



# Quarkonium studies at BaBar



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for the BaBar Collaboration



# Outline

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## Charmonium and charmonium-like states

- $X(3872) \rightarrow J/\psi \omega$  in B decays  
[BaBar, arXiv:1005.5190, accepted by PRD-RC]
- Two-photon production of  $\chi_c(2P)$   
[BaBar, PRD 81 - 092003 (2010)]

## Bottomonium

- $\Upsilon(1^3D_J) \rightarrow \pi^+ \pi^- \Upsilon(1S)$   
[BaBar, arXiv:1004.0175 submitted to PRL]

# Charmonium

# Charmonium production

- **Color-suppressed B decays:**

- $0^{-+}, 1^{--}, 1^{++}$

- inclusive BF's  $\sim 10^{-2}$

- **Two-photon processes:**

- $0^{-+}, 0^{++}, 2^{-+}, 2^{++}, 3^{++}$

- $C=+$

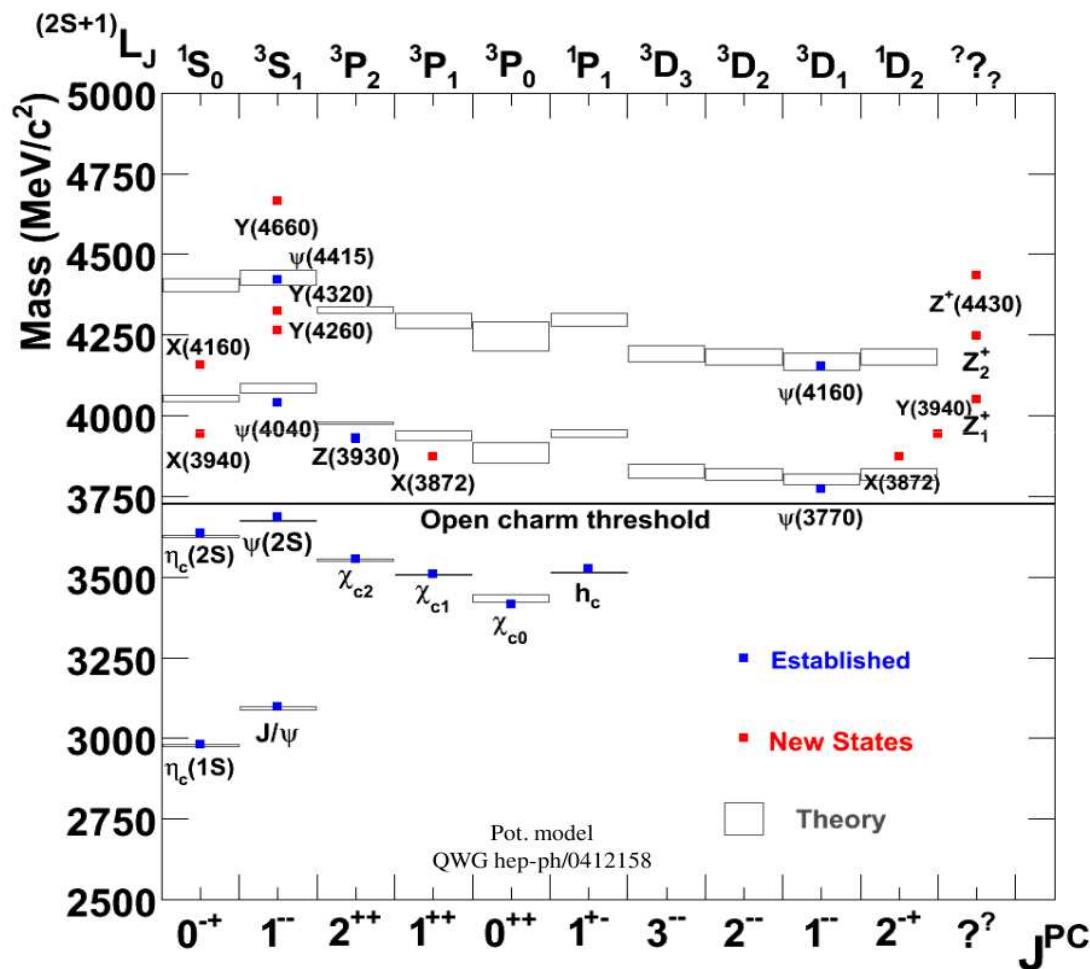
- $J=1$  forbidden for real photons  
[C. N. Yang, Phys. Rev. 77, 242 (1950)]

- complementary to  $e^+ e^-$  annihilation

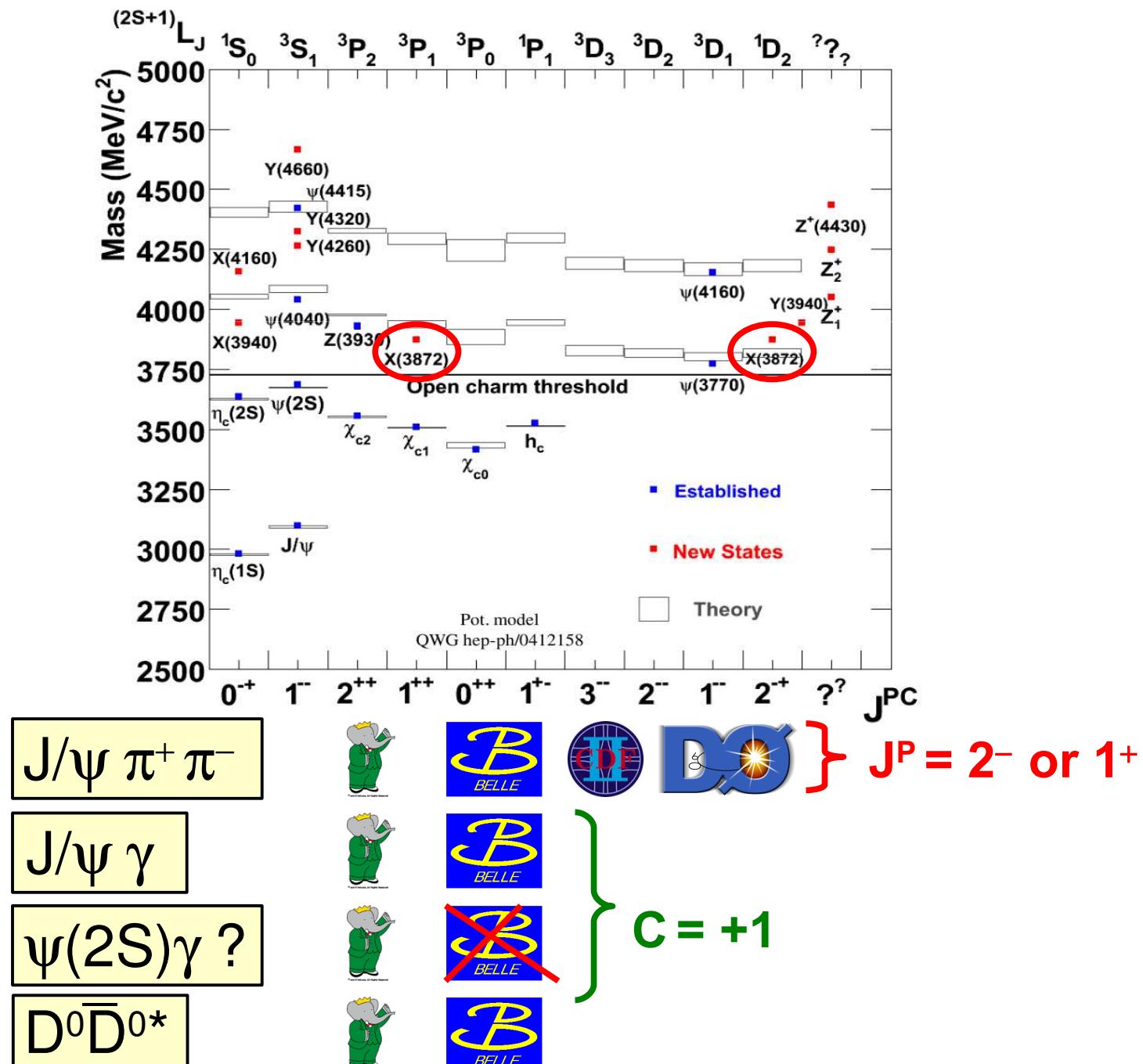
- Radiative return (ISR):  $1^{--}$

- B-factories: comparable sensitivity to energy scanning (CLEO-c, BES)

