

# Quarkonium

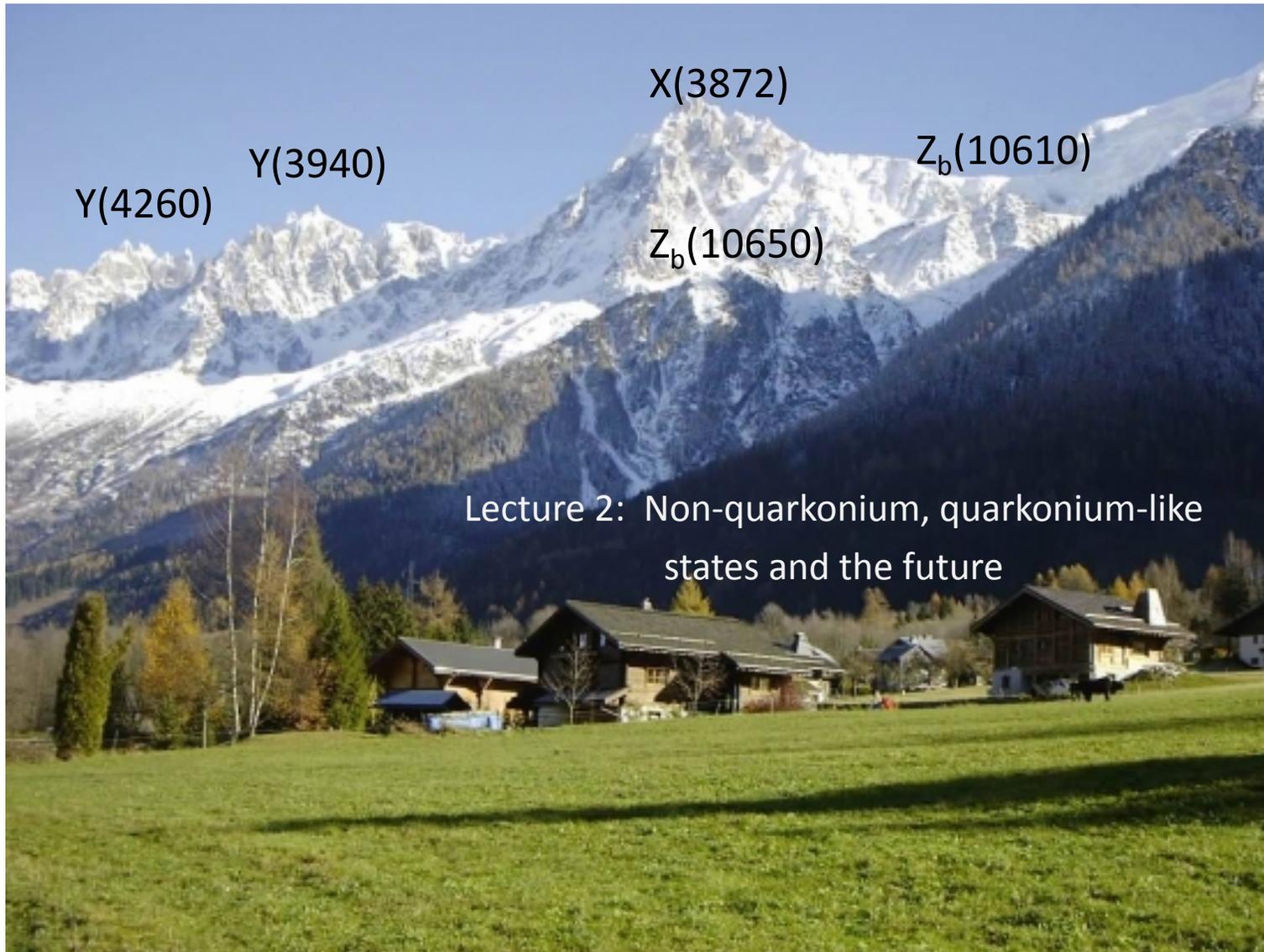
## experimental overview II



Stephen Lars Olsen  
Seoul National University

France-Asia Particle Physics School, Les Houches, FRANCE  
October 11-12, 2011

# Outline

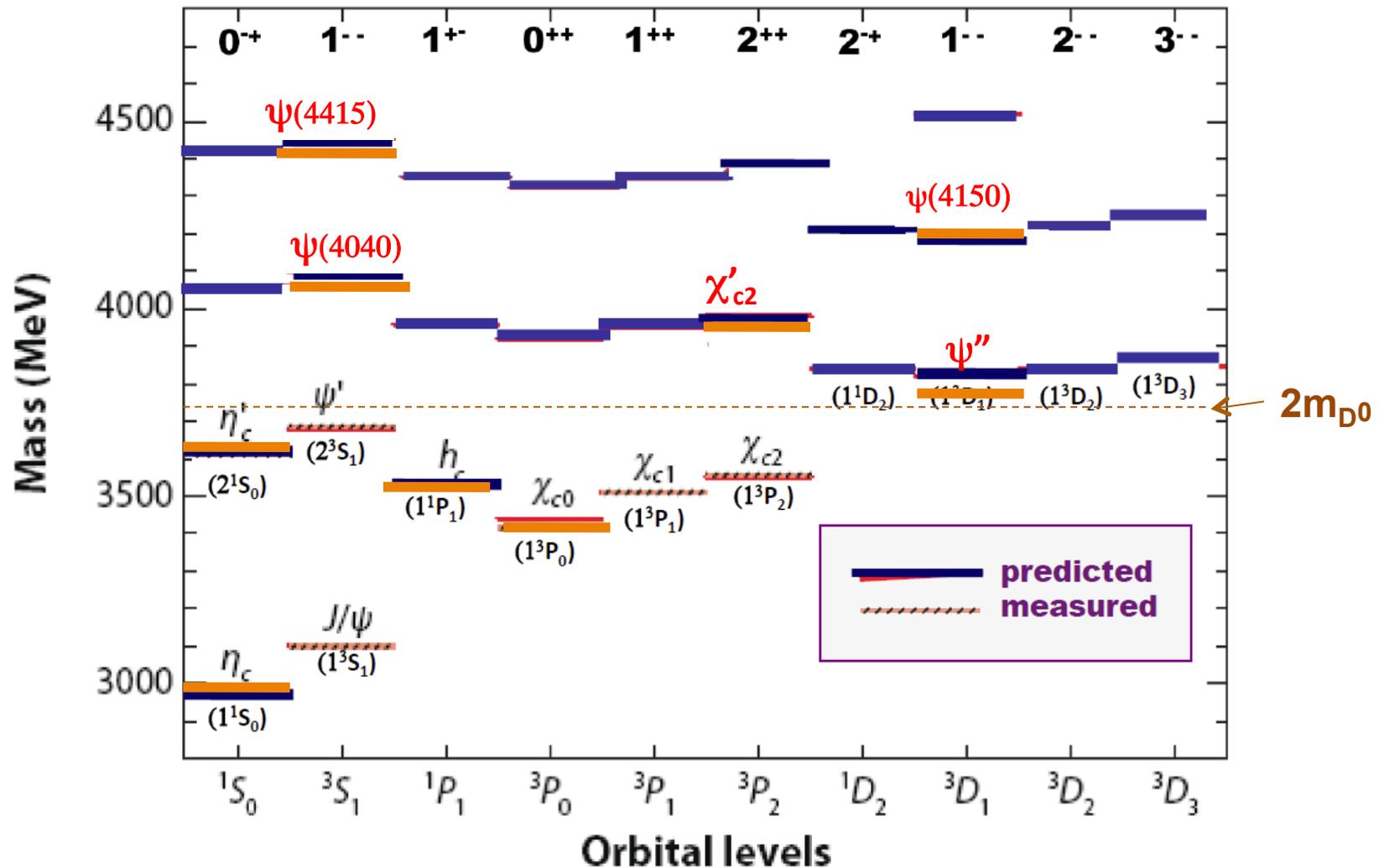


# Summary (lecture 1)

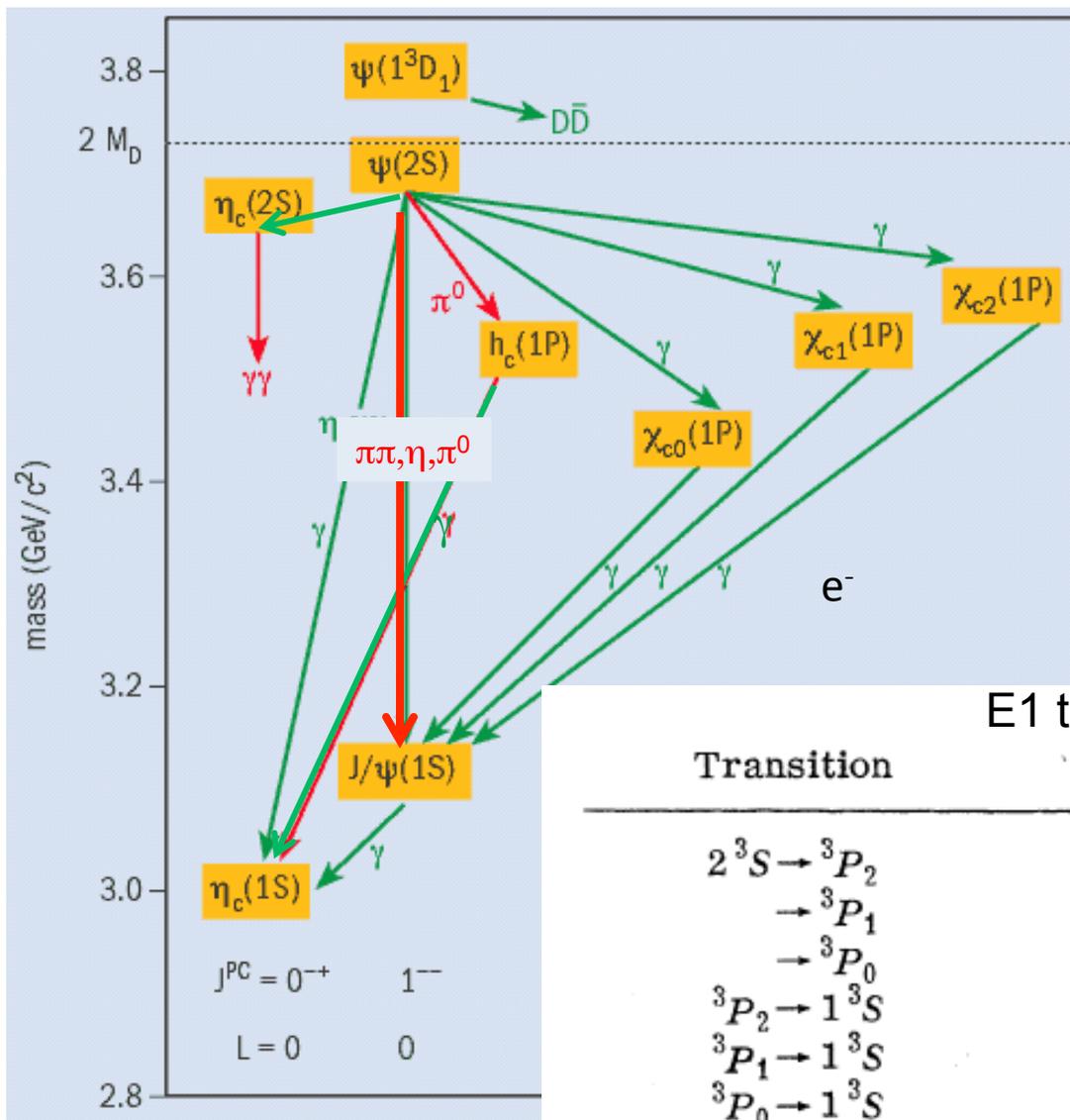
- The quarkonium spectra are strong evidence that hadrons are composed of spin=1/2 constituent particles
- All of the charmonium states below the  $M=2m_D$  “open charm” threshold have been found
  - most of the bottomonium states below  $M=2m_B$  have been identified
- Above the threshold, most of the  $1^-$  states, but only one of the others (the  $\chi_{c2}'$ ) have been discovered.
- The masses of the assigned states match theory predictions
  - variations are less than  $\sim 50$  MeV
- Transitions between quarkonium states are in reasonably good agreement with theoretical expectations

# Charmonium spectrum today

Masses in pretty good agreement with theoretical expectations  
 -- biggest discrepancies ~ 50 MeV --



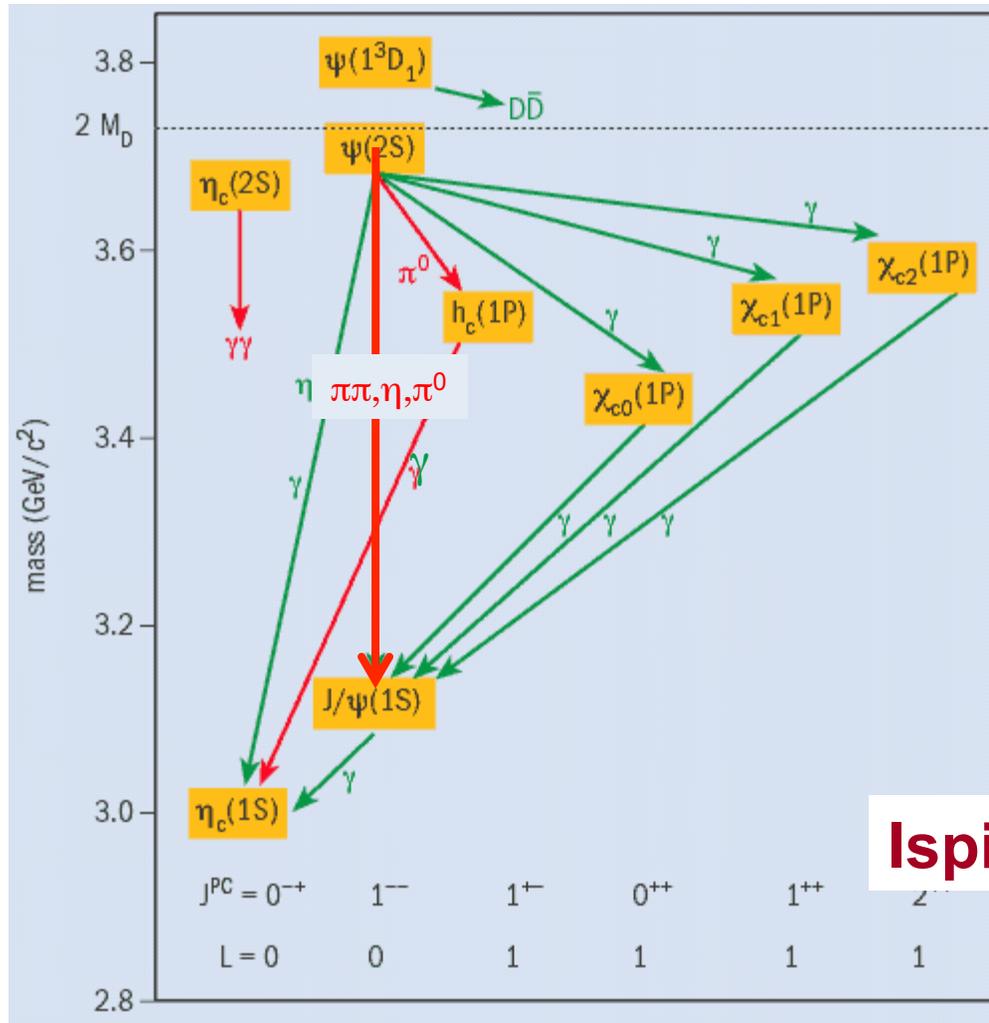
# $\gamma$ Transitions



M1 transitions ( $\Gamma(\text{keV})$ )

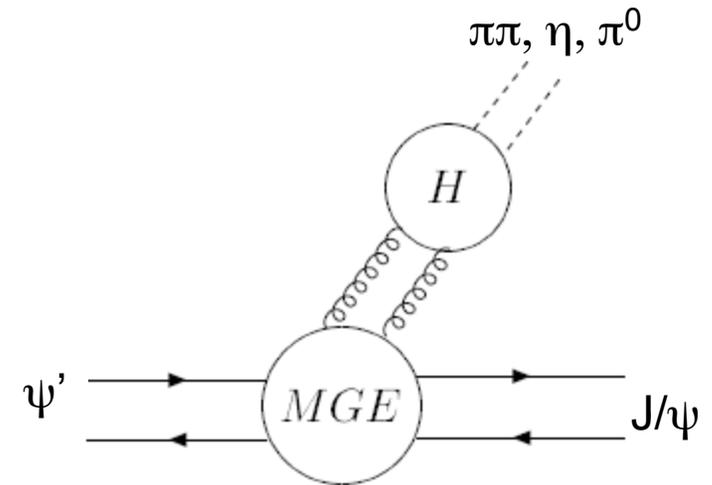
	<i>Th.</i>	<i>Expt</i>
$J/\psi \rightarrow \gamma \eta_c$	2.4	$1.6 \pm 0.4$
$\psi' \rightarrow \gamma \eta_c$	4.6	$1.1 \pm 0.2$

# Hadronic transitions



$\psi' \rightarrow J/\psi + \text{hadrons}$

	$\Gamma_{\text{exp}}(\text{keV})$
$\psi' \rightarrow \pi^+\pi^- J/\psi$	$88 \pm 7$
$\psi' \rightarrow \eta J/\psi$	$9 \pm 1$
$\psi' \rightarrow \pi^0 J/\psi$	$0.4 \pm 0.1$



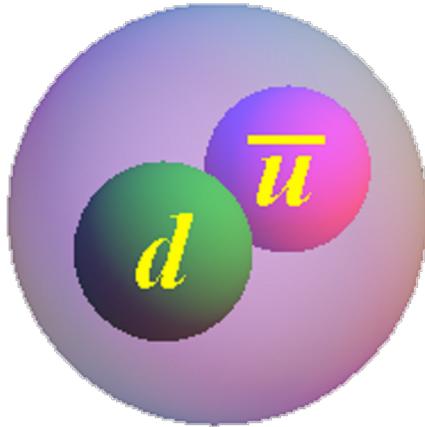
**Ispin violation:**

$$\frac{\psi' \rightarrow \pi^0 J/\psi}{\psi' \rightarrow \pi\pi J/\psi} \sim 1/200$$



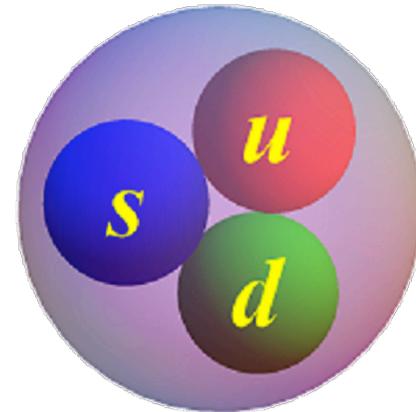
# Constituent Quark Model

$$\pi^- = (d\bar{u})$$



Mesons are quark-antiquark pairs

$$\Lambda = (uds)$$



Baryons are quark-quark-quark triplets

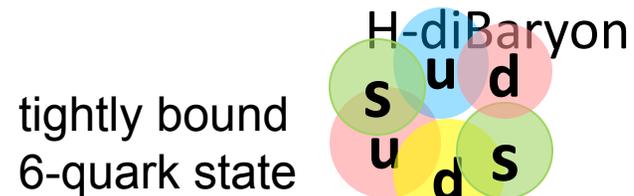
**Fabulously successful**

Quarks are probably the most well known particle physics quantity among the general public

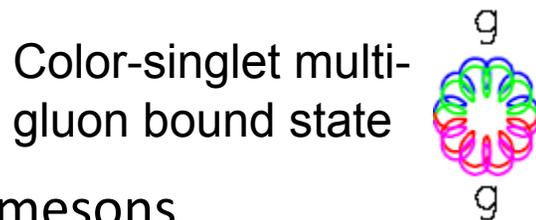
# Why no other color-singlet combinations?

Other possible "white" combinations of quarks & gluons:

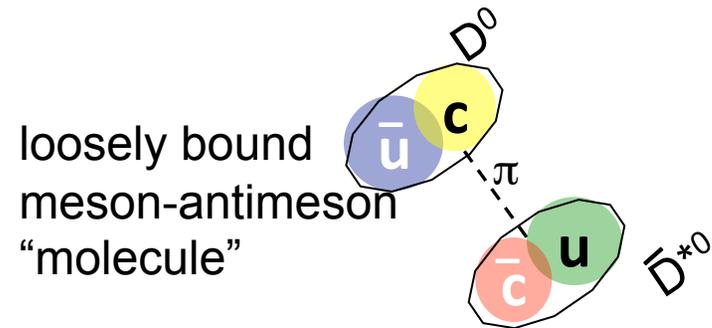
Pentaquark:



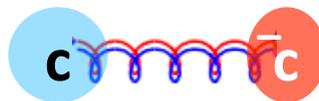
Glueball



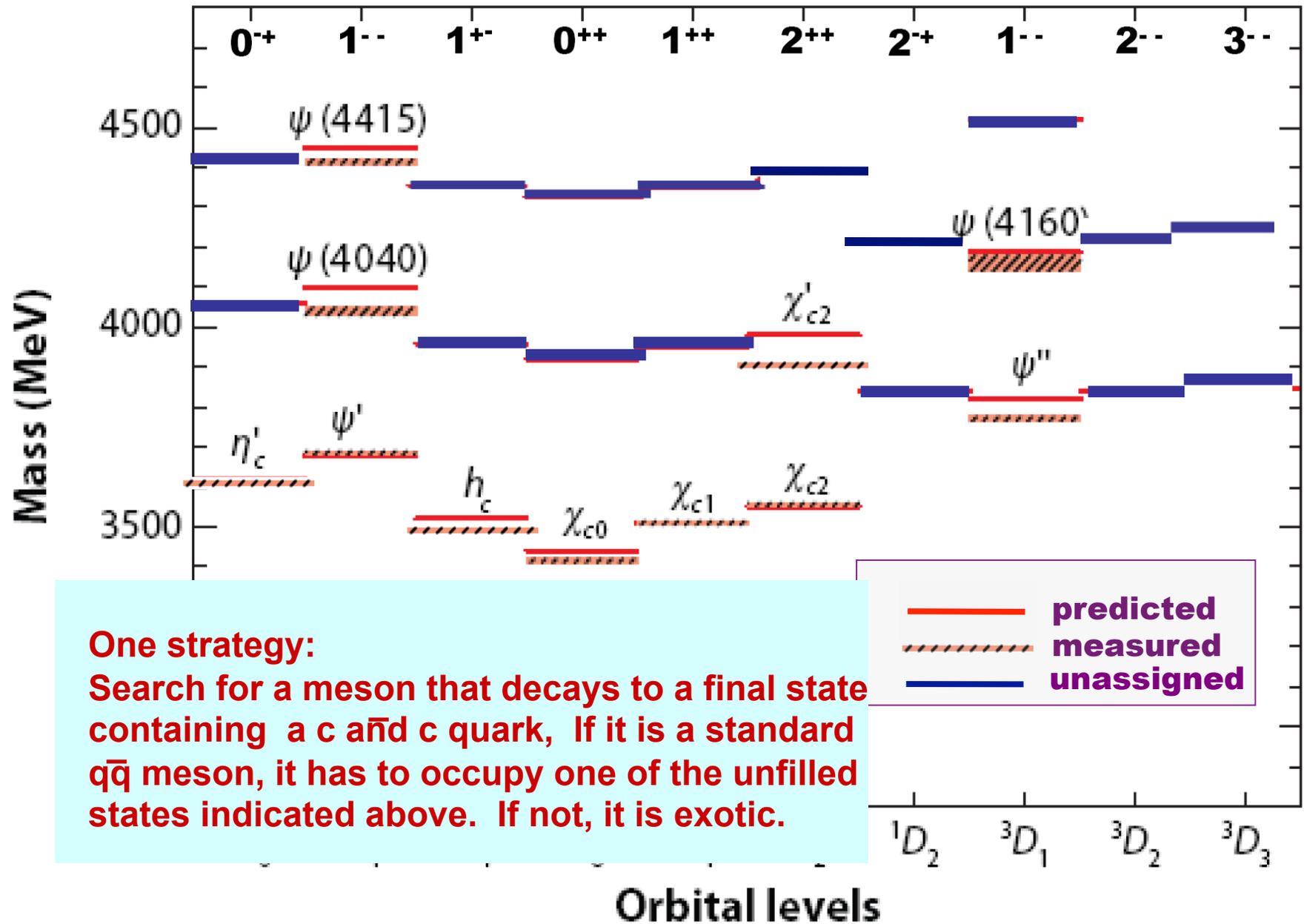
Tetraquark mesons



$q\bar{q}$ -gluon hybrid mesons

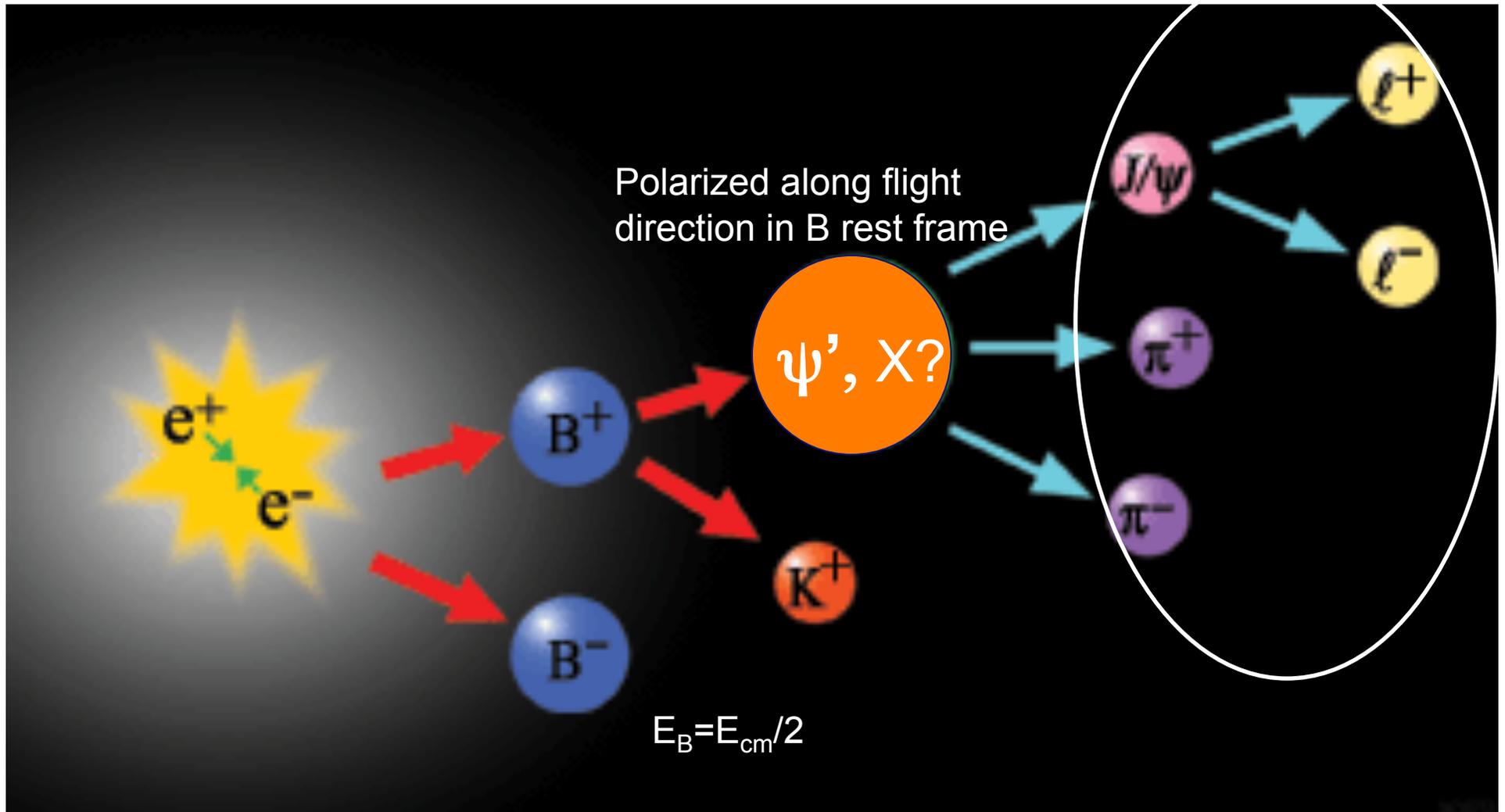


## Charmonium mesons



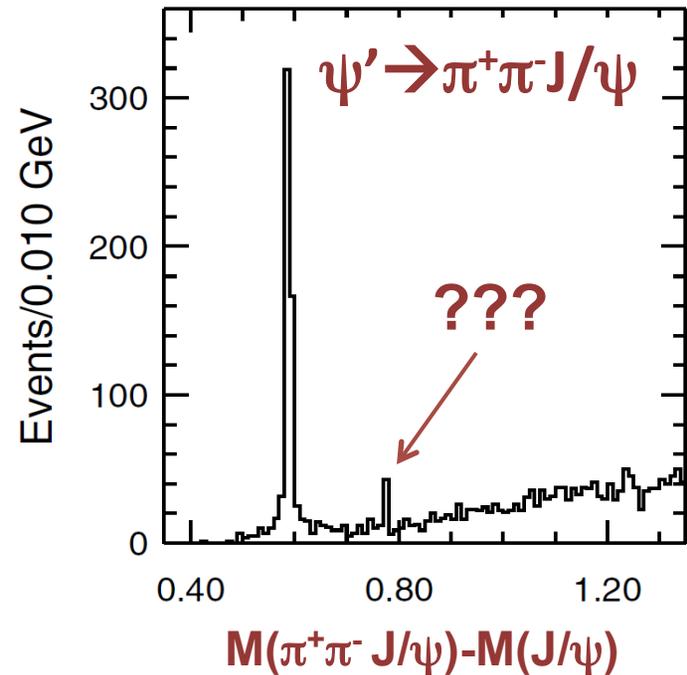
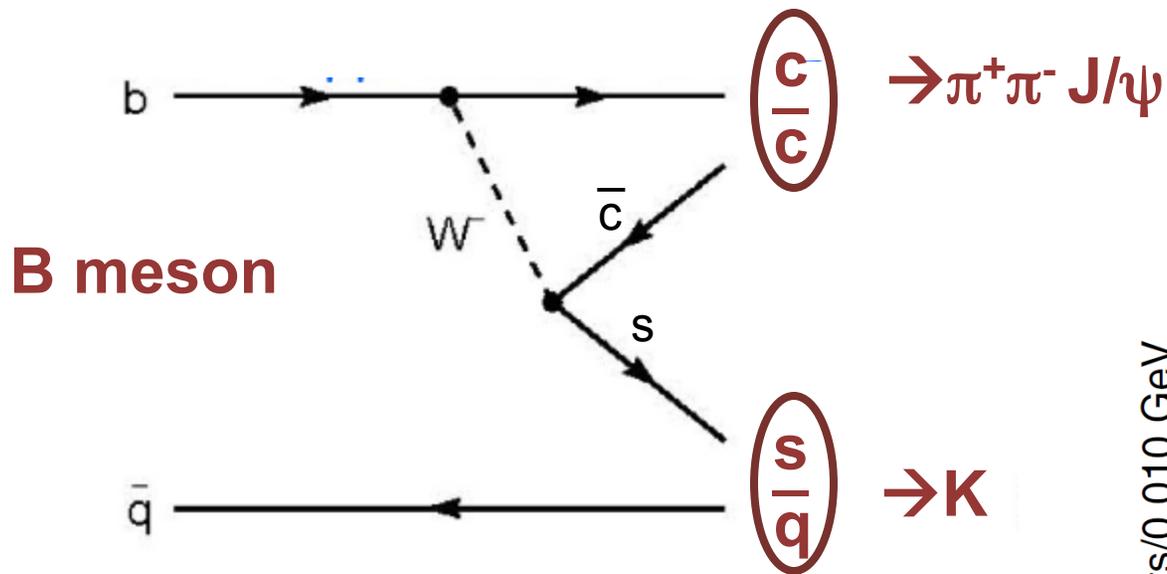
**One strategy:**  
 Search for a meson that decays to a final state containing a c and  $\bar{c}$  quark. If it is a standard  $q\bar{q}$  meson, it has to occupy one of the unfilled states indicated above. If not, it is exotic.

