New Spectroscopy @ B-Factories: status and perspectives

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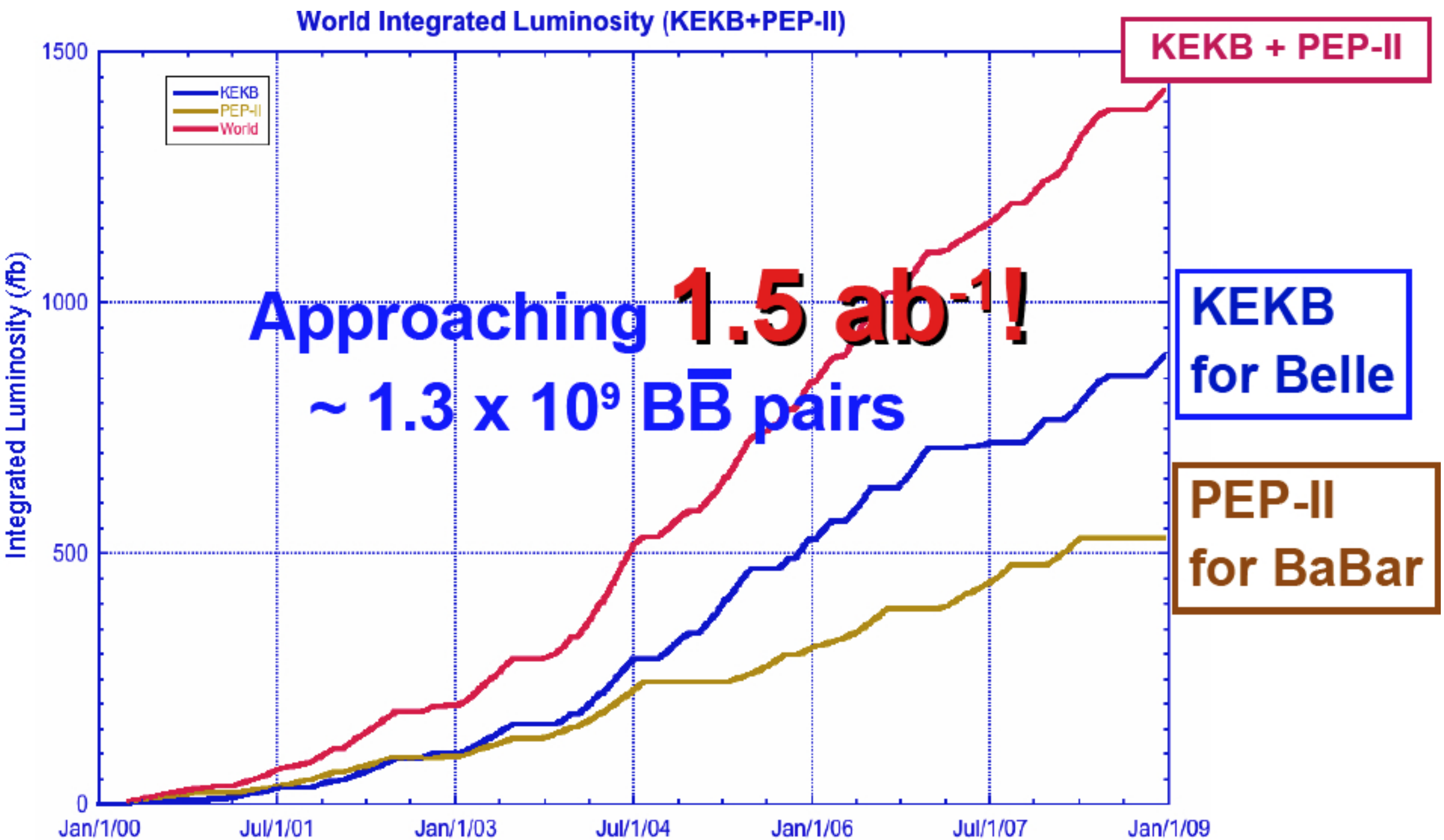
Outline

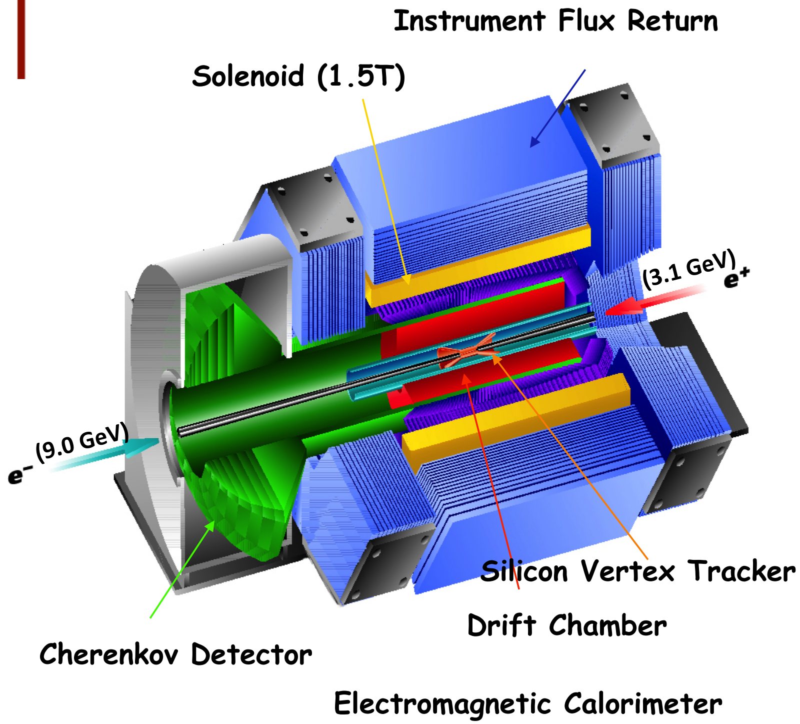
- Introduction
- Charmonium-like exotics
  - X(3872)
  - The Y ISR saga
  - The 3940 family
  - Z(4430)-, Z1-, Z2-
- Search for bottomonium-like exotics

The B factories

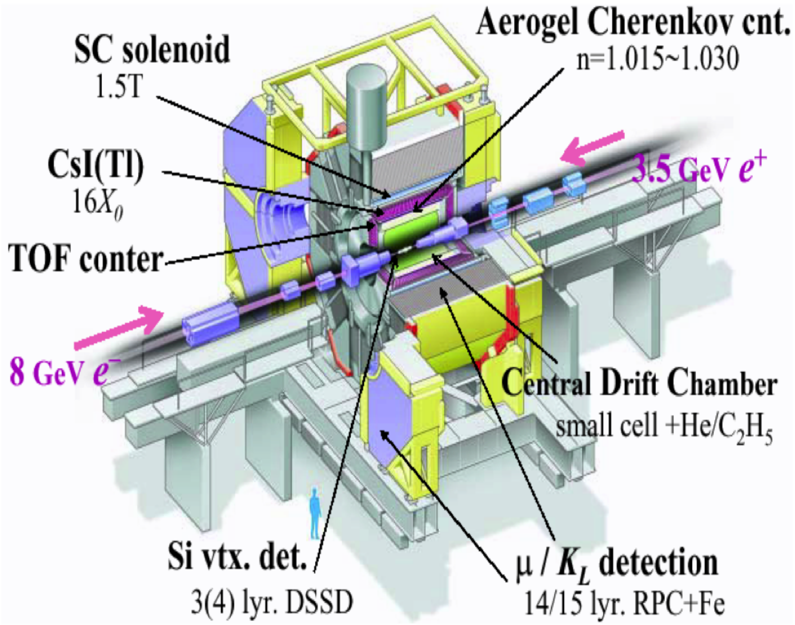


The detectors

BaBar

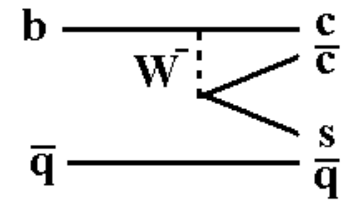


Belle

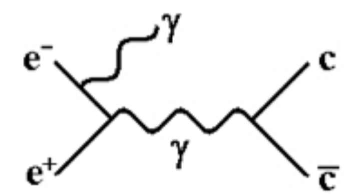


Charmonium production at the B factories

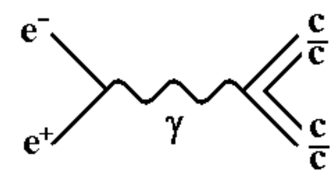
- Color-suppressed b -> c decay
  Predominantly from B -> $c\bar{c}$ K



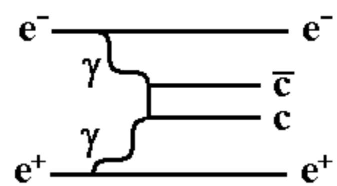
- Initial State Radiation (ISR)
  e^+e^- collision below nominal c.m. energy
  $J^{PC} = 1^{--}$



- Double charmonium production
  Typically one J/ψ or ψ(2S), plus second $c\bar{c}$ state



- Two-photon production
  Access to C = + states



Charmonium spectrum before the B factories

1.3. SPETTRO E DECADIMENTI DEL CHARMONIO 13

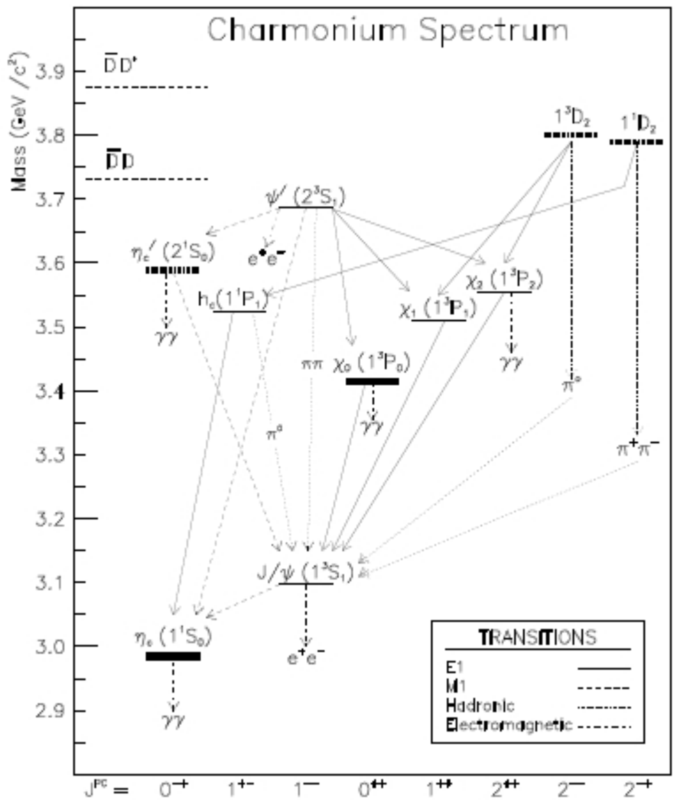
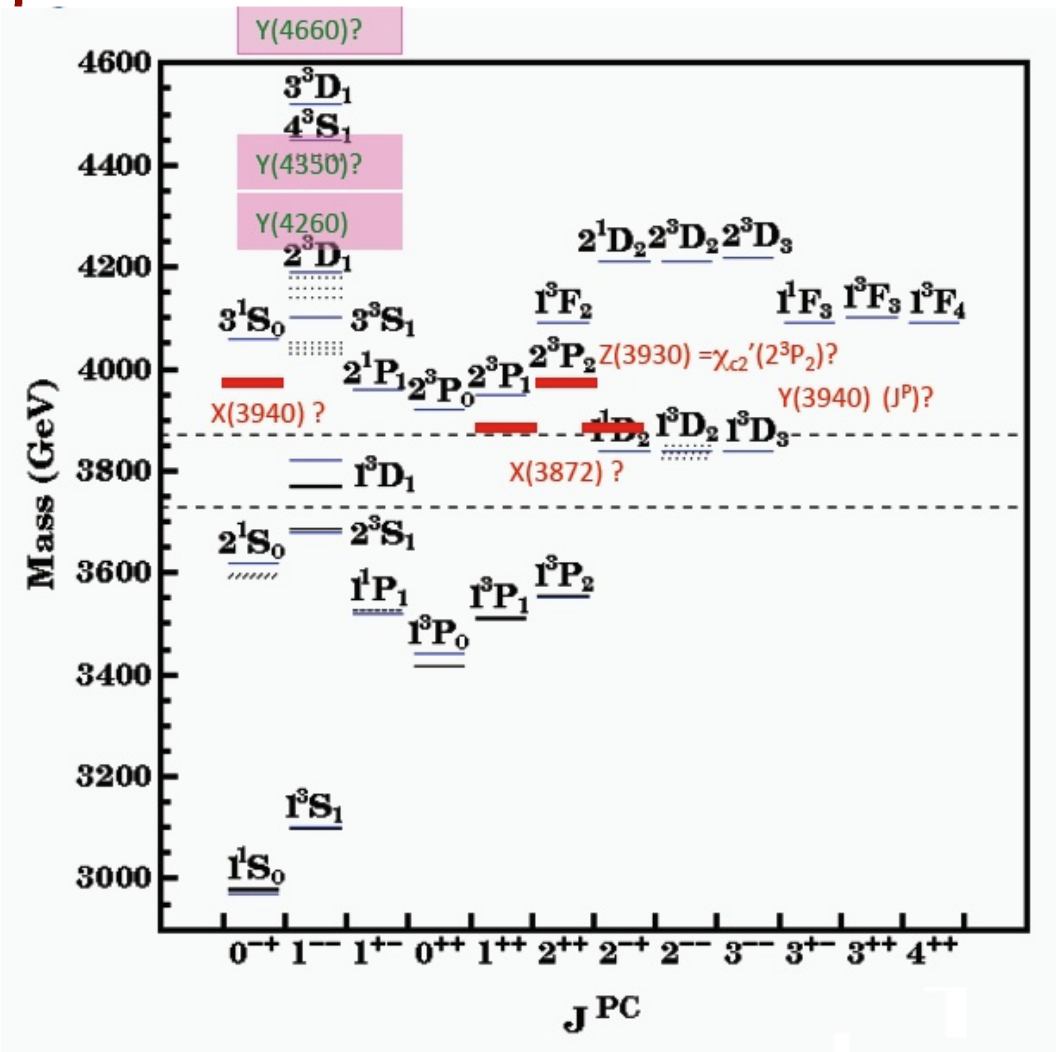


Figura 1.7: Spettro del charmonio.

- From my graduation thesis (E835 experiment - year 2000).
- Charmonium spectrum well known up to the open charm threshold with some missing pieces.
- In the same year the B-factories started taking data.

Charmonium spectrum: today

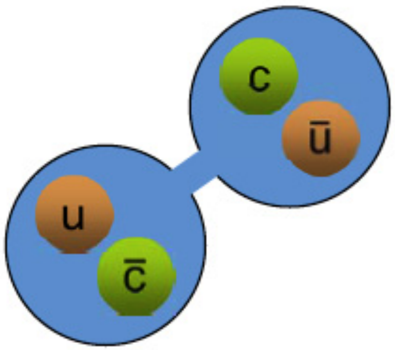


Charmonium properties are well understood up to about the $D\bar{D}$ threshold.

$c\bar{c}$ states above open charm threshold are expected to have significant width values and to decay mainly to open charm channels.

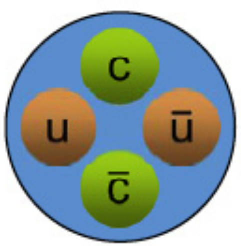
But now there are many states which don't fit with any conventional charmonium interpretation

What's in there (I)



Molecular state:
loosely bound state of a pair of mesons.
The dominant binding mechanism should be pion exchange.
Being weakly bound, 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)
MB Voloshin PLB 579, 316 (2004)
F Close & P Page PLB 578,119 (2004)
X Liu arXiv 0708..4167
...

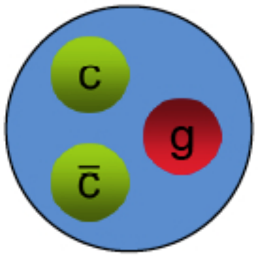


Tetraquark:
Bound state of four quarks, i.e. diquark-antidiquark in which the quarks group into color triplet scalar or vector clusters.
Strong decays proceed via rearrangement processes.

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.

