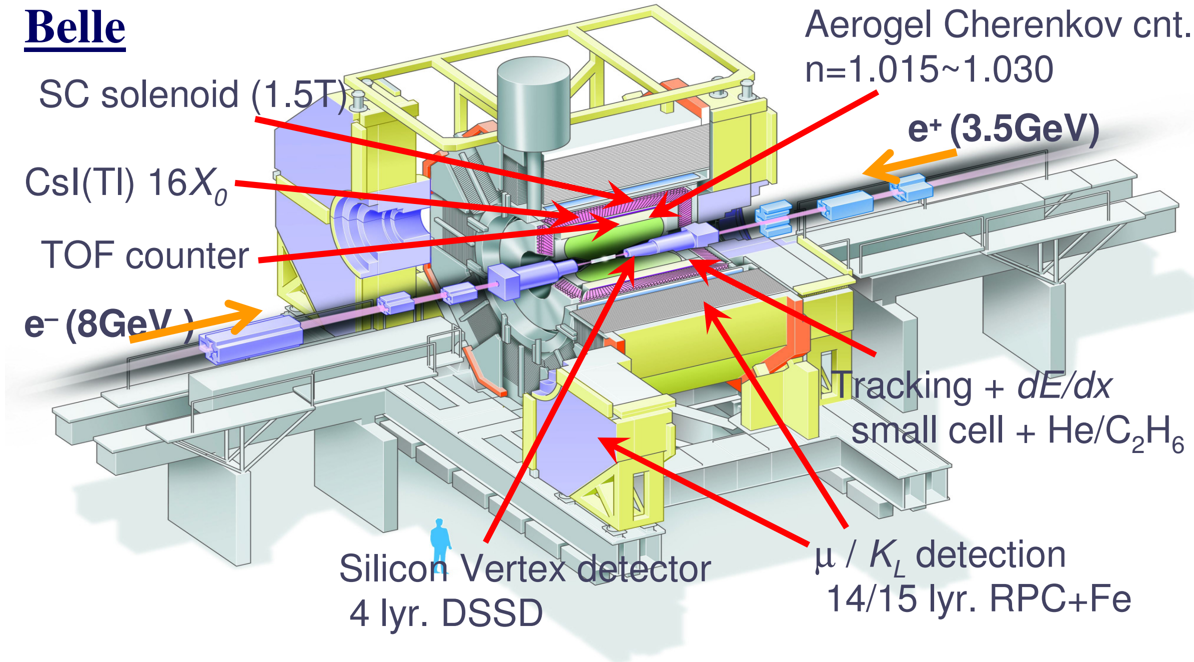
CHARMONIUM AND NEW STATES

that still can surprise us

P.Pakhlov (ITEP, Moscow)

Belle



B-factories

$e^+e^- \rightarrow \Upsilon(4S)$ and nearby continuum: E_{cms} ~ 10.6GeV

L ~ $10^{34}/cm^2/s$ (> 1/ab in total during 7 years of data taking)

Charmonium from

- **B-decays**
- **γγ-fusion**
- ***e⁺e⁻* annihilation via ISR**
- **$e^+e^- \rightarrow \gamma^* \rightarrow X_{cc}^1 X_{cc}^2$**

Charm factories

CLEO-c

$e^+e^- \rightarrow J/\psi, \psi(2S), \psi(3770)$,
scan 3.8-4.8 GeV
L~$10^{33}/cm^2/s$

BES-II

Tevatron

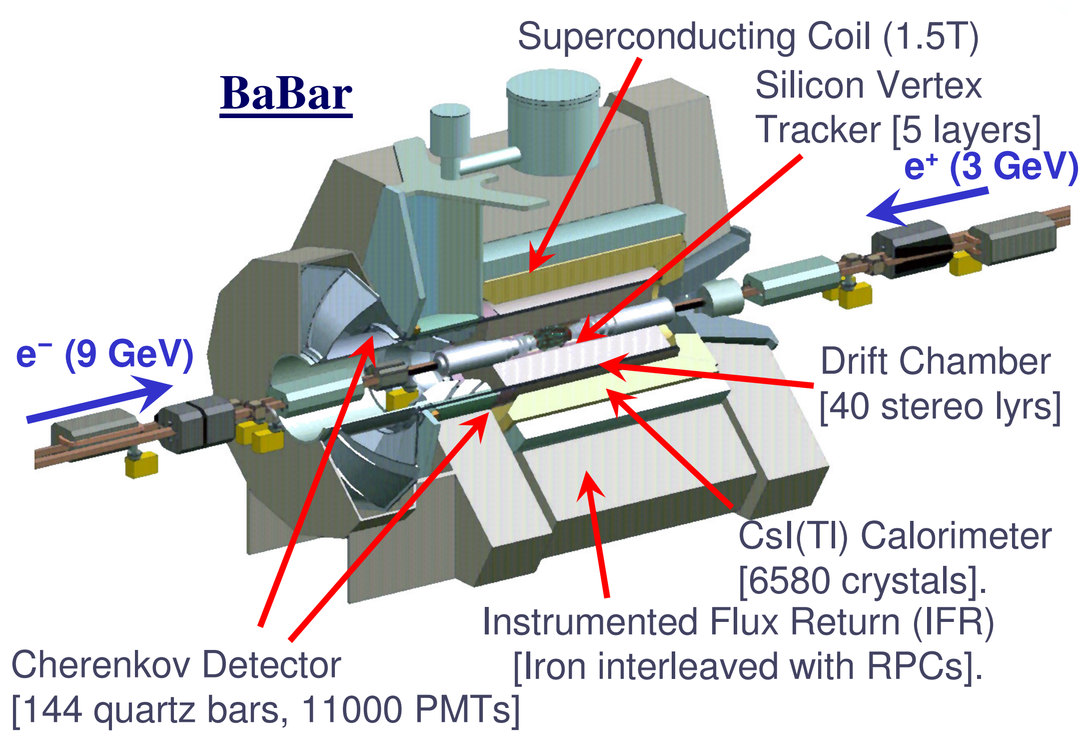
pp̄ collider

D0

CDF

E ~ 1.8 TeV
L~ 1/fb per experiment

BaBar

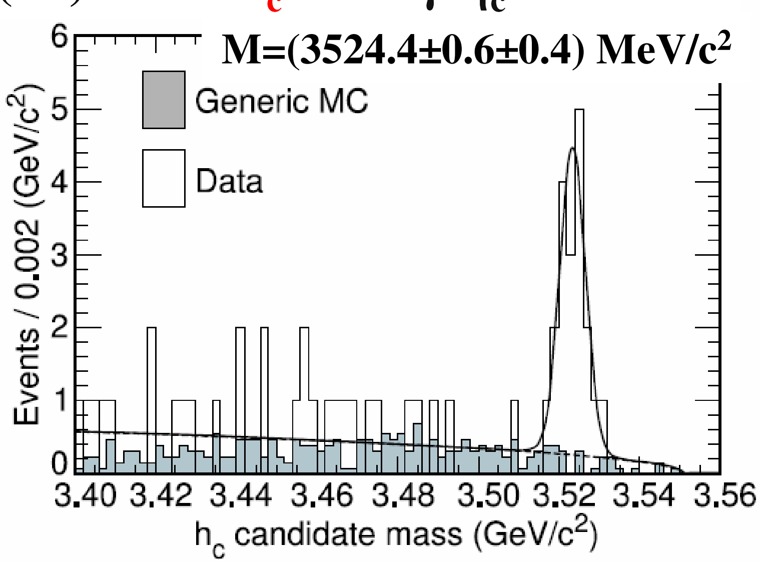


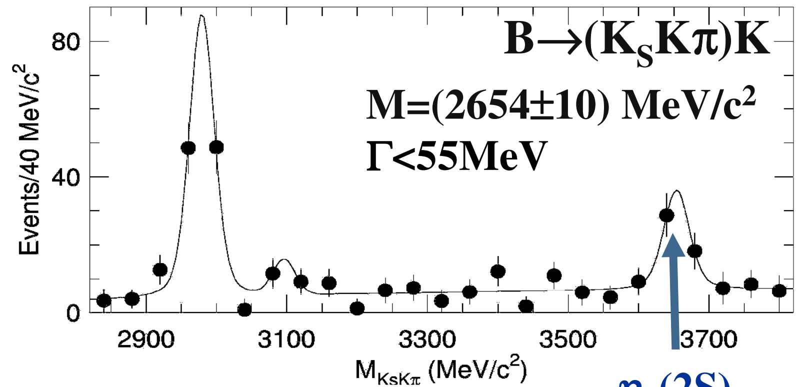
CLEO, 2005

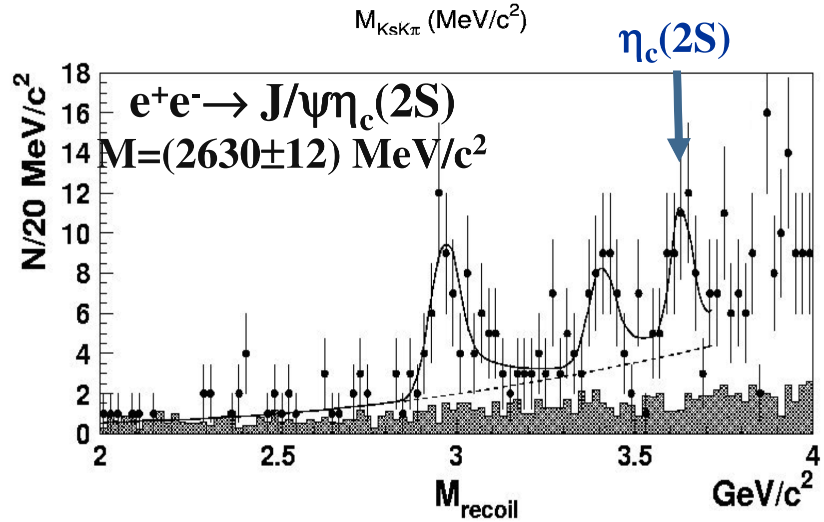
Belle, 2002

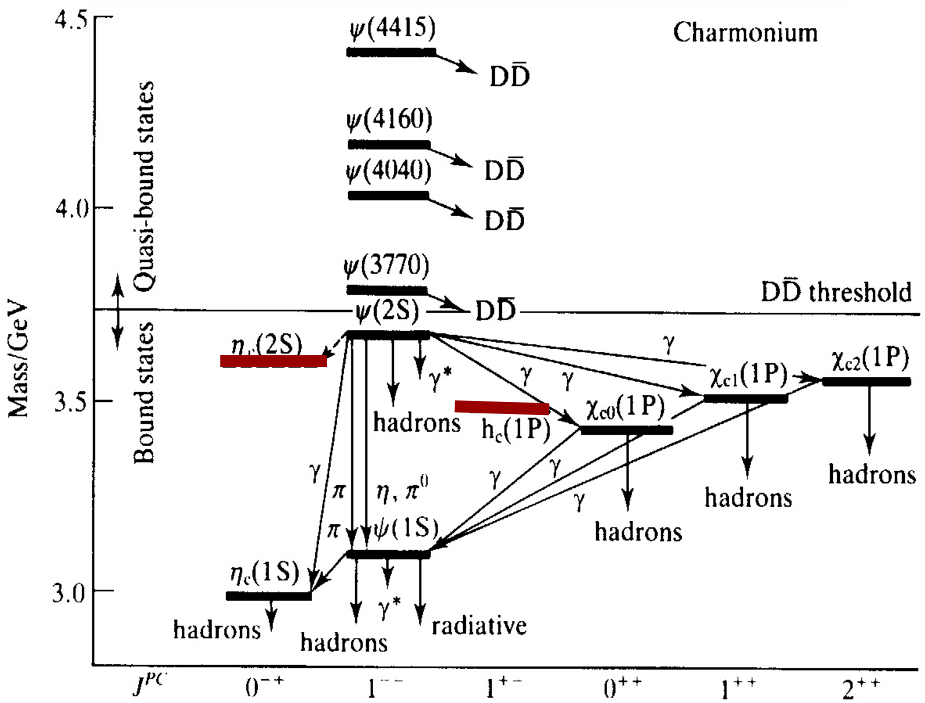
Observation of h_c and $\eta_c(2S)$

$\psi(2S) \rightarrow \pi^0 h_c \rightarrow \pi^0 \gamma \eta_c$









confirmed by CLEO, BaBar & Belle in $\gamma\gamma$

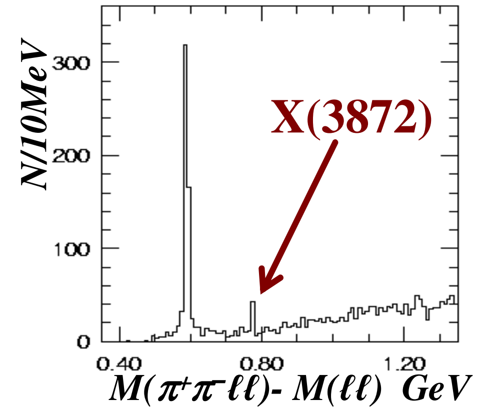
the properties are in a good agreement with the potential model expectations (mass, total width, $\gamma\gamma$-width)

Charmonium table below DD threshold is complete!

Belle, 2003

The particle that starts new era

X(3872) – the first in “X” series, introduces a new particle naming scheme: X, Y, Z ...



