Istituto Nazionale
di Fisica Nucleare

Recent Results in Charmonium Spectroscopy at *B*-factories

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BELLE

Overview

Charmonium spectroscopy got renewed interest after many results from *B*-factories, especially concerning unpredicted states.

The focus of this talk is to show experimental results that may give new inputs to help the theoretical understanding of such states.

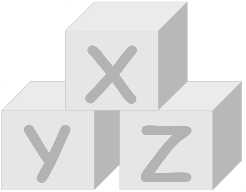
Too much material to be covered in one talk, I will skip discussion of the following states (material is in backup):

- X(3940)
- 1^{--} states, such as Y(4260)

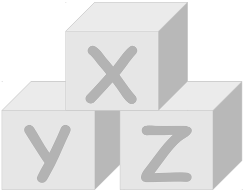
The most debated argument over last two years is the existence of charged charmonium-like states $Z(4330)^-$, $Z_1(4050)^-$ and $Z_2(4250)^-$.

Unfortunately, there are no new experimental results on this subject, so I will present just a short summary concerning these states.

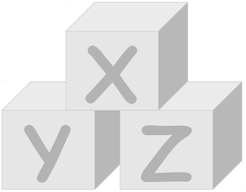
Introduction



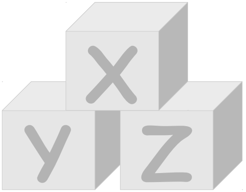
X(3872)



The 3940 Family

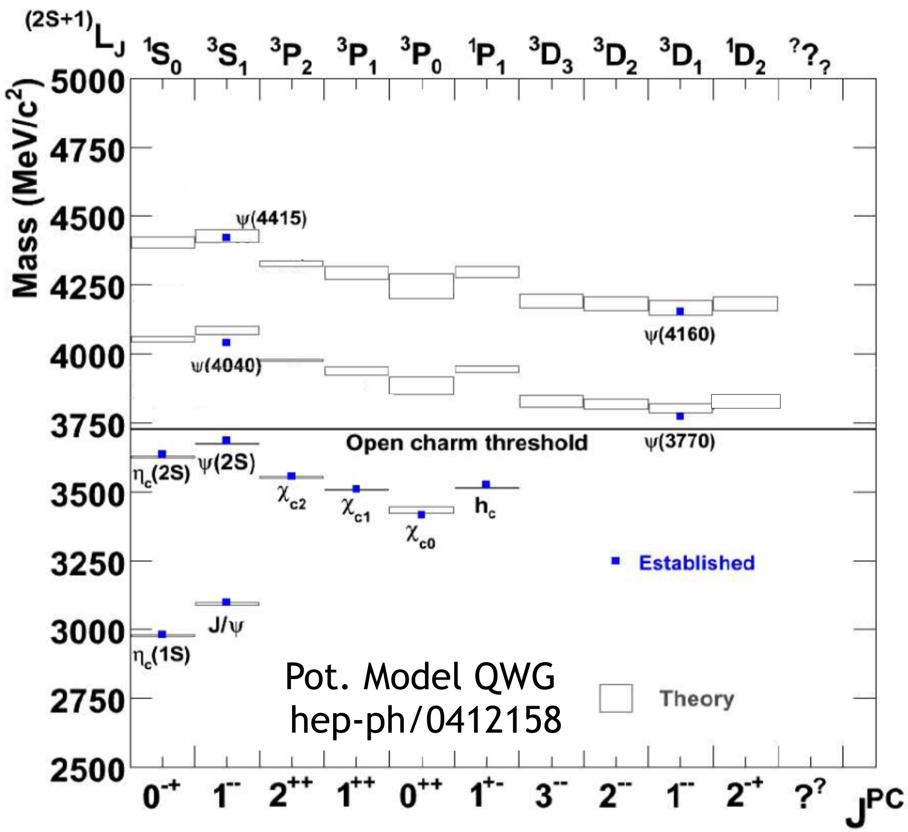


New $J/\psi\,\phi$ states



Charged States

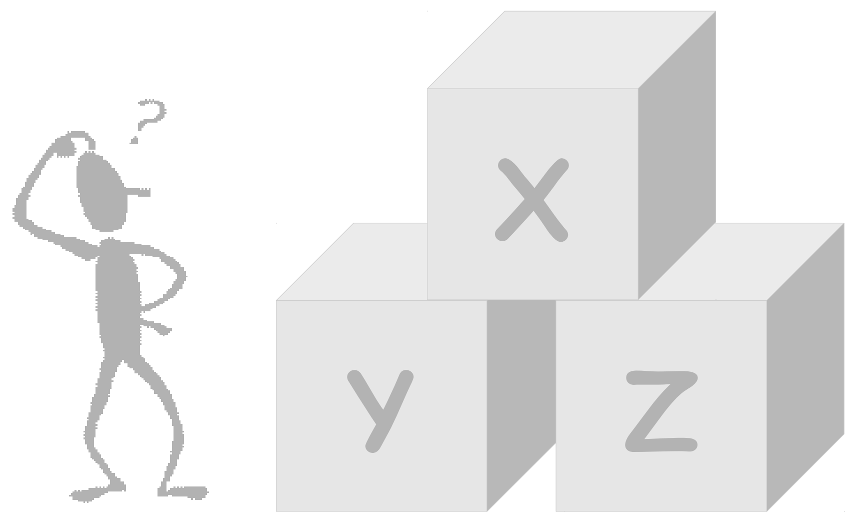
Charmonium Spectrum



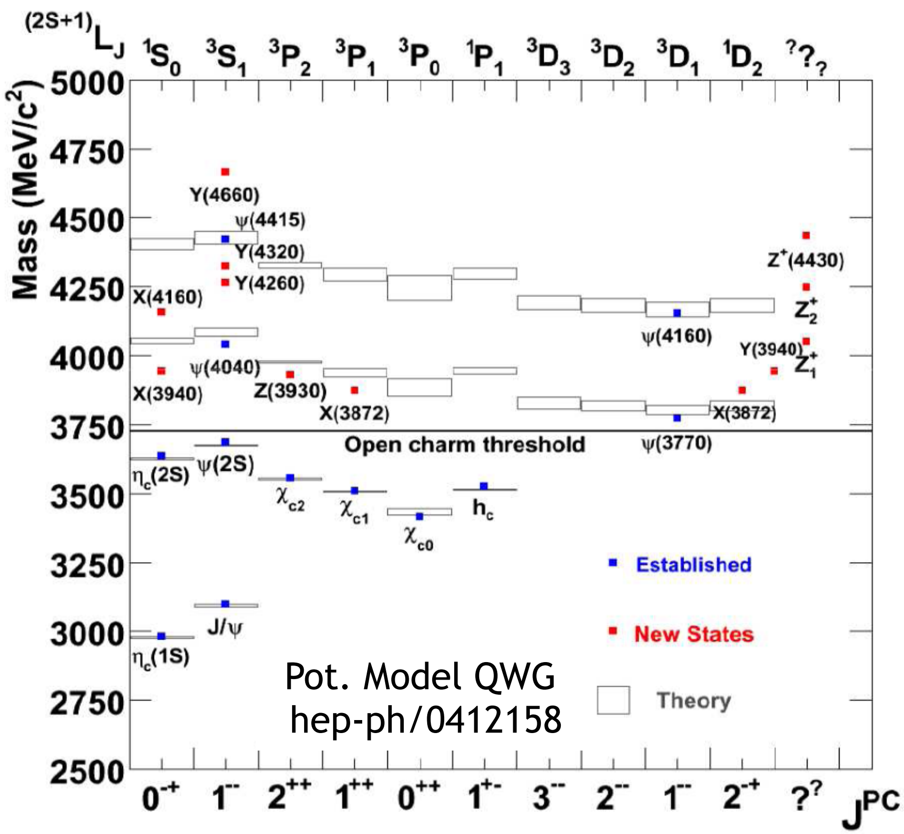
Charmonium is a $c\bar{c}$ bound state: constraints on J^{PC}.

Decay properties:

- below $D\bar{D}$ threshold NARROW STATES: due to electromagnetic or multigluon (OZI suppressed) transitions.
- above $D\bar{D}$ threshold BROAD STATES.
- Good agreement with theory predictions, but:



Charmonium Spectrum



A review of experimental results and theoretical interpretation may be found, for example, in:
E.Eichten *et al.* Rev. Mod. Phys. **80**, 1161 (2008)

Charmonium is a $c\bar{c}$ bound state: constraints on J^{PC}.

Decay properties:

- below $D\bar{D}$ threshold NARROW STATES: due to electromagnetic or multigluon (OZI suppressed) transitions.
- above $D\bar{D}$ threshold BROAD STATES.
- Good agreement with theory predictions, but:

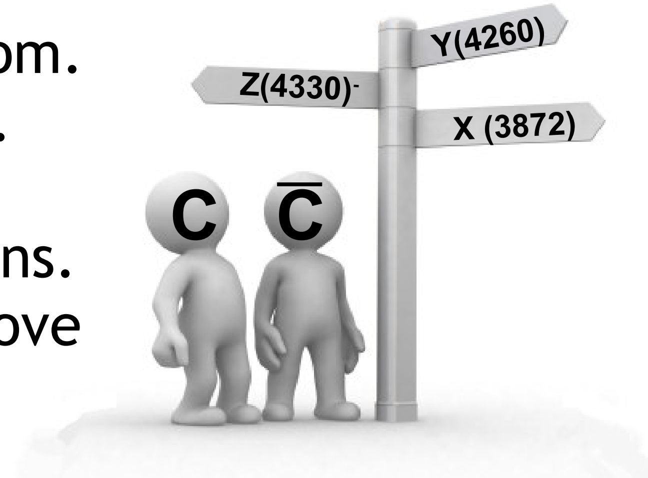
WELCOME TO WORLD FAMOUS $C\bar{C}$ ZOO

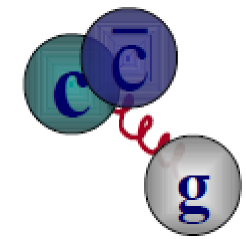
- In 2003 Belle observed the narrow state $X(3872) \rightarrow J/\psi \pi^+\pi^-$ above the $D\bar{D}$ threshold.
- Evidence for more than 10 new states up to now.
- Experimental and theoretical debate about some of these states.

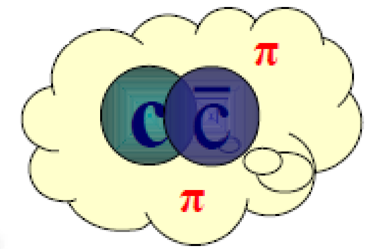
Charmonium Zoo Directions

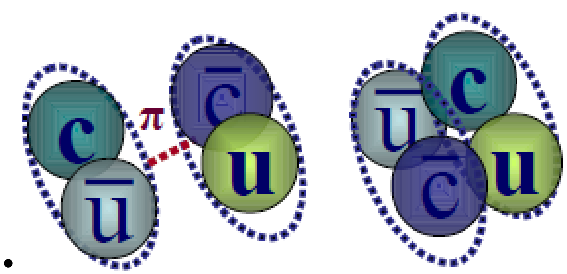
New states may be exotics somehow expected by QCD, but never observed so far:

- Hybrids:
  - Excited gluonic degree of freedom.
  - Lowest mass states ~4.2 GeV/c^2.
- Hadrocharmonium:
  - $c\bar{c}$ state "coated" by light hadrons.
  - Compatible with small width above threshold and non-zero charge.
- Multiquark states:
  - Tetraquarks of $D^{(*)}\bar{D}^{(*)}$ molecules.
  - Compatible with small width above threshold and non-zero charge.
  - Few molecular, lot of tetraquark states expected.
- Threshold effects (npQCD at work):
  - Virtual states/cusps at threshold openings.
  - Charmonium with mass shifted by nearby $D^{(*)}\bar{D}^{(*)}$ thresholds.



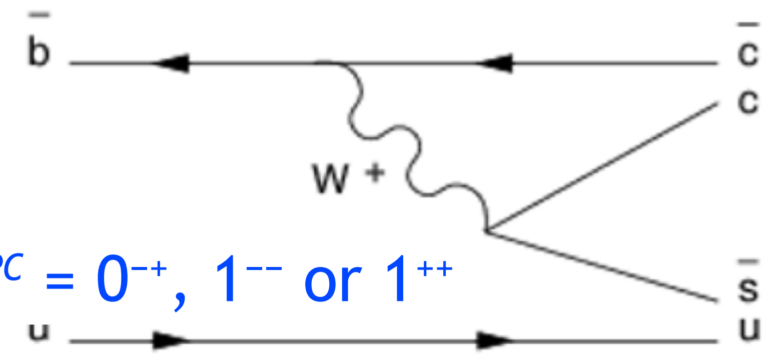






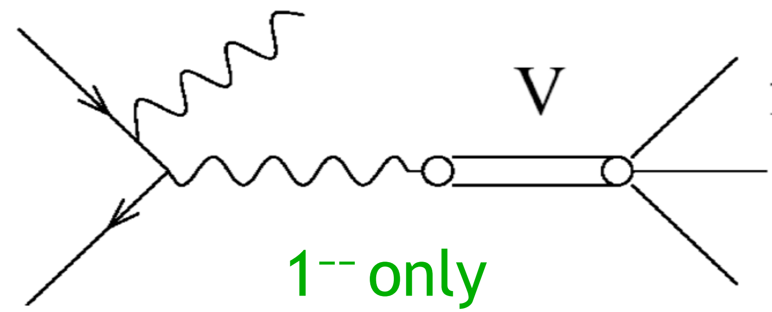
Charmonium Production at *B*-factories

$B \rightarrow c\bar{c}\, K^{(*)}$ decays



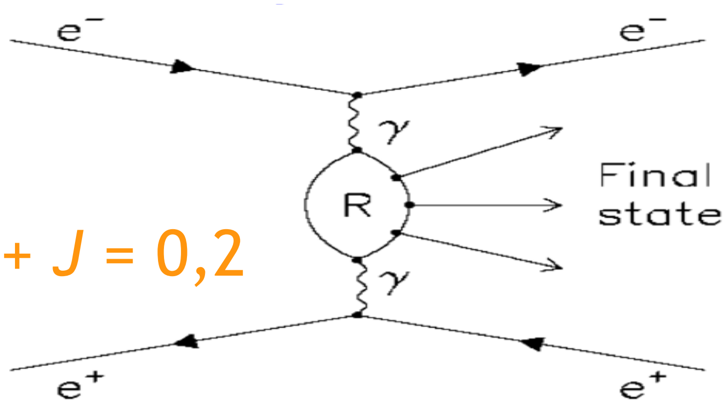
$J^{PC} = 0^{-+}$, 1^{--} or 1^{++}

Initial State Radiation (*ISR*)



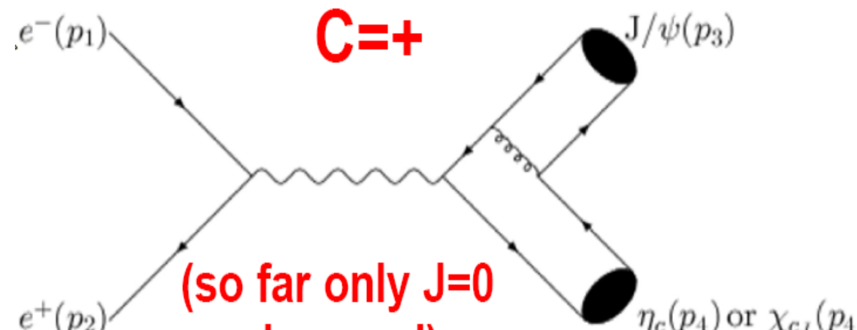
1^{--} only

Two-photon fusion



C=+ J = 0,2

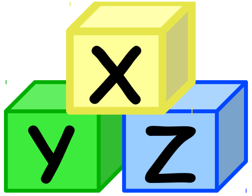
Double charmonium



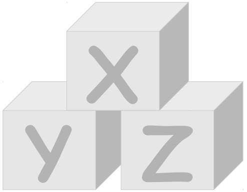
C=+

(so far only J=0 observed)

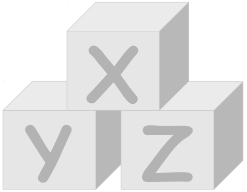
Introduction



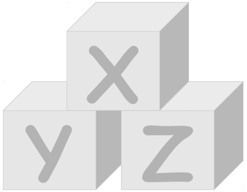
X(3872)



The 3940 Family



New $J/\psi\,\phi$ states

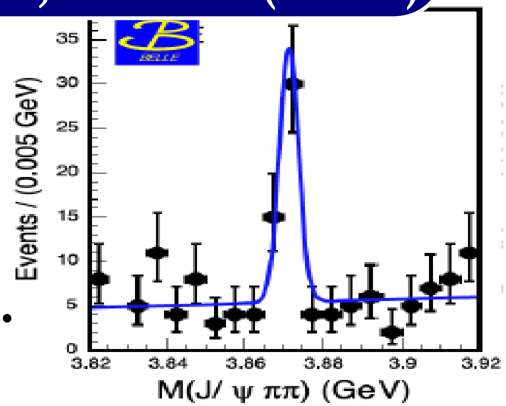


Charged States

$X(3872)$ in $J/\psi\pi\pi$

X(3872) discovered in $B^+ \to J/\psi\, \pi^+\pi^- K^+$ by Belle, soon confirmed by CDF, D0 and BaBar.

