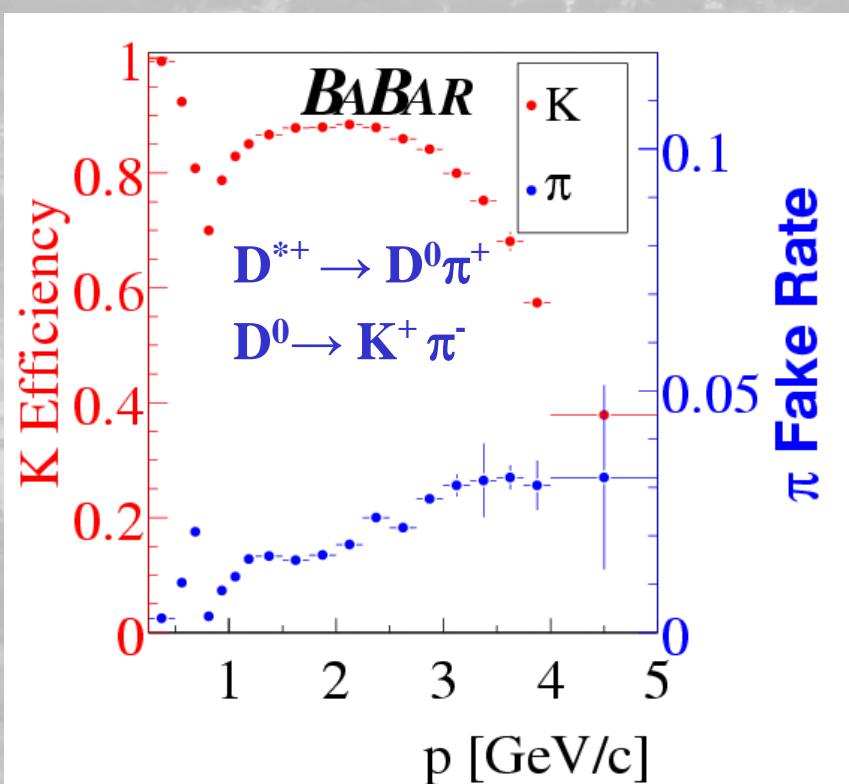
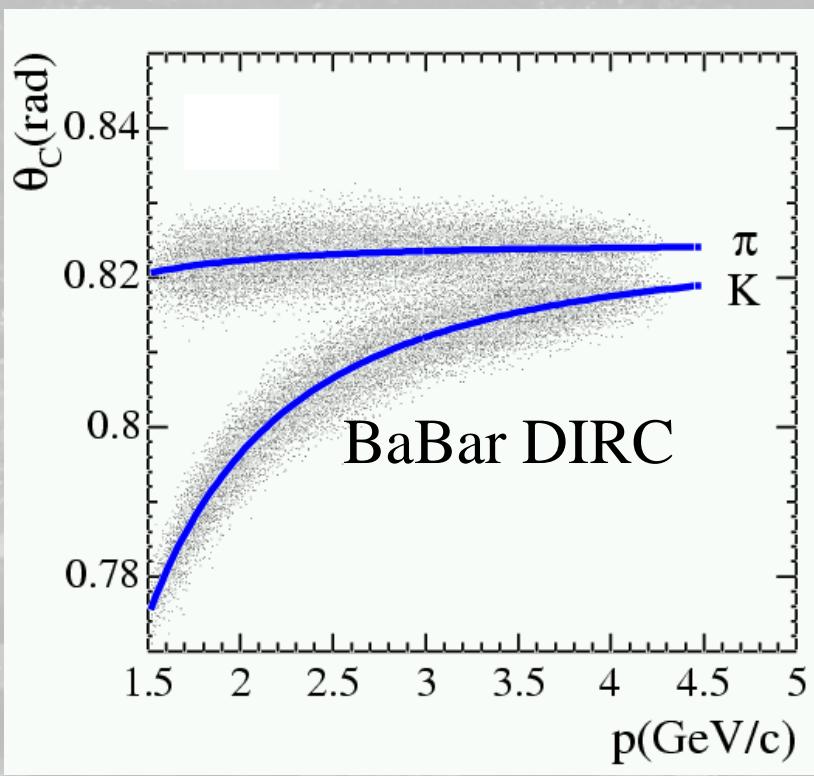