# $\pi^+\pi^-/J\psi$ systems produced in B decay



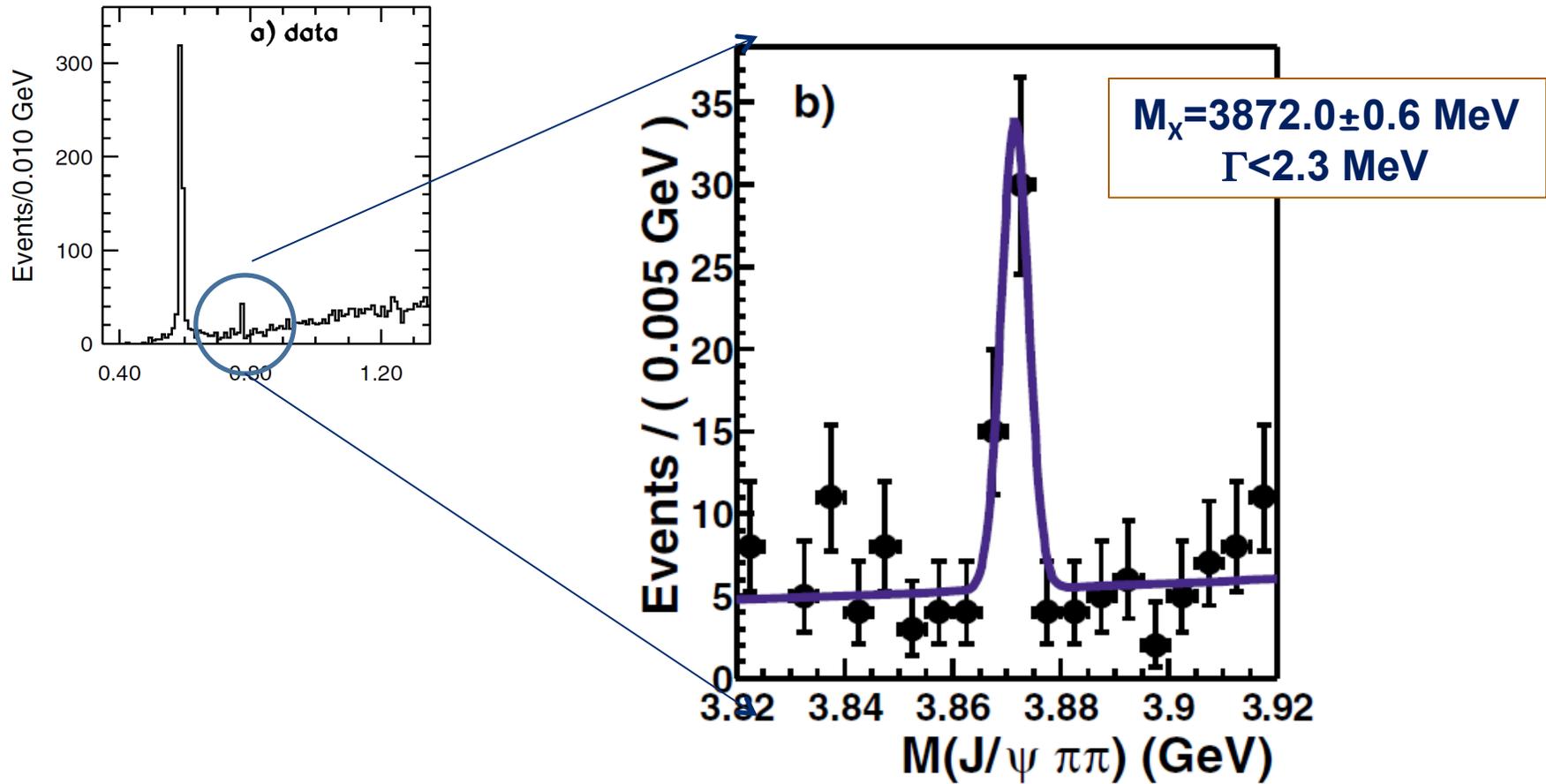
$B^0 \rightarrow K_S \psi'$ ;  $\psi' \rightarrow \pi^+ \pi^- J/\psi$  are very useful decays for CP violation studies

# $M(\pi^+\pi^-J/\psi)$ in $B \rightarrow K(\pi^+\pi^-J/\psi)$



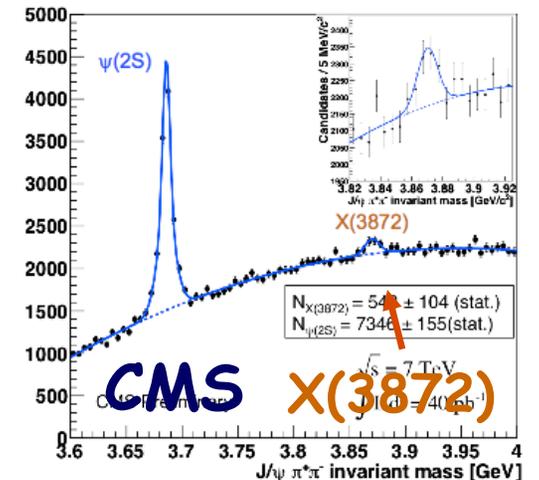
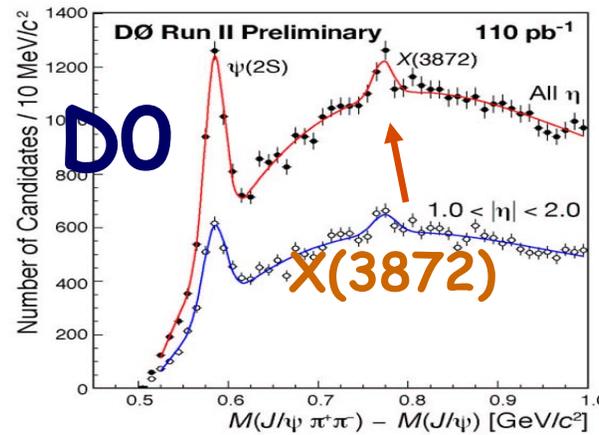
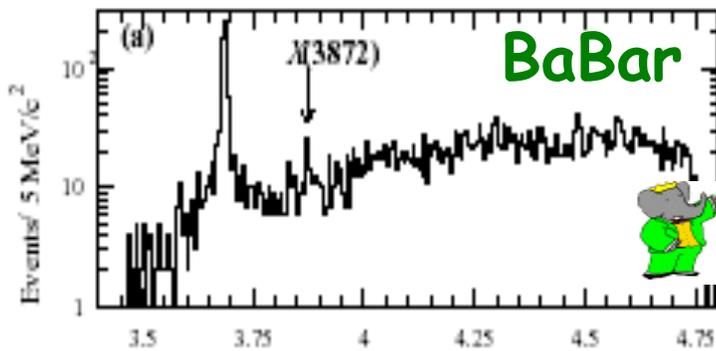
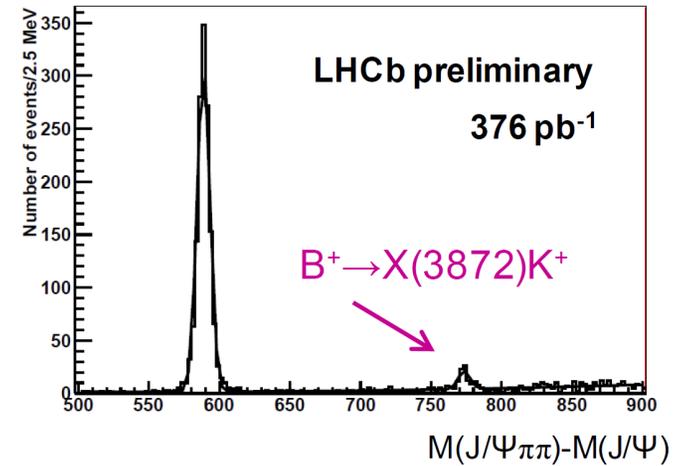
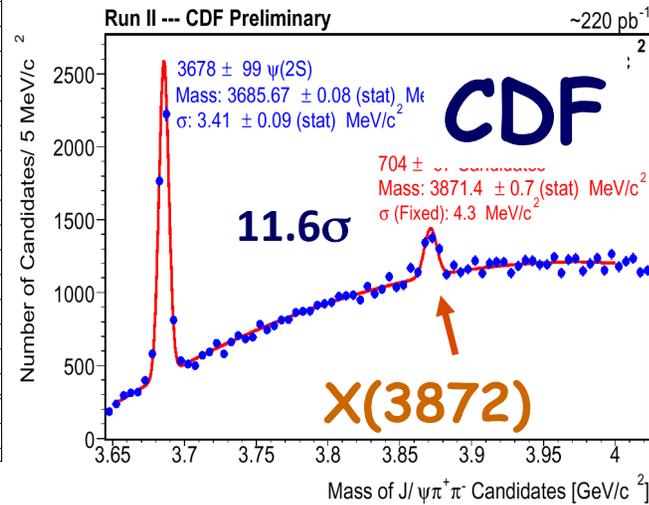
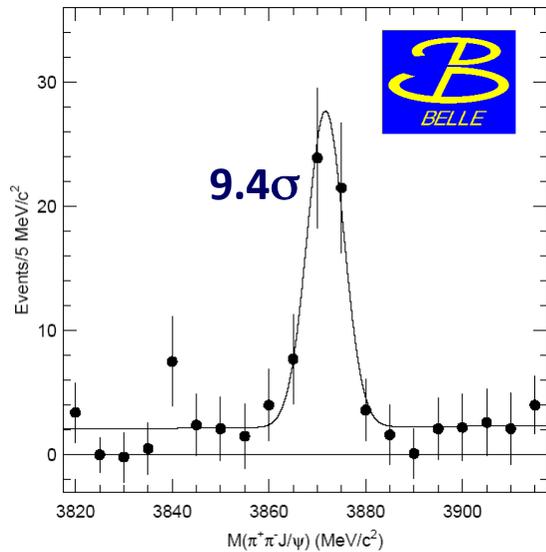
Belle PRL **91**, 262001 (2003)

# X(3872)

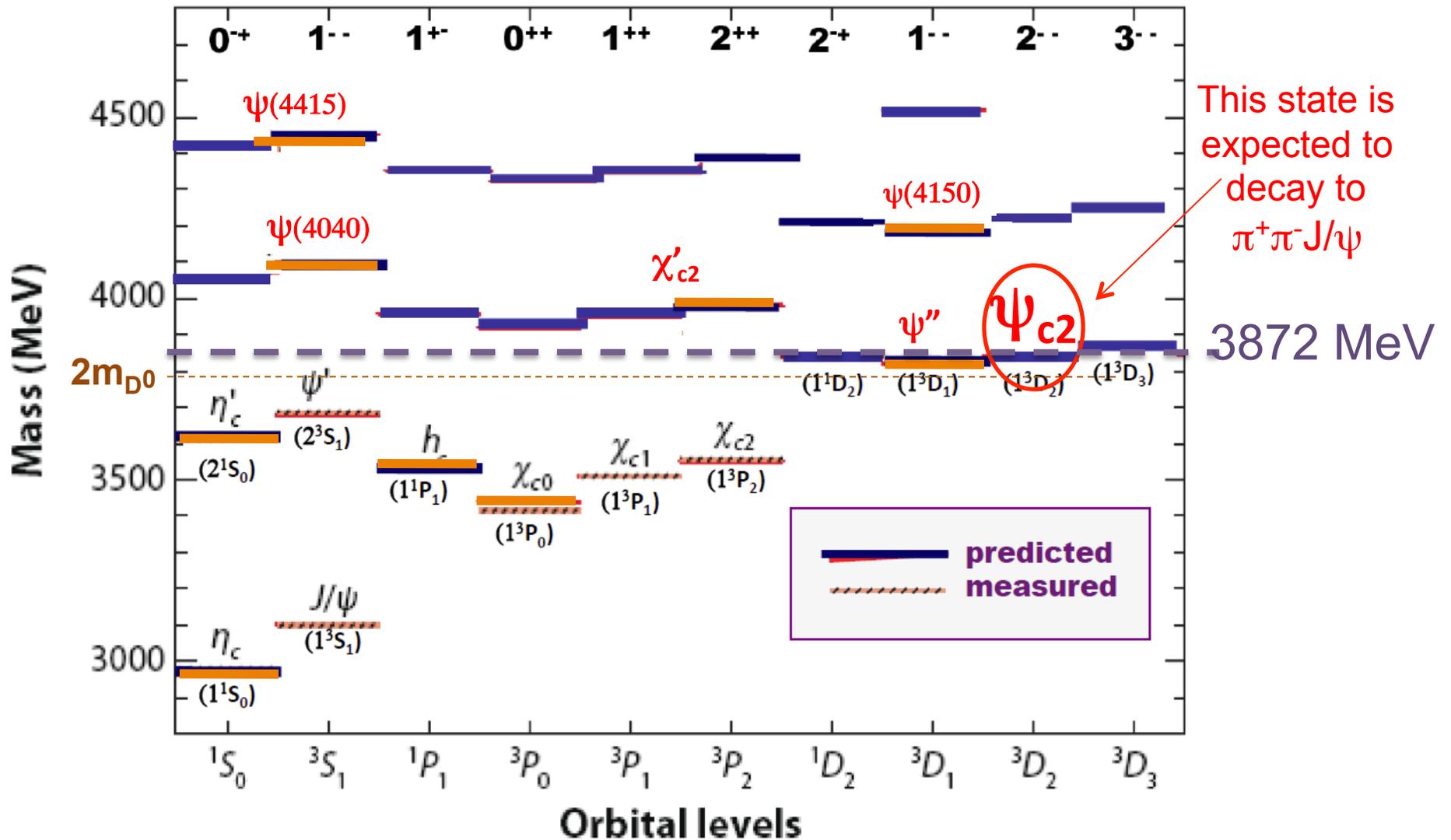


Belle PRL **91**, 262001 (2003)

# $X_{3872}$ is seen in many experiments

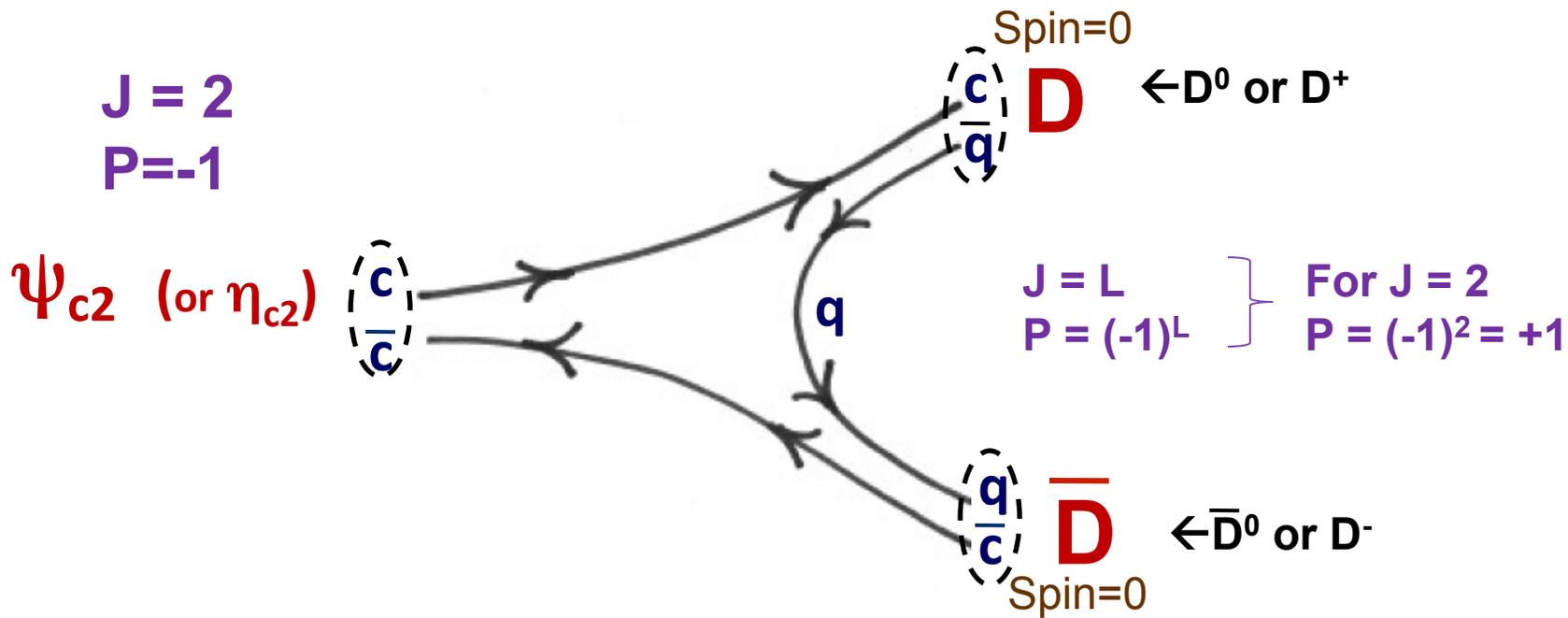


# Does it fit into the $c\bar{c}$ spectrum?



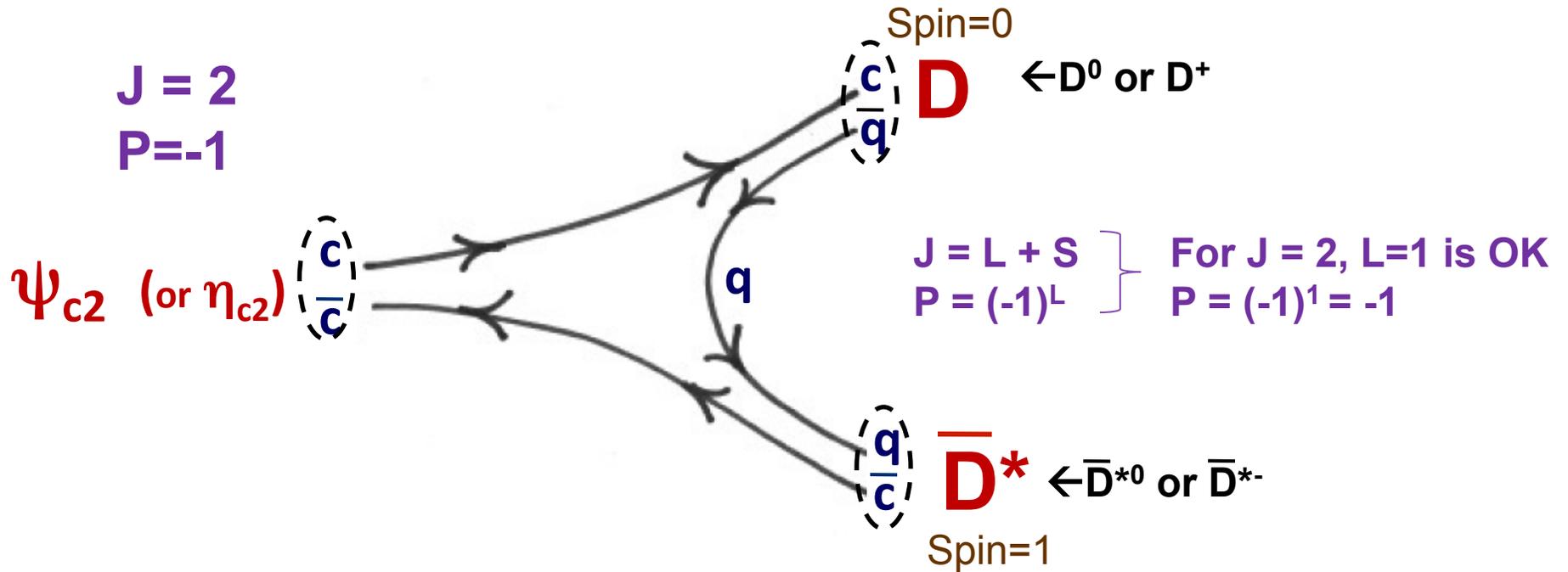
$J^{PC} = 2^{--}$  (&  $2^{-+}$ )  $\rightarrow$   $D\bar{D}$  not allowed

$\psi_{c2}$        $\eta_{c2}$



$\psi_{c2}$  ( $\eta_{c2}$ )  $\rightarrow D\bar{D}$  violates parity

Lowest possibility is  $D\bar{D}^*$  (or  $D^*\bar{D}$ )



$\psi_{c2} (\eta_{c2}) \rightarrow D\bar{D}^*$  doesn't violate parity

$M_D + M_{D^*}$  is the "open charm threshold" for  $\psi_{c2}$  (&  $\eta_{c2}$ )

# Is the X(3872) the $\psi_{c2}$ ?

Eichten et al:  
PRL 98, 162002 (2002)

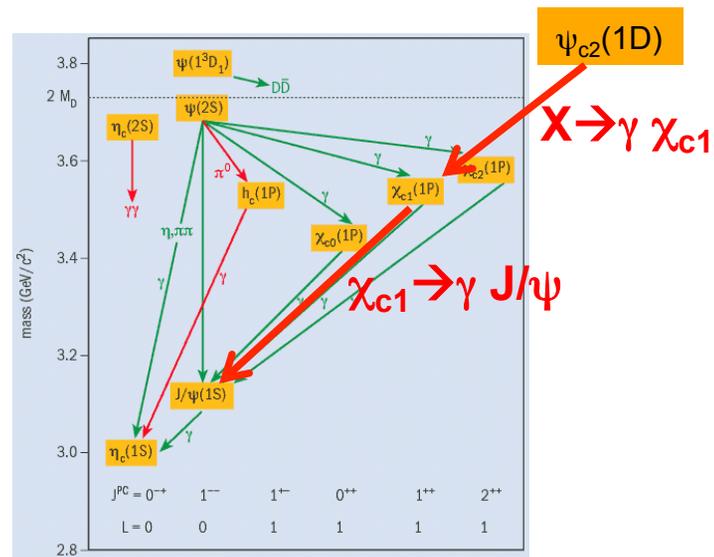
$$\frac{\text{Bf}(\psi_{c2} \rightarrow \gamma \chi_{c1})}{\text{Bf}(\psi_{c2} \rightarrow \pi^+ \pi^- J/\psi)} > 5$$

Fermilab 2003

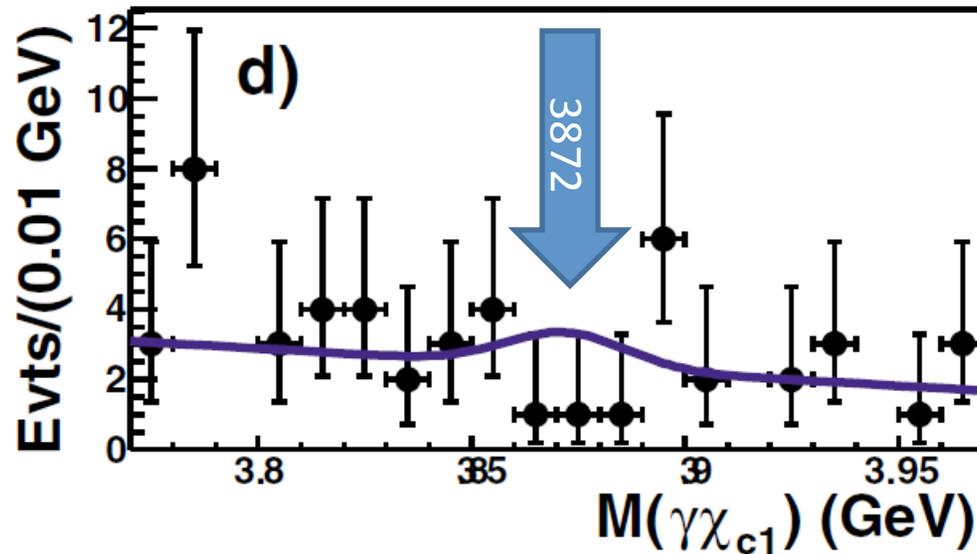


Eichten

“Look for  $X \rightarrow \gamma \chi_{c1}$ , you should be flooded by events”



$$X(3872) \rightarrow \gamma \chi_{c1} \text{??}$$



Belle PRL **91**, 262001 (2003)

$$\frac{\text{Bf}(\psi_{c2} \rightarrow \gamma \chi_{c1})}{\text{Bf}(\psi_{c2} \rightarrow \pi^+ \pi^- J/\psi)} < 0.9$$

**The X(3872) is not the  $\psi_{c2}$ !!**

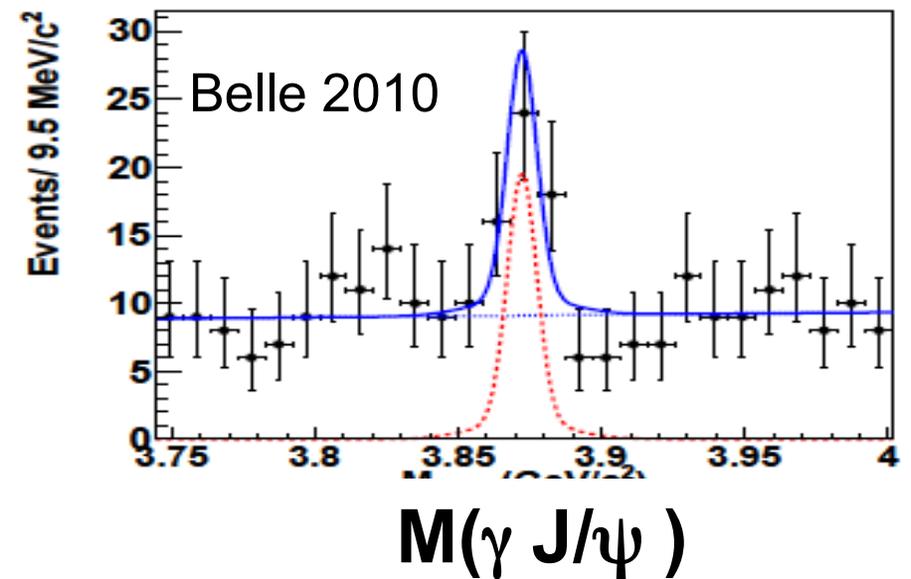
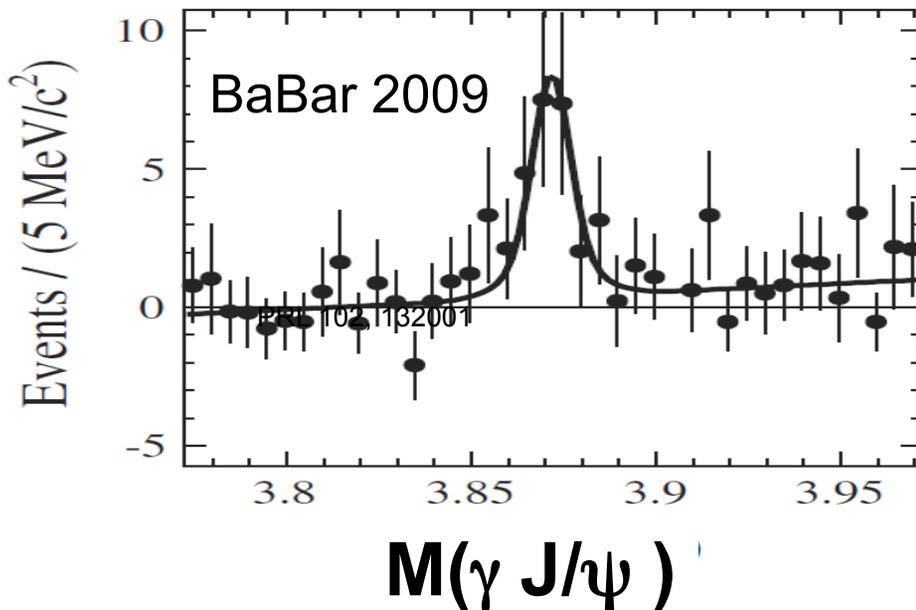
# If not $\psi_{c2}$ , what???

Measure  $J^{PC}$  quantum numbers

1<sup>st</sup> : find other decay modes:

**X(3872)  $\rightarrow$   $\gamma$  J/ $\psi$  is observed:**  $\Gamma_{\pi^+\pi^- J/\psi} = (3.4 \pm 1.2) \Gamma_{\gamma J/\psi}$

**B  $\rightarrow$  K  $\gamma$  J/ $\psi$**

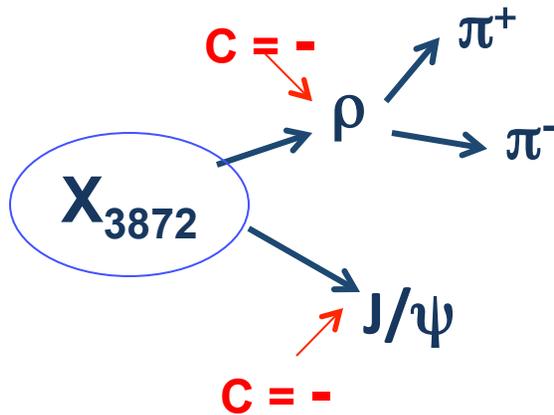


$$C(X_{3872}) = +$$

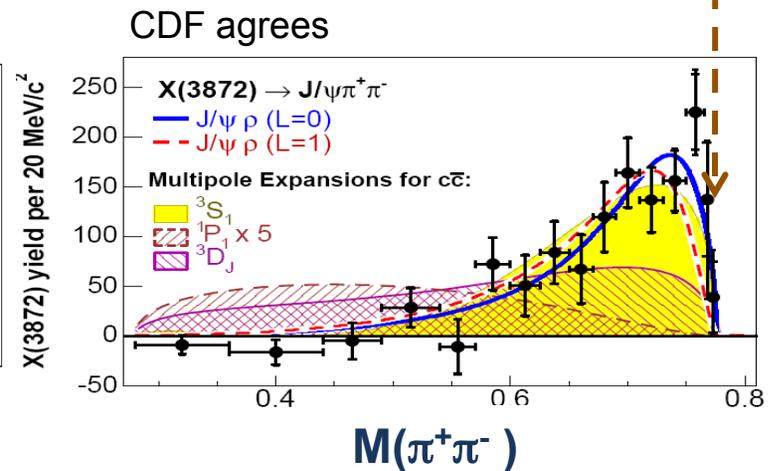
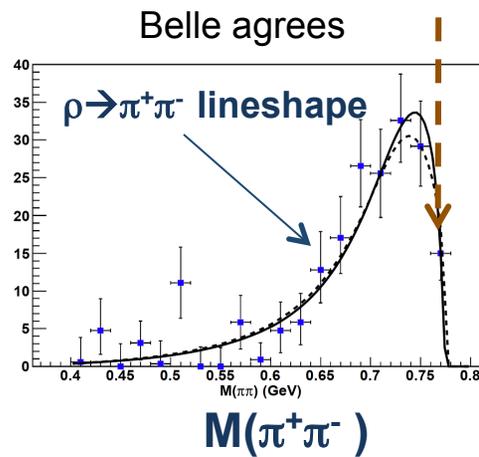


if  $C(X_{3872})$  is + :

$\pi^+\pi^-$  system in  $X_{3872} \rightarrow \pi^+\pi^- J/\psi$  must come from  $\rho \rightarrow \pi^+\pi^-$

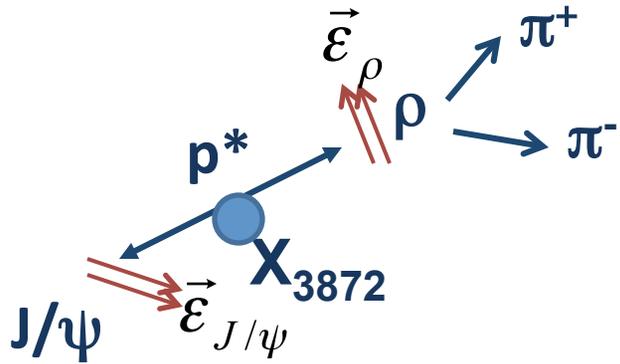


$m_\rho = 775 \text{ MeV}$  is at kinematic limit



# $J^{PC}$ of $X_{3872}$

is it  $0^{-+}$  ??



