Charmonium-Like States at the B Factories

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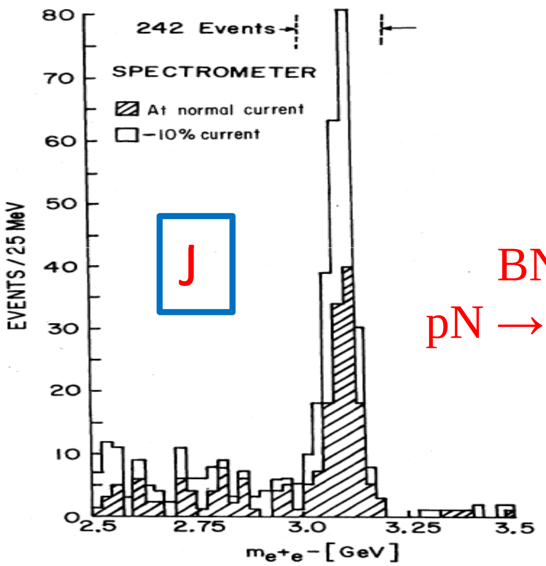
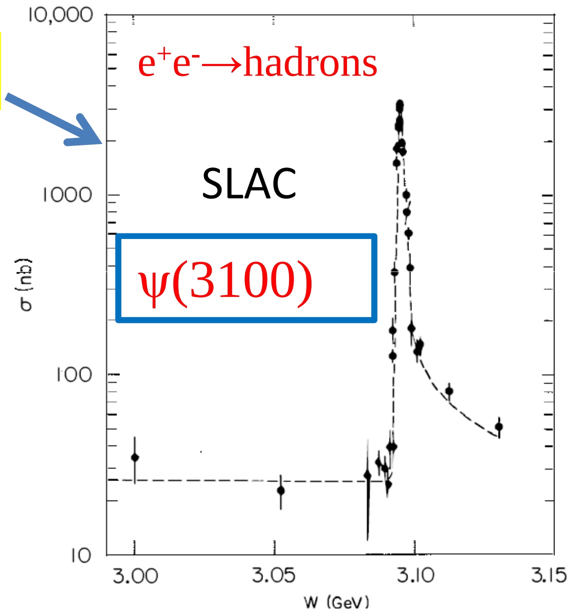
*"… this is not about making **honey**…"*
Bill Clinton, announcing funding of the B(ee)-Factory Project at SLAC

The Discovery of J/ψ

- **1974 Nov.** Revolution: SLAC & BNL discovered independently the J & ψ particle **PRL 33, 1406 (1974); PRL 33, 1404 (1974)**
- This discovery was another potential evidence for the charm quark
- Strong confirmation of the quark model



J/ψ resonance



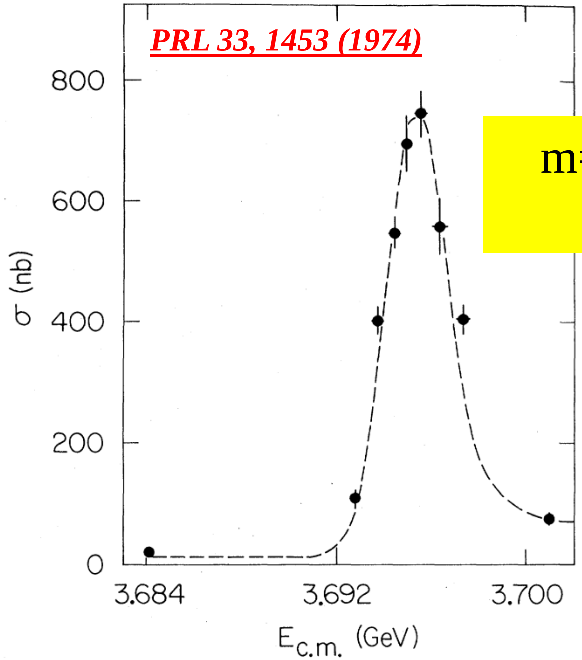
- J/ψ can couple directly to virtual photons produced in e^+e^- collisions
- Burton Richter (SLAC) & Samuel Ting (MIT) were awarded the **Nobel Prize** in 1976 for the J/ψ discovery

The discovery of ψ’ PRL 33, 1453 (1974)

Discovery of a Second Narrow Resonance in e^+e^- Annihilation*†

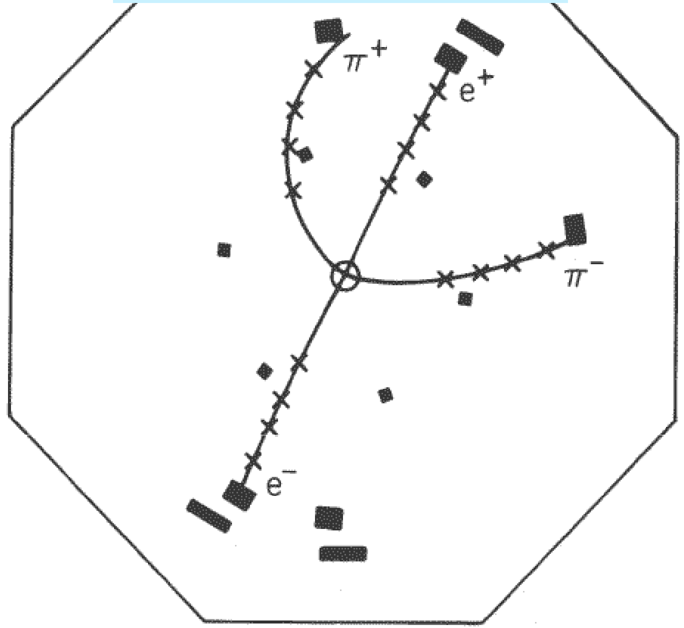
G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, A. Litke, B. Lulu, F. Pierre,‡ B. Sadoulet, G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 9472
and
J.-E. Augustin,§ A. M. Boyarski, M. Breidenbach, F. Bulos, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,§ R. R. Larsen, V. Luth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. Tanenbaum, and F. Vannucci‖
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 November 1974)

We have observed a second sharp peak in the cross section for $e^+e^- \rightarrow$ hadrons at a center-of-mass energy of 3.695± 0.004 GeV. The upper limit of the full width at half-maximum is 2.7 MeV.



m=3.695±0.004 GeV/c^2
Γ<2.7 MeV

ψ'→J/ψπ$^+$π$^-$
MARK-I Experiment



Computer reconstruction of the decay of a *ψ'*, an excited state of the *J/ψ*, as measured in the Mark I detector at SLAC in 1974

Charmonium Basic Theoretical Description

- Charmonium potential models (phenomenological):
  - **non-relativistic** (charm quark is "heavy" compared to binding energy)
  - quark confinement (increases linearly with separation)
  - simple QCD-inspired phenomenological potential (**Cornell model**) :

$$V(r) = -\frac{\kappa}{r} + \frac{r}{a^2}, \quad \kappa = 0.61, m_c = 1.84\,\text{GeV}, \text{a} = 2.38\,\text{GeV}^{-1}$$

Eichten et. al., PRD 17, 3090 (1978)
Godfrey & Isgur, PRD 32, 189 (1985)
Barnes et. al., PRD 72, 054026 (2005)

  - Potential is Coulomb-like for small radius and Harmonic Oscillator like for large radius.
  - The model can be extended to include spin-dependent terms, relativistic corrections, etc.

- Lattice QCD predicts the masses and widths of charmonium states

The Quark Model

- Gell-Mann/Zweig Quark Model: M. Gell-Mann PL 8, 214 (1964)

  "Baryons can now be constructed from quarks using combinations (qqq), (qqqq$\bar{q}$), etc., while mesons are made of (q$\bar{q}$), (qq$\bar{q}\bar{q}$), etc."

- Gell-Mann: **q$\bar{q}$** for mesons, but **q$\bar{q}$q$\bar{q}$** were not a priori excluded

- We have been seeking evidence for the higher configuration states

- Baryon sector: resonant structure in KN system➔ five-quark state

- Many searches for pentaquark baryons have been performed. Most prominent candidate is $\theta(1540)^{+}$. Today: the existence of pentaquarks must be considered to be in doubt G. Trilling, J. Phys. G 33, 1019 (2006)

- Meson sector: attention has been focused over the years on $a_0(980)$ and $f_0(980)$ as possible four-quark states

Charmonium States So Far

- **Charmonium is a $c\bar{c}$ bound state** ; Analogous to hydrogen, **positronium**

Notation:

$^{2S+1}[L]_J$

L=S,P,D (0,1,2)
(No cand. with L>=3)

J = L+S

$S(q\bar{q})$ = 0 or 1

Parity: **P = $(-1)^{L+1}$**

Charge conjugation eigenvales: **C=$(-1)^{L+S}$**

N: Radial Quantum Numbers

C. Amsler, et. al., PLB 667, 1 (2008)

Quantum numbers				Name	Mass (MeV/c^2)	width(MeV)
N	L	J^{PC}	$N^{2S+1}L_J$			
1	0	0^{-+}	1^1S_0	$\eta_c(1S)$	2980.4±1.2	26.7±3
1	0	1^{--}	1^3S_1	J/ψ	3096.916±0.011	93.2±0.02 $\times 10^{-3}$
1	1	0^{++}	1^3P_0	χ_{c0} (1P)	3414.75±0.31	10.2±0.7
1	1	1^{++}	1^3P_1	χ_{c1}(1P)	3510.66±0.07	0.89±0.05
1	1	2^{++}	1^3P_2	χ_{c2}(1P)	3556.20±0.09	2.03±0.12
1	1	1^{+-}	1^1P_1	h_c(1P)	3525.93±0.27	<1
1	2	1^{--}	1^3D_1	$\psi(3770)$	3772.92±0.35	27.3±1.0
2	0	0^{-+}	2^1S_0	$\eta_c(2S)$	3637±4	14±7
2	0	1^{--}	2^3S_1	$\psi(2S)$	3686.09±0.04	317±9 $\times 10^{-3}$
2	1	2^{++}	2^3P_2	χ_{c2}(2P)	3929±5	29±10
3	0	1^{--}	3^3S_1	$\psi(4040)$	4039±1	80±10
2	2	1^{--}	2^3D_1	$\psi(4160)$	4153±3	103±8
4	0	1^{--}	4^3S_1	$\psi(4415)$	4421±4	62±20

Charmonium-like States

- Charmonium-like states are particles that usually decay to $c\bar{c}$ state and others (e.g. $X \rightarrow J/\psi\pi^{+}\pi^{-}$) but not yet clear if it is consistent with a conventional $c\bar{c}$ states

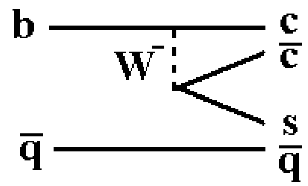
- Their nature has not yet been completely understood

- Some of their decay modes are as expected; others are puzzling

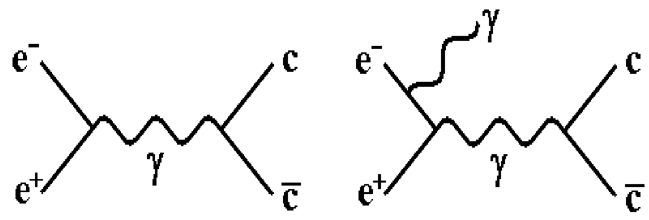
- Their spin-parity assignment are NOT yet established

Production of $c\bar{c}$-States

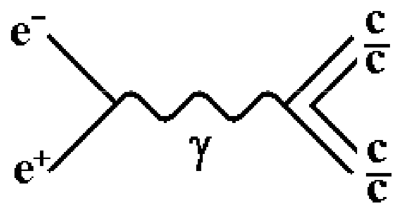
- Color-suppressed b→c decay
  - Predominantly from **B-meson** decays



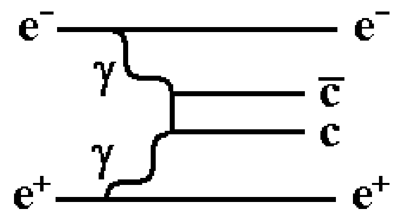
- e^+e^- Initial State Radiation (**ISR**)
  - e^+e^- collision below nominal c.m. energy
  - $J^{PC}=1^{--}$



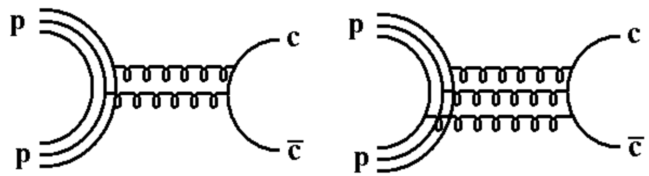
- **Double** charmonium production
  - Typically one J/ψ or ψ, plus second $c\bar{c}$ state



- **Two-photon** production
  - Access to C=+1 states

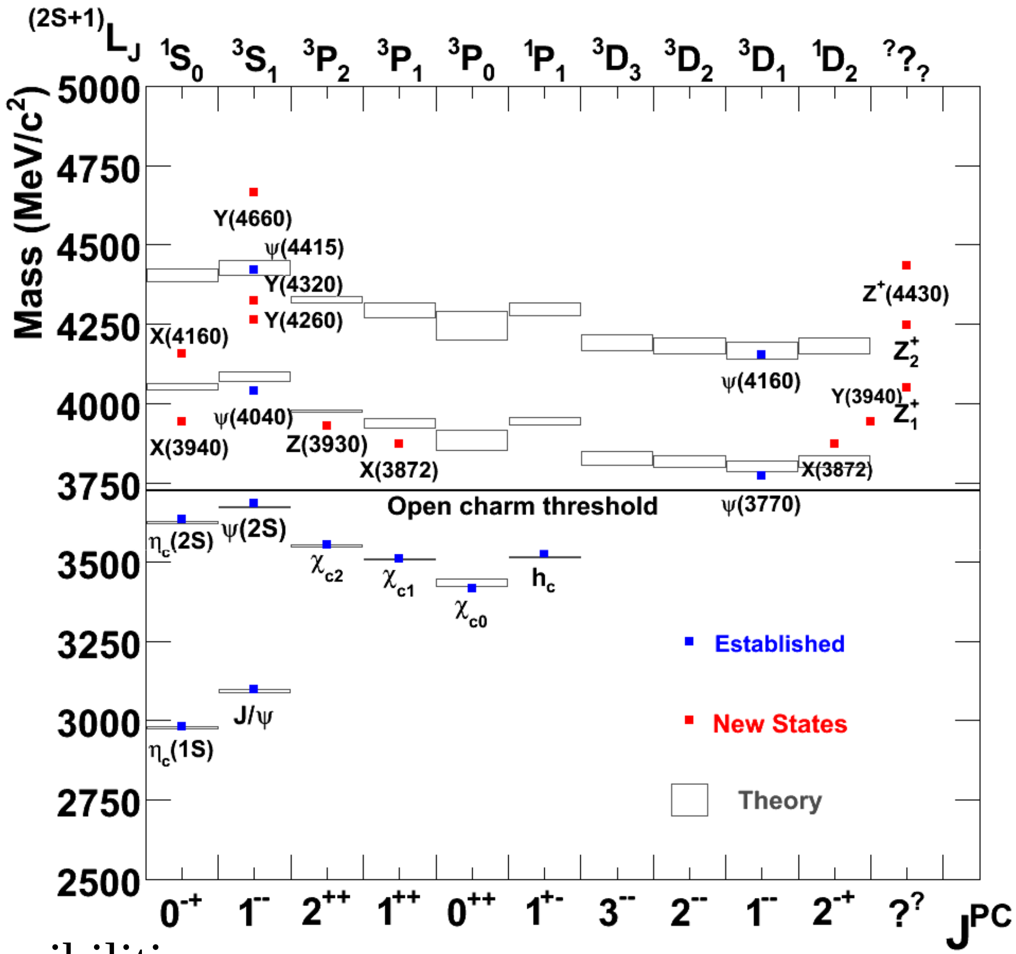


- $p\bar{p}$ /pp interactions (Tevatron)
  - All quantum numbers available



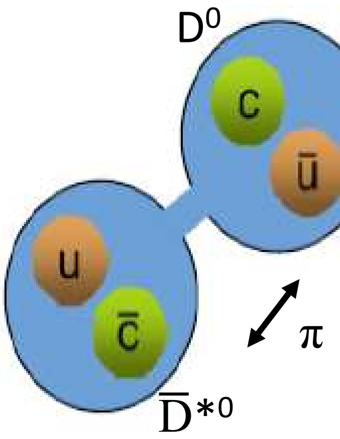
Charmonium States

- Many states are predicted above open charm threshold
- <u>All predicted</u> states below the open charm threshold have been observed
- During the last several years, many states have been discovered above the open charm threshold; Not always their properties agree with the $c\bar{c}$ predictions



- QCD allows for more "exotic" possibilities
  - hybrids, tetraquark states, four-quark molecules
- Are we seeing the <u>**first evidence**</u> of something **new** or **different**?

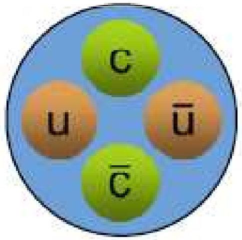
Proposed Alternative Models-I



Molecular

Loosely bound state of a pair of mesons. The dominant binding mechanism should be **pion exchange**. Being weakly bound the mesons tend to decay as if they were free

NA Tornqvist PLB 590, 209 (2004); ES Swanson PLB 598, 197 (2004); E Braaten & T Kusunoki PRD 69, 074005 (2004); CY Wong PRC 69, 055202 (2004); M. Voloshin PLB 579, 316 (2004); F Close & P Page PLB 578, 119 (2004); X Liu arXiv:0708.4167



Tetraquark

Bound state of four quarks, i.e. **$q\bar{q}q\bar{q}$** in which the quarks group into color triplet scalar or vector clusters.

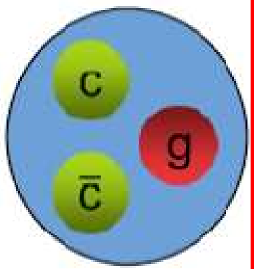
Strong decays proceed via rearrangement processes

L Maiani et al PRD 71, 014028 (2005); T-W Chiu & TH Hsieh PRD 73, 111503 (2006); D Ebert et. al., PLB 634, 214 (2006)

Distinctive features of multi-quark picture with respect to charmonium:

- prediction of many new states
- possible existence of states with non-zero charge, strangeness or both.

Proposed Alternative Models-II

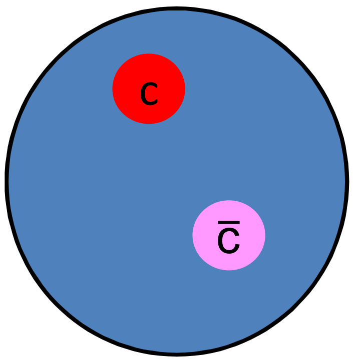


Charmonium hybrids

States with excited gluonic degrees of freedom; 0^{+-}, 1^{-+}, 2^{+-}…quantum numbers are not possible for $c\bar{c}$ states, but are possible for hybrids; would unambiguously signal an exotic state.

Lattice and potential model predictions for the lowest-mass hybrid: m ~ 4.2 GeV/c^2

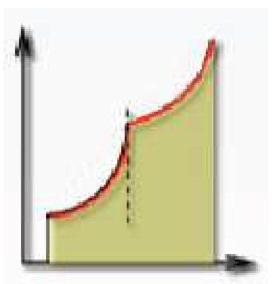
P Lacock et al (UKQCD) PLB 401, 308 (1997);
SL Zhu PLB 625, 212 (2005);
F. Close, PR Page PLB 628, 215 (2005);
E Kou &O Pene PLB 631, 164 (2005)



OR

Conventional charmonium

C. Meng & KT Chao, PRD 75, 114002 (2007);
O. Zhang, C Meng & HQ Zheng arXiv:0901.1553



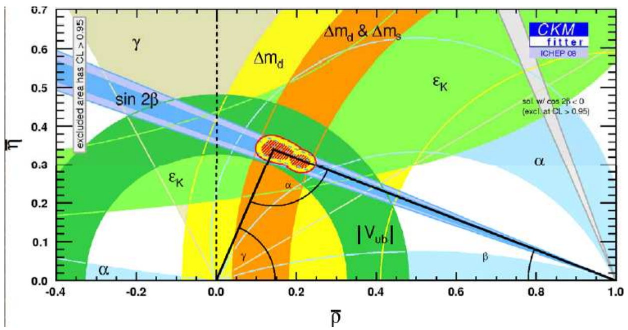
OR

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

The Theme of the B Factories

- The B-factories were built to study charge and parity (CP) symmetry violation
- Redundant measurements of CP violation in the B^0 system, and to probe possible physics beyond the SM
- With these mesons, we can study at the same time three elements of the **quark mixing matrix**

2008 Physics Nobel Prize



Yoichiro Nambu

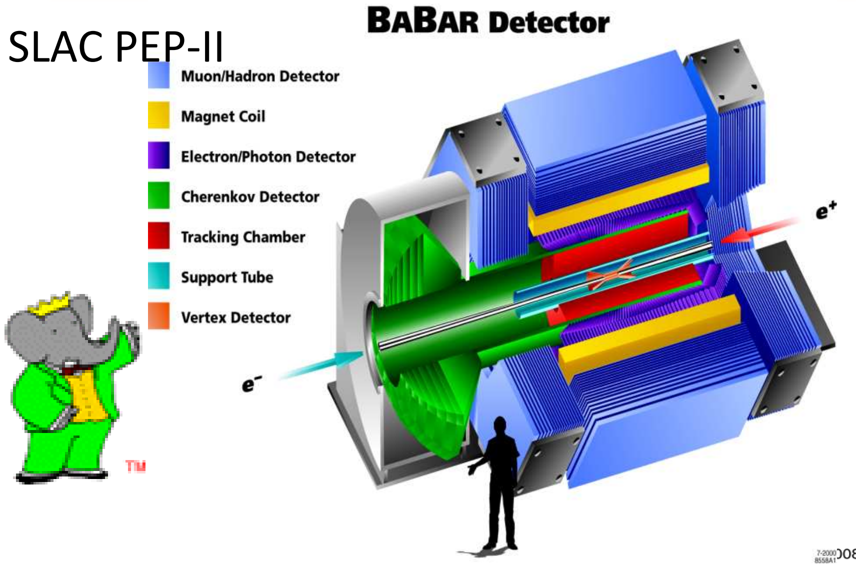
Makoto Kobayashi

Toshihide Maskawa

BABAR and Belle's experimental **evidence** of **CP violation** in asymmetric B^0 and $\overline{B}^0$ decays into CP eigenstates provided **verification** of the Kobayashi-Maskawa model predictions of a 3×3 quark mixing matrix with a complex phase.

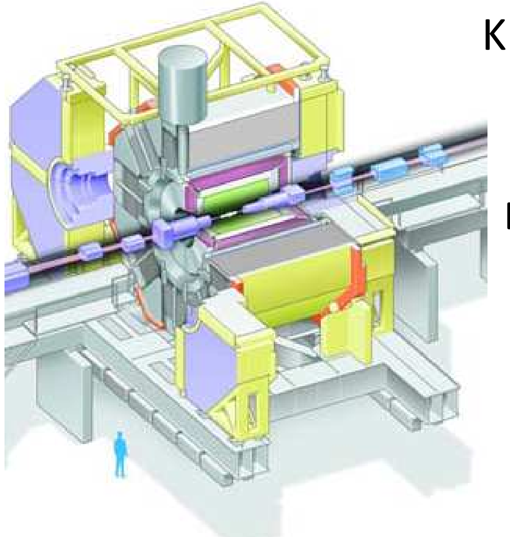
The BABAR and Belle Detectors

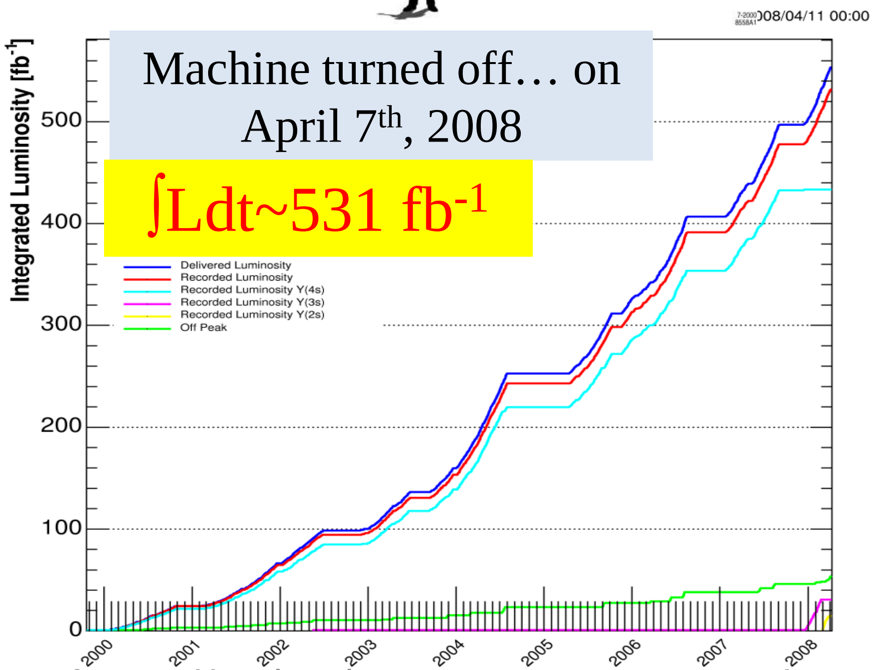
SLAC PEP-II

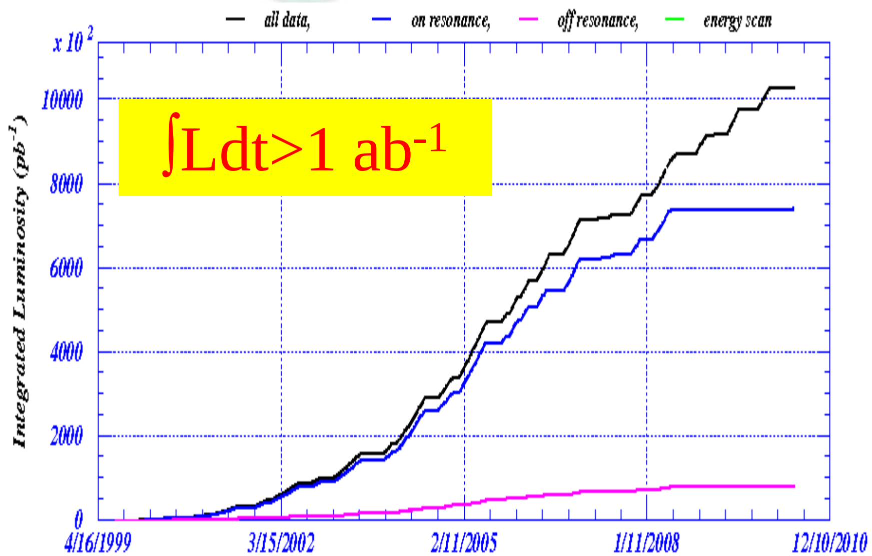


KEK-B

Belle Detector

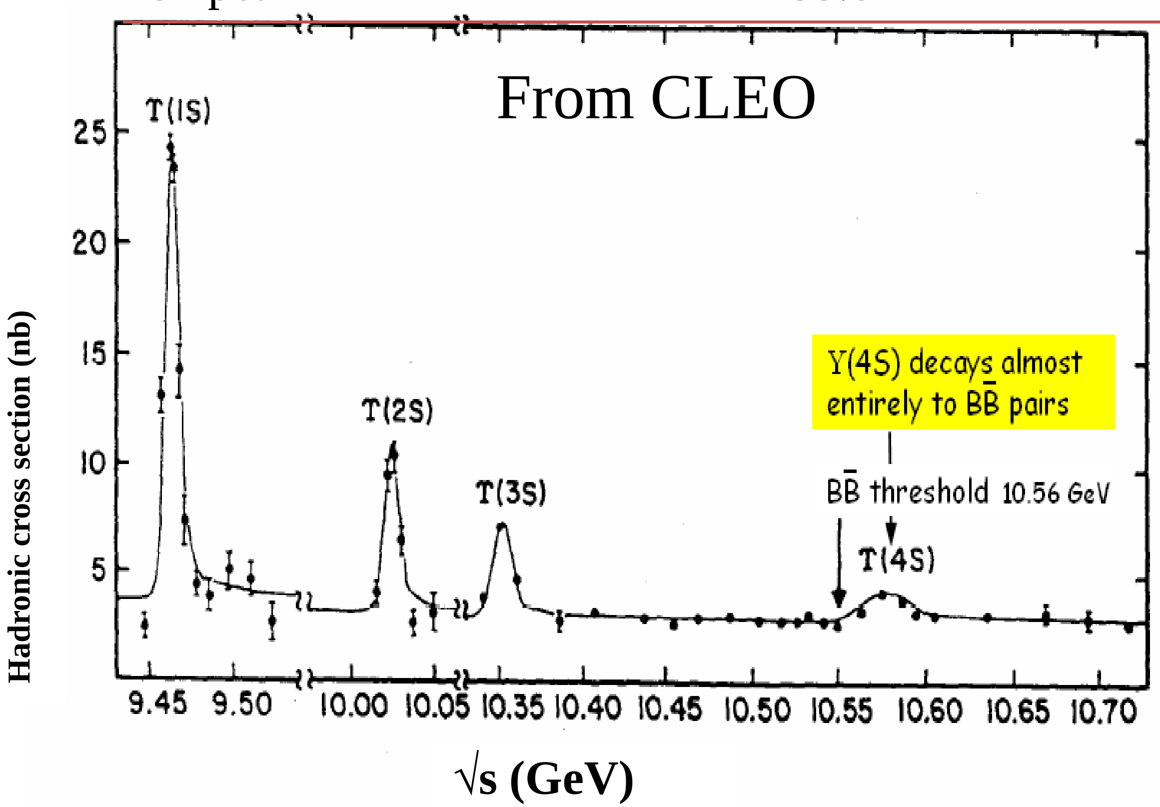






The BABAR Data-Taking

Data Sample	Integrated Lumi (fb^{-1})	~Events(10^6)
Υ(4S)	432.9	470
Υ(3S)	30.2	122
Υ(2S)	14.5	100
Offpeak	53.8	NA



