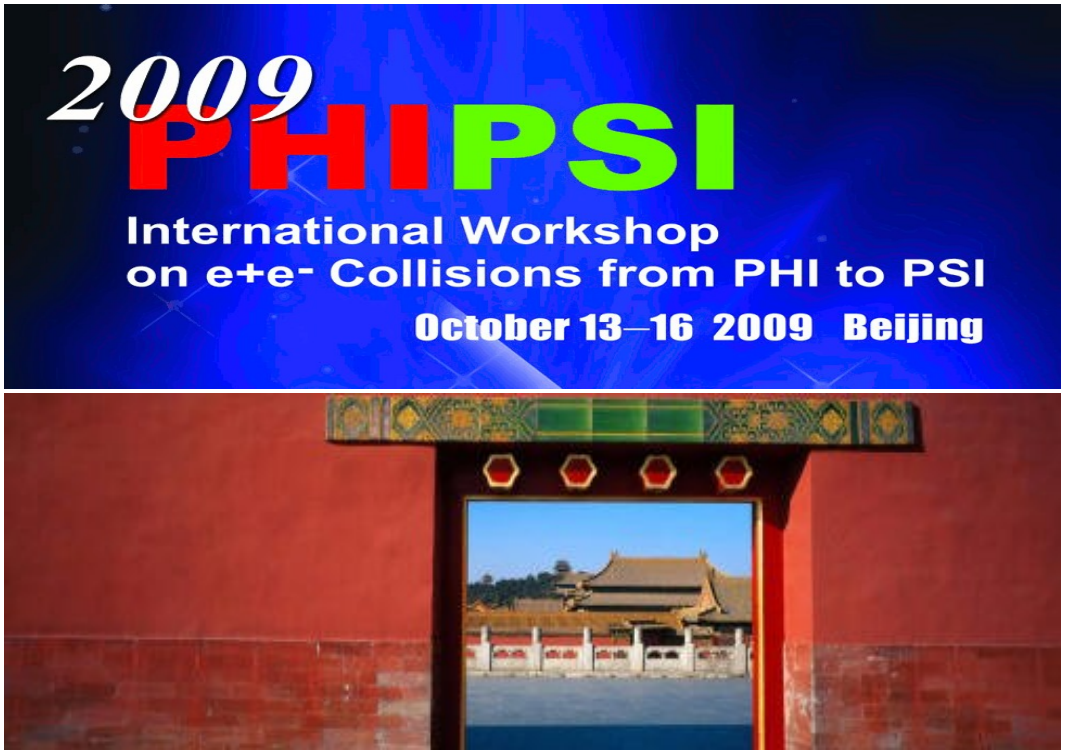
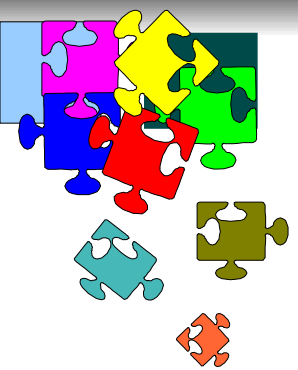


XYZ particles

at

BaBar

Elisabetta Prencipe (LAPP, France)
On behalf of the BABAR collaboration

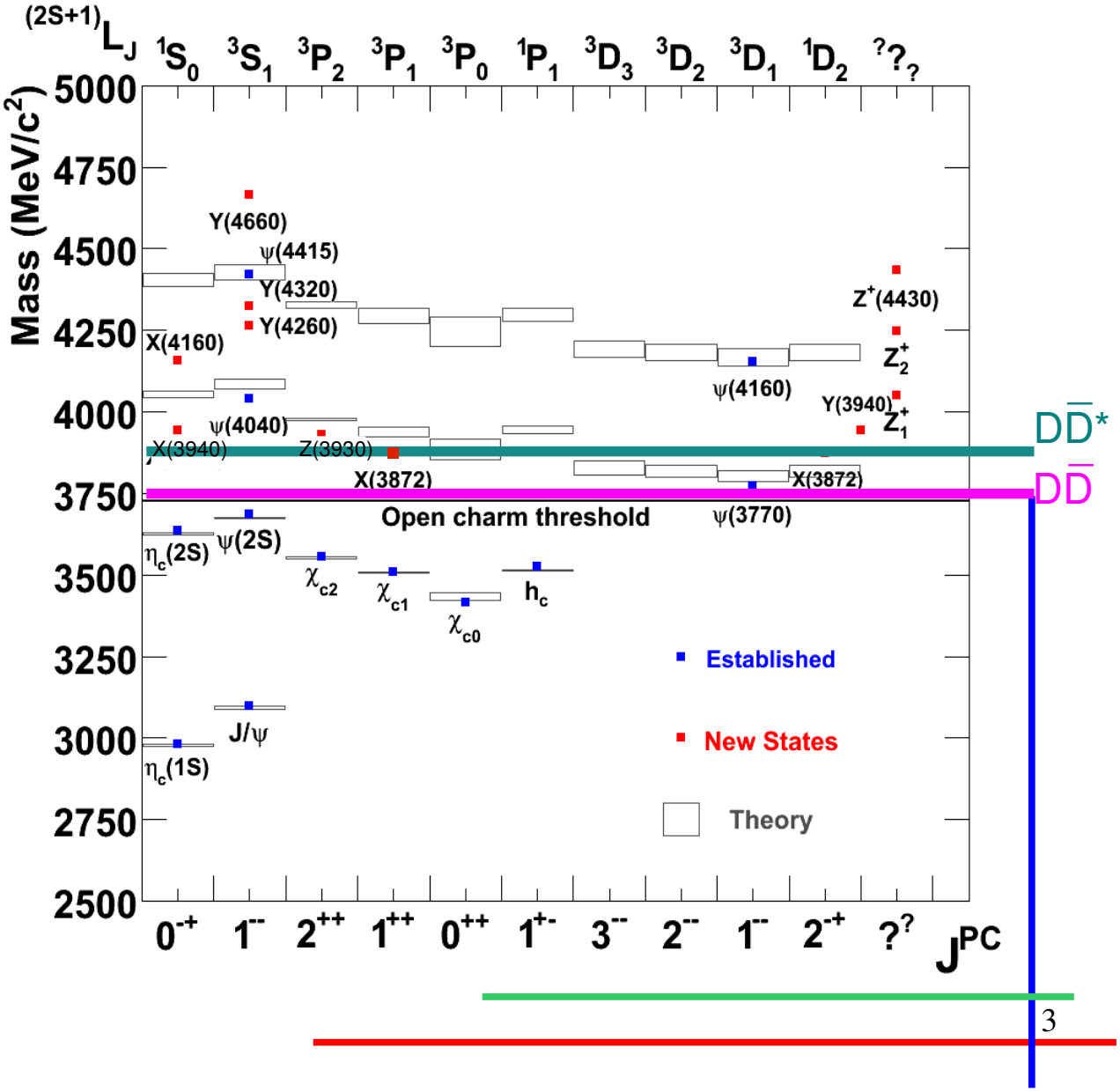


Outline

- Introduction
- Motivation
- B →X(3872)K
- B →Y(3940)K
- B →Z(4430)K
- $e^+e^- \rightarrow \gamma_{ISR} Y(4260)$
- $e^+e^- \rightarrow \gamma_{ISR} Y(4350)$
- Summary

Introduction

- Recent observations of (unexpected) new states have been performed.
- Several resonances do not fit theoretical predictions.
- Many subsequent interpretations of these new states and methods were suggested to analyse their structure (HQT, chiral symmetries, 4-quark models, bag model, Lattice...)



Motivations

- **BaBar** is a B-factory:

  1999-2007 ☞ ~ 433fb^{-1} @ Y(4S) (on-peak data)
  end of Dec07- end of Feb08 ☞ 30fb^{-1} @ Y(3S)
  end of Feb08-6th of April08 ☞15fb^{-1} @ Y(2S)
  scan around Y(4S) (25pb^{-1} every 5 MeV)

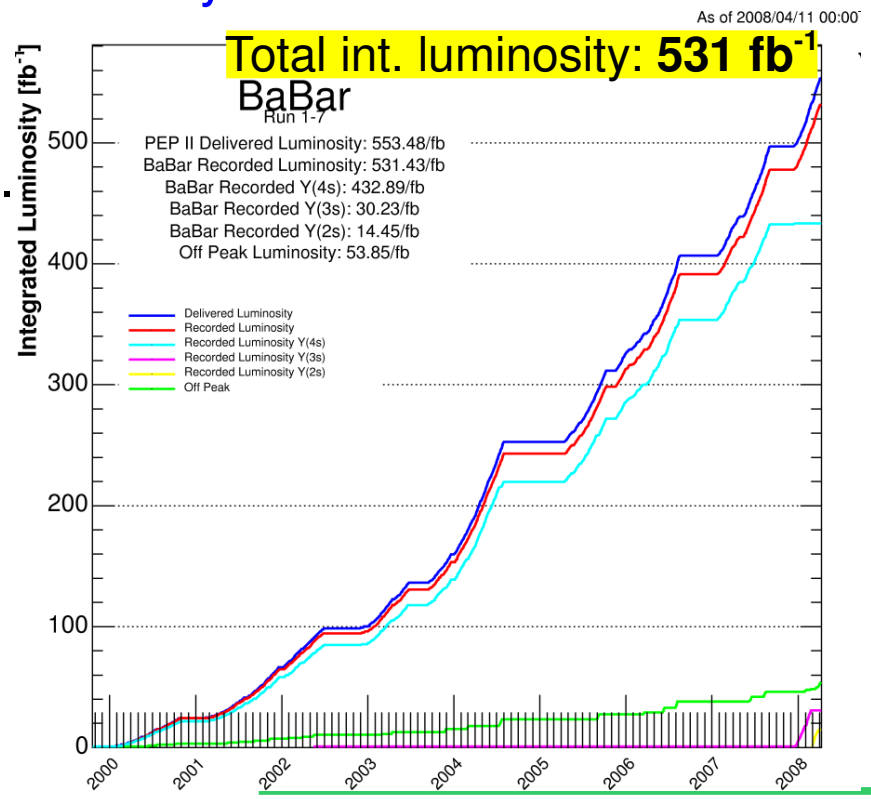
- The main goal of the BaBar Physics has been the measurement of the sides and angles of the Unitarity Triangle, and rare decays.

- B-factories have been demonstrated to be also a **huge source of $c\bar{c}$ production.** [$\sigma(e^+e^- \to c\bar{c}) = 1.30$ nb]

- The spectrum of Heavy Quarkonium states is an ideal place to provide precision tests of QCD.

- Very accurate calculations are possible using Lattice techniques.

  $M_c \sim 1.5$ GeV/c^2 is high enough to try to describe QCD in term of NRPM.



Spectroscopy

BABAR

- Production in continuum:
  - $e^+e^- \rightarrow J/\psi X$ (C_X=+)
  - $e^+e^- \rightarrow \gamma_{ISR} X$ (only $J^{PC}=1^{--}$)
- Production B decays:
  - $b \rightarrow c$ (color suppressed decay)
  - open-charm and charmonium
    ($c\bar{s}$ and $c\bar{c}$ meson, cqq baryons; $c\bar{c}$ +...)

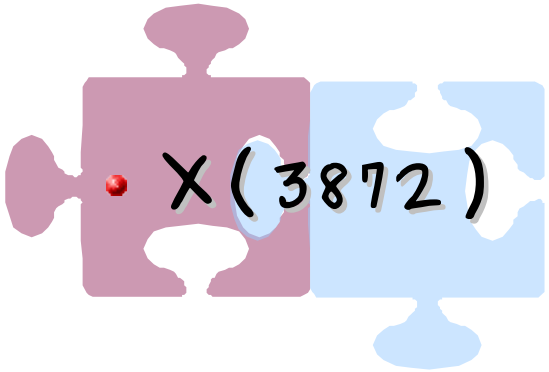
charm and charmonium spectroscopy

- Transition $\Upsilon(4S) \rightarrow \Upsilon(2S)\pi^+\pi^-$, $\Upsilon(4S) \rightarrow \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(4S) \rightarrow \Upsilon(1S)\eta$

bottomonium spectroscopy

The main goal of the physics @ ***Y(3S)*** and ***@Y(2S)*** is the search of **bottomonium** states and **light Higgs**.