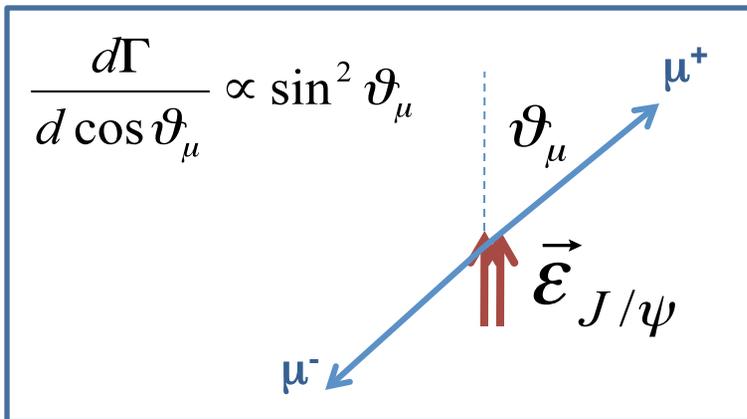
spin polarization  
vectors

$$L_{\text{int}} \propto (\vec{\epsilon}_\rho \times \vec{\epsilon}_{J/\psi}) \cdot \vec{p}^*$$

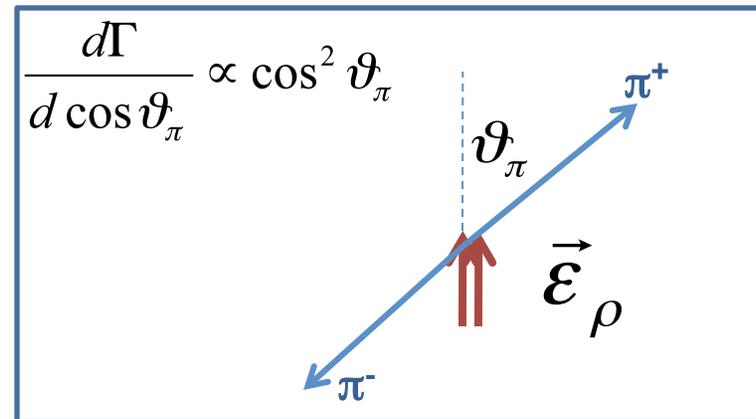
$$\vec{p}^* \perp \vec{\epsilon}_\rho \perp \vec{\epsilon}_{J/\psi}$$

mutually perpendicular

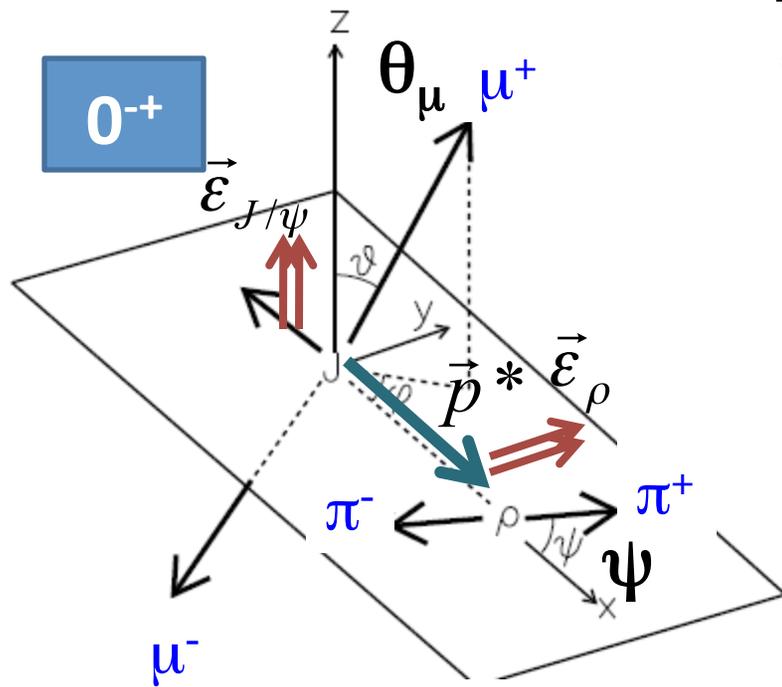
Decays of polarized  $J/\psi$ 's



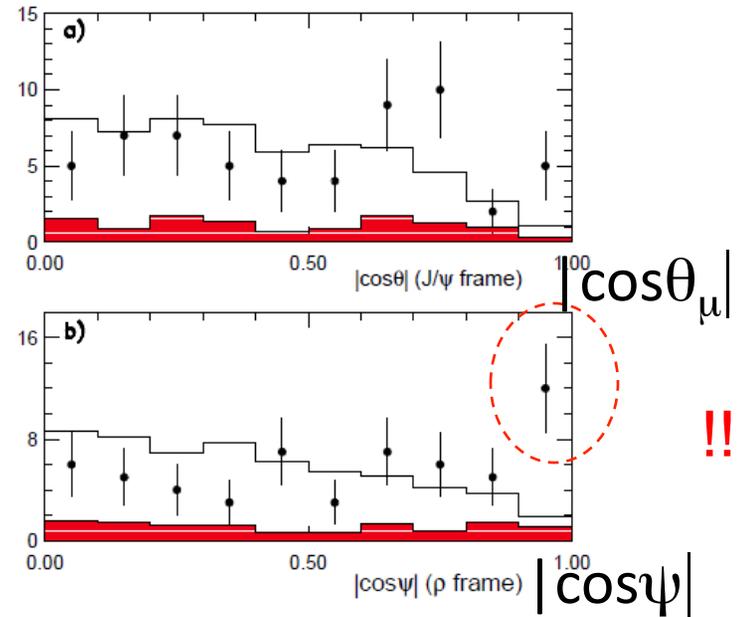
Decays of polarized  $\rho$ 's



# Does the X(3872) $J^{PC} = 0^{-+}$ ??



$$\frac{d\Gamma}{d\cos\psi d\cos\vartheta_\mu} \propto \sin^2\psi \sin^2\vartheta_\mu$$



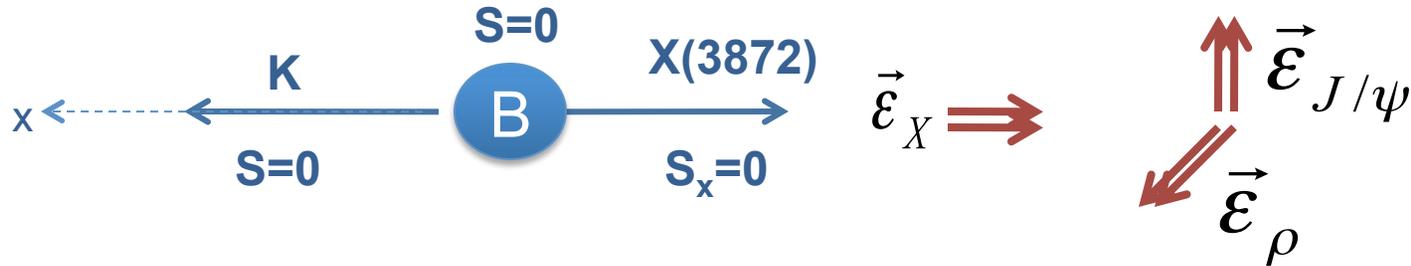
no, the X(3872) cannot be  $0^{-+}$

# Does the $X(3872) J^{PC} = 1^{++} ??$

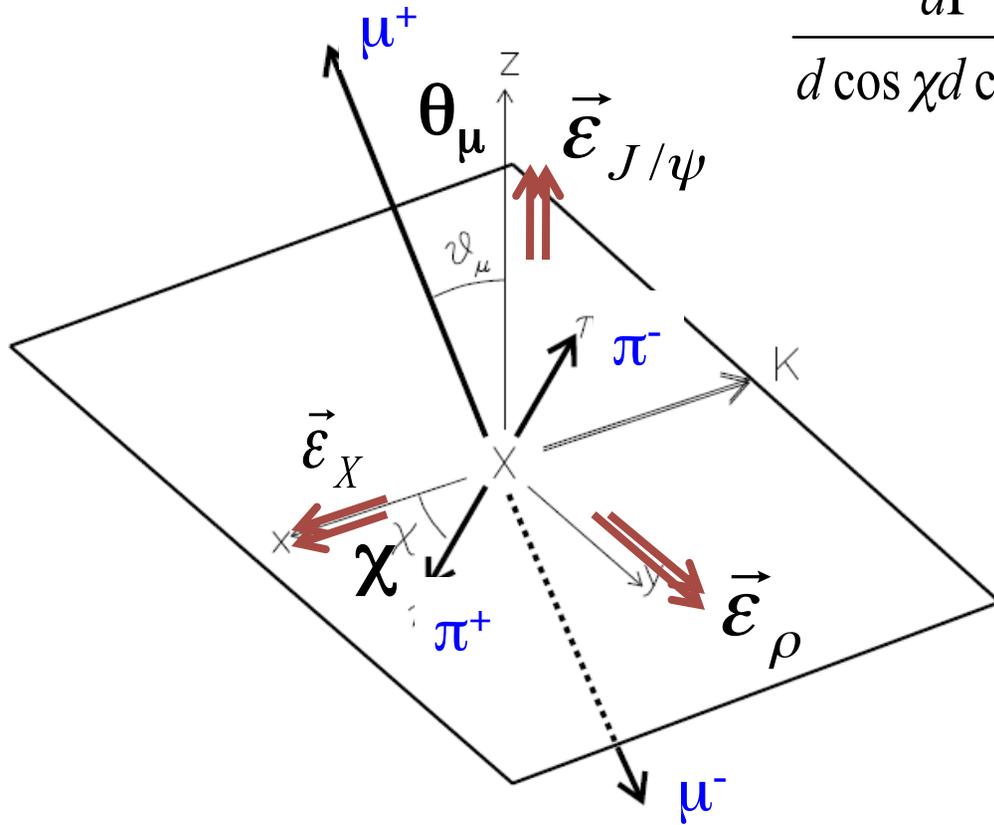
$$L_{\text{int}} \propto (\vec{\epsilon}_\rho \times \vec{\epsilon}_{J/\psi}) \cdot \vec{\epsilon}_X$$


 $\vec{\epsilon}_X \perp \vec{\epsilon}_\rho \perp \vec{\epsilon}_{J/\psi}$

mutually perpendicular

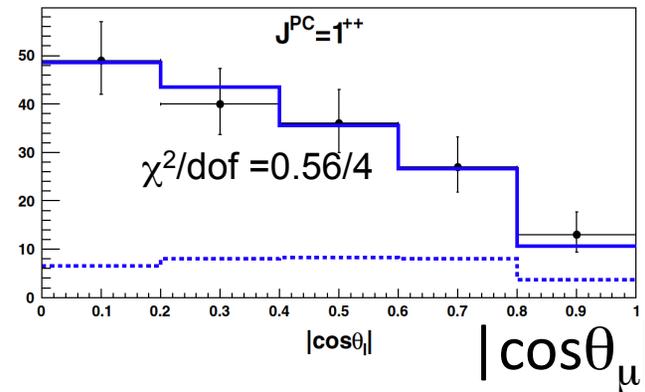
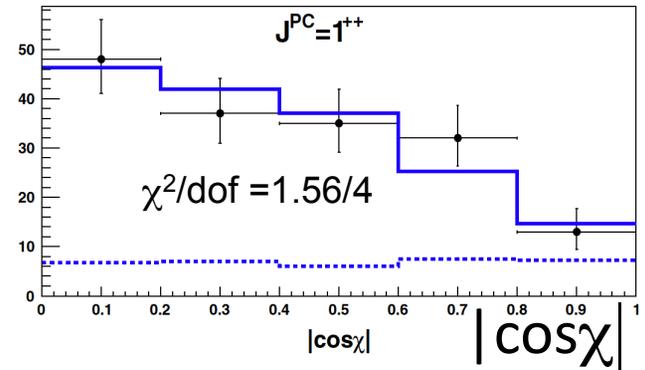


# 1<sup>++</sup> fits well



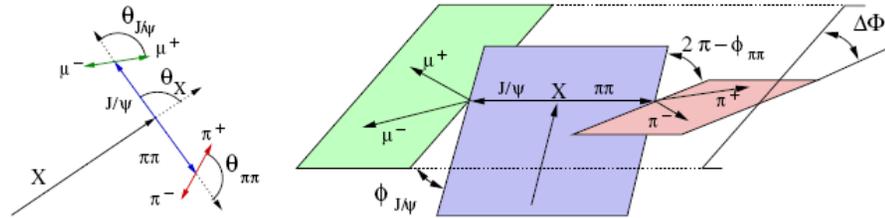
$$\frac{d\Gamma}{d \cos \chi d \cos \vartheta_\mu} \propto \sin^2 \chi \sin^2 \vartheta_\mu$$

Belle Data

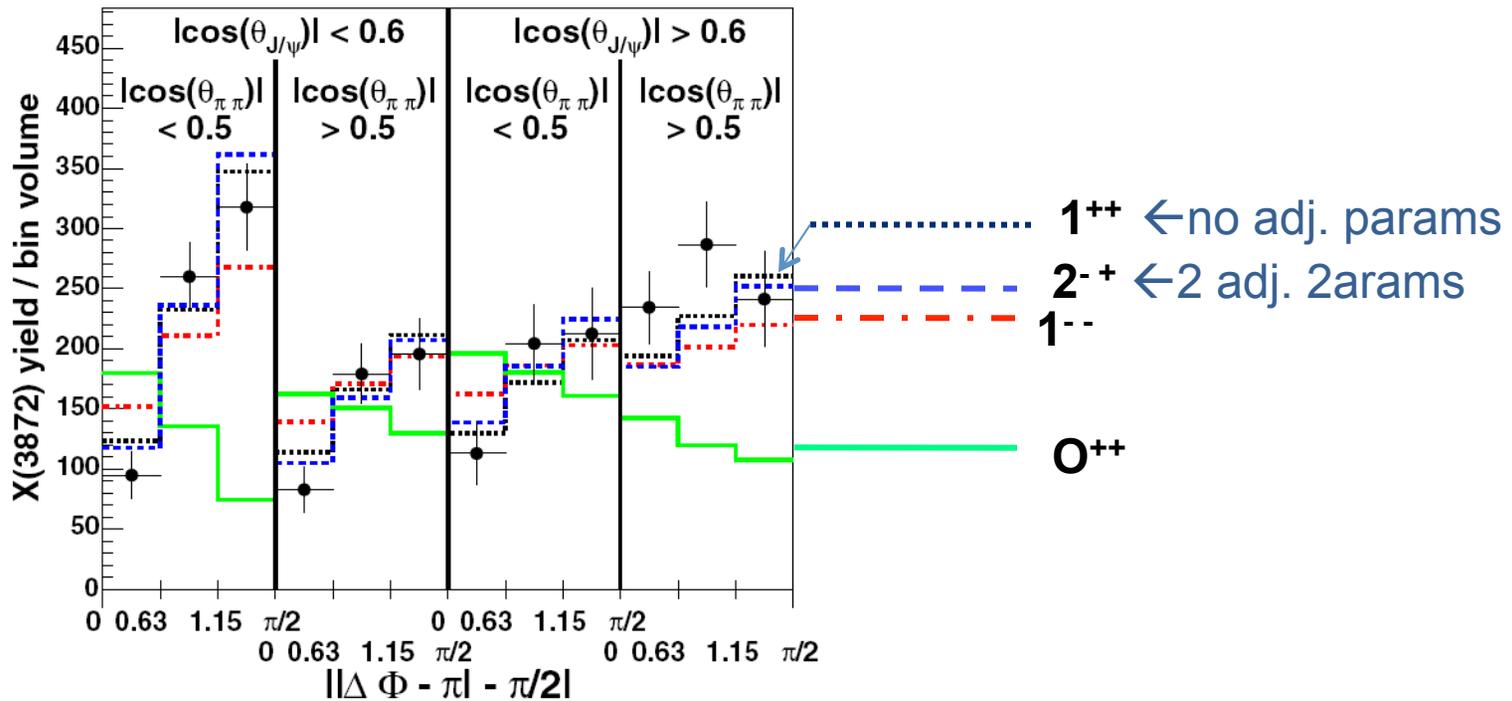


# CDF angular correlation analysis

Only  $1^{++}$  or  $2^{-+}$  fit data



32002



$1^{++}$  fits well with no adjustable parameters

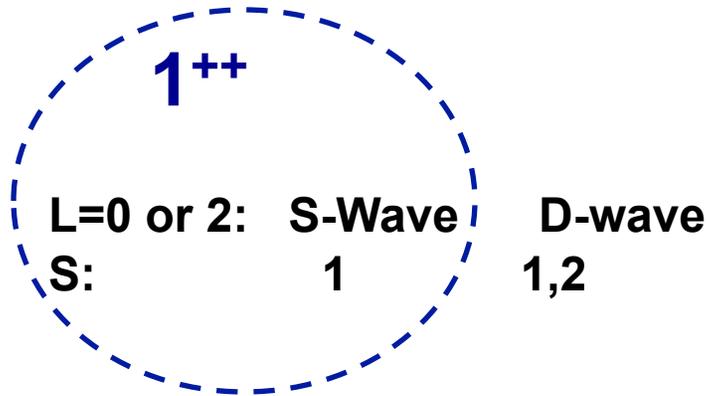
$2^{-+}$  has one complex adjustable parameter

# $J^{PC}$ of the $X(3872) = 1^{++}$ ? ...or $2^{-+}$ ?

Partial Wave basis: 775 MeV

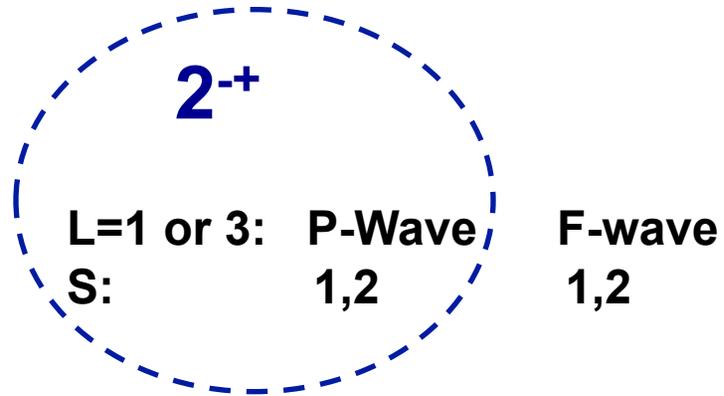
$X(3872) \rightarrow \rho J/\psi$  is right at threshold  $\rightarrow$  neglect higher partial waves

3872 MeV  $\swarrow$   $\nwarrow$  3097 MeV



Only 1 amplitude:  $B_{LS} = B_{01}$

$\rightarrow$  1 free parameter:  
normalization



2 amplitudes:  $B_{LS} = B_{11}$  &  $B_{12}$

$\rightarrow$  3 free parameters  
normalization

$$\alpha = \frac{B_{11}}{B_{12}} = \delta e^{i\phi}$$

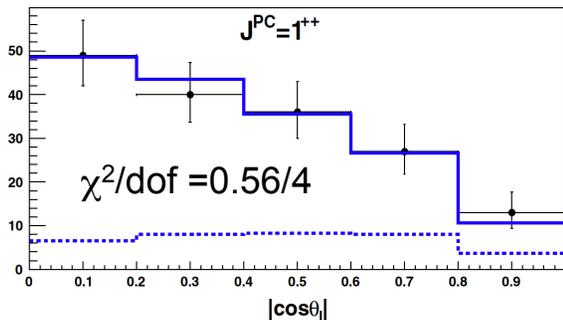
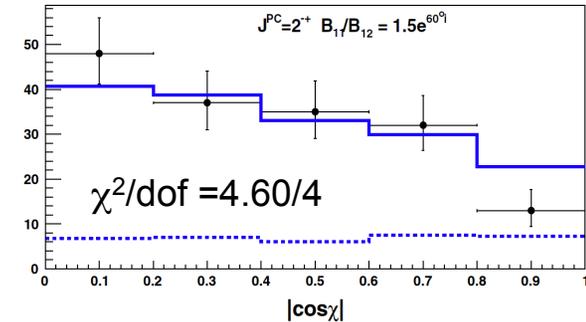
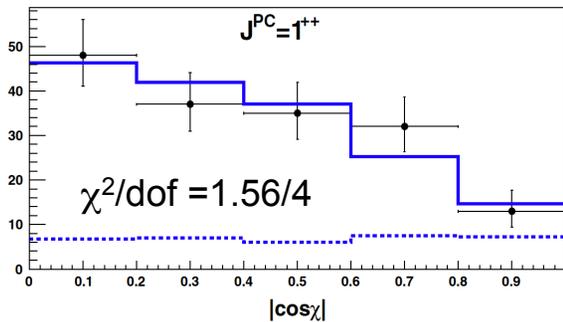
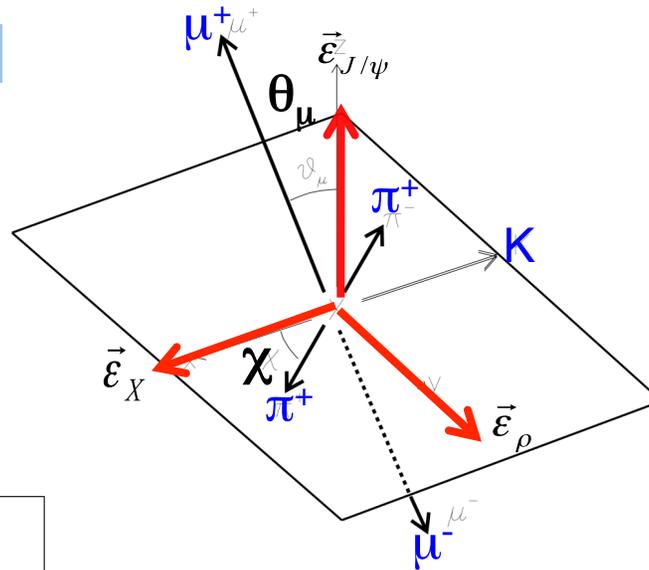
$\leftarrow$  complex  
 Include relative phase  $\phi$

# $J^{PC}$ of the $X(3872)$

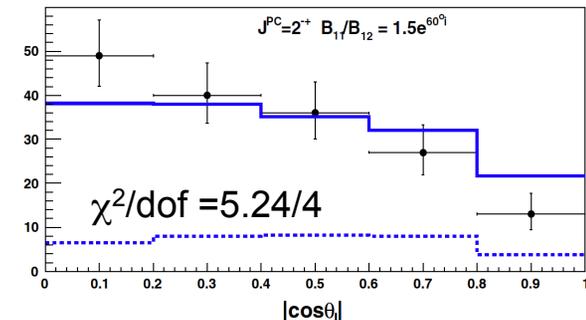
J. Rosner PRD 70, 092023 (2004)

$$\mathcal{L}_{int} \propto \vec{\epsilon}_X \cdot \vec{\epsilon}_{J/\psi} \times \vec{\epsilon}_\rho$$

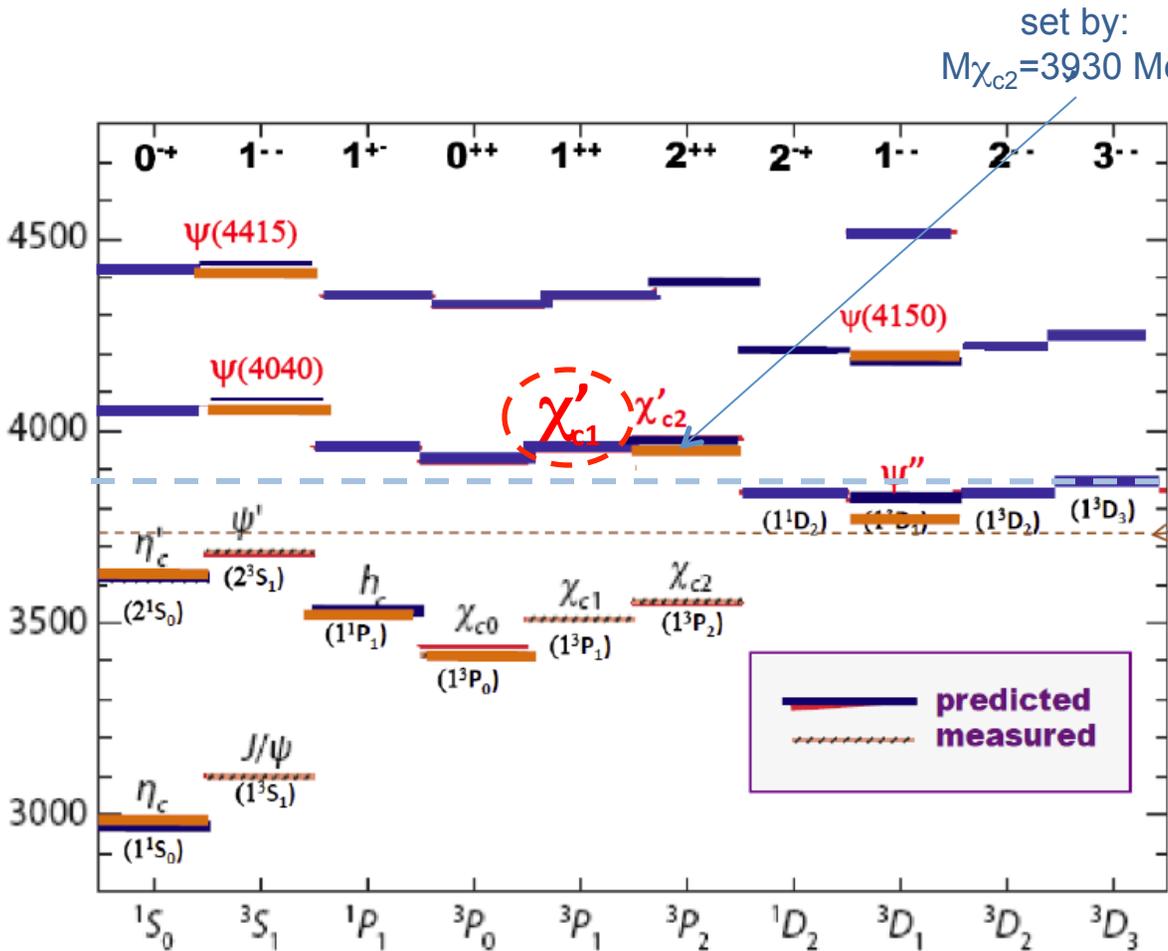
$$\frac{d\Gamma(1^{++})}{d\cos\chi d\cos\vartheta_\mu} \propto \sin^2\chi \sin^2\vartheta_\mu$$



1<sup>++</sup> fits data well with no free parameters. 2<sup>-+</sup> has a free complex parameter; one value gives an acceptable fit



# Is there a $1^{++} c\bar{c}$ state for the $X_{3872}$ ?



- Mass is too low?
  - 3872 vs 3905 MeV

## theory

- $\Gamma(\chi'_{c1} \rightarrow \gamma \psi') \sim 180 \text{ keV}$
- $\Gamma(\chi'_{c1} \rightarrow \gamma J/\psi) \sim 14 \text{ keV}$

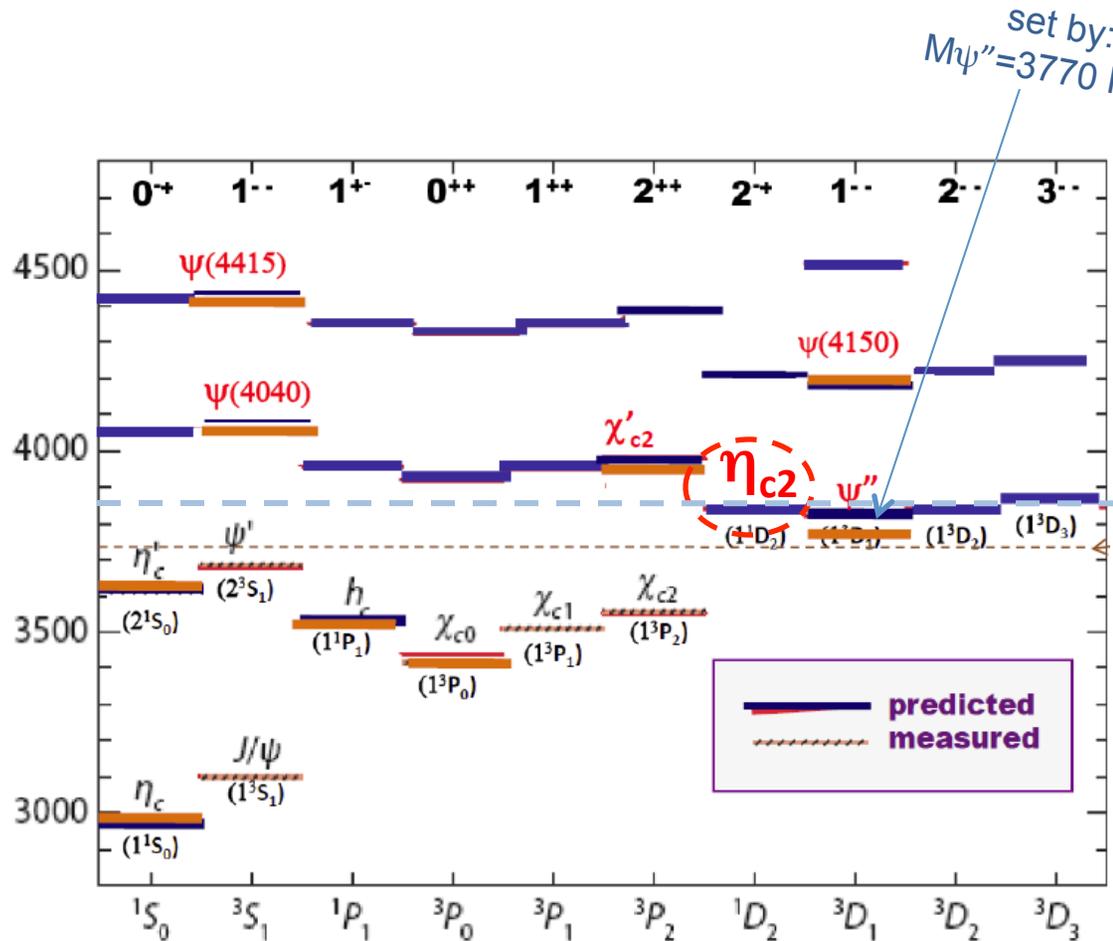
T. Barnes *et al* PRD 72, 054026

$\rightarrow \Gamma(\gamma \psi') / \Gamma(\gamma J/\psi) \gg 1$   
 measurement:  $< 2$

- $\Gamma_{\pi^+\pi^- J/\psi} = (3.4 \pm 1.2) \Gamma_{\gamma J/\psi} \sim 45 \text{ keV}$

$\sim 100x$  expectations for an  
 Isospin-violating decay  
*c.f.:*  $\Gamma(\psi' \rightarrow \pi^0 J/\psi) \approx 0.4 \text{ keV}$

# Is there a $2^{-+}$ $c\bar{c}$ state for the $X_{3872}$ ?



• Mass is too high?