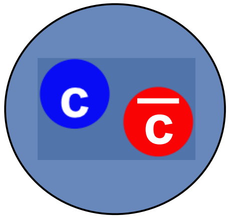
What's in there (II)



Charmonium hybrids
States with an excited gluonic degree 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 model predictions for the lowest lying hybrid:

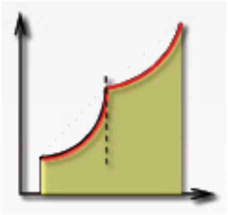
M ~4200 MeV

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



Conventional charmonium

C Meng & KT Chao
PRD 75, 114002 (2007)
W Dunwoodie & V Ziegler
PRL 100 062006 (2008)
O Zhang, C Meng & HQ Zheng
arXiv:0901.1553
…



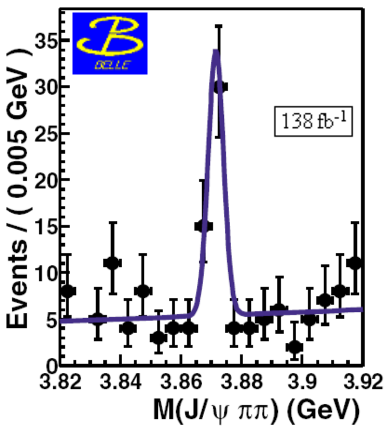
Threshold effects
Virtual enhancement of cross section that may not indicate a resonance.

The X(3872): where it all began

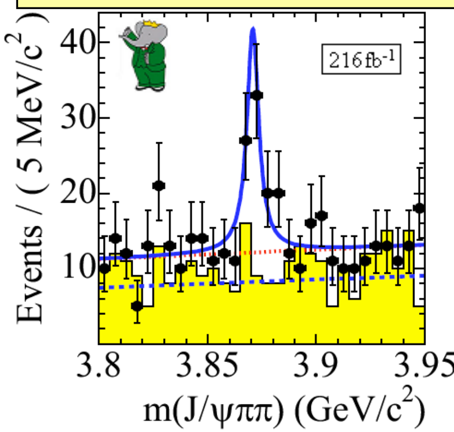
The discovery

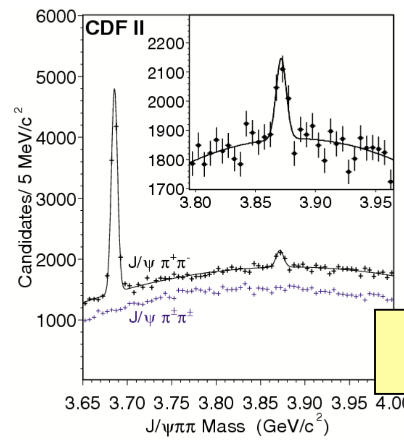
Discovered by Belle in B -> $J/\psi\pi^+\pi^-$ K; confirmed by CDF, D0 and BaBar
Narrow (Γ<2.3MeV) particle with mass m(X)=3871.4+/-0.6 MeV/c²

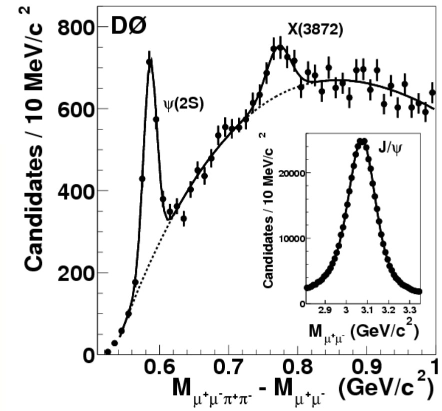
Phys. Rev. Lett. 91, 262001 (2003)



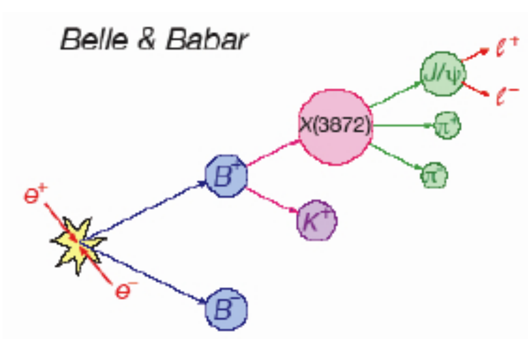
Phys. Rev. D 71, 071103 (2005)
Phys. Rev. D 73, 011101 (2006)

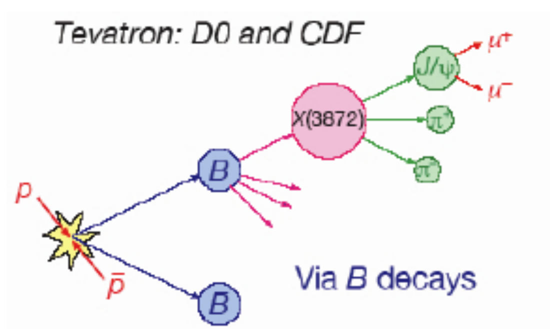


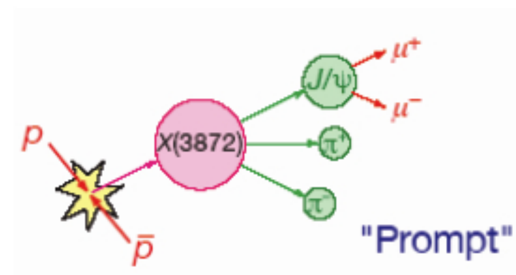




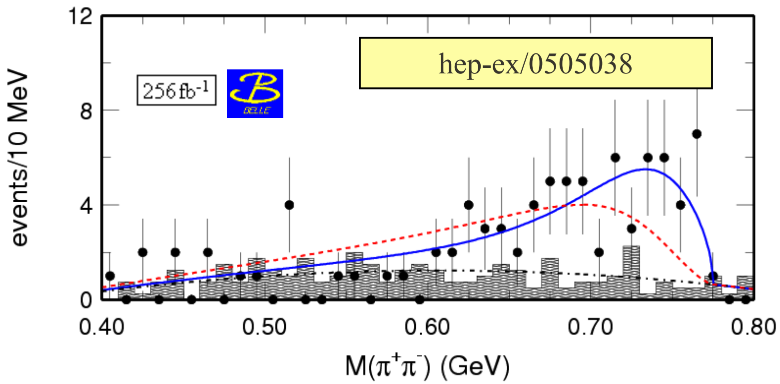
Phys. Rev. Lett. 93, 072001 (2004)
Phys. Rev. Lett. 93, 162002 (2004)







Feature: Dipion mass

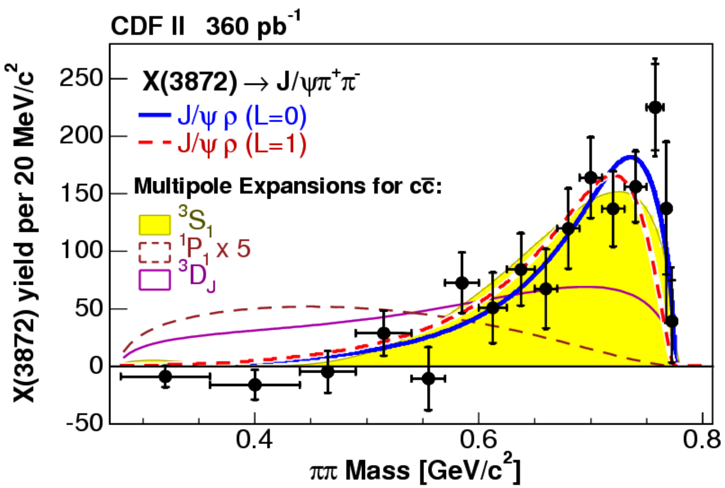


Belle and CDF analyzed the $\pi^+\pi^-$ mass distribution from X -> $J/\psi\ \pi^+\pi^-$

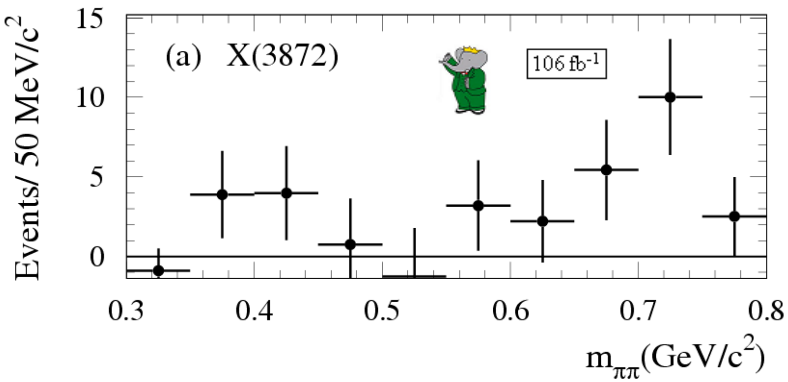
Both seem to favor a "ρ-like" shape, with J/ψ-ρ in an S-wave

Shape in BaBar is similar, no attempt to fit

Disfavor charmonium interpretation



Phys. Rev. Lett. 96, 102002 (2006)



Phys. Rev. D 71, 071103 (2005)

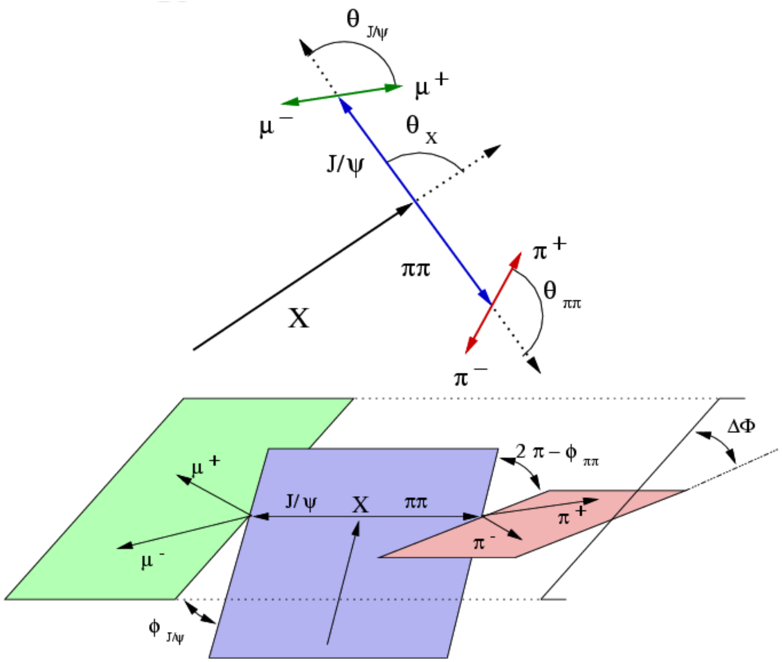
Feature: angular analysis

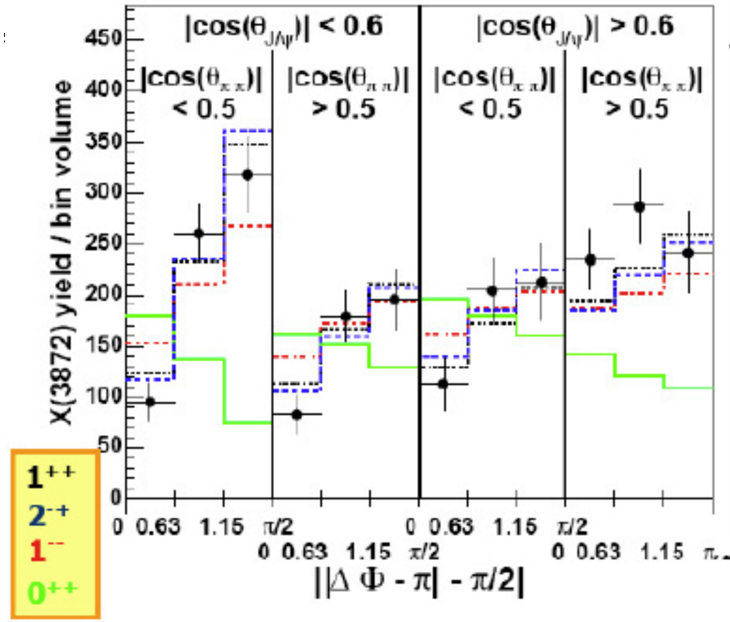
hep-ex/0611004

CDF analyzed angular distribution of daughters, and tested against various J^{PC} assignments

Angular analysis compatible with both 1^{++} and 2^{-+}
χ^2 prob.(1^{++})=27.8%, (2^{-+})=25.8%

- Method tested using $\psi(2S) \to J/\psi\pi\pi$ decays





J^{PC}	χ^2 prob.
1^{++}	27.8%
2^{-+}	25.8%
1^{--}	0.02%
2^{+-}	$5.5 \cdot 10^{-5}$
1^{+-}	$3.8 \cdot 10^{-5}$
2^{--}	$3.8 \cdot 10^{-5}$
3^{+-}	$3.8 \cdot 10^{-5}$
3^{--}	$2.4 \cdot 10^{-5}$
2^{++}	$1.1 \cdot 10^{-5}$
1^{-+}	$4.1 \cdot 10^{-6}$
0^{-+}	$3.5 \cdot 10^{-17}$
0^{+-}	$<1 \cdot 10^{-20}$
0^{++}	$<1 \cdot 10^{-20}$

Angular analysis from Belle
favours 1^{++}
disfavours 0^{++}, 0^{-+}, 1^{+-}

hep-ex/0505038

If charmonium:
η_{c2} (1^1D_1) -> 2-+
χ_{c1} (2^3P_1) -> 1++

Null results

Upper limits and null results:

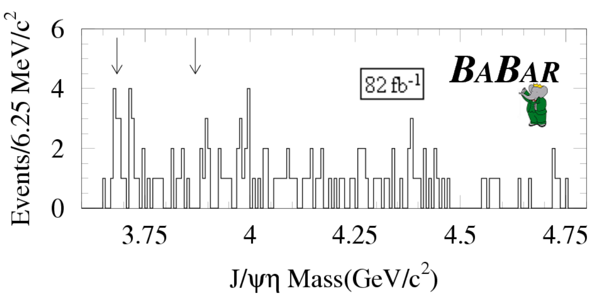
- X -> $J/\psi\eta$ = consistent with "molecule"
- X -> $D\bar{D}$ = rules out 0^+, 1^-, 2^+, ...
- X -> $\chi_{c1,2}\,\gamma$ = against charmonium possibilities
- X -> $J/\psi\,\pi^-\,\pi^0$ = no charged partner

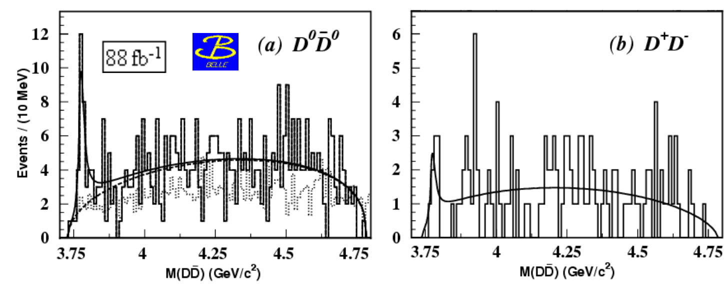
Phys. Rev. Lett. 93, 041801 (2004)

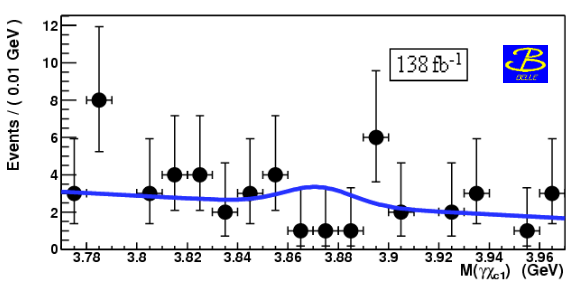
Phys. Rev. Lett. 93, 051803 (2004)

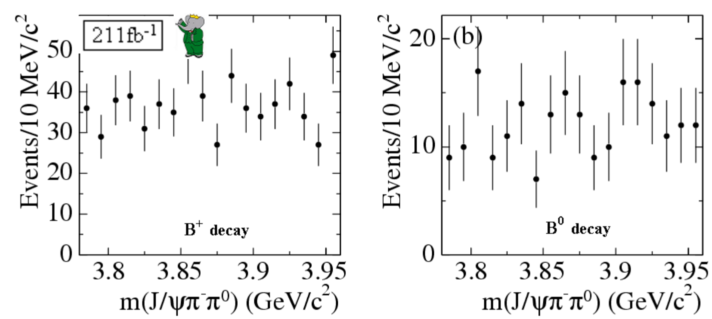
Phys. Rev. Lett. 91, 262001 (2003)

