

# Quarkonium spectroscopy and search for new states at BaBar

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on behalf of the BaBar collaboration*

E.P.S conference on H.E.P. – Manchester, July 19-25  
2007



## Outline

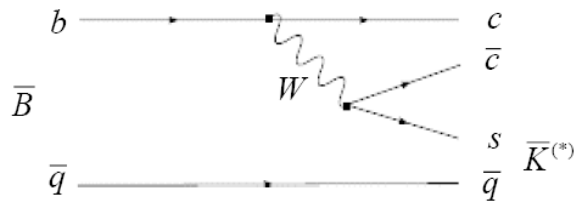
- ✓ Charmonium and charmonium like states at BaBar
- ✓ Update on X(3872)
- ✓ Y(3940): [new result from BaBar](#)
- ✓ The Y(4260) and a structure at 4350 MeV/c<sup>2</sup>
- ✓ Summary and outlook

# Charmonium production



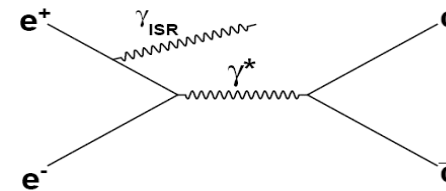
## ✗ Production in B decay

Color suppressed  $b \rightarrow c$  transition



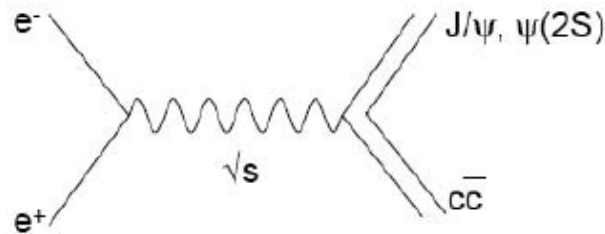
## ✗ Initial state radiation

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



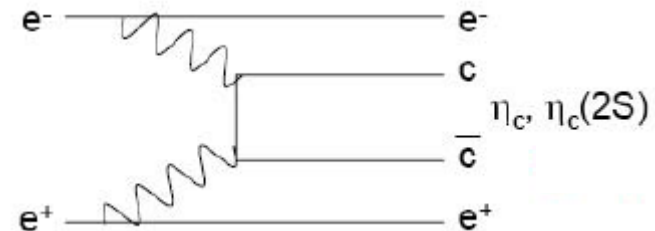
## ✗ Double charmonium production

Reconstruct a  $J/\psi$  and compute the recoiling invariant mass.



## ✗ Two photons production

Production of  $C=+1$  states



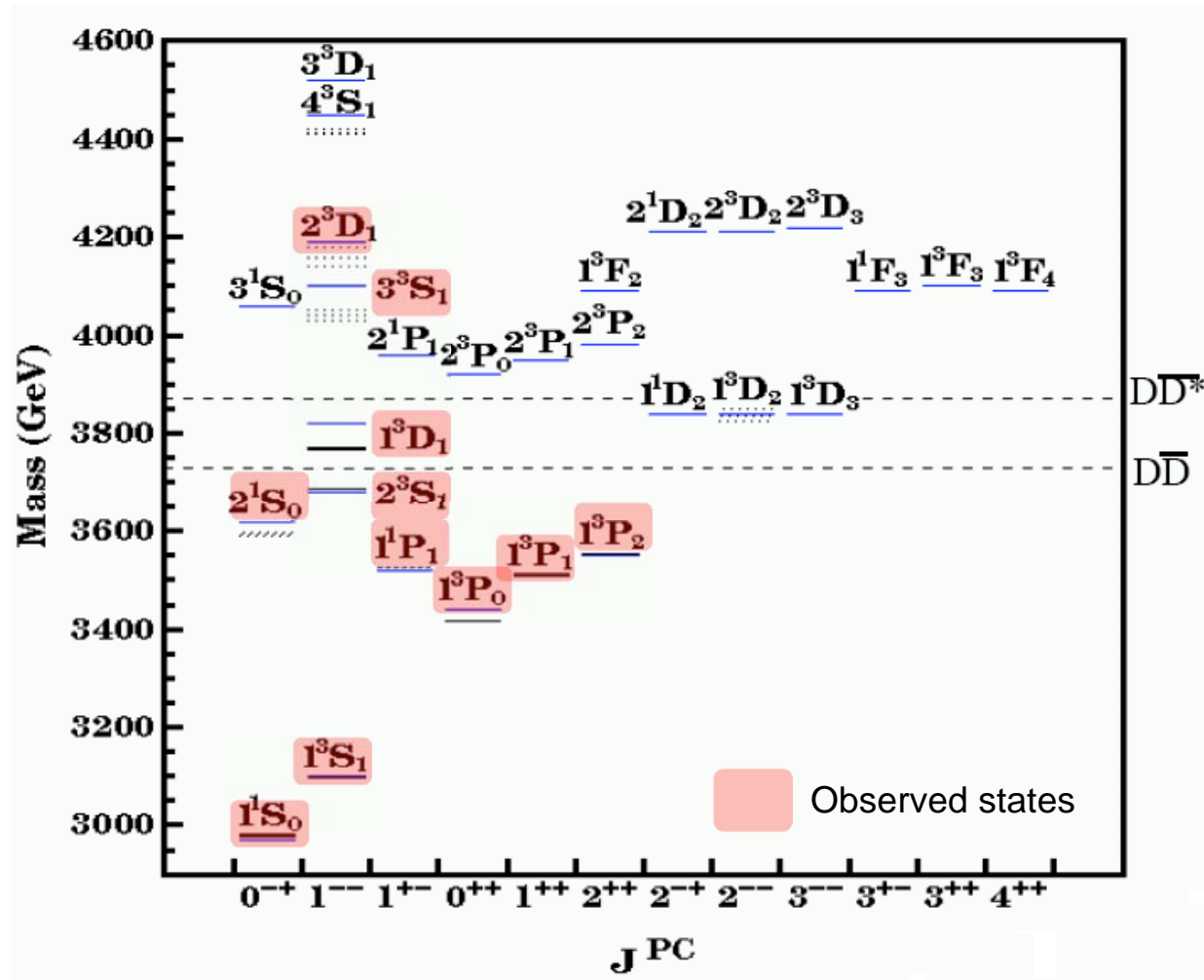
In our data sample

	$J/\psi$	$\psi(2S)$
In B decays	9 M	3 M
In ISR	16.5 M	6 M

# The charmonium spectrum



- Charmonium properties are well understood and until  $D\bar{D}$  threshold. Good agreement between data and prediction until new states have been discovered.
- Region above the  $D\bar{D}$  threshold (3.73 GeV) is very poorly known.
- $c\bar{c}$  states above open charm threshold are expected to be not narrow and decay mainly to open charm channels.



# Update on X(3872)



First observation by BELLE in B decays:  $B^\pm \rightarrow X(3872)K^\pm$  with  $X(3872) \rightarrow J/\psi \pi^+\pi^-$

PRL 91, 262001 (2003)

Confirmed by

✘ BaBar PRD 71, 071103 (2005)

✘ CDF PRL 93, 072001 (2004)

✘ D0 PRL 93, 162002 (2004)

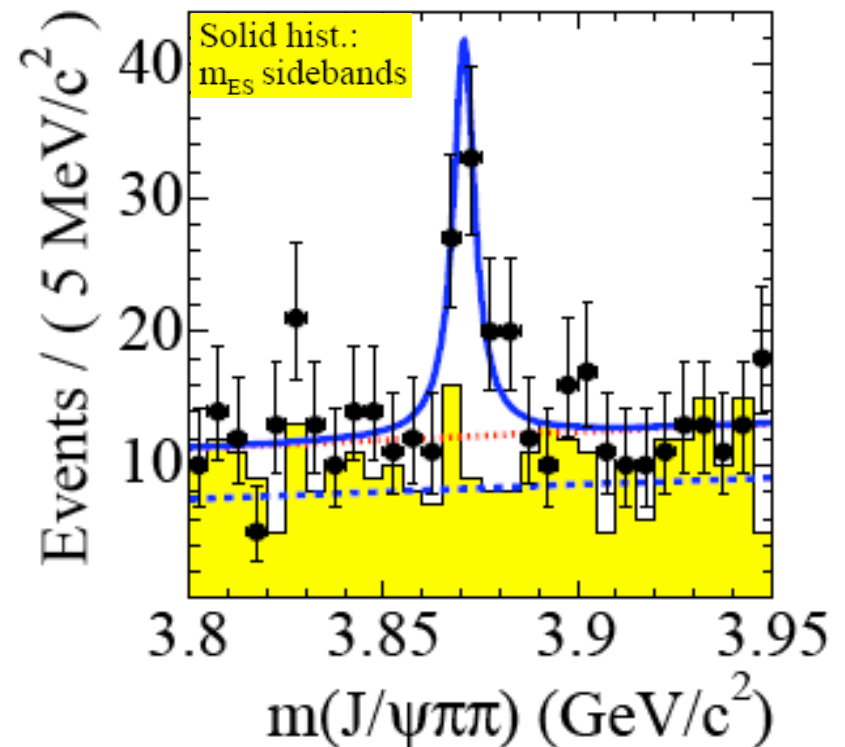
Update by BaBar with 232 M  $B\bar{B}$

PRD 73, 011101 (2006)

$$B(B \rightarrow KX(3872), X(3872) \rightarrow \pi^+\pi^-J/\psi) = (10.1 \pm 2.5 \pm 1.0) \times 10^{-6}$$