• 3872 vs 3837 MeV

T.J. Burns *et al* arXiv:1008.0018

•  $\Gamma(\eta_{c2} \rightarrow \gamma \psi')$   $\sim 0.4$  keV

•  $\Gamma(\eta_{c2} \rightarrow \gamma J/\psi)$   $\sim 9$  keV

Y. Jia *et al* arXiv:1007.4541

•  $\Gamma_{\pi^+\pi^- J/\psi} = (3.4 \pm 1.2) \Gamma_{\gamma J/\psi} \sim 30$  keV

• huge for Ispin-violating decay  
c.f.:  $\Gamma(\psi' \rightarrow \pi^0 J/\psi) \approx 0.4$  keV

•  $B \rightarrow K \eta_{c2}$  violates factorization

•  $B \rightarrow K h_c$  not seen

•  $B \rightarrow K \chi_{c2}$  barely seen

•  $\eta_{c2} \rightarrow DD^*$  expected to be tiny

Y. Kalasnakova *et al* arXiv:1008.2895

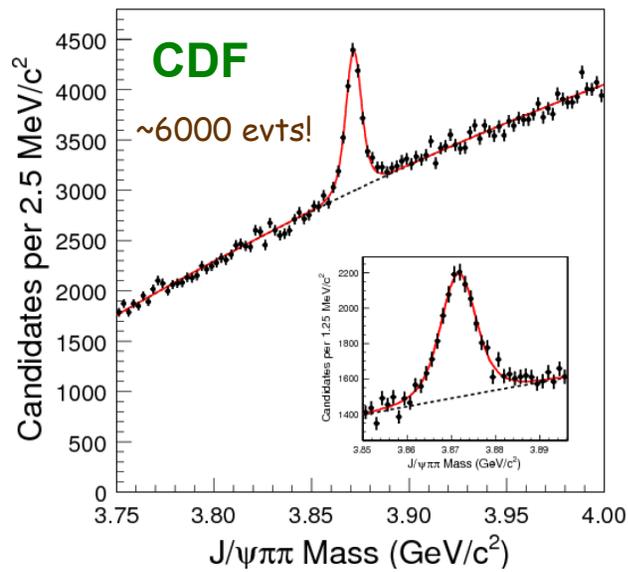
expt:

$$\Gamma(X \rightarrow DD^*) / \Gamma(X \rightarrow \pi\pi J/\psi) = 9.5 \pm 3.1$$

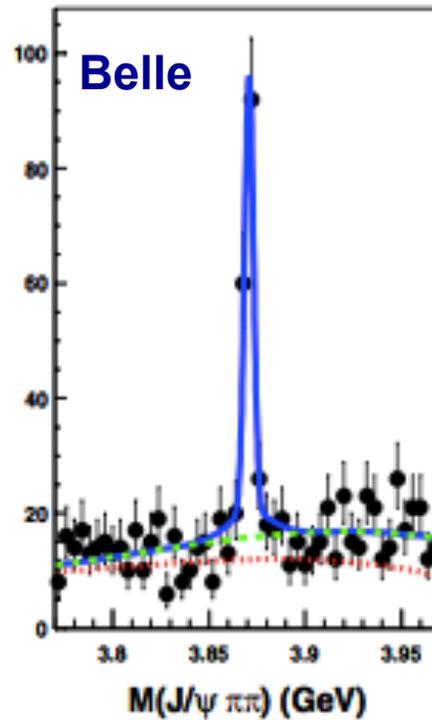
If not charmonium, what is it?

# $\chi(3872) \rightarrow \pi^+ \pi^- J/\psi$ Mass

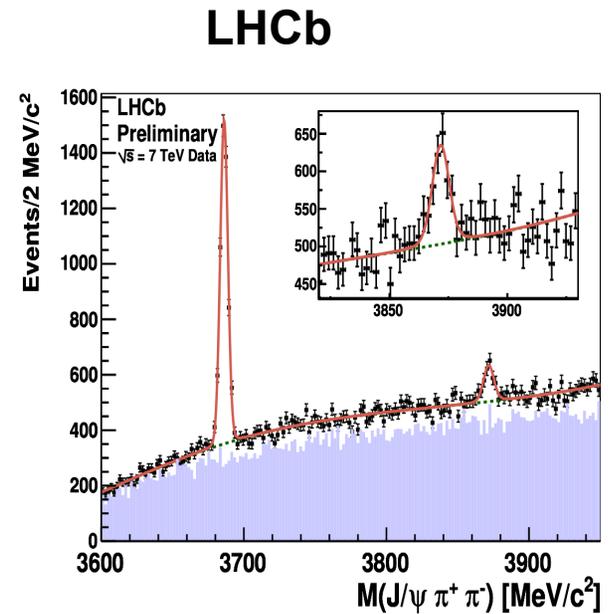
recent results



$$M_X = 3871.61 \pm 0.16 \pm 0.19 \text{ MeV}$$



$$M_X = 3871.85 \pm 0.27 \pm 0.19 \text{ MeV}$$

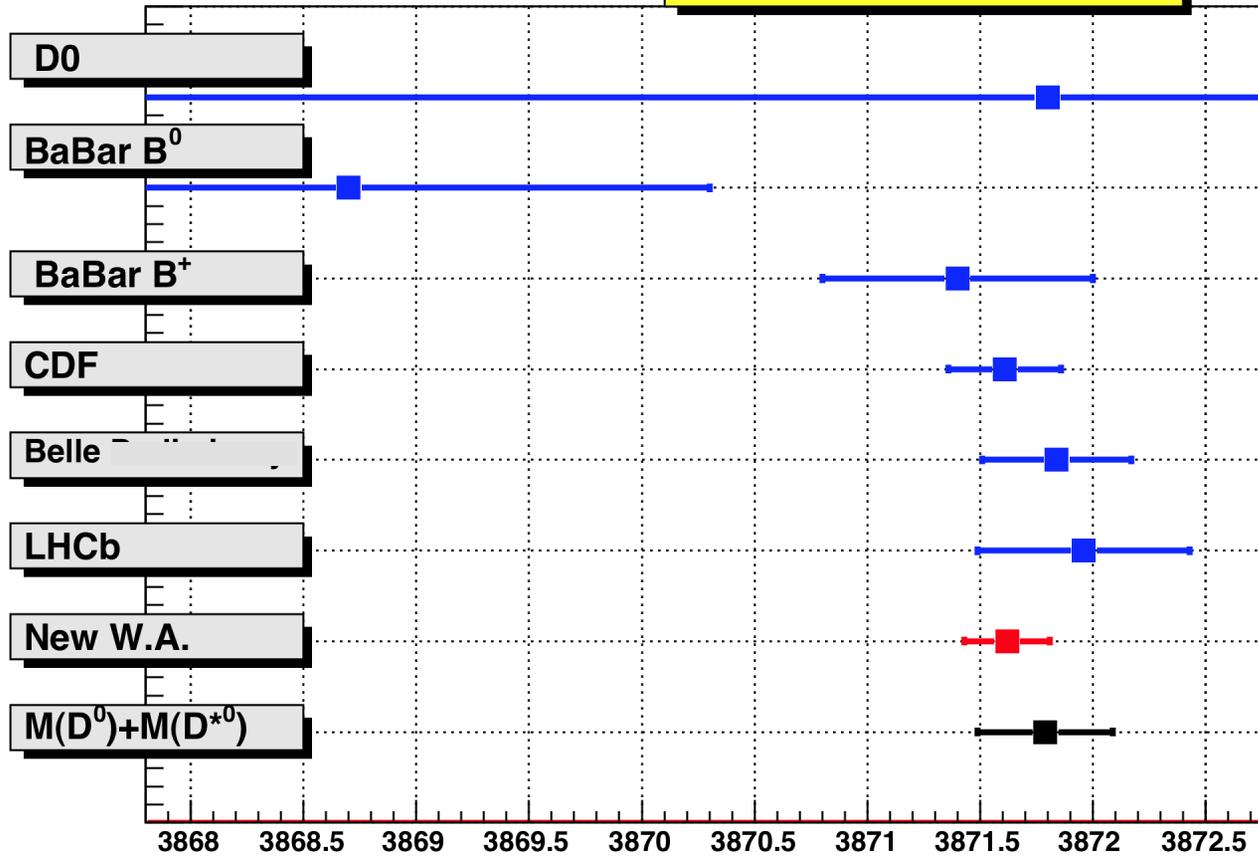


$$M_X = 3871.96 \pm 0.46 \pm 0.10 \text{ MeV}$$

# X(3872) mass (in $\pi^+\pi^-J/\psi$ channel only)

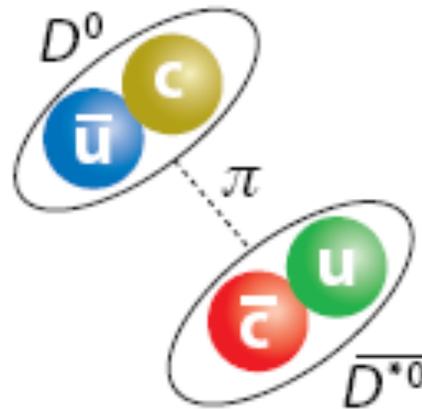
X(3872) mass measurements

New W.A. 3871.67  $\pm$  0.17



$$M_{X(3872)} - (M_{D^0} + M_{D^{*0}}) = -0.12 \pm 0.35 \text{ MeV}$$

# $D^0\bar{D}^{*0}$ molecule?



$D^0\text{-}\bar{D}^{*0}$  "Binding Energy" small  
 $\Delta m = -0.12 \pm 0.35 \text{ MeV}$   
...coincidence??

$D^0\text{-}\bar{D}^{*0}$  "molecule"

an "old" idea

# De Rujula, Glashow & Georgi (1976)

PRL 38, 317 (1976)

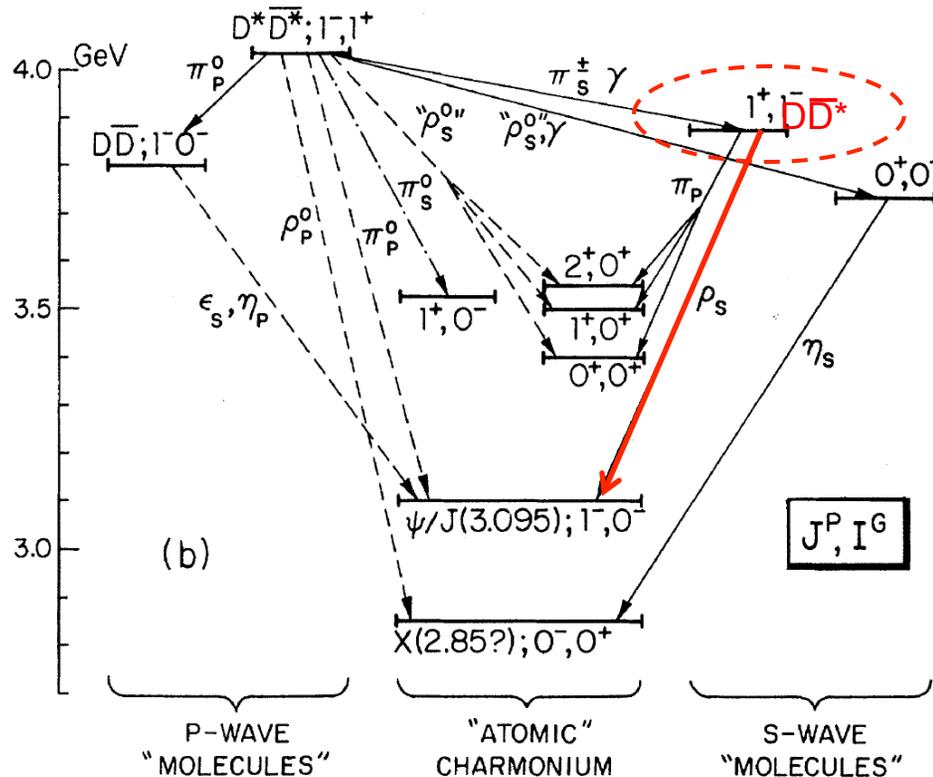
## Molecular Charmonium: A New Spectroscopy?\*

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.



**predictions:**

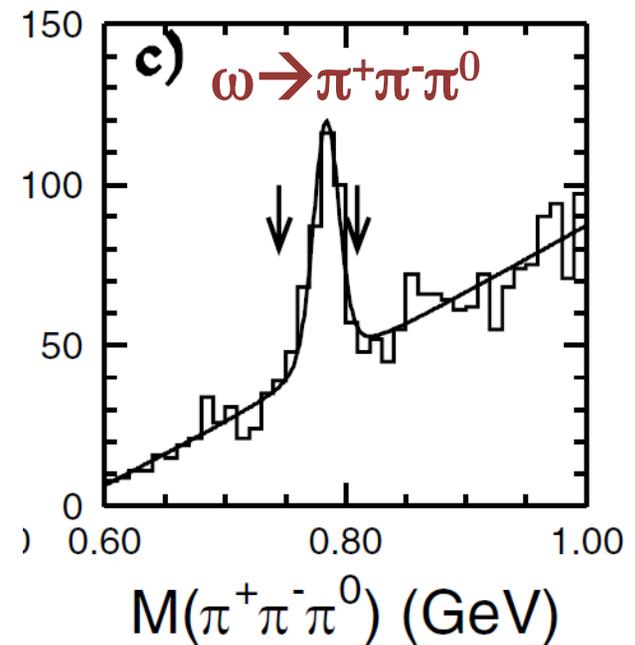
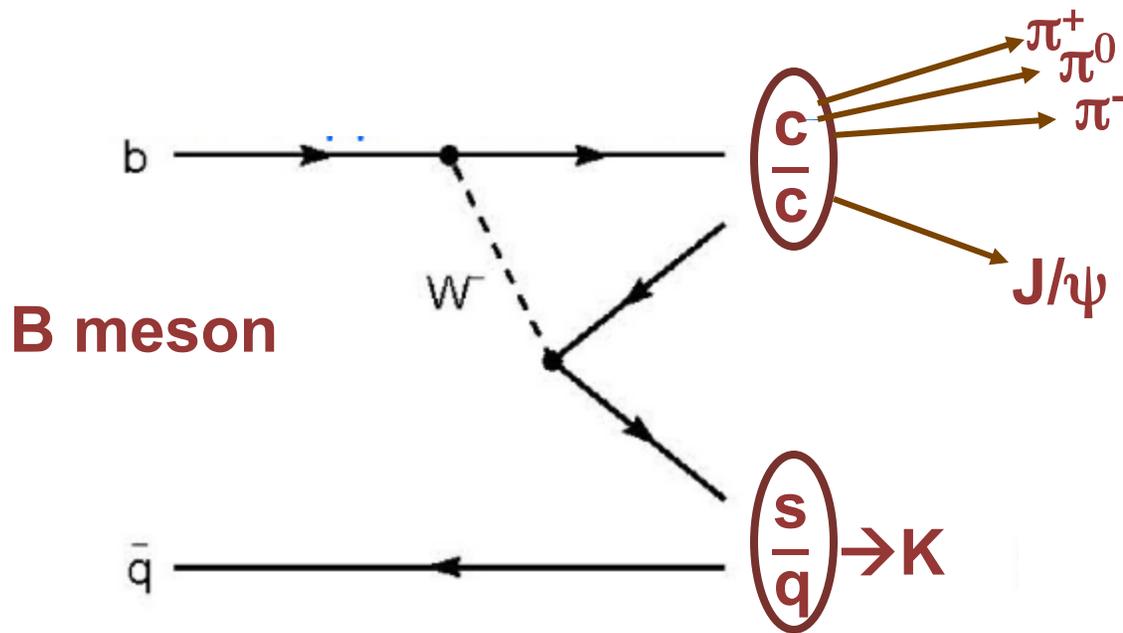
$J^{PC} = 1^{++}$

$(D\bar{D}^*)_{mol} \rightarrow \rho J/\psi$   
 $\searrow$   
 $\pi^+ \pi^-$

Also: L. Okun & M. Voloshin  
 JETP Lett. **23**, 333 (1974)

Search for other states

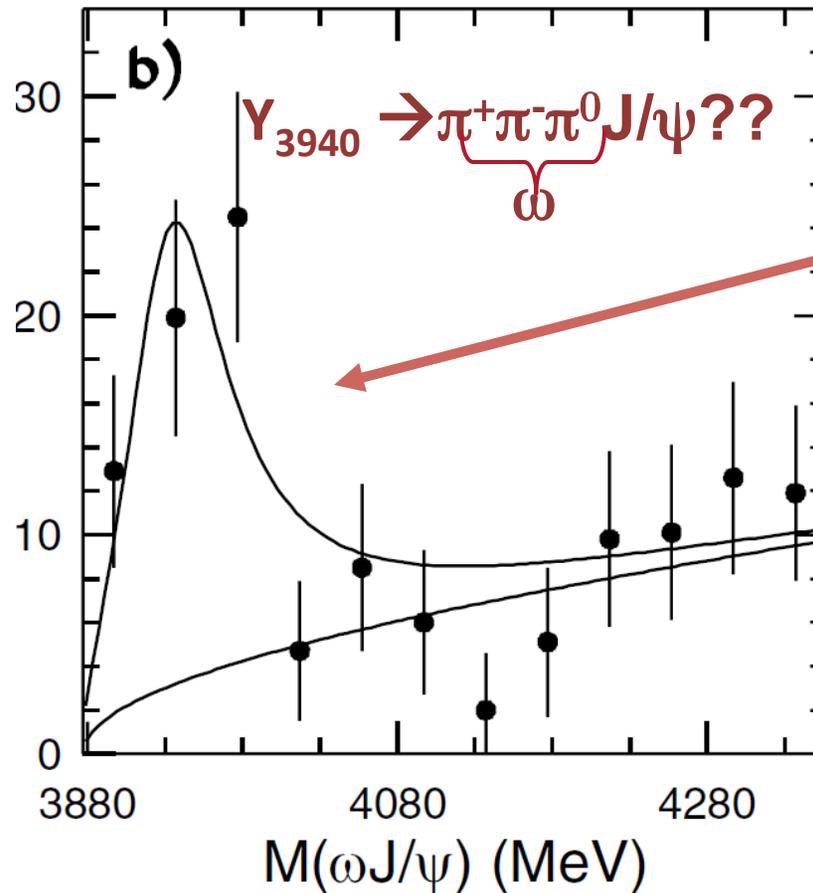
# Search for other states in $B \rightarrow K \pi^+ \pi^- \pi^0 J/\psi$ decays



# M( $\omega$ J/ $\psi$ )

unexpected peak at 3940 MeV

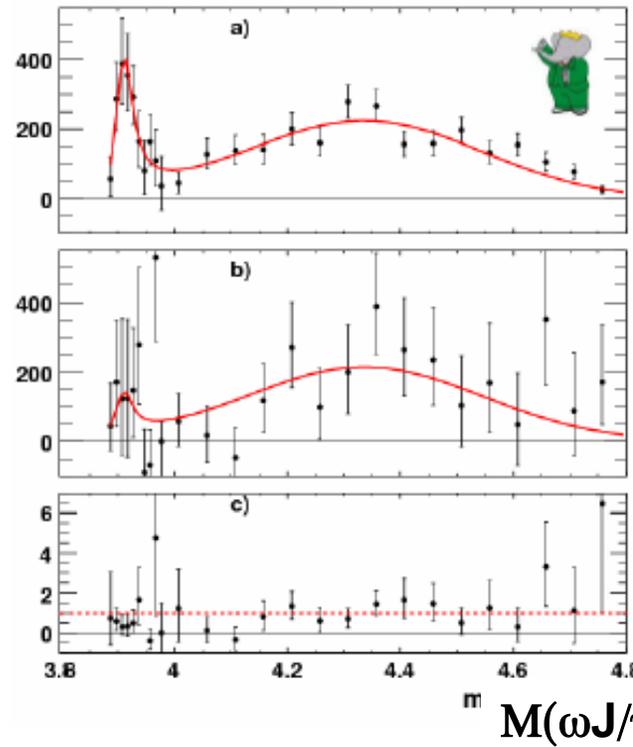
**Y(3940)**



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

# $\Upsilon(3940)$ confirmed

BaBar PRL 101, 082001



$B^\pm \rightarrow K^\pm \omega J/\psi$

$B^0 \rightarrow K_s \omega J/\psi$

ratio

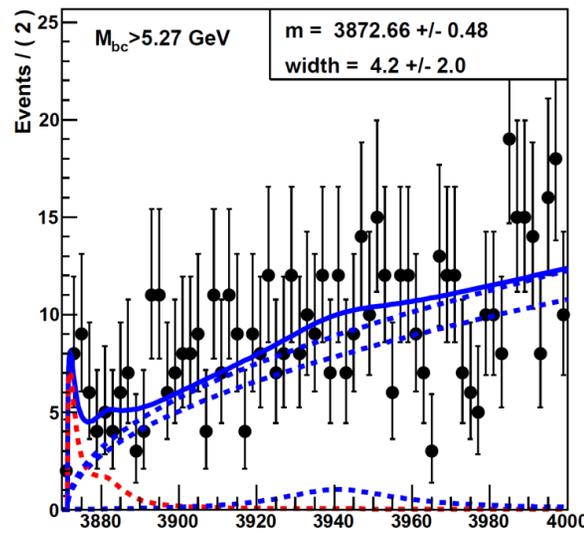
	Mass (MeV)	$\Gamma$ (MeV)
Belle 253 fb <sup>-1</sup>	$3943 \pm 11(stat) \pm 13(syst)$	$87 \pm 22(stat) \pm 26(syst)$
BaBar 350 fb <sup>-1</sup>	$3914.3^{+3.8}_{-3.4}(stat)^{+1.6}_{-1.6}(syst)$	$33^{+12}_{-8}(stat)^{+0.6}_{-0.6}(syst)$

Some discrepancy in  $M$  &  $\Gamma$ ; general features agree

# Does $Y(3940) \rightarrow D\bar{D}^*$ ?

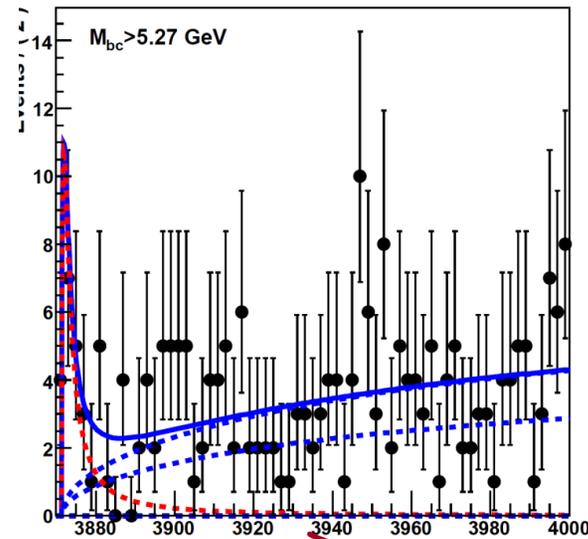
$B \rightarrow K D\bar{D}^*$

Belle: PRD 81, 031103



3940 MeV

$M(D\bar{D}^*)$



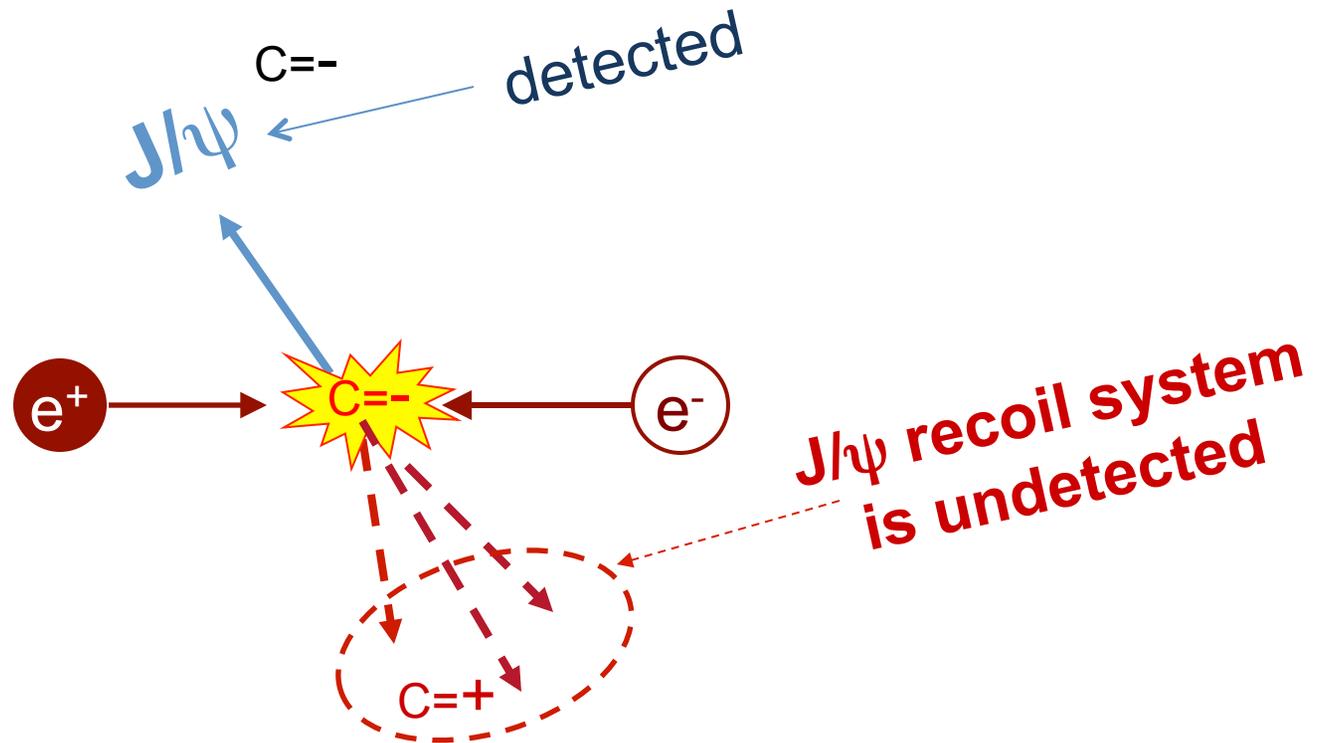
3940 MeV

$M(D\bar{D}^*)$

**No signal:**  $\frac{\mathcal{B}(Y(3940) \rightarrow \omega J/\psi)}{\mathcal{B}(Y(3940) \rightarrow D^{*0}\bar{D}^0)} > 0.75$

3940 MeV is well above  $D\bar{D}$  &  $D\bar{D}^*$  threshold

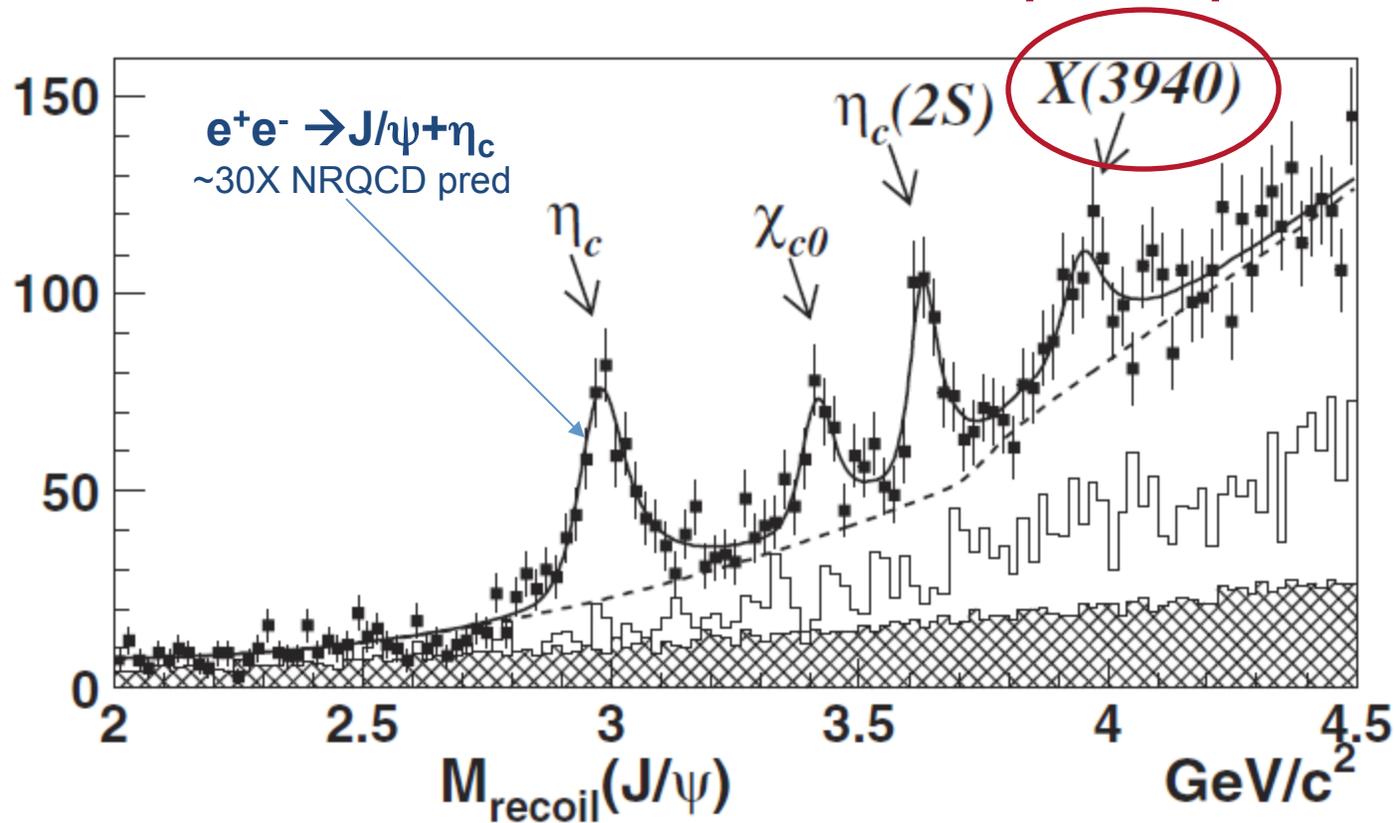
# Study $e^+e^- \rightarrow J/\psi + \text{anything}$