Everything is surprising:

- **observed in the decay $B^+ \to (J/\psi\pi\pi)K^+$**
- **$M_X = (3872.0 \pm 0.6 \pm 0.5)$ MeV/c^2 in close vicinity of $D^0\ D^{*0}$ threshold:**

$$M_X - M_{DD^*} = (-0.4 \pm 0.7)\ \text{MeV/c}^2\ \text{(PDG'07)}$$

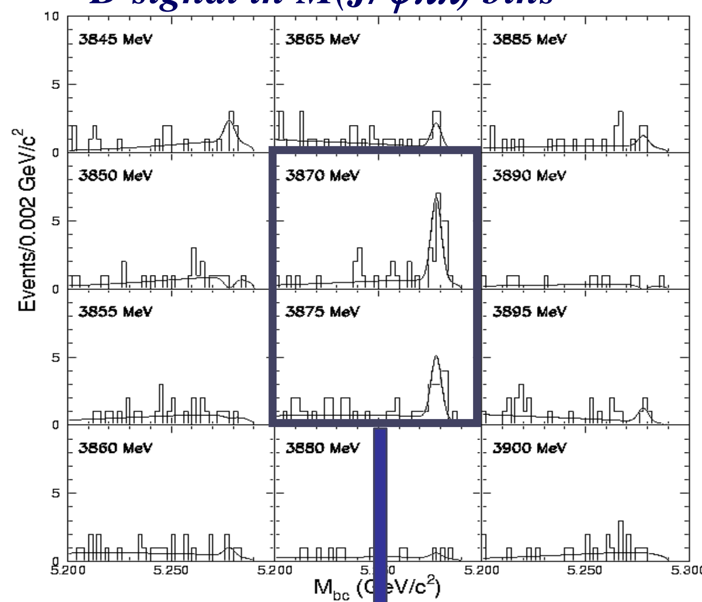
- **well above DD threshold but narrow:**

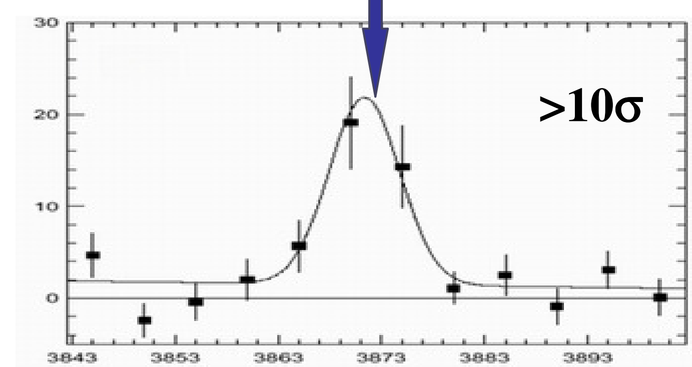
$$\Gamma < 2.3\text{MeV at } 90\%\ \text{C.L.}$$

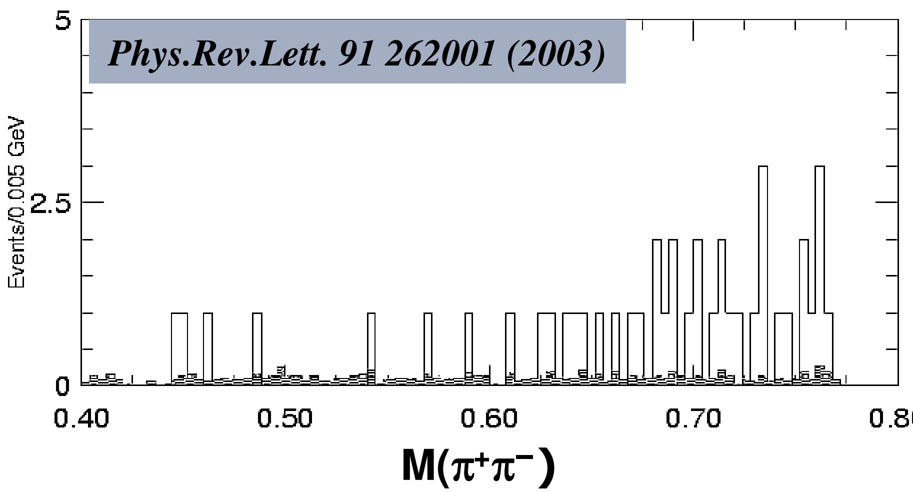
unnatural spin-parity? In this case $\chi_c\gamma$ transition should be strong, not seen in the data.

- **decay dynamics: $M_{\pi+\pi-}$ tends to peak around limit ($J/\psi\ \rho^0$ is isospin violating decay)**

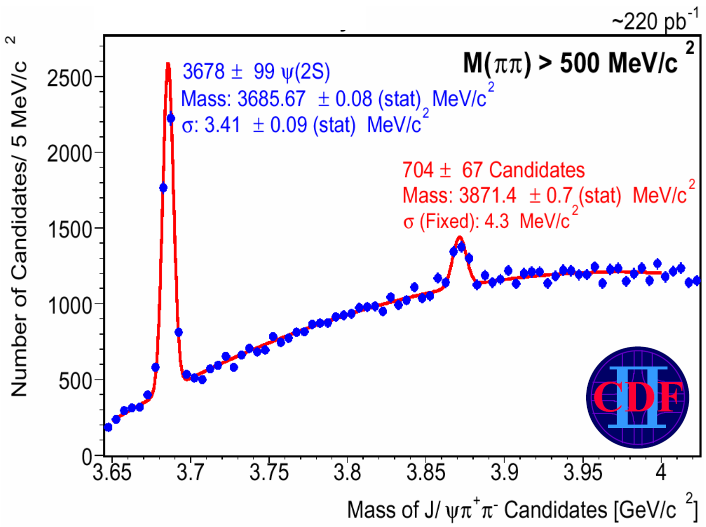
B-signal in M(J/ψππ) bins

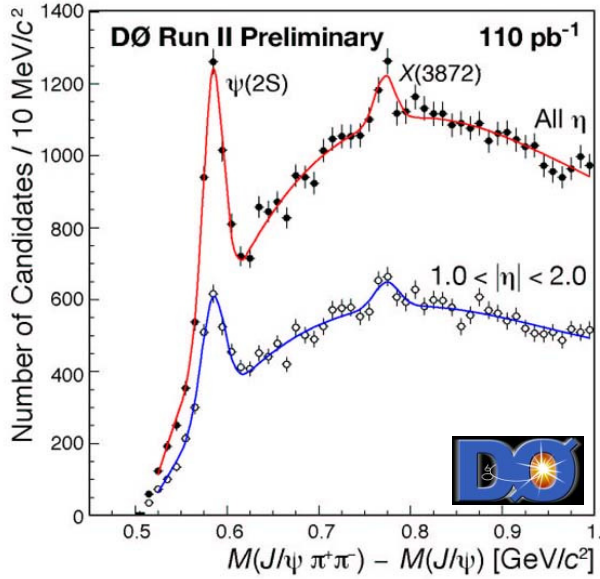




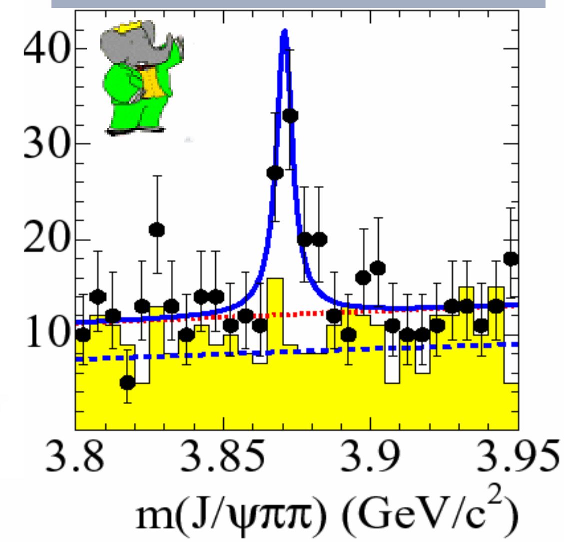


Confirmed by CDF, D0, BaBar





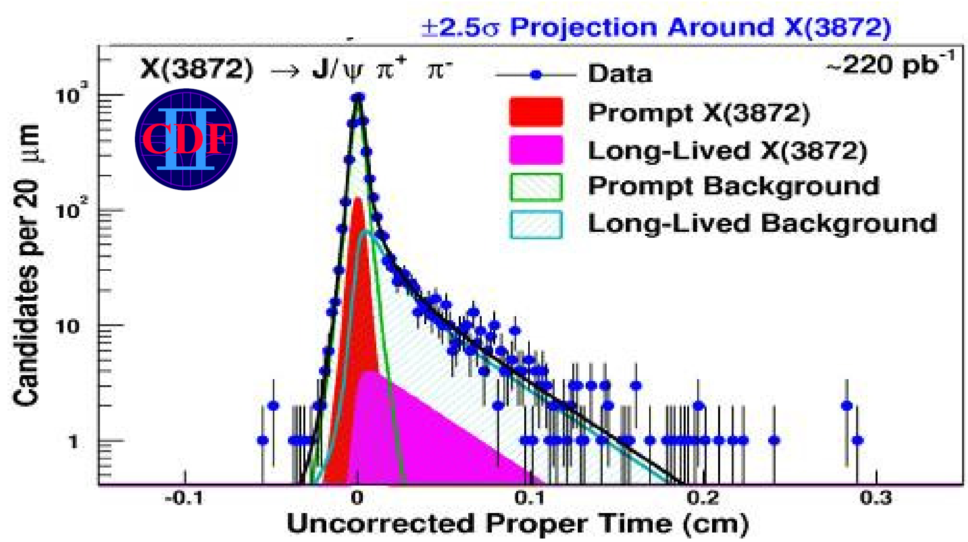
Phys.Rev.D71, 071103 (2005)



with significance > 10σ/experiment

- The X(3872) is well established, can not be attributed to experimental mistake
- in PDG full listing starting 2005

In p$\bar{p}$ collision 16.1±4.9(stat.)±1.0(syst.)% of X are from B-decays, others are prompt (CDF).



more information – more understanding?

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

► X decays to $J/\psi\,\gamma$, but very rarely (Belle 2004, BaBar 2006).
This observation fixes C_X=+1, and confirms that in the $X \to J/\psi\pi\pi$ decay $(\pi\pi)=\rho$.

► X decays to $J/\psi\,\omega$ with Br ~ Br $(X \to J/\psi\pi\pi)$, confirms isospin violation.

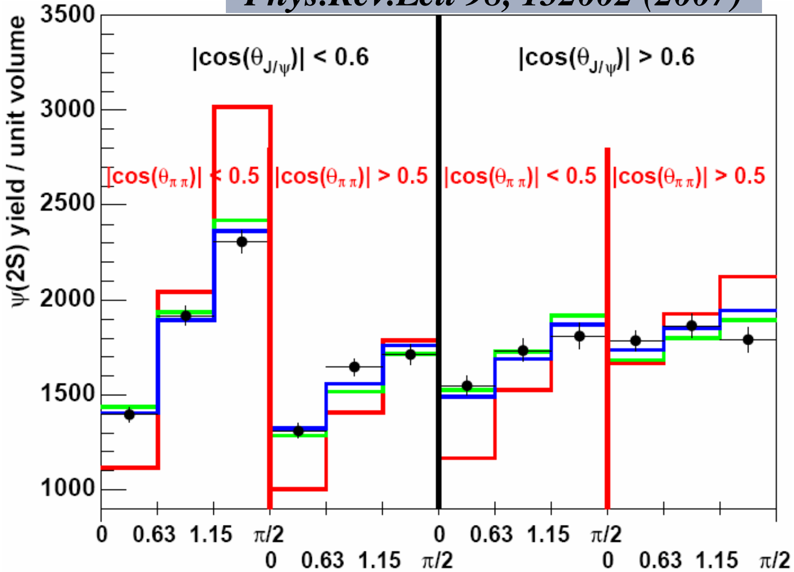
► Fit to $M(\pi\pi)$ favours L=0 ⇒ P_X= +1.

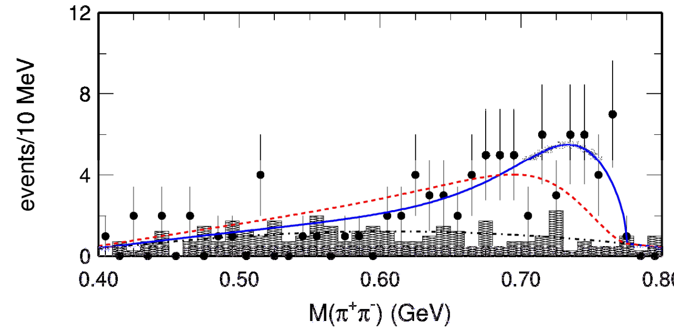
► Angular analysis:

Belle, 2004
CDF, 2006

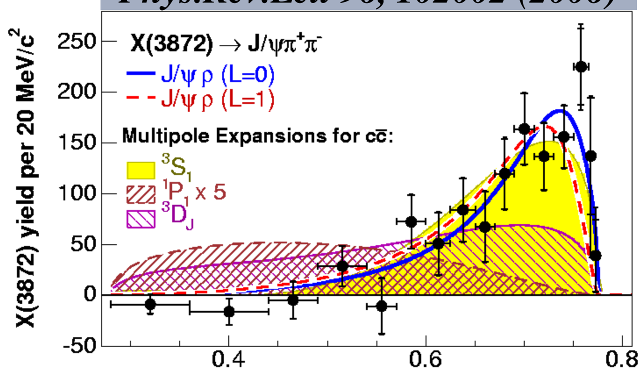
hypothesis	χ^2 prob.
1^{++}	27.8%
2^{-+}	25.8%
1^{--}	0.02%
2^{+-}	$5.5\cdot10^{-5}$
1^{+-}	$3.8\cdot10^{-5}$
2^{--}	$3.8\cdot10^{-5}$
3^{+-}	$3.8\cdot10^{-5}$
3^{--}	$2.4\cdot10^{-5}$
2^{++}	$1.1\cdot10^{-5}$
1^{-+}	$4.1\cdot10^{-6}$
0^{-+}	$3.5\cdot10^{-17}$
0^{+-}	$\leq1\cdot10^{-20}$
0^{++}	$\leq1\cdot10^{-20}$

Phys.Rev.Lett 98, 132002 (2007)





Phys.Rev.Lett 96, 102002 (2006)



$J^{PC}=1^{++}$ corresponds to $\chi_{c1}(2^3P_1)$ if X-charmonium:

- $\chi_{c1}' \to J/\psi\gamma$ should be much stronger than $\chi_{c1}' \to J/\psi\pi\pi$ (measured ratio ~ 0.2 , expected ~ 30)
- ~ 100MeV/c² lighter than expected.

