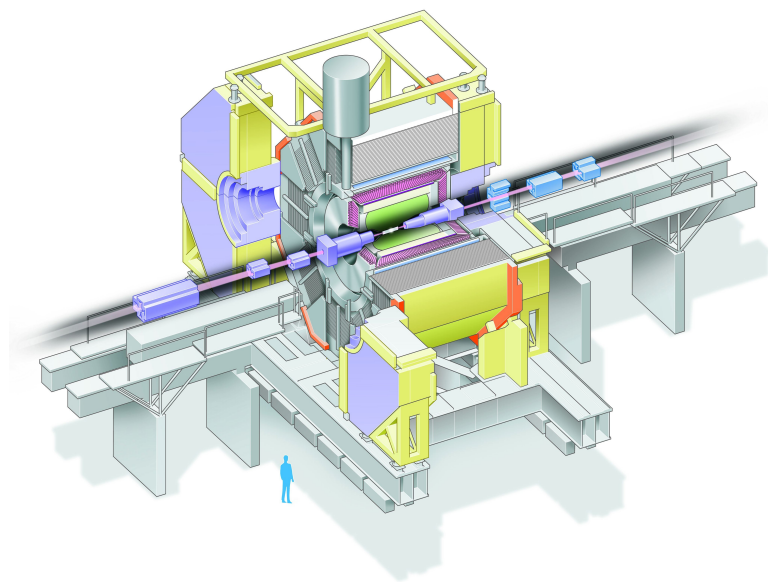


# Hadron physics and spectroscopy

("decade of the revival of hadron spectroscopy")

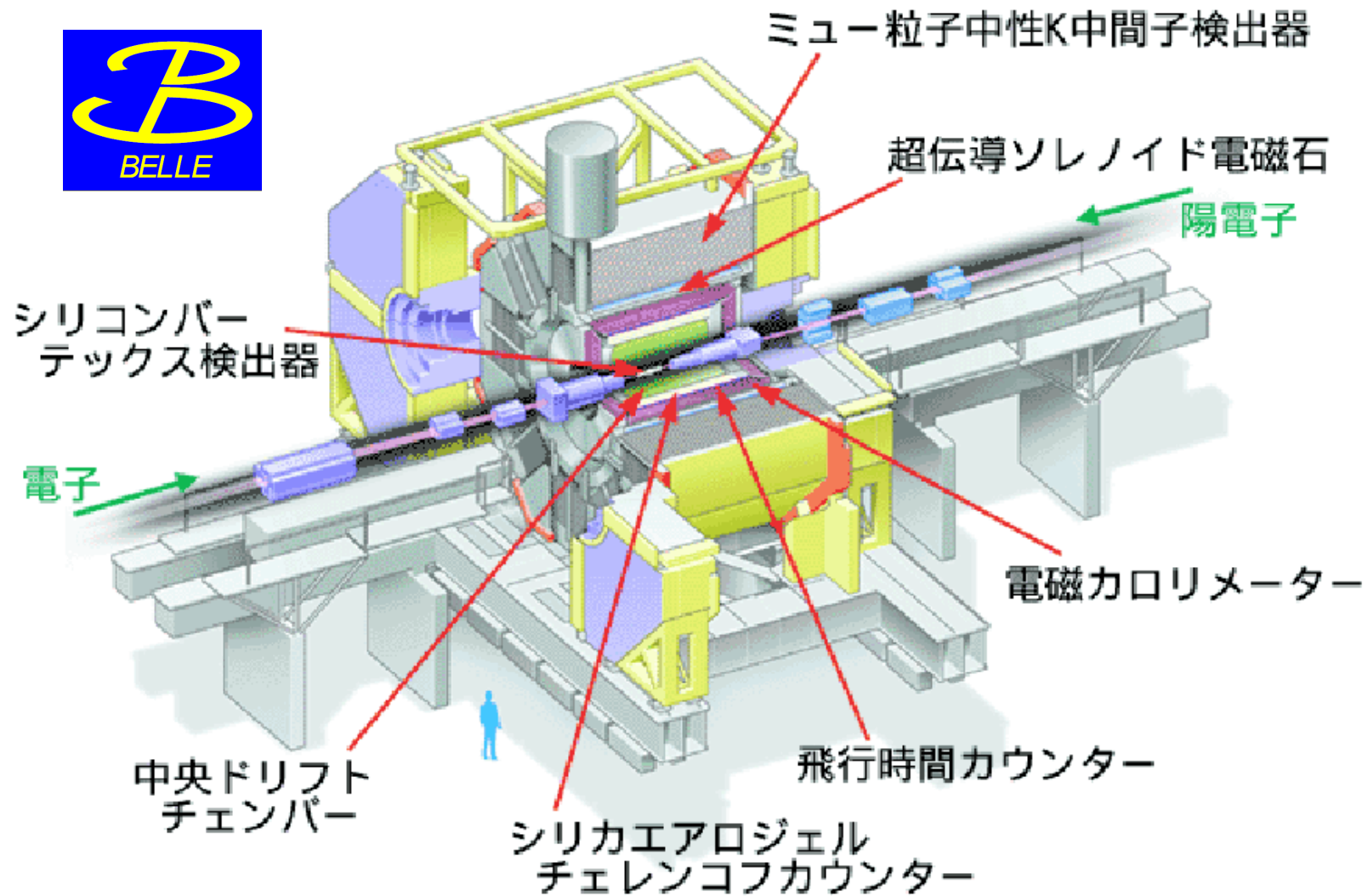


K.Trabelsi  
([karim.trabelsi@kek.jp](mailto:karim.trabelsi@kek.jp))

50 Cracow School of Theoretical Physics

Zakopane, 15<sup>th</sup> June, 2010

# Belle, one of the 2 factories (see H.Palka' talk)

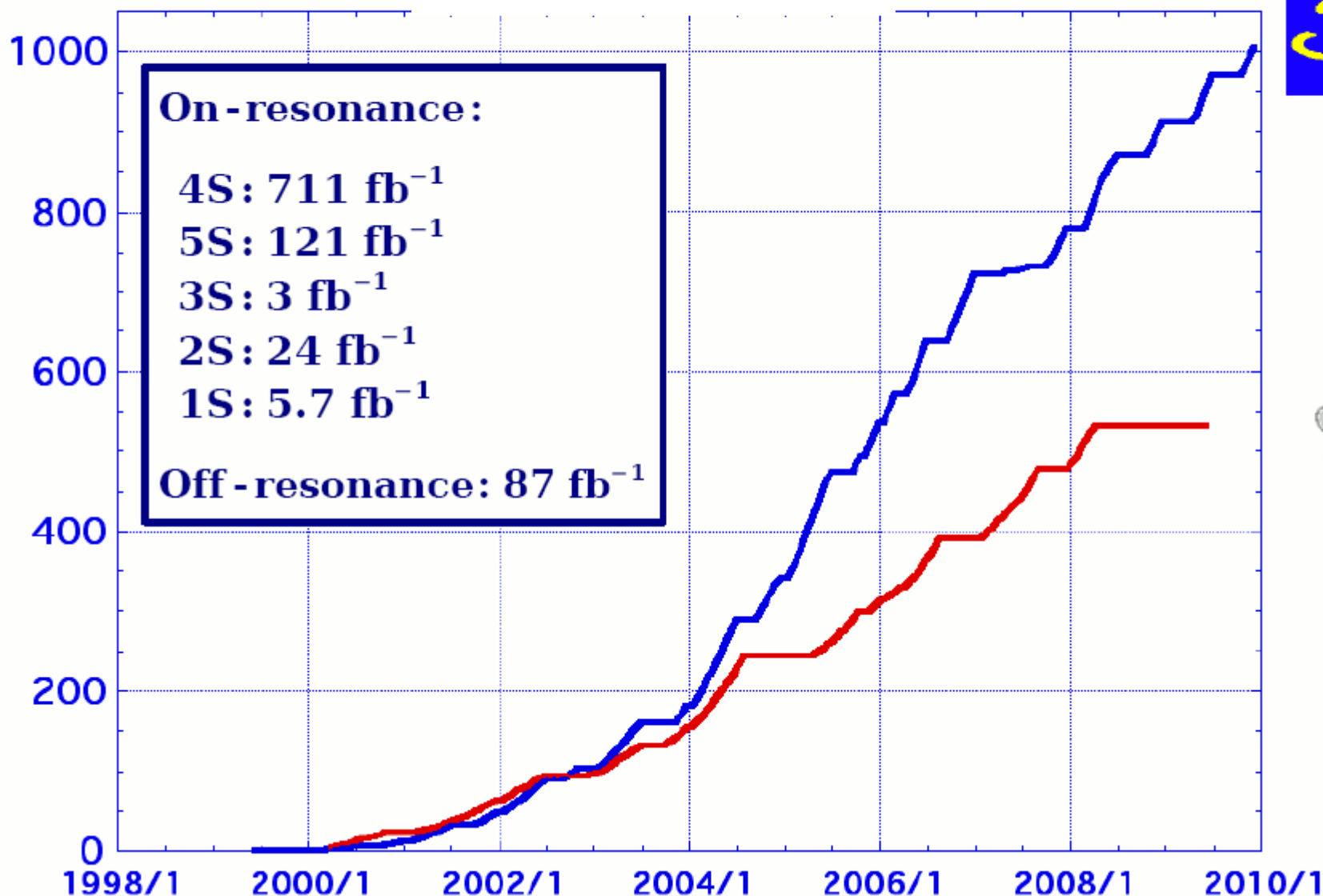


constructed to test the Standard Model mechanism for CP violation  
⇒ charmonium modes ( $B \rightarrow J/\psi K^0$ ) (see A.Buras' talk)

unexpected contribution to the field of hadron spectroscopy (charmonium)

# Integrated luminosity ( $\text{fb}^{-1}$ )

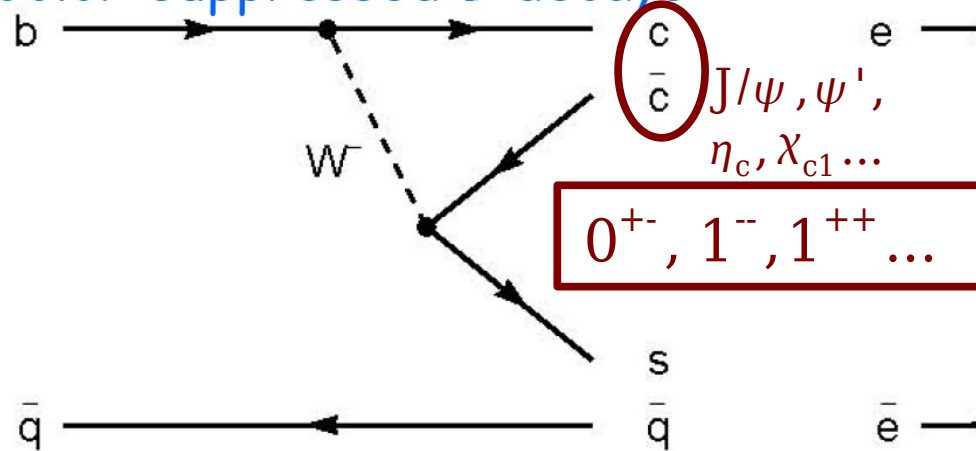
$> 1 \text{ ab}^{-1}$  !