$B \rightarrow XK$



X(3872)

Belle: PRL 91, 262001 (2003), cited 412

CDF: PRL 91, 262001 (2003) PRL 93, 072001 (2004)

D0: PRL 93, 162002 (2004))

BABAR: PRD 72, 054026(2005) PRD 73, 014014(2006)

- Final result from BABAR on the study:

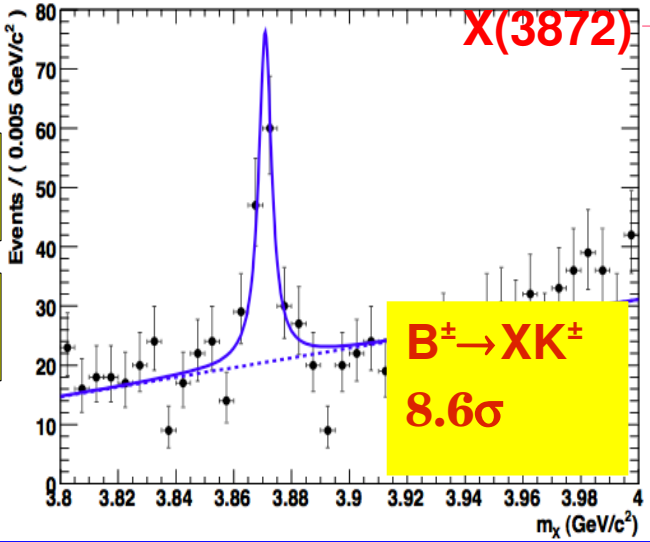
  $B \to XK,\ X \to J/\psi\pi^+\pi^-$

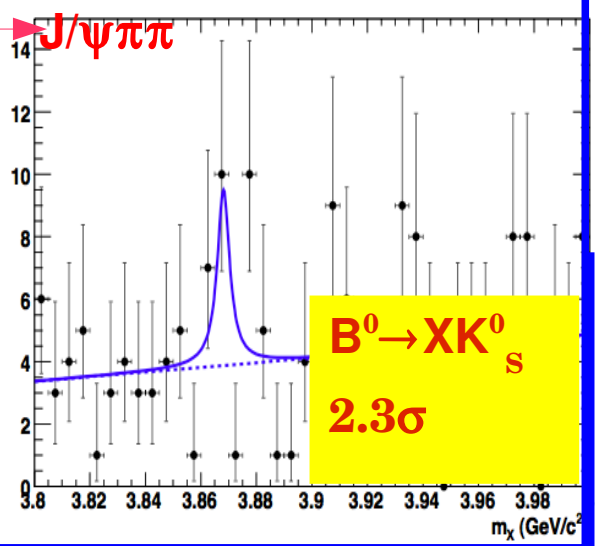
[413fb^{-1}] PRD77,111101(2008)

$R(B^0/B^\pm) = 0.41 \pm 0.24 \pm 0.05$

$\Delta M = (2.7 \pm 1.6 \pm 0.4)$ MeV/c^2

$\Gamma < 3.3$ MeV @90%CL





$BF(B^+ \to XK^+, X \to J/\psi\pi^+\pi^-) = (8.4 \pm 1.5 \pm 0.7) \times 10^{-6}$

$BF(B^0 \to XK^0, X \to J/\psi\pi^+\pi^-) = (3.5 \pm 1.9 \pm 0.4) \times 10^{-6}$

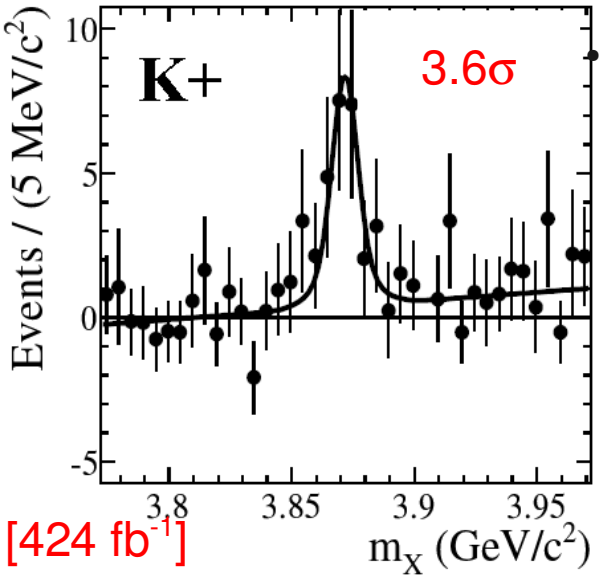
$< 6.0 \times 10^{-6}$ @ 90% C.L.

Narrow resonance!

Molecular model predicts $R(B^0/B^\pm) < 0.1$

What is this state?

Final result from BABAR on the analysis: $B^+ \to X(3872)K^+$, **X(3872) → J/ψ γ**



[424 fb^{-1}]

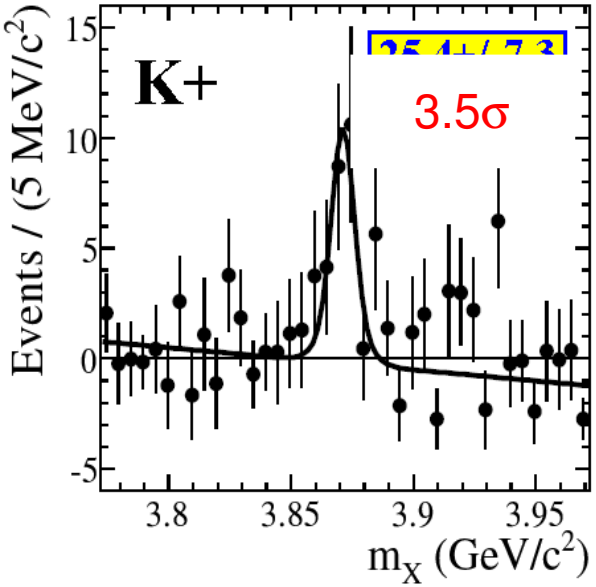
$BF(B^+ \to X(3872)K^+) \times (X(3872) \to J/\psi\gamma) =$
$(2.8 \pm 0.8 \pm 0.2) \times 10^{-6}$

23.0±6.4 events measured

PRD 74, 071101 (2006)
PRL 102, 132001 (2009)

C-parity: 1^+

First evidence for $B^+ \to X(3872)K^+$,
X(3872)→ψ(2S) γ

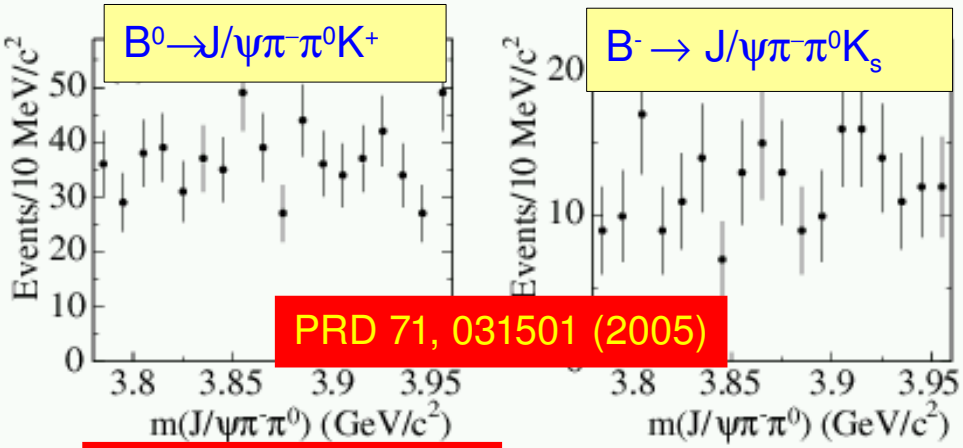


$BF(B^+ \to X(3872)K^+) \times (X(3872) \to \psi(2S)\gamma) =$
$(9.5 \pm 2.7 \pm 0.9) \times 10^{-6}$

$BF(X(3872) \to \psi(2S)\gamma) / BF(X(3872) \to J/\psi\gamma =$
3.4 ± 1.4

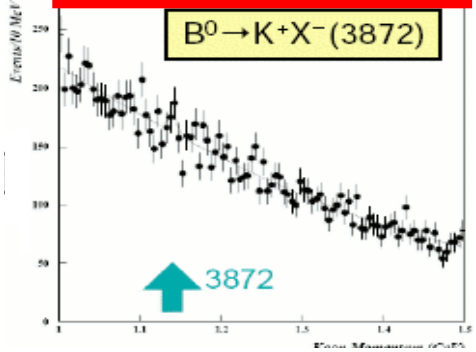
ππ invariant mass study (X →J/ψππ):

- ππ inv. mass compatible with ρ
  ⇨ I = 1; but:
  forbidden J/ψπ⁰π⁰, J/ψπ⁰, J/ψη
- Decay X(3872)J/ψρ against charmonium hypothesis
- **I=0 favored** for X(3872)→ J/ψππ



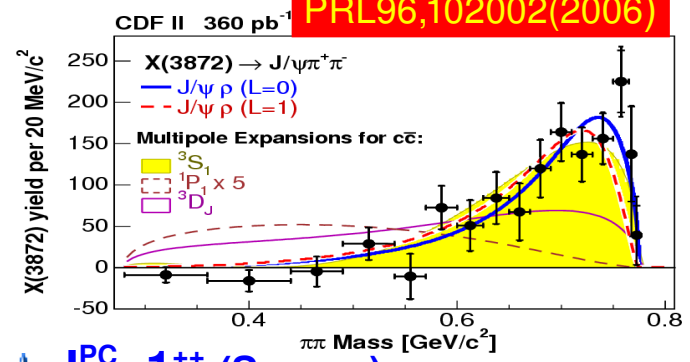
PRD 71, 031501 (2005)

PRL 96, 052002 (2006)

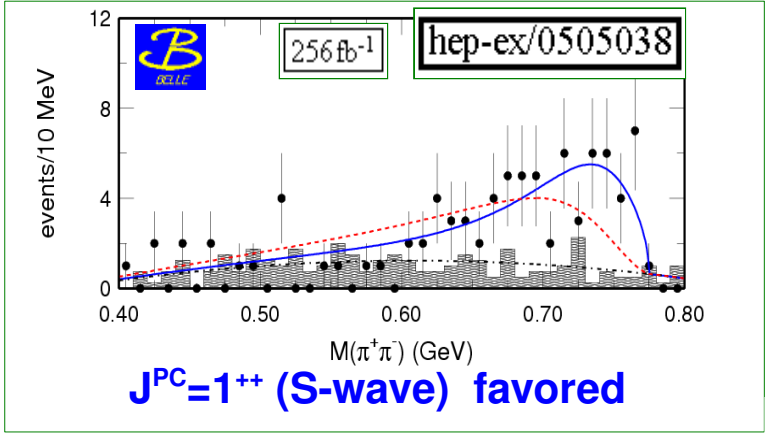


No evidence
of charged partners

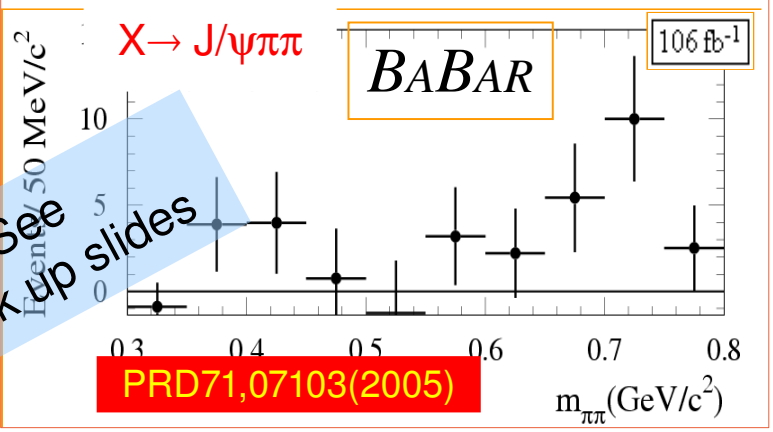
PRL96,102002(2006)



★ $J^{PC}=1^{++}$ (S-wave) or
★ $J^{PC}=2^{-+}$ (P-wave, ρ–ω interference)



$J^{PC}=1^{++}$ (S-wave) favored



PRD71,07103(2005)

See back up slides

BABAR:
PRD 77, 011102 (2008)

BaBar studied additional 8 channels:

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

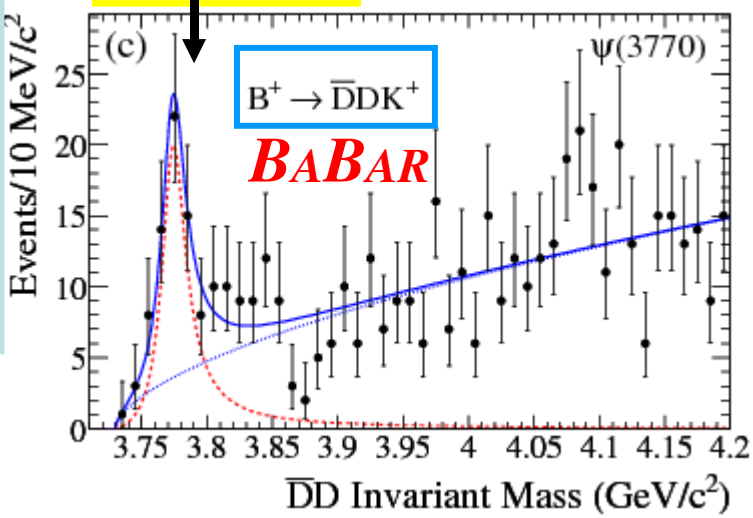
$B^0 \to D^0\bar{D}^{*0}K^0 + D^{*0}\bar{D}^0K^0$

$D^* \to D^0\gamma$ and $D^0\pi$

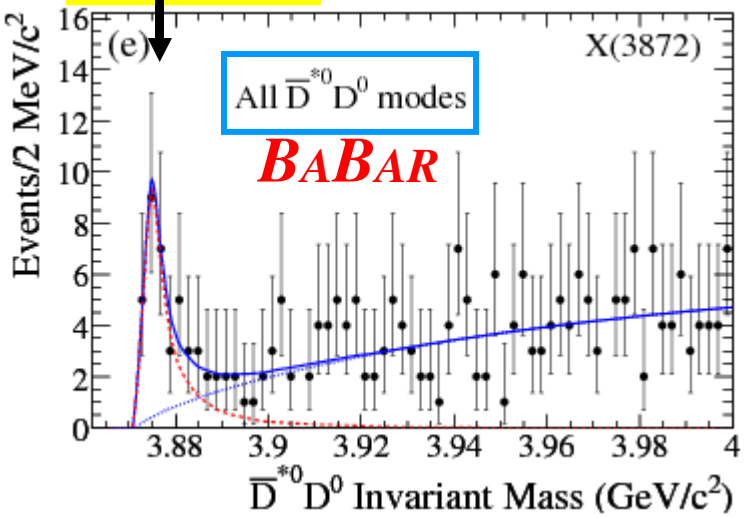
[347 fb^{-1}]

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

$\psi(3770)$



X(3872)



experiment		mass (MeV/c²)	Branching fraction
BABAR	$D^0\pi+D^0\gamma$	$3875.1\pm1.1\pm0.5$	$(1.67\pm0.36\pm0.47)\times10^{-4}$ B^+
BELLE	Only $D^0\pi$	$3875.2^{+0.3}_{-1.6}\pm0.8$	$(1.22\pm0.31^{+0.23}_{-0.30})\times10^{-4}$ B^0+B^+
	$D^0\pi+D^0\gamma$	$3872.6^{+0.5}_{-0.4}\pm0.4$	$(0.73\pm0.17\pm0.08)\times10^{-4}$

[arXiv:0810.0358]: Belle has recently reported a new mass value.