$J^{PC}=2^{-+}$ $\eta_{c2}(1^1D_2)$: is expected to decay into light hadrons rather than into isospin violating mode.

Options for X(3872)

- Voloshin-Okun JETP Lett. 23, 333 (1976): discuss existence of molecular-like states when $m_c \to \infty$
- De Rujula-Georgy-Glashow PRL, 38, 317 (1977) apply to ψ(4040)
- the idea was abandoned for many years
- X(3872) enigmatic properties flashed back to the early ideas: Close-Page; Voloshin; Swanson; Tornqvist supposed that X(3872) is a

Hydronic molecules and the charmonium atom

M. B. Voloshin and L. B. Okun'

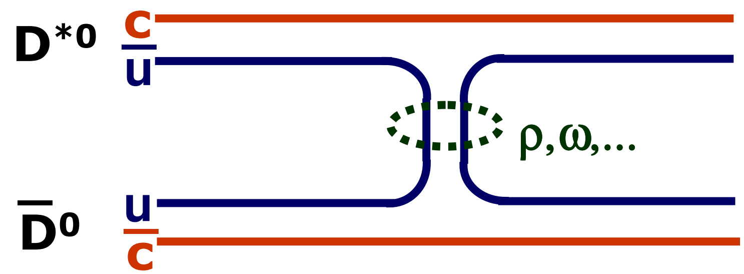
Institute of Theoretical and Experimental Physics
(February 16, 1976)
Pis'ma Zh. Eksp. Teor. Fiz. **23**, No. 6, 369–372 (20 March 1976)

We consider the possible existence of levels in a system consisting of a charmed particle and a charmed antiparticle; these levels result from exchange of ordinary mesons (ω,ρ,ε,φ, etc.). An interpretation of the resonances in e^+e^- annihilation in the region 3.9–4.8 GeV is proposed.

Molecular Charmonium: A New Spectroscopy?*

A. De Rújula, Howard Georgi,† and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 23 November 1976)

Recent data compel us to interpret several peaks in the cross section of e^-e^+ annihilation into hadrons as being due to the production of four-quark molecules, i.e., resonances between two charmed mesons. A rich spectroscopy of such states is predicted and may be studied in e^-e^+ annihilation.



D^0D^{*0} molecular state:

- $M_X \sim M_{D^0} + M_{D^{*0}}$ is not accidental
- $J^{PC}=1^{++}$ has been predicted (D^0D^{*0} in S-wave)
- Isospin violation has been expected:

  $M_{D^-} + M_{D^{*+}}$ is by $\Delta \sim 8$ MeV higher; $\Delta >> \omega$ – binding energy
- Small X(3872) → J/ψ γ has been expected
- Absolute winner by popularity: > 50% of theoretical papers consider molecular model

Other options:

- Tetraquark (cq)(cq): predicts three states (cu)(cu), (cd)(cu), (cd)(cd) with a few MeV mass splitting between them.
- Hybrid (ccg) state.
- Threshold cusp (not in contradiction to the molecular model)

} $M_X \sim M_{D^0} + M_{D^{*0}}$ is accidental?

Tetraquark hypothesis

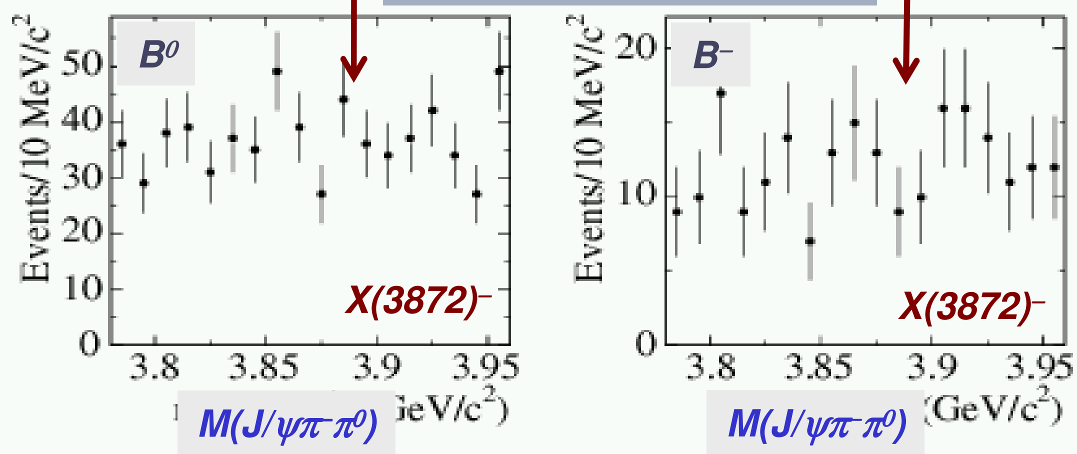
Predictions:

#1 there should be charged $X^-(3872) \rightarrow J/\psi\pi^-\pi^0$ state

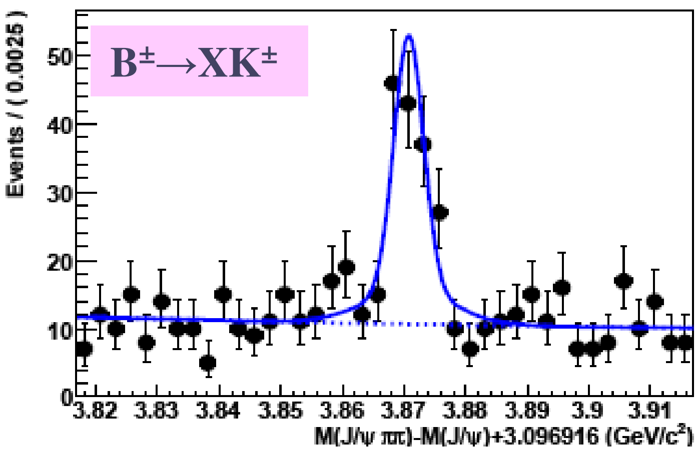
No evidence

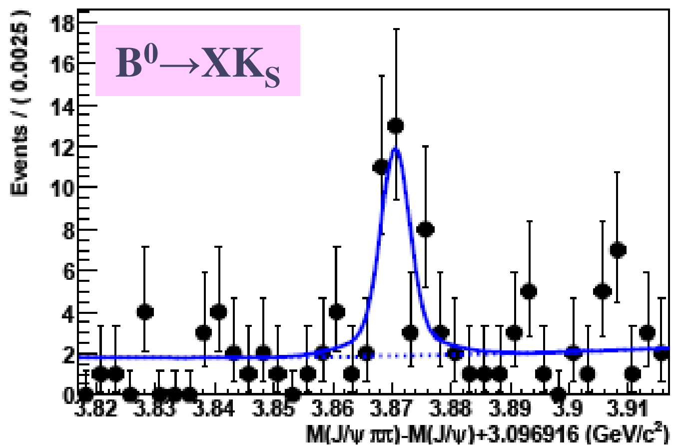
Isovector hypothesis is excluded

Phys.Rev.D71, 031501 (2005)

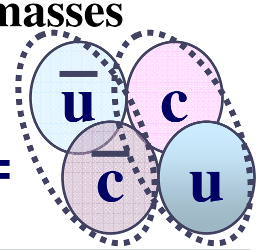


#2 the X-states produced in B^0 and B^+ are different and should have different masses



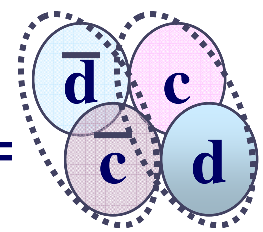


X_u =



Contr.paper to EPS (2007)

X_d =



$\Delta M_X = M(X \text{ from } B^\pm) - M(X \text{ from } B^0) = (0.22 \pm 0.90 \pm 0.27) MeV/c^2$

- *No mass splitting*

$Br(B^0 \rightarrow X(3872)K^0)/Br(B^\pm \rightarrow X(3872)K^\pm) = 0.94 \pm 0.24 \pm 0.10$

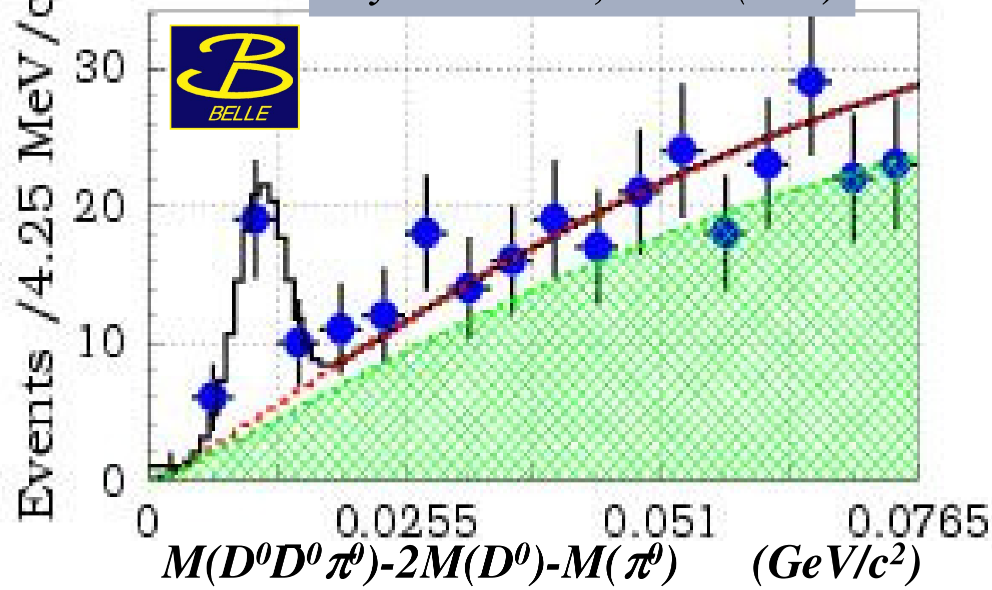
- *equal BR for neutral and charged B, is this a big problem for molecular model? Pure molecular models predicts this ratio ~ 1/10. DD*-molecule should mix with charmonium.*

Decay to $D^0D^0\pi^0$

Looking for $B \to XK$, $X \to D^0D^0\pi^0$ (may be D^0D^{*0} - it is difficult to resolve due to tight phase space)

Belle 2006

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

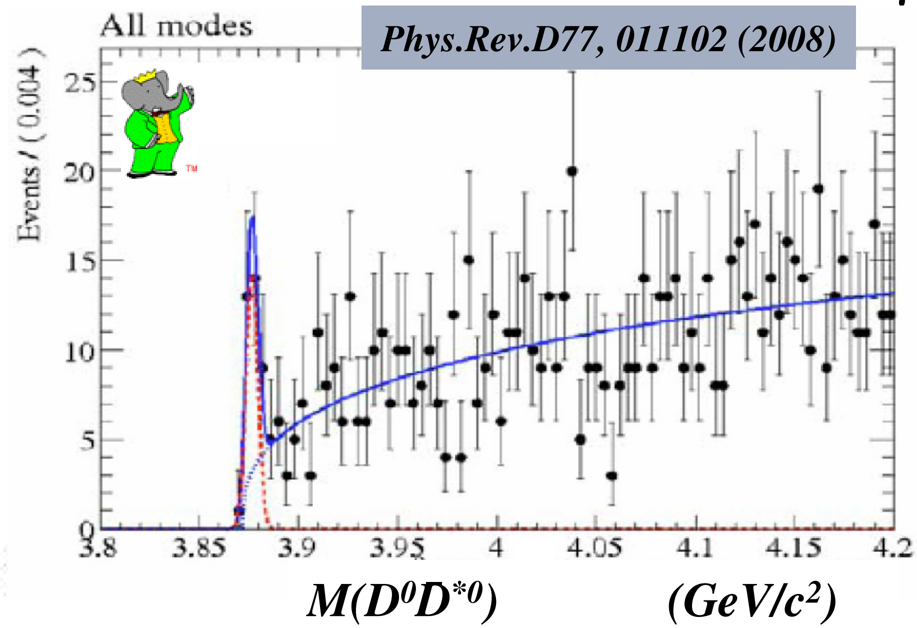


$M=(3875.4\pm0.7^{+1.2}_{-2.0})$ MeV/c²

BaBar 2007

Also seen $X \to D^0D^0\gamma$

Phys.Rev.D77, 011102 (2008)



$M=(3875.2\pm1.1\pm0.5)$ MeV/c²

Good agreement between Belle & BaBar, ...but 4σ from $M(X \to J/\psi\pi\pi)$ peak

Is this a new state, different from X(3872)?
If X(3872) is virtual (rather than bound) state this observation is not surprising.
Such model expects Flattè-like coupled channel effect:

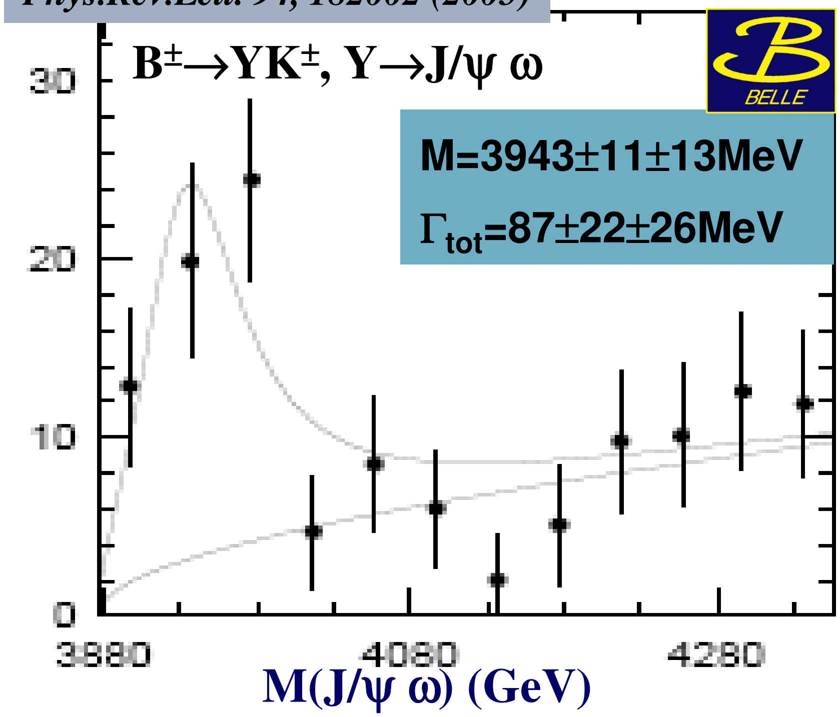
Hanhart, Kalashnikova, Kudryavtsev, Nefediev Phys.Rev.D71, 034007 (2007)

- **$X \to D^0D^0\pi^0$ – peak shifted by few MeV off $M_{D0} + M_{D^{*}0}$**
- **$X \to J/\psi\pi\pi$ – the DD* threshold cusp with a sharp maximum at $M_{D0} + M_{D^{*}0}$**

Belle, 2004
BaBar, 2007

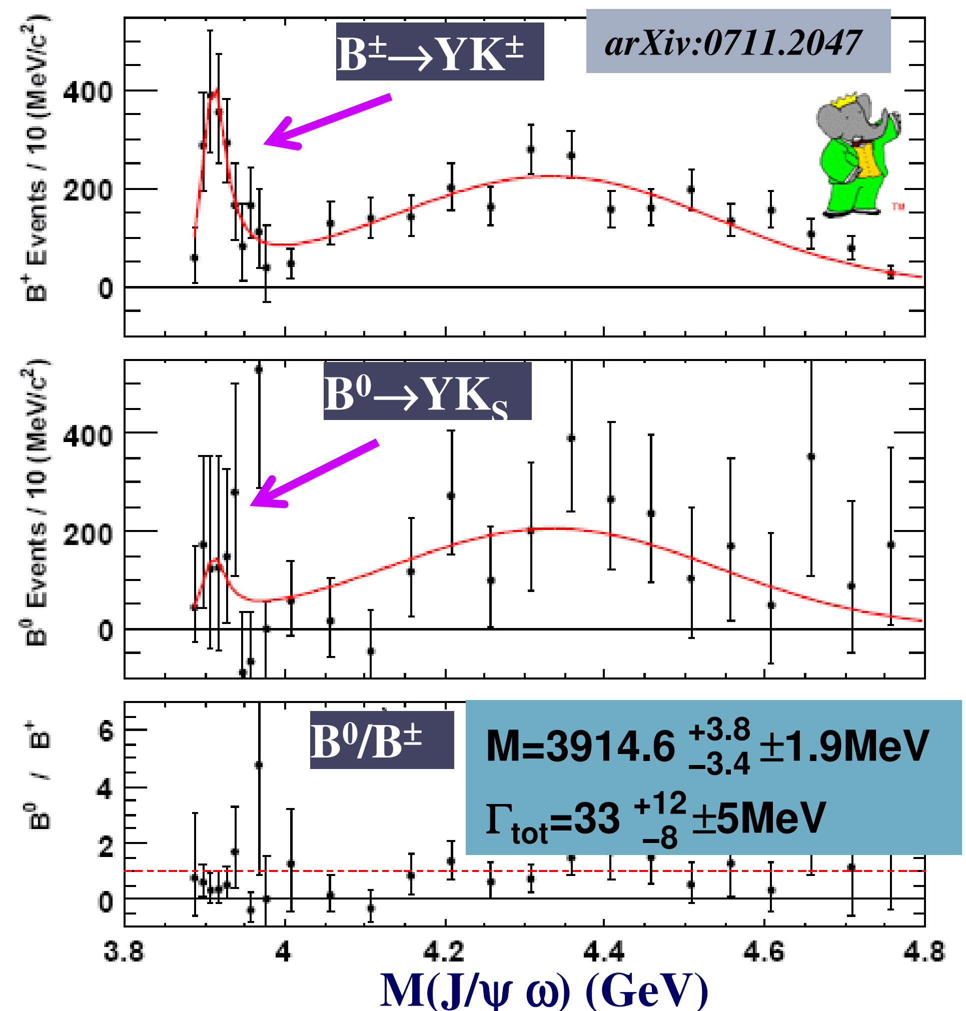
One more mysterious state, Y(3940)

Phys.Rev.Lett. 94, 182002 (2005)



$B(B\to YK)\times B(Y\to J/\psi\omega)=(7.1\pm1.3\pm3.1)\times10^{-5}$

arXiv:0711.2047



$B(B\to YK)\times B(Y\to J/\psi\omega)=(4.9\pm1.0\pm0.5)\times10^{-5}$

The state is well above both DD and DD* thresholds. At least decay to DD* is allowed for charmonim. Why it is observed in hadronic transition to charmonium?

The new BaBar measurement slightly reduces the mystery: the width is smaller and the state is closer to DD* threshold.

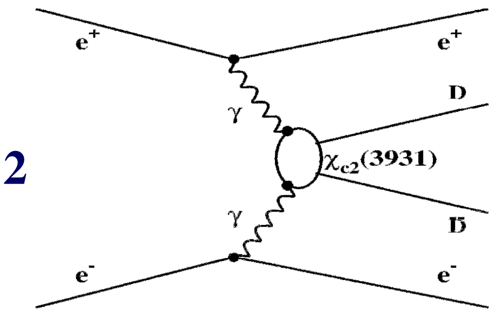
More experimental information (Y→DD*; angular analysis) is required

Belle, 2006

χ_{c2}' in $\gamma\gamma$ production

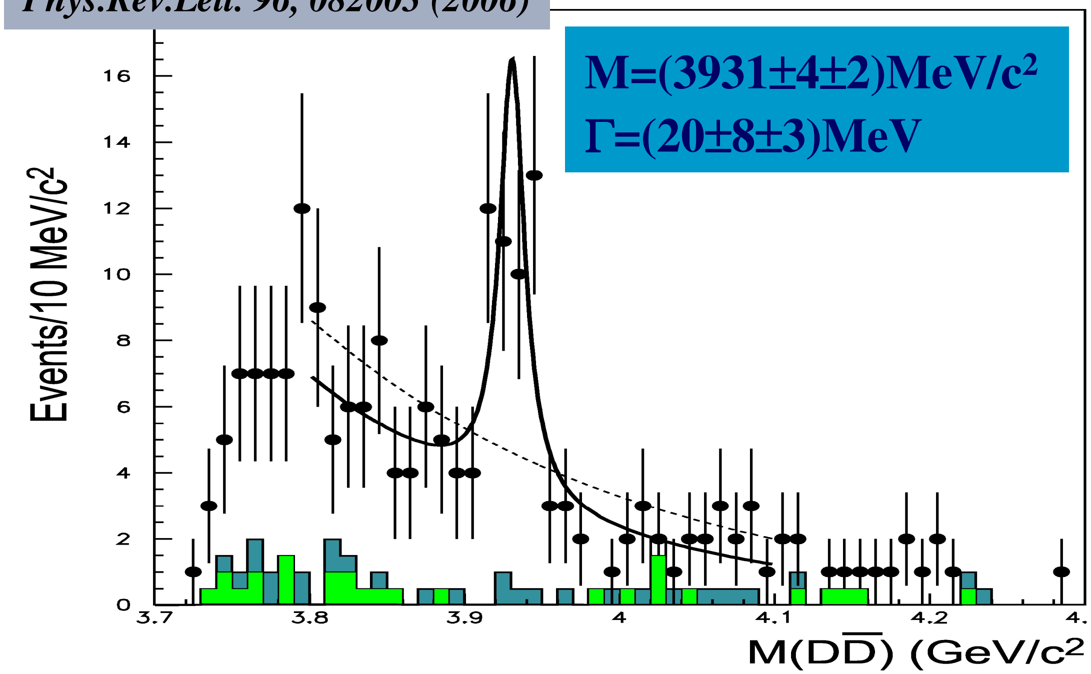
Observed as a peak at M_{DD}~3.930 GeV/c^2 in selected $\gamma\gamma$ events

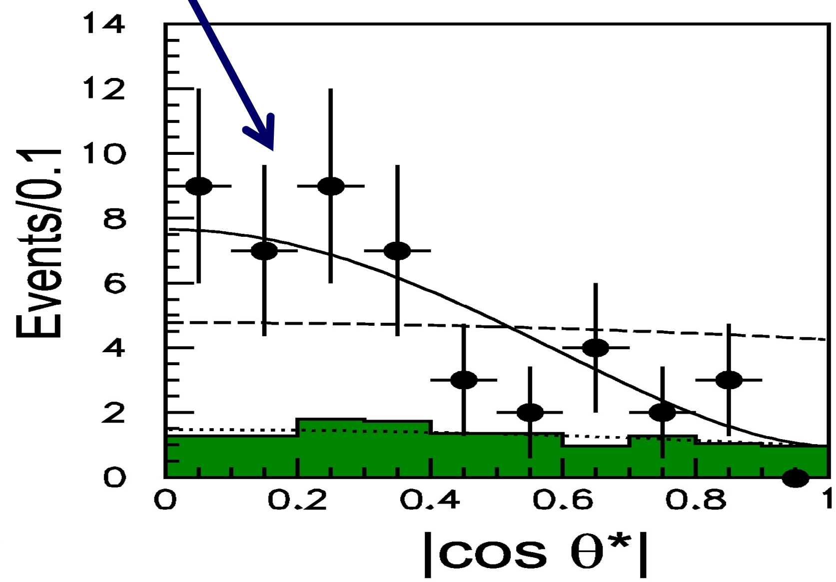
p_t distribution consistent with $\gamma\gamma$ production



Helicity distribution favors spin = 2 while J=0 disfavored

Phys.Rev.Lett. 96, 082003 (2006)





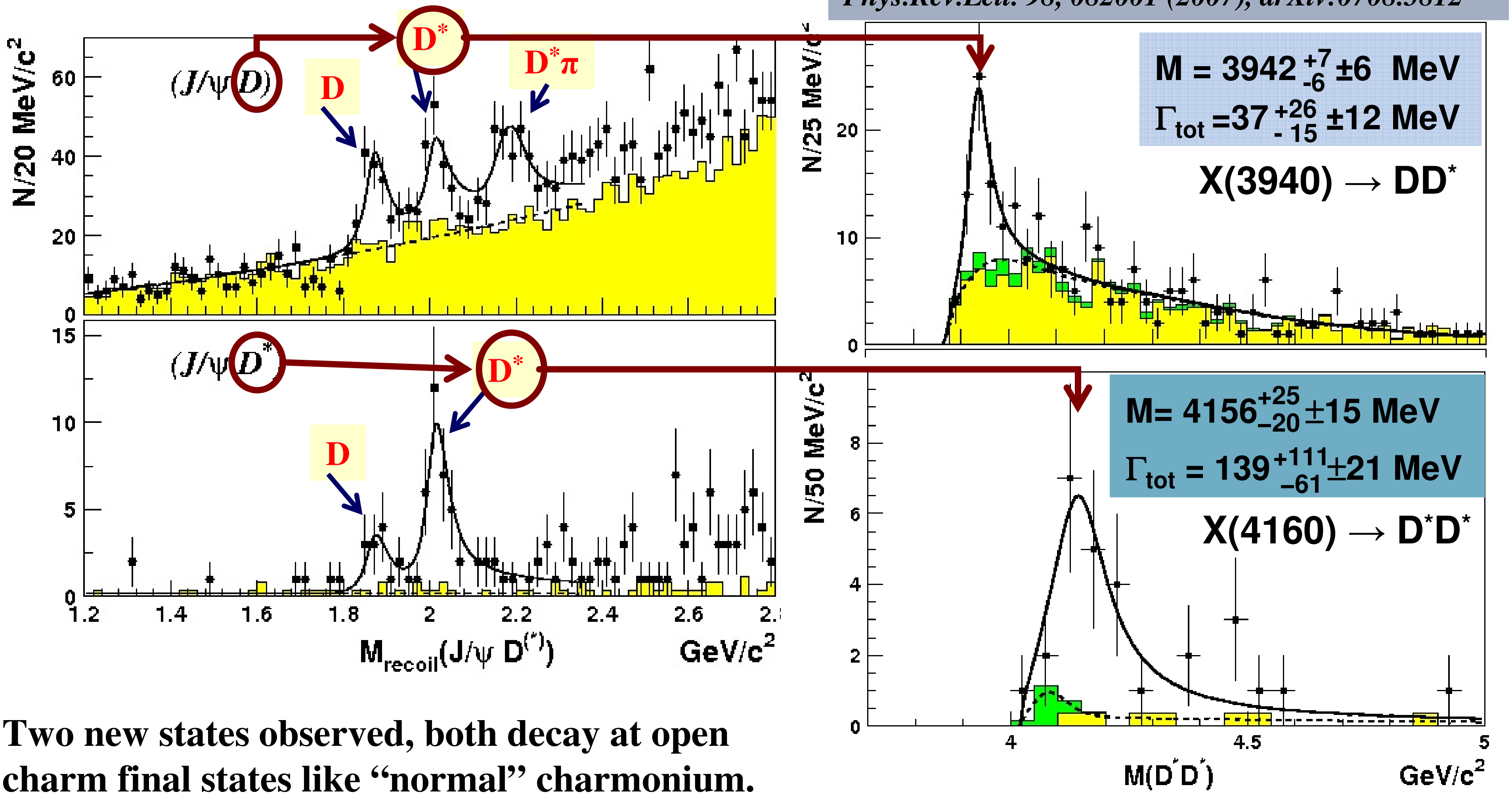
$(2J+1)\Gamma_{\gamma\gamma} \times B(Z\rightarrow DD)=(1.13\pm0.30)$keV

Production mechanism, helicity distribution and measured $\gamma\gamma$ width unambigously indicate that the observed state is χ_{c2}';
However, the mass is ~80-100 MeV lighter than expected by potential models

Belle, 2005
Belle, 2007

New states in $e^+e^- \to J/\psi\, D^{(*)}D^{(*)}$

Phys.Rev.Lett. 98, 082001 (2007), arXiv:0708.3812

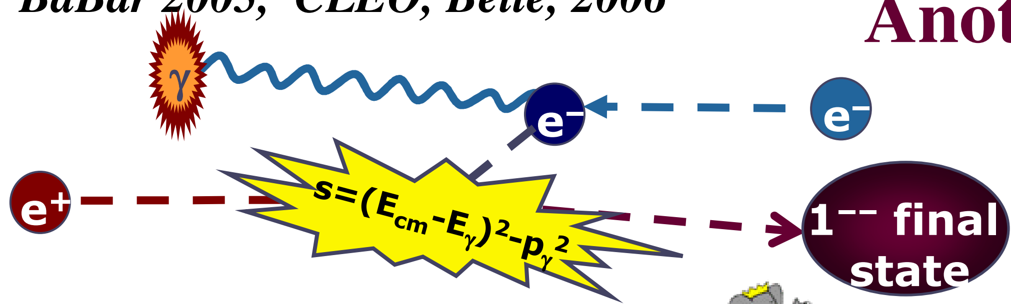


Two new states observed, both decay at open charm final states like "normal" charmonium.