**data taken mostly at  $\Upsilon(4S)$  ( $\sqrt{s} = 10.58 \text{ GeV}$ )**  
(but not only: largest samples of  $\Upsilon(1S)$ ,  $\Upsilon(2S)$ ,  $\Upsilon(5S)$ )

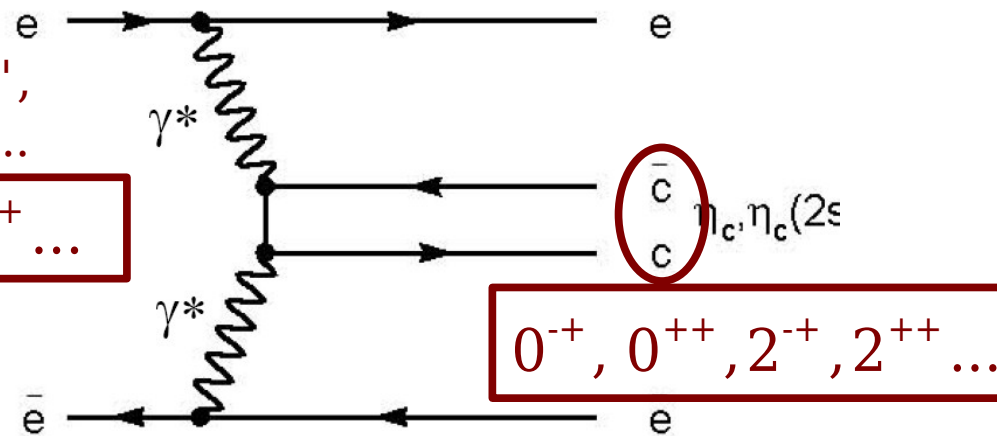
# B-factories produce lots of $c\bar{c}$ -like pairs

## Color-suppressed B decays



$\text{Brs} \sim 10^{-2}$  (inclusive)

## Two photon Production



At  $\Upsilon(4S)$  peak,  $\sigma(B\bar{B}) \sim 1.2 \text{ nb}$   
 $\Rightarrow \text{fb}^{-1} \equiv 10^6 B\bar{B}$  pairs

B mesons decay with a  $\sim 10^{-3}$  probability to  $c\bar{c}$  and  $K^{(*)}$

reconstruction with low bckg

$J^{PC}$  from angular analysis

initial  $e^-$  and  $e^+$  emit  $\gamma$  at small angles  
 hadronic system (H) produced in  $\gamma^* \gamma^*$   
 has small total energy, small  $P_t$   
 $e^+$  and  $e^-$  not detected

$\Rightarrow c\bar{c}$  states produced without additional hadrons: clean conditions

H has  $C=+$

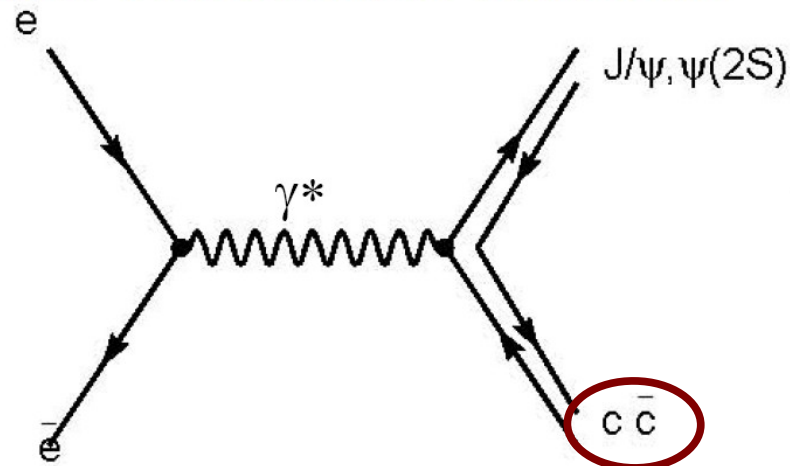
# B-factories produce lots of $c\bar{c}$ -like pairs

reconstruct one  $c\bar{c}$  ( $J/\psi$ )  
look at recoil mass  
other  $c\bar{c}$  not fully reconstructed  
 $\Rightarrow$  higher efficiency

hard  $\gamma$  emitted by an initial  $e^-$  ( $e^+$ )  
before annihilation  
 $\Rightarrow$  annihilation at smaller energy !  
whole continuous spectrum can be studied

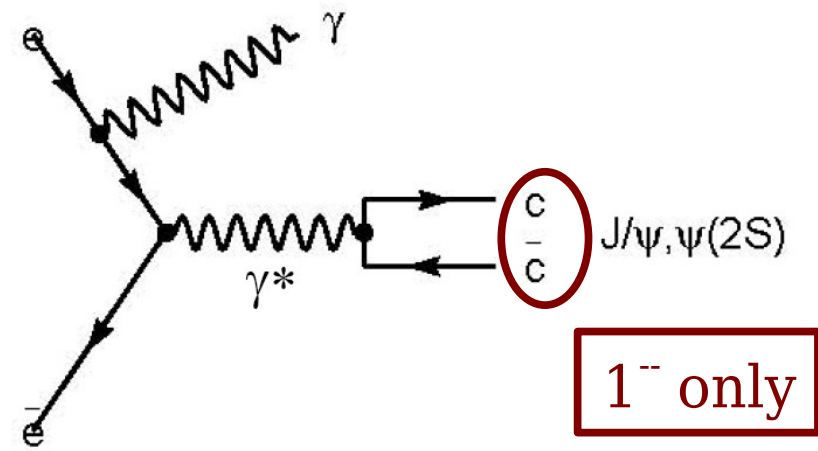
$$J^{PC} = 1^{--} \text{ only}$$

Double Charmonium Production



$C = +$  states

Initial State Radiation



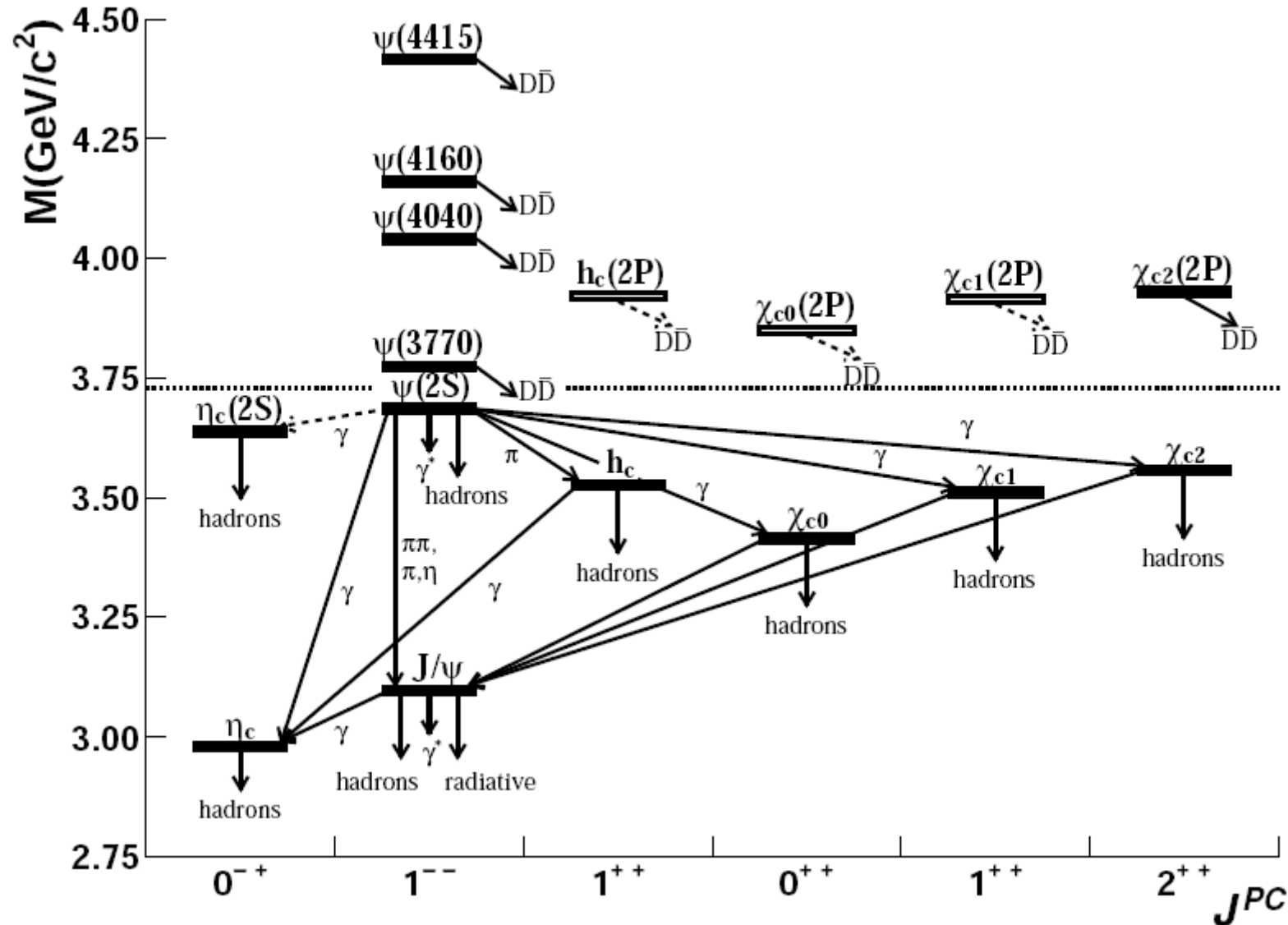
$1^{--}$  only

# Charmonium system

Ten  $c\bar{c}$  states found in 1974-1980:

$\Rightarrow J/\psi, \eta_c(1S), \chi_{c0}(1P), \chi_{c1}(1P), \chi_{c2}(1P), \psi(2S)$  below