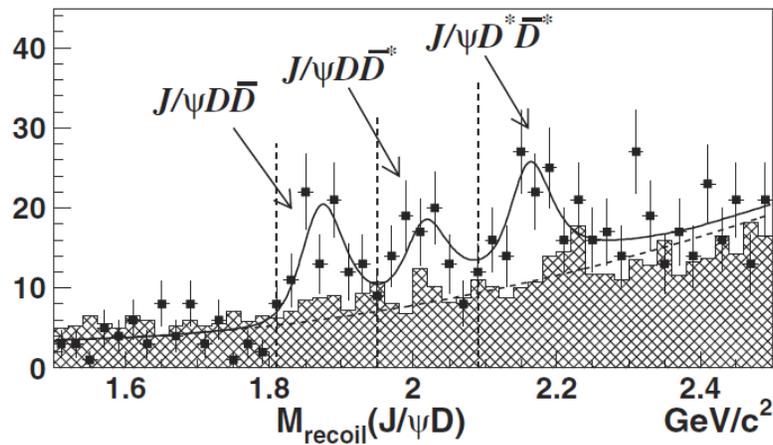
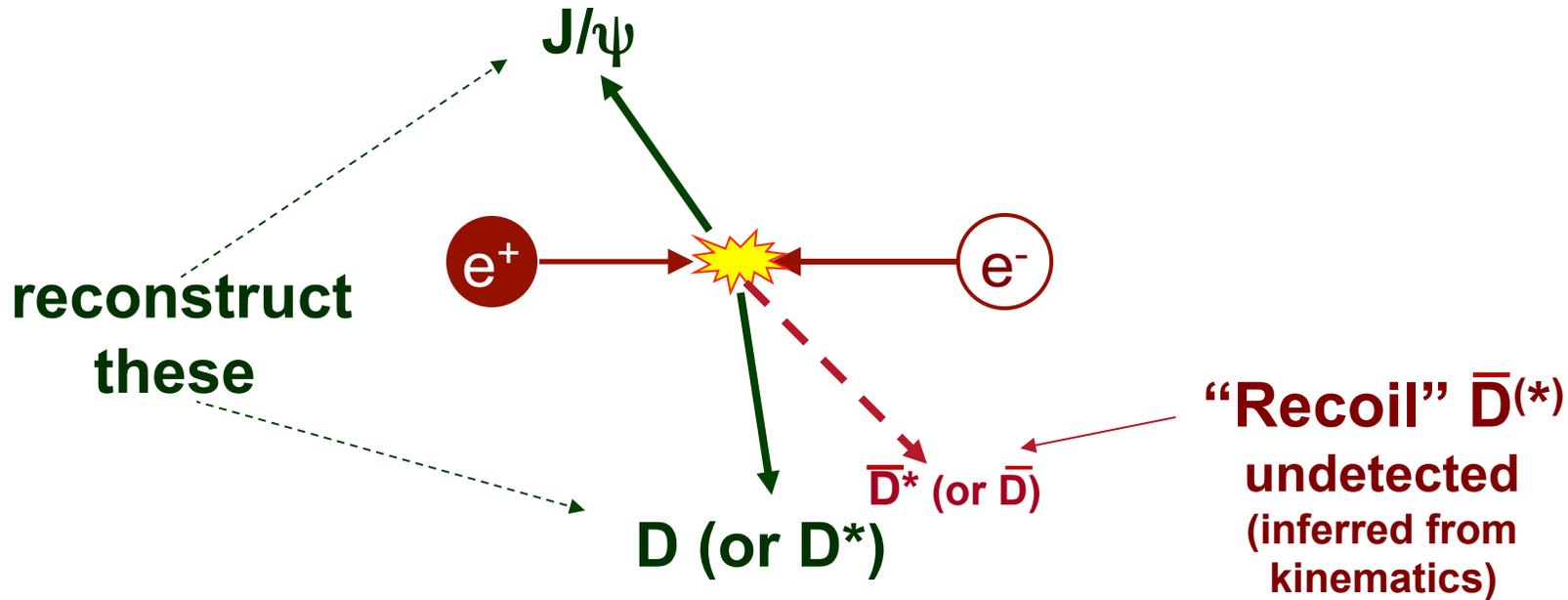
**Recoil Mass:** 
$$M_{recoil} = \sqrt{(E_{cm} - E_{J/\psi})^2 - (-\vec{p}_{J/\psi})^2}$$

# $\sigma(e^+e^- \rightarrow J/\psi + c\bar{c})$ unexpectedly big

Unexpected peak at 3940 MeV



Use “partial reconstruction” to  
study  $X_{3940} \rightarrow D\bar{D}$  or  $D\bar{D}^*$

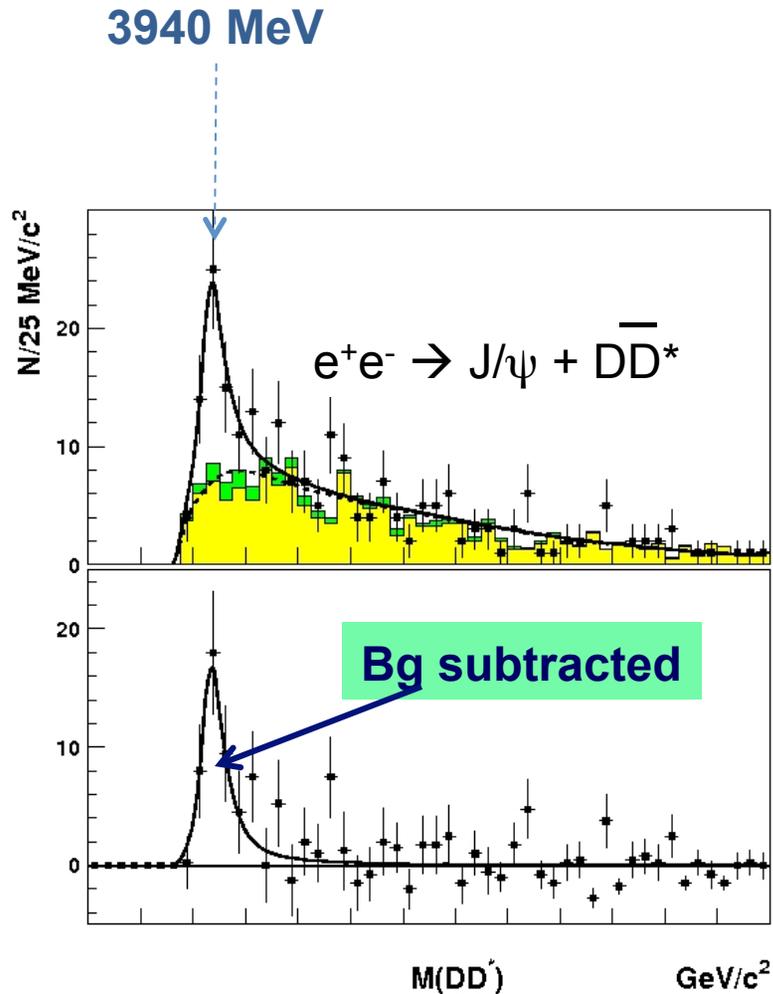


$$M_{\bar{D}^{(*)}} = \sqrt{(E_{cm} - E_{J/\psi} - E_{D^{(*)}})^2 - (\vec{p}_{J/\psi} + \vec{p}_{D^{(*)}})^2}$$

$$E_{recoil} \quad -\vec{p}_{recoil}$$

$$p_{\bar{D}^{(*)}} = (E_{recoil}, \vec{p}_{recoil})$$

$B_f(X(3940) \rightarrow D\bar{D}^*)$  is large



$$M = 3942^{+7}_{-6} \pm 6 \text{ MeV}$$

$$\Gamma_{\text{tot}} = 37^{+26}_{-15} \pm 12 \text{ MeV}$$

$$N_{\text{sig}} = 52^{+24}_{-16} \pm 11 \text{ evts}$$

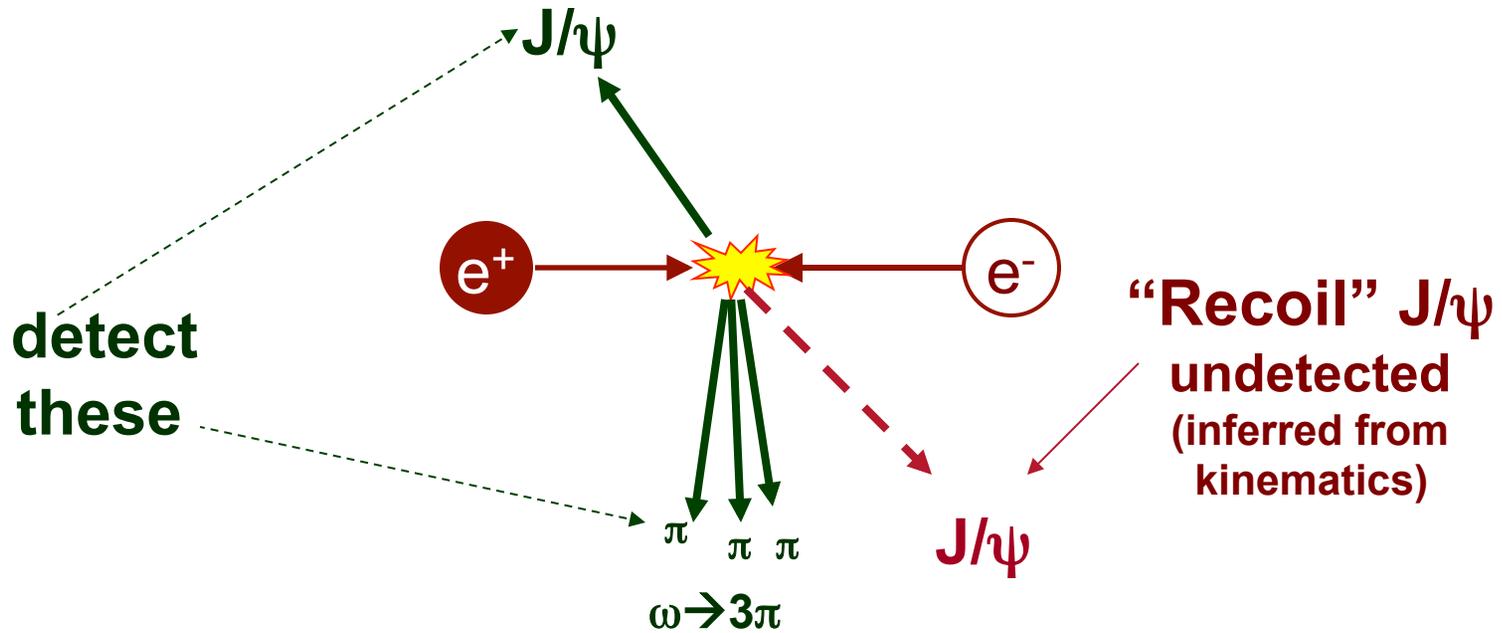
arXiv:0708.3812

PRL 98, 802001 (2007)

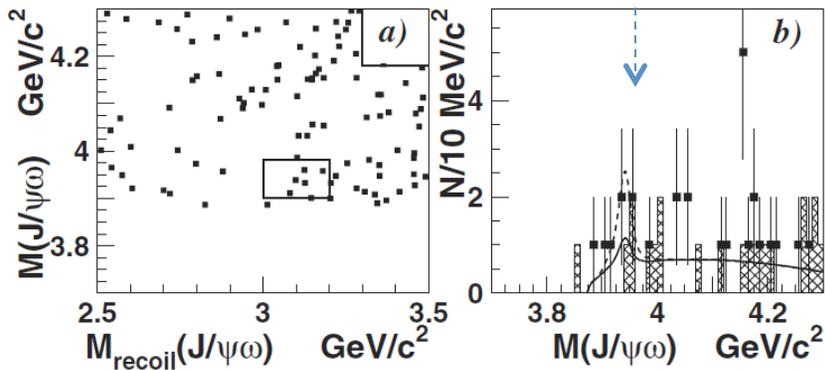
$$B_{>2}(X(3940) \rightarrow D^*\bar{D}) = (96^{+45}_{-32} \pm 22)\%$$

( $>45\%$  at 90% C.L.)

# Use “partial reconstruction” to search for $X(3940) \rightarrow \omega J/\psi$



3940 MeV

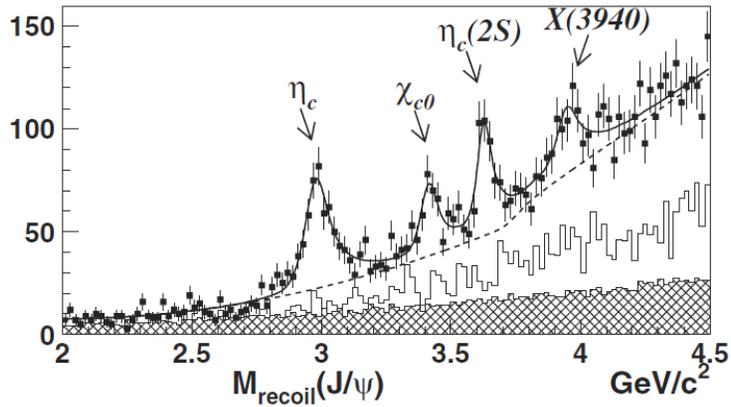


**no signal:**

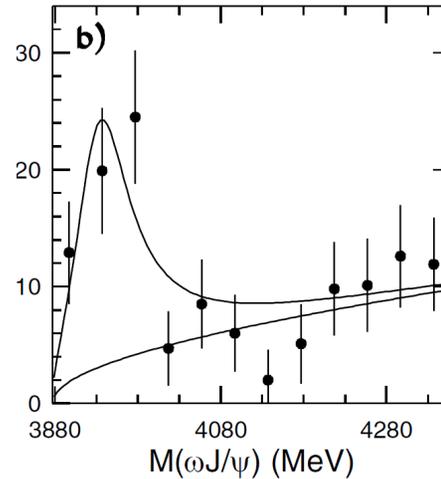
$$\mathcal{B}(X(3940) \rightarrow J/\psi\omega) < 26\% \quad \text{at } 90\% \text{ C.L.}$$

# $X_{3940}$ & $Y_{3940}$ are not the same

from:



from:

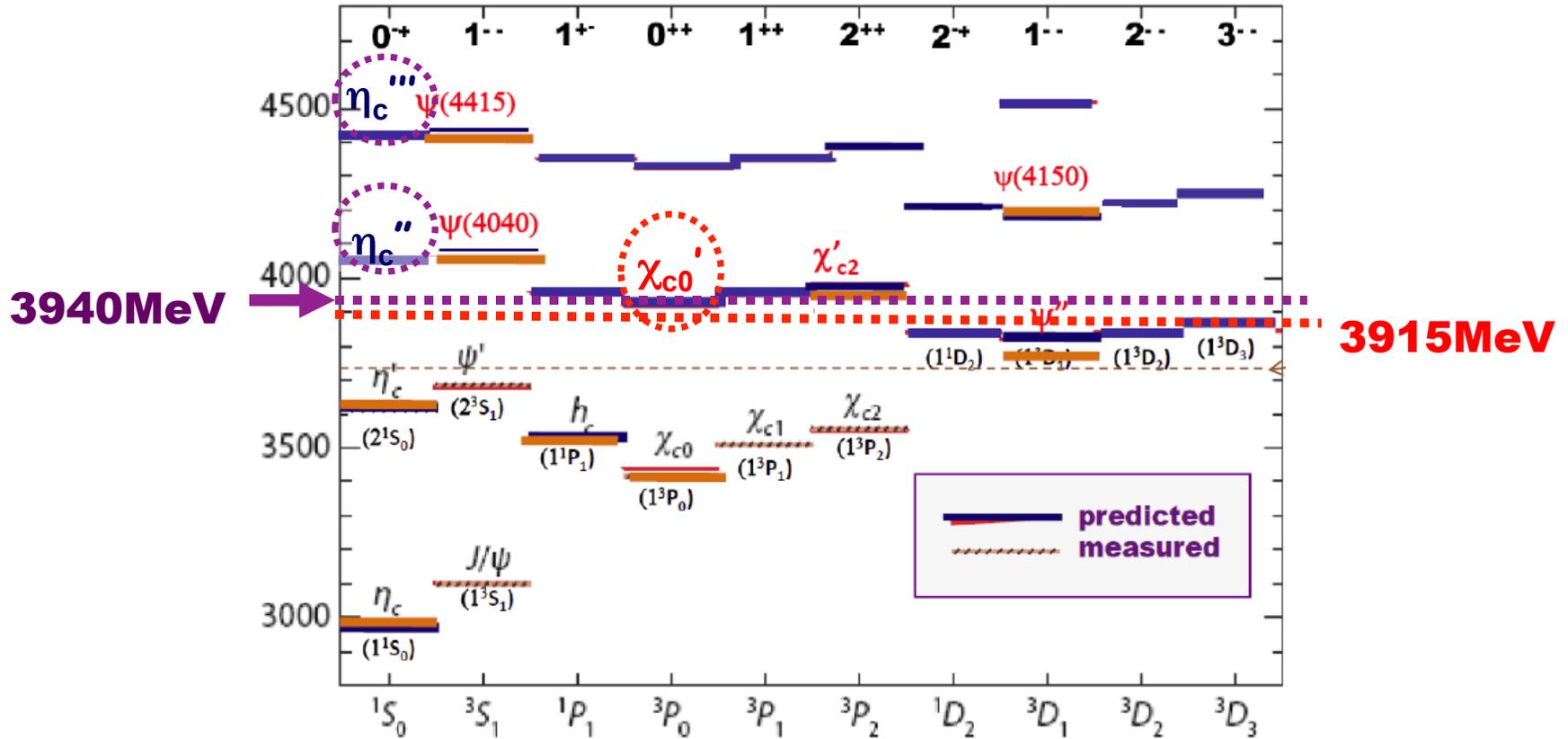


$$\frac{\mathcal{B}(X(3940) \rightarrow \omega J/\psi)}{\mathcal{B}(X(3940) \rightarrow D^{*0} \bar{D}^0)} < 0.6$$

$$\frac{\mathcal{B}(Y(3940) \rightarrow \omega J/\psi)}{\mathcal{B}(Y(3940) \rightarrow D^{*0} \bar{D}^0)} > 0.75$$

contradiction

# $c\bar{c}$ assignments for X(3940), Y(3915) & X(4160)?

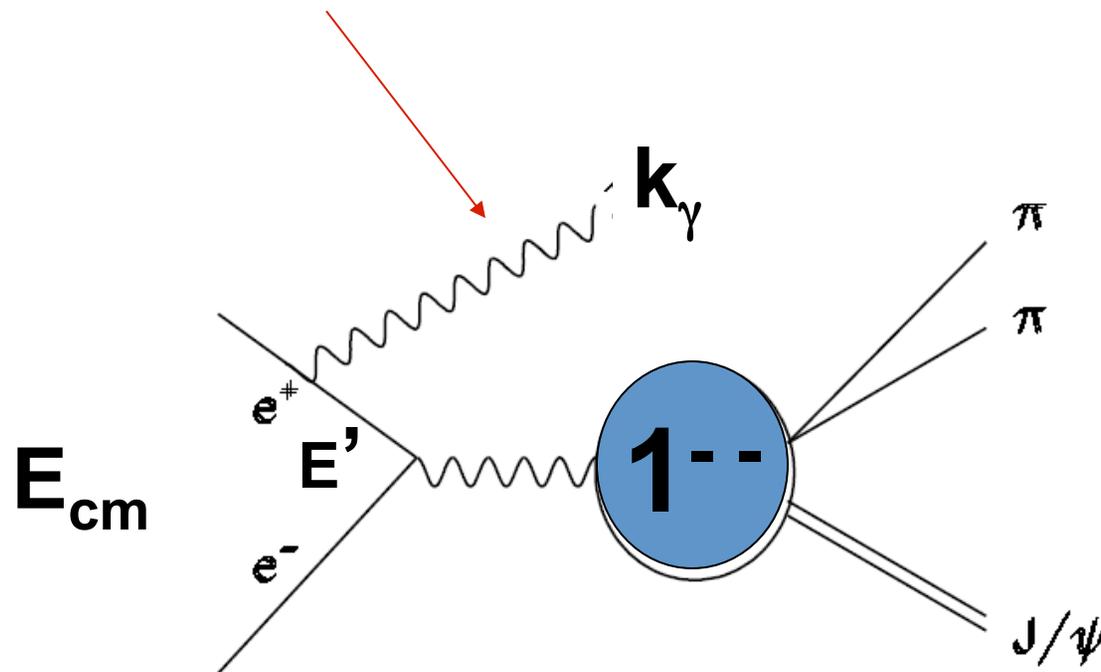


•  $Y(3915) = \chi_{c0}'$ ?  $\leftarrow \Gamma(\omega J/\psi)$  too large?

•  $X(3940) = \eta_c'''$ ?  $\leftarrow$  mass too low?

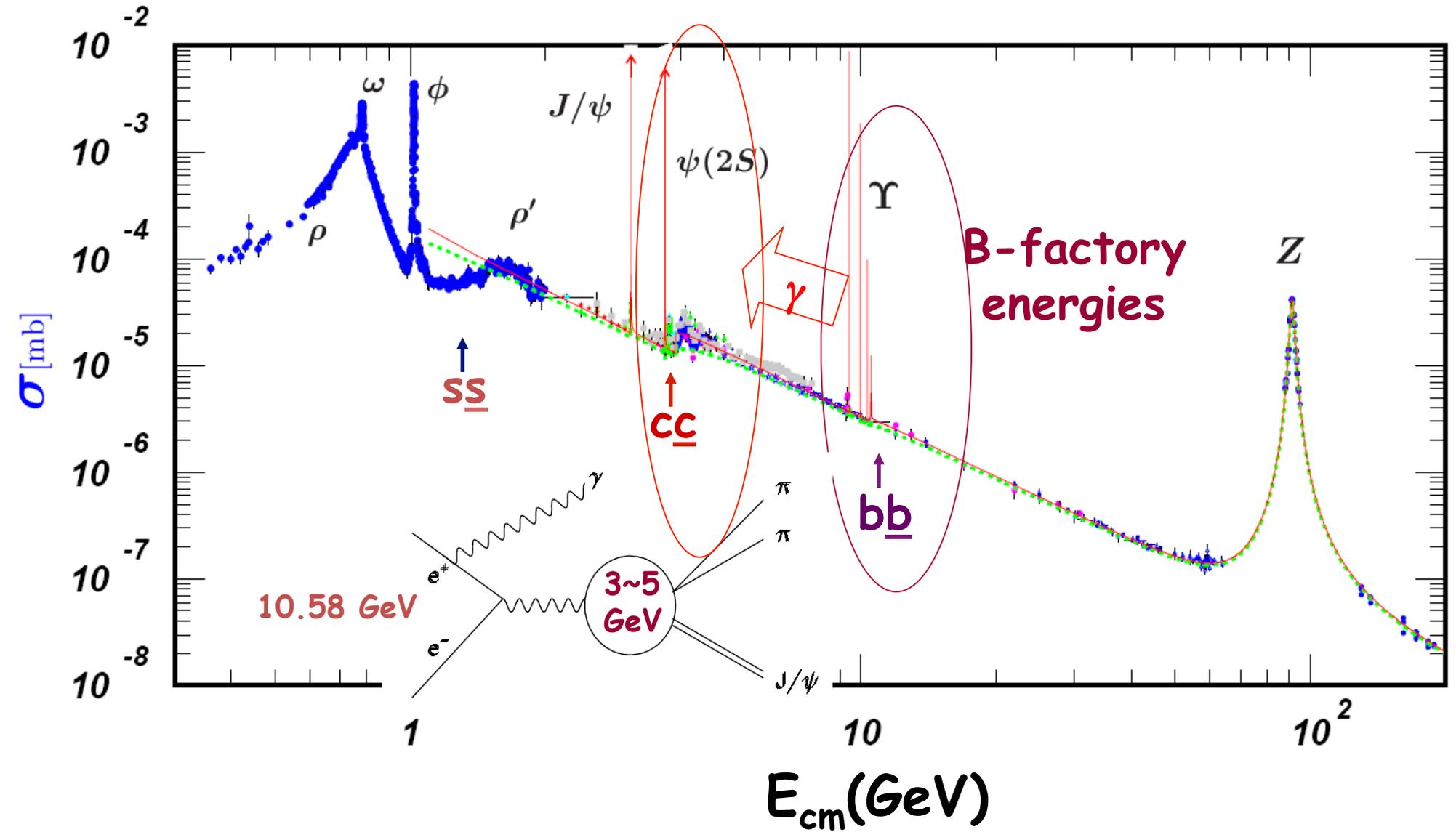
# $1^{--}$ states seen via “radiative return”

“initial-state-radiation” photon:  $\gamma_{ISR}$



if  $k_\gamma = 3.8 \sim 4.5$  GeV,  $E' = 3 \sim 5$  GeV

# Radiative return

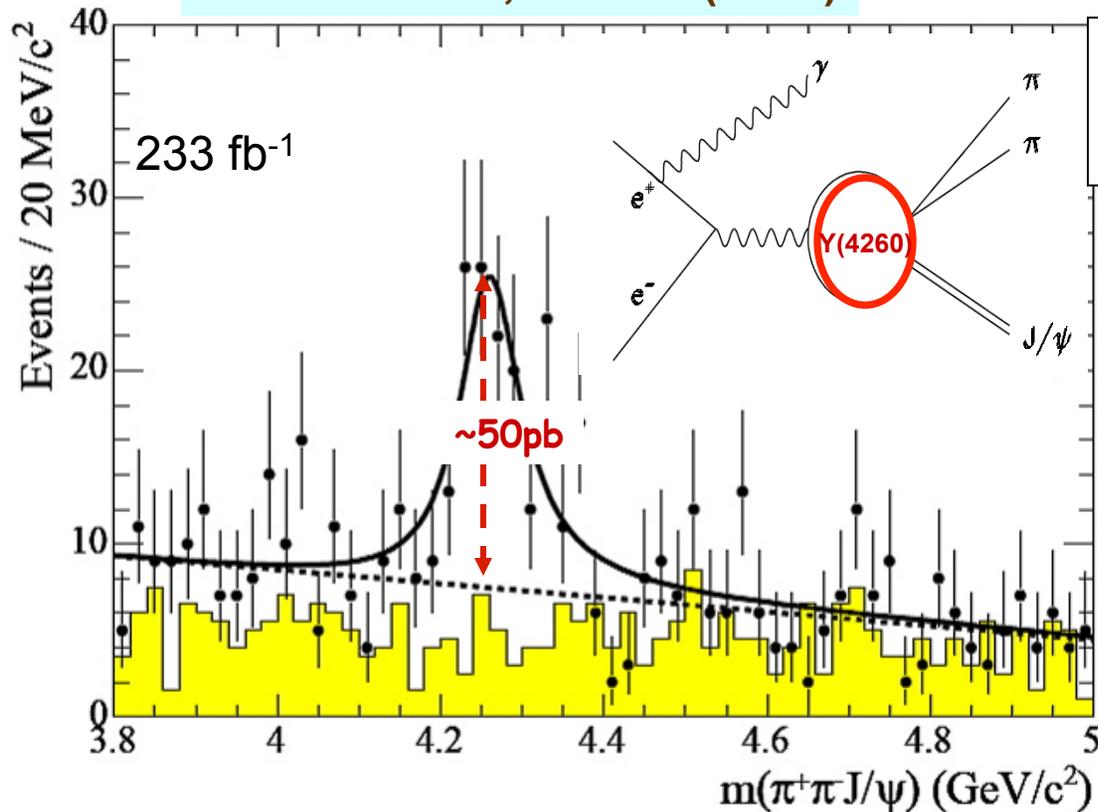


# $e^+e^- \rightarrow \gamma_{\text{ISR}} \Upsilon(4260)$ at BaBar

$\Upsilon(4260) \rightarrow \pi^+\pi^- J/\psi$

BaBar PRL95, 142001 (2005)

fitted values:



$$M = 4259 \pm 8 \begin{matrix} +2 \\ -6 \end{matrix} \text{ MeV}$$

$$\Gamma = 88 \pm 23 \begin{matrix} +6 \\ -9 \end{matrix} \text{ MeV}$$

# (4260) Confirmed

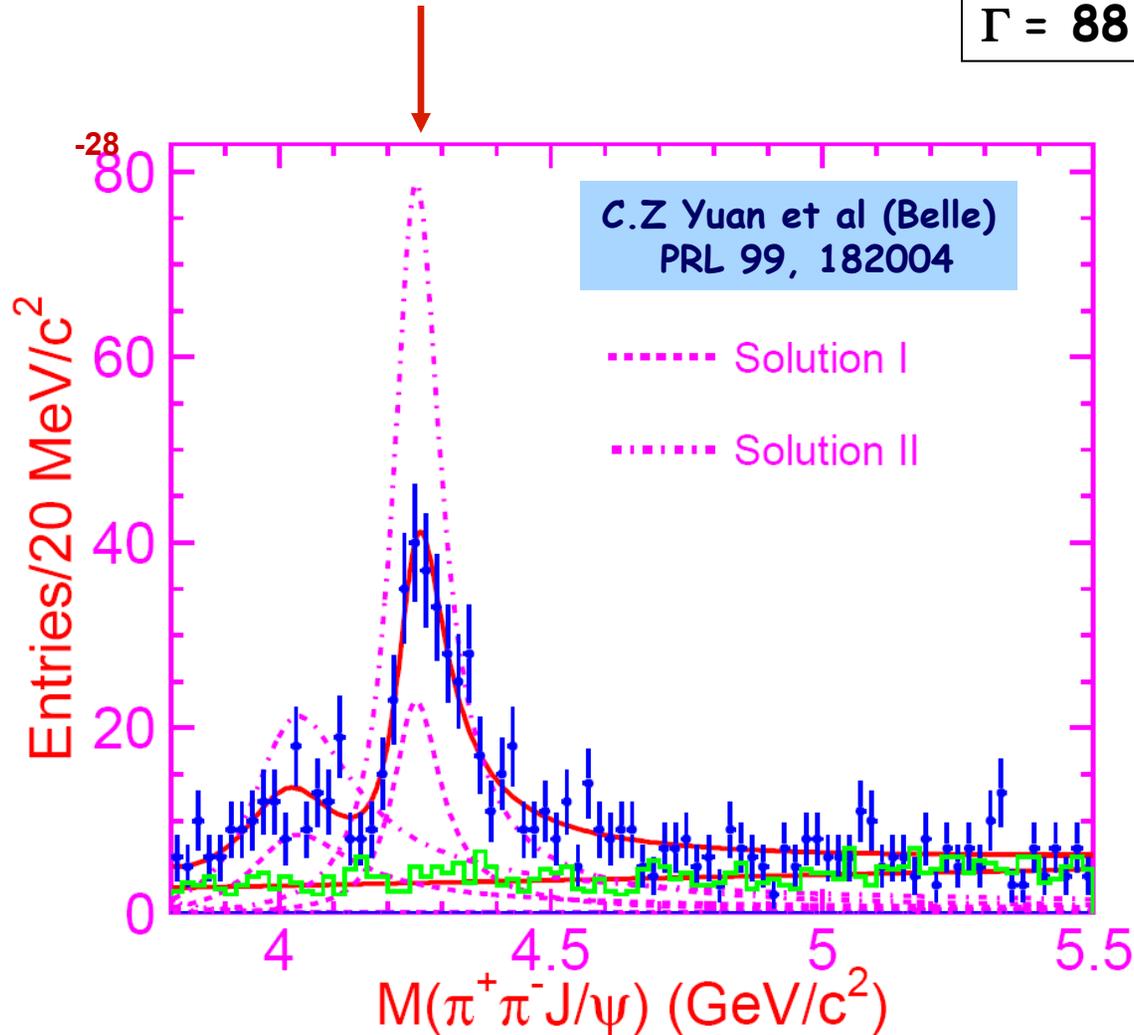
$$M = 4247 \pm 12 \begin{matrix} +17 \\ -32 \end{matrix} \text{ MeV}$$

$$\Gamma = 108 \pm 19 \pm 10 \text{ MeV}$$

BaBar values:

$$M = 4259 \pm 8 \begin{matrix} +2 \\ -6 \end{matrix} \text{ MeV}$$

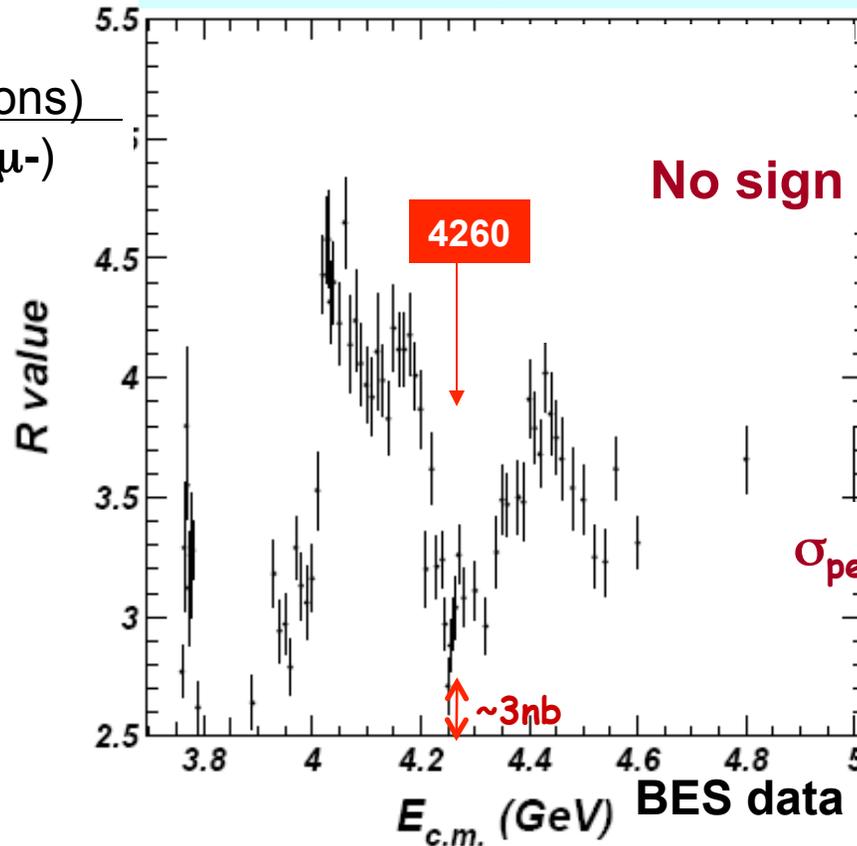
$$\Gamma = 88 \pm 23 \begin{matrix} +6 \\ -9 \end{matrix} \text{ MeV}$$