- Double cc production:  $C=+, J=0 \dots$



# X(3872)



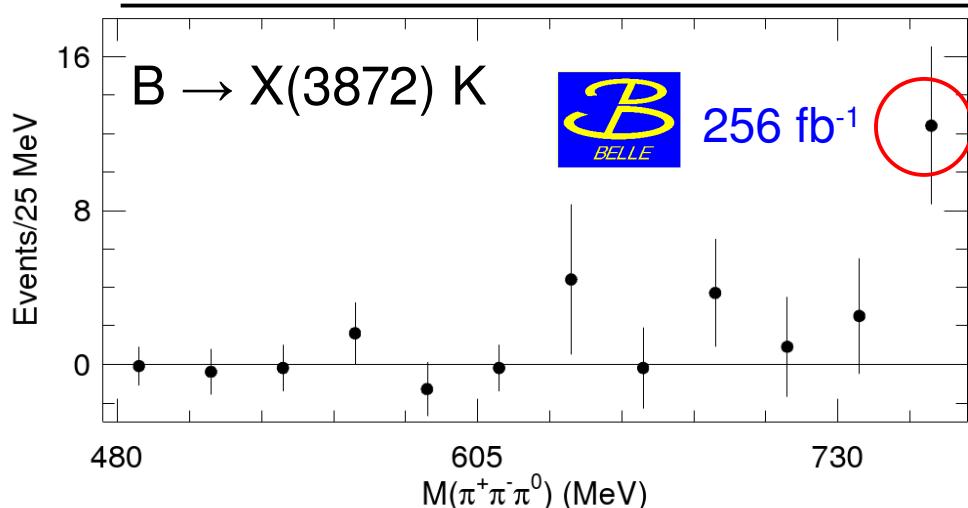
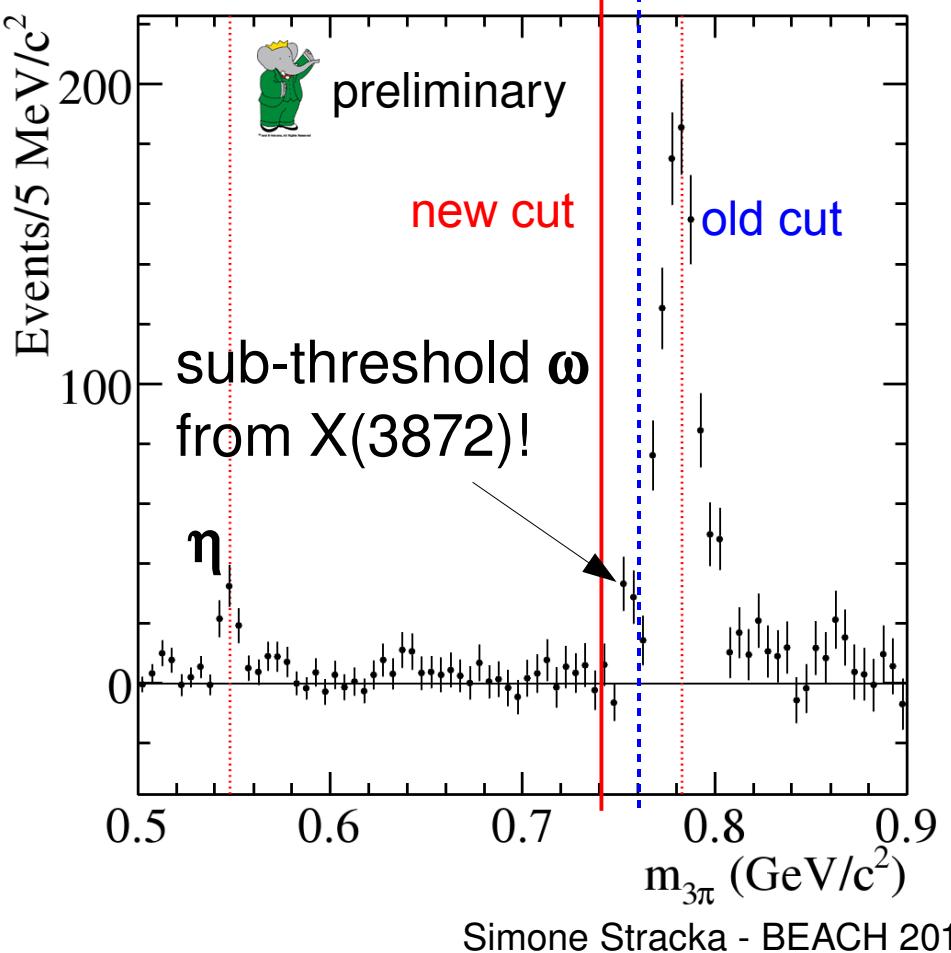
# $B \rightarrow K J/\psi \pi^+ \pi^- \pi^0$

Hint at Belle:  $12.4 \pm 4.1$  evts.

$750 < M_{3\pi} < 775$  MeV/c $^2$

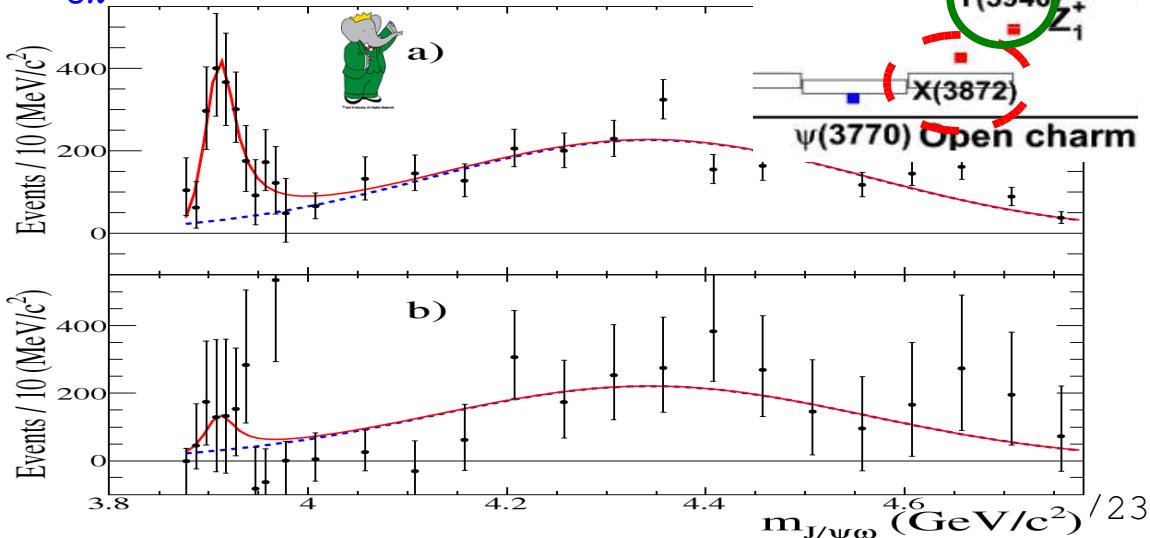
interpreted as a  $\omega(780)$

[hep-ex/0505037]



BaBar previously analyzed this final state while looking for  $B \rightarrow K Y(3940)$  [PRL 101, 082001 (2008)] (348 fb $^{-1}$ )

$Y(3940)$  confirmed! No  $X(3872)!$   
 $M_{3\pi} > 769.5$  MeV/c $^2$



# Evidence for $X(3872) \rightarrow J/\psi \omega$

arXiv:1005.5190

- $m_{ES}$  fits in  $m_{J/\psi 3\pi}$  intervals (after  $\Delta E$  requirement) to extract B-signal
- simultaneous ( $B^+ + B^0$ ) fit to efficiency corrected  $m_{J/\psi \omega}$  distribution

• 4.0  $\sigma$  significance ( $27 \pm 8$  evts)

$$\text{BR} = \frac{BF(X \rightarrow J/\psi \omega)}{BF(X \rightarrow J/\psi \pi\pi)}$$

