

# Charmonium(-like) and Bottomonium(-like) States Results from Belle and BaBar

Mostly  $X(3872)$ .

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Justus-Liebig-Universität Gießen

MENU10

12<sup>th</sup> International Conference on Meson-Nucleon Physics and the Structure of the Nucleon

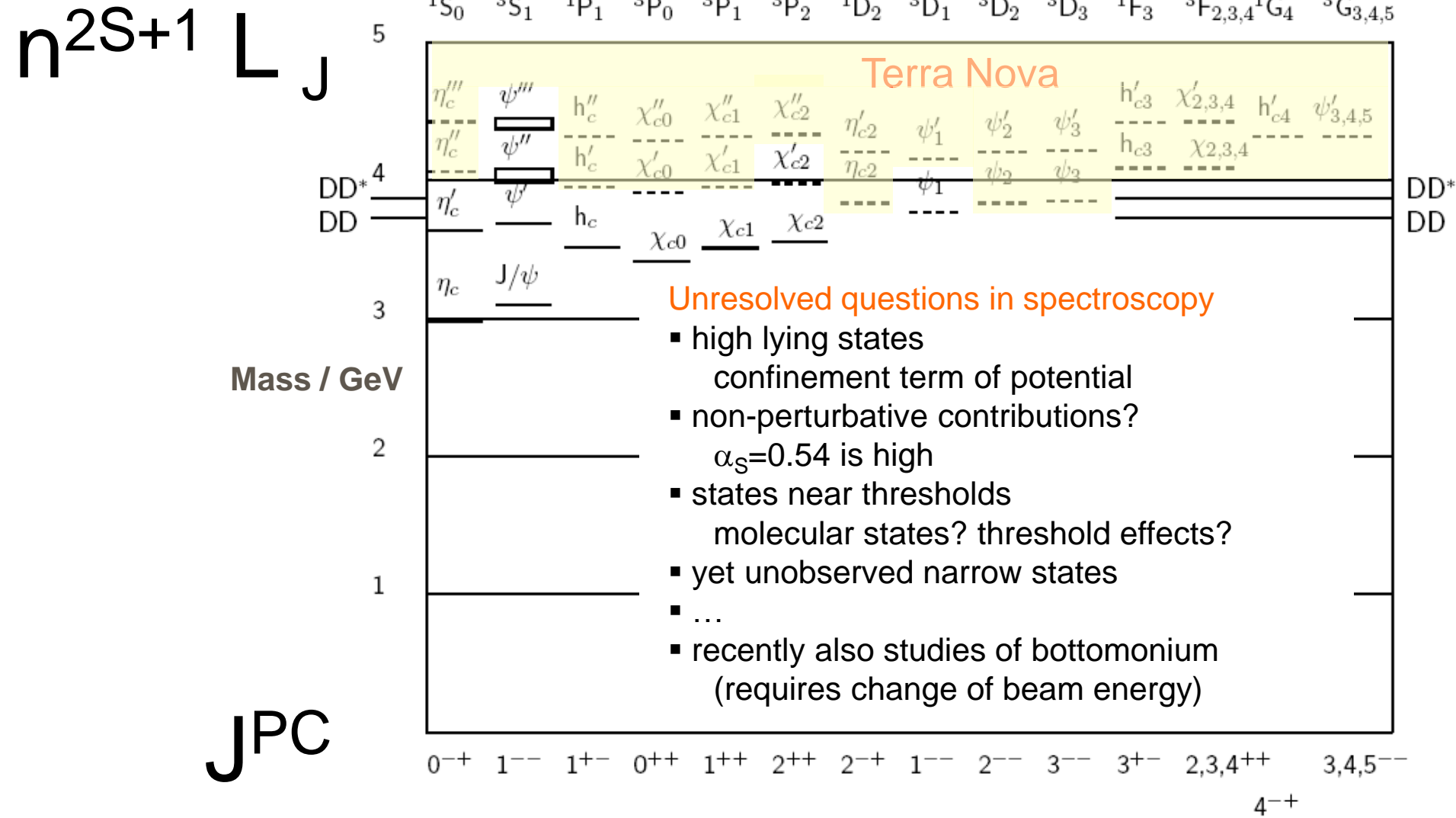
05/31-06/04, 2010

College of William and Mary

Williamsburg, Virginia

# Charmonium Excited States $n \leq 3, L \leq 4$

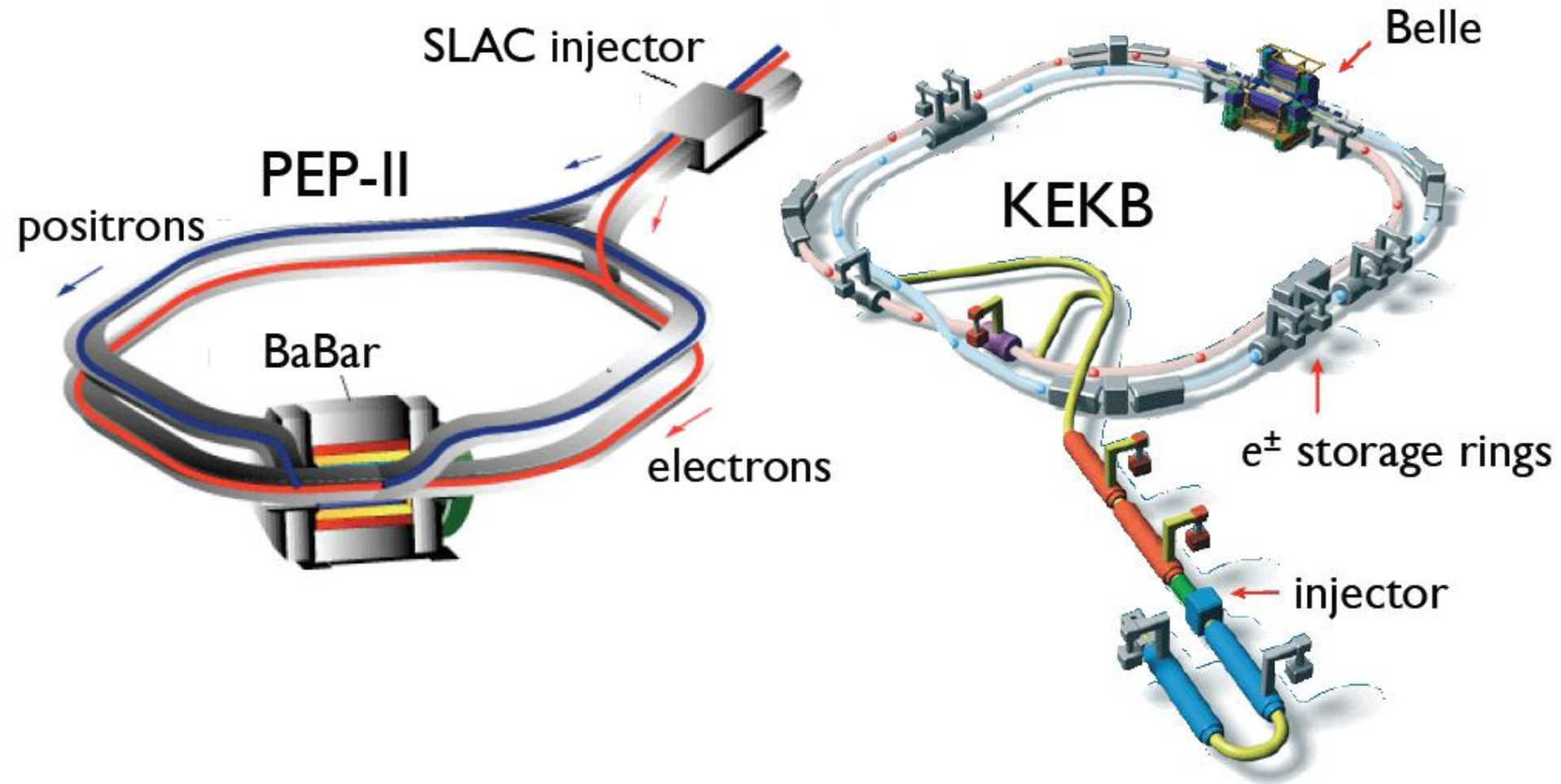
Barnes, Godfrey, Swanson, Phys. Rev. D72(2005)054026



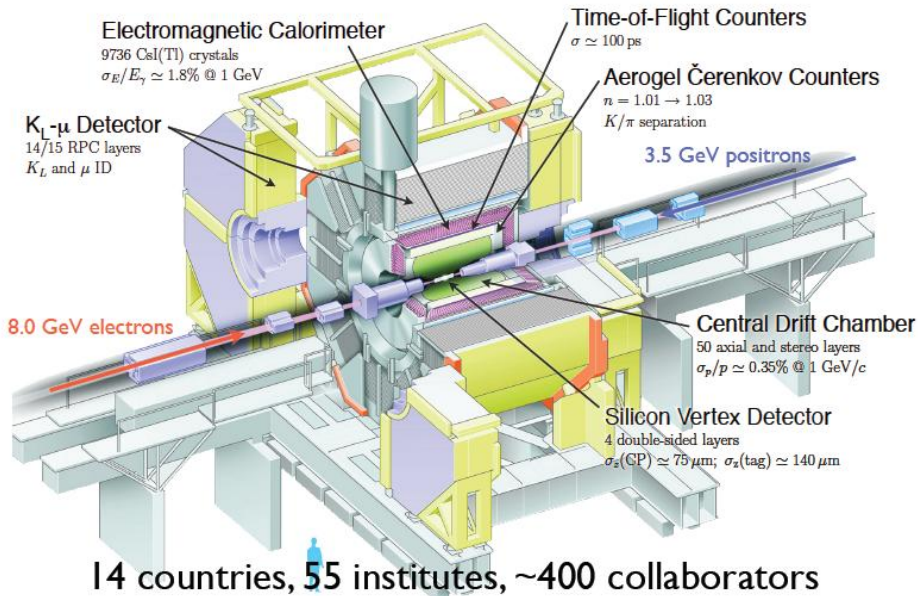
# Outline

- Width of  $\eta_c$
- X(3872) Radiative Decays
- X(3872) and Y(3940) into  $J/\psi$   $3\pi$
- Y(1S) Radiative Decays to X(3872)
- Y(1D)

# B Factories



# Belle at KEKB



**~952 /fb**

On-resonance samples:

Y(4S): 711 /fb

Y(5S): 121 /fb

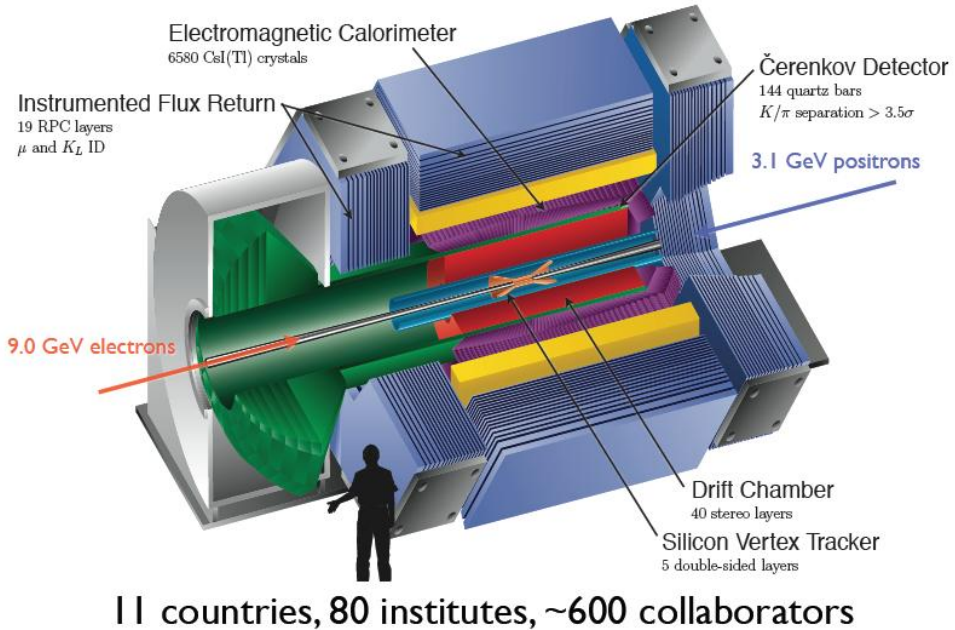
Y(3S): 3.0 /fb

Y(2S): 24 /fb

Y(1S): 5.7 /fb

Off-resonance: 87 /fb

# BaBar at PEP-II



**~553 /fb**

On-resonance samples:

Y(4S): 433 /fb

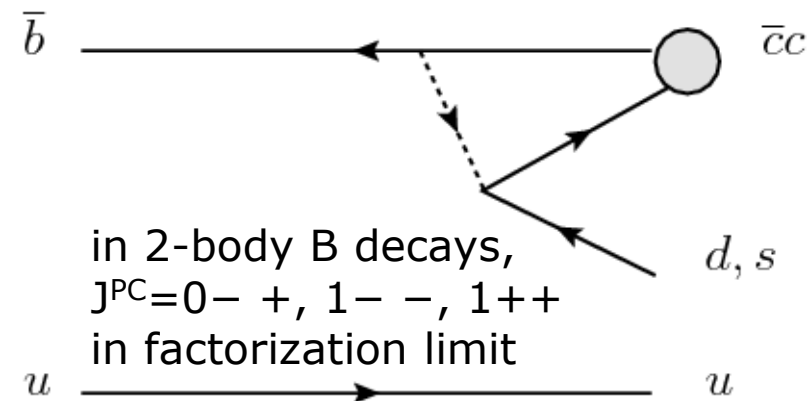
Y(3S): 30 /fb

Y(2S): 14 /fb

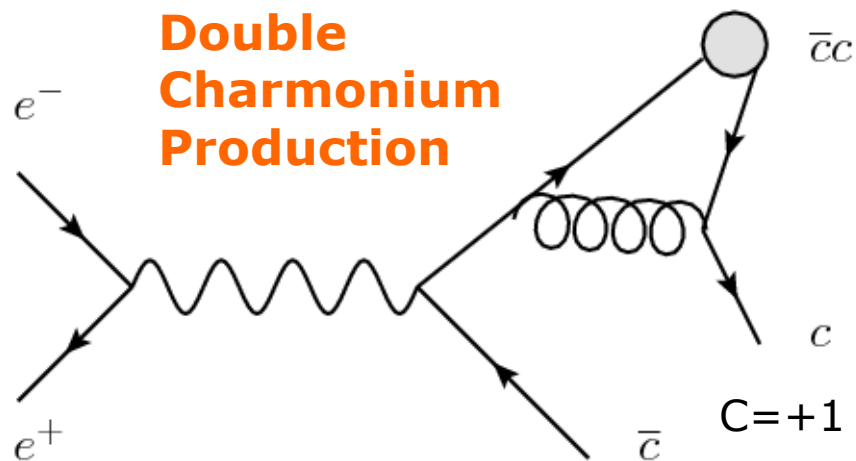
Off-resonance: 54 /fb

# Production of Charmonium

## B Decays

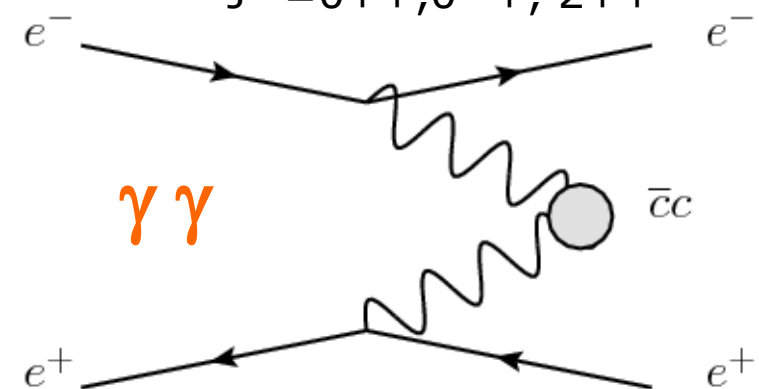


## Double Charmonium Production

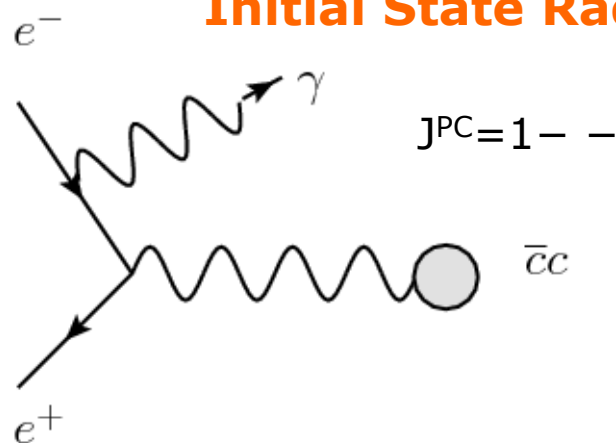


$J^{PC}=0^{++}, 0^{-+}, 2^{++}$

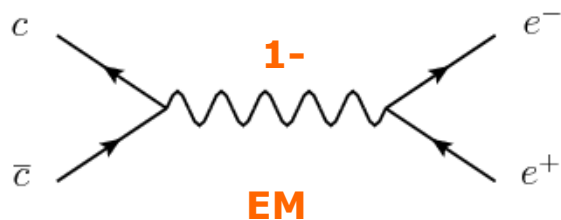
$\gamma\gamma$



## Initial State Radiation

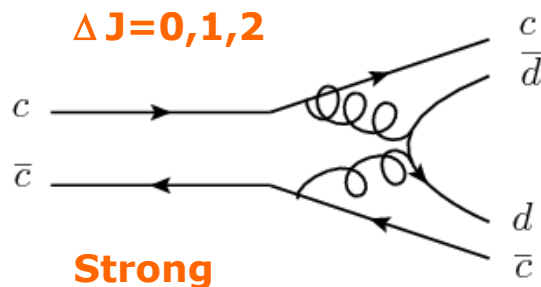


# Decays of Charmonium States



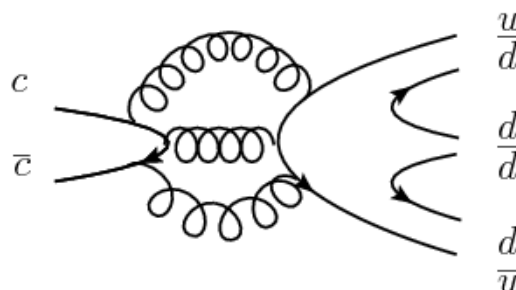
**Annihilation**

**e.g.  $J/\psi \rightarrow \pi^+ \pi^- \pi^0$   
OZI suppressed**

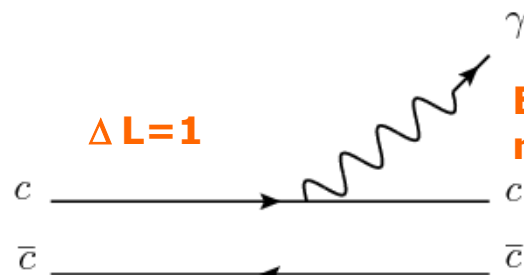


**$D^0(*)$**

**$\bar{D}^0(*)$**

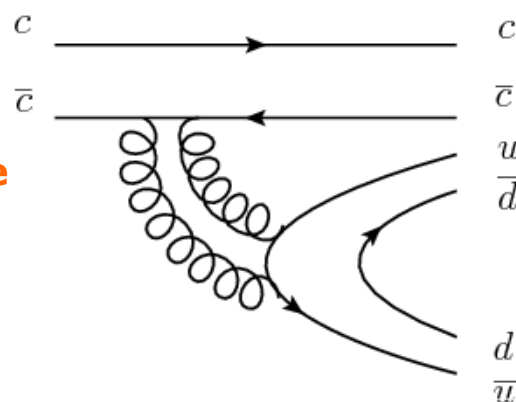


**Strong  
 $\sim 1/\alpha_S^2$**



**EM  
radiative**

**e.g.  $\psi' \rightarrow \chi_{cJ} \gamma$**



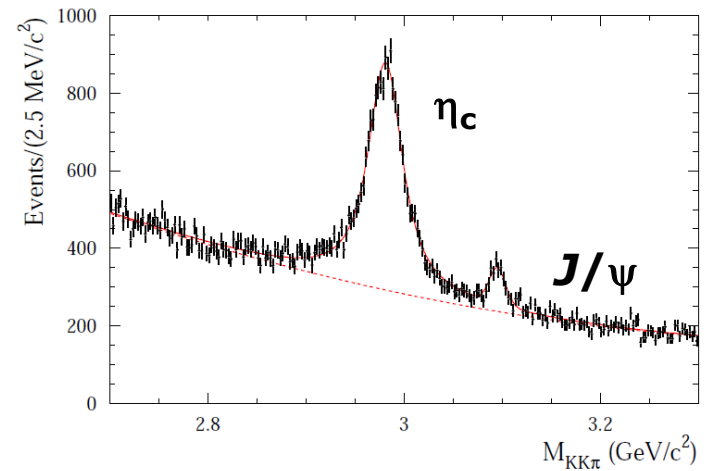
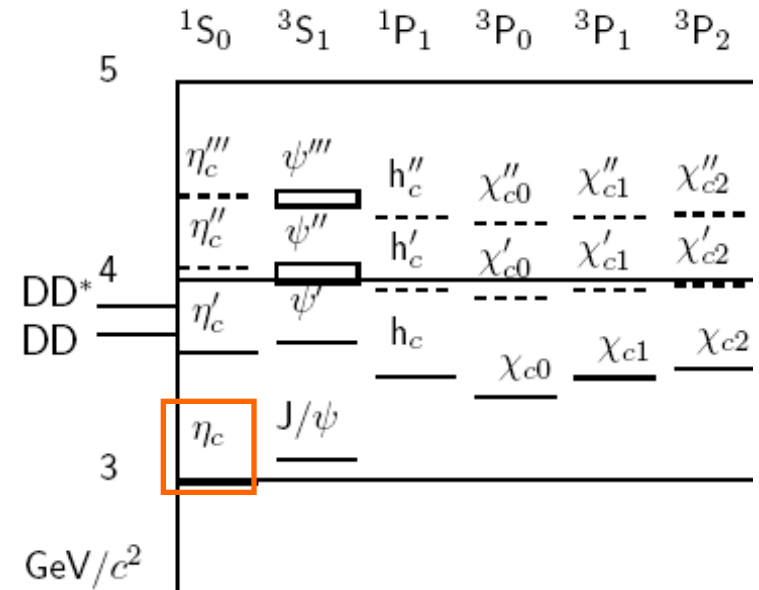
**Strong  
spectator  
isospin  
transition ?  
(if  $(\pi\pi)=\rho$ )  
 $\sim 1/\alpha_S^2$   
e.g.  $\psi' \rightarrow J/\psi \pi^+ \pi^-$**

$\eta_c$

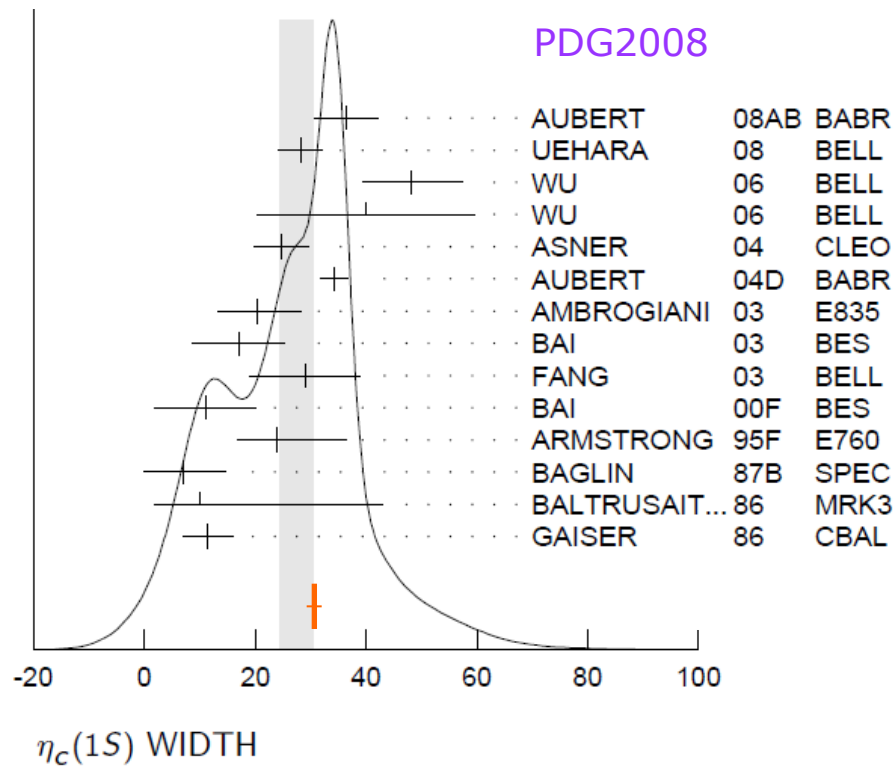


# $\eta_c$

- Ground state of Charmonium  $J^{PC}=0^{-+}, 1S_0$
- Observed e.g. in  $J/\psi$  and  $\psi'$  radiative decays, but cross section varies according to  $E_\gamma^a, a=3\dots7$ 
  - modifies lineshape
  - width determination non-trivial
- $\gamma\gamma \rightarrow \eta_c$  Breit-Wigner line shape is appropriate approximation
- new high statistics measurement BaBar, 469/fb  
**Phys. Rev. D81(2010)052010**  
 14090  $\eta_c$  events



# Precise Measurement of $\eta_c$ Mass and Width



BaBar

Phys. Rev. D81(2010)052010  
arXiv: 1002.3000 [hep-ex]

$$m_{\eta_c} = 2982.2 \pm 0.4 \pm 1.6 \text{ MeV}/c^2$$

$$\Gamma = 31.7 \pm 1.2 \pm 0.8 \text{ MeV}$$

Improvement by factor  $\sim 3$   
in stat. and syst. error  
compared to BaBar'08 (B meson decays) and Belle'08 ( $\gamma\gamma$ )

**X(3872)**

A molecular state?