BABAR and **Belle** disagree on this analysis!

Remarks on the X(3872)

- X(3872)→ψγ ⇨ C=+1

Belle: arXiv:0505038
BABAR: PRD 74, 071101(2006)
PRL 102, 132001 (2009))

- No charged partner found for X(3872)$^-$ ➔ I=0

BABAR: PRD 73, 011101 (2006)

- X(3872) quantum numbers
  - Belle: $J^{PC}=1^{++}$ favored (ω-ρ interference is not included)
  - CDF: ππ mass distribution analysis and the angular distribution study ➔ $J^{PC}=1^{++}$ or 2^{-+}

Belle: arXiv:0505038

CDF: PRL 96, 102002 (2006)
PRL 98, 132002 (2007)

- What is the nature of X(3872)?
  - Hybrid?.... BUT m(cc̄g)>4.2GeV/c^2
  - Tetraquark?... BUT
    No evidence for charged X(3872)$^\pm$
  - Charmonium?... mass is OK for 2^{-+} state (η_{c2}, the $^1D_2$ cc ground state)
  - Molecular?
    - m(D^0) + m(D^{0*}) = 3871.8 ± 0.4 MeV/c^2
    - Decays to X(3872) →J/ψρ, D^0D^{0*}, J/ψω expected; but we observe X →ψ(2S)γ
    - Compatible with J^{PC} = 1^{++} assignment

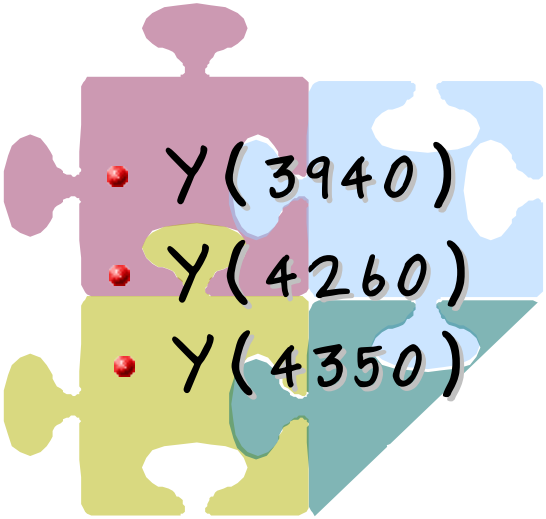
- R(B0/B+) = 0.50±0.30±0.05 in J/ψ π π
- R(B0/B+) = 1.33±0.69±0.52 in $D^0\bar{D}^{*0}$

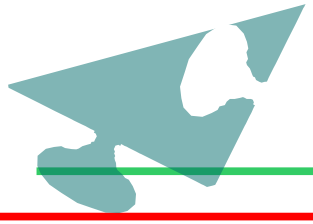
- Δm =2.7±1.3±0.2 MeV/c^2 in J/ψ π π
- Δm =0.7±1.9±0.3 MeV/c^{2}in $D^0\bar{D}^{*0}$

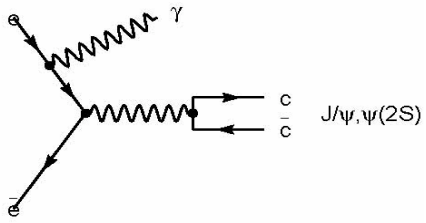
- M_X = 3871.4±0.6 MeV/c^2 in J/ψ π π
- M_X= 3875.1±1.1 MeV/c^2 in $D^0\bar{D}^{*0}$

$B \to YK$

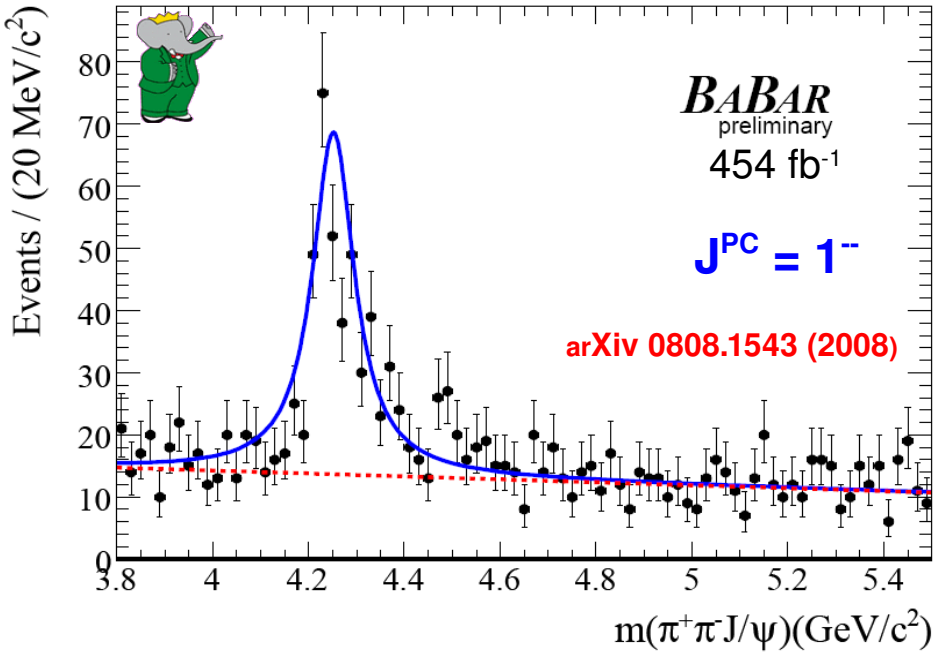
$e^+e^- \to \gamma_{ISR} Y$







Y(4260)



- Discovered from BaBar in ISR events

$e^+e^- \to \gamma_{ISR} Y(4260) \to J/\psi\pi^+\pi^-$

PRL 95, 142001 (2006) , PRD 73, 011101(2005)

$m_Y = 4259 \pm 8^{+2}_{-6}$ MeV/c²

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

- Confirmed by CLEO-c (scan), CLEO III (ISR), and Belle (PRL 96, 162003 (2006), PRD 74, 091104 (2006), PRL 99, 142002 (2007))

- No evidence for $Y(4260) \to \pi^+\pi^-\varphi$, $D\bar{D}$, $p\bar{p}$ (PRD 74, 091103 (2006) , PRD 76, 111105 (2007), PRD 73, 012005 (2006))

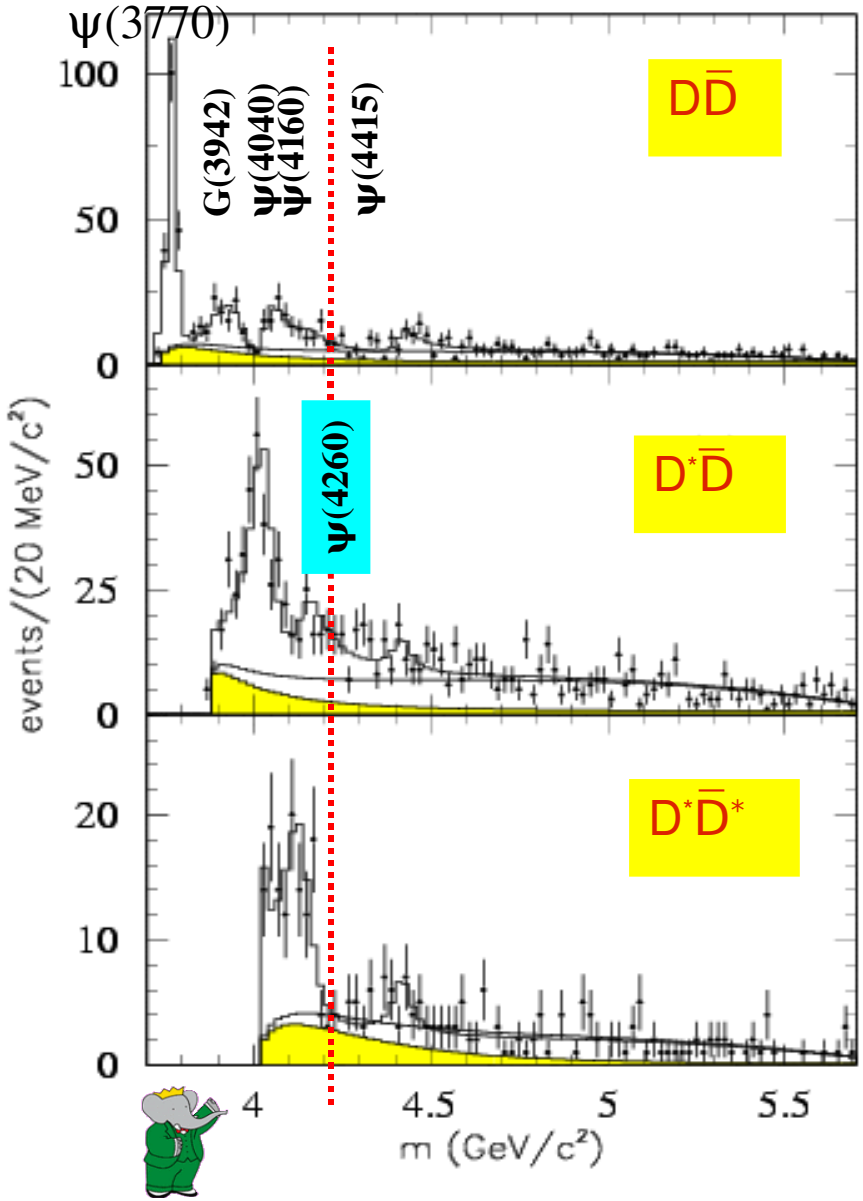
BABAR update on Y(4260) (preliminary):

$m = 4252 \pm 6(\text{stat})\ ^{+2}_{-3}(\text{syst})$ MeV/c²

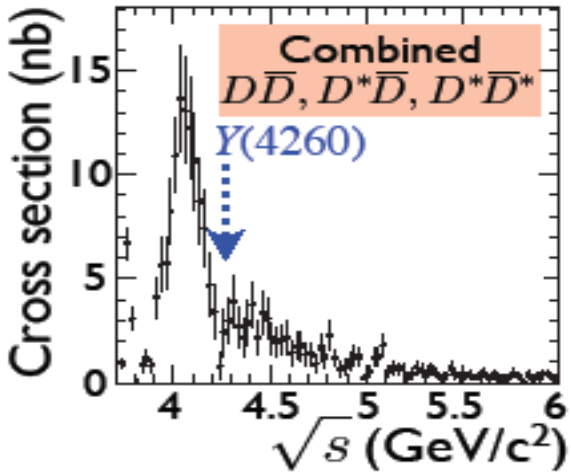
$\Gamma_Y = 105 \pm 18(\text{stat})\ ^{+4}_{-6}(\text{syst})$ MeV

No evidence for enhancement at ~4050 MeV/c² reported by Belle (*PRL 99, 182004 (2007)*)

Search for Y(4260)→DD̄, D*D̄, and D*D̄*



Limits on Y(4260)



$$\frac{\mathcal{B}(D\bar{D})}{\mathcal{B}(J/\psi\pi\pi)} < 1.0$$

$$\frac{\mathcal{B}(D^*\bar{D})}{\mathcal{B}(J/\psi\pi\pi)} < 34$$

$$\frac{\mathcal{B}(D^*\bar{D}^*)}{\mathcal{B}(J/\psi\pi\pi)} < 40$$

NEW

at 90% C.L.

PRD 72, 054026(2005), PRD 73, 014014(2006), arXiv:0808.1543

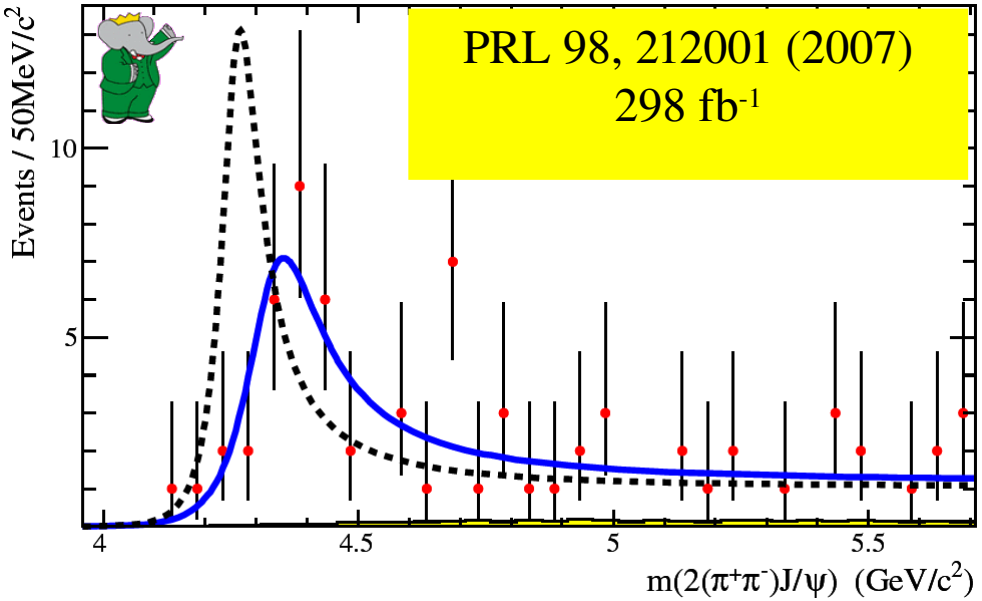
- If Y(4260) is charmonium, it should decay mainly to DD̄, D*D̄ and D*D̄*.

No evidence found!

What is Y(4260)?

Hybrid?
Baryonium?
Tetraquark?
Molecular state?

