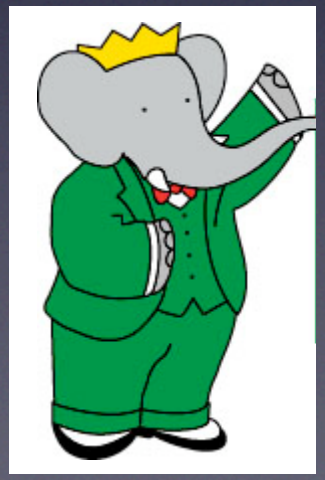
Searches for, and properties of, new Charmonium-like states

Paul D. Jackson
Universita di Roma “La Sapienza” and INFN Rome

Presented at Flavor Physics & CP Violation 2008, Taipei, Taiwan
on behalf of the BaBar collaboration

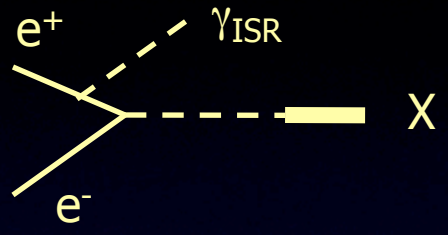


Only charmonium considered here!

Quarkonium for Pedestrians

- Quarkonium is a bound state of a quark and its antiquark
  - Relevant quantum numbers: n,L,S,J
  - Relationship with Parity and Charge Conjugate:
    - $P=(-1)^{L+1}$, $C=(-1)^{L+S}$
  - **Not all J^{PC} allowed** (e.g. 0^{+-},0^{--},1^{-+},2^{+-} forbidden)
- Decay Properties:
  - Below open charm threshold (e.g. $(c\bar{c})\rightarrow D\bar{D}$) only electromagnetic or α_s suppressed decays allowed → mostly narrow states
  - Above open charm threshold (if $D\bar{D}$ decays allowed)→ mostly broad states
- What can we learn?
  - Understanding of QCD:
    - 'regular quarkonium' → tests of NRQCD, potential models, …
    - 'new states' → new forms of aggregation (or aggravation) mediated by the strong interactions (e.g. $q\bar{q}q\bar{q}$, molecular states, $q\bar{q}g$ hybrids, etc)

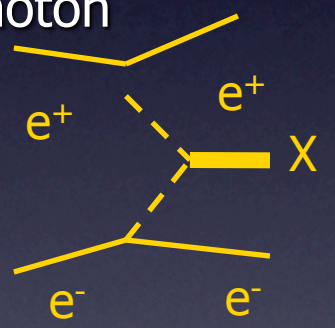
Measuring the quantum numbers



- Production:
  - ISR only produces states with same quantum numbers as the photon ($J^{PC}=1^{--}$)
  - $\gamma\gamma$ only produces states with C=+
  - Double charmonium production mainly through single photon

    $e^+e^- \rightarrow \gamma^* \rightarrow X_{cc}{}^1 X_{cc}{}^2$

    Possible only if quantum numbers of the two charmonia can be combined to give a 1^{--}.

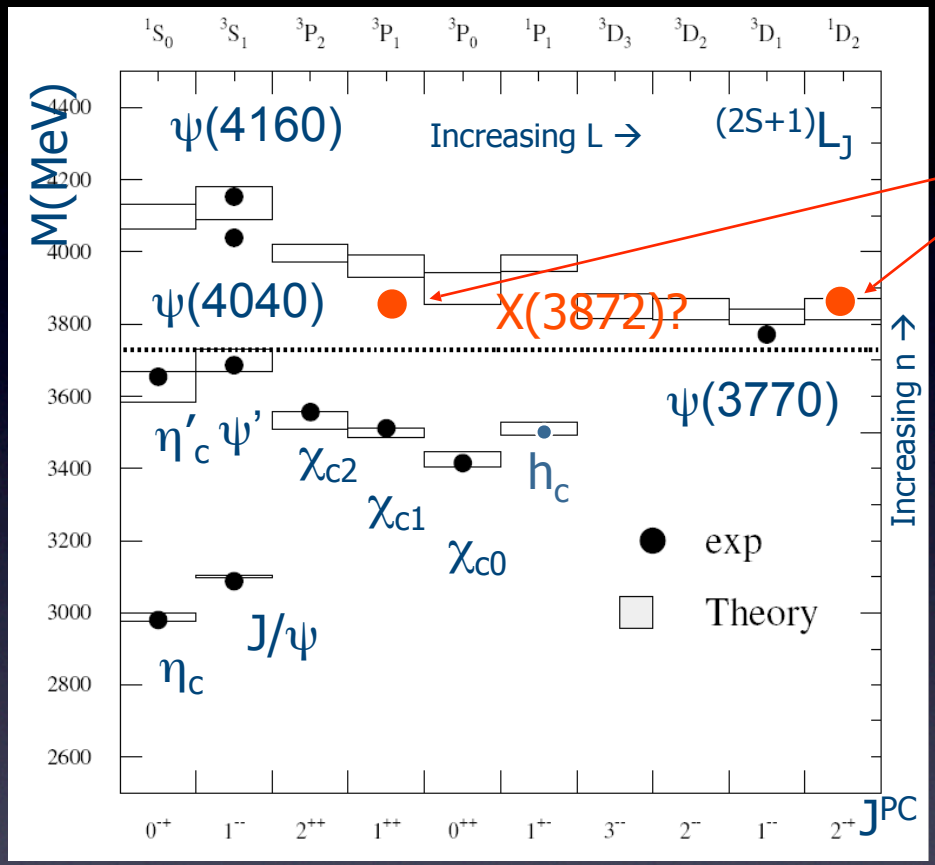


- Decay:
  - Angular distributions of decay products depend on J^P.
  - Selection rules
    - Conservation of J
    - Conservation of P,C in strong and e.m. decays, I in strong decays

The new "Exotica"

- X(3872)
- The 1-- family Y(4260) etc
- The 3940 family X(3940)
- Charged State(s)

The X(3872) puzzle



Not matching any predicted state?

Above $D\bar{D}$ threshold (allowed): should have large width but it is narrow

Charmonium is suppressed due to decay into $J/\psi\,\rho$ (isospin violation)

More from theorists…

Open options

- $D\bar{D}^*$ molecule
  - Right at the threshold
  - favours $D\bar{D}^*$ decay over $J/\psi\pi\pi$ over $J/\psi\gamma$ (as observed)
- Tetraquark
  - Explains small width
  - Predicts a set of 4 states (2 charged and 2 neutral).
    - Finding the charged states is critical
- Charmonium
  - Not ruled out, but which state is it?

X(3872): "known facts"

- Decays
  - X→J/ψ ππ (original observation)
    - Maybe J/ψ ρ
  - BF(X→J/ψ ω)~ BF(X→J/ψ ρ)
  - X→J/ψ γ

$$\frac{\mathcal{B}(X\to J/\psi\gamma)}{\mathcal{B}(X\to J/\psi\pi\pi)} = 0.19 \pm 0.07$$

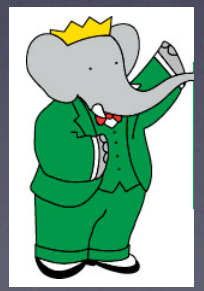
Belle+BaBar

Implications:

- C(X)=+1
- C(ππ in J/ψ ππ decay)=-1
- I(ππ)=1 L(ππ)=odd ➔ consistent with J/ψρ decay hypothesis

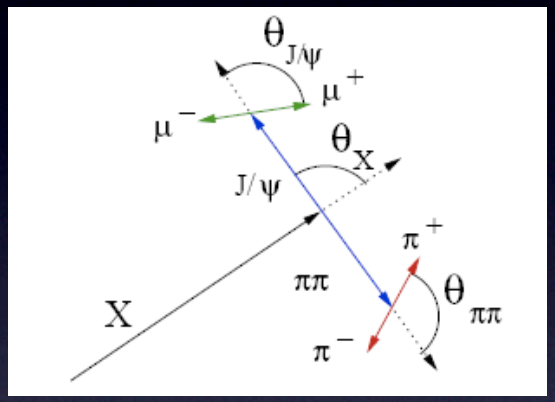
- Exclusive Production
  - only B decays so far
  - No prompt e^+e^- production observed (BaBar **PRD 76, 071102 (2007)**)

$$\sigma(e^+e^-\to X(3872)X)\cdot\mathcal{B}(X(3872)\to\gamma J/\psi)\cdot\mathcal{B}(X\to(N_{ch}>2))$$
$$= (-3\pm4\pm1)\text{fb}\ (<5.1\text{fb}\ @90\%\ \text{CL})$$

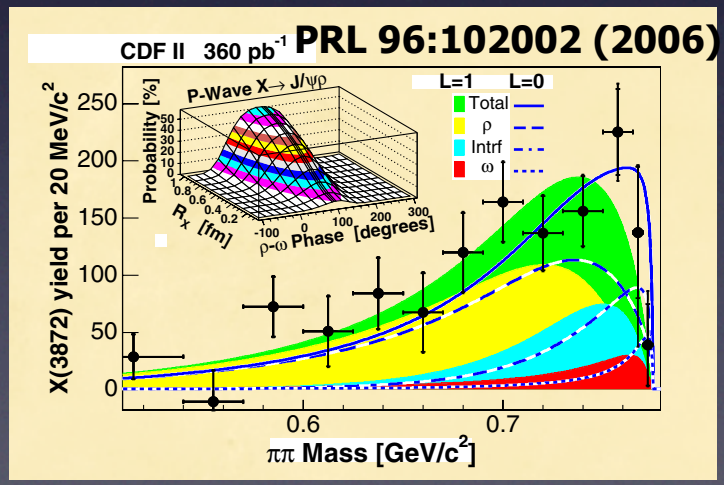


Analysis of J^{PC} of X(3872)