# X(3872)

- observed in more than one decay channel

$$X(3872) \rightarrow J/\psi \pi^+ \pi^-$$

$$X(3872) \rightarrow J/\psi \gamma$$

$$X(3872) \rightarrow J/\psi \pi^+ \pi^- \pi^0$$

$$X(3872) \rightarrow D^0 \bar{D}^0 \pi^0$$

$$X(3872) \rightarrow D^0 \bar{D}^0 \gamma$$

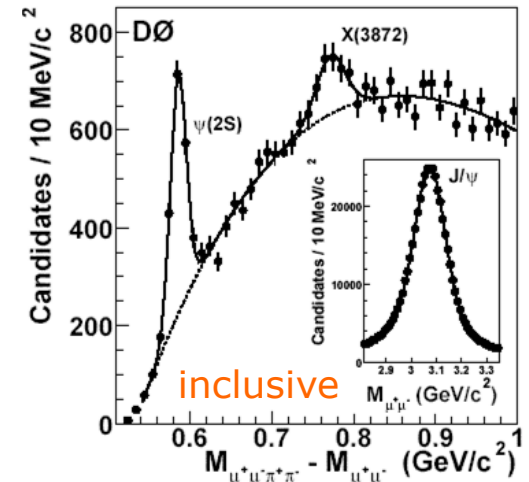
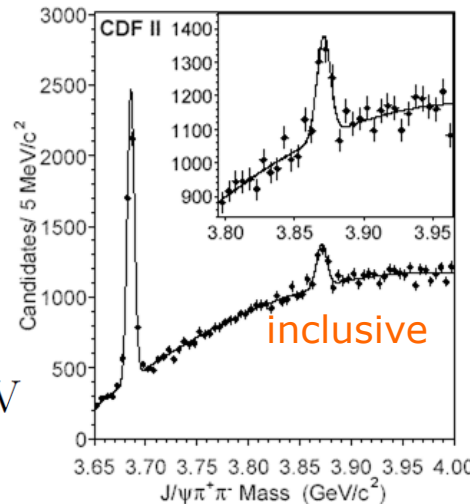
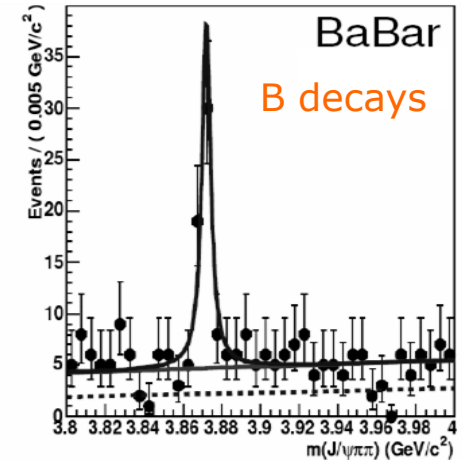
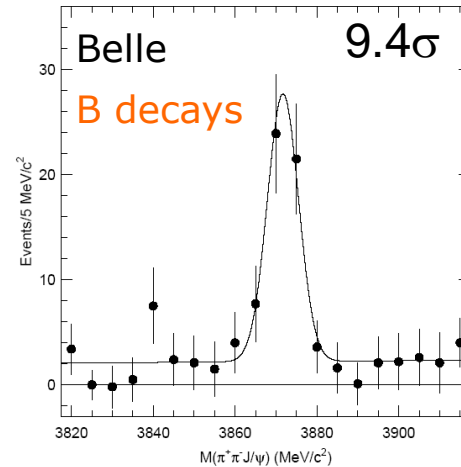
$$X(3872) \rightarrow \psi' \gamma$$

- narrow width  $\Gamma < 2.3$  MeV although above  $DD^{(*)}$  threshold
- Mass  $3872.3 \pm 0.8$  MeV (PDG2008) very close to threshold

$$M_X - (m_{D^*} + m_{\bar{D}^0}) = -0.6 \pm 0.6 \text{ MeV}$$

S-wave molecular state?

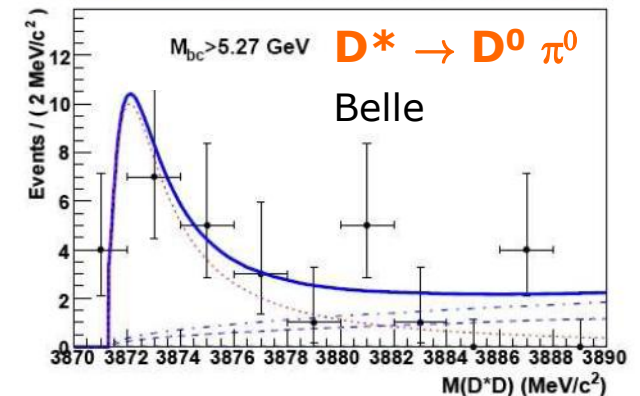
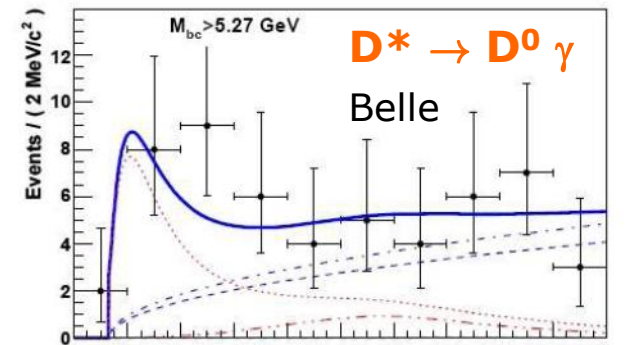
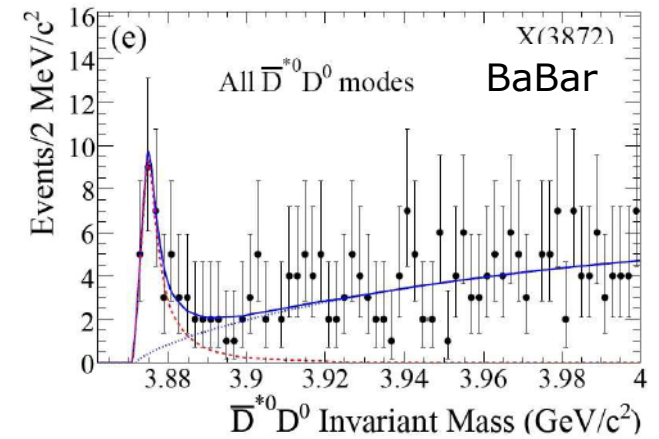
Belle, Phys. Rev. Lett.91(2003)262001  
 CDF-II, Phys. Rev. Lett.93(2004)072001  
 D0, Phys. Rev. Lett.93(2004)162002  
 BaBar, Phys. Rev. D71(2005)071103



pp,  $\sqrt{s} = 1.8$  TeV

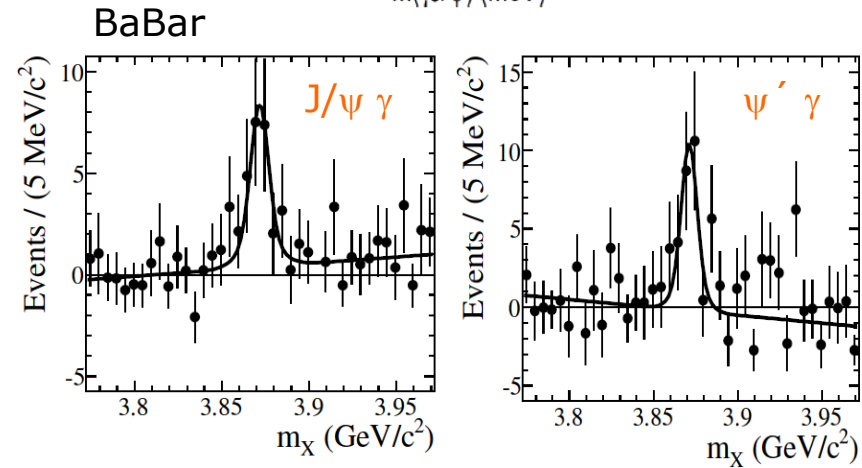
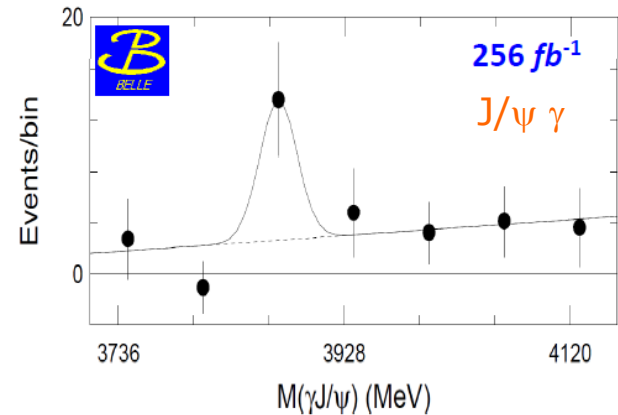
# Strong Decay $X(3872) \rightarrow \bar{D}D^*$

- Decay into  $\bar{D}D^*$  is dominant  
BR is factor  $9.4^{+3.6}_{-4.3}$   
higher than for  $J/\psi \pi^+ \pi^-$
- BaBar, Phys. Rev. D77(2008)011102(R)  
 $m=3875.1^{+0.7}_{-0.5} \pm 0.5$  MeV
  - binned maximum likelihood fit
  - 1-dim fit,  $M(D^*D)$
  - signal pdf from MC
  - exponential function background
- Belle, Phys. Rev. D81(2010)031103  
 $m=3872.9^{+0.6+0.4}_{-0.4-0.5}$  MeV
  - unbinned maximum likelihood fit
  - 2-dim fit
    - beam constraint mass  
Gaussian signal  
Argus function for background
    - $M(D^*D)$   
Breit-Wigner signal  
square root for background



# Radiative Decay $X(3872) \rightarrow J/\psi \gamma, \psi' \gamma$

- Rare Decay  
BR is factor  $\sim 6$   
smaller than  $\text{BR}(X \rightarrow J/\psi \pi^+ \pi^-)$   
Combined branching fraction  
 $\text{BR}(\text{B decay}) \times \text{BR}(X \text{ decay}) \simeq 10^{-6}$
- Evidence for  $X(3872) \rightarrow J/\psi \gamma$  by Belle  
256/fb  
 $13.6 \pm 4.4$  events  
arXiv:hep-ex/0505037
- Confirmed by BaBar  
424/fb  
 $23.0 \pm 6.4$  events  
Phys. Rev. D 74(2006)071101
- **Proof for positive C parity**
- BaBar found evidence  
for  $X(3872) \rightarrow \psi' \gamma$   
424/fb  
 $25.4 \pm 7.4$  events  
Phys. Rev. Lett. 102(2009)132001

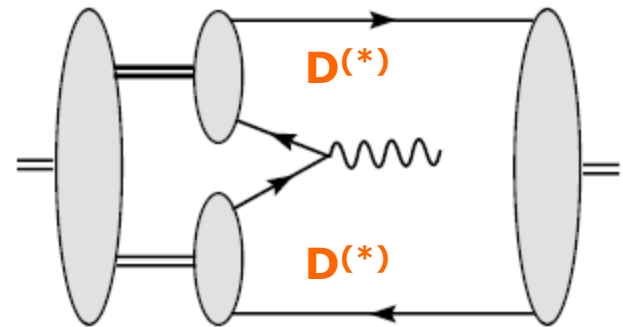
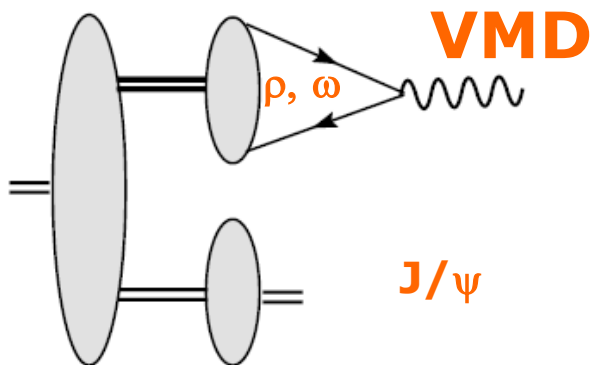
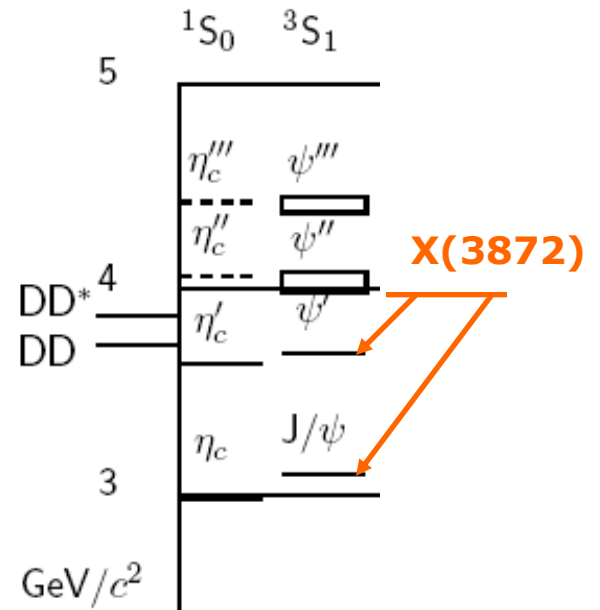


$$\frac{\mathcal{B}(X(3872) \rightarrow \psi' \gamma)}{\mathcal{B}(X(3872) \rightarrow J/\psi \gamma)} = 3.4 \pm 1.4$$