Combined results:

- ✘  $m_X = (3871.2 \pm 0.6) \text{ MeV}/c^2$
- ✘  $\Gamma_X < 2.3 \text{ MeV}$  @ 90% CL
- ✘ Very close to  $m(D^0) + m(\bar{D}^{*0})$

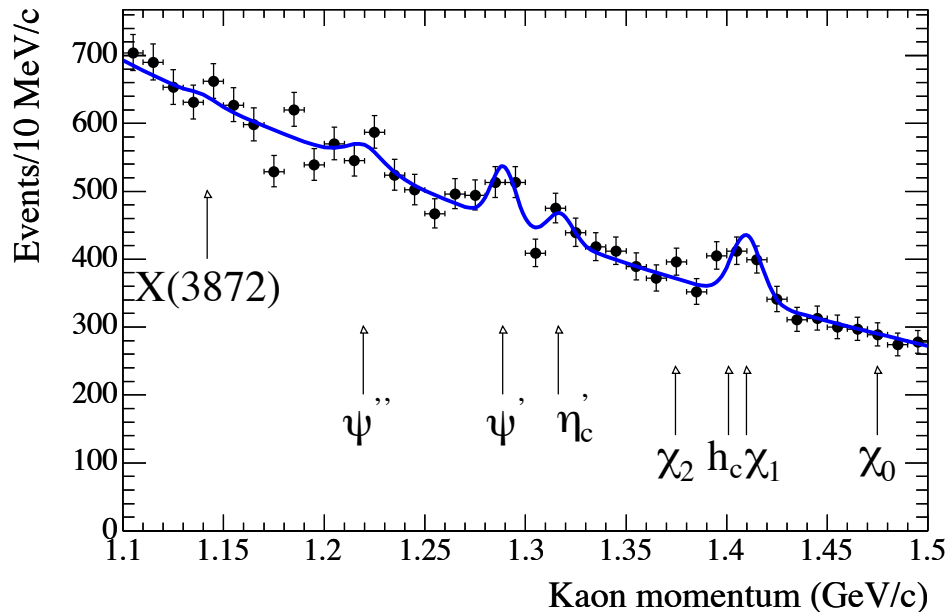
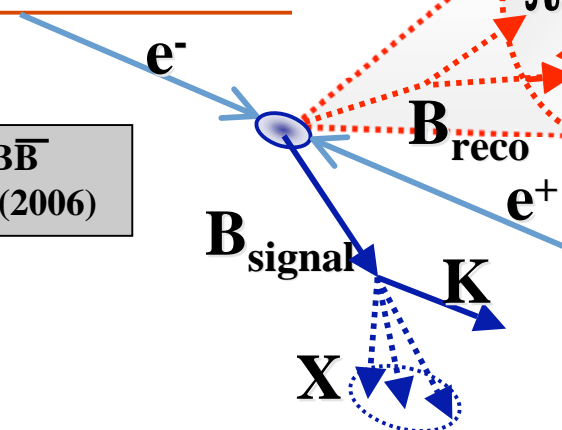


# Inclusive search for $B \rightarrow KX(3872)$



- ✘ Fully reconstruct one B
- ✘ Measure  $p(K)$  in the other B frame
- ✘ Calculate  $m(X)$  based on  $p(K)$

BABAR: 232M  $B\bar{B}$   
PRL 96, 052002 (2006)



$B(B^\pm \rightarrow K^\pm c\bar{c})$  are consistent with PDG values for known charmonia

✘ No  $X(3872)$  signal observed  
 $BR(B^\pm \rightarrow X(3872)K^\pm) < 3.2 \cdot 10^{-4}$  at 90% CL

✘ From BaBar-Belle average:  
 $BR(B^\pm \rightarrow X(3872)K^\pm, X(3872) \rightarrow J/\psi\pi^+\pi^-) = (13.3 \pm 2.5) \cdot 10^{-6}$

✘  $BR(X(3872) \rightarrow J/\psi\pi^+\pi^-) > 4.2\%$  at 90% CL

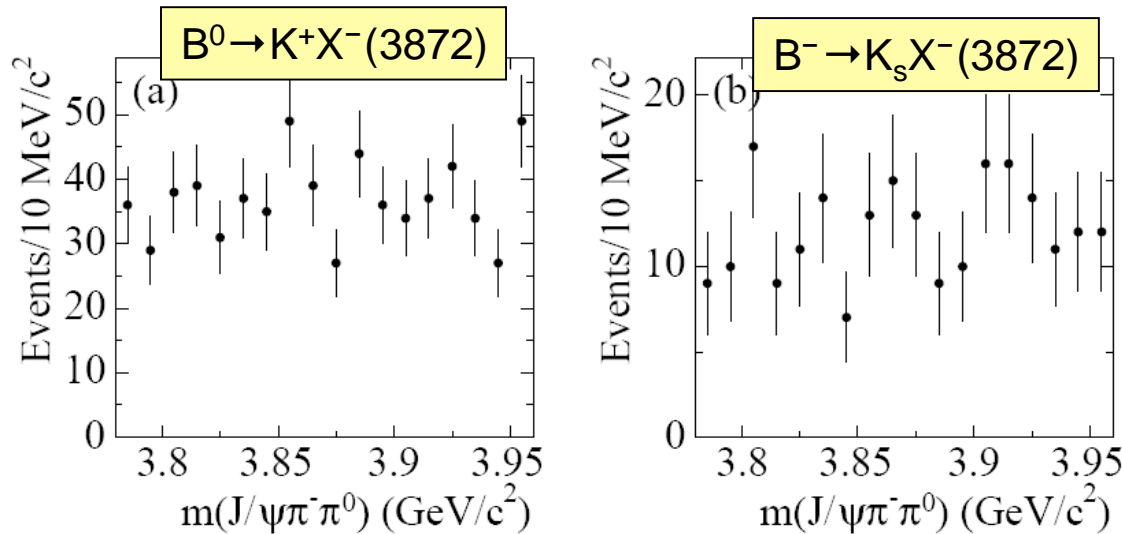
# X(3872) search for charged partners



## ✘ Exclusive reconstruction technique

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

PRD 71, 031501 (2005)



No charged partner observed

$BR(B^0 \rightarrow X(3872)^- K^+, X(3872)^- \rightarrow J/\psi \pi^- \pi^0) < 5.4 \cdot 10^{-6}$  at 90% CL

$BR(B^- \rightarrow X(3872)^- K^0, X(3872)^- \rightarrow J/\psi \pi^- \pi^0) < 22 \cdot 10^{-6}$  at 90% CL

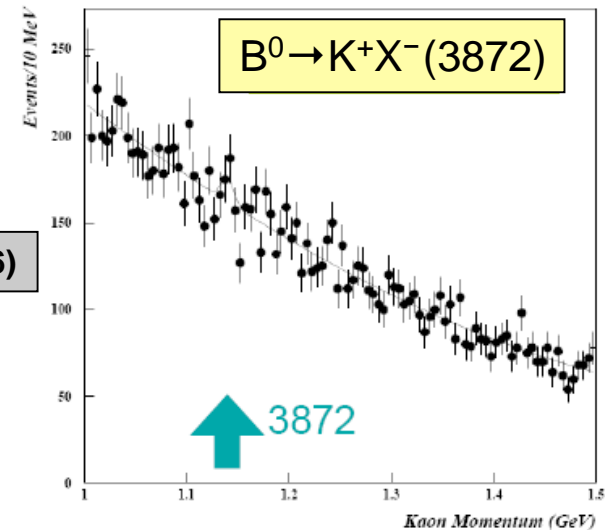
## ✘ Inclusive search using recoil technique