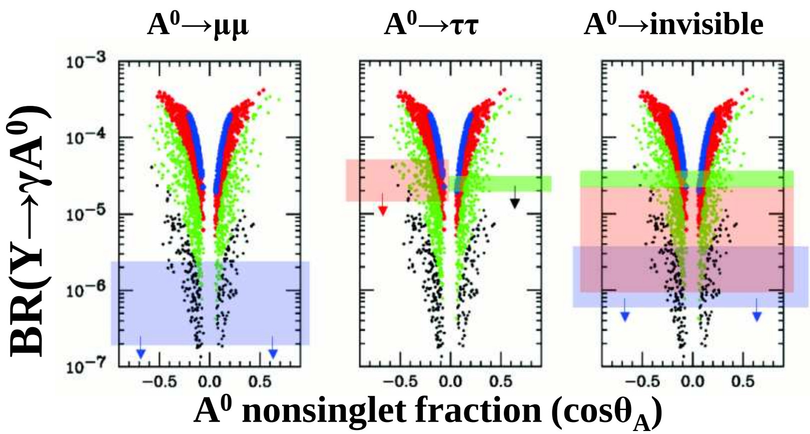
BF(Υ(4S)→BB̄)>96%

PDG, PLB 667, 1 (2008)

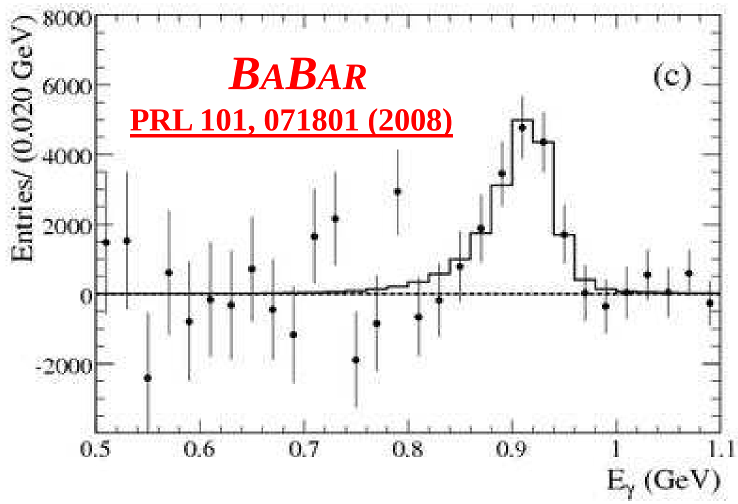
We need B Factories!

Highlights From the Y(3S) and Y(2S) Data

- ϒ(3S) & ϒ(2S) samples:
  - search for **new physics** such as **light-higgs** boson and light **dark matter** (PRL103, 081803 (2009); PRL 103, 181801 (2009); hep-ex/0808.0017)



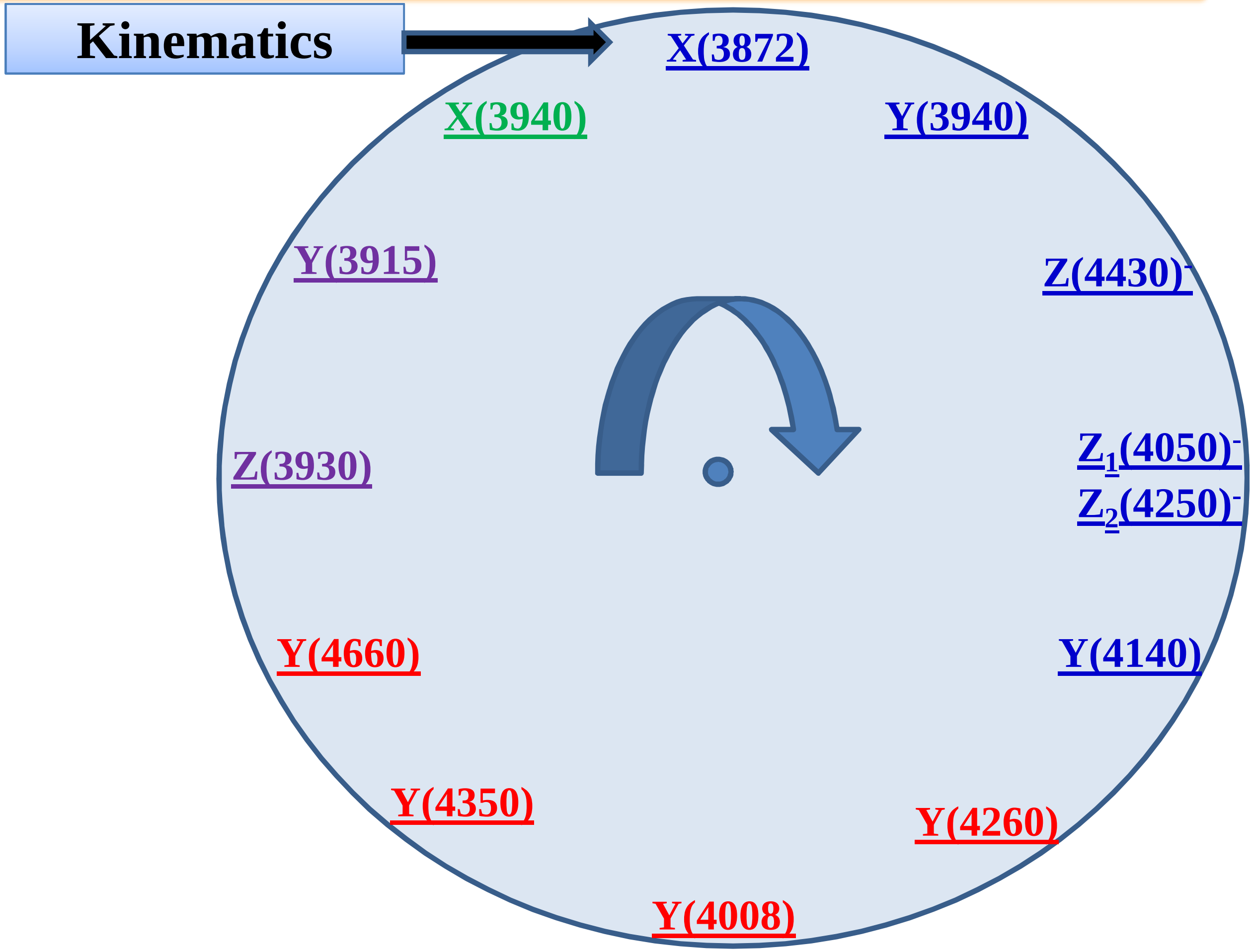
  - Study bottomonium physics, in particular search for the bottomonium ground state, $\eta_b(1S)$



- 2008: *BABAR* **observed** the $\eta_b(1S)$ signal in $\Upsilon(3S)\rightarrow\gamma\eta_b$ & $\Upsilon(2S)\rightarrow\gamma\eta_b$ (PRL 101, 071801 (2008) & PRL 103, 161801 (2009))

Outline

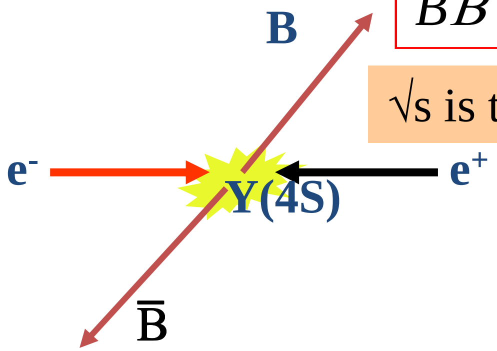
- From B decays:
  - **X(3872)**
  - **Y(3940)**
  - **$Z(4430)^-$**
  - **$Z_1(4050)^-$**
  - **$Z_2(4250)^-$**
  - **Y(4140)**
- From ISR
  - **Y(4260)**
  - **Y(4008)**
  - **Y(4350)**
  - **Y(4660)**
- From $\gamma\gamma$ production
  - **Z(3930)**
  - **Y(3915)**
- From double $c\bar{c}$ production
  - **X(3940)**



Ad-hoc names!

Kinematic variables for B-decays

$B\bar{B}$ are not back-to-back in the lab frame



√s is the cm energy

$$m_{ES} = \sqrt{\left(\frac{\frac{s}{2} + \vec{P}_{e^+e^-} \cdot \vec{P}_B}{E_{e^+e^-}}\right)^2 - \vec{P}_B^{\,2}} \sim m_B$$

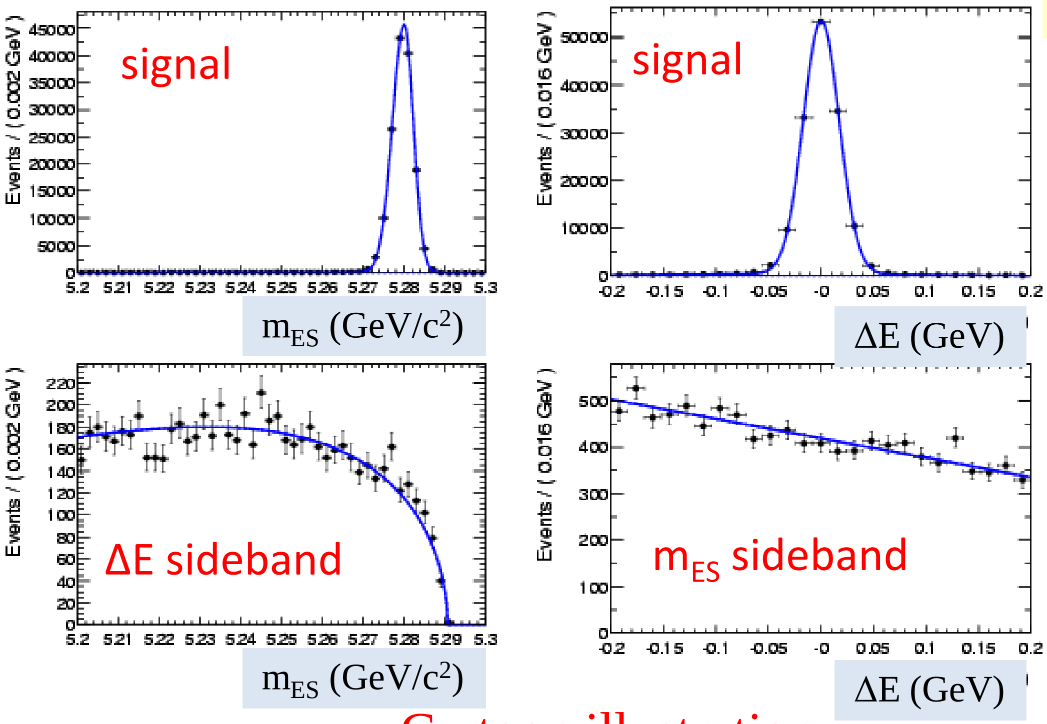
$$\Delta E = E_B^* - \frac{\sqrt{s}}{2}$$

s: cms energy

$E^*_B = \Sigma\, E^*_i$ over the B-candidate

$\sigma_{mES} \sim 2.5$ MeV/c^2

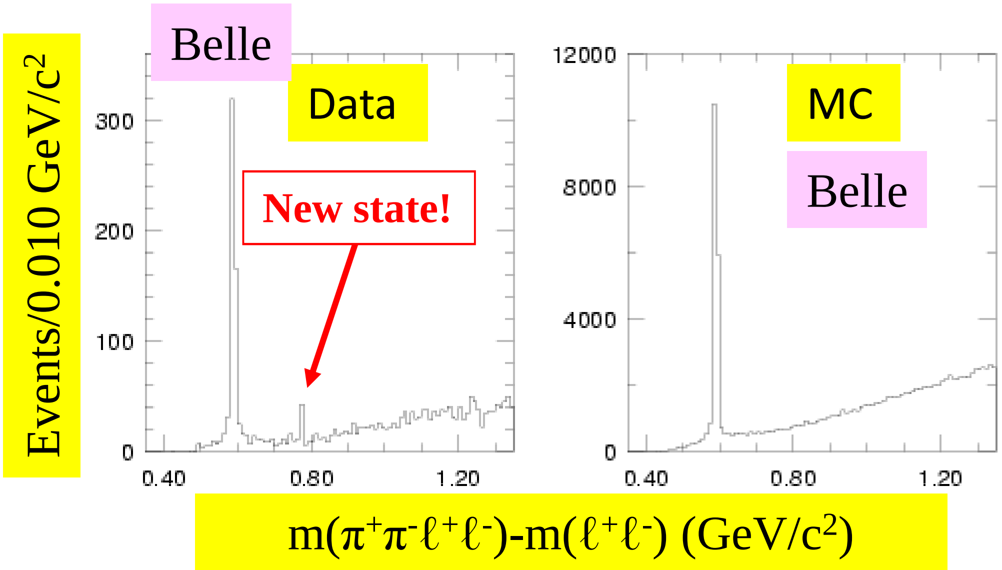
$\sigma_{\Delta E} \sim 15$ MeV



Cartoon illustration

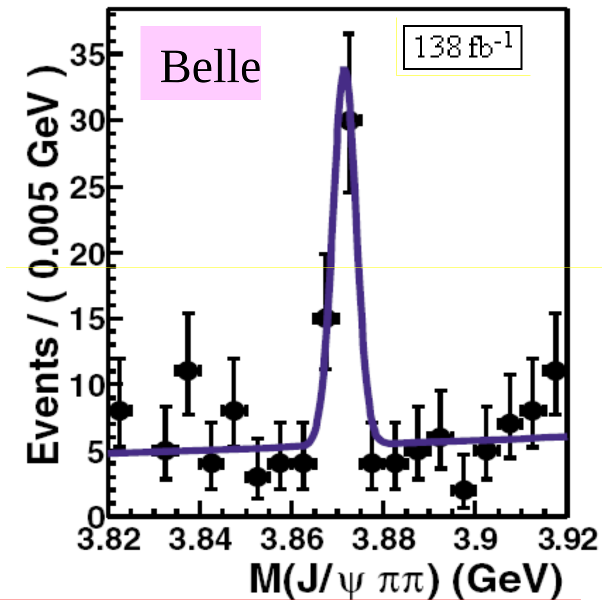
The X(3872): the Belle Discovery

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

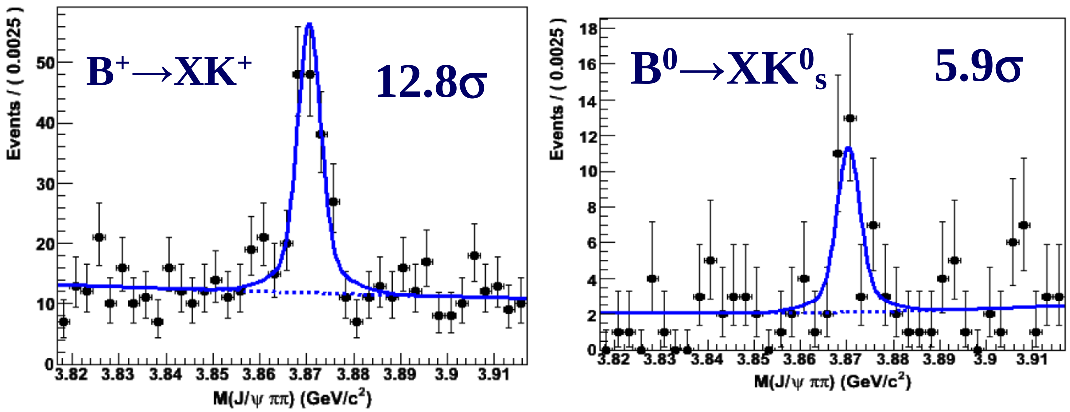


PRL 91, 262001 (2003)

cited ~500 times!

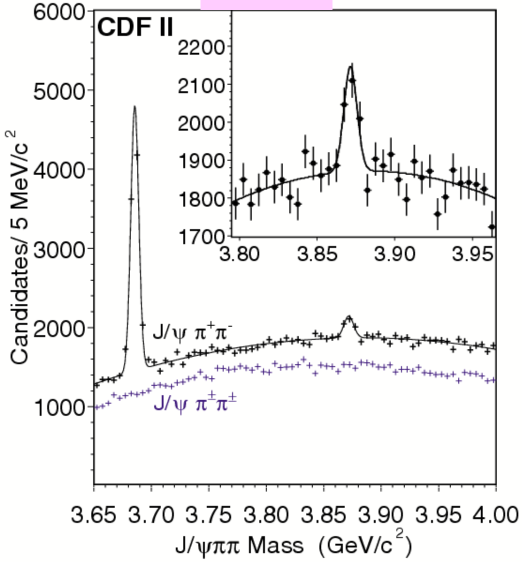


10σ new resonance!

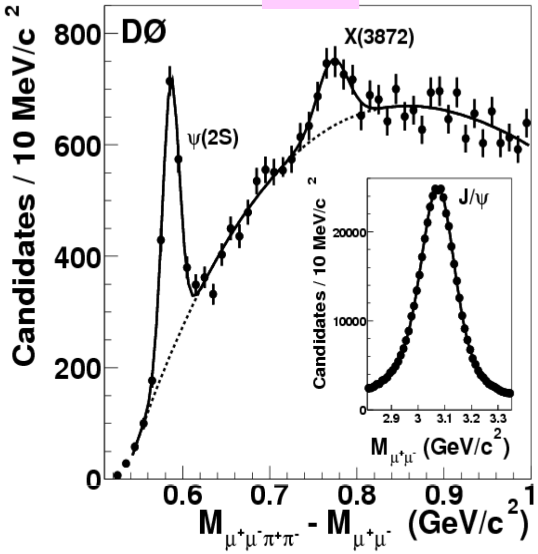


The X(3872): The Confirmation

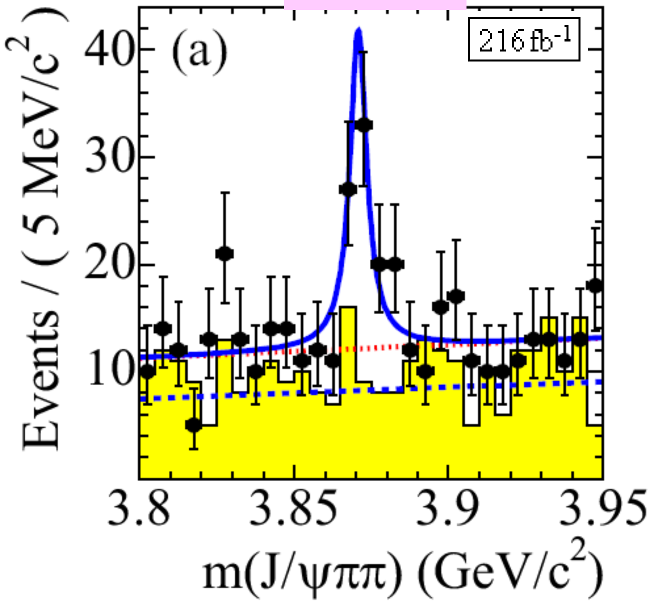
CDF



D0



BABAR



CDF
PRL 93, 072001 (2004)

D0
PRL 93, 162002 (2004)

BABAR
PRD 71, 071103 (2005)
PRD 73, 011101 (2006)

@ the Tevatron

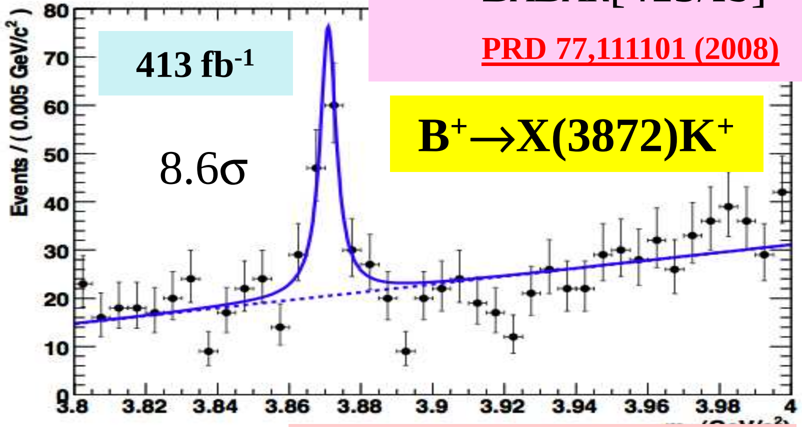
$p\bar{p}$ Inclusive $J/\psi\pi^+\pi^-$ production

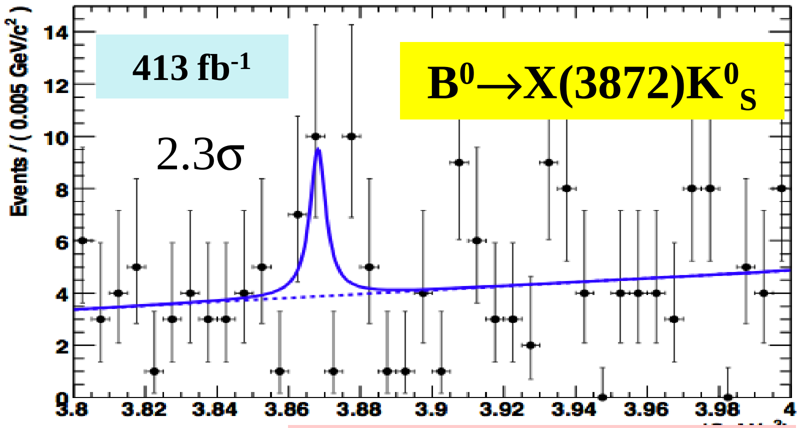
$B \rightarrow J/\psi\pi^+\pi^-K$

The X(3872):BABAR Full Dataset

BABAR[413/fb]

PRD 77,111101 (2008)





Tetraquark models: $\Delta m = |m(3872)K^+ - m(3872)K^0_S| = 8 \pm 3$ MeV/c^2
BABAR : $\Delta m = (2.7 \pm 1.6 \pm 0.4)$ MeV/c^2

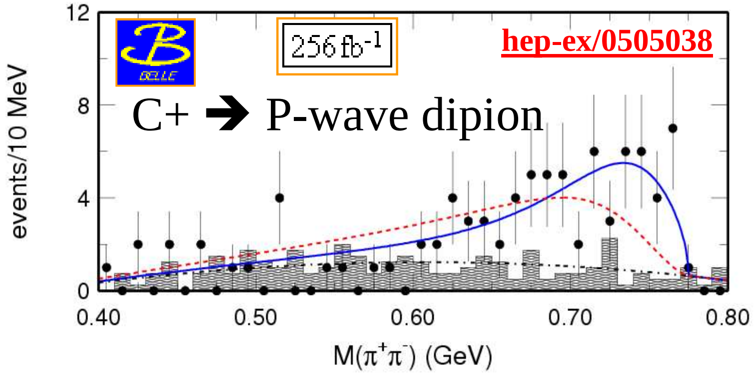
BF($B^+ \to XK^+$, $X \to J/\psi\pi^+\pi^-$) = $(8.4 \pm 1.5 \pm 0.7) \times 10^{-6}$

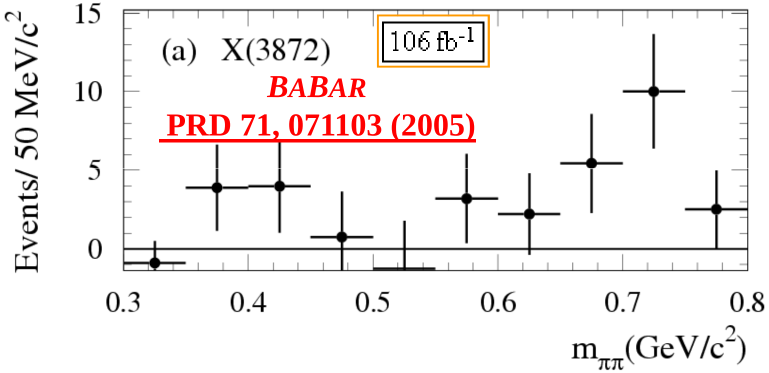
BF($B^0 \to XK^0$,$X \to J/\psi\pi^+\pi^-$)= $(3.5 \pm 1.9 \pm 0.4) \times 10^{-6}$ $<6.0\times10^{-6}$ @ 90% C.L.