Phys. Rev. D 71, 031501 (2005)









$D\bar{D}^{0*}$ DECAYS

Belle discovered X(3872) in B $D^0\bar{D}^0\pi^0K$

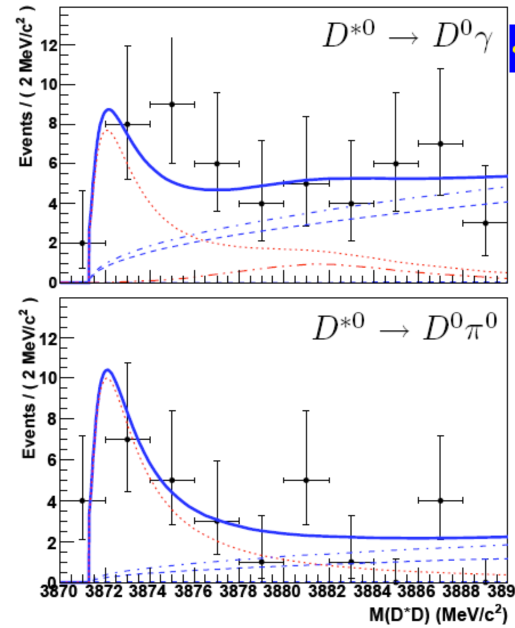
Found mass 2.0σ higher than W.A. for X(3872)

Phys. Rev. Lett. 97, 162002 (2006)

Recent update confirms $D^0\bar{D}^{0*}$ decay (8.8σ)

Compute m(X)=3872.60.50.4 MeV/c^2

arXiv:0810.0358



605 fb^{-1}

BaBar search confirms X(3872) signal (4.9σ)

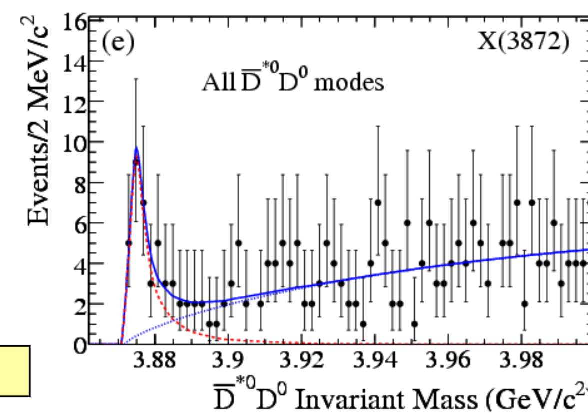
Ratio of $D^0\bar{D}^0\pi^0/D^0\bar{D}^0\gamma$ matches $\bar{D}^{0*}$ expectation

Mass ~4.5σ above X(3872)

Angular study inconclusive

Width also measured

Phys. Rev. D 77, 011102 (2008)



347 fb^{-1}

Radiative decays

Radiative decays may discriminate between η_{c2}, $\chi_{c1}(2P)$, and $D^0\bar{D}^{0*}$

Electromagnetic transitions for charmonium:

- η_{c2} (1^1D_1) $\psi(nS)\gamma$ forbidden (M2)
- χ_{c1} (2^3P_1) $[J/\psi,\psi(2S)]\gamma$ allowed (E1)
- Predictions for relative rate varies, but are of similar order

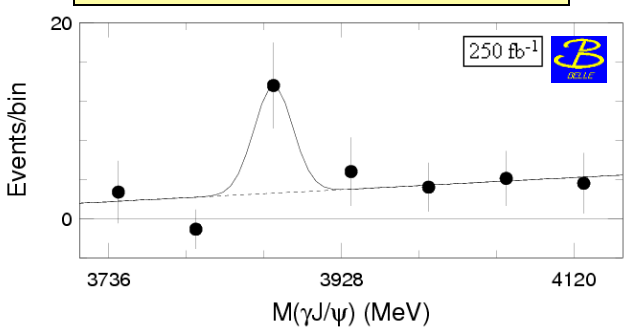
Radiative decays of the $D^0\bar{D}^{0*}$ molecule:

- Decay to $J/\psi\gamma$ is possible in vector meson dominance scenario
- $\psi(2S)\gamma$ proceeds via annihilation, highly disfavored

Both BaBar and Belle have found evidence for this radiative decay

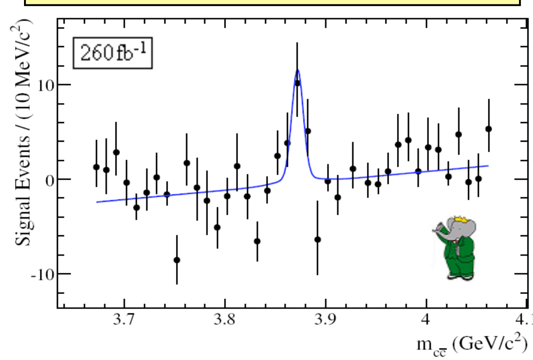
J/ψ and γ have charge parity C = –, implies X(3872) C = +

hep-ex/0505037



$$BF(B \to XK)(X \to J/\psi\ \gamma)$$
$$= (1.8 \pm 0.6 \pm 0.1)\times 10^{-6}\ (4.0\sigma)$$

Phys. Rev. D 74, 071101 (2006)

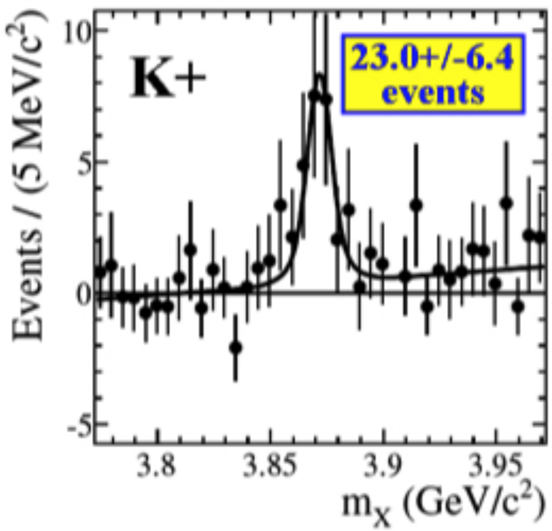


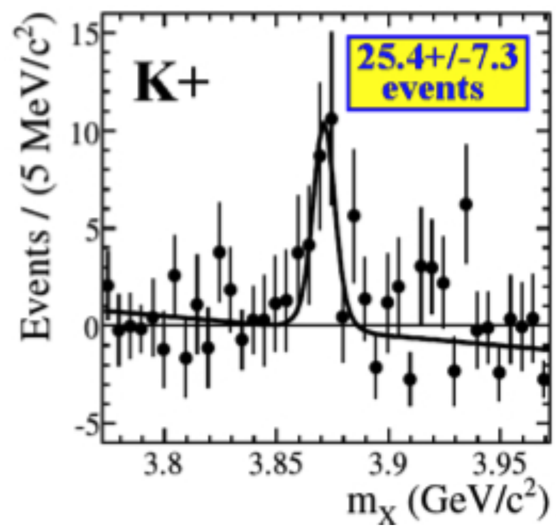
$$BF(B^{\pm} \to XK^{\pm})(X \to J/\psi\ \gamma)$$
$$= (3.3 \pm 1.0 \pm 0.3)\times 10^{-6}\ (3.4\sigma)$$

Radiative decays

arXiv:0809.0042

424fb-1





Find ~3.6σ evidence for
X(3872) -> J/ψ γ

Measure:
BF(B^+ X(3872) K^+) x
(X(3872) J/ψ γ) =
(2.8+/-0.8+/-0.2) x 10^{-6}

Consistent with previous:
(3.3+/-1.0+/-0.3) x 10^{-6}

Evidence for
X(3872) ψ(2S) γ
(~3.5σ significance)

Measure:
BF(B^+ X(3872) K^+) x
(X(3872) ψ(2S) γ) =
(9.5+/-2.7+/-0.9) x 10^{-6}

Ratio of BFs:
(X(3872) ψ(2S) γ)
/ (X(3872) J/ψ γ)
= 3.4 1.4

Interpretations

Summary of X(3872) Properties

Narrow with mass $m(X)=3871.4 +/- 0.6\ MeV/c^2$
Observed in X(3872) $J/\psi\pi\pi$, dipion mass is "ρ-like"
Also seen in decays $X(3872) \to D^0\overline{D}^{0*}$ and $X(3872) \to J/\psi\ \gamma$
Spin-parity identified as either $J^{PC} = 1^{++}$ or 2^{-+}

Charmonium Hybrid

Lightest mass prediction $m(c\bar{c}g) > 4.2 GeV/c^2$

Tetraquark State

No evidence for charged partners

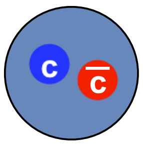
Conventional Charmonium

Angular analysis: $\chi_{c1}(2^3P_1)$ (1^{++}) or $\eta_{c2}(1^1D_1)$ (2^{-+})
Not expected to violate isospin, $X \to J/\psi\ \rho$
X(3872) is narrow and does not decay $X \to D\overline{D}$
Expect $\eta_{c2} \to J/\psi\ \gamma$ to be suppressed
$\chi_{c1}(2P)$ somewhat inconsistent with predicted mass

$D^0\overline{D}^{0*}$ Molecular interpretation

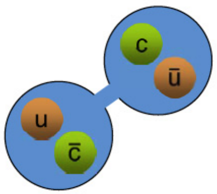
$m(D^0) + m(\overline{D}^{0*}) = 3871.8 +/- 0.4\ MeV/c^2$
Decays to $X(3872) \to J/\psi\ \rho$, $D^0\overline{D}^{0*}$, $J/\psi\ \omega$ expected
Compatible with $J^{PC} = 1^{++}$ assignment
Expect $X \to \psi(2s)\ \gamma$ to be suppressed
Successful predictions vary by model

X(3872) OUTLOOK



Can X(3872) = $\chi_{c1}(2P)$ fit into the charmonium model?

- $\chi_{c1}(2P)$ mass prediction is too high
- Explanation for isospin violation and $\chi_{c1}(2P) \to D\bar{D}$ suppression



Can X(3872) -> $\psi(2S)\gamma$ be reconciled with molecular model?

- Theoretical work needed to explain large BF($D^0\bar{D}^{*0} \to \psi(nS)\,\gamma$)

What do we know regarding X(3872) structure?

- Perhaps neither purely molecular nor charmonium
- $D^0\bar{D}^{*0} - \chi_{c1}(2P)$ mixing or other phenomena?

The Y-isr saga

Discovery...

Phys. Rev. Lett. 95 (2005) 142001

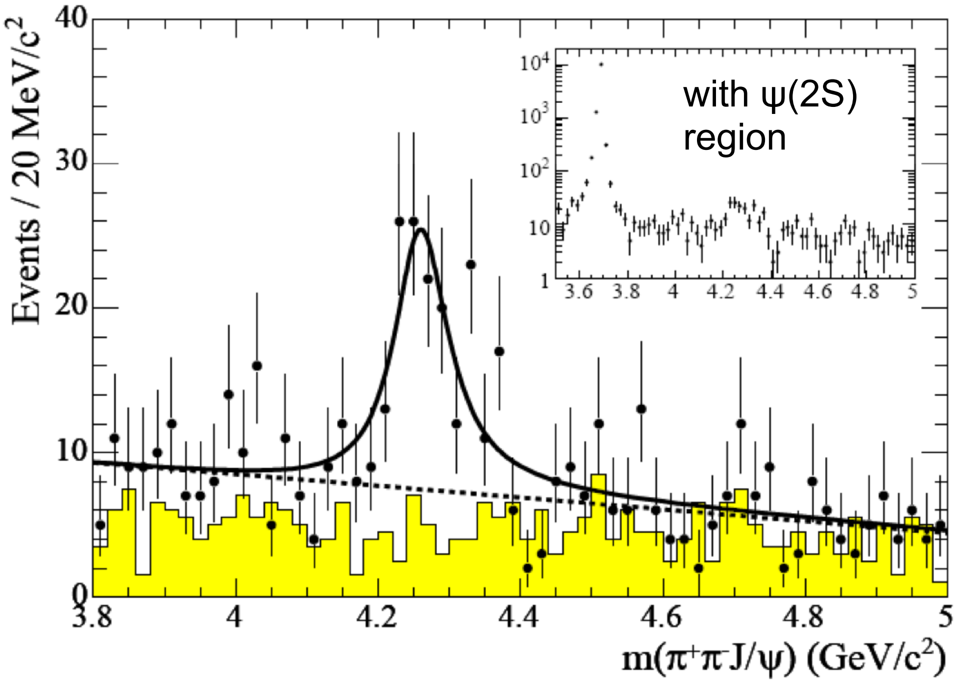
Discovered at BaBar in ISR-produce $J/\psi\pi^+\pi^-$ events in 2005 (233 fb^{-1})

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

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

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

Background estimated by the J/ψ sidebands

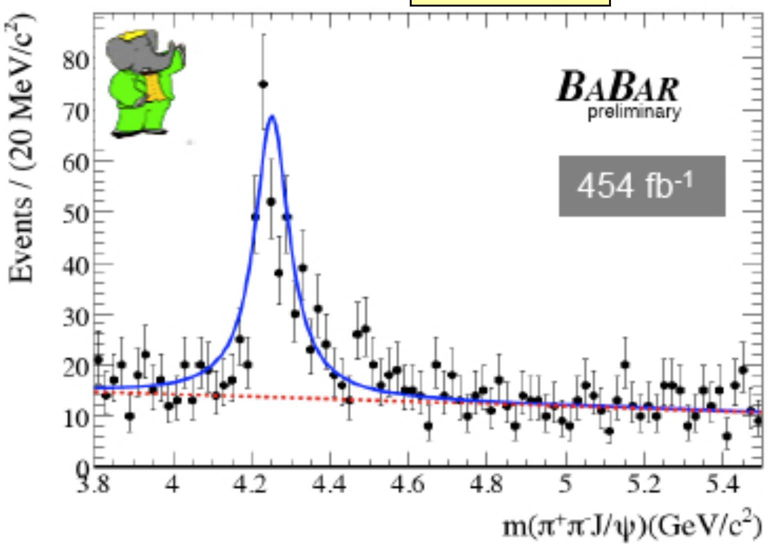


Confirmations by CLEO-c, CLEO-III and Belle with some spread in the resonance parameters.