Evidence for Y(4350)→ψ(2S)π⁺π⁻ in ISR



M=4324±24 MeV/c²

Γ = 172±33 MeV

It was natural to search for the decay Y(4260)→ψ(2S)π⁺π⁻

e⁺e⁻ requires this state to be $J^{PC} = 1^{--}$ ➔ overpopulated

Seems impossible to assign both as charmonium; but, there are two $c\bar{c}$ 1^{--} states, which might mix to yield the observed spectrum

Y(4350) has been confirmed by Belle (PRL 99, 142002 (2007))

Belle reports another state: m=4660±12 MeV/c², Γ=48±15 MeV

Y(3940)→J/ψω

- Confirmed by *BABAR* in B→J/ψωK (347 fb^{-1})

PRL101,082001 (2008)

- B^+ and B^0 BF's measured separately
- B^0/B^+ in the Y-resonant region:
  - $R_Y = 0.27\ ^{+0.28\ +0.04}_{-0.23\ \ -0.01}$

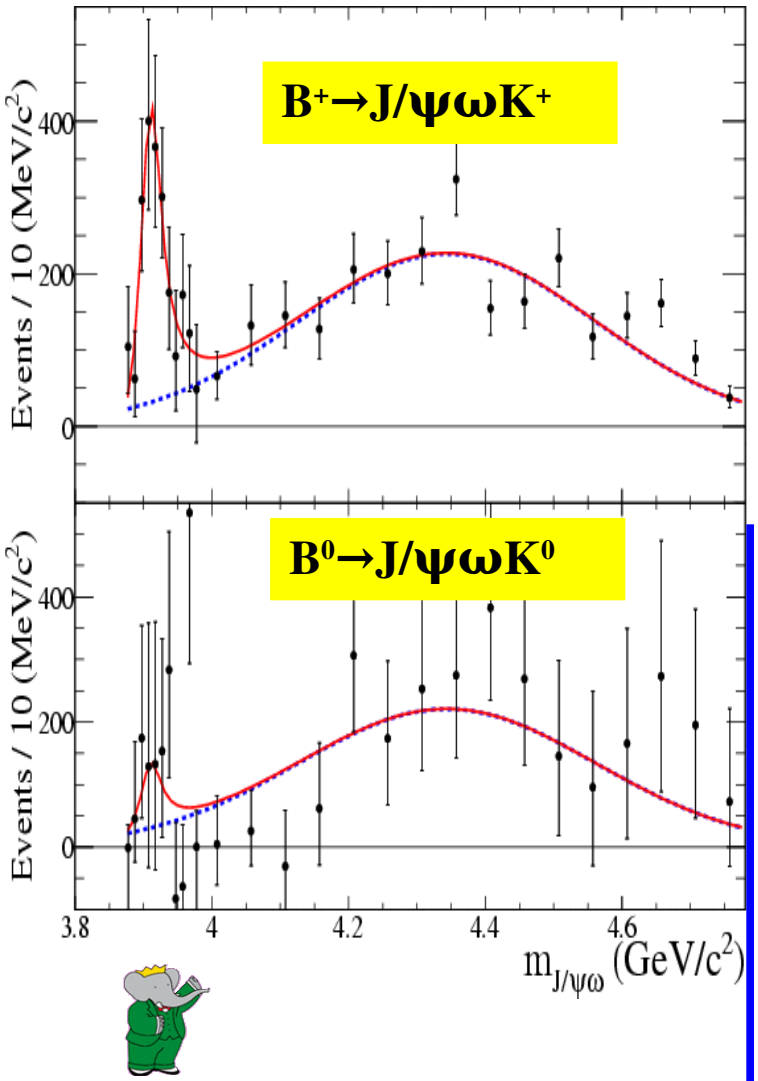
  3σ below the isospin expectation
  - The ratio is consistent with isospin expectation in the non-resonant region
- Similar to X(3872) from *BABAR*:

  [PRD 77, 111101(2008)]
  - $R_X = 0.41 \pm 0.24 \pm 0.05$

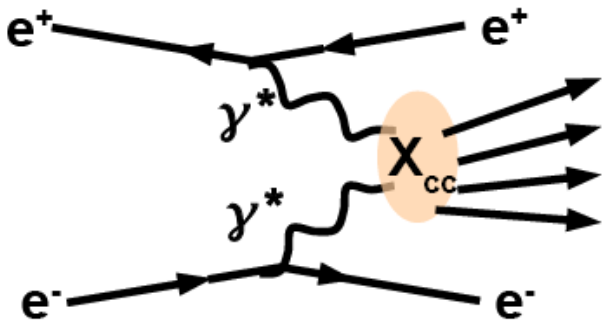
To compare with...

cf. $R_{\psi(2S)} = 0.81 \pm 0.05 \pm 0.01$;

$R_{J/\psi} = 0.865 \pm 0.044$ (PDG)



	BABAR	*BELLE*
Mass (MeV/c^2)	$3914.6^{+3.8}_{-3.4} \pm 2.0$	$3943 \pm 11 \pm 13$
Width (MeV)	$34^{+12}_{-8} \pm 5$	$87 \pm 22 \pm 26$
BF: $B^+ \to YK^+$, $Y \to J/\psi\omega$ ($\times 10^{-5}$)	$4.9^{+1.8}_{-0.9} \pm 0.5$	$7.1 \pm 1.3 \pm 3.1$
BF: $B^0 \to YK^0$, $Y \to J/\psi\omega$ ($\times 10^{-5}$)	$1.3^{+1.3}_{-1.1} \pm 1.1$	combined ↑
BF: $B^+ \to J/\psi\omega K^+$ ($\times 10^{-4}$)	$3.5 \pm 0.2 \pm 0.4$	–
BF: $B^0 \to J/\psi\omega K^0$ ($\times 10^{-4}$)	$3.1 \pm 0.6 \pm 0.3$	–

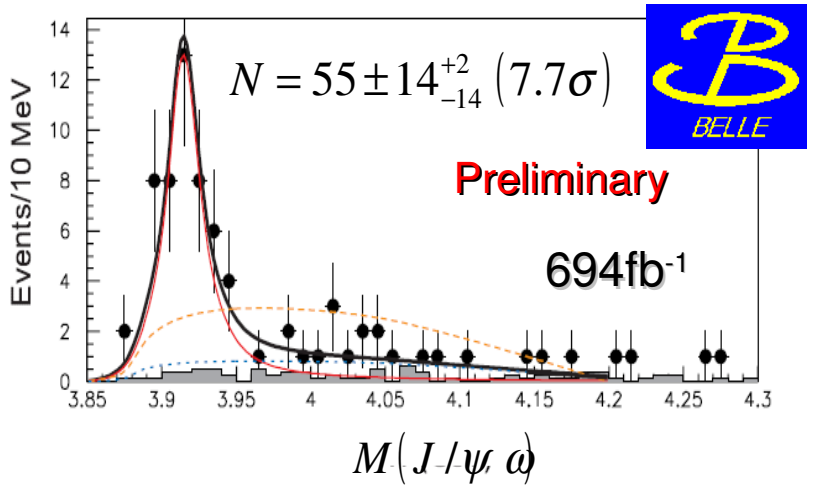


M: 3914 ± 3 ± 2 MeV

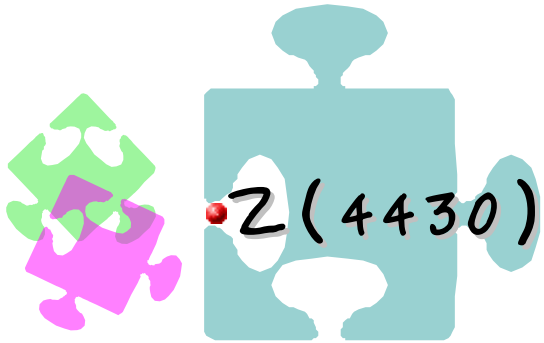
Γ: 23 ± 10 $^{+2}_{-8}$ MeV

N_{res} = 55 ± 14 $^{+2}_{-14}$ events

Signif. = 7.7σ



$B \rightarrow ZK$



Observation of $Z(4430)^-$

Belle

- Belle has reported a new charged charmonium-like state in the decay:
  $B \to Z^- K$, $Z^- \to \psi(2S)\pi^-$ (PRL *100, 142001 (2008)*)

- The reported mass and width are:

  $M = 4433 \pm 4(stat) \pm 2(syst)$ MeV/c^2

  $\Gamma = 45^{+18}_{-13}(stat)^{+30}_{-13}(syst)$ MeV

- Significance: 6.5σ

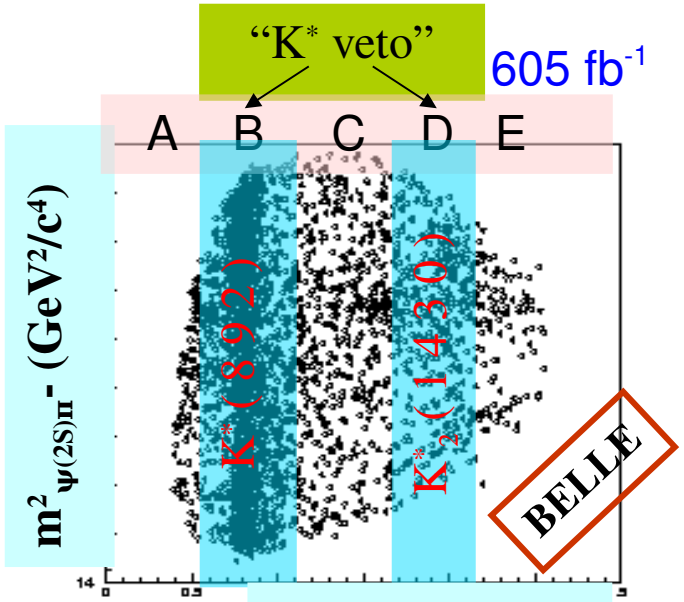
- If this result is confirmed ➔ first observation of a genuine $c\bar{c}u\bar{d}$ "tetraquark" state, since it is charged and carries hidden charm

$M = (4443^{+15}_{-12}{}^{+17}_{-13})$ MeV/c^2

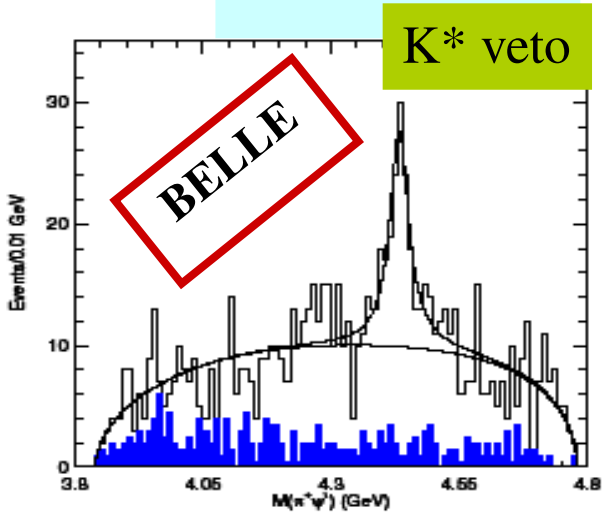
$\Gamma = (109^{+86}_{-43}{}^{+57}_{-52})$ MeV

NEW

PRD 80, *031104 (2009)*



PRL *100, 142001 (2008)*



BABAR search for Z(4430)$^-$

PRD 79, 112001 (2009)

413 fb^{-1}

- Search for the Z(4430)$^-$ in the decay modes $B^{-0} \to \psi\pi^- K^{0+}$ (*)
- Describe the $K\pi^-$ system in detail, since structure in the $K\pi^-$ mass and angular distributions dominates each Dalitz plot
- Correct the data for efficiency event-by-event across the Dalitz plot, and describe using only S-, P-, and D-wave intensity contributions
- Project each $K\pi^-$ description onto the relevant $\psi\pi^-$ mass distribution to investigate the need for Z(4430)$^-$ signal above this "$K\pi^-$ background"

Mass resolution at m_Z : ~ 7 MeV/c^2 for $J/\psi\pi^-$ and ~4 MeV/c^2 for $\psi(2S)\pi^-$

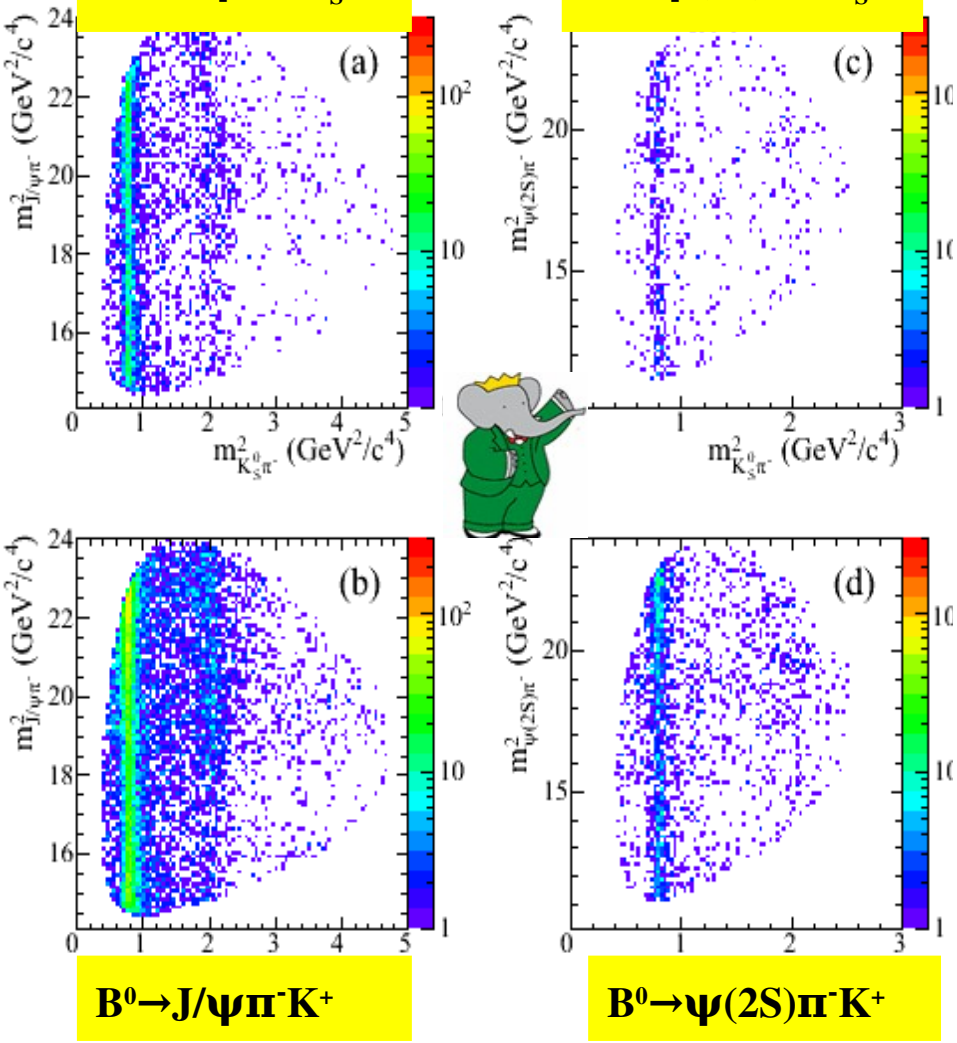
➔ no significant effect on any Z(4430)$^-$ signal

