Elisabetta Prencipe
on behalf of the
BaBar Collaboration

Charmonium Physics:

RECENT RESULTS
from BaBar

Quarkonium Working Group 2007 – Hamburg, DESY

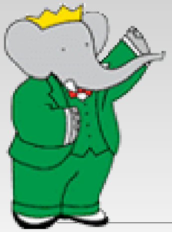
Outline

Charmonium physics at the *B-factories*:

☑ motivations
☑ status of the works
☑ results

- *X(3872)*
- *Y(3940)*

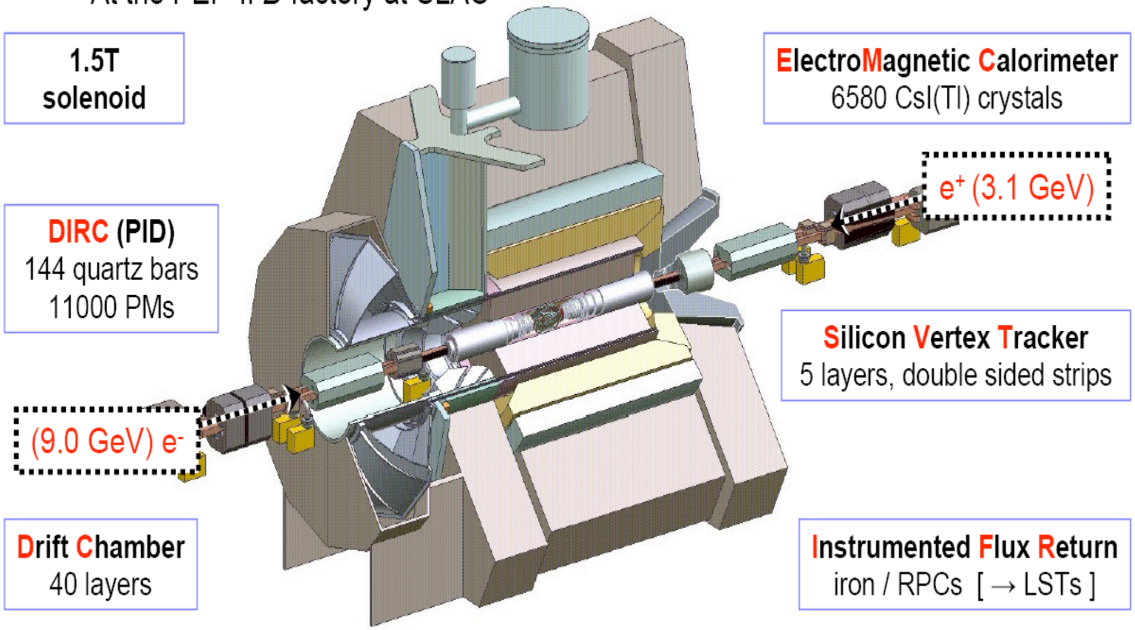
☑ interpretations
☑ outlook



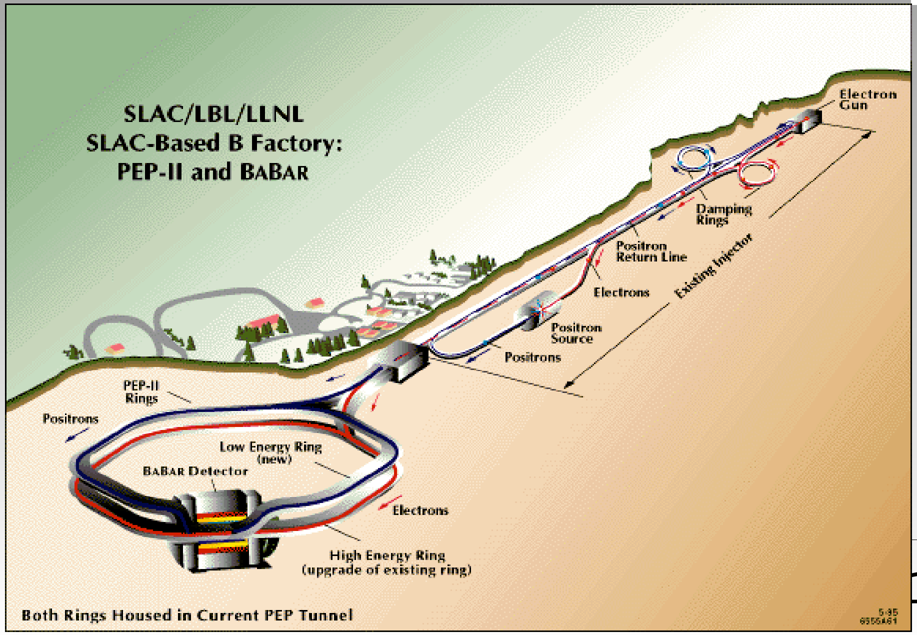
BaBar: Who? Where? What?

- Asymmetric e^+e^- beam @ PEPII
- Peak luminosity: $1.2\times10^{34}cm^{-2}s^{-1}$
- 500M $B\bar{B}$ produced (2007)

- At the PEP-II *B*-factory at SLAC



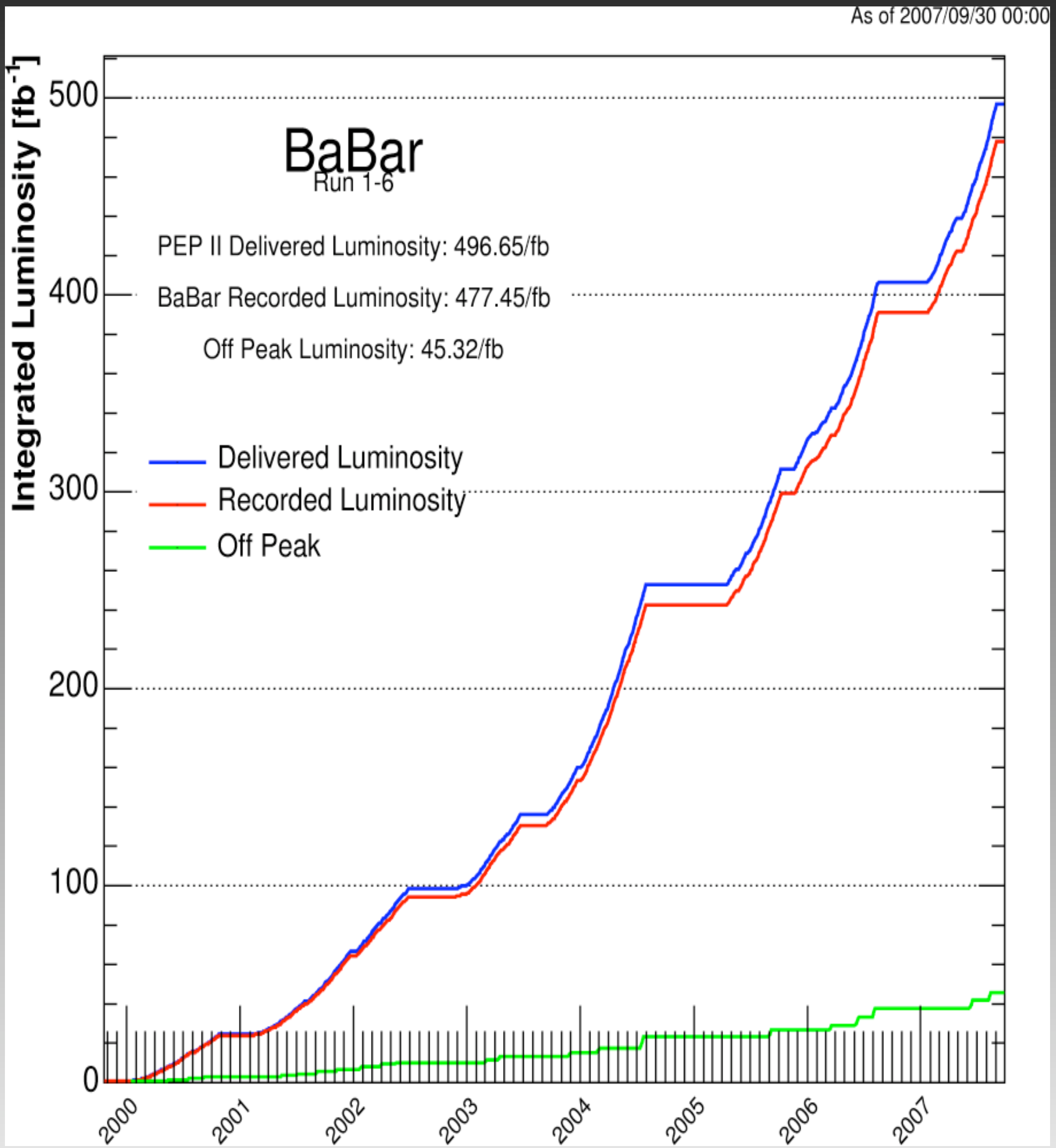
- *BABAR* collaboration consists 11 countries and 630 physicists!



$$\sqrt{s} = 10.58 \text{ GeV}$$

Charmonium Production at BaBar

- BaBar is a B-factory.
- The main goal of the BaBar Physics has been the measurement of the sides and the angles of the Unitarity Triangle, and rare decays.
- B-factories have been demonstrated to be also a huge source of $c\bar{c}$ production.