–  $\text{BR}(B^+) = 0.7 \pm 0.3$

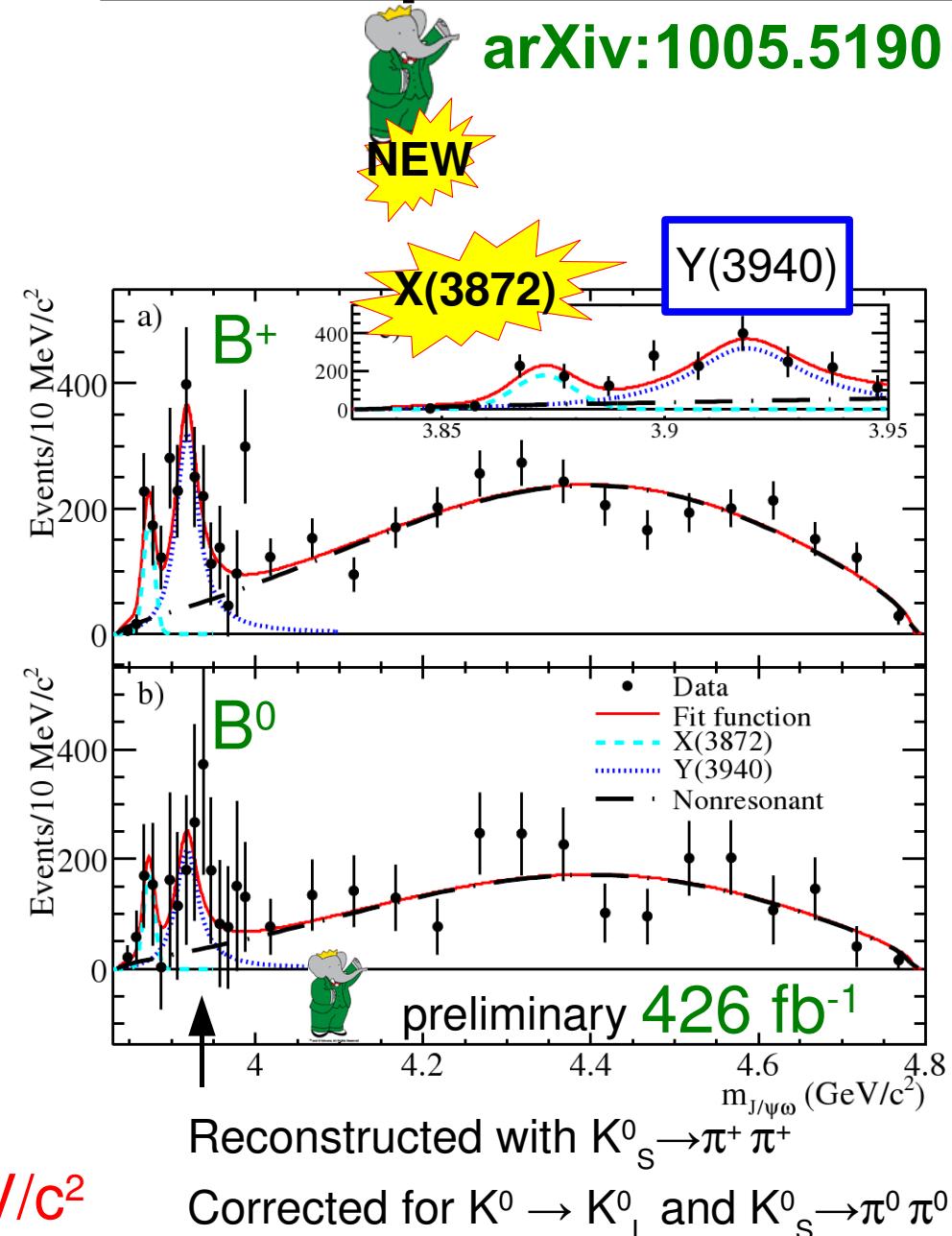
–  $\text{BR}(B^0) = 1.7 \pm 1.3$

–  $\text{BR}(\text{average}) = 0.8 \pm 0.3$

$\text{BR}(\text{Belle}) = 1.0 \pm 0.4 \pm 0.3$

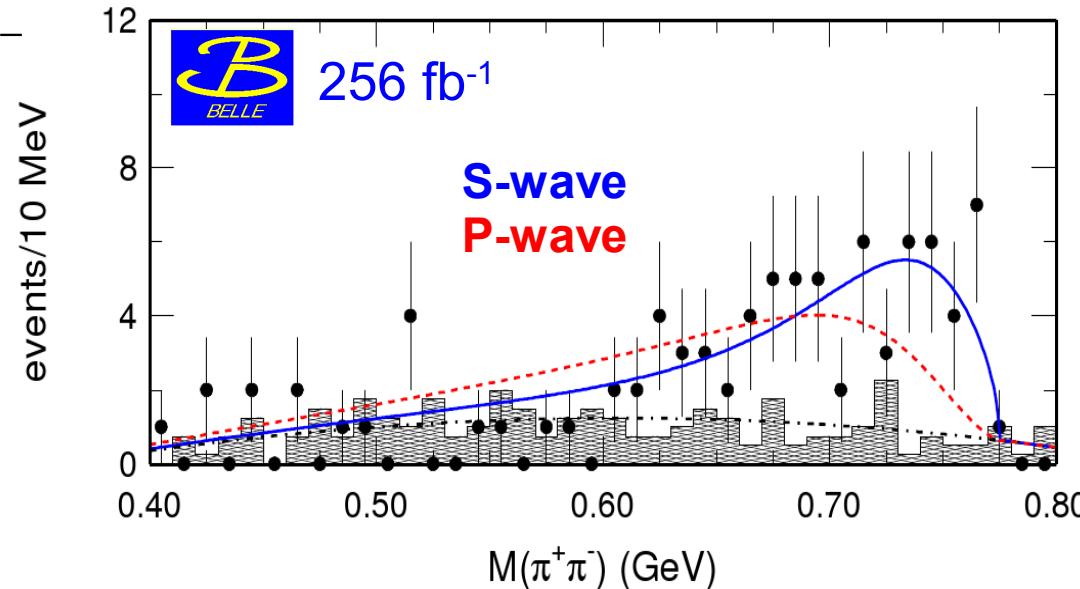
•  $M[X(3872)] = (3873.0^{+1.8}_{-1.6} \pm 1.3) \text{ MeV}/c^2$

neglect  $\Gamma_X < 3 \text{ MeV}$  - r.m.s. =  $6.7 \text{ MeV}/c^2$



# X(3872) – $J^P$ from $J/\psi \pi^+ \pi^-$

- $\pi^+ \pi^-$  mass spectrum in  $J/\psi \pi^+ \pi^-$   
[Belle, hep-ex/0505038]
  - assuming  $\pi\pi = \rho$   
 $\Rightarrow$  favor  $L=0 \Rightarrow P = +1$



- Angular analysis of  $B \rightarrow K J/\psi \pi^+ \pi^-$   
[CDF: PRL 98, 132002 (2007)]
  - Allow for  $(\pi\pi)_{S\text{-wave}}$  and  $\rho$  contributions, with lowest P-conserving L
  - Subthreshold  $\pi\pi = \rho$  favored
  - $J^P = 2^-$  or  $1^+$  (similar  $\chi^2$  prob.)

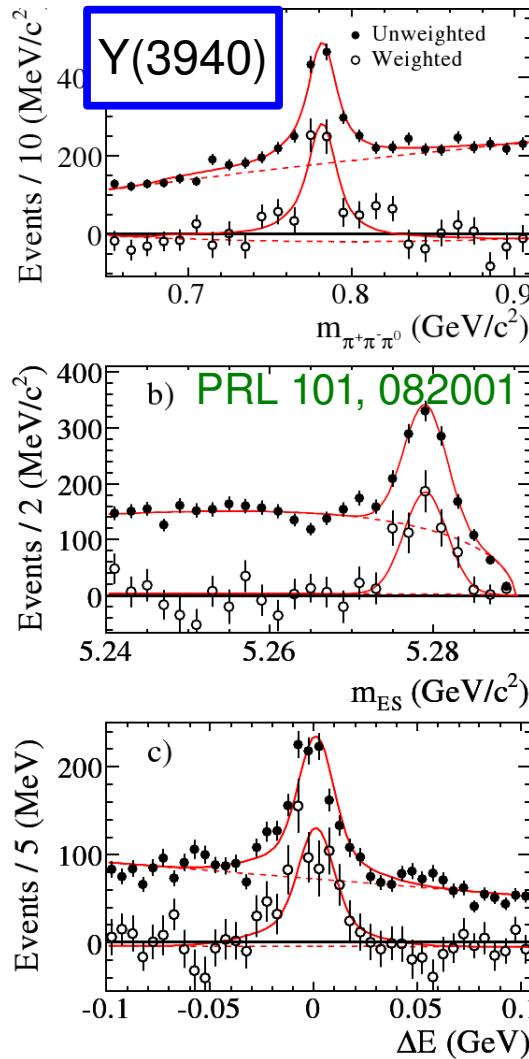
$J^{PC}$	decay	LS	$\chi^2$ (11 d.o.f.)	$\chi^2$ prob.
1 <sup>++</sup>	$J/\psi \rho^0$	01	13.2	0.28
2 <sup>+-</sup>	$J/\psi \rho^0$	11,12	13.6	0.26
1 <sup>--</sup>	$J/\psi(\pi\pi)_S$	01	35.1	$2.4 \times 10^{-4}$
2 <sup>+-</sup>	$J/\psi(\pi\pi)_S$	11	38.9	$5.5 \times 10^{-5}$
1 <sup>+-</sup>	$J/\psi(\pi\pi)_S$	11	39.8	$3.8 \times 10^{-5}$
2 <sup>--</sup>	$J/\psi(\pi\pi)_S$	21	39.8	$3.8 \times 10^{-5}$
3 <sup>+-</sup>	$J/\psi(\pi\pi)_S$	31	39.8	$3.8 \times 10^{-5}$
3 <sup>--</sup>	$J/\psi(\pi\pi)_S$	21	41.0	$2.4 \times 10^{-5}$
2 <sup>++</sup>	$J/\psi \rho^0$	02	43.0	$1.1 \times 10^{-5}$
1 <sup>-+</sup>	$J/\psi \rho^0$	10,11,12	45.4	$4.1 \times 10^{-6}$
0 <sup>+-</sup>	$J/\psi \rho^0$	11		$3.5 \times 10^{-17}$
0 <sup>--</sup>	$J/\psi(\pi\pi)_S$	11		$\leq 1 \times 10^{-20}$
0 <sup>++</sup>	$J/\psi \rho^0$	00		$\leq 1 \times 10^{-20}$



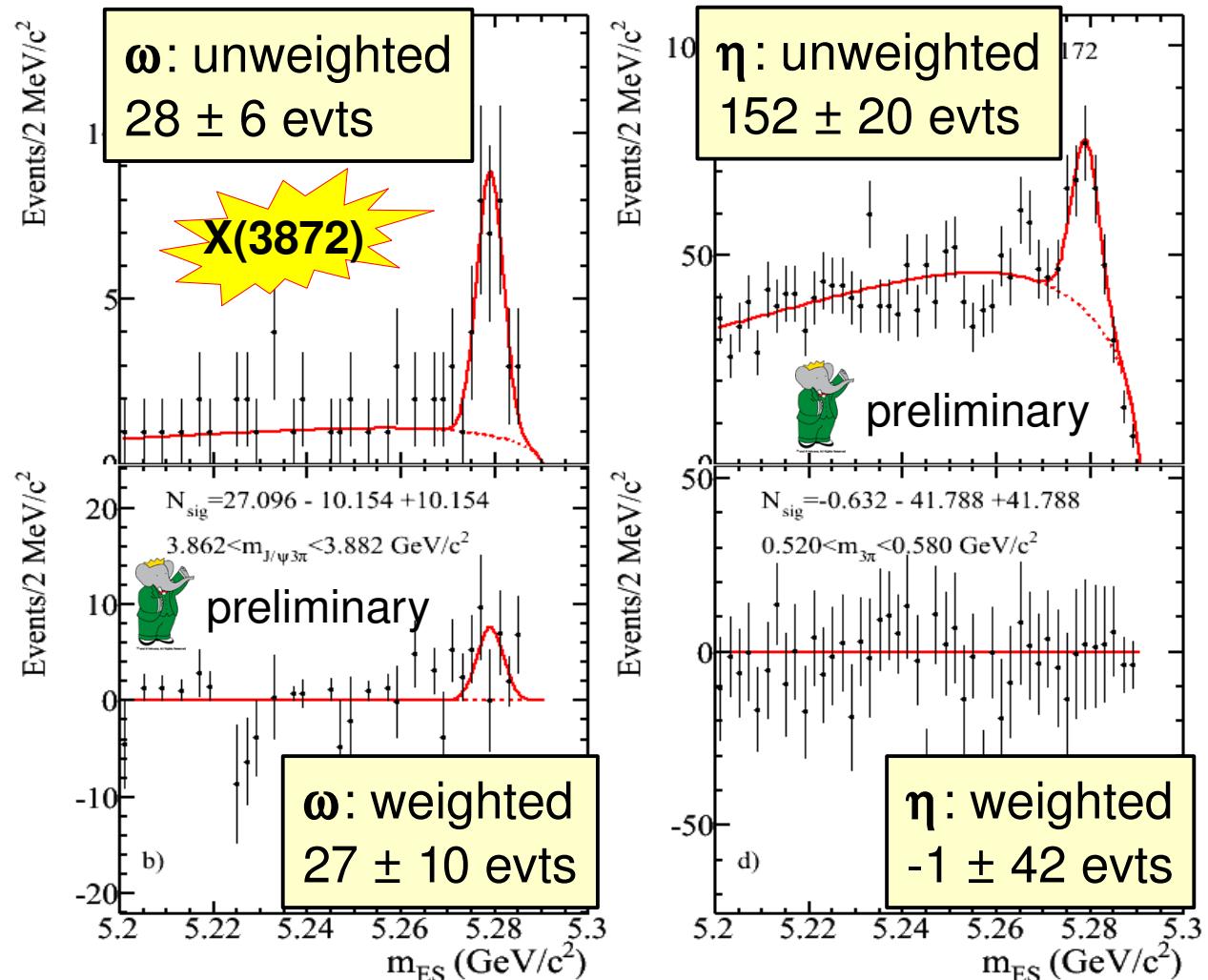
# Is $3\pi$ an $\omega$ ?

arXiv:1005.5190

- For an  $\omega$ ,  $\frac{d\Gamma}{d\cos^2\theta_h} \propto \sin^2\theta_h$  [  $\theta_h = \pi^+ - \pi^0$  angle in  $\pi^+\pi^-$  rest frame ]
  - Dalitz Plot weighting  $w_i = \frac{5}{2}(1 - 3\cos^2\theta_h^i)$  projects away non- $\omega$  events