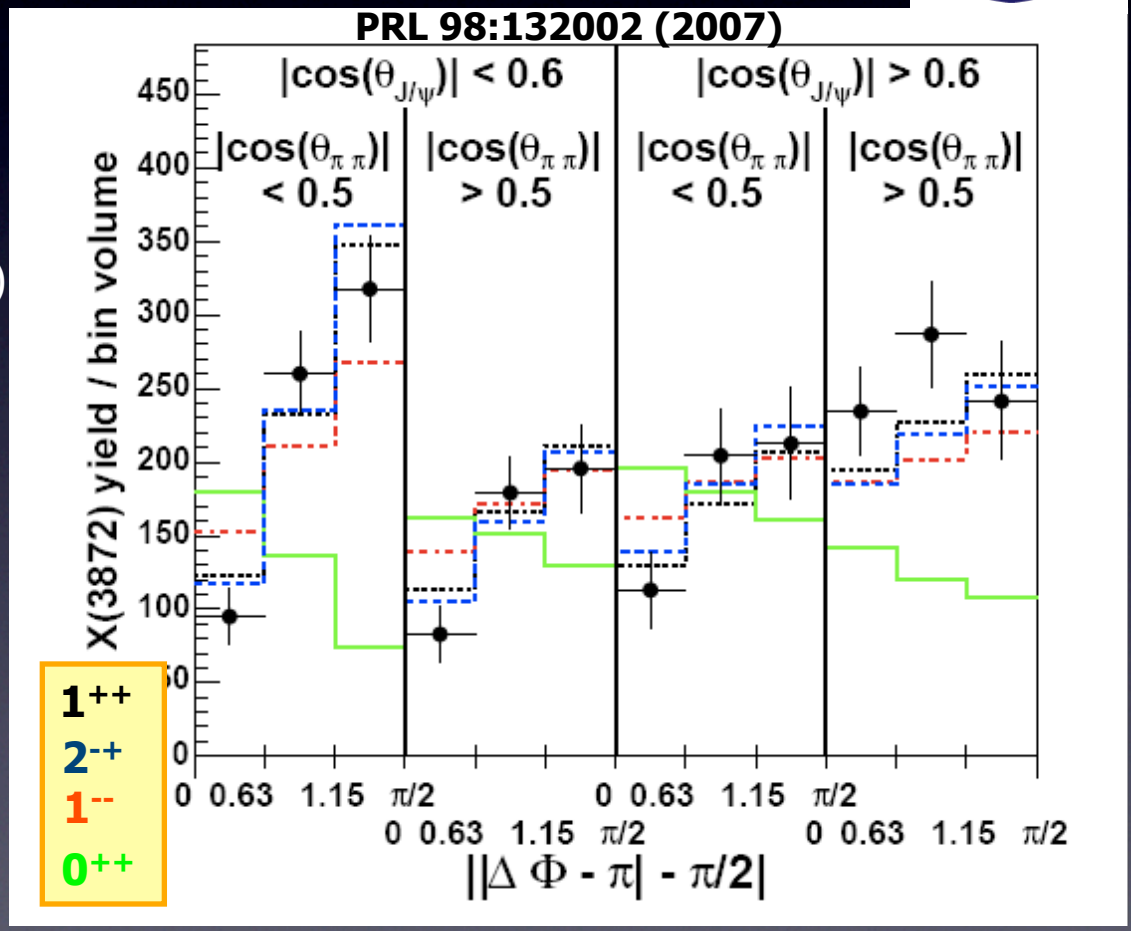
Full angular analysis of X→J/ψππ decays



Only compatible options:
$J^{PC}=1^{++}$ or 2^{-+}
(and with J(ππ)=1)



ρ-ω interference enables good description of data with L=0,1



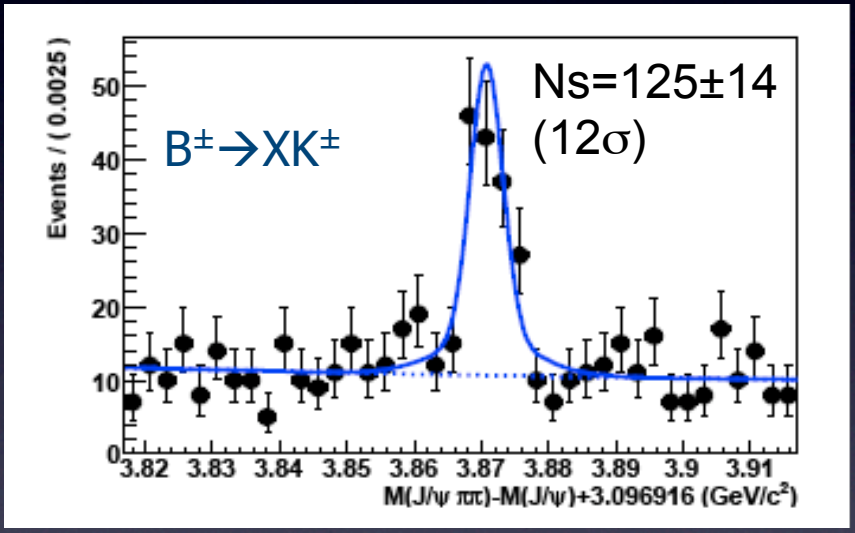
Belle (**hep-ex/0505038**) disfavours P=- → $J^{PC}=1^{++}$

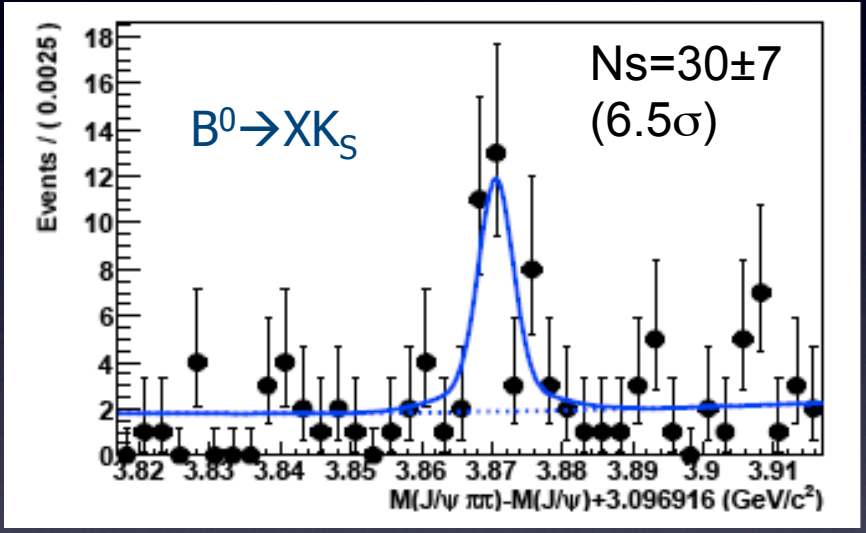
X(3872): update on J/ψππ

Belle-CONF-0711

Update mass and BF in B→XK, X→J/ψ ππ

605 fb^{-1}





Consistent with:
no mass difference
no rate difference

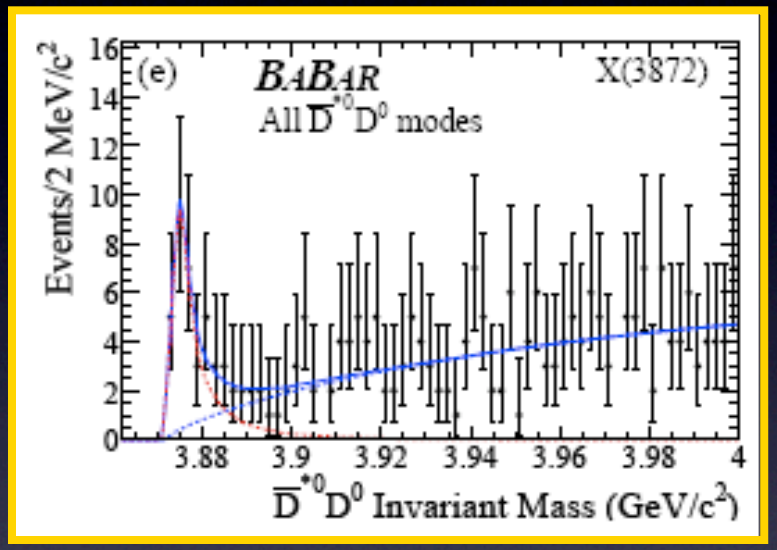
$$\Delta M = (0.22 \pm 0.90 \pm 0.27) MeV$$

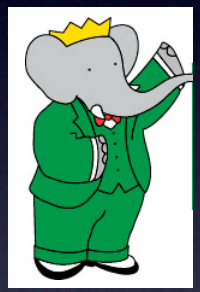
$$\frac{\mathcal{B}(B^0 \to X K^0, X \to J/\psi\pi\pi)}{\mathcal{B}(B^+ \to X K^+, X \to J/\psi\pi\pi)} = 0.94 \pm 0.24 \pm 0.10$$

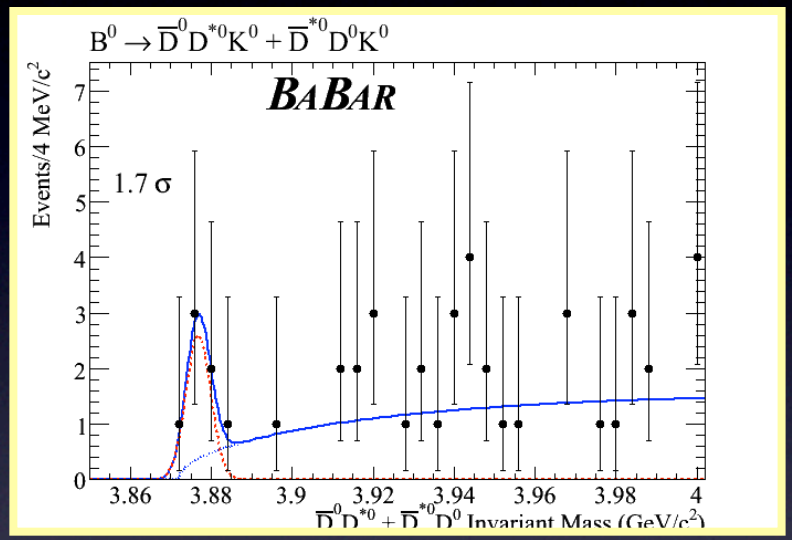
X(3872)→$D^0\bar{D}^{*0}$

- Belle [**PRL 97, 162002 (2006)**] observed X(3872)→$D^0\bar{D}^0\pi^0$
- Confirmation and integration from BaBar in B→$D\bar{D}^*K$

B^+ & B^0 → $D^0\bar{D}^{*0}K$ PRD 77, 011102 (2008)







Mass and BR measurement

$$M = (3875.1^{+0.7}_{-0.5} \pm 0.5) MeV$$
$$\mathcal{B}(B^+ \to XK^+, X \to D^0\bar{D}^{*0}) = (1.7 \pm 0.4 \pm 0.6)10^{-4}$$

Danger! very low significance

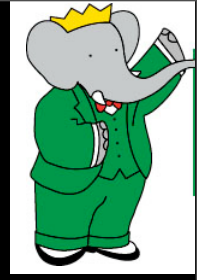
Hints of X in neutral B decays

$$\Delta M = (0.7 \pm 1.9) MeV$$
$$\mathcal{B}(B^0 \to XK^0, X \to D^0\bar{D}^{*0}) = (2.2 \pm 1.1 \pm 0.4)10^{-4}$$