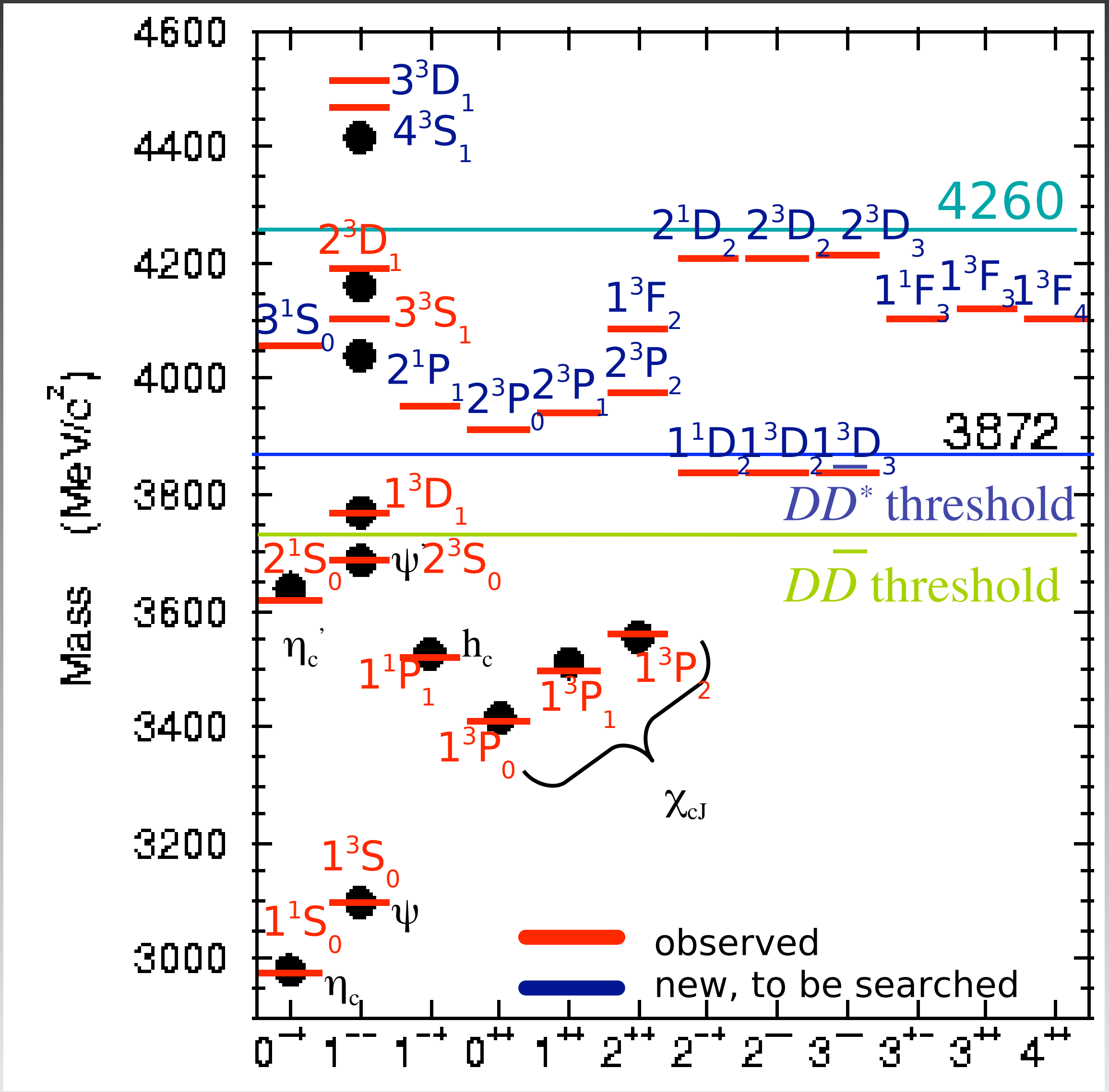
Some numbers:

469×10^6 $N(B\bar{B})$, 581×10^6 $N(c\bar{c})$

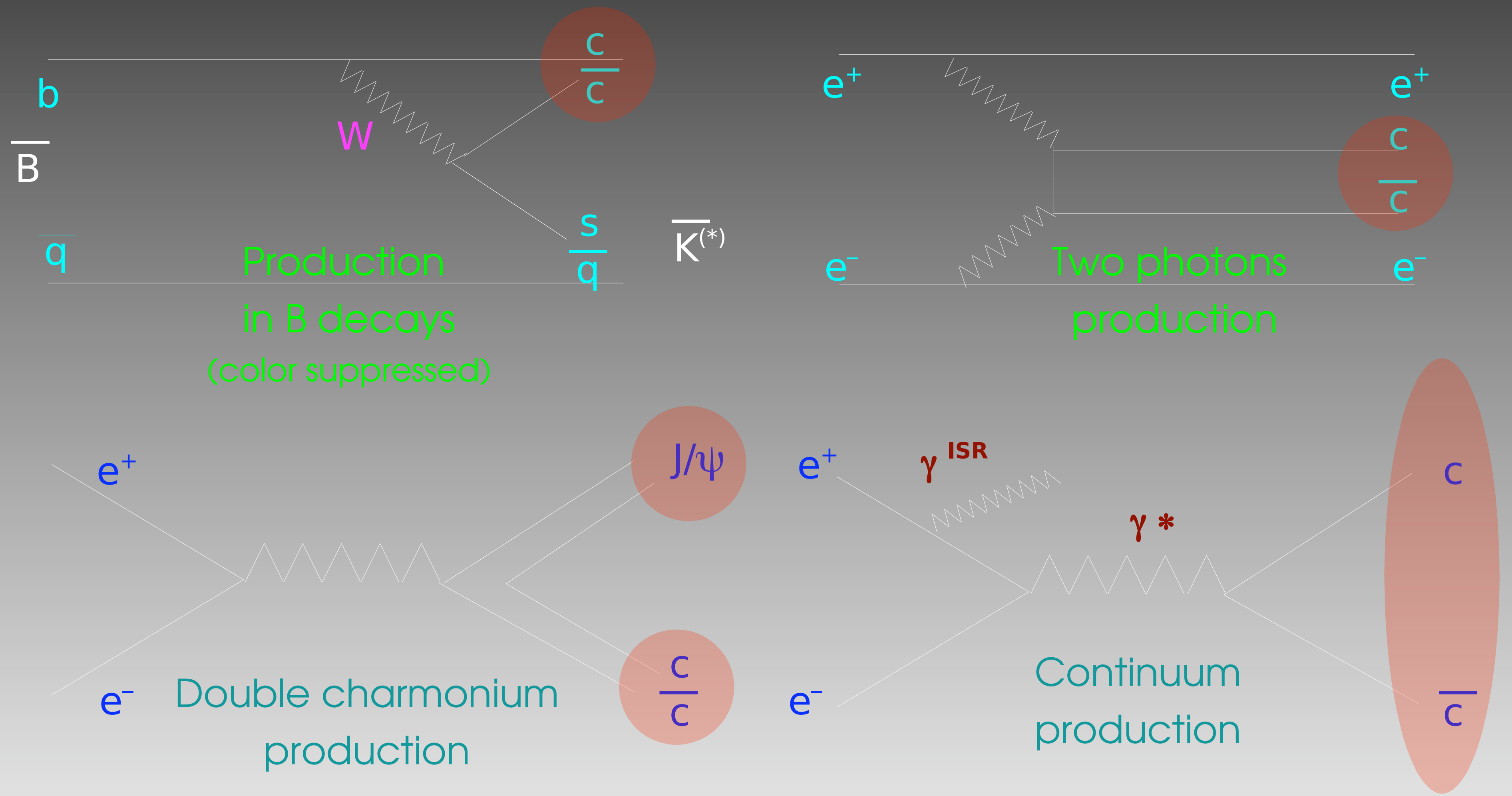
- 16M J/ψ, 6M $\psi(2S)$ in ISR
- 9M J/ψ, 3M $\psi(2S)$ in B decays