PRL 96, 052002 (2006)

$K^\pm$  momentum on  $B^0$  recoil

No signal is observed for charged partners

$BR(B^0 \rightarrow X(3872)^+ K^-) < 5 \cdot 10^{-4}$  at 90% CL



No evidence found:  $\rightarrow I=0$  favored for X(3872)



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

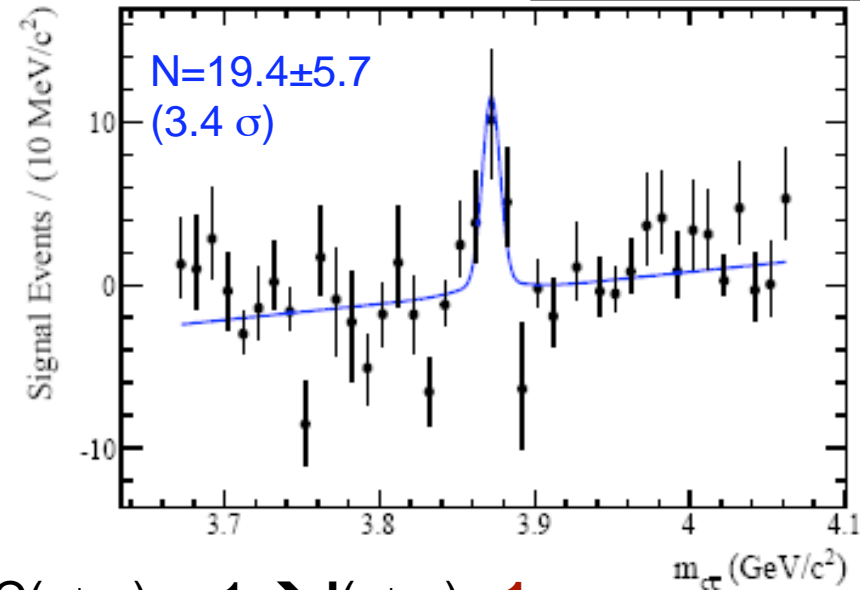


✘ *BABAR*: 287M  $B\bar{B}$

$$\mathcal{B}(B^+ \rightarrow X(3872)K^+, X \rightarrow J/\psi \gamma) = (3.4 \pm 1.0 \pm 0.3) \times 10^{-6}$$

✘ Belle/*BABAR* average:

$$\frac{\mathcal{B}(X \rightarrow J/\psi \gamma)}{\mathcal{B}(X \rightarrow J/\psi \pi^+ \pi^-)} = 0.19 \pm 0.07$$



- ✘ Establish  $C(X_{3872}) = +1 \rightarrow C(\pi^+\pi^-) = -1 \rightarrow I(\pi^+\pi^-) = 1$
- ✘ Forbidden  $J/\psi \pi^0 \pi^0$ ,  $J/\psi \pi^0$ , and  $J/\psi \eta$  decays
- ✘ Consistent with  $\rho$ -like  $\pi^+\pi^-$  in  $X \rightarrow J/\psi \pi^+\pi^-$
- ✘  $I=0$  favored for  $X(3872)$  - the  $J/\psi \pi^+\pi^-$  decay is isospin violating (small width)

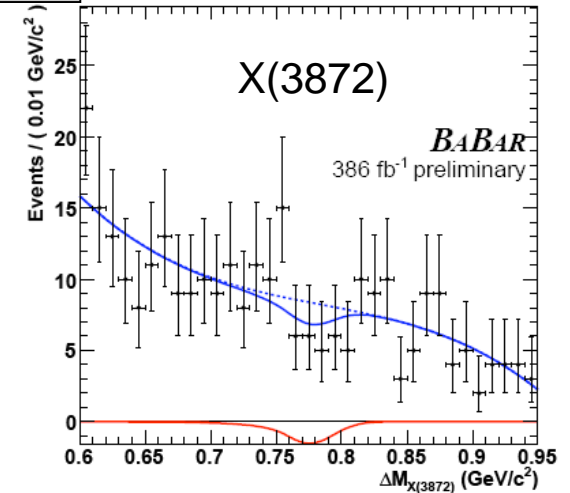
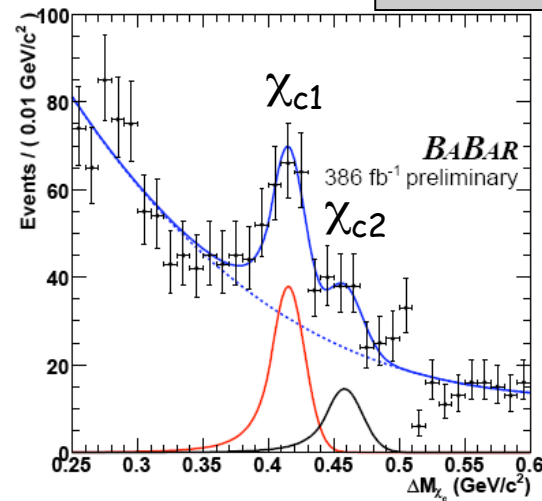
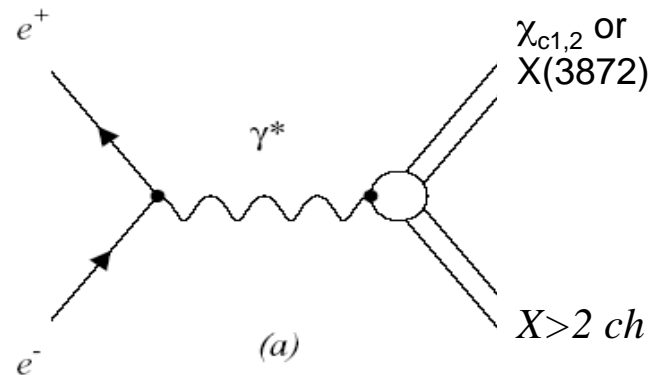
# Search for $X(3872) \rightarrow J/\psi \gamma$ in continuum



386fb<sup>-1</sup>

arXiv:0707.1633

$J/\psi$  production observed in continuum while no evidence of  $\chi_c$  states.



$\chi_c$  production is consistent with the expected contributions from prompt  $\psi(2S)$  production feed-down to  $\chi_c$ : **no evidence of prompt  $\chi_{c1,2}$**

**No evidence of X(3872) production in  $e^+e^-$  annihilation.**

$$\sigma(e^+e^- \rightarrow \chi_{c1,direct} X) \cdot \mathcal{B}(X \rightarrow (N_{ch} > 2)) = (41.1 \pm 18.0 \pm 20.6) \text{ fb}$$

$$(< 77 \text{ fb @90\% C.L.}),$$

$$\sigma(e^+e^- \rightarrow \chi_{c2,direct} X) \cdot \mathcal{B}(X \rightarrow (N_{ch} > 2)) = (23.2 \pm 27.7 \pm 26.1) \text{ fb}$$

$$(< 79 \text{ fb @90\% C.L.}).$$

$$\sigma(e^+e^- \rightarrow X(3872) X) \cdot \mathcal{B}(X(3872) \rightarrow \gamma J/\psi) \cdot \mathcal{B}(X \rightarrow (N_{ch} > 2))$$

$$= (-2.7 \pm 3.7 \pm 1.0) \text{ fb} \quad (< 5.1 \text{ fb @90\% C.L.}).$$



# Search for $\bar{D}^{(*)}D^{(*)}$ resonances



BELLE observed of:  $B \rightarrow X(3872)K^\pm$ ,  $X(3872) \rightarrow D^0 \bar{D}^0 \pi^0$