PRL 91, 262001(2003)



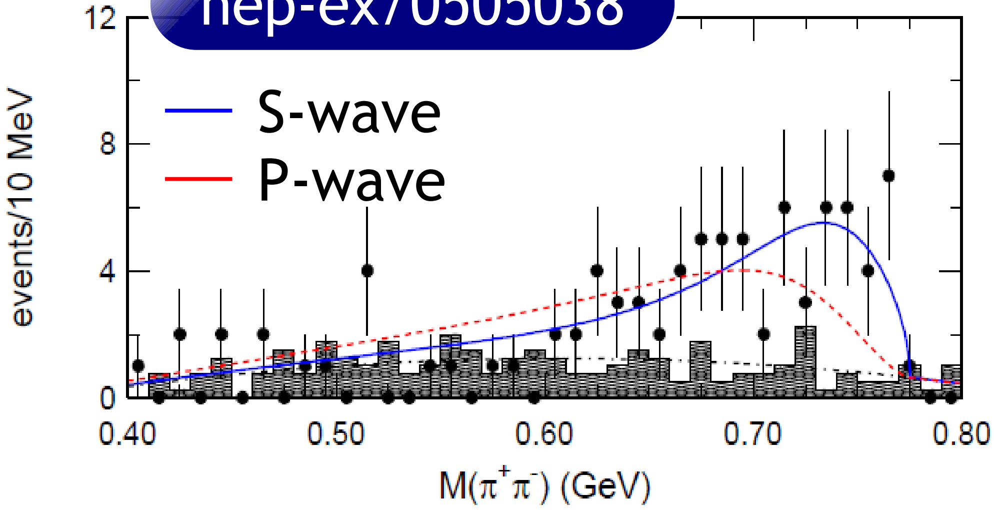
Current PDG average:

Mass: 3872.3 ± 0.8 MeV/c² Width: $3.0^{+2.1}_{-1.7}$ MeV/c²

$\pi^+\pi^-$ mass distribution consistent with sub-threshold ρ.

Belle's analysis of angular distributions favors $J^{PC} = 1^{++}$.

hep-ex/0505038



$\pi^+\pi^-$ kinematic boundary is suppressed by a $(q^*_{J/\psi})^{2L+1}$ barrier:

P = + implies J/ψ and ρ in S-wave.

P = – implies J/ψ and ρ in P-wave.

$[J]^-$ inconsistent with $\pi^+\pi^-$ mass distribution.

CDF angular analysis indicates $J^{PC} = 1^{++}$ or 2^{-+}

PRL 98,132002 (2007)

$X(3872)$ in $J/\psi\pi\pi\pi^0$ Final State

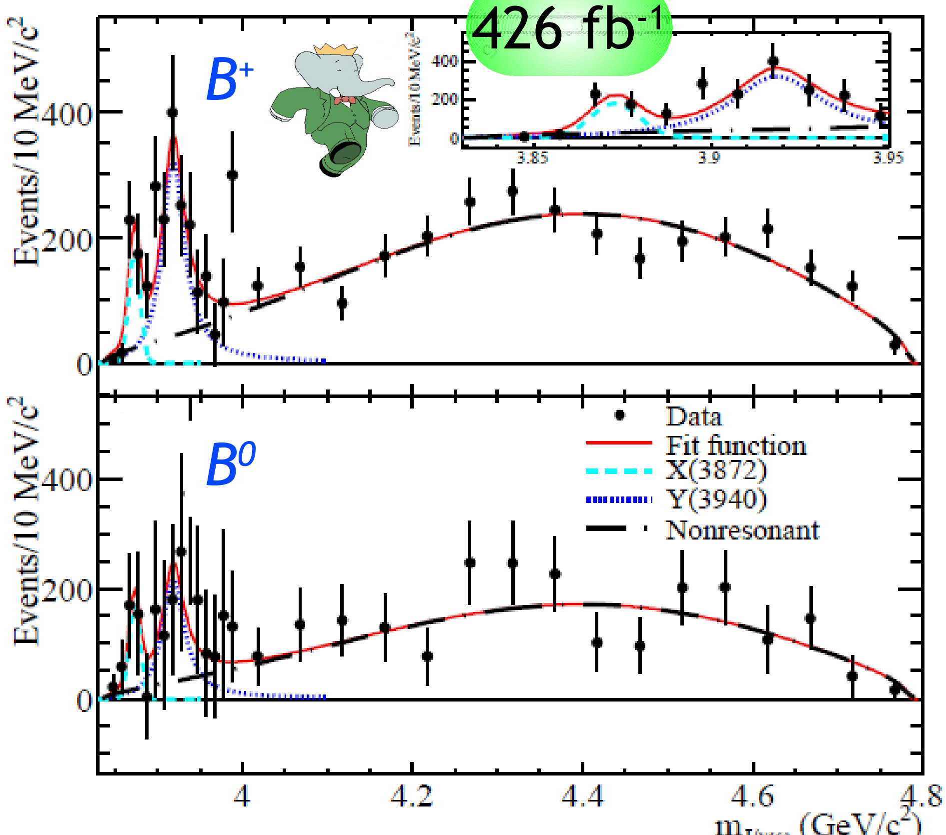
Preliminary Belle result reports 4.3σ evidence of $X(3872)$ decay to $J/\psi\pi\pi\pi^0$

$\pi^+\pi^-\pi^0$ mass distribution consistent with sub-threshold ω.

$$\frac{\mathcal{B}(X\to\pi^+\pi^-\pi^0 J/\psi)}{\mathcal{B}(X\to\pi^+\pi^- J/\psi)} = 1.0 \pm 0.4(\mathrm{stat}) \pm 0.3(\mathrm{syst})$$

hep-ex/0505037

256 fb^{-1}



BABAR preliminary @ QWG

4.0σ evidence of $X(3872)$ decay into $J/\psi\omega$ by BaBar.

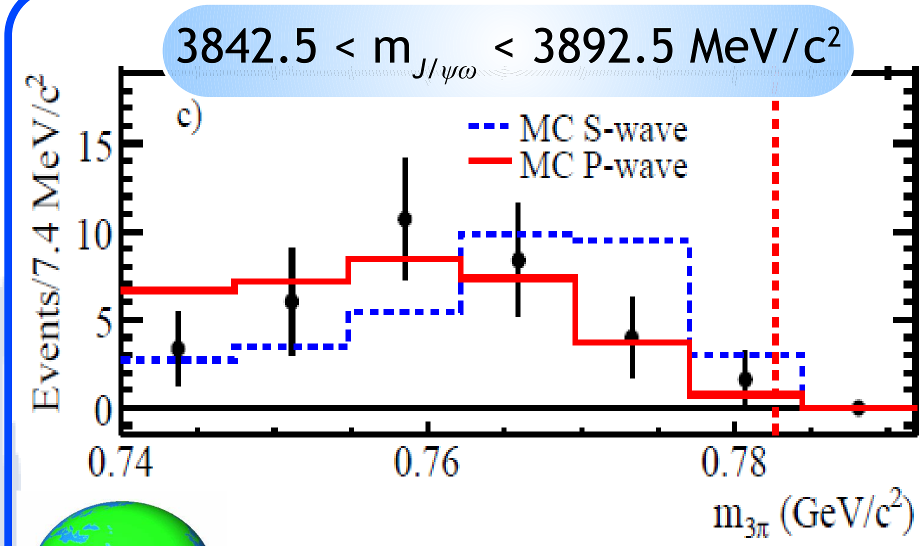
Signal size (signal yield divided by its errot is 3.5σ).

$$m(X(3872)) = 3873.0^{+1.8}_{-1.6} \pm 1.3\ MeV/c^2$$

$$\mathcal{BR}(B^+) = \frac{\mathcal{B}(X\to J/\psi\omega)}{\mathcal{B}(X\to J/\psi\pi^+\pi^-)} = 0.7 \pm 0.3$$

$$\mathcal{BR}(B^0) = \frac{\mathcal{B}(X\to J/\psi\omega)}{\mathcal{B}(X\to J/\psi\pi^+\pi^-)} = 1.7 \pm 1.3$$

$X(3872)$ in $J/\psi\pi\pi\pi^0$ Final State



BABAR preliminary @ QWG

Pions mass distribution can give some insight on *X(3872)* parity:

S-wave MC-data agreement at 7.1%

P-wave MC-data agreement at 61.9%.

Taking into account CDF analysis, BaBar favors $J^{PC} = 2^{-+}$

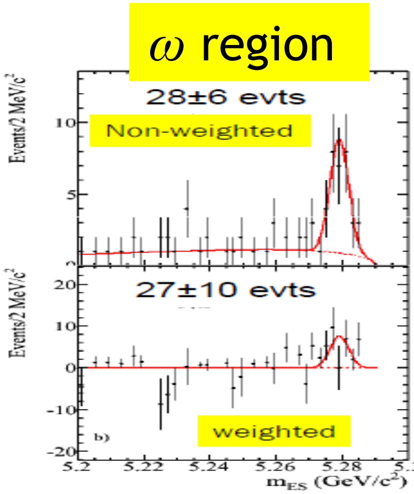
X(3872) mass consistent with $\eta_{c2}(1D)$.

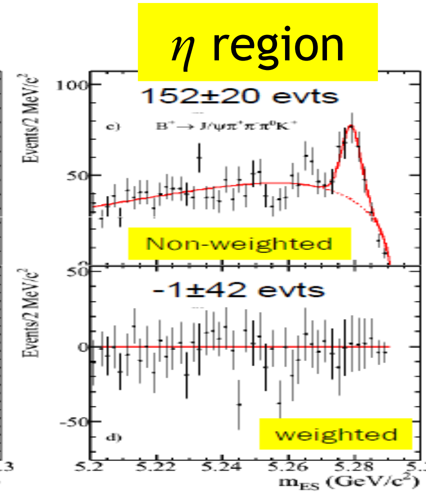
S.Godfrey and N. Isgur, PRD 32, 189 (1985)
E. Eichten et al., Rev. Mod.Phys 80, 1161 (2008)

Are you sure that this distribution is from ω signal?

Each event is given a weight related to ω angular information, non-ω component is projected away.

Sum of weights is consistent with number of fitted events.





X(3872) Radiative Decays into $J/\psi\gamma$

Why Radiative Decays?

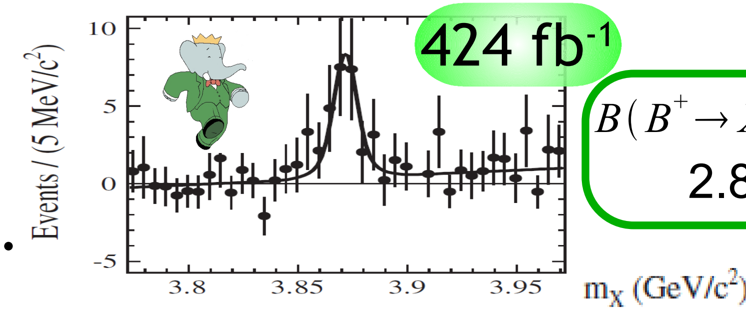
BF expected large for $J/\psi\gamma$ and small for $\psi(2S)\gamma$ in molecular picture.

Large $\psi(2S)\gamma$ BF may be accommodated through large $D\bar{D}^*$ - $c\bar{c}$ mixing.

Large $\psi(2S)\gamma$ rate disfavors $J^{PC} = 2^{-+}$. E.S. Swanson, Phys. Lett. B598, 197 (2004)

PRL 102, 132001 (2009)

BaBar observed the radiative decay $X(3872)\to J/\psi\gamma$ in $B^+\to XK^+$.



424 fb^{-1}

$$B(B^+\to X K^+)\times B(X\to J/\psi\gamma)$$
$$2.8 \pm 0.8 \pm 0.1$$

γ energy >470 MeV, π^0 veto.

$B \to \chi_{c1} K$ used as control sample.