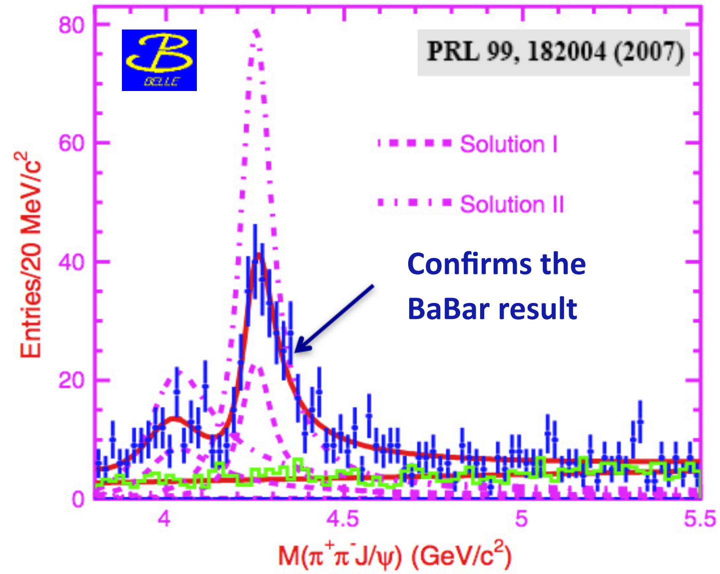
All the 1^{--} slots in the charmonium spectrum were already filled

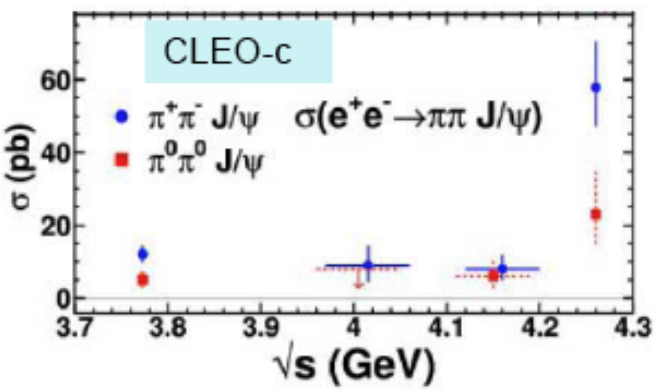
… AND CONFIRMATIONS

arXiv:0808.1543



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





$J/\psi\pi^+\pi^- = 11\sigma$

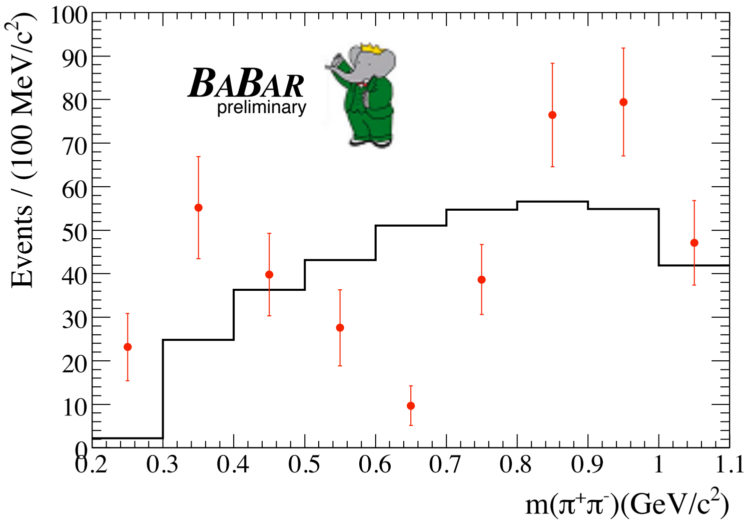
$J/\psi\pi^0\pi^0 = 5.1\sigma$

$(\pi^+\pi^-)/(\pi^0\pi^0) \approx 2 \rightarrow I=0$

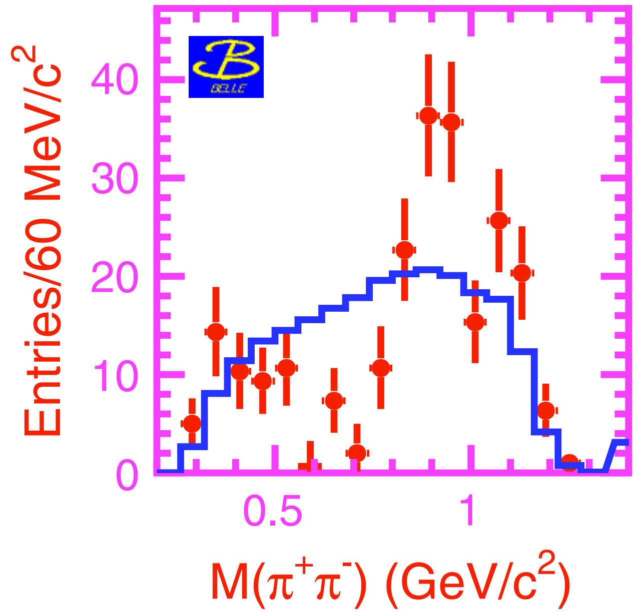
State	M, MeV/c^2	Γ_{tot}, MeV
Y(4008)	$4008 \pm 40^{+114}_{-28}$	$226 \pm 44 \pm 87$
Y(4260)	$4259 \pm 8^{+2}_{-6}$	$88 \pm 23^{+6}_{-4}$
Y(4260)	$4252 \pm 6^{+2}_{-3}$	$105 \pm 18^{+4}_{-6}$
Y(4260)	$4284^{+17}_{-16} \pm 4$	$73^{+39}_{-25} \pm 5$
Y(4260)	$4247 \pm 12^{+17}_{-32}$	$108 \pm 19 \pm 10$

Feature of the $\pi^+\pi^-$ mass

arXiv:0808.1543



PRL 99, 182004 (2007)



Tetraquark interpretation predicts: Y(4260)->J/ψf_0(980)

How to make things more unclear

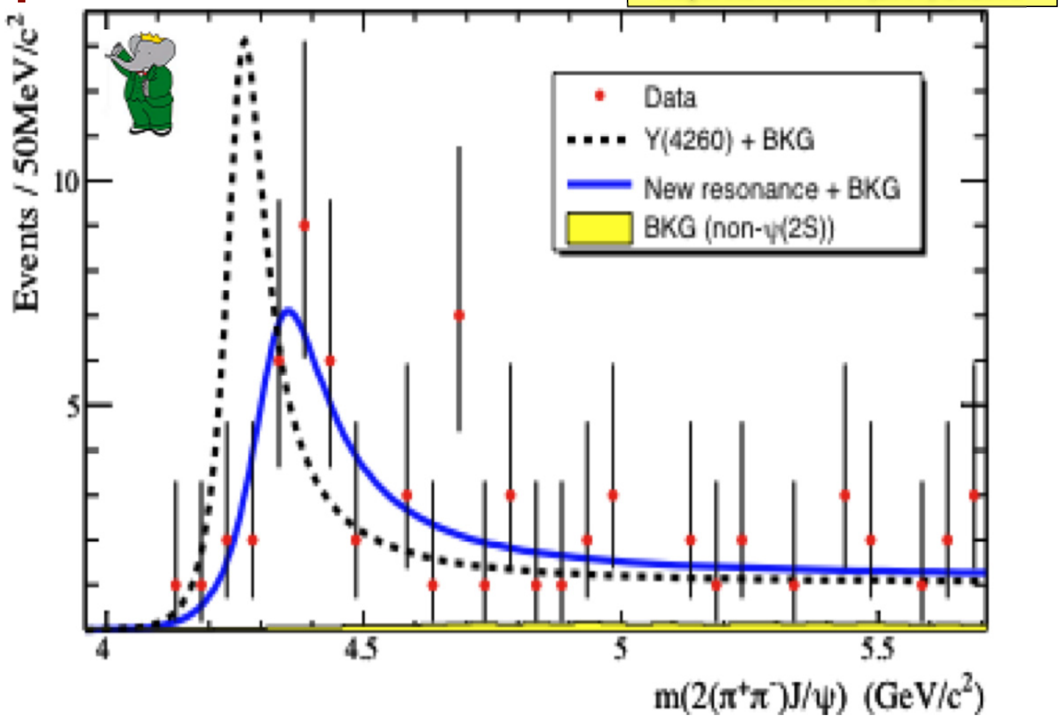
Search for Y(4260)-> $\pi^+\pi^-\psi(2S)$

Y(4260) discovered in ISR $\pi^+\pi^-J/\psi$.

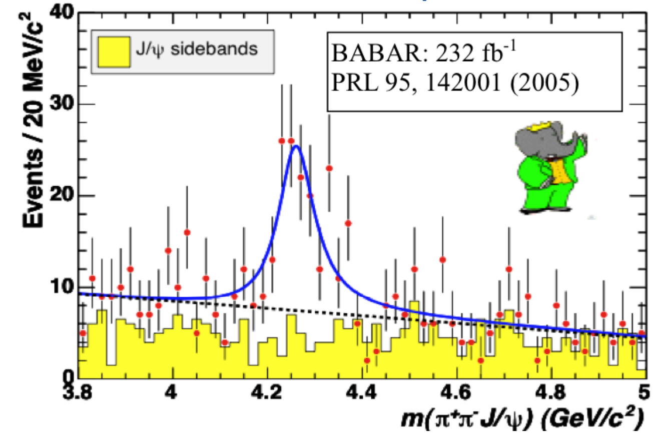
How about $\pi^+\pi^-\psi(2S)$ in ISR?

298 fb^{-1}

Phys. Rev. Lett. 98 (2007) 212001



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



Single resonance fit => mass=(4324±24) MeV/ c^2, Γ=(172±33) MeV

Incompatible with ψ(4415); Poorly described by Y(4260)

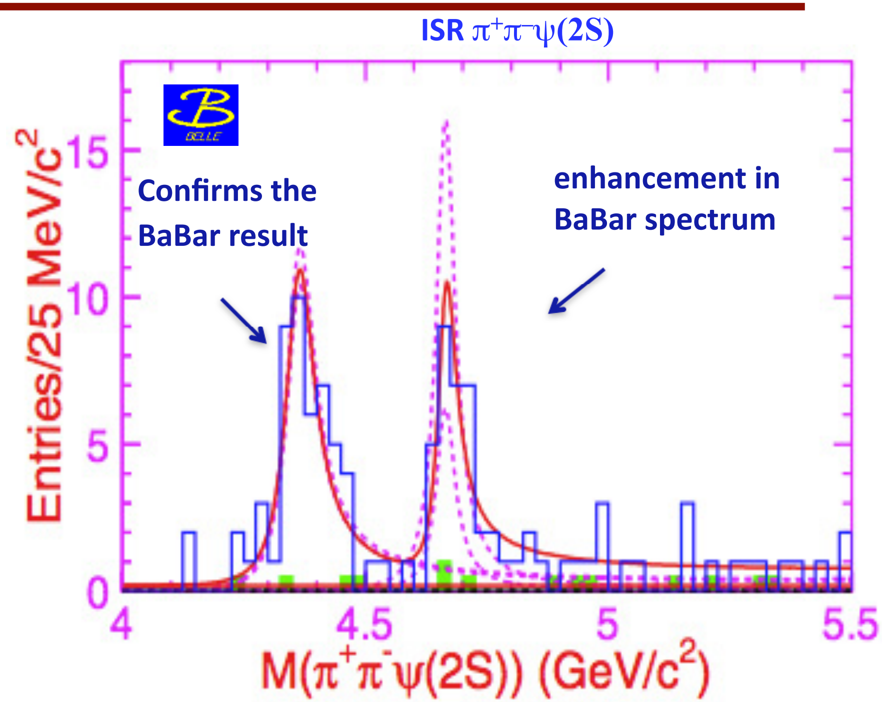
Prob=4.5 x10^{-3} that the two structures are the same

BELLE RESULTS

PRL 99, 142002 (2007)

Belle confirmed the observation of the Y(4340)

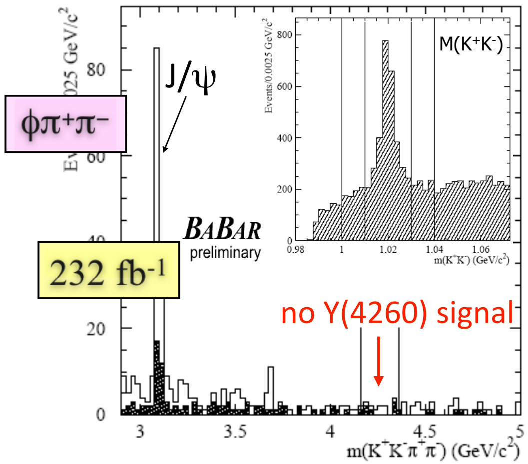
In addition it has been reported a state around 4660 MeV.



State	M, $\mathrm{MeV/c^2}$	Γ_{tot}, MeV
Y(4325)	4324 ± 24	172 ± 33
Y(4325)	$4361 \pm 9 \pm 9$	$74 \pm 15 \pm 10$
Y(4660)	$4664 \pm 11 \pm 5$	$48 \pm 15 \pm 3$

Analysis on going at BaBar to confirm the Y(4660)

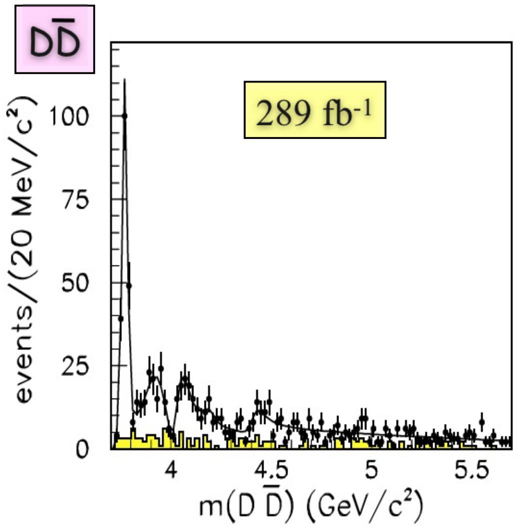
Other decay modes



$$\Gamma_{ee}^{Y} \times B(Y(4260) \to \phi\pi^{+}\pi^{-}) \to 0.4eV \quad @90\%CL$$

No signal

Phys. Rev. D74 091103, (2006)



$$\frac{B(Y(4260) \to p\bar{p})}{B(Y(4260) \to \pi^{+}\pi^{-}J/\psi)} < 0.13 \quad @90\%CL$$

No signal

Phys. Rev. D73 091103, (2006)

$$\frac{B(Y(4260) \to D\bar{D})}{B(Y(4260) \to \pi^{+}\pi^{-}J/\psi)} < 1 \quad @95\%CL$$

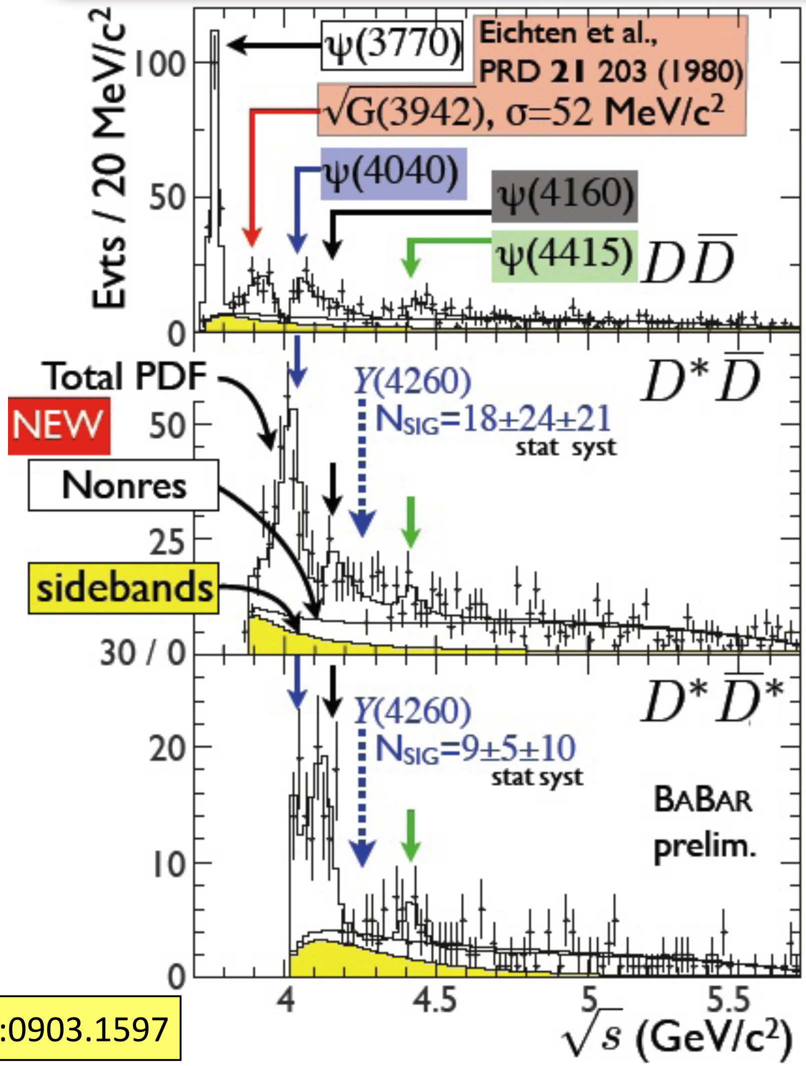
No signal

Phys. Rev. D76 111105, (2007)

There has been much speculation about the nature of this state

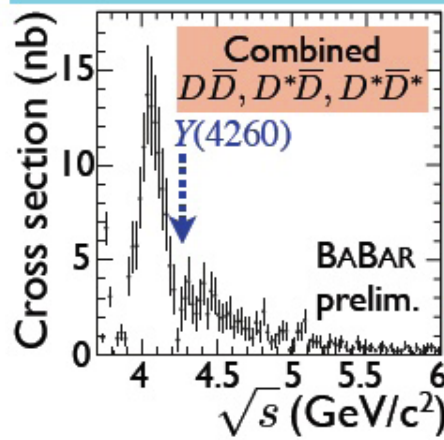
Exclusive Initial-State Radiation Production of $D\bar{D}$, $D^*\bar{D}$, and $D^*\bar{D}^*$

384 fb-1



arXiv:0903.1597

Limits on $Y(4260)$



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

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

NEW

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

at 90% C.L.

