Candidates for Hybrids and Exotics from the B Factories

Tom Browder (University of Hawaii)

Will discuss results from BaBar, Belle, CLEO, CDF and D0 in this talk.

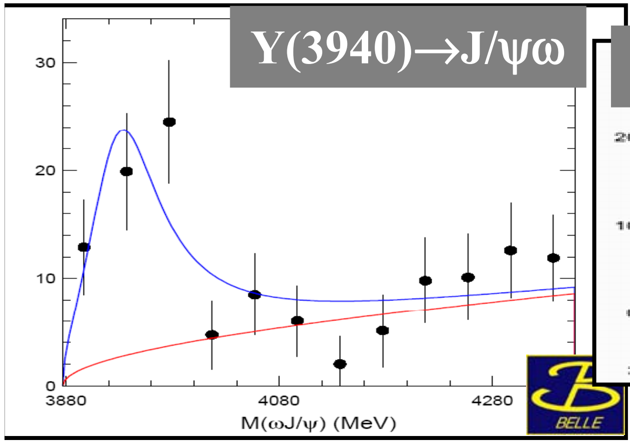
[Thanks to S. Olsen, B. Yabsley (Belle) and J. Olsen (BaBar)]

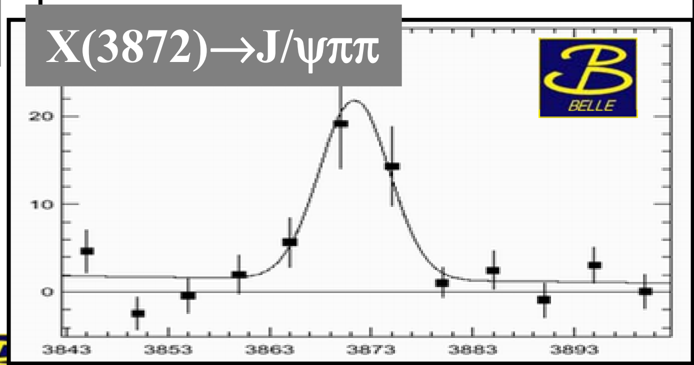
Textbook of Perkins, Introduction to High Energy Physics p.118

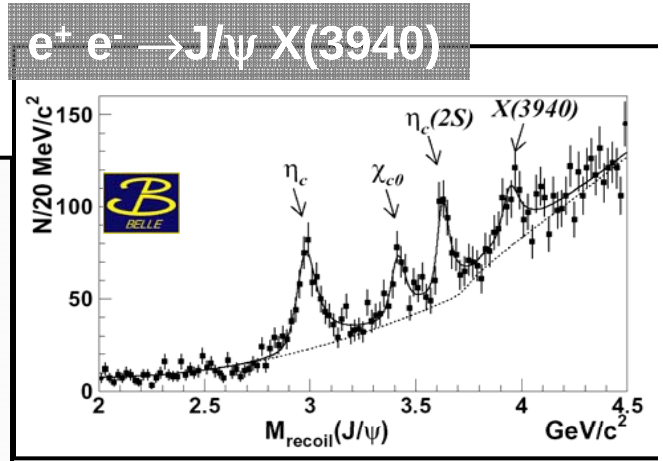
“The states observed in nature consist of three-quark combinations (the baryons) and quark-antiquark combinations (the mesons).”

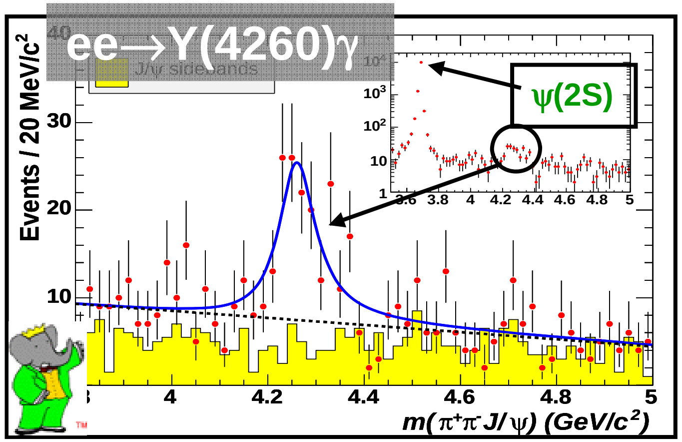
Yes, but other possibilities such as 4-quark or quark-antiquark-glue combinations are not forbidden by any conservation law.

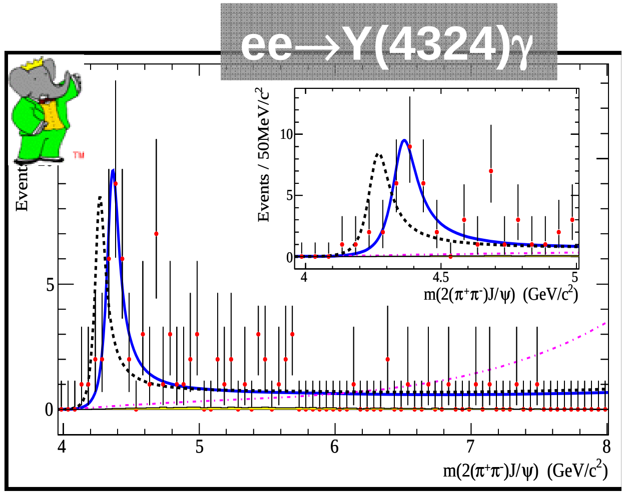
Unexpected New Particles: (X and Y)









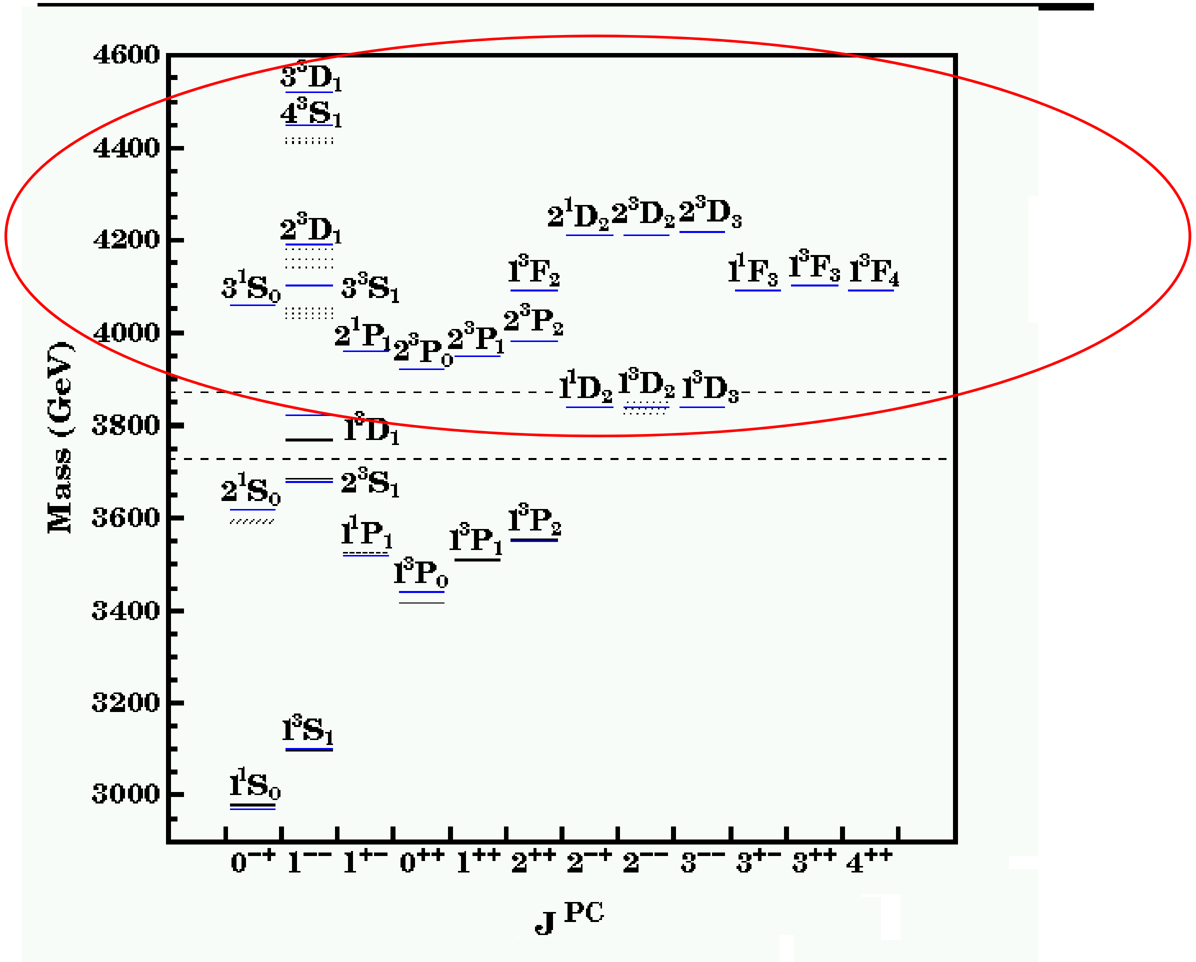


Six new charmonium states were found above DD threshold (incl Z)
Most of these heavy charmonium-like states were not anticipated by theory

Are any of these new states 4-quark combinations or hybrids ?

Charmonium is a good place to look for non-q qbar mesons:

A new q qbar meson decaying to c cbar has to fit into these slots:



X and Y particles

- **X(3940)**
  - **$e^+e^- \rightarrow J/\psi\ X$ & $e^+e^- \rightarrow J/\psi\ DD^*$**

- **X(3872)**
  - **$\pi^+\pi^-$ J/ψ in $B \rightarrow K\pi^+\pi^- J/\psi$**

- **Y(3940)**
  - **ωJ/ψ in B→K ωJ/ψ**

- **Y(4260)**
  - **$\pi^+\pi^- J/\psi$ in $e^+e^- \rightarrow \gamma\,\pi^+\pi^-\,J/\psi$**

- **Y(4324)**
  - **$\pi^+\pi^-\psi'$ in $e^+e^- \rightarrow \gamma\,\pi^+\pi^-\psi'$**

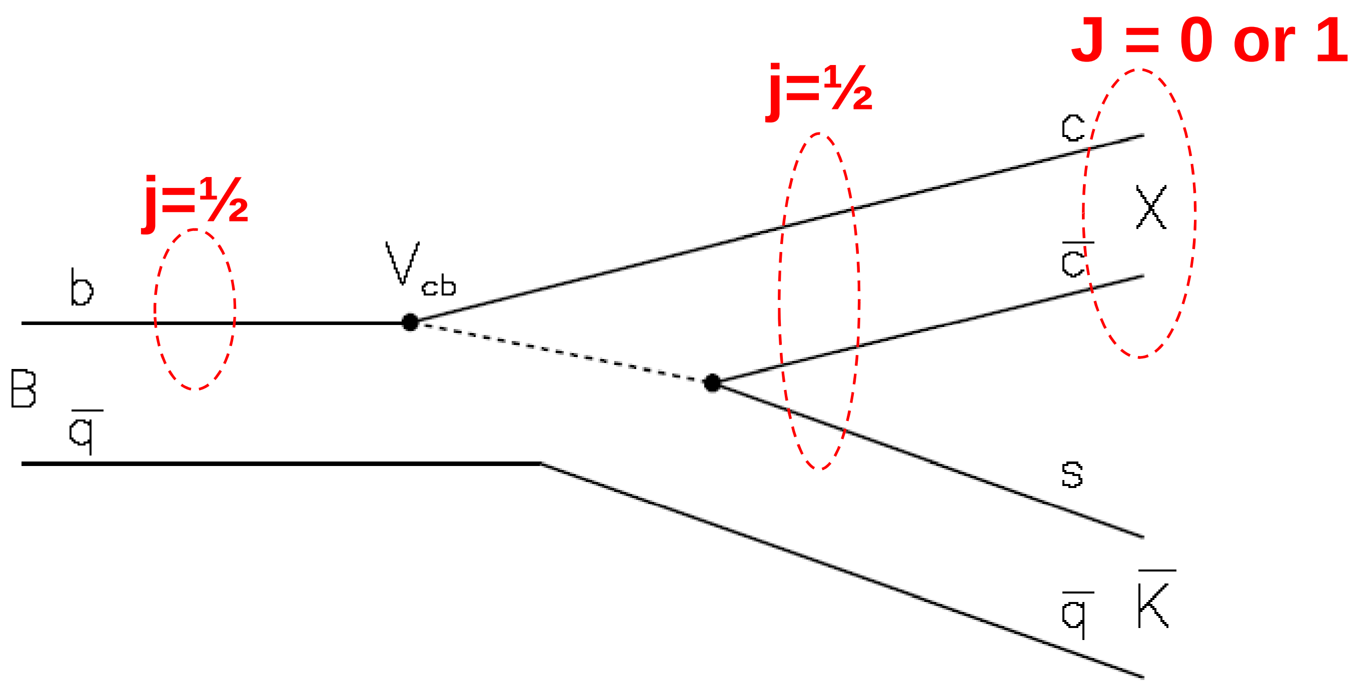
Are these all conventional charmonium states ?

B-factories are Charmonium factories

$c\underline{c}$ production mechanisms @ a B factory:

- B meson decays
- e^+e^- annihilation
- $\gamma\gamma$ collisions
- e^+e^- radiative return (ISR)

c<u>c</u> production in B decays



Spectator model suggests $J_{c\bar{c}}$ = 0 or 1 should dominate exclusive B→K(cc) decays.

Allowed decays all have BF's~10^{-3}

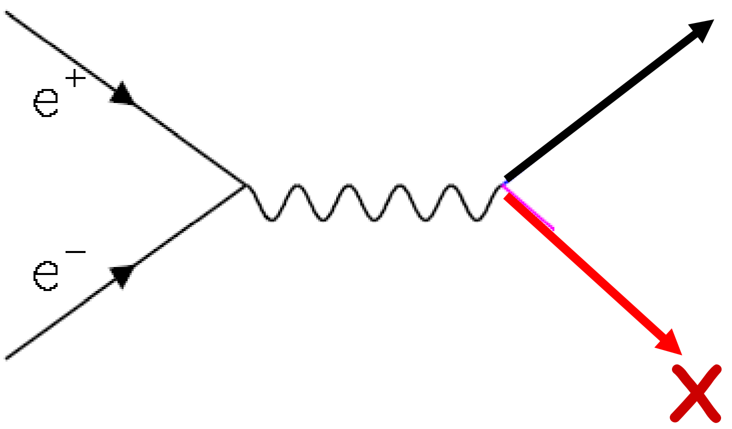
from PDG2004

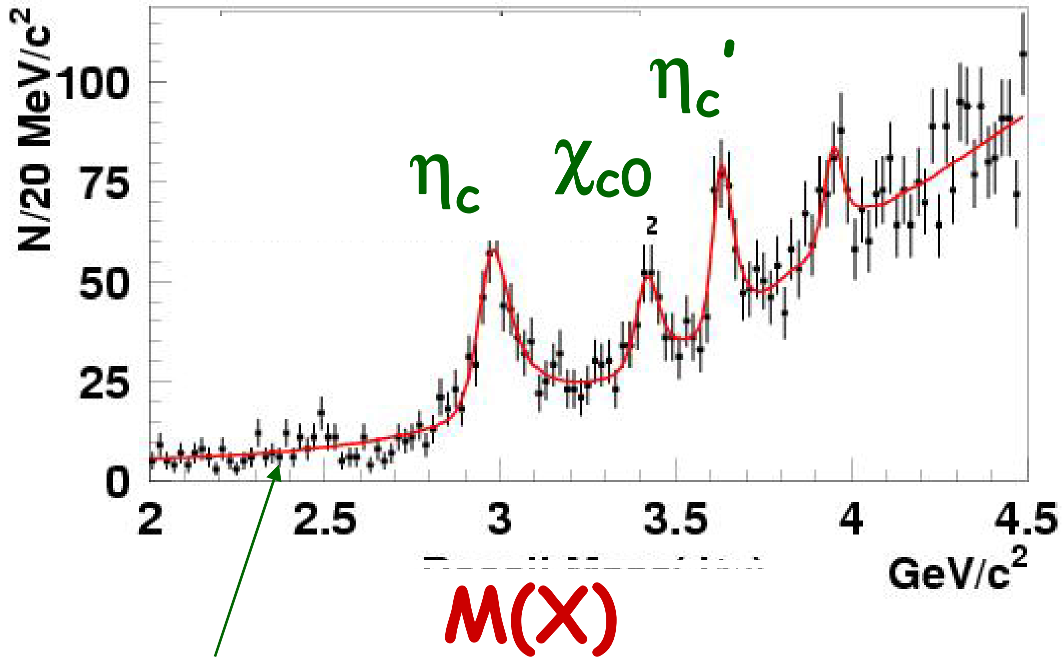
Charmonium modes

Γ_{99}	$\eta_c K^+$	$(9.0 \pm 2.7) \times 10^{-4}$	η_cK 0.9 x10^{-3}
Γ_{100}	$J/\psi(1S)K^+$	$(1.00 \pm 0.04) \times 10^{-3}$	J/ψK 1.0 x10^{-3}
Γ_{101}	$J/\psi(1S)K^+\pi^+\pi^-$	$(7.7 \pm 2.0) \times 10^{-4}$	
Γ_{102}	$X(3872)K^+$	seen	
Γ_{103}	$J/\psi(1S)K^*(892)^+$	$(1.35 \pm 0.10) \times 10^{-3}$	J/ψK* 1.4 x10^{-3}
Γ_{104}	$J/\psi(1S)K(1270)^+$	$(1.8 \pm 0.5) \times 10^{-3}$	J/ψK_{1270}1.8 x10^{-3}
Γ_{105}	$J/\psi(1S)K(1400)^+$	$< 5 \times 10^{-4}$	
Γ_{106}	$J/\psi(1S)\phi K^+$	$(5.2 \pm 1.7) \times 10^{-5}$	
Γ_{107}	$J/\psi(1S)\pi^+$	$(4.0 \pm 0.5) \times 10^{-5}$	
Γ_{108}	$J/\psi(1S)\rho^+$	$< 7.7 \times 10^{-4}$	
Γ_{109}	$J/\psi(1S)a_1(1260)^+$	$< 1.2 \times 10^{-3}$	
Γ_{110}	$J/\psi(1S)p\overline{\Lambda}$	$(1.2\ ^{+0.9}_{-0.6}) \times 10^{-5}$	
Γ_{111}	$\psi(2S)K^+$	$(6.8 \pm 0.4) \times 10^{-4}$	ψ'K 0.7 x10^{-3}
Γ_{112}	$\psi(2S)K^*(892)^+$	$(9.2 \pm 2.2) \times 10^{-4}$	ψ'K* 0.9 x10^{-3}
Γ_{113}	$\psi(2S)K^+\pi^+\pi^-$	$(1.9 \pm 1.2) \times 10^{-3}$	
Γ_{114}	$\chi_{c0}(1P)K^+$	$(6.0\ ^{+2.4}_{-2.1}) \times 10^{-4}$	χ_{c0}K 0.6 x10^{-3}
Γ_{115}	$\chi_{c1}(1P)K^+$	$(6.8 \pm 1.2) \times 10^{-4}$	χ_{c1}K 0.7 x10^{-3}
Γ_{116}	$\chi_{c1}(1P)K^*(892)^+$	$< 2.1 \times 10^{-3}$	

Note that B→K c$\underline{c}$(J=2) still not seen

Mechanism: $e^+e^- \rightarrow J/\psi + (c\bar{c})$



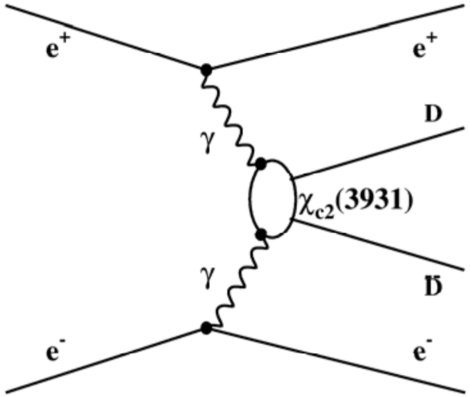


X (almost) always contains ($c\underline{c}$)

C(X) = +1

e.g. $J/\psi\ J/\psi$ is forbidden

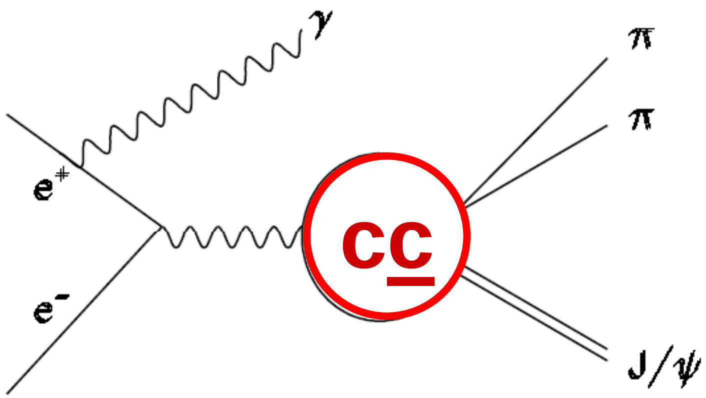
$\gamma\gamma \rightarrow D\underline{D}$



$J^{PC} = 0^{++},\ 2^{++}$

ISR

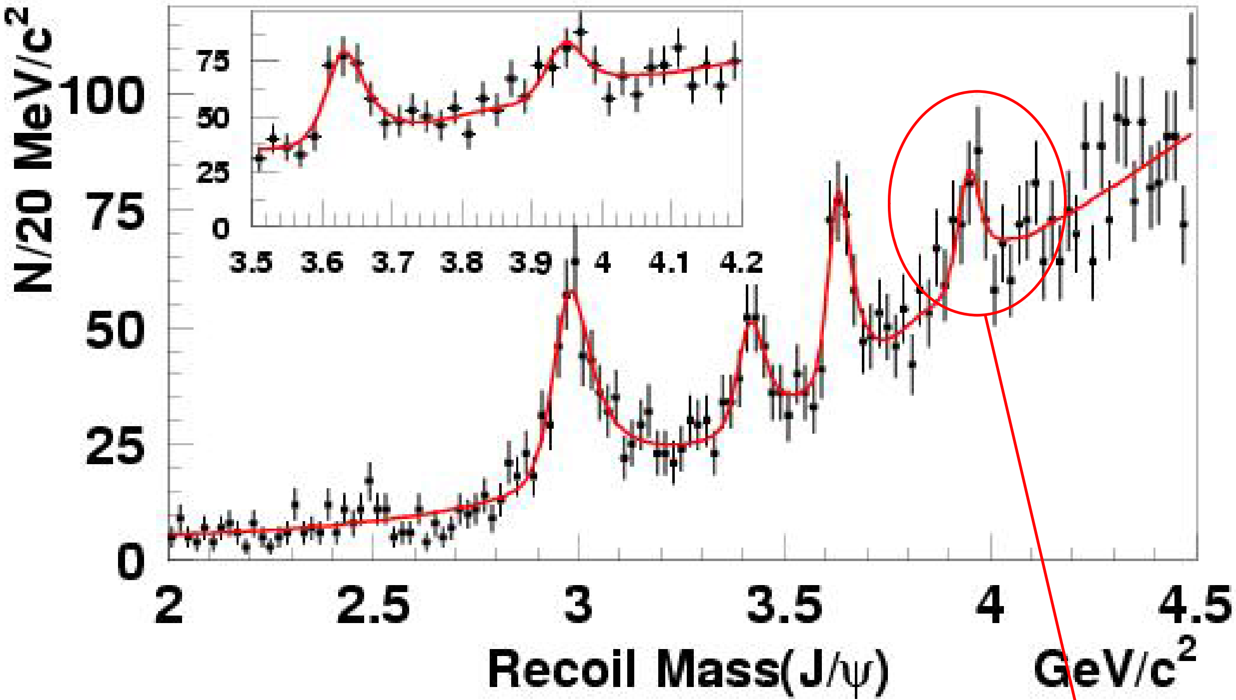
$e^+e^- \rightarrow \gamma\ (c\underline{c})$



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

1st state to be discussed today:

$e^+e^- \rightarrow J/\psi$ X(3940)



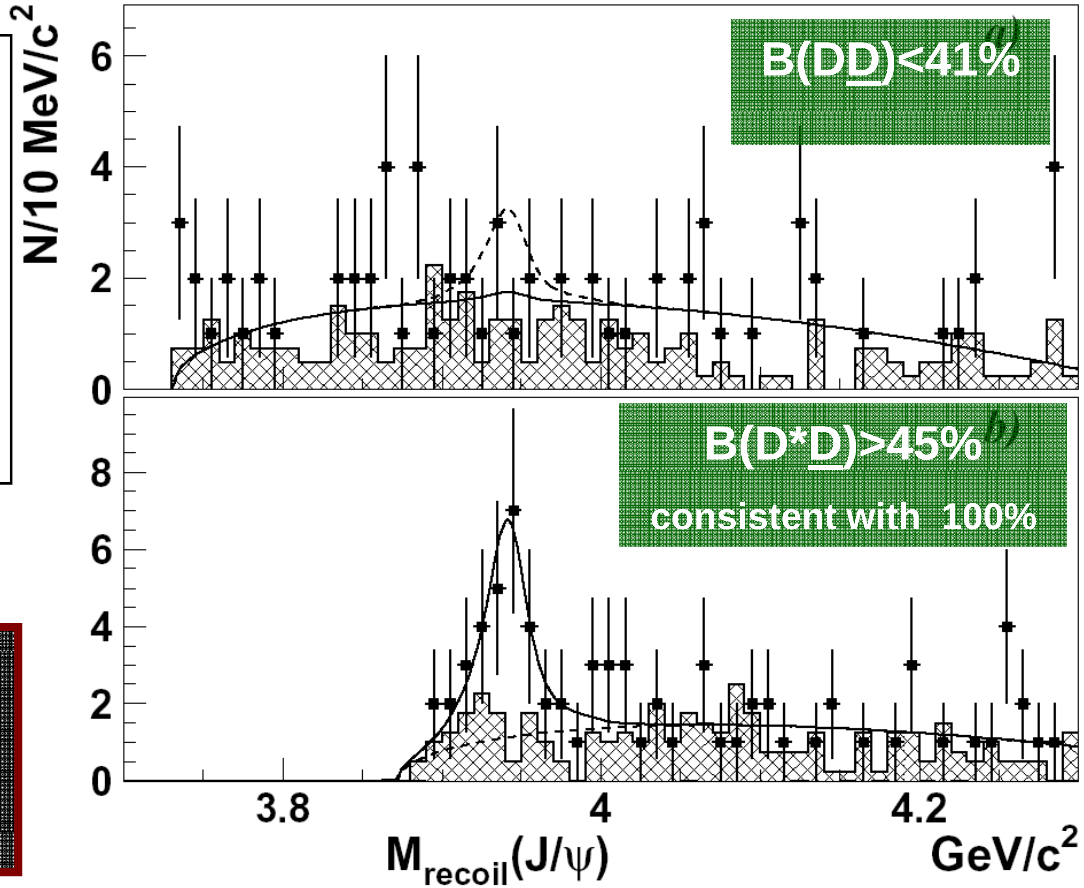
for $e^+e^- \rightarrow J/\psi + X$

$(c\bar{c})_{res}$	N	$M\,[\mathrm{GeV}/c^2]$	σ
η_c	501 ± 44	2.970 ± 0.005	15.3
χ_{c0}	230 ± 40	3.406 ± 0.007	6.3
$\eta_c(2S)$	311 ± 42	3.626 ± 0.005	8.1
$X(3940)$	266 ± 63	3.936 ± 0.014	5.0

hep-ex 0507019, K. Abe et al, (Belle collab). PRL 98, 082001 (2007)