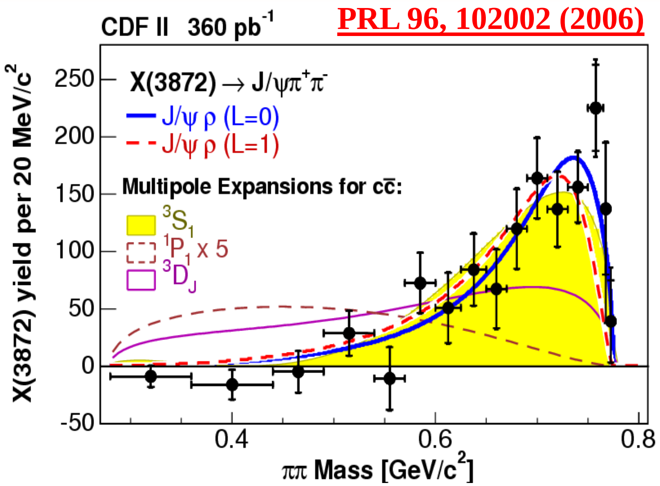
R(X)= *BF*(B^0)/*BF*(B^+) = $0.41 \pm 0.24 \pm 0.05$ (Molecular models predict R(X)<0.1)

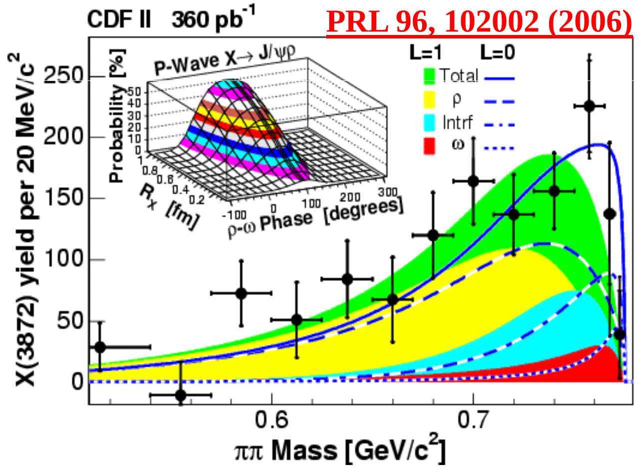
Γ(X)<3.3 MeV @ 90% C.L.

The Di-pion Mass Distribution









- Belle and CDF analyzed the $\pi^+\pi^-$ mass distribution; both described in terms of ρ-like shape
- Belle favors $J^{PC} = 1^{++}$ (S-wave) ; CDF either 1^{++} or 2^{-+} (P-wave, with ω-ρ interference)
- Shape in *BABAR* is similar; no attempt to fit the mass spectrum

The X(3872): Charged Partner?

❖ *BABAR* searched for the charged partner of the X(3872) in the decay mode **$B \to J/\psi\pi^-\pi^0K$** , using 234 million $B\bar{B}$ events

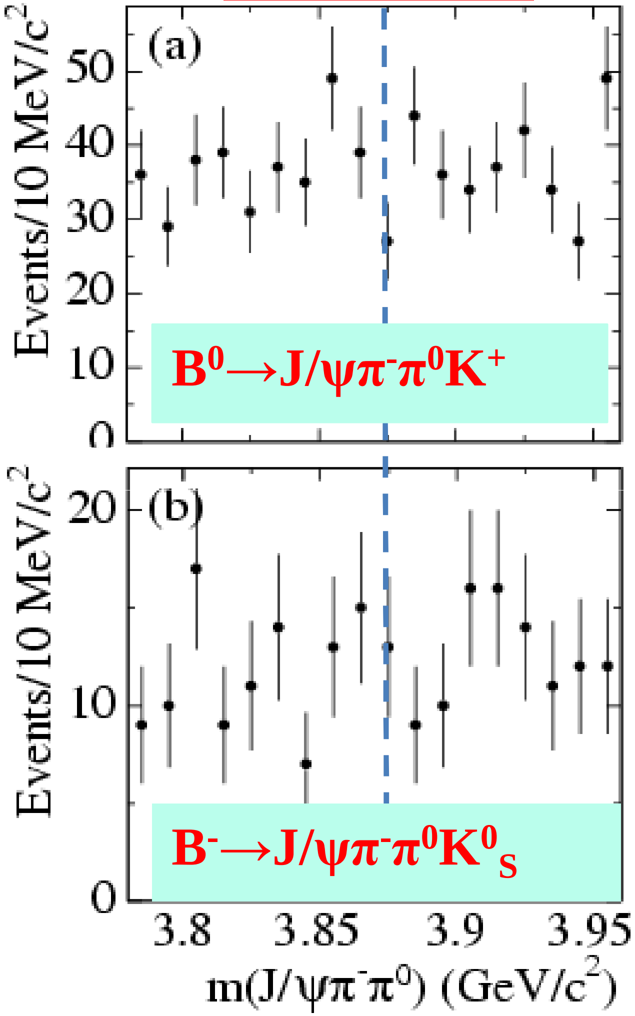
❖ **No evidence** for **$X(3872)^-$** was found:

- $\mathcal{B}(B^0 \to X^-K^+, X^- \to J/\psi\pi^-\pi^0) < 5.4 \times 10^{-6}$ @ 90% C.L.
- $\mathcal{B}(B^- \to X^-K^0, X^- \to J/\psi\pi^-\pi^0) < 22 \times 10^{-6}$ @ 90% C.L.

Isovector hypothesis excluded➔ I=0

❖ This search could be repeated with the full datasets at the B-factories (~2 times @ *BABAR* and ~4 times @ Belle)

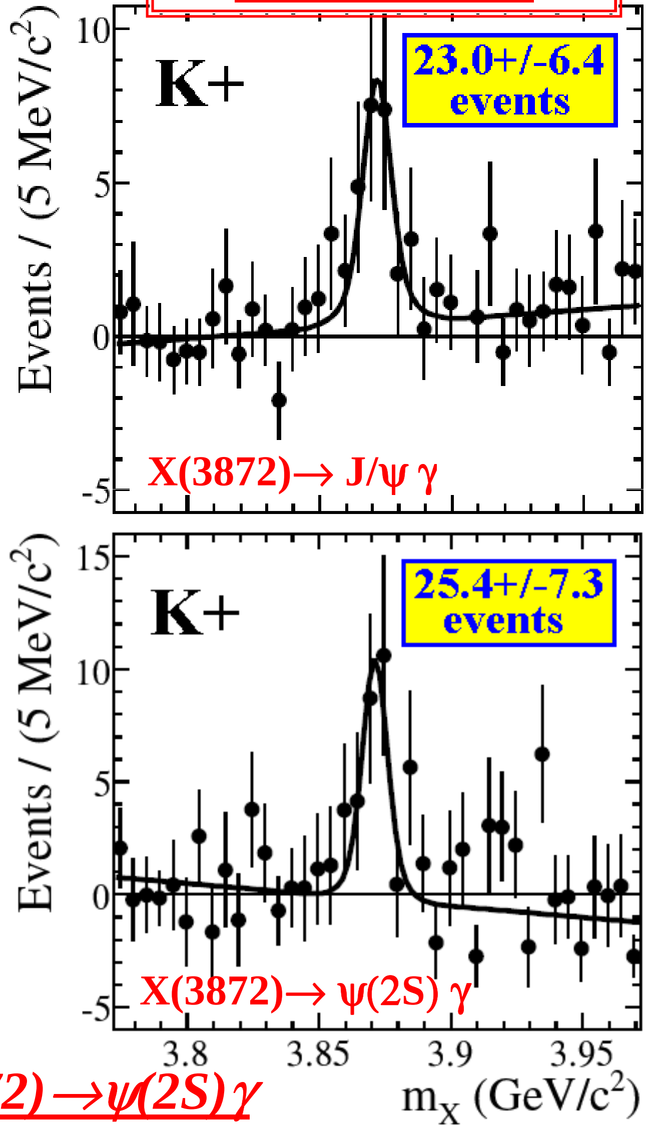
BABAR
PRD 71, 031501 (2005)



The X(3872): $X \to \gamma\psi$

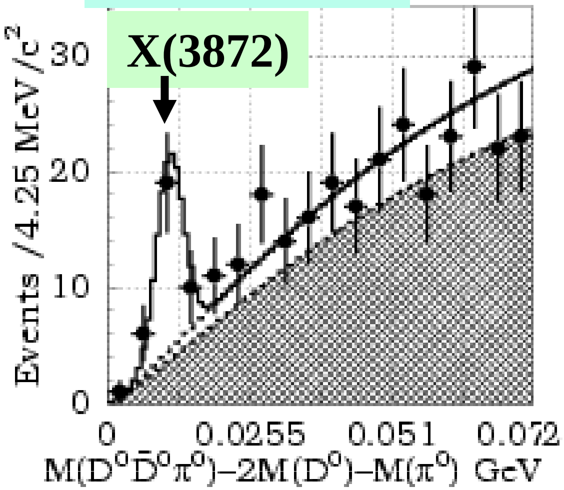
- Evidence for
  $B^+ \to K^+ X(3872)$, $X(3872) \to J/\psi\,\gamma$ (3.6σ)
- $BF(B^+ \to X(3872)\,K^+) \times (X(3872) \to J/\psi\,\gamma) = (2.8 \pm 0.8 \pm 0.2) \times 10^{-6}$
  ➔ **Establishes positive C-parity**
- Evidence for
  $B^+ \to K^+$ $X(3872) \to \psi(2S)\,\gamma$ (~3.5σ)
- $BF(B^+ \to X(3872)\,K^+) \times (X(3872) \to \psi(2S)\gamma) = (9.5 \pm 2.7 \pm 0.9) \times 10^{-6}$
- Ratio of BFs:
  $(X(3872) \to \psi(2S)\,\gamma) / (X(3872) \to J/\psi\,\gamma)$
  $= 3.4 \pm 1.4$
  ➔ inconsistent with the molecular interpretation

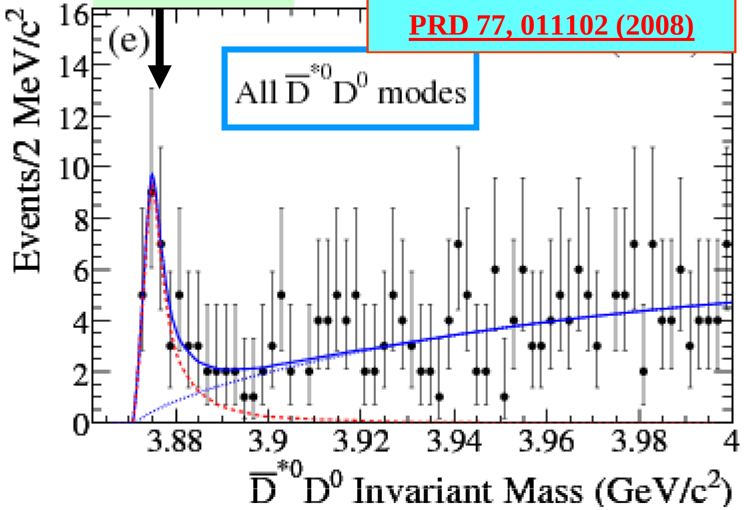
BABAR
PRL 102, 132001 (2009)



QWG2010: Belle doesn't confirm the decay $X(3872) \to \psi(2S)\gamma$

The X(3872): $X \to D^0 \overline{D}^{*0}$

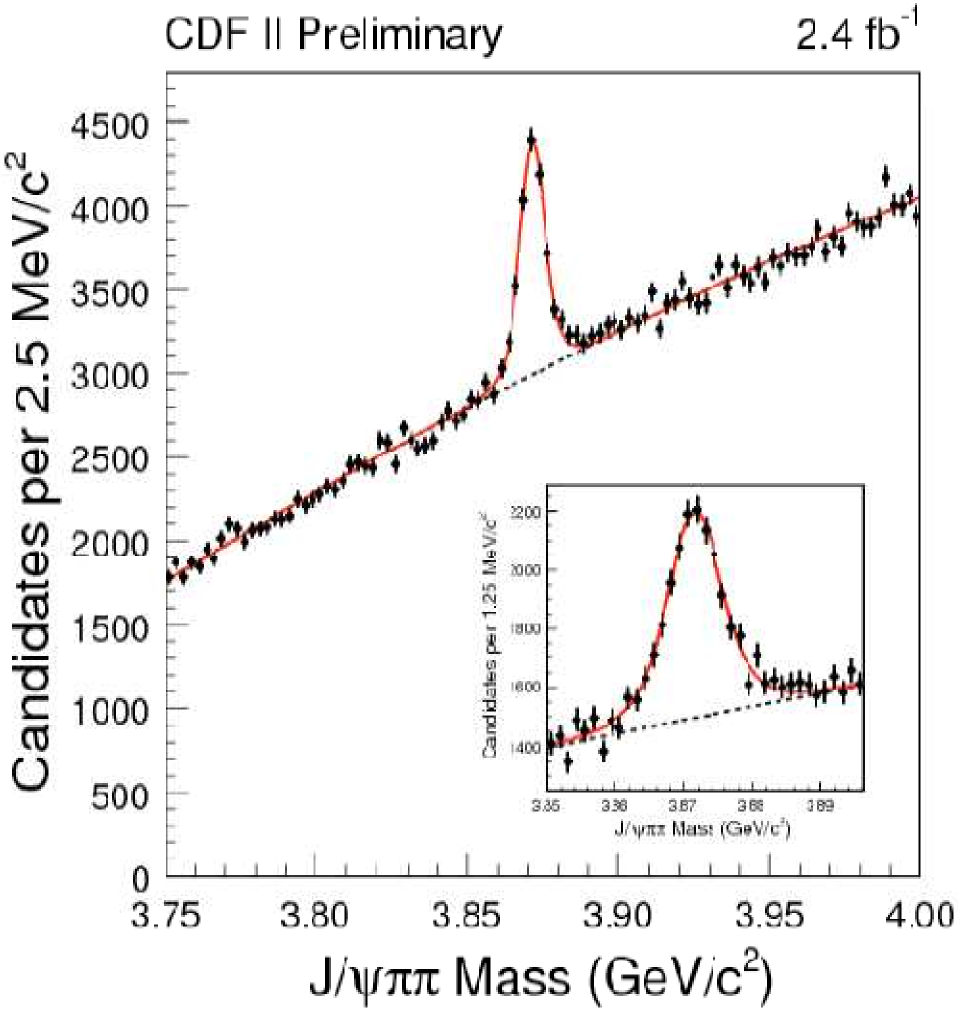




- Belle measured $X(3872) \to D^0\overline{D}^0\pi^0$; *BaBar* measured $D^0\overline{D}^{*0}$
- m(*BaBar*) = $3875.1\,^{+0.7}_{-0.5} \pm 0.5$ MeV/c² PRD 77, 011102(R) (2008)
- m(Belle) = $3875.2 \pm 0.7\,^{+0.9}_{-0.8}$ MeV/c² PRL 97, 162002 (2006)

  i.e. a mass shift (relative to $J/\psi\pi^+\pi^-$) of 3.5 MeV/c²
- **Recent** Belle paper: No shift on X(3872) mass… PRD 81, 031103 (2010)

The X(3872): Largest Data Sample



- This provides the most precise mass measurement of the X(3872):

m=3871.61±0.16±0.19 MeV/c^2

m(D^0) + m($\bar{D}^{0*}$)=3871.8±0.4 MeV/c^2

- PDG: m=3872.2±0.8 MeV/c^2, but includes $D^0\bar{D}^{*0}$ measurements; $J/\psi\pi^+\pi^-$ alone gives 3871.4±0.6 MeV/c^2

- $D^0\bar{D}^{*0}$ mass shift could result from one unit of orbital angular momentum ➔ $J^P=2^-$

Dunwoodie and Ziegler

PRL 100, 062066 (2008)

The X(3872): Questions

❑ Are the X(3872) and the X(3875) the same state?
If it is related to a mass shift, then they are one state…

❑ If they are the same state, how can the mass shift be explained?

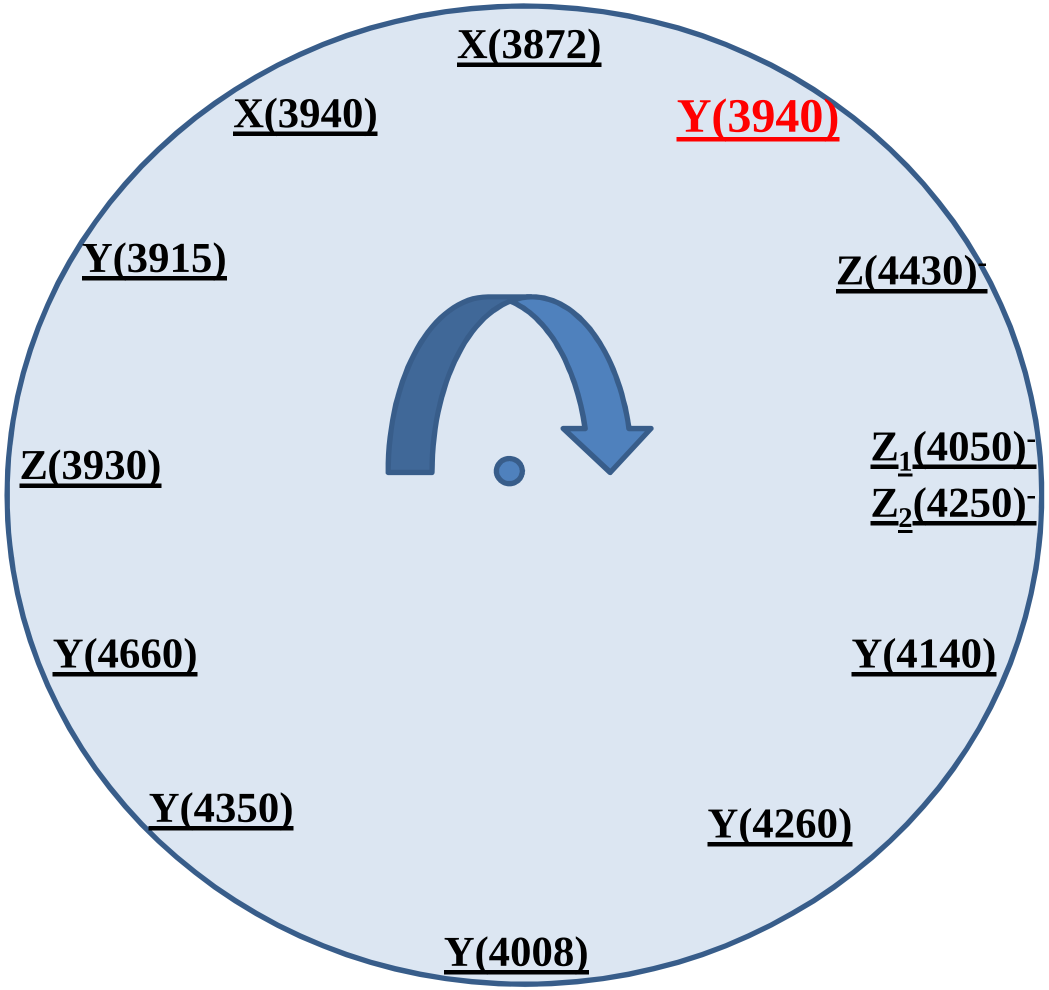
$D^0\overline{D}^{*0}$ mass shift could result from one unit of orbital angular momentum ➔ $J^P=2^-$

Dunwoodie and Ziegler ***PRL 100, 062066 (2008)***

❑ What are the quantum numbers of the X(3872)?
CDF: **1^{++} or 2^{-+}**
Belle: **1^{++}**
BABAR: **???**

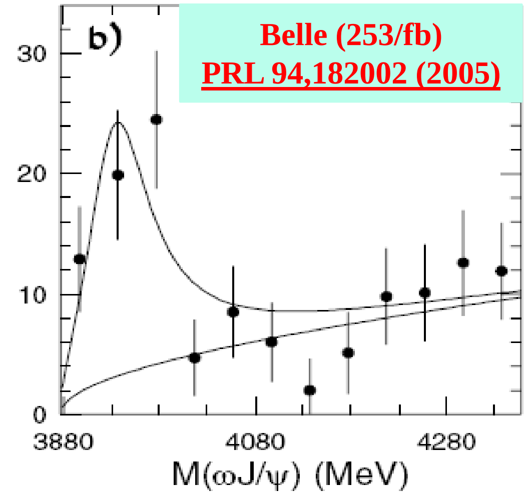
❑ Could the X(3872) be a molecular bound state? Or just a conventional charmonium state?

The Y(3940)

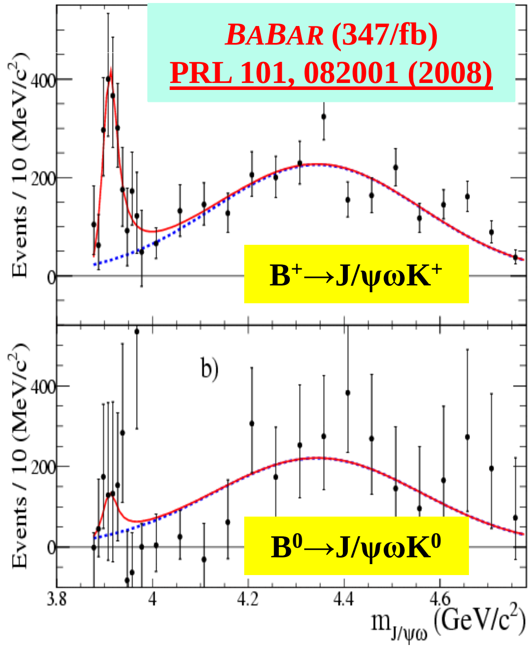

X(3872)
X(3940)
Y(3940)
Y(3915)
Z(4430)-
Z(3930)
Z_1(4050)-
Z_2(4250)-
Y(4660)
Y(4140)
Y(4350)
Y(4260)
Y(4008)

The Y(3940): The Discovery & Confirmation

- The Y(3940) was discovered by Belle in $B \to YK$, $Y \to J/\psi\omega$ (Significance = 8σ)



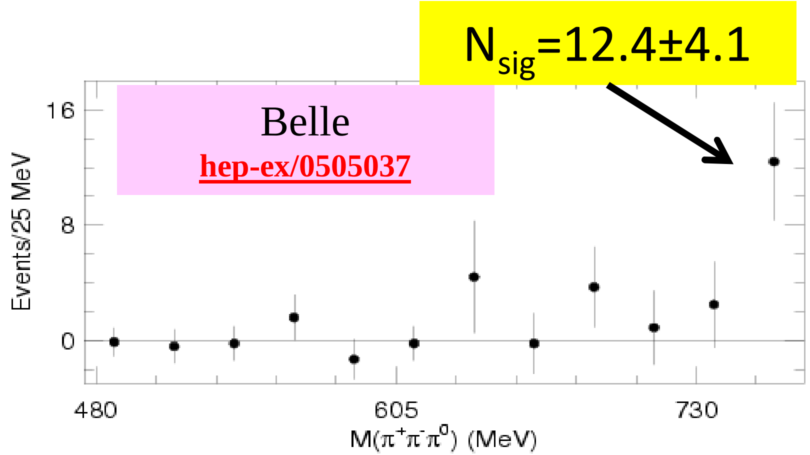
- *BABAR* confirmed the Y(3940) existence but with a lower mass and a narrower width



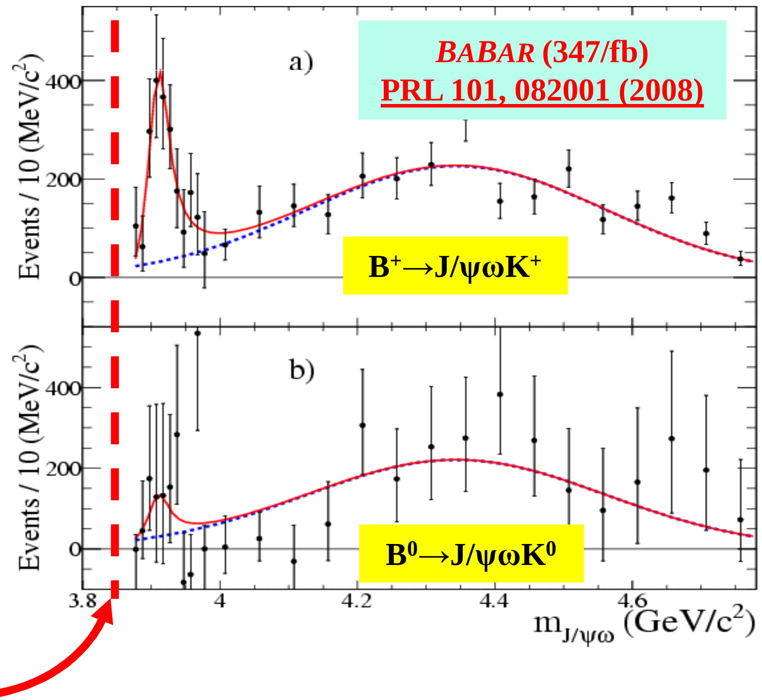
	Belle	*BABAR*
Mass (MeV/c^2)	$3943 \pm 11 \pm 13$	$3914.6^{+3.8}_{-3.4} \pm 2.0$
Width (MeV)	$87 \pm 22 \pm 26$	$34^{+12}_{-8} \pm 5$
BF: $B^+ \to YK^+$, $Y \to J/\psi\omega$ ($\times 10^{-5}$)	$7.1 \pm 1.3 \pm 3.1$	$4.9^{+1.0}_{-0.9} \pm 0.5$
BF: $B^0 \to YK^0$, $Y \to J/\psi\omega$ ($\times 10^{-5}$)	(Combined)	$1.3^{+1.3}_{-1.1} \pm 0.2$
BF: $B^+ \to J/\psi\omega K^+$ ($\times 10^{-4}$)	Not reported	$3.5 \pm 0.2 \pm 0.4$
BF: $B^0 \to J/\psi\omega K^0$ ($\times 10^{-4}$)	Not reported	$3.1 \pm 0.6 \pm 0.3$

The X(3872): $X \to J/\psi\omega$

- Belle reported an excess of events in $m_{3\pi}$ above 750 MeV/c^2 and interpreted as evidence for $X(3872) \to J/\psi\omega$



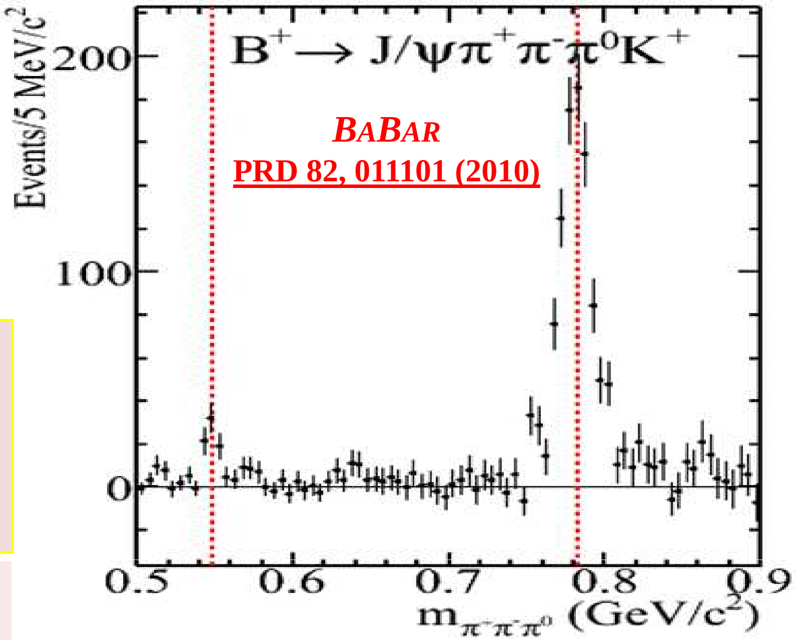
- *But… why didn't BABAR* observe such a signal when searching for the Y(3940) in the decays $B \to J/\psi\omega K$, $\omega \to \pi^+\pi^-\pi^0$?