SVT, DCH: charged particle tracking: vertex & mom. resolution,  $K_s^0/\Lambda$

EMC: electromagnetic calorimeter:  $\gamma/e/\pi^0/n$

DIRC, IFR, DCH: charged particle ID:  $\pi/\mu/K/p$

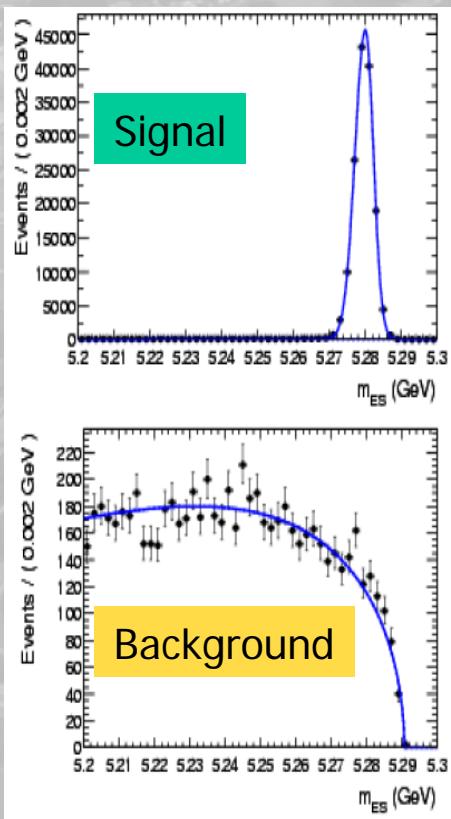
Highly efficient trigger for B mesons



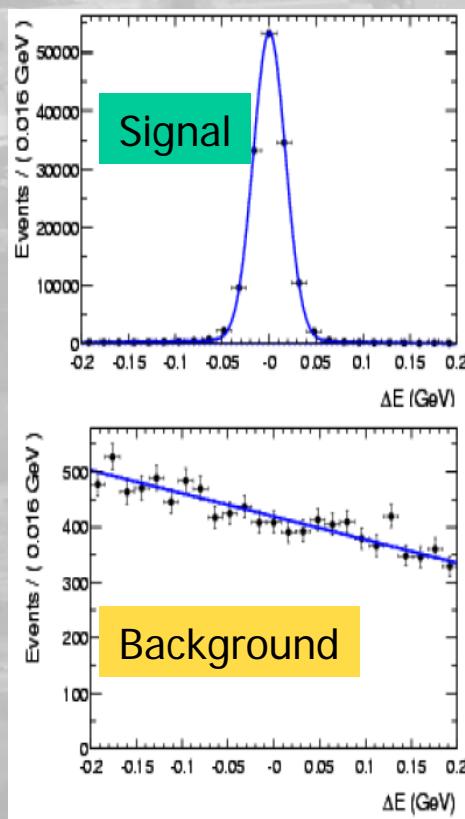
# Analysis Technique

Threshold kinematics: we know the initial energy ( $E_{beam}^*$ ) of the  $\Upsilon(4S)$  system  
 Therefore we know the energy & magnitude of momentum of each B meson

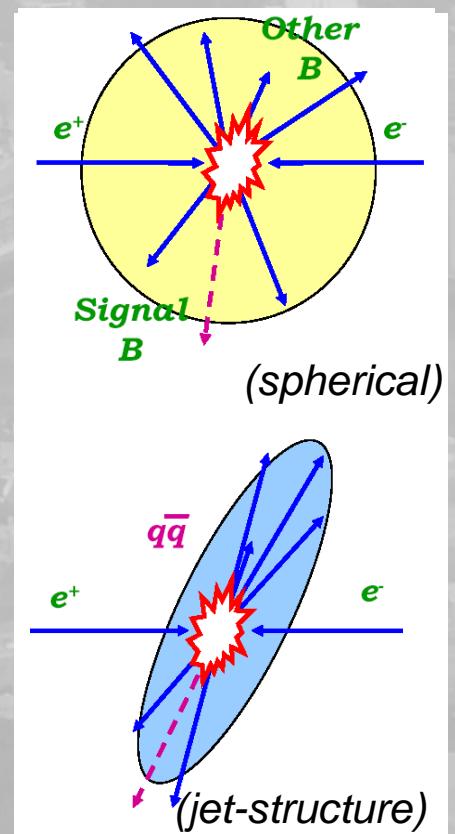
$$m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$$



$$\Delta E = E_B^* - E_{beam}^*$$



Event topology



Also, use neural networks + unbinned maximum likelihood fits

# Charmonium-like States

**Over 16 new resonances only 5 have been seen by more than one experiment**

OK = confirmed by different experiments  
 N.C. = Seen by only one experiment not by other  
 N.Y.C= Not yet confirmed