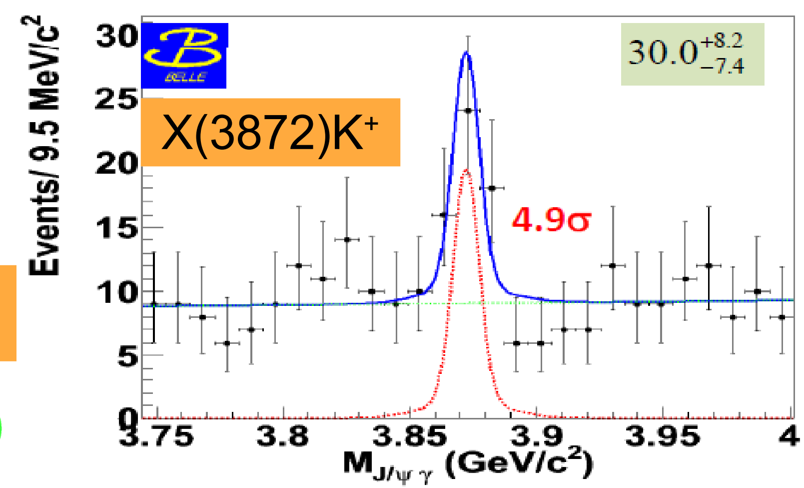
BREAKING NEWS

X(3872) mass and width referred to χ_{c1}

$$B(B^+\to X K^+)\times B(X\to J/\psi\gamma)=1.78^{+0.48}_{-0.46}\pm 0.12$$

Belle preliminary @ QWG

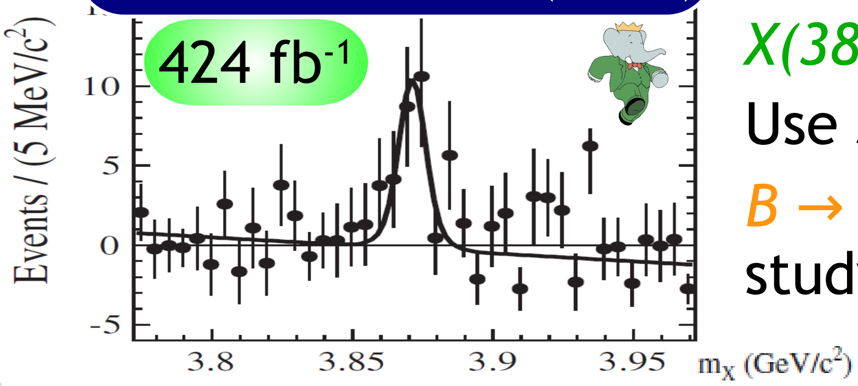
850 fb^{-1}



$X(3872)$ Radiative Decays into $\psi(2S)\gamma$

PRL 102, 132001 (2009)

424 fb^{-1}



BaBar also reports evidence of $X(3872)\rightarrow\psi(2S)\gamma$ in $B^+\rightarrow X(3872)K^+$ at 3.5σ.

Use *sPlot* to project signal events on m_X.

$B \rightarrow \psi(2S)(K\pi)$ background included in MC study.

$$\frac{\mathcal{B}(X(3872)\rightarrow\psi(2S)\gamma)}{\mathcal{B}(X(3872)\rightarrow J/\psi\gamma)} = 3.4 \pm 1.4$$

Loose cut on γ energy.

BREAKING NEWS

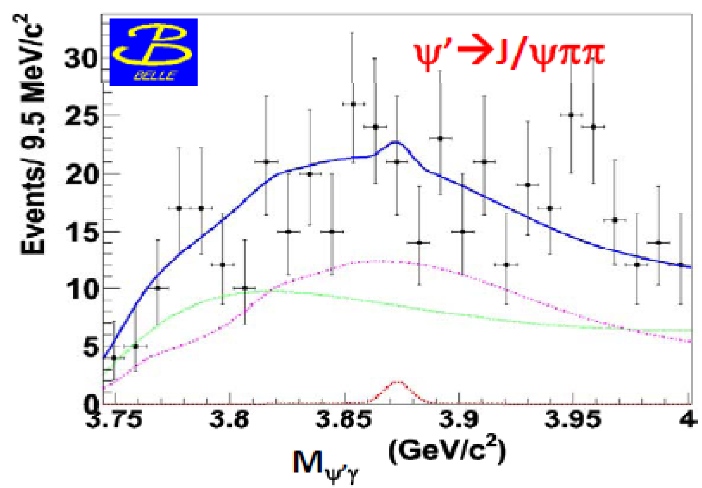
850 fb^{-1}

Explicit $\psi(2S)K^*$ veto:

- Look for $\pi^{0/+}$'s and combine with $\psi(2S)K$
- Reject events consistent with $\psi(2S)K^*$

Fit to extract signal events.

$B \rightarrow \psi(2S)K^{(*)}$ background parametrized with MC and fixed in the fit.



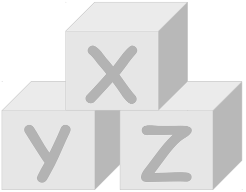
Belle preliminary @ QWG

No Signal Observed!

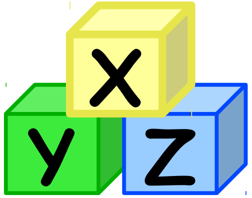
$$\frac{\mathcal{B}(X(3872)\rightarrow\psi(2S)\gamma)}{\mathcal{B}(X(3872)\rightarrow J/\psi\gamma)} < 2.1$$

@90%CL

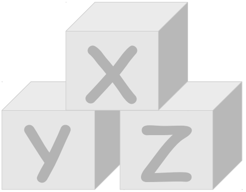
Introduction



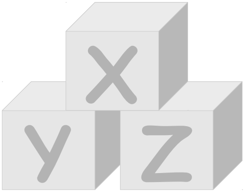
X(3872)



The 3940 Family



New $J/\psi\,\phi$ states

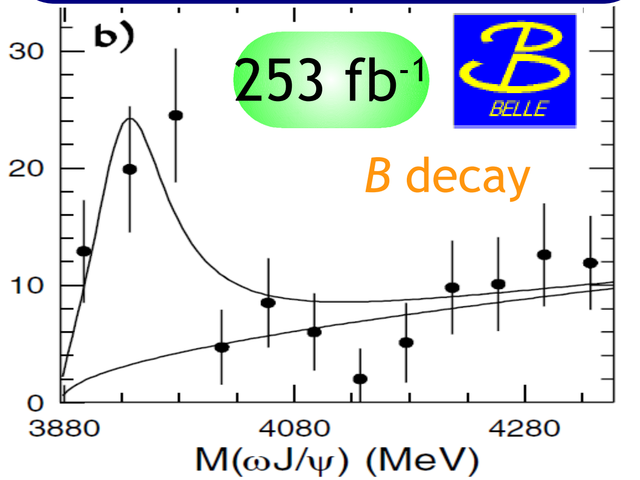


Charged States

Y(3940) in $J/\psi\omega$ Final State

- Observed by both BaBar and Belle in *B* decays.
  - No evidence of $D\bar{D}^*$ final state with the same production process.
- Belle reports a peak in $\gamma\gamma \to J/\psi\omega$ ($J^C = 0^+, 2^+$) [also dubbed *X(3915)*]:
  - $\Gamma_{\gamma\gamma}(Y(3940)) \times B(Y(3940) \to J/\psi\omega) = (61 \pm 17 \pm 8)$ eV for $J^P = 0^+$.
  - $\Gamma_{\gamma\gamma}(Y(3940)) \times B(Y(3940) \to J/\psi\omega) = (18 \pm 5 \pm 2)$ eV for $J^P = 2^+$.
- Assuming $\Gamma_{\gamma\gamma} \sim 1$ keV: $B(Y(3940) \to J/\psi\omega) \sim (1\text{-}6)\%$ large for conventional $c\bar{c}$.

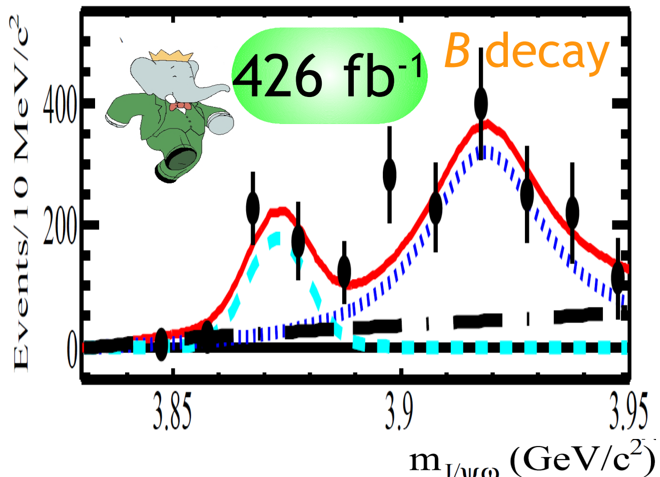
PRL 94, 182002 (2005)



$M = 3943 \pm 11 \pm 13$ MeV/c^2

$\Gamma = 87 \pm 22 \pm 26$ MeV/c^2

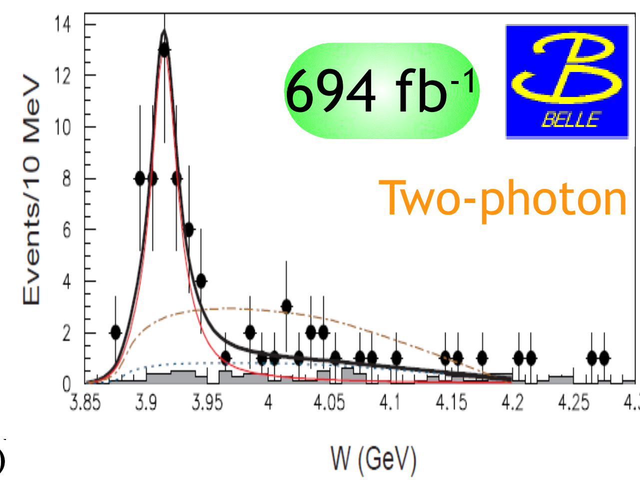
BABAR preliminary



$$M = 3919.1^{+3.8}_{-3.5} \pm 2.0\ MeV/c^2$$

$$\Gamma = 31^{+10}_{-8} \pm 5\ MeV/c^2$$

PRL 104, 092001 (2010)



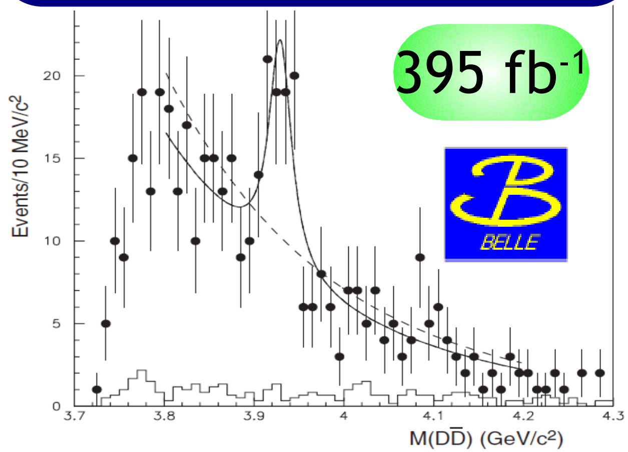
$M = 3914 \pm 3 \pm 2$ MeV/c^2

$\Gamma = 17 \pm 10 \pm 3$ MeV/c^2

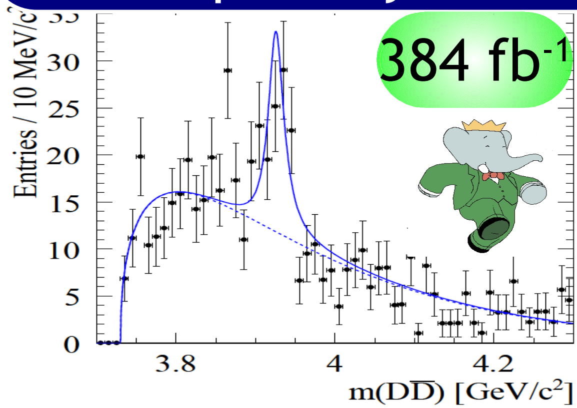
$Z(3930)$ in Two-Photon Collisions

$Z(3930)$ observed in $\gamma\gamma \to D\bar{D}$ process by Belle and confirmed by BaBar

PRL 96, 082003 (2006)



hep-ex/1002.0281
Accepted by PRD



Mass:

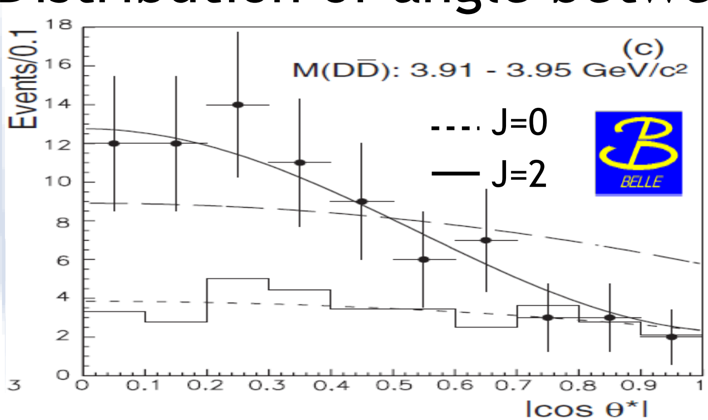
- Belle: $3929 \pm 5 \pm 2$ MeV/c^2
- BaBar: $3927 \pm 2 \pm 1$ MeV/c^2

Width:

- Belle: $29 \pm 10 \pm 2$ MeV/c^2
- BaBar: $21 \pm 7 \pm 4$ MeV/c^2

Two-photon production and spin zero final state constrain J^{PC} = [*even*]$^{++}$.

Distribution of angle between $D\bar{D}$ system and beam direction sensitive to J.

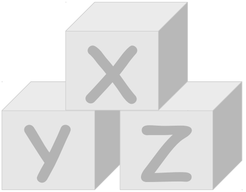


BaBar confirms Belle's 2^{++} assignment: mass and J^{PC} are consistent with $\chi'_{c2}(2P)$ $c\bar{c}$ state.

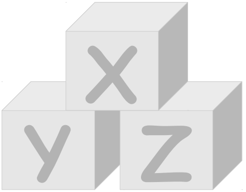
Belle reports $\dfrac{B(Z(3930)\to D^+ D^-)}{B(Z(3930)\to D^0 \bar{D}^0)} = 0.74 \pm 0.43 \pm 0.16$

Consistent with isospin expectation.

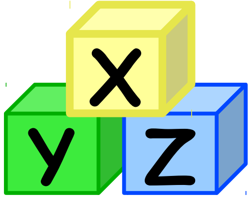
Introduction



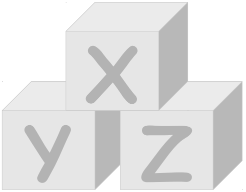
X(3872)



The 3940 Family



New $J/\psi\phi$ states



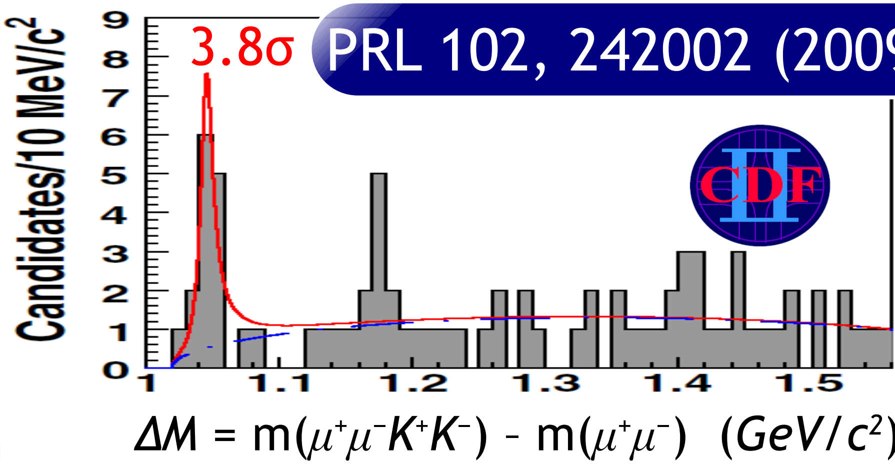
Charged States

Y(4140) in *B* decays

Search of chrmonium-like resonance in $J/\psi\,\phi$ final state to look for predicted $c\bar{c}s\bar{s}$ tetraquark[†] in 4270 - 4350 MeV/c² mass range.