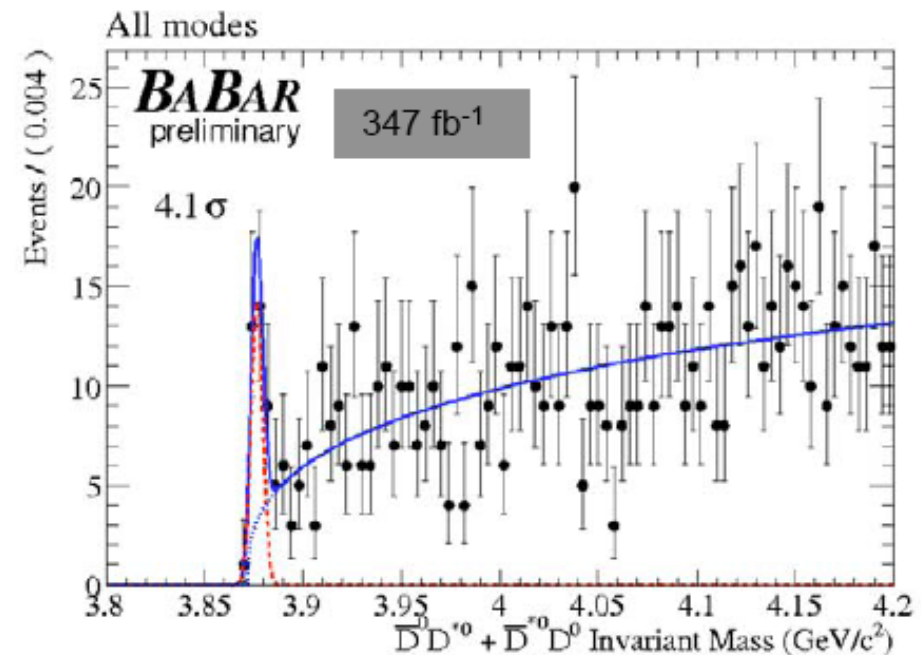
PRL 97, 162002(2006)

BaBar studied 8 channels:



with  $D^{*0} \rightarrow D^0 \pi^0$  and  $D^0 \gamma$

$$M = 3875.4_{-2.0}^{+1.2} \pm 0.7 \text{ MeV}/c^2$$



The mass is in good agreement with Belle's result in the same final state, but  $2.5\sigma$  higher than the world average.

$$\Delta m(B^0/B^+) = 0.2 \pm 1.6 \text{ MeV}/c^2$$

# X(3872) interpretation



- Angular distribution (from CDF and Belle) compatible with  $1^{++}$  state.
- The decay to  $\chi_{c1,2} \gamma$  has been searched by Belle but **not observed**.
- The decay to  $J/\psi \eta$  was searched by Babar but **not observed**.
- The **charmonium interpretation starts being in trouble**.
- $D^0 \bar{D}^{*0}$  molecule? (E. Braaten and M. Kusunoki)
  - $B^0 \rightarrow X(3872)K^0$  **suppressed** by a **factor 10** compared to  $B^+ \rightarrow X(3872)K^+$
  - **Measurements:**
    - $R(B^0/B^+) = 0.50 \pm 0.30 \pm 0.05$  in  $B \rightarrow J/\psi \pi^+ \pi^-$  BaBar: Phys. Rev. D73 (2006) 011101
    - $R(B^0/B^+) = 2.23 \pm 0.93 \pm 0.55$  in  $B \rightarrow \bar{D}^0 D^{*0} K$  BaBar: Preliminary
- 4 quark state? (L. Maiani, F. Piccinini, A. D. Polosa, V. Riquer)
  - Predict **2 neutral states** and **2 charged states**
    - Neutral states produced in  $B^0$  and  $B^+$  decays:  $\Delta m \approx (7 \pm 2) \text{ MeV}/c^2$
  - **Measurements:**
    - $\Delta m = (2.7 \pm 1.3 \pm 0.2) \text{ MeV}/c^2$  in  $B \rightarrow J/\psi \pi^+ \pi^-$  BaBar: Phys. Rev. D73 (2006) 011101
    - $\Delta m = (0.7 \pm 1.9 \pm 0.3) \text{ MeV}/c^2$  in  $B \rightarrow \bar{D}^0 D^{*0} K$  BaBar: Preliminary
- Glueball? Hybrid? ...

NEW

# The $Y(3940)$ state



- Discovered by Belle in  $B \rightarrow K \omega J/\psi$  (Based on  $253 \text{ fb}^{-1}$ )

PRL 94, 182002 (2005)

Babar preliminary

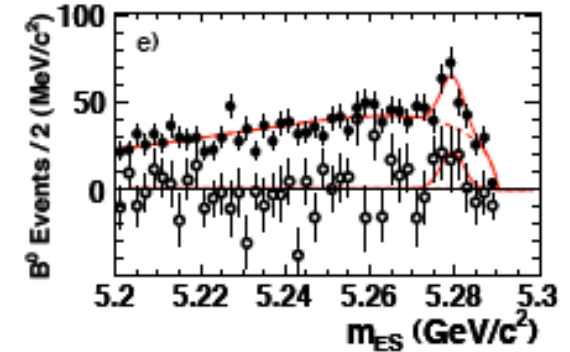
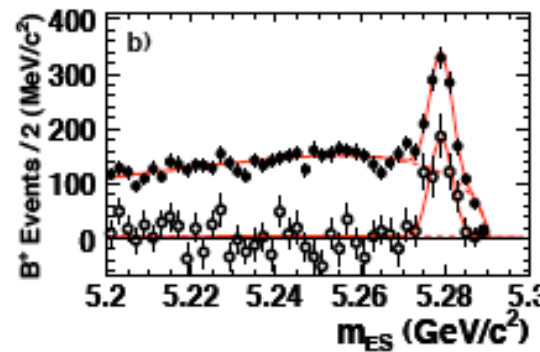
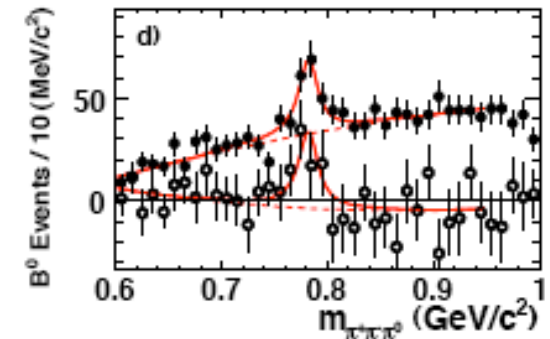
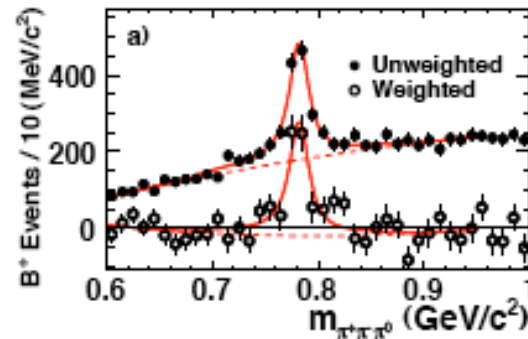
New result based on  $350 \text{ fb}^{-1}$

$B^\pm \rightarrow YK^\pm$

$B^0 \rightarrow YK_s$

$B^\pm \rightarrow YK^\pm$ ,  $Y \rightarrow J/\psi \omega$ ,  
 $J/\psi \rightarrow \ell^+ \ell^-$  ( $\ell = e, \mu$ )  
 $\omega \rightarrow \pi^+ \pi^- \pi^0$   
 $\pi^0 \rightarrow \gamma \gamma$

$B^0 \rightarrow YK_s$ ,  $Y \rightarrow J/\psi \omega$ ,  
 $J/\psi \rightarrow \ell^+ \ell^-$  ( $\ell = e, \mu$ )  
 $\omega \rightarrow \pi^+ \pi^- \pi^0$   
 $\pi^0 \rightarrow \gamma \gamma$ ,  $K_s \rightarrow \pi^+ \pi^-$