X(3940)→D*D̲ is strong (N.B.→DD̲ & →ωJ/ψ not seen)

Only one D is fully reconstructed



J.Rosner: hep-ph/0609195

Since the X(3940) recoils against J/ψ it has J=0. Since it decays to D D* but not to D Dbar, it is probably the $\eta_c(3S)$ rather than the χ_{c0}'

From X(3940) → D*D:

M = (3943 ± 6 ± 6) MeV

Γ = (15.4 ± 10.1) MeV

Γ < 52 MeV at 90%CL

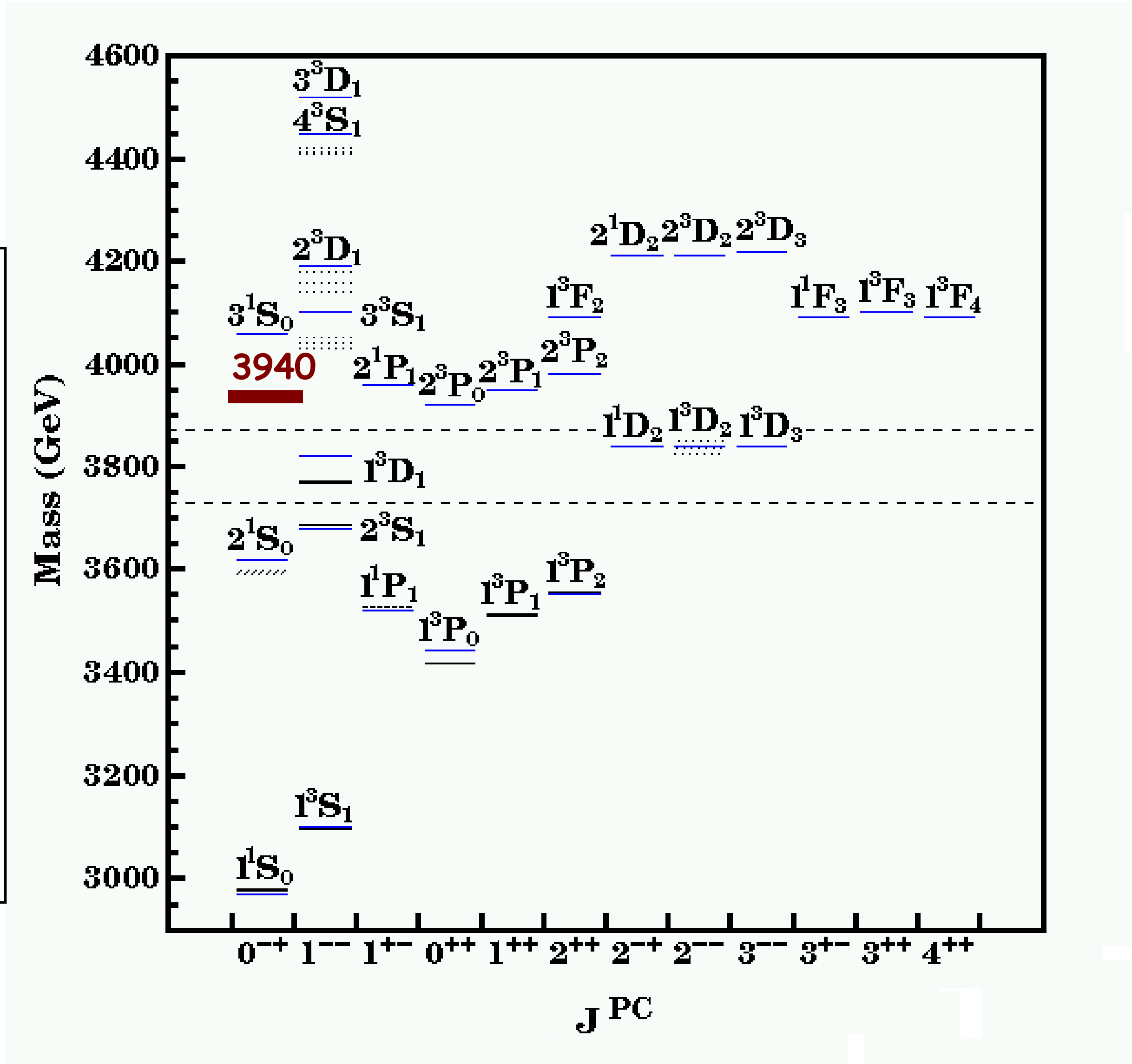
K. Abe et al, (Belle collab). PRL 98, 082001 (2007)

Is the X(3940) the η_c''?

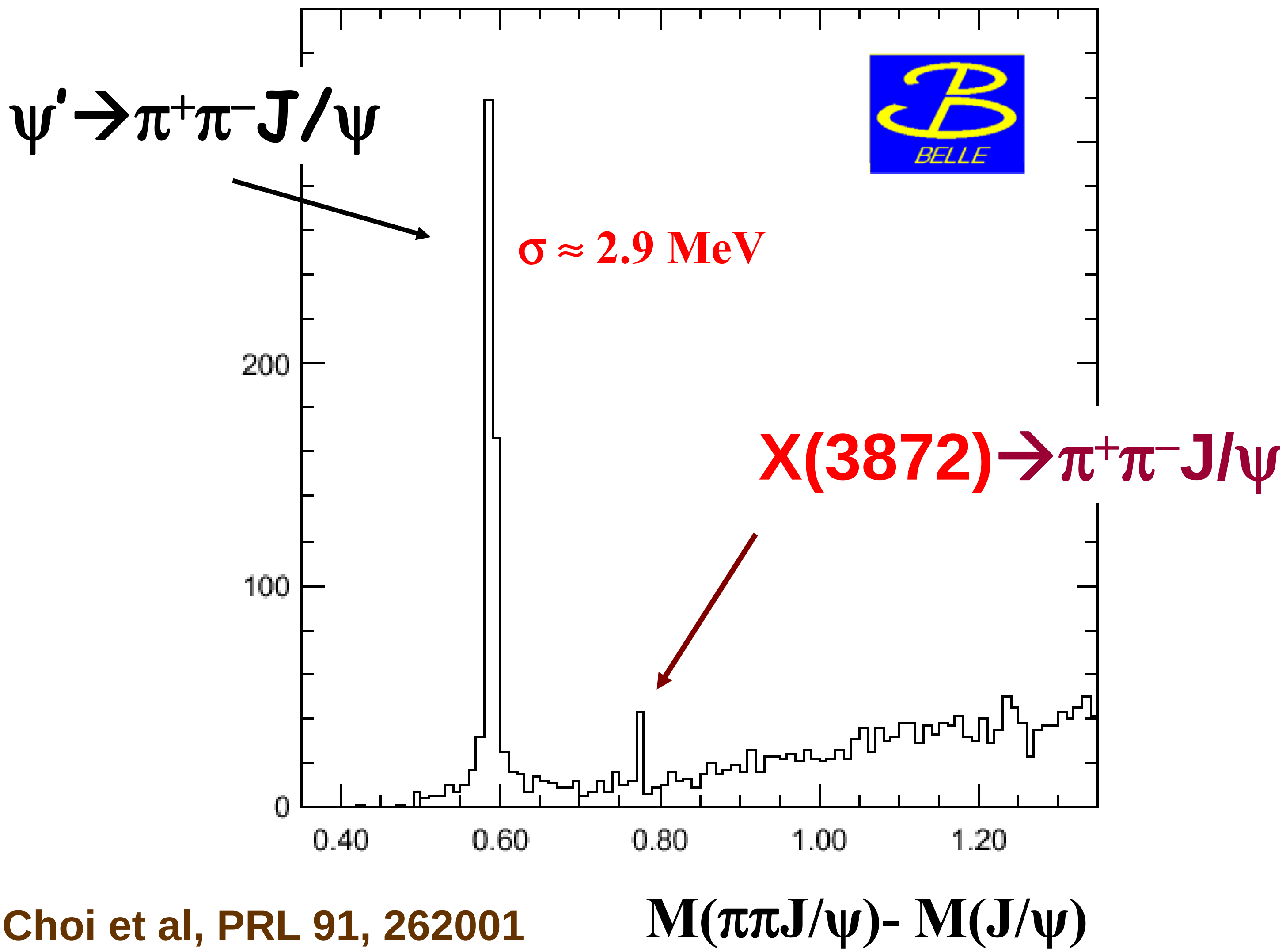
M= 3943 MeV is ~150 MeV low

Γ<52 MeV too narrow?

Other more exotic possibilities to be mentioned by F. Close

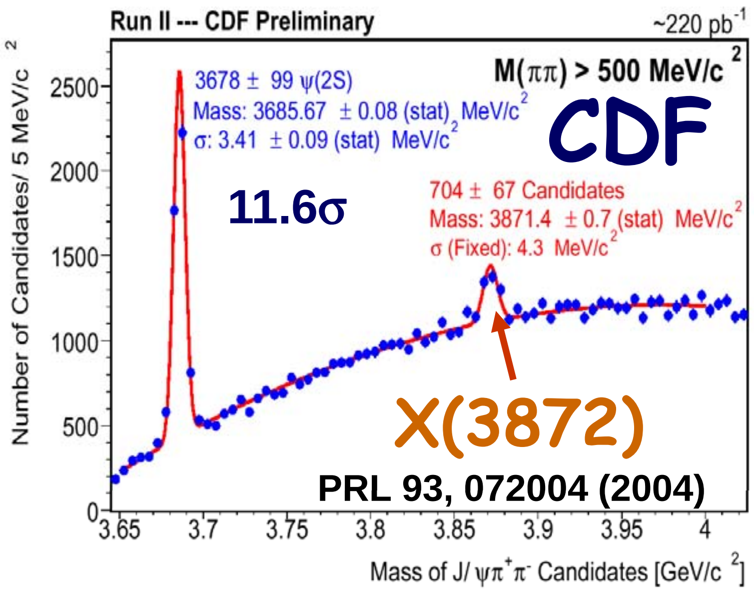


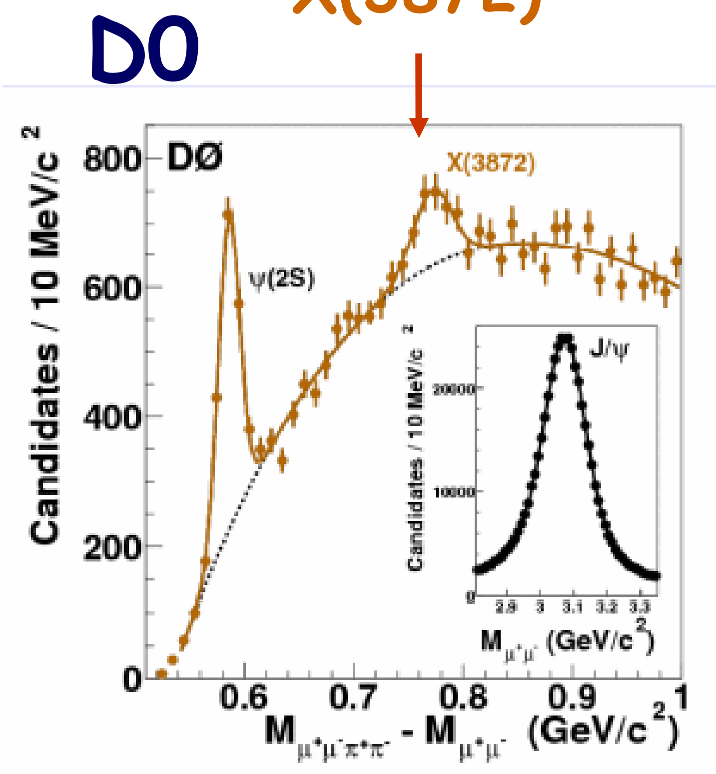
X(3872) in B→$K\pi^+\pi^- J/\psi$



S. K. Choi et al, PRL 91, 262001

X(3872) is also seen in p pbar



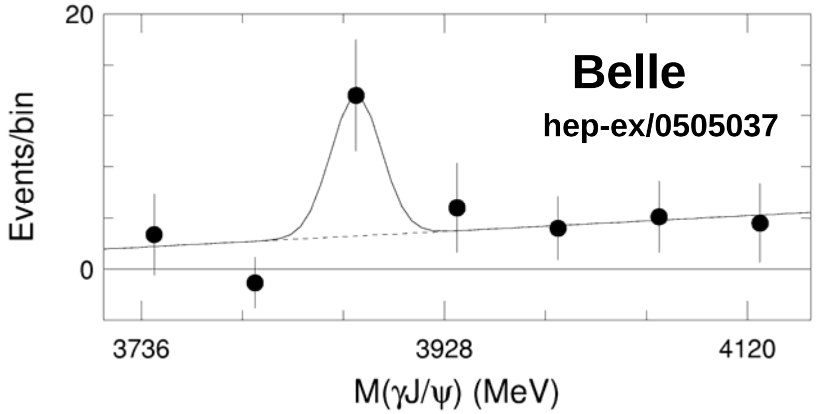


PRL 93, 162002 (2004)

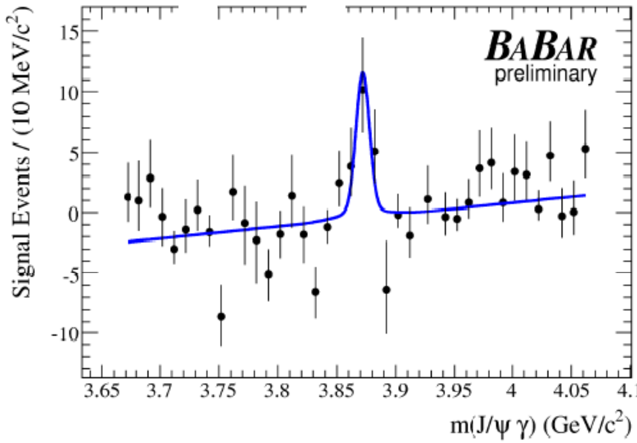
Production properties similar to those of the ψ'

C=+1 assignment for the X(3872) is established by a variety of modes

A small signal for X(3872)→ γJ/ψ seen in:



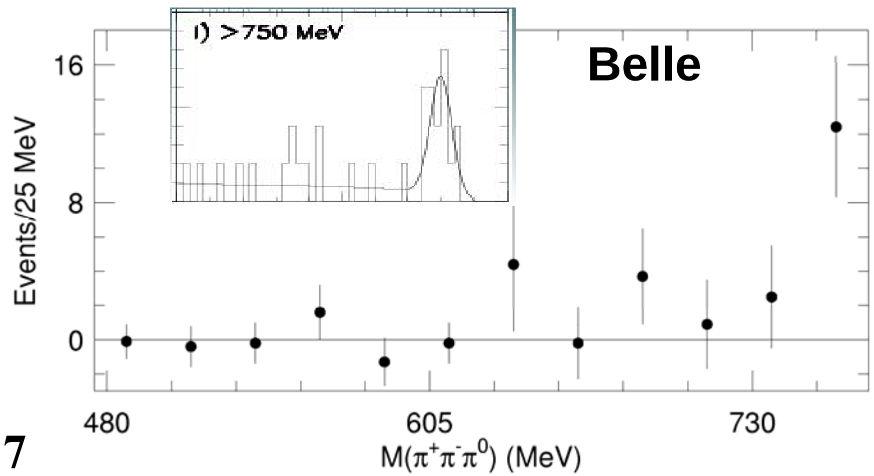
&



$$\Gamma(X \to \gamma J/\psi)/\Gamma(X \to \pi\pi J/\psi) = 0.14 \pm 0.05$$

Expect radiative mode is dominant for a normal charmonium state

X(3872)→"ω"J/ψ seen



hep-ex/0505037

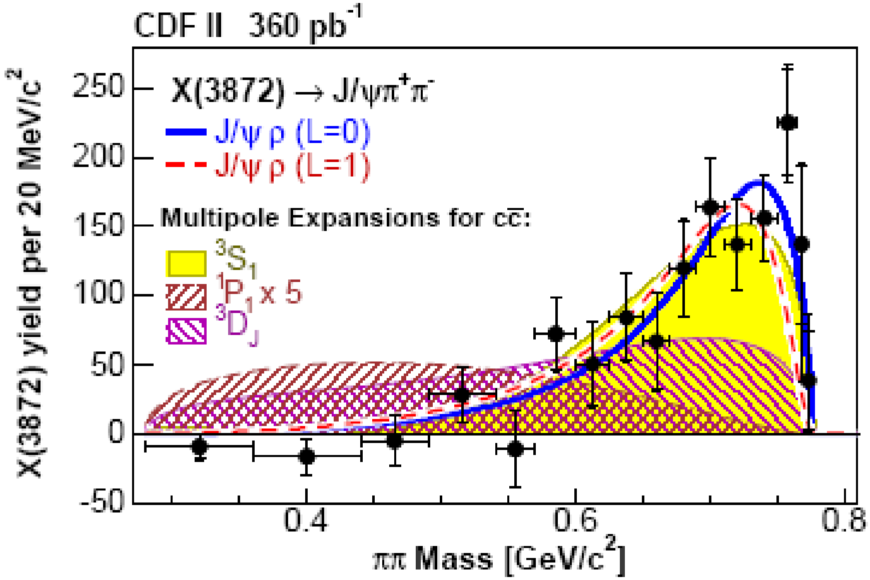
E. Swanson, hep-ph/0311229
PLB 588, 189 (2004)

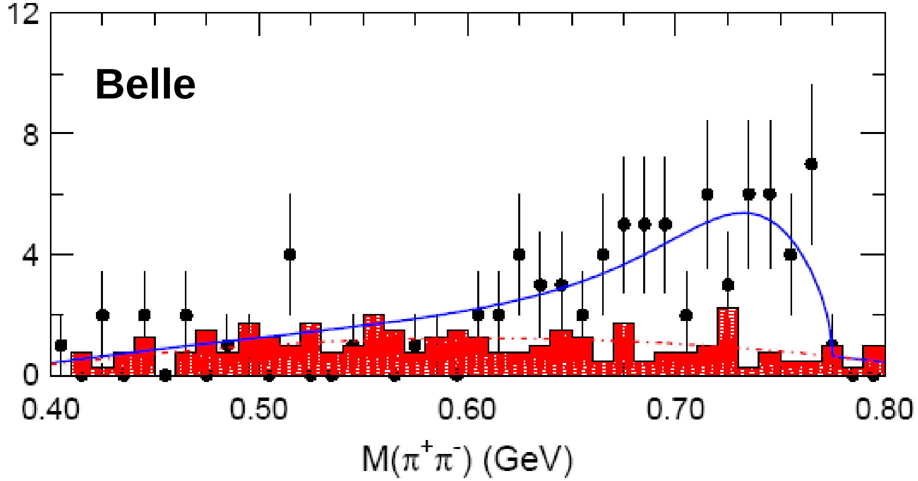
C=+1 assignment for the X(3872) (cont'd)

M(ππ) looks like a ρ

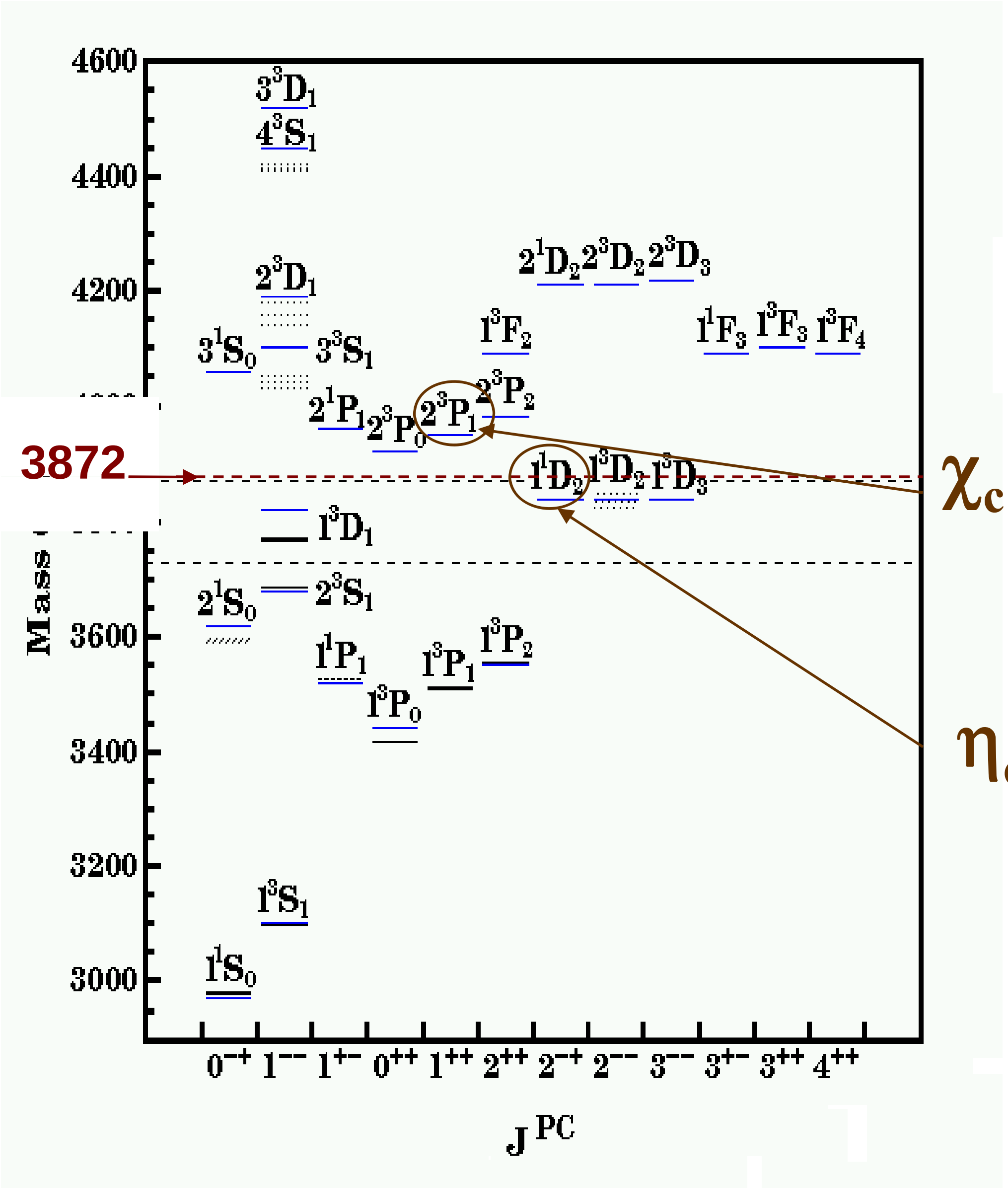
CDF

PRL **96** 102002 (2006)





X(3872) has no satisfactory c$\underline{c}$ assignment



χ_{c1}' Br($\gamma J/\psi$) too small & Br($\rho J/\psi$) too large

η_{c2}
- $\eta_{c2} \rightarrow \rho J/\psi$ isospin forbidden
- $B \rightarrow K c\underline{c}(J=2)$ suppressed

What is the X(3872) ?

The mass, width and decay modes do not appear to correspond to those of any predicted charmonium state.

One possibility suggested by a number of authors is a loosely bound S-wave molecule of charm mesons. $1/\sqrt{2}(D^0\ D^{*0}bar + D^0bar\ D^{*0})$

F. Close, P.R. Page, Phys. Lett. B 578, 119 (2003)

N.. A. Tornqvist, Phys Lett. B 590, 209(2004)

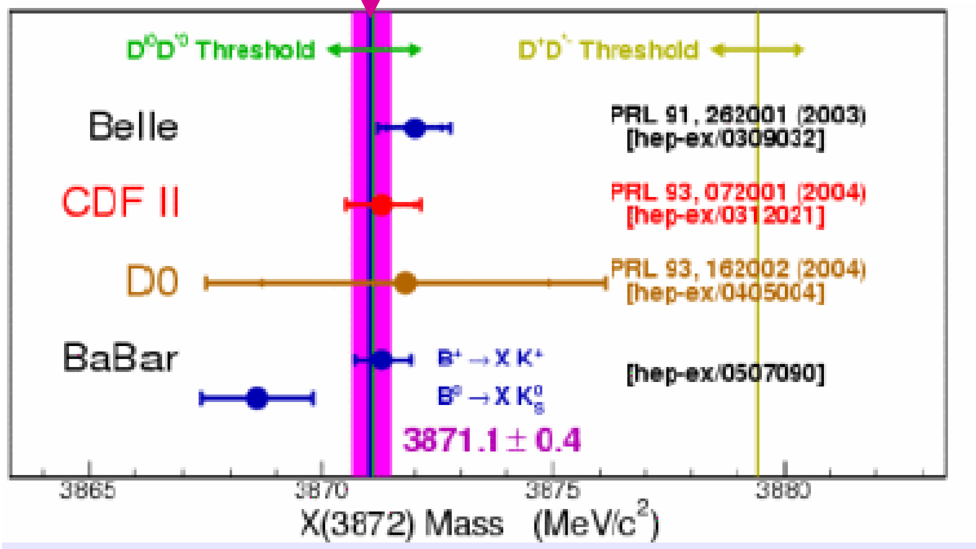
E. Braaten, M. Kusunoki, S. Nussinov, Phy. Rev. Lett. 93, 162001 (2004)

Another intriguing idea: X(3872)= c cbar u ubar state. In such a 4-quark picture there should be two neutral states, X^0, c cbar u ubar, c cbar d dbar as well as charged states, X^+, c cbar u dbar, c cbar d ubar etc….