Charmonium Spectroscopy

- Charmonia are important for full understanding of the **STRONG INTERACTIONS**.
- Well known charmonium states below the D$\bar{D}$ threshold and some 1^{--} states above threshold
- States below the D$\bar{D}$ threshold in good agreement with theoretical models
- New states recently observed at the B factories **do not fit theoretical expectations**
- BaBar results on the **X(3872)** and **Y(3940)** will be presented



B-factory: charmonium production processes



X(3872)

X(3872): Discovery

Belle: PRL 91 (2003) 262003
BaBar: PRD71 (2005) 071103
BaBar: PRD73 (2006) 011101
BaBar: PRD74 (2006) 071101
CDF: PRL93 (2004) 072001
D0: PRL93 (2004) 162002

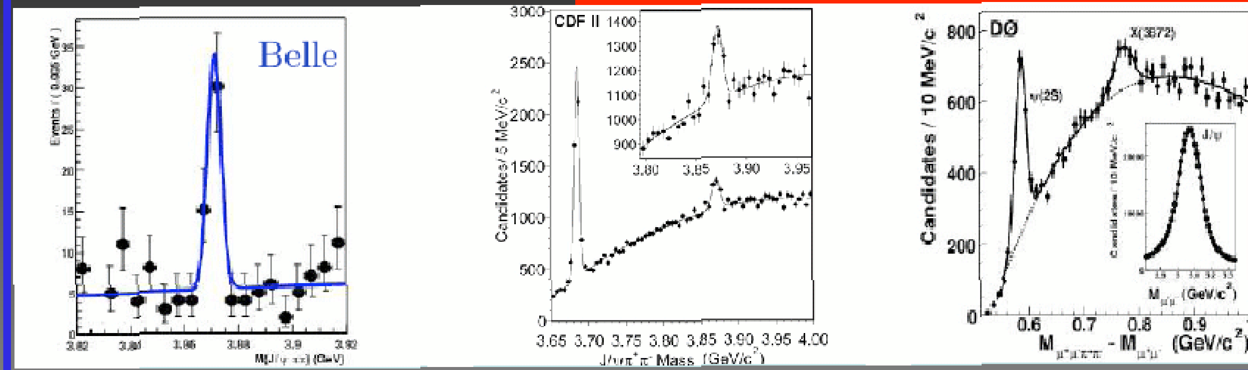
Discovered by Belle:

$M_X = (3871.2 \pm 0.5)$ MeV/c^2

Confirmed by:

- BABAR
- CDF
- D0

old value



$B^+ \rightarrow X(3872) K^+$

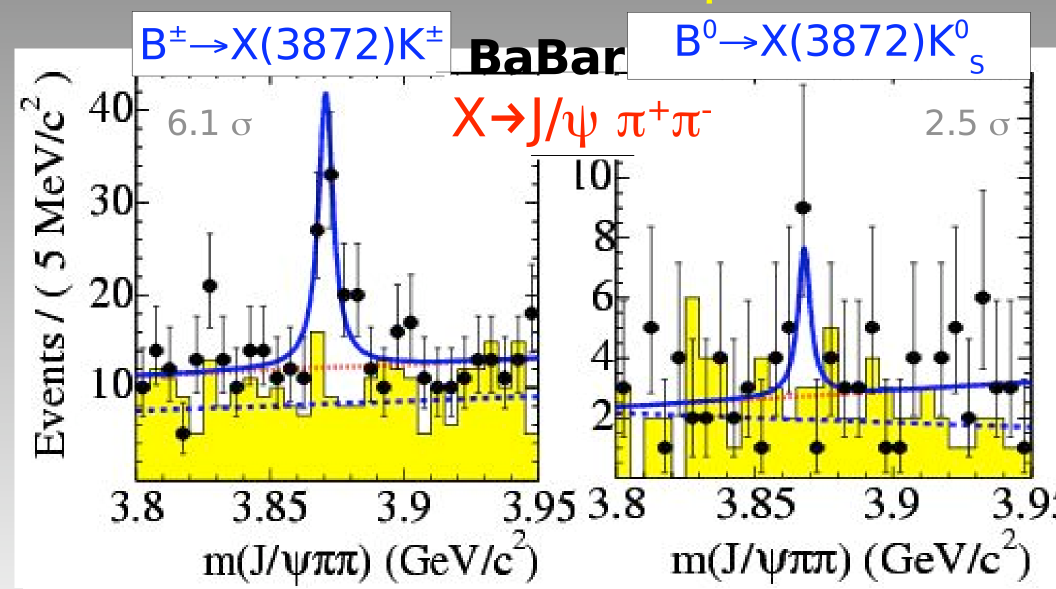
$\rightarrow J/\psi\ \pi^+\pi^-$

Now (PDG07):

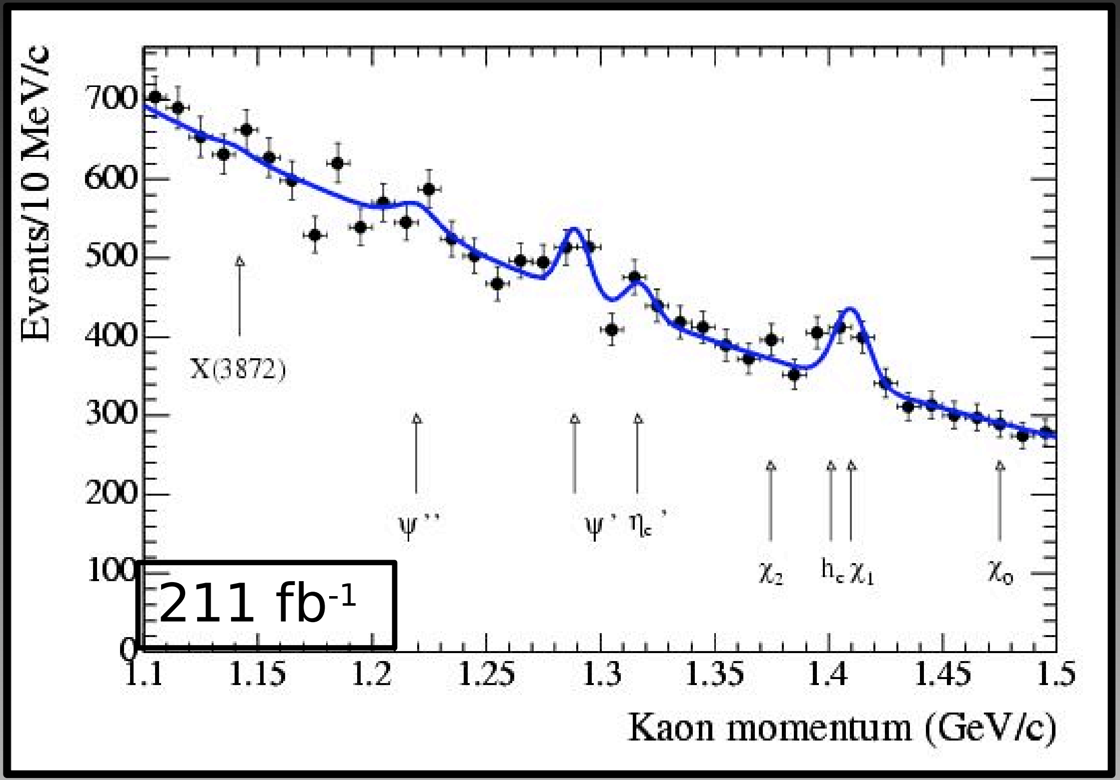
$M = 3871.4 \pm 0.6$ MeV/c^2

$\Gamma < 2.3$ MeV @90% CL

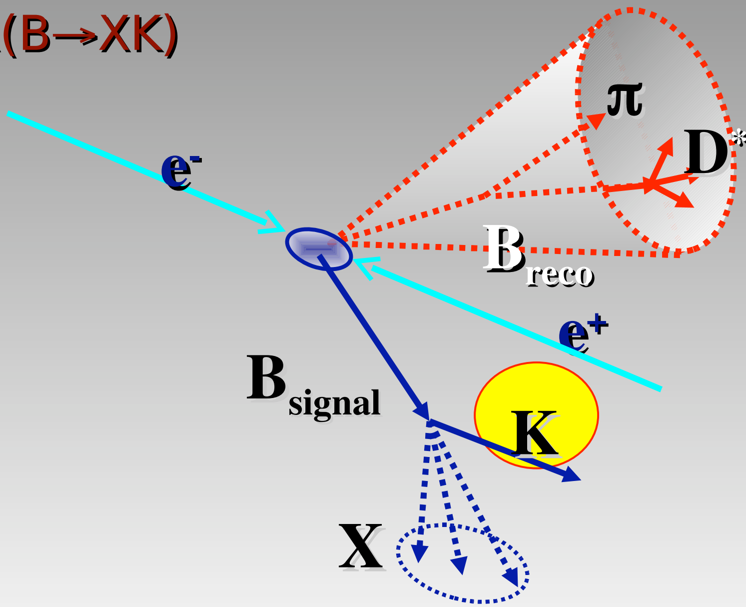
Combined results



Inclusive searches



- Fully reconstruct B_{reco} in hadronic modes
- The **X** mass distribution can be obtained from the momentum distribution of **$K^{\pm}$**
- Huge background due to secondary $K^{\pm}$ tracks
- Observation of X states independent from the decay mode
- Absolute measurement of BR(B→XK)