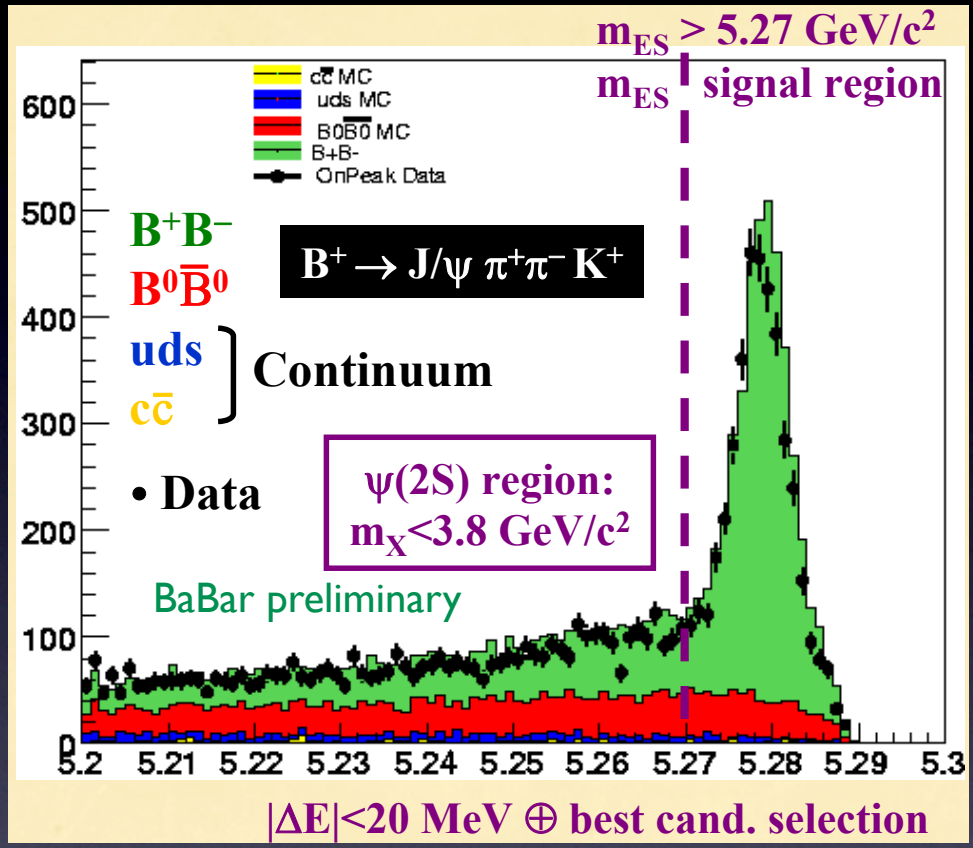
N.B. $\mathcal{B}(B^+ \to XK^+, X \to J/\psi\pi^+\pi^-) = (1.14 \pm 0.20) \times 10^{-5} [PDG'06]$

arXiV:0803.2838

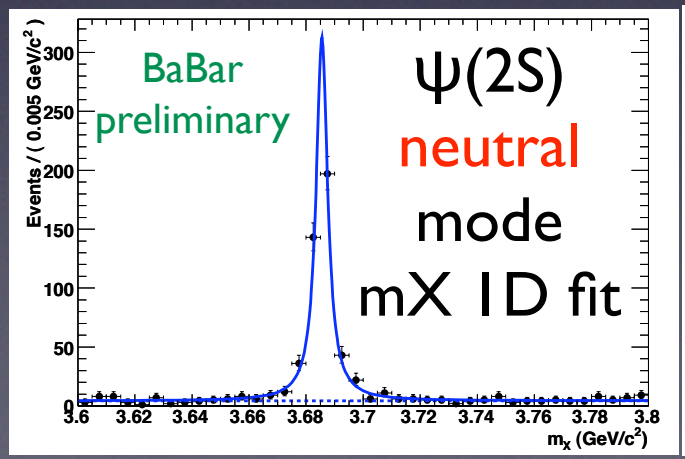
X(3872): update on J/ψππ

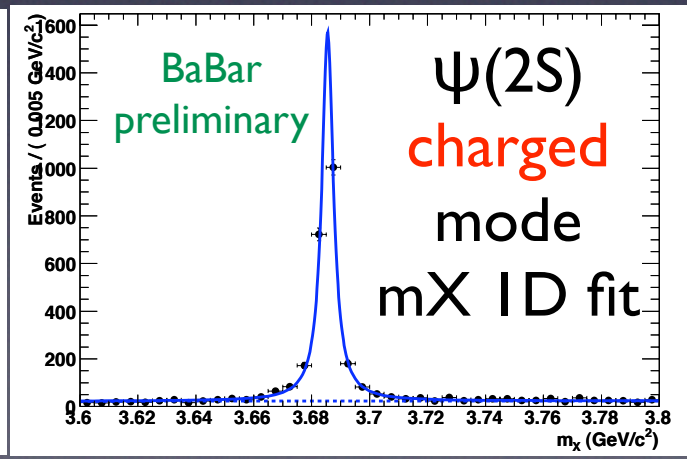


- Update of previous BaBar analysis $211fb^{-1} \rightarrow 413fb^{-1}$
- charged and neutral Kaon final states
- Perform 1D unbinned max. likelihood fits to mX in mES signal region



- ψ(2S) control sample:
  ↳ $J/\Psi\pi^+\pi^-$
- Fit results agree with PDG stat. error smaller for B.F.

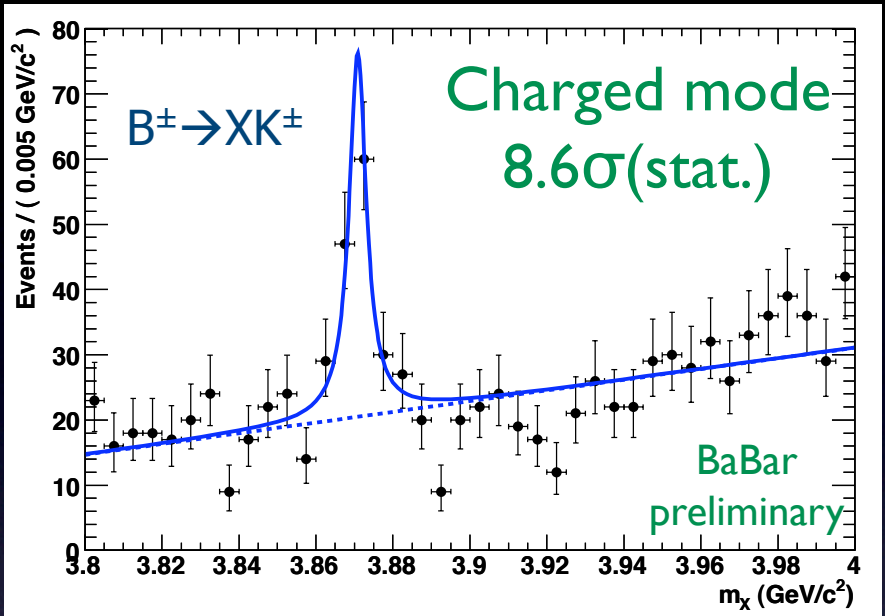


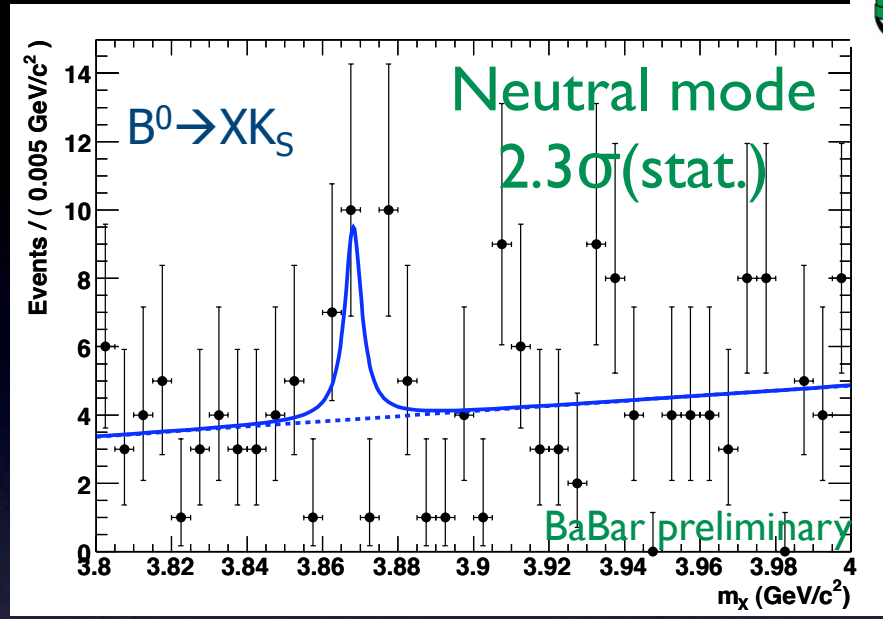


Accepted by PRD-RC

arXiV:0803.2838

X(3872): m_X Fit Results





Width fixed to the charged mode value

$$\mathcal{B}(B^+ \to X(3872)K^+, X \to J/\psi\pi^+\pi^-) = (8.40 \pm 1.55 \pm 0.74) \times 10^{-6}$$
$$\mathcal{B}(B^0 \to X(3872)K^0, X \to J/\psi\pi^+\pi^-) = (3.46 \pm 1.93 \pm 0.40) \times 10^{-6}$$
$$\mathcal{B}(B^0 \to X(3872)K^0, X \to J/\psi\pi^+\pi^-) < 6.03 \times 10^{-6} \ @\ 90\%\ C.L.$$

$R(X)=B^0/B^+=0.41\pm0.25\pm0.05$
<0.73 @ 90% CL

$R(\psi(2S))=B^0/B^+=0.81\pm0.05\pm0.01$
better than PDG

1D Fits ⇒ more parameters floated

⇒ significantly reduced systematics

Consistent with previous analysis with errors largely reduced

arXiV:0803.2838

X(3872): mass and width estimates

- Use the ψ(2S) results to correct the X(3872) measured masses:

$$m_X = m_{X,fit} - M_{\psi(2S),fit} + \boxed{m_{\psi(2S)}}$$

PDG 2007: 3686.09 ± 0.04 MeV/c^2
$m_{fit} - m_{PDG} \approx -0.6$ MeV/c^2

$m_X = 3871.4 \pm 0.6 \pm 0.1$ MeV/c^2 for $B^+ \to X K^+$
$= 3868.7 \pm 1.5 \pm 0.4$ MeV/c^2 for $B^0 \to X K^0$

In excellent agreement with previous measurements

$\Rightarrow \Delta m = m_{X,\text{ charged mode}} - m_{X,\text{ neutral mode}} = 2.7 \pm 1.6 \pm 0.4$ MeV/c^2

- Natural width Γ_N determined from the charged mode

→ m_X shape ⇔ convolution of two BW: signal & resolution

Determined from signal MC (X generated with no width)

$$\Rightarrow \Gamma_N = \boxed{\Gamma_{fit}} \ominus \Gamma_{MC}$$

FWHM

→ Procedure tested and validated using the ψ(2S) control samples

→ Result: $\Gamma_N < 3.3$ MeV @ 90% C.L. (stat. ⊕ syst.)
$= 1.05 \pm 1.52 \pm 0.24$ MeV