L. Maiani, F. Piccinini, A. D. Polosa, V. Riquer, Phys Rev. D71: 014028 (2005)

X mass is near the D^0D^{*0} threshold

PDG M_{X3872}: 3871.2 ± 0.5 MeV



PDG06: $m_{D0} + m_{D^*0}$ = 3871.1 ± 0.8 MeV

Use CLEO hep-ex/0701016 3871.7 ± 0.4 MeV

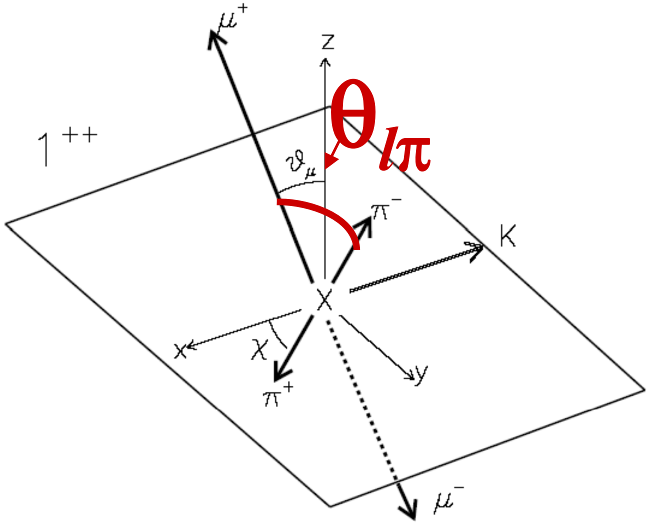
Average for threshold: 3871.6 ± 0.4 MeV

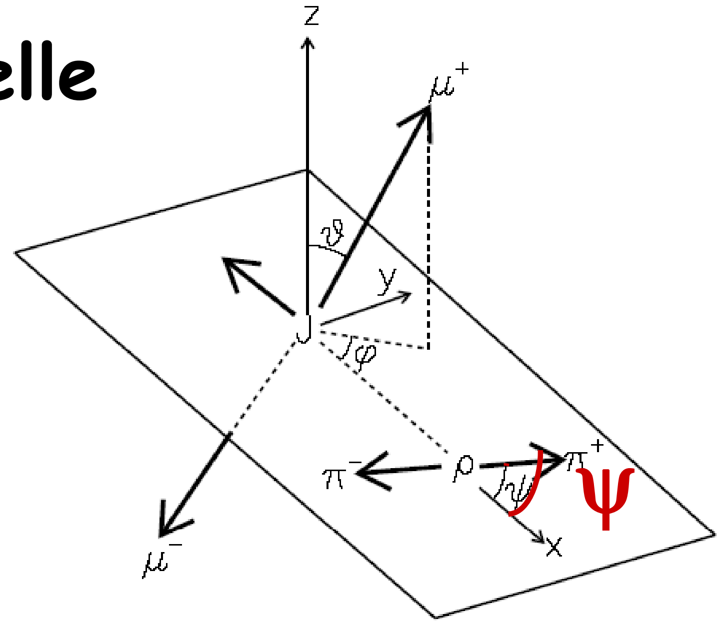
$D^{*0}\underline{D^0}$ "binding energy" = 0.4 ± 0.6 MeV

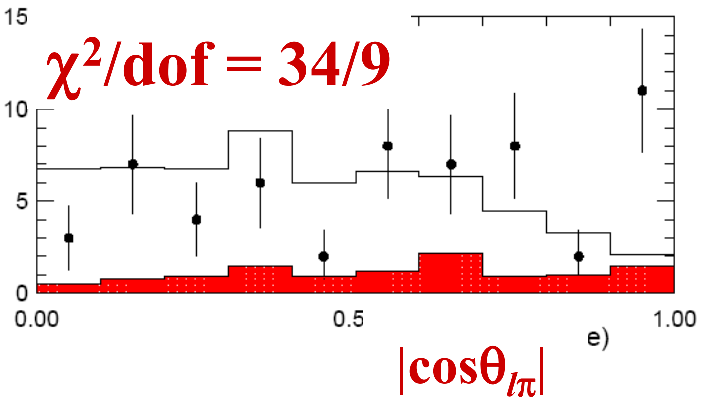
0^{++} $\vec{\varepsilon}_\rho \cdot \vec{\varepsilon}_{J/\psi}$

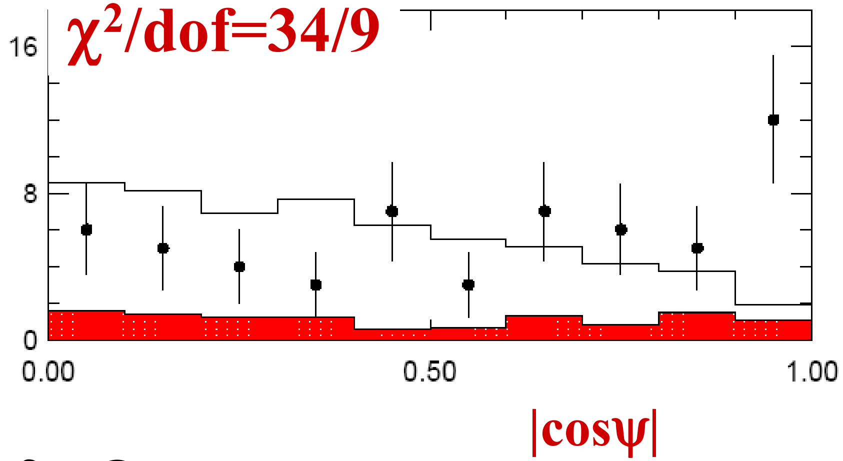
0^{-+} $\vec{k} \cdot (\vec{\varepsilon}_\rho \times \vec{\varepsilon}_{J/\psi})$

Ruled out by Belle



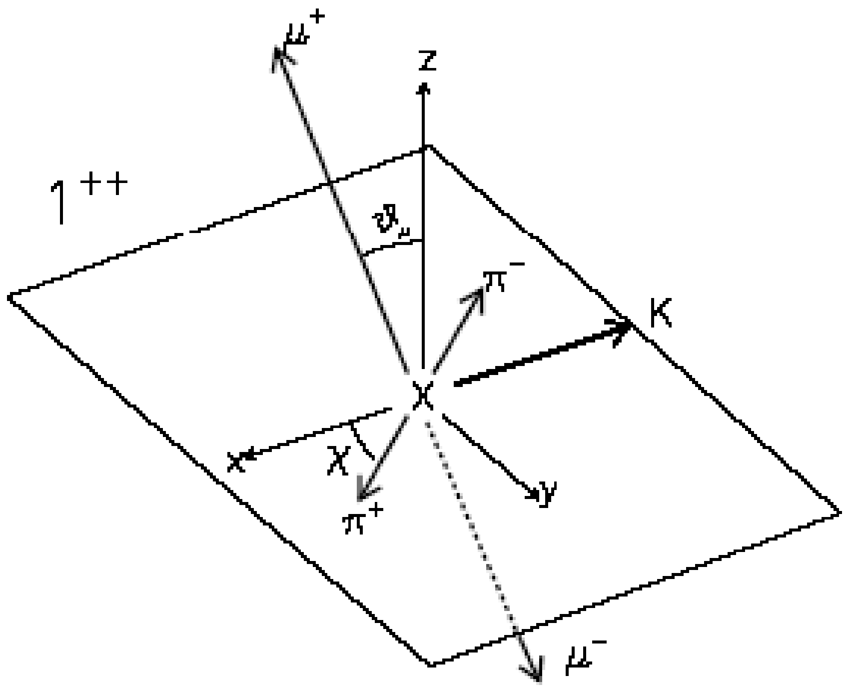


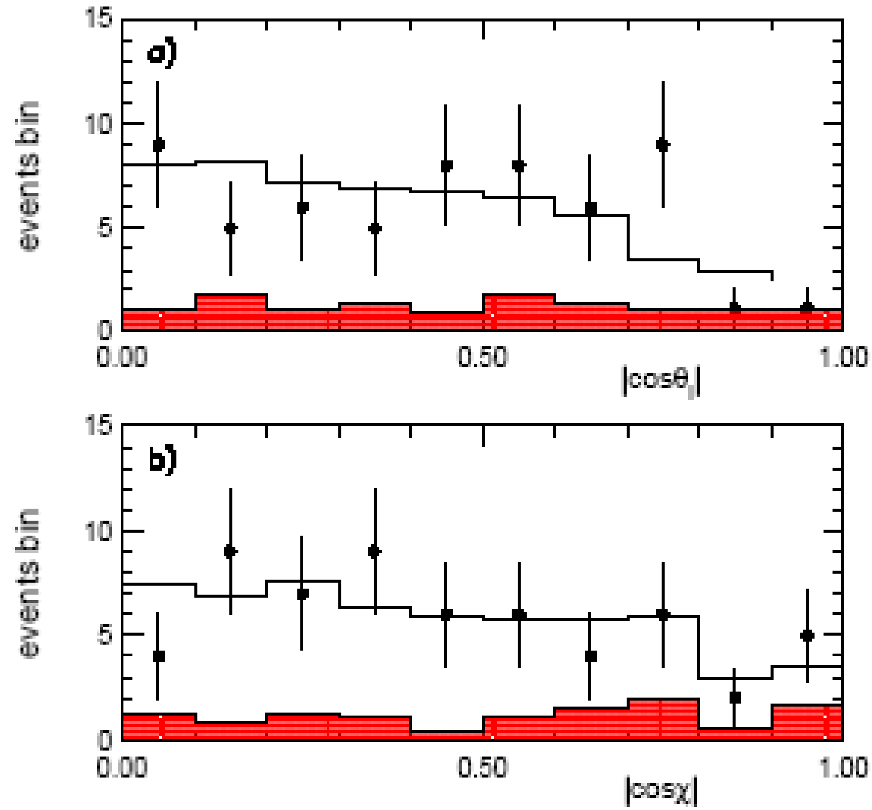




rule out 0^{++} & 0^{-+}

Belle Angular Analysis of X(3872)

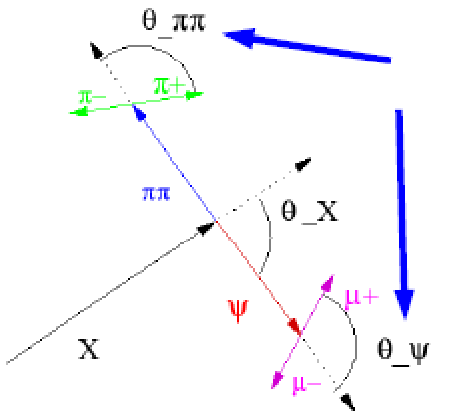


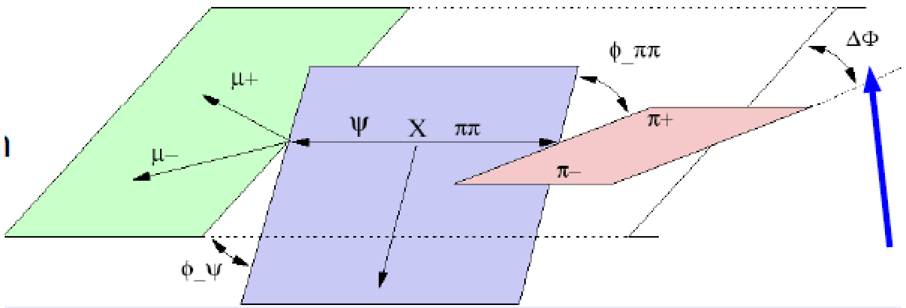


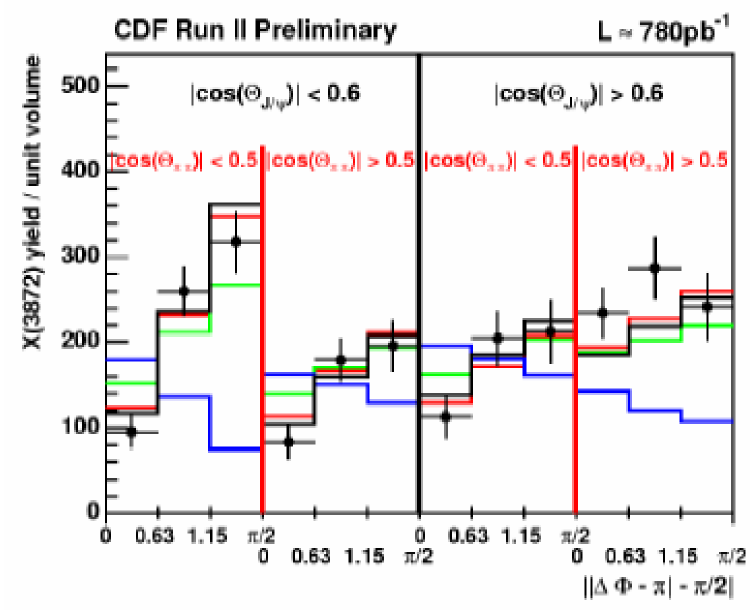
$\chi^2/d.o.f. = 11.4/9$ and $5.0/9$: ALLOWED

1++ assignment consistent with data

X(3872) angular analysis from CDF







Check χ^2

Fit model

3 best:

- 1^{++}_p
- 2^{-+}_p
- ~~1^{--}_s~~

the worst

- 0^{++}_p

⇒ **1^{++} or 2^{-+}**

A.Abulencia et al, CDF, hep-ex/0612053, PRL 96, 102002 (2006).

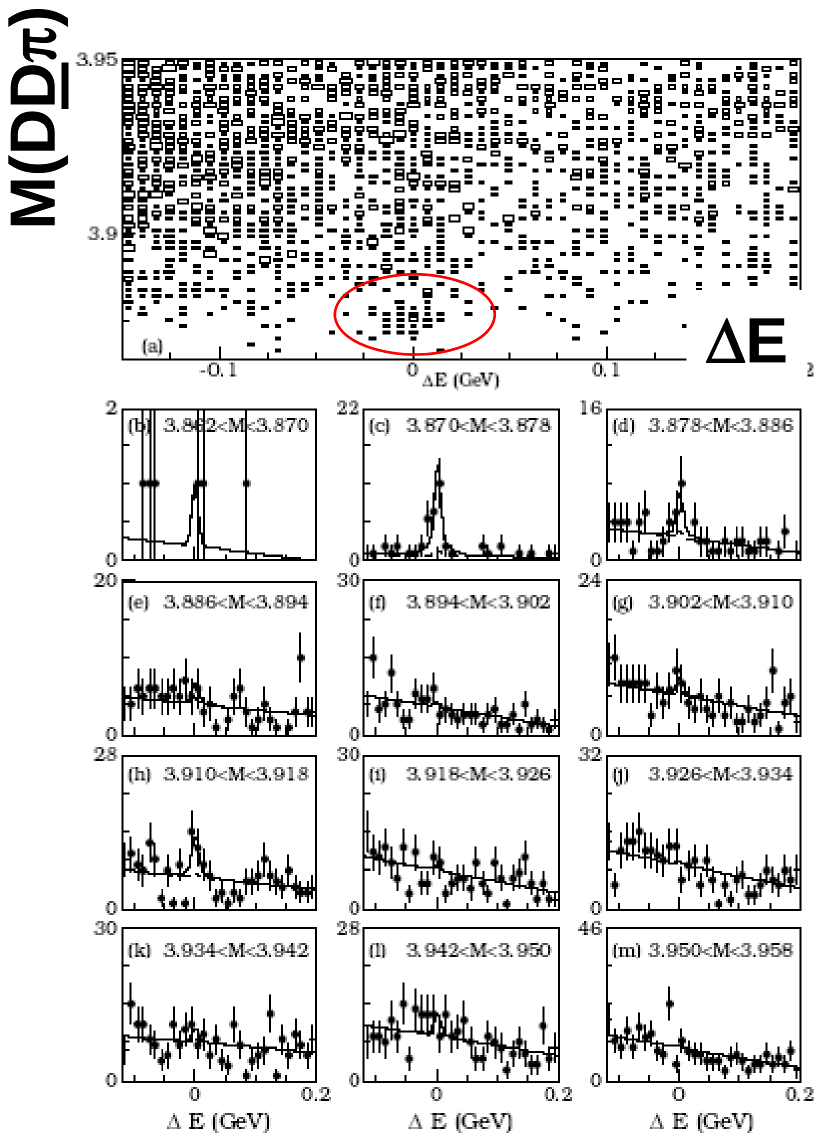
If the X(3872) is a D^0 D^{*0} molecular resonance with $\omega J/\psi$ and $\rho J/\psi$ in its wavefunctions, then expect decays to D^0 D^0 π^0 and D^0 D^0 γ

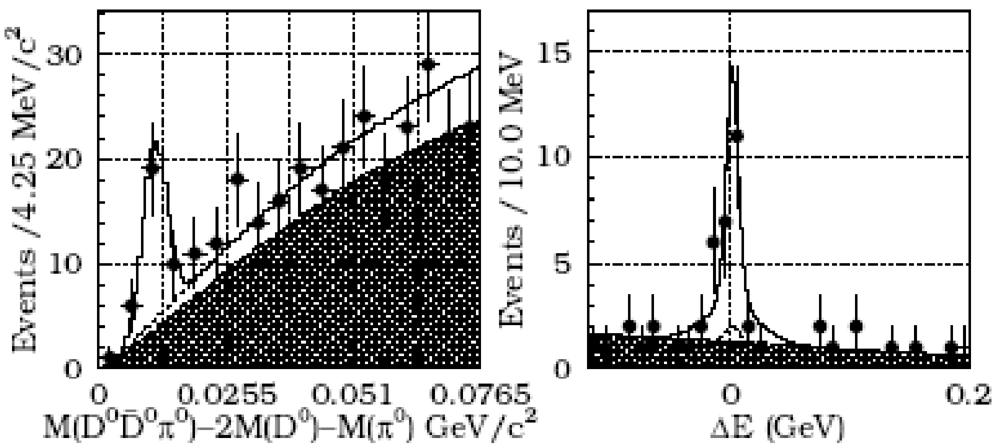
E.S. Swanson, Phys. Lett, B588 189(2004)

Also see M. B. Voloshin, Phys. Lett. B579, 316 (2004)

Belle: *Threshold peak in B → K* ($D^0\underline{D}^0\pi^0$)

Belle hep-ex/0606055 ← published in PRL





$M = 3875.4 \pm 0.7 \, ^{+0.3}_{-1.6} \pm 0.8$ MeV

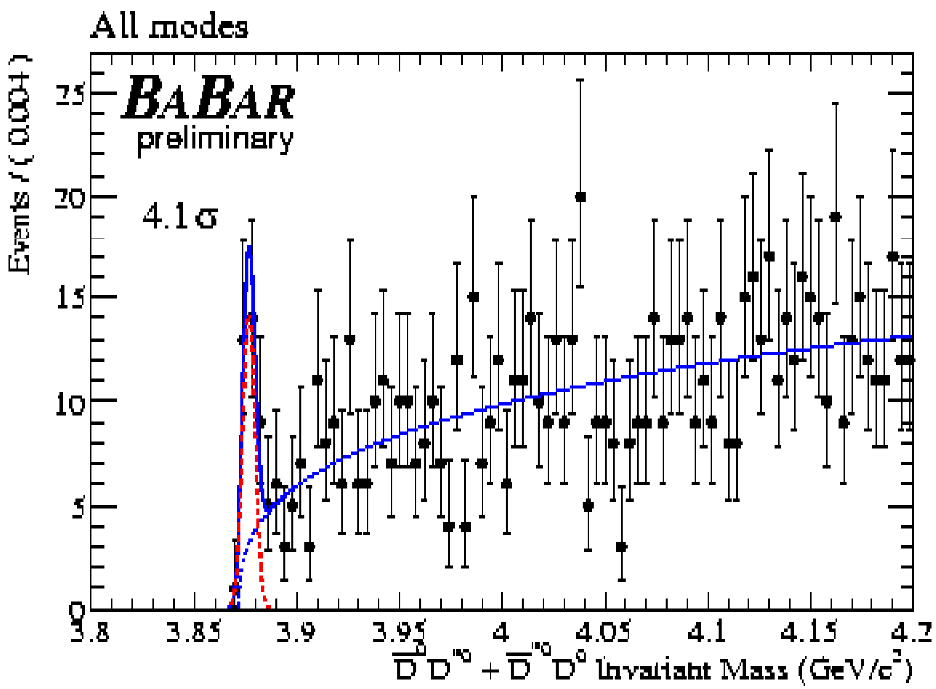
$Br(B \to KX) Bf(X \to D^0\underline{D}^0\pi^0)$

$= (1.27 \pm 0.31 \, ^{+0.22}_{-0.39}) \times 10^{-4}$

$$\frac{Br(X \to D^0\underline{D}^0\pi^0)}{Br(X \to \pi^+\pi^- J/\psi)} \sim 9$$

BaBar
@Moriond
2007

Threshold enhancement in B→(D^0 D^{*0}) K



$$M = 3875.6 \pm 0.7^{+1.4}_{-1.5}\,MeV$$

The mass is also 2.5σ above the nominal X(3872) mass (puzzling…is this the same beast ?)

BaBar 2007

Threshold enhancement in B→(D^0 D^{*0}) K

Hints of signals are seen in both B^+ and B^0 modes

Table 4: Number of data events obtained from the fit and branching fractions, $\mathcal{B}$, of $B \to X(3872)K$ followed by $X(3872) \to \bar{D}^{*0}D^0$ or $X(3872) \to \bar{D}^0D^{*0}$. A 90% confidence level limit on the branching fraction is also given. First error on $\mathcal{B}$ is statistical and second error is systematic.

B mode		Yield	$\mathcal{B}$ (10^{-4})	Limit (10^{-4})
$B^0 \to X(3872)K^0$	$[\bar{D}^{*0}D^0/\bar{D}^0D^{*0}]$	7.1 ± 2.9	$2.13 \pm 0.73\,^{+0.98}_{-0.82}$	7.30
$B^+ \to X(3872)K^+$	$[\bar{D}^{*0}D^0/\bar{D}^0D^{*0}]$	20.2 ± 5.7	$0.96 \pm 0.23\,^{+0.42}_{-0.28}$	3.48

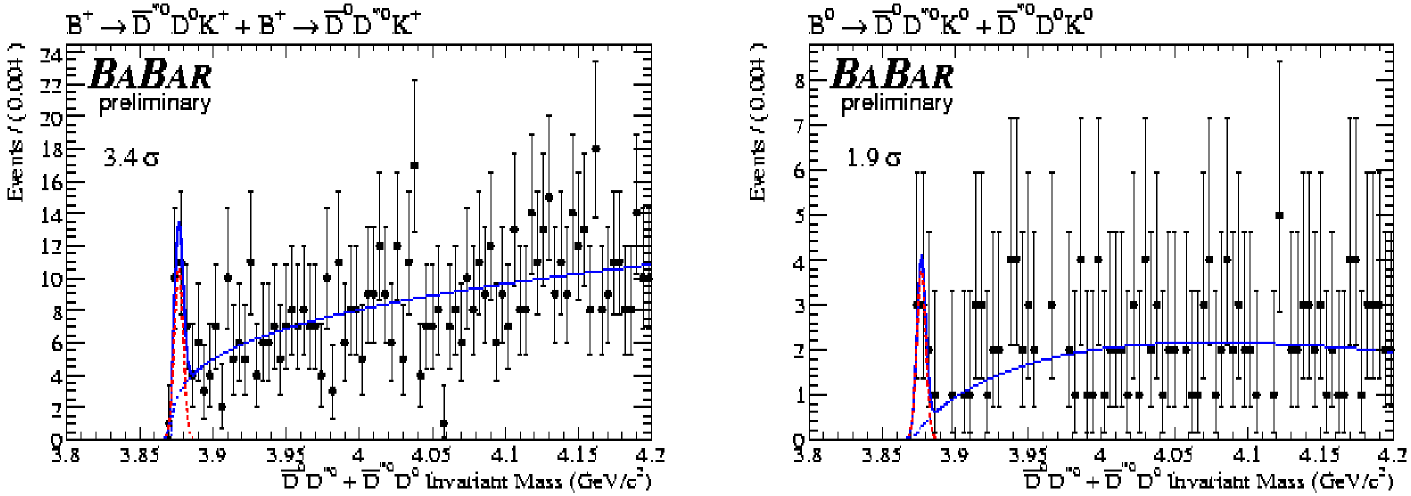
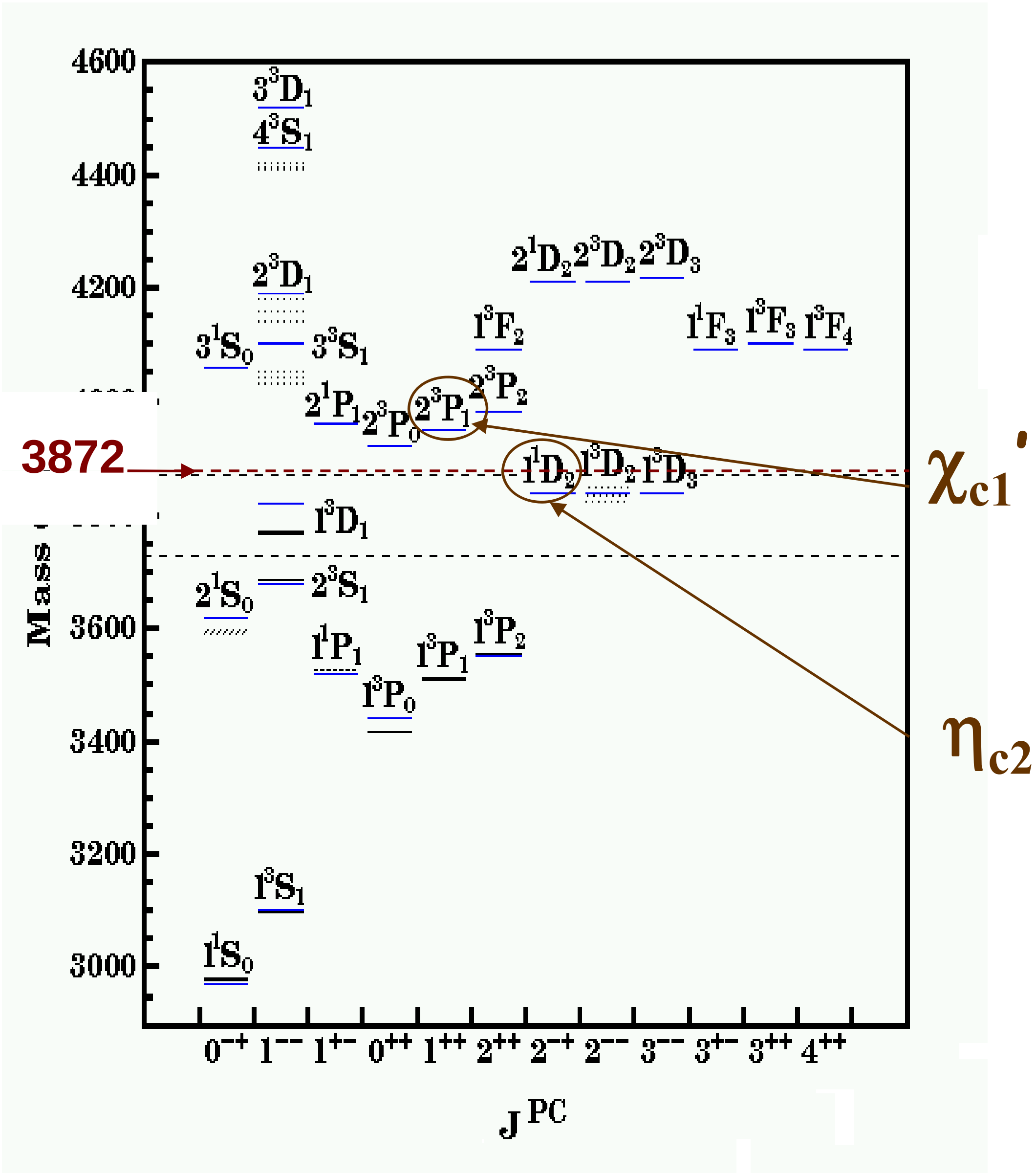


Figure 8: Fit of the $\bar{D}^0D^{*0} + \bar{D}^{*0}D^0$ invariant mass in the data for mode $B^+ \to \bar{D}^0D^{*0}K^+ + \bar{D}^{*0}D^0K^+$ (left-hand plot) and for mode $B^0 \to \bar{D}^0D^{*0}K^0 + \bar{D}^{*0}D^0K^0$ (right-hand plot). Dots are data, the plain line represents the fit to the data, the red dashed line shows the signal-only contribution and the dotted line shows the background contribution. Statistical significance of the fit is indicated in the figures.