No $X(3872) \to J/\psi\omega$ signal observed when using ***$0.7695 < m_{3\pi} < 0.7965$*** *($B^+$) as obtained from optimization*

The Y(3940): Reanalyzing the BaBar Data

- *BaBar* has reanalyzed the same final state: $B \to J/\psi \omega K$, $\omega \to \pi^+\pi^-\pi^0$ using the full *BaBar* dataset of 467 million $B\bar{B}$ candidates



BaBar studied the events in the region:

$0.5 < m_{3\pi} < 0.9$ GeV/c²

Clear η and ω signals are observed!

Criterion (GeV/c²)

$0.7695 < m_{3\pi} < 0.7965$ (B^+)
$0.7605 < m_{3\pi} < 0.8055$ (B^0)
} *Old Analysis*

BaBar (347/fb)
PRL 101, 082001 (2008)

0.7400$< m_{3\pi} <$ **0.7965 (B^+)**
0.7400$< m_{3\pi} <$ **0.8055 (B^0)**
} *New Analysis*

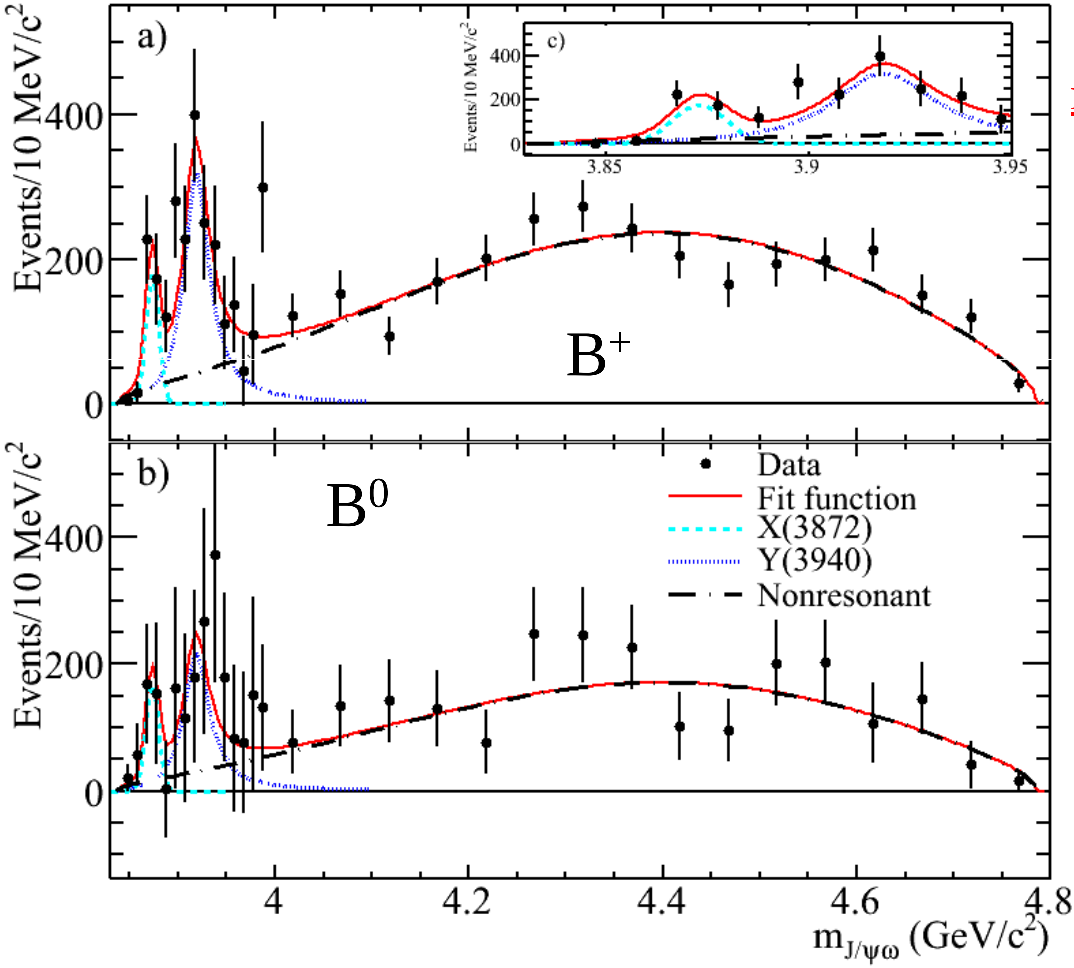
BaBar (426/fb)
PRD 82, 011101 (2010)

Fitting the Corrected Data

✓Correct the yields for efficiency (4- 7%) interval-by-interval

✓ Correct the B^0 sample for $\mathbf{K^0_L}$ **&** $\mathbf{K^0_S \rightarrow \pi^0\pi^0}$

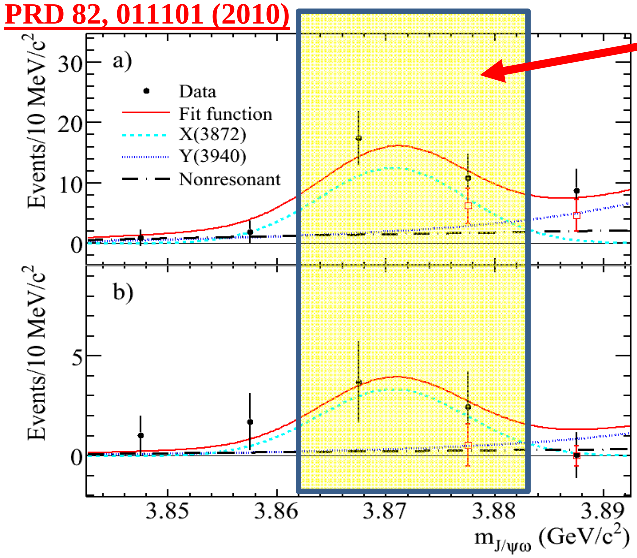
✓Perform simultaneous fit to B^+ and B^0 samples



BaBar
PRD 82, 011101 (2010)

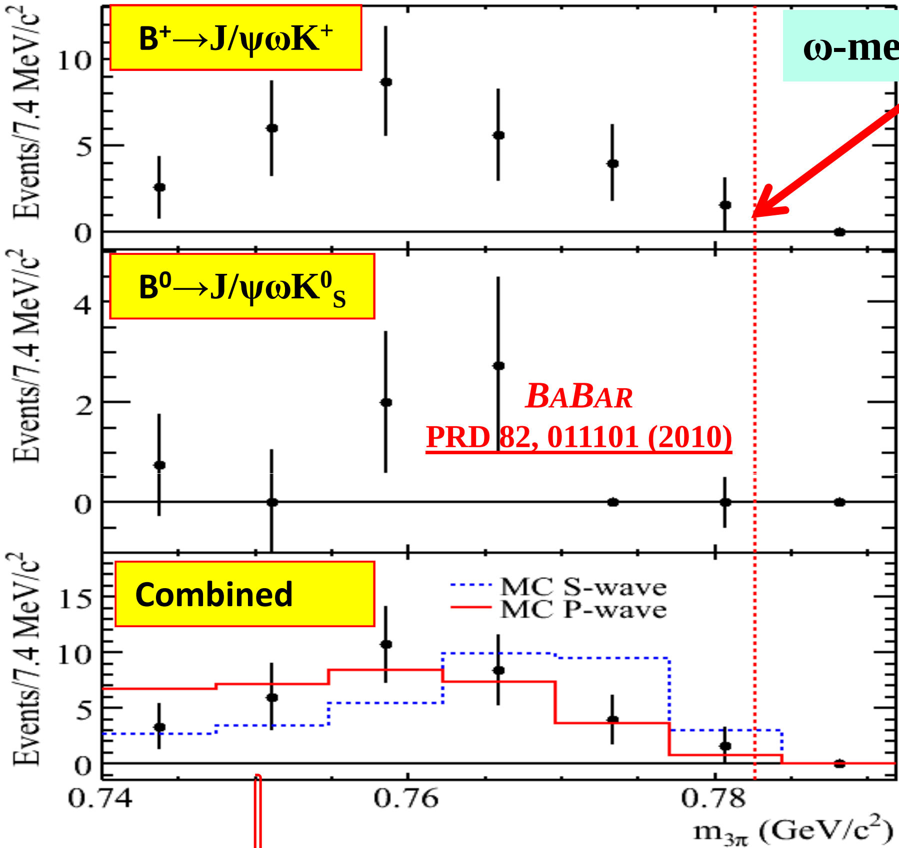
The X(3872): $J^{PC}=1^{++}$ Vs. 2^{-+}

BABAR
PRD 82, 011101 (2010)



Events with: 3.8625<$m_{J/\psi\omega}$<3.8825 GeV/c²

ω-meson mass



S-wave: χ^2/NDF=10.17/5
P(χ^2/NDF)=7%

P-wave: χ^2/NDF=3.53/5
P(χ^2/NDF)=62%

Shape is different from ω lineshape!

→ Negative Parity favored ($J^P=2^-$)

How do we justify calling such a distribution ω signal?

The X(3872): Remarks

- X(3872)→ψγ (*)➔ C=+1
- No $X(3872)^-$ ➔ I=0
- X(3872) quantum numbers:
  - Belle: $J^{PC} = 1^{++}$ favored (no ω-ρ interference)
  - CDF: ππ mass & angular distribution ➔ $J^P = 1^+$ or 2^-
  - *BABAR*: $J^P = 2^-$ is favored
- What is the **nature** of X(3872)?
  - Hybrid?.... BUT $m(c\bar{c}g) > 4.2 GeV/c^2$…
  - Tetraquark?... BUT No evidence for $X(3872)^-$
  - Charmonium?... mass is OK for 2^{-+} state (η_{c2}, the $^1D_2$ $c\bar{c}$ ground state)
  - Molecular?
    - $m(D^0) + m(\bar{D}^{0*}) = 3871.8 \pm 0.4\ MeV/c^2$
    - Decays to $X(3872) \rightarrow J/\psi\rho$, D^0D^{0*}, $J/\psi\omega$ expected
    - Compatible with $J^{PC} = 1^{++}$ assignment

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

BABAR: PRD 71, 031501 (2005)

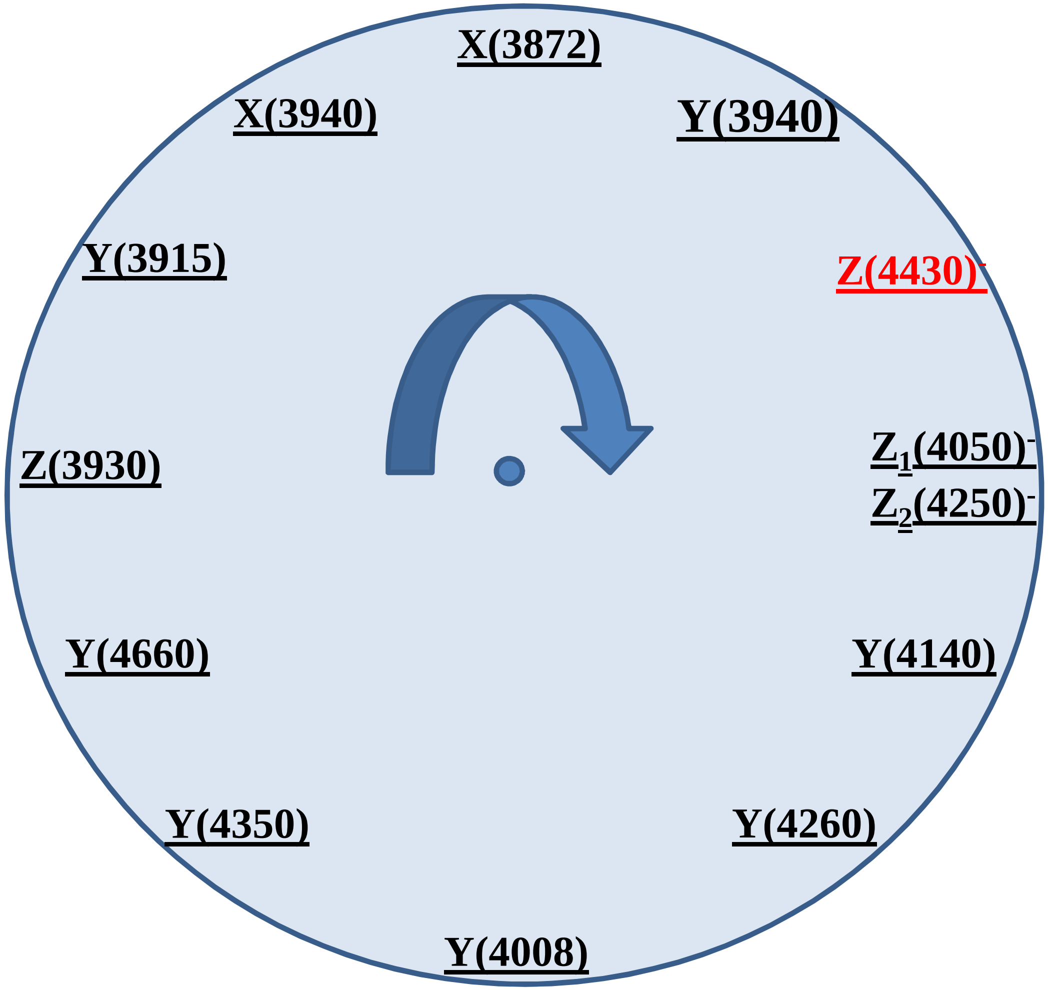
Belle: **arXiv:0505038 (2005)**

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

BABAR: **PRD 82, 011101 (2010)**

* "ψ" denotes "J/ψ or ψ(2S)" unless otherwise indicated

The Z(4430)⁻


X(3872)
X(3940)
Y(3940)
Y(3915)
Z(4430)-
Z(3930)
Z1(4050)-
Z2(4250)-
Y(4660)
Y(4140)
Y(4350)
Y(4260)
Y(4008)

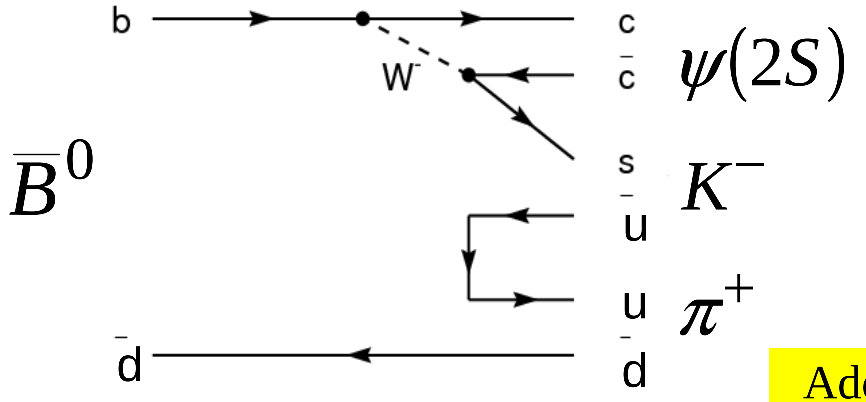
The Z(4430)$^-$: The Belle Observation

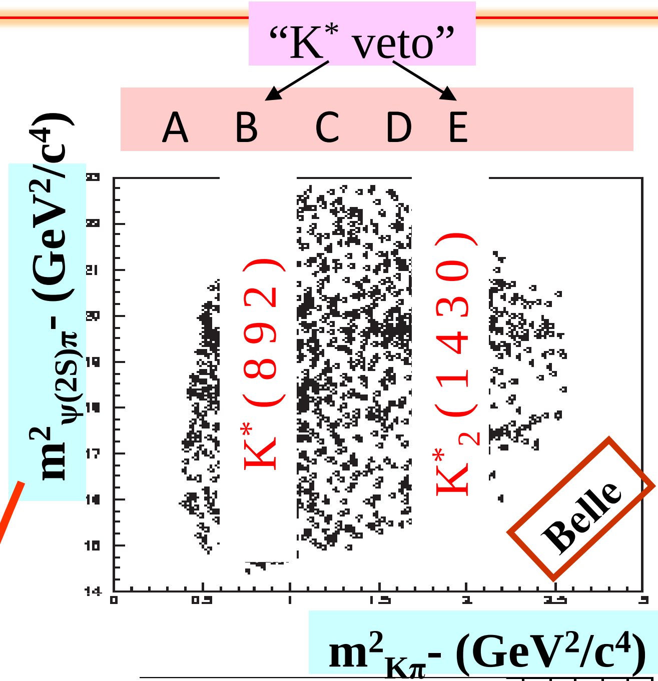
- Belle reported a charged charmonium-like state in $B \to Z^- K$, $Z^- \to \psi(2S)\pi^-$ (PRL 100, 142001 (2008))

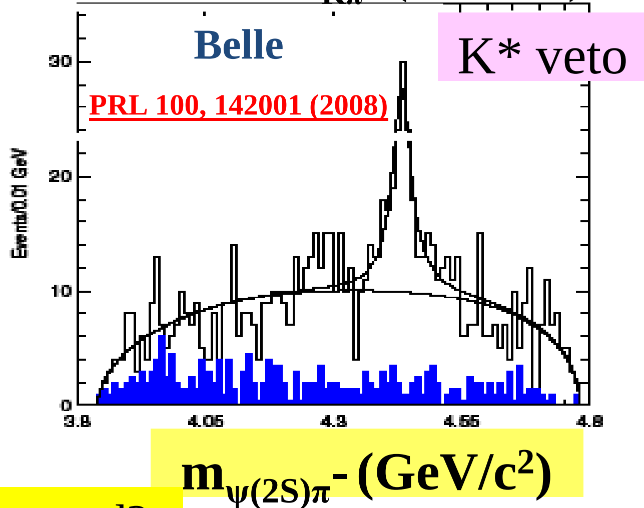
- Mass and width:
  - **m=4433 ± 4(stat) ± 2(syst) MeV/c^2**
  - **Γ=45^{+18} (stat)$^{+30}$ (syst) MeV**

- 121 ± 30 events; 6.5σ significance

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







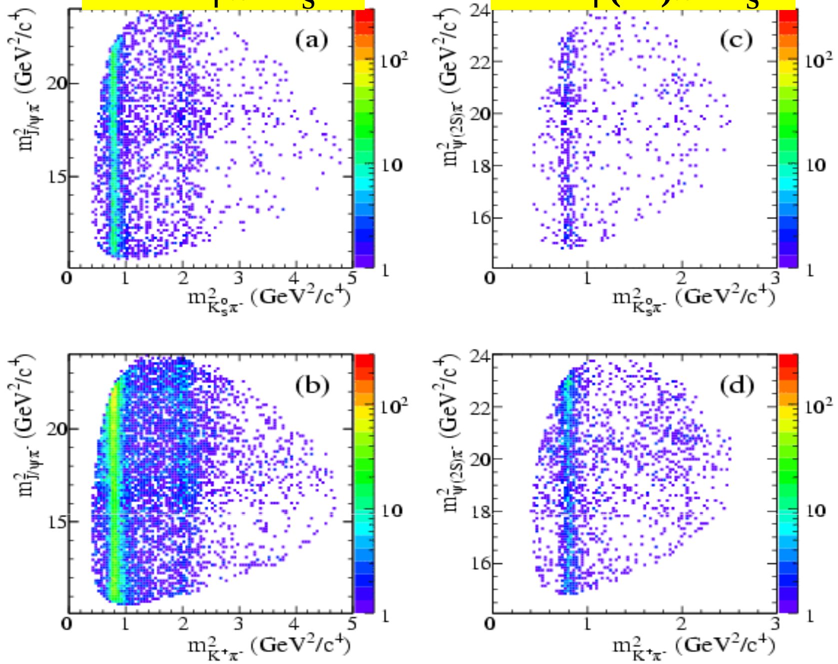
Add-hoc background?

The Z(4430)$^-$: The BABAR Search PRD 79, 112001 (2009)

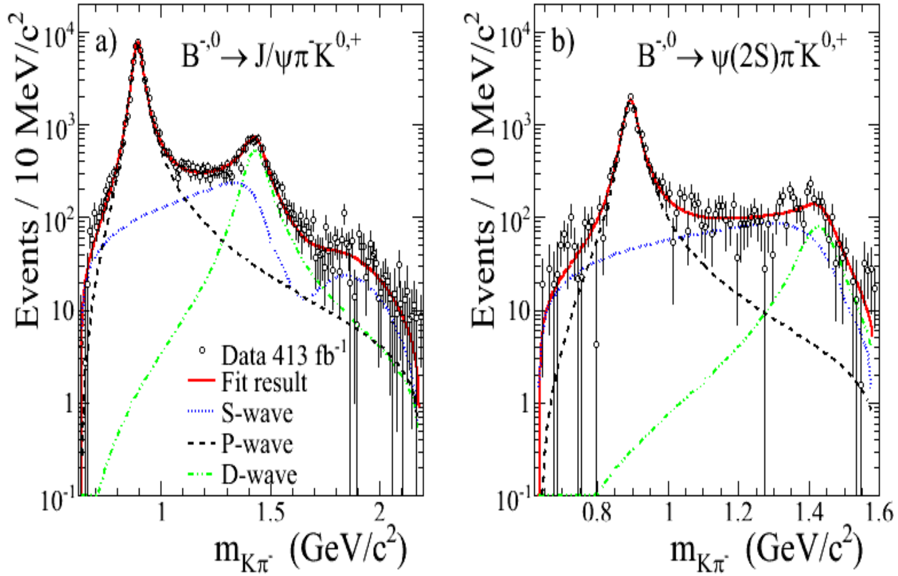
- Search for the Z(4430)$^-$ in four decay modes: $B^{-0} \rightarrow \psi\pi^- K^{0+}$ (Four decay modes), using 413 fb^{-1}
- Describe the $K\pi^-$ system in detail, since structure in the $K\pi^-$ mass and angular distributions dominates each Dalitz plot
- Subtract background, efficiency-correct event-by-event across the Dalitz plot; describe using only $K\pi^-$ 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"

The Z(4430)⁻: The BABAR Search (II)

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



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



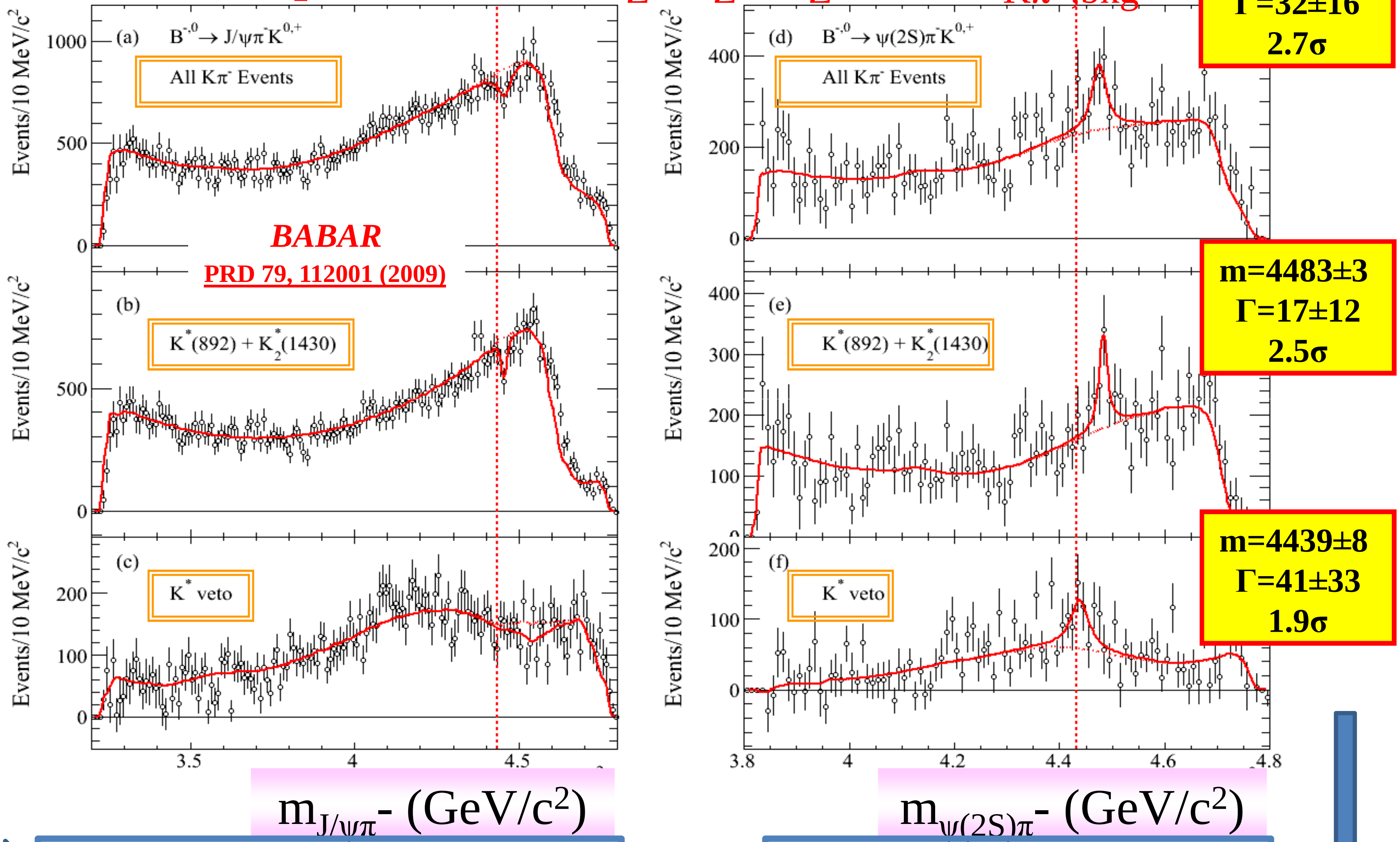
BABAR

PRD 79, 112001 (2009)

Mode	Events corrected	m(K*(892)) (MeV/c2)	Γ(K*(892)) (MeV)	S-wave (%)	P-wave (%)	D-wave (%)
$B^0 \to J/\psi \pi^- K^+$	57231±561	895.5±0.4	48.9±1.0	15.7±0.8	73.5±0.7	10.8±0.5
$B^- \to J/\psi \pi^- K^0_S$	20985±393	892.9±0.8	49.0±1.9	17.0±1.6	72.5±1.3	10.5±1.0
$B^0 \to \psi(2S) \pi^- K^+$	13237±377	895.8±1.0	43.8±3.0	25.4±2.2	68.2±2.0	6.4±1.2
$B^- \to \psi(2S) \pi^- K^0_S$	5016±292	891.6±2.1	44.8±6.0	23.4±4.5	71.3±4.4	5.3±2.7