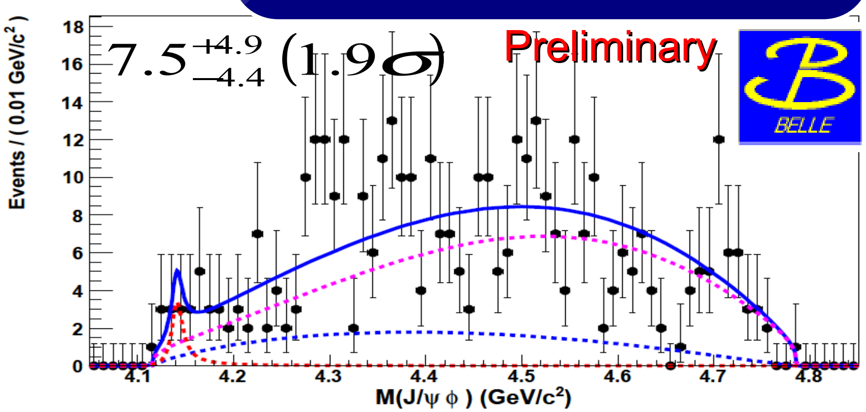
- CDF reports a peak in $J/\psi\,\phi$ mass spectrum in B^+ decays.
- Preliminary Belle analysis finds no peak, but results are consistent.

PRL 102, 242002 (2009)



$$M = 4143.0 \pm 2.9 \pm 1.2\ MeV/c^2$$
$$\Gamma = 11.7^{+8.3}_{-5.0} \pm 3.7\ MeV/c^2$$

Yuan @ PIC09



$B(B^+ \rightarrow Y(4140)K^+) \times B(Y(4140) \rightarrow J/\psi\,\phi)$

Belle: $< 6 \times 10^{-6}$ @ 90% CL

CDF: $(9.0 \pm 3.4 \pm 2.9) \times 10^{-6}$ ‡

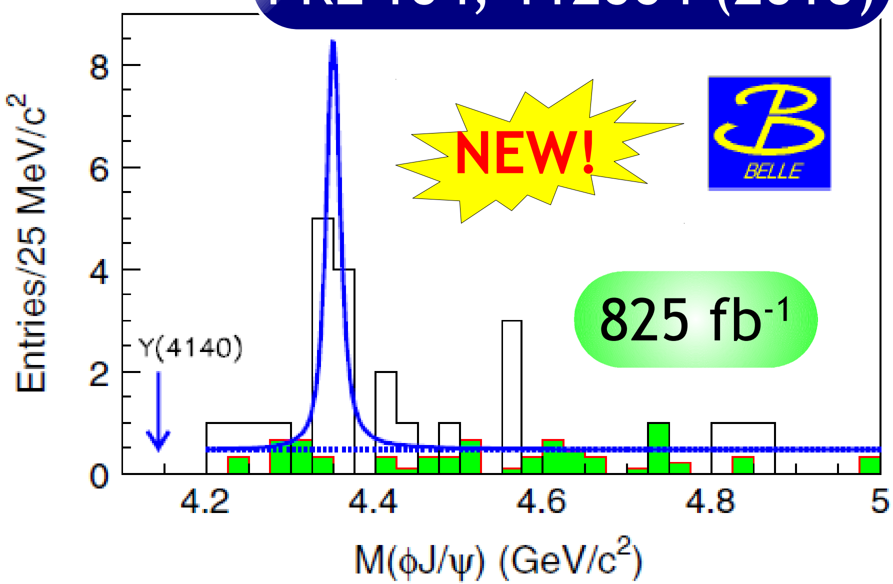
In Belle analysis *Y(4140)* parameters are fixed to CDF values.

† N.V. Dresnska *et al.* PRD **79**, 077502 (2009)
‡ K.Yi, hep-ex/0910.3163v3

Search for Y(4140) in Two-Photon Collisions

Several interpretations for Y(4140) proposed[†‡], including $D_s^{*+}D_s^{*-}$ molecule. $\Gamma_{\gamma\gamma}(Y(4140)) \times B(Y(4140)\to J/\psi\,\phi)$ using CDF mass and width values is expected $176^{+137}_{-97}\,(189^{+147}_{-100})$ eV for $J^{PC} = 0^{++}\ (2^{++})$[¶].

PRL 104, 112004 (2010)



$$M = 4350.6^{+4.6}_{-5.1} \pm 0.7\ MeV/c^2$$
$$\Gamma = 13^{+18}_{-9} \pm 4\ MeV/c^2$$

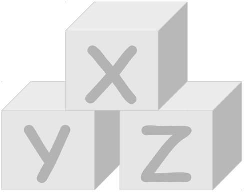
No events in Y(4140) region
$\Gamma_{\gamma\gamma}(Y(4140)) \times B(Y\to J/\psi\,\phi) < 41(6)$eV
for $J^{PC} = 0(2)$++

Evidence (3.2σ) of a new narrow state dubbed *X(4350)*

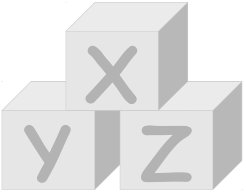
Mass consistent with prediction for $c\bar{c}s\bar{s}$ tetraquark[#] or $D_s^{*+}D_{s0}^{*-}$ molecular state[o].

[†] N. V. Dresnska *et al.* PRD **79**, 077502 (2009)
[‡] N. Mahajan, hep-ph/0903.3107
[¶] T.Branz *at al.*, PRD **80**, 054019 (2009)
[#] Fl. Stancu, hep-ph/0906.2485
[o] J.R. Zhang and M.Q. Huang, hep-ph/0905.4672

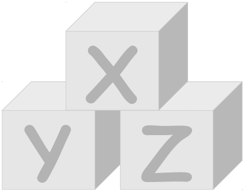
Introduction



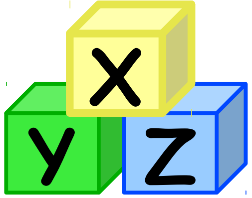
X(3872)



The 3940 Family



New $J/\psi\,\phi$ states



Charged States

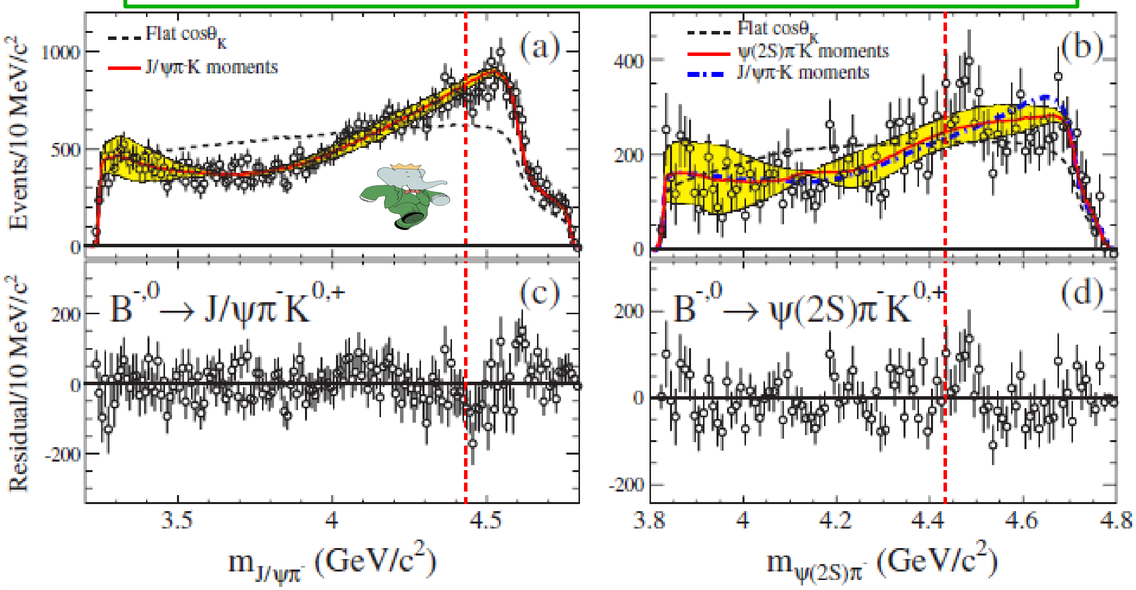
$Z(4430)^-$ BaBar Analysis

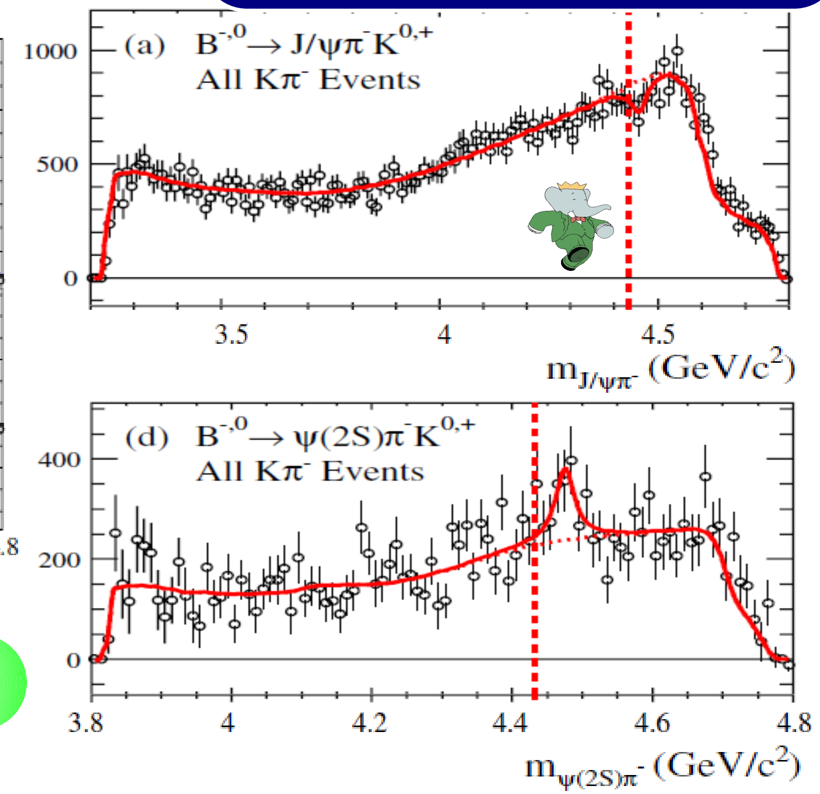
PRL 100, 142001 (2008) Belle observed $Z(4330)^-$ in $B\to\psi(2S)\pi^-K$ decay.

BaBar performs a detailed study of $K\pi$ mass and angular distribution to draw projections of the $K\pi$ system on $\psi(2S)\pi^-$ mass.

$K\pi$ reflection reproduces data well

PRD 79, 112001 (2009)





- No signal for $J/\psi\pi^-$.
- $\psi(2S)\pi^-$ analysis:
  - 1.9σ @ $M = 4476 \pm 3$ MeV/c^2.
  - 3.1σ using Belle parameters.

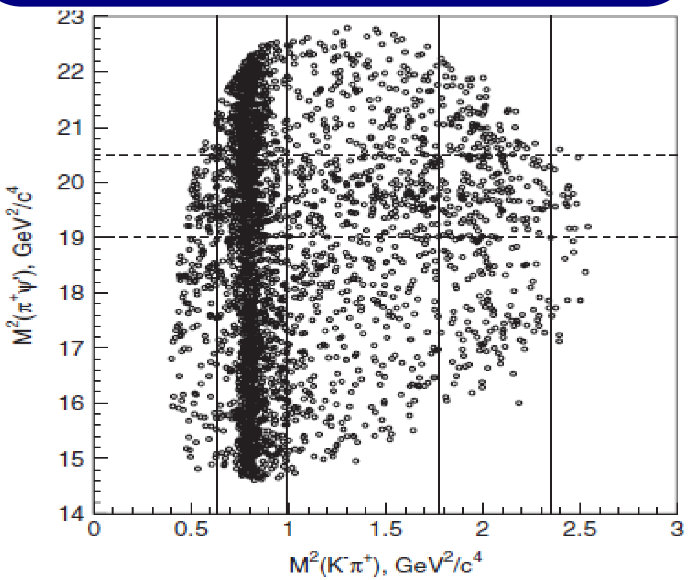
413 fb^{-1}

$Z(4330)^-$ not confirmed

$Z(4430)^-$ Belle Reanalysis

Belle performs a new analysis of its data using a Dalitz Plot formalism:

PRD 80, 031104(R) (2009)



Include relativistic Breit-Wigner for $K\pi$ resonances (S, P, D waves)

$$M = 4433 \pm 4 \pm 2\ MeV/c^2$$
$$\Gamma = 45^{+18}_{-13}\ {}^{+30}_{-13}\ MeV/c^2$$

Old analysis approach

$$M = 4433^{+15}_{-12}\ {}^{+19}_{-13}\ MeV/c^2$$
$$\Gamma = \boxed{107^{+86}_{-43}\ {}^{+74}_{-56}}\ MeV/c^2$$

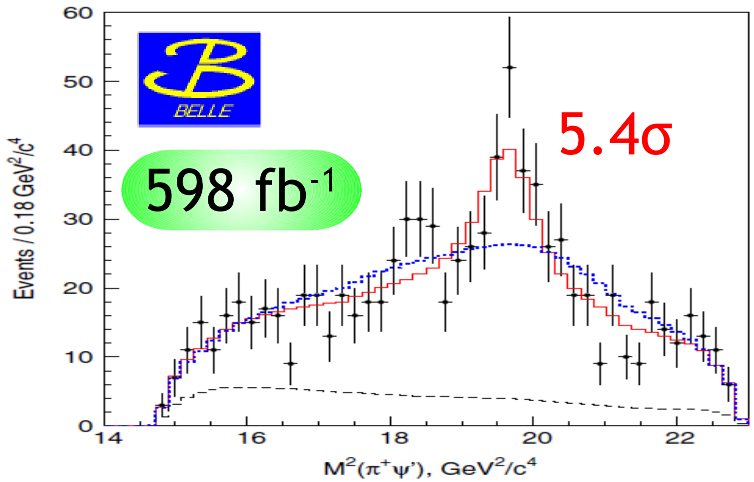
Dalitz Plot approach

$B(B^0 \to Z(4430)^- K^+) \times B(Z(4430)^- \to \psi(2S)\pi^-)$

$< 3.1\ 10^{-5}$ @ 90% CL

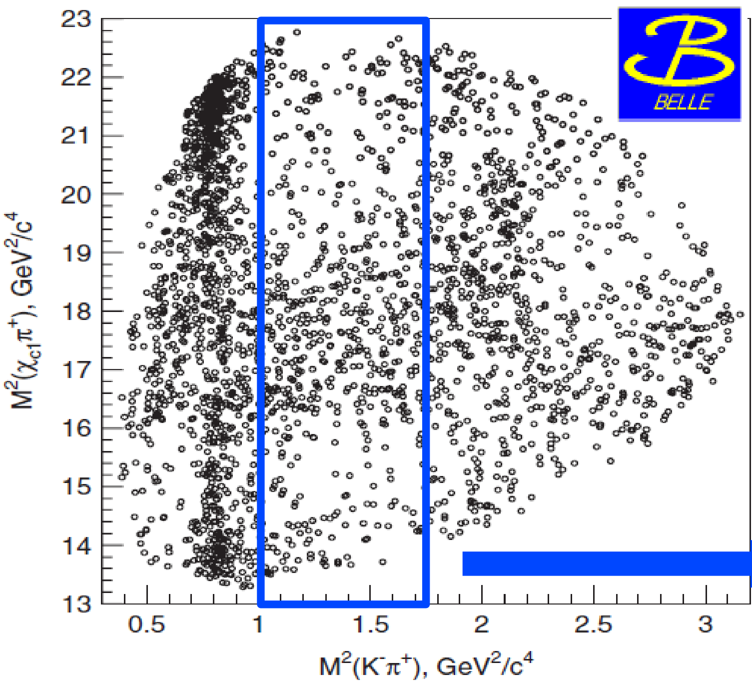
$= (3.2^{+1.8}_{-0.9}\ {}^{+5.3}_{-1.6}) \times 10^{-5}$

$J/\psi\pi^-$ analysis by Belle may be a useful cross-check.