X(3872) has no satisfactory $c\underline{c}$ assignment

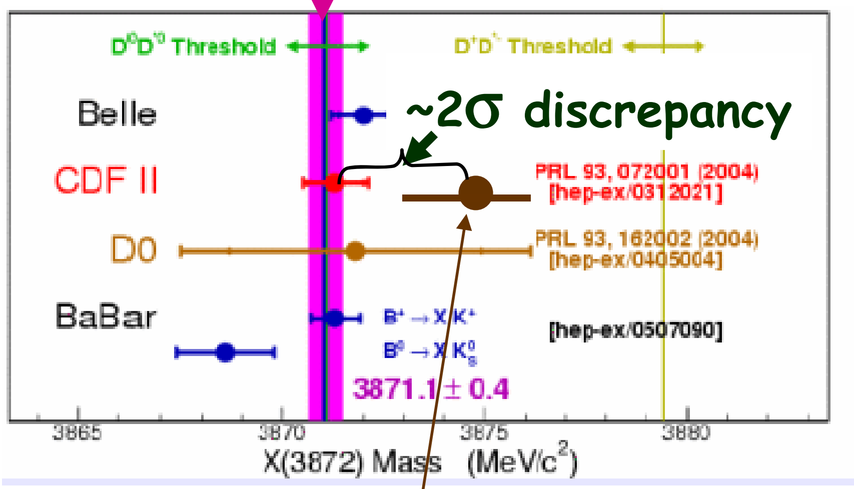


Br($\gamma J/\psi$) too small
& Br($\rho J/\psi$) too large

- $\eta_{c2} \rightarrow \rho J/\psi$ ispin forbidden
- $D^0\underline{D}^0\pi^0$ @ thresh. suppressed
- $B \rightarrow Kc\underline{c}(J=2)$ suppressed

Comments on the $D^0\underline{D}^0\ \pi^0$ mass peak

PDG M_{X3872}: 3871.2 ± 0.5 MeV



Fitted M: 3875.4 ± 0.7 $^{+0.3}_{-1.6}$ ± 0.8 MeV

2xPDG06 error on m_{D0} (could be ± 2.0 MeV)

DD* "Binding Energy?":

$$M-(m_{D0}+m_{D^{*}0}) = +4.3 \pm 0.7\ ^{+0.3}_{-1.6}\ \text{MeV}$$

Here error on m_{D0} drops out

Caution: nominally ~2.3σ above $D^0\underline{D}^{*0}$ threshold
(but errors are non-Gaussian)

Braaten et al: X→D D^{*0} mass spectrum

Theoretical prediction for a loosely bound D D^* state.

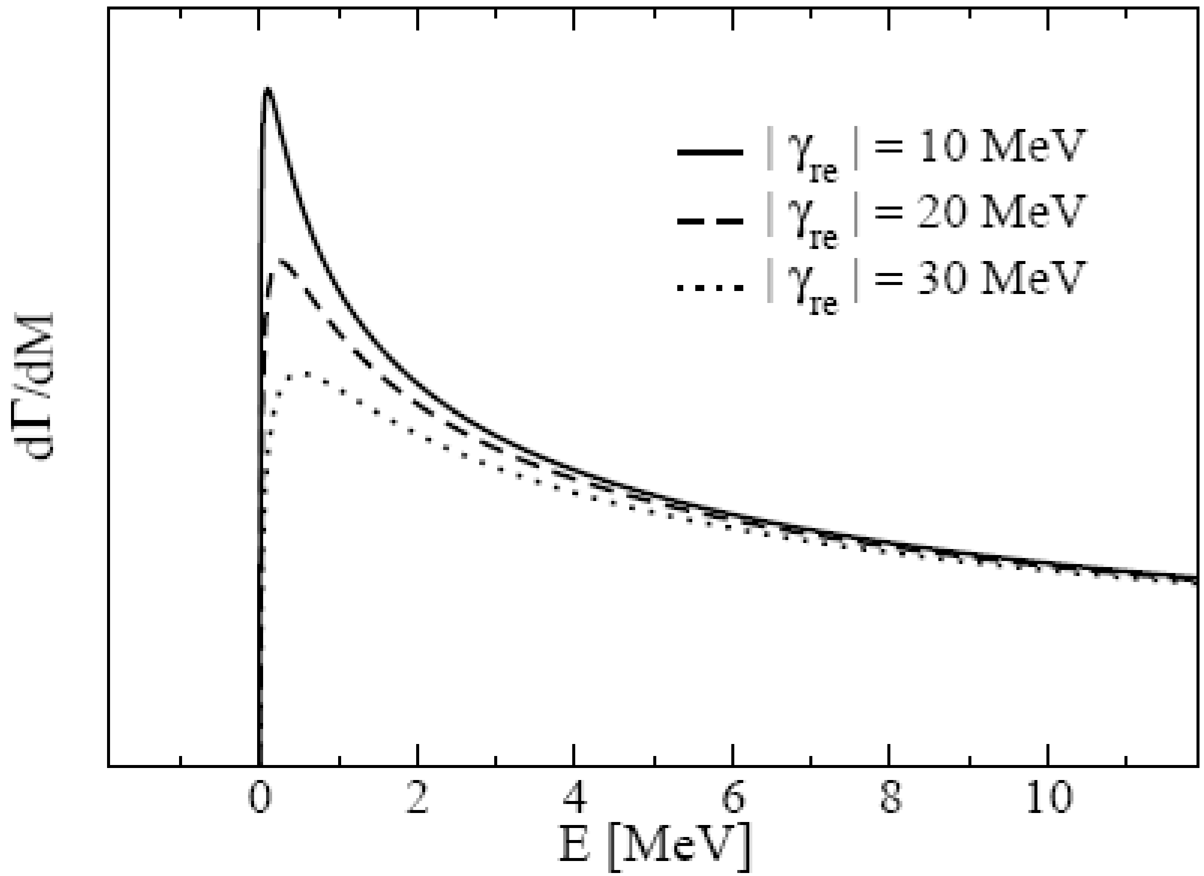
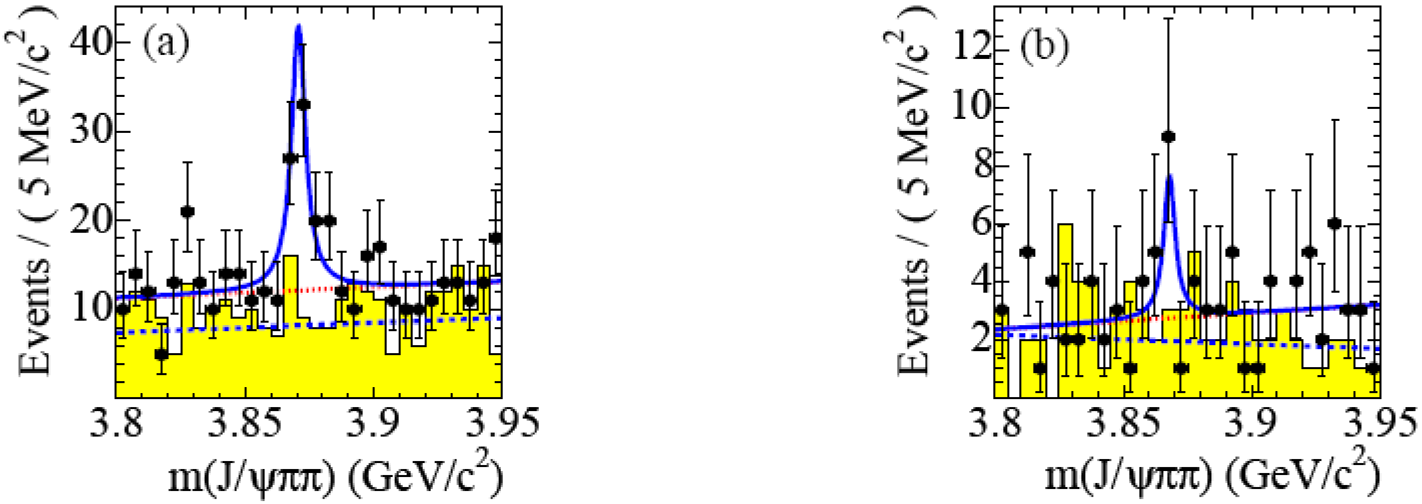


FIG. 6: The DD^* invariant mass distribution in $B \to D^0 \bar{D}^{*0} K$ for $\gamma_{\rm im} = 10$ MeV and various values of $|\gamma_{\rm re}|/\gamma_{\rm im}$. The horizontal axis is the difference $E = M - (m_{D^0} + m_{D^{*0}})$ between the invariant mass M and the $D^0 \bar{D}^{*0}$ threshold.

Signals for X(3872) in B^0 and B^+ modes

BaBar: B. Aubert *et al.*, *PRD* **73**, 011101(R) (2006)



$B^+ \to K^+ X(3872)$: 61.2 ± 15.3 events
$\mathcal{B}^+ \equiv \mathcal{B} \times \mathcal{B} = (10.1 \pm 2.5 \pm 1.0) \times 10^{-6}$

$B^0 \to K^0[K^0_S]\, X(3872)$: 8.3 ± 4.5 events
$\mathcal{B}^0 \equiv \mathcal{B} \times \mathcal{B} = (5.1 \pm 2.8 \pm 0.7) \times 10^{-6}$

- $R \equiv \mathcal{B}^0/\mathcal{B}^+ = 0.50 \pm 0.30 \pm 0.05$ and $\Delta m = m^+ - m^0 = (2.7 \pm 1.3 \pm 0.2)$ MeV/c^2
- $qq\bar{q}\bar{q}$ model: $R = 1$, $|\Delta m| = (7 \pm 2)$ MeV/c^2
- molecular model: $R < 0.1$, $\Delta m = 0$ *cf.* $R \in [0.13, 1.10]$ @ 90% CL
- data (weakly) favours $qq\bar{q}\bar{q}$; no-one believes $D^0\overline{D}^{*0}$ is sole Fock component

B. Yabsley

Important to confirm with higher statistics.

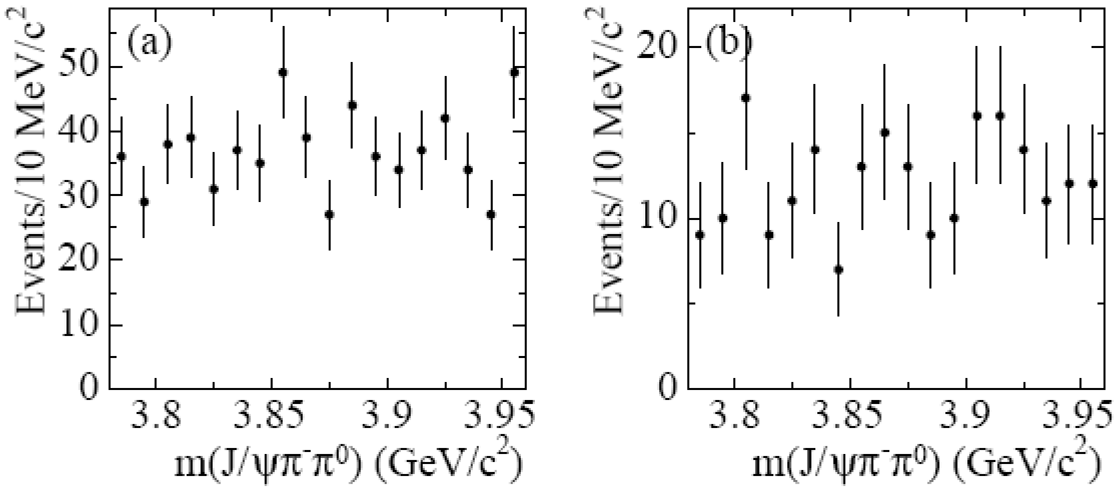
BaBar looked for a charged partner of the X(3872) and excluded isospin 1:

$$BF(B^0 \rightarrow X^- K^+)\ BF(X \rightarrow J/\psi\ \pi^-\ \pi^0) < 5.4 \times 10^{-6}$$

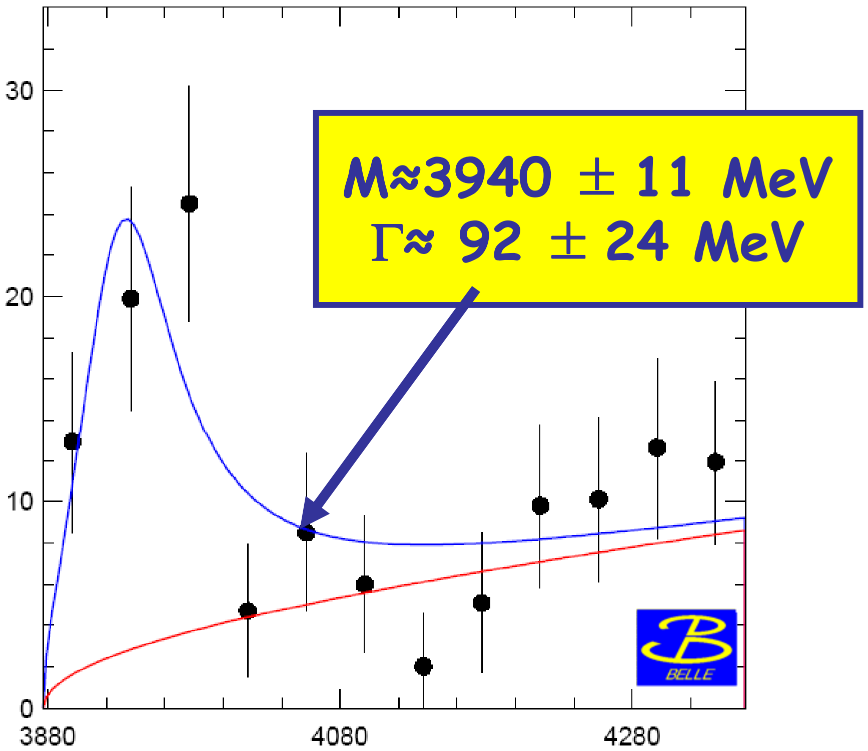
$$BF(B^- \rightarrow X^-\ K^0)\ BF(X \rightarrow J/\psi\ \pi^-\ \pi^0) < 2.2 \times 10^{-5}$$

$$c.f\ BF(B^0 \rightarrow X^0\ K+)\ BF(X^0 \rightarrow J/\psi\ \pi^-\ \pi^+) = (1.28 \pm 0.41) \times 10^{-5}$$

BaBar: B. Aubert *et al.*, *PRD* **71**, 031501 (2005)



Next State: *Y(3940) in B→K ω J/ψ*



M(ωJ/ψ) MeV

S. K Choi et al, (Belle) PRL94, 182002 (2005)

Reconstruct, B→K ω J/ψ.

Cut on K ω mass to remove contributions from K^{**} resonances.

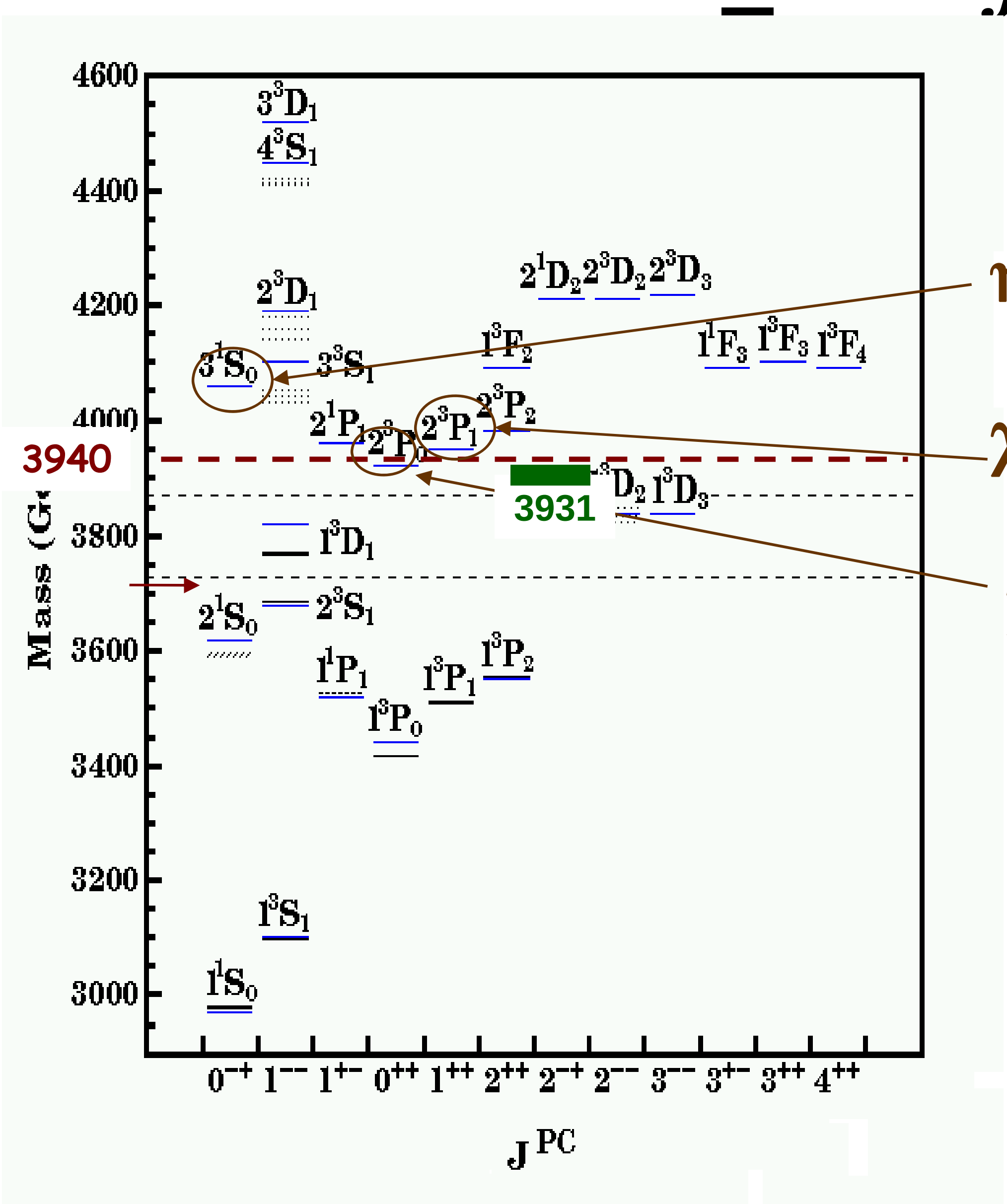
$\Gamma(Y_{3940} \rightarrow \omega J/\psi) \gtrsim 7$ MeV
(an $SU_F(3)$ violating decay)

this is $10^3 \times \Gamma(\psi' \rightarrow \eta J/\psi)$
(another $SU_F(3)$ violating decay)

If the Z(3930) is the χ_{c2}' the Y(3940) mass is too high for it to be the χ_{c1}'

Rosner: However, $\chi_{b1,2}$' states are seen to decay to ω Υ(1S)

Is there a c$\underline{c}$ slot for the Y(3940) ?



η_c'' Mass is low

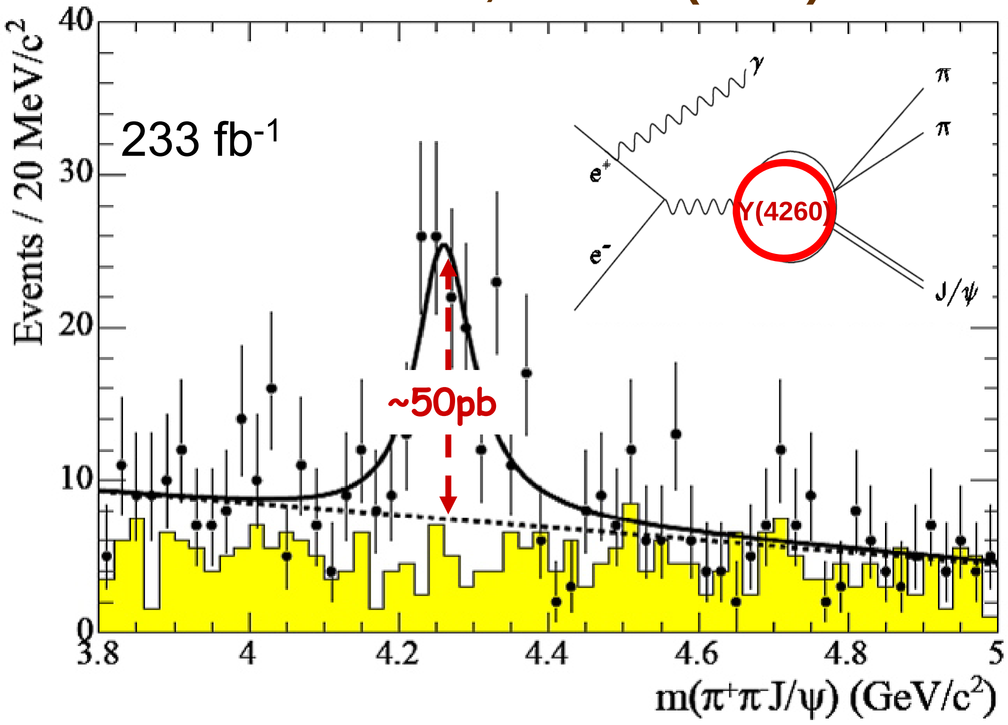
χ_{c1}' Can $M(\chi_{c1}')>M(\chi_{c2}')$?

χ_{c0}' " " " "

Might be a hybrid but the mass is too low. Hybrids expected at 4300-4500 MeV.