Possible assignments are $\eta_c(3S)$ and $\eta_c(4S)$. But in both cases the masses predicted by the potential models are ~100-150 MeV higher than observed.
Theory probably needs more elaborated model to take into account charmonium couplimg to charmed meson pairs.

BaBar 2005, CLEO, Belle, 2006

Another enigmatic particle(s)

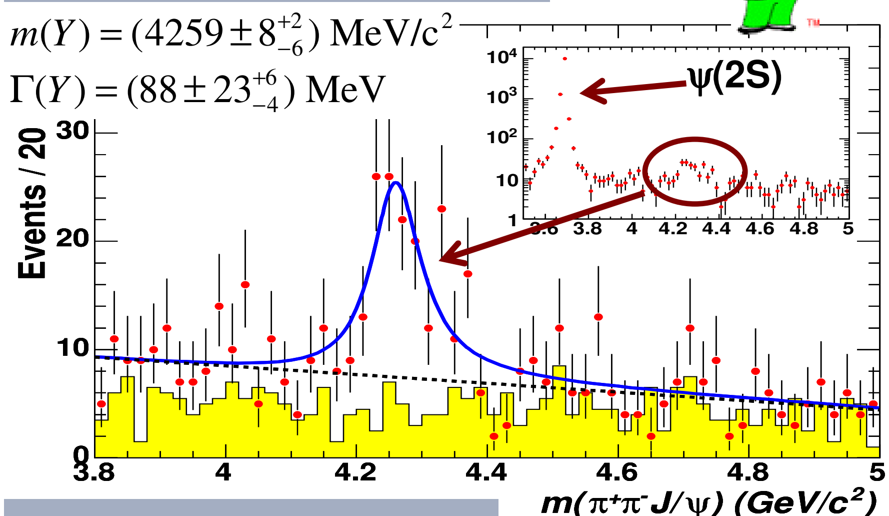


Y(4260)→J/ψππ

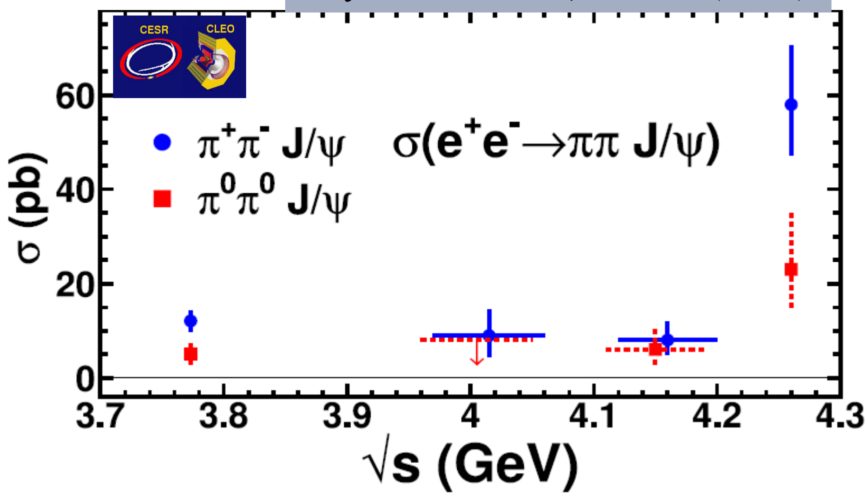
Phys.Rev.Lett. 95, 142001 (2005)

$m(Y)=(4259\pm8^{+2}_{-6})$ MeV/c^2

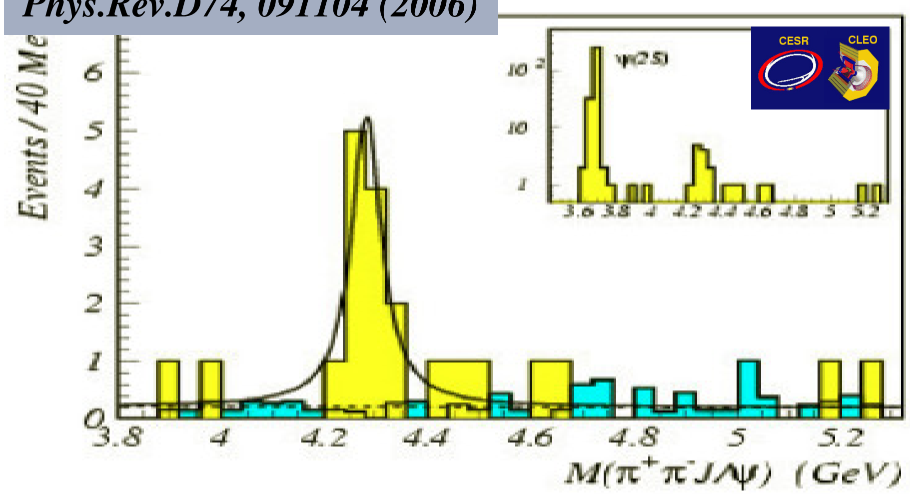
$\Gamma(Y)=(88\pm23^{+6}_{-4})$ MeV



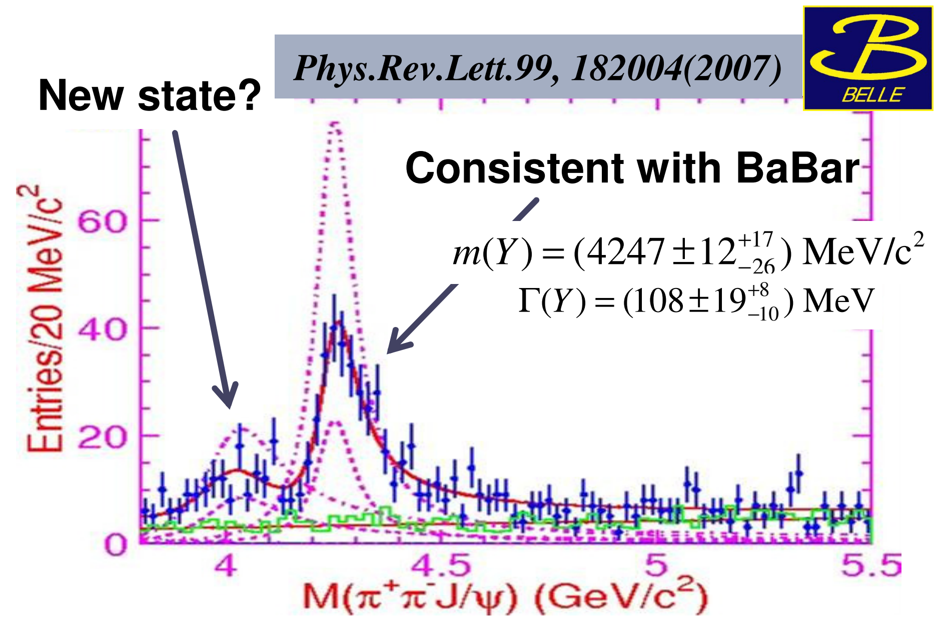
Phys.Rev.Lett. 96, 162003 (2006)



Phys.Rev.D74, 091104 (2006)



Phys.Rev.Lett.99, 182004(2007)

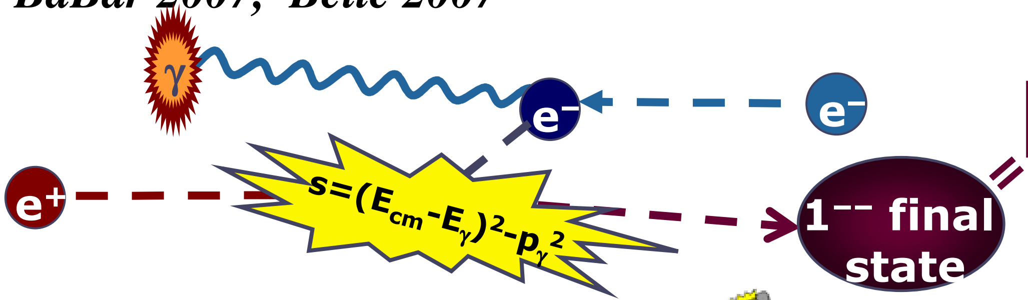


$m(Y)=(4247\pm12^{+17}_{-26})$ MeV/c^2

$\Gamma(Y)=(108\pm19^{+8}_{-10})$ MeV

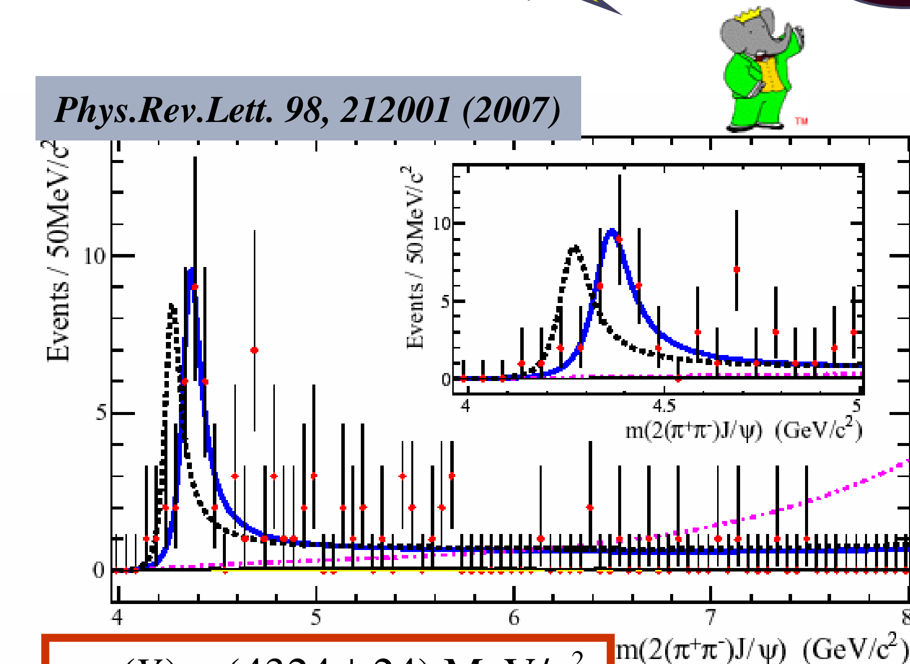
BaBar 2007, Belle 2007

More states?