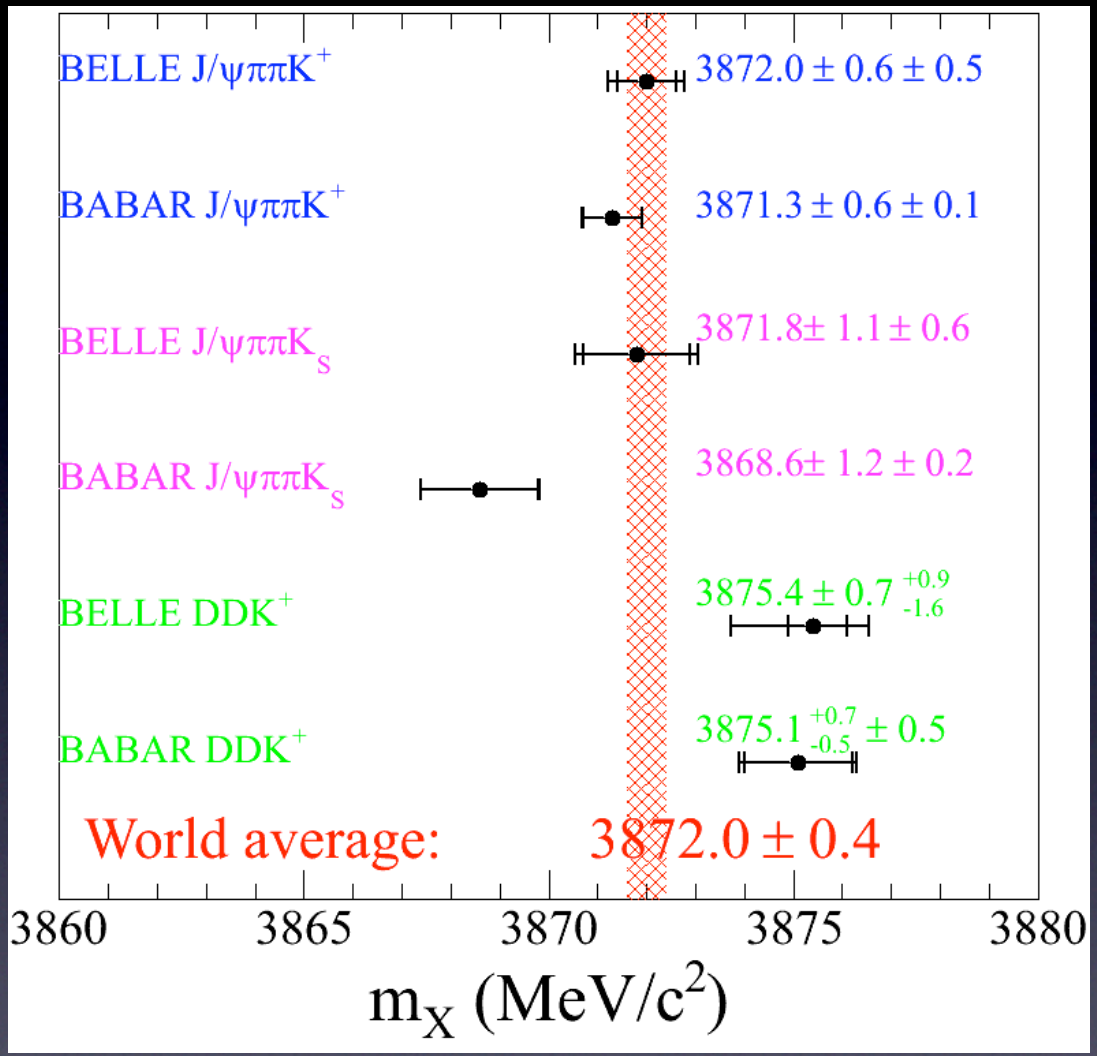
Syst. error estimated by varying PDF shapes

X(3872) mass

Poor agreement among mass measurements:

<u>X→J/ψππ and X→D$\bar{D}^{(*)}$ differ by ~4σ</u>

Neutral and charged B mesons in X→J/ψππ by 1.5σ



Predicted by tetraquark model (but why so close to threshold?) ←

TWO STATES? X(3872) & X(3876) ?

Perhaps also just one state: PRL 100, 062006 (2008) W. Dunwoodie and V.Ziegler

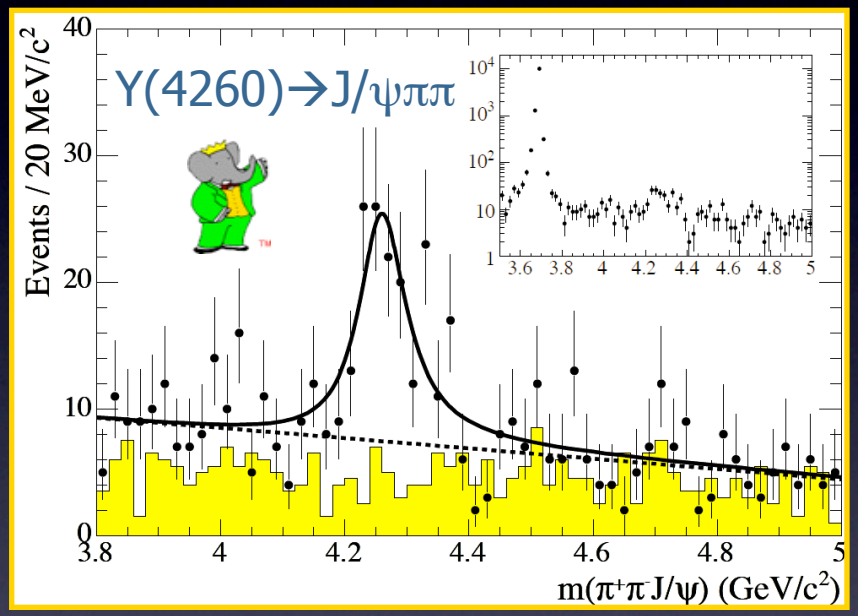
The new "exotica"

- X(3872)
- The 1-- family Y(4260) etc
- The 3940 family X(3940)
- Charged State(s)

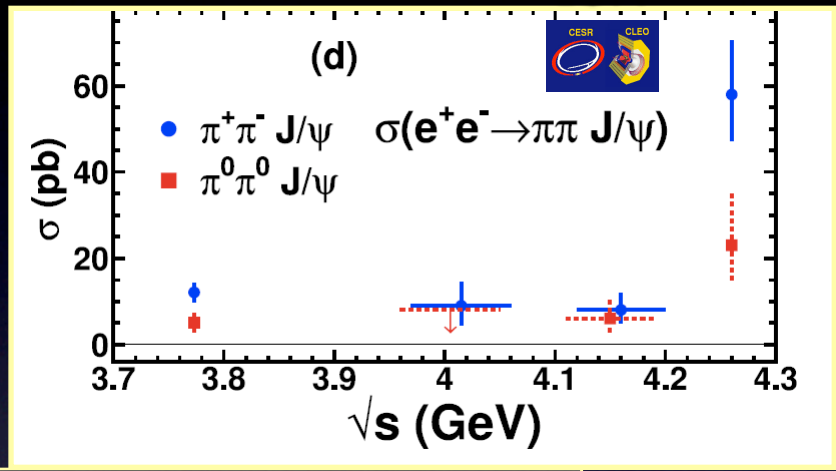
The 1^{--} family

Several bumps observed in $e^+e^- \rightarrow Y\gamma_{ISR}$

(certainly $J^{PC}=1^{--}$)

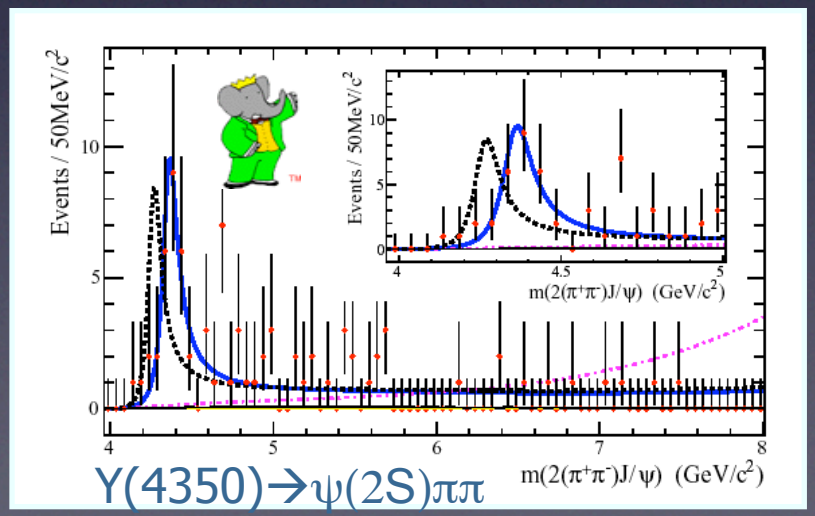


A new state: Y(4260)
PRL 95, 142001 (2005)



Confirmation + $J/\psi\pi^0\pi^0$:
CLEO PRD74, 091104 (2006)
CLEO-c PRL 96, 162003 (2006)

$\pi^0\pi^0$ cross section ⇒ I=0



Yet another state Y(4350)
PRL 98, 212001 (2007)