$e^+e^- \to \gamma_{isr}$ Y(4260) at BaBar

BaBar PRL95, 142001 (2005)

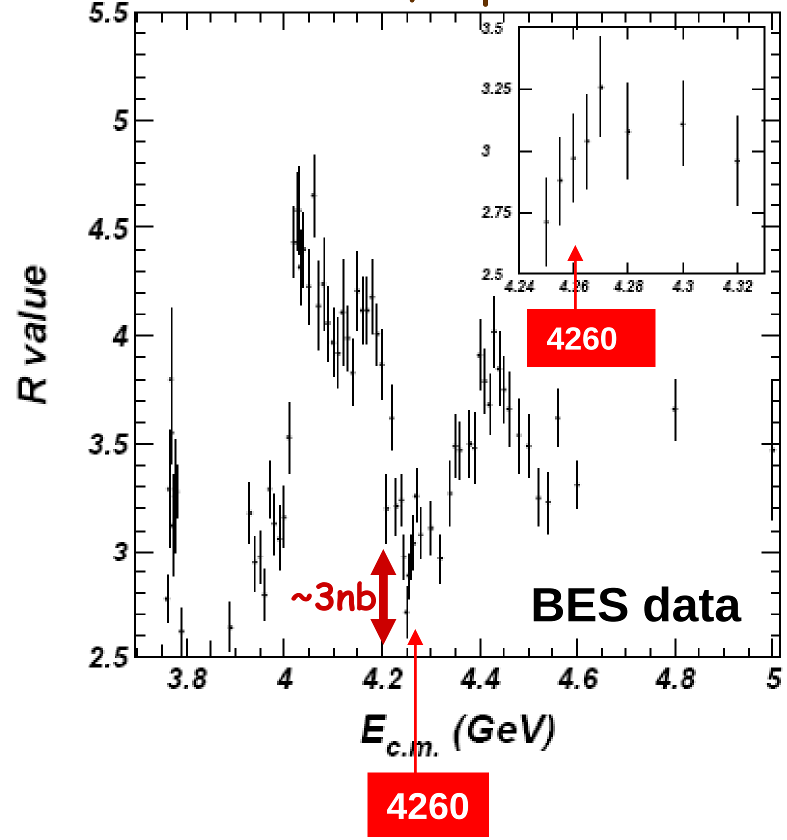


$\sigma(e^+e^- \to \pi^+\pi^- J/\psi) \sim 50$ pb

Γ(Y4260→$\pi^+\pi^-$ J/ψ) > 1.6 MeV @ 90% CL

Not seen in $e^+e^- \to$ hadrons

X.H. Mo *et al*, hep-ex/0603024



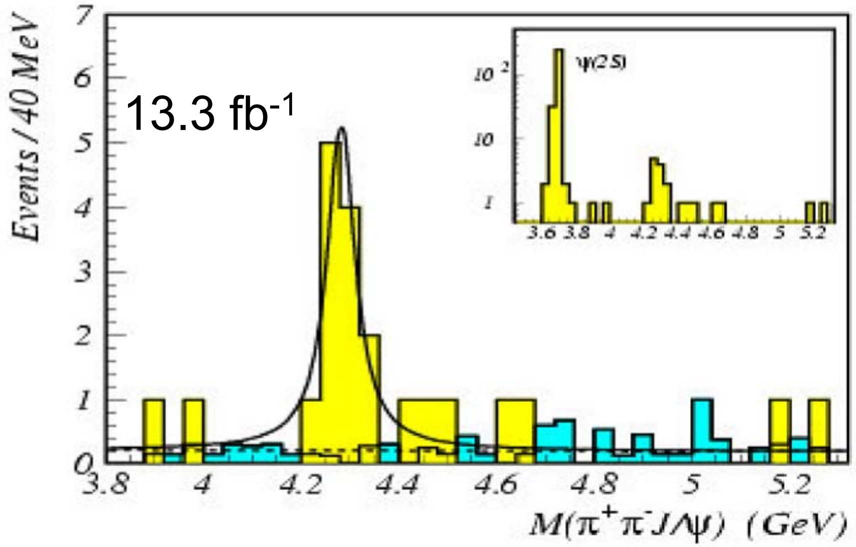
(there is a dip here !)

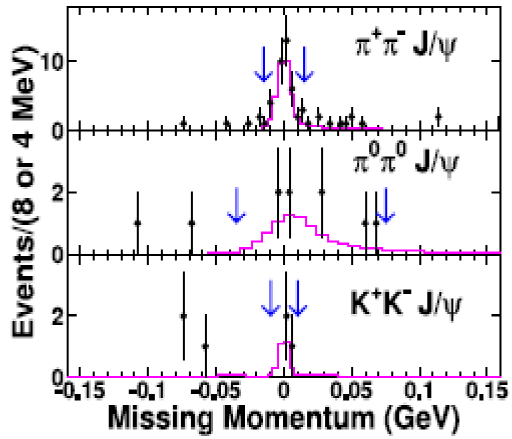
Y(4260) at CLEO-III

ISR

$\Upsilon(1S)$-$\Upsilon(4S)$

13.3 fb^{-1}





$\pi^+\pi^- J/\psi$: $\sigma = (58^{+12}_{-10} \pm 4)$ pb

$\pi^0\pi^0 J/\psi$: $\sigma = (23^{+12}_{-8} \pm 1)$ pb

$K^+K^- J/\psi$: $\sigma = (9^{+9}_{-5} \pm 1)$ pb

disfavour some non-$c\bar{c}g$ exotic hyp.

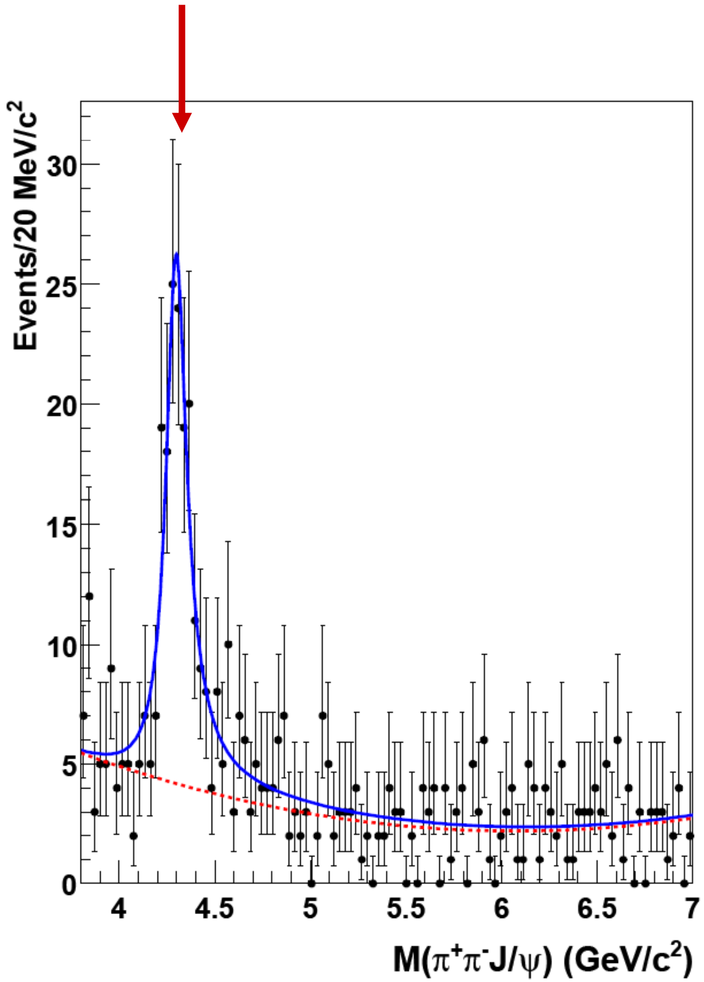
Consistent results

$$M = 4284^{+17}_{-16} \pm 4 \quad \text{MeV}$$
$$\Gamma = 73^{+39}_{-25} \pm 5 \quad \text{MeV}$$

CLEO PRD 74 091104 (2006)

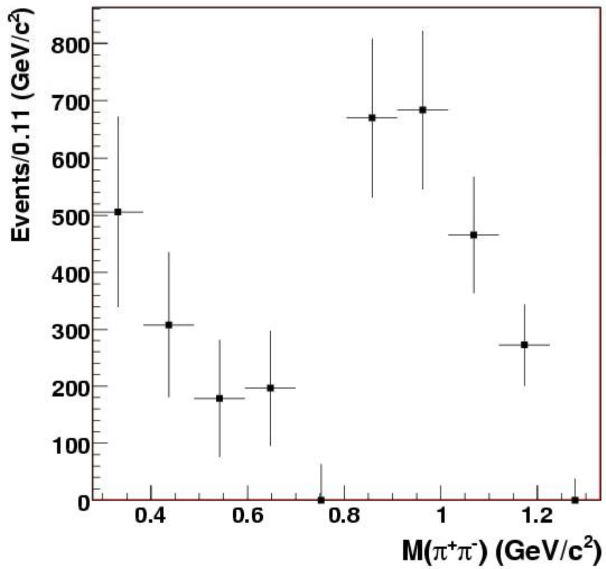
T.E. Coan et al., PRL 96, 162003 (2006)

Confirmation of Y(4260) in ISR at Belle



$$M = 4295 \pm 10^{+10}_{-3}\ MeV$$

$$\Gamma = 133 \pm 26^{+13}_{-6}\ MeV$$



$M(\pi^+ \pi^-)$

For $\psi' \rightarrow \pi^+\pi^- J/\psi$ in the same dataset:

$M(\psi')$ = 3685.3 ± 0.1 MeV
(PDG: $M(\psi')$=3686.09 ± 0.04)

Y(4260) at BaBar / CLEO / Belle

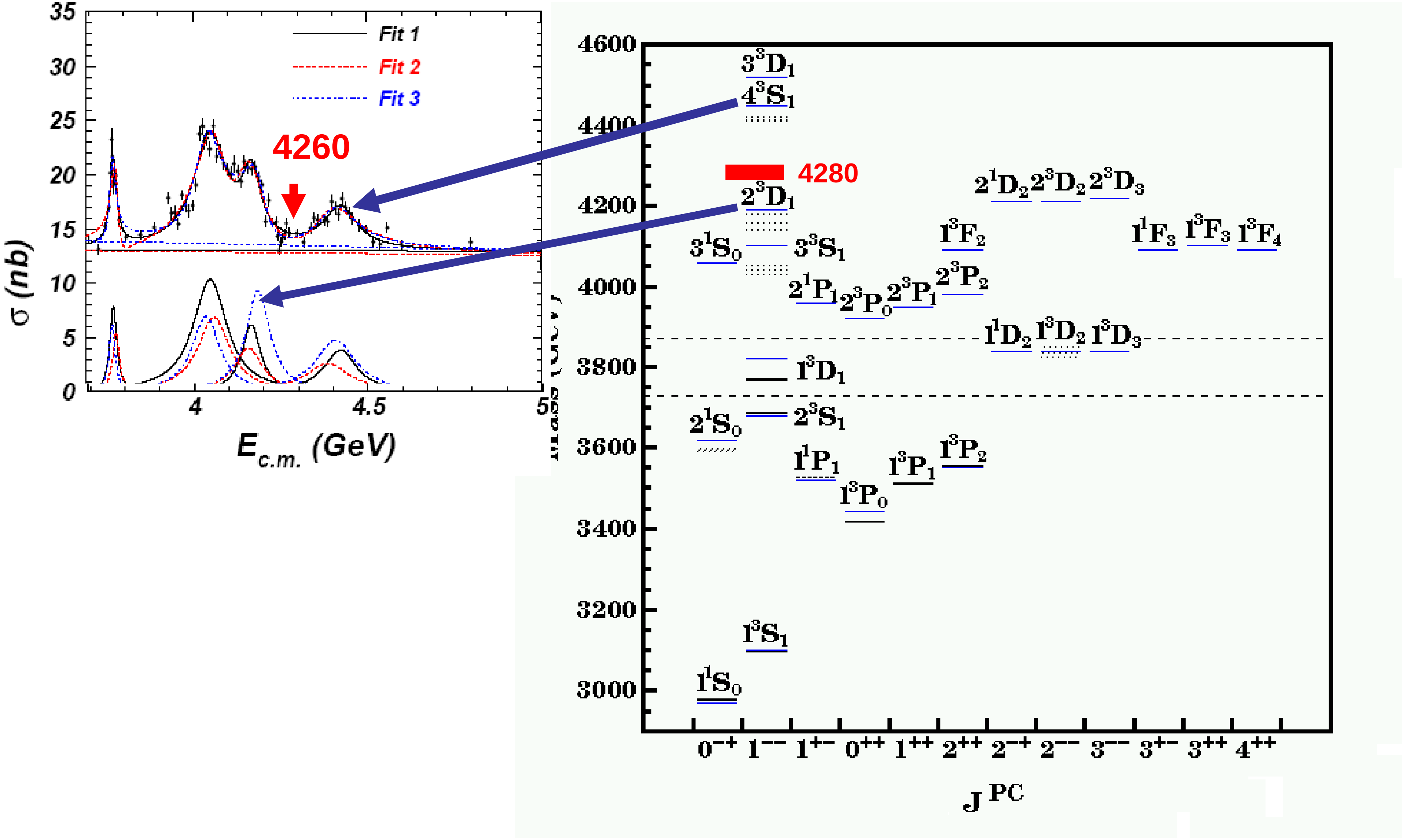
Roughly consistent, within ~2.5σ

	BaBar	CLEO III	**Belle** ***(prelim)***
N	125 ± 23 (~8σ)	$14.1^{+5.2}_{-4.2}$ (4.9σ)	**165 ± 24(stat) (>7σ)**
Mass(MeV)	$4259 \pm 8^{+2}_{-6}$	$4283^{+17}_{-16} \pm 4$	**$4295 \pm 10^{+10}_{-3}$**
Width	$88 \pm 23^{+6}_{-4}$	$73^{+39}_{-25} \pm 5$	**$133 \pm 26^{+13}_{-6}$**
$\Gamma_{ee}B(\pi^+\pi^- J/\psi)$(eV)	$5.5 \pm 1.0^{+0.8}_{-0.7}$	$8.9^{+3.9}_{-3.1} \pm 1.8$	$8.7 \pm 1.1^{+0.3}_{-0.9}$

No 1⁻⁻ c$\underline{c}$ slot for the Y(4260)

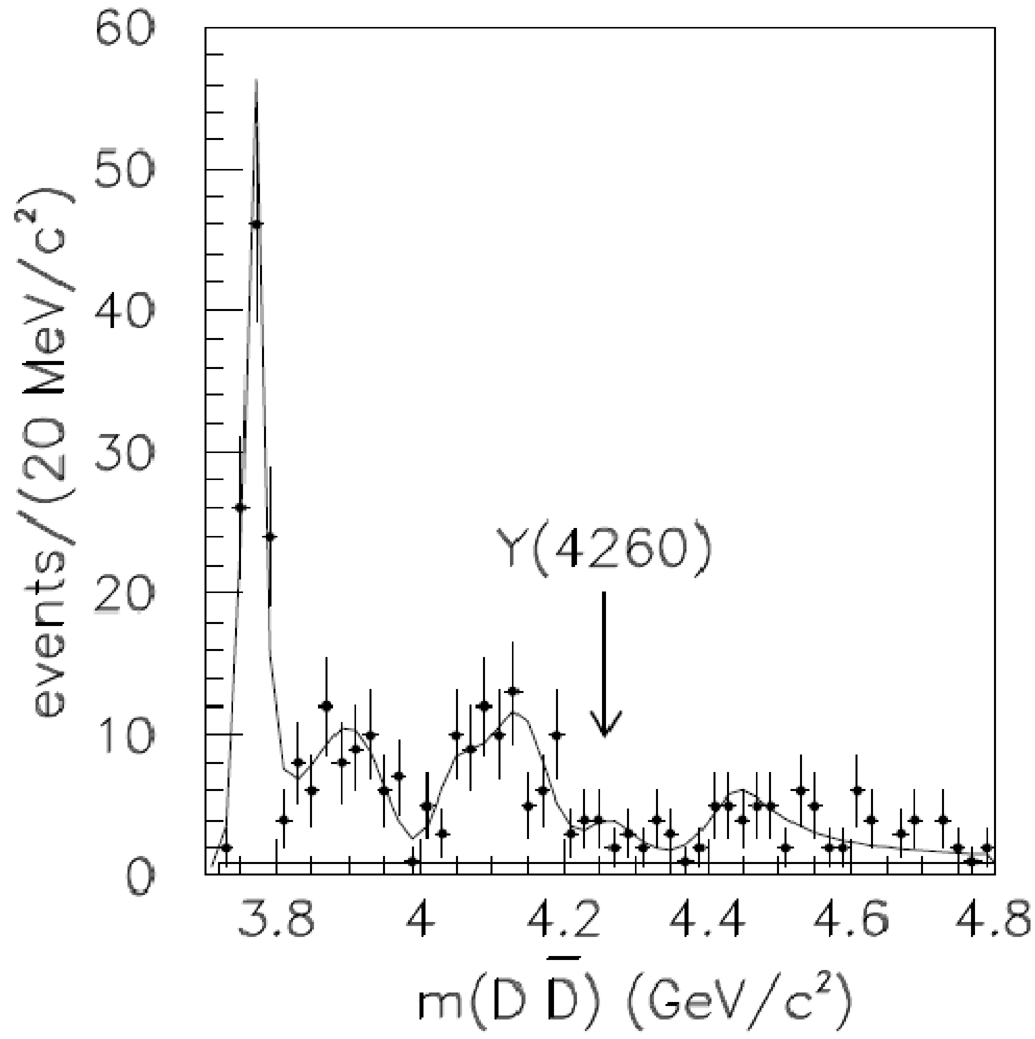
X.H. Mo *et al*, hep-ex/0603024

PLB 640, 182 (2006)



$\sigma(e^+e^- \rightarrow D\underline{D})$ using ISR

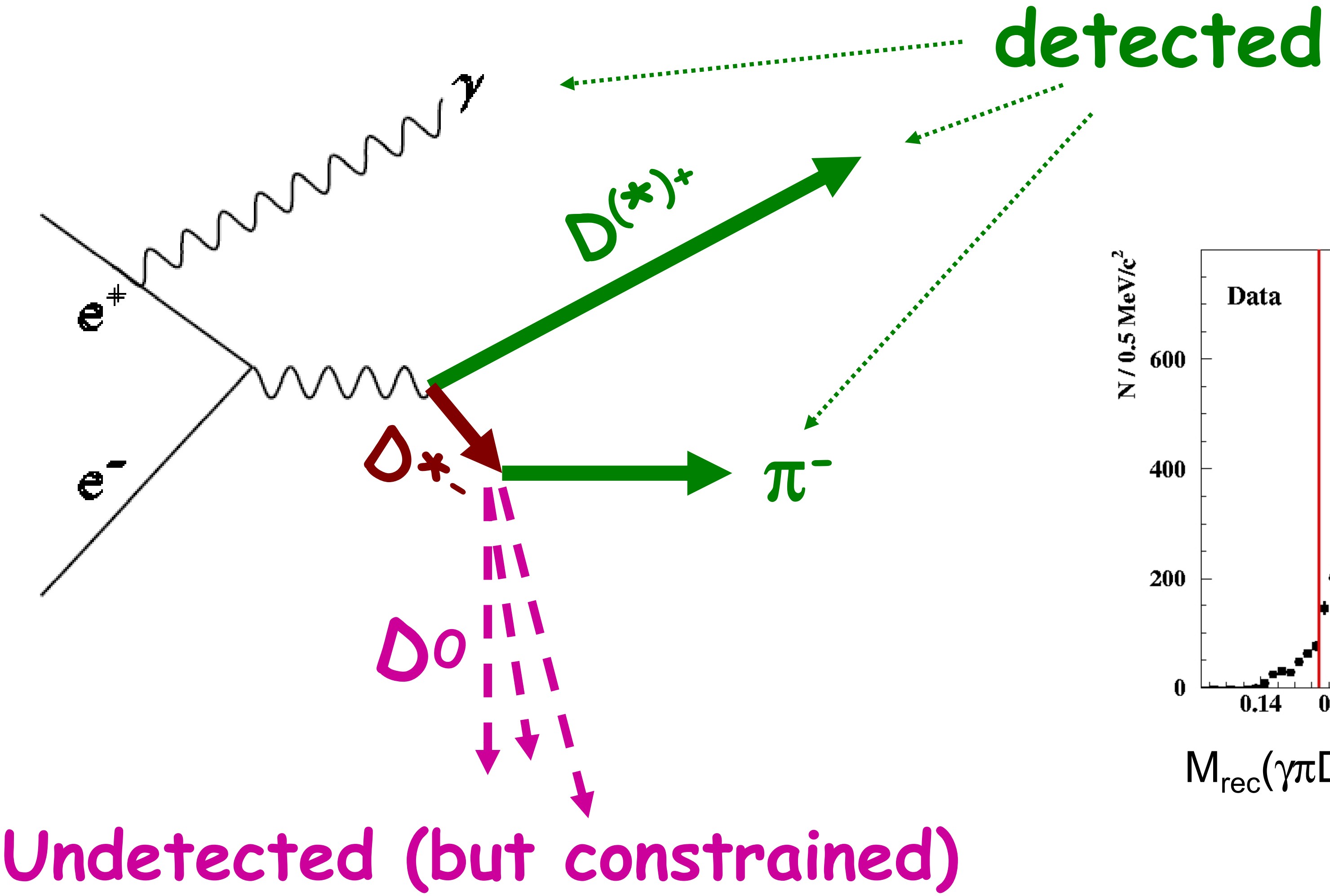
BaBar hep-ex/0607083

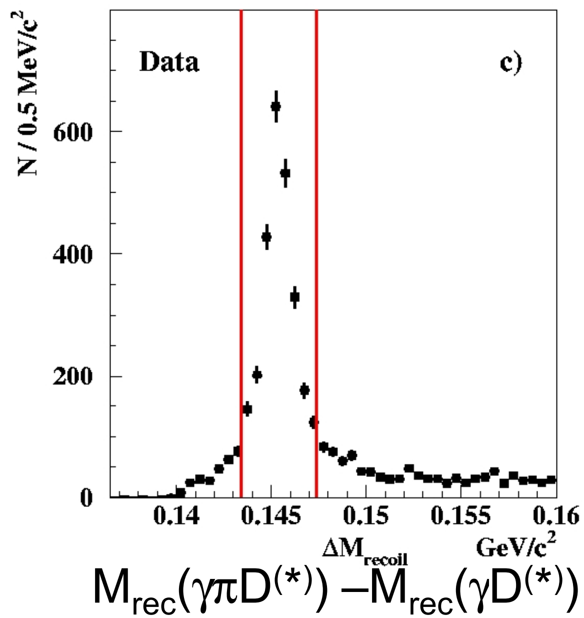


$\sigma(e^+e^- \rightarrow D^*D^{(*)})$ @ $\sqrt{s} \approx 4$ GeV

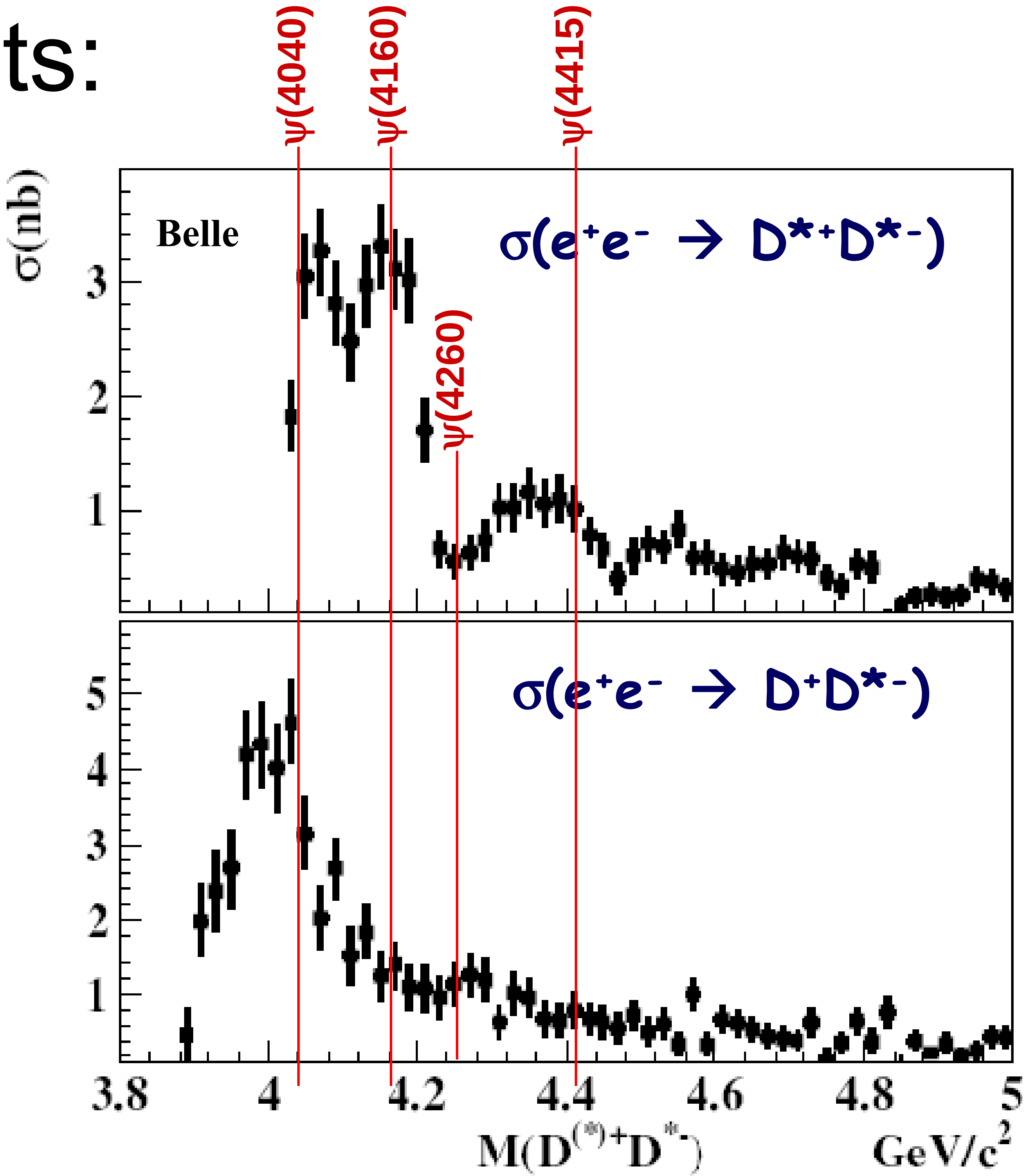
Belle: ISR + Partial Reconstruction

hep/ex0608018, to appear in PRL



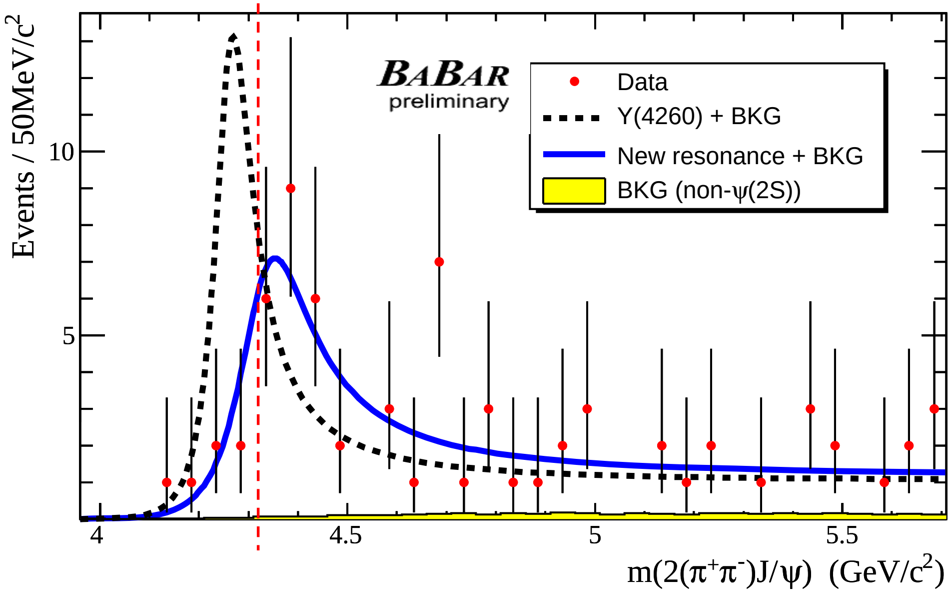


results:


ψ(4040)
ψ(4160)
ψ(4415)
ψ(4260)
Belle
σ(nb)
σ(e⁺e⁻ → D*⁺D*⁻)
σ(e⁺e⁻ → D⁺D*⁻)
3.8
4
4.2
4.4
4.6
4.8
5
M(D^(*)+D*-)
GeV/c²

The Y(4324) structure from BaBar

$e^+e^- \rightarrow \gamma_{ISR}\ (\pi^+\pi^-\ \psi')$



298 fb^{-1}: hep-ex

Nevt = 68 (<5.7 GeV/c^2)

Nbkg = 3.1 ±1.0

M=4324 ± 24 MeV

Γ = 172 ± 33 MeV

above all DD thresholds**

Not compatible with the Y(4260)

Incompatible with **ψ(4415), nor is it well described by the Y(4260)** A single resonance can describe the structure (<5.7 GeV/c2) well

⇒ **mass=(4324±24) MeV/c2, Γ=(172±33) MeV**

(statistical errors only)

χ^2-prob	< 5.7 GeV/c^2
Y(4260)	**6.5×10^{-3}**
ψ(4415)	**1.2×10^{-13}**
Y(4320)	**29%**

Another new structure ($\varphi\ f_0$) in ISR found by BaBar

(hep-ex/0610018)

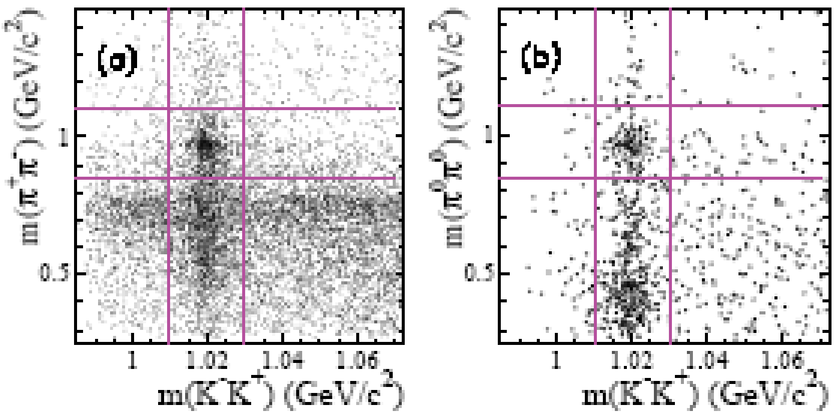


FIG. 2: The scatter plots of the reconstructed a) $m(\pi^+\pi^-)$ and b) $m(\pi^0\pi^0)$ versus $m(K^+K^-)$ for selected events in the data. The vertical (horizontal) lines bound a ϕ ($f_0(980)$) signal region.

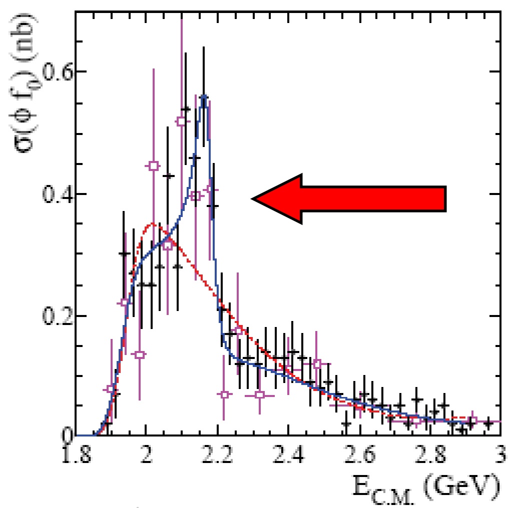


FIG. 6: The $e^+e^- \to \phi(1020)f_0(980)$ cross section, with about 10% of the $\phi\pi\pi$ contribution, obtained via ISR in the $K^+K^-\pi^+\pi^-$ (circles) and $K^+K^-\pi^0\pi^0$ (squares) final states. The curves represent results of the fits described in the text.

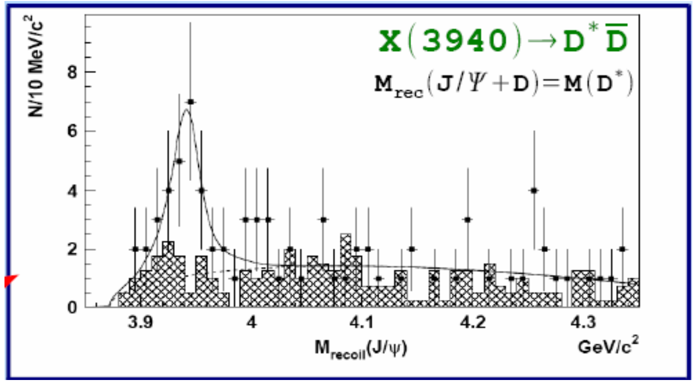
$$\sigma_0 = 0.13 \pm 0.04 \pm 0.02 \text{ nb},$$
$$m_x = 2.175 \pm 0.010 \pm 0.015 \text{ GeV}/c^2,$$
$$\Gamma_x = 0.058 \pm 0.016 \pm 0.020 \text{ GeV}/c^2, \text{ and}$$
$$\psi_x = -0.57 \pm 0.30 \pm 0.20 \text{ rad}.$$

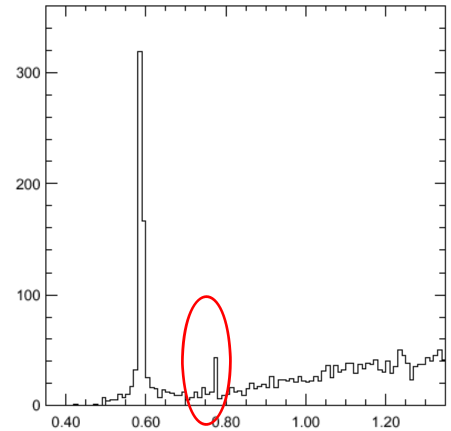
Is this the s sbar analogue of the Y(4260) ?

New Particle Summary+Guesses

- X(3940) ($e^+e^- \rightarrow J/\psi\ X$)
  - C=+1
  - Might be the η_c"

D*D





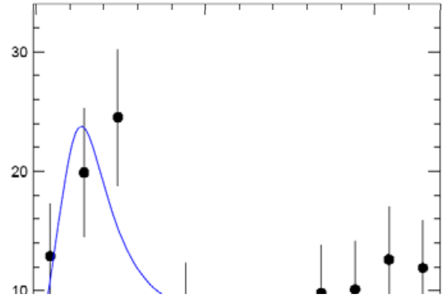
- X(3872):
  - $J^{PC} = 1^{++}$
  - $Br(X \rightarrow \pi^+\pi^- J/\psi)$ large
  - $Br(X \rightarrow D^0 \underline{D}^0 \pi^0)$ seen; ~ $9 \times Br(X \rightarrow \pi^+\pi^- J/y)$

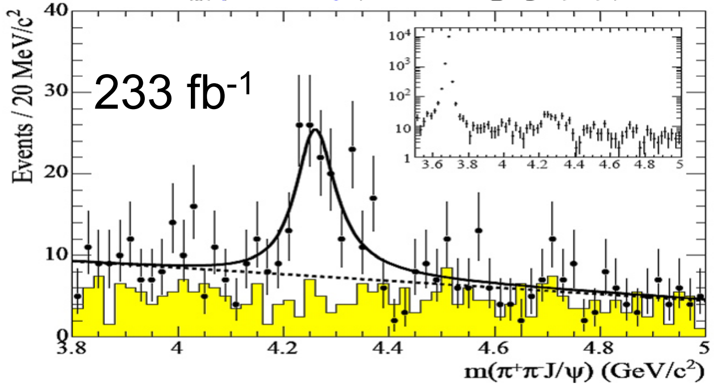
A 4-quark or D D^{*0} molecule candidate

summary cont'd

- Y(3940)→ωJ/ψ
  - Γ(Y_{3940}→ ωJ/ψ)>7 MeV (large!)

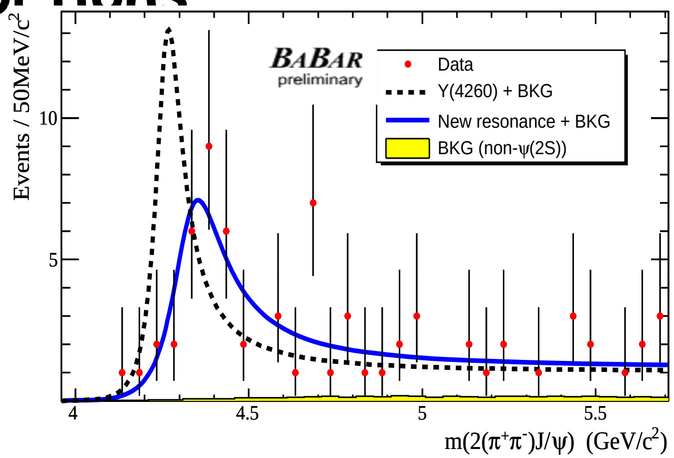
    But other properties compatible with a radially excited $\chi_{c1,2}$ state





- "Y(4260)"→$\pi^+\pi^-$J/ψ
  - Γ(Y_{4260}→$\pi^+\pi^-$J/ψ)>1.6 MeV
  - $J^{PC}=1^{--}$, not seen in e^+e^-→ hadrons
  - no obvious D**D threshold distortions

A good c cbar hybrid candidate



- "Y(4324)"→$\pi^+\pi^-$ψ'
  - above all D**D thresholds

Personal Conclusions

(Not endorsed by the management of any experiment.)

- Two intriguing exotic candidates: the X(3872) and the Y(4260).
- *Additional measurements of more modes and with higher statistics will clarify the interpretation of the above two states.*
- It is important to confirm the X(3940), Y(3940) and Y(4324) states and learn more about them.
- *Frank Close will discuss the interpretation in greater depth with a stronger dose of theory.*

Back-up slides

BaBar: $e^+e^- \rightarrow \gamma_{ISR} (\pi^+\pi^- \psi')$

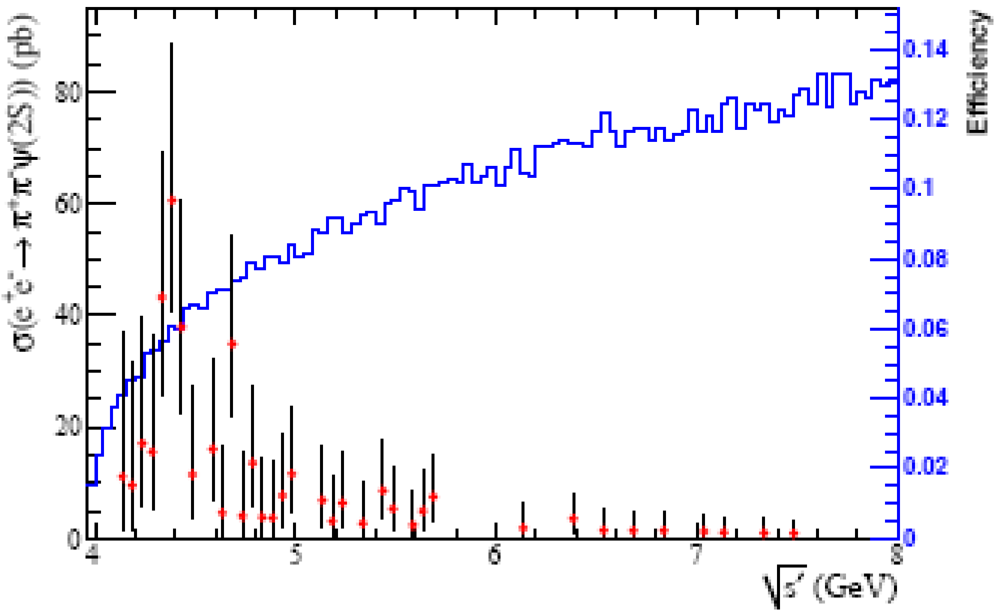
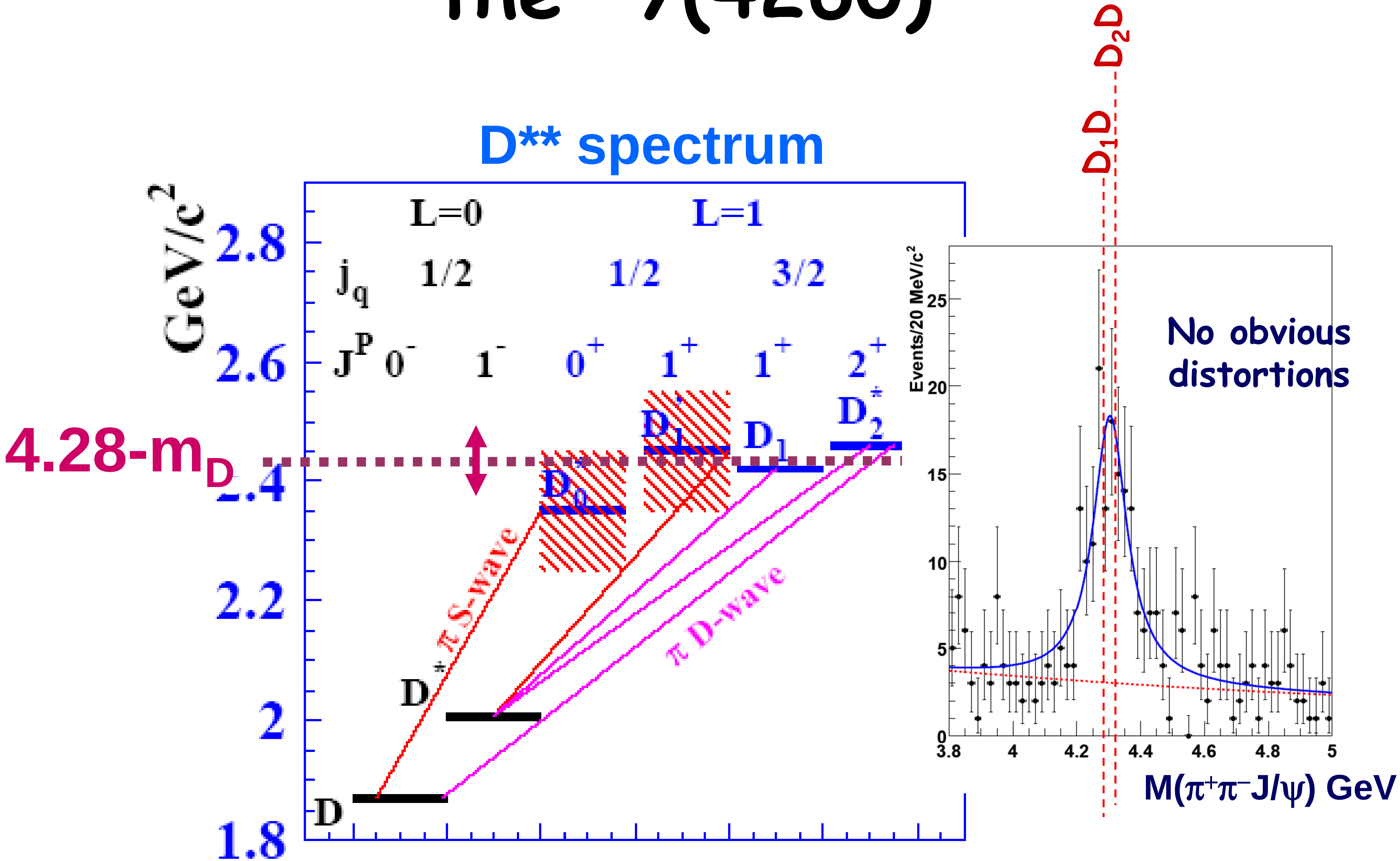
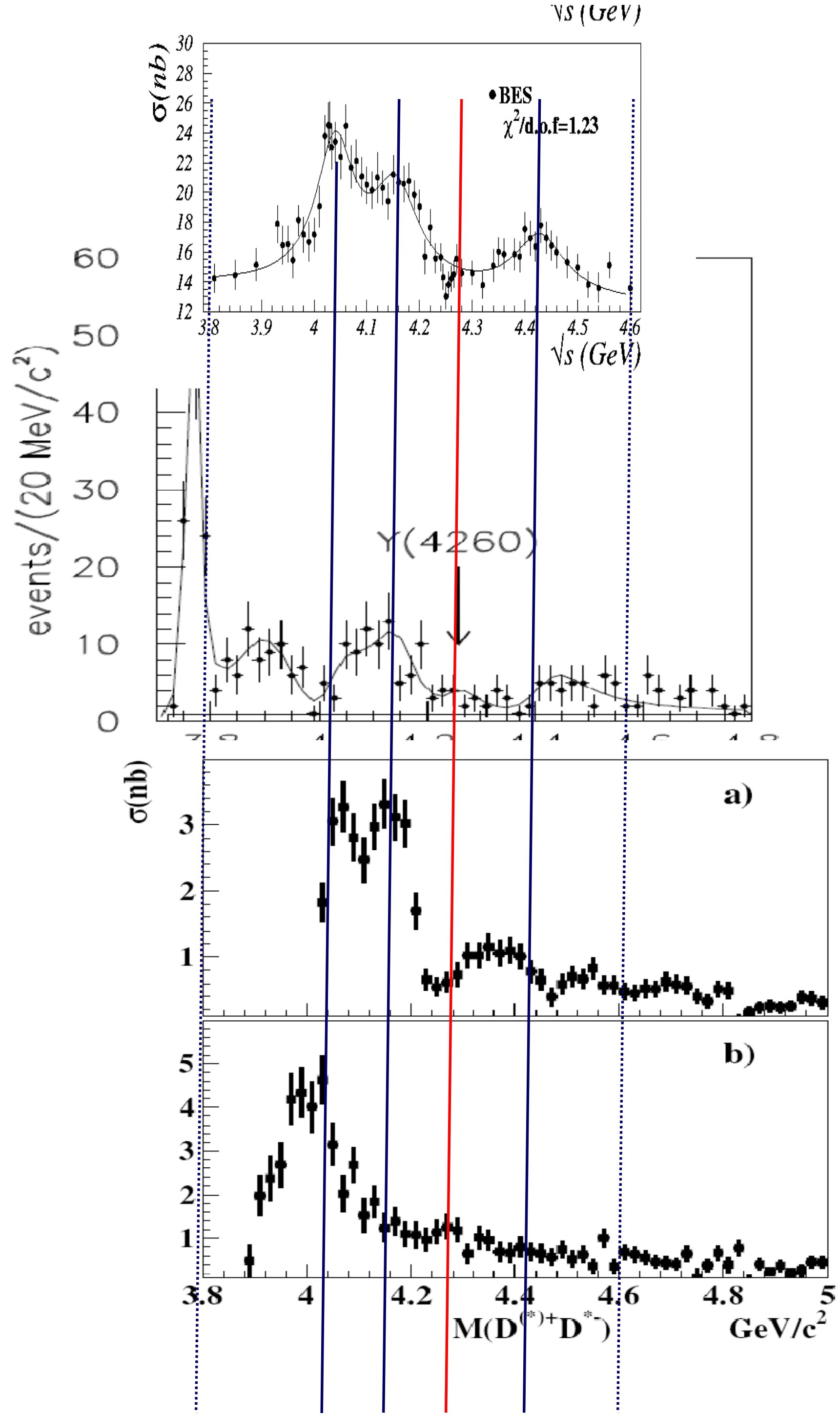


FIG. 5: The measured CM energy dependence of the cross section (points with error bars) for $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ after background subtraction. The solid histogram shows the energy-dependent selection efficiency.

Efficiency is changing rapidly near threshold

D$\underline{D}$** threshold in relation to the "Y(4260)"

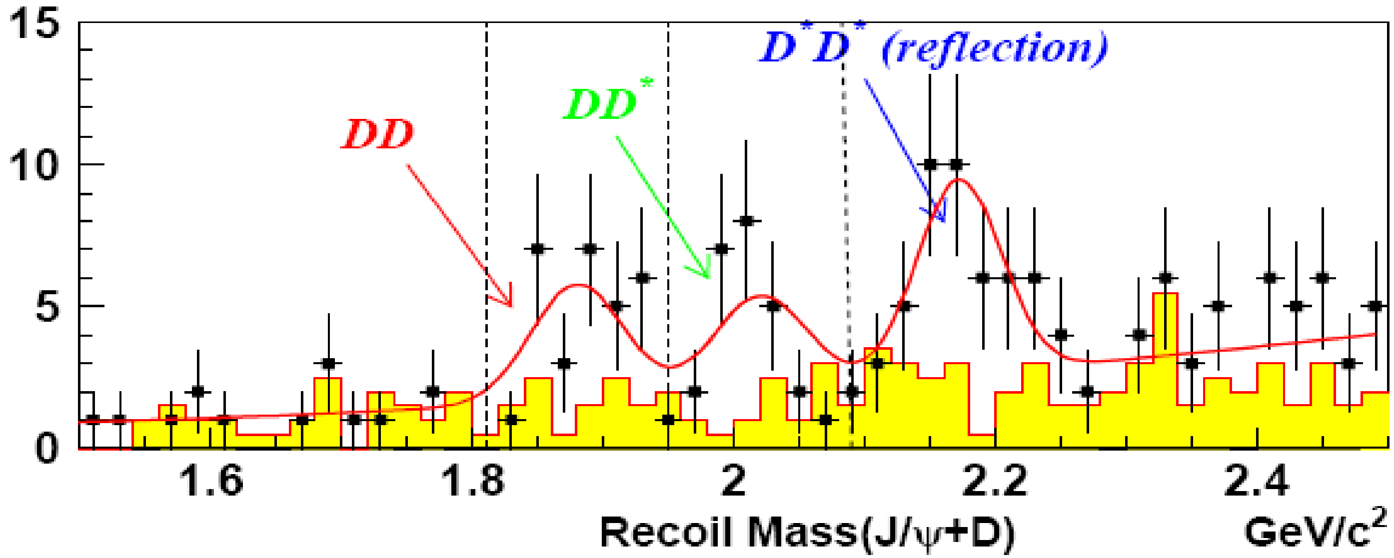




√s (GeV)
σ(nb)
BES
χ²/d.o.f=1.23
√s (GeV)
events/(20 MeV/c²)
Y(4260)
σ(nb)
a)
b)
M(D(*)+D*-)
GeV/c²

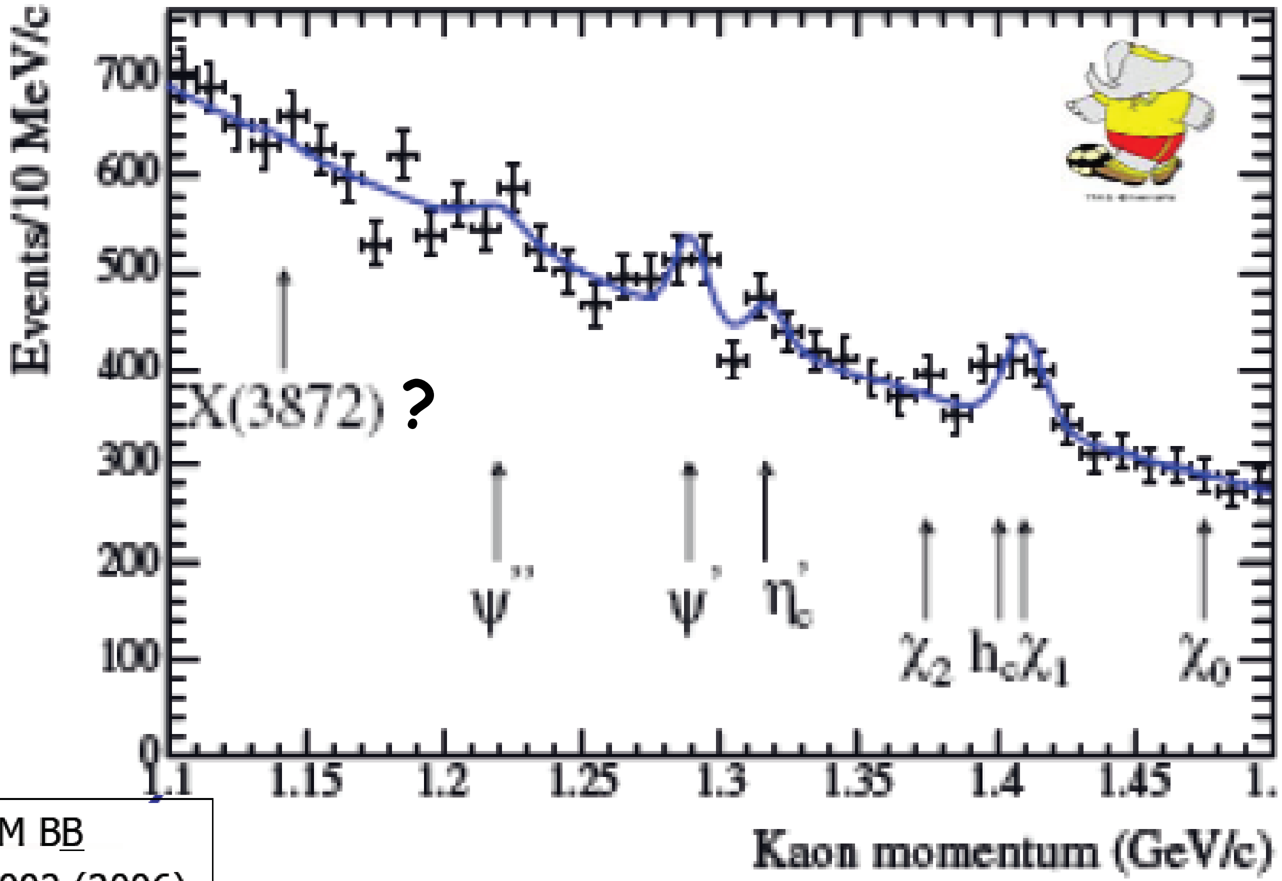
Look at $e^+e^- \rightarrow J/\psi\ D(D^{(*)})$