Y(4320)→ψ(2S)ππ

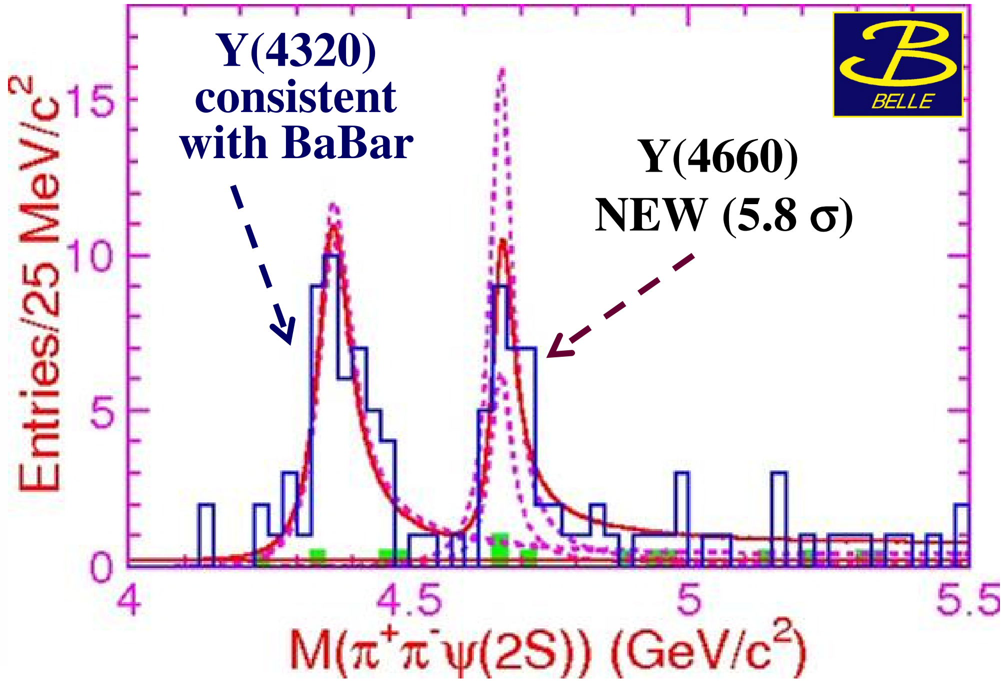
Phys.Rev.Lett. 98, 212001 (2007)



$$m(Y) = (4324 \pm 24)\ \mathrm{MeV/c^2}$$
$$\Gamma(Y) = (172 \pm 33)\ \mathrm{MeV}$$

Different structure ≠ Y(4260)

Phys.Rev.Lett. 99, 142002 (2007)

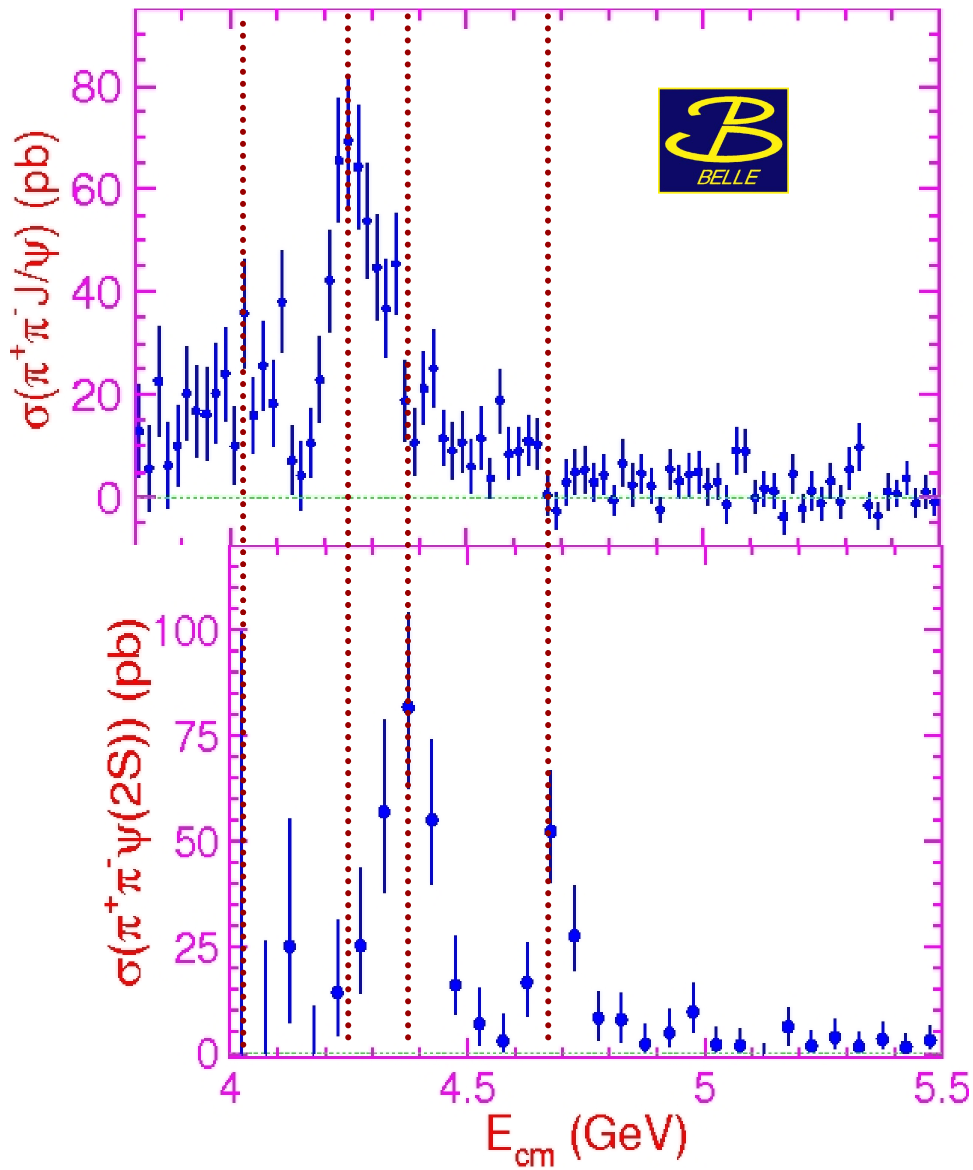


$$m(Y) = (4361 \pm 9 \pm 9)\ \mathrm{MeV/c^2}$$
$$\Gamma(Y) = (74 \pm 15 \pm 10)\ \mathrm{MeV}$$

$$m(Y) = (4664 \pm 11 \pm 5)\ \mathrm{MeV/c^2}$$
$$\Gamma(Y) = (48 \pm 15 \pm 3)\ \mathrm{MeV}$$

a statistically insignificant excess in the Y(4660) region in BaBar analysis

$e^+e^- \to J/\psi\pi^+\pi^-$ & $e^+e^- \to \psi(2S)\pi^+\pi^-$

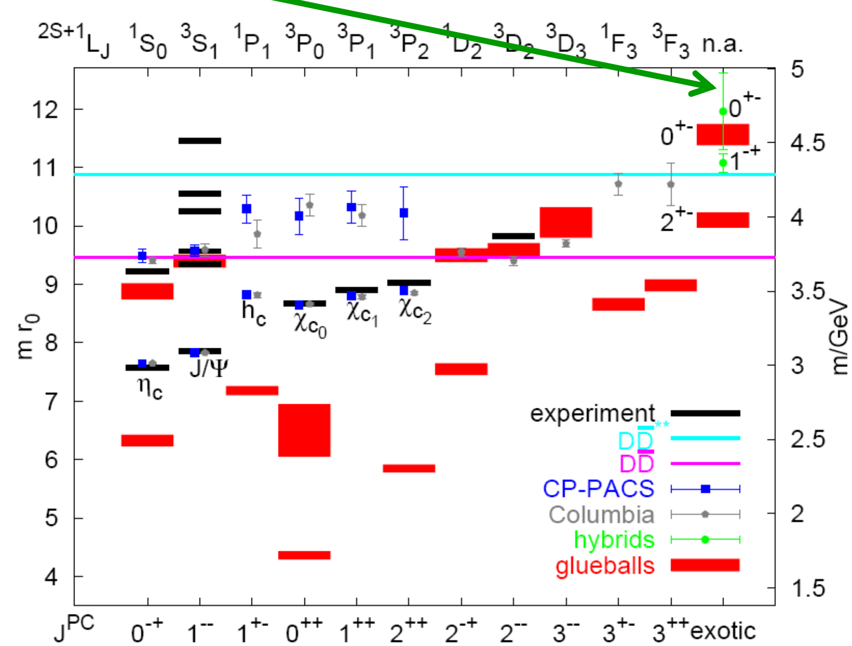


Peak positions in $M(J/\psi\pi\pi)$ & $M(\psi(2S)\pi\pi)$ significantly different.

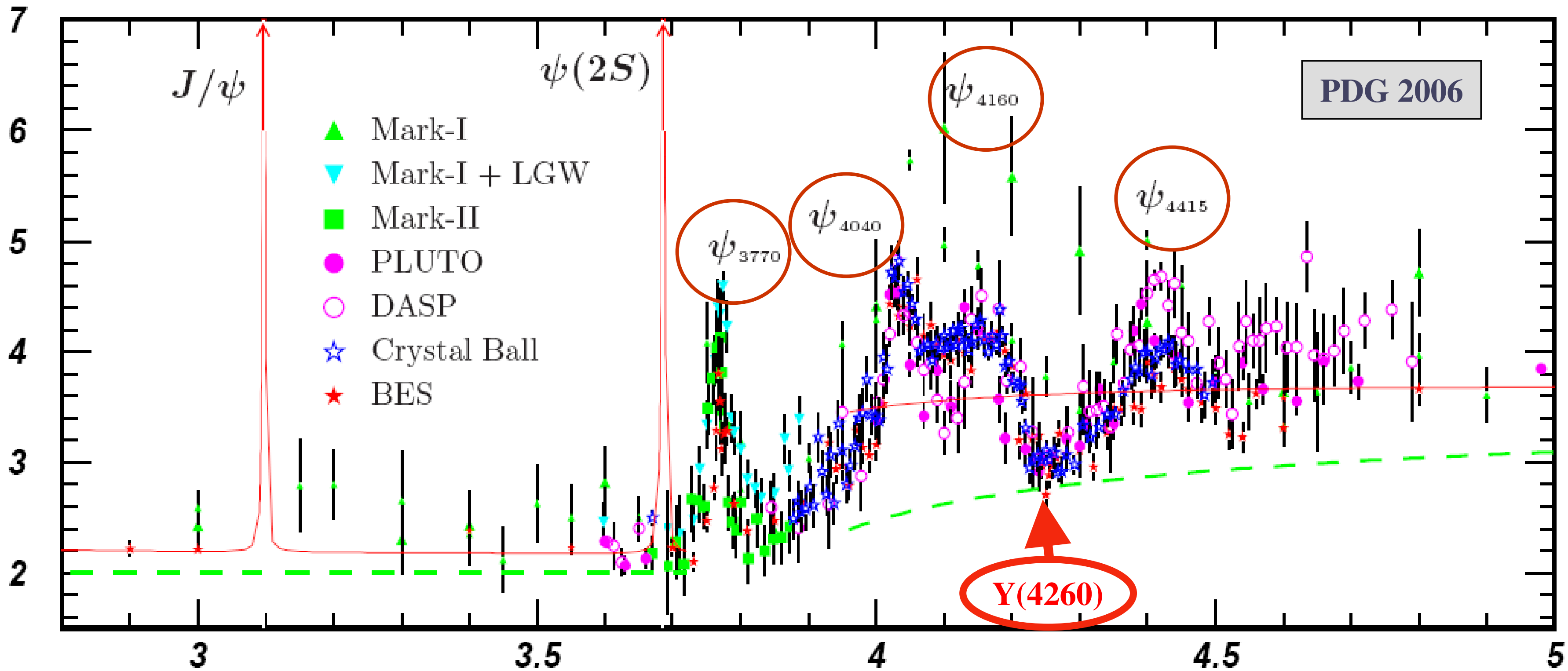
There is no place in the 1^{--} charmonium spectrum even for one state...

Options for Y states:

- **Threshold effect; note of D_sD_{s0} threshold at 4280 MeV;**
- **Tetraquark;**
- **Hybrid (ccg); note that hybrid states are expected by LQCD calculations in region 4.2-5 GeV.**



Inclusive cross section around 4 GeV

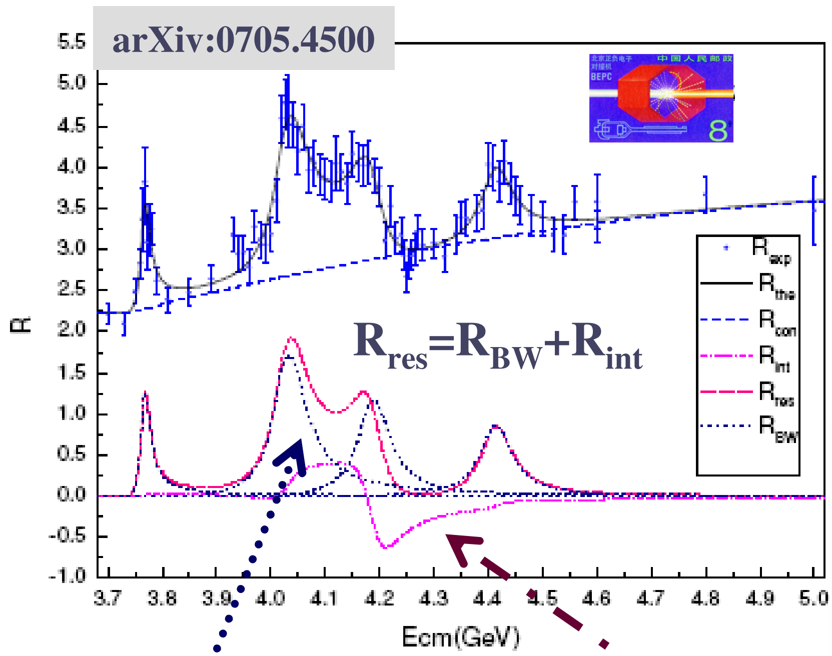


Although ψ(3770), ψ(4040), ψ(4160), ψ(4415) are know for more 25 years, their parameters M, Γ, Γ_{ee} are quite uncertain:

- **To fix the parameters we need to know their decays channels (to take into account their interference: if two states decays into the same final state they should interfere, if into different final states their contribution are incoherent)**
- **How to take into account non-resonance contribution?**
- **How to take into account many DD thresholds?**

BES-II 2007

New fit to the inclusive spectrum



Resonance shapes   Interference term

$$\psi(3770) \Rightarrow D\bar{D};$$
$$\psi(4040) \Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, \bar{D}D^*, D_s\bar{D}_s;$$
$$\psi(4160) \Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, \bar{D}D^*, D_s\bar{D}_s, D_s\bar{D}_s^*;$$
$$\psi(4415) \Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, \bar{D}D^*, D_s\bar{D}_s, D_s\bar{D}_s^*, D_s^*\bar{D}_s^*.$$