(*) We use "ψ" to denote "J/ψ or ψ(2S)" unless otherwise indicated

Dalitz plots & $K\pi^-$ mass distribution

$B^- \to J/\psi \pi^- K^0_S$

$B^- \to \psi(2S) \pi^- K^0_S$

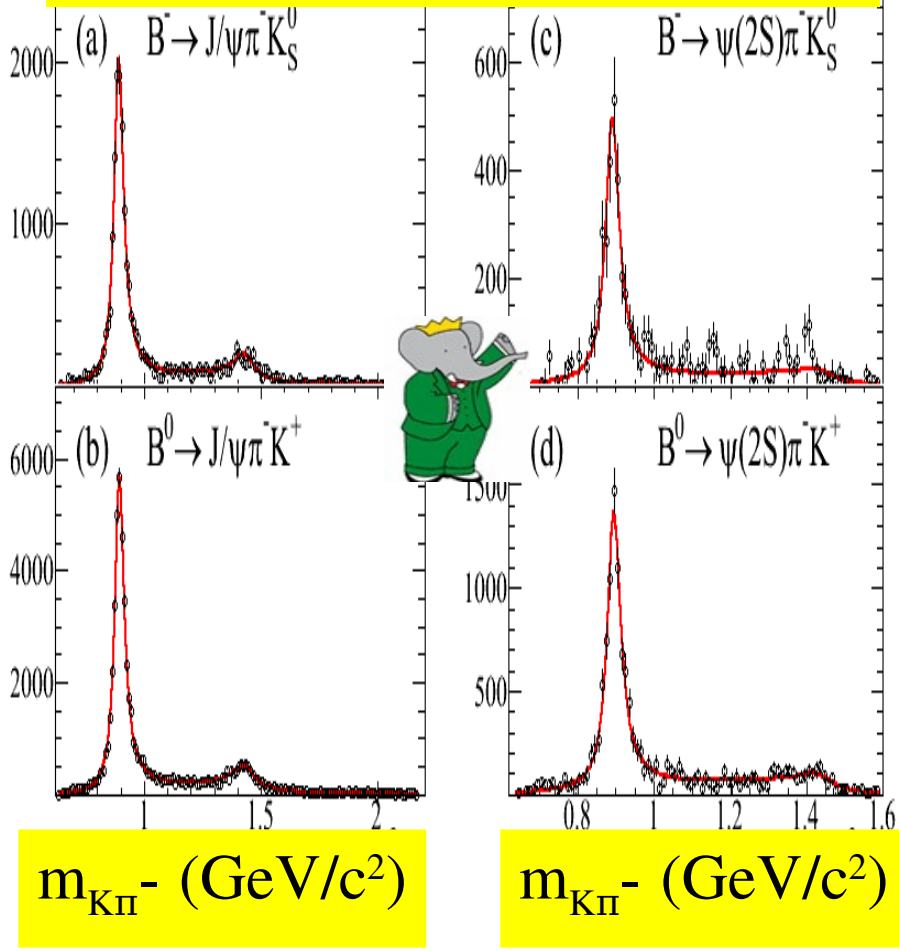


$B^0 \to J/\psi \pi^- K^+$

$B^0 \to \psi(2S) \pi^- K^+$

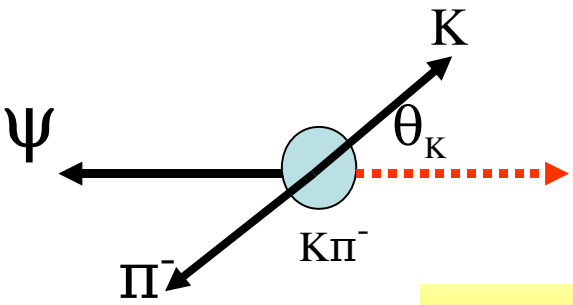
Fitted with S- (LASS), P-,

and D-wave intensity



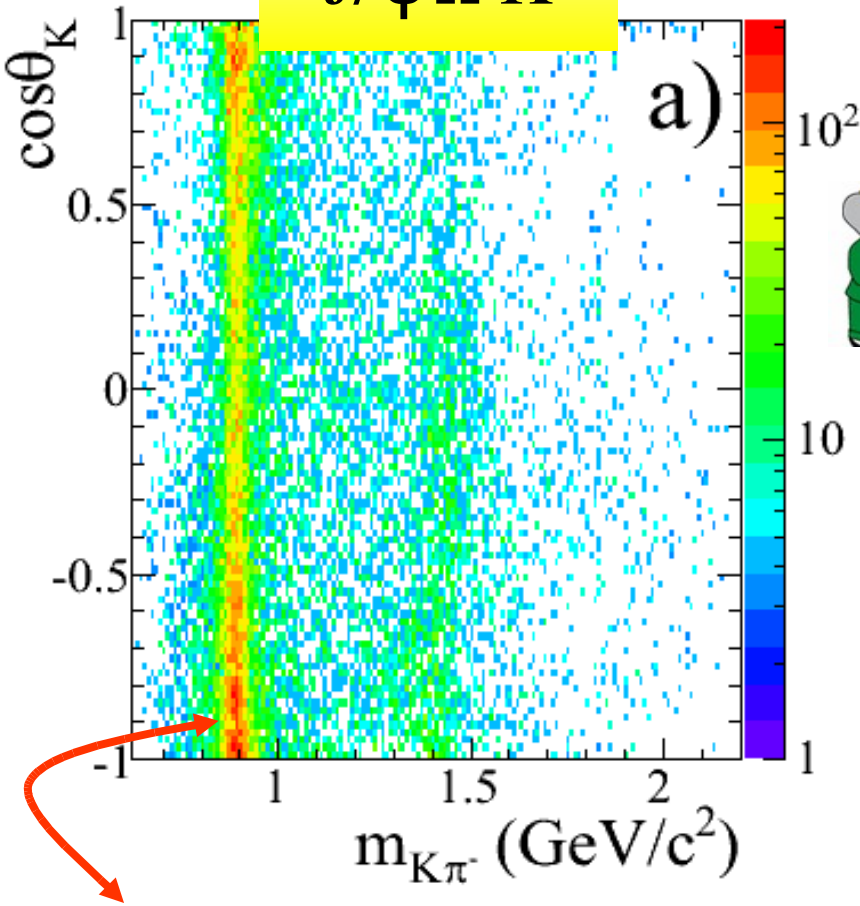
Good descriptions of the $m_{K\pi}$ distributions are obtained

The Legendre Polynomial moments

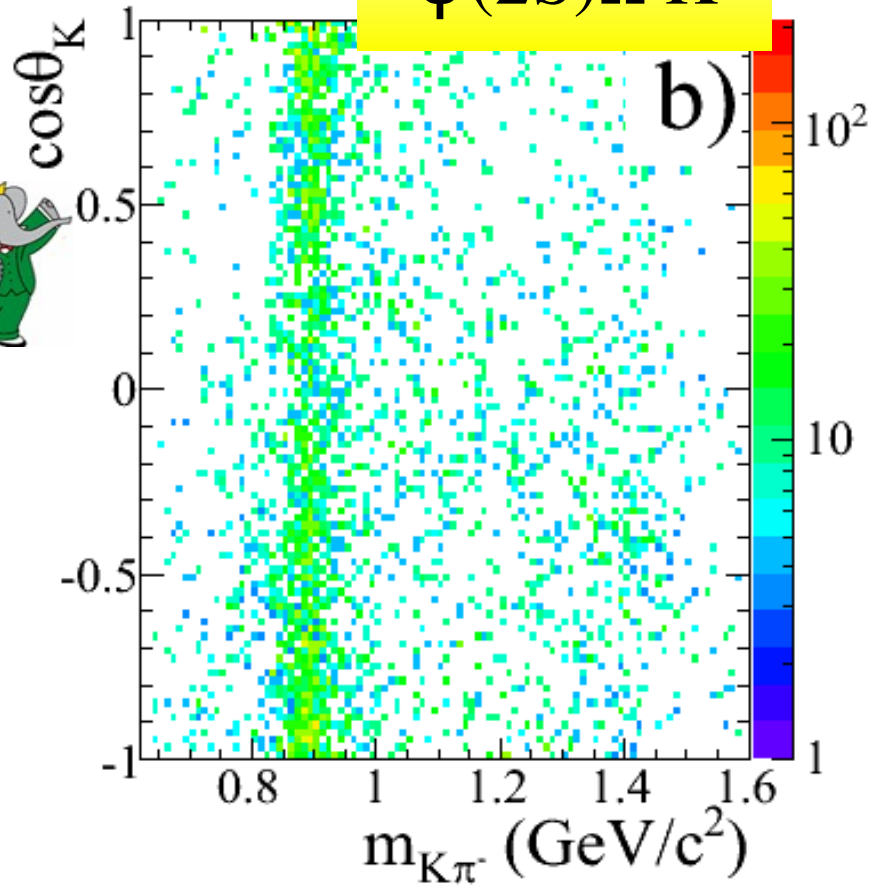


$$\frac{dN}{d\cos\theta_K} = N\sum_{i=0}^{4} \langle P_i \rangle P_i(\cos\theta_K) = \frac{N}{2} + \sum_{i=1}^{4} \underbrace{(N\langle P_i \rangle)}_{\text{Unnormalized moment } \langle P_i^U \rangle} P_i(\cos\theta_K)$$