The Z(4430)$^-$: Fits to the $m_{\psi\pi}$- Distributions

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

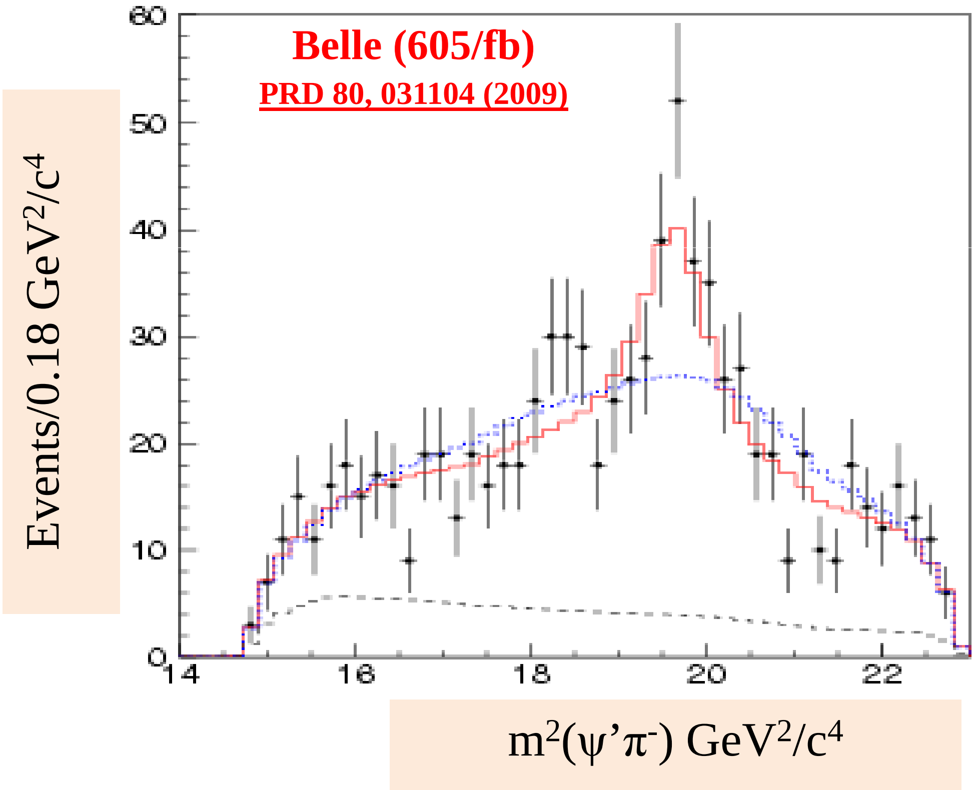


No evidence for the Z(4430)$^- \to J/\psi\pi^-$

< 3σ for the Z(4430)$^- \to \psi(2S)\pi^-$

The Z(4430)⁻: The Belle Dalitz-Plot Analysis

- In response to the [*BABAR* analysis](), Belle performed a Dalitz-Plot analysis
- In the new Belle analysis, a 6.4σ signal significance was reported



The Z(4430)$^-$: BABAR & Belle Results

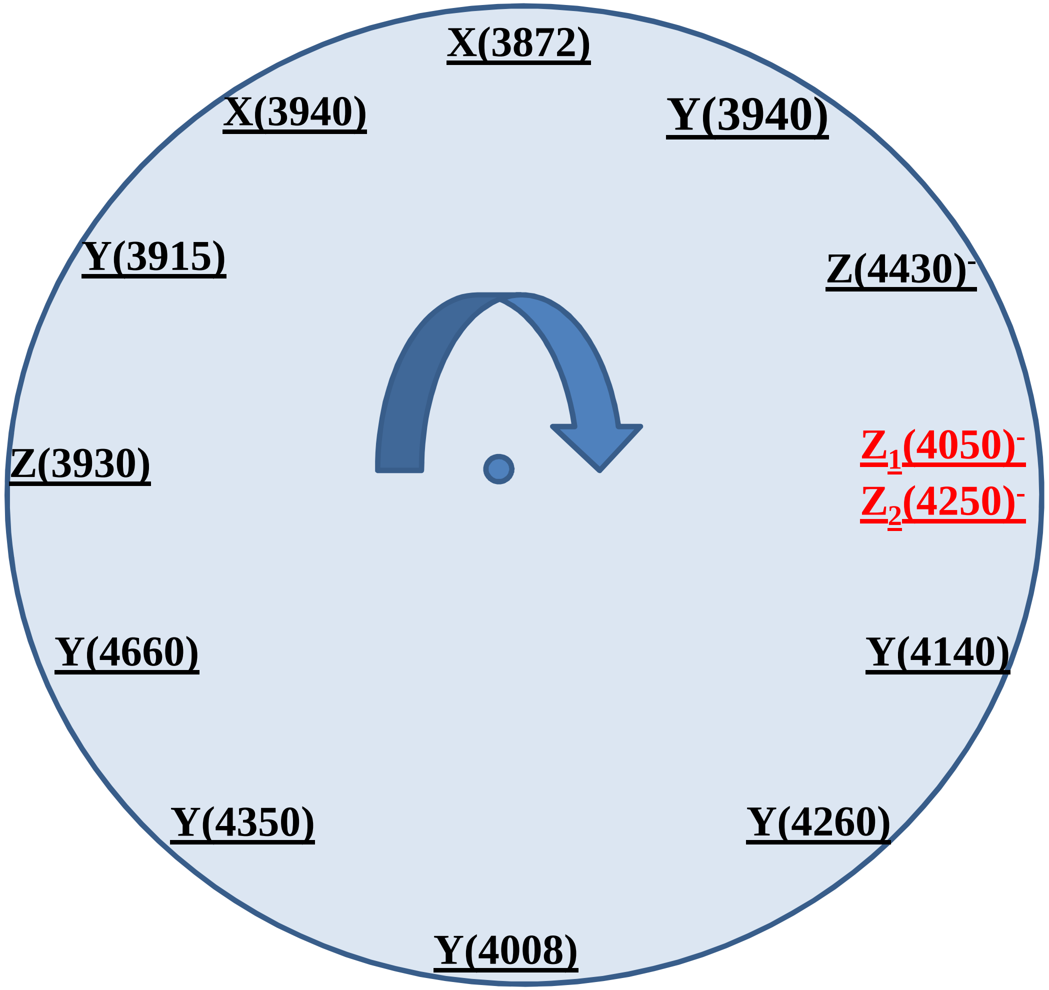
Parameter	Belle	Belle (DP)	BABAR
Mass (MeV/c^2)	$4433 \pm 4 \pm 2$	$4443_{-12}^{+15}\,{}_{-13}^{+19}$	J/ψ: 4455 ± 8 ψ(2S): 4476 ± 8
Width (MeV)	$45_{-13}^{+18}\,{}_{-13}^{+30}$	$107_{-43}^{+86}\,{}_{-56}^{+74}$	J/ψ: 42 ± 27 ψ(2S): 32 ± 16
$B(B^0 \to Z^- K^+) \times B(Z^- \to \psi(2S)\pi^-)$ ($\times 10^{-5}$)	$4.1 \pm 1.0 \pm 1.4$	$3.2_{-0.9}^{+1.8}\,{}_{-1.6}^{+5.3}$	1.9 ± 0.8
$B(B^- \to Z^- K^0) \times B(Z^- \to \psi(2S)\pi^-)$ ($\times 10^{-5}$)	Not reported	Not reported	2.0 ± 1.7
$B(B^0 \to Z^- K^+) \times B(Z^- \to J/\psi\pi^-)$ ($\times 10^{-5}$)			-0.1 ± 0.8
$B(B^- \to Z^- K^0) \times B(Z^- \to J/\psi\pi^-)$ ($\times 10^{-5}$)			-1.2 ± 0.4
Significance	6.5σ	6.4σ	ψ(2S): 2-3σ

Belle PRL 100, 142001 (2008)

Belle PRD 80, 031104 (2009)

BABAR PRD 79, 112001 (2009)

The $Z_1(4050)^-$ and $Z_2(4250)^-$

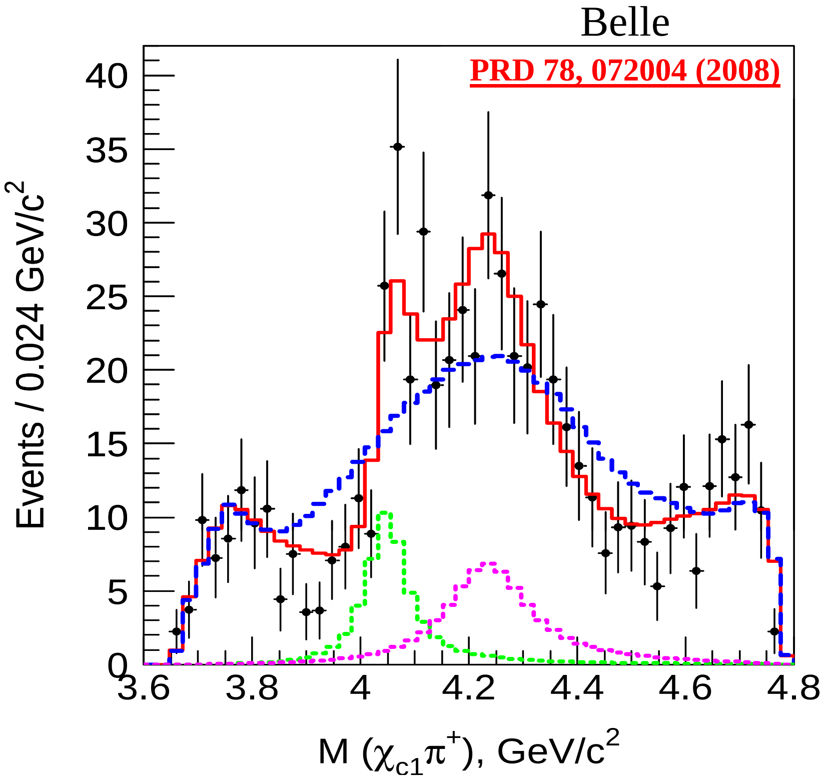


The $Z_1(4050)^-$ & $Z_2(4250)^-$: The Belle Report

- Belle: Two more new signals, $Z_1(4050)^-$ and $Z_2(4250)^-$ in $B \to Z^- K$, $Z^- \to \chi_c \pi^-$, $\chi_c \to \gamma J/\psi$

- The $K\pi$ mass region extends beyond the $F_3^*(1780)$ F-wave ➔ S-, P-, D-, and F- waves are kinematically allowed and used in the fit

- Data favor two signals hypothesis over one signal by 5.7σ



$$M_1 = (4051 \pm 14^{+20}_{-41})\ \mathrm{MeV}/c^2,$$
$$\Gamma_1 = (82^{+21+47}_{-17-22})\ \mathrm{MeV},$$

$Z_1(4050)^-$

$$M_2 = (4248^{+44+180}_{-29-35})\ \mathrm{MeV}/c^2,$$
$$\Gamma_2 = (177^{+54+316}_{-39-61})\ \mathrm{MeV},$$

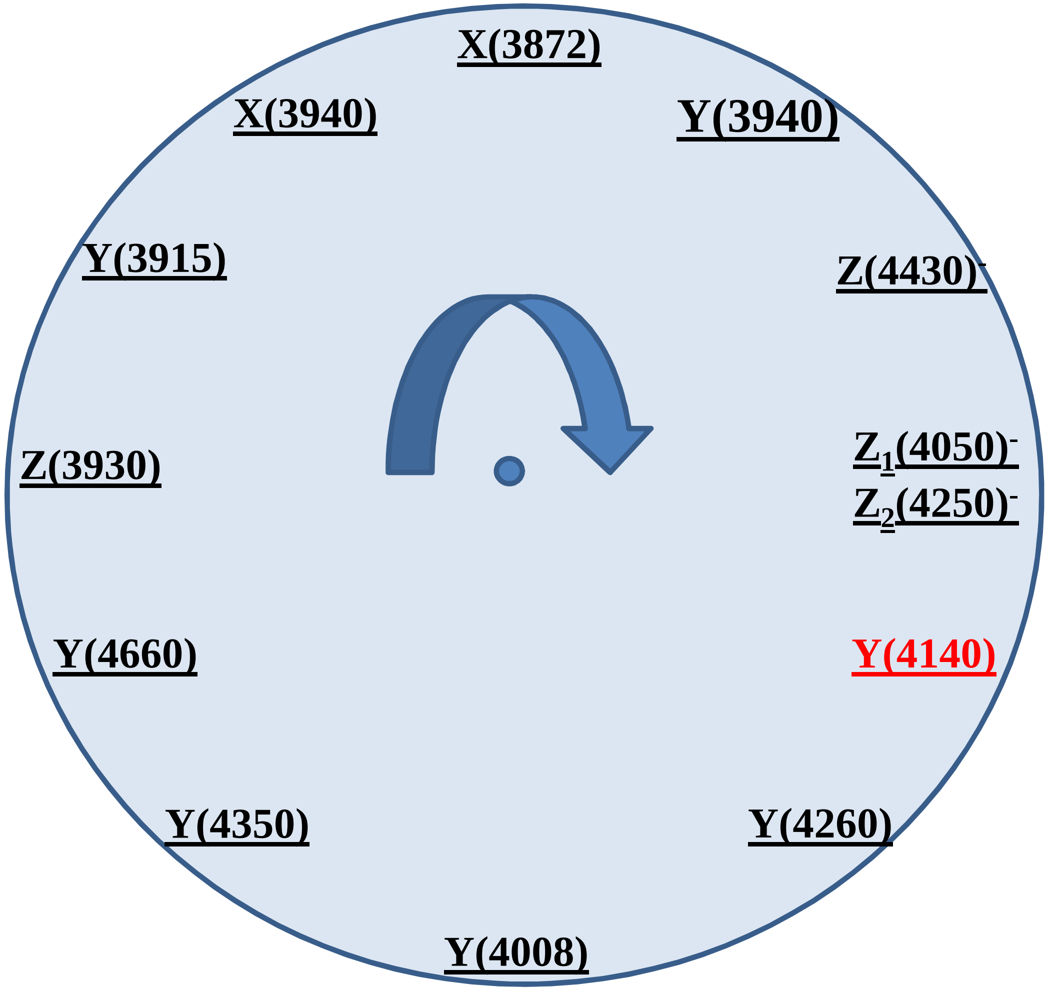
$Z_2(4250)^-$

with the product branching fractions of

$$\mathcal{B}(\bar{B}^0 \to K^- Z_1^+) \times \mathcal{B}(Z_1^+ \to \pi^+ \chi_{c1}) = (3.0^{+1.5+3.7}_{-0.8-1.6}) \times 10^{-5},$$
$$\mathcal{B}(\bar{B}^0 \to K^- Z_2^+) \times \mathcal{B}(Z_2^+ \to \pi^+ \chi_{c1}) = (4.0^{+2.3+19.7}_{-0.9-0.5}) \times 10^{-5}.$$

Similar to those for X, Y, and $Z(4430)^-$!

The Y(4140)

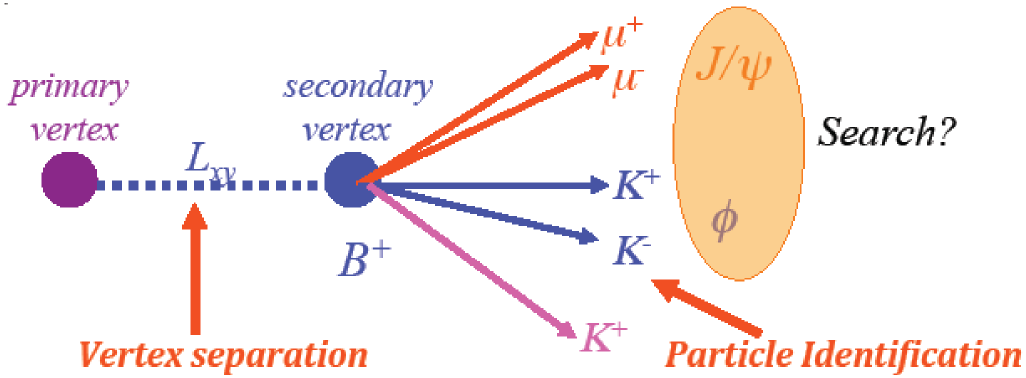

X(3872)
X(3940)
Y(3940)
Y(3915)
Z(4430)$^-$
Z(3930)
$Z_1(4050)^-$
$Z_2(4250)^-$
Y(4660)
Y(4140)
Y(4350)
Y(4260)
Y(4008)

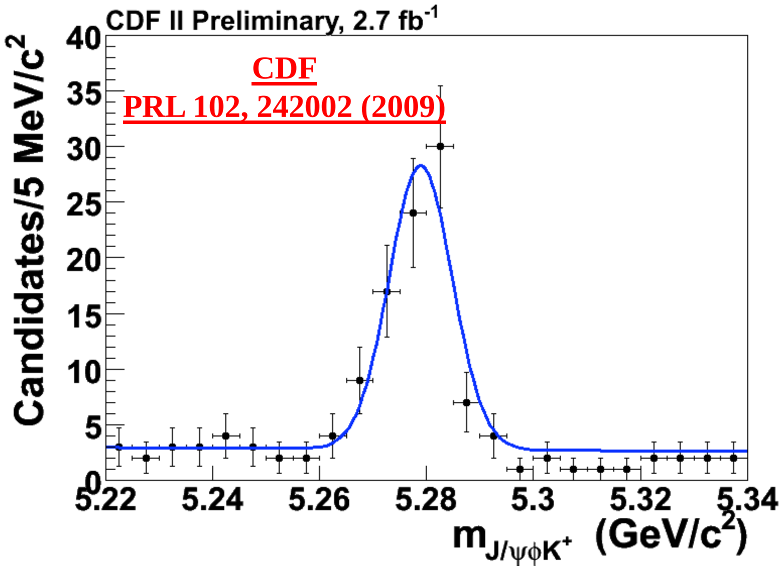
The Y(4140): The CDF Report

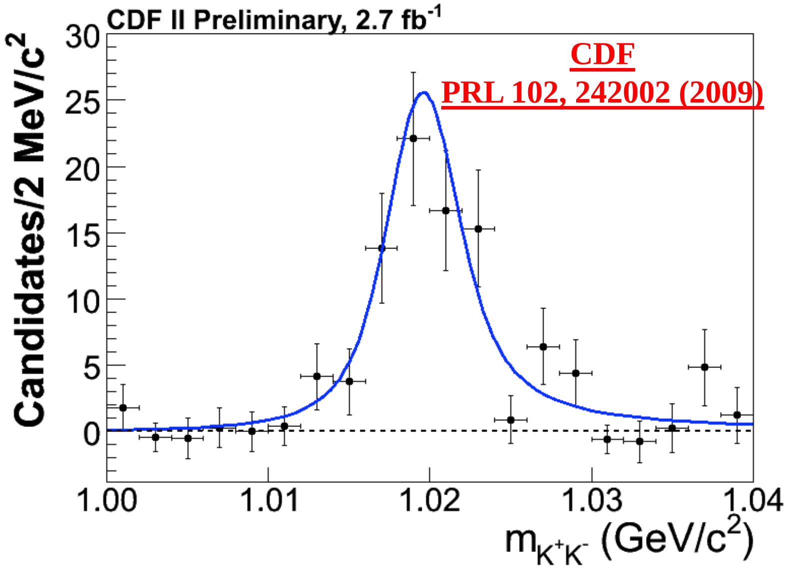
1. Reconstruct B$^+$ as:

$$B^+ \rightarrow J/\psi\phi\, K^+$$
$$J/\psi \rightarrow \mu^+\mu^-$$
$$\phi \rightarrow K^+K^-$$

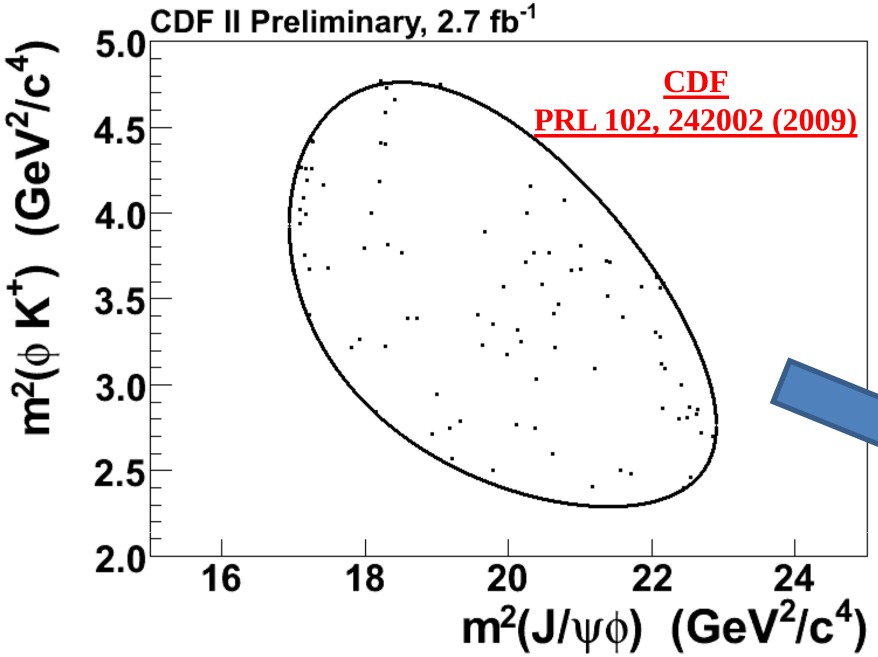
1. *Search for structure in J/ψφ mass spectrum inside B+ mass window*

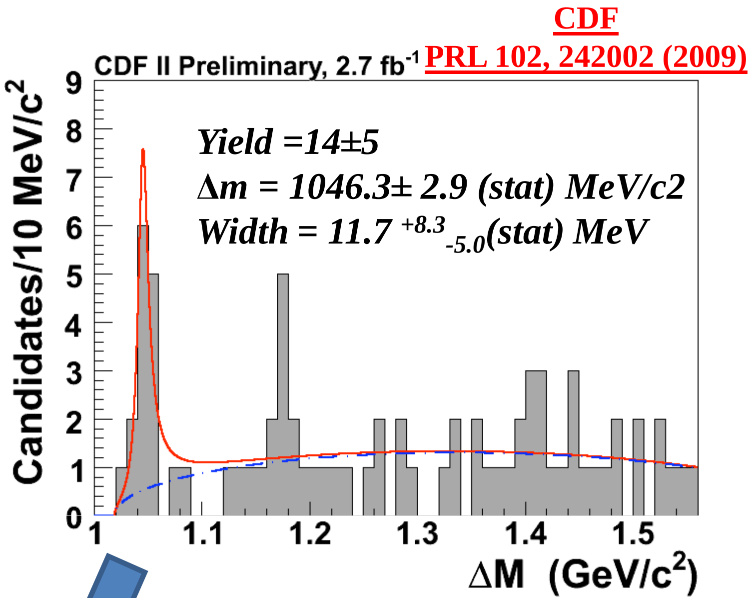






The Y(4140): The CDF Report





Convolved with a mass resolution of 1.7 MeV/c^2

Mass=4143.0 ± 2.9 (stat)± 1.2 (syst) MeV/c^2

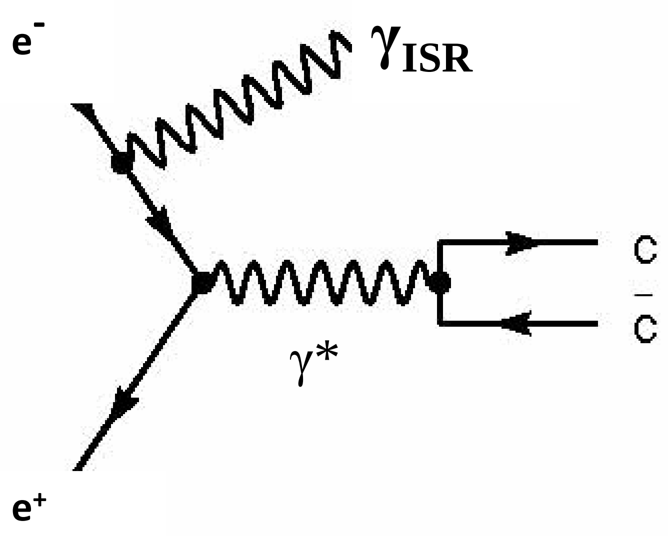
Width = 11.7 $^{+8.3}_{-5.0}$ (stat) ± 3.7(syst) MeV

B[$B^+ \rightarrow Y(4140)K^+$, $Y(4140) \rightarrow J/\psi\varphi$]= (9±3.4(stat)±2.9(syst))×10^{-6}

CDF will update this analysis using the full data set (factor of ~4 by the end of 2011)

*Belle does **NOT confirm** the CDF **Y(4140)** state! **(PRL 104, 112004 (2010))***

ISR Production of Charmonium-like states



J/ψ
ψ(2S)
ψ(3770)
etc

- *BABAR*) has produced ~6×10^8 $c\bar{c}$ pairs at center of mass (c.m.) energy ~10.58 GeV

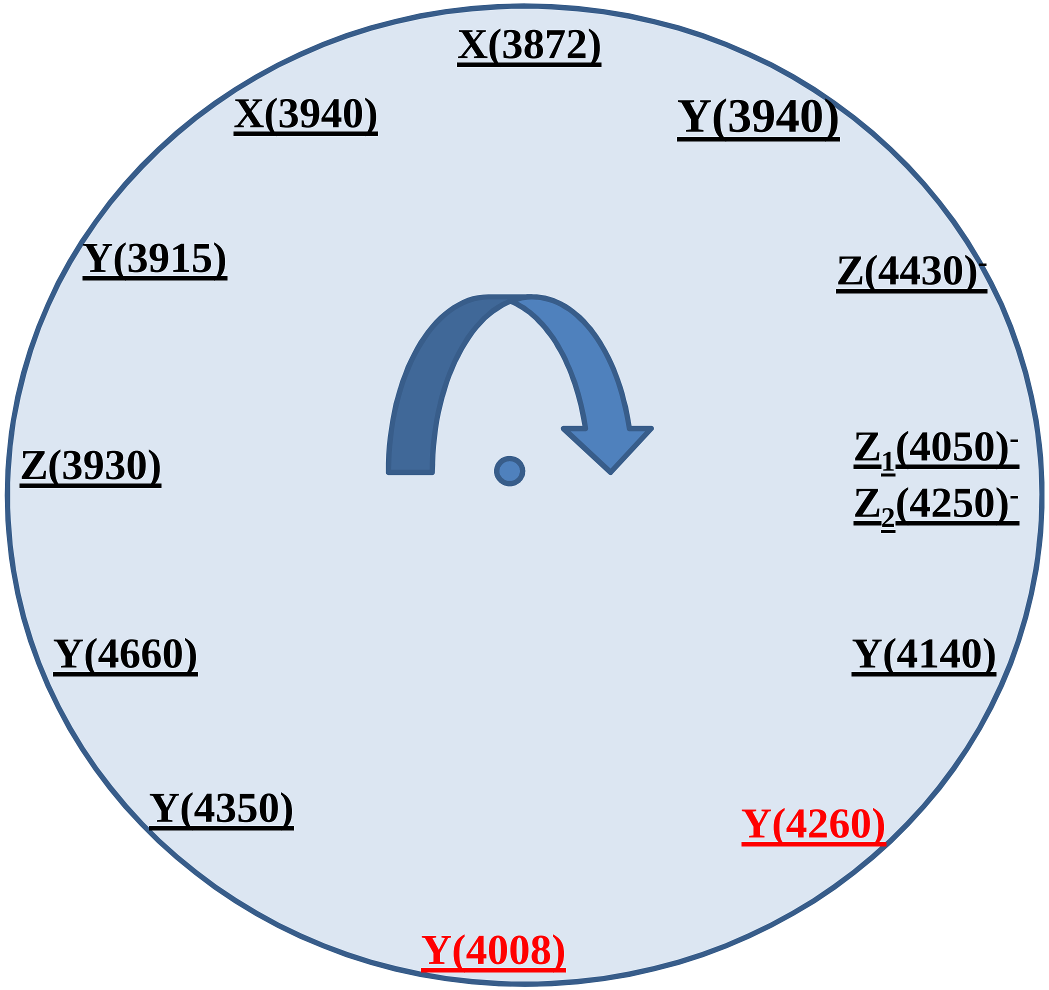
- **ISR** can lead to the production of charmonium states at **lower c.m. energy**