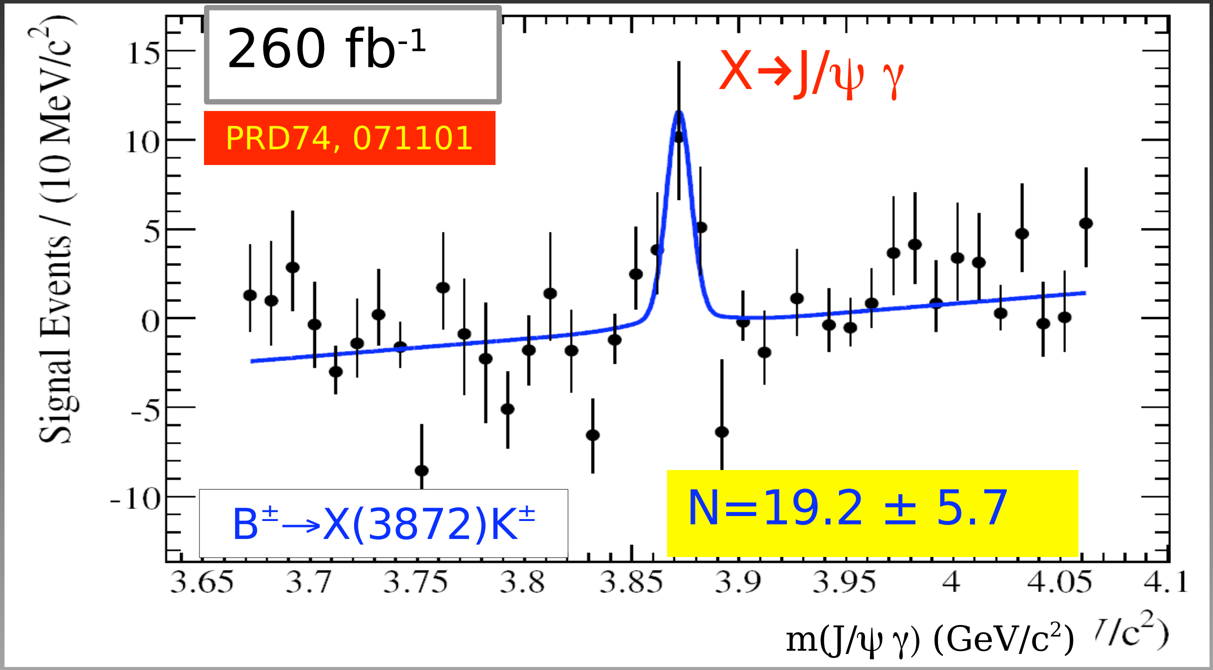
From BaBar-Belle average:
$BR(B^{\pm}\rightarrow X(3872)K^{\pm}, X(3872)\rightarrow J/\psi\pi^{+}\pi^{-})=$
$=(13.3\pm2.5)\cdot10^{-6}$

$BR(B^{\pm}\rightarrow X(3872)K^{\pm})<3.2\cdot10^{-4}$ at 90% CL
$BR(X(3872)\rightarrow J/\psi\pi^{+}\pi^{-})>4.2\%$ at 90% CL

Exclusive searches in BABAR

- $B^{\pm} \to J/\psi\, \gamma\, K^{\pm}$

confirms the Belle result



Implications:

- C=+1 for the X(3872)
- I=1 for the ($\pi\pi$) in $J/\psi\pi^+\pi^-$
- forbidden $J/\psi\pi^0\pi^0$, $J/\psi\pi^0$,
- and $J/\psi\eta$ decays, but:

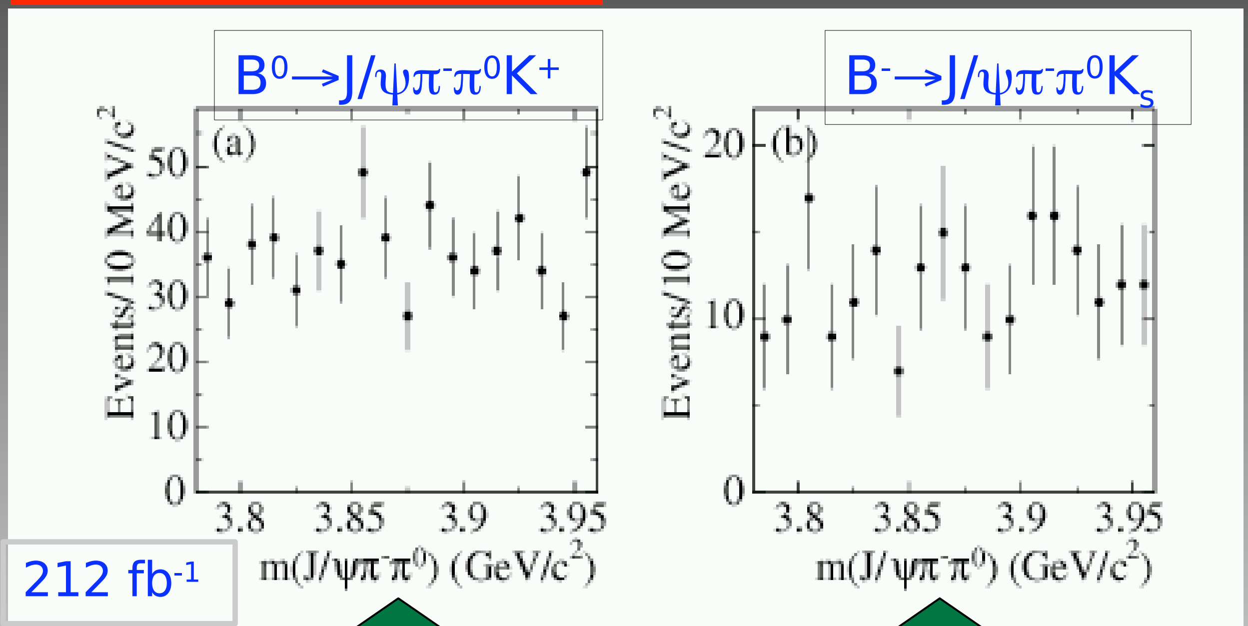
I=0 favored for X(3872), so the $J/\psi\pi^+\pi^-$ decay is isospin violating (small width)

$$\mathcal{B}(B^+ \to X(3872)K^+;\, X \to J/\psi\, \gamma) = (3.4 \pm 1.0 \pm 0.3) \times 10^{-5}$$

Search for X(3872) charged partners

- Decay $X(3872) \to J/\psi\rho$ against charmonium hypothesis
- If X(3872) is not charmonium it could be isospin multiplet
- $BR(B \to X^- K) \sim 2\ BR(B \to X^0 K)$

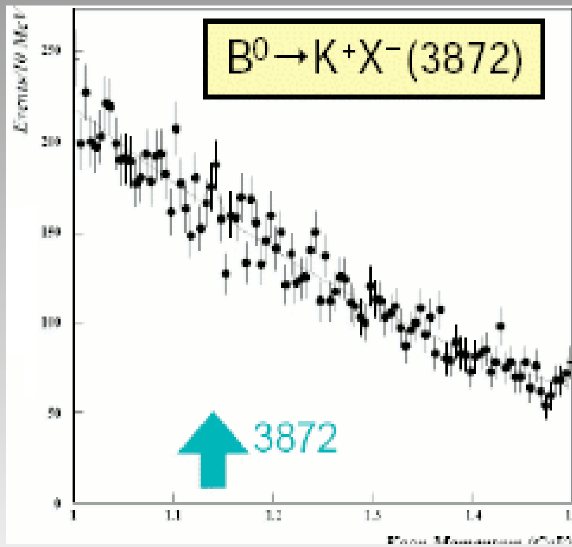
PRD 71, 031501 (2005)



No charged partner observed

No evidence found!
I = 0 favored for X(3872)

PRL 96, 052002 (2006)