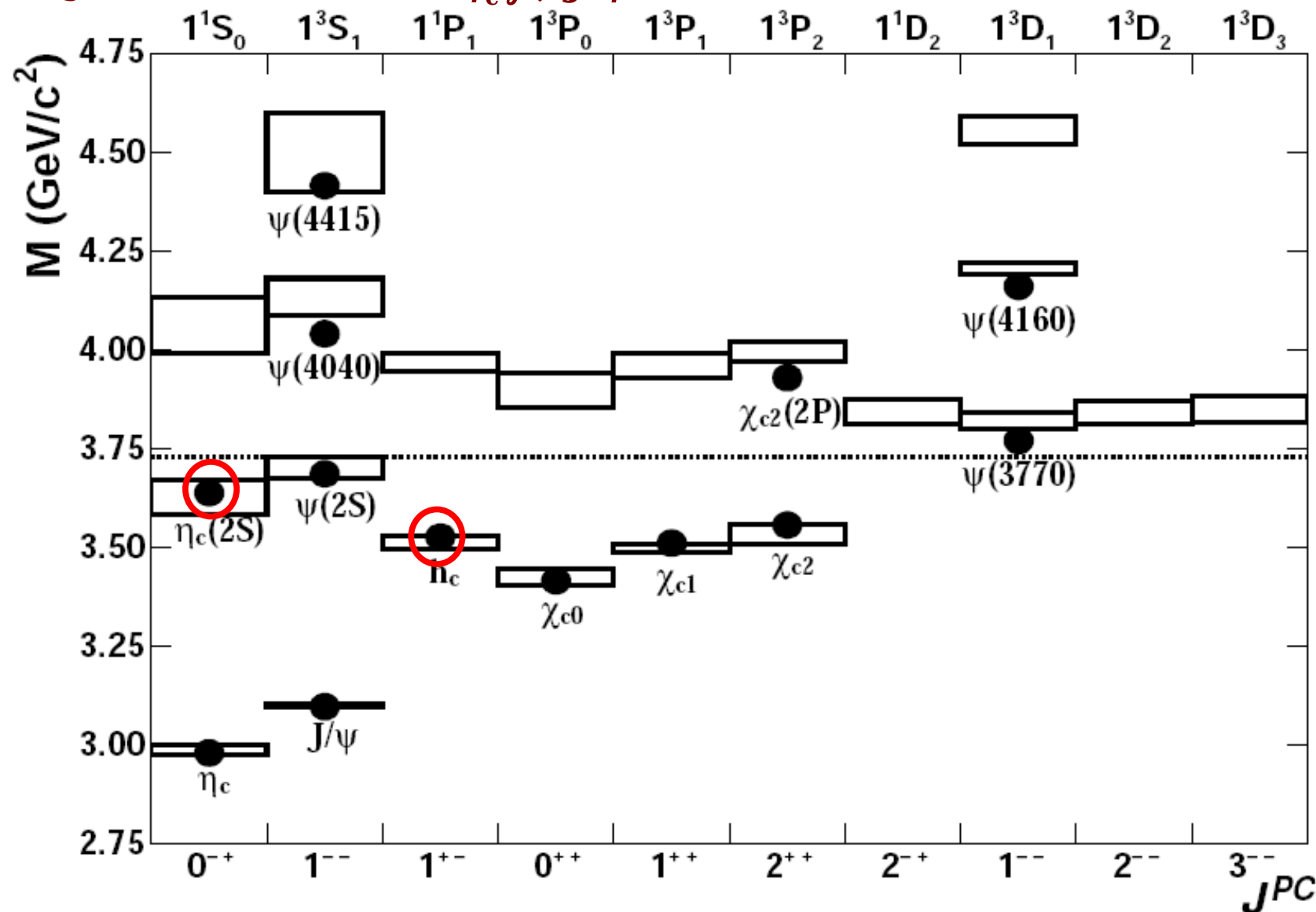
$\Rightarrow \psi(3770), \psi(4040), \psi(4160), \psi(4415)$  above the open charm threshold



with  $\eta_c(2S)$  (in 2002) and  $h_c(1P)$  (in 2005) the  $c\bar{c}$  system seemed understood...

# Predictions of Potential Model

with  $\eta_c(2S)$  (in 2002) and  $h_c(1P)$  (in 2005) the  $c\bar{c}$  system seemed understood...  
 $\rightarrow K_S K \pi$   $\rightarrow \eta_c \gamma, J/\psi \pi^0$



remain some  $c\bar{c}$  to observe above  $D\bar{D}$  threshold

the only difficulties: broad resonances, expected decay modes are  $DD^{(*)}$  etc...



# Many ( $> 10$ ) states poorly consistent with quark model (observed last 6 years by B-factories)

(decaying to  $c\bar{c}X$  rather than to open charm unexpectedly found)

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) $J/\psi \rightarrow \eta Y_s(2175)$
$X(3872)$	$3871.4 \pm 0.6$	$< 2.3$	$1^{++}$	$\pi^+\pi^- J/\psi,$ $\gamma J/\psi, D\bar{D}^*$	$B \rightarrow KX(3872), p\bar{p}$
$X(3915)$	$3914 \pm 4$	$23 \pm 9$	$0/2^{++}$	$\omega J/\psi$	$\gamma\gamma \rightarrow X(3915)$
$Z(3930)$	$3929 \pm 5$	$29 \pm 10$	$2^{++}$	$D\bar{D}$	$\gamma\gamma \rightarrow Z(3940)$
$X(3940)$	$3942 \pm 9$	$37 \pm 17$	$0^{?+}$	$D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$ )	$e^+e^- \rightarrow J/\psi X(3940)$
$Y(3940)$	$3943 \pm 17$	$87 \pm 34$	$?^{?+}$	$\omega J/\psi$ (not $D\bar{D}^*$ )	$B \rightarrow KY(3940)$
$Y(4008)$	$4008^{+82}_{-49}$	$226^{+97}_{-80}$	$1^{--}$	$\pi^+\pi^- J/\psi$	$e^+e^-$ (ISR)
$X(4160)$	$4156 \pm 29$	$139^{+113}_{-65}$	$0^{?+}$	$D^*\bar{D}^*$ (not $D\bar{D}$ )	$e^+e^- \rightarrow J/\psi X(4160)$
$Y(4260)$	$4264 \pm 12$	$83 \pm 22$	$1^{--}$	$\pi^+\pi^- J/\psi$	$e^+e^-$ (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)
$Z(4050)$	$4051^{+24}_{-23}$	$82^{+51}_{-29}$	$?$	$\pi^\pm \chi_{c1}$	$B \rightarrow KZ^\pm(4050)$
$Z(4250)$	$4248^{+185}_{-45}$	$177^{+320}_{-72}$	$?$	$\pi^\pm \chi_{c1}$	$B \rightarrow KZ^\pm(4250)$
$Z(4430)$	$4433 \pm 5$	$45^{+35}_{-18}$	$?$	$\pi^\pm \psi'$	$B \rightarrow KZ^\pm(4430)$
$Y_b(10890)$	$10,890 \pm 3$	$55 \pm 9$	$1^{--}$	$\pi^+\pi^- \Upsilon(1, 2, 3S)$	$e^+e^- \rightarrow Y_b$