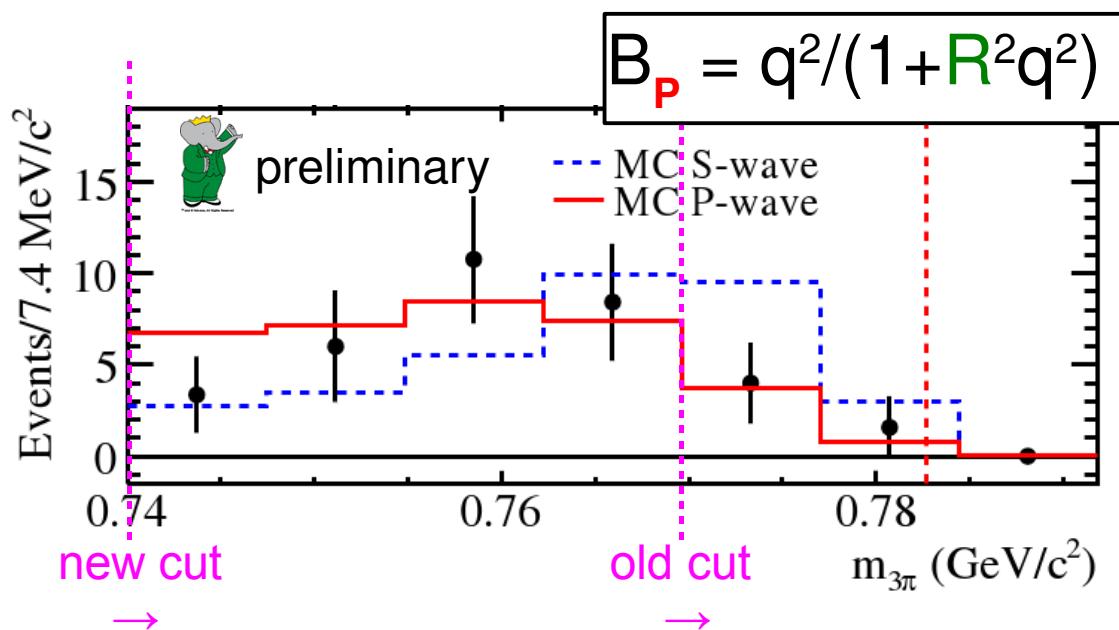
Establish correlation between  $m_{ES}$  and  $\omega$  signals!



# Orbital angular momentum

arXiv:1005.5190

- Select  $3862.5 < m_{J/\psi 3\pi} < 3882.5 \text{ MeV}/c^2$
- Study angular momentum impact on  $\omega$  lineshape
  - S-wave:  $P(\chi^2) = 7\%$  vs. P-wave:  $P(\chi^2) = 62\%$
  - Negative parity favored: **2<sup>-</sup> favored** over 1<sup>+</sup> (1<sup>+</sup> not ruled out)
  - Consistent with  $\eta_{c2}(1D)$  charmonium interpretation



# Updated Y(3940) results

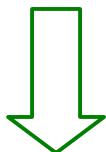
$$M = (3914.6^{+3.8}_{-3.4} \pm 2.0) \text{ MeV}/c^2$$

$$\Gamma = (34^{+12}_{-8} \pm 5) \text{ MeV}$$

$$\Pi \text{ BF } (B^+) = (4.9^{+1.0}_{-0.9} \pm 0.5) \times 10^{-5}$$

$$\Pi \text{ BF } (B^0) = (1.3^{+1.3}_{-1.1} \pm 0.2) \times 10^{-5}$$

[PRL 101, 082001 (2008)]



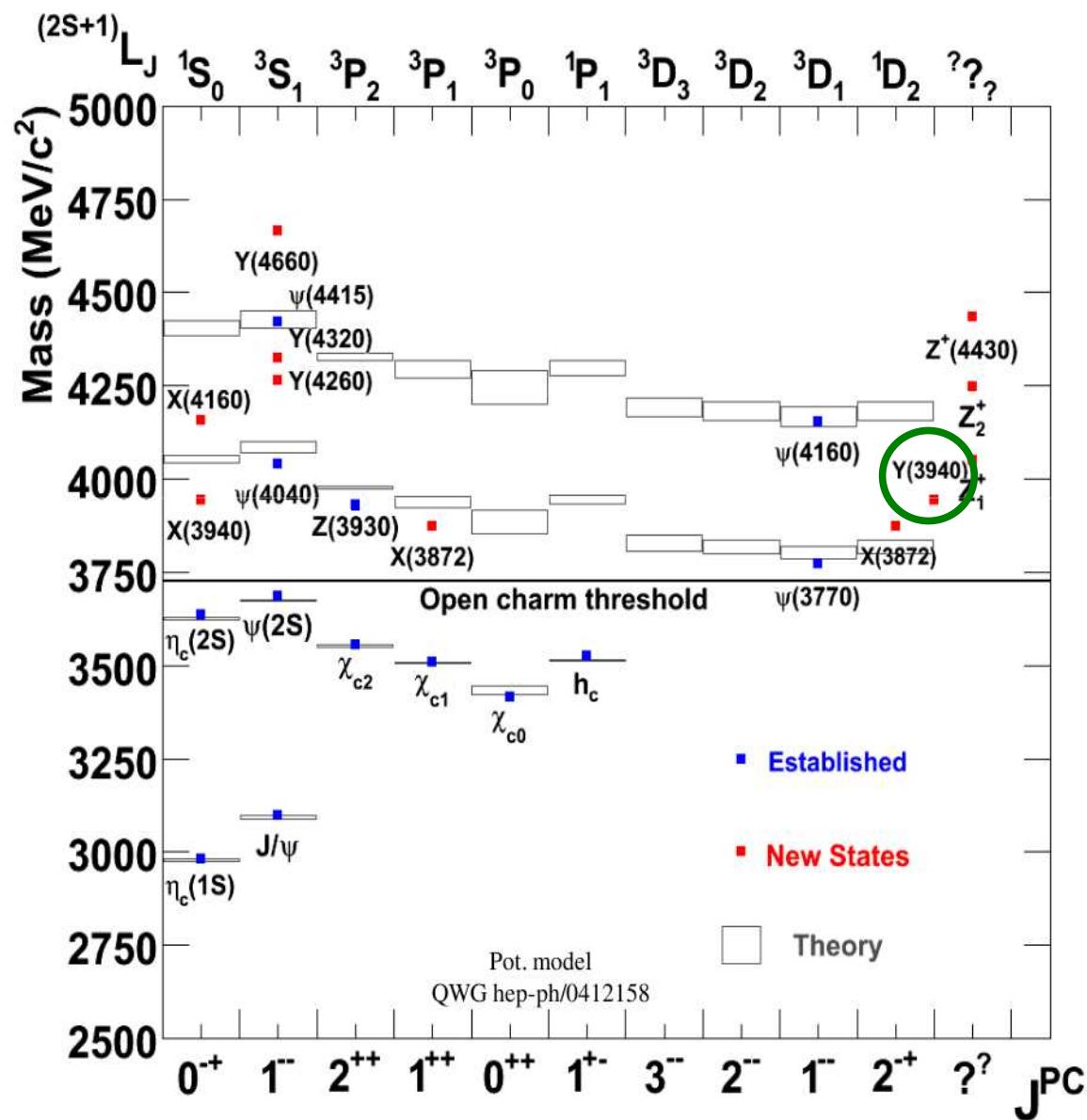
$$M = (3919.1^{+3.8}_{-3.4} \pm 2.0) \text{ MeV}/c^2$$

$$\Gamma = (31^{+10}_{-8} \pm 5) \text{ MeV}$$

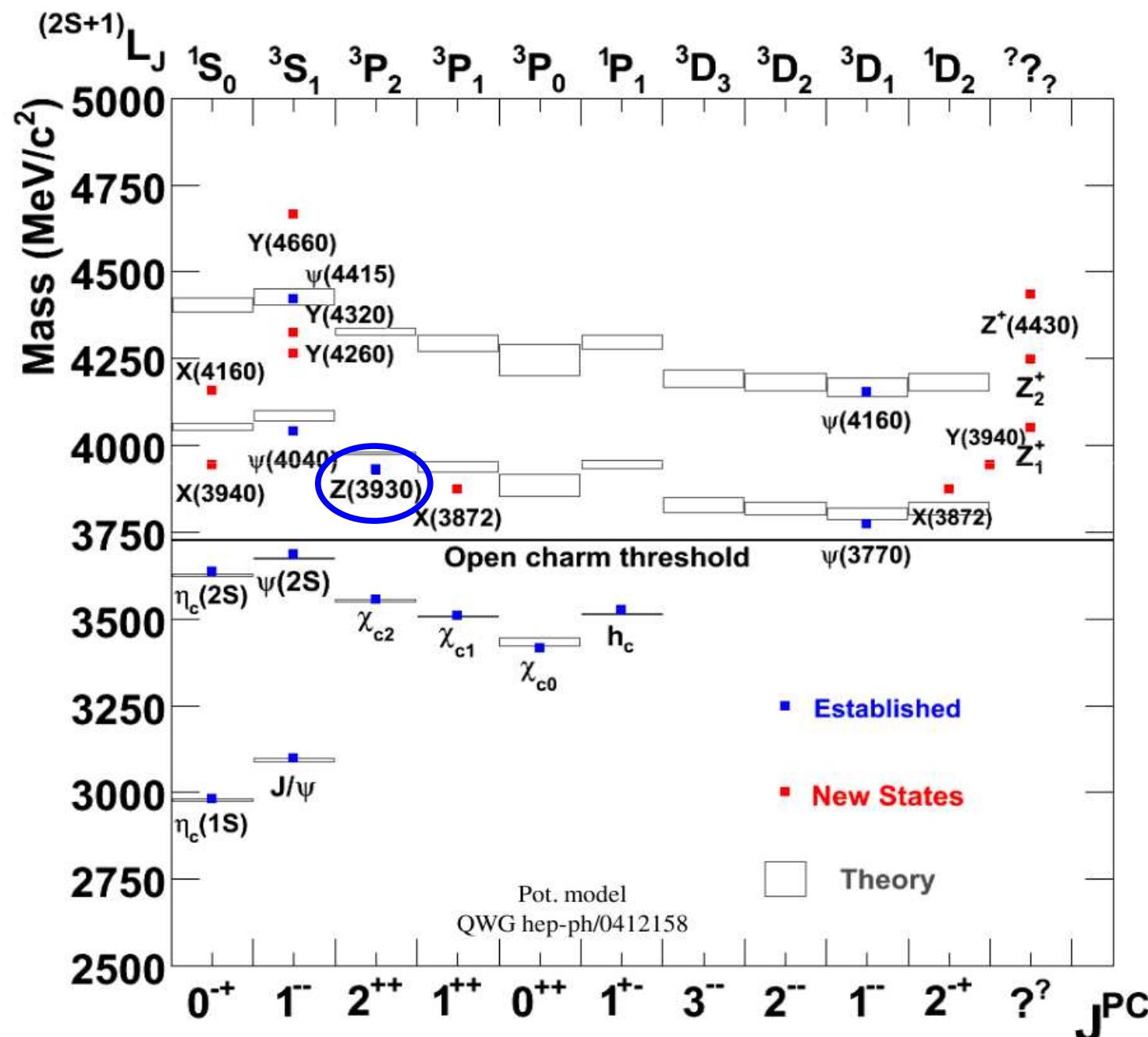
$$\Pi \text{ BF } (B^+) = (3.0^{+0.7}_{-0.6} {}^{+0.5}_{-0.3}) \times 10^{-5}$$

$$\Pi \text{ BF } (B^0) = (2.1 \pm 0.9 \pm 0.3) \times 10^{-5}$$

[arXiv:1005.5190]