Resonance parameters

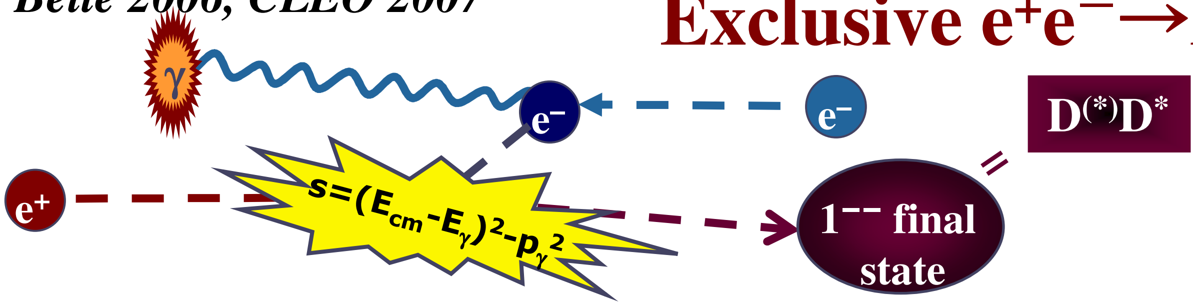
		$\psi(3770)$	$\psi(4040)$	$\psi(4160)$	$\psi(4415)$
M (MeV/c^2)	PDG2004	3769.9±2.5	4040±10	4159±20	4415±6
	PDG2006	3771.1±2.4	4039±1.0	4153±3	4421±4
	CB(Seth)	-	4037±2	4151±4	4425±6
	BES(Seth)	-	4040±1	4155±5	4455±6
	BES(this work)	3771.3±1.7	4042.7±5.8	4193.2±6.7	4417.2±9.1
Γ_{tot} (MeV)	PDG2004	23.6±2.7	52±10	78±20	43±15
	PDG2006	23.0±2.7	80±10	103±8	62±20
	CB(Seth)	-	85±10	107±10	119±16
	BES(Seth)	-	89±6	107±16	118±35
	BES(this work)	25.6±6.3	88.9±12.4	78.8±16.1	80.4±24.7
Γ_{ee} (keV)	PDG2004	0.26±0.04	0.75±0.15	0.77±0.23	0.47±0.10
	PDG2006	0.24±0.03	0.86±0.08	0.83±0.07	0.58±0.07
	CB(Seth)	-	0.88±0.11	0.83±0.08	0.72±0.11
	BES(Seth)	-	0.91±0.13	0.84±0.13	0.64±0.23
	BES(this work)	0.19±0.04	0.94±0.19	0.50±0.28	0.40±0.15
δ(degree)	BES(this work)	0	135±58	306±40	247±75

The interference is taken into account for the first time (model dependent)
Significant difference with fit without interference

Need to measure exclusive cross sections $e^+e^-\to D^{(*)}D^{(*)}$ for model independent fit

Exclusive $e^+e^- \to D^{(*)}D^*$ cross-sections

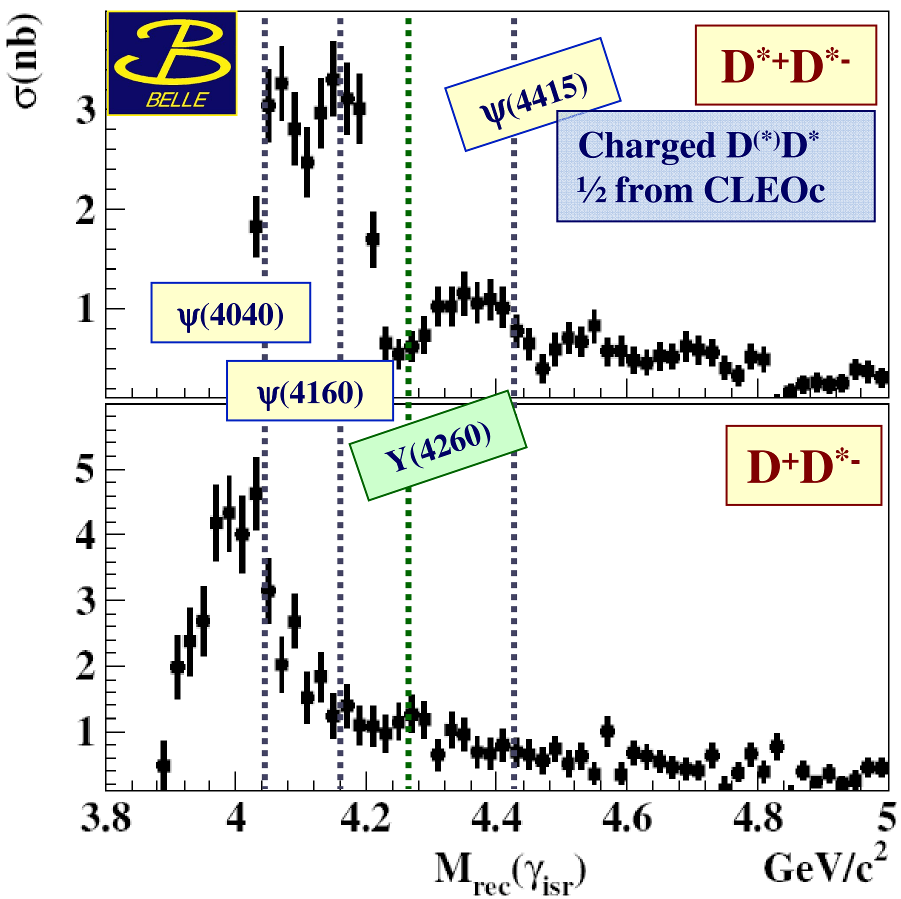
Belle 2006, CLEO 2007



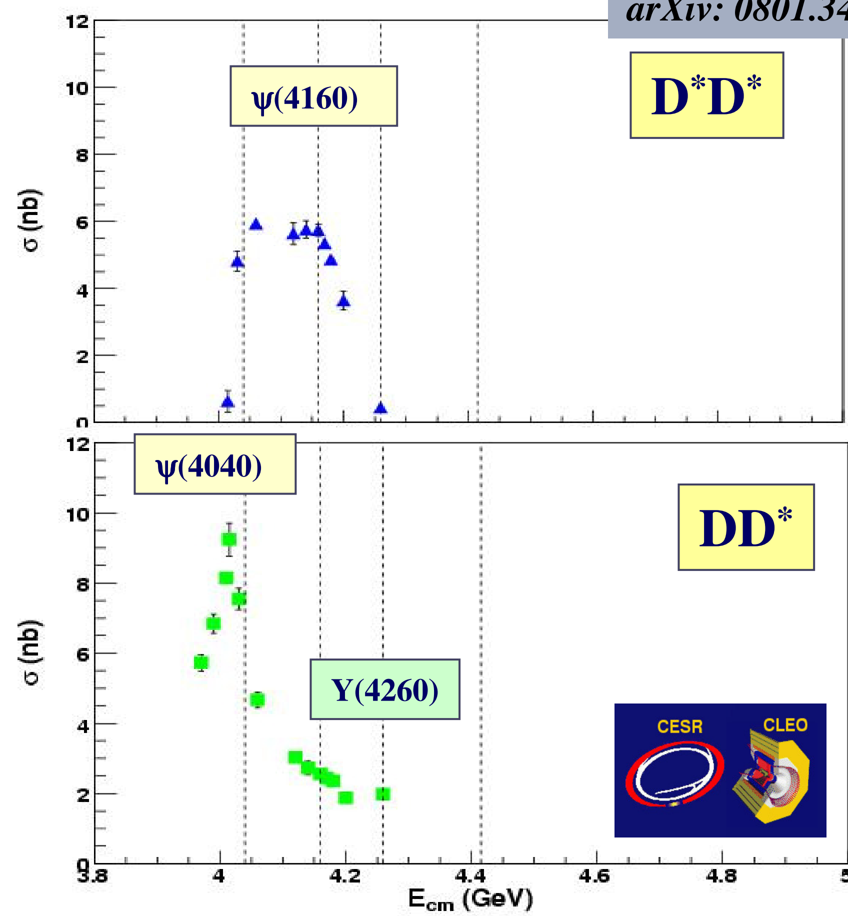
Y(4260) signal

- DD^* : hint, but not significant
- D^*D^* : clear dip

Phys.Rev.Lett. 98, 092001 (2007)

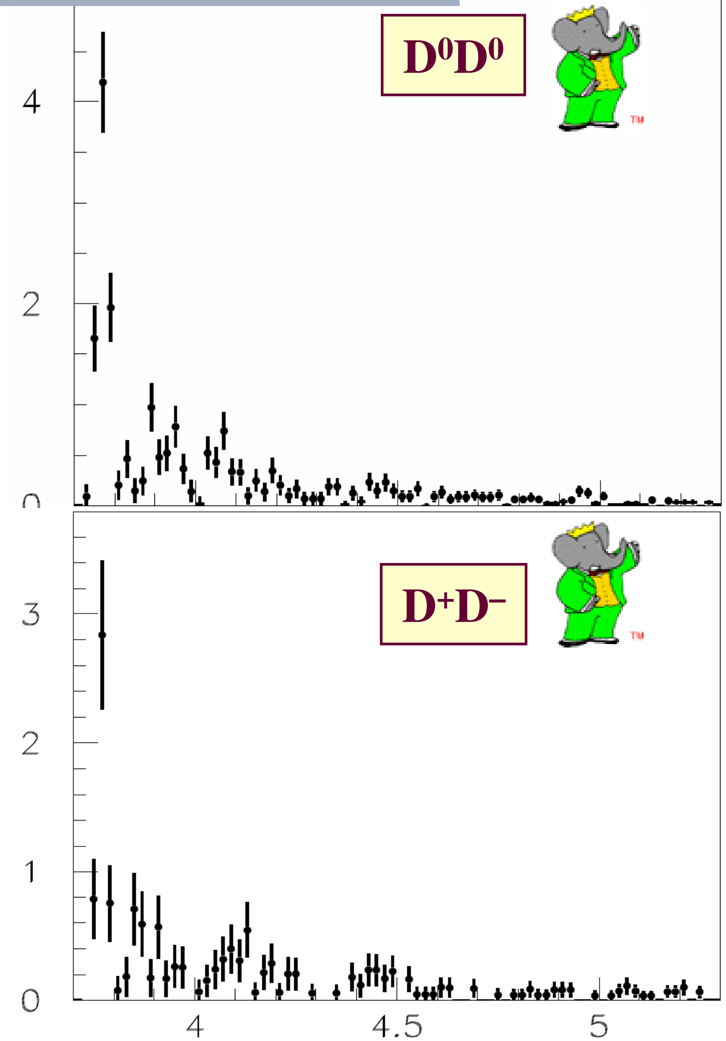


arXiv: 0801.3418

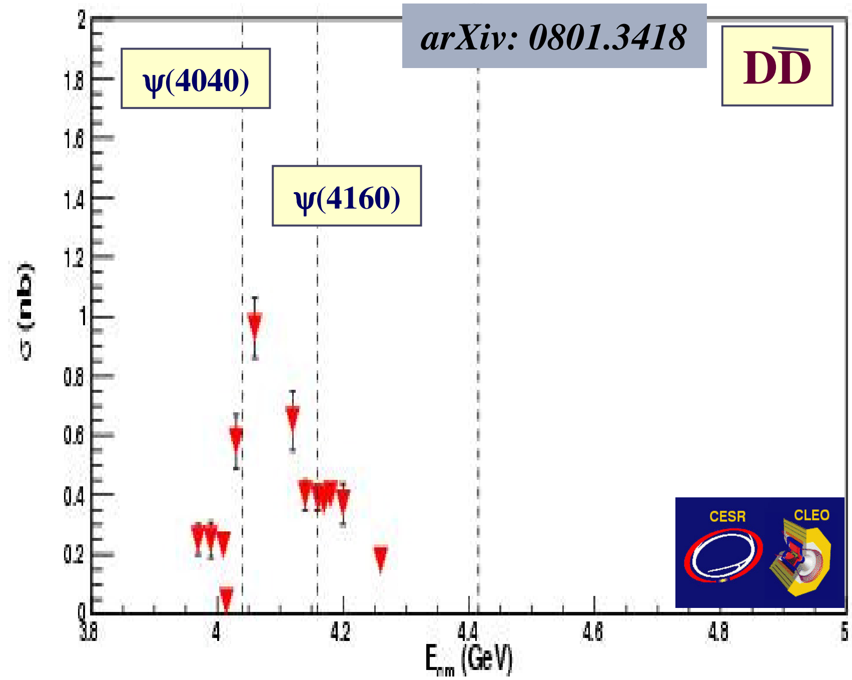


Exclusive $e^+e^- \rightarrow DD$ cross-sections

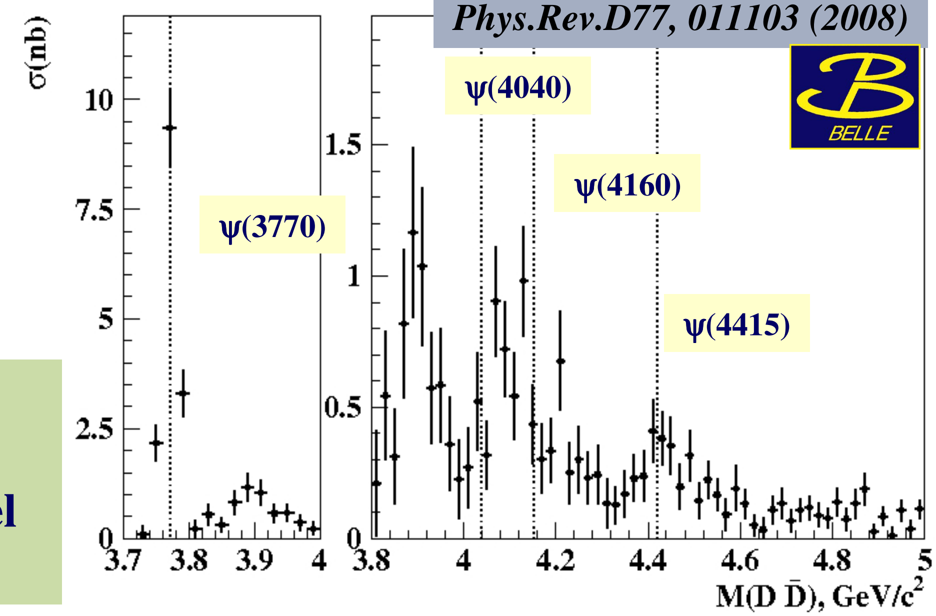
Phys.Rev. D76, 111105 (2007)



arXiv: 0801.3418



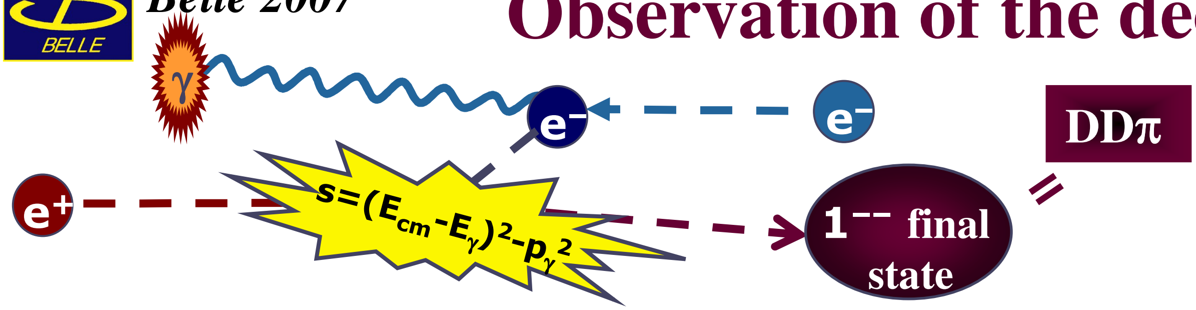
Phys.Rev.D77, 011103 (2008)