Branching fraction ratios

ψ	BF Ratios (± stat ± syst) NEW
4040	$\mathcal{B}(D\bar{D})/\mathcal{B}(D^*\bar{D}) = 24 \pm 5 \pm 12$
"	$\mathcal{B}(D^*\bar{D}^*)/\mathcal{B}(D^*\bar{D}) = 18 \pm 14 \pm 3$
4160	$\mathcal{B}(D\bar{D})/\mathcal{B}(D^*\bar{D}^*) = 2 \pm 3 \pm 2$
"	$\mathcal{B}(D^*\bar{D})/\mathcal{B}(D^*\bar{D}^*) = 34 \pm 14 \pm 5$
4415	$\mathcal{B}(D\bar{D})/\mathcal{B}(D^*\bar{D}^*) = 14 \pm 25 \pm 3$
"	$\mathcal{B}(D^*\bar{D})/\mathcal{B}(D^*\bar{D}^*) = 17 \pm 25 \pm 3$

All the decay modes

Γ_i	Mode			Fraction (Γ_i / Γ)
Γ_1	$e^+ e^-$			
Γ_2	$J/\psi\, \pi^+ \pi^-$	BaBar BELLE CLEO		seen
Γ_3	$J/\psi\, \pi^0 \pi^0$	CLEO	[a]	seen
Γ_4	$J/\psi\, K^+ K^-$		[a]	seen
Γ_5	$J/\psi\, \eta$		[a]	notseen
Γ_6	$J/\psi\, \pi^0$		[a]	notseen
Γ_7	$J/\psi\, \eta'$		[a]	notseen
Γ_8	$J/\psi\, \pi^+ \pi^- \pi^0$		[a]	notseen
Γ_9	$J/\psi\, \eta\, \eta$		[a]	notseen
Γ_{10}	$\psi(2S)\, \pi^+ \pi^-$		[a]	notseen
Γ_{11}	$\psi(2S)\, \eta$		[a]	notseen
Γ_{12}	$\chi_{c0}\, \omega$		[a]	notseen
Γ_{13}	$\chi_{c1}\, \gamma$		[a]	notseen
Γ_{14}	$\chi_{c2}\, \gamma$		[a]	notseen
Γ_{15}	$\chi_{c1}\, \pi^+ \pi^- \pi^0$		[a]	notseen
Γ_{16}	$\chi_{c2}\, \pi^+ \pi^- \pi^0$		[a]	notseen
Γ_{17}	$\phi\, \pi^+ \pi^-$		[a]	notseen
Γ_{18}	$\phi\, f_0(980) \rightarrow \phi\, \pi^+ \pi^-$			
Γ_{19}	$D \bar{D}$			notseen
Γ_{20}	$p \bar{p}$			
Γ_{21}	$K^0_S K^\pm \pi^\mp$			
Γ_{22}	$K^+ K^- \pi^0$			

Possible interpretations

Theoretical interpretations include:

- ✓ $c\bar{c}g$ hybrid state.
  - ✓ $J/\psi\pi^0\pi^0$, $J/\psi\eta\eta$, $\omega+\chi_{c0,c1,c2}$

Shi-Lin Zhu, Phys. Lett. B 625 212 (2005)

- ✓ the first orbital excitation of a diquark-antidiquark state $[cs,\bar{c}\bar{s}]$
  - ✓ Dominant decay Y(4260)->$D_s\bar{D}_s$
  - ✓ Favored if Y(4260)->$J/\psi f_0(980)$

L.Maiani et al. ,Phys.Rev.D72 031502,2005.

- ✓ Baryonium state (Λ^+_C- $\bar{\Lambda}^+_C$)
  - ✓ 2 new resonances (4330)(charged) (4560)(neutral)

C. F. Qiao , J. Phys. G 35 075008 (2008)

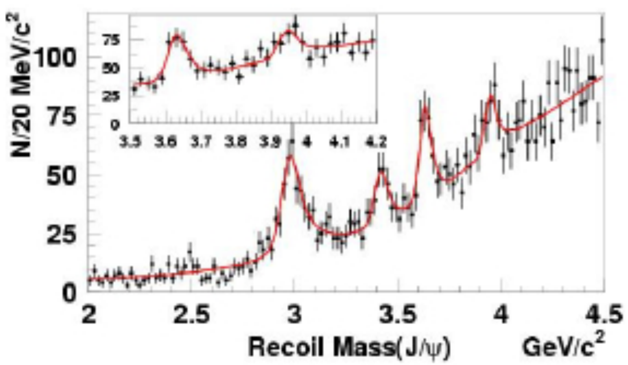
3940 Family

3940 FAMILY

Belle has reported 3 states near 3940 MeV/c^2

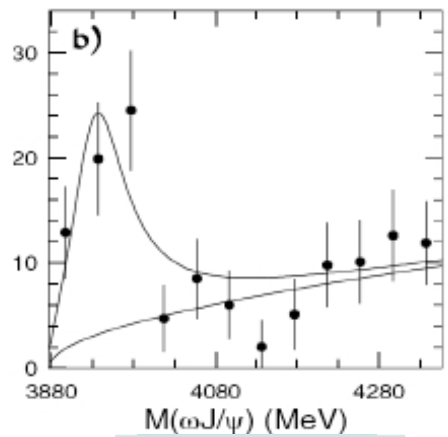
State	Process	M(MeV/c^2)	Γ(MeV)
X	$e^+e^- \to J/\psi X$	3943±8	<39
Y	$B \to YK$, $Y \to J/\psi\omega$	3943±17	87±34
Z	$\gamma\gamma \to Z$, $Z \to D\bar{D}$	3929±5	29±10

$e^+e^- \to J/\psi X$



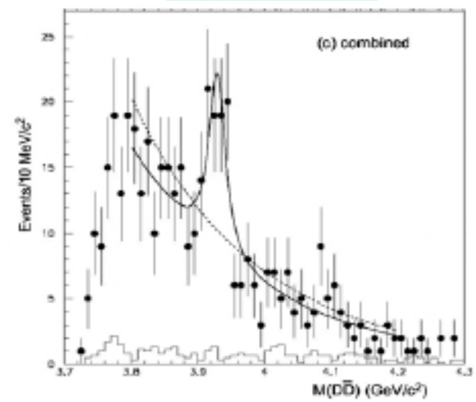
PRD 98, 082001(2007)

$B \to YK$, $Y \to J/\psi\omega$



PRD 94, 182002(2005)

$\gamma\gamma \to Z$, $Z \to D\bar{D}$



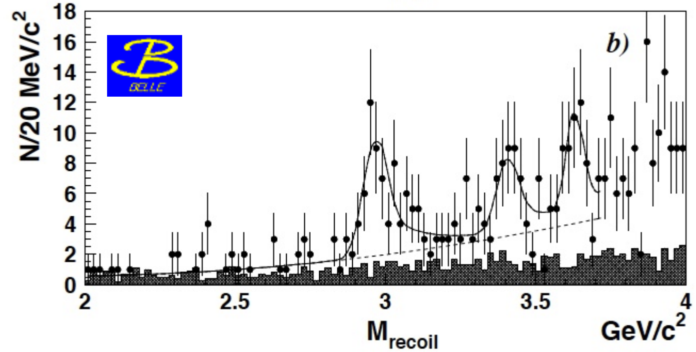
PRD 96, 082003(2006)

X(3940) IN DOUBLE CHARMONIUM PRODUCTION

Discovery of double charmonium production

$e^+e^- \rightarrow J/\psi + X$ arXiv:hep-ex/0205104

BELLE 46 fb^{-1}



Double charmonium cross section production is about one order of magnitude larger than the theoretical prediction of NRQCD

Observation of processes:

$e^+e^- \rightarrow J/\psi\eta_c$, $e^+e^- \rightarrow J/\psi\chi_{c0}$, $J/\psi\eta_c(2S)$

BELLE 140 fb^{-1}

Phys. Rev. D70 071102, (2004)

BABAR 124 fb^{-1}

Phys. Rev. D 70 31101, (2005)

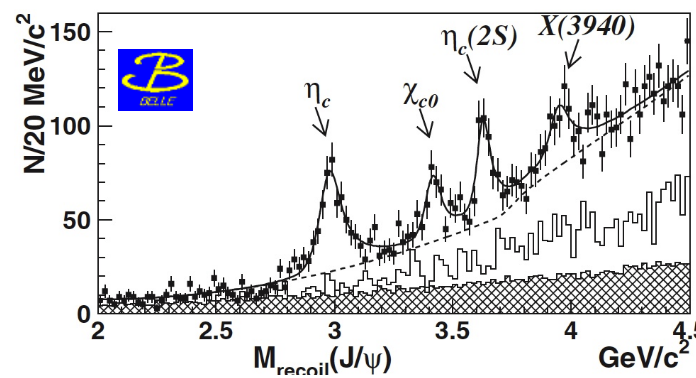
BELLE 373 fb^{-1}

PRL 98 082001, (2007)

Confirm the processes previously observed and set an upper limit on $e^+e^- \rightarrow J/\psi J/\psi$

Confirms the BELLE result

New state recoiling against the J/ψ: X(3940)



BELLE 673 fb^{-1}

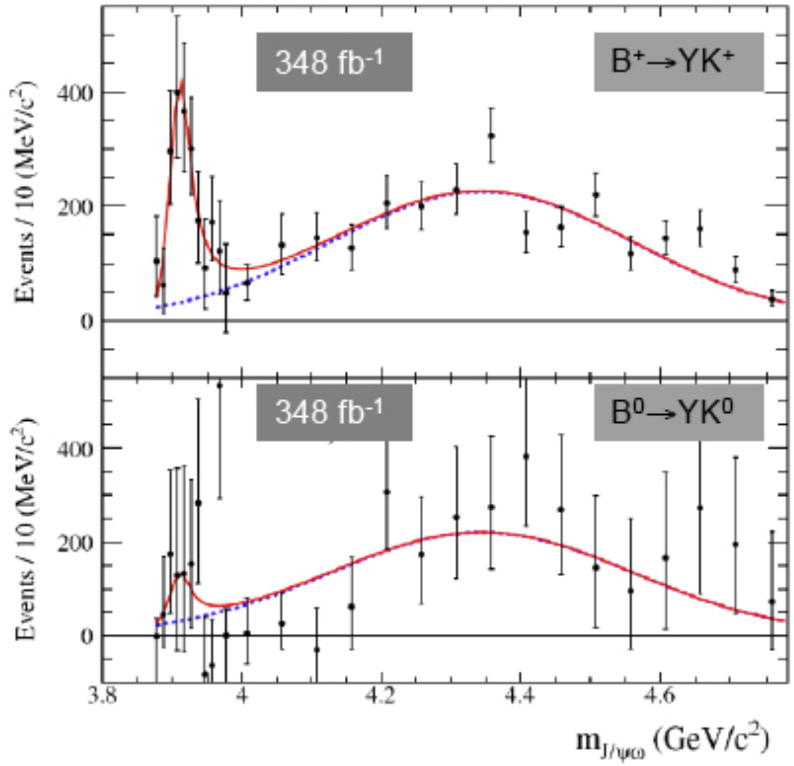
arXiv:hep-ex/0901.2775

Y(3940)

BaBar confirmation: B→Y(3940)K, Y(3940)→J/ψω

PRL 101, 082001 (2008)

- ➢ m_Y = 3.915 ± 0.003 GeV
- ➢ Γ = 40 ± 10 MeV
- ➢ BF ~ (5 ± 1) 10^{-5}



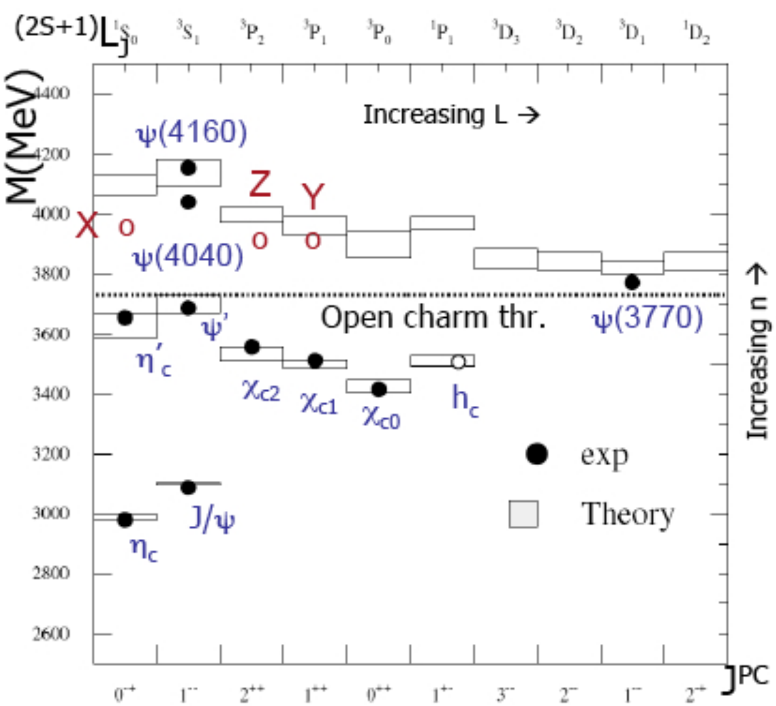
- **Evidence for B→YK (Y→J/ψω) is confirmed**
  - ➢ ~30MeV lower mass than Belle's
  - ➢ Narrower width
  - ➢ BF similar to the Belle's
  - ➢ No evidence for B→X(3872)K (X→J/ψω)

3940s interpretations

Are all these states regular Charmonium states?

Masses do not match predictions ...?

All states should have E1 transitions to lower $c\bar{c}$



X(3940) possible candidate: $\eta_c''(3^1S_0)$

Y(3940) possible candidate: χ_{c1}' (2^3P_1)

Z(3930) possible candidate: χ_{c2}' (2^3P_2)

X(3940)/Z(3930) analysis on-going at BaBar

$Z(4430)^+$, $Z1^+$ and $Z2^+$

THE Z(4430)-

PRL *100, 142001 (2008)*

Use 548 fb^{-1}

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

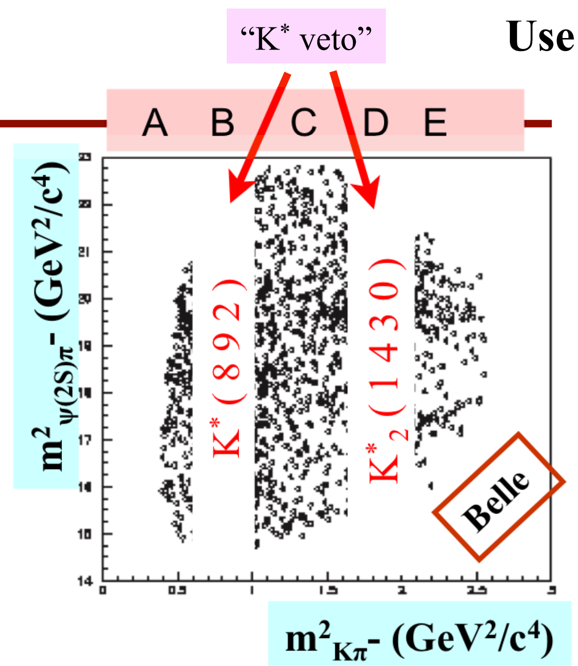
- The reported mass and width are:

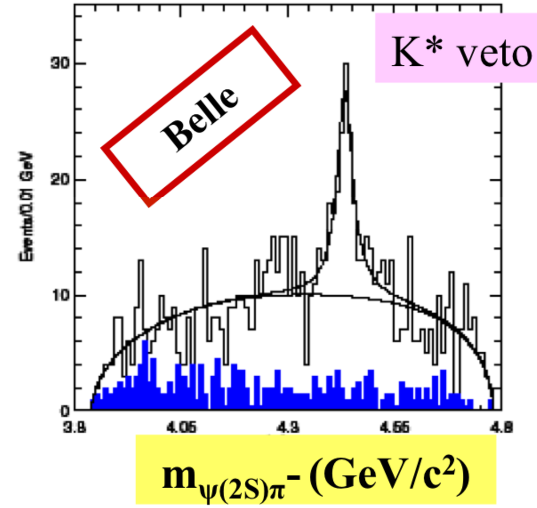
$m = 4433 \pm 4(stat) \pm 2(syst)$ MeV/c^2

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

121 ± 30 events; significance 6.5σ

- If this result is confirmed first observation of a genuine $c\bar{c}d\bar{u}$ "tetraquark" state, since it is charged and carries hidden charm (e.g. Maiani: 0708.3997 (hep-ph) , Karliner & Lipkin arxiv: 0802.0649 (hep-ph))