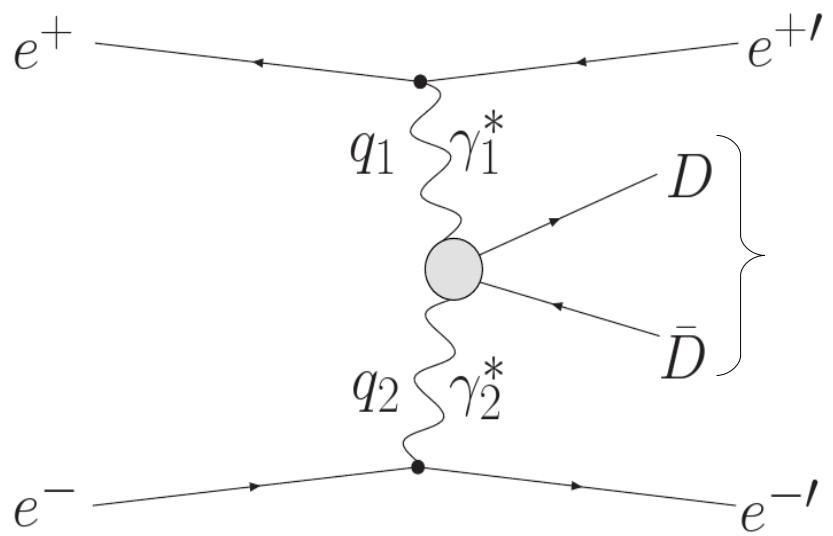


**Z(3930)**



# $\chi_{c2}(2P)$ in two photon production

[PRD 81 - 092003]



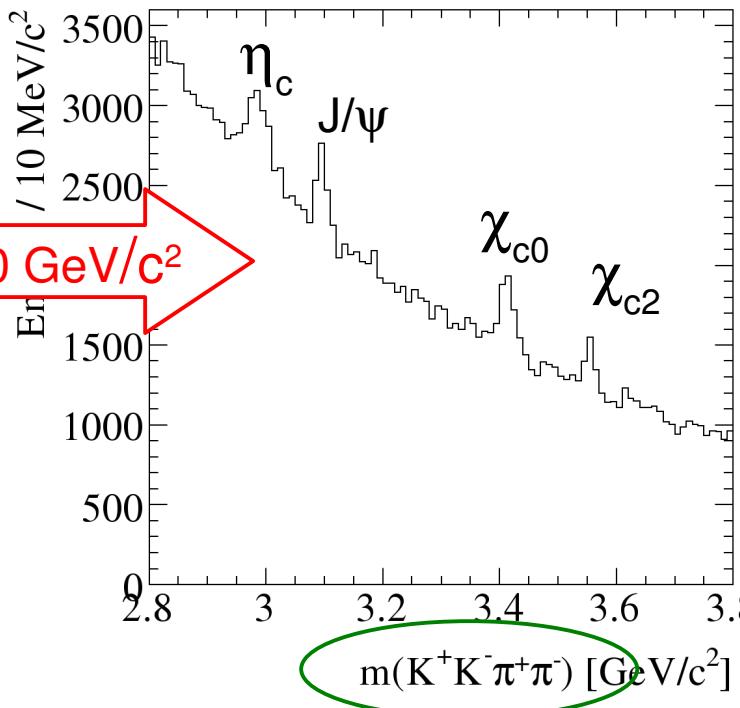
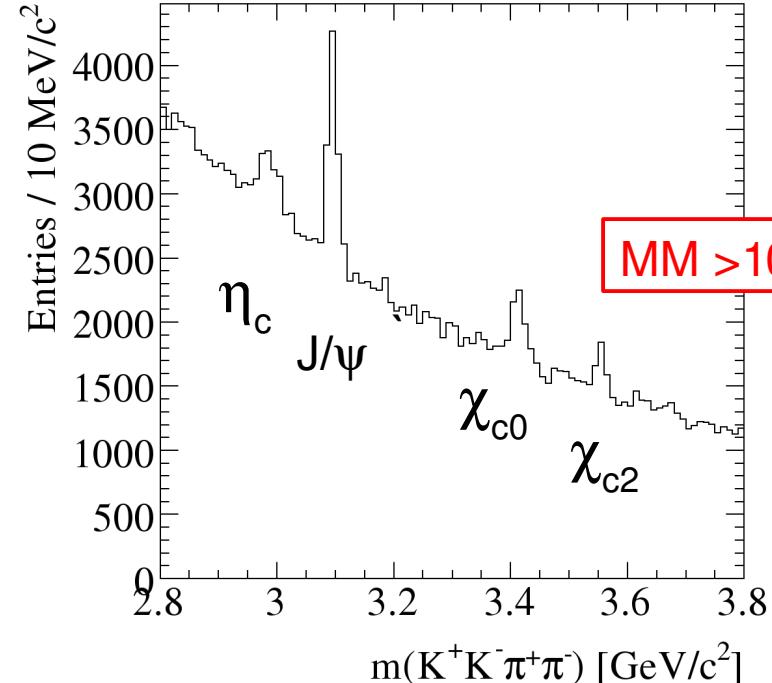
Channel	$D$ decay mode	$\bar{D}$ decay mode	
N4	$D^0 \bar{D}^0$	$D^0 \rightarrow K^- \pi^+$	$\bar{D}^0 \rightarrow K^+ \pi^-$
N5	$D^0 \bar{D}^0$	$D^0 \rightarrow K^- \pi^+$	$\bar{D}^0 \rightarrow K^+ \pi^- \pi^0$
N6	$D^0 \bar{D}^0$	$D^0 \rightarrow K^- \pi^+$	$\bar{D}^0 \rightarrow K^+ \pi^- \pi^- \pi^+$
N7	$D^0 \bar{D}^0$	$D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$	$\bar{D}^0 \rightarrow K^+ \pi^- \pi^0$
C6	$D^+ D^-$	$D^+ \rightarrow K^- \pi^+ \pi^+$	$D^- \rightarrow K^+ \pi^- \pi^-$

reconstructed in several exclusive decay modes (including KK $\pi\pi$ )

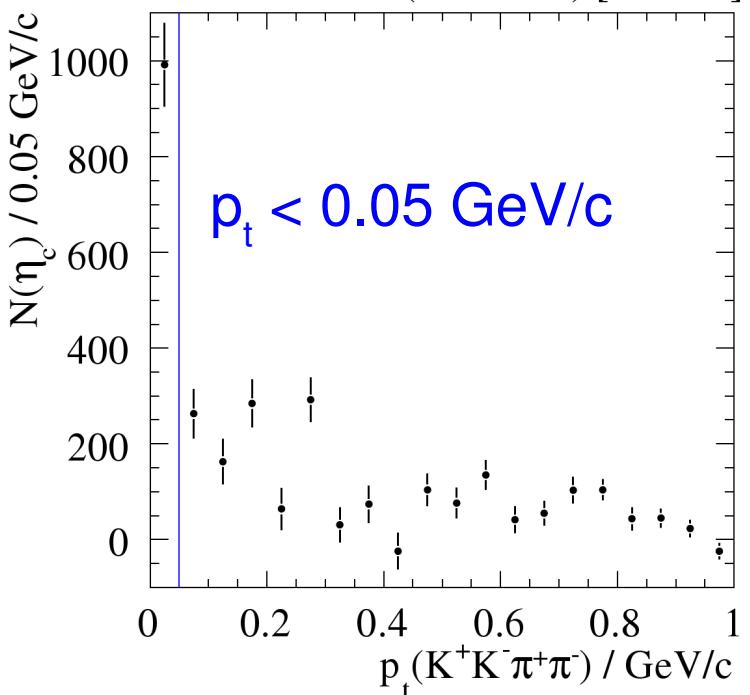
- Clean environment to study radial excitation of  $\chi_c$  states (and other new states near DD threshold)
- Untagged mode:
  - $e^+e^-$  are lost in the beampipe
  - $q^2 \sim 0$ : “quasi real” photons

# $\gamma\gamma \rightarrow \chi_{c2}(2P) \rightarrow DD$ - Selection

[PRD 81 - 092003]