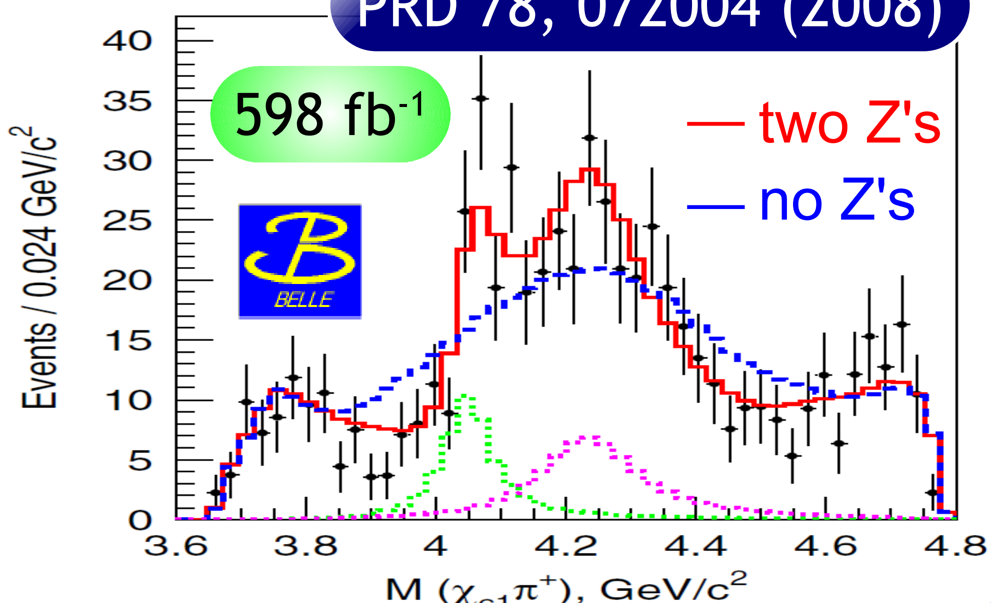
More Charged States in $\chi_{c1}\pi^-$ Decays

Search of other tetraquark states motivated by *Z(4430)*$^-$ claim.



- $B\to\chi_{c1}\pi K$ DP dominated by K^* contribution.
- DP analysis includes $K\pi$ resonances.
- Fit performed with both one or two resonance-like structures in m($\chi_{c1}\pi^-$).
- Two resonances scenario favored at 5.7σ level.

PRD 78, 072004 (2008)



$$M(Z_1)=4051\pm14^{+20}_{-41}\,MeV/c^2$$
$$\Gamma(Z_1)=82^{+21}_{-17}\,{}^{+47}_{-22}\,MeV/c^2$$

$$M(Z_2)=4248^{+44}_{-28}\,{}^{+180}_{-35}\,MeV/c^2$$
$$\Gamma(Z_2)=177^{+54}_{-39}\,{}^{+316}_{-61}\,MeV/c^2$$

Conclusions

Charmonium spectroscopy had renewed experimental and theoretical interest after the *X(3872)* discovery.

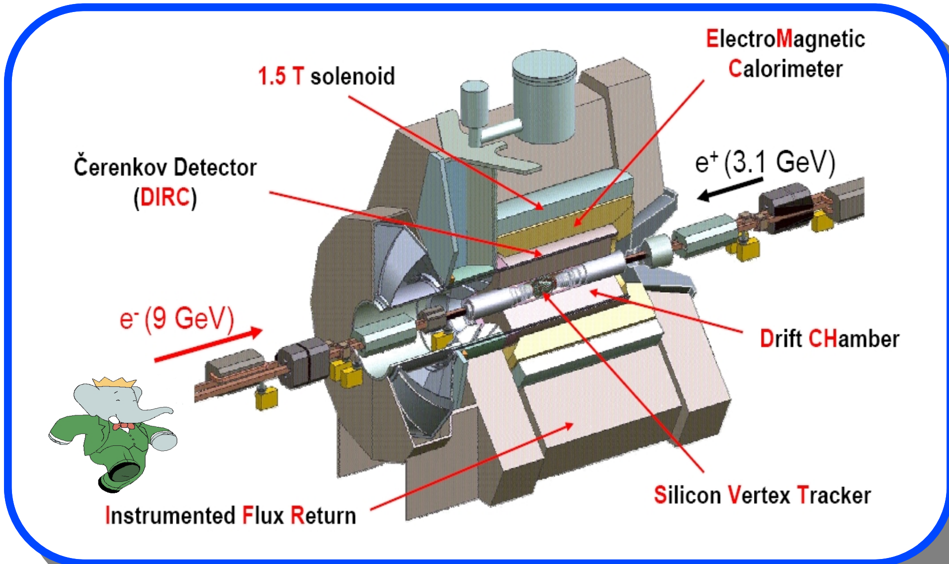
- *X(3872)* widely studied, but no definitive answers ($D\bar{D}^*$ molecule? conventional $c\bar{c}$?).
  - BaBar favors 2^{-+} consistent with expectations for $\eta_{c2}(1D)$;
  - Belle and some theoretical arguments favor 1^{++}.
- 3940 MeV/c^2 region quite crowded: *Y(3940)* good non-$c\bar{c}$ candidate?
- Charged states are not well established:
  - confirmation of $Z(4430)^-$ may come with more data or from analysis at hadronic machines;
  - $Z_1(4050)^-$ and $Z_2(4250)^-$ are tricky at hadronic machines.

Many works are on going in this field: *B*-factories potentiality not exhausted yet, hadronic machines (CDF, D0, LHC experiments) may look for some states.

New and exciting results may come in near future!

Backup

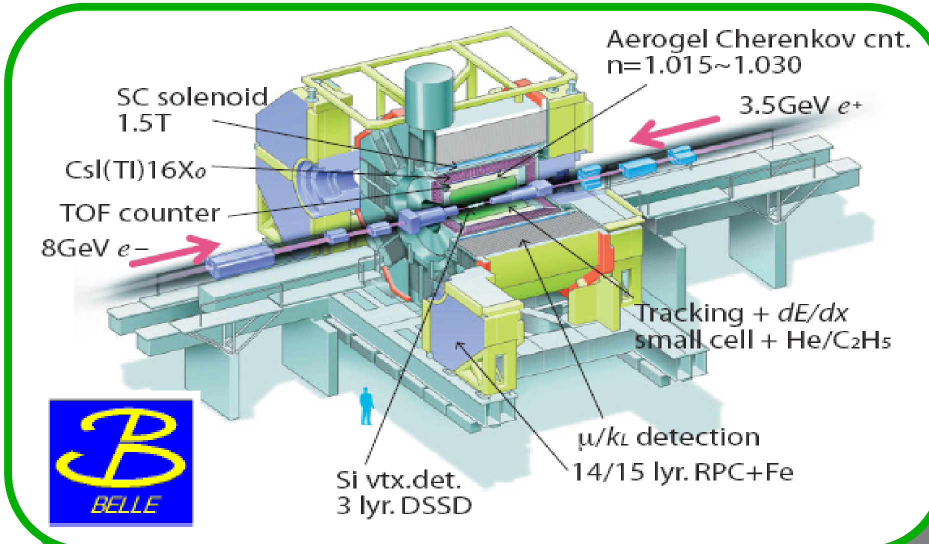
B-factories Experiments



BaBar operated at PEP-II at SLAC National Accelerator Laboratory until April 2008.

Belle operated at KEKB at Tsukuba

Asymmetric e^+e^- colliders with $\sqrt{s}$~10.6 GeV



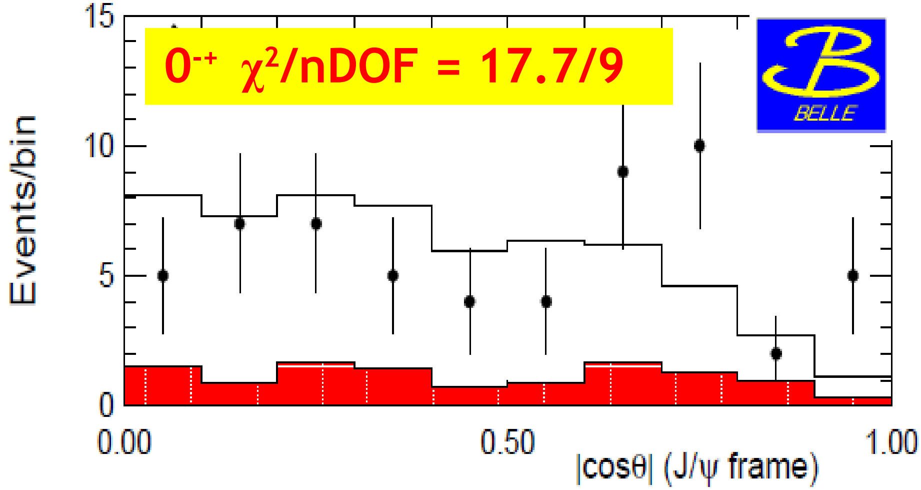
Integrated luminosity:

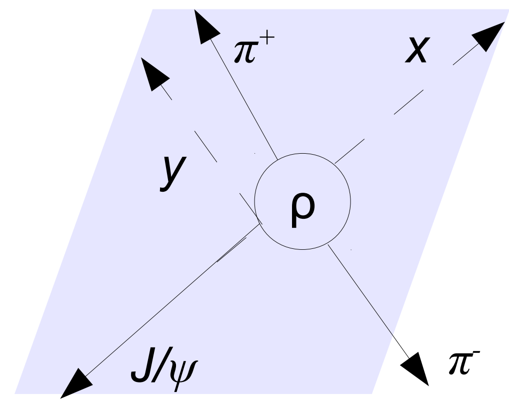
BaBar ~530 fb^{-1} Belle ~1000 fb^{-1}

BaBar also collected world-largest samples at Υ(2S) and Υ(3S)

Belle also collected samples at Υ(1S) and Υ(5S)

$X(3872)$ $0^{\pm -}$ Angular Distributions by Belle



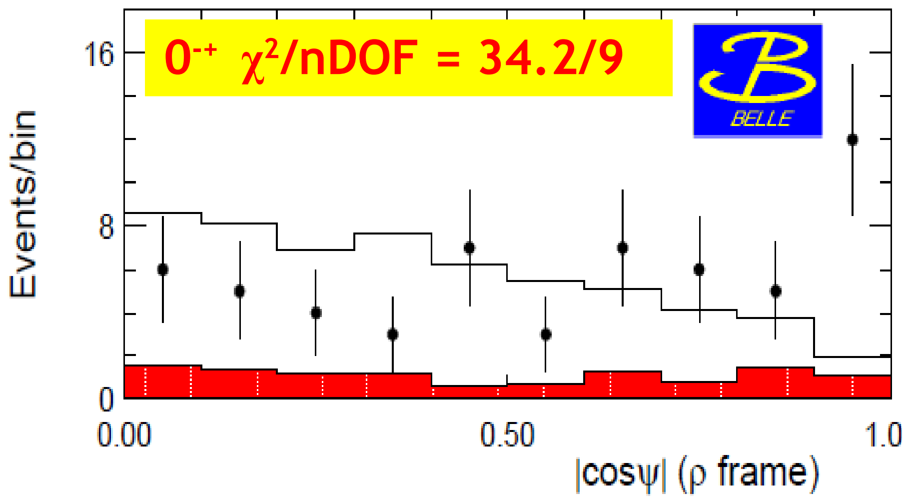


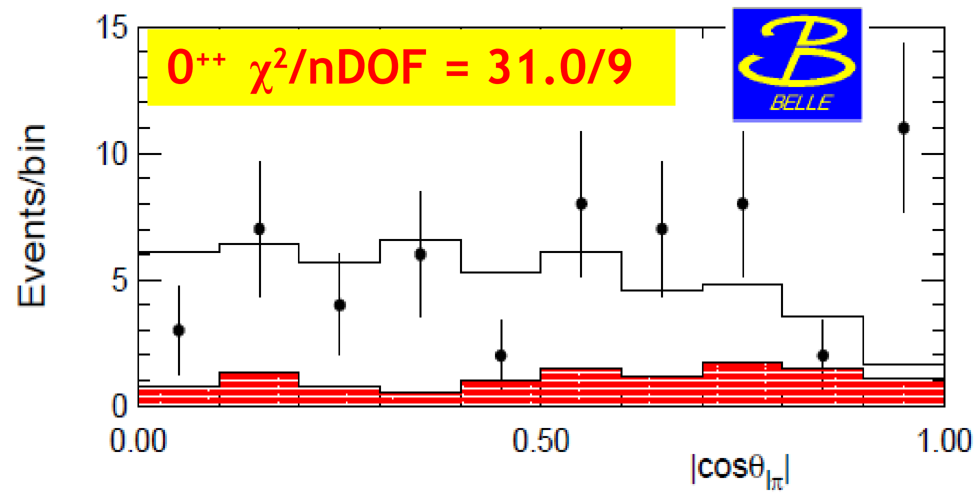
ρ frame

xy plane defined by J/ψ and π^+

z forms a right-handed coordinate system with x and y

J.L Rosner PRD70 094023 (2004)