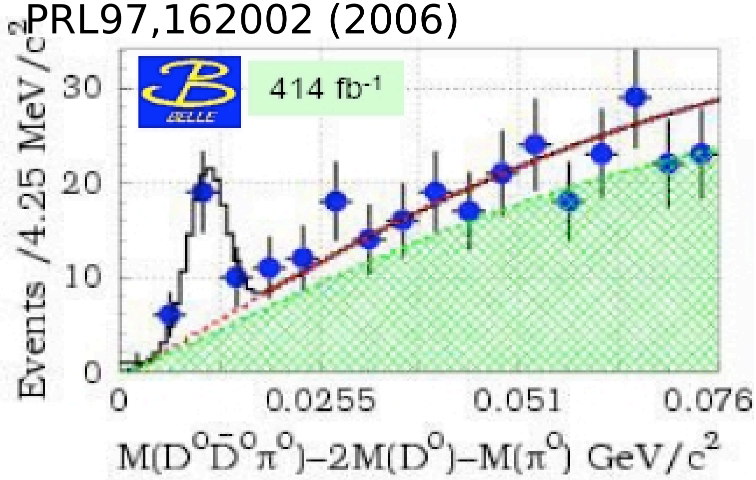
$BR(B^0 \to X^- K^+) \cdot BR(X^- \to J/\psi\pi^-\pi^0) < 5.4 \cdot 10^{-6}$ at 90% CL

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

X(3872): Still some surprises…

- Belle: looking at $B \to \bar{D}^0 D^0 \pi^0 K$

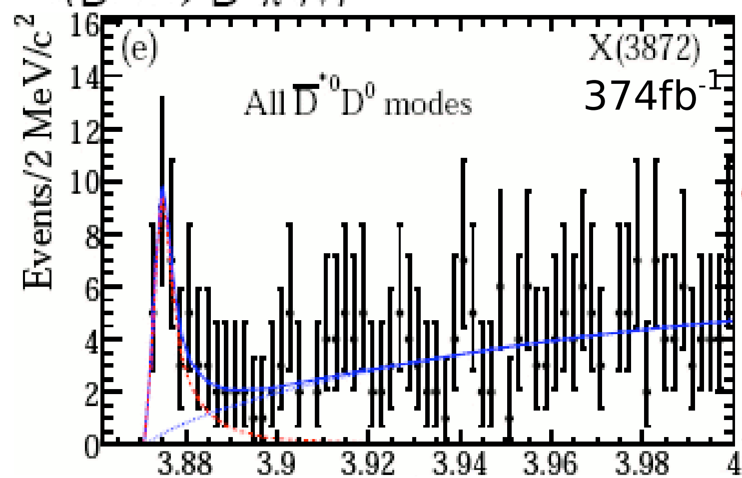
PRL97,162002 (2006)



- Excess in the $\bar{D}^0 D^0 \pi^0$ invariant mass
  - $M = 3875.4 \pm 0.7\ ^{+1.2}_{-2.0}$ MeV/c^2

- BaBar: looking at $B \to \bar{D}^0 D^{*0} K$

$(D^{*0} \to D^0\pi^0/\gamma)$

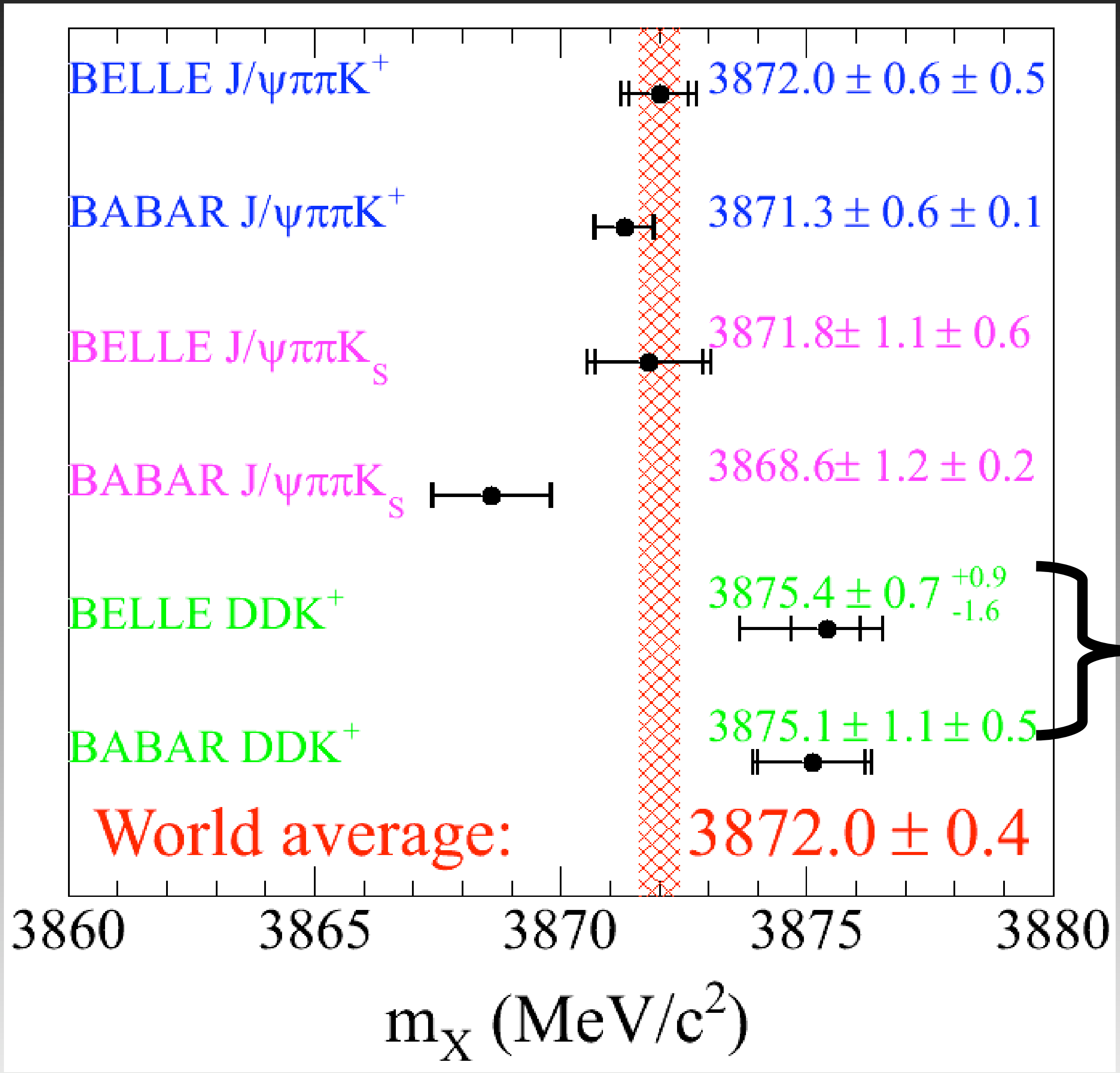


- Excess in the $\bar{D}^0 D^{*0}$ invariant mass
  - $M = 3875.1 \pm 1.1 \pm 0.5$ MeV/c^2

experiment	mass (MeV/c²)	Branching fraction
BELLE	$3875.2 \pm 0.7^{+0.3}_{-1.6} \pm 0.8$	$(1.22 \pm 0.31^{+0.23}_{-0.30}) \times 10^{-4}$ B^0+B^+
BABAR	$3875.1 \pm 1.1 \pm 0.5$	$(1.67 \pm 0.36 \pm 0.58) \times 10^{-4}$ B^+

Good agreement between BaBar and Belle, BUT 4σ away from $m_{J/\psi\pi\pi}$!

X(3872) mass values



Not included in the average

$X \rightarrow D(*)\bar{D}(*)$

BaBar: hep-ex/0708.1565
submitted to PRD-RC

347 fb^{-1}

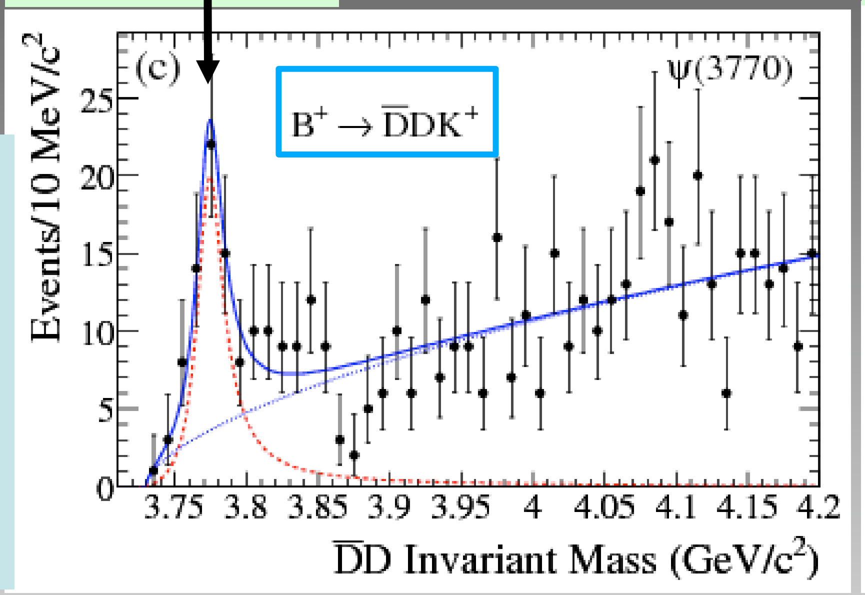
BaBar studied 8 channels:

$B^+ \rightarrow \bar{D}^0 D^{*0} K^+ + \bar{D}^{*0} D^0 K^+$
$B^0 \rightarrow \bar{D}^0 D^{*0} K^0 + \bar{D}^{*0} D^0 K^0$

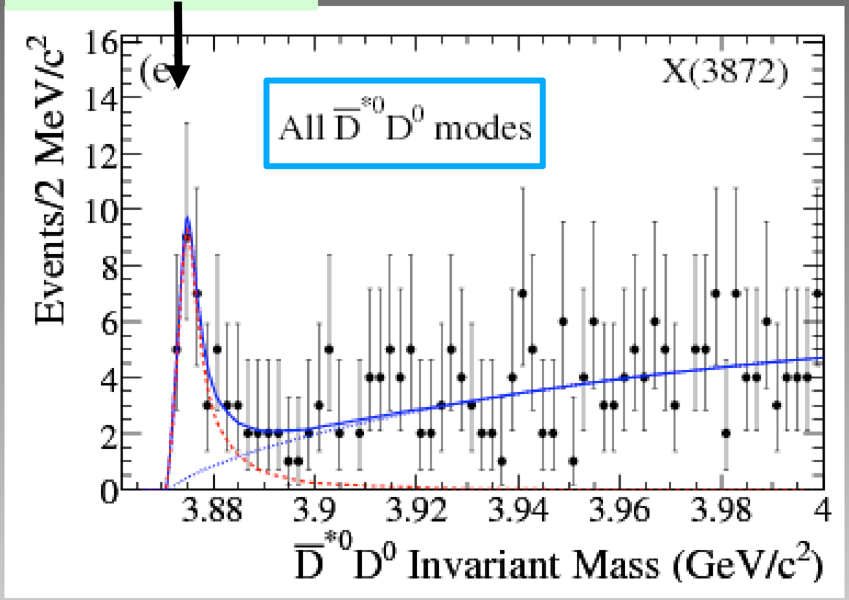
$D^{*0} \rightarrow D^0\gamma$ and $D^0\pi$

No $X \rightarrow D^0\bar{D}^0$

ψ (3770)



X(3872)



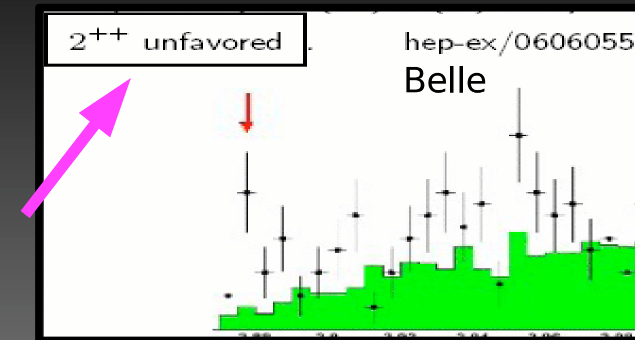
<u>Measured</u>:

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

$m - m_{D0+D0^*} = (4.3 \pm 0.7) \mathrm{GeV}/c^2$

Which Consequences?

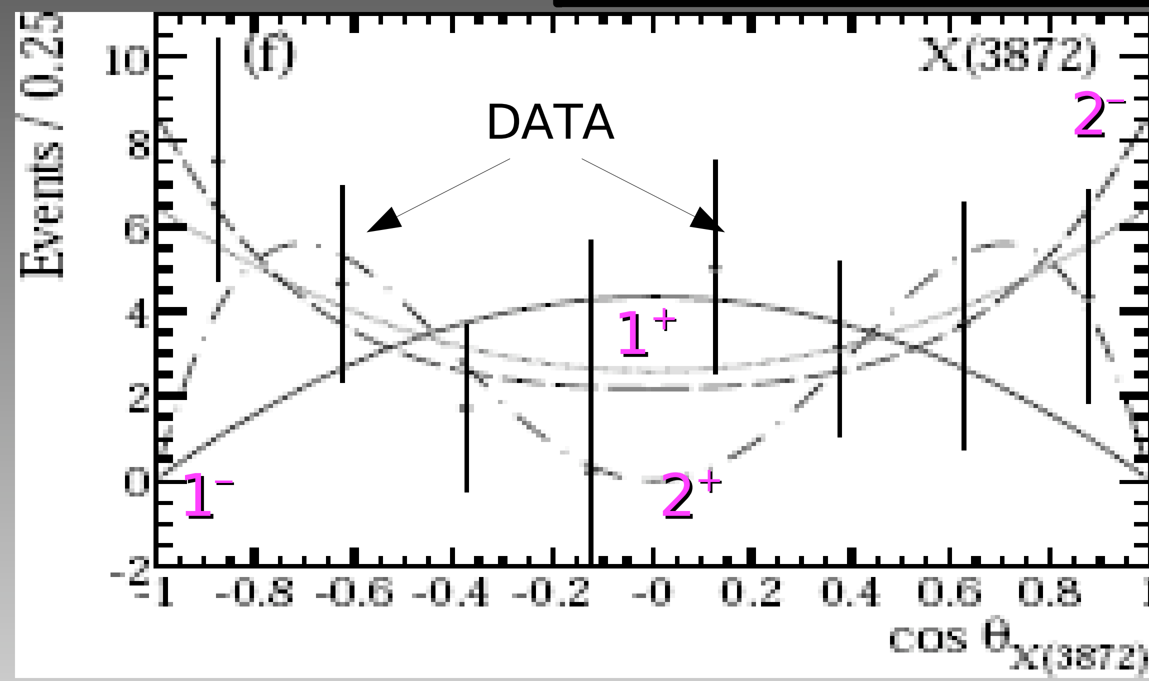
BaBar: hep-ex/0708.1565
submitted to PRD-RC



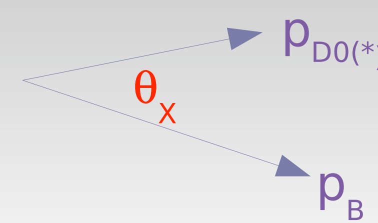
- 1^{++}: DD* in a S-wave $\propto$ q*
- 2^{++}:DDπ in a D-wave $\propto$ q^{*5}

q is the momentum of D in the X(3872) frame

J^P	$\chi^2/n.d.f$
1^-	9.8/7 S-wave
1^+	3.9/7 S-wave
1^+	2.5/6 S+D-wave
2^+	5.9/7
2^-	2.7/6



- $R = \frac{X(3872) \to D^0\bar{D}^0\pi^0}{X(3872) \to D^0\bar{D}^0\gamma} = 1.37 \pm 0.56$



Expected: 1.30 for a state proceeding only via $D^0\bar{D}^{0}$*

X(3872): interpretation

X(3872) likely NOT a charmonium state

Radial excitation of χ_{1c} (1^{++}) expected at 3950 MeV/c^2
No satisfactory $c\bar{c}$ assignment

Measurements:

- R(B0/B+) = 0.50±0.30±0.05 in $J/\psi\ \pi\ \pi$
- R(B0/B+) = 1.33±0.69±0.52 in $D^0\bar{D}^{*0}$

BaBar: PRD73 (2006) 011101

BaBar Preliminary

- Δm =2.7±1.3±0.2 MeV/c^2 in $J/\psi\ \pi\ \pi$
- Δm =0.7±1.9±0.3 MeV/c^2in $D^0\bar{D}^{*0}$

BaBar: PRD73 (2006) 011101

- M_X = 3871.4±0.6 MeV/c^2 in $J/\psi\ \pi\ \pi$
- M_X= 3875±1.1 MeV/c^2 in $D^0\bar{D}^{*0}$

Is it a molecular state?

PRD71 (2005) 074005

Is it a 4-quark state?