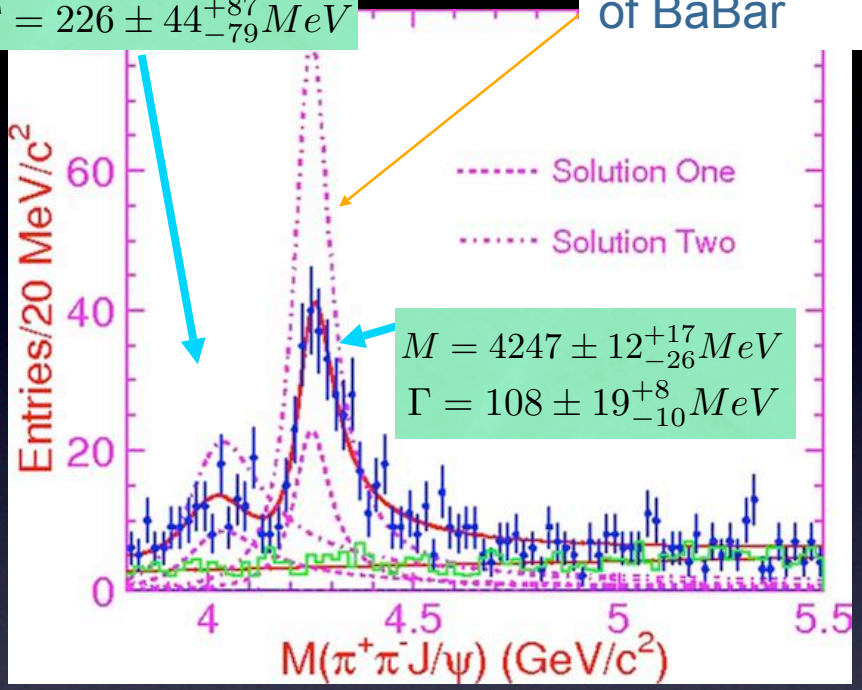
The youngest of the 1^{--} family

arXiv:0707.2541

$M = 4008 \pm 40^{+72}_{-28} MeV$

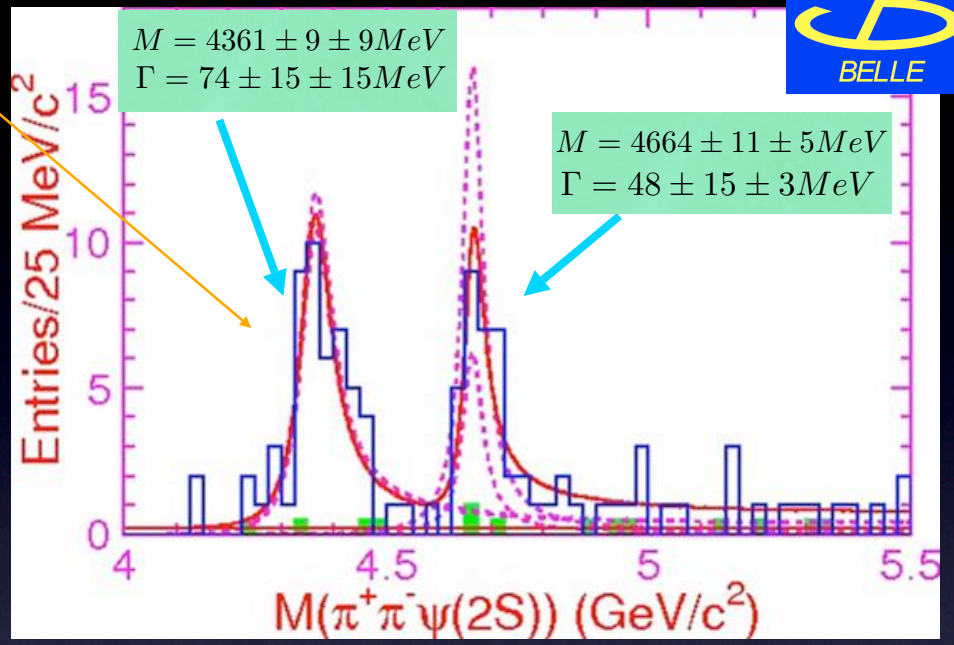
$\Gamma = 226 \pm 44^{+87}_{-79} MeV$

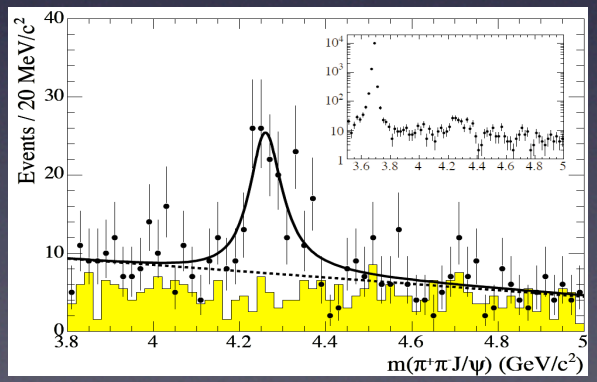
Confirmation of BaBar



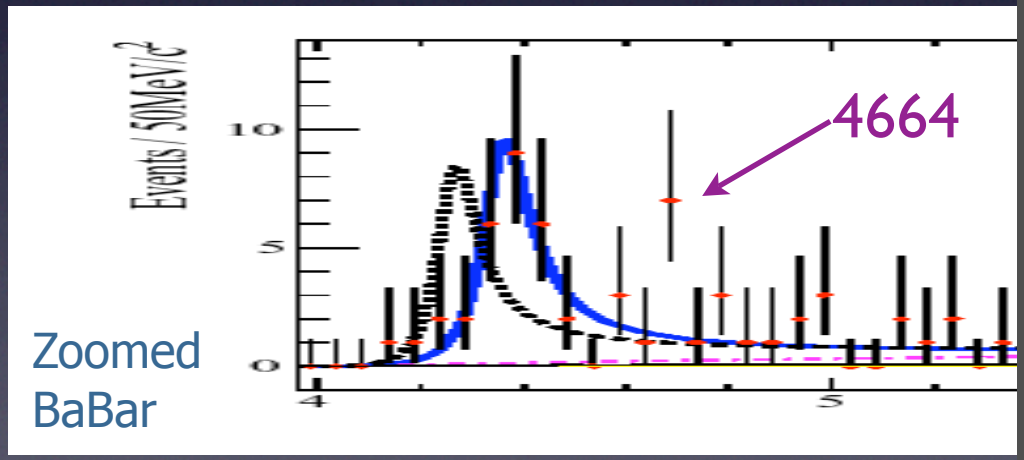
arXiv:0707.3699

BELLE





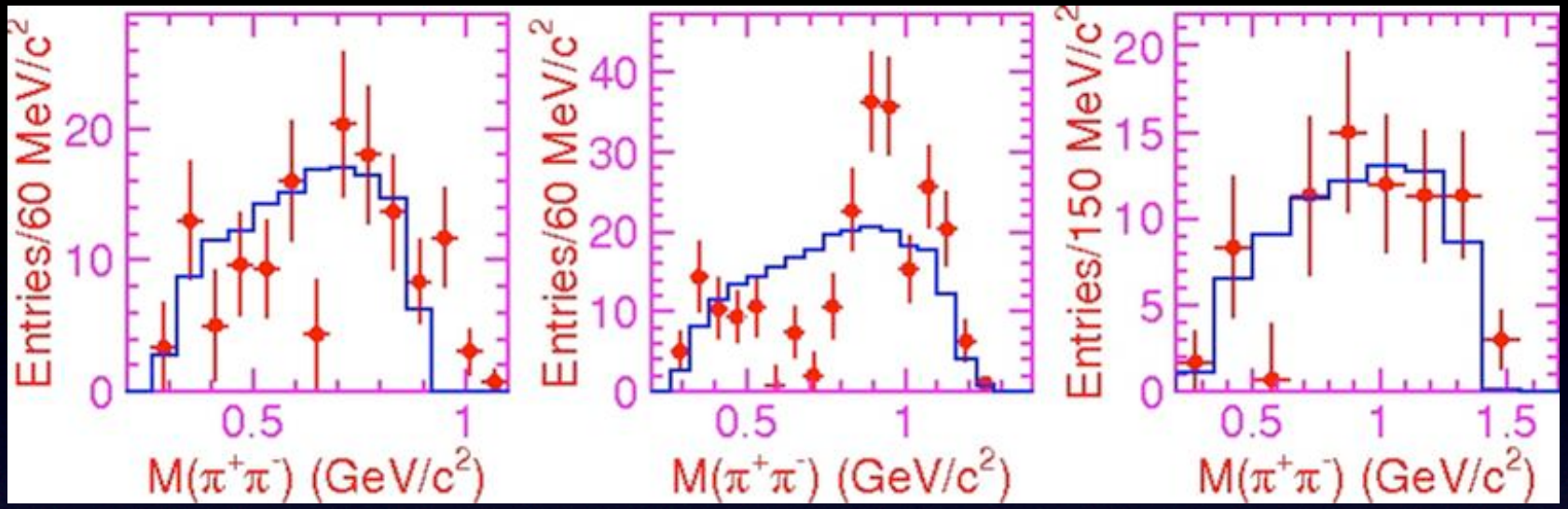
Υ→J/ψππ

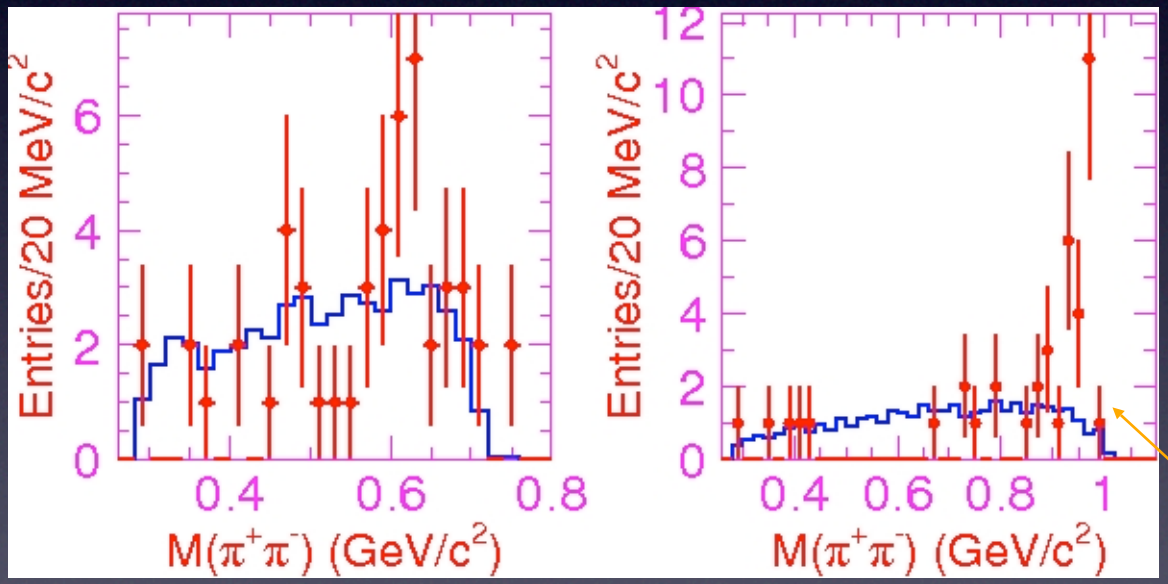


Υ→ψ(2S)ππ

DECAY PROPERTIES

Y(4008) Y(4260) High mass region





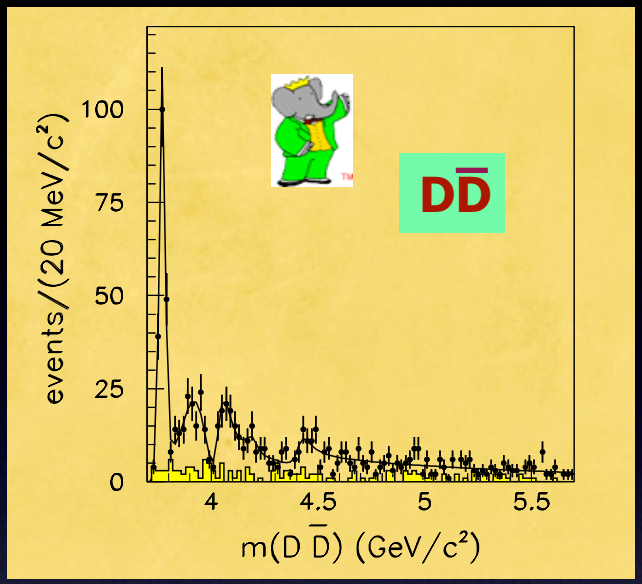
Y(4350) Y(4660)