# Not seen in $e^+e^- \rightarrow$ hadrons

J.Z. Bai *et al* (BES), PRL 88, 101802 (2006)

$$\frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$



No sign of  $Y(4260) \rightarrow D^{(*)}D^{(*)}$

$\sigma_{\text{peak}}(Y(4260) \rightarrow \pi^+\pi^- J/\psi) \sim 50 \text{ pb}$

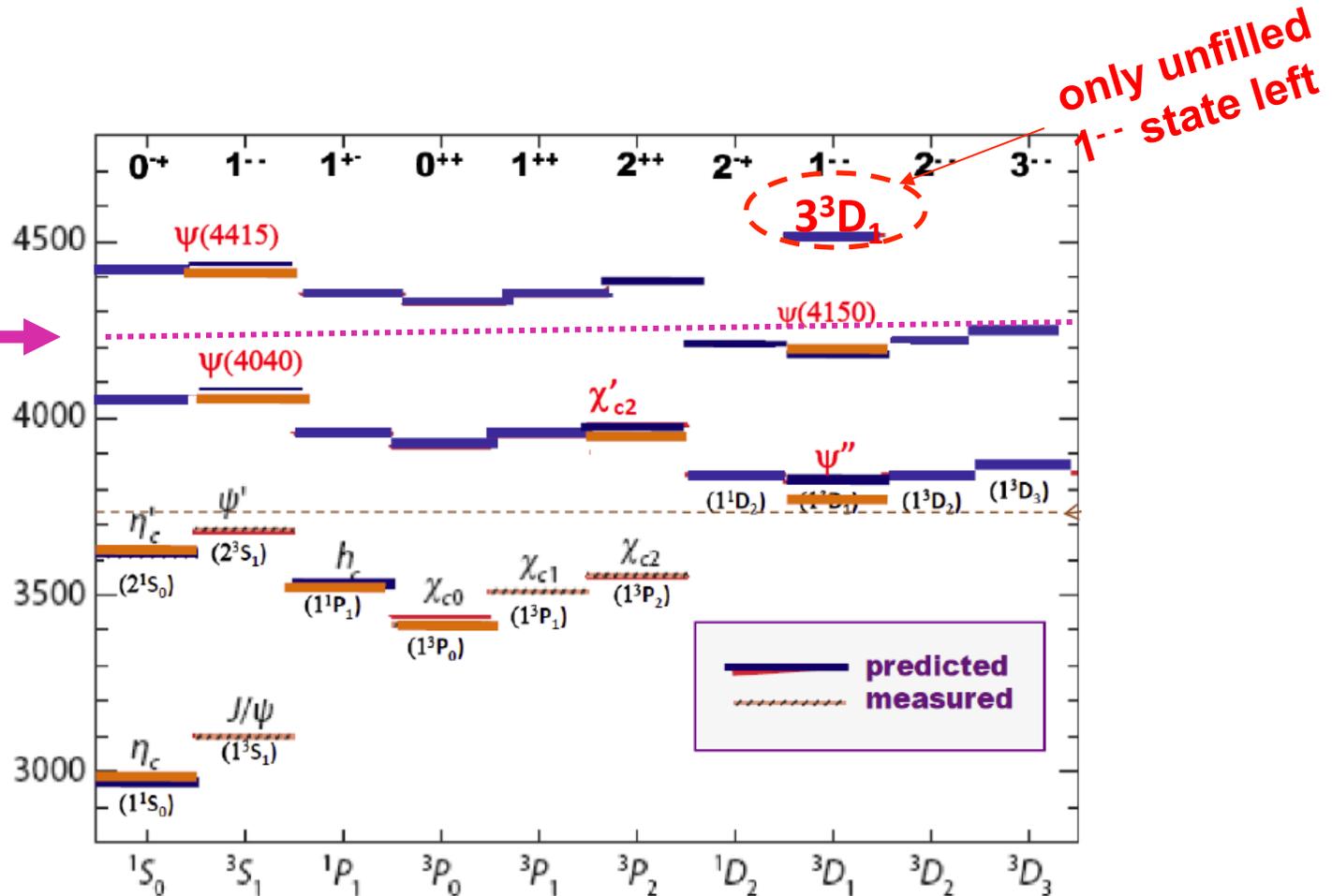
Huge by charmonium standards

$\Gamma(Y_{4260} \rightarrow \pi^+\pi^- J/\psi) > 1.6 \text{ MeV} @ 90\% \text{ CL}$

X.H. Mo *et al*, PL B640, 182 (2006)

# cc assignment for the $Y(4260)$ ??

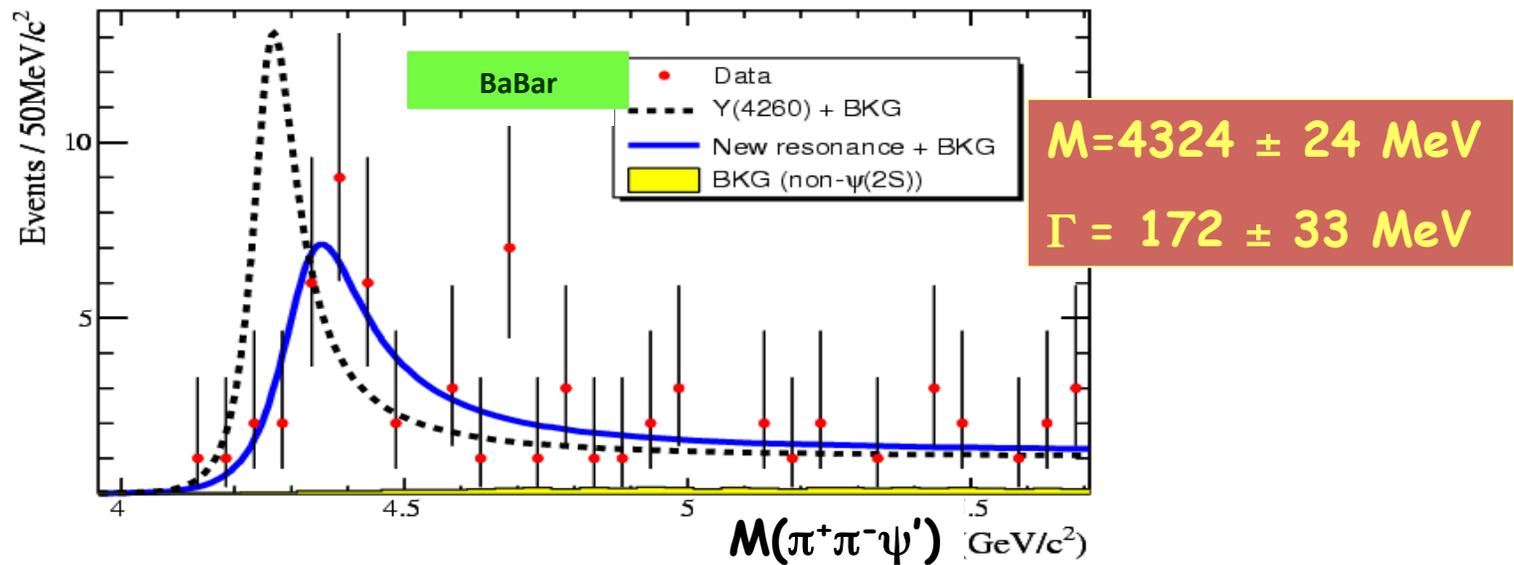
4260 MeV →



$Y(4260) = 3^3D_1?$  ← mass too low &  $\Gamma(\pi^+\pi^-J/\psi)$  too large

peaks in  $e^+e^- \rightarrow \gamma_{\text{ISR}} \pi^+\pi^-\psi'$

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



Peak is 4324 MeV, distinct from 4260 MeV

# 4325 MeV $\pi^+\pi^-\psi'$ peak also seen

Two peaks! (both relatively narrow)  
(& neither consistent with 4260)

$$M = 4361 \pm 9 \pm 9 \text{ MeV}$$

$$\Gamma = 74 \pm 15 \pm 10 \text{ MeV}$$

X.L. Wang et al (Belle)  
PRL 99, 142002 (2007)

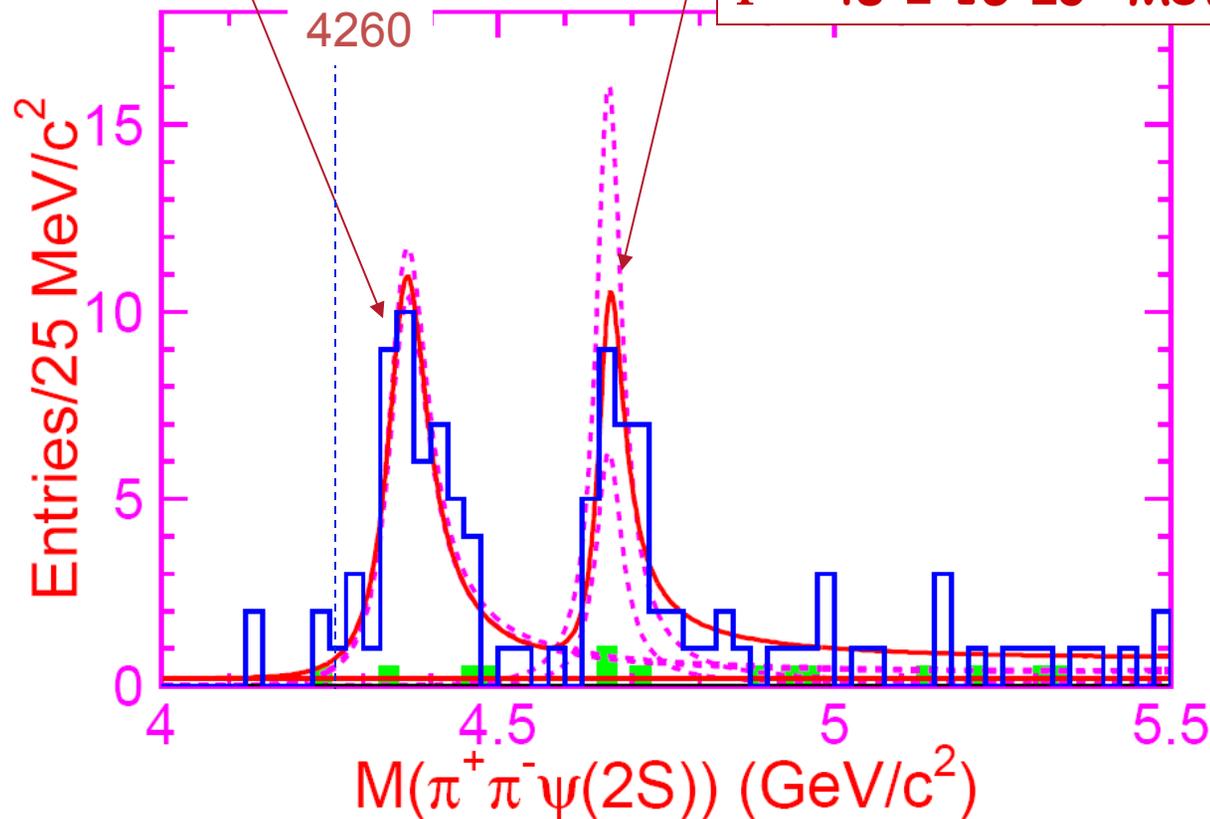
$$M = 4664 \pm 11 \pm 5 \text{ MeV}$$

$$\Gamma = 48 \pm 15 \pm 3 \text{ MeV}$$

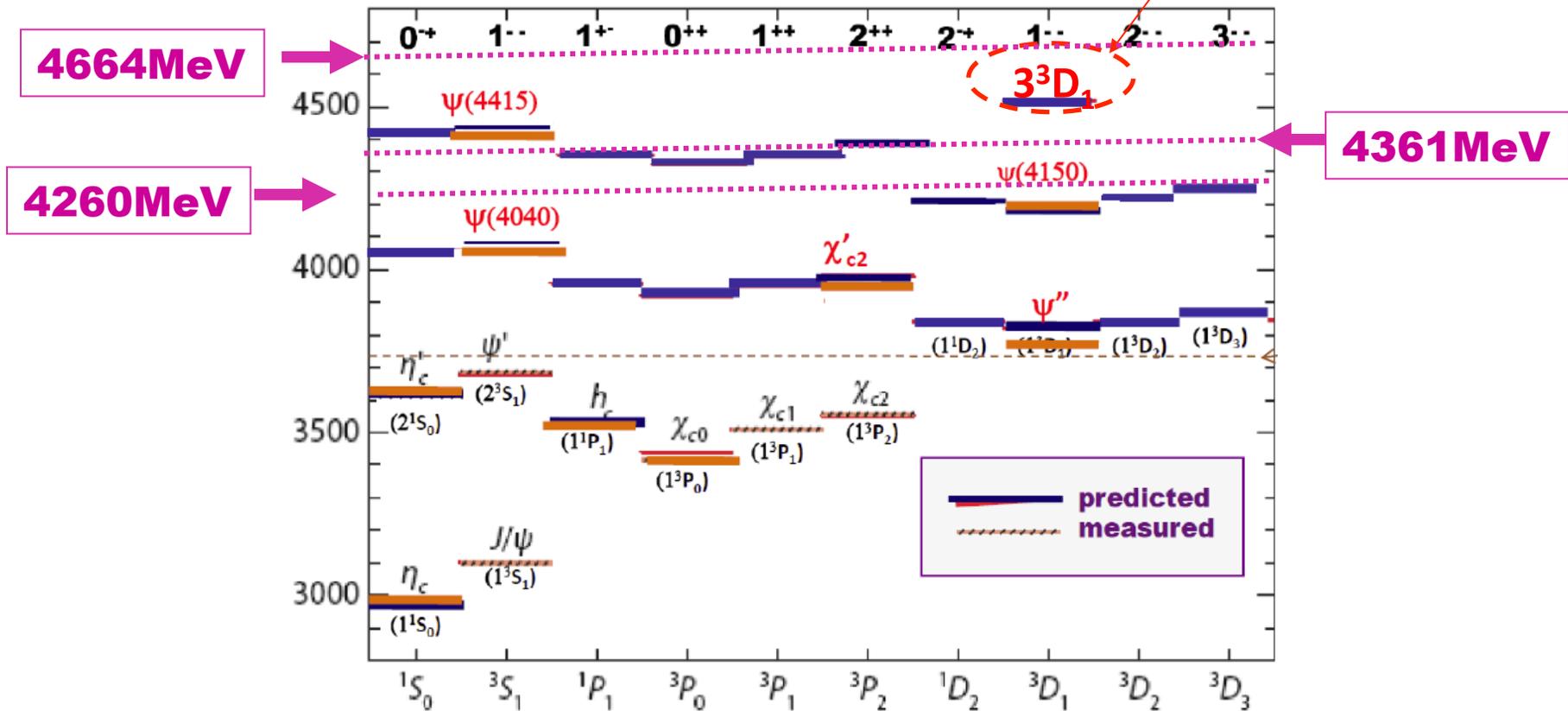
BaBar values

$$M = 4324 \pm 24 \text{ MeV}$$

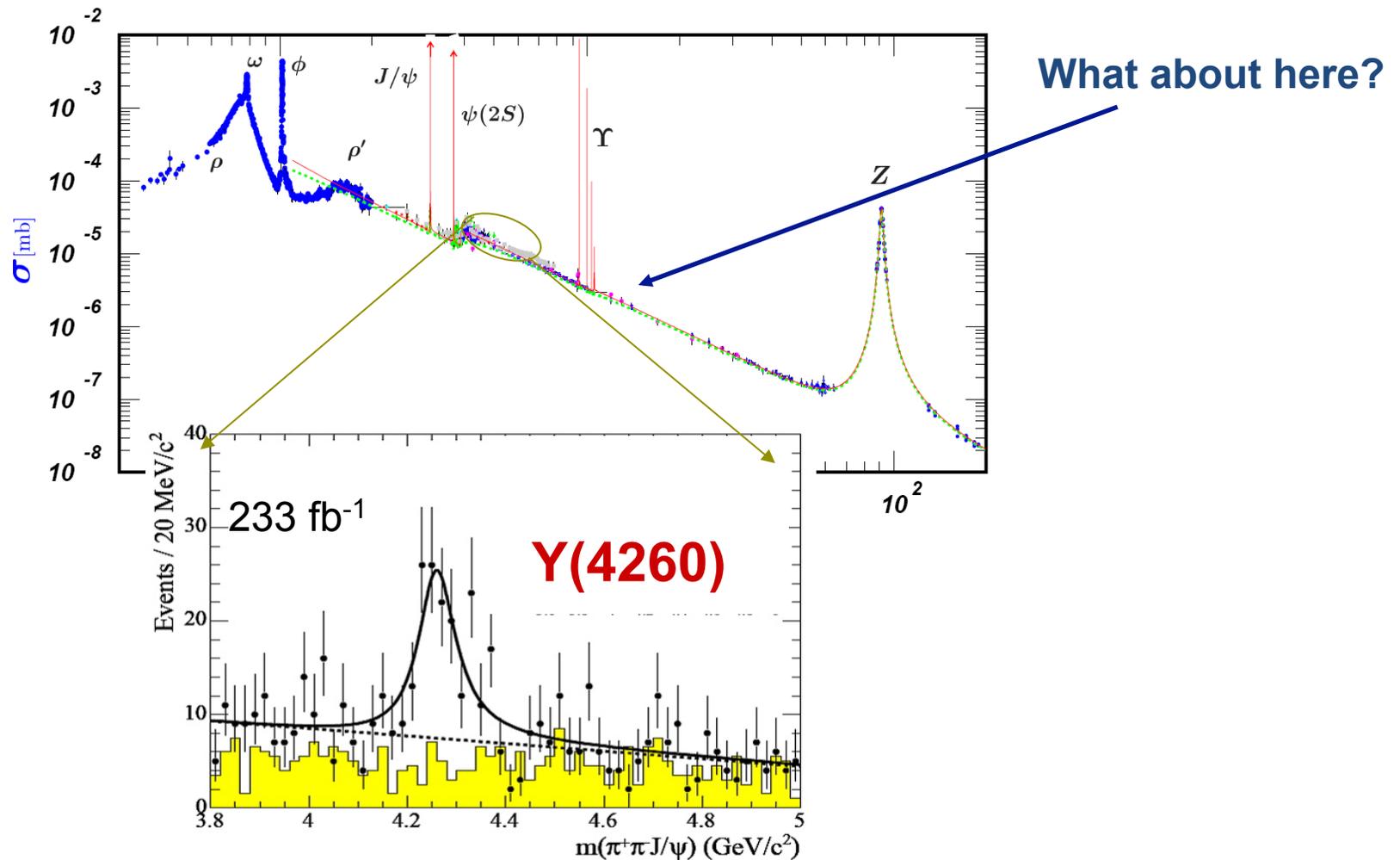
$$\Gamma = 172 \pm 33 \text{ MeV}$$



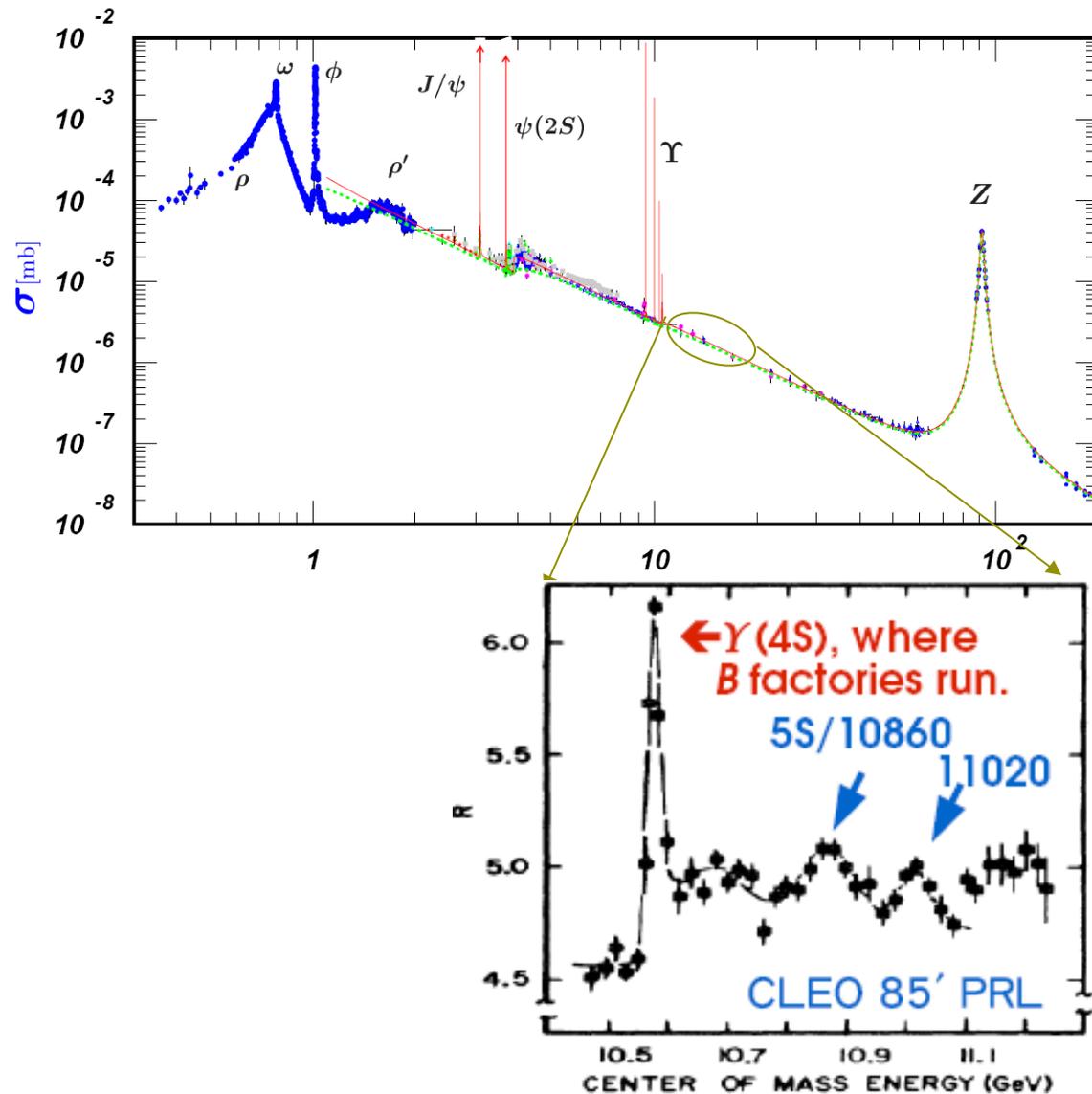
At least three peaks for only one unassigned  $1^-$  level



# Are there XYZ counterparts in the b- and s-quark sectors?

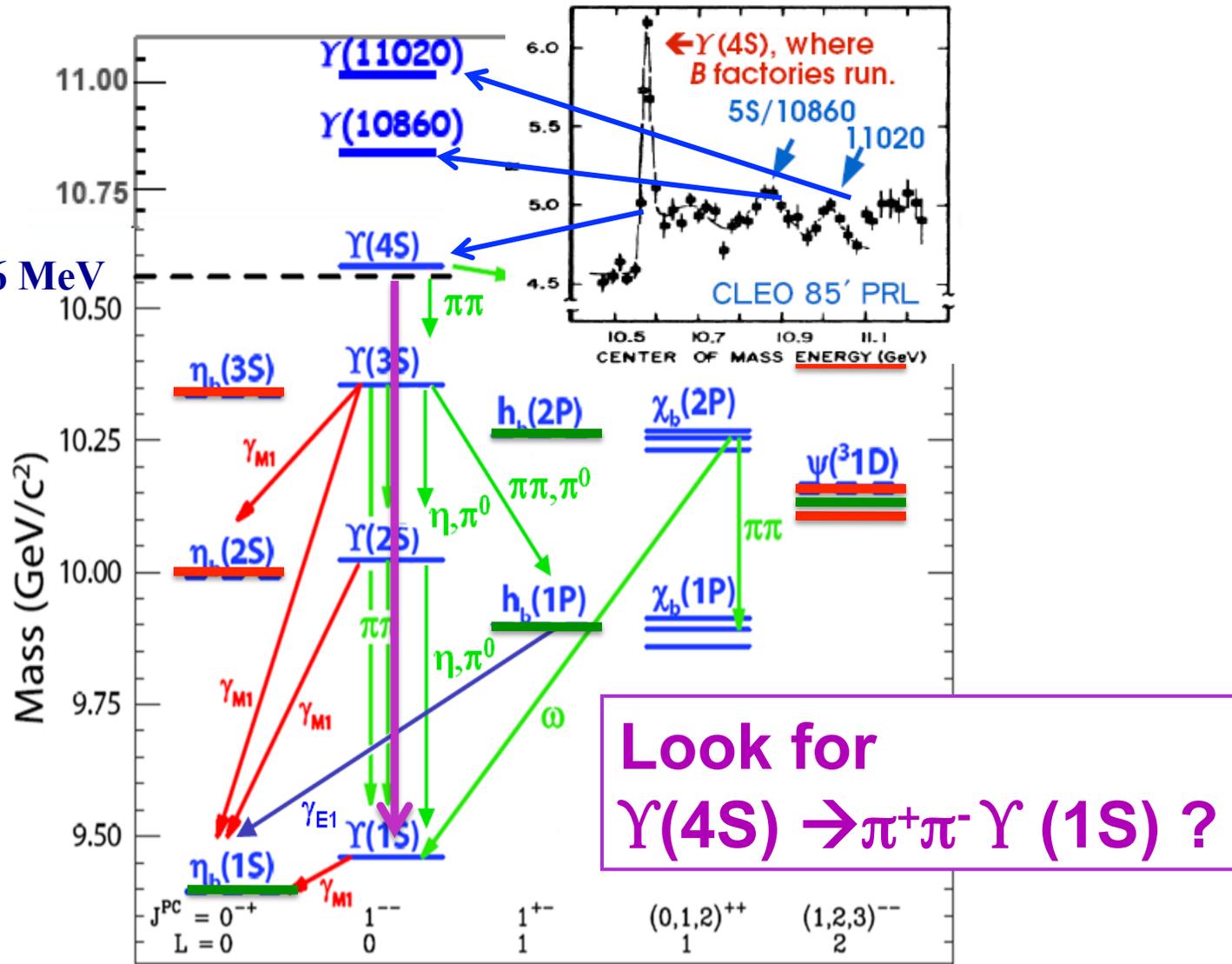


# b-quark threshold region



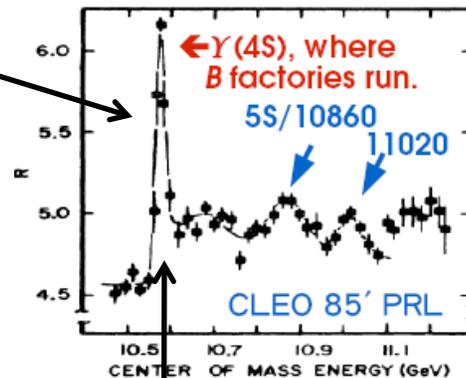
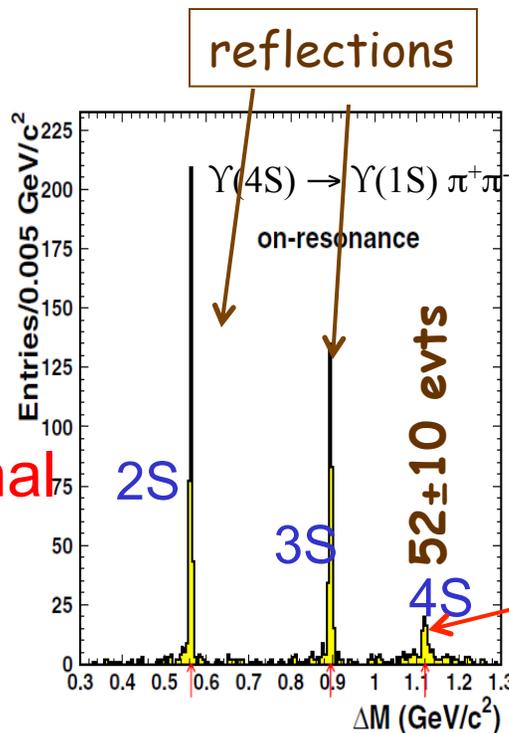
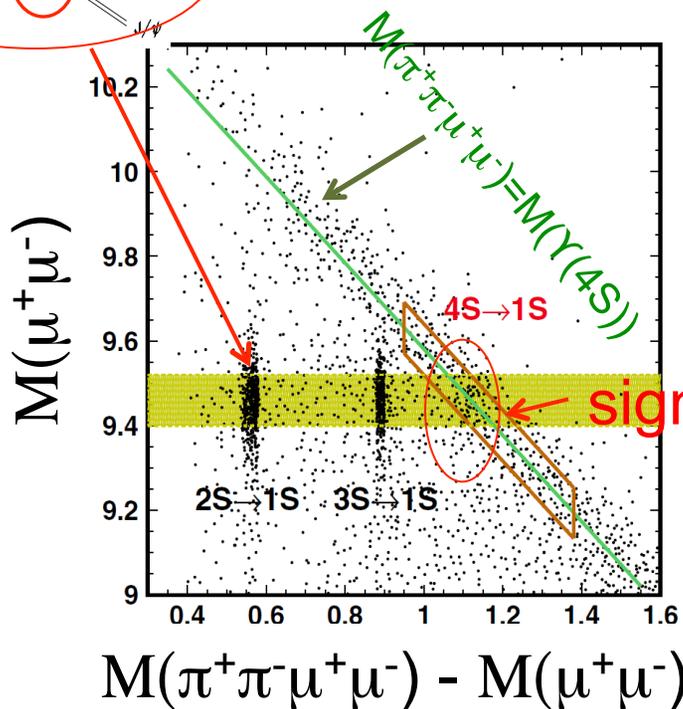
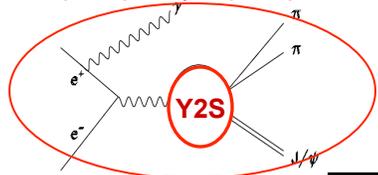
# Bottomonium spectrum