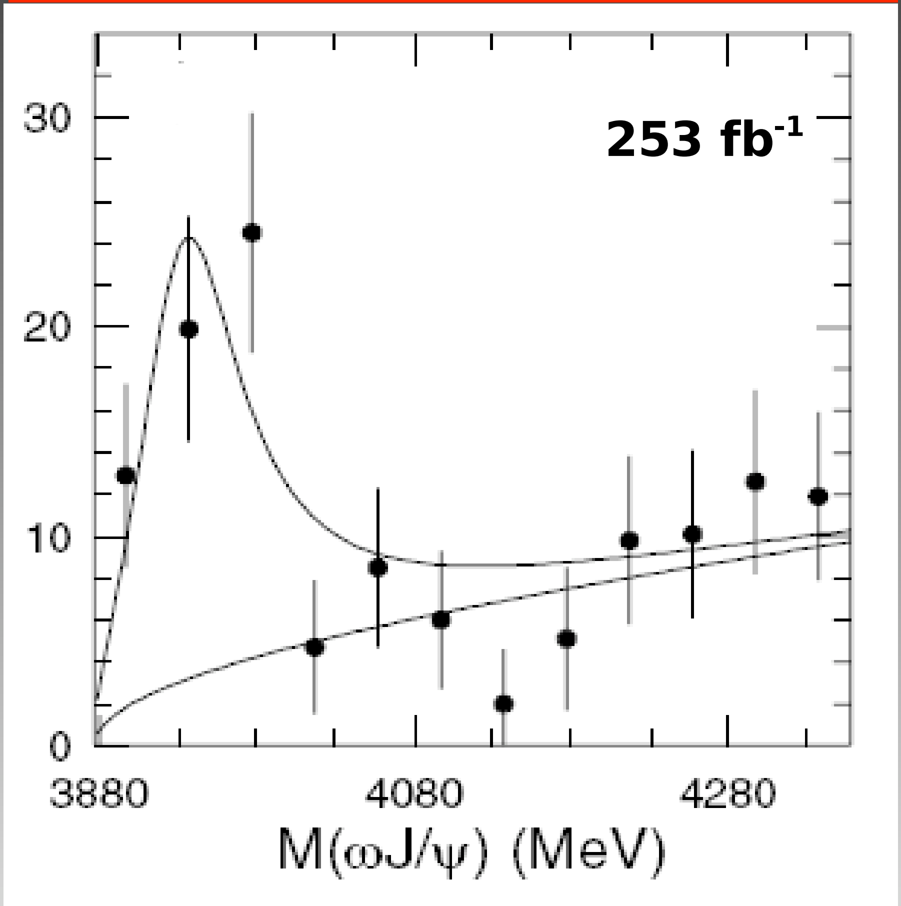
PRD71 (2005) 014028

...*what else?*

Y(3940)

Y(3940): the Discovery

BELLE: PRL 94, 182002 (2005)



- BELLE analysis of **$Y \to J/\psi\, 3\pi$**, with 3π mass in the ω region **($0.76 < m_{3\pi} < 0.805$ GeV/c^2)**.
- The analysis fits the m_{ES} distributions to extract the genuine signal as a function of 40 MeV $J/\psi\, 3\pi$ mass bins.
- Large enhancement seen near $J/\psi\, \omega$ threshold in plot below that combines both K^+ and K_S modes.

Searching in $B \to J/\psi\, \omega\, K$: Y(3940)

• To check purity of the sample, each event is weighted with $-\sqrt{10} * P_2(\cos(\theta))$, where P_2 is the second order Legendre polynomial (θ is ω -Dalitz-plot helicity angle)

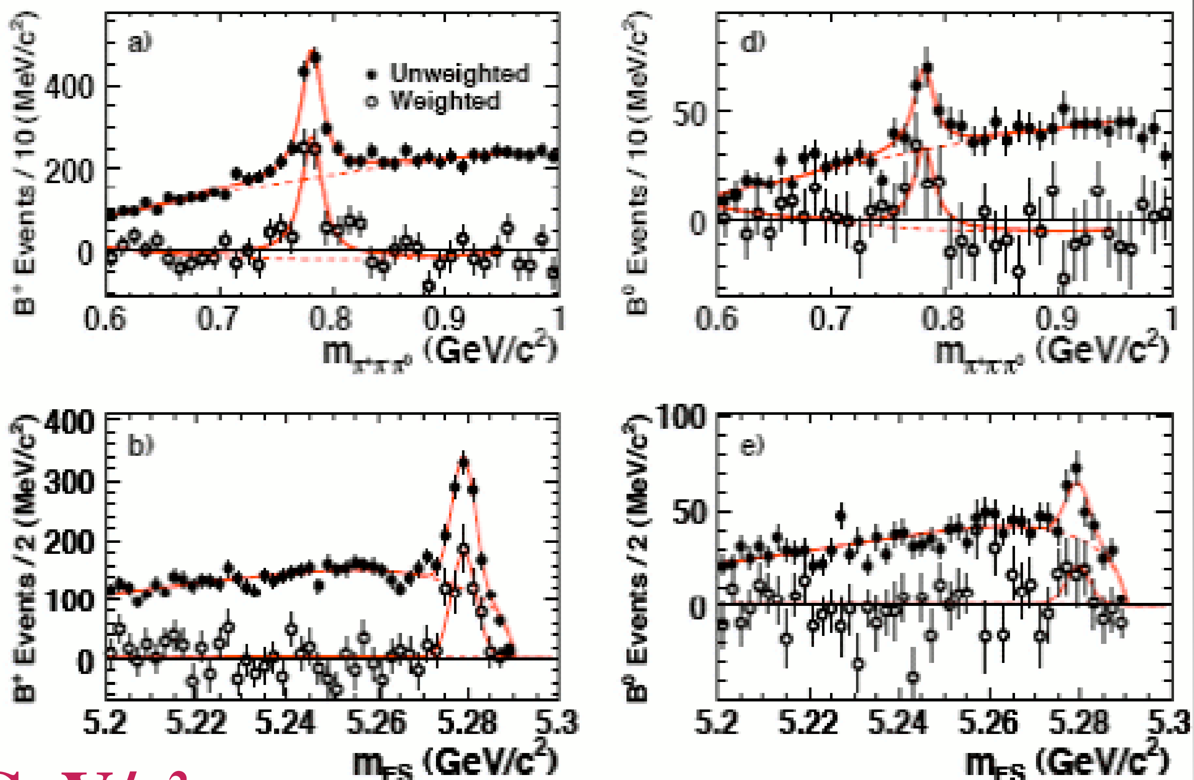
New result based on 350 fb^{-1}

Babar preliminary

$B^\pm \to YK^\pm$ $B^0 \to YK_s$

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

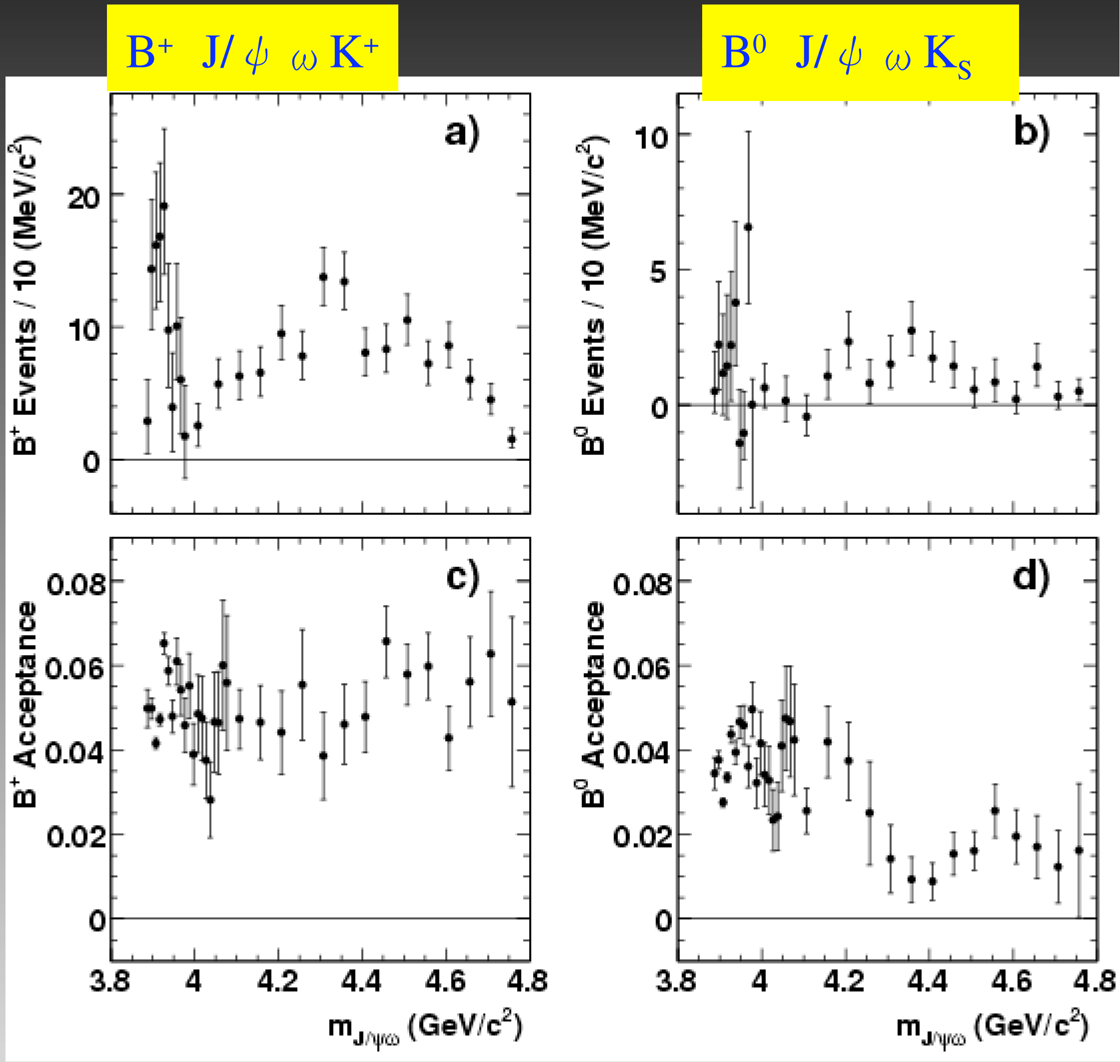
$B^0 \to YK_s$, $Y \to J/\psi\omega$,
$J/\psi \to \ell^+ \ell^-$ (ℓ =e,μ),
$\omega \to \pi^+\pi^-\pi^0$
$\pi^0 \to \gamma\gamma$, $K_s \to \pi^+\pi^-$