Tune selection  
on  $KK\pi\pi$  control  
sample



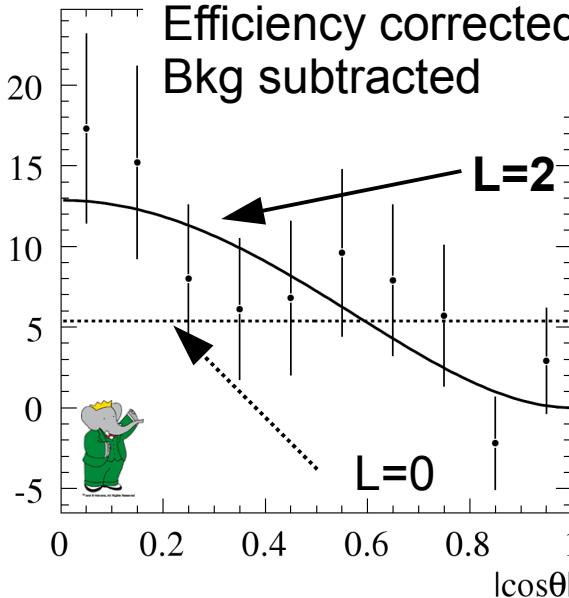
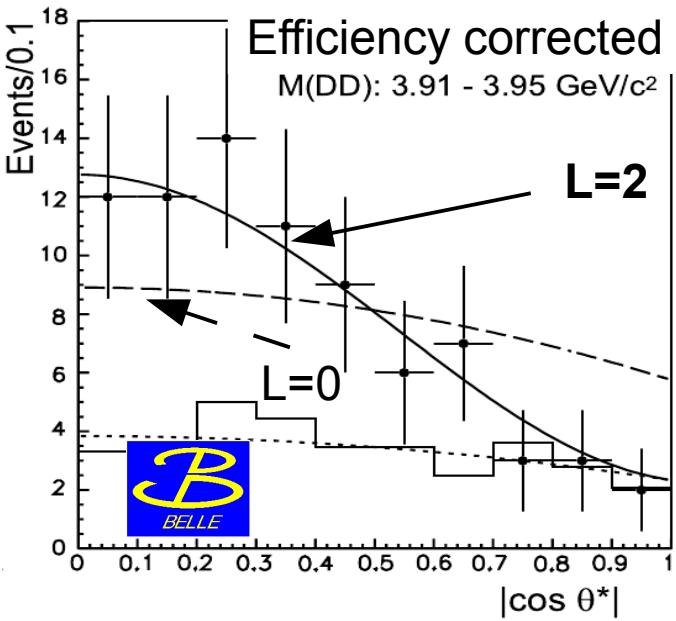
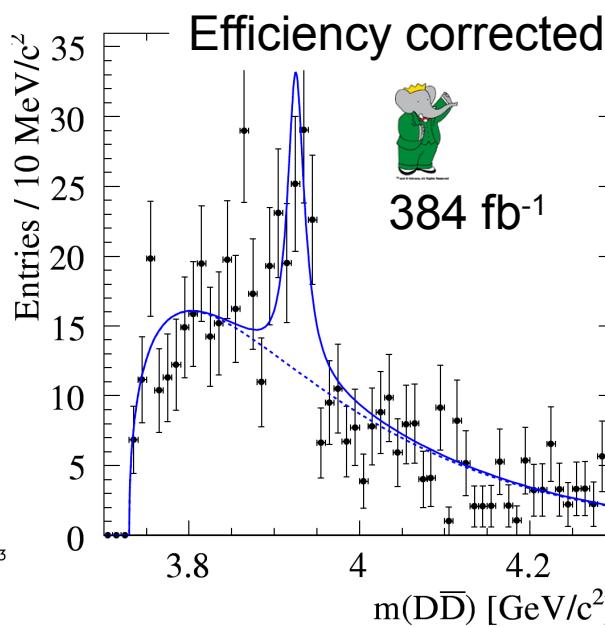
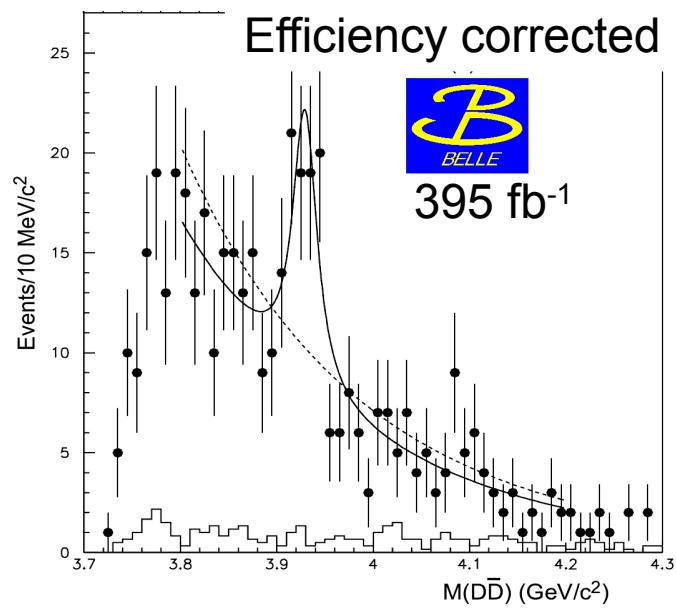
Large missing mass MM to reject ISR

$$MM = (p_{e^+} + p_{e^-} - \sum_{final} p_i)$$

Scattered electrons have high momentum  
and small angles  
⇒ tight cut around small final state  $p_t$  to  
reject  $e^+e^-$  annihilation

# Fit to DD mass spectrum

[PRD 81 - 092003]



[PRL 96 - 082003]

[PRD 81 - 092003]

New observation by BaBar

$$M = (3926.7 \pm 2.7 \pm 1.1) \text{ MeV}/c^2$$

$$\Gamma = (21.3 \pm 6.8 \pm 3.6) \text{ MeV}$$

$$N = 76 \pm 17 (5.8 \sigma)$$

Full consistency with Belle

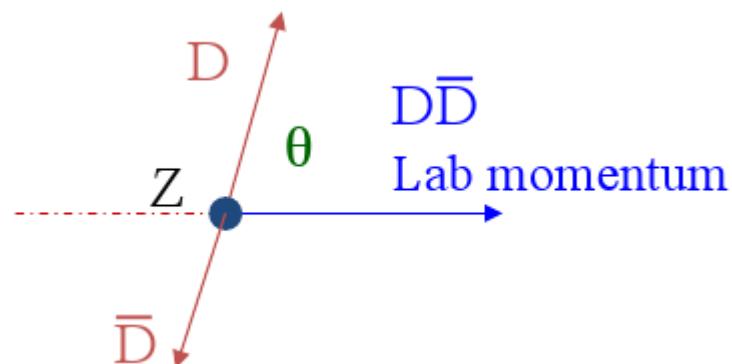
$$M = (3929 \pm 5 \pm 2) \text{ MeV}/c^2$$