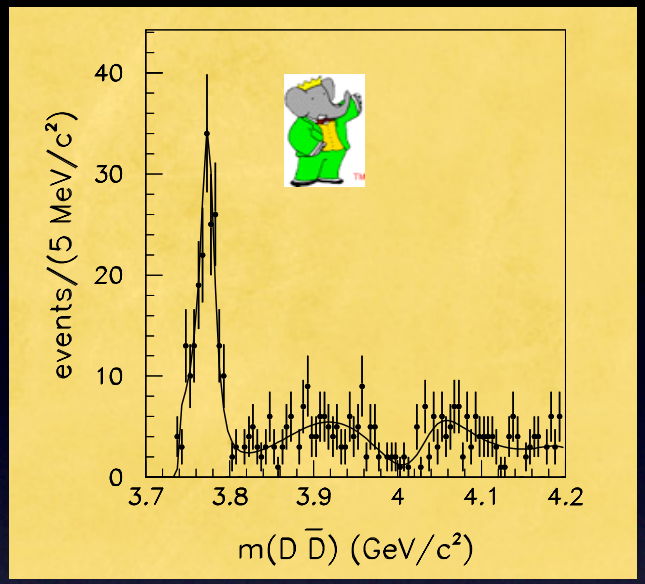
f_0 dominating?
Threshold effects?

data overlaid on 3 body
phase-space distributed MC

$D^{(*)}\bar{D}^{(*)}$ in ISR

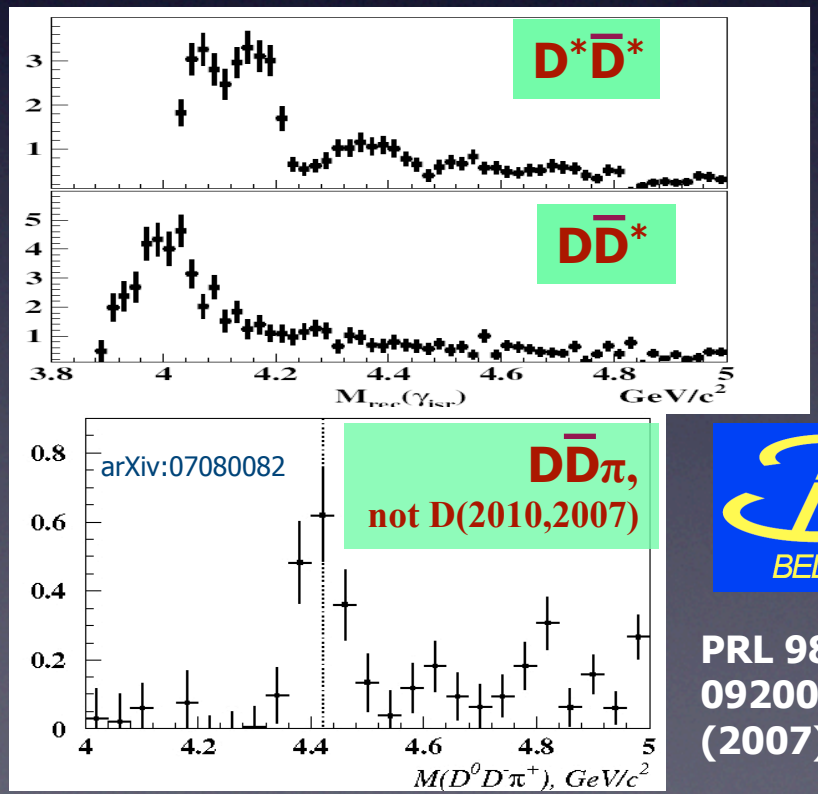
PRD 76, 111105 (2007)





Most of these 1-- states should preferentially decay into D(*)D(*) states. Can we see them?

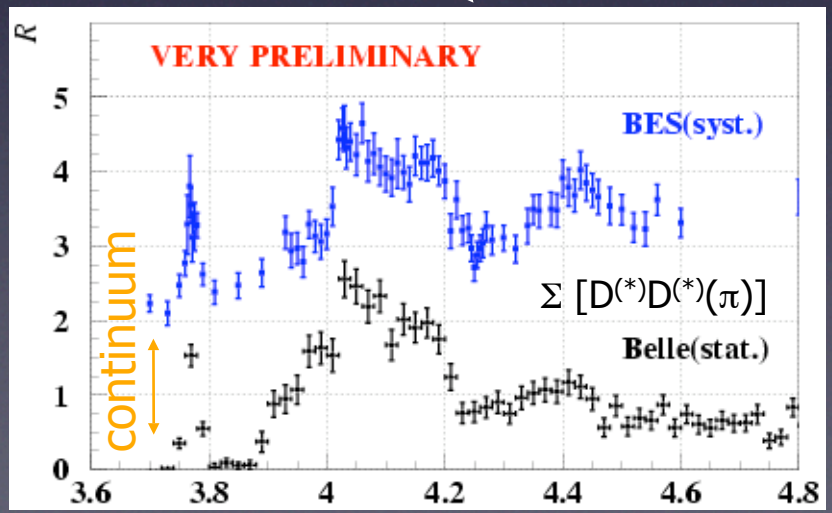
ψ(3770), ψ(4040), ψ(4415) [regular charmonia] clearly visible, nothing else



BELLE

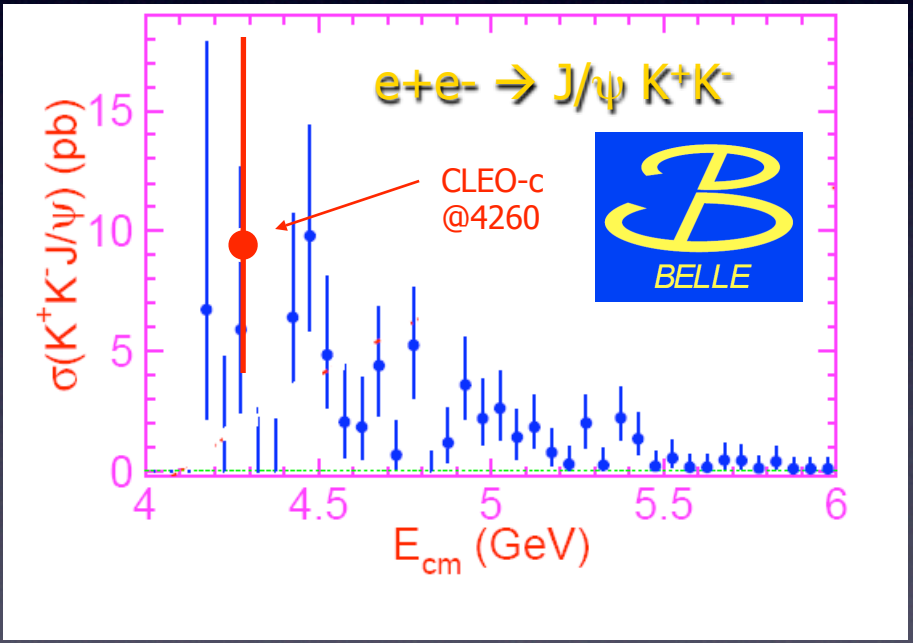
PRL 98, 092001 (2007)

➔ Basically all R scan other than non-resonant continuum understood

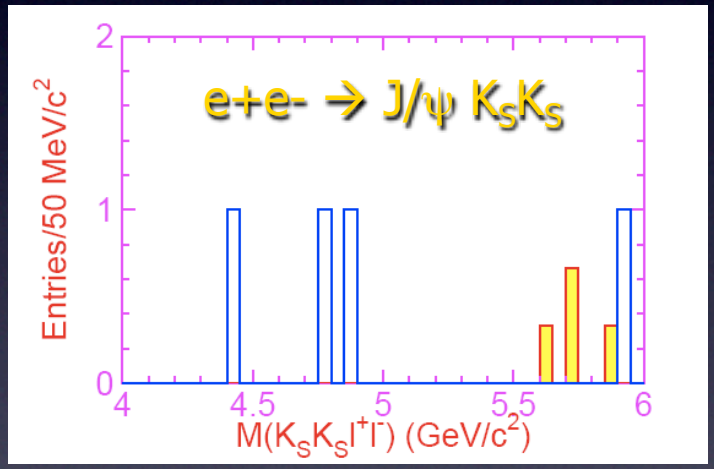


J/ψ KK in ISR

- Knowledge of the strangeness content of these resonances is important to disentangle their nature
- CLEO-c already showed few e^+e^- → Y(4260)→J/ψ K^+K^-
- Belle (ISR): first observation of e^+e^- → J/ψ K^+K^- and J/ψ K_sK_s



BELLE-CONF-0772



$\sigma(e^+e^- \rightarrow J/\psi K_sK_s)/ \sigma(e^+e^- \rightarrow J/\psi K^+K-) = 0.6^{+0.5}_{-0.4}$

1^{--} family: recap

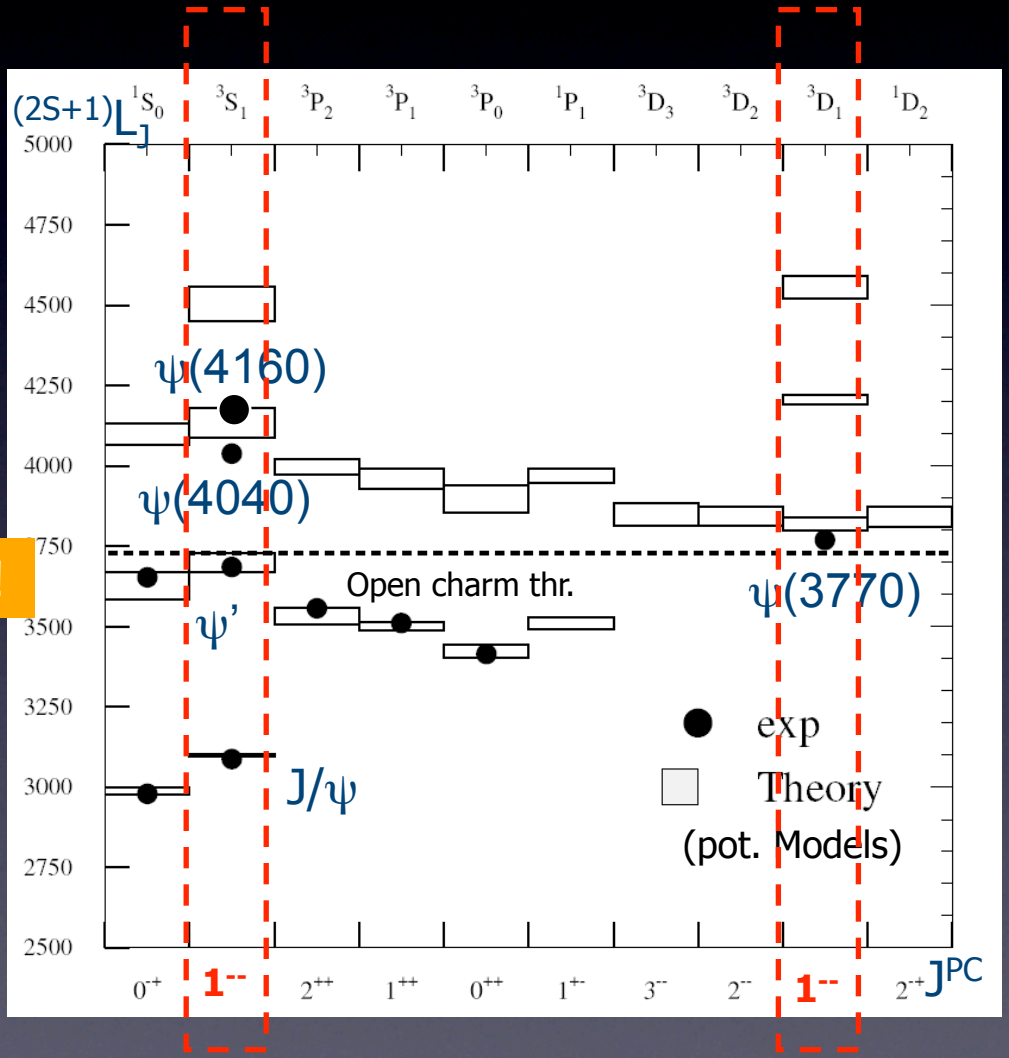
Only seen in $\psi(2S)\pi\pi$

4660
4350
4260
4008

M(MeV)

4 Ys to place !

Why not the ordinary Y (4040)?