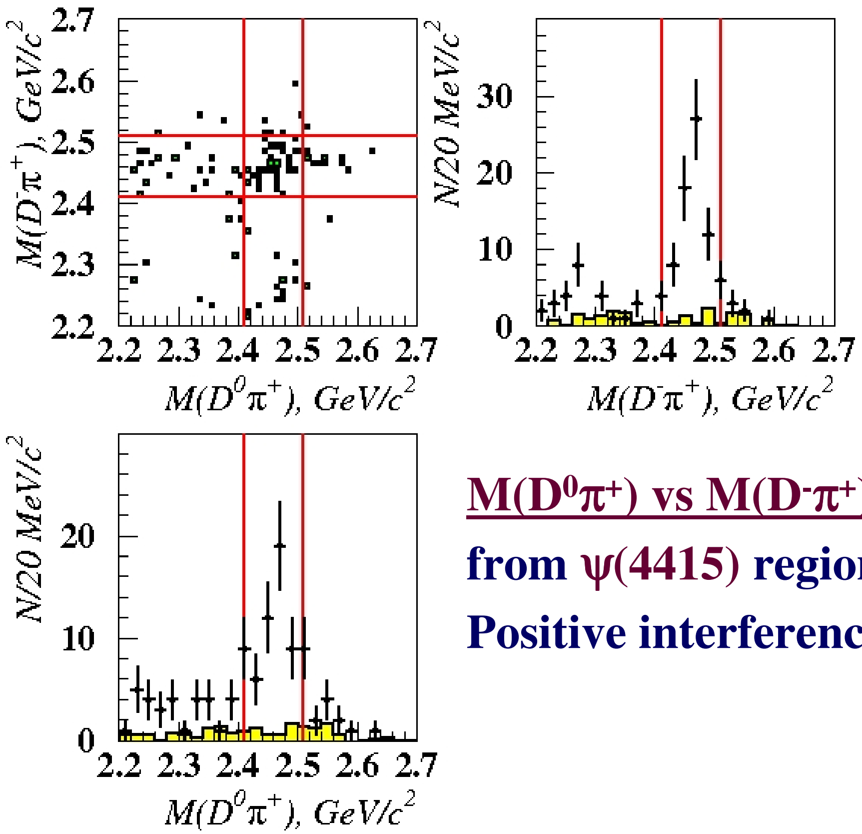
A broad structure around 3.9 GeV
(seen by BaBar and Belle) in a qualitive
agreement with a coupled-channel model
Phys. Rev. D21, 203 (1980)

Belle 2007

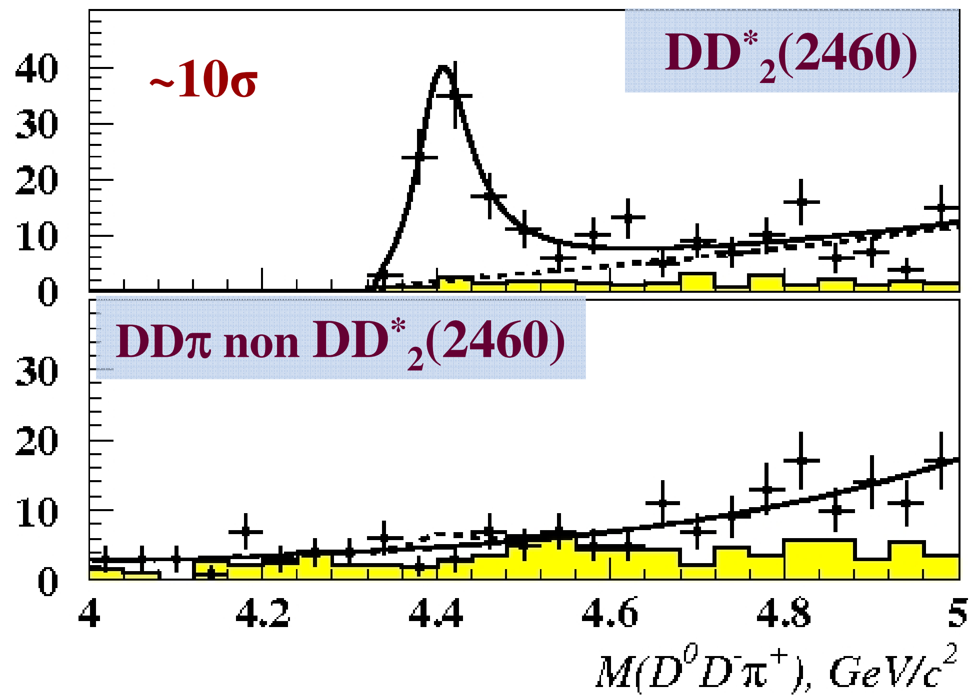
Observation of the decay $\psi(4415) \to DD\pi$



$M = 4411 \pm 7$ MeV
$\Gamma_{tot} = 77 \pm 20$ MeV
$N_{ev} = 109 \pm 25$



$M(D^0\pi^+)$ vs $M(D^-\pi^+)$
from $\psi(4415)$ region
Positive interference

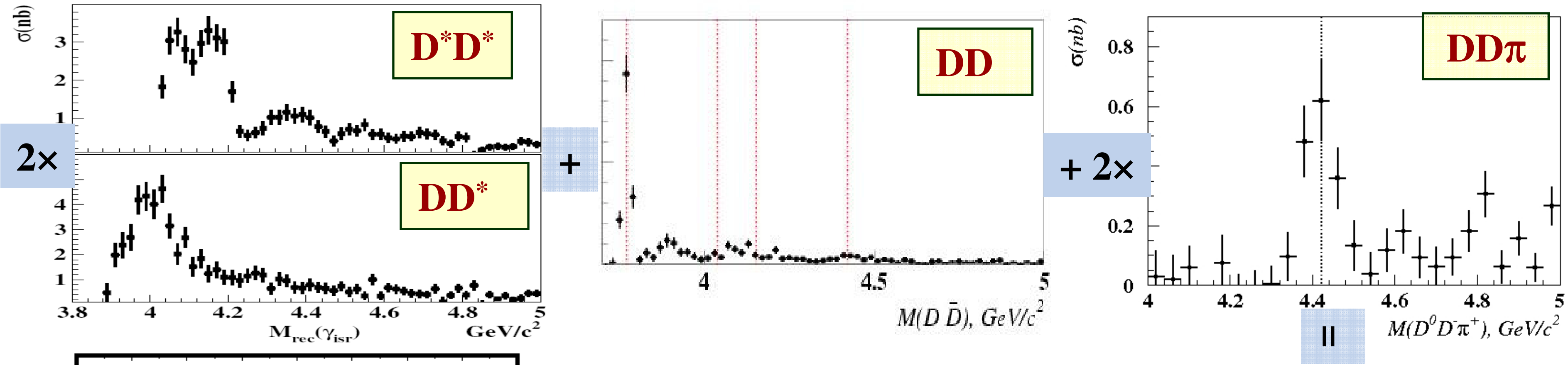


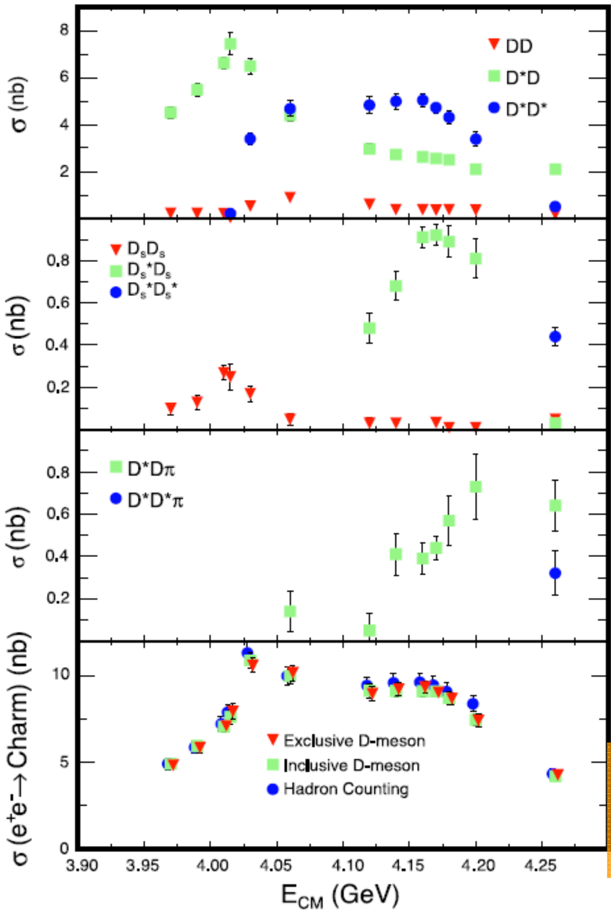
Non $D^*_2(2460)$ contribution is not seen

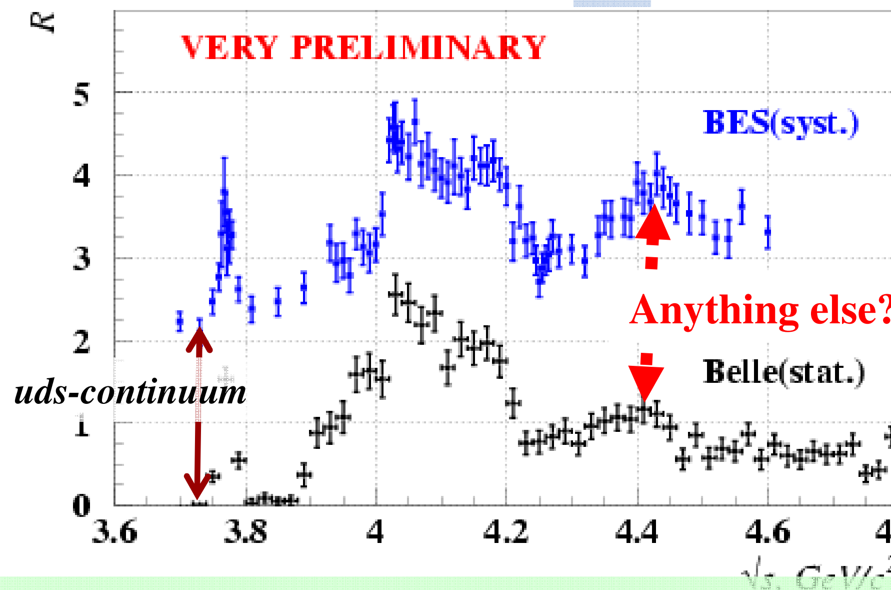
$\sigma(e^+e^- \to \psi(4415)) \times Br(\psi(4415) \to DD^*_2(2460)) \times Br(D^*_2(2460) \to D\pi) = (0.74 \pm 0.17 \pm 0.07)$nb

$Br(\psi(4415) \to D(D\pi)\text{non } D^*_2(2460))/Br(\psi(4415) \to DD^*_2(2460)) < 0.22$

Contributions to the inclusive cross-section







These 4 final states almost saturate inclusive cross section, still many missing f.s. *e.g.* $D_s^{(*)}D_s^{(*)}$

CLEO add all final states to check: ∑ = inclusive cross section. Nice agreement (only small √s region <4.26 GeV)

New charmonium /charmonium-like states:

- Two new states below open charm threshold, h_c and $\eta_c(2S)$, are well identified and well fit the potential model predictions.
- Three new states, $\chi_{c2}(2P)$, X(3940), X(4160), behave like a "normal" charmonium, but all three are significantly lighter than expected by potential models.
- The state X(3872) is very probably to be a D^0D^{*0} molecular state with a mixture of $\chi_{c1}(1P)$, $\chi_{c1}(2P)$. At least this explanation is self consistent and no better one is suggested.
- The state Y(3940) has a surprising decay mode, may be a "normal" charmonium – experimental information is still poor.
- Four Y states in 1^{--} spectrum are the most problematic: no place in the standard charmonium table. LQCD calculations expect hybrids in this mass region.
- A lot of experimental information on the exclusive cross sections $e^+e^-\to D^{(*)}D^{(*)}$ related to the knowm ψ states above DD threshold and new Y's.
- More about new charmonium(botommonium) states in the next talk.

Can the charmonium table accomodate the new states?