$$\Gamma = (29 \pm 10 \pm 2) \text{ MeV}$$

$$N = 64 \pm 18 (5.3 \sigma)$$

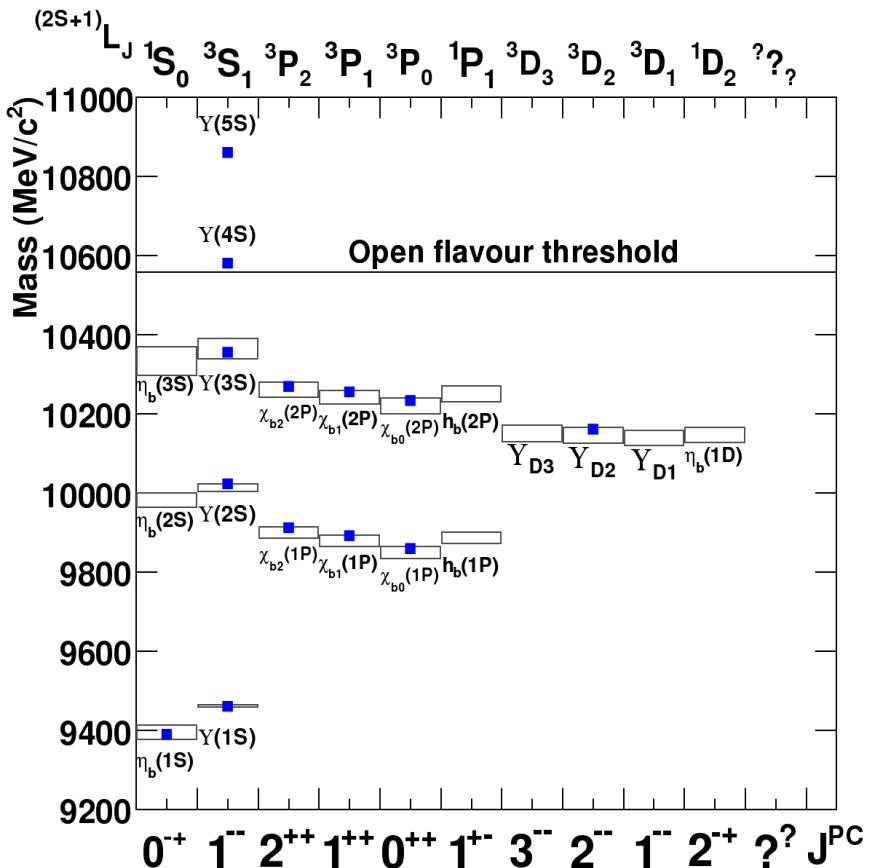
$L = 2$  is favored

⇒ Confirm interpretation:  
 $Z(3930) \leftrightarrow \chi_{c2}(2P)$

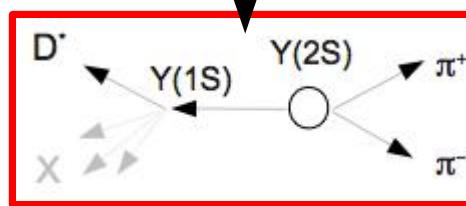


# **Bottomonium**

# Bottomonium production



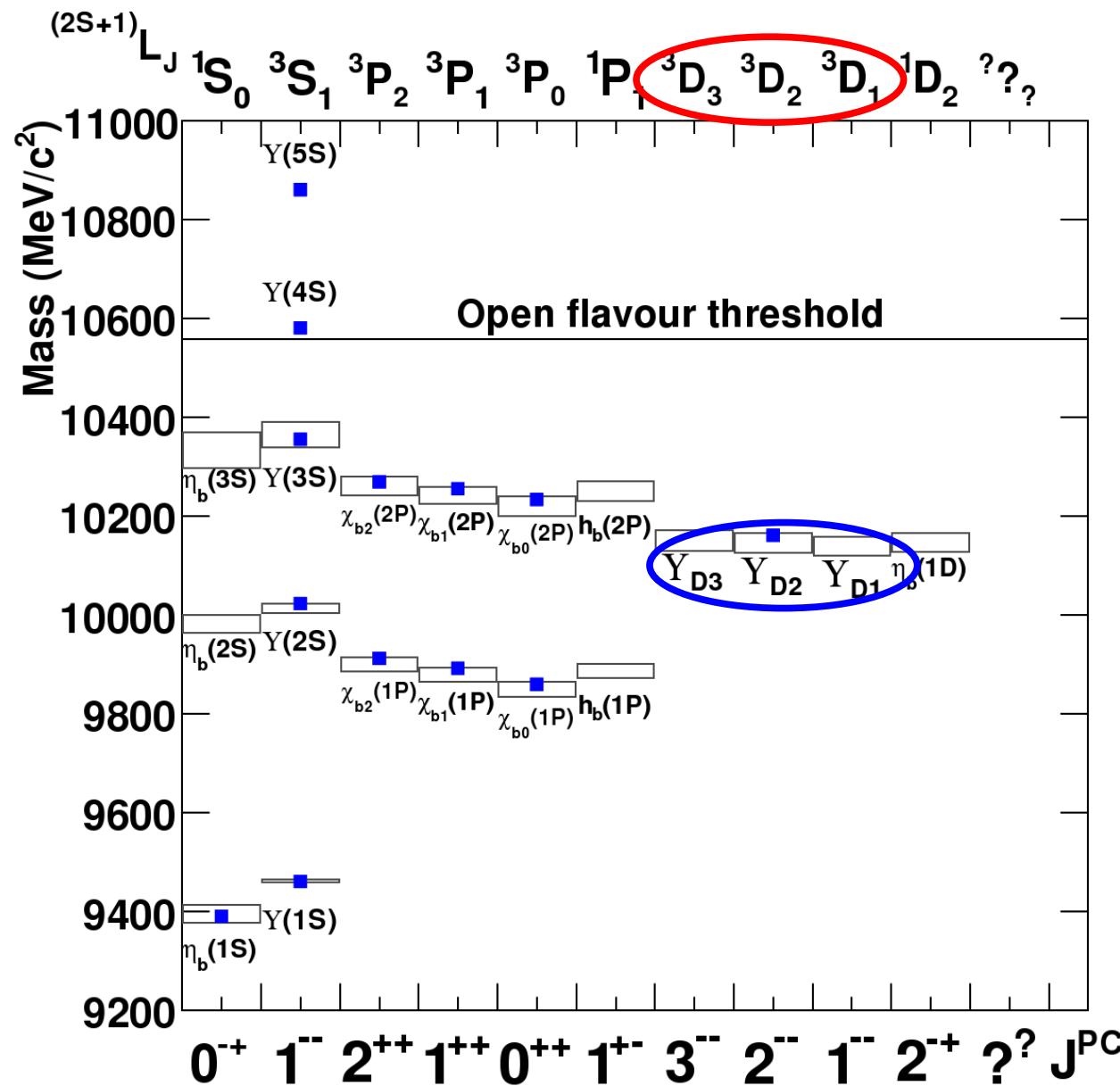
	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
	[19+5] M	100 M	120 M
	100 M	175 M	11 M
	20 M	9 M	6 M



$\Upsilon(1S)$  not collected at BaBar  
Use di-pion tag to study  $\Upsilon(1S)$  decays

- Most BaBar data collected at  $\Upsilon(4S)$  – decays to BB dominate
  - Lower narrow resonances produced by ISR
- Dedicated running periods at the  $\Upsilon(3S)$  and  $\Upsilon(2S)$  energies
- 4 fb<sup>-1</sup> scan above  $\Upsilon(4S)$

# $\Upsilon(1^3D_J)$



L=2, S=1 triplet states

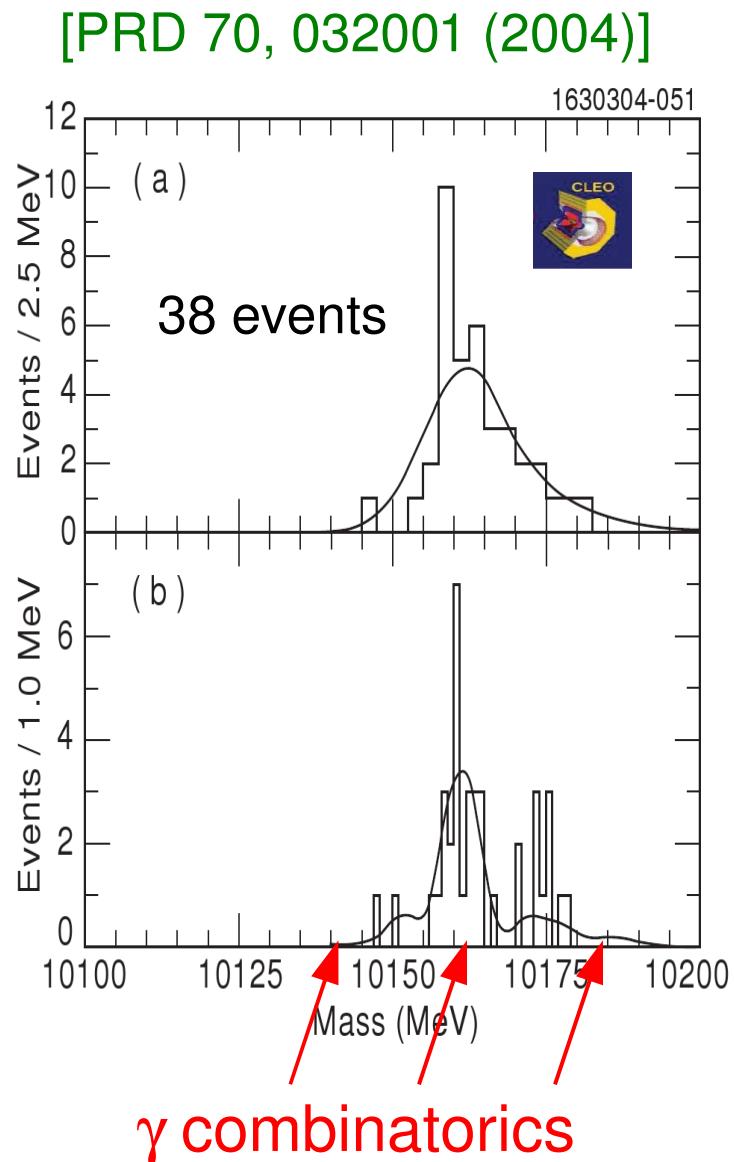
Narrow (30 keV)

O(10 MeV) separation

$M_{th} \sim (10160 \pm 10) \text{ MeV}/c^2$

# $\Upsilon(1^3D_J)$ at CLEO

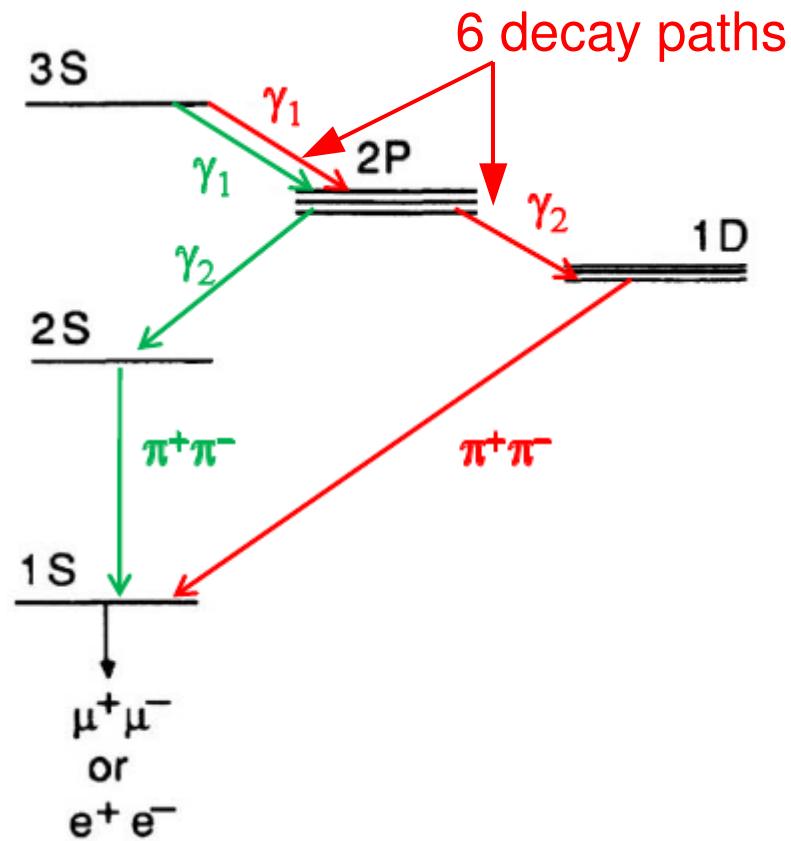
- A single state observed by CLEO in  $\Upsilon(3S) \rightarrow \gamma\gamma[\gamma\gamma\Upsilon(1S)]$ 
  - $M = (10161.1 \pm 0.6 \pm 1.6) \text{ MeV}/c^2$
  - Interpreted as  $J=2$
- $J=1,3$  states still unobserved  
Awaiting L,J,P confirmation
  - motivation to study of  $\pi^+\pi^-$  mass and angular distributions in  $\Upsilon(1^3D_J) \rightarrow \pi^+\pi^-\Upsilon(1S)$
- Predictions span 0.2% → 40% range
- UL from CLEO:  $\text{BF} < 4\% @ 90\%\text{CL}$   
[PRD 70, 032001 (2004)]



# $\Upsilon(1^3D_J) \rightarrow \pi^+ \pi^- \Upsilon(1S)$

NEW! [arXiv:1004.0175]

- Very good mass resolution: 3 MeV/c<sup>2</sup>  
Photon energy resolution: 7 MeV
- 6 decay paths for photons
  - pure E1 transitions w/ corresponding angular distributions
  - $E_{\gamma_1} = [86, 122]$  MeV,  $E_{\gamma_2} = [80, 117]$  MeV
  - Efficiencies differ up to 7.5% for different photon combinations
    - Use the dominant decay modes from theory and vary for systematics
- Reconstruct the full exclusive decay chain
  - Exactly 4 tracks in the event
  - In case of multiple photon combinations, choose the one that maximizes  $\chi^2$