BaBar search for Z-

- Search for the $Z(4430)^-$ with 413 fb^{-1} in the decay modes

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

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

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

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

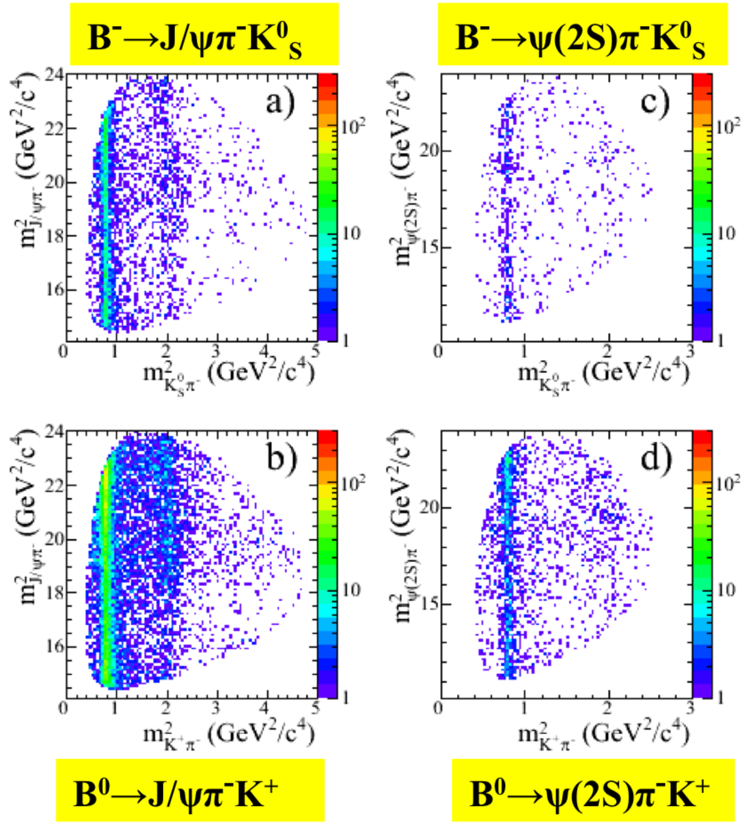
We will use "ψ" to denote "J/ψ or $\psi(2S)$" unless otherwise indicated

- Describe the $K\pi^-$ system in detail, since structure in the $K\pi^-$ mass and angular distributions dominates each Dalitz plot

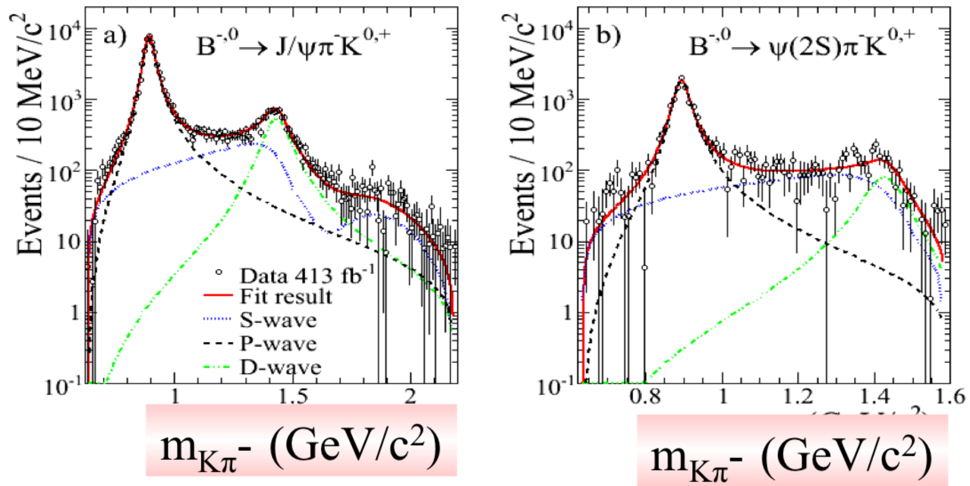
- Correct the data for efficiency event-by-event across the Dalitz plot, and describe using only $K\pi^-$ S-, P-, and D-wave intensity contributions

- 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"

Kπ REFLECTIONS



Event-by-event efficiency correction



- Generated 10M events per sample according to the $m_{K\pi^-}$ fit function, and normalize to the corrected data
- Generate angular distributions flat in $\cos\theta_K$ and calculate the $\psi\pi^-$ mass for each generated event
- Each event is given weight based on the Legendre polynomial moment.
- The psi pi projection has been used as background shape to fit the data.

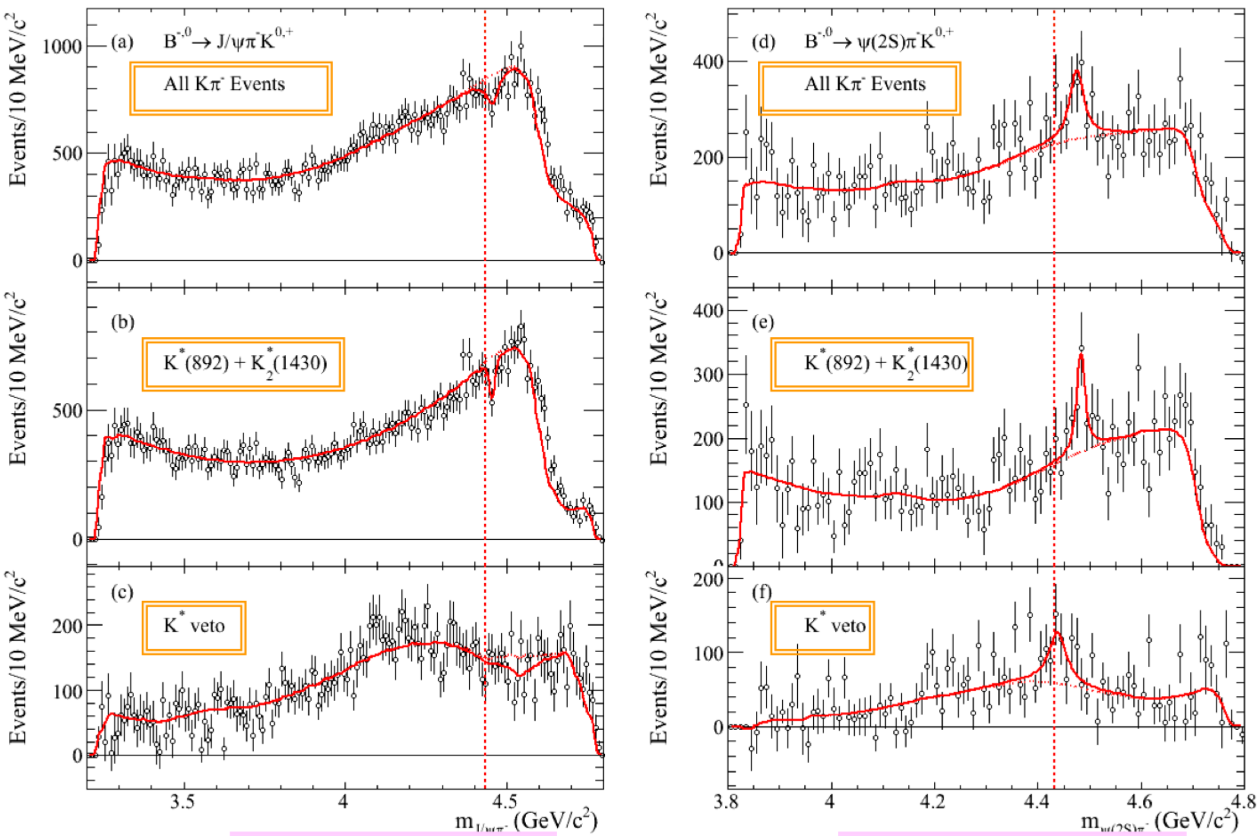
FIT TO $\psi\pi$ DISTRIBUTION

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

NO OR NEGATIVE SIGNAL

NO OR NEGATIVE SIGNAL

NO OR NEGATIVE SIGNAL



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

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

m=4476±8
Γ=32±16
2.7σ

m=4483±3
Γ=17±12
2.5σ

m=4439±8
Γ=41±33
1.9σ

Summary of BaBar results

- $B \to J/\psi \pi^- K$ (mass & width free) negative, or no, BW signal is obtained
- $B \to \psi(2S) \pi^- K$ (mass and width free):
  - Shifted mass enhancement for overall $K\pi^-$ range:
    - m=4476±8 MeV/c^2; Γ=32±16 MeV; signal size: 2.7σ
  - Shifted mass enhancement in the $K^*(892)$ and $K^*_2(1430)$ region:
    - m=4483±3 MeV/c^2; Γ=17±12 MeV; signal size 2.5σ
  - mass enhancement with the K^* veto:
    - m=4439±8 MeV/c^2; Γ=41±33 MeV; signal size 1.9σ

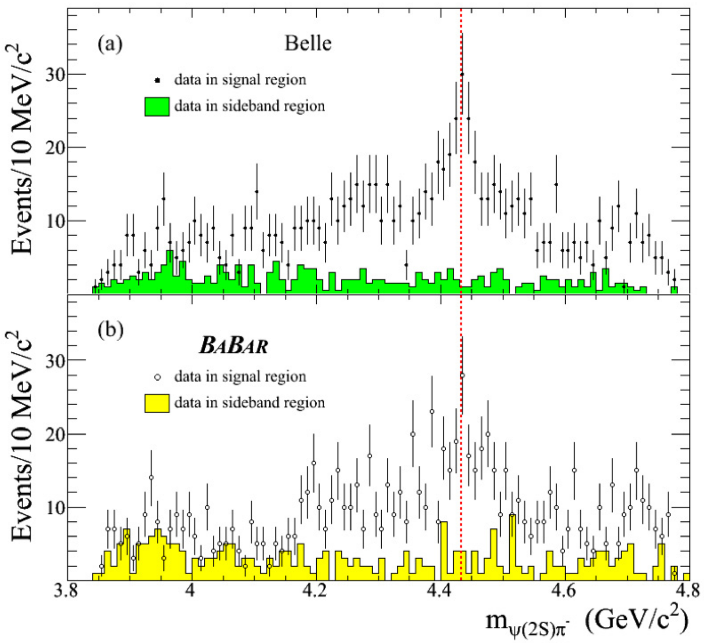
arXiv:0811.0564

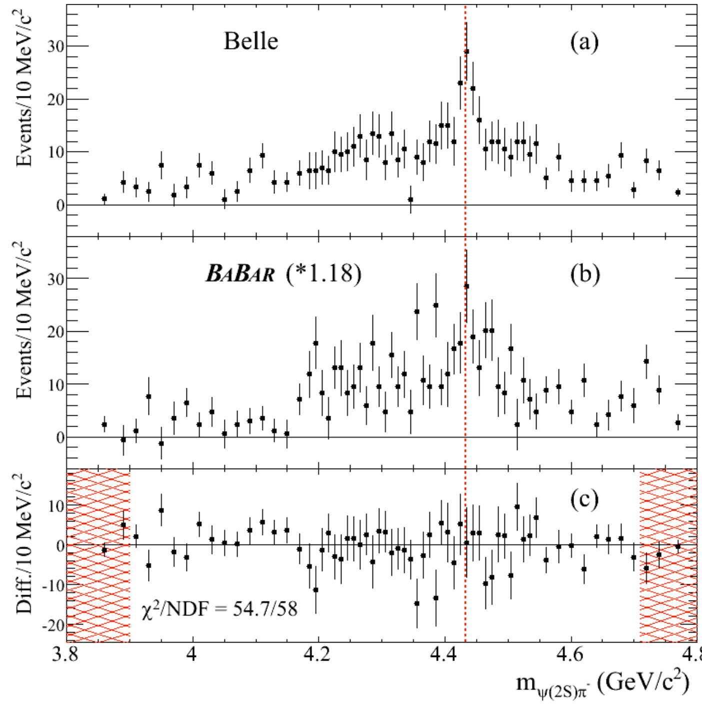
Summary of BaBar results

Decay mode	$Z(4430)^-$ signal	Branching fraction ($\times 10^{-5}$)	Upper limit ($\times 10^{-5}$) (@95% C.L.)
$B^- \to Z^- \overline{K}^0, Z^- \to J/\psi \pi^-$	-17 ± 140	-0.1 ± 0.8	1.5
$B^0 \to Z^- K^+, Z^- \to J/\psi \pi^-$	-670 ± 203	-1.2 ± 0.4	0.4
$B^- \to Z^- \overline{K}^0, Z^- \to \psi(2S) \pi^-$	148 ± 117	2.0 ± 1.7	4.7
$B^0 \to Z^- K^+, Z^- \to \psi(2S) \pi^-$	415 ± 170	1.9 ± 0.8	3.1

Belle: $BF(B^0 \to Z^- K^+, Z^- \to \psi(2S)\pi^-) = (4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$

BaBar-Belle comparison





Both Belle and *BABAR* data are re-binned (to calculate χ^2) and side-band subtracted

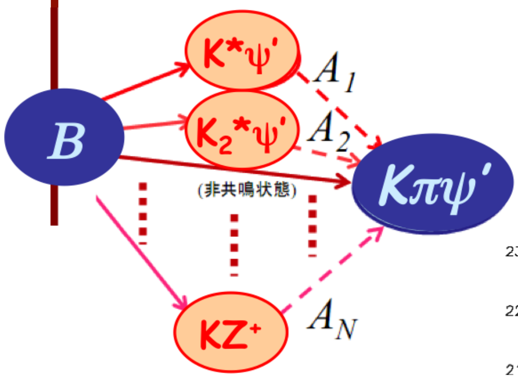
The *BABAR* data are normalized to the Belle sample.

The data distributions are statistically consistent (χ^2=54.7/58)

Why different significances are reported? (6.4σ Belle vs. 1.9–3.1σ BaBar) ⇔ assumption about background is crucial.

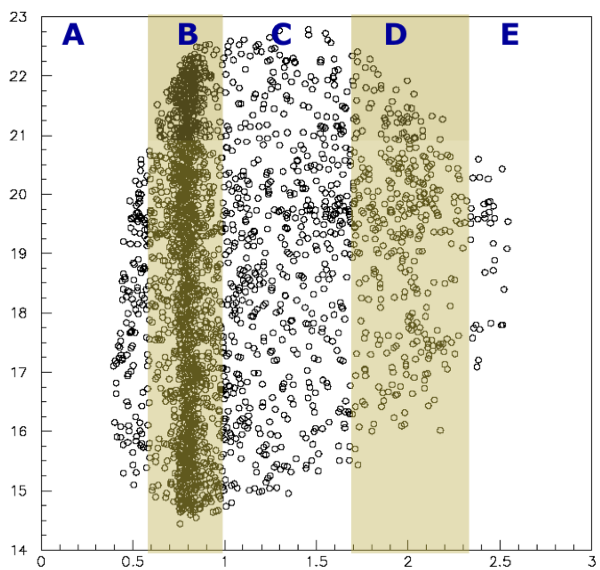
Belle's Dalitz Analysis

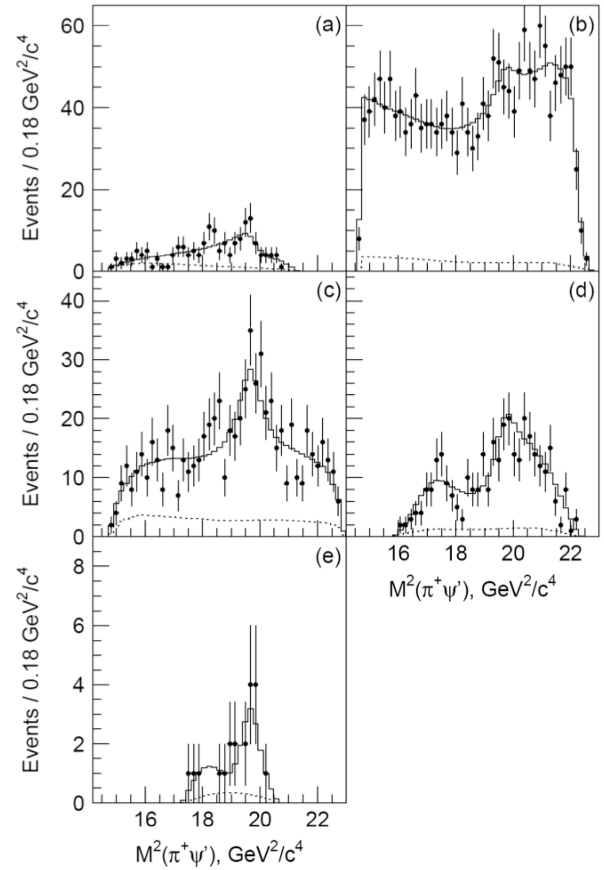
2-body isobar model for Kπψ'



Consider intermediate resonances

κ, $K^*(892)$, $K^*(1410)$, $K_0(1430)$, $K_2(1430)$, $K^*(1680)$, $Z(4430)^+ \to \pi^+ \psi'$

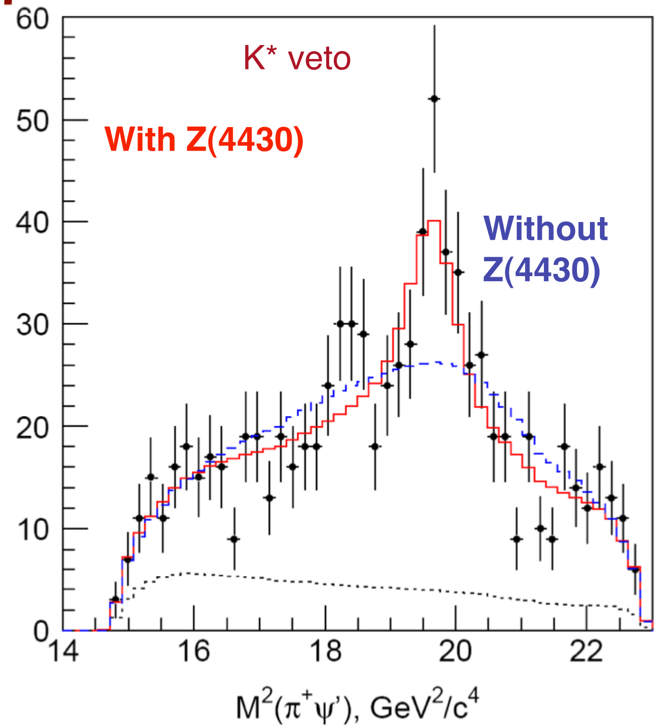




DP analysis results

The Dalitz analysis confirms the main conclusions of Belle's first analysis (PRL 100, 142001); the DP-determined errors are larger.