- The γ_{ISR} often **escapes** detection **along** the **beam** axis, and is treated as a missing particle

- The γ_{ISR} energy range **changes** the center of mass **energy**

- **Several** charmonium states were **discovered** in **ISR** events

The Y(4260)


X(3872)
X(3940)
Y(3940)
Y(3915)
Z(4430)⁻
Z(3930)
Z_1(4050)⁻
Z_2(4250)⁻
Y(4660)
Y(4140)
Y(4350)
Y(4260)
Y(4008)

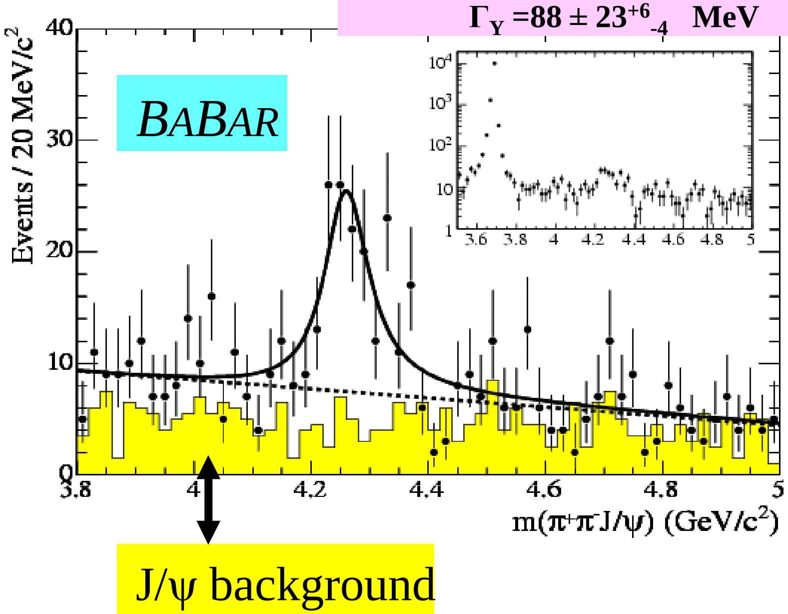
The Y(4260): The BABAR Observation

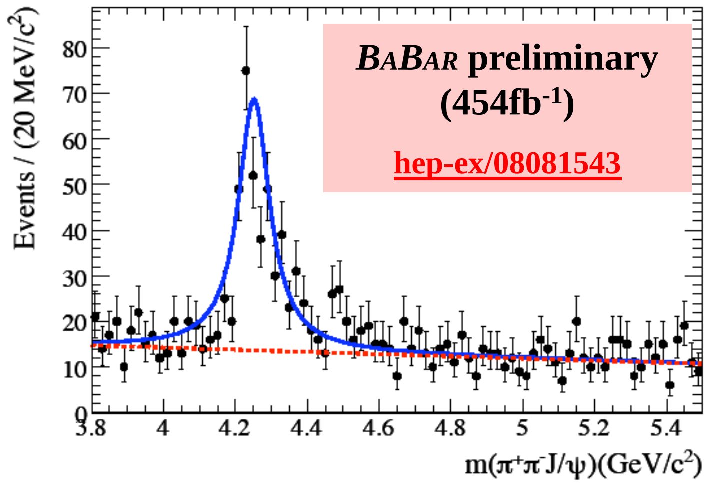
- Discovered by *BABAR* in ISR events: $e^+e^- \rightarrow \gamma_{ISR} Y(4260) \rightarrow J/\psi \pi^+\pi^-$ (PRL 95, 142001 (2006))

- Confirmed by CLEO-c (scan) [➔ I=0] , CLEO III (ISR), and Belle (PRL 96, 162003 (2006), PRD 74, 091104 (2006), PRL 99, 142002 (2007))

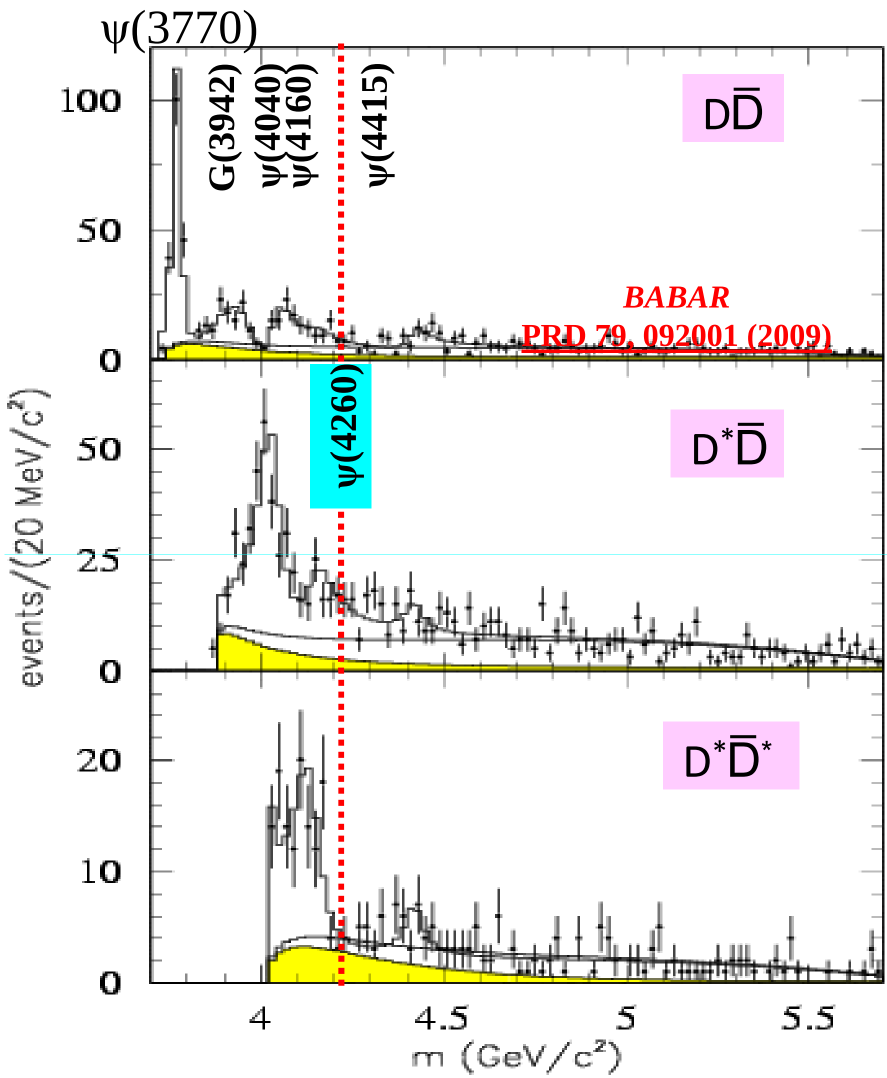
- No evidence for $Y(4260) \rightarrow \pi^+\pi^-\varphi$, $D\bar{D}$, $p\bar{p}$ (PRD 74, 091103 (2006) , PRD 76, 111105 (2007), PRD 73, 012005 (2006))

$m_Y = 4259 \pm 8^{+2}_{-6}$ MeV/c^2
$\Gamma_Y = 88 \pm 23^{+6}_{-4}$ MeV





The Y(4260): Y(4260)→$D\bar{D}$?

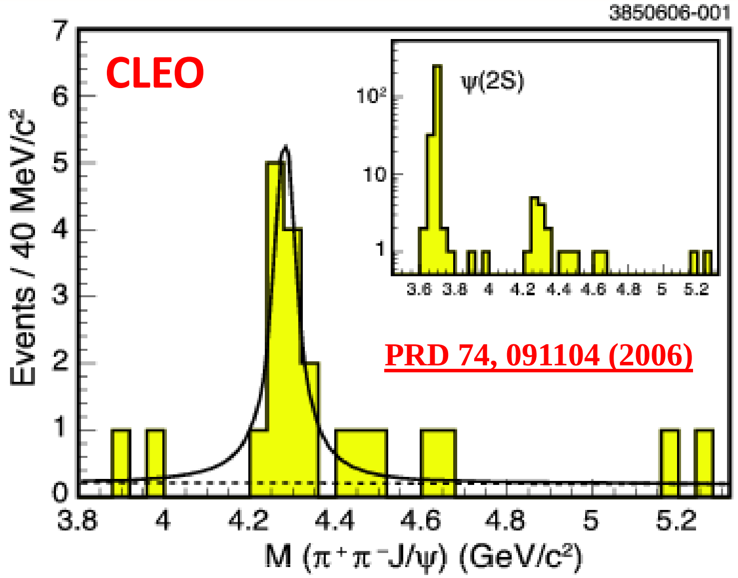


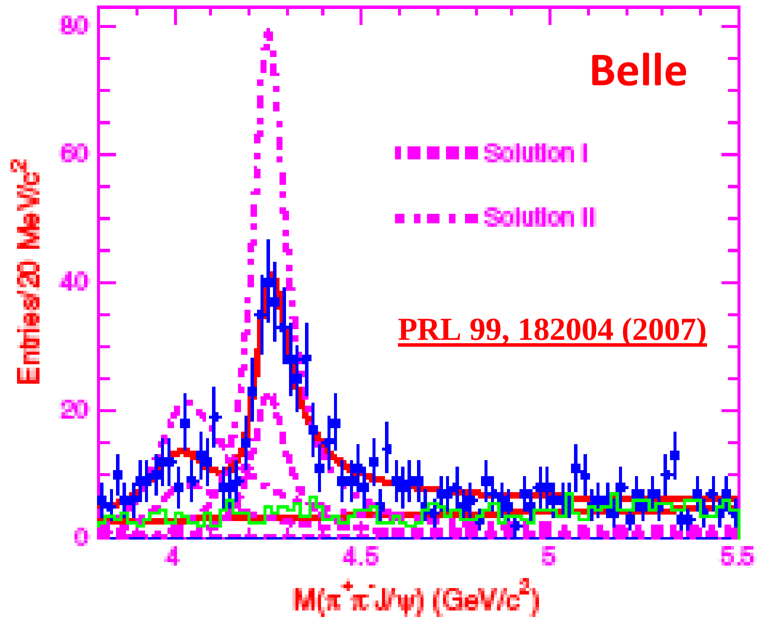
- If Y(4260) is 1^{--} **charmonium state** ➔ should decay **predominantly** to $D\bar{D}$ (PRD 72, 054026(2005), PRD 73, 014014(2006))

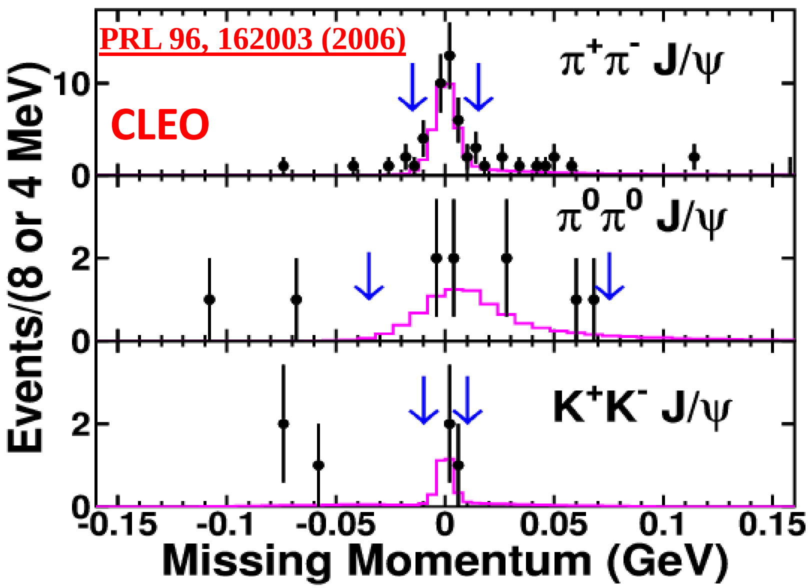
- No evidence for Y(4260)→$D\bar{D}$

- If Y(4260) is hybrid state➔decay rates to $D\bar{D}$ are small (Ref 10,24 in **PRD 79, 092001 (2009)**)

The Y(4260): The Confirmation





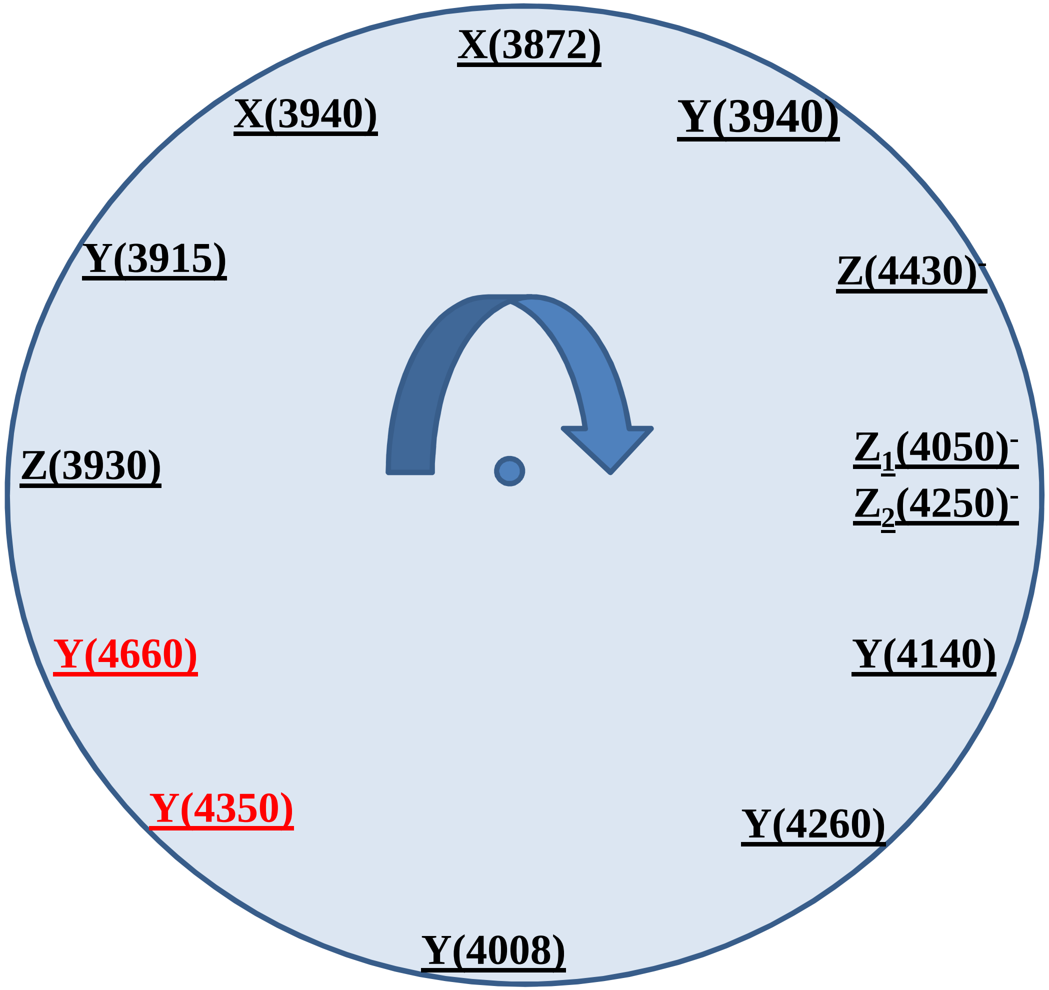


The Y(4260) was confirmed by CLEO & Belle

Y(4260)	BABAR	Belle	CLEO
Mass (MeV/c²)	$4259\pm8_{-6}^{+2}$	$4247\pm12_{-32}^{+17}$	$4284_{-16}^{+17}\pm4$
Width (MeV)	$88\pm23_{-4}^{+6}$	$108\pm19\pm10$	$73_{-25}^{+39}\pm5$

Also, Belle reported a new resonance at 4008 MeV/c²: mass=$4008\pm40_{-28}^{+114}$ & width=$226\pm44\pm87$

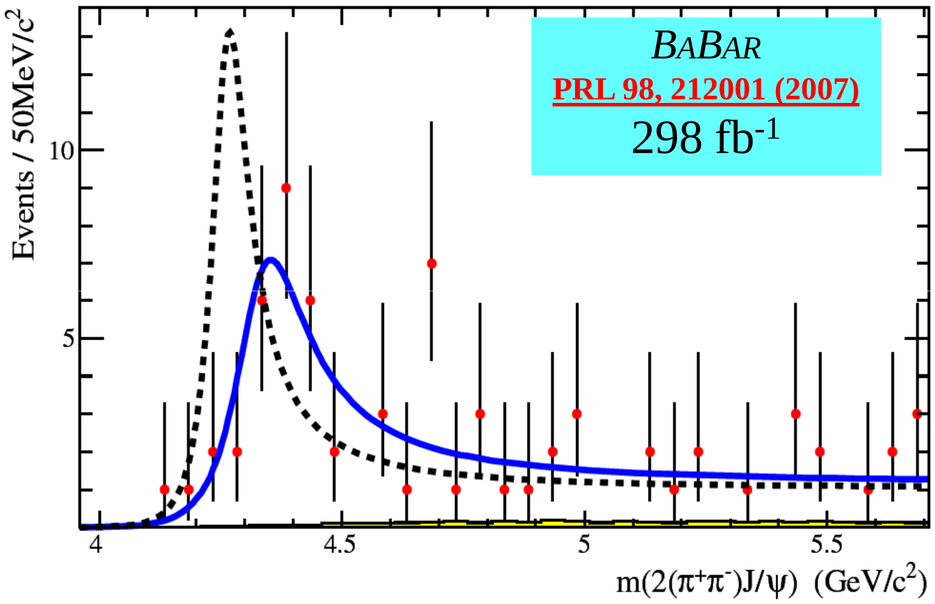
The Y(4350)


X(3872)
X(3940)
Y(3940)
Y(3915)
Z(4430)$^-$
Z(3930)
$Z_1(4050)^-$
$Z_2(4250)^-$
Y(4660)
Y(4140)
Y(4350)
Y(4260)
Y(4008)

The Y(4350): The BABAR Observation

- It was natural to search for the decay to $Y(4260) \to \psi(2S)\pi^+\pi^-$
- *BABAR* found a new peak that did not match the Y(4260)!

- Seems to be a **different structure**:
  - $M = 4324 \pm 24$ MeV/c^2
  - $\Gamma = 172 \pm 33$ MeV



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

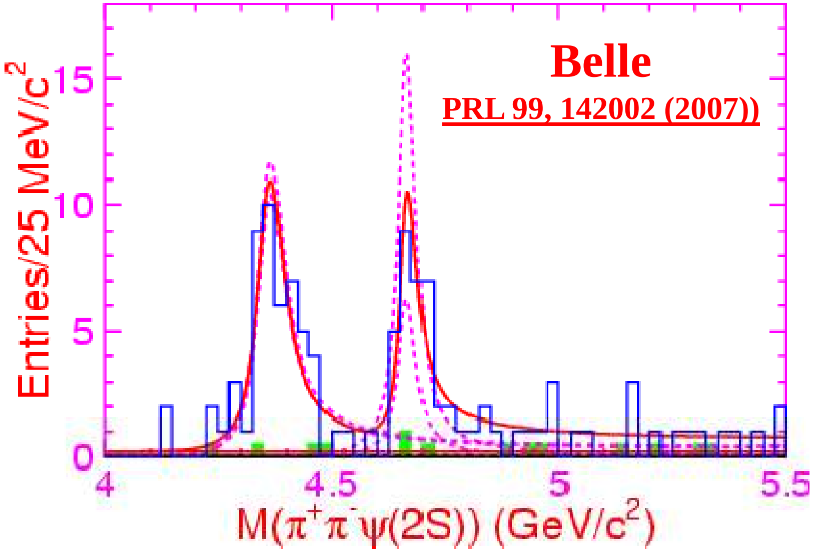
- Seems impossible to assign both as charmonium; however, there are two $c\bar{c}$ 1^{--} states, which might mix to yield the observed spectrum

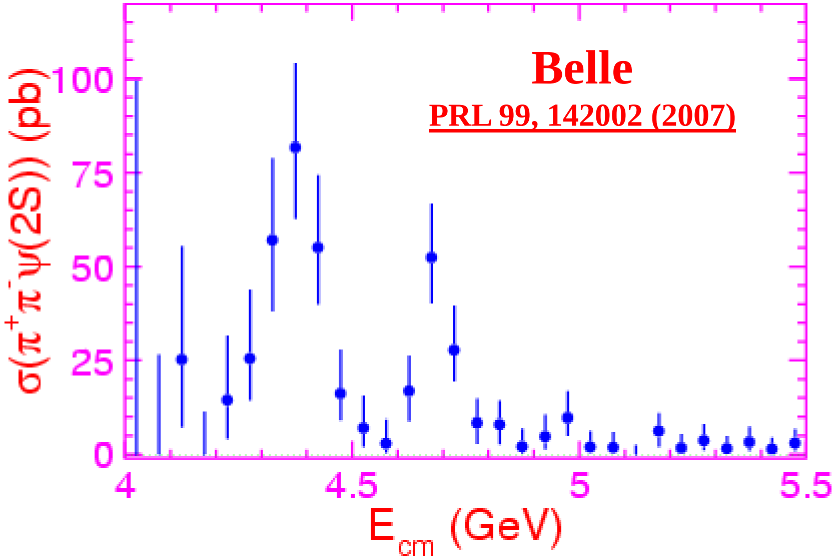
The Y(4350): The Belle Confirmation

✓ Belle studied the reaction $ee \rightarrow \gamma_{ISR}\psi(2S)\pi^+\pi^-$

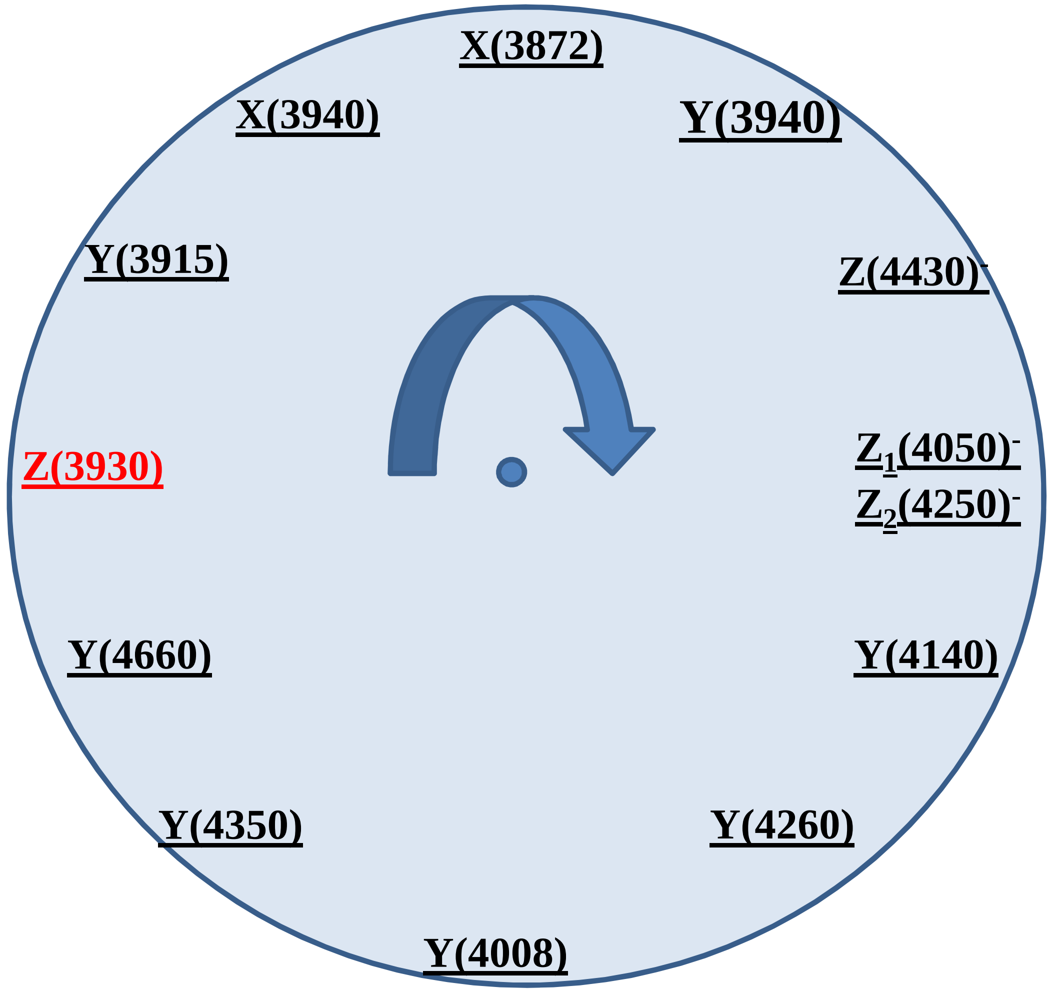
✓ Belle confirmed the existence of the Y(4350) and report a new state Y(4660)!