**NEW Results from BaBar**

State	$m(\text{MeV}/c^2)$	$\Gamma(\text{MeV})$	$J^{PC}$	Process (mode)	Experiment	Year	Status
X(3823)	$3823.5 \pm 2.8$	$4 \pm 6$	?/2 <sup>-+</sup>	$B \rightarrow K(\chi_{c1}\gamma)$	Belle	2012	N.Y.C
X(3872)	$3871.52 \pm 0.20$	$1.3 \pm 0.6$	1 <sup>++</sup> /2 <sup>++</sup>	$B \rightarrow K(\pi^+\pi^-J/\psi)$ $p\bar{p} \rightarrow (\pi^+\pi^-J/\psi) + \dots$ $B \rightarrow K(J/\psi\omega)$ $B \rightarrow K(D^{*0}\bar{D}^0)$ $B \rightarrow K(J/\psi\gamma)$ $B \rightarrow K(\psi(2S)\gamma)$	Belle, BABAR, LHCb CDF, DØ, CMS Belle, BABAR Belle, BABAR Belle, BABAR BABAR	2003	OK
X(3915)	$3915.6 \pm 3.1$	$28 \pm 10$	0/2 <sup>++</sup>	$B \rightarrow K(J/\psi\omega)$	Belle, BABAR	2004	OK
X(3940)	$3942^{+9}_{-8}$	$37^{+27}_{-17}$	? <sup>?</sup> +	$e^+e^- \rightarrow e^+e^-(J/\psi\omega)$ $e^+e^- \rightarrow J/\psi(D\bar{D}^*)$	Belle, BABAR	2007	N.Y.C.
Y(4008)	$4008^{+121}_{-10}$	$226 \pm 97$	1 <sup>--</sup>	$e^+e^- \rightarrow \gamma J/\psi\pi^+\pi^-$	Belle	2007	N.C.
Z <sub>1</sub> (4050) <sup>+</sup>	$4051^{+24}_{-43}$	$82^{+51}_{-55}$	?	$B \rightarrow K(\pi^+\chi_{c1}(1P))$	Belle	2008	N.C.
Y(4140)	$4143 \pm 3.0$	$15^{+11}_{-7}$	? <sup>?</sup> +	$B \rightarrow K(\phi J/\psi)$	CDF	2009	N.C.
X(4160)	$4156^{+29}_{-37}$	$139^{+113}_{-65}$	? <sup>?</sup> +	$e^+e^- \rightarrow J/\psi(D\bar{D}^*)$	Belle	2007	N.Y.C.
Z <sub>2</sub> (4250) <sup>+</sup>	$4248^{+185}_{-45}$	$177^{+321}_{-72}$	?	$B \rightarrow K(\pi^+\chi_{c1}(1P))$	Belle	2008	N.C.
Y(4260)	$4263 \pm 5$	$108 \pm 14$	1 <sup>--</sup>	$e^+e^- \rightarrow \gamma J/\psi\pi^+\pi^-$	BABAR, CLEO, Belle	2005	OK
Y(4274)	$4274.4^{+8.4}_{-6.7}$	$32^{+22}_{-15}$	? <sup>?</sup> +	$e^+e^- \rightarrow J/\psi\pi^0\pi^0$ $B \rightarrow K(\phi J/\psi)$	CLEO		
X(4350)	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	0, 2 <sup>++</sup>	$e^+e^- \rightarrow e^+e^-(\phi J/\psi)$	CDF	2009	N.Y.C.
Y(4360)	$4353 \pm 11$	$96 \pm 42$	1 <sup>--</sup>	$e^+e^- \rightarrow \gamma\psi(2S)\pi^+\pi^-$	BABAR, Belle	2007	OK
Z(4430) <sup>+</sup>	$4443^{+24}_{-18}$	$107^{+113}_{-71}$	?	$B \rightarrow K(\pi^+\psi(2S))$	Belle	2007	N.C.
X(4360)	$4634 \pm 12$	$92^{+41}_{-32}$	1 <sup>--</sup>	$e^+e^- \rightarrow \gamma\Lambda_c^+\Lambda_c^-$	Belle	2007	N.Y.C.
Y(4660)	$4664 \pm 12$	$48 \pm 15$	1 <sup>--</sup>	$e^+e^- \rightarrow \gamma\psi(2S)\pi^+\pi^-$	Belle, BABAR	2007	OK