$0.7695 < m_{3\pi} < 0.7965$ GeV/c^2

Searching in B→J/ψ ω K: Y(3940)

- The J/ψ ω mass resolution is 5-7 MeV/c² near threshold and up to 10 MeV/c² at higher masses
- We fit m_{ES} in 10 MeV/c² bins of J/ψ 3π near threshold and in 50-MeV/c² bins at higher masses
- The measured values are corrected for efficiency and resolution effects (acceptance corrections)
- Lower acceptance at higher masses in the B^0 mode due to reduced efficiency for $K_S\pi^+\pi^-$ reconstruction



Y(3940): Results

BABAR on 350 fb^{-1}

BABAR Preliminary

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

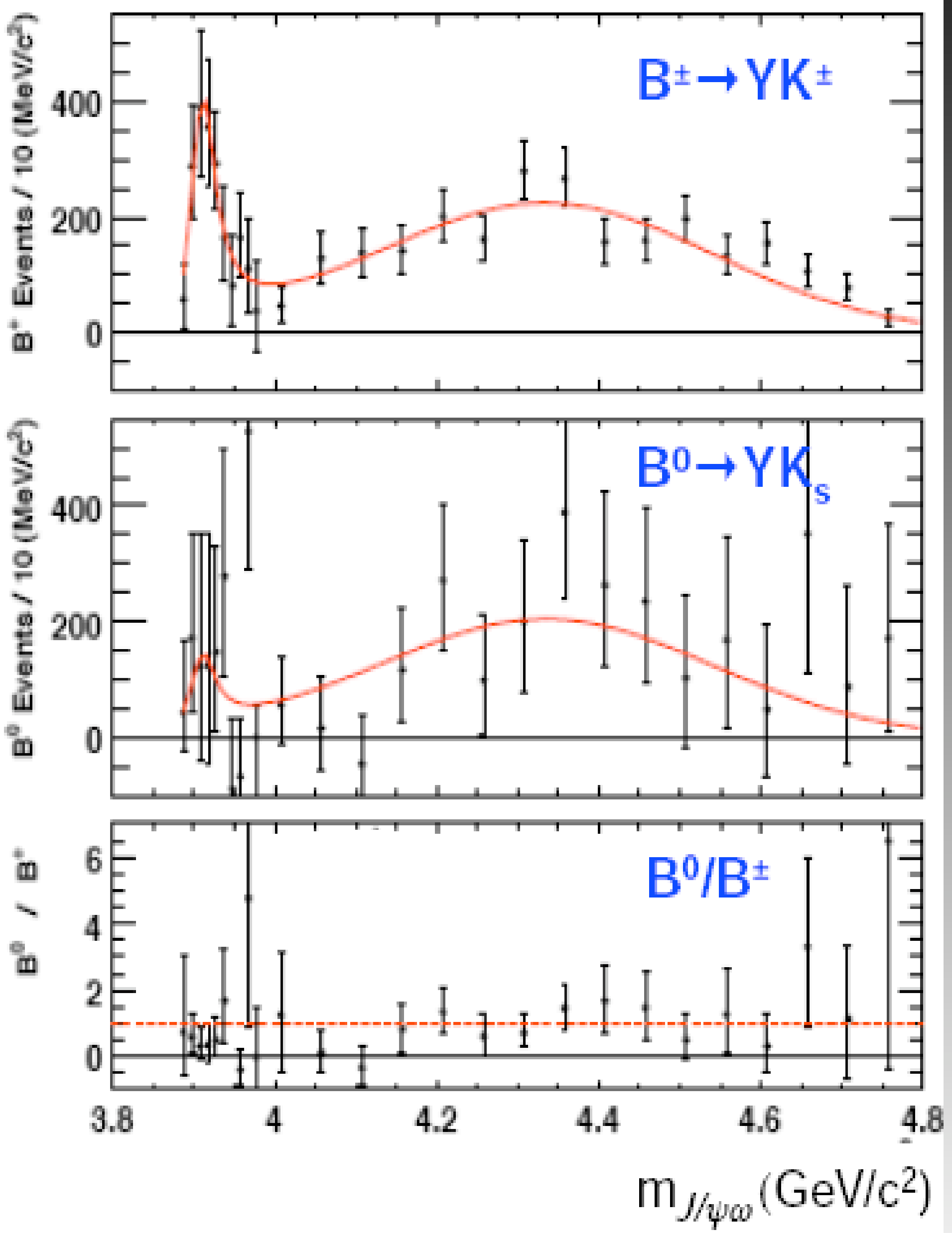
$$\Gamma(Y) = (33^{+12}_{-8}(stat)^{+0.6}_{-0.6}(syst))\ \mathrm{MeV}.$$

- Belle's Evidence for B→YK (Y→J/ψω) is confirmed
  - ~30MeV lower mass than Belle's
  - Narrower width
  - Preliminary BF estimate similar to the Belle's (~10^{-5})
  - No evidence for B→X(3872)K (X→J/ψω)

BELLE on 253 fb^{-1}

Belle's results

- M = 3943 ± 11(stat) ± 13(syst) MeV/c^2
- Γ = 87 ± 22(stat) ± 26(syst) MeV



Summary of Y(3940) measurements

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

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

BABAR preliminary

BELLE: m(Y)=3943±11(stat)±13(syst) MeV/c²
Γ(Y)=87±22(stat)±26(syst) MeV

BELLE PRL 94, 182002 (2005)

$$R_1 = 0.31^{+0.29}_{-0.24}(stat)^{+0.04}_{-0.01}(syst)$$

$$R_2 = 0.90^{+0.23}_{-0.21}(stat)^{+0.03}_{-0.02}(syst)$$

BABAR preliminary

B→X(3872)K:	$R_1 = 0.50 \pm 0.31$	***BABAR*** **PRD 73, 011101 (2006)**
B→J/ψ K:	$R_1 = 0.865 \pm 0.044$	*PDG*
B→ ψ(2S)K:	$R_1 = 0.957 \pm 0.106$	*PDG*

$$BR(B^+ \to YK^+) = (5.0^{+1.0}_{-1.0}(stat)^{+0.5}_{-0.5}(syst))\times 10^{-5}$$

$$BR(B^0 \to YK^0) = (1.6^{+1.4}_{-1.2}(stat)^{+0.2}_{-0.2}(syst))\times 10^{-5}$$

$$BR(B^+ \to J/\psi\omega K^+) = (3.5^{+0.2}_{-0.2}(stat)^{+0.4}_{-0.4}(syst))\times 10^{-4}$$

$$BR(B^0 \to J/\psi\omega K^0) = (2.9^{+0.6}_{-0.6}(stat)^{+0.3}_{-0.3}(syst))\times 10^{-4}$$

BABAR preliminary

- R_1: ratio of the B^0 to B^+ in the Y(3940) signal region
- R_2: ratio of the B^0 to B^+ in the non-resonant contributions

Final remarks

- ***Charmoium Physics*** *continues to be interesting.*
- *Several unexpected states have been observed!*
- *Possible charmonium states observed: X(3940), Y(3940), Z(3930). Possible NON-charmonium states: Y(4260), Y(4350), X(3872).*
- *What are really the X(3872) and Y(3940)? Need to investigate more to understand their nature*
- *Need to know the full spectrum (so far...)*
- *More data are essential to the resolution of this challenging situation.*
- *Theorists, give us a hint: where we have to focus on?*

Thanks for your attention!