J/ψπ-K

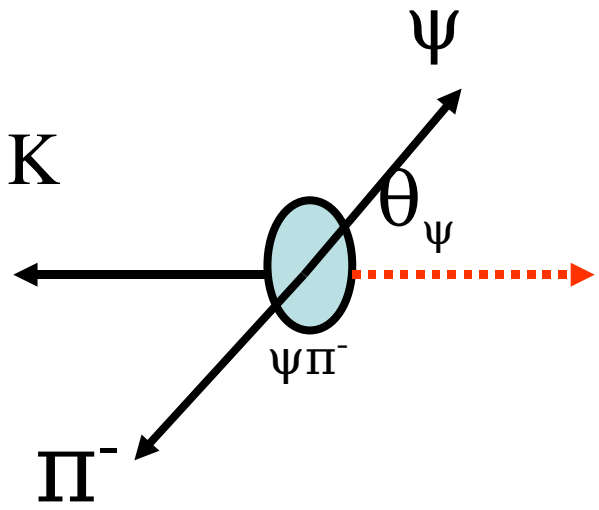


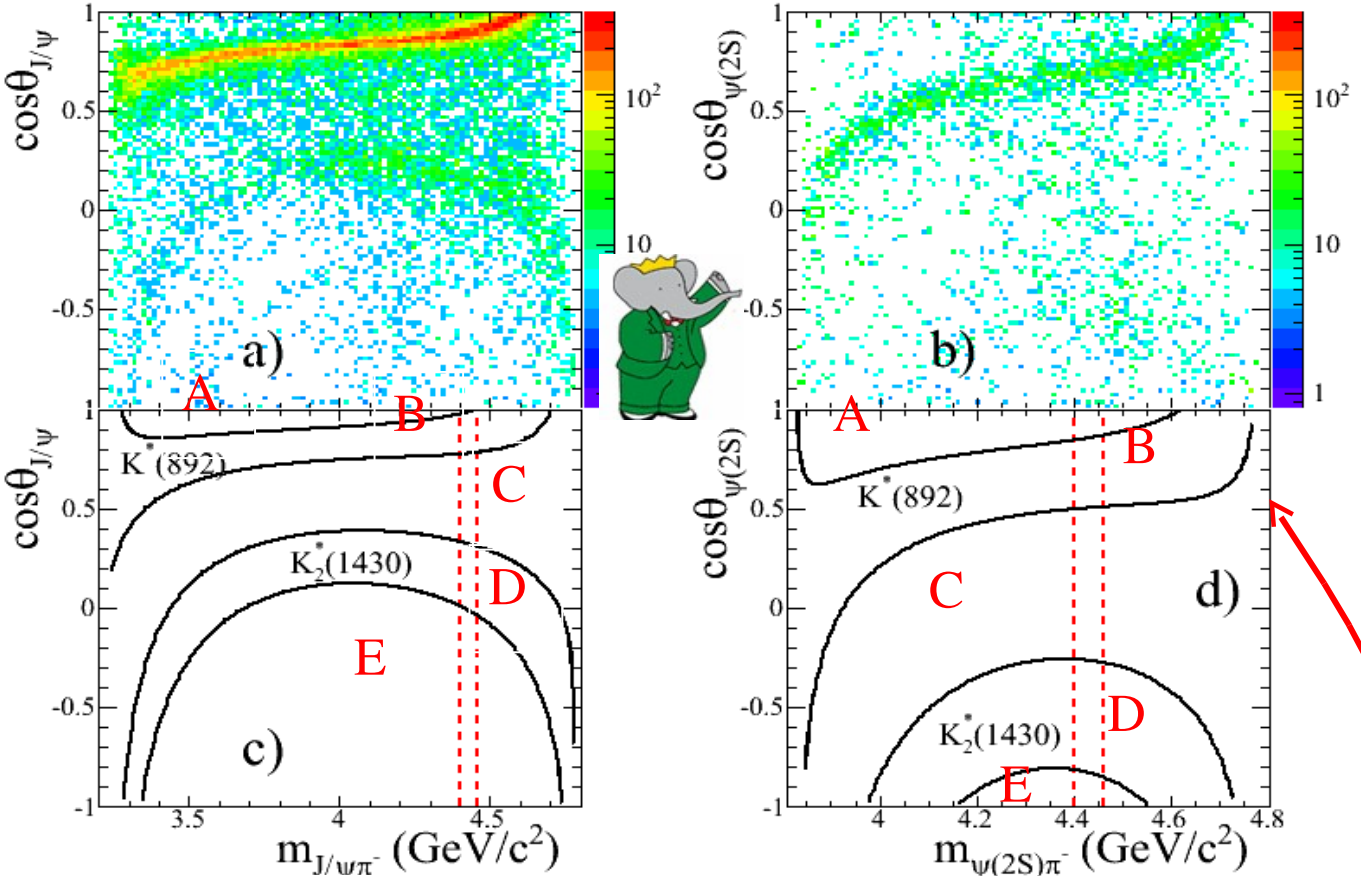
ψ(2S)π-K



Clear backward-forward asymmetry

The Z(4430)$^-$ and the Kπ reflections



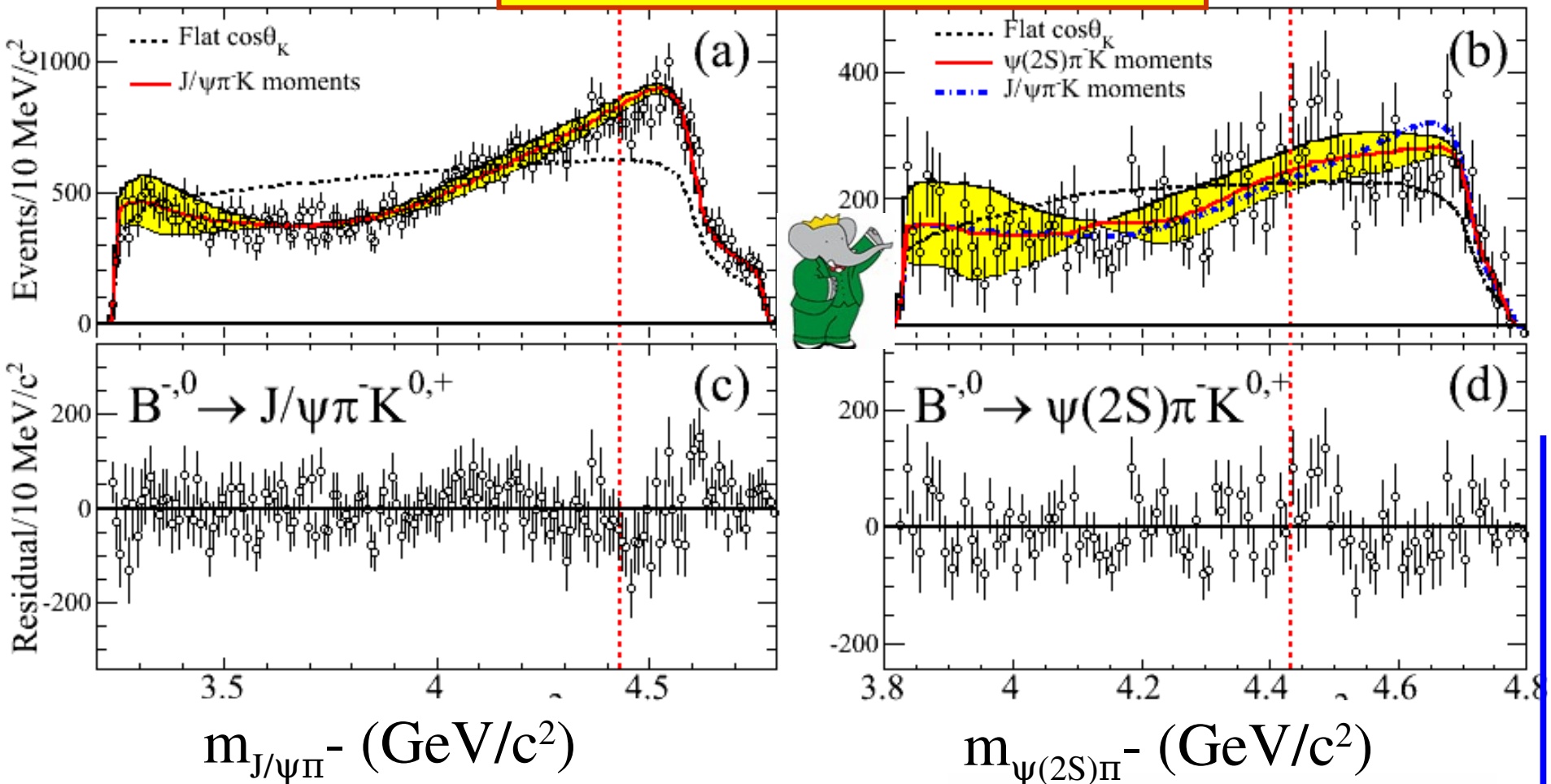


$m_{J/\psi\pi}$- (GeV/c^2) $m_{\psi(2S)\pi}$- (GeV/c^2)

- $m_{\psi\pi}$ peaks at high values because of the asymmetry in the $\cos\theta_K$ distributions
- The K^* regions dominate, and affect different regions of $\cos\theta_\psi$ for J/ψ and ψ(2S)
- The K^* veto removes approximately half of the angular distribution at the Z(4430)$^-$

The corrected $m_{\psi\pi}$ - distributions

All Kπ mass values

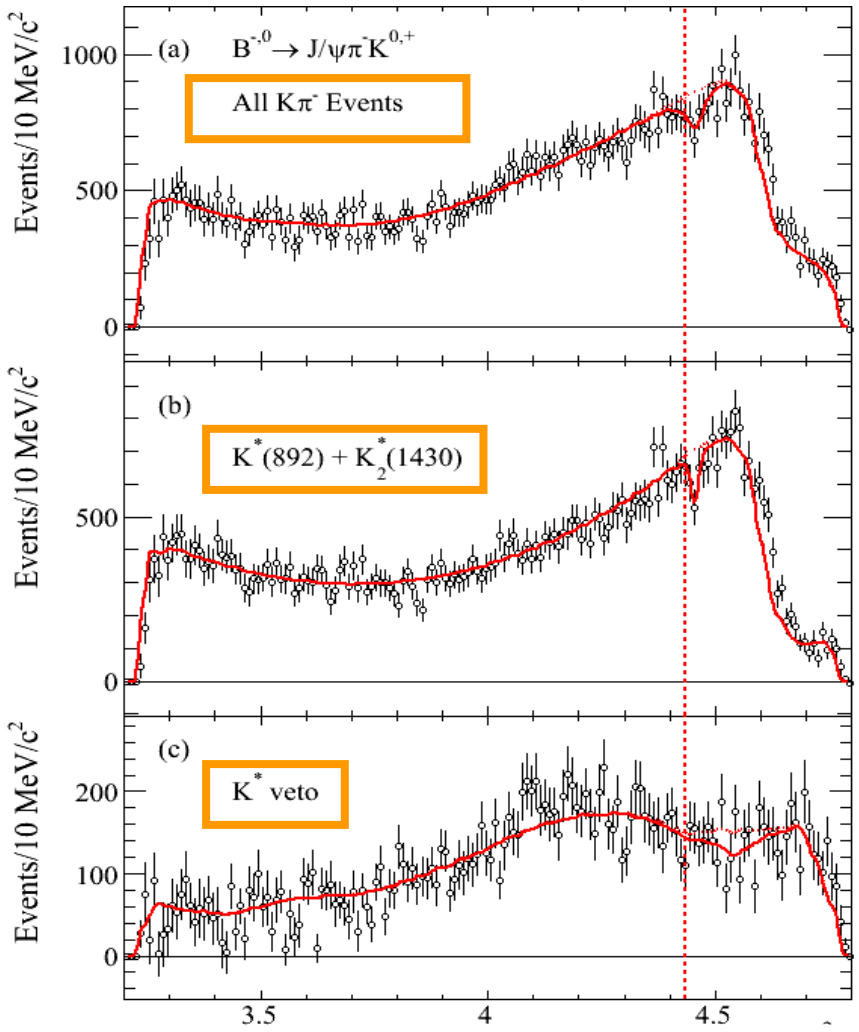


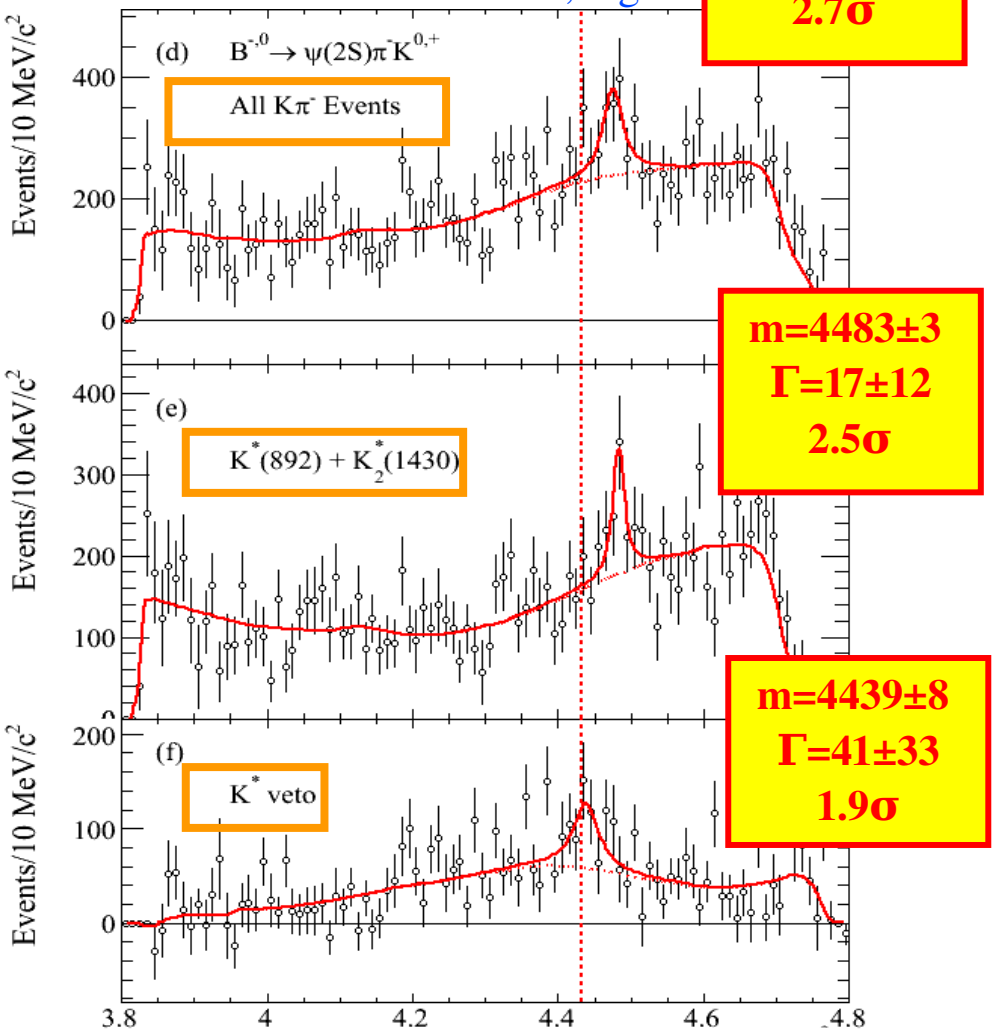
The Kπ⁻ reflections reproduce the data;

no need for additional structure

Fits to the corrected $m_{\psi\pi}$ - distributions

Four free parameters; m_Z, Γ_Z, N_Z, and $N_{K\pi^-,bkg}$





m=4476±8
Γ=32±16
2.7σ

m=4483±3
Γ=17±12
2.5σ

m=4439±8
Γ=41±33
1.9σ

No significant Z(4430)$^-$ signal on 413fb^{-1}…

Summary

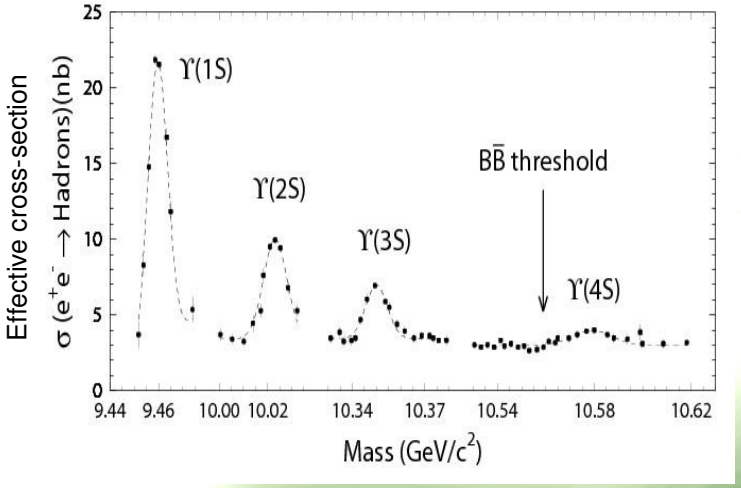
State	J^{PC}	Mass (MeV/c^2)	Width (MeV)
X(3872)	1^{++} or 2^{-+}	3871.80 ± 0.25	< 2.3
Y(3940)	$?^{?+}$	3916 ± 6	40 ± 22
Y(4260)	1^{--}	4264 ± 12	83 ± 22
Y(4350)	1^{--}	4361 ± 13	74 ± 18
Z(4430)	$?^{??}$	4443^{+15}_{-12}	109^{+86}_{-43}

What about Y(4143)? BaBar analysis is ongoing...