- **Reconstruct a J/ψ & a D**
  - **use $D^0 \rightarrow K^-\pi^+$ & $D^+ \rightarrow K^-\pi^+\pi^+$**
- **Determine recoil mass**



Inclusive B→Kx from BaBar

Fully reconstructed B⁻ tags



BABAR: 232M BB̲
PRL 96, 052002 (2006)

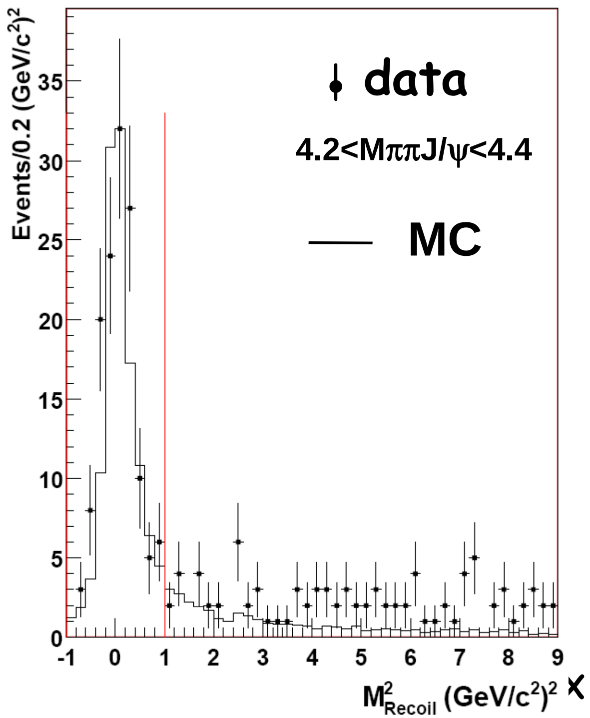
$$\mathrm{B}(B^{\pm} \rightarrow K^{\pm}\ X^{0}(3872)) < 3.2\times 10^{-4}\ @\ 90\%\,\mathrm{CL}$$

$$\mathrm{B}(X^{0}(3872) \rightarrow \pi^{+}\pi^{-}\ \mathrm{J}/\psi) > 0.042\ @\ 90\%\,\mathrm{CL}$$

Y(4260) at Belle

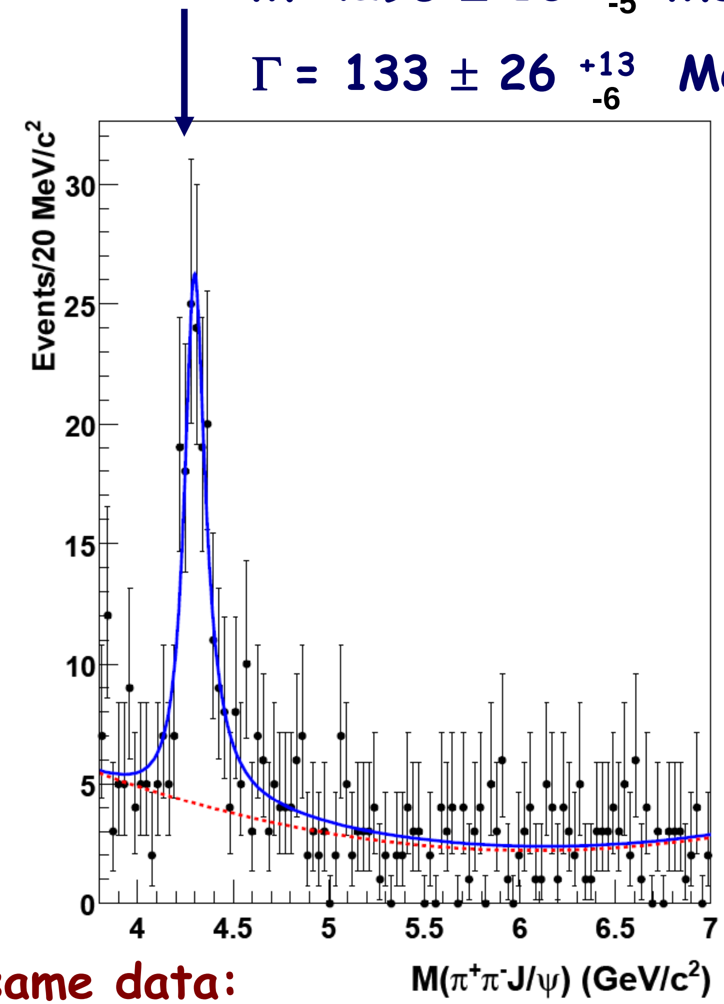
Select $e+e- \rightarrow \pi^+\pi^- \ell^+\ell^- +X$; $N_{chg}=4$

$M_{\ell+\ell-}=M_{J/\psi}\pm30MeV$; $p_{J/\psi}>2$ GeV; $M_{\pi\pi}>0.4GeV$



$M=4295 \pm 10\ ^{+11}_{-5}$ MeV

$\Gamma = 133 \pm 26\ ^{+13}_{-6}$ MeV

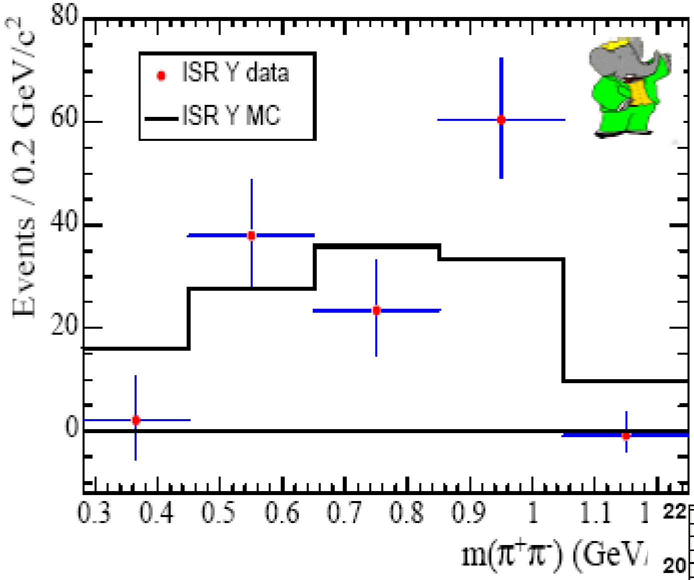


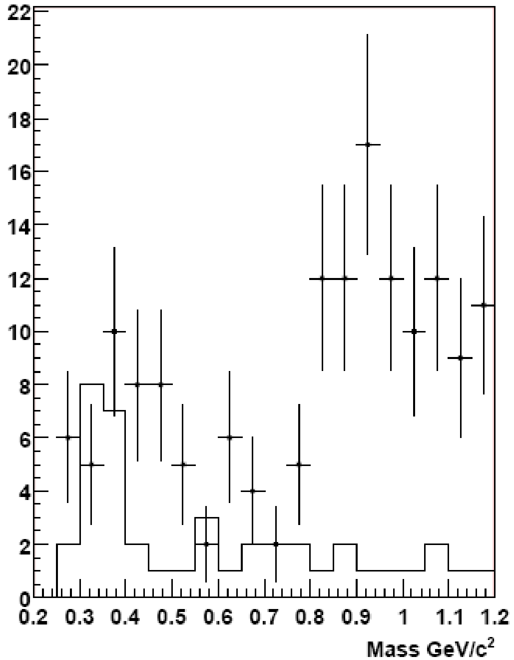
For $\psi' \rightarrow \pi^+\pi^- J/\psi$ in the same data:

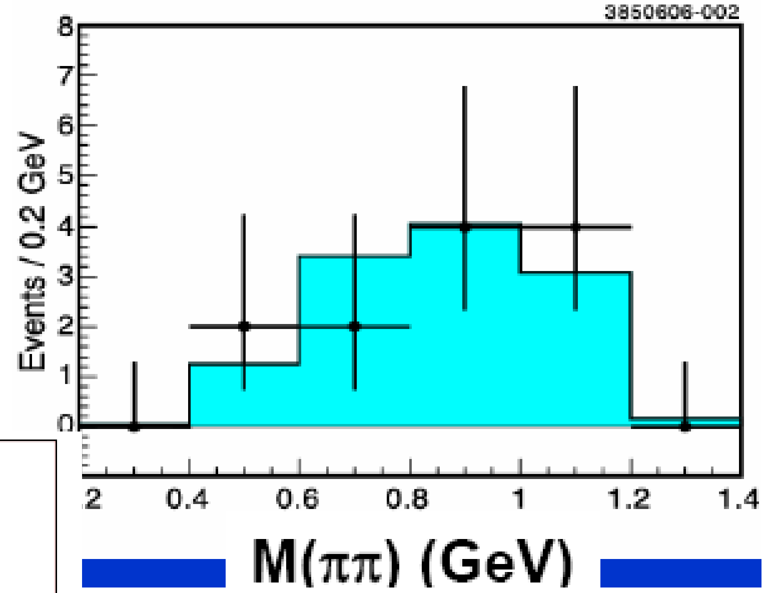
$M(\psi') = 3685.3 \pm 0.1$ MeV

(PDG: $M(\psi')=3686.09 \pm 0.04$)

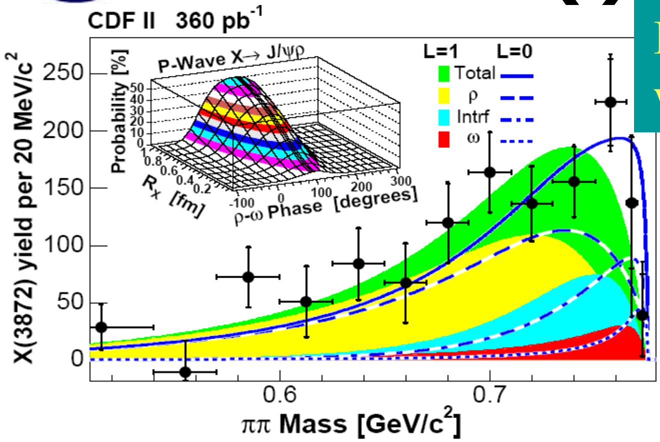
Mππ


ISR Y data
ISR Y MC
Events / 0.2 GeV/c²
m(π⁺π⁻) (GeV/

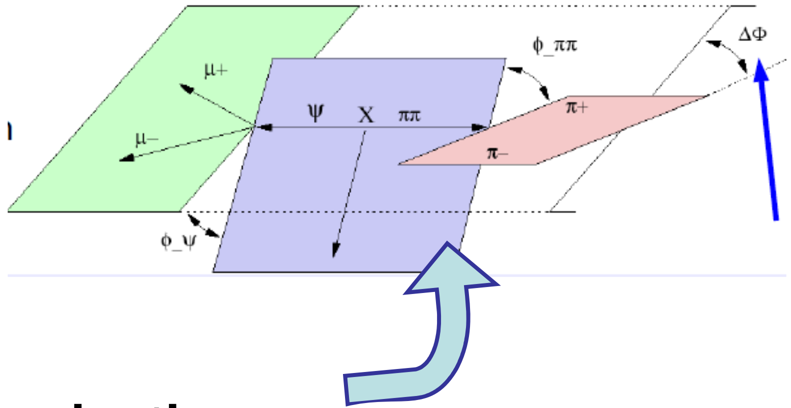

Mass GeV/c²


3850606-002
Events / 0.2 GeV
M(ππ) (GeV)

M(ππ) spectrum

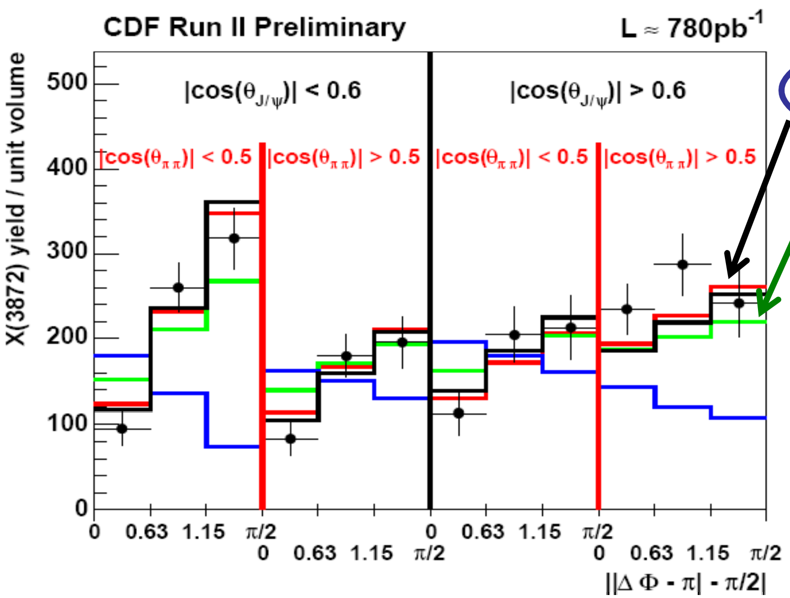


L=0,1 compatible with the data



Angular analysis at CDF

3 angles



Inclusive X production:

- Fit to 3 (only) angular variables simultaneously

High statistics: angular analysis of 3000 events

hypothesis	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^{+-}	$\leq 1 \cdot 10^{-20}$
0^{++}	$\leq 1 \cdot 10^{-20}$

Angular analysis at Belle

Exclusive X production:
6 angles

0^{++}, 0^{-+}, 1^{-+} excluded
1^{++} favored
J>2 not checked but disfavored by obsv $D^0 D^0 \pi^0$

Two hypothesis survived: 1^{++} & 2^{-+}

X(3872)

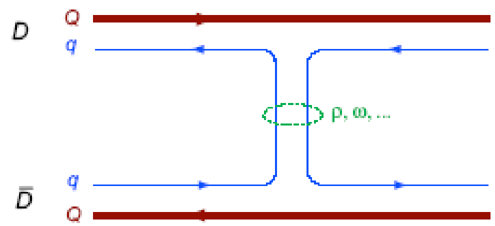
Quantum numbers are fixed: $J^{PC}=1^{++}$ corresponds to χ_{c1}', but

- ✓ $\chi_{c1}' \to J/\psi\gamma$ should be much stronger than $\chi_{c1}' \to J/\psi\pi\pi$

measured ratio ~ 0.19 (average Belle & BaBar), expected ~ 30

- ✓ ~100 MeV/c^2 lighter than expected.

Possible interpretations:



D^0D^{*0} molecule:

- ✓ Large isospin violation expected
- ✓ $J^{PC}=1^{++}$ predicted
- ✓ New Cleo D^0 mass measurement: binding energy +0.1±1.0 MeV→ -0.4±0.7 MeV

Tetraquark molecule:

predicts mass splitting for $B^0 \to X_{dd} K^0$ and $B^+ \to X_{uu} K^+$, errors still too large to check

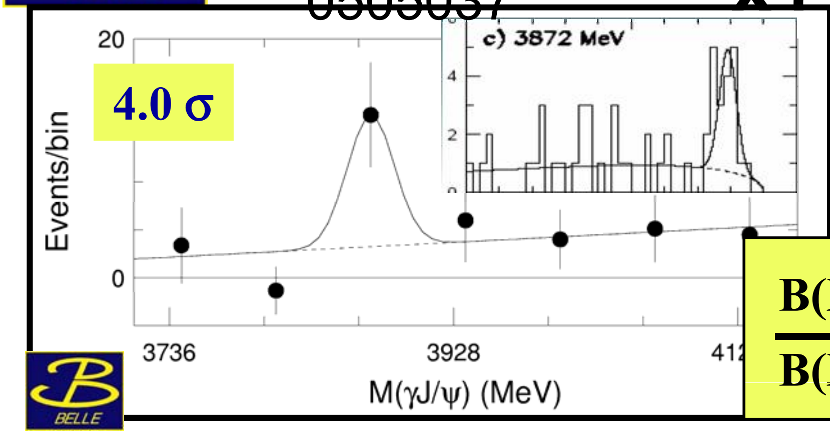
ΔM = 1.7± 1.3 ±0.2
consistent with 0

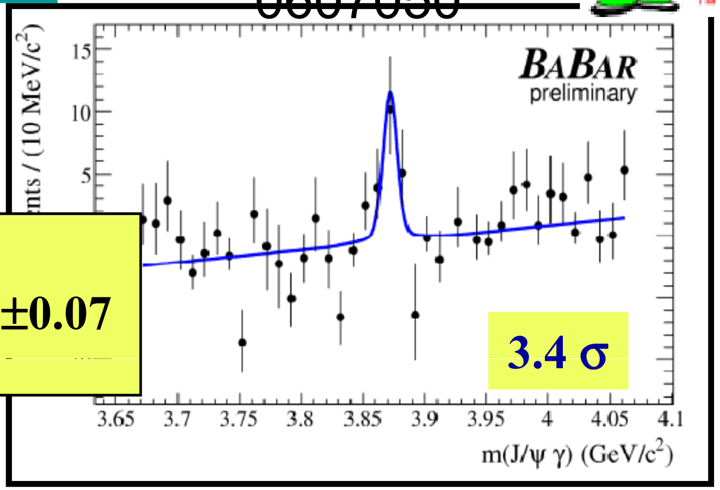
hep-ex 0505037

X(3872)

$X(3872) \to J/\psi\gamma$

hep-ex 0607050



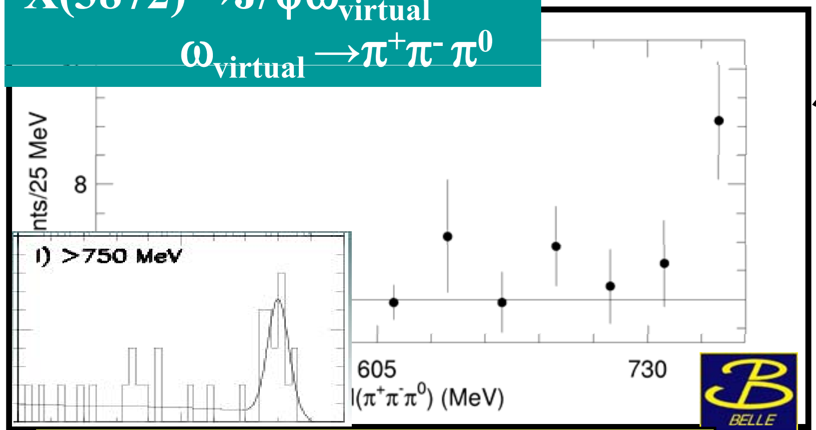


Belle/*BABAR* average:

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

$X(3872) \to J/\psi\,\omega_{virtual}$

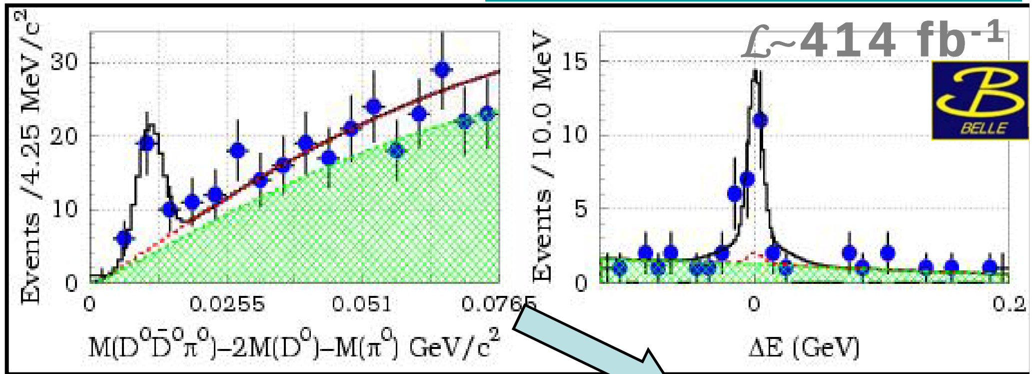
$\omega_{virtual} \to \pi^+\pi^-\pi^0$



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

C = +1

$X(3872) \to D^0 \bar{D}^0 \pi^0$



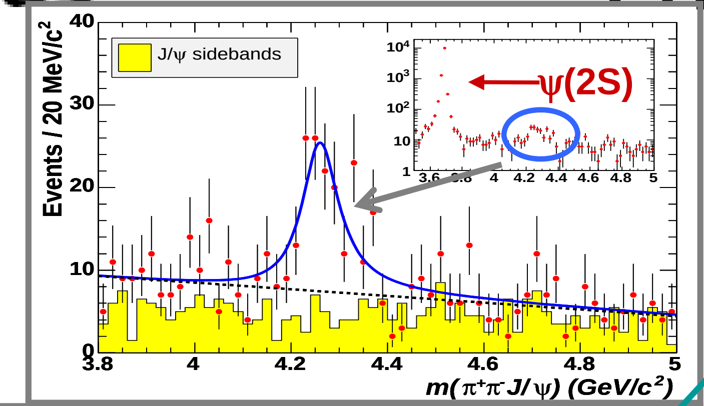
$$\frac{Br(X\to D^0\bar{D}^0\pi^0)}{Br(X\to\pi^+\pi^- J/\psi)} = 9 \pm 4$$

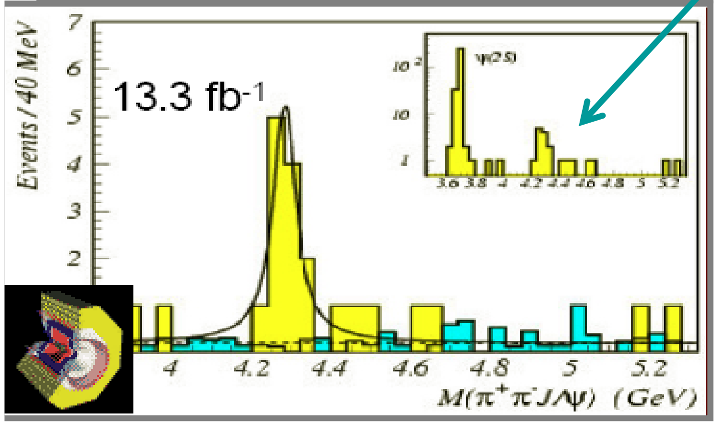
J > 1 unlikely

$$M = 3875.4 \pm 0.7\,^{+0.7}_{-1.7} \pm 0.8\ \text{MeV}$$

Y(4260)

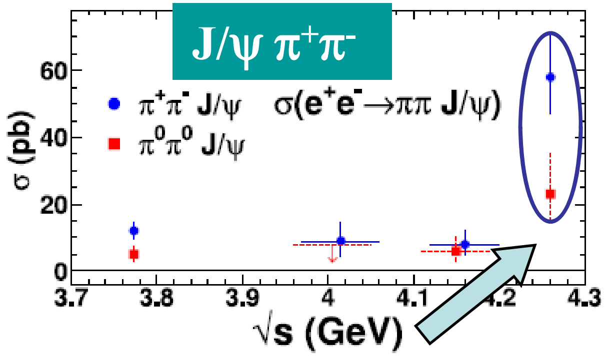
Observed by BaBar

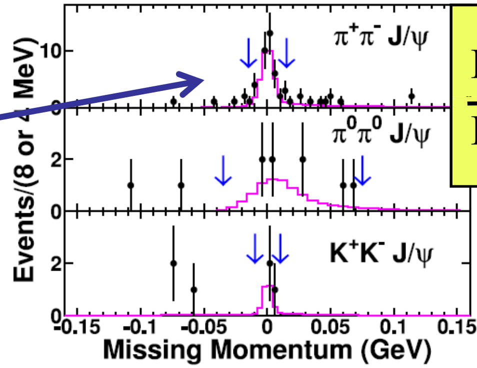




Confirmed by

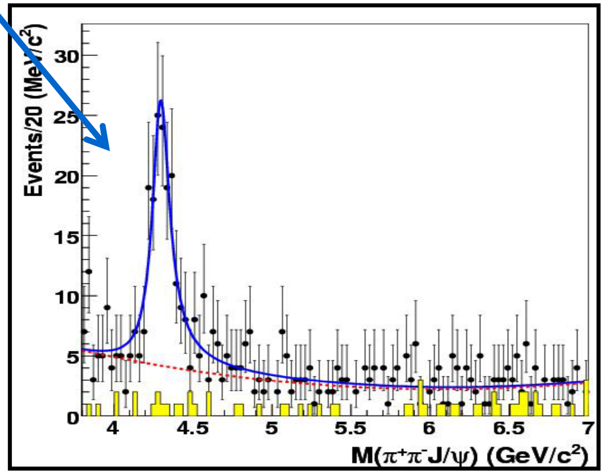
- ✓ CLEO
- ✓ CLEOc scan
- ✓ Belle





$$\frac{B(Y\rightarrow\pi^0\pi^0 J/\psi)}{B(Y\rightarrow\pi^+\pi^- J/\psi)} \sim 0.5$$