NEW

# Y(3940): new result

Babar preliminary



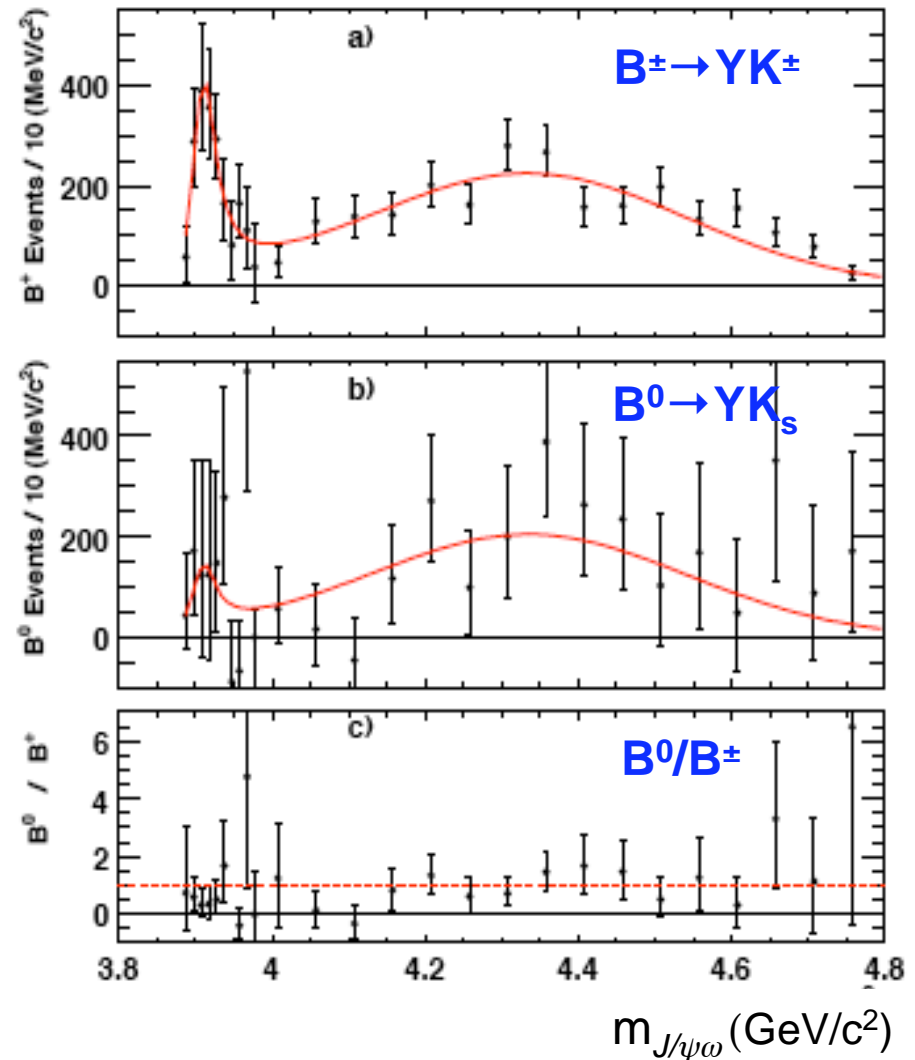
$$M(Y) = (3914.3^{+3.8}_{-3.4}(\text{stat})^{+1.6}_{-1.6}(\text{syst})) \text{ MeV}/c^2$$

$$\Gamma(Y) = (33^{+12}_{-8}(\text{stat})^{+0.6}_{-0.6}(\text{syst})) \text{ MeV}.$$

- **Belle's Evidence for  $B \rightarrow YK$  ( $Y \rightarrow J/\psi\omega$ ) is confirmed**
  - $\sim 30\text{MeV}$  lower mass than Belle's
  - Narrower width
  - Preliminary BF estimate similar to the Belle's ( $\sim 10^{-5}$ )
  - No evidence for  $B \rightarrow X(3872)K$  ( $X \rightarrow J/\psi\omega$ )

### Belle's results

- $M = 3943 \pm 11(\text{stat}) \pm 13(\text{syst}) \text{ MeV}/c^2$
- $\Gamma = 87 \pm 22(\text{stat}) \pm 26(\text{syst}) \text{ MeV}$



# Discovery of the $Y(4260)$



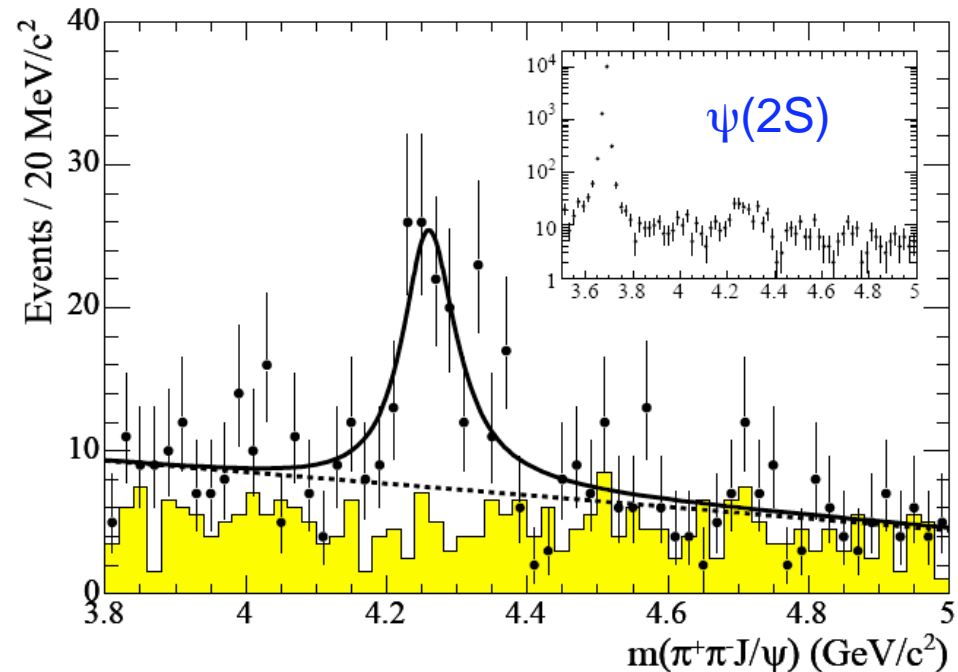
Phys. Rev. Lett. 95 (2005) 142001

Babar discovered in ISR events ( $233 \text{ fb}^{-1}$ )  $\rightarrow$

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

Study of  $J/\psi\pi^+\pi^-$  production

- ✗ ISR  $\psi(2S)$  as good benchmark
- ✗ Small mass recoiling against final state
- ✗ Low missing transverse momentum
- ✗  $\gamma_{\text{ISR}}$  detection not required