(large)

# Radiative Decay $X(3872) \rightarrow J/\psi \gamma, \psi' \gamma$

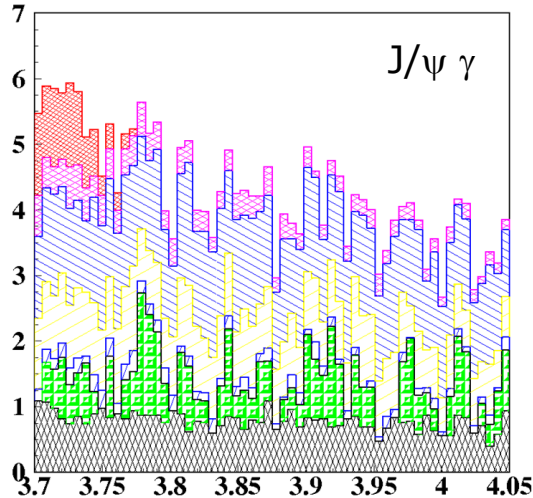
- $X(3872) \rightarrow J/\psi \gamma, E_\gamma = 775 \text{ MeV}$   
VMD contributes ( $\rho, \omega$ )
- $X(3872) \rightarrow \psi' \gamma, E_\gamma = 186 \text{ MeV}$   
can only proceed through  
light quark annihilation  
→ expected small  
→ BaBar measurement surprising
- **New measurement by Belle**  
**Preliminary, QWG10, 711/fb**



Swanson, Phys. Rept. 429(2006)243

# New Measurement of X(3872) Radiative Decays

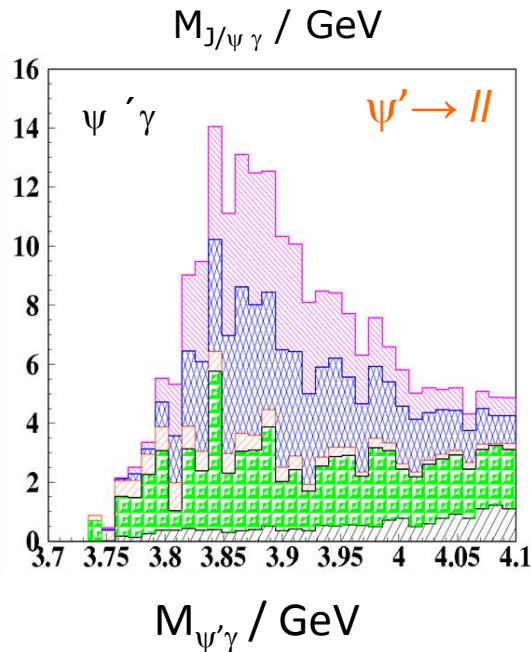
## $X(3872) \rightarrow J/\psi \gamma$ and $X(3872) \rightarrow \psi' \gamma$



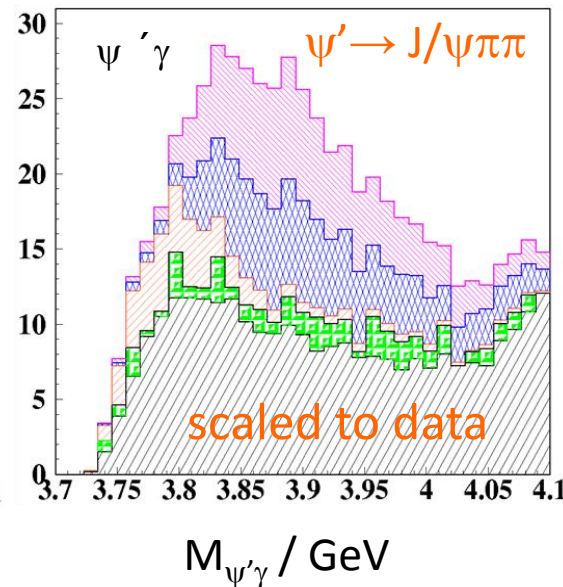
$B^+ \rightarrow \psi' K^+$   
 $B^0 \rightarrow J/\psi K^{*0}$   
 $B^+ \rightarrow J/\psi K^{*+}$   
 $J/\psi K(1270), J/\psi K_2^*(1430)$   
 non- $J/\psi$  (data sideband)






Combinatorial

# MC Background



Belle, Preliminary, QWG'10



  $B^0 \rightarrow \psi' K^{*0}$   
  $B^+ \rightarrow \psi' K^{*+}$   
  $B^0 \rightarrow \psi' K_S^0$   
 Combinatorial  
 Non- $\psi$  (data sideband)

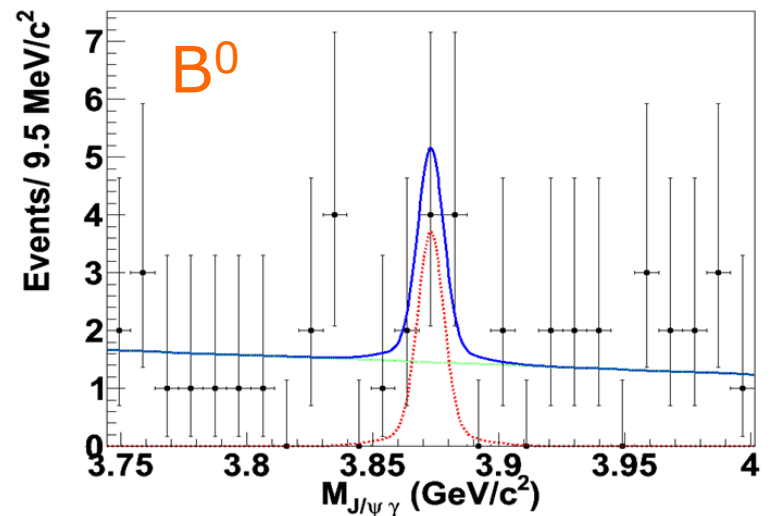
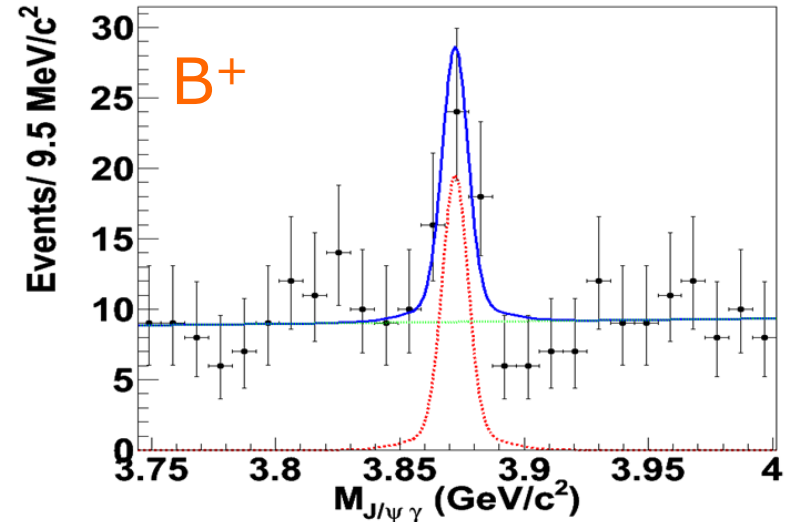


# New Measurement of X(3872) Radiative Decays

## X(3872) $\rightarrow$ J/ $\psi$ $\gamma$

- Signal PDF  
1 double Gaussian
- (Flat) background  
by 1<sup>st</sup> order  
Chebyshev polynomial
- 1-dim unbinned  
fit to mass(J/ $\psi$   $\gamma$ )
- X(3872) mass is fixed
- Signal is clearly  
(re-)established
- B<sup>+</sup>  $\rightarrow$  K<sup>+</sup> X(3872)  
30.0<sup>+8.2</sup><sub>-7.4</sub> events (4.9 $\sigma$ )
- B<sup>0</sup>  $\rightarrow$  K<sup>0</sup> X(3872)  
5.7<sup>+3.5</sup><sub>-2.8</sub> (2.4 $\sigma$ )

Belle, Preliminary, QWG '10, 711/fb



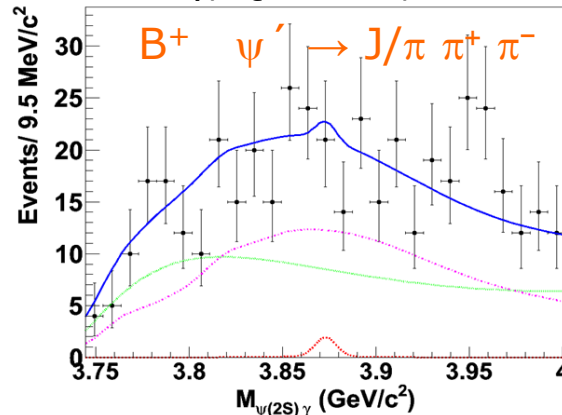
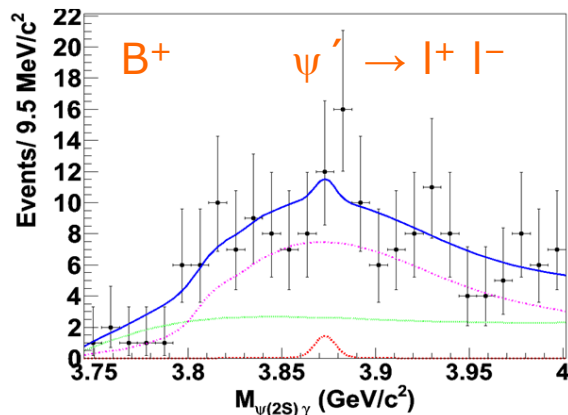
# New Measurement of X(3872) Radiative Decays

## $X(3872) \rightarrow \psi' \gamma$

$\psi' K$  and  $\psi' K^*$  background is different for  $I=0$  and  $J/\psi \pi\pi$   
 $\rightarrow$  simultaneous fit required, 2<sup>nd</sup> order Chebyshev polynomial

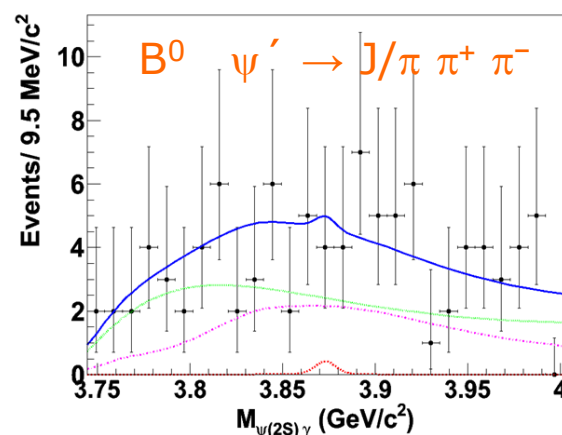
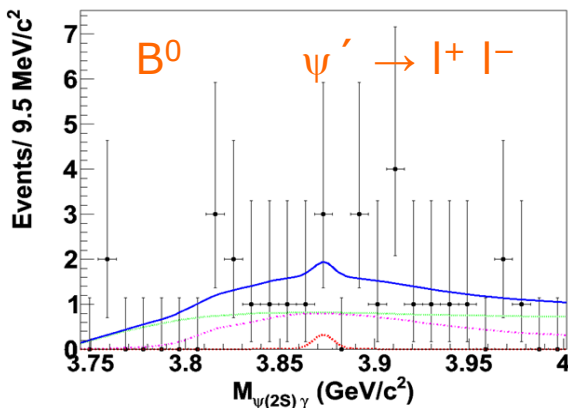
## Combinatorial Background