$2M_B = 10.56 \text{ MeV}$



# Belle: $\Gamma_{\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(1S)}$

undetected  
 $\Upsilon(4S) \rightarrow \gamma \Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$

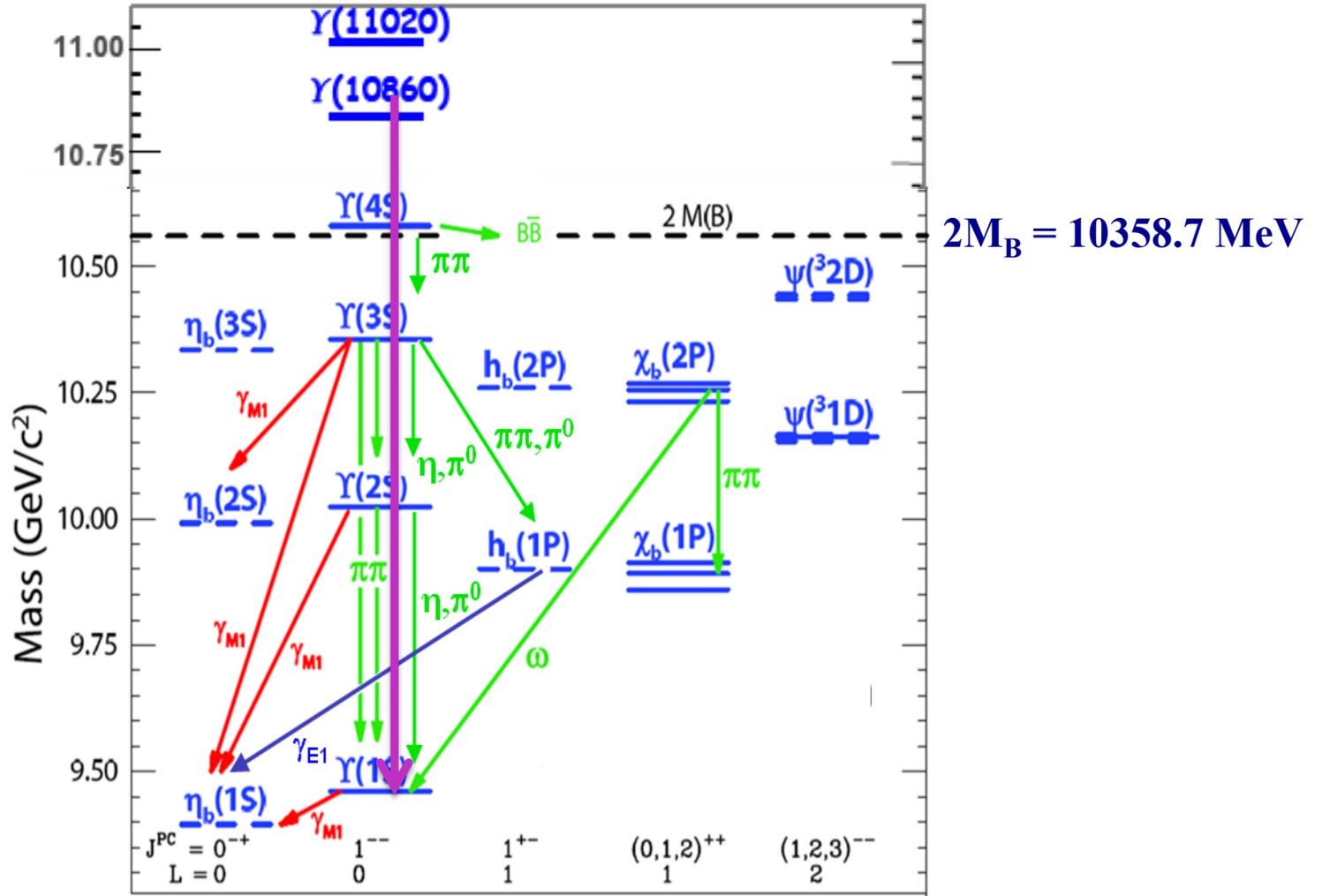


$\Upsilon(4S)$   
 $477 \text{ fb}^{-1}$

$N(\Upsilon_{4S})$	$N(\pi^+\pi^-\Upsilon_{1S})$	$B(\Upsilon_{4S} \rightarrow \pi\pi\Upsilon_{1S})$	$\Gamma(\Upsilon_{4S} \rightarrow \pi\pi\Upsilon_{1S})$	$\Gamma_{\text{theory}}$
$535 \times 10^6$	$52 \pm 10$	$9 \pm 2 \times 10^{-5}$	$1.75 \pm 0.35 \text{ keV}$	$1.47 \pm 0.03 \text{ keV}$

experiment  $\approx$  theory

# $\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ ?



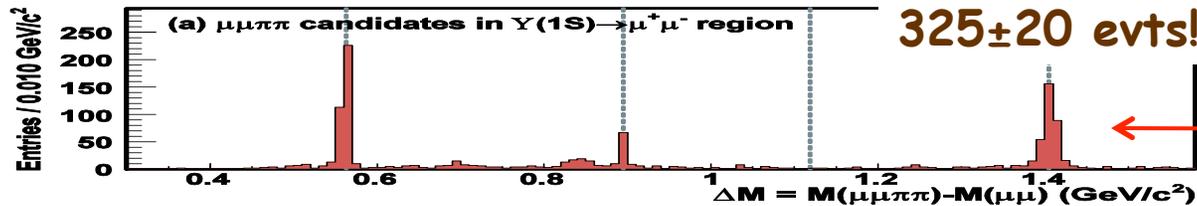
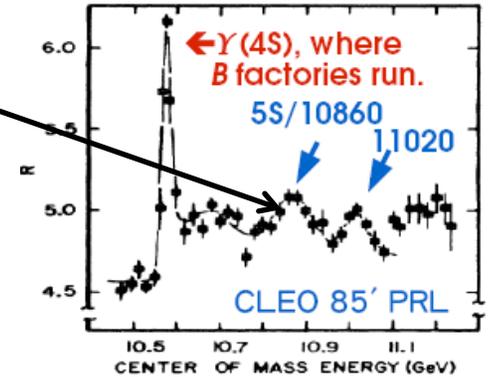
# Belle: $\Gamma_{\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(1S)}$

$\sim 1/20^{\text{th}}$  the data

23.6 fb<sup>-1</sup> vs 477 fb<sup>-1</sup>

$\sim 1/5^{\text{th}}$  the cross-sect.

Expect  $\sim 1/2$  evt



>6 times as many events!  
 $\sim 500\times$  expectations

# Partial Widths

Assuming the source is the  $\Upsilon(5S)$

PDG value taken for  $\Upsilon(nS)$  properties

Process	$N_s$	$\Sigma$	Eff.(%)	$\sigma(\text{pb})$	$\mathcal{B}(\%)$	$\Gamma(\text{MeV})$
$\Upsilon(1S)\pi^+\pi^-$	$325^{+20}_{-19}$	$20\sigma$	37.4	$1.61 \pm 0.10 \pm 0.12$	$0.53 \pm 0.03 \pm 0.05$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(2S)\pi^+\pi^-$	$186 \pm 15$	$14\sigma$	18.9	$2.35 \pm 0.19 \pm 0.32$	$0.78 \pm 0.06 \pm 0.11$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(3S)\pi^+\pi^-$	$10.5^{+4.0}_{-3.3}$	$3.2\sigma$	1.5	$1.44^{+0.55}_{-0.45} \pm 0.19$	$0.48^{+0.18}_{-0.15} \pm 0.07$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(1S)K^+K^-$	$20.2^{+5.2}_{-4.5}$	$4.9\sigma$	20.3	$0.185^{+0.048}_{-0.041} \pm 0.028$	$0.061^{+0.016}_{-0.014} \pm 0.010$	$0.067^{+0.017}_{-0.015} \pm 0.013$

PRD **98**, 052001 (2007) [Belle]

>300 times bigger than that for the  $\Upsilon_{4S}$ !!  
(theory says it should be smaller)

c.f.

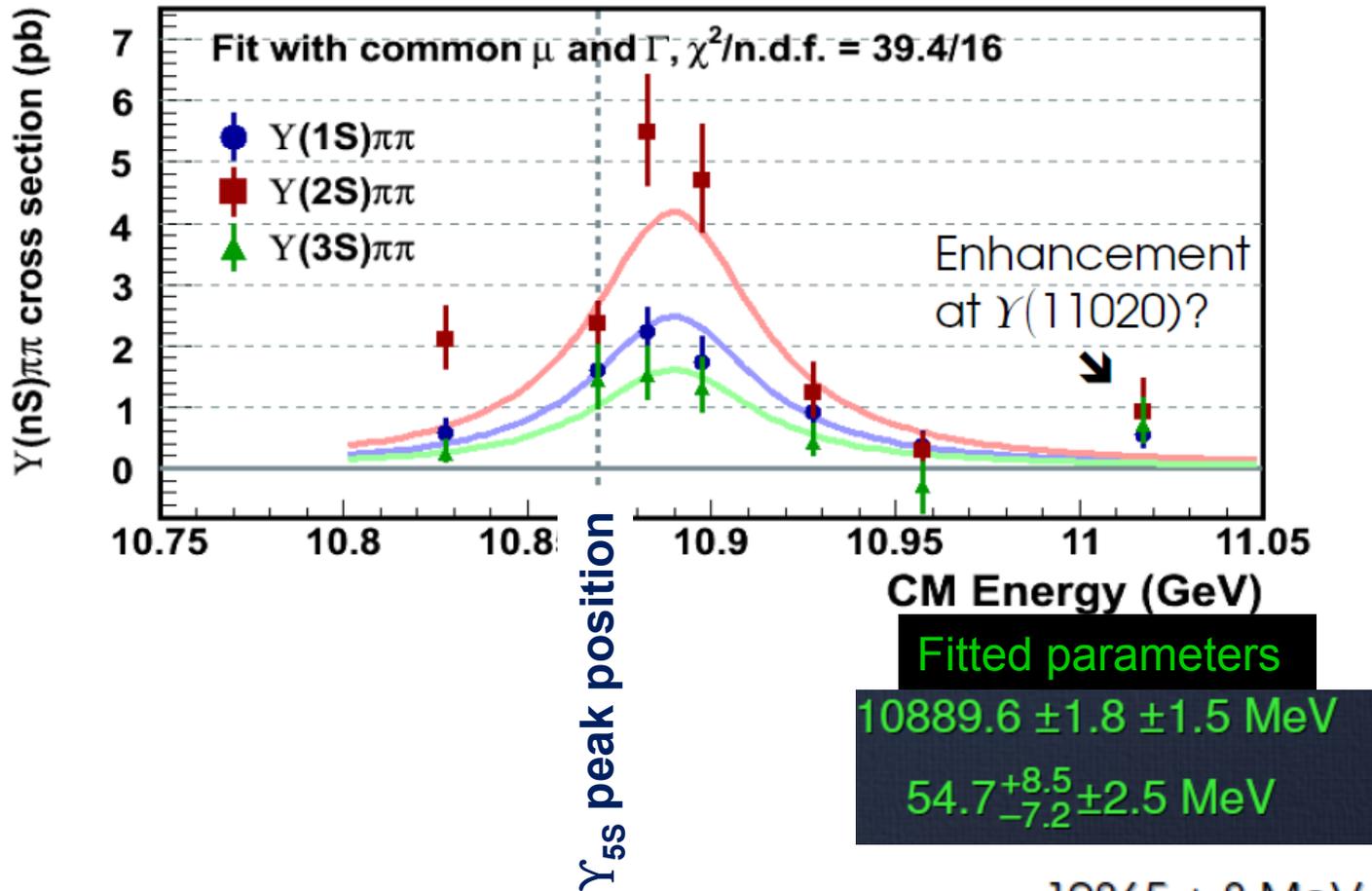
$\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^- \sim 6 \text{ keV}$

$\Upsilon(3S) \quad \quad \quad 0.9 \text{ keV}$

$\Upsilon(4S) \quad \quad \quad 1.8 \text{ keV}$

# Are these events from the $\Upsilon_{5S}$ ?

$\sigma(e^+e^- \rightarrow \pi^+\pi^-\Upsilon_{nS})$  from a cm energy scan

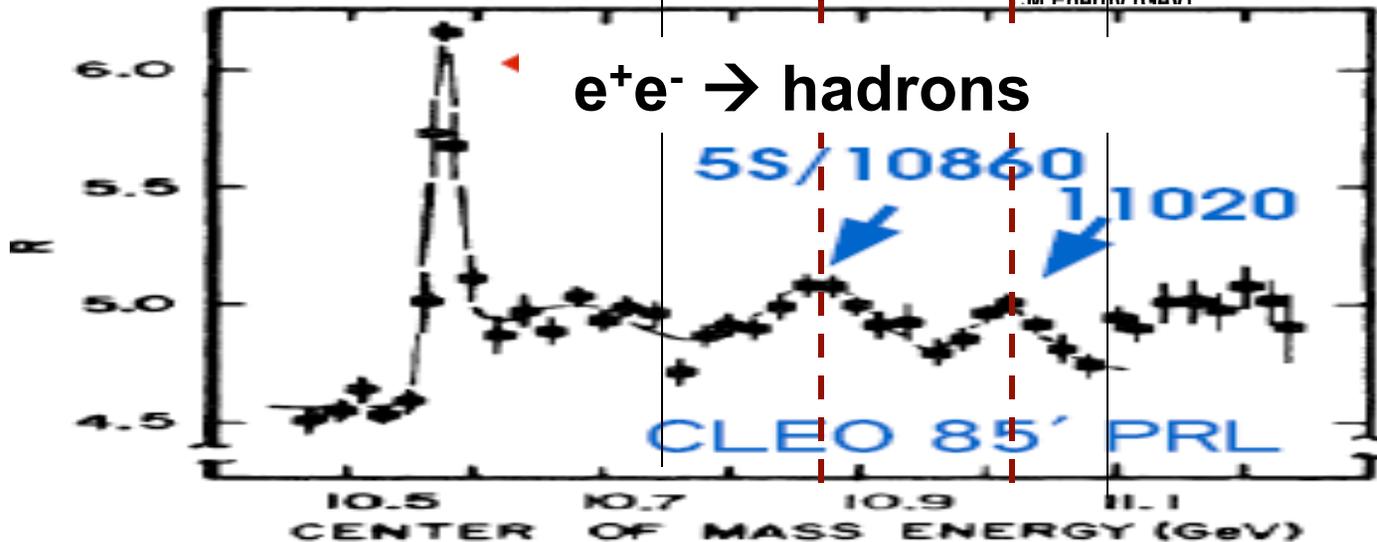
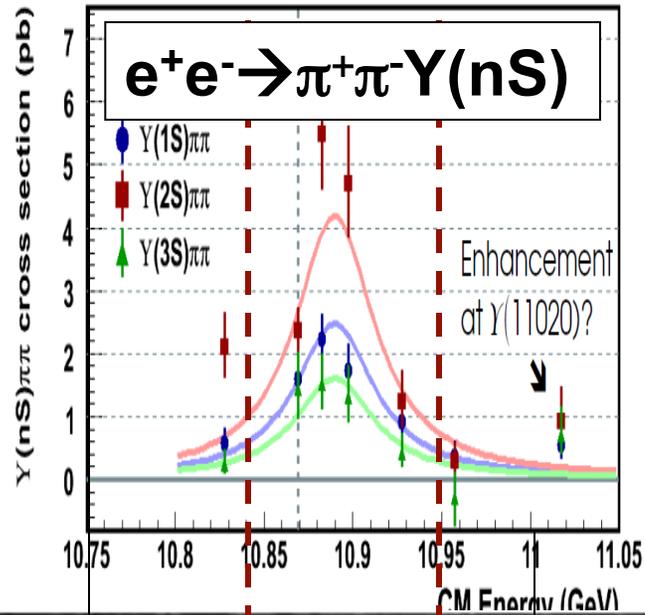


K.F. Chen et al (Belle)  
arXiv: 0810.3829

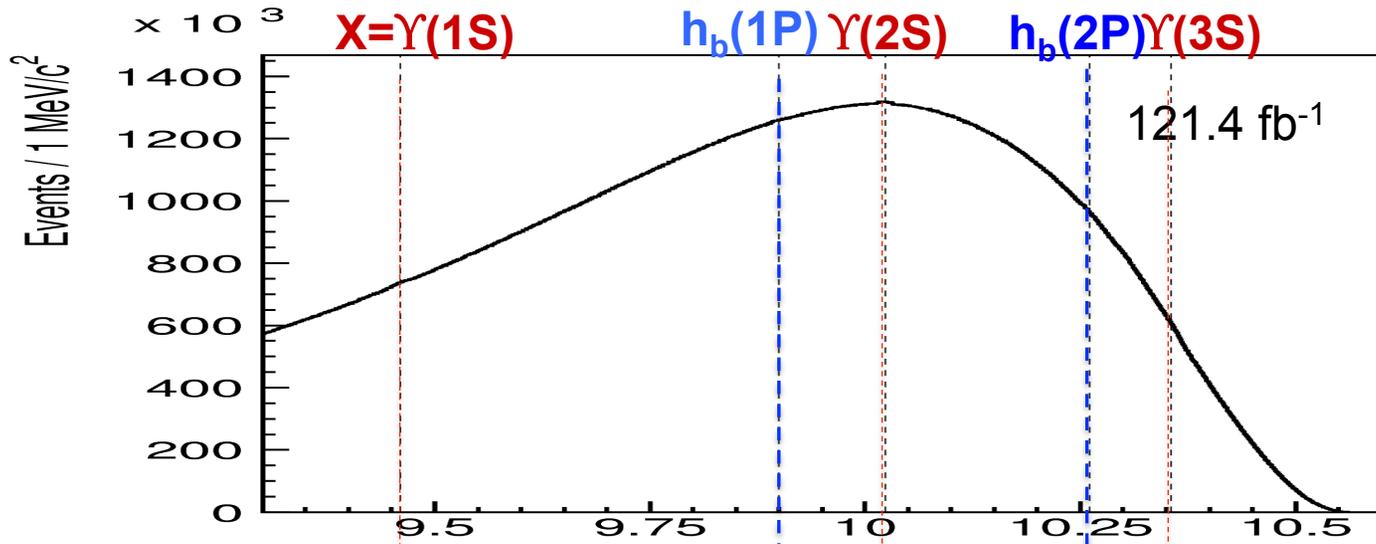
PDG( $\Upsilon_{5S}$ ):  
 $\mu = 10865 \pm 8$  MeV  
 $\Gamma = 110 \pm 13$  MeV

# Peak & width in $\pi^+\pi^-\Upsilon(nS)$ different from $\Upsilon(5S)$ & $\Upsilon(6S)$

Simplest interpretation:  
b-quark-sector equivalent to  
the c-quark-sector's  $\Upsilon(4260)$

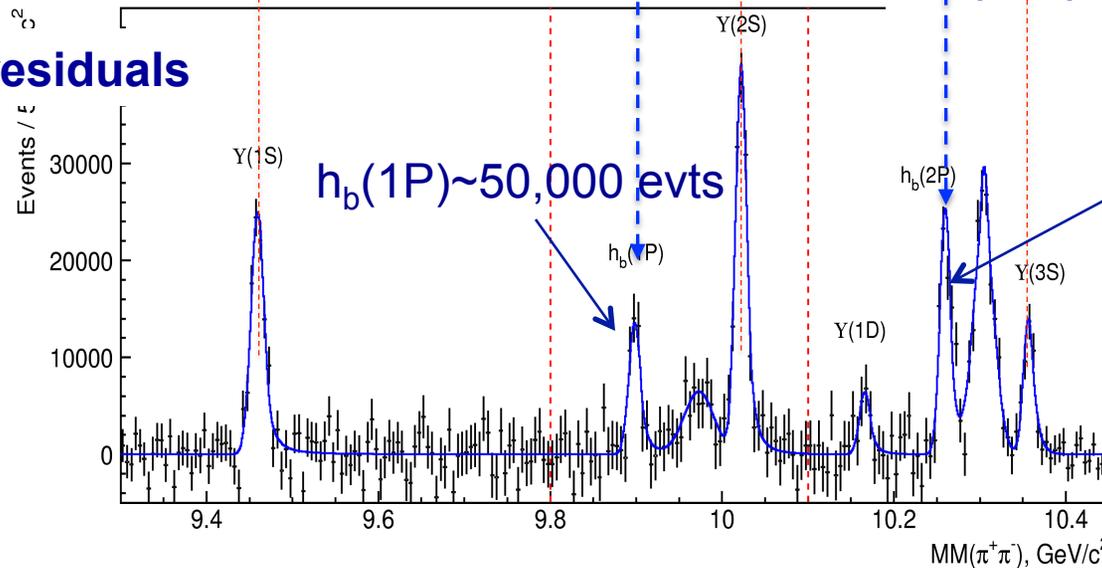


# Look at $\pi^+\pi^-$ recoil mass in $\Upsilon(5S) \rightarrow \pi^+\pi^- + X$



**MM( $\pi^+\pi^-$ ) spectrum**

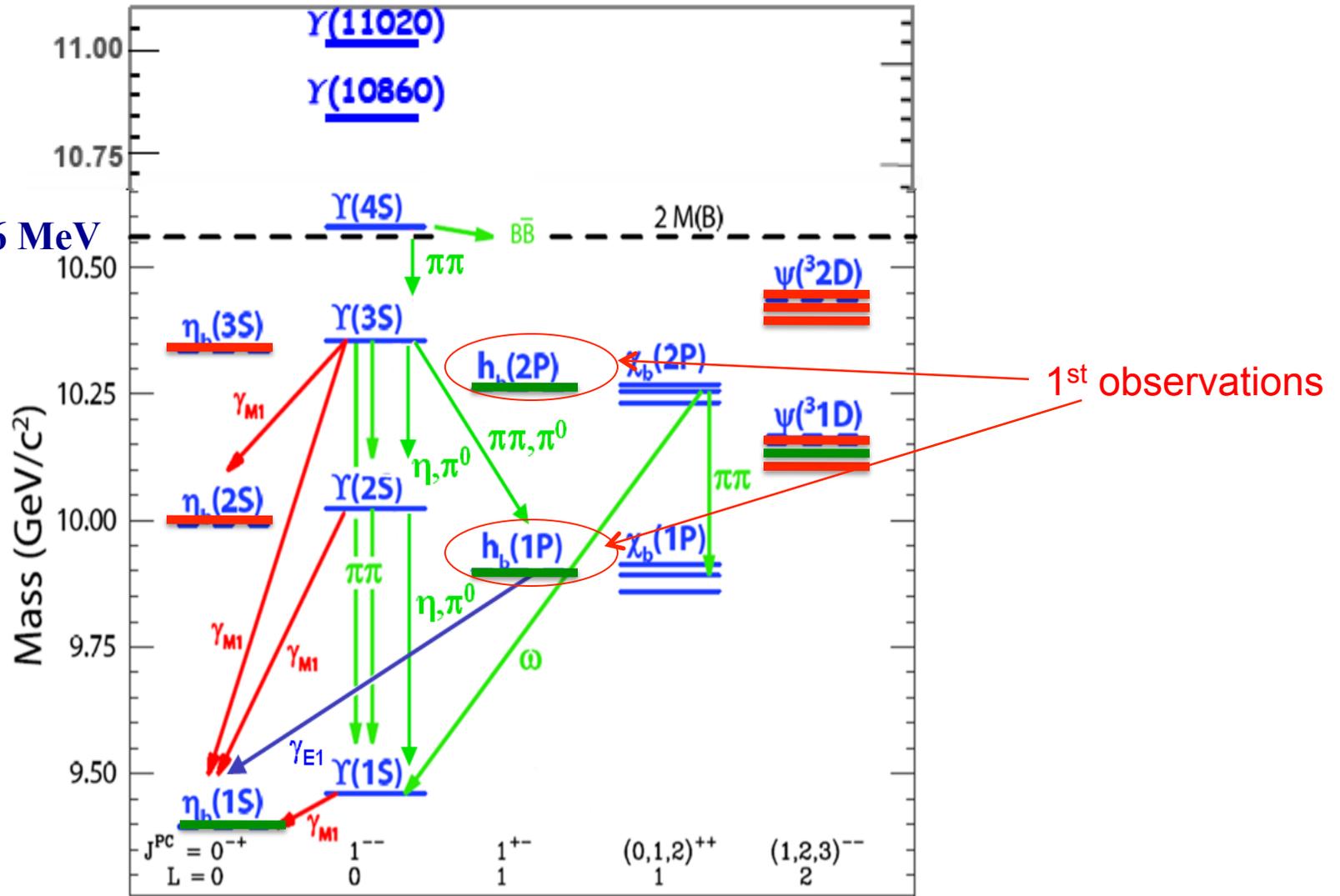
**MM( $\pi^+\pi^-$ ) residuals**



**h<sub>b</sub>(nP) → J<sup>PC</sup>=1<sup>+-</sup>**

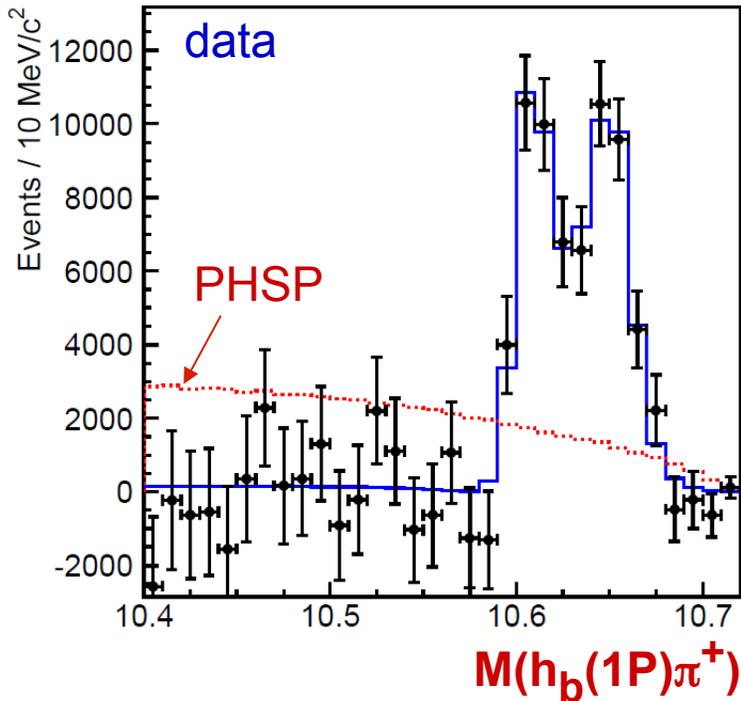
# Bottomonium spectrum

$2M_B = 10.56 \text{ MeV}$



# Resonant structure of “ $\Upsilon(5S)$ ” $\rightarrow h_b(nP)\pi^+\pi^-$

$\Rightarrow$  measure  $\Upsilon(5S) \rightarrow h_b \pi \pi$  yield in bins of  $MM(\pi)$



$$M_1 = 10605.1 \pm 2.2^{+3.0}_{-1.0} \text{ MeV}/c^2$$

$$\Gamma_1 = 11.4^{+4.5}_{-3.9} {}^{+2.1}_{-1.2} \text{ MeV}$$

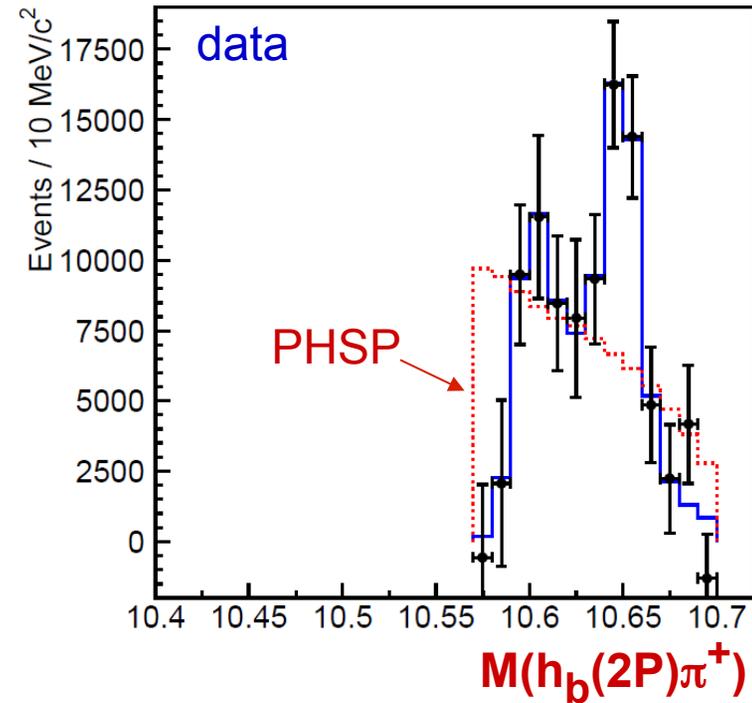
$$M_2 = 10654.5 \pm 2.5^{+1.0}_{-1.9} \text{ MeV}/c^2$$

$$\Gamma_2 = 20.9^{+5.4}_{-4.7} {}^{+2.1}_{-5.7} \text{ MeV}$$

non-res.  $\sim 0$

$\sim \bar{B}B^*$  threshold

$\sim B^*\bar{B}^*$  threshold



$$10596 \pm 7^{+5}_{-2} \text{ MeV}/c^2$$

$$16^{+16}_{-10} {}^{+13}_{-4} \text{ MeV}$$

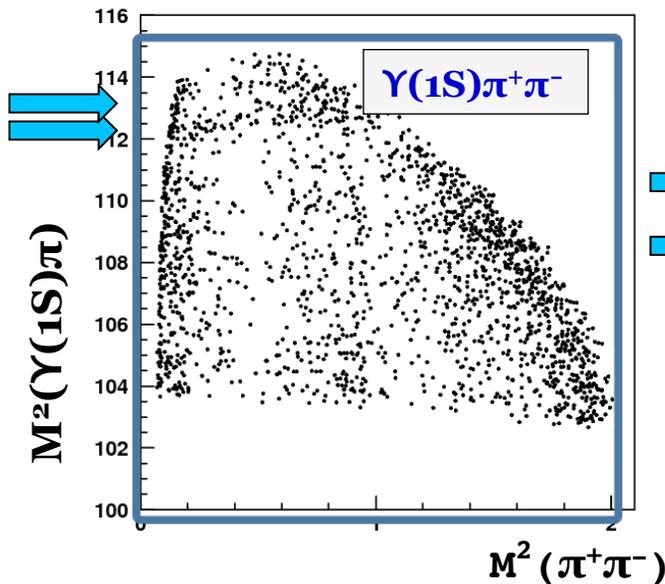
$$10651 \pm 4 \pm 2 \text{ MeV}/c^2$$

$$12^{+11}_{-9} {}^{+8}_{-2} \text{ MeV}$$

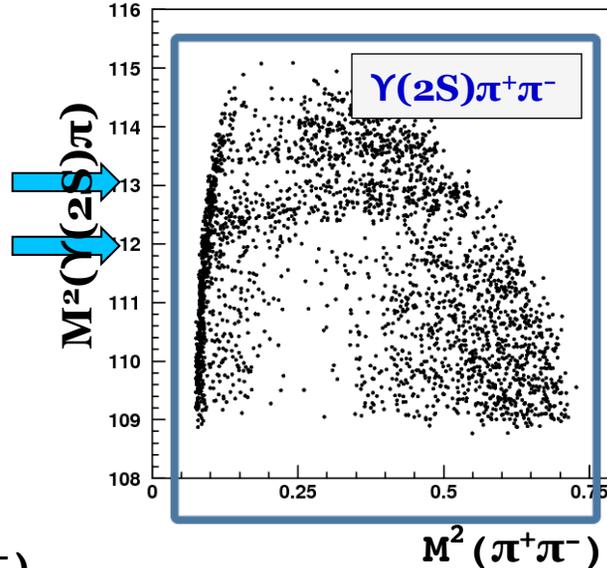
# Look at “ $\Upsilon(5S)$ ” $\rightarrow \Upsilon(nS) \pi^+ \pi^-$