謝謝

Backup slides

BABAR @ SLAC



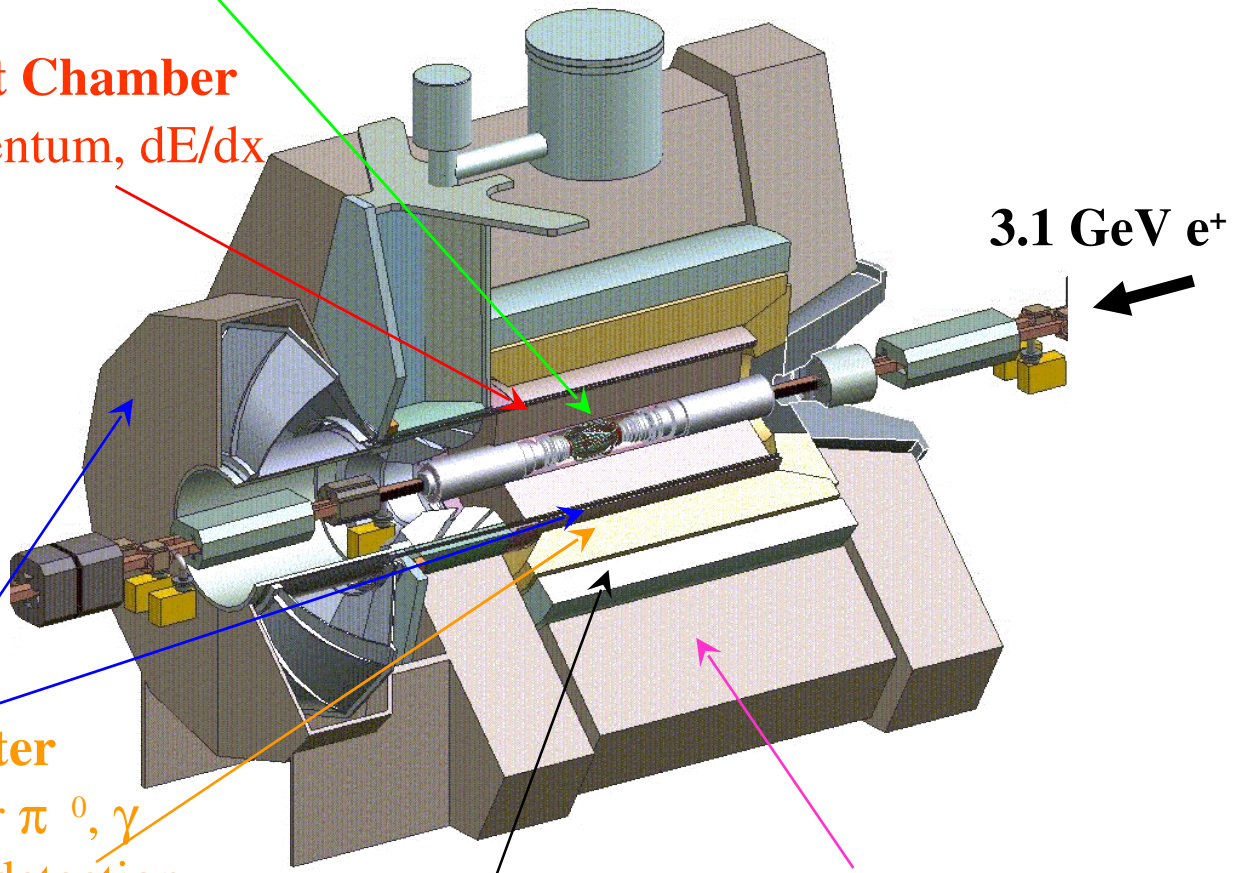
Center of mass: 10.58 GeV

$e^+ e^- \rightarrow \Upsilon(4S)\ (b\bar{b}) \rightarrow B\bar{B}$

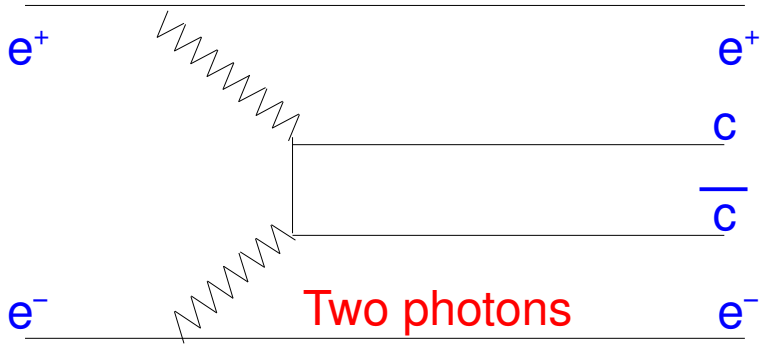
Peak luminosity:

$\mathbf{L} = 12.1\ 10^{33} cm^{-2} s^{-1}$

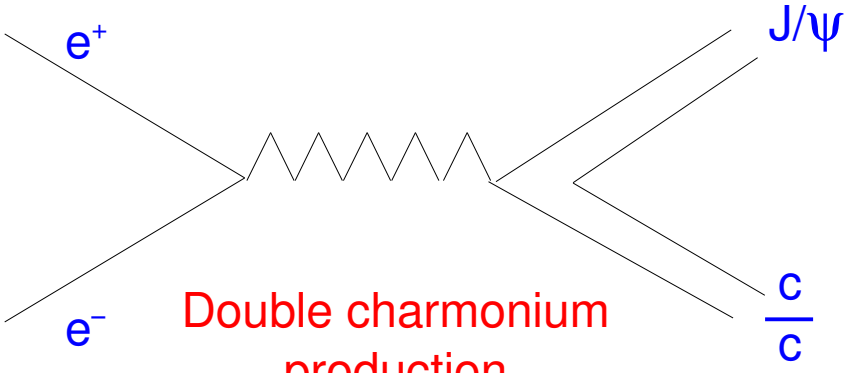
The BaBar detector



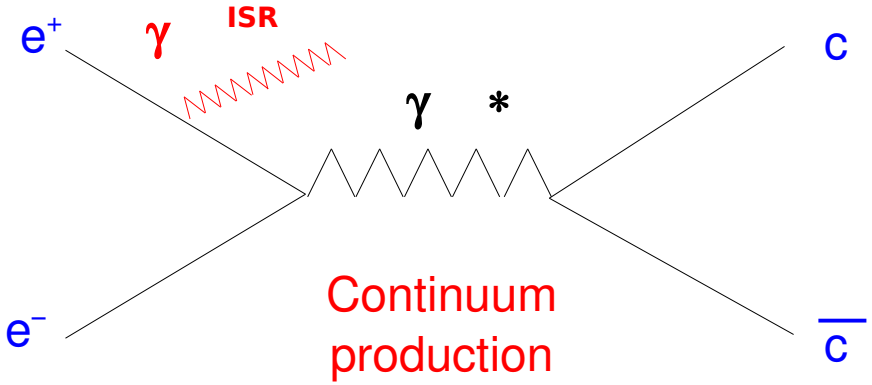
Hadron spectroscopy at the B-Factory



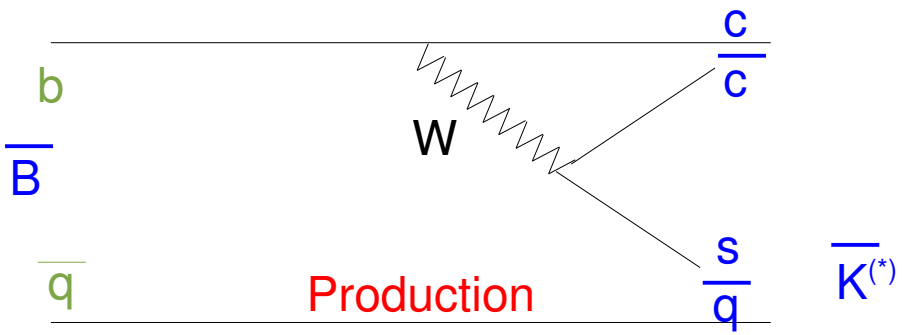
Two photons production



Double charmonium production



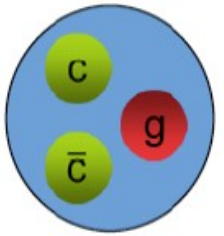
Continuum production



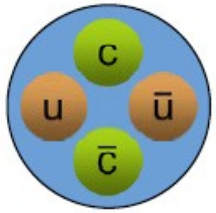
Production in B decays

Beyond Charmonium

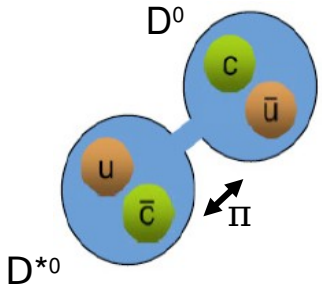
- Hybrids
  - States with **excited gluonic** degrees of freedom
  - Lattice and model predictions for the **lowest-mass** hybrid
    - M ~ **4.2 GeV/c^2**
  - Dominant decay into **DD***



- Tetraquarks
  - Bound states of **4 quarks**
  - **Large number** of states expected
  - **Small widths** above threshold



- Molecular states
  - Loosely bound states of a **pair of mesons**
  - **Small number** of states
  - **Small widths** above threshold



- Other possibilities
  - **Threshold**, **cusp**, or **coupled-channel** effect
  - Give a **cross section enhancement** which may not correspond to resonance production at all

X(3872): Discovery

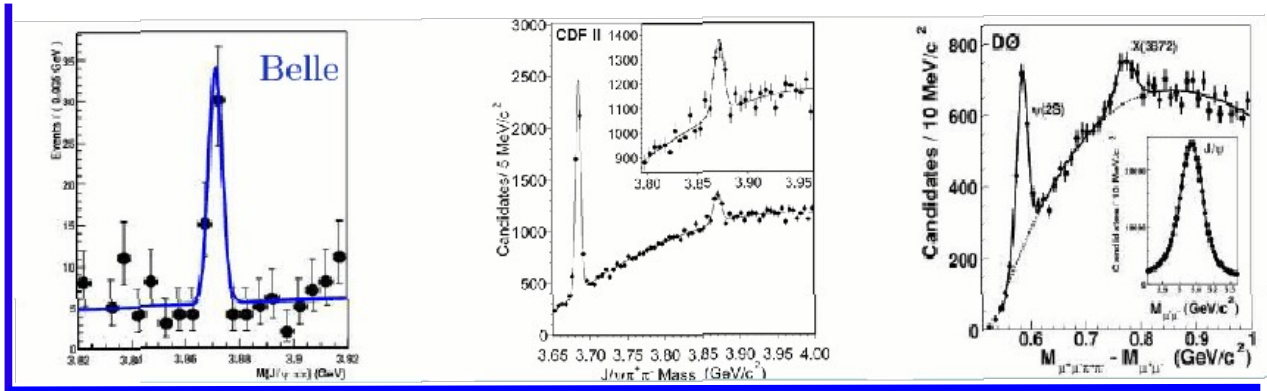
Discovered by Belle:

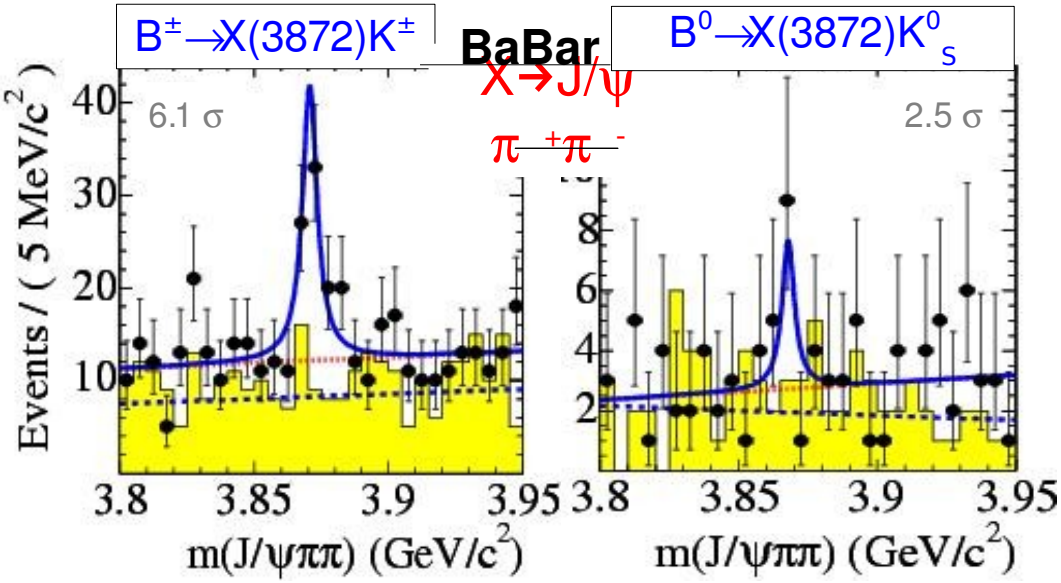
M_X=(3871.2±0.5) MeV/c

Confirmed by:

old value

- BABAR
- CDF
- D0





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

X(3872)

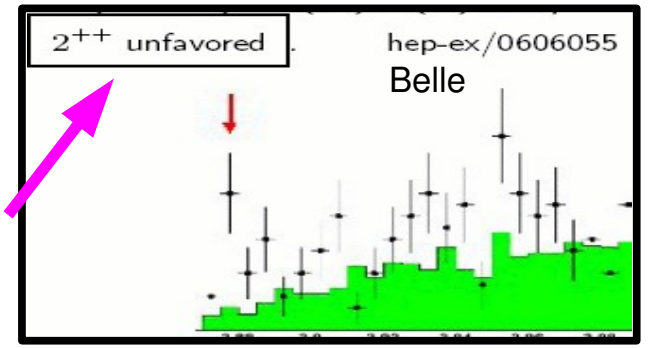
Low statistics in BaBar to conclude on $J^{P\,i}$