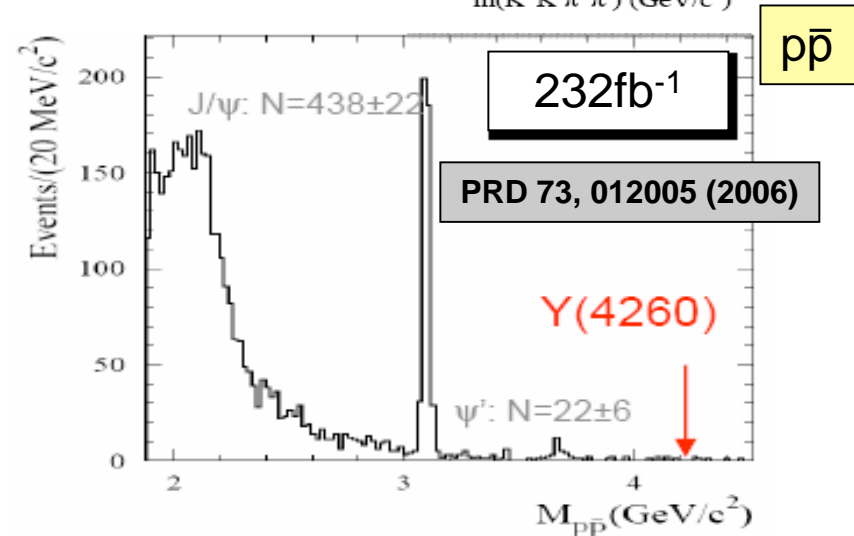
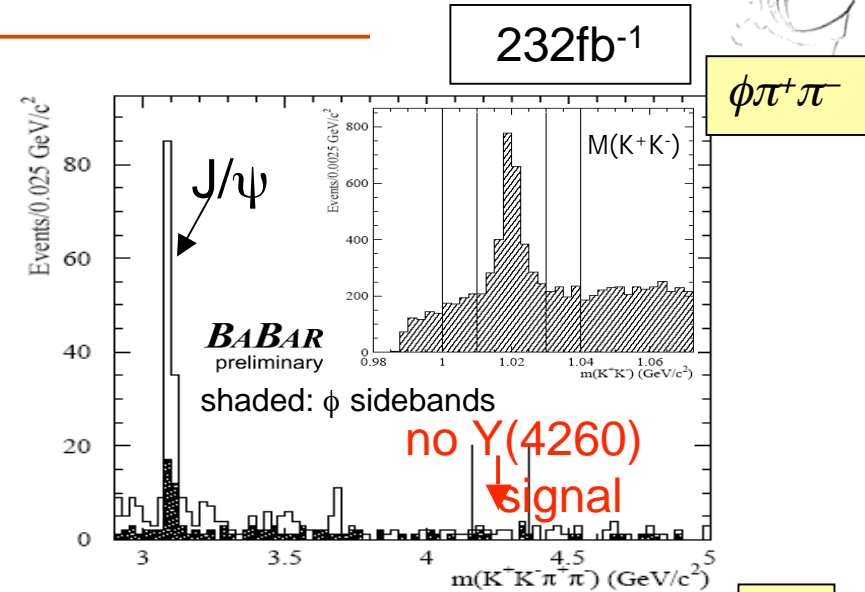
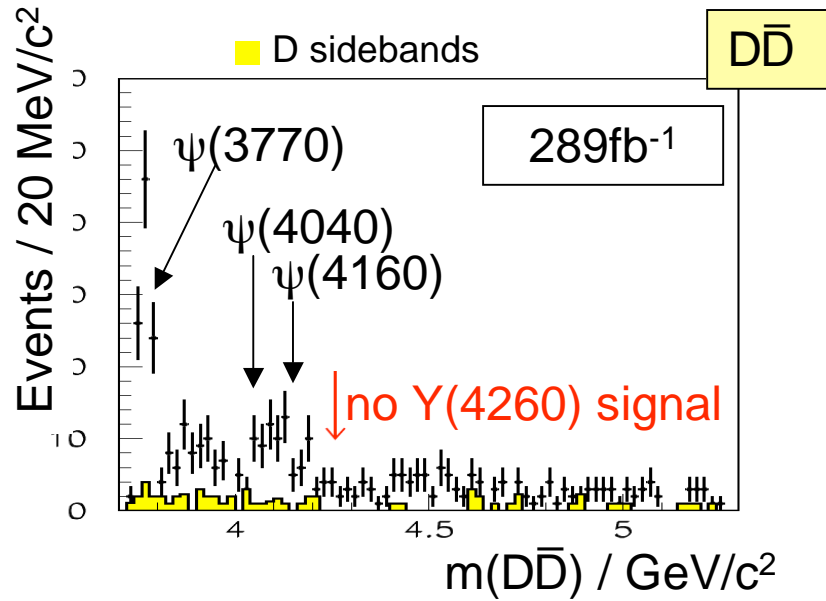
Broad structure  $Y(4260)$ :

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

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

Confirmations from CLEO-c, CLEO-III and Belle with some spread in the resonance parameters.

# Other $Y(4260)$ decays



$$\Gamma_{ee}^Y \times B(Y(4260) \rightarrow \pi^+ \pi^- \phi) < 0.4 \text{ eV} \quad 90\% \text{ CL} \quad \text{No signal}$$

$$\frac{B(Y(4260) \rightarrow D \bar{D})}{B(Y(4260) \rightarrow \pi^+ \pi^- \psi)} < 7.6 \quad 95\% \text{ CL} \quad \text{No signal}$$

$$\frac{B(Y(4260) \rightarrow p \bar{p})}{B(Y(4260) \rightarrow \pi^+ \pi^- \psi)} < 0.13 \quad 90\% \text{ CL} \quad \text{No signal}$$

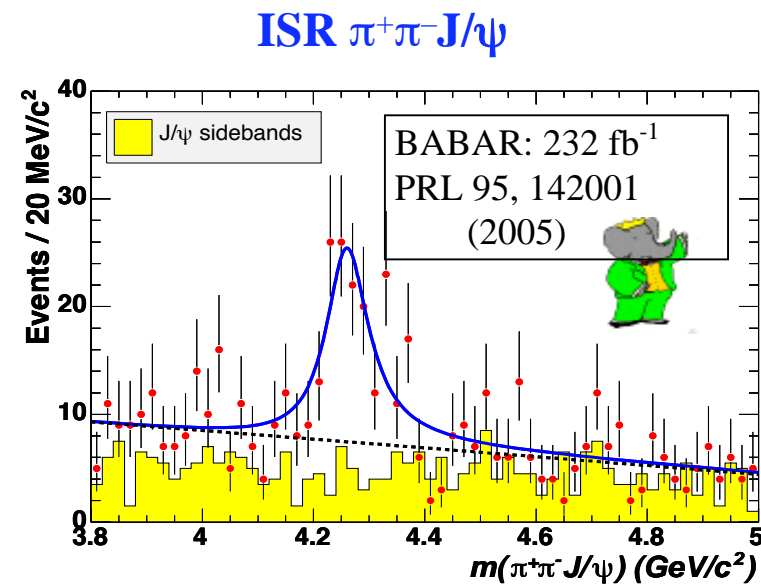
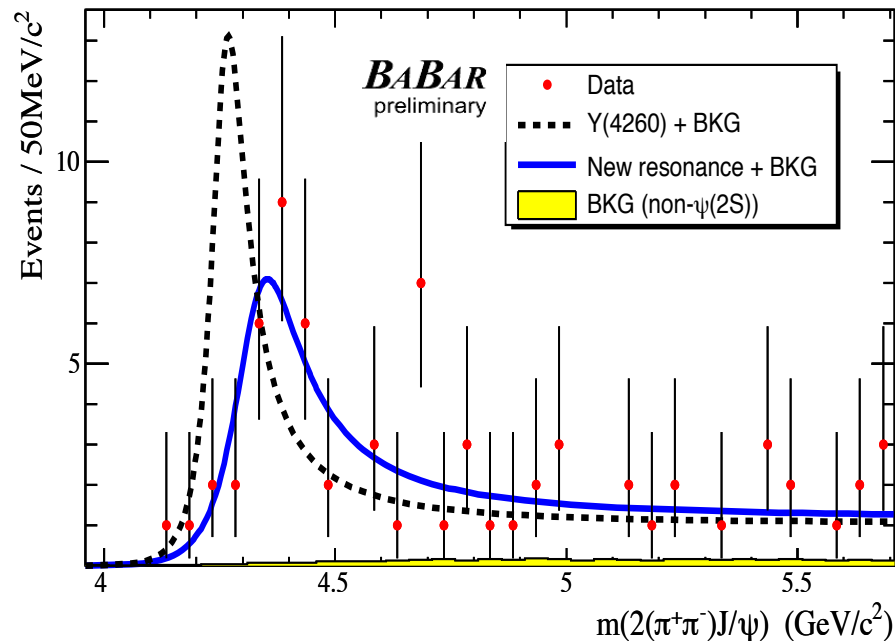
# Search for ISR $Y(4260) \rightarrow \pi^+\pi^-\psi(2S)$



$Y(4260)$  discovered in ISR  $\pi^+\pi^-J/\psi$ . How about  $\pi^+\pi^-\psi(2S)$  in ISR?

Search for  $Y(4260) \rightarrow \pi^+\pi^-\psi(2S)$ ,  $\psi(2S) \rightarrow \pi^+\pi^-J/\psi$

298 fb<sup>-1</sup>, hep-ex/0610057 Submitted to PRL



Single resonance fit  $\Rightarrow$  **mass=(4324 $\pm$ 24) MeV/c<sup>2</sup>,  $\Gamma$ =(172 $\pm$ 33) MeV** (statistical errors only)