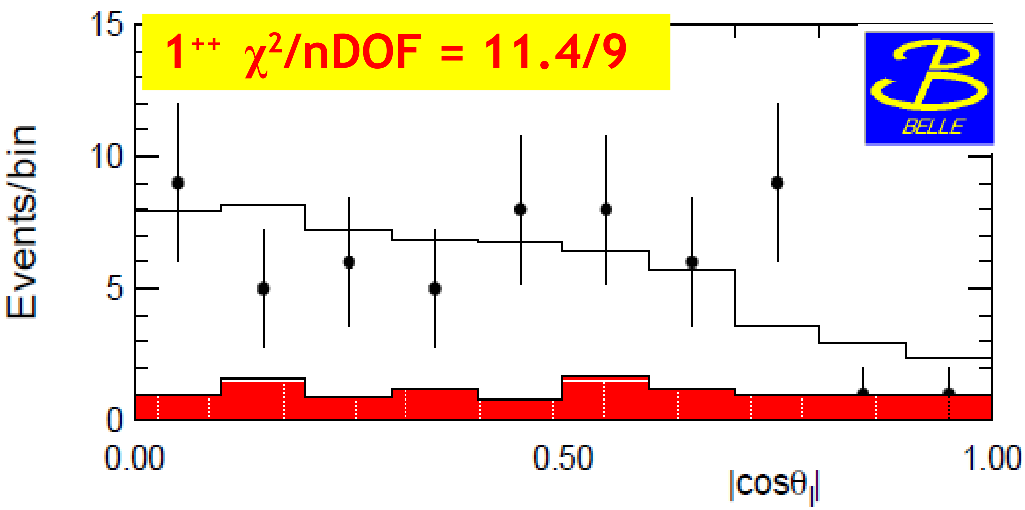
θ: angle beween l^+ and z in J/ψ frame

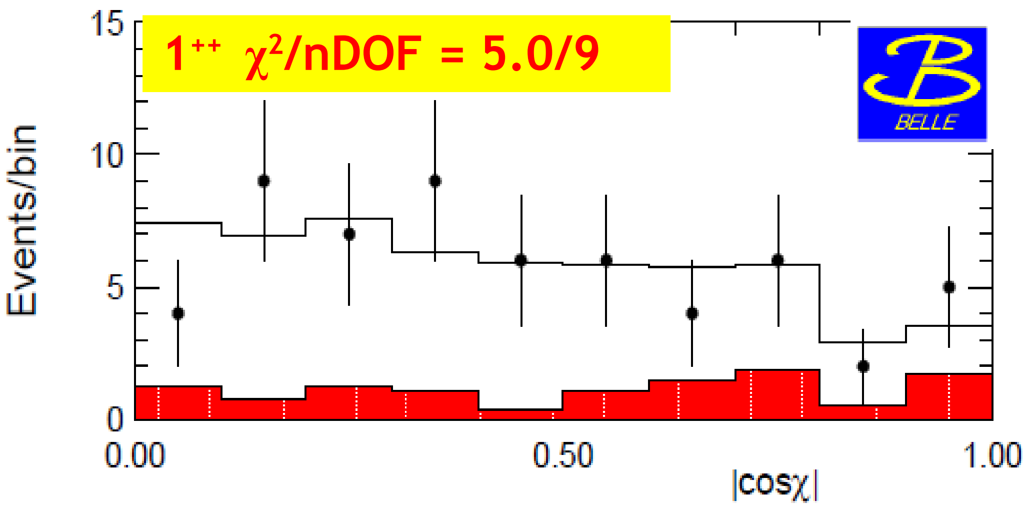
ψ: angle between π^+ and x in ρ frame

$\theta_{l\pi}$: angle beween l^+ and π^+ in X frame

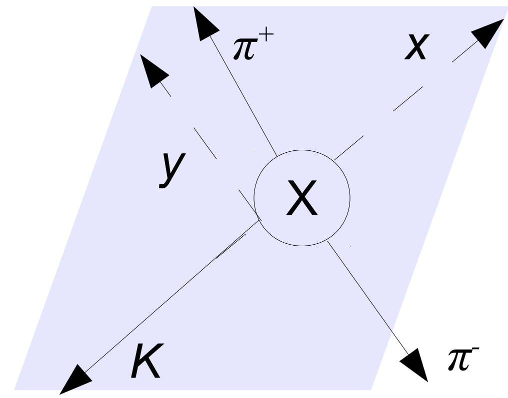
hep-ex/0505038

$X(3872)$ 1^{++} Angular Distributions by Belle





hep-ex/0505038



X frame

xy plane defined by K^+ and π^+

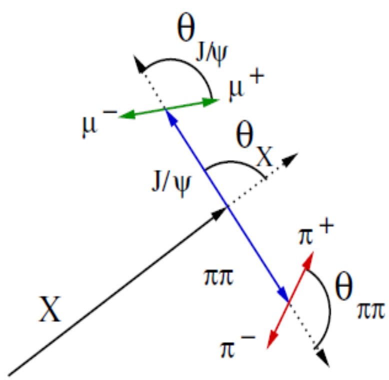
z forms a right-handed coordinate system with x and y

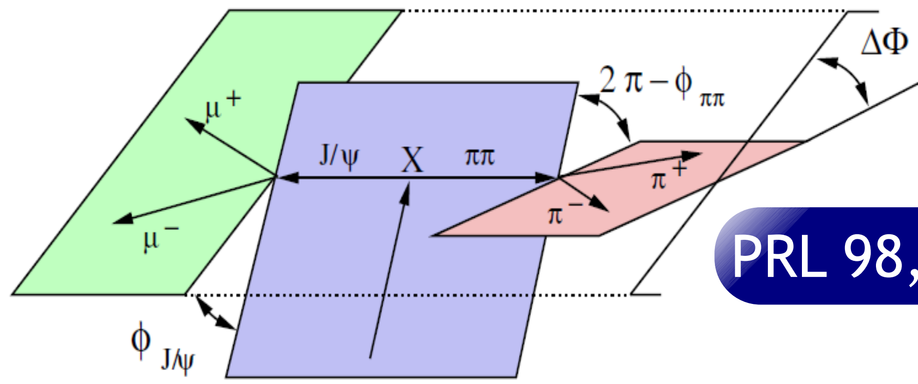
J.L Rosner PRD70 094023 (2004)

θ_l: angle beween l^+ and z

χ: angle between π^+ and x

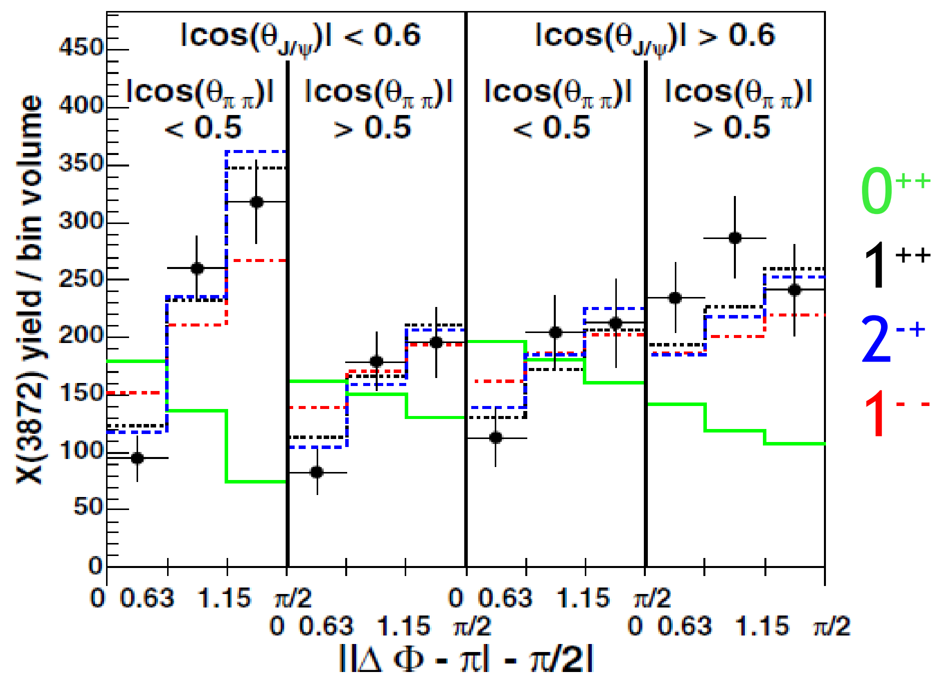
X(3872) Angular Analysis by CDF





PRL 98,132002 (2007)

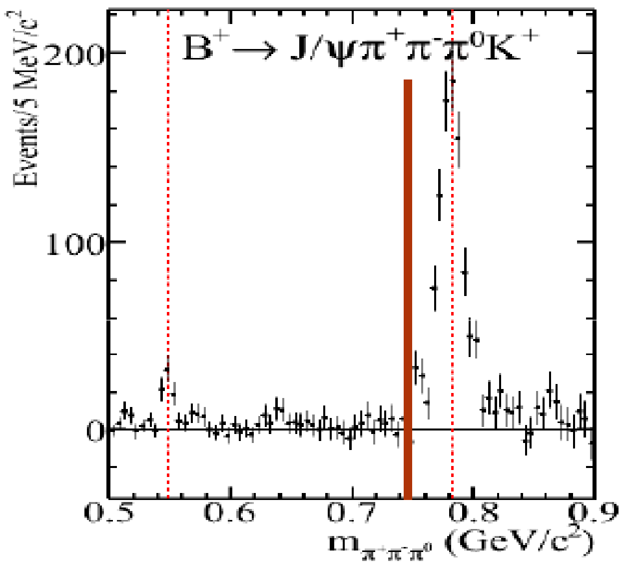
J^{PC}	decay	LS	χ^2 (11 d.o.f.)	χ^2 prob.
1^{++}	$J/\psi\rho^0$	01	13.2	0.28
2^{-+}	$J/\psi\rho^0$	11,12	13.6	0.26
1^{--}	$J/\psi(\pi\pi)_S$	01	35.1	2.4×10^{-4}
2^{+-}	$J/\psi(\pi\pi)_S$	11	38.9	5.5×10^{-5}
1^{+-}	$J/\psi(\pi\pi)_S$	11	39.8	3.8×10^{-5}
2^{--}	$J/\psi(\pi\pi)_S$	21	39.8	3.8×10^{-5}
3^{+-}	$J/\psi(\pi\pi)_S$	31	39.8	3.8×10^{-5}
3^{--}	$J/\psi(\pi\pi)_S$	21	41.0	2.4×10^{-5}
2^{++}	$J/\psi\rho^0$	02	43.0	1.1×10^{-5}
1^{-+}	$J/\psi\rho^0$	10,11,12	45.4	4.1×10^{-6}
0^{-+}	$J/\psi\rho^0$	11	104	3.5×10^{-17}
0^{+-}	$J/\psi(\pi\pi)_S$	11	129	$\leq 1\times10^{-20}$
0^{++}	$J/\psi\rho^0$	00	163	$\leq 1\times10^{-20}$

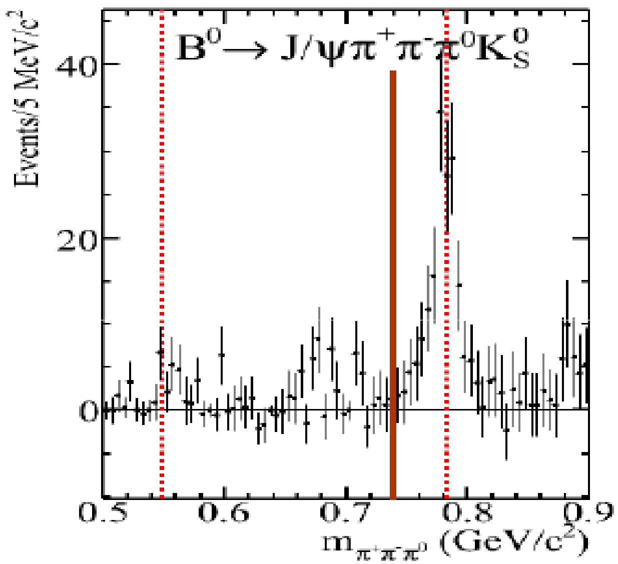


Signal yields obtained by fit to $J/\psi\pi\pi$ mass

$X(3872)$ in $J/\psi\pi\pi\pi^0$ by BaBar

BABAR preliminary

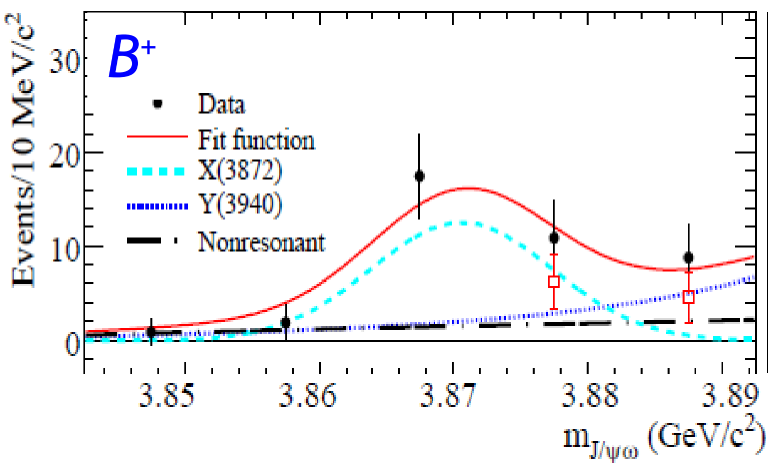


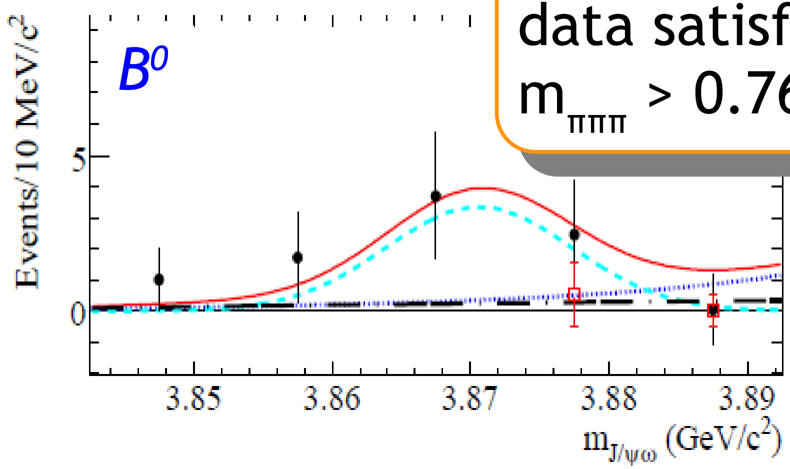


$m_{\pi\pi\pi} > 0.740$ GeV/c²

Previous analysis used

$m_{\pi\pi\pi} > 0.769$ GeV/c²





Open red sqares are data satisfing $m_{\pi\pi\pi} > 0.769$ GeV/c²

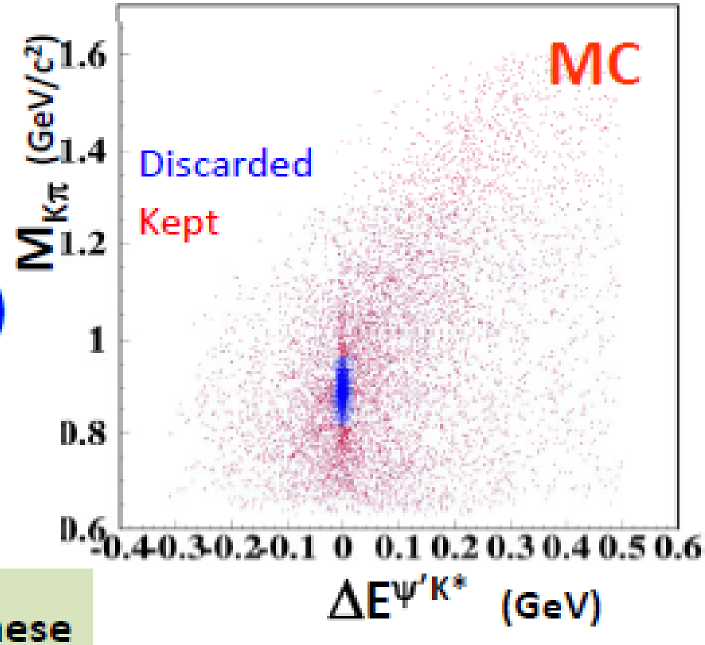
$X(3872)$ decay to $\psi(2S)\gamma$

Bhardwaj @ QWG2010

Veto to reduce background coming from $\psi' K^*$

- Look for additional $\pi^{+/0}$ in the event
- Associate this $\pi^{+/0}$ with ψ' and K (from X(3872) K candidates) to form $\psi' K^*$