Belle, Preliminary, QWG '10, 711/fb



$B^+ \rightarrow K^+ X(3872)$   
 $5.0^{+11.9}_{-11.0}$  events  
 $(0.4\sigma)$

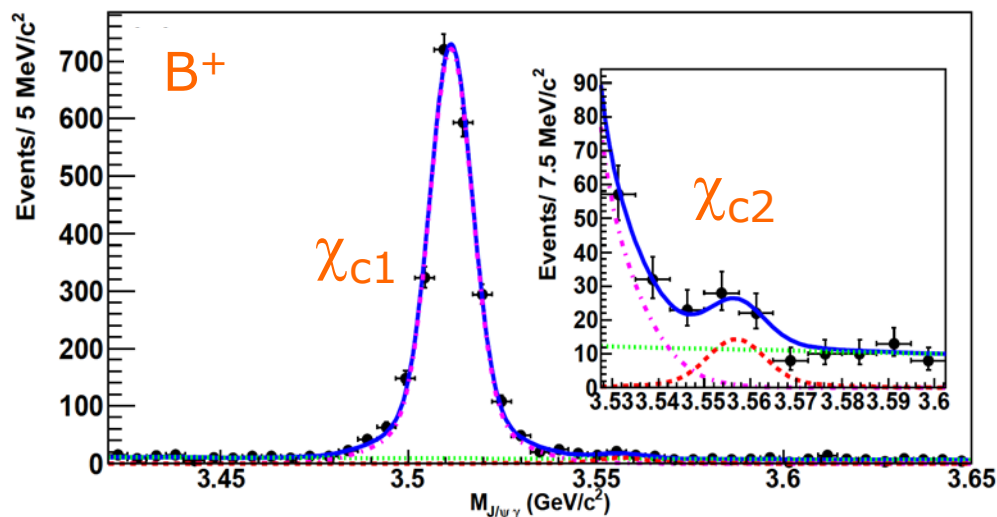
$B^0 \rightarrow K^0 X(3872)$   
 $1.5^{+4.8}_{-3.9}$   
 $(0.2\sigma)$



No signal observed

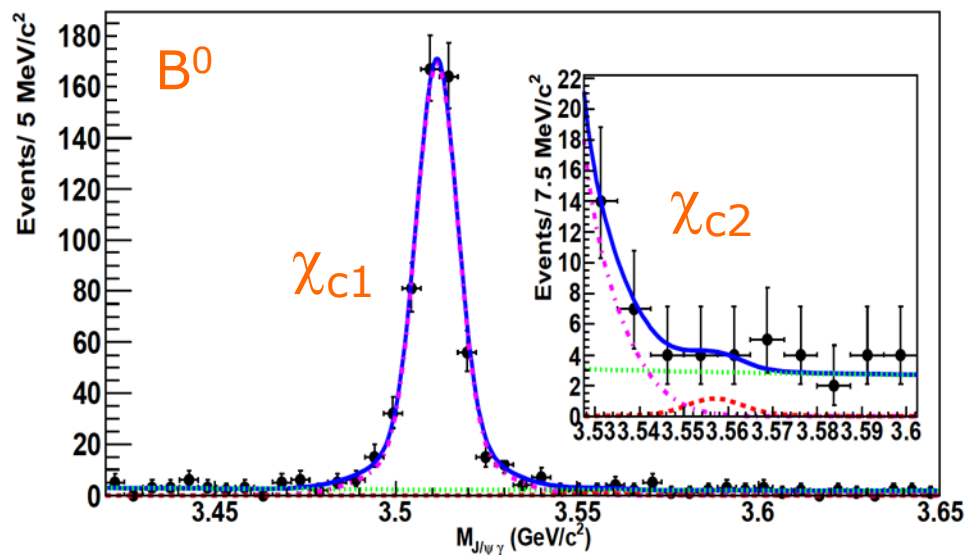
No indication, that  
 $X \rightarrow (n=2)$  charmonium  
is stronger than  
 $X \rightarrow (n=1)$  charmonium

# Same Analysis, but reference signal $\chi_{c1,2} \rightarrow J/\psi\gamma$



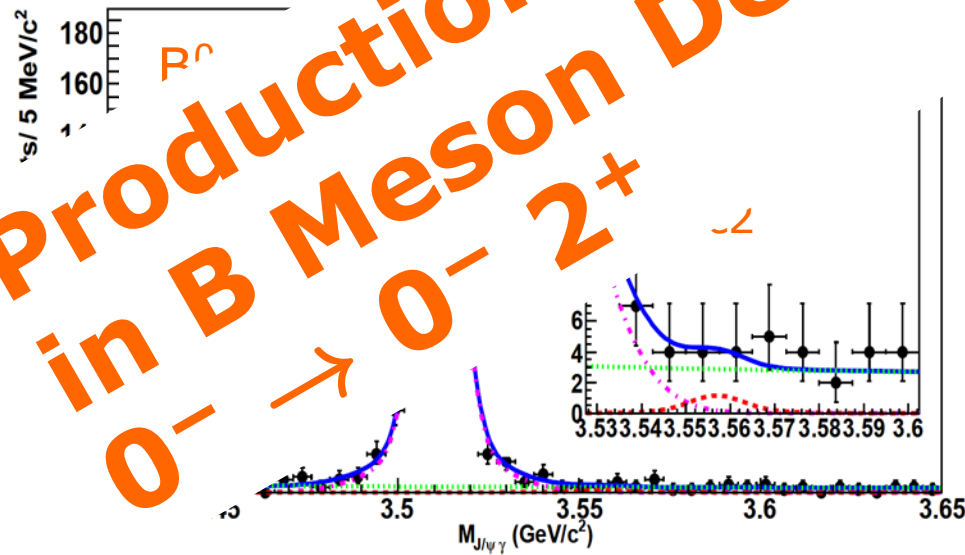
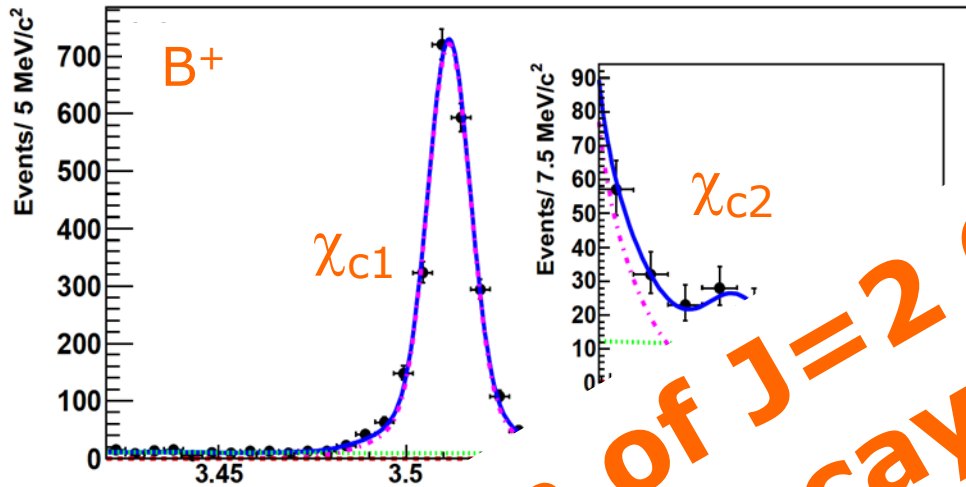
## First Evidence for $B^\pm \rightarrow \chi_{c2} K^\pm$

$B^+ \rightarrow K^+ \chi_{c2}$   
 $32.8^{+10.9}_{-10.2}$  events  
 $3.6\sigma$  (stat. and syst.)



$B^0 \rightarrow K^0 \chi_{c2}$   
 $2.8^{+4.7}_{-3.9}$  events  
 $0.7\sigma$  (stat. and syst.)

Same Analysis, but reference signal  $\psi\gamma$



**Production of J=2 Charmonium in B Meson Decays**  
 $0^- \rightarrow 0^- 2^+$

**Fit**

**Charmonium**

$2.8^{+4.7}_{-3.9}$  events  
 (stat. and syst.)

$\psi^0 \rightarrow K^0 \chi_{c2}$   
 $2.8^{+4.7}_{-3.9}$  events  
 0.7 $\sigma$  (stat. and syst.)

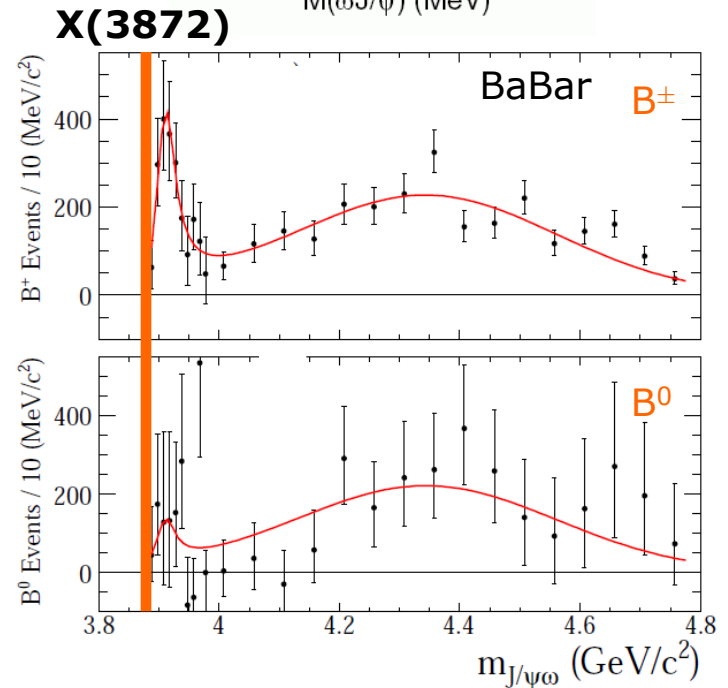
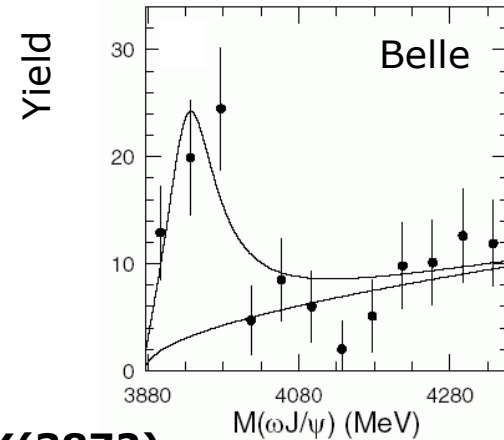
**$X(3872) \rightarrow J/\psi \ 3\pi$**

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

- $X(3872)$  breaks isospin in the strong decay  
 $X(3872) \rightarrow J/\psi \rho (\rightarrow \pi^+ \pi^-)$
- $\rho/\omega$  mixing?  
 Terasaki, Prog. Theor. Phys. 122(2010)1285
- $\rightarrow$  Investigation of  
 $X(3872) \rightarrow J/\psi \omega (\rightarrow \pi^+ \pi^- \pi^0)$
- Difficulty: nearby  $Y(3940)$  also decays to same final state

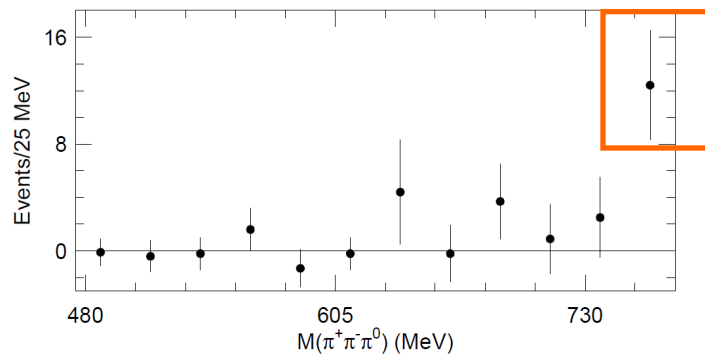
Belle, Phys. Rev. Lett. 94(2005)182002  
 $275 \times 10^6$  B meson pairs  
 mass  $3943 \pm 11(\text{stat.}) \pm 13(\text{syst.})$  MeV  
 width  $87 \pm 22(\text{stat.}) \pm 26(\text{syst.})$  MeV

BaBar, Phys. Rev. Lett. 101(2008)082001  
 $383 \times 10^6$  B meson pairs  
 mass  $3914.6^{+3.8}_{-3.4}(\text{stat.}) \pm 2.0(\text{syst.})$  MeV  
 width  $34^{+12}_{-8}(\text{stat.}) \pm 5(\text{syst.})$  MeV