## “Dalitz Plots”

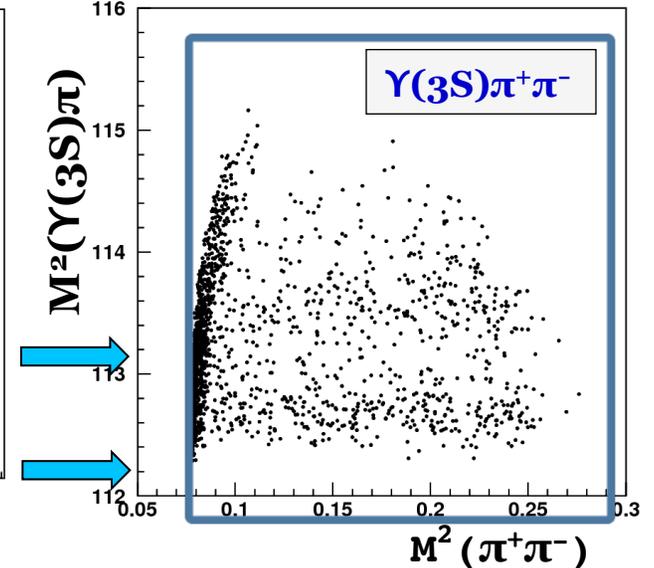
9.43 GeV < MM( $\pi^+ \pi^-$ ) < 9.48 GeV



10.05 GeV < MM( $\pi^+ \pi^-$ ) < 10.10 GeV



10.33 GeV < MM( $\pi^+ \pi^-$ ) < 10.38 GeV



To exclude contamination from gamma conversions we require:

$$M^2(\pi^+\pi^-) > 0.20 \text{ GeV}^2$$

$$M^2(\pi^+\pi^-) > 0.16 \text{ GeV}^2$$

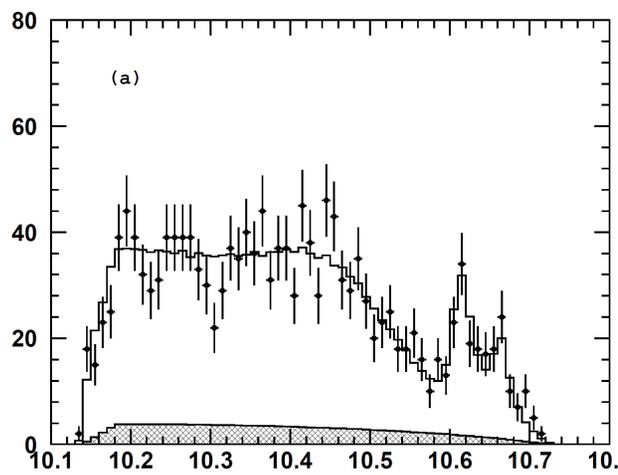
$$M^2(\pi^+\pi^-) > 0.10 \text{ GeV}^2$$

# Fit results

$$\Upsilon(5S) \rightarrow \Upsilon(1S)\pi^+\pi^-$$

$$\Upsilon(5S) \rightarrow \Upsilon(2S)\pi^+\pi^-$$

$$\Upsilon(5S) \rightarrow \Upsilon(3S)\pi^+\pi^-$$



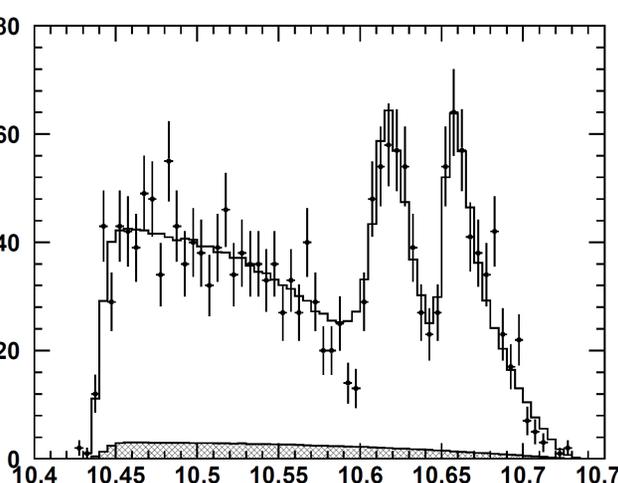
$M(\Upsilon(1S)\pi)_{\max}$

$$Z_{b1} \quad M=10611 \pm 4 \pm 3 \text{ MeV}$$

$$\Gamma=22.3 \pm 7.7 \pm 4.0 \text{ MeV}$$

$$Z_{b2} \quad M=10657 \pm 6 \pm 3 \text{ MeV}$$

$$\Gamma=16.3 \pm 9.8 \pm 6.0 \text{ MeV}$$



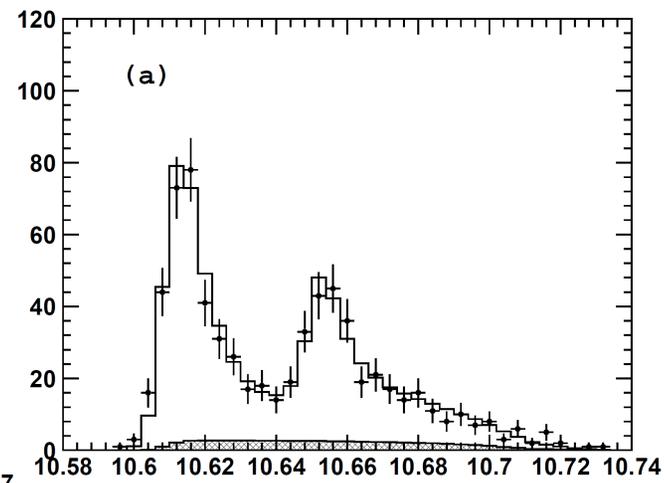
$M(\Upsilon(2S)\pi)_{\max}$

$$M=10609 \pm 2 \pm 3 \text{ MeV}$$

$$\Gamma=24.2 \pm 3.1 \pm 3.0 \text{ MeV}$$

$$M=10651 \pm 2 \pm 3 \text{ MeV}$$

$$\Gamma=13.3 \pm 3.3 \pm 4.0 \text{ MeV}$$



$M(\Upsilon(3S)\pi)_{\max}$

$$M=10608 \pm 2 \pm 3 \text{ MeV}$$

$$\Gamma=17.6 \pm 3.0 \pm 3.0 \text{ MeV}$$

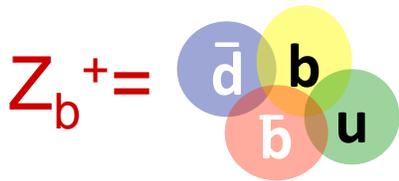
$$M=10652 \pm 1 \pm 2 \text{ MeV}$$

$$\Gamma=8.4 \pm 2.0 \pm 2.0 \text{ MeV}$$

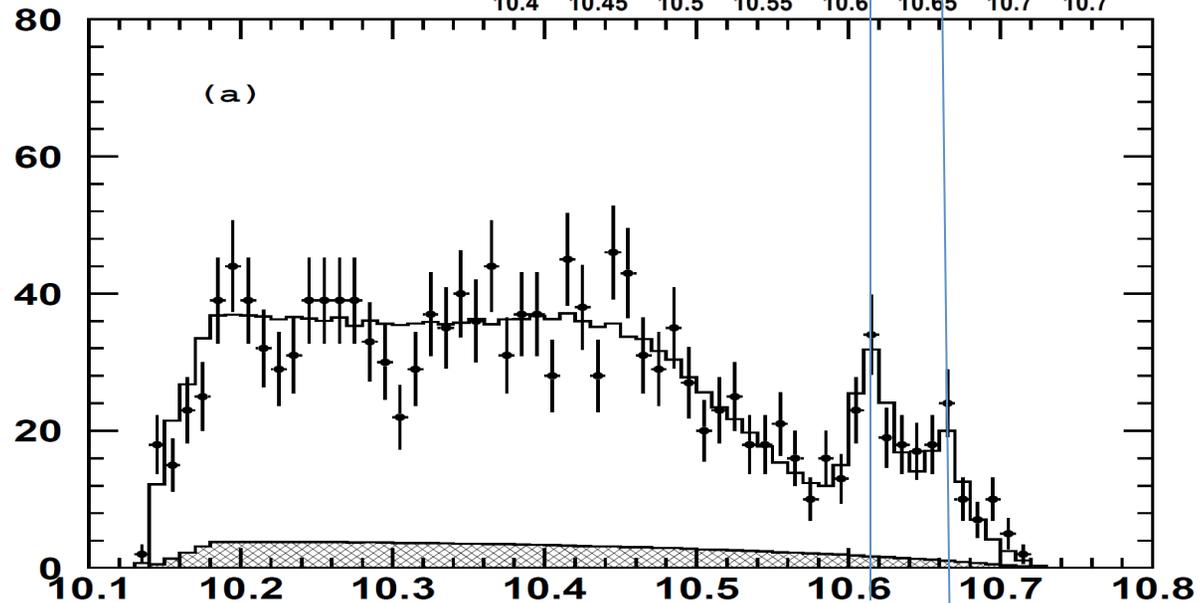
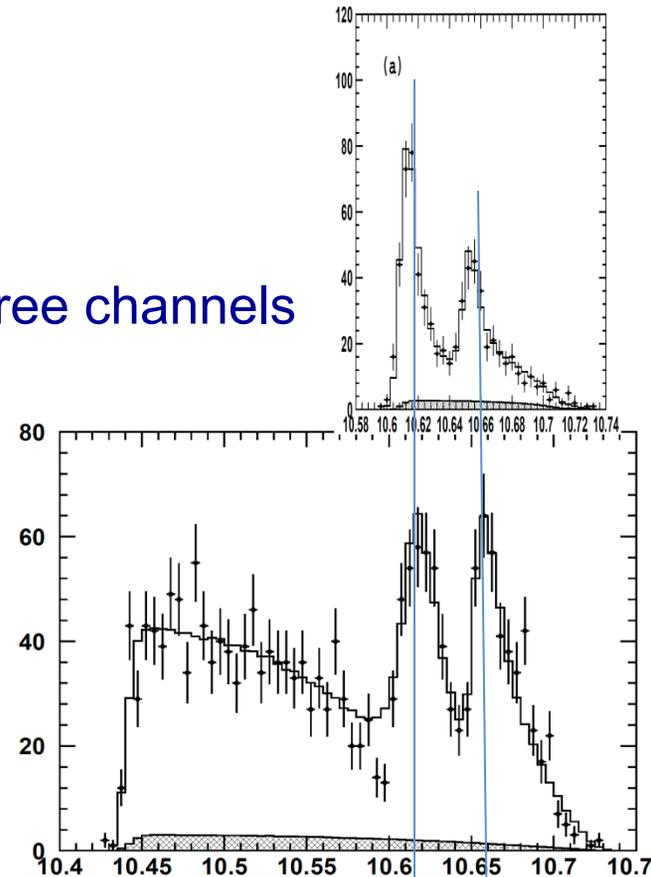
## Consistent peaks in all three channels

$Z_b \rightarrow Y(1S)\pi \rightarrow Z_b s$  must contain  
a  $b\bar{b}$  quark pair

charge =  $\pm 1 \rightarrow Z_b s$  must contain  
additional quarks

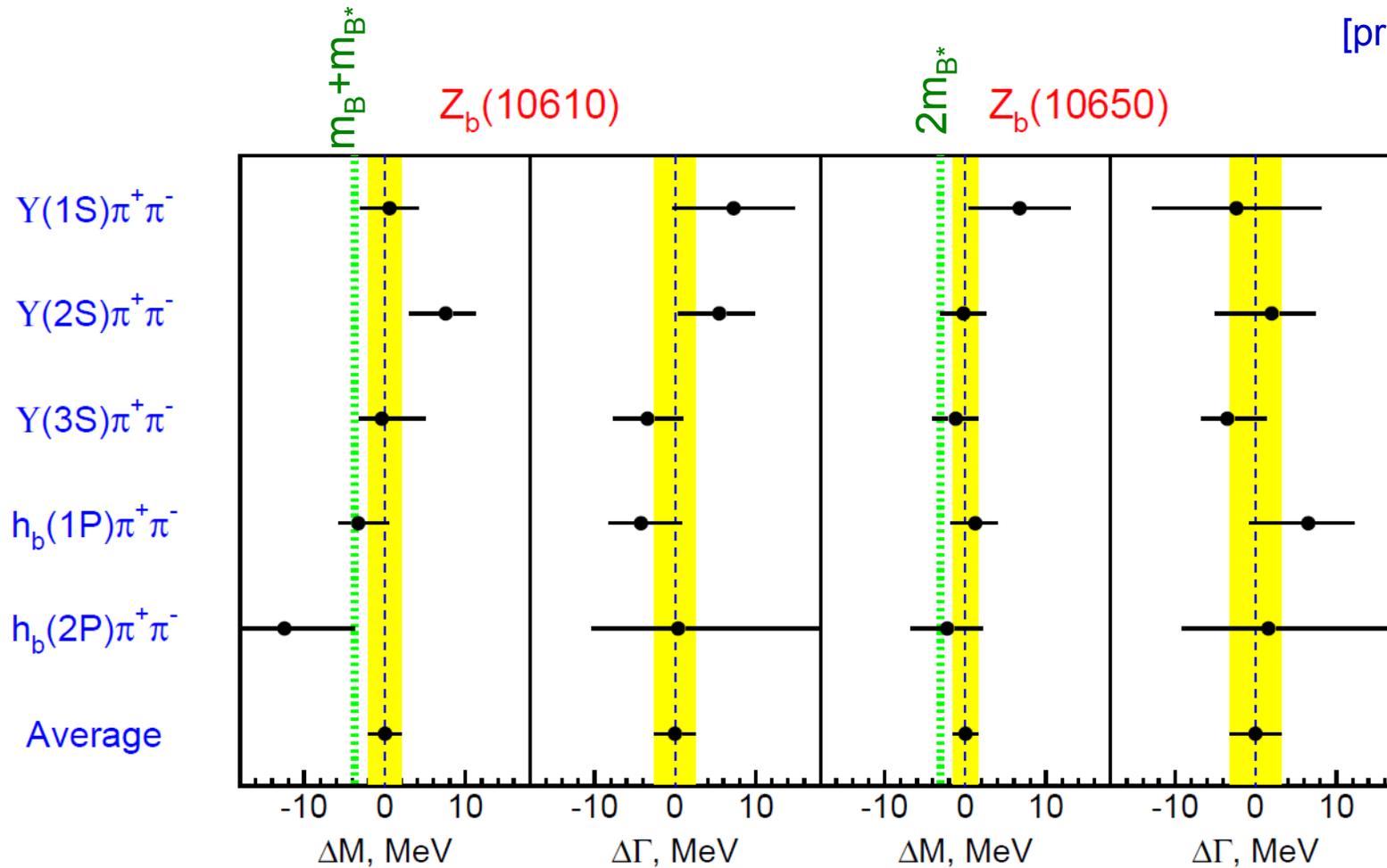


“minimal” quark  
configuration



# Summary of parameter measurements

[preliminary]



**$Z_b(10610)$**

**$M=10607.2 \pm 2.0$  MeV**

**$\Gamma=18.4 \pm 2.4$  MeV**

**$Z_b(10650)$**

**$M=10652.2 \pm 1.5$  MeV**

**$\Gamma=11.5 \pm 2.2$  MeV**

# $Z^\pm$ states cannot be bottomonium

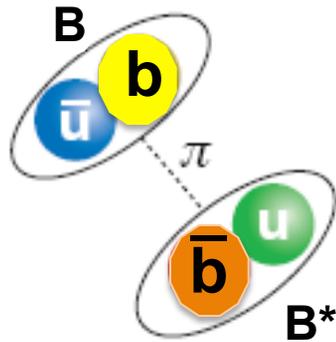


Decays to  $h_b(nP)$  or  $\Upsilon(nS) \rightarrow$  must contain a  $b\bar{b}$  pair

Has electric charge  $\rightarrow$  must contain u & d quarks

# $B-\bar{B}^*$ & $B^*-\bar{B}^*$ molecules??

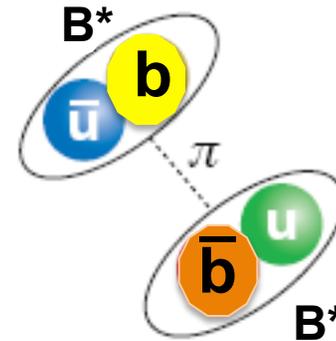
$Z_b(10610)^\pm$



$B-\bar{B}^*$  “molecule”

$$M_{Z_b(10610)} - (M_B + M_{B^*}) = + 3.6 \pm 1.8 \text{ MeV}$$

$Z_b(10650)^\pm$



$B^*-\bar{B}^*$  “molecule”

$$M_{Z_b(10650)} - 2M_{B^*} = + 3.1 \pm 1.8 \text{ MeV}$$

Slightly unbound threshold resonances??

Belle  
preliminary

$$M = 10608.1 \pm 1.7 \text{ MeV}$$

$$\Gamma = 15.5 \pm 2.4 \text{ MeV}$$

$$M = 10653.3 \pm 1.5 \text{ MeV}$$

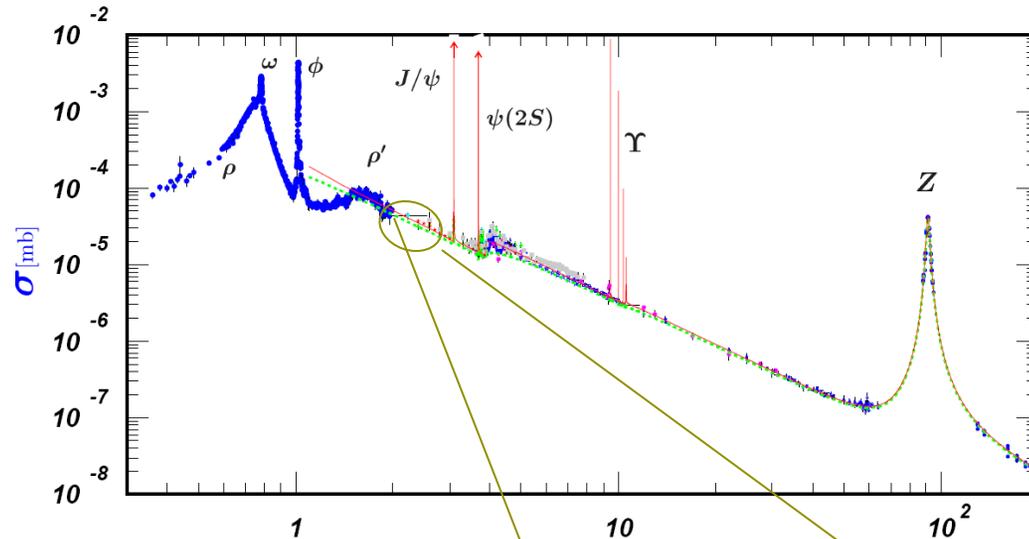
$$\Gamma = 14.0 \pm 2.8 \text{ MeV}$$

**PDG:**  $M_B + M_{B^*} = 10604.5 \pm 0.6 \text{ MeV}$

$M_{B^*} + M_{B^*} = 10650.2 \pm 1.0 \text{ MeV}$

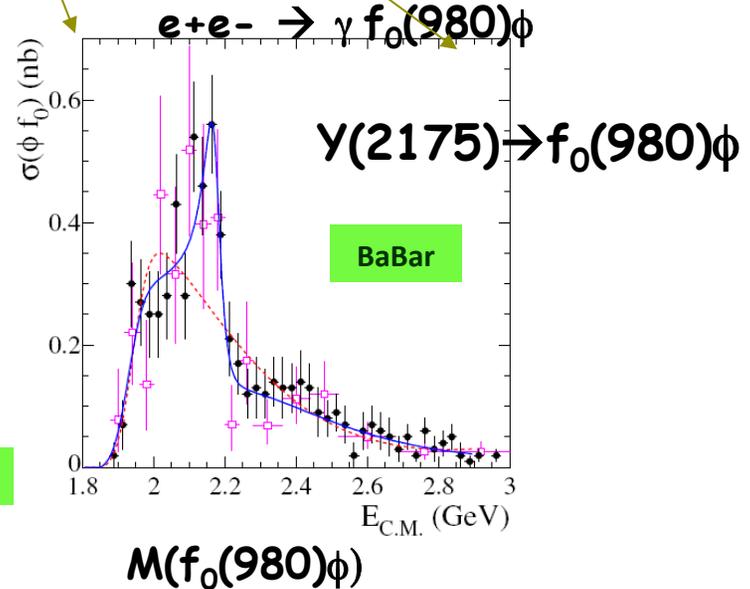
What about the s-quark sector?

# $\Upsilon(4260)$ equivalent with s-quarks?



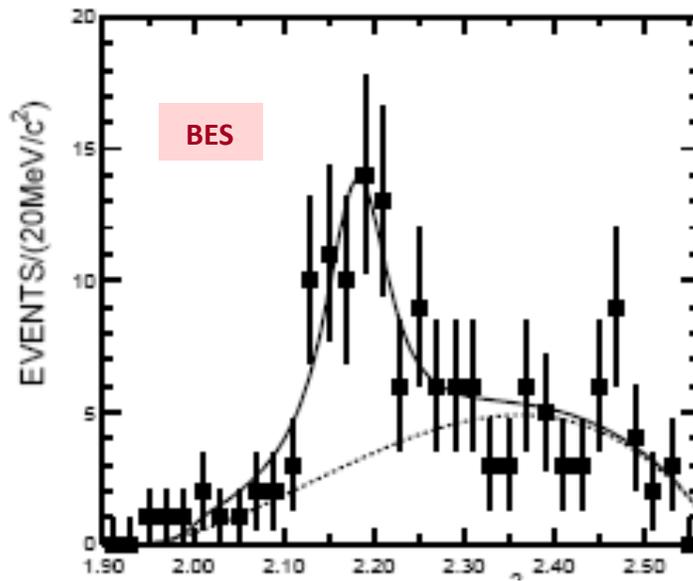
$$\sigma(e^+e^- \rightarrow \underbrace{\pi^+\pi^-}_{f_0(980) \rightarrow \pi^+\pi^-} \phi(1020))$$

BaBar, PRD 74, 091103



# Confirmed by BES & Belle

confirmed by BESII  
in  $J/\psi \rightarrow \eta \phi f_0(980)$



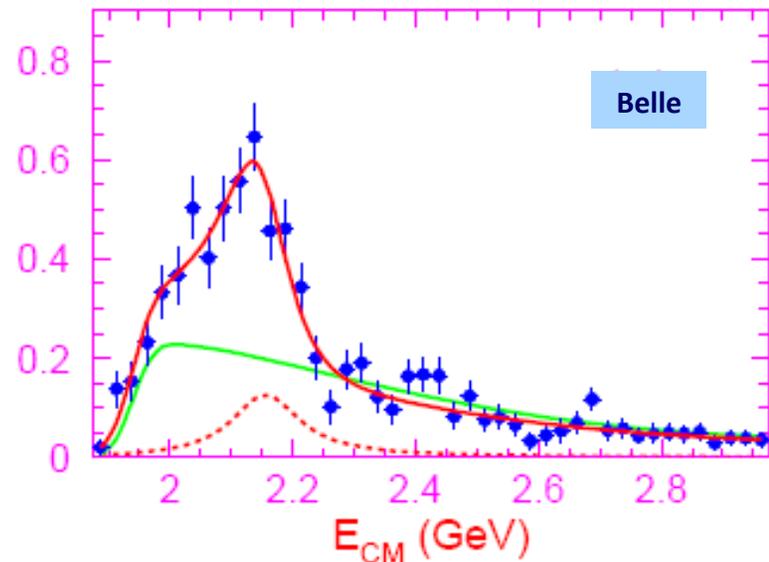
$M(f_0(980)\phi)$  GeV

$J/\psi \rightarrow \eta \phi f_0(980)$

X. Wan X.Y. Shen F. Liu

**M. Ablikim et al (BES)**  
**PRL 100, 102003 (2008)**

$\sigma(e^+e^- \rightarrow f_0(980)\phi(1020))$



C.P. Shen et al (Belle) arXiv: 0808.0006

# Summary

# XYZ meson candidates

State	$M$ (MeV)	$\Gamma$ (MeV)	$J^{PC}$	Decay Modes	Production Modes
$Y_s(2175)$	$2175 \pm 8$	$58 \pm 26$	$1^{--}$	$\phi f_0(980)$	$e^+e^-$ (ISR) $J/\psi \rightarrow \eta Y_s(2175)$
$X(3872)$	$3871.4 \pm 0.6$	$< 2.3$	$1^{++}$	$\pi^+\pi^- J/\psi,$ $\gamma J/\psi, DD^*$	$B \rightarrow KX(3872), p\bar{p}$
$X(3915)$	$3914 \pm 4$	$23 \pm 9$	$0/2^{++}$	$\omega J/\psi$	$\gamma\gamma \rightarrow X(3915)$
$Z(3930)$	$3929 \pm 5$	$29 \pm 10$	$2^{++}$	$DD$	$\gamma\gamma \rightarrow Z(3940)$
$X(3940)$	$3942 \pm 9$	$37 \pm 17$	$0^{?+}$	$DD\bar{D}^*$ (not $DD\bar{D}$ or $\omega J/\psi$ )	$e^+e^- \rightarrow J/\psi X(3940)$
$Y(3940)$	$3943 \pm 17$	$87 \pm 34$	$?^{?+}$	$\omega J/\psi$ (not $DD\bar{D}^*$ )	$B \rightarrow KY(3940)$
$Y(4008)$	$4008^{+82}_{-49}$	$226^{+97}_{-80}$	$1^{--}$	$\pi^+\pi^- J/\psi$	$e^+e^-$ (ISR)
$X(4160)$	$4156 \pm 29$	$139^{+113}_{-65}$	$0^{?+}$	$D^*\bar{D}^*$ (not $DD\bar{D}$ )	$e^+e^- \rightarrow J/\psi X(4160)$
$Y(4260)$	$4264 \pm 12$	$83 \pm 22$	$1^{--}$	$\pi^+\pi^- J/\psi$	$e^+e^-$ (ISR)
$Y(4350)$	$4361 \pm 13$	$74 \pm 18$	$1^{--}$	$\pi^+\pi^- \psi'$	$e^+e^-$ (ISR)
$X(4630)$	$4634^{+9}_{-11}$	$92^{+41}_{-32}$	$1^{--}$	$\Lambda_c^+\Lambda_c^-$	$e^+e^-$ (ISR)
$Y(4660)$	$4664 \pm 12$	$48 \pm 15$	$1^{--}$	$\pi^+\pi^- \psi'$	$e^+e^-$ (ISR)
$Z(4050)$	$4051^{+24}_{-23}$	$82^{+51}_{-29}$	$?$	$\pi^\pm \chi_{c1}$	$B \rightarrow KZ^\pm(4050)$
$Z(4250)$	$4248^{+185}_{-45}$	$177^{+320}_{-72}$	$?$	$\pi^\pm \chi_{c1}$	$B \rightarrow KZ^\pm(4250)$
$Z(4430)$	$4433 \pm 5$	$45^{+35}_{-18}$	$?$	$\pi^\pm \psi'$	$B \rightarrow KZ^\pm(4430)$
$Z_b(10610)$	$10608 \pm 2$	$15 \pm 3$	$1^+$	$\pi^\pm \eta_b(1,2P), \pi^\pm Y(1,2,3S)$	" $Y_{5S}$ " $\rightarrow \pi Z_b(10610)^\pm$
$Z_b(10610)$	$10653 \pm 2$	$14 \pm 3$	$1^+$	$\pi^\pm \eta_b(1,2P), \pi^\pm Y(1,2,3S)$	" $Y_{5S}$ " $\rightarrow \pi Z_b(10650)^\pm$

Large partial widths for decays to hidden quarkonium states

# remarks

- **Quarkonium mesons are strong evidence for quarks**
  - All the lowest-lying charmonium states have been found
  - Good agreement between their measured properties & theory
  - Charmonium is the “best understood” hadronic system
  - Most of the lowest-lying bottomonium states have been found
- **Higher-mass  $QQ$  meson searches produced surprises**
  - A number of non-quarkonium meson candidates have been found.
  - They have strong transitions to ordinary quarkonium states
  - Corresponding states may exist in the s-quark sector
- **The  $b\bar{b}$  system in the  $\Upsilon(5S)$  vicinity is very mysterious**
  - “factory” for producing charged bottomonium-like states
- **Lots to do at current & future experiments**

Thank You

Merci

どもう ありがとう

감사합니다

謝謝