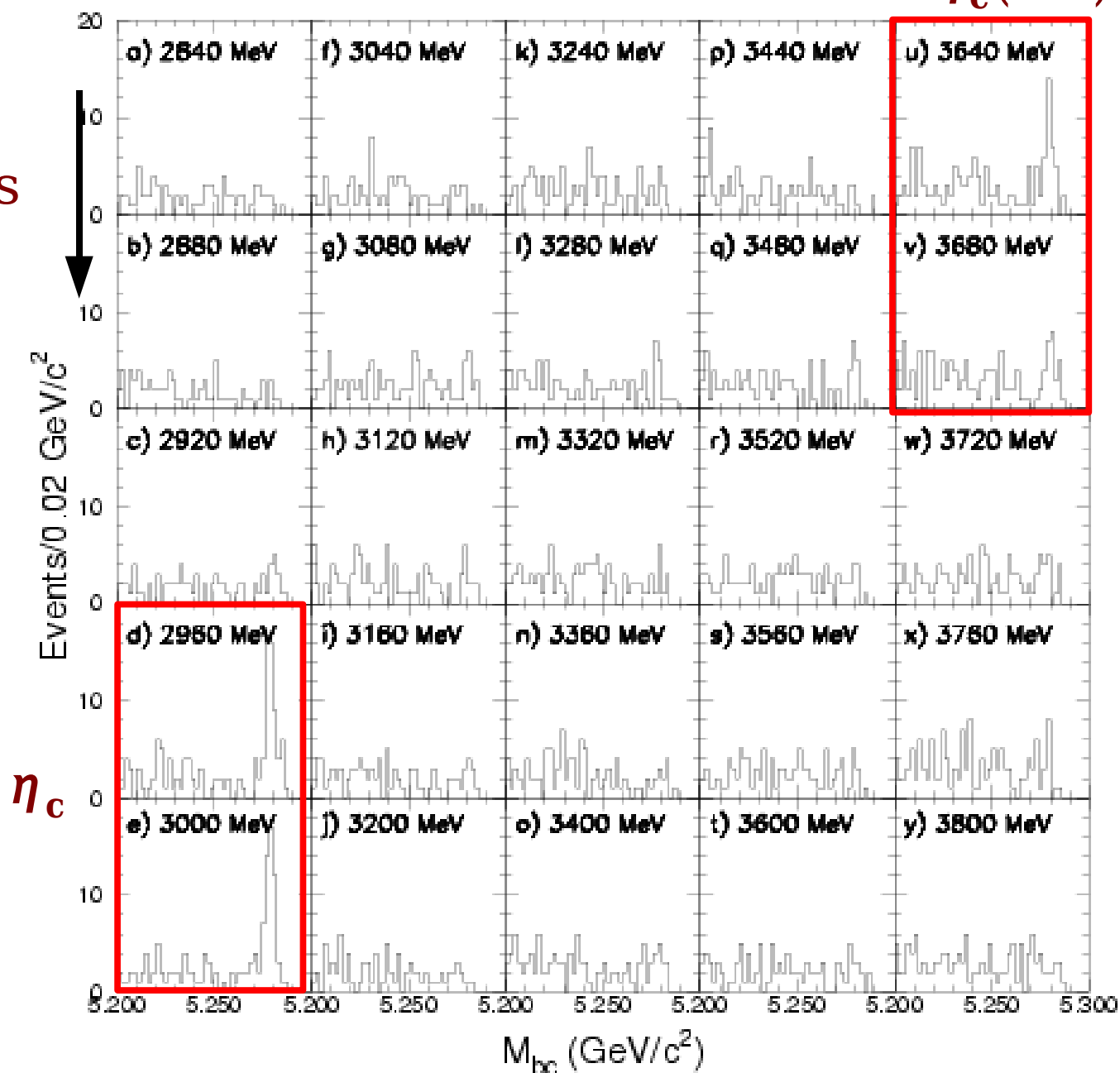


# A typical example : reconstruct $B \rightarrow K(K_S K^- \pi^+)$

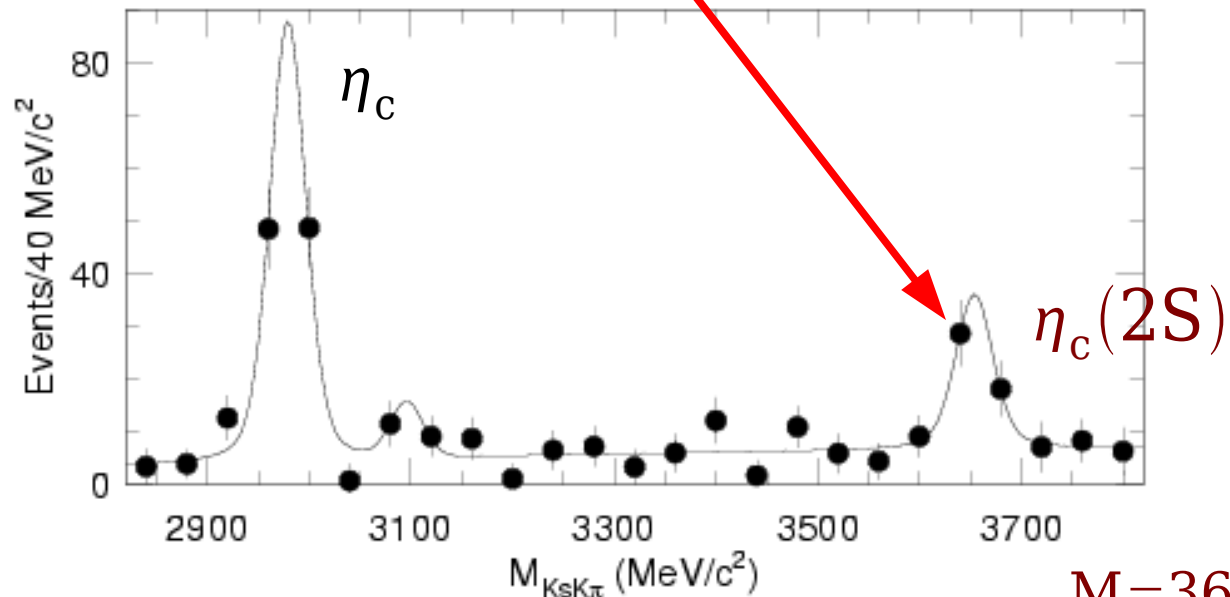
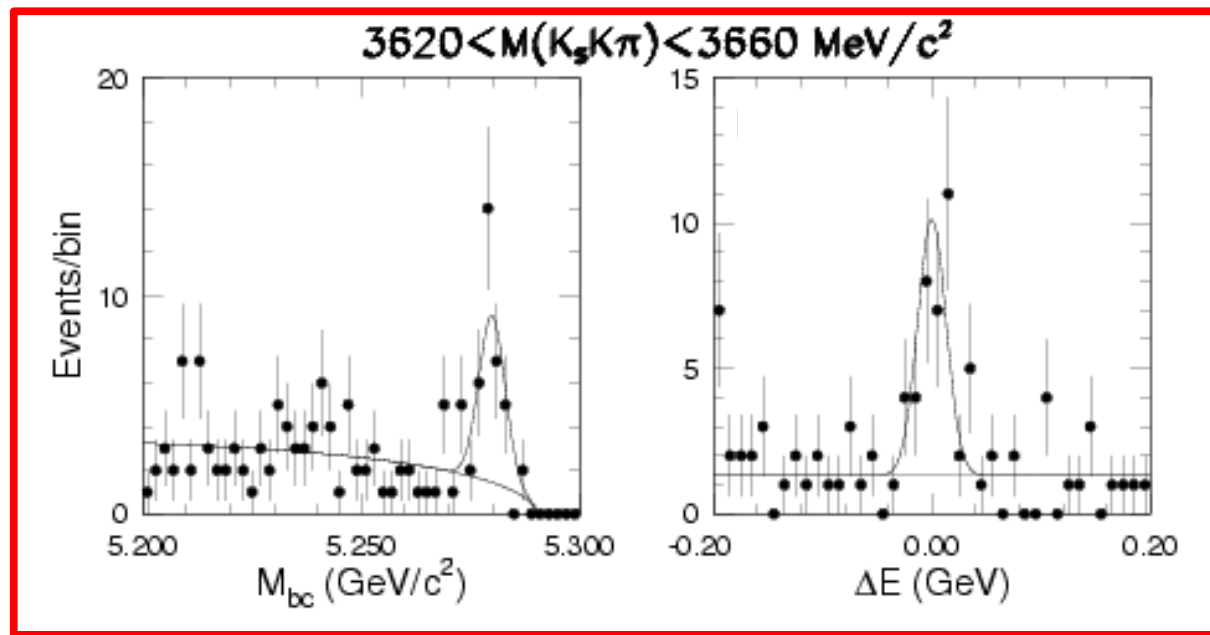
PRL89,102001(2002)

$\eta_c(2S)$

Fit  $M_{bc}$  in bins of  
 $K_S K^- \pi^+$  invariant mass  
of  $40 \text{ MeV}/c^2$



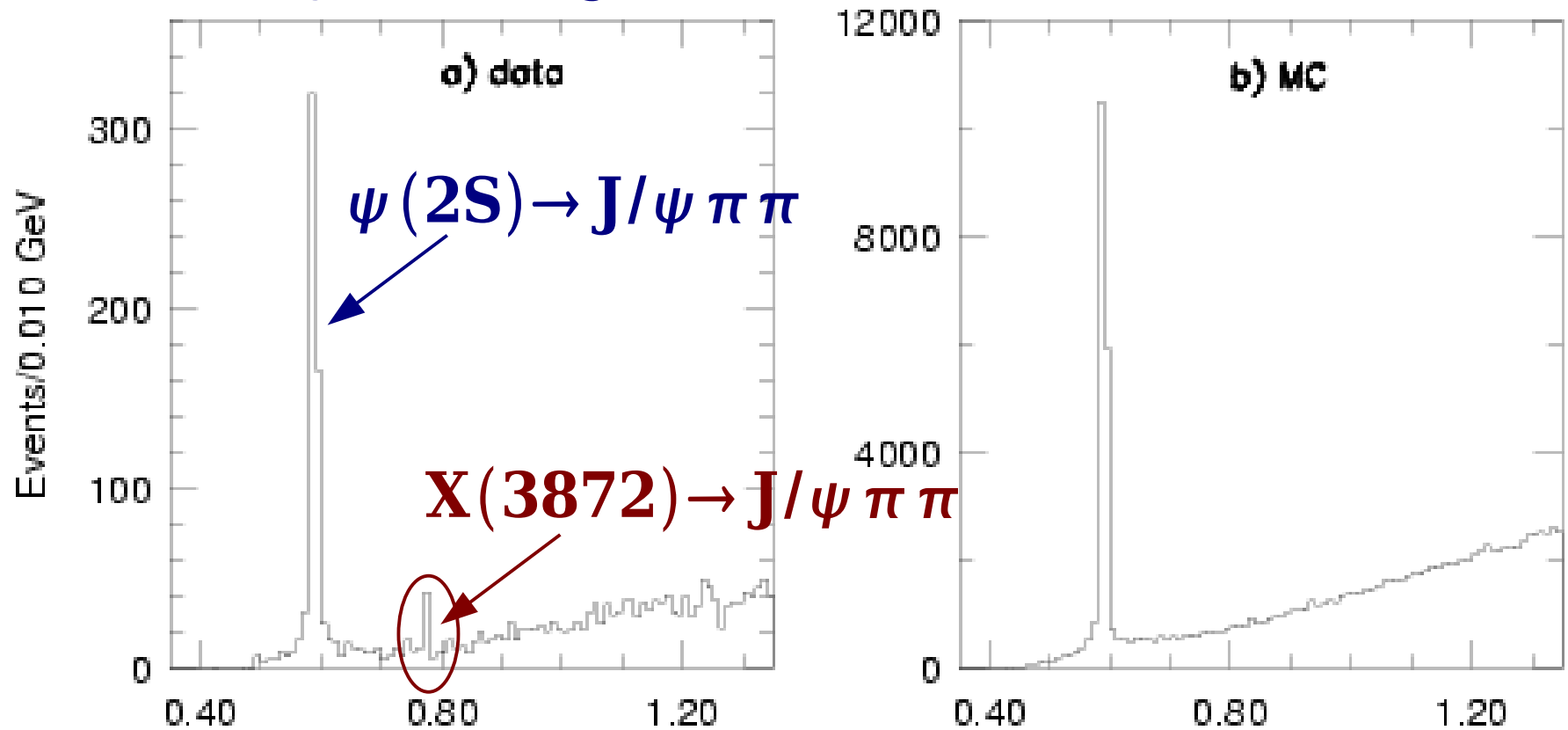
# $B \rightarrow K K_s K^- \pi^+$ to see $\eta_c(2S)$ PRL89,102001(2002)



$\Sigma > 6\sigma$   
 $M = 3654 \pm 6 \pm 8 \text{ MeV/c}^2$   
 $\Gamma < 55 \text{ MeV/c}^2$

# X(3872) first observation PRL91,262001 (2003)

$B \rightarrow K \pi^+ \pi^- J/\psi$  using  $140 \text{ fb}^{-1}$



$M(\pi^+ \pi^- J/\psi) - M(J/\psi)$  (GeV)

$N = 35.7 \pm 6.8$

significance  $10 \sigma$

$M(\pi^+ \pi^- J/\psi) - M(J/\psi)$  (GeV)

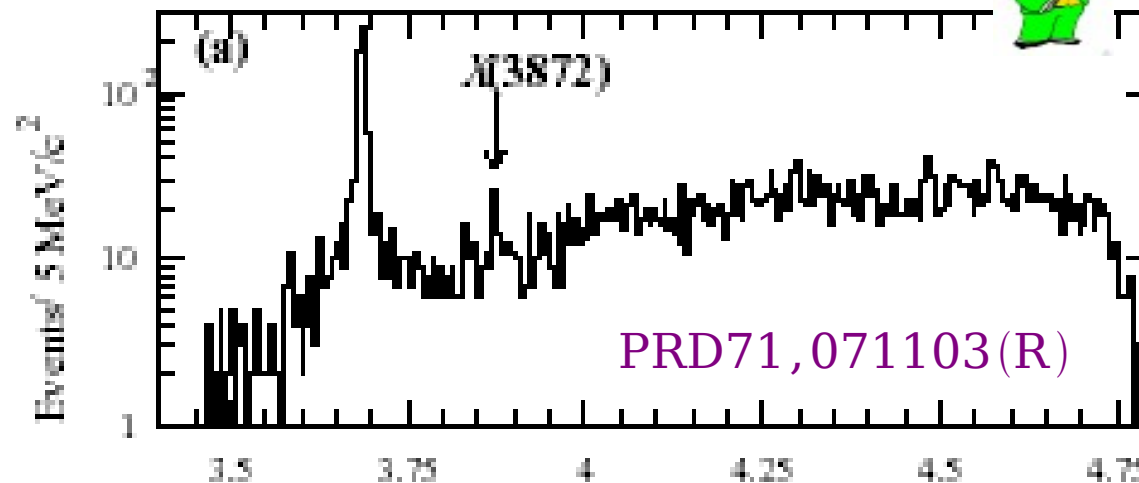
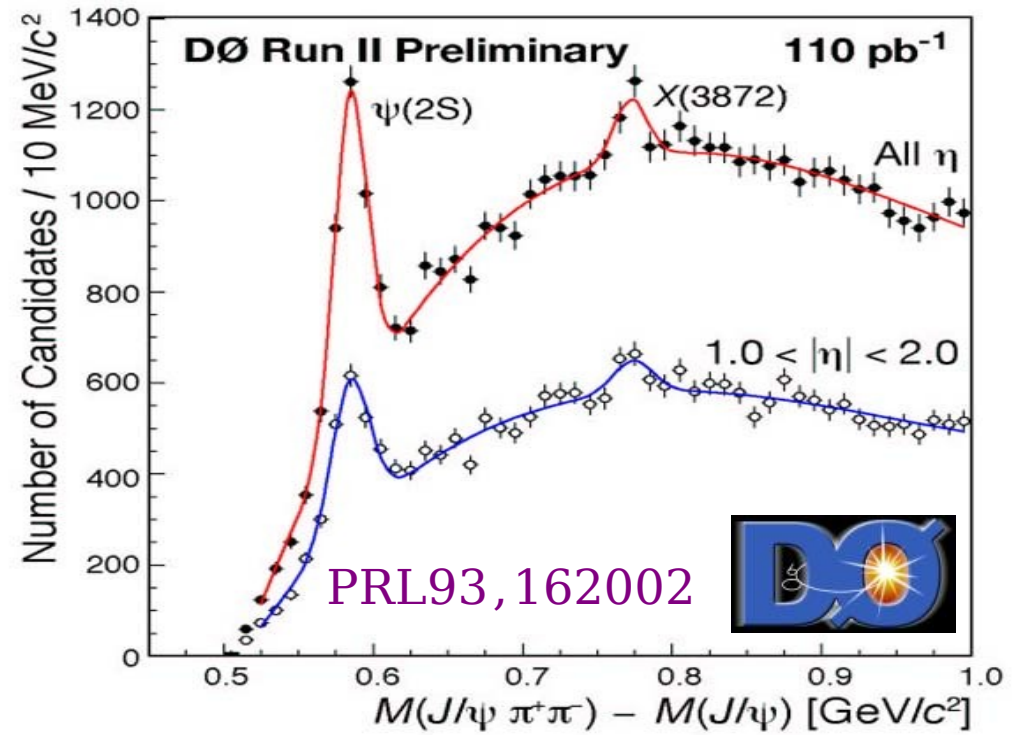
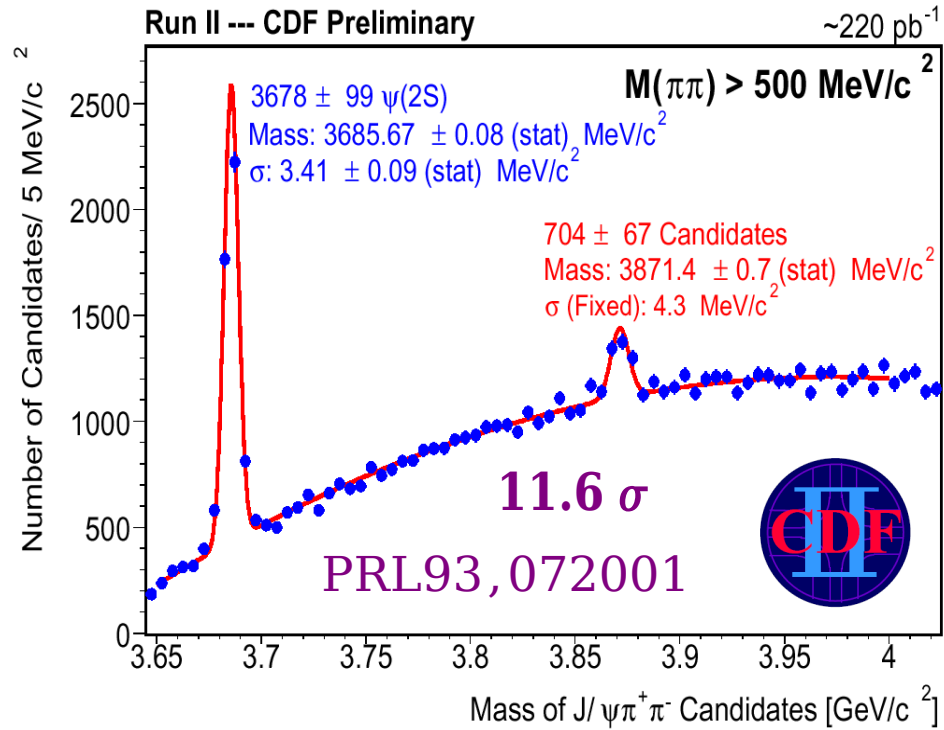
$(3872 \pm 0.6 \pm 0.5) \text{ MeV}/c^2 \sim m_{D^0} + m_{D^{*0}}$