$e^+e^- \rightarrow \gamma_{\text{isr}} J/\Psi \pi^+ \pi^-$ 

TABLE I. Systematic uncertainty estimates for the Y(4260) parameter values.  
**BaBar Preliminary**

Source	$\Gamma_{e^+e^-} \cdot \mathcal{B}(\%)$	Mass (MeV/c <sup>2</sup> )	$\Gamma$ (MeV)
Fit procedure	$^{+1.5}_{-0.5}$	$^{+0}_{-1}$	$^{+2}_{-1}$
Mass Scale	-	$\pm 0.6$	-
Mass resolution	-	-	$\pm 1.5$
MC dipion model	$\pm 3.6$	-	-
Decay angular momentum	$\pm 3.6$	$\pm 3.5$	$\pm 7$
Luminosity, etc. (see text)	$\pm 5.4$	-	-

$$\sigma_{\text{BW}}(m) = \frac{12\pi C}{m^2} \cdot \frac{PS(m)}{PS(m_Y)} \cdot \frac{\Gamma_{e^+e^-} \cdot \mathcal{B}(J/\psi \pi^+ \pi^-) \cdot m_Y^2 \cdot \Gamma_Y}{(m_Y^2 - m^2)^2 + m_Y^2 \Gamma_Y^2},$$

$$\sigma_i = \frac{n_i^{\text{obs}} - n_i^{\text{bkg}}}{\epsilon_i \cdot \mathcal{L}_i \cdot \mathcal{B}(J/\psi \rightarrow l^+l^-)}$$

$$e^+ e^- \rightarrow \gamma_{\text{isr}} \Psi(2S) \pi^+ \pi^-$$

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

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

BaBar Preliminary

TABLE III. Systematic uncertainty estimates for the parameter used in the fit to the data of Fig. 1(a).

Source	$\Gamma_{e^+ e^-} \cdot \mathcal{B}$ (%) [constructive interference]	$\Gamma_{e^+ e^-} \cdot \mathcal{B}$ (%) [destructive interference]	Mass (MeV/c <sup>2</sup> )	$\Gamma$ (MeV)
Fit procedure for the Y(4360)	$\pm 2.5$	$\pm 1.4$	$\pm 9$	$\pm 13$
Fit procedure for the Y(4660)	$\pm 14$	$\pm 3.3$	$\pm 3$	$\pm 10$
Mass Scale	-	-	$\pm 0.5$	-
Mass resolution	-	-	-	$\pm 1.3$
MC dipion model	$\pm 6.8$	$\pm 6.8$	-	-
$\mathcal{B}_{(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)}$	$\pm 1.1$	$\pm 1.1$	-	-
$\mathcal{B}_{(J/\psi \rightarrow l^+ l^-)}$	$\pm 1$	$\pm 1$	-	-
PID, Luminosity and Tracking	-	-	-	-
Total (Y(4360))	$\pm 8$	$\pm 8$	$\pm 9$	$\pm 13$
Total (Y(4660))	$\pm 16$	$\pm 6$	$\pm 3$	$\pm 10$

$\gamma\gamma \rightarrow X \rightarrow \eta_c(1S)\pi^+\pi^-$ 
**BaBar Preliminary**

TABLE I: Results of the step-2 fits. For each resonance  $X$ , we show the peak mass and width used in the PDF (from Refs. [1, 15, 22]); the mass range of the fit; the efficiency; the bias-corrected signal yield with statistical and systematic uncertainties; the product of the  $\gamma\gamma \rightarrow X$  production cross section and  $X \rightarrow \eta_c\pi^+\pi^-$  branching fraction, and the 90% CL upper limit (UL) on this product; the product of the two-photon partial width  $\Gamma_{\gamma\gamma}$  and the  $X \rightarrow \eta_c\pi^+\pi^-$  branching fraction, and the 90% CL upper limit on this product. For the  $X(3872)$  and the  $X(3915)$  we assume  $J = 2$ .