Incompatible with  $\psi(4415)$ ; **Poorly described by  $Y(4260)$**

**Prob=4.5  $\cdot$  10<sup>-3</sup> that the two structures are the same**

# Interpretation of the $Y(4260)$



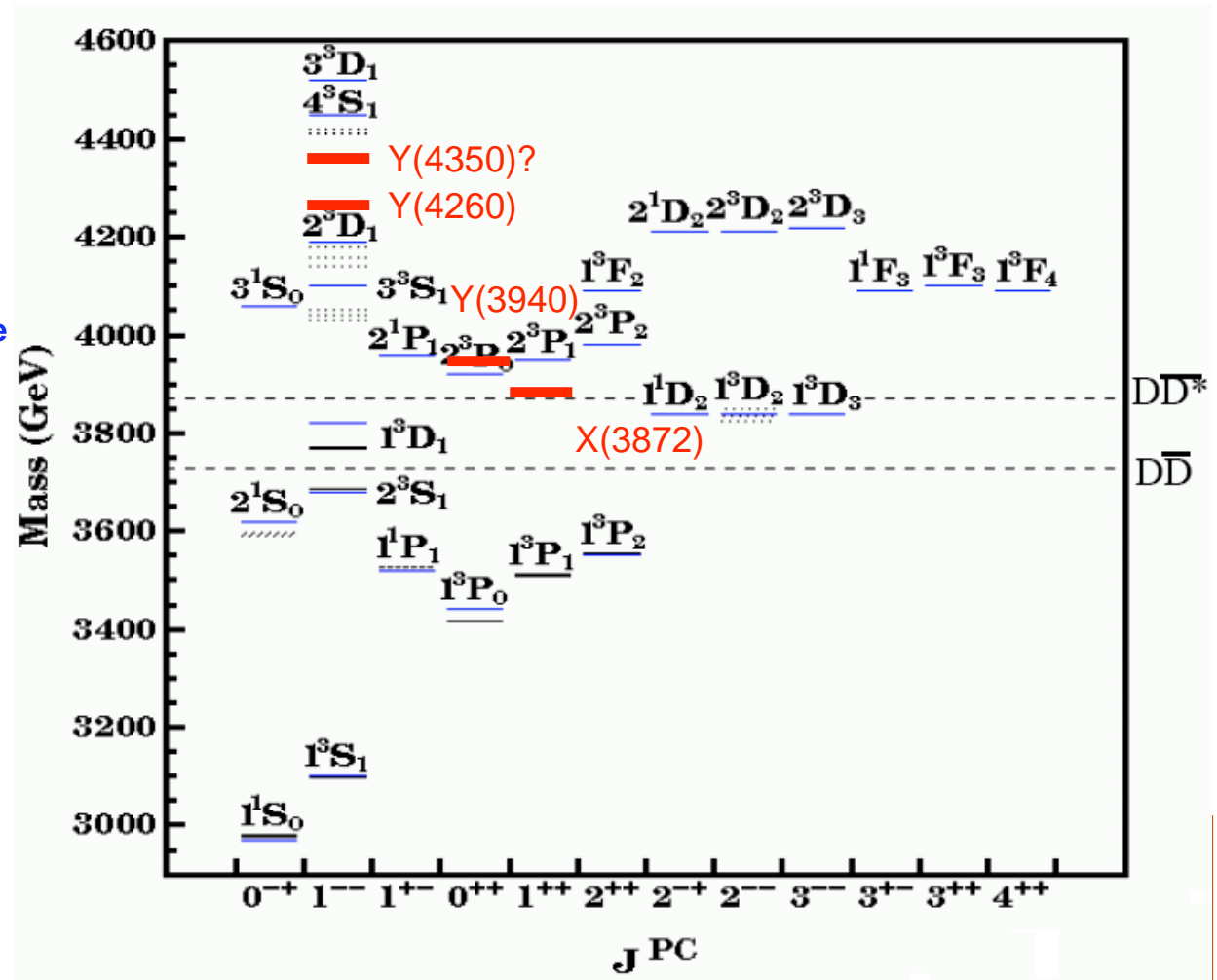
- No  $c\bar{c}$  assignment for  $1^{--}$  state
- Probably not a **glueball**
  - No evidence for  $Y(4260) \rightarrow \phi\pi\pi$
- **4 quark** state  $[cs][\bar{c}\bar{s}]$ ? (I. Bigi, L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer)
  - Should decay dominantly to  $\bar{D}_s D_s$
- **Hybrid** meson? (many authors)
  - $D\bar{D}$ ,  $D^*\bar{D}^*$ ,  $D\bar{D}^*$  decays suppressed
  - $D\bar{D}_1(2420)$  decays should dominate
- What if there are 2 different states?



# Summary and Outlook



- ✘ Several **new states** have been recently observed in the charmonium mass region.
- ✘ Their nature is still unknown
  - Update on X(3872)
  - New result for Y(3940)
  - Y(4260) and a new structure at 4350 MeV/c<sup>2</sup>
- ✘ Several hypothesis have been formulated
- ✘ Need **more experimental data to discriminate** among the different models:
  - Quantum numbers
  - Decay modes
  - Branching ratios
  - Angular distributions
  - Charged partners



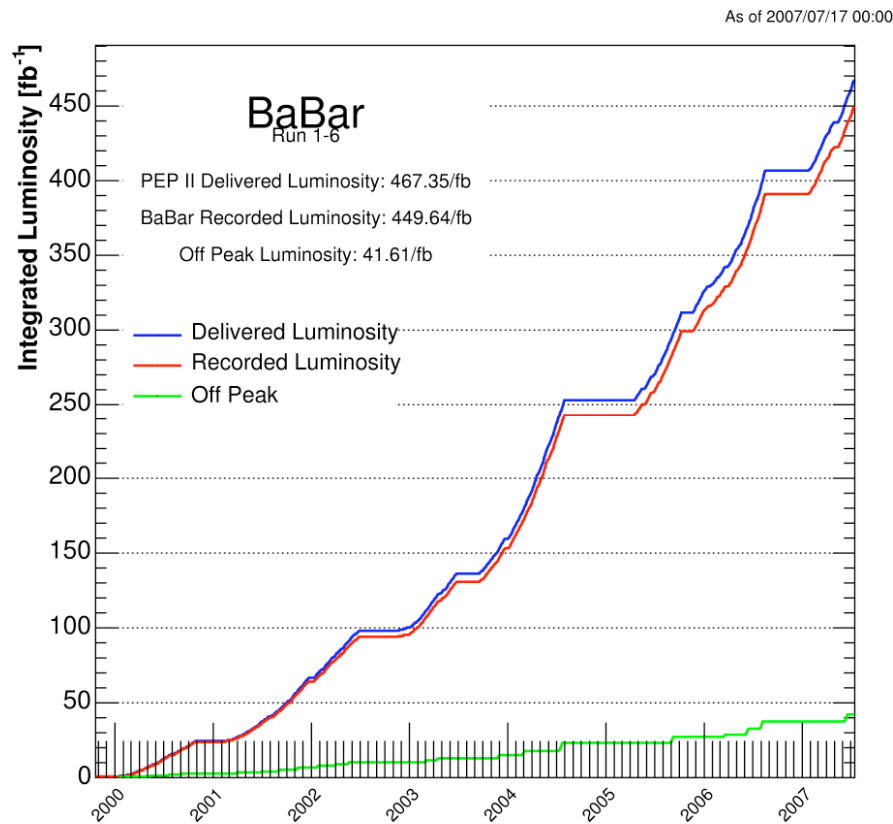


**Backup slides**

# BaBar experiment at SLAC



- ✘ Peak luminosity  $1.12 \times 10^{34} \text{cm}^{-2} \text{sec}^{-1}$
- ✘ Recorded  $\sim 450 \text{fb}^{-1}$  on the Y(4S) peak



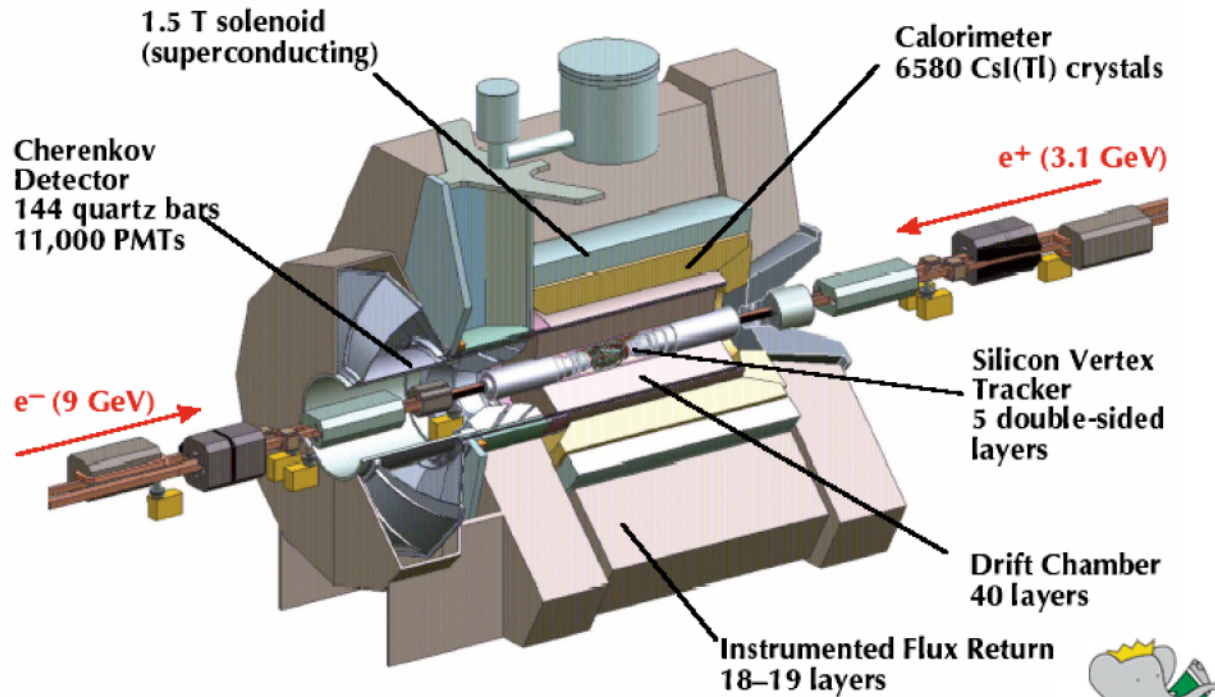
- ✘  $e^+e^-$  CM energy  $\sim 10.58 \text{ GeV}$
- ✘ boost  $\beta\gamma \sim 0.56$
- ✘  $\sim 600$  physicist from 80 institution in 11 countries