$[m_{D^0} + m_{D^{*0}} = (3871.55 \pm 0.44) \text{ MeV}/c^2]$

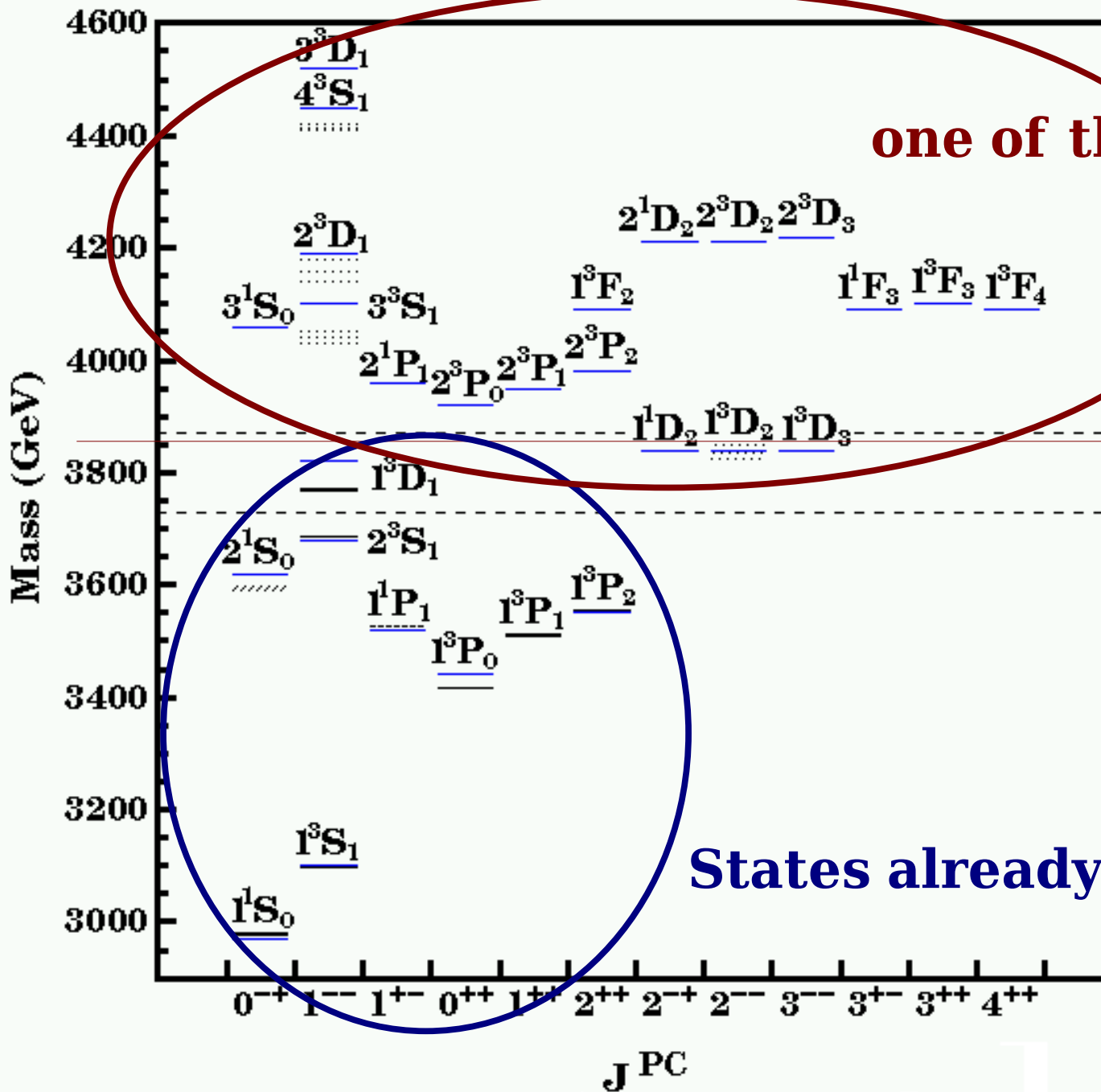
$\Gamma < 2.3 \text{ MeV}$

X is narrow and doesn't decay to  $D \bar{D}$  [PRL93, 051803 (2004)]

# X(3872) confirmed by 3 other experiments



# Is it a $c\bar{c}$ meson ?



**one of these states ?**

# 3872 MeV

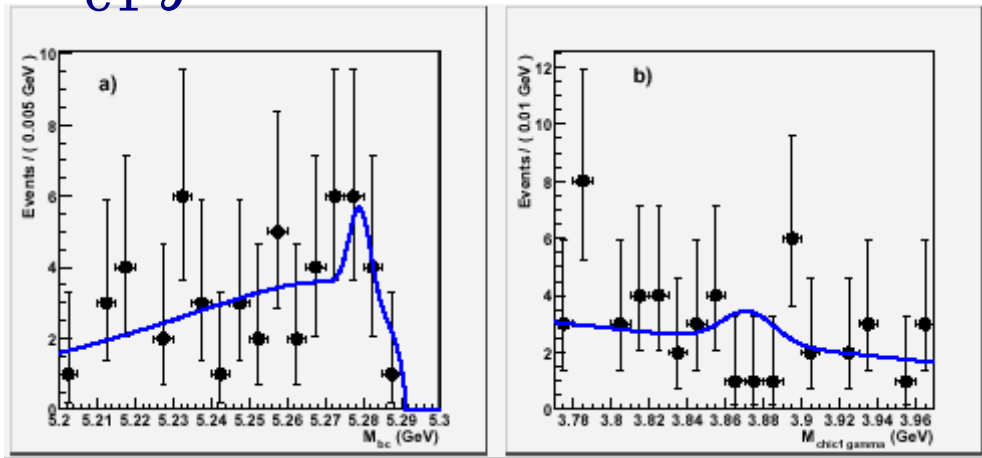
## States already identified

# Non observation of $X(3872) \rightarrow \chi_{cJ} \gamma$ decays

PRL91,262001(2003)

The radiative decays to  $\chi_{cJ} \gamma$  expected to be large for some charmonium states... but not found