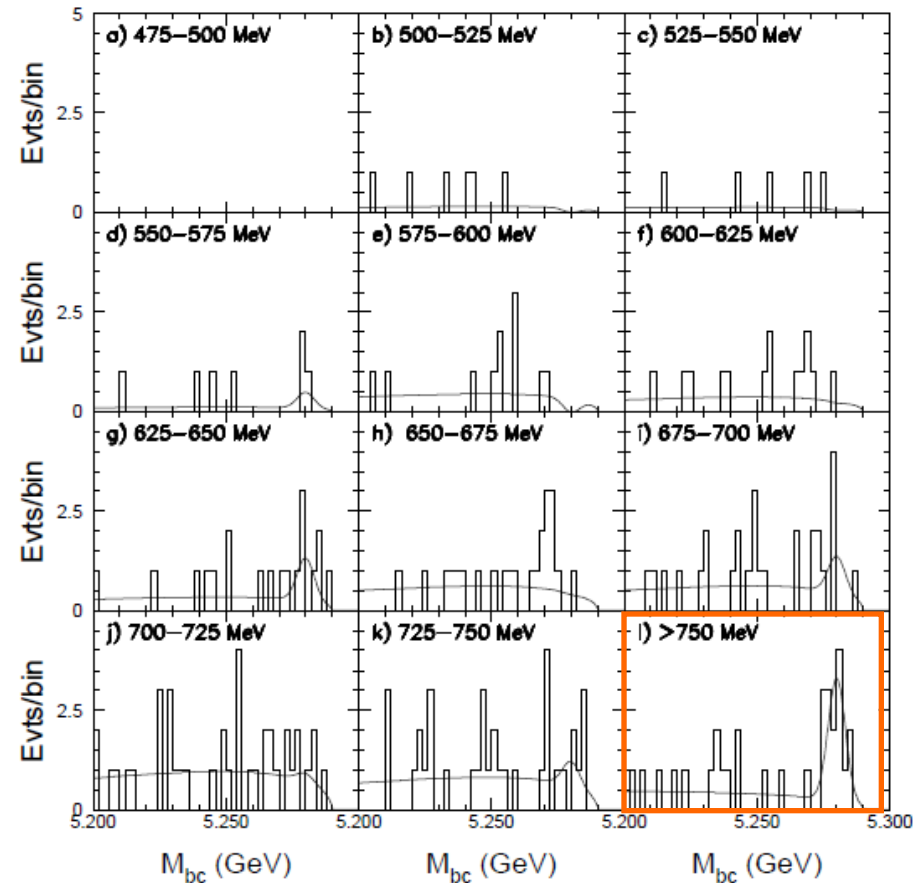


# Observation of $X(3872) \rightarrow J/\psi \omega (\rightarrow \pi^+ \pi^- \pi^0)$

- Belle, arXiv:hep-ex/0505037  
256/fb
- in order to establish a signal in B meson decays:  
check  $M_{BC}$  in slices  
of invariant mass



$$M_{bc} \equiv \sqrt{(E_{\text{beam}}^{\text{cms}})^2 - (p_B^{\text{cms}})^2}$$



4.3 $\sigma$  significance (stat.)

# New analysis of $X(3872) \rightarrow J/\psi \omega (\rightarrow \pi^+ \pi^- \pi^0)$

- Isospin violation (additional  $\pi^0$ ) seems large

$$\frac{\mathcal{B}(X \rightarrow \pi^+ \pi^- \pi^0 J/\psi)}{\mathcal{B}(X \rightarrow \pi^+ \pi^- J/\psi)} = 1.0 \pm 0.4(\text{stat}) \pm 0.3(\text{syst})$$

- BaBar re-analysis of Phys. Rev. Lett.101(2008)082001 with new  $\omega$  mass cut  
BaBar, QWG10 preliminary  
arXiv:1005.5190, 433/fb

Belle  
MC efficiency corrected

BaBar, arXiv:1005.5190, 433/fb

	Belle hep-ex/0505037	BaBar Phys. Rev. Lett.101(2008)082001	BaBar QWG10
Cut on $\Delta E$ $= \sqrt{(E_B^{cms})^2 - (p_B^{cms})^2}$	$\pm 35$ MeV (charged only)	$\pm 20$ MeV ( $B^+$ ) $\pm 15$ MeV ( $B^0$ )	$\pm 20$ MeV ( $B^+$ ) $\pm 15$ MeV ( $B^0$ )
Cut on $m(3\pi)$	$\geq 0.7500$ GeV (charged only)	0.7695-0.7965 GeV ( $B^+$ ) 0.7605-0.8055 GeV ( $B^0$ )	0.7400-0.7965 GeV ( $B^+$ ) 0.7400-0.8055 GeV ( $B^0$ )

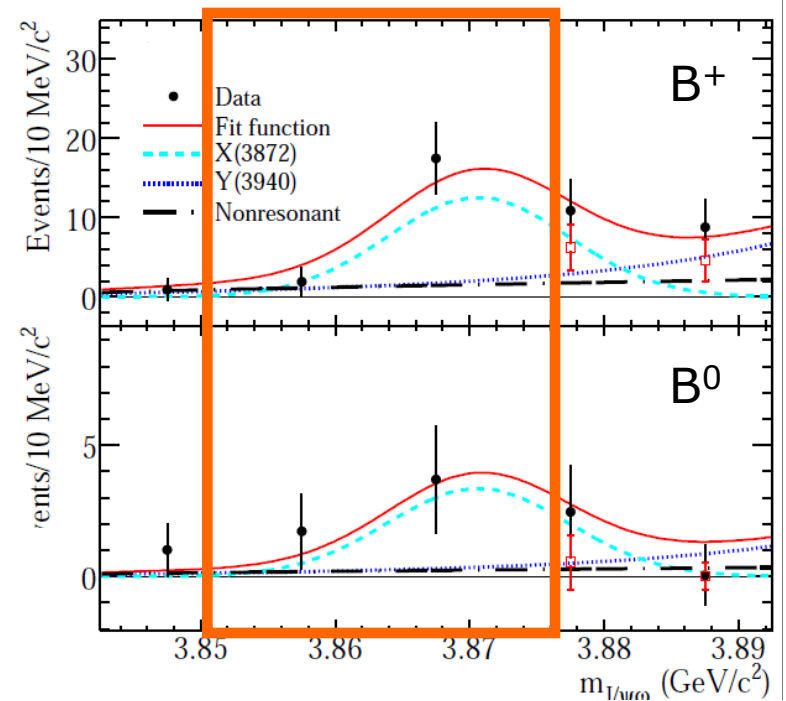
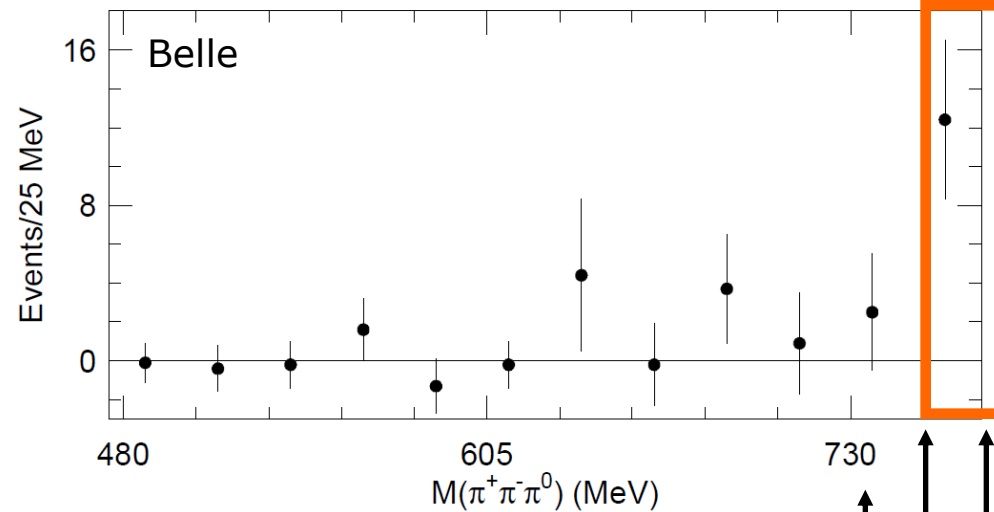
PDG2008  $m(\omega) = 0.78265 \pm 0.00012$  MeV



# Confirmation of $X(3872) \rightarrow J/\psi \omega$

BaBar, arXiv:1005.5190, 433/fb

Belle, hep-ex/0505037, 256/fb



**3.877 GeV preliminary**

**3.852 GeV**

**3.827 GeV**

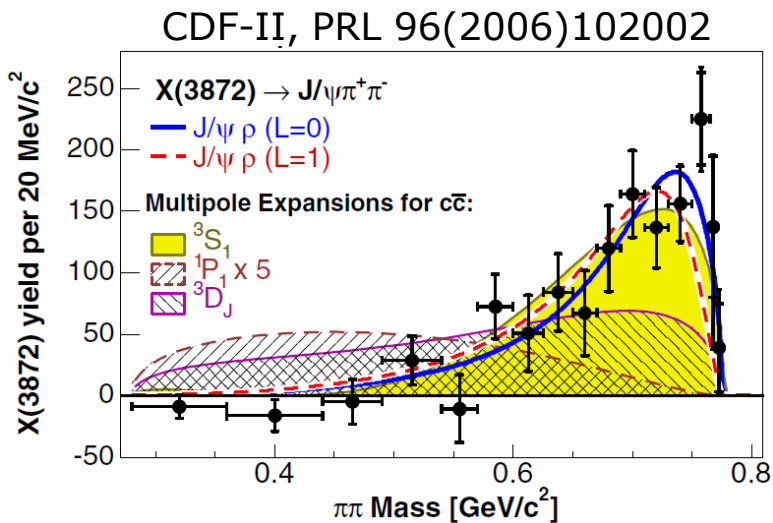
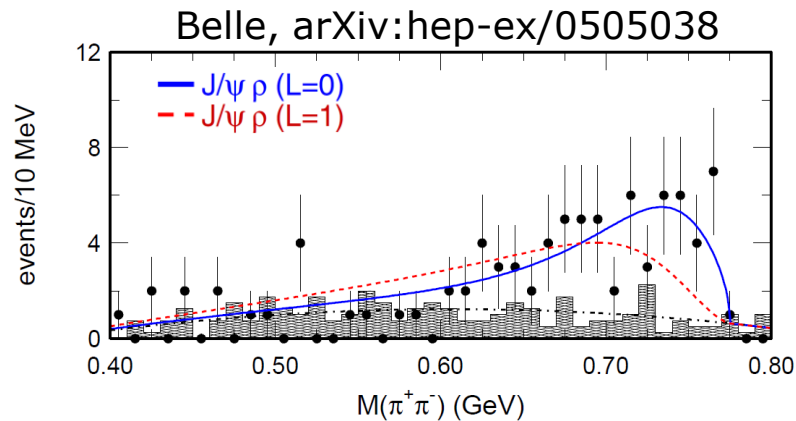
$$\frac{\mathcal{B}(X(3872) \rightarrow J/\psi\omega)}{\mathcal{B}(X(3872) \rightarrow J/\psi\pi\pi)} = 0.7 \pm 0.3$$

$$\frac{\mathcal{B}(X(3872) \rightarrow J/\psi\omega)}{\mathcal{B}(X(3872) \rightarrow J/\psi\pi\pi)} = 1.7 \pm 1.3$$

**Large isospin violation confirmed**

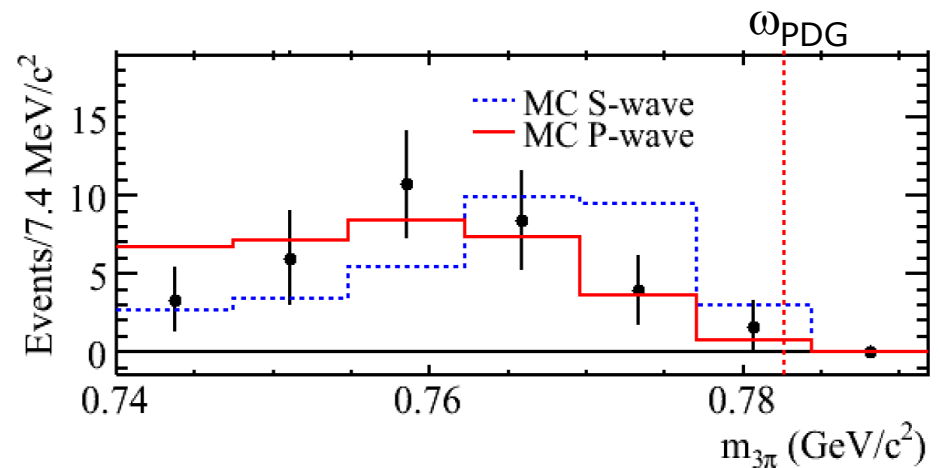
# Testing the Quantum Numbers of the X(3872)