Including B->$K_3^*(1780)\psi'$ as a dominant decay mode, the significance of the $Z(4430)^+$ signal to below 5σ: in that case, the significance of the $Z(4430)^+$ signal is 4.7σ.



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

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

Published results

$M = 4433 \pm 4 \pm 2\ \mathrm{MeV/c^2}$
$\Gamma_{tot} = 45\ ^{+18}_{-13}\ ^{+30}_{-13}\ \mathrm{MeV}$
Nsig $= 121 \pm 30$ evts
$\chi^2/\mathrm{dof} = 80.2/94.0 \quad 6.5\ \sigma$

Mass & significance similar, width & errors are larger

BaBar: $BF(B^0 \to Z^+K) \times BF(Z^+ \to \psi(2S)\pi^+) < 3.1 \times 10^{-5}$

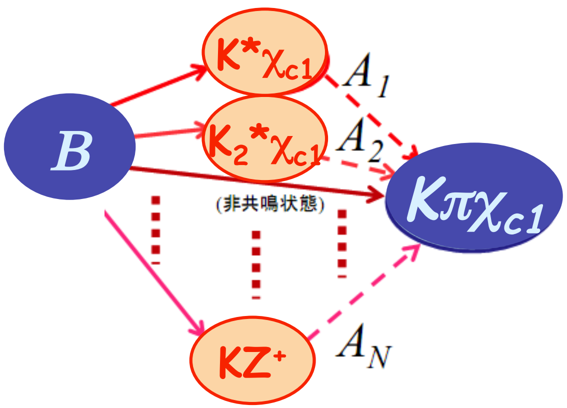
Belle: $= (3.2^{+1.8+9.6}_{0.9-1.6}) \times 10^{-5}$

No big contradiction

Z1 and Z2

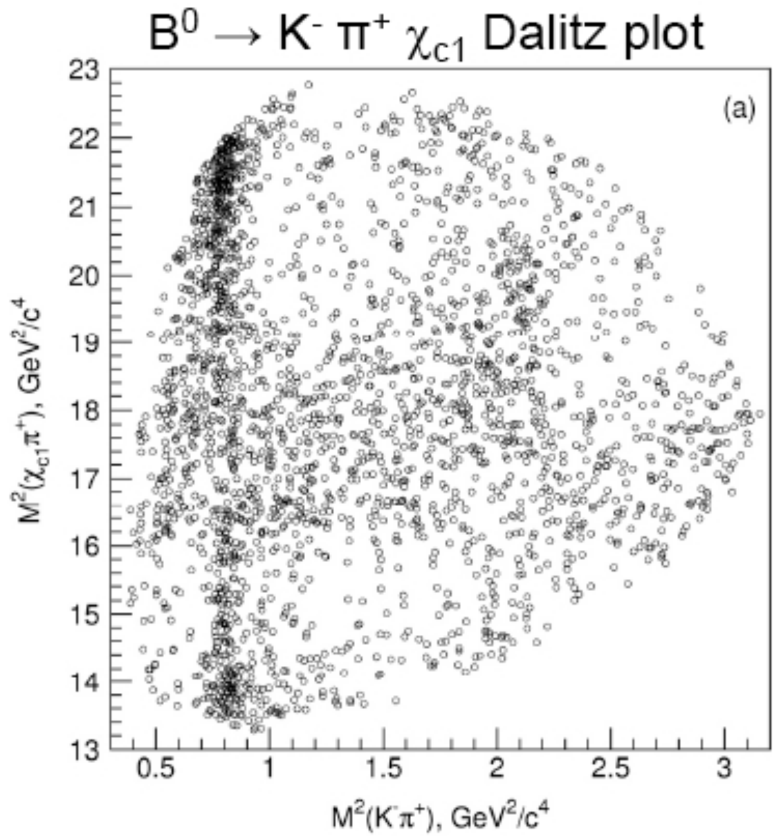
The $Z_1(4050)^+$ & $Z_2(4250)^+$ -> $\pi^+\chi_{c1}$

R. Mizuk et al (Belle), PRD 78,072004 (2008)

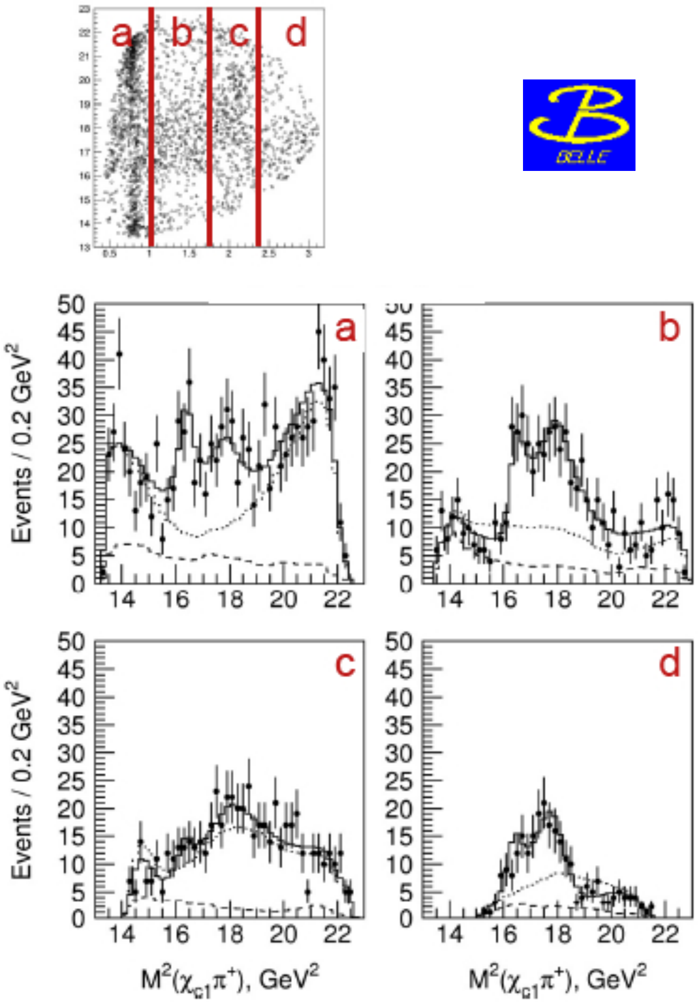


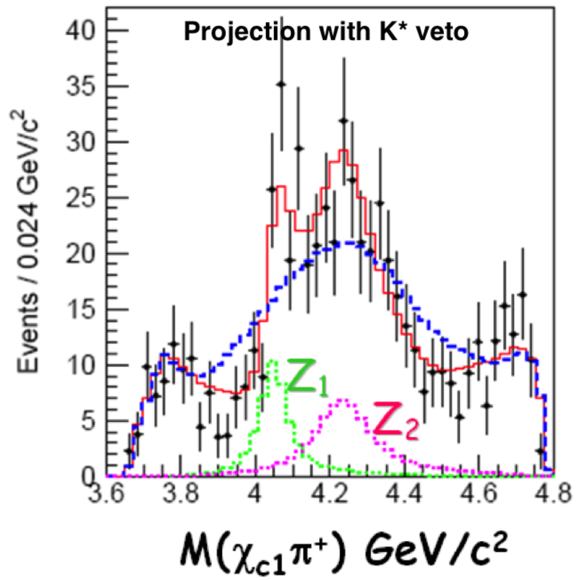
Consider intermediate

κ, K(892), K*(1410),*
$K_0(1430)$, $K_2(1430)$,
K(1680), $K^*_3(1780)$,*
$Z^+ \rightarrow \pi^+\chi_{c1}$



Z1 and Z2





$$M_1 = (4051 \pm 14^{+20}_{-41})\ \mathrm{MeV}/c^2,$$
$$\Gamma_1 = (82^{+21+47}_{-17-22})\ \mathrm{MeV},$$
$$M_2 = (4248^{+44+180}_{-29-35})\ \mathrm{MeV}/c^2,$$
$$\Gamma_2 = (177^{+54+316}_{-39-61})\ \mathrm{MeV},$$

with the product branching fractions of

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

Search for bottomonium-like exotics

The R scan at BaBar

A “new” charmonium spectroscopy emerged from the discovery of new resonances that does not fit in the “standard” charmonium model.

Is there a “new” bottomonium spectroscopy?

$$m(bottomonium) = m(charmonium) + m(\Upsilon(1S)) - m(J/\Psi)$$

Works fine for standard bottomonium!

New bottomonium resonances can be searched for with an energy scan above the Y(4S) resonance.

$$Y(4260) \rightarrow Y_b(10620)???$$

$$Y(4350) \rightarrow Y_b(10710)???$$

$$Y(4660) \rightarrow Y_b(11020)???$$

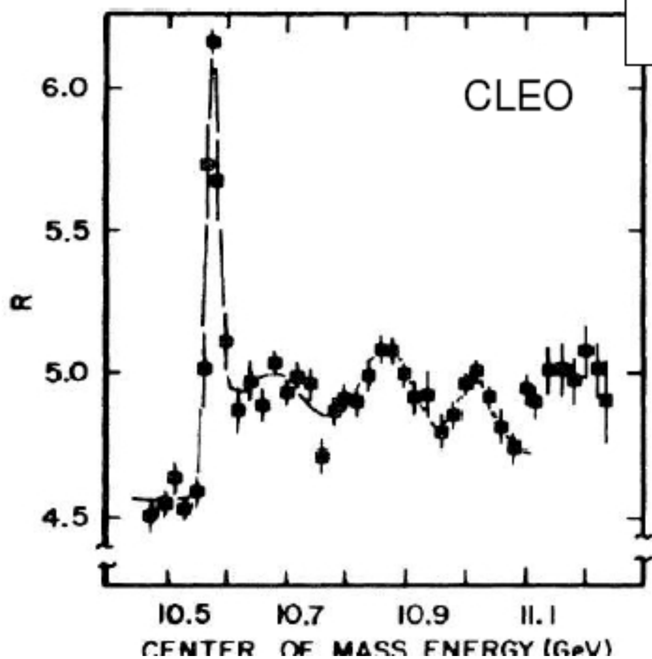
- *Inclusive approach:*
  - Search for unexpected structures in the inclusive hadronic cross section:

$$R_b(s) = \frac{\sigma_{bb(\gamma)}(s)}{\sigma^0_{\mu\mu}(s)}$$

$s_b(s)$: total cross section for e^+e^- -> bb(gamma)
$s_{\mu}(s)$: 0^{th} order cross section for e^+e^- -> $\mu^+\mu^-$

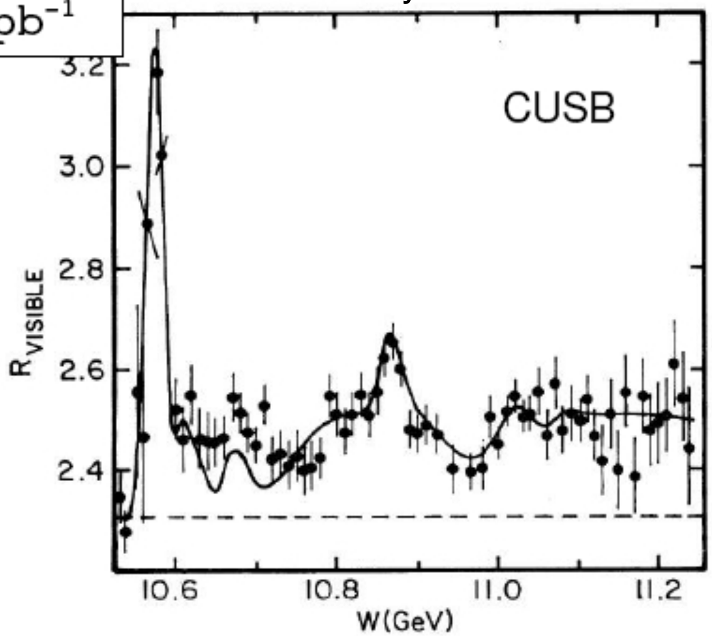
Previous results

CLEO: Phys.Rev.Lett.54:381,1985



CESR
~130 pb^{-1}

CUSB: Phys.Rev.Lett.54:377,1985



Scan from 10.54 to 11.20 GeV in 5 MeV steps.
25/pb per step, plus 600/pb around (11020MeV)

30 times more luminosity
and
4 times finer steps
w.r.t. CESR scan

Strategy

For each point and for a "reference" point (10.54 GeV) we select:

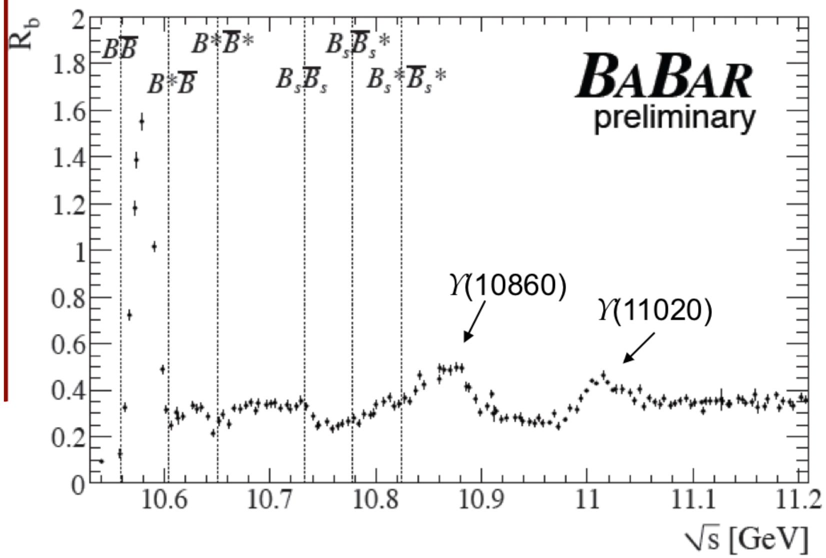
- $b\bar{b}$ sample, according to a multi-hadron selection;
- mumu sample;

- At the "reference" point:
  - Estimate of backgrounds, scaled to other energies according to the expected *s* dependence;

- Across the scan:
  - R_b extracted from a combination of the $b\bar{b}$ and mumu yields, subtracting the non-$b\bar{b}$ background.