✓ $\Delta E^{\psi' K^*}$ $(\equiv E_{\psi'} + E_K + E_\pi - E^{cm}{}_{beam})$,
✓ $M_{K\pi}$, invariant mass of K π.
✓ $M_{bc}{}^{\psi' K^*} = \sqrt{(E^{cm}{}_{beam}{}^2 - (p_{\psi'} + p_K + p_\pi)^2)}$



if

$|\Delta E^{\psi' K^*}| < 20$ MeV
$M_{K\pi} \in (892 \pm 75)$ MeV/c^2
$M_{bc}{}^{\psi' K^*} > 5.27$ GeV/c^2

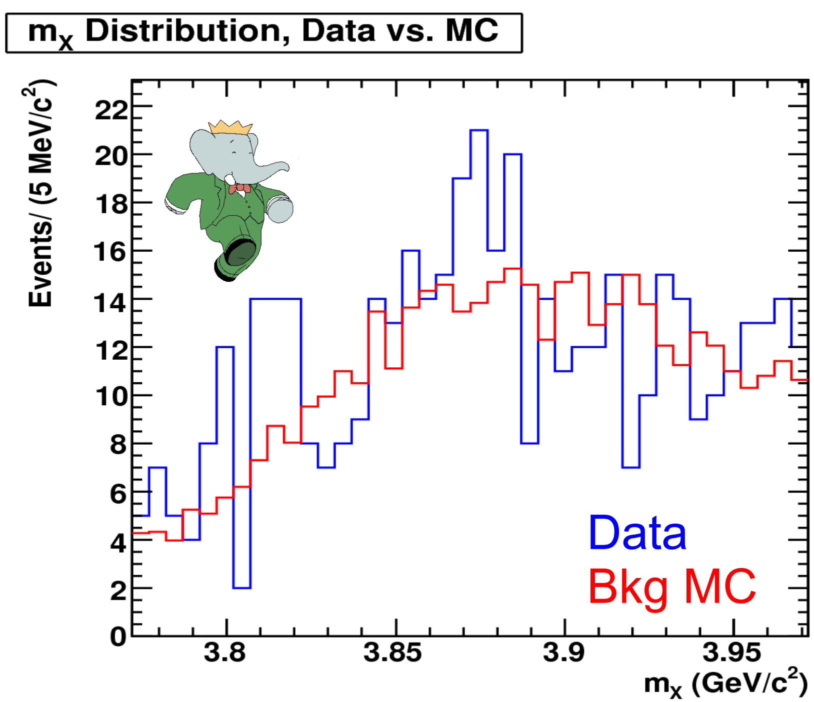
⇒ **Rejected these events**

❖ $\psi' K^*$ background is reduced by ~40%

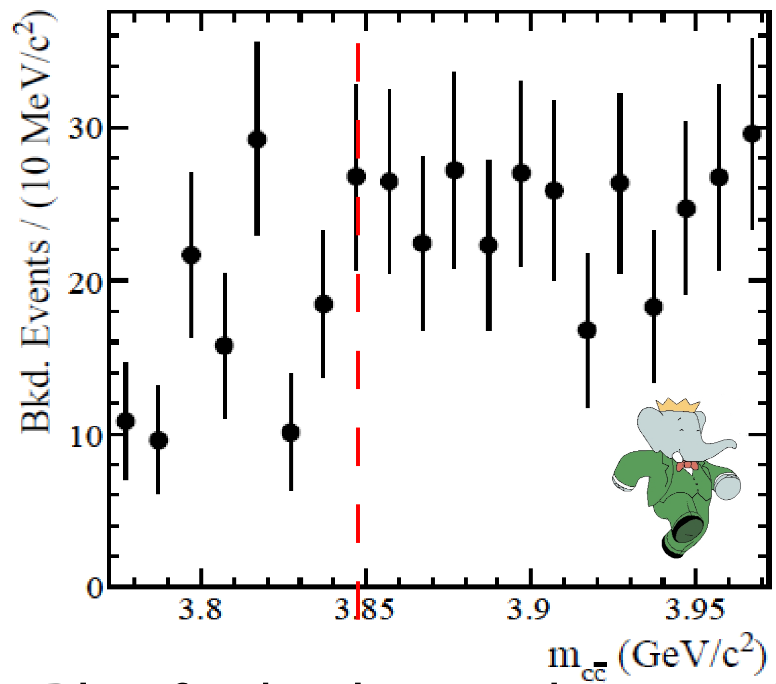
$X(3872)$ decay to $\psi(2S)\gamma$

$B \to \psi(2S)(K\pi)$ background is included in MC studies in BaBar analysis.

Background material for PRL 102, 132001 (2009)
See B. Fulsom UBC Thesis (SLAC-R-949)



Raw $\psi(2S)\gamma$ mass distribution



sPlot for background events in $B \to \psi(2S)\gamma K^{+}$

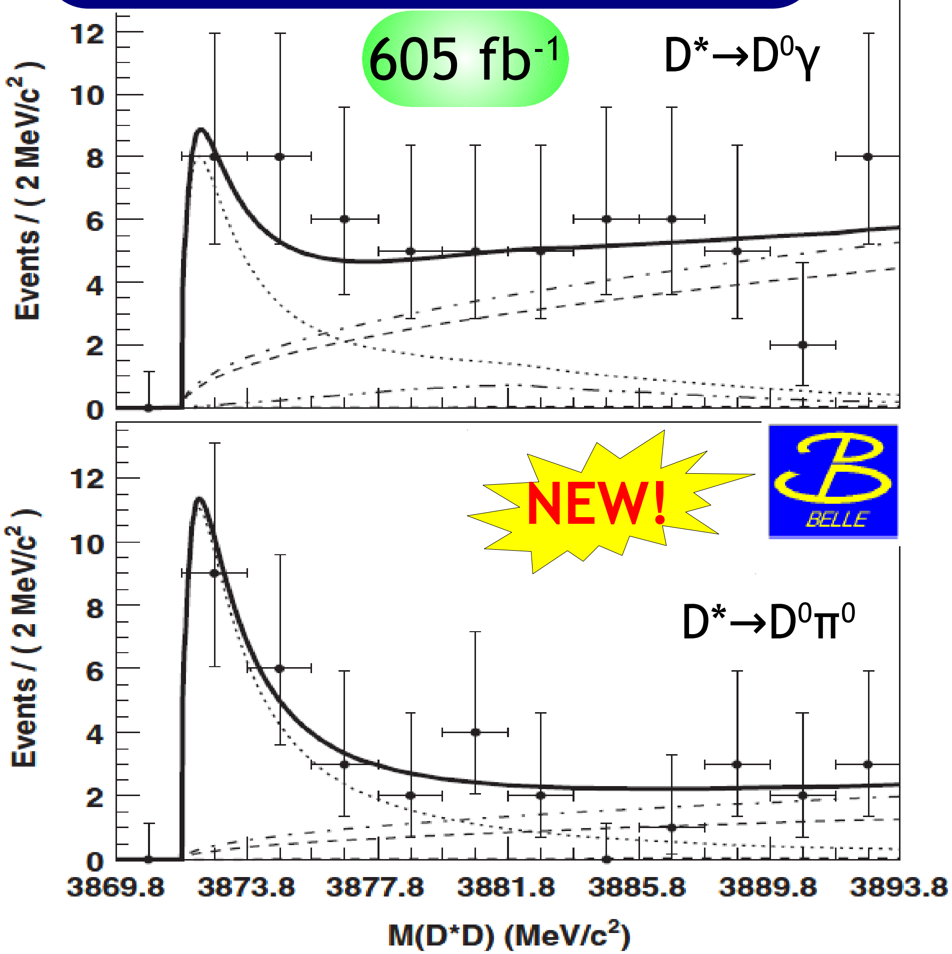
$X(3872)$ in $D^0\bar{D}^{*0}$ Final State

First enhancement in $D^0\bar{D}^0\pi^0$ observed by Belle near $D\bar{D}^*$ threshold.

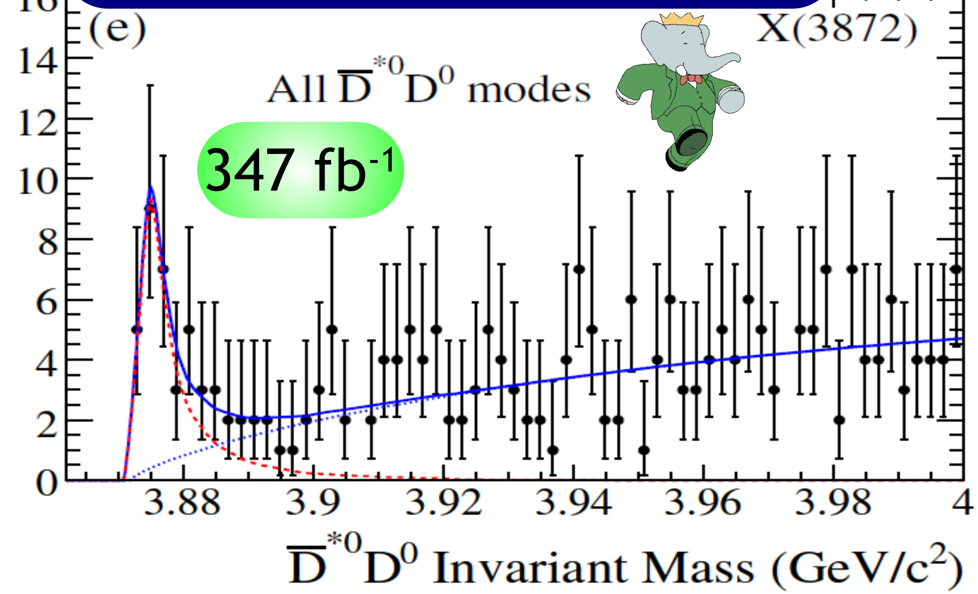
No possibility to discriminate $D\bar{D}^*$ against non-resonant $D^0\bar{D}^0\pi^0$.

BaBar and improved Belle analysis observe $D\bar{D}^*$ final state.

PRD 81, 031103(R) (2010)



PRD 77, 011102(R) (2008)

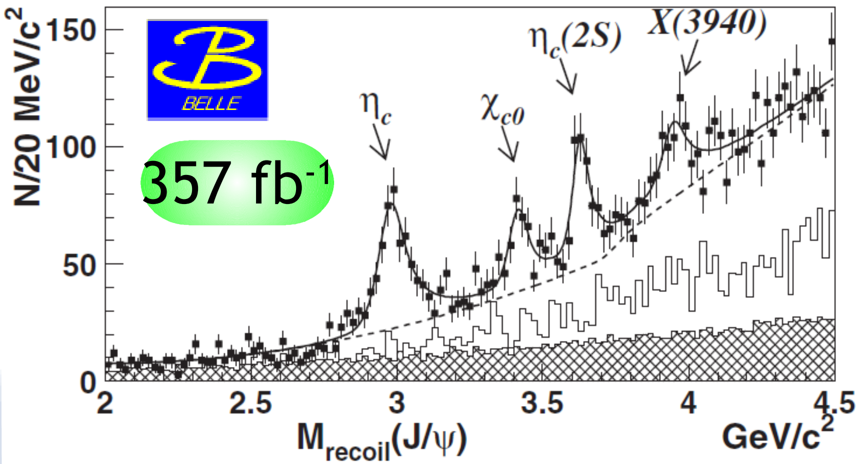


$D\bar{D}^*$ lineshape difficult to model.

D and D^* mass are constrained in both analyses: constrain $X(3872)$ mass above threshold.

X(3940) in Double Charmonium

Many results in 3940 MeV/c^2 region: at least two different states.



PRL 98, 082001 (2007)

- First observed in inclusive $e^+e^- \to J/\psi X$.
- Peak may receive contributions from different processes.
- No evidence of decay into $J/\psi\omega$,

- *X(3940)* decays to $D\bar{D}^*$ observed with significance of 5.7σ

$$M = 3942^{+7}_{-6} \pm 6\ MeV/c^2$$
$$\Gamma = 37^{+26}_{-15} \pm 8\ MeV/c^2$$

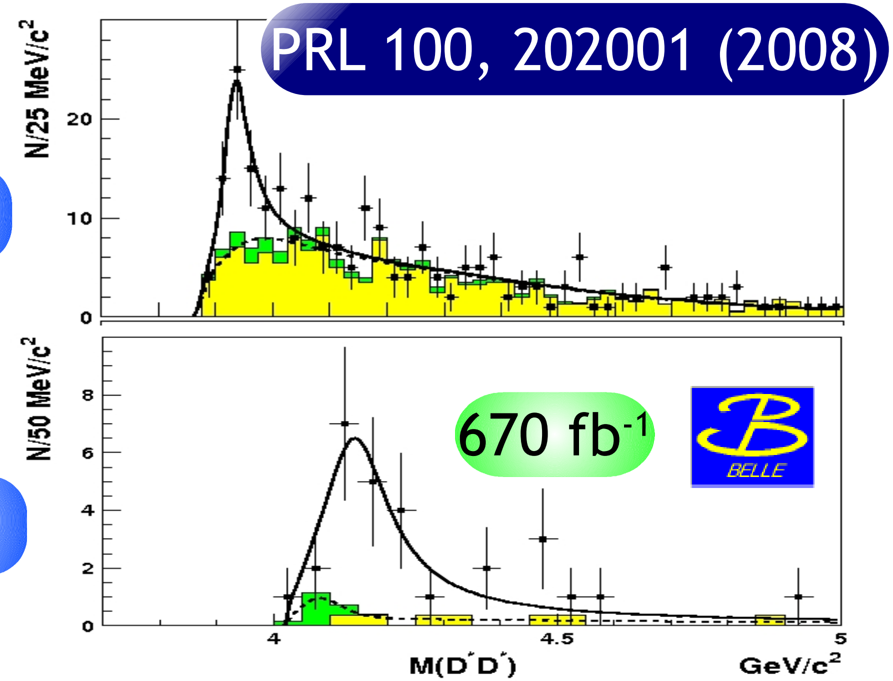
$\eta_c(3S)$?

- Peak found in $D^{*+}D^{*-}$ spectrum with a significance of 5.1σ

$$M = 4156^{+25}_{-20} \pm 15\ MeV/c^2$$
$$\Gamma = 139^{+111}_{-61} \pm 21\ MeV/c^2$$

$\eta_c(4S)$?