	Y(4350)	Y(4660)
Mass (MeV/c²)	**4361±9±9**	**4664±15±5**
Width (MeV)	**74±15±10**	**48±15±3**



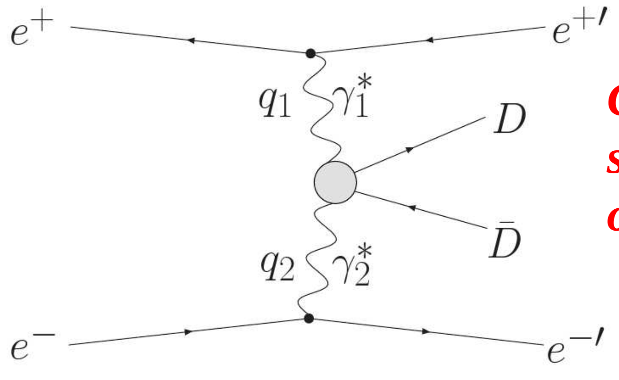


The Z(3930)

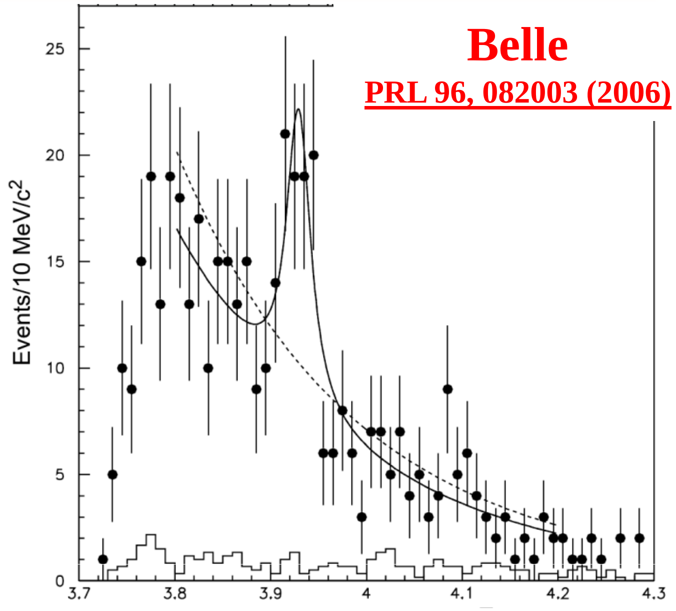


X(3872)
X(3940)
Y(3940)
Y(3915)
Z(4430)⁻
Z(3930)
$Z_1(4050)^-$
$Z_2(4250)^-$
Y(4660)
Y(4140)
Y(4350)
Y(4260)
Y(4008)

Two-Photon Production: The Z(3930)



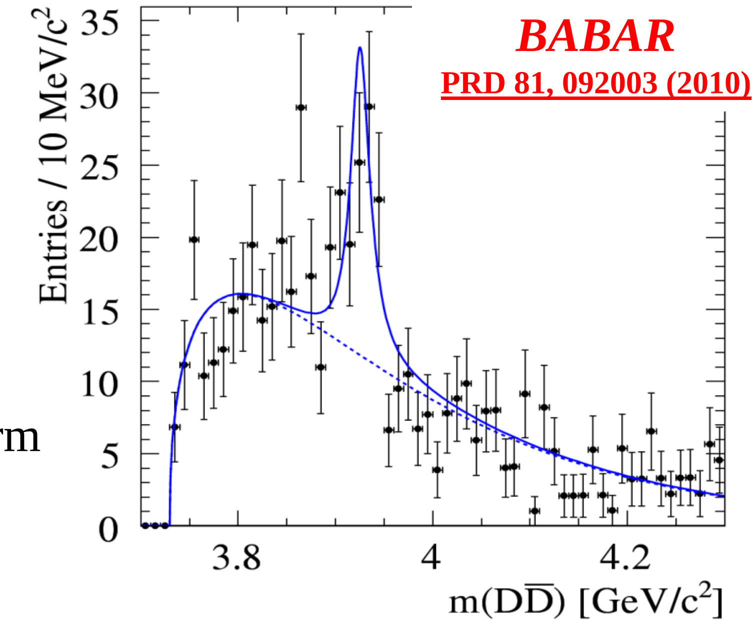
Clean environment to study radial excitation of χ_c states



- Belle observed the Z(3930) state in $e^+e^- \rightarrow e^+e^- D\bar{D}$

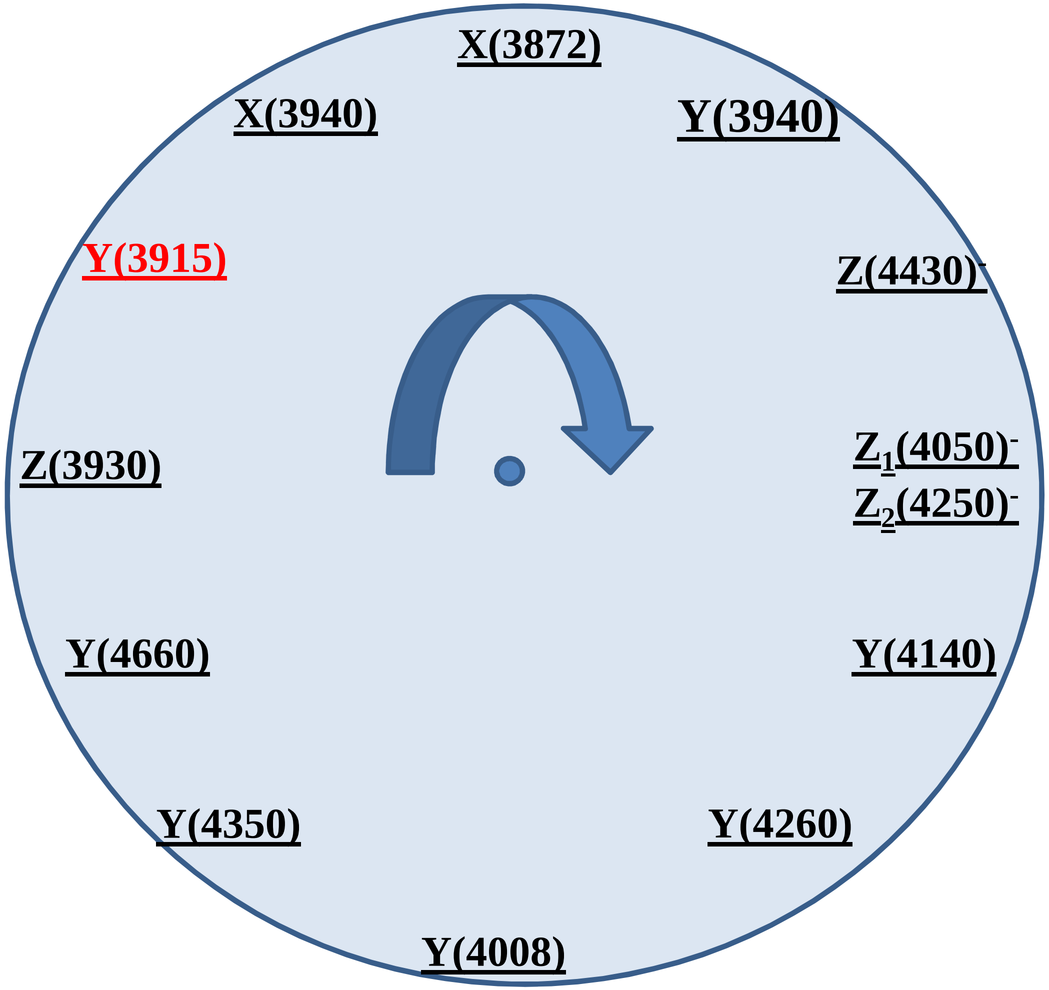
- *B*A*B*AR confirmed the existence of the Z(3930)

	Belle	BABAR
Mass (MeV/c2)	3929±5±2	3926.7±2.7 ± 1.1
Width (MeV)	29±10±2	21.3 ± 6.8 ± 3.6



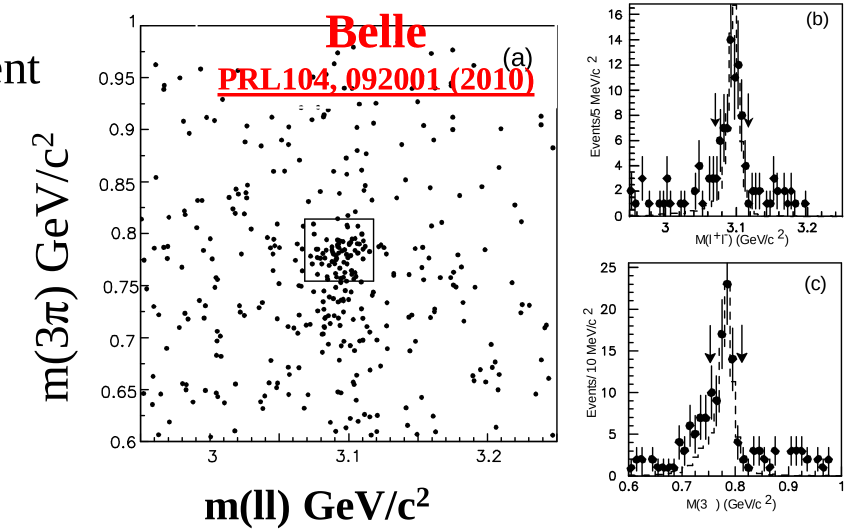
L = 2 is favored by Belle and *B*A*B*AR data➔ Confirm interpretation: **Z(3930) is the χ_{c2}(2P)**

The Y(3915)


X(3872)
Y(3940)
Z(4430)⁻
Z1(4050)⁻
Z2(4250)⁻
Y(4140)
Y(4260)
Y(4008)
Y(4350)
Y(4660)
Z(3930)
Y(3915)
X(3940)

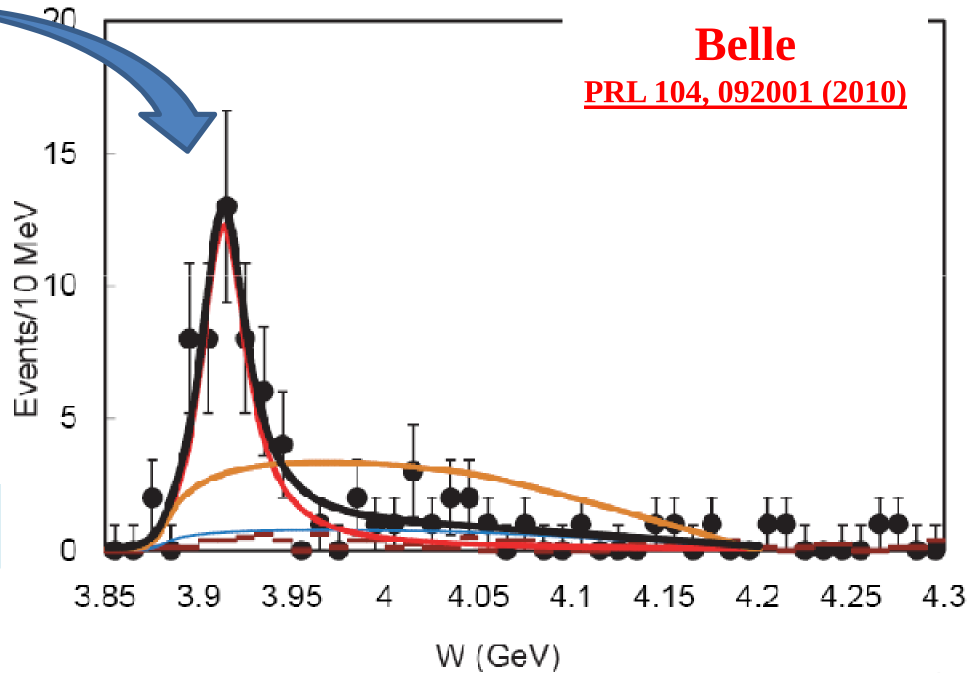
Two-Photon Production: The X(3915)

- Belle observed a charmonium-like enhancement in $e^+e^- \to e^+e^-\gamma\gamma$, $\gamma\gamma \to J/\psi\omega$
- The final state electrons are not detected
- Clear J/ψ and ω signals are obtained



The X(3915)!

Mass: $3914 \pm 3 \pm 2$ MeV/c2
Width: $17 \pm 10 \pm 3$ MeV
$N_{res} = 55 \pm 14\ ^{+2}_{-14}$
Significance = 7.7σ



New state or new decay mode?

The 4 states near 3940

Range: ±(σ(stat.)+σ(sys.))

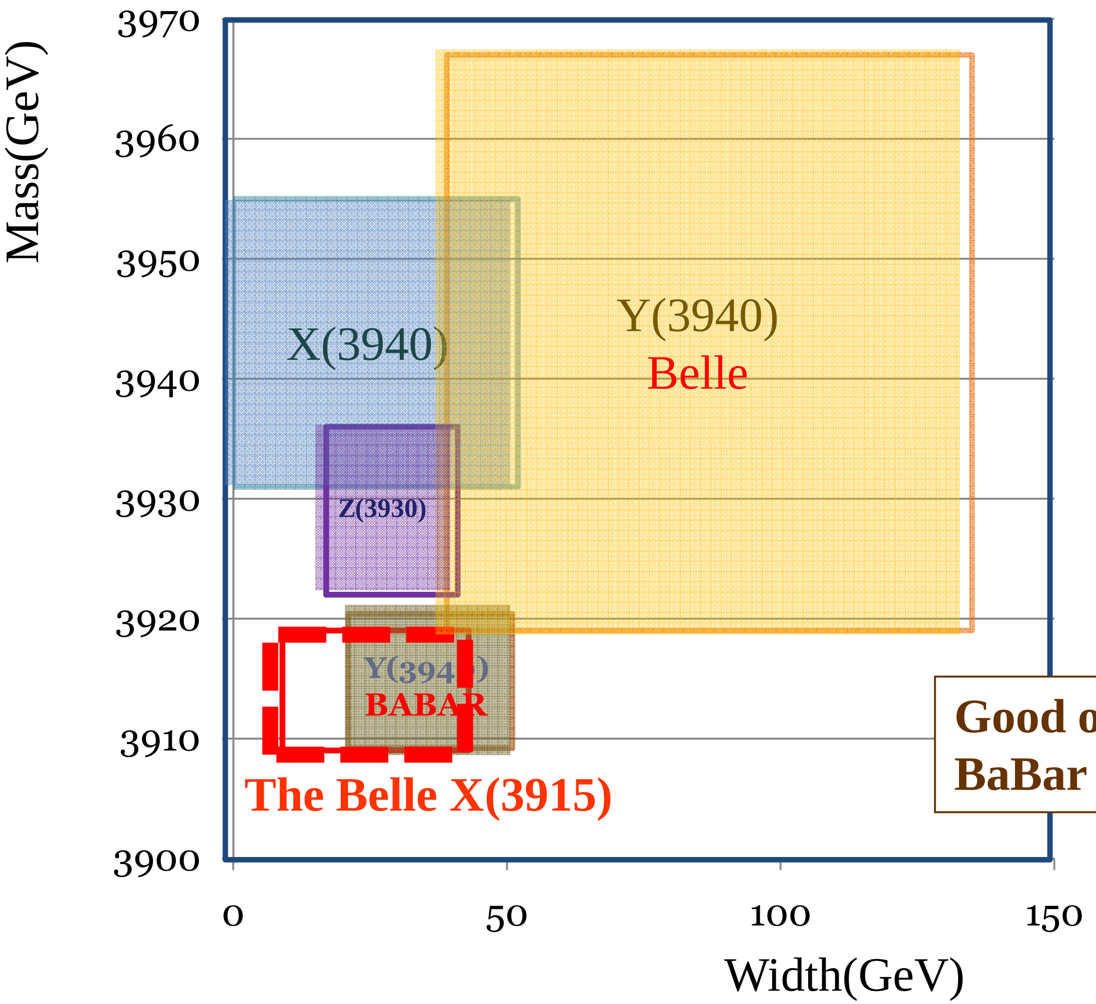
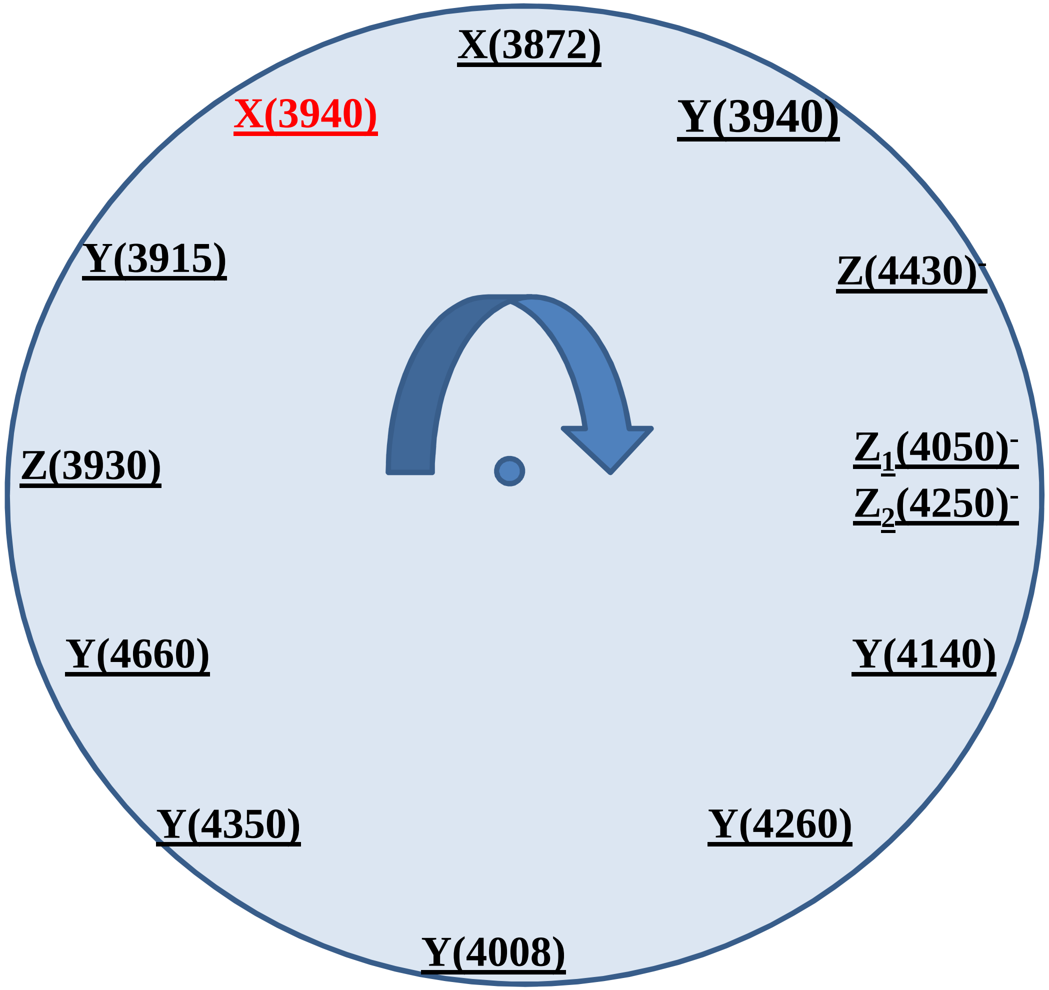


Figure from S. Olsen

Good overlap with BaBar "Y(3940)" values

How many states have we found?

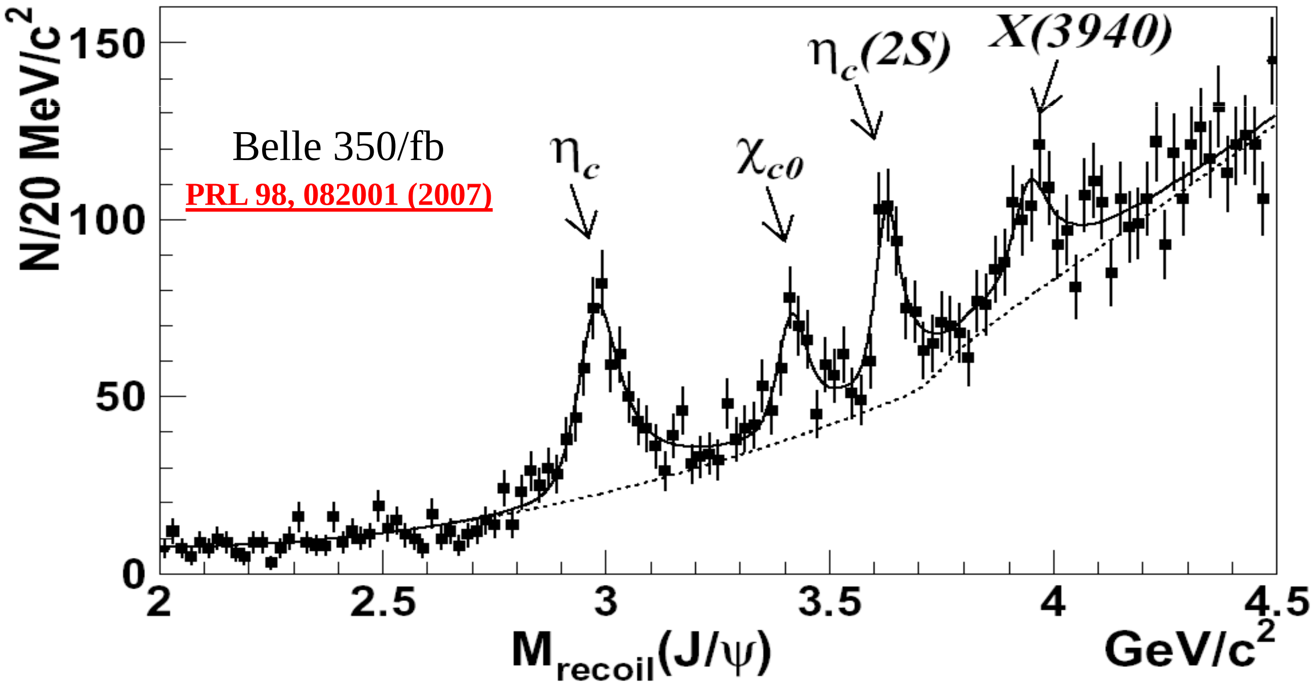
The X(3940)



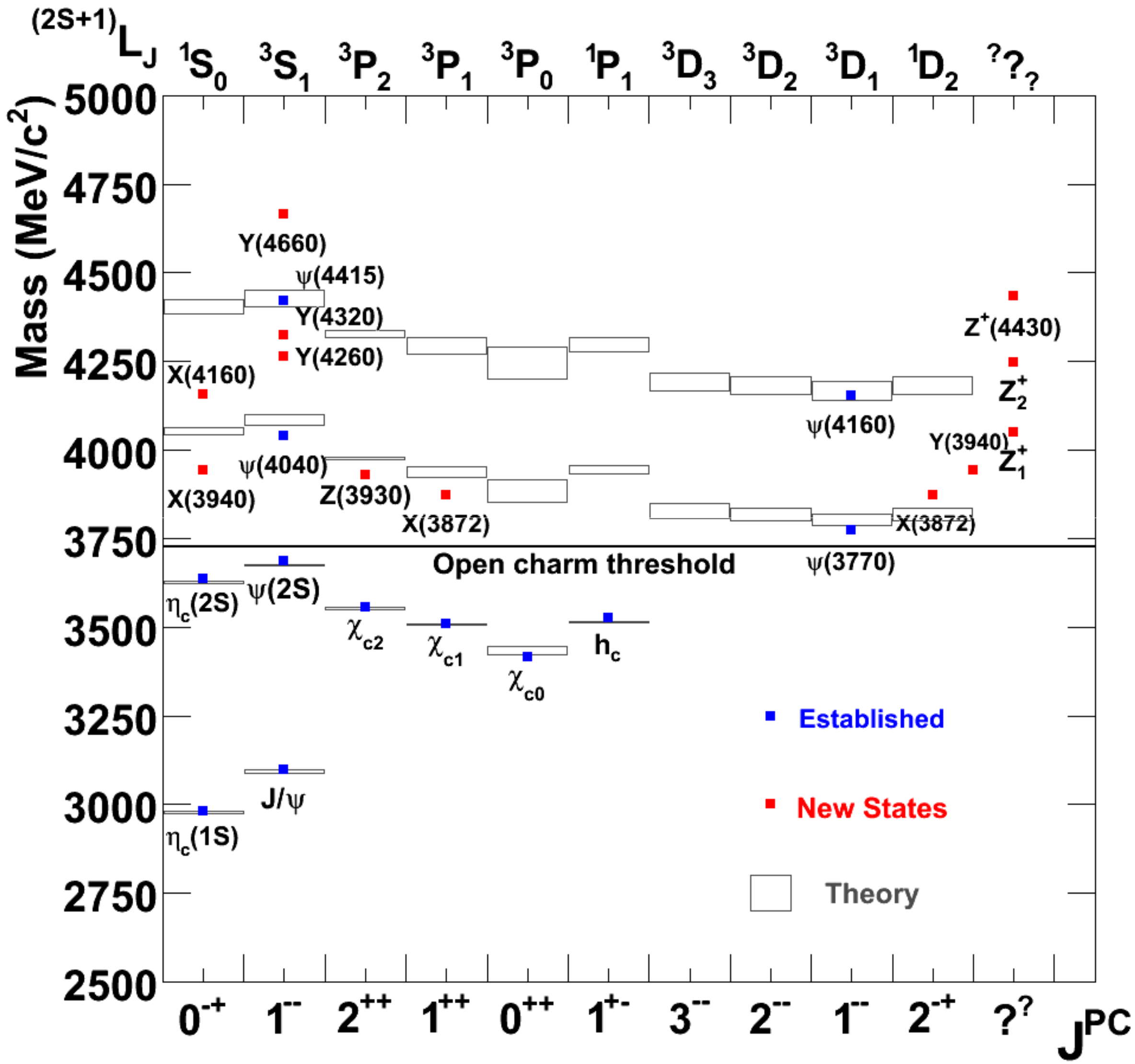
X(3872)
Y(3940)
$Z(4430)^-$
$Z_1(4050)^-$
$Z_2(4250)^-$
Y(4140)
Y(4260)
Y(4008)
Y(4350)
Y(4660)
Z(3930)
Y(3915)
X(3940)

Double Charmonium Production

- Belle discovered X(3940) in double charmonium production: $e^+e^- \to J/\psi\ X(3940)$
- Are X(3940) and Y(3940) the same state?
- This discovery needs confirmation…



Summary-I



(2S+1)L_J
1S0 3S1 3P2 3P1 3P0 1P1 3D3 3D2 3D1 1D2 ??
Mass (MeV/c²)
5000
4750
4500
4250
4000
3750
3500
3250
3000
2750
2500
Y(4660)
ψ(4415)
Y(4320)
Y(4260)
X(4160)
Z⁺(4430)
Z₂⁺
ψ(4160)
Y(3940)
Z₁⁺
ψ(4040)
X(3940)
Z(3930)
X(3872)
X(3872)
ψ(3770)
Open charm threshold
ψ(2S)
ηc(2S)
χc2
χc1
χc0
hc
J/ψ
ηc(1S)
Established
New States
Theory
0⁻⁺ 1⁻⁻ 2⁺⁺ 1⁺⁺ 0⁺⁺ 1⁺⁻ 3⁻⁻ 2⁻⁻ 1⁻⁻ 2⁻⁺ ??
J^PC

Summary-II

- At the **B Factories**, many charmonium-like states were discovered
- The nature of these states is not yet completely understood
- Among them, the charged states reported by Belle are most puzzling…
- More data are needed to understand the nature of these states
- The LHC experiments have the potential to improve our understanding of these states
- Super-B (Belle-II) with ~50-100 times more statistics, many properties of these charmonium-like states will be understood
- With ~1/ab of data, many charmonium-like states have been discovered; no reason to believe that this won't continue in the many-ab^{-1} territory

Backup Slides

The PEP-II Storage Rings at SLAC

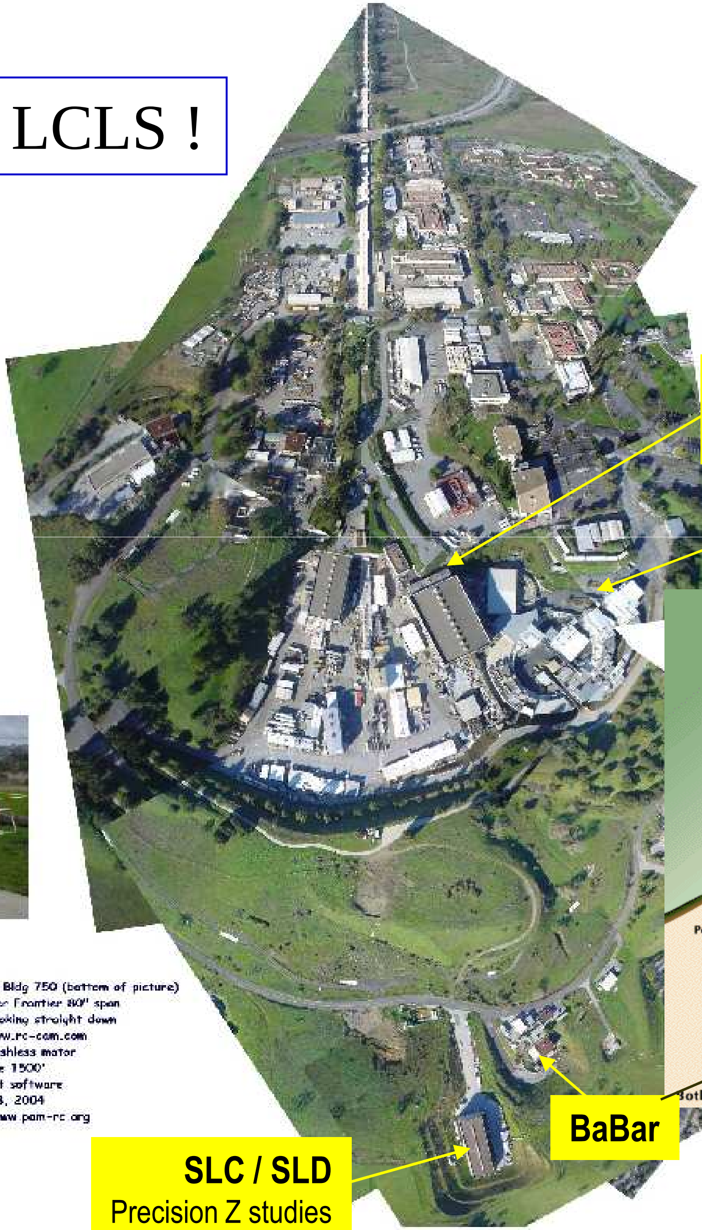
Pre LCLS !