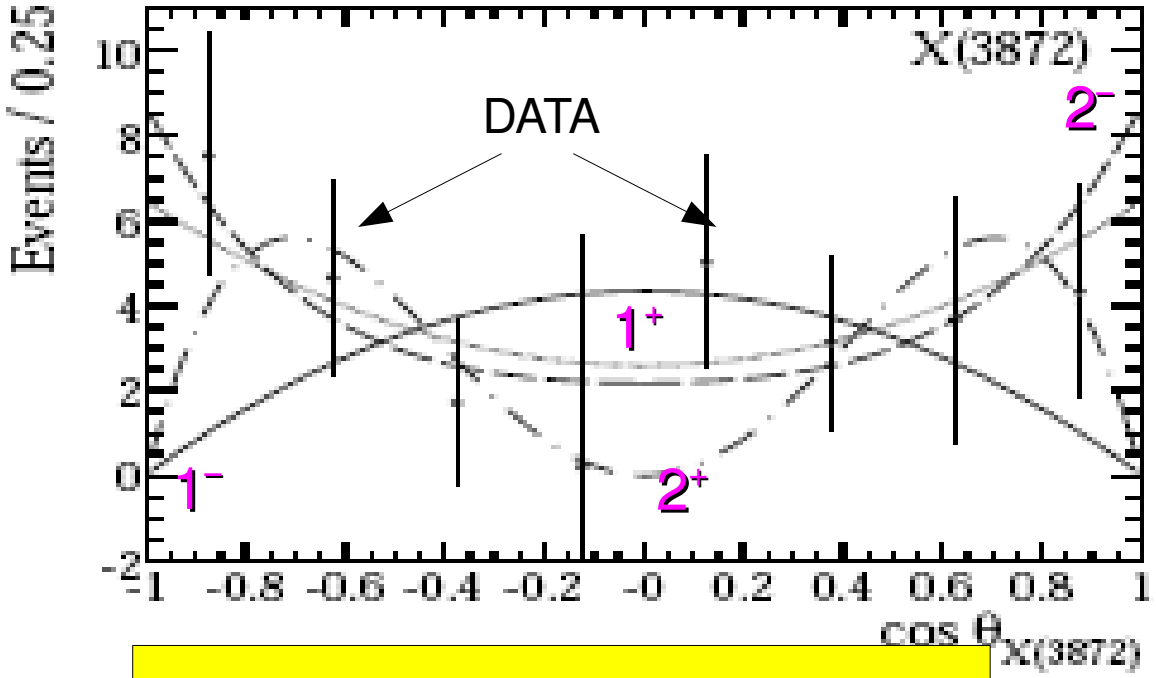
Measured in X→DD:

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

- 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

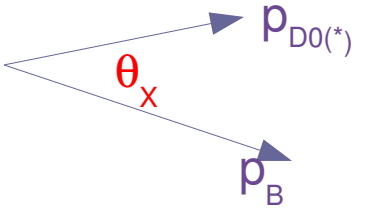




J^P	χ^2/n.d.f	
1^-	9.8/7	S-wave
1^+	3.9/7	S-wave
1^+	2.5/6	S+D-wave
2^+	5.9/7	
2^-	2.7/6	

$$R\left(\frac{X(3872)\to D^0\bar{D}^0\pi^0}{X(3872)\to D^0\bar{D}^0\gamma}\right) = 1.37\pm0.56$$

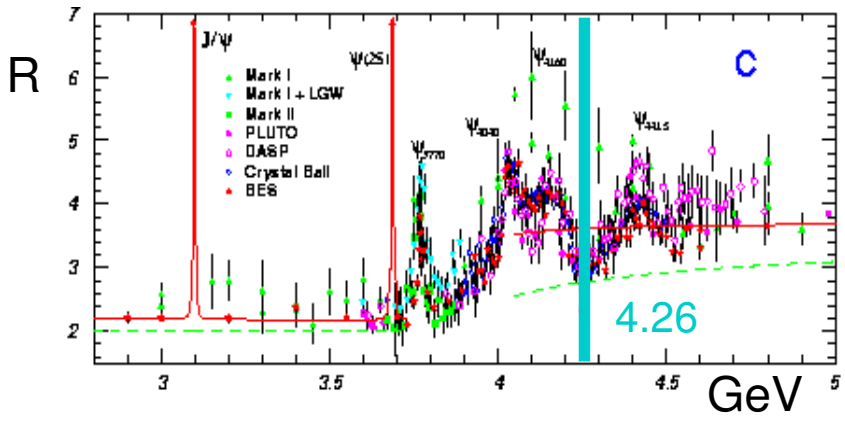
Expected: 1.30 for a state proceeding only via $D^0\bar{D}^{0*}$



Y(4260): Discovery

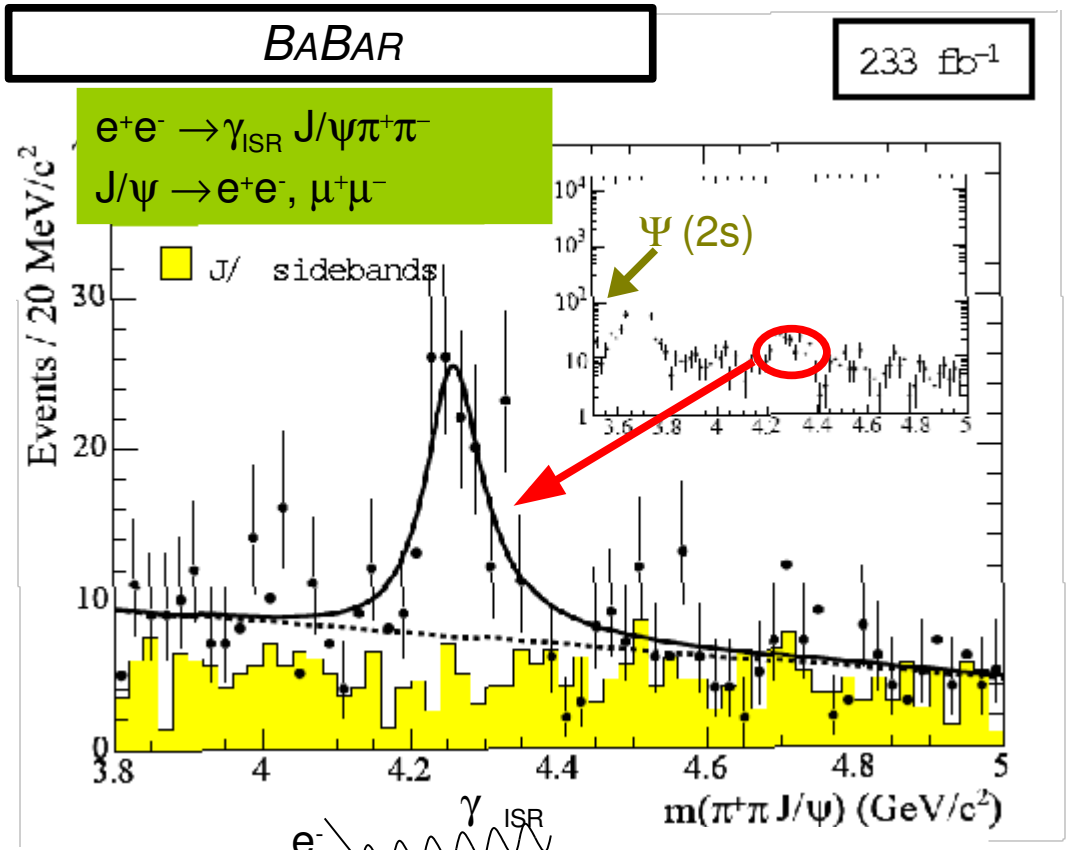
PRL 95, 142001 (2005)

- Observed in ISR events
- Confirmed by Cleo-c (scan) and Cleo III (ISR)



Study of $J/\psi\,\pi^+\pi^-$ production in ISR
- γ_{ISR} not necessarily detected
- Small mass recoiling against final state
- Low missing transverse momentum
- Good benchmark channel ISR

$\psi(2S)$



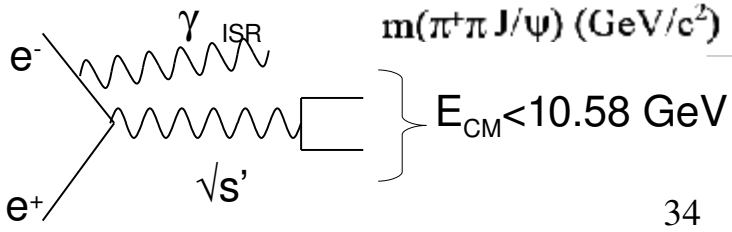
$M_Y = 4259 \pm 8^{+2}_{-6}$ MeV/c²

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

- $N = 125 \pm 23$

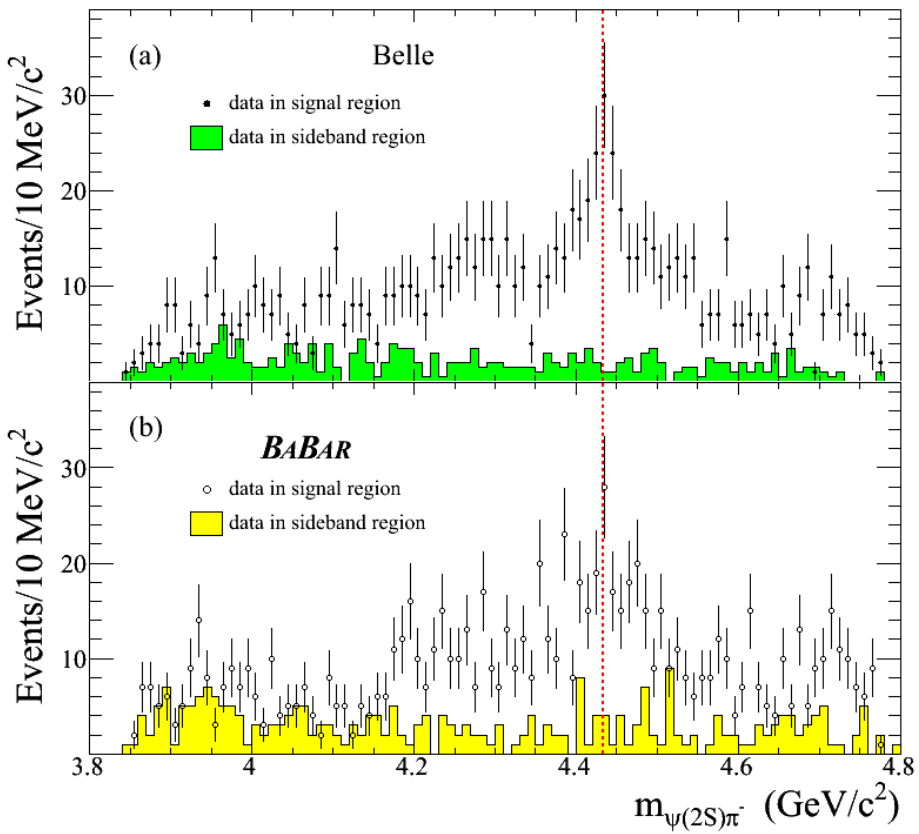
$J^{PC} = 1^{--}$

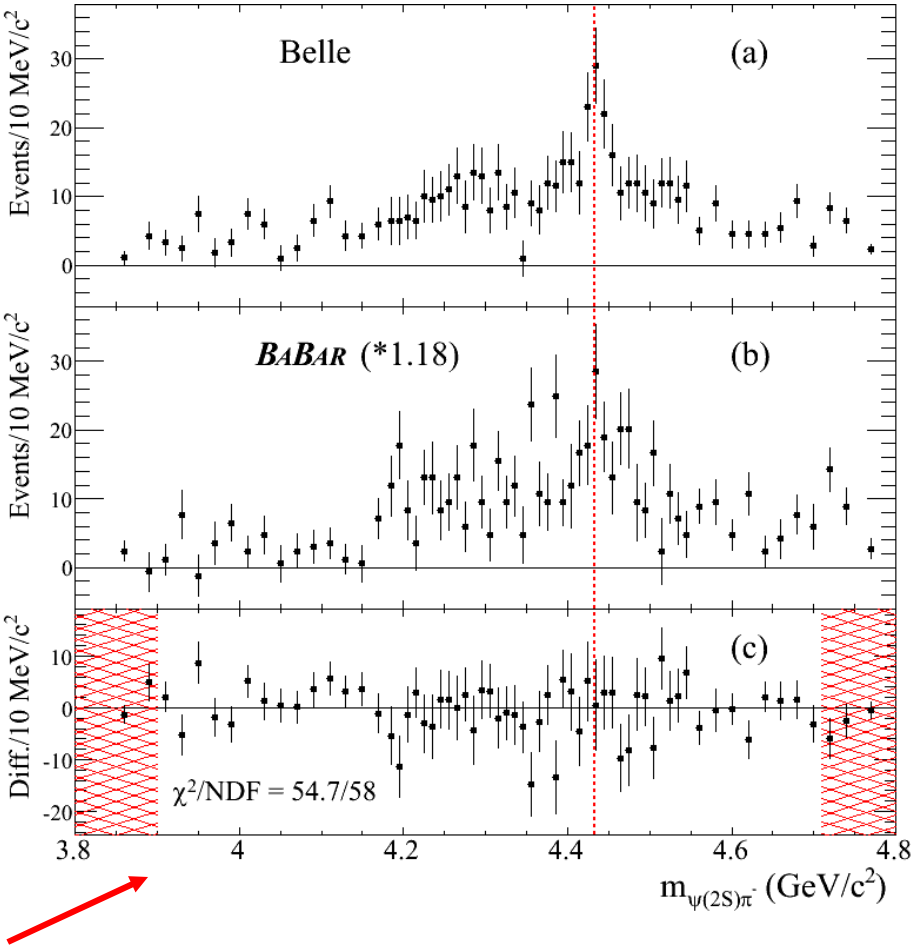
$\Gamma^Y_{ee} \times B(Y(4260) \to \pi^+\pi^- J/\psi) = (5.5 \pm 1.0^{+0.8}_{-0.7})$ eV



$Z(4430)^-$

- Belle-BaBar comparison





- Both Belle and BaBar data are re-binned (to calculate χ^2) and sideband subtracted
- The BaBar data are normalized (x1.18) to the Belle sample (luminosity ratio is 1.46)
- The data distributions are statistically consistent (χ^2=54.7/58)

⇒Main difference is treatement of background

BaBar: PRD 79, 112001 (2009)