- Not matching any potential model prediction
- Too narrow

"new physics"?

4260 can be fit by a tetraquark model (decaying into $J/\psi f_0$ ...) or a hybrid (with $g \rightarrow \pi\pi$)

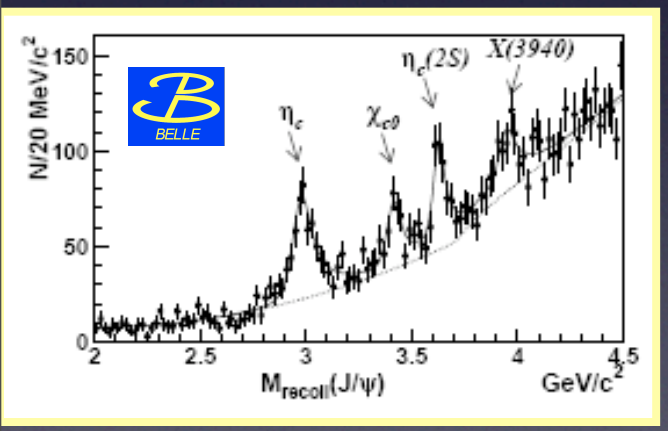
The new "exotica"

- X(3872)
- The 1-- family Y(4260) etc
- The 3940 family X(3940)
- Charged State(s)

The 3940 family

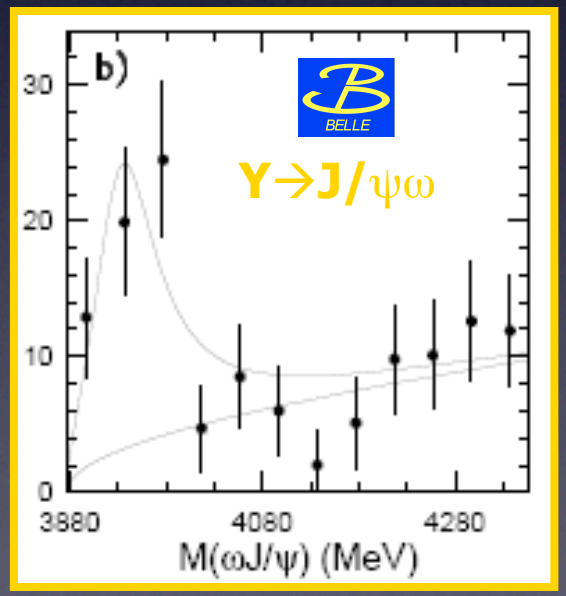
	Observed in	J^{PC} (?)	M (MeV)	Γ (MeV)
X	$e^+e^- \to J/\psi X$	$0^{-+}, 1^{++}$	3943±8	<39
Y	$B \to YK$ ($Y \to J/\psi\omega$)	1^{++},...	3943±17	87±34
Z	$\gamma\gamma \to Z$ ($Z \to D\bar{D}$)	2^{++}	3929±5	29±10

PRL 98, 082001 (2007)

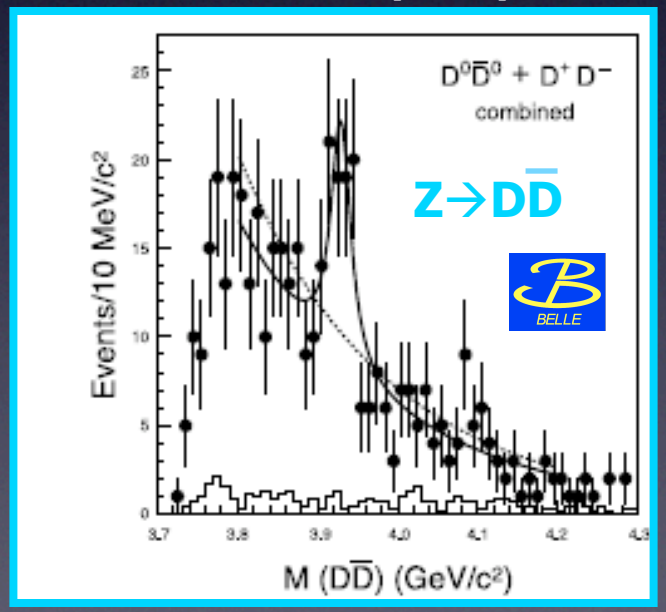


X dominated by $D\bar{D}^*$ from further investigation

PRL 94, 182002 (2005)



PRL 96, 082003 (2006)



Confirmation of Y(3940) ($B \to K \underbrace{\omega J/\psi}_{\pi^+\pi^-\pi^0}$)

arxiv:0711.2047v2

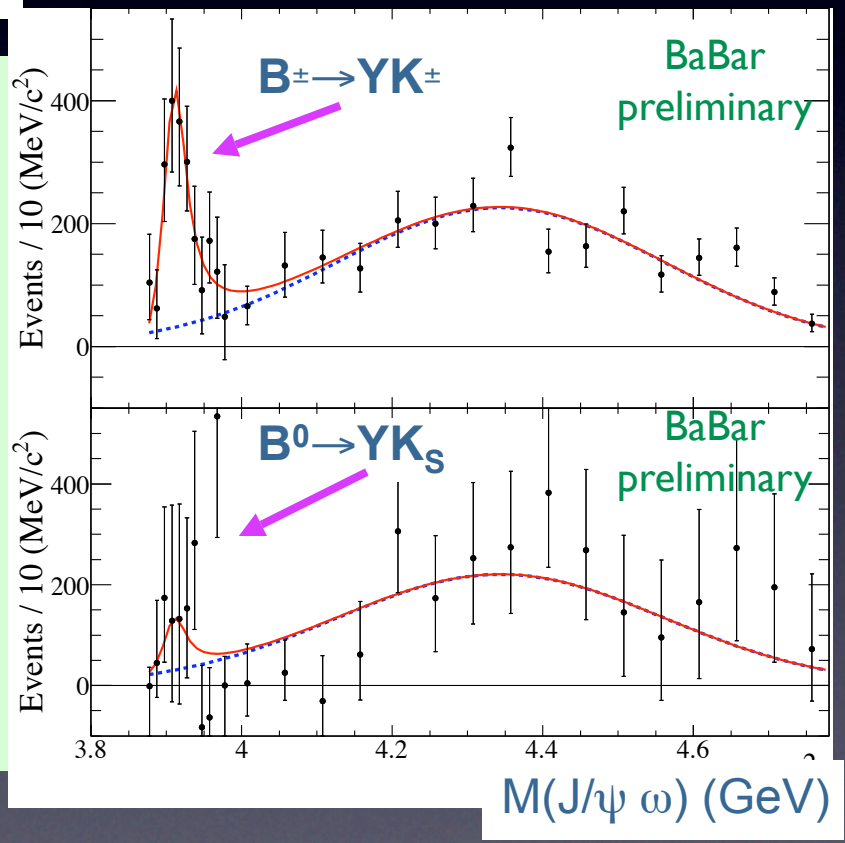
New result, based on 350 fb^{-1}:

$$M(Y) = (3914.6^{+3.8}_{-3.4}(stat.) \pm 1.9(syst.))\mathrm{MeV}/c^2$$

$$\Gamma(Y) = (34^{+12}_{-8}(stat.) \pm 5(syst.))\mathrm{MeV}$$

Belle's evidence for $B \to YK$, $Y \to J/\psi\omega$ confirmed

- ~30MeV lower mass than Belle's
- Narrower width
- Clear demonstration of decay into ω
- Preliminary BF estimate similar to Belle's (~10^{-5})



Y(3940) closer to X(3940)
Can they be the same state?

X(4160)→ $D^*\bar{D}^*$

Obtain $J/\psi D^{(*)}\bar{D}^{(*)}$ samples through kinematic separation, look at $m(D^{(*)}\bar{D}^{(*)})$ after background subtraction:

$e^+ e^- \rightarrow J/\psi\, D^{(*)}\bar{D}^{(*)}$

reconstructed

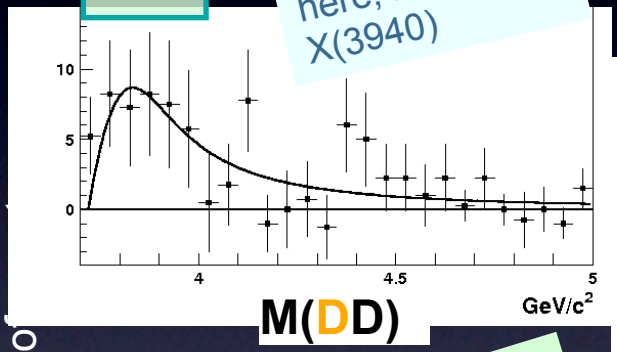
Inferred (Recoil mass)

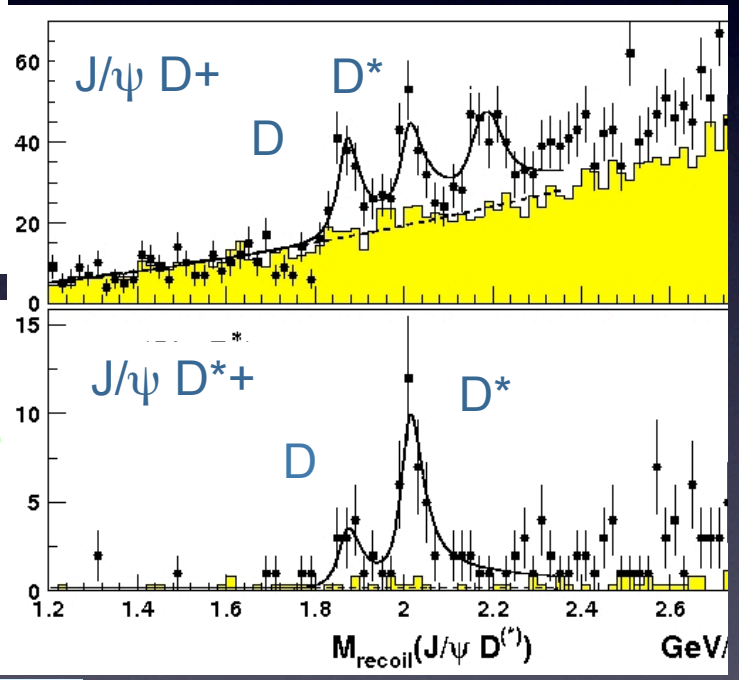
BELLE-CONF-0705

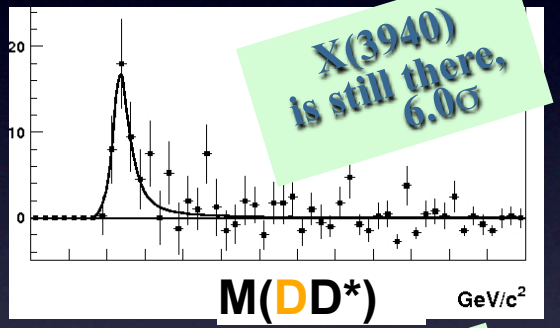
M = 3942 ±6 MeV
Γ_{tot} =37 ±12 MeV
N_{ev}= 52 ±11