$X(3872) \rightarrow J/\psi 2\pi$   
S-wave preferred



$X(3872) \rightarrow J/\psi 3\pi$   
P-wave preferred

BaBar, arXiv:1005.5190, 433/fb

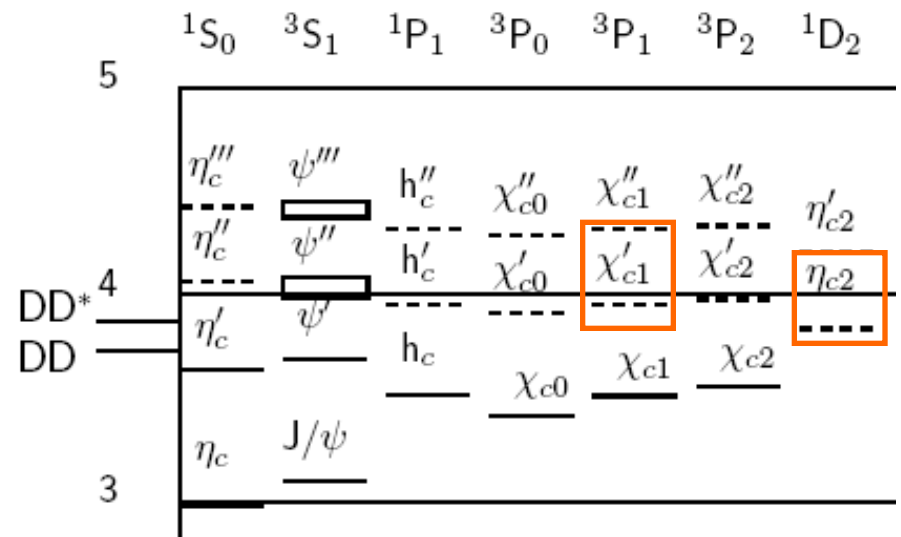
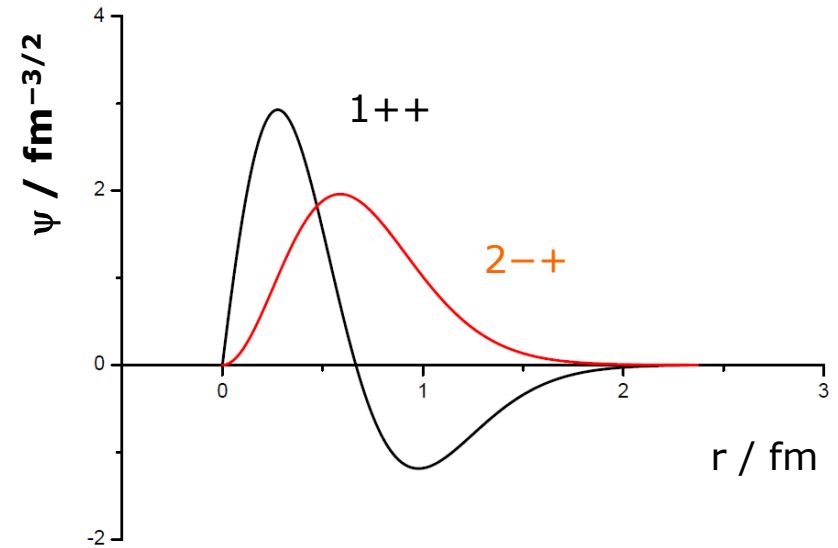


# Implication for X(3872) possible Charmonium Assignment

- Case  $2\pi \rightarrow P=+$   
 $1^{++}$   
 $\chi_{c1}' \quad ^3P_1$   
 predicted mass 3953 MeV  
 $n=2$   
 supported by angular analysis  
 CDF-II, PRL98(2007)132002  
 Belle, hep-ex/0505037

- Case  $3\pi \rightarrow P=-$   
 $2^{-+}$   
 $\eta_{c2} \quad ^1D_2$   
 $\leq 100$  MeV lower than  $\chi_{c1}'$   
 predicted mass 3837 MeV  
 $n=1$   
 (would be a L=2 meson)

Mass predictions by  
 Barnes, Godfrey, Swanson  
 Phys. Rev. D72(2005)054026

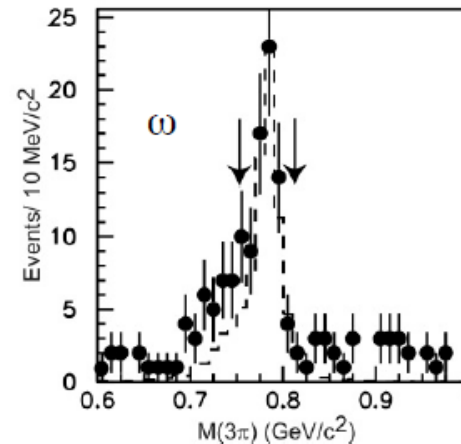
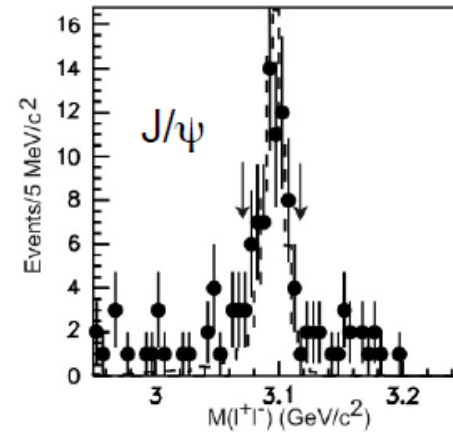
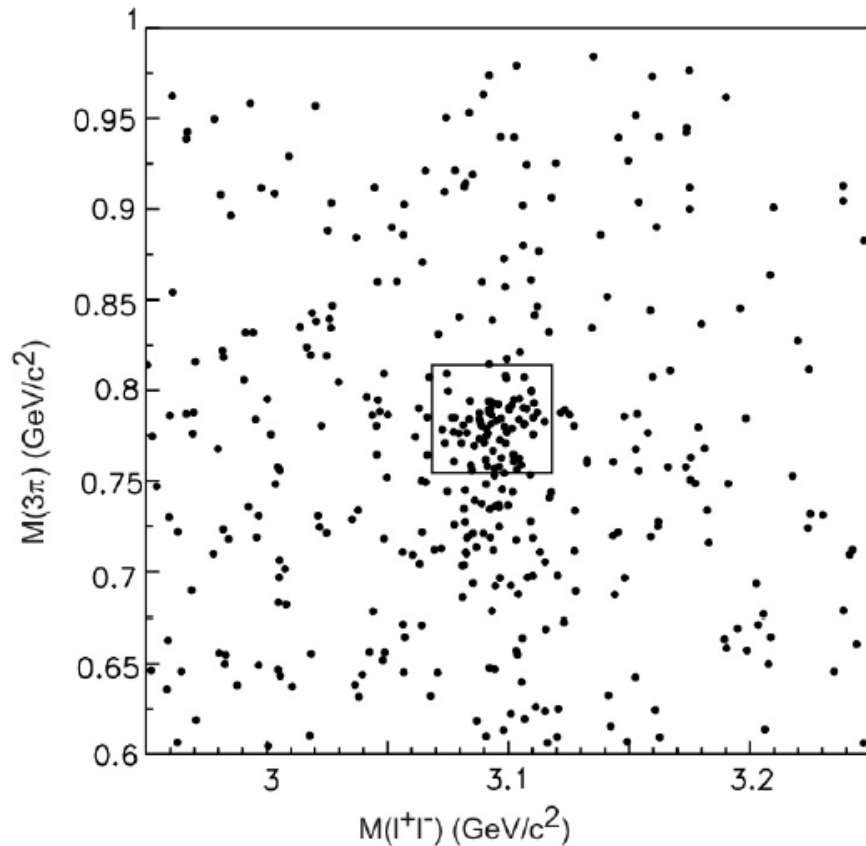


$J/\psi\omega$  in  $\gamma\gamma$  collisions

# $\gamma\gamma \rightarrow J/\psi \omega$

694/fb  
includes Y(3S) and Y(5S) data

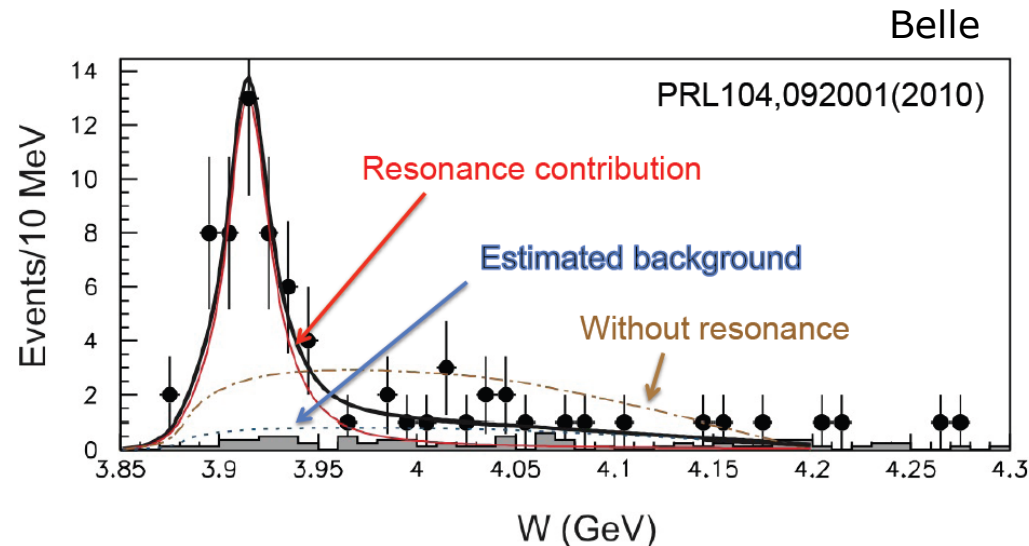
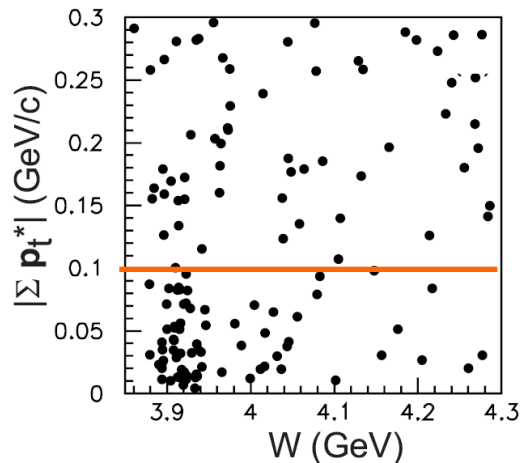
- Belle, Phys. Rev. Lett. 104(2010)092001
- Final state 2 vector mesons with  $I=0$



Event selection:  
4 tracks  
Net charge=0  
 $\pi^0$  candidate  
Lepton ID  
K rejection  
 $P_T$  balance

# $\gamma\gamma \rightarrow J/\psi \omega$

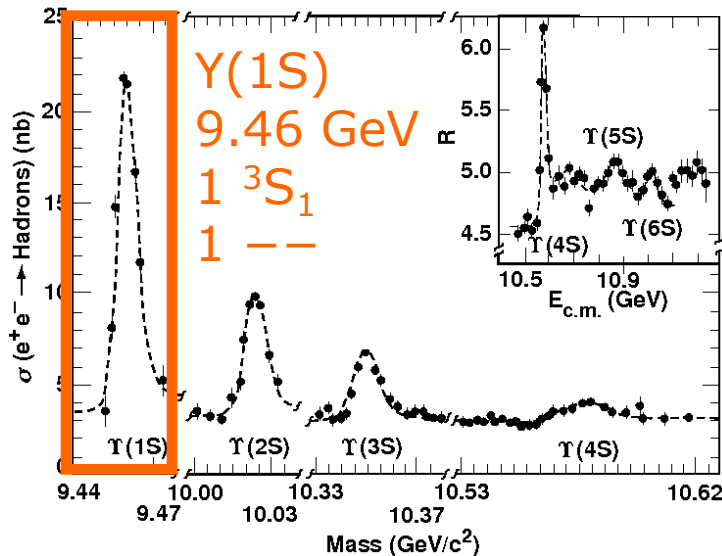
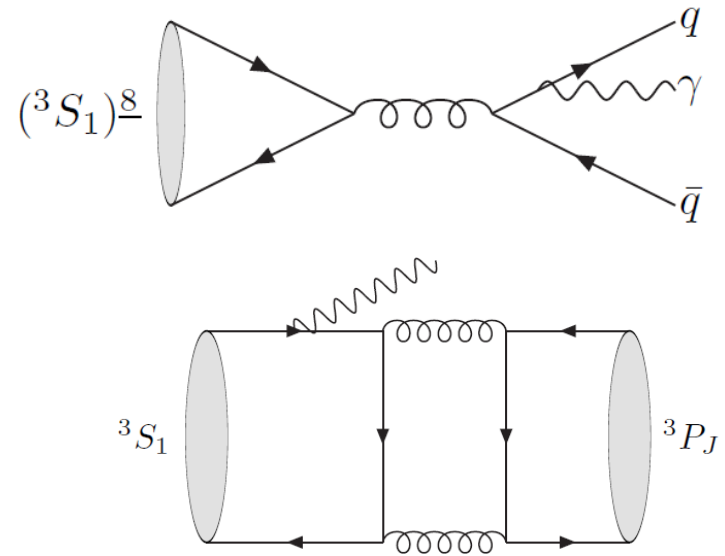
- $\gamma\gamma$  collision signal region ( $P_T < 0.1$  GeV)
- Clear enhancement seen just above  $J/\psi \omega$  threshold
- $7.7\sigma$  (stat.)  
 $49 \pm 14(\text{stat.}) \pm 4(\text{syst.})$  events
- $M = 3915 \pm 3(\text{stat.}) \pm 2(\text{syst.})$  MeV
- $\Gamma = 17 \pm 10(\text{stat.}) \pm 3(\text{syst.})$  MeV
- $C = \text{even}$ , but  $J^P$  not yet determined (need much more statistics)
- **Is this the  $Y(3940)$ ? (in a 2<sup>nd</sup> production mode)**