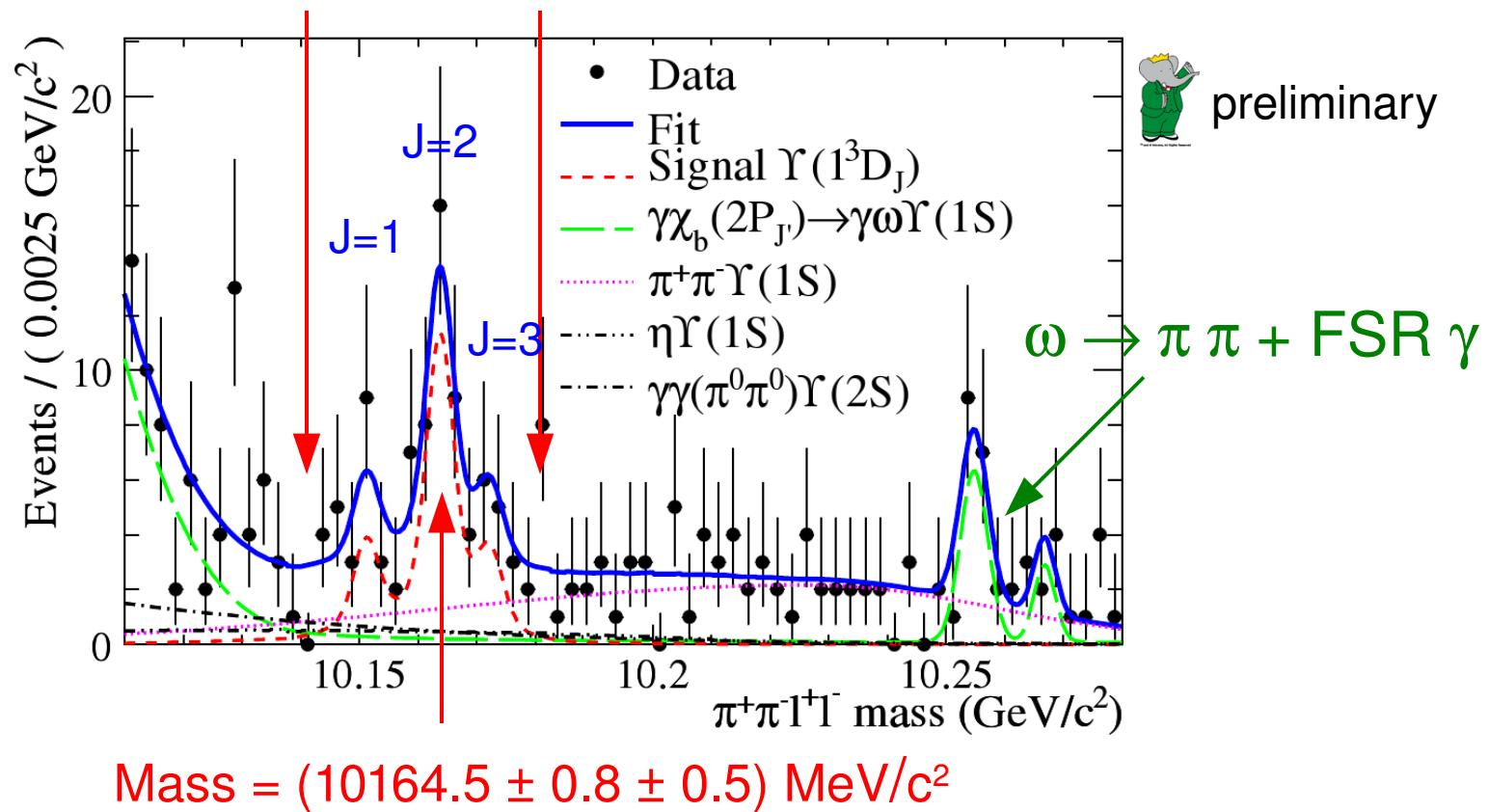
$\Upsilon(3S) \rightarrow \Upsilon(2S) \gamma \gamma$ ,  $\Upsilon(2S) \rightarrow \Upsilon(1S) \pi \pi$   
mass calibration with  $\Upsilon(2S)$  mass:  
0.7 MeV/c<sup>2</sup> shift; 0.5 MeV/c<sup>2</sup> sys.

$$\chi^2 = \sum_{i=1,2} (E_{\gamma_i} - E_{expect,i})^2 / \sigma_{E_{\gamma_i}}^2$$

# $\Upsilon(1^3D_J)$ results

[arXiv:1004.0175]

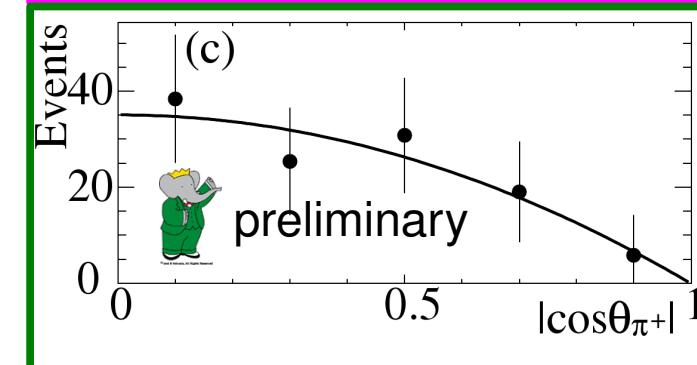
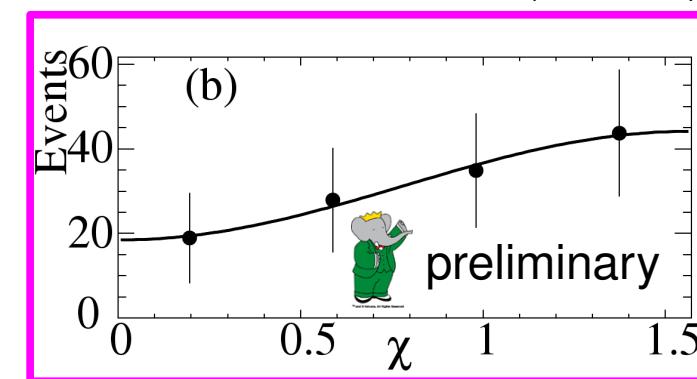
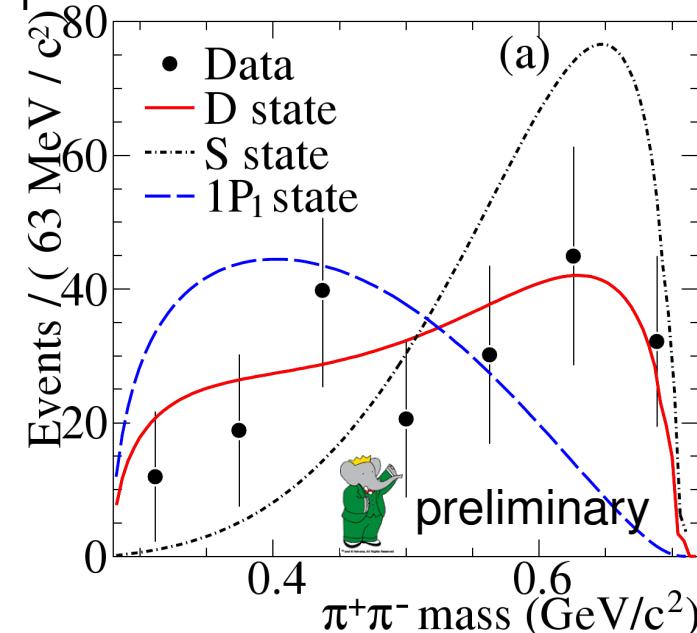
signal region: 10.14 – 10.18 GeV/c<sup>2</sup>



$1^3D_J$	Event yields	Sign.	Branching fraction	90% CL UL	Kwang & Yan (1981)	Ko (1993)	Moxhay (1988)
J=1	$10.6^{+5.7}_{-4.9}$	$1.8 \sigma$	$(0.42^{+0.27}_{-0.23} \pm 0.10)\%$	$< 0.82\%$	40%	1.6%	0.20%
J=2	$33.9^{+8.2}_{-7.5}$	$5.8 \sigma$	$(0.66^{+0.15}_{-0.14} \pm 0.06)\%$		46%	2.0%	0.25%
J=3	$9.4^{+6.2}_{-5.2}$	$1.7 \sigma$	$(0.29^{+0.22}_{-0.18} \pm 0.06)\%$	$< 0.62\%$	49%	2.2%	0.27%
Combined	$53.8^{+10.2}_{-9.5}$	$6.2 \sigma$					

# L, J, P of $\Upsilon(1^3D_J)$

[arXiv:1004.0175]



## Determine L from $\pi\pi$ mass spectrum

- Select  $M = [10.14 - 10.18] \text{ GeV}/c^2$  (all signal region)
- $P(\chi^2) = \underline{84.6\% \text{ (D)}}, 3.1\% \text{ (S)}, 0.3\% \text{ }(^1P_1 \text{ state)}$   
[Yan, PRD 22, 1652 (1980); Kuang et al., PRD 37, 1210 (1988)]

## Test $J^P$ on angular distributions

- Select  $M = [10.155 - 10.168] \text{ GeV}/c^2$  (central peak,  $J=2$ )

### Angle $\chi$ between $\pi^+\pi^-$ and $l^+l^-$ planes

- $dN / d\chi \sim 1 + \beta \cos(2\chi) \quad \text{sign}(\beta) = (-1)^J P$
- $\beta = -0.41 \pm 0.29 \pm 0.10$ , consistent with  $J=2, P=-1$   
[Dell'Aquila and Nelson, PRD 33, 80 (1986)]

### $\pi^+$ helicity angle $\theta_\pi$ :

- $dN / d\cos\theta_\pi \sim 1 + \xi (3 \cos^2\theta_\pi - 1)/2$
- $\xi = -1.0 \pm 0.4 \pm 0.1$  (would be 0 for S-wave)
- Consistent with  $L=2 \Rightarrow J=2$

# Summary

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- BaBar analysis of  $X(3872)$  decays to  $J/\psi \omega$  favors  $J^{PC} = 2^{-+}$ :  $\eta_{c2}(1D)$ ?
  - ... but  $J^{PC} = 1^{++}$  not excluded
- BaBar confirms Belle's observation of  $Z(3930)$  in two-photon production
  - Analysis of angular distributions confirms  $\chi_{c2}(2P)$  interpretation
- Observation of  $\Upsilon(1^3D_J) \rightarrow \pi^+ \pi^- \Upsilon(1S)$  with  $\Upsilon(3S)$  data
  - A possible indication of  $J=1,3$
  - Establish  $L=2$ ,  $J=2$  for the central peak
- High statistics  $\Upsilon(1S,2S,3S,4S)$  data allow for wide experimental program in charmonium and bottomonium spectroscopy
  - Mass and angular distributions are key observables