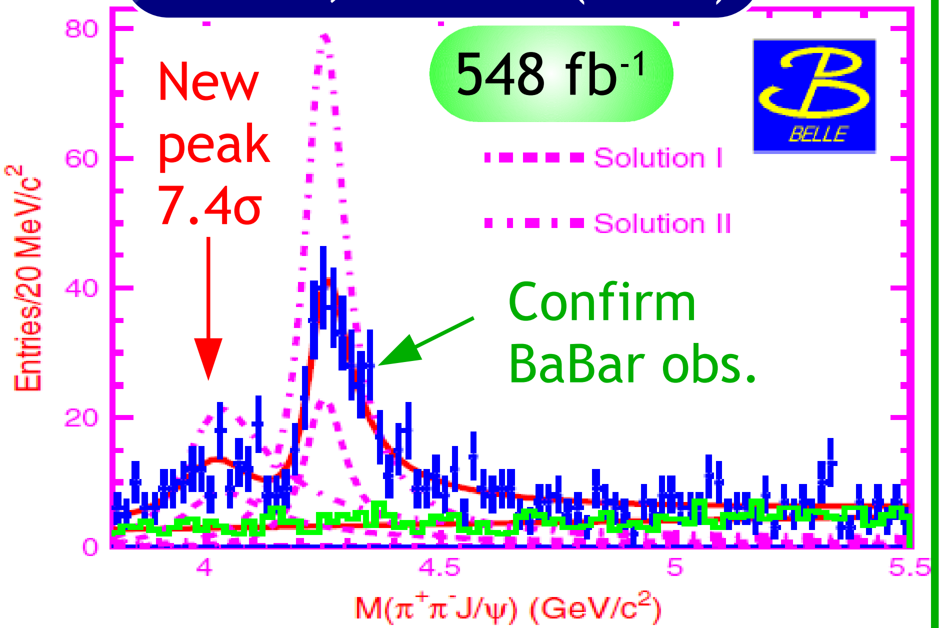
- Contribution from $\psi(4160)$ negligible.



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

Y(4260) discovered in $J/\psi\pi^+\pi^-$ using *ISR* production by BaBar.

PRL 99, 182004 (2007)



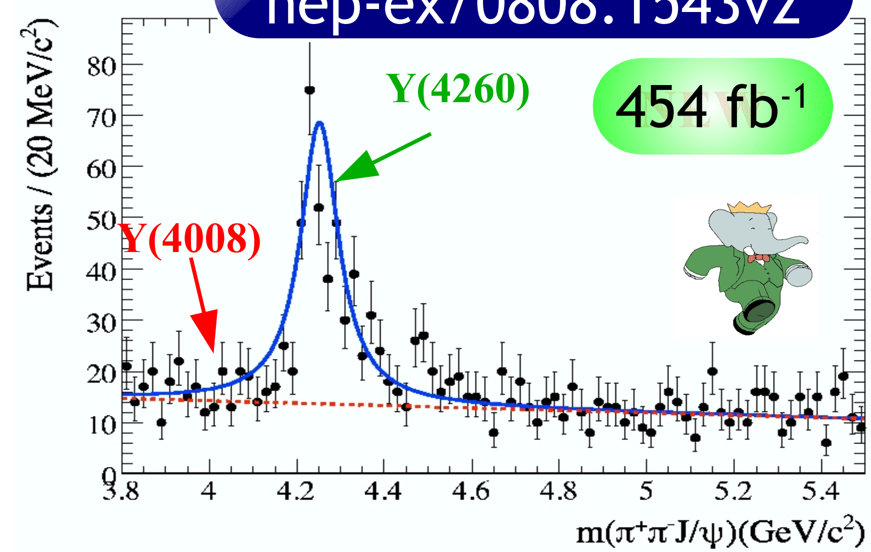
Fit accounts for interference

$$M = 4008 \pm 40^{+114}_{-28}\ MeV/c^2$$
$$\Gamma = 226 \pm 44 \pm 87\ MeV/c^2$$

$$M = 4247 \pm 12^{+17}_{-32}\ MeV/c^2$$
$$\Gamma = 108 \pm 19 \pm 10\ MeV/c^2$$

Confirmed by CLEO and Belle

BaBar Update
hep-ex/0808.1543v2



$$M = 4252 \pm 6^{+2}_{-3}\ MeV/c^2$$
$$\Gamma = 105 \pm 18^{+4}_{-6}\ MeV/c^2$$

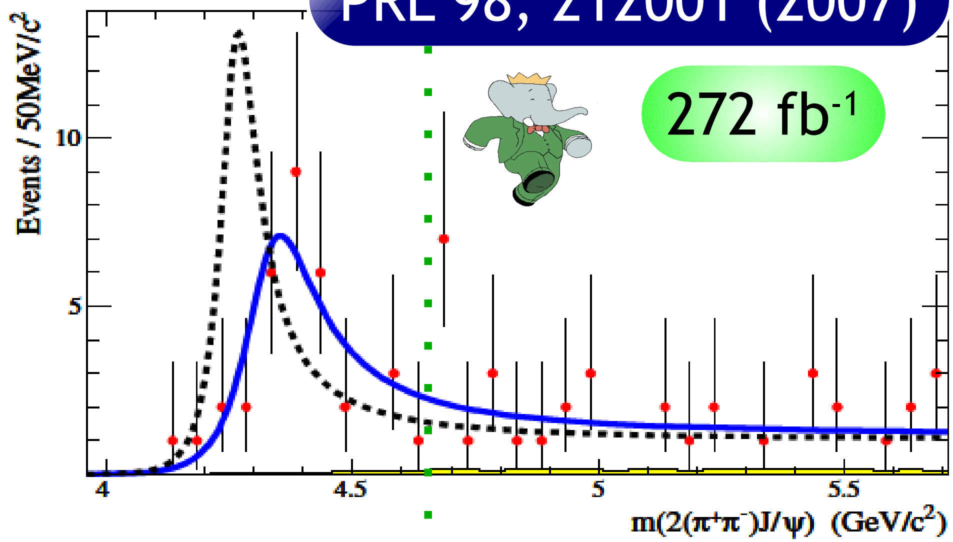
In previous analysis fit with second resonance at 4330 MeV/c^2 gave no improvements [PRL 98, 212001 (2007)]

$\psi(2S)\pi^+\pi^-$ in *ISR*

Search of $\psi(2S)\pi^+\pi^-$ in *ISR* motivated by *Y(4260)*.

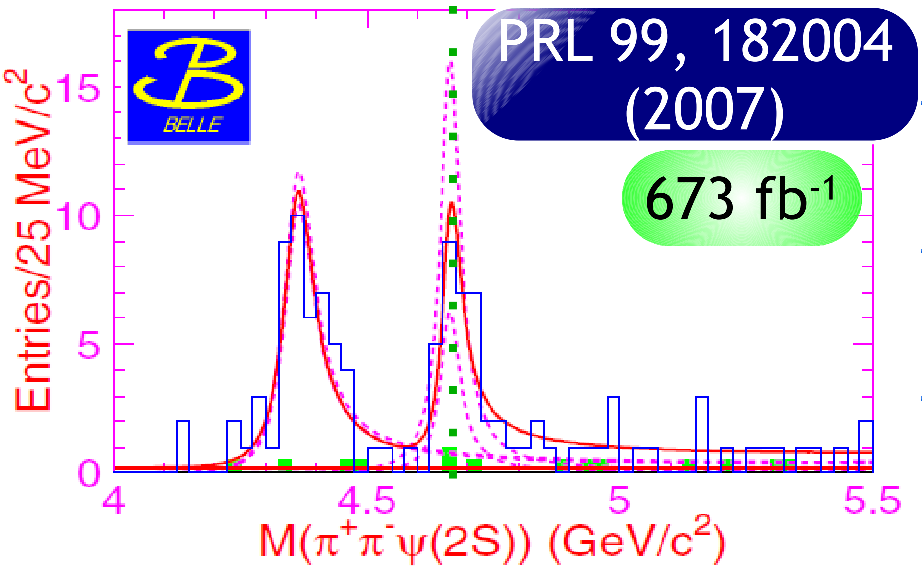
PRL 98, 212001 (2007)

272 fb^{-1}



PRL 99, 182004 (2007)

673 fb^{-1}



Y(4350)

BaBar: $M = 4324 \pm 24(stat.)\ MeV/c^2$

Belle: $M = 4361 \pm 9 \pm 9\ MeV/c^2$

BaBar: $\Gamma = 172 \pm 33(stat.)\ MeV/c^2$

Belle: $\Gamma = 74 \pm 15 \pm 10\ MeV/c^2$

Y(4350)

Belle:
$M = 4664 \pm 11 \pm 5\ MeV/c^2$
$\Gamma = 48 \pm 15 \pm 3\ MeV/c^2$

- Search for ISR $D^{(*)}D^{(*)}$ yields no *Y* signal (BaBar, Belle, CLEO, BES).
- Absence of open charm and large $\psi\pi\pi$ width disfavors conventional $c\bar{c}$.
- 1^{--} observed states are more than predicted by potential model, favor exotics (hybrid, molecule, tetraquark).

η_c Transition Form Factor

Study of $\gamma\gamma^* \to \eta_c$ with $\eta_c \to K^0_s K\pi$ *to extract F(Q²).*

$$F(Q^2) = \int T(x, Q^2)\,\phi(x, Q^2)\,dx \quad with \quad Q^2 \gg M_{\gamma\gamma}$$

$T(x,Q^2)$ calculable $\gamma\gamma^* \to q\bar{q}$

$\phi(x,Q^2)$ non perturbative

x: fraction of η_c moment carried by a quark

No tag mode (no electron detected):

- η_c mass and width measurement.
- Determination of *F(0)*.

$M = 2982.2 \pm 0.4 \pm 1.6\ \mathrm{MeV}/c^2$

$\Gamma = 31.7 \pm 1.2 \pm 0.8\ \mathrm{MeV}/c^2$

Single tag mode (one electron detected):

- Fit to Form Factor distribution.

$$F(Q^2) = \frac{F(0)}{1 + Q^2/\Lambda}$$

$\Lambda = 8.5 \pm 0.6 \pm 0.7\ \mathrm{GeV}/c^2$

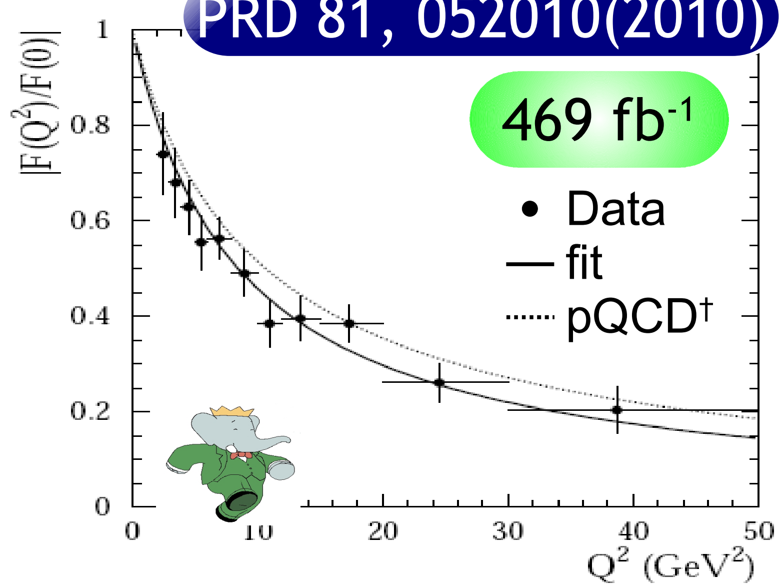
Consistent with theory predictions

[Dukek, Edwards PRL**97**, 172001 (2006)] :

VMD: $\Lambda = m^2_{J/\psi} = 9.6\ \mathrm{GeV}/c^2$

Lattice QCD: $\Lambda = 8.4 \pm 0.4\ \mathrm{GeV}/c^2$

PRD 81, 052010(2010)

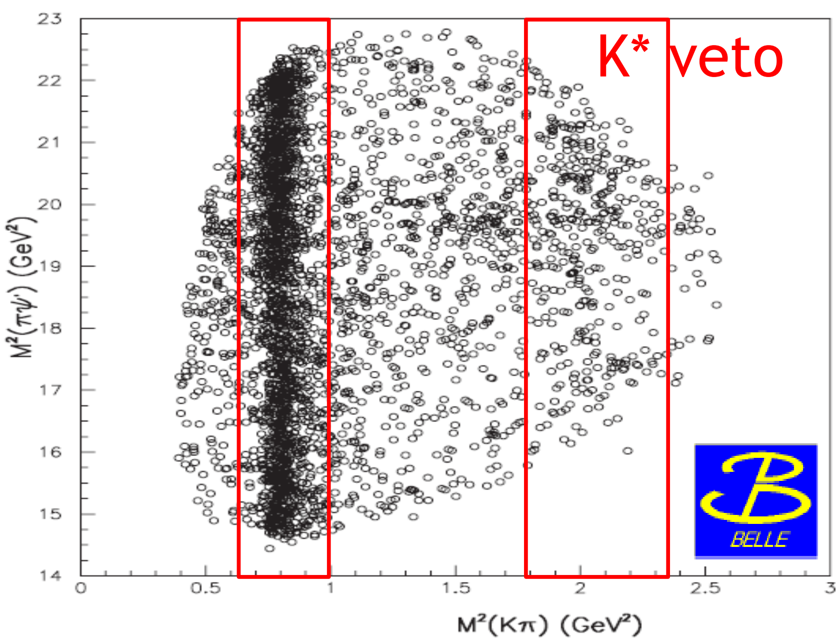


†Feldmann, Kroll PLB**413**, 410 (1997)

$Z(4430)^-$ Observation

Belle reports observation of a peak in $\psi(2S)\pi^-$ mass.

If confirmed this will be first genuine tetraquark candidate.



$$M = 4433 \pm 4 \pm 2\ MeV/c^2$$
$$\Gamma = 45^{+18}_{-13}\ {}^{+30}_{-13}\ MeV/c^2$$

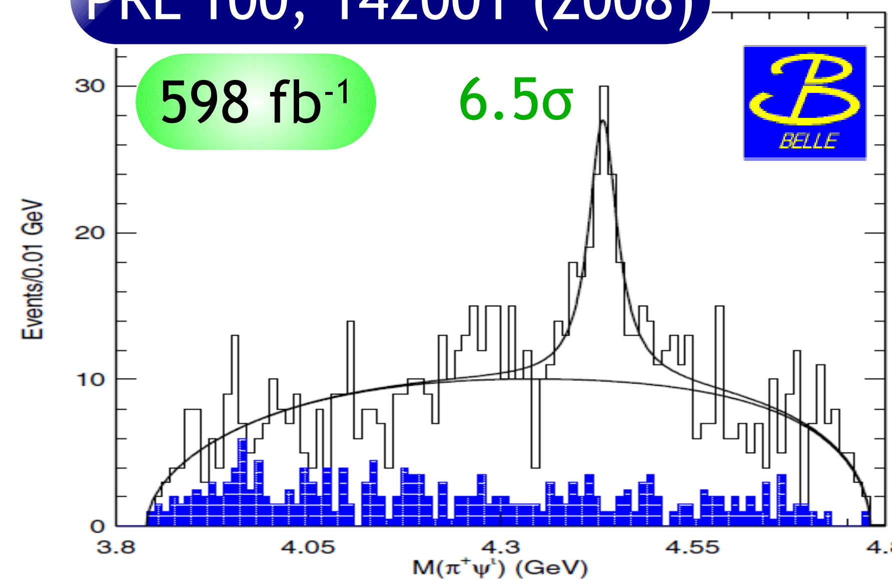
S, P, D $K\pi$ waves cannot reproduce such a narrow peak.

$B \to \psi(2S)\pi K$ ($\psi(2S) \to \ell\ell$ or $J/\psi\pi\pi$)

DP dominated by K^* contribution

First Belle analysis: apply a K^* veto

PRL 100, 142001 (2008)



Fit with a *S*-wave BW and phase space background.