Positron –Electron ~~Proton~~ Project (original idea)

Positron – Electron Project Symmetric-energy collider- single ring

Positron – Electron Project II Asymmetric-energy collider-
HER: old PEP ring
LER: new ring built on top of HER

* Steve Williams piloting from Bldg 750 (bottom of picture)
* World Models Super Frontier 80" span
* Sony U30 2 MP looking straight down
*e-switch by www.rc-com.com
* electric brushless motor
* altitude 1500'
* Picture-It software
* Feb 28, 2004
* more pix at www.pam-rc.org

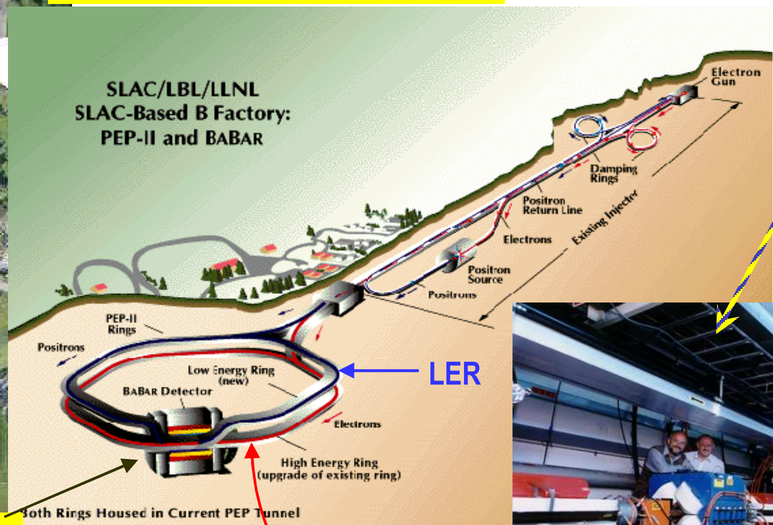


End Station A
DIS / partons

SPEAR / SSRL
J/ψ , charm mesons, τ lepton

BaBar

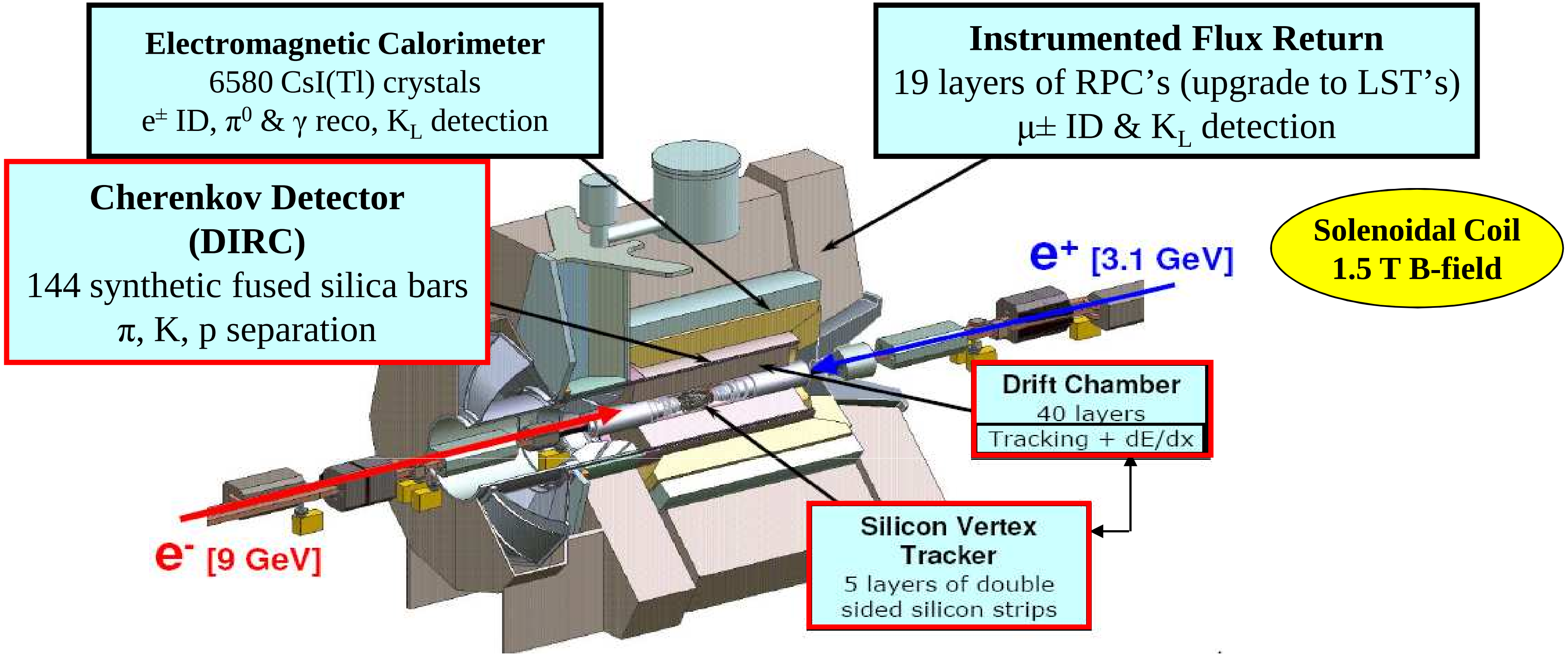
SLC / SLD
Precision Z studies

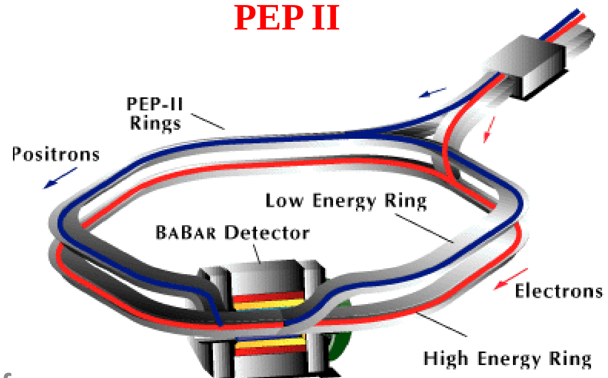


LER

HER

PEP-II & BABAR Detector



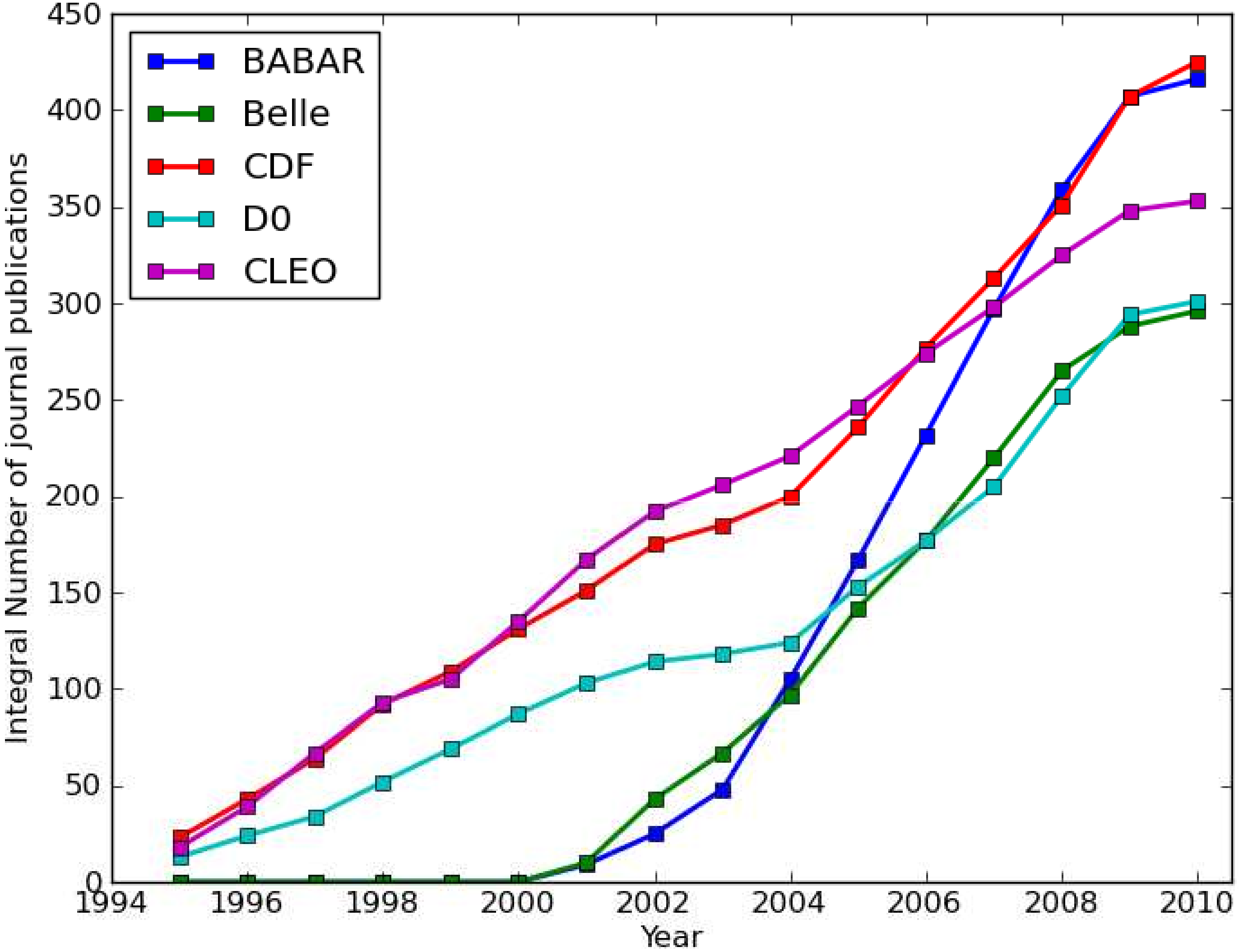


Peak Luminosity

12.069×10^{33} cm^{-2}sec^{-1} August 16, 2006

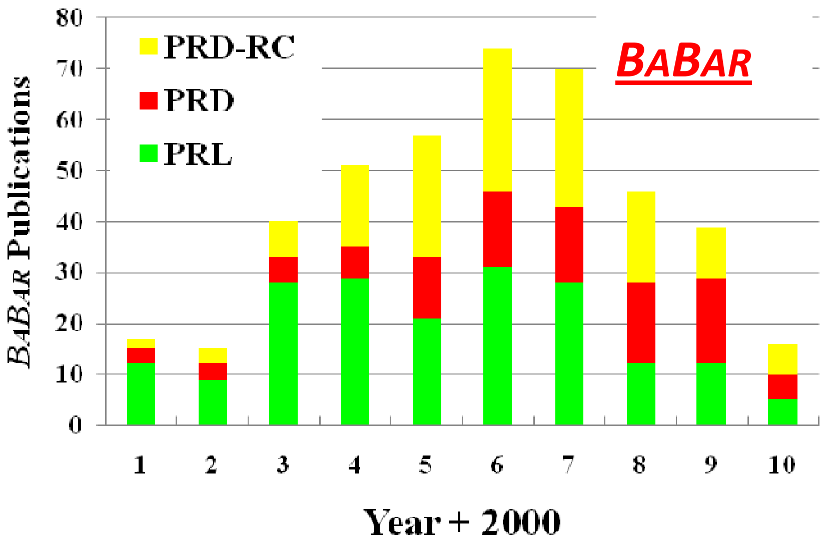
1722 bunches 2900 mA LER 1875 mA HER

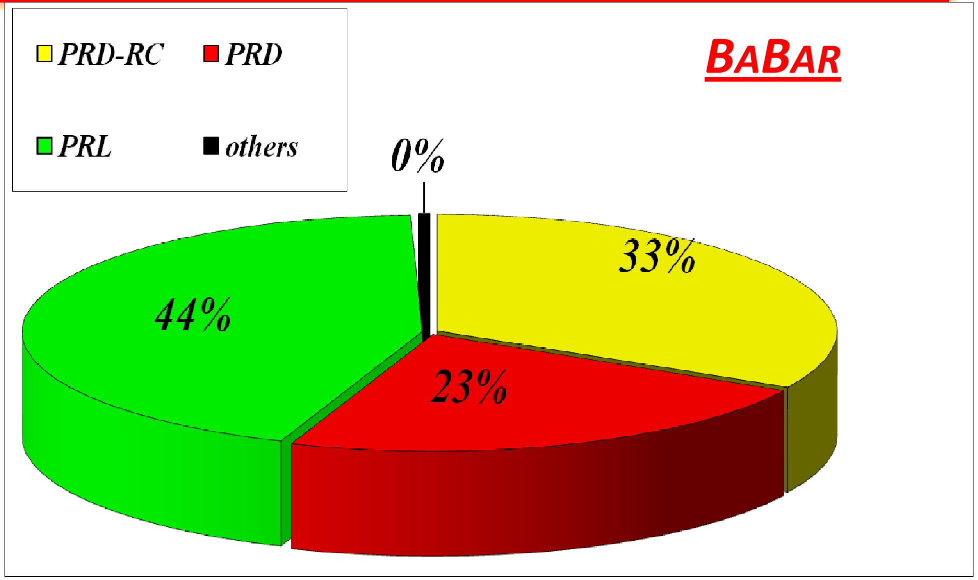
Publication Factories

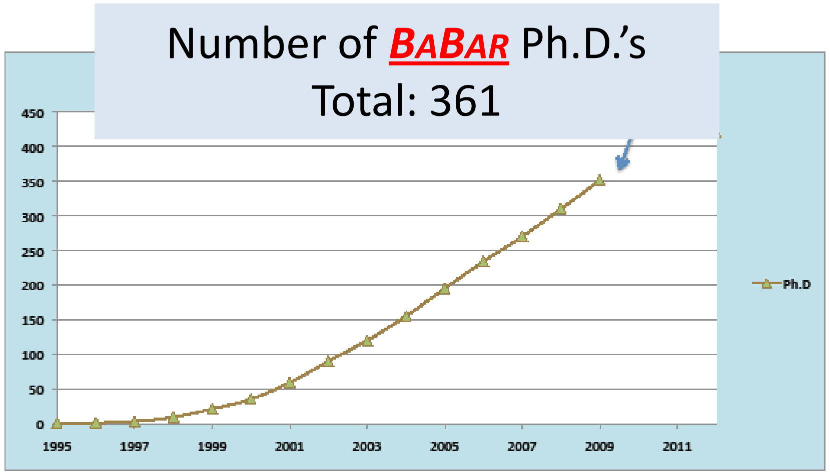


B Factories are also publication factories!

BABAR Publications & Ph.D.'s as of June/2010



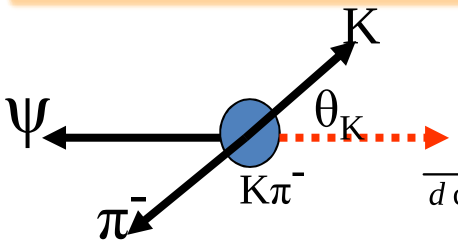




Journal	#Publications
PRD-RC	141
PRD	97
PRL	187
Others	2
Total	**427**

What a performance!

The Z(4430)⁻: Legendre Poly. Moments



Only S-, P-, and D-waves

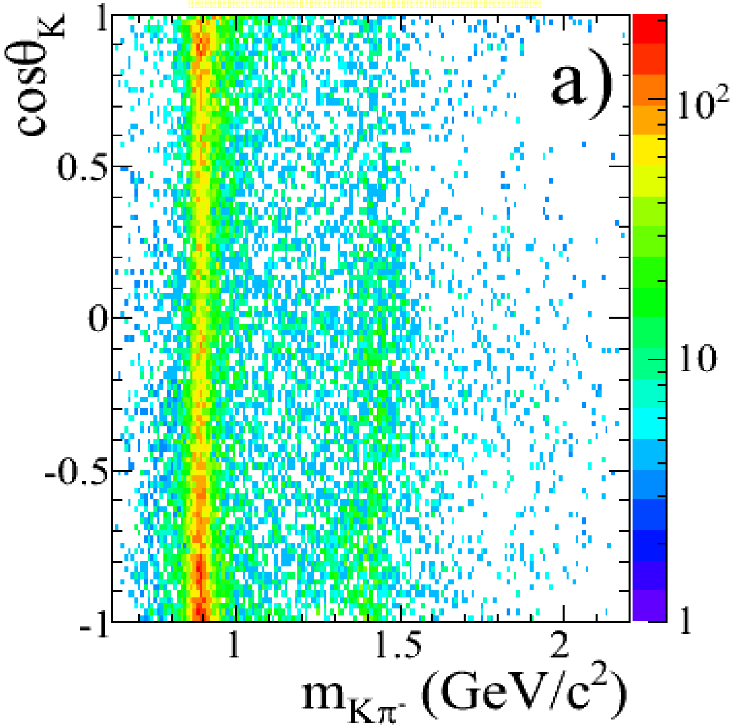
$$\frac{dN}{d\cos\theta_K} = N\sum_{i=0}^{4} < P_i > P_i(\cos\theta_K) = \frac{N}{2} + \sum_{i=1}^{4} \underbrace{(N < P_i >)}_{\text{Unnormalized moment } <P_i^U>} P_i(\cos\theta_K)$$

Unnormalized moment $<P_i^U>$

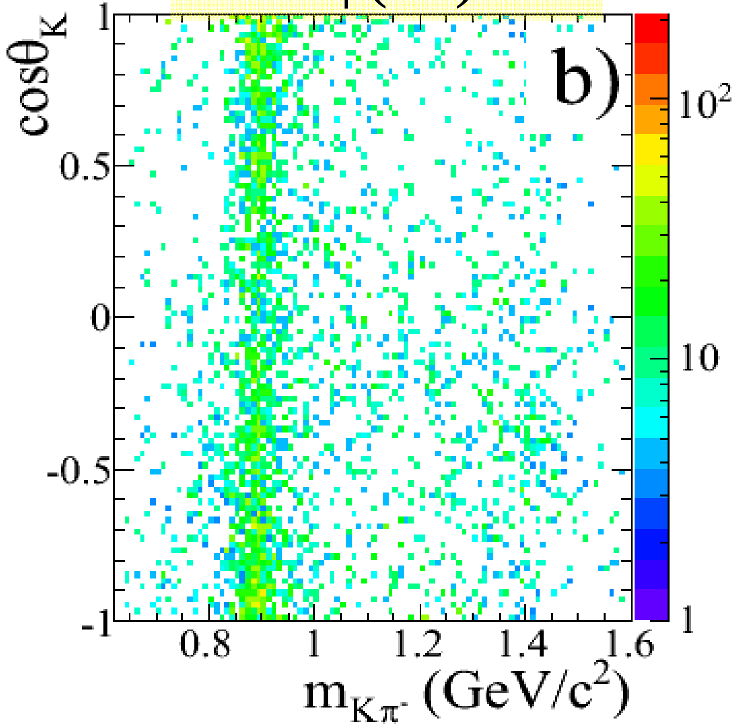
BABAR

PRD 79, 112001 (2009)

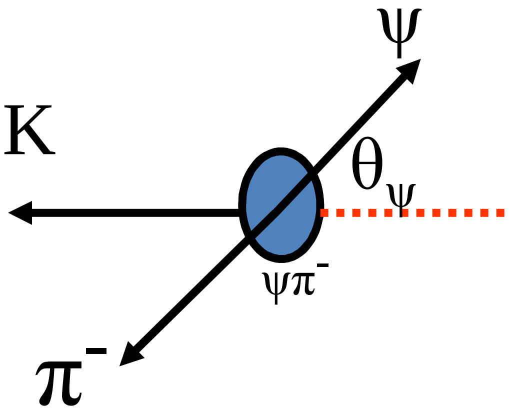
$B \rightarrow J/\psi\pi^- K$

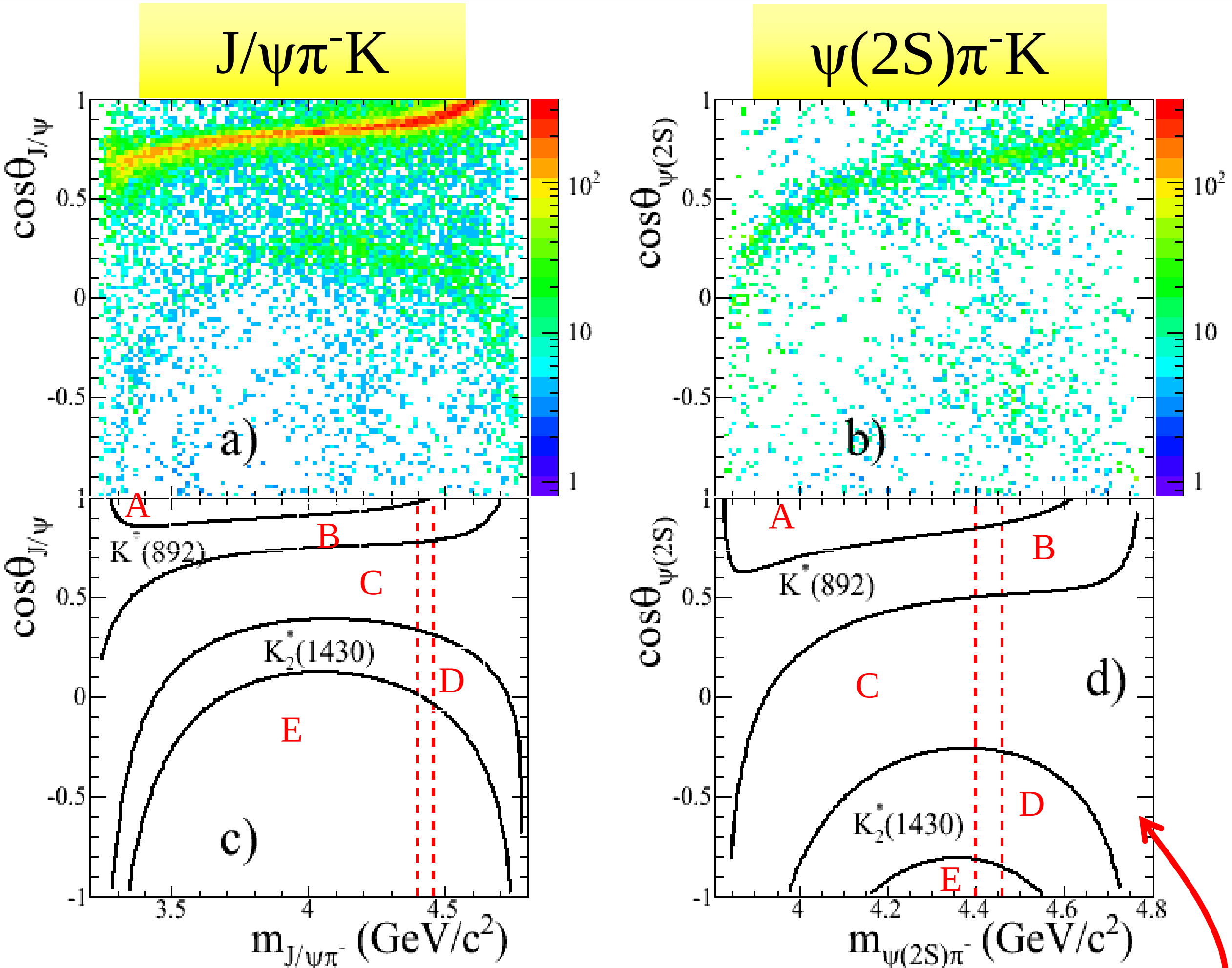


$B \rightarrow \psi(2S)\pi^- K$



The Z(4430)-: The Kπ Reflections





BABAR

PRD 79, 112001 (2009)

- ✓ $m_{\psi\pi}$ 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 $\psi(2S)$
- ✓ The K^* veto removes approximately half of the angular distribution at the $Z(4430)^-$

Dalitz-Plot Weighting Technique

Each event is given weight of $(5/2)(1-3\cos^2\theta_h)$, where θ_h is the angle between the π^+ and π^0 in the $\pi^+\pi^-$ rest frame

Non-ω events projected away