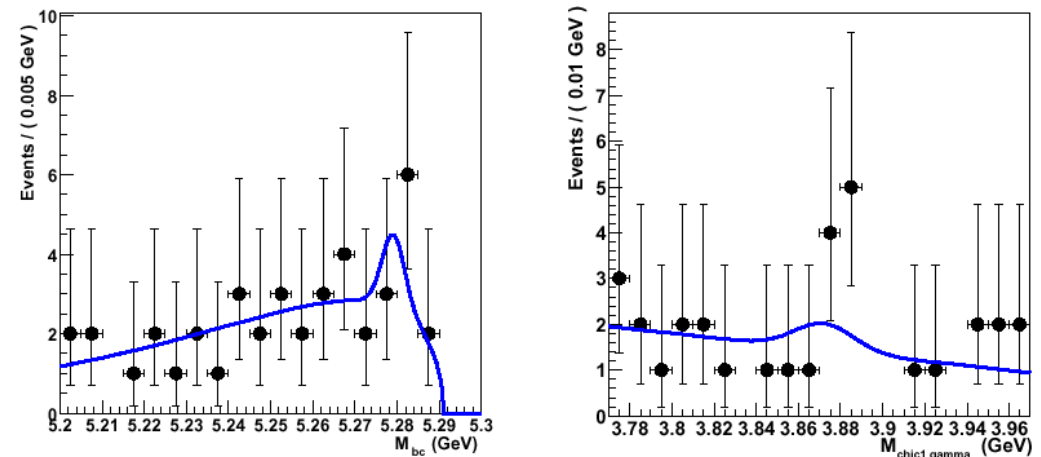
$\chi_{c1} \gamma K$



$M_{bc}$

$M(\chi_{c1} \gamma)$

$\chi_{c2} \gamma K$



$M_{bc}$

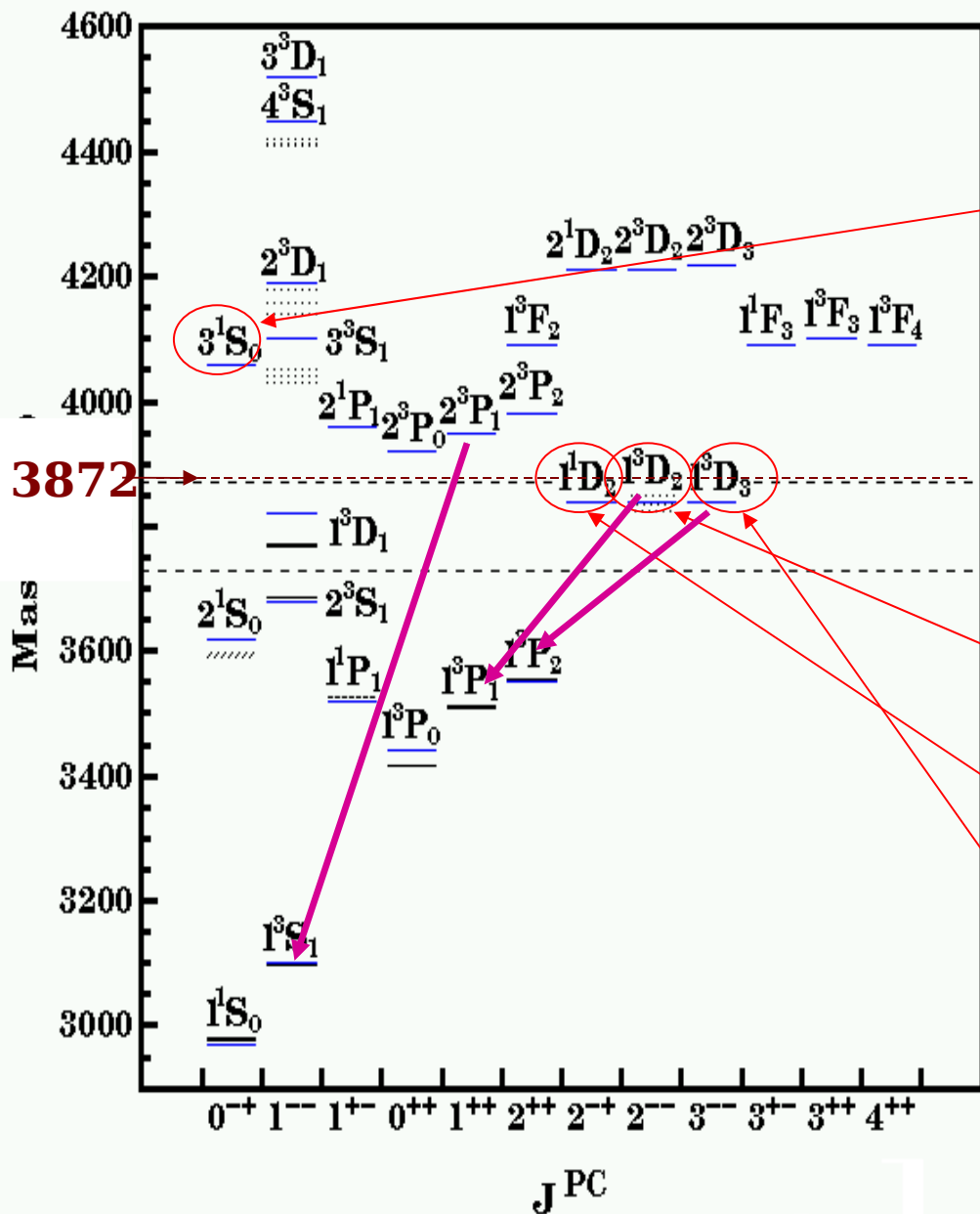
$M(\chi_{c2} \gamma)$

**$B(X \rightarrow \chi_{c1} \gamma) / B(X \rightarrow J \psi \pi^+ \pi^-) < 0.9$  at 90%CL  $X \equiv \psi_2$  expect  $> 1.6$**   
 [potential/ $\psi''$  Wigner-Eckart]

**$B(X \rightarrow \chi_{c2} \gamma) / B(X \rightarrow J \psi \pi^+ \pi^-) < 1.1$  at 90%CL  $X \equiv \psi_3$  expect  $> 3.5$**

# c $\bar{c}$ assignment ?

hep-ex/0407033



$\eta_c''$   $M$  too low and  $\Gamma$  too small

$\psi_2$   $\Gamma(\gamma \chi_{c1})$  too small  
 $M(\pi^+ \pi^-)$  wrong

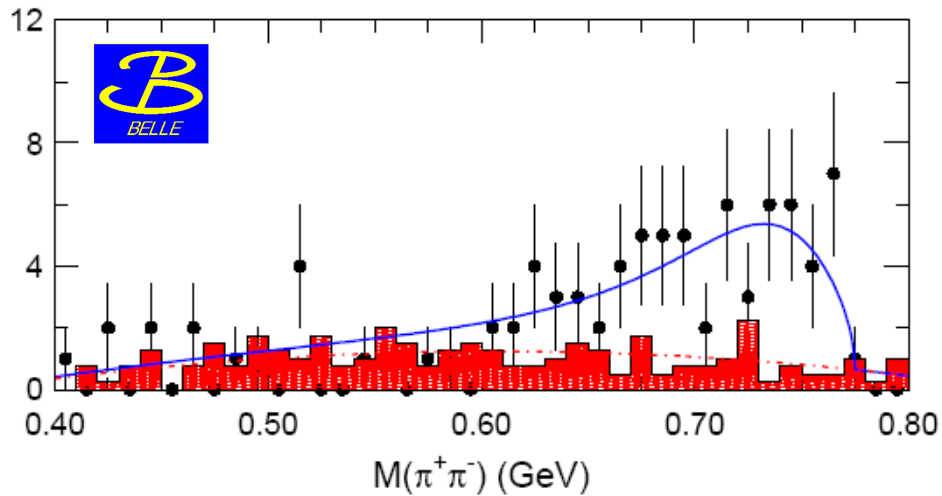
$\eta_{c2}$   $\pi \pi \eta_c$  should dominate

$\psi_3$   $\Gamma(\gamma \chi_{c2} \&\& D \bar{D})$  too small



# $M_{\pi\pi}$ looks like a $\rho$

concentration  $\rightarrow$  high  $M(\pi^+ \pi^-)$  favouring  $X(3872) \rightarrow \rho J/\psi$   
and hence  $C = +1$



charmonium states all Isosinglets  
decay charmonium  $\rightarrow \rho J/\psi$  violates isospin  
(should be strongly suppressed)

see also angular analysis

[[hep-ex/0505038](#)]

disfavouring  $0^{++}$ ,  $0^{-+}$

see also angular analysis

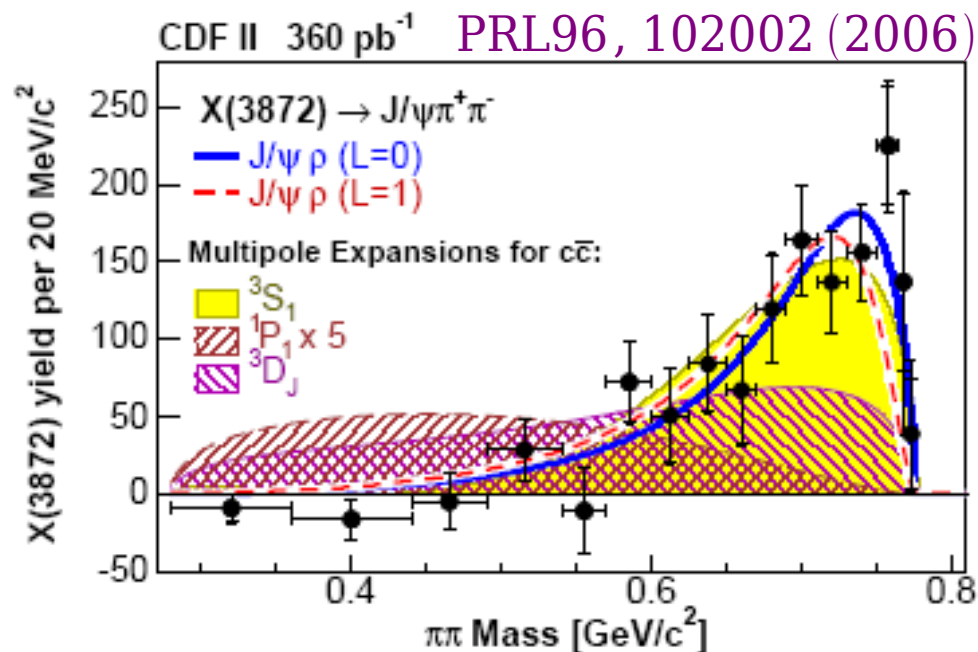
[[PRL98, 132002 \(2007\)](#)]

rules out  $h_c'$ ,  $\psi_J$  ...

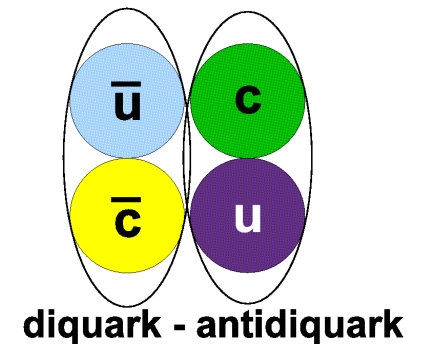
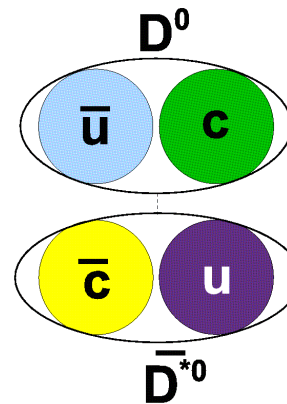
reinforces  $X(3872) \rightarrow \rho J/\psi$  ( $L=0$ ),  
 $J^{PC} = 1^{++}$  interpretation

puts  $L=1$ ,  $J^{PC}=2^{-+}$  possibility back  
in play:  $\eta_{c2}$  ... but

$\Gamma(\eta_{c2} \rightarrow \pi^+ \pi^- \eta_c)$  sh<sup>d</sup> be  $\gg \Gamma(\eta_{c2} \rightarrow \pi^+ \pi^- J/\psi)$



# Possible exotic interpretations...



## ○ four-quark model

(L.Maiani et al, PRL99: 182003, 2007)

$X_u = [cu][\bar{c}\bar{u}] = X$  state decaying into  $D^0 \bar{D}^0 \pi^0 = X(3876)$

$X_d = [cd][\bar{c}\bar{d}] = X$  state decaying into  $J/\psi \pi^+ \pi^- = X(3872)$

(finding the charged partner is critical)

(mass splitting ?)