3.8 σ

Something's here, but it's not X(3940)



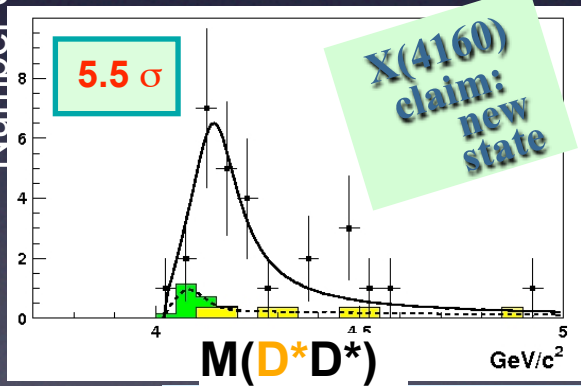


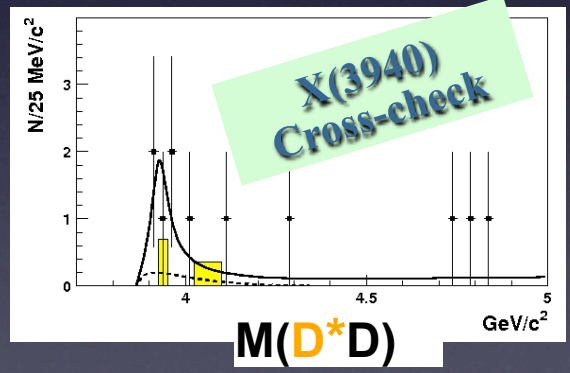


Number o

5.5 σ

X(4160) claim: new state





M = 4156 $^{+25}_{-20}$ ±15MeV
Γ_{tot} = 37 $^{+111}_{-61}$ ±21MeV
N_{ev}= 24 $^{+12}_{-8}$

→ One more particle to explain …
$J^{CP}=0^{-+}$ not excluded ($\eta_c(3S)$)

The new "exotica"

- X(3872)
- The 1-- family Y(4260) etc
- The 3940 family X(3940)
- Charged State(s)

The first charged state: Z(4430)

$B^{\pm} \to Z^{\pm} K_s$ or $B^0 \to Z^{\mp} K^{\pm}$

$Z^{\pm} \to \psi(2S)\pi^{\pm}$

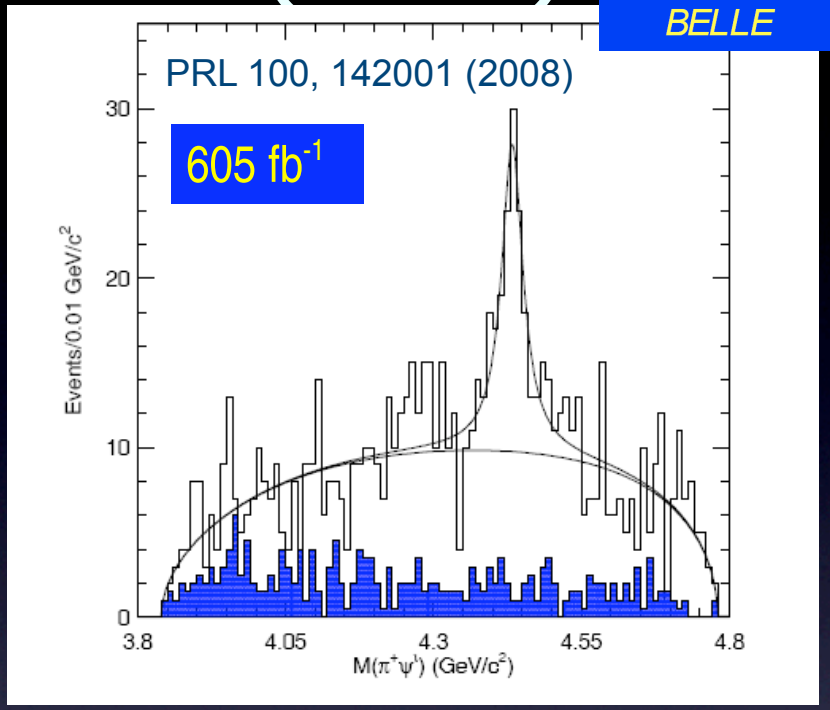
Total significance: 6.5 sigma

M = (4433±5) MeV

$\Gamma = (45^{+30}_{-17})$ MeV

Too narrow to be a reflection

$BF(B \to KZ) \times BF(Z \to \psi(2S)\pi) = (4.1 \pm 1.0 \pm 1.4)\ 10^{-5}$



Subset	Mass (GeV)	Width (GeV)	Significance (σ)	Constr. yield ($\Gamma = 0.045$ GeV)
$\pi^+\pi^- J/\psi$	4.435 ± 0.004	$0.026^{+0.013}_{-0.008}$	4.5	64 ± 15
$\ell^+\ell^-$	4.435 ± 0.010	$0.094^{+0.042}_{-0.030}$	4.7	59 ± 13
e^+e^-	4.430 ± 0.009	$0.056^{+0.028}_{-0.020}$	3.5	41 ± 12
$\mu^+\mu^-$	4.434 ± 0.004	$0.038^{+0.023}_{-0.013}$	5.2	80 ± 16
$K^{\pm}\pi^{\mp}\psi'$	4.434 ± 0.005	$0.048^{+0.019}_{-0.014}$	6.0	102 ± 18
$K^0_S\pi^{\mp}\psi'$	4.430 ± 0.009	0.048-fixed	2.0	19 ± 8
K^* veto	4.437 ± 0.005	$0.063^{+0.024}_{-0.017}$	7.1	170 ± 26

Crosschecks: separate into subsamples

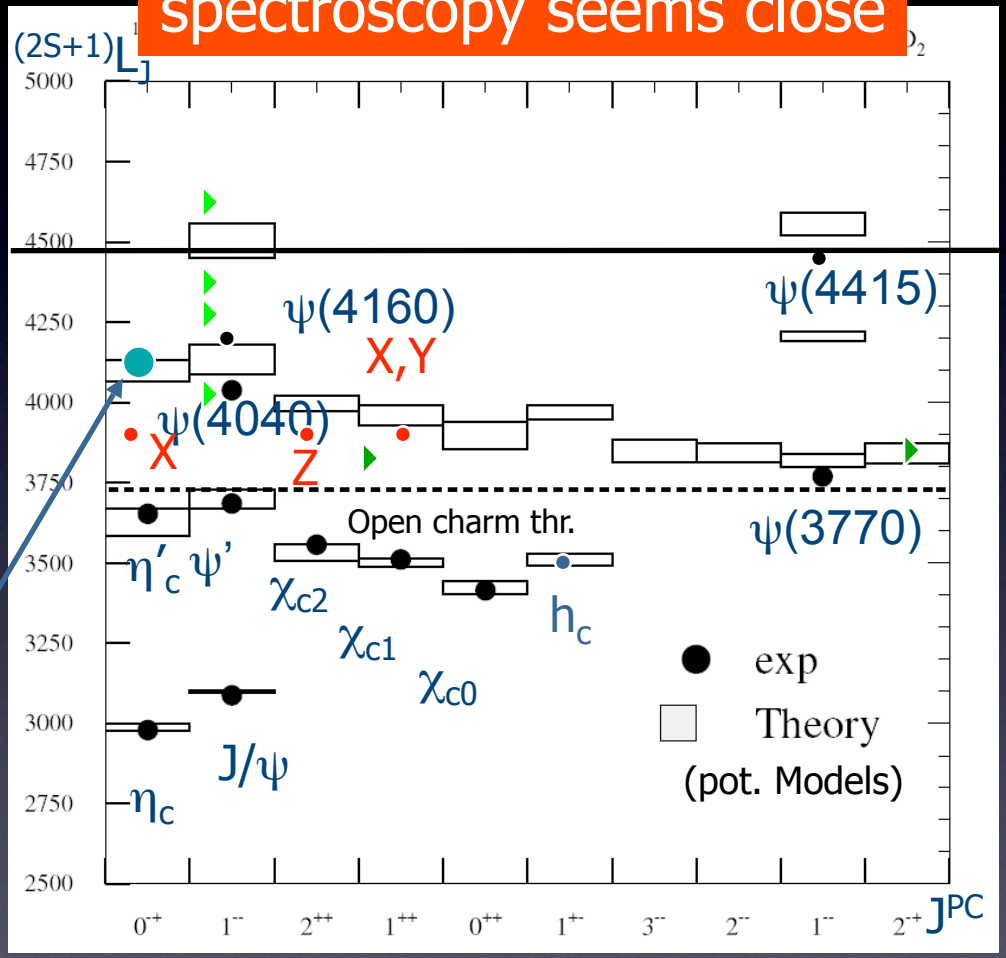
BF and mass consistent between $B^{\pm}$ and B0 within large errors [in $B^{\pm}$ decays M= (4430±9) MeV ; $BF_{\pm}/BF_0 = 1.0 \pm 0.4$]

Prior search with no evidence:
$B \to X^+ K$ with $X+ \to J/\psi\ \pi\pi^0$

PRD 71, 031501 (2005)

The 1^{--} family: Charmonia, tetraquarks, molecules, hybrids?!?

The discovery and identification of a new spectroscopy seems close

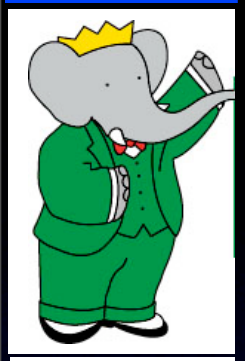


Z(4430): the first charged state

News on the 3940 family

X(3872) the best tetraquark candidate(?)

Yet another particle: X (4160) [$\eta_c(3S)$?]



Summary

- A branch of physics where it seems evident that 'something new' is going on
  - Deserves full investigation!
- A long way to go before the picture is clear
- A Super Flavour Factory might be (probably is) needed to give the final word on the matter.