# **Upsilon(1S) Radiative Decays**

# Radiative Upsilon Decays to Charmonium

- $(b \bar{b}) \rightarrow (c \bar{c}) \gamma$
- Predictions  
e.g. Gao, Zhang, Chao,  
hep-ph/0701009
- $^3S_1$  is e.g.  $\Upsilon(1S)$
- $^3P_J$  may be  $1^{++}$   
e.g.  $X(3872)$
- rare events  
 $BR \leq 10^{-5}$  expected

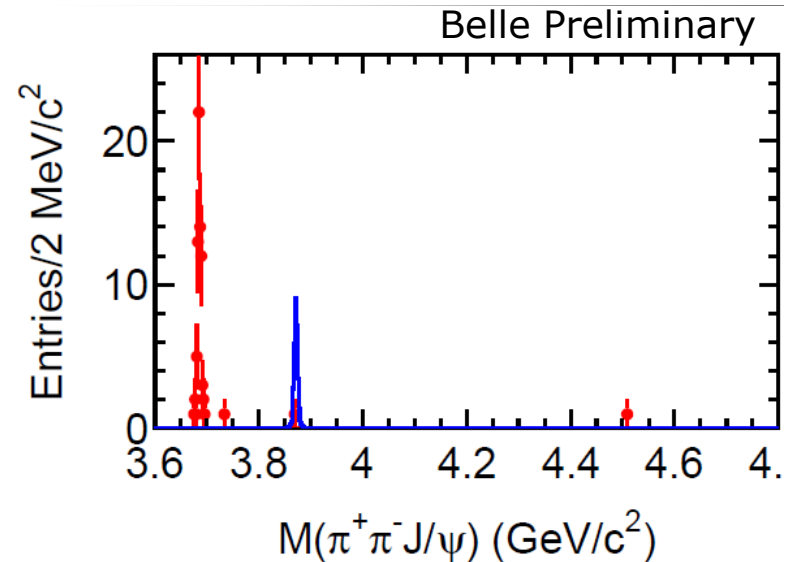
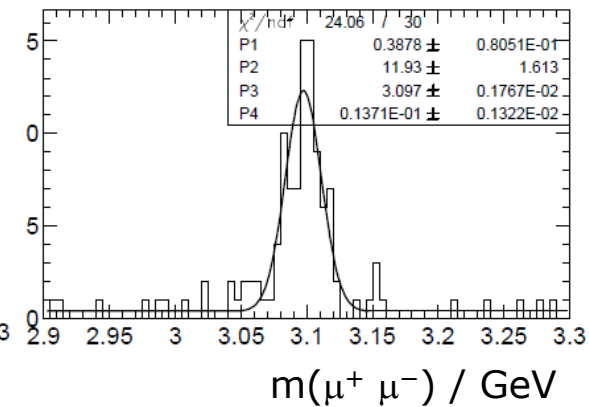
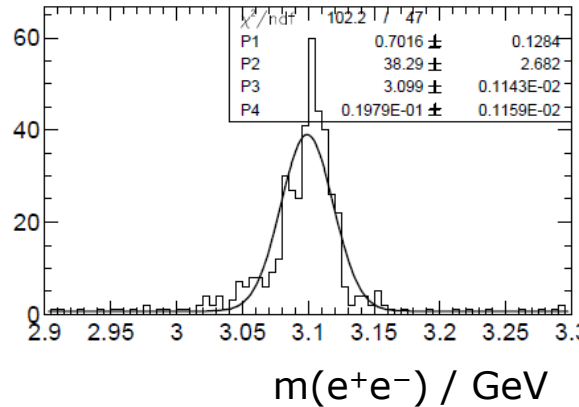


Interference between  
QED and QCD  
amplitudes expected



# Search for $Y(1S) \rightarrow \gamma X(3872) (\rightarrow J/\psi \pi^+ \pi^-)$

- Belle  
5.712/fb on  $Y(1S)$   
88 million  $Y(1S)$  decays
- *Selection:*
  - 4 charged tracks, net charge = 0
  - PID
  - $2.5\sigma$  cut on  $J/\psi$  mass
  - $E_\gamma > 3.5$  GeV
  - Recoil Mass on 4 charged tracks consistent with a photon ( $m_\gamma = 0$ )  
 $-2 < M_{\text{recoil}} < 2$  GeV<sup>2</sup>
  - reject ISR events by  $|\cos \vartheta_\gamma^*| < 0.9$
- Crosscheck  $\psi'$  (same final state)  
 $\sigma(e^+e^-) \rightarrow \psi' = 20.2 \pm 1.1$  (stat.) pb
- $\text{BR}(Y(1S) \rightarrow \gamma X(3872)) \times$   
 $\text{BR}(X(3872) \rightarrow J/\psi \pi^+ \pi^-) < 2.2 \times 10^{-6}$   
at 90% CL

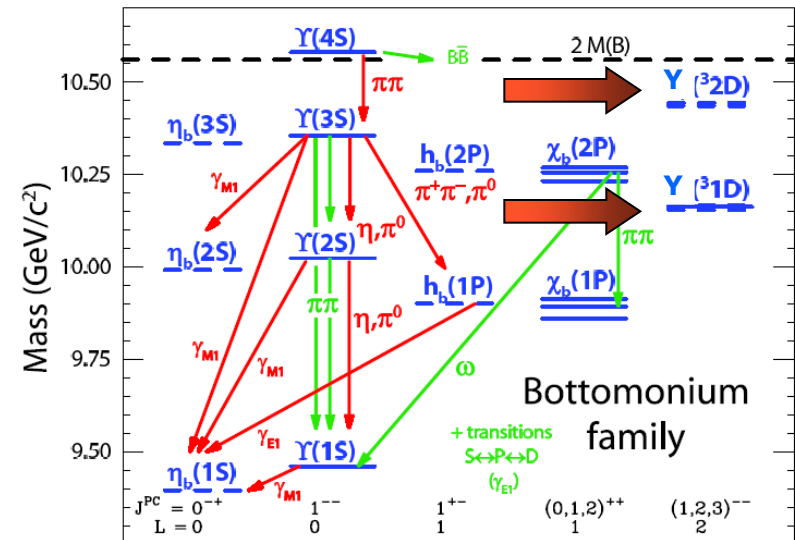
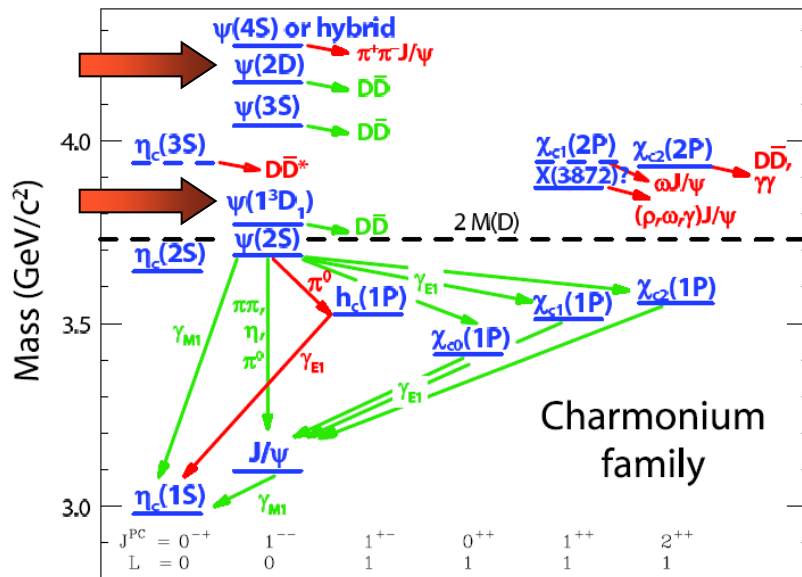


# **Upsilon(1D)**

An  $L=2$  Meson.

# D-Wave States (L=2)

Eichten, Godfrey, Mahlke, Rosner,  
Rev. Mod. Phys. 80(2008)1161  
hep-ph/0701208



2 D-wave states **above** threshold  
 $\psi(3770)$  (n=1) and  $\psi(4153)$  (n=2)  
 both 1 --  
 → broad  
 > 20 MeV (exp.)

2 D-wave states **below** threshold  
 → predicted to be narrow  
 (hadronic width  $< \sim 30$  keV,  
 see e.g. Kwong,  
 Phys. Rev. D38(1988)279)  
 possible to resolve triplet?  
 0--, 1--, 2--

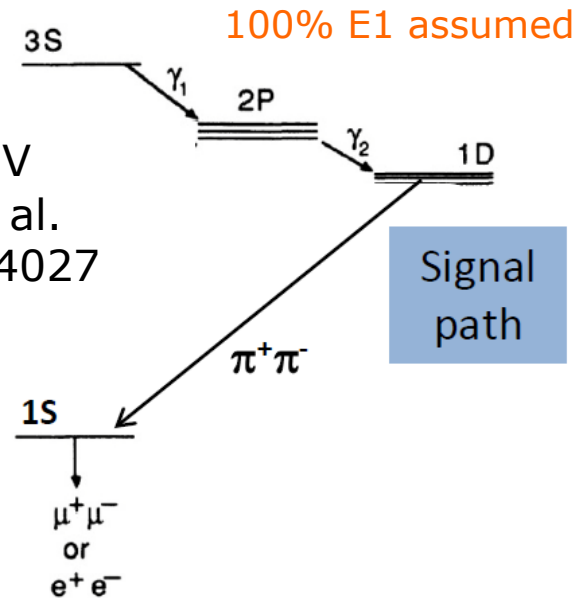
# Confirmation of Upsilon(1 $^3D_2$ )

- $Y(3S) \rightarrow \gamma\gamma Y(1D)$   
 $\rightarrow \gamma\gamma\pi^+\pi^-Y(1S)$   
 $\rightarrow \gamma\gamma\pi^+\pi^-|+|^-$

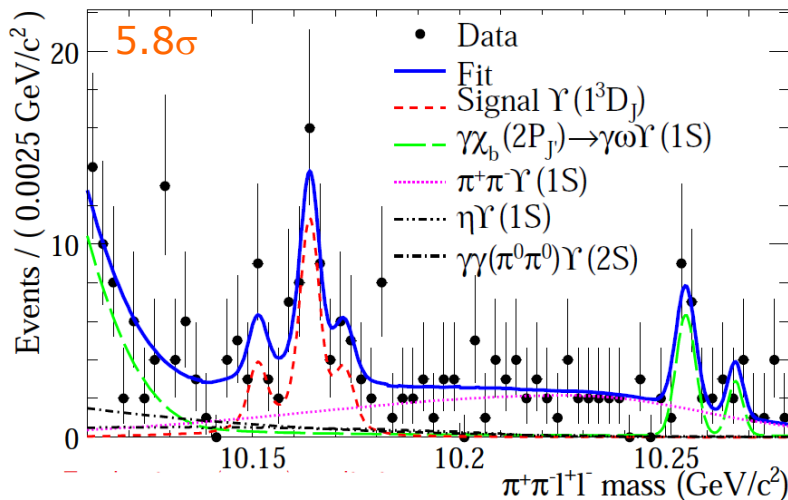
both electrons and muons

- $122 \times 10^6$   $Y(3S)$  events
- $33.9_{-7.5}^{+8.2}$   $Y(1D)$  events

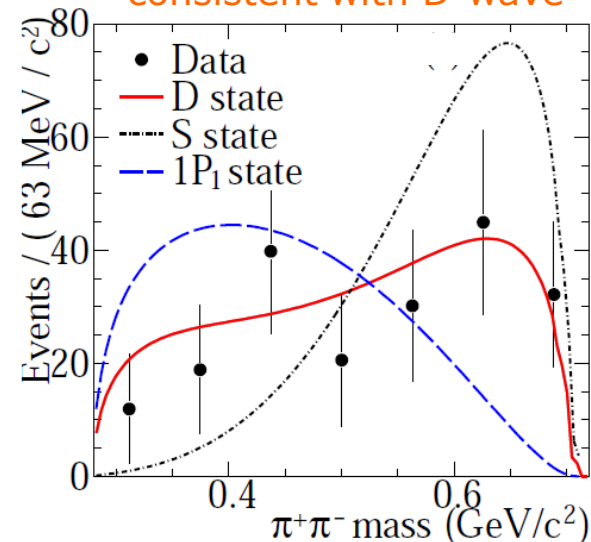
$m = 10164.5 \pm 0.8 \pm 0.5$  MeV  
 Potential Model, Ebert et al.  
 Phys. Rev. D67(2003)014027  
 $m = 10.158$  MeV



BaBar, arXiv:1004.0175 [hep-ex]



consistent with D-wave



# Summary

B Factories continue to provide exciting results:

- Charmonium spectroscopy
  - in B meson decays
  - in  $\gamma\gamma$  collisions
  - in Upsilon decays
- Bottomonium spectroscopy
- Many more analyses ongoing ...