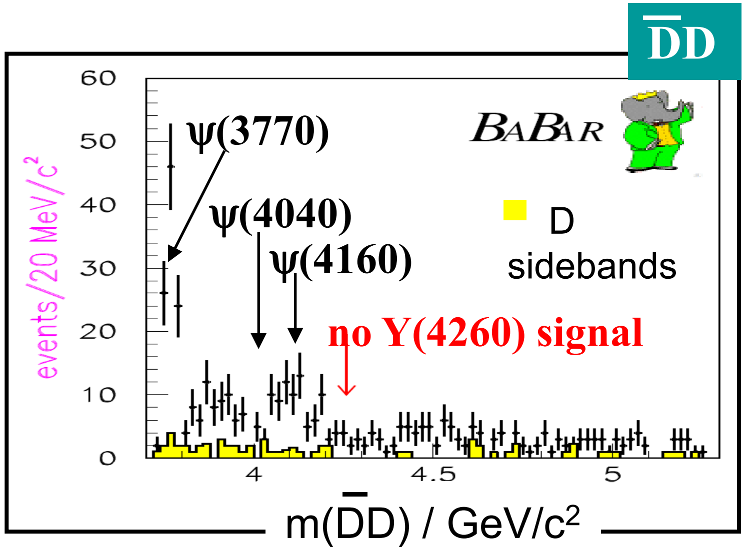
I=0



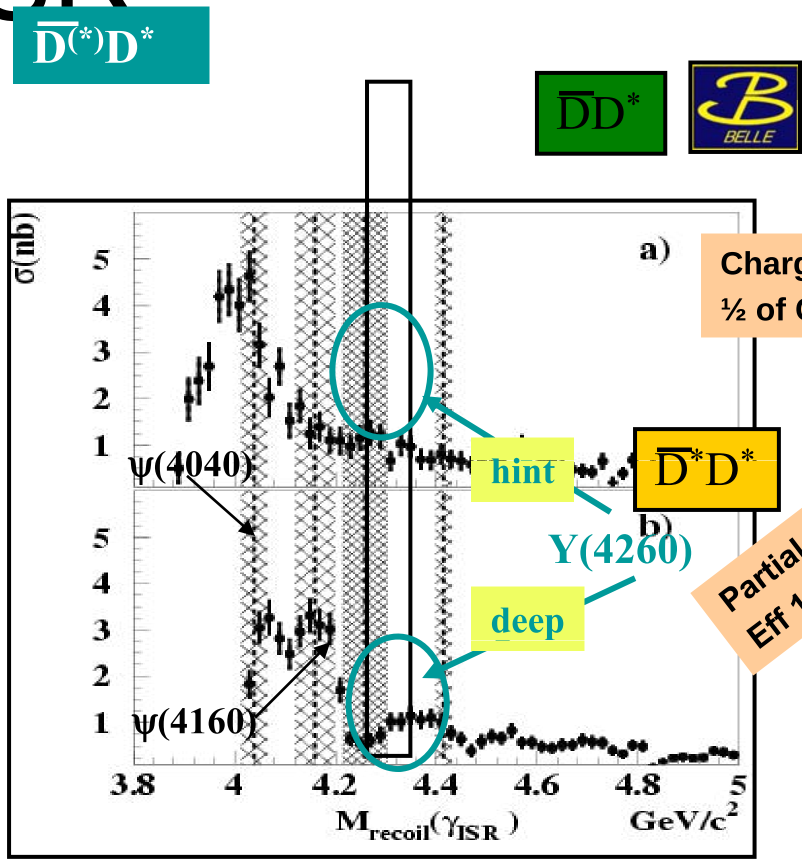
ISR $\pi^+\pi^-J/\psi$	BaBar	CLEO-III	Belle (Preliminary)
Yield	125 ± 23 (>8σ)	$14.1^{+5.2}_{-4.2}$ (4.9σ)	165 ± 24 (>7σ)
Mass(MeV/c²)	$4259\pm8^{+2}_{-6}$	$4283^{+17}_{-16}\pm4$	$4295\pm10^{+11}_{-5}$
	$88\pm23^{+6}_{-4}$	$70^{+40}_{-25}\pm5$	$133\pm26^{+13}_{-6}$

exclusive X-sections using ISR

Can we see Y(4260) in decays to $D^{(*)}D^{(*)}$



No signal is seen, instead there is a dip in the DD cross section



Charged D only!
½ of CLEOc

Partial reconstruction
Eff 10-20 times higher

A hint of the Y signal in D^*D
Clear dip in D^*D^* (similar to incl. R)

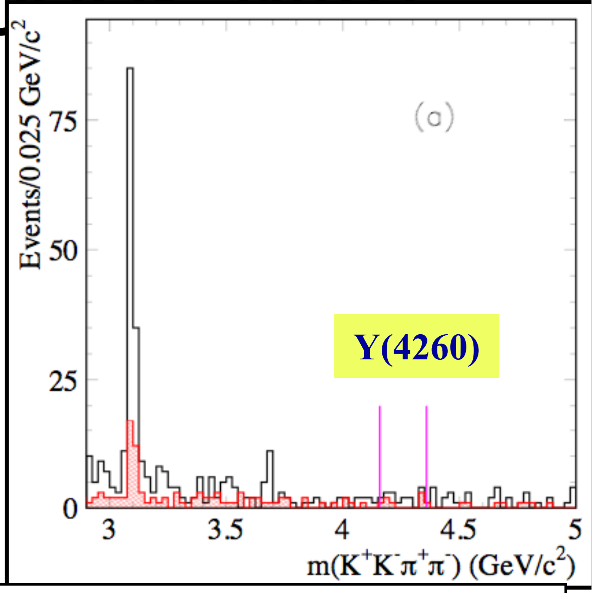
Y(4260): other modes with ISR

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

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

Light hadrons

PRD 73, 012005 (2006)



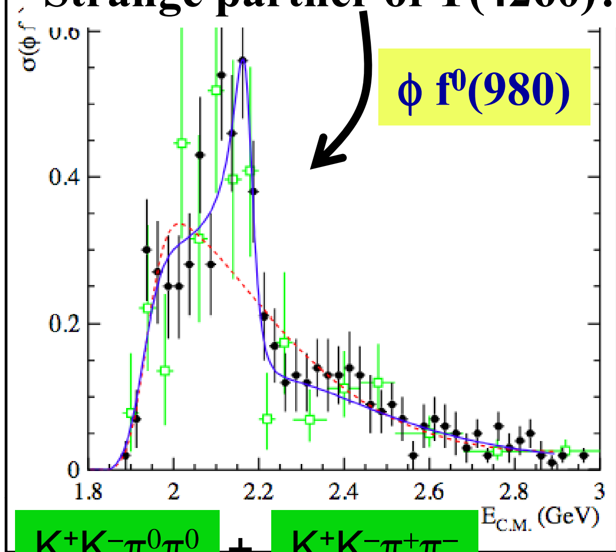
Charmonium modes

Channel (X)	J/ψ η	J/ψπ0	$\chi_{c1}\gamma$	$\chi_{c2}\gamma$	J/ψγ γ
B(Y→X)/B(Y→π⁺π⁻	<	<	< 3.6	< 2.6	<1.2

$$\frac{B(Y(4260) \to D\bar{D})}{B(Y(4260) \to J/\psi\pi^+\pi^-)} < 7.6 \text{ (95\% CL)}$$

DD

Strange partner of Y(4260)?



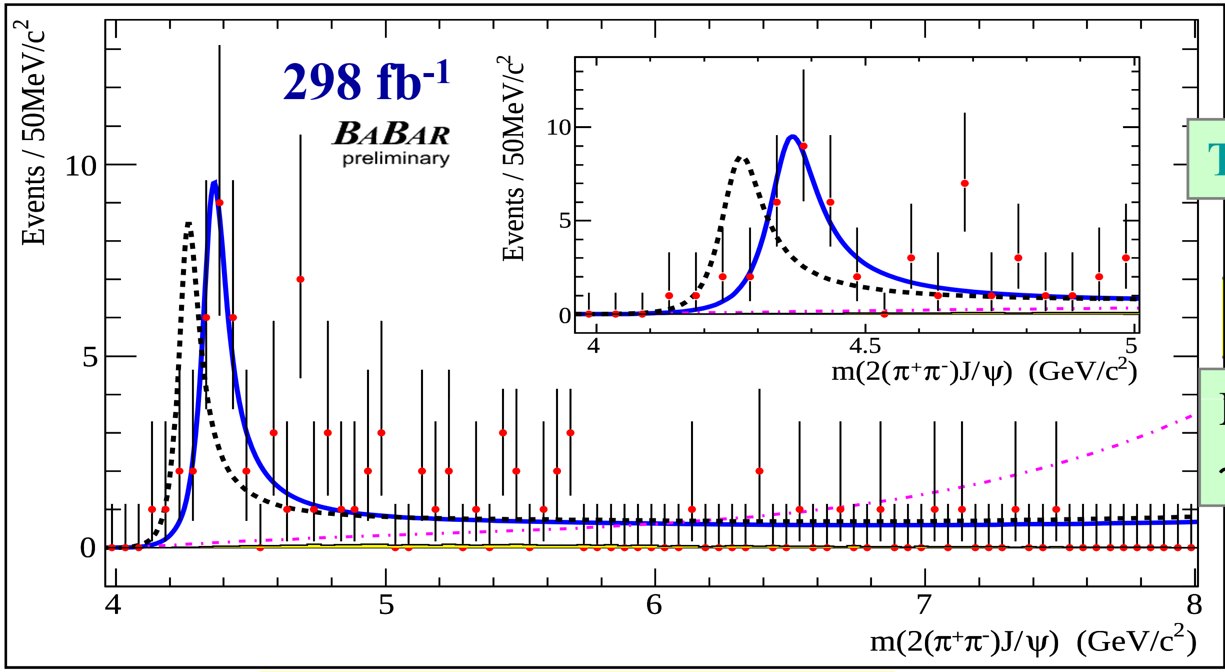
Too large π π J/ψ width:

	ψ(2S)	ψ(3770)	Y(4260)
$\Gamma(\to\pi^+\pi^- J/\psi)$	89 keV	45 keV	>1 MeV

Difficult to interpret as a conventional charmonium state

new Charmonium like state in ISR?

The maximum cross section is ~60 pb at 4.35 GeV



Total Nevt = 78

N_{bkg} = 3.8 ±1.1

Mass resolution ~7 MeV

Study $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)\gamma_{ISR}$

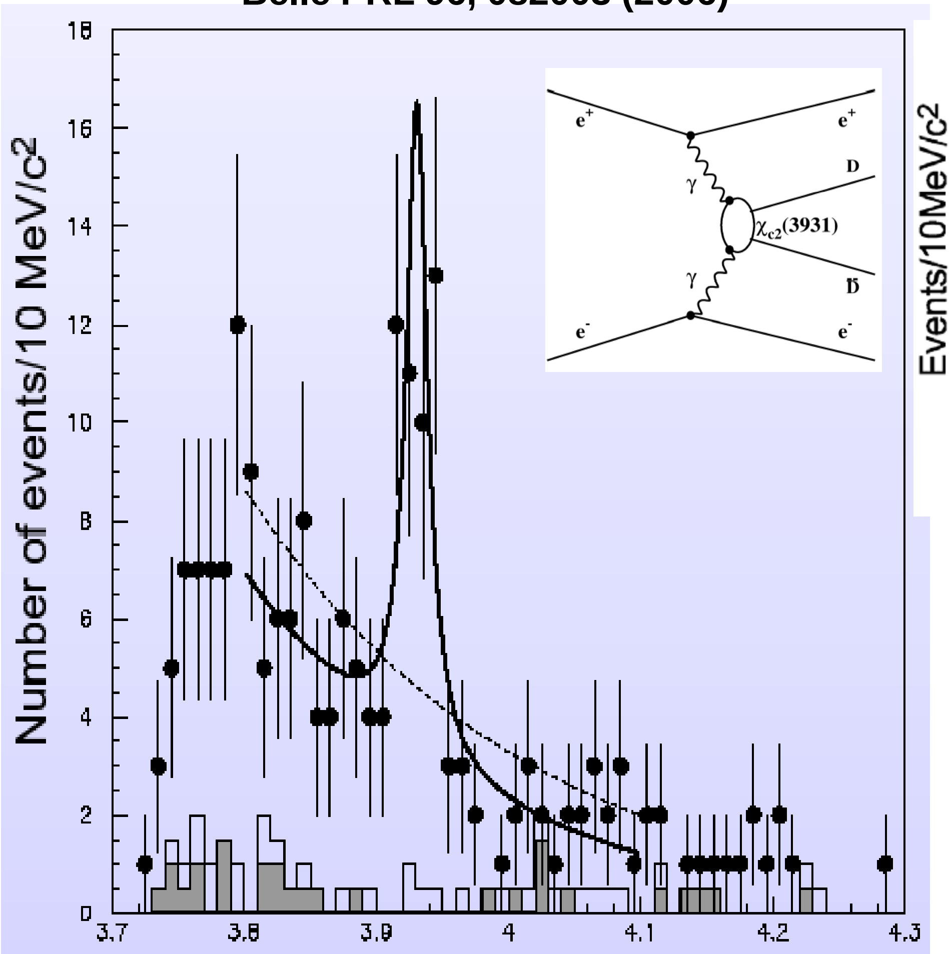
Incompatible with Y(4260), ψ(4415), or *S*-wave 3-body phase-space production

Another enigmatic $J^{PC}=1^{--}$ particle

M=(4354±16) MeV/c2, Γ=(106±19) MeV

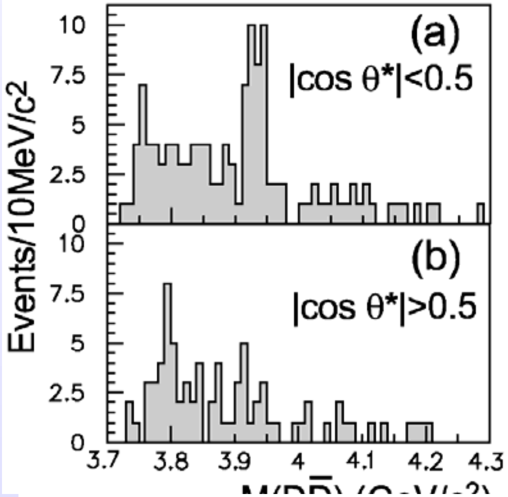
$\gamma\gamma \rightarrow Z(3931) \rightarrow D\bar{D}$ at Belle

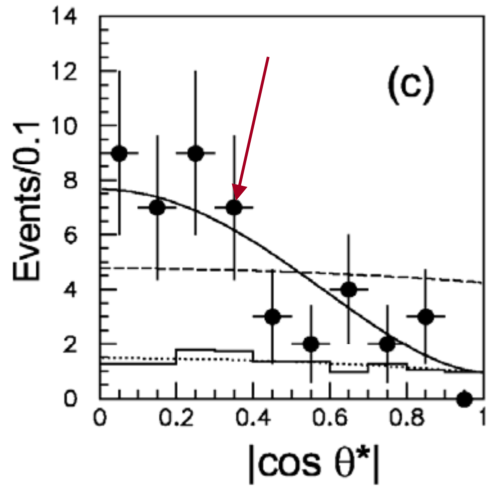
Belle PRL 96, 082003 (2006)



M(DD) GeV

$\sin^4\theta$ (J=2)

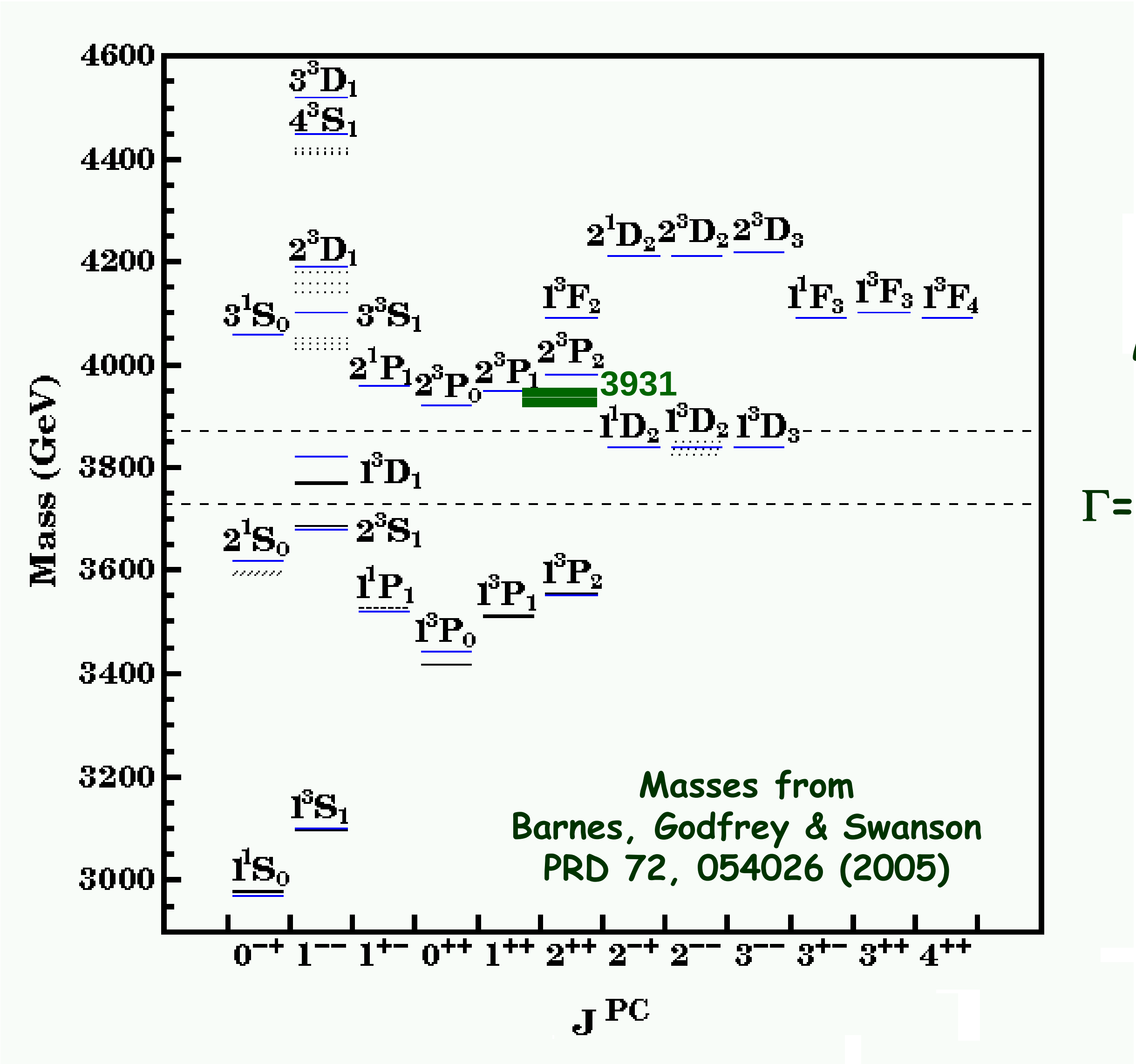




41± 11 evts (5.5σ)
M=3931 ± 4 ± 2 MeV
Γ=20±8 ±3 MeV

Matches well to χ_{c2}' expectations

Z(3930): candidate for the χ_{c2}'



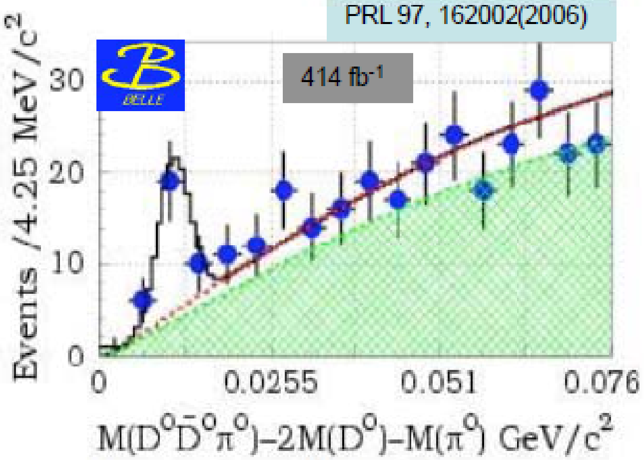
M= 3931 MeV is ~45 MeV low

Γ=20MeV too narrow?

Study of B → D(*)D(*)K decays: X(3875)?

BELLE: observation of: $B \to X(3872)K^{\pm}$, $X(3872) \to D^0\bar{D}^0\pi^0$

PRL 97, 162002(2006)



$$M = 3875.4 \pm 0.7^{+1.2}_{-2.0}\ MeV/c^2$$

$$B(B^{\pm} \to K^{\pm}X, X \to D^0\overline{D}^0\pi^0) = (1.27 \pm 0.31^{+0.22}_{-0.39})10^{-4}$$

$$\frac{B(X \to D^0\overline{D}^0\pi^0)}{B(X \to J/\psi\pi\pi)} = 9.7 \pm 3.4$$

BABAR: $B \to \bar{D}^{(*)}D^{(*)}K^+$

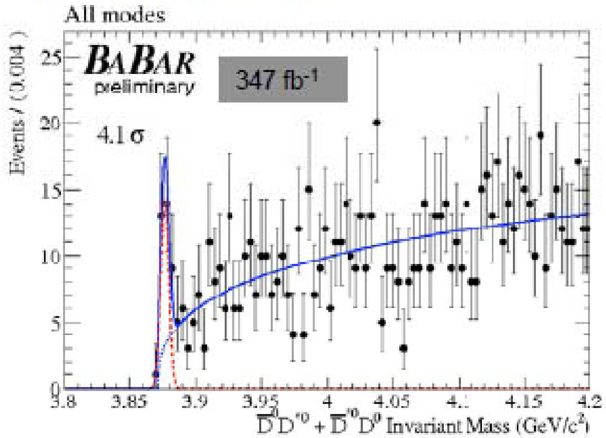
New Result-Preliminary

II- search for $\bar{D}^{(*)}D^{(*)}$ resonances

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

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

with $D^{*0} \to D^0\pi^0$ and $D^0\gamma$



$$M = 3875.6 \pm 0.7^{+1.4}_{-1.5}\ MeV/c^2$$

$R(B^0/B^+) = 2.23 \pm 0.93 \pm 0.55$

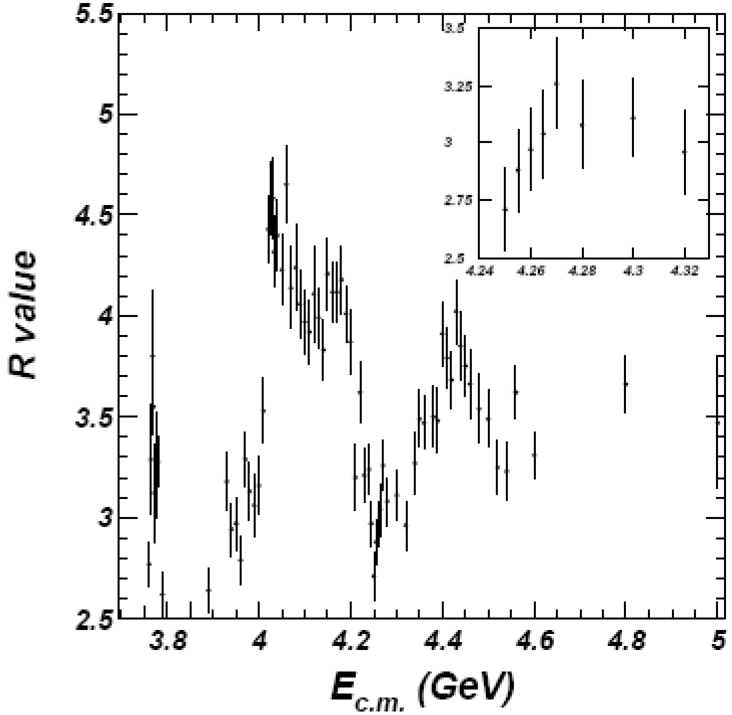
$\Delta m(B^0/B^+) = 0.2 \pm 1.6\ MeV/c^2$

also: $\psi(3770) \to \bar{D}D$: $M = 3777.5 \pm 3.2\ MeV/c^2$

Mass:

- ✓ very good agreement btw experiments
- ✓ 2.5σ away from $X \to J/\psi\pi^+\pi$: X(3875)?

THRESHOLD IMPORTANCE



Dip is just below threshold of lowest-mass charmed meson pair $D^0\bar{D}_1^*$ produced in an S-*wave.*
(Lower thresholds: P-wave production.)

This channel is the expected decay of $Y(4260)$ if it is a hybrid. But it is closed, so other modes (such as $\pi\pi J/\psi$) may be favored instead.

Many other dips are correlated with thresholds [e.g., in $\pi\pi$ S-wave near $2M(K)$; $\gamma^* \to 6\pi$ near $2M(p)$; see PR D **74**, 076006 (2006).]

BaBar [hep-ex/0610018]: Analogous structure in $e^+e^- \to \phi f_0(980)$ at 2175 MeV

$X(2175)$ as hybrid $s\bar{s}$ candidate in the same way that $Y(4260)$ is a hybrid $c\bar{c}$ candidate? Makes sense if $m_c - m_s \simeq (M_Y - M_X)/2 = 1.04$ GeV

Dip in $e^+e^- \to D^*\bar{D}^*$ (major charm channel) [Belle hep-ex/0608018] at 4250 MeV

$Y(4320) \to \pi^+\pi^-\psi(2S)$ [BaBar hep-ex/0610057]: $M = 4324 \pm 24$, $\Gamma = 172 \pm 33$

- There seems to be a new hadron spectroscopy in the 3.5-4.5 GeV mass region
  - Maybe more than one

Several new states have large partial widths (BF’s) to hadrons+J/y

  - $Br(X(3872) \rightarrow \rho J/\psi) > 4.3\%$ (Isospin=1)
  - $\Gamma(Y(3940) \rightarrow \omega J/\psi) > 7$ MeV (SU(3) octet)
  - $\Gamma(Y(4260) \rightarrow \pi^+\pi^- J/\psi) > 1.6$ MeV

- There is no apparent transition at the D**D mass threshold

Jump at 4220MeV? **(=2m$_{Ds*}$)**

Voloshin
hep-ph/0602233