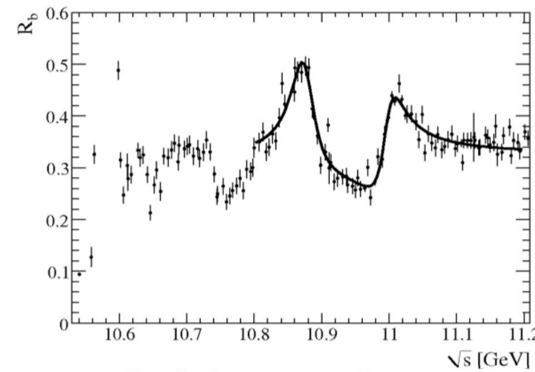
SCAN RESULTS

arXiv:0809.4120



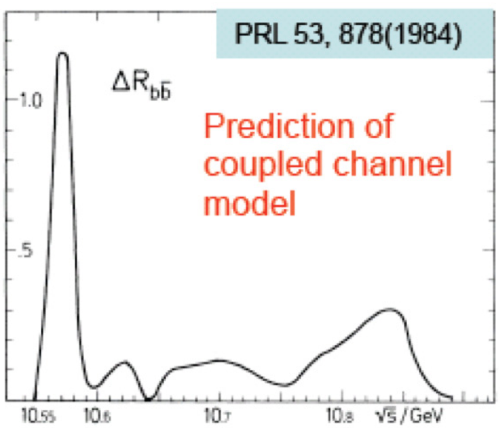
Region explored with unprecedented detail.

Interpretation of structures made difficult by threshold effects.



	$\Upsilon(10860)$	$\Upsilon(11020)$
mass (GeV)	10.876 ± 0.002	10.996 ± 0.002
width (MeV)	43 ± 4	37 ± 3
ϕ (rad)	2.11 ± 0.12	0.12 ± 0.07
PDG mass (GeV)	10.865 ± 0.008	11.019 ± 0.008
PDG width (MeV)	110 ± 13	79 ± 16

N. Törnqvist (1984) predicted structures between Y(4S) and Y(5S) and an asymmetric Y(5S) shape



Thresholds and interferences make also difficult the extraction of the Y(5S) and Y(6S) parameters

Tried with a fit including Y(5S), Y(6S) and continuum, interfering among them, plus a non interfering continuum.

Next steps: study of exclusive final states.

Summary and conclusions

Summary and conclusions

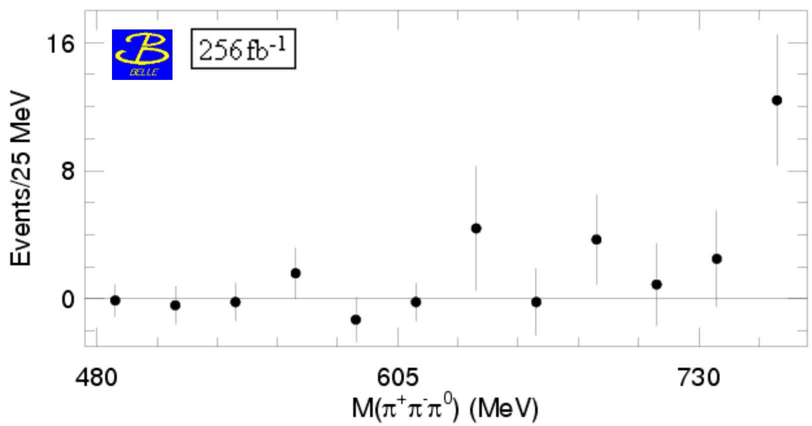
- Charmonium spectroscopy has been revitalized by the discovery of many new states above the open charm threshold.
- A review of some of these new states has been presented.
- Many experimental results have been shown, but not enough to understand the the nature of some of them.
- Bottomonium spectroscopy can be as exciting as the charmonium.
- ...

Still a lot of work to do

- For the present B factories
  - Some important channels need to be investigated and many old analysis to be updated
- For theorists
  - Can X(3872) -> $\psi(2S)\gamma$ be reconciled with molecular model? Can it fit into the charmonium model? What about $D0\overline{D}{}^{*}0$ – $\chi c1(2P)$ mixing or other phenomena?
  - What about the different approaches by BaBar and Belle with the Z(4430) analysis?
  - ...
- For super B

Backup Slides

X(3872) J/ψ ω Conflict

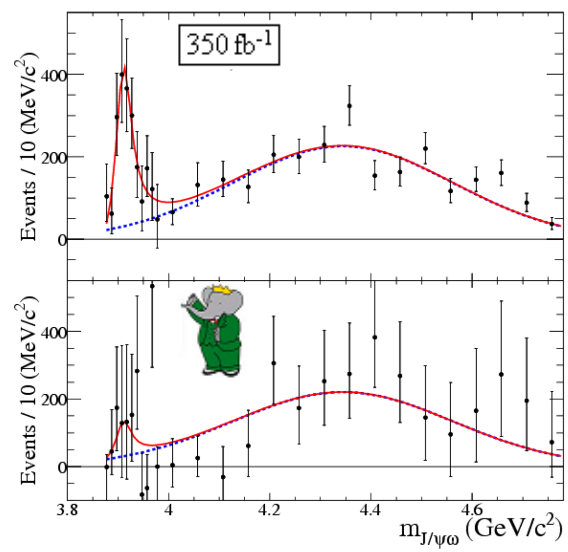


Belle searched for B X(3872)[XJ/ψ $\pi^+\pi^-\pi^0$] K
3π-invariant mass shows enhancement assumed to be ω $\pi^+\pi^-\pi^0$

hep-ex/0505037

Separate BaBar analysis of B KωJ/ψ
Observe Y(3940), no evidence for X(3872)
ie: X J/ψ $\pi^+\pi^-\pi^0$ not necessarily X J/ψω

Phys. Rev. Lett. 101, 082001 (2008)



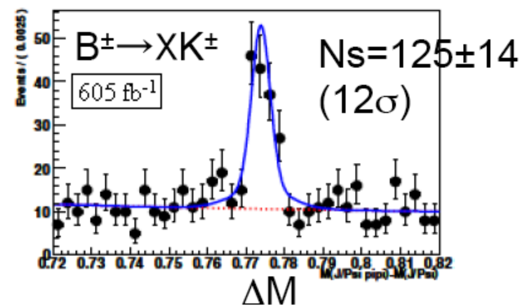
X(3872) to J/ψπ+π– Updates

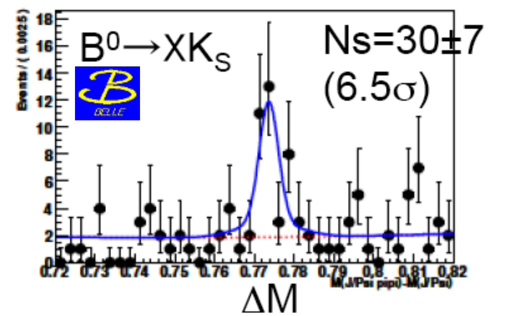
- Both Belle and BaBar have updated $B \to X(3872)[X \to J/\psi\pi^+\pi^-]$ K results
- Belle finds no mass splitting, equal ratio between the B^0 and B^+ decay modes:

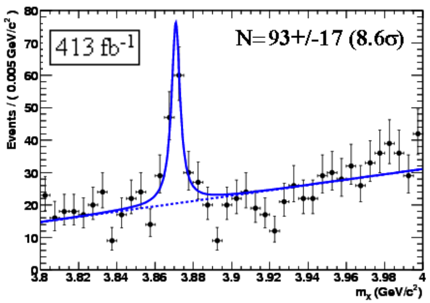
$$\Delta M_X = (0.18 \pm 0.89 \pm 0.26) MeV/c^2$$

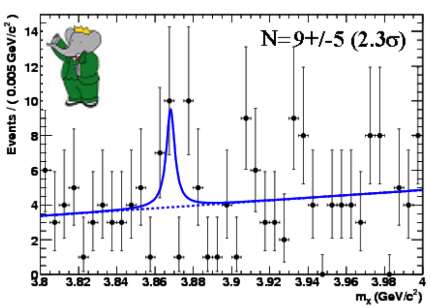
$$R = \frac{BR(B^0 \to X(3872)K^0)}{BR(B^\pm \to X(3872)K^\pm)} = 0.82 \pm 0.22 \pm 0.05$$

arXiv:0809.1224









- BaBar measurement confirms, though suffers statistically
- mit on width: $\Gamma<3.3$ MeV

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

$$R = \frac{BR(B^0 \to X(3872)K^0)}{BR(B^\pm \to X(3872)K^\pm)} = 0.41 \pm 0.24 \pm 0.05$$

Phys. Rev. D77 111101 (2008)

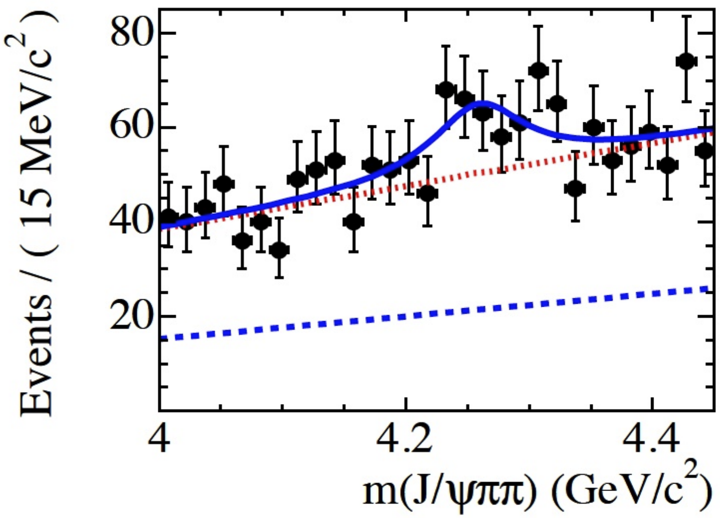
Y(4260) in B decays

Phys. Rev. D73 011101, (2006)

BaBar searched for the Y(4260) in

$B^{\pm} \longrightarrow K^{\pm}$, $Y(4260) \longrightarrow J/\psi\pi^{+}\pi^{-}$

211 fb^{-1}



Hint of a signal in B decays

Combinatorial background (dashed blue line)

Combinatorial + peaking background (dotted red line)

$$B(B^{-} \rightarrow Y(4260)K^{-}, Y(4260) \rightarrow J/\psi\pi^{+}\pi^{-}) < 2.9 \times 10^{-5}$$

Variation on a theme

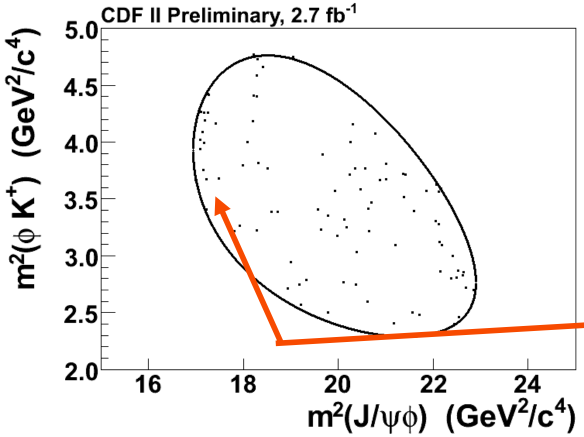
	Model	Significan
1	default	$6.4\,\sigma$
2	no $K_0^*(1430)$	$6.6\,\sigma$
3	no $K^*(1680)$	$6.6\,\sigma$
4	release constraints on κ mass & width	$6.3\,\sigma$
5	new K^* $(J=1)$	$6.0\,\sigma$
6	new K^* $(J=2)$	$5.5\,\sigma$
7	add non-resonant $\psi' K^-$ term	$6.3\,\sigma$
8	add non-resonant $\psi' K^-$ term, release constraints on κ mass & width	$5.8\,\sigma$
9	add non-resonant $\psi' K^-$ term, new K^* $(J=1)$	$5.5\,\sigma$
10	add non-resonant $\psi' K^-$ term, new K^* $(J=2)$	$5.4\,\sigma$
11	add non-resonant $\psi' K^-$ term, no $K^*(1410)$	$6.3\,\sigma$
12	add non-resonant $\psi' K^-$ term, no $K^*(1680)$	$6.6\,\sigma$
13	LASS parameterization of S-wave component	$6.5\,\sigma$

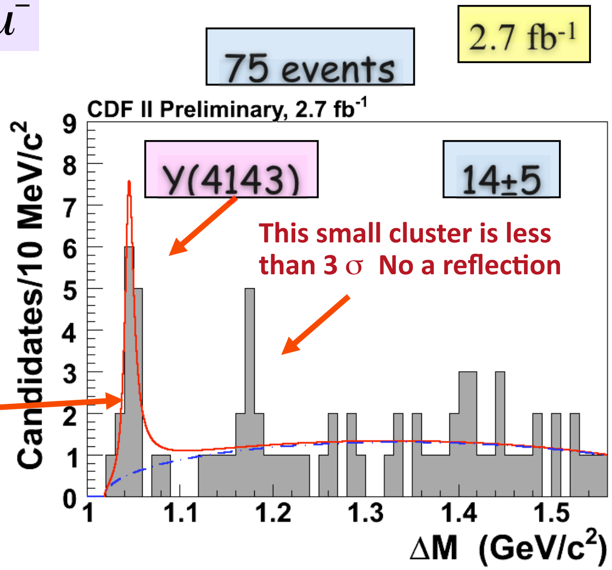
J/psi phi at CDF

J/PSI PHI

A new recent state found by CDF

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





$M_{Y4143} = 4143 \pm 2.9 \pm 1.2$ MeV/c^2

$\Gamma_{Y4143} = 11.7\ ^{+8.3}_{-5} \pm 3.7$ MeV

$\Delta M = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$

Events in the B$^+$ mass window

sqrt(-2log(L_{max}/L_0))=5.3

Significance: it would be 5.3σ with Log of the Likelihood, from MC studies and dependency of the background shape 3.8σ

Relativistic B-W convolved with a Gaussian resolution function + 3 body-phase space function for the background

J/PSI PHI

BaBar studied the neutral and charged channels:

BaBar Result

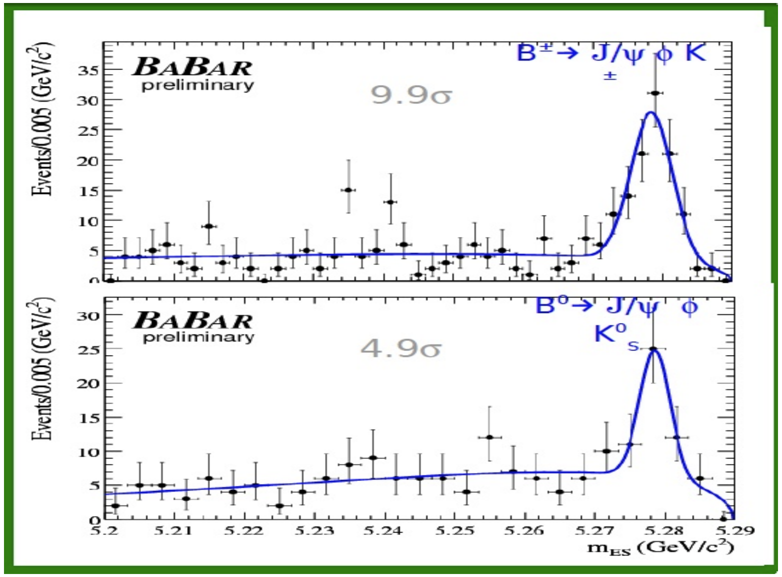
$B^{\pm} \rightarrow J/\psi\phi K^{\pm},\ \phi \rightarrow K^{+}K^{-}$

$B^{0} \rightarrow J/\psi\phi K_{s}^{0},\ \phi \rightarrow K^{+}K^{-}$

$J/\psi \longrightarrow e^{+}e^{-}$ $J/\psi \longrightarrow \mu^{+}\mu^{-}$

ICHEP08 result

Channel	Measured events	Efficiency	B.R. (10^{-5})
$B^{\pm} \to J/\psi\phi K^{\pm}$	79 ± 12	$(11.19 \pm 0.08)\%$	(5.57 ± 0.85)
$B^{0} \to J/\psi\phi K^{0}_{S}$	42 ± 10	$(8.91 \pm 0.07)\%$	(2.69 ± 0.61)



The BaBar number of events for the charged decay is very comparable with the CDF one