# The Babar detector



The BaBar Detector

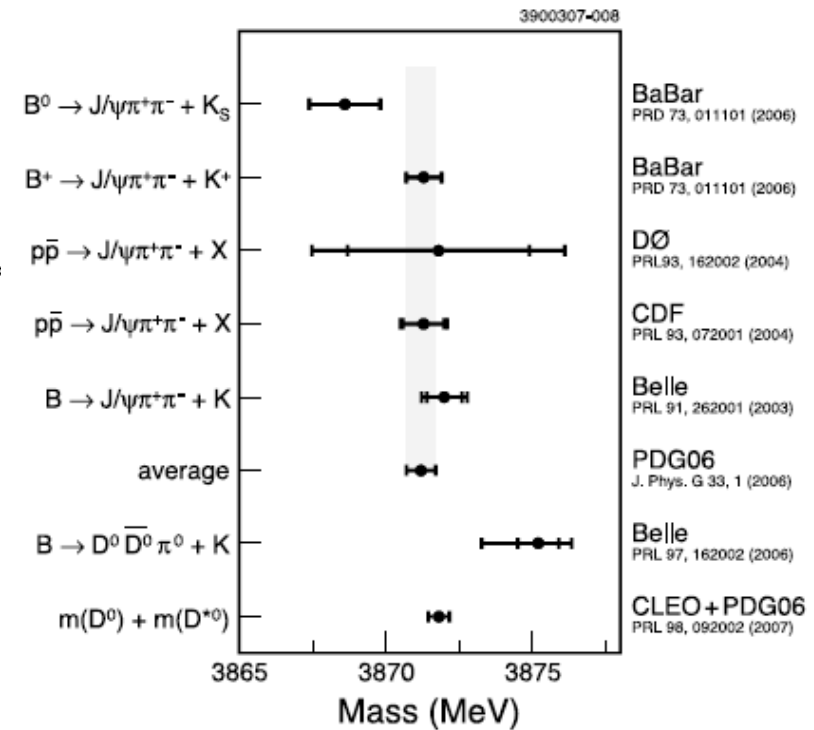


Peak luminosity:  $12.1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

# X(3872)



final state	X(3872) branching fraction
$\pi^+\pi^-J/\psi$	$(11.6 \pm 1.9) \times 10^{-8} / \mathcal{B}_{B^+ \rightarrow X(3872)K^+} (> 10\sigma)$
$\pi^-\pi^0J/\psi$	not seen
$\gamma\chi_{c1}$	$< 0.9 \times \mathcal{B}_{\pi^+\pi^-J/\psi}$
$\gamma J/\psi$	$(3.3 \pm 1.0 \pm 0.3) \times 10^{-6} / \mathcal{B}_{B^+ \rightarrow X(3872)K^+} (> 4\sigma)$ $(0.14 \pm 0.05) \times \mathcal{B}_{X(3872) \rightarrow \pi^+\pi^-J/\psi} (4.0\sigma)$
$\eta J/\psi$	$< 7.7 \times 10^{-6} / \mathcal{B}_{B^+ \rightarrow X(3872)K^+}$
$\pi^+\pi^-\pi^0J/\psi$	$(1.0 \pm 0.4 \pm 0.3) \times \mathcal{B}_{X(3872) \rightarrow \pi^+\pi^-J/\psi} (4.3\sigma)$
$D^0\bar{D}^0$	$< 6 \times 10^{-5} / \mathcal{B}_{B^+ \rightarrow X(3872)K^+}$
$D^+D^-$	$< 4 \times 10^{-5} / \mathcal{B}_{B^+ \rightarrow X(3872)K^+}$
$D^0\bar{D}^0\pi^0$	$(12.2 \pm 3.1^{+2.3}_{-3.0}) \times 10^{-5} / \mathcal{B}_{B^+ \rightarrow X(3872)K^+}^a (6.4\sigma)$

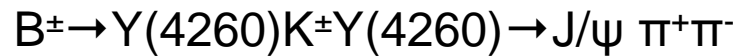


# Y(4260) in B decays



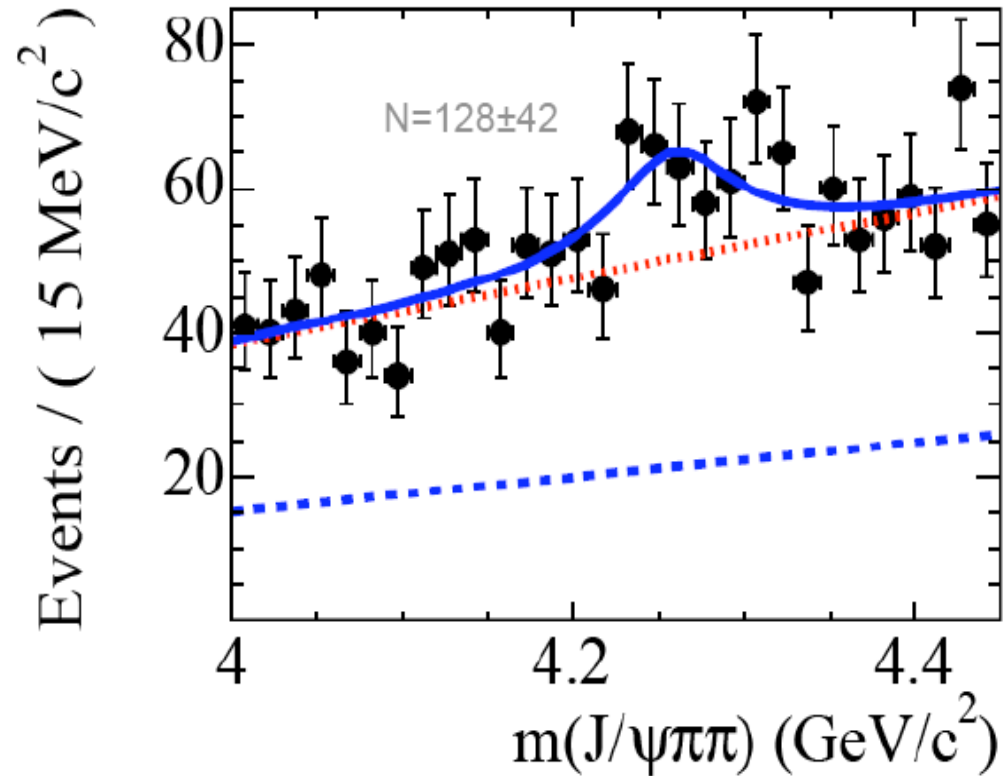
PRD 73,011101 (2006)

Weak indication of Y(4260) production in exclusive B decay:



✗ 3σ excess

✗ Need confirmation



$$B(B^- \rightarrow Y(4260)K^-) \times B(Y(4260) \rightarrow \psi\pi^+\pi^-) = (2.0 \pm 0.7 \pm 0.2) \times 10^{-5}$$

211 fb<sup>-1</sup>

# No $Y(4260)$ in R scan



$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