Resonance	$M_X$ ( MeV/ $c^2$ )	$\Gamma_X$ ( MeV)	$m_5$ Range ( GeV/ $c^2$ )	$\varepsilon$ (%)	$N_{\text{sig}}$	$\sigma\mathcal{B}(\text{fb})$		$\Gamma_{\gamma\gamma}\mathcal{B}(\text{eV})$	
						Central value	UL	Central value	UL
$\chi_{c2}(1P)$	$3556.20 \pm 0.09$	$1.97 \pm 0.11$	3.500-3.612	$3.60 \pm 0.39$	$10.2^{+7.7}_{-6.3} \pm 3.5$	$37^{+28}_{-23} \pm 15$	80	$7.2^{+5.5}_{-4.4} \pm 2.9$	15.7
$\eta_c(2S)$	$3638.5 \pm 1.7$	$13.4 \pm 5.6$	3.565-3.728	$3.53 \pm 0.35$	$17^{+12}_{-11} \pm 3$	$61^{+41}_{-41} \pm 16$	123	$65^{+47}_{-44} \pm 18$	133
$X(3872)$	$3871.57 \pm 0.25$	$3.0 \pm 2.1$	3.807-4.047	$3.92 \pm 0.38$	$-4.7^{+7.9}_{-6.9} \pm 2.8$	$-16^{+26}_{-23} \pm 10$	38	$-4.5^{+7.7}_{-6.7} \pm 2.9$	11.1
$X(3915)$	$3915.0 \pm 3.6$	$17.0 \pm 10.4$	3.807-4.047	$3.79 \pm 0.37$	$-13^{+11}_{-11} \pm 7$	$-44^{+38}_{-38} \pm 25$	53	$-13^{+12}_{-12} \pm 8$	16
$\chi_{c2}(2P)$	$3927.2 \pm 2.6$	$24 \pm 6$	3.807-4.047	$3.75 \pm 0.36$	$-15^{+14}_{-13} \pm 4$	$-53^{+49}_{-46} \pm 18$	60	$-16^{+15}_{-14} \pm 6$	19

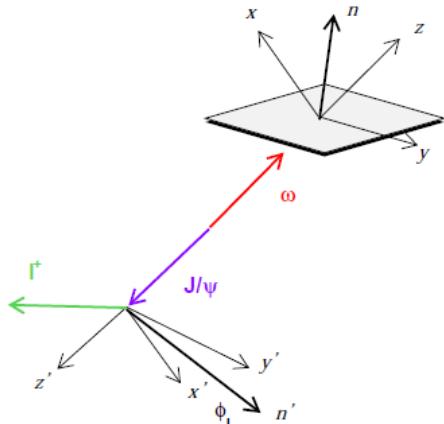


FIG. 5: Diagram illustrating the reference frames involved in the definition of  $\phi_l$ .

TABLE I: Functional shapes and  $\chi^2$  for the different spin hypotheses. NDF=9.

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Angle	$J^P = 0^-$	$J^P = 0^+$	$J^P = 0^\pm$	$J^P = 2^+$
$\theta_l^*$			1	$1 + \cos^2 \theta_l^*$
$\chi^2$		11.2		16.9
$\theta_n^*$		1		$\sin^2 \theta_n^*$
$\chi^2$		6.9		65.9
$\theta_{ln}$			$\sin^2 \theta_{ln}$	$7 - \cos^2 \theta_{ln}$
$\chi^2$			12.5	18.0
$\theta_h$			1	
$\chi^2$			12.2	
$\theta_n$	$\sin^2 \theta_n$	1		
$\chi^2$	77.6		16.3	
$\theta_l$	$1 + \cos^2 \theta_l$	1		
$\chi^2$	8.7		8.3	
$\phi_l$	$2 - \cos(2 \cos \phi_l)$	$2 + \cos(2 \cos \phi_l)$		
$\chi^2$	21.7		9.6	

$\Theta^*_l$ =angle between  $l^+$  from  $J/\Psi$  and beam axis in  $J/\Psi\omega$  rest frame (RF)

$\Theta^*_n$ =angle between the normal of the decay plane of the  $\omega$  &  $\gamma\gamma$  axis

$\Theta_{ln}$ =angle between  $l^+$  from  $J/\Psi$  and the  $\omega$  decay plane

$\Theta_h$ =angle between  $J/\Psi$  momentum in  $J/\Psi\omega$  RF wrt  $J/\Psi\omega$  direction in lab frame

$\Theta_n$ = boost all the 4-vectors into the  $J/\Psi\omega$  RF, then boost the 2 pions from the  $\omega$  decay into the  $\omega$  RF and obtain the normal to the  $\omega$  decay plane by the cross product vector of the 2 charged pions.

$\Theta_n$ =angle between this normal and the  $\omega$  direction in the  $J/\Psi\omega$  RF.

$\Theta_l$ =angle between  $l^+$  from  $J/\Psi$  and the  $J/\Psi$  direction in the  $J/\Psi\omega$  RF.