## ○ molecule model ( $D^{*0} \bar{D}^0$ bound state)

$M_X$  close to the  $D^{*0} \bar{D}^0$  threshold

$1^{++}$ , favors  $D \bar{D} \pi^0$  decay over  $J/\psi \pi \pi$  over  $J/\psi \gamma$

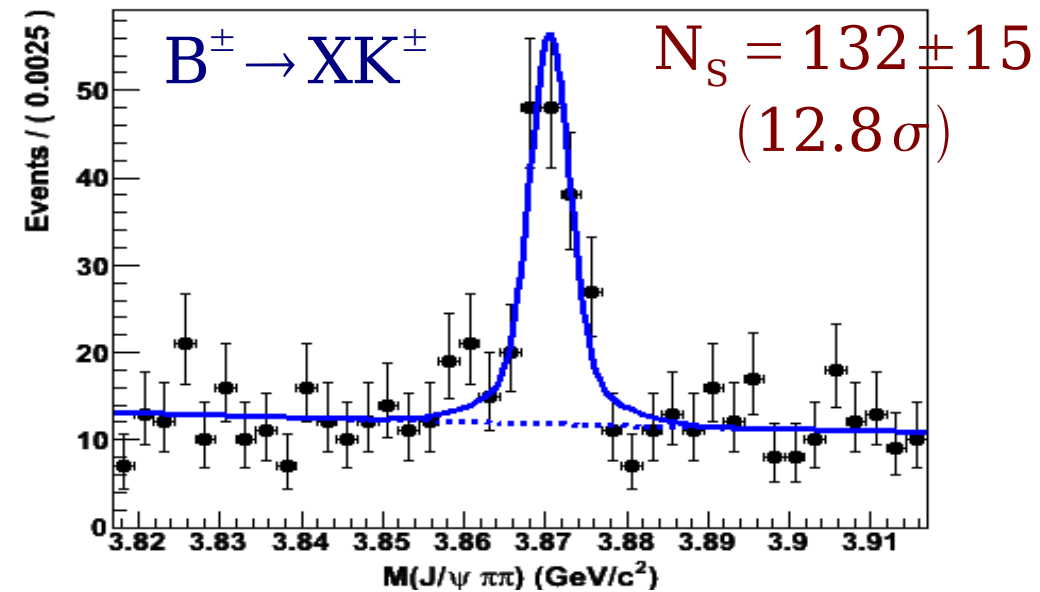
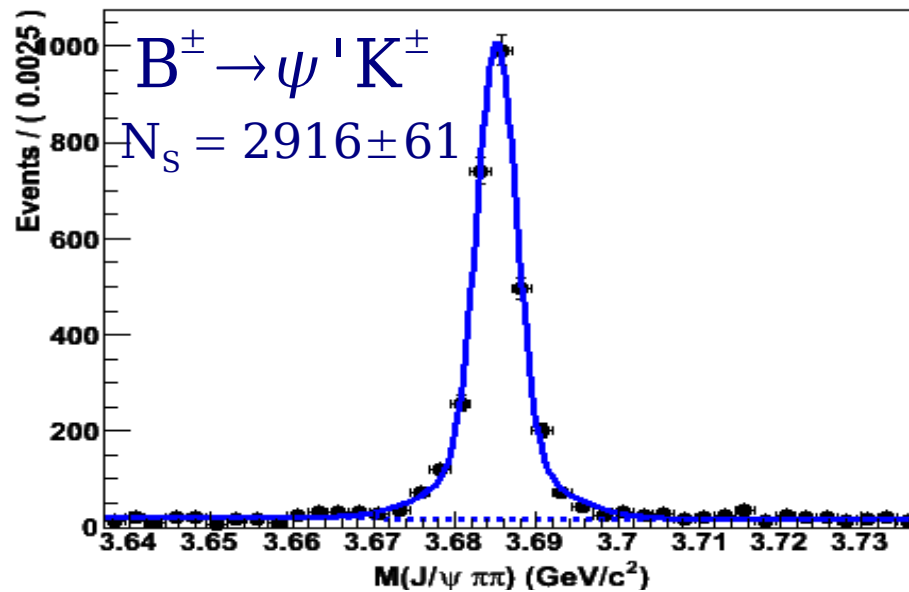
(E.Braaten et al, PRD77: 014029, 2008)

(line shapes of the X depends on its decay channel,  
different in  $B^+$  or  $B^0$  decays)

# Latest update with $605 \text{ fb}^{-1}$

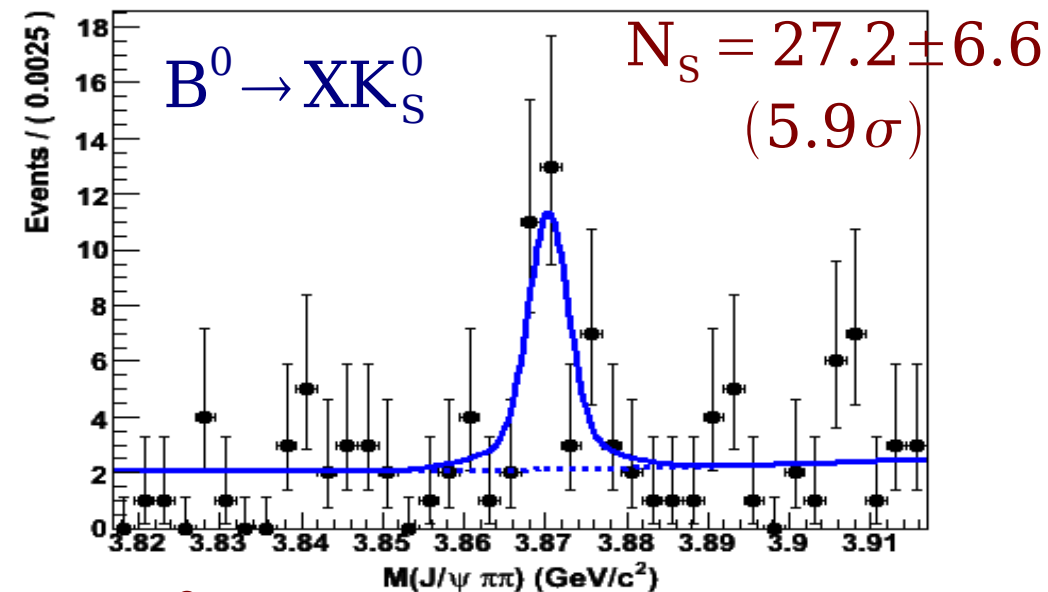
ArXiv:0809.1224

$B^\pm \rightarrow X(3872)K^\pm$  and  $B^0 \rightarrow X(3872)K_S^0$



distributions for  $\psi'$  and  $X(3872)$  are fitted simultaneously:

detector resolution effect is automatically calibrated by  $\psi'$



**First observation of  $B^0 \rightarrow X(3872)K_S^0$**

# $B^\pm \rightarrow X(3872) K^\pm$ and $B^0 \rightarrow X(3872) K^0$

ArXiv:0809.1224

$$\circ R = \frac{\text{BR}(B^0 \rightarrow X(3872) K^0)}{\text{BR}(B^\pm \rightarrow X(3872) K^\pm)} = 0.82 \pm 0.22 \pm 0.05$$

charged and neutral B mesons decay into  $X(3872)$  with comparable BR

$$\begin{aligned} \delta M_X &= M(X \text{ from } B^\pm) - M(X \text{ from } B^0) \\ &= (0.18 \pm 0.89 \pm 0.26) \text{ MeV} \end{aligned}$$

No mass splitting signature

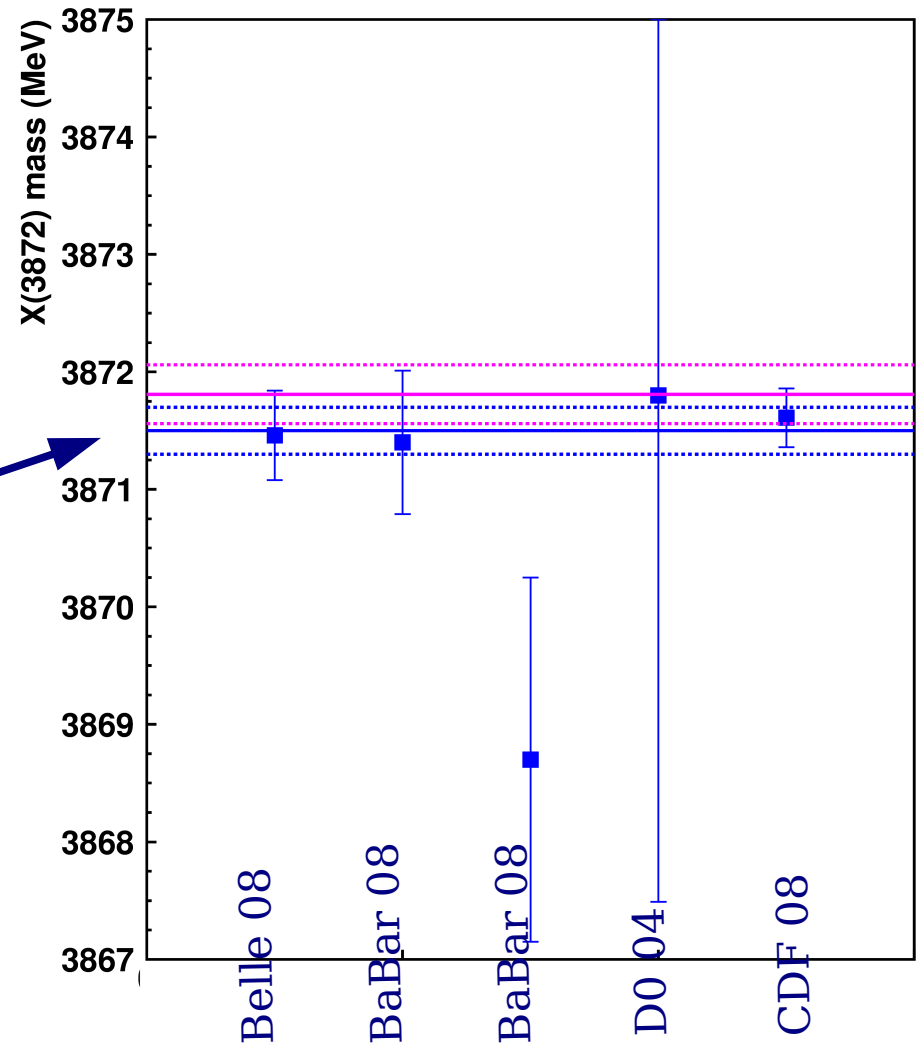
$$\mathbf{M_X = (3871.46 \pm 0.37 \pm 0.07) \text{ MeV}}$$

$$m_{D^0} + m_{D^{*0}} = 3871.81 \pm 0.36 \text{ MeV}$$

my naive average:

$$M_X = 3871.50 \pm 0.20 \text{ MeV}$$

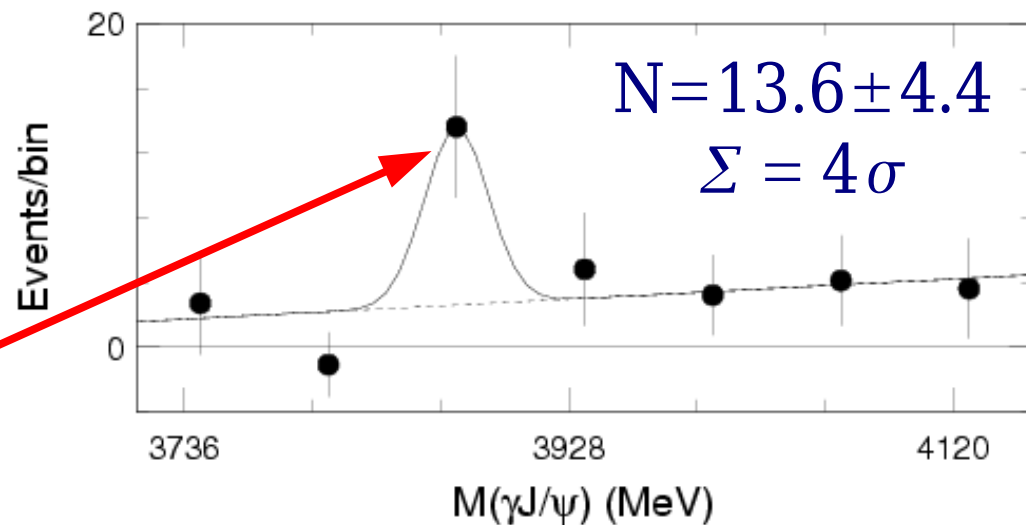
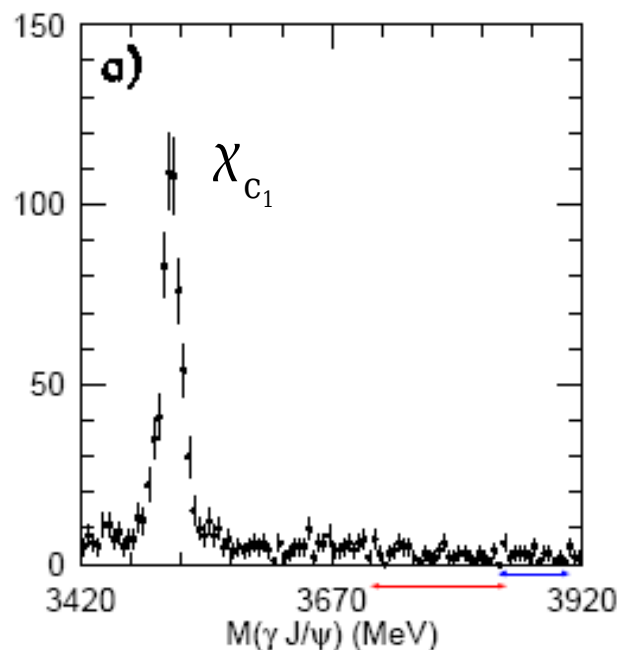
$$(\text{CDF: } M_X = 3871.61 \pm 0.16 \pm 0.19 \text{ MeV})$$



# Evidence for $X(3872) \rightarrow J/\psi \gamma$

hep-ex/0505037  
(256 fb<sup>-1</sup>)

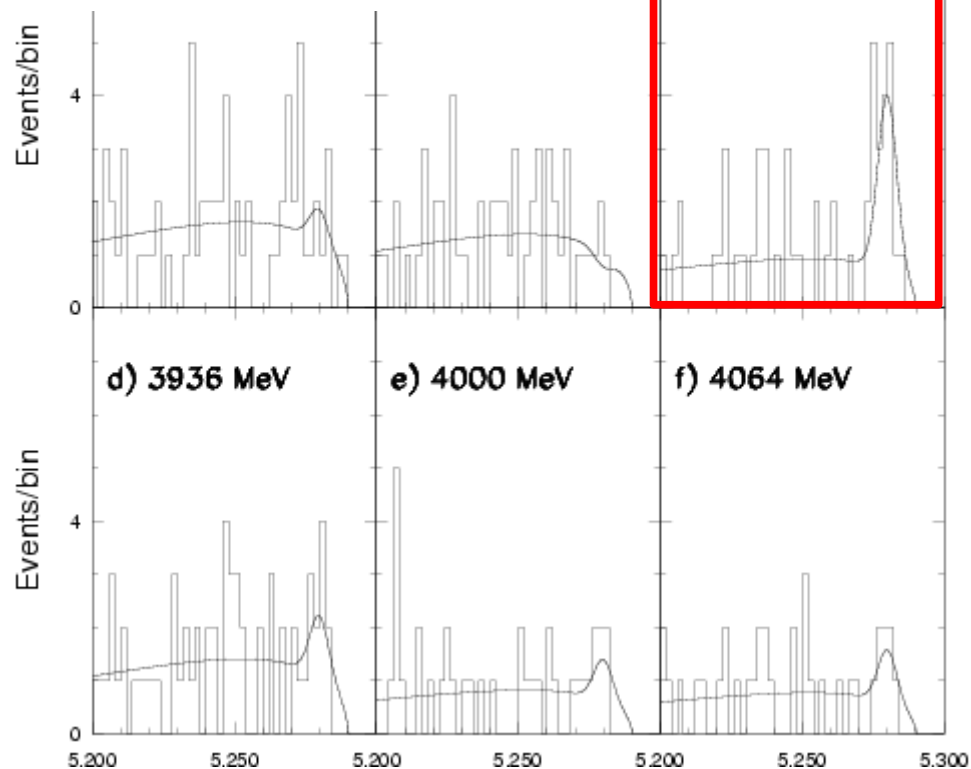
Look for  $B^+ \rightarrow XK^+$  where  $X \rightarrow J/\psi \gamma$   
 $\chi_{c1} \rightarrow J/\psi \gamma$  as calibration mode



Strong evidence for  $X \rightarrow J/\psi \gamma$  decay

$$\frac{\text{BR}(X \rightarrow J/\psi \gamma)}{\text{BR}(X \rightarrow J/\psi \pi^+ \pi^-)} = 0.14 \pm 0.05$$

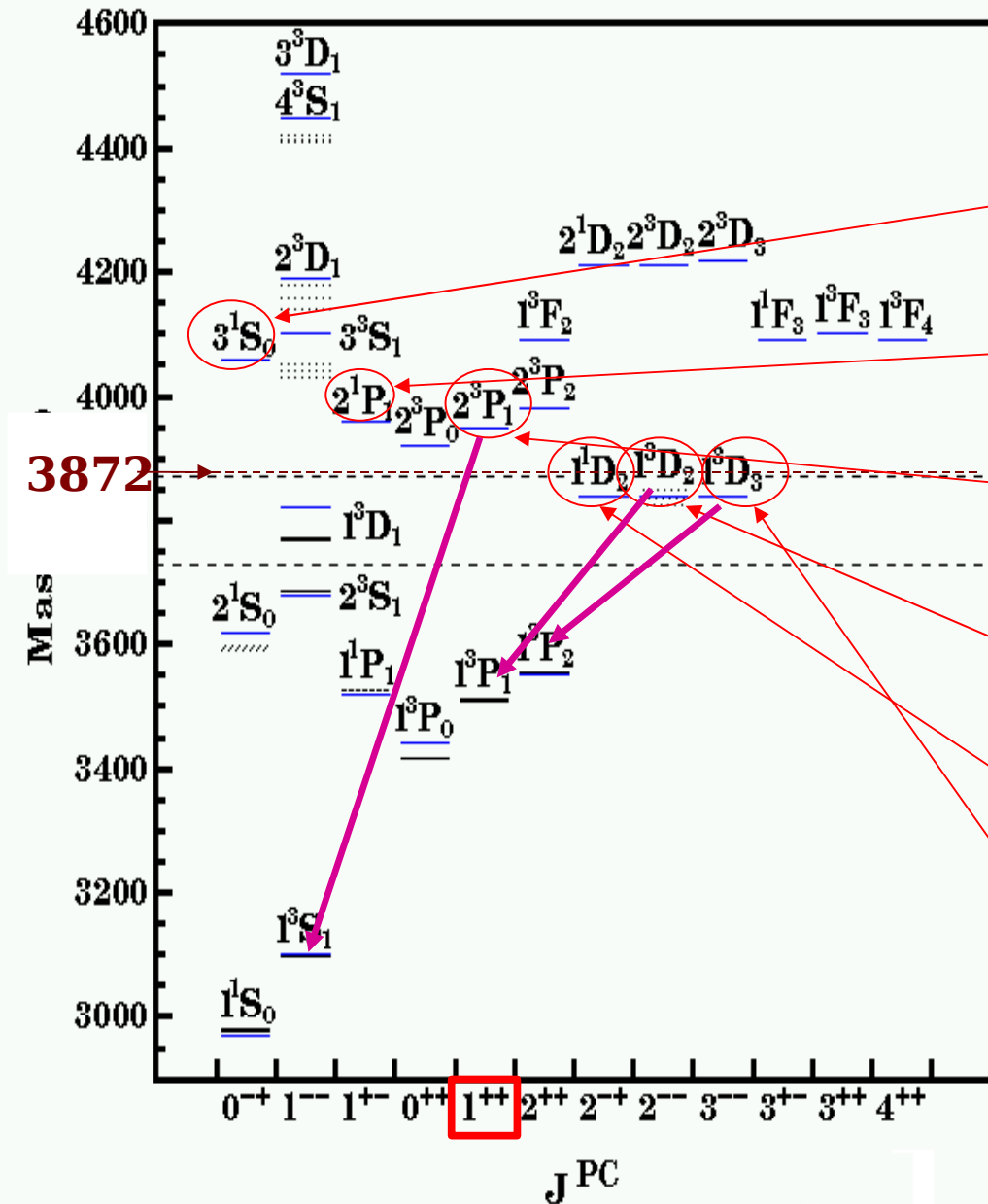
→ C-parity positive !



# No obvious $c\bar{c}$ assignment

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

hep-ex/0407033



$\eta_c''$  M too low and  $\Gamma$  too small

$h_c'$  angular dist rules out  $1^{+-}$

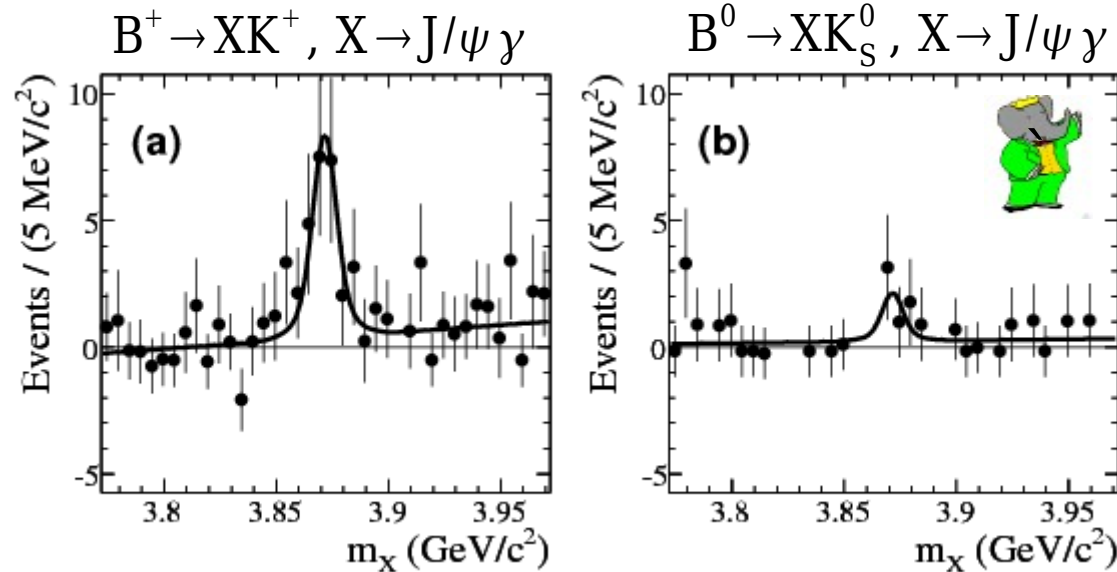
$\chi_{c1}'$   $\Gamma(\gamma J/\psi)$  way too small

$\psi_2$   $\Gamma(\gamma \chi_{c1})$  too small  
 $M(\pi^+ \pi^-)$  wrong

$\eta_{c2}$   $\pi \pi \eta_c$  should dominate

$\psi_3$   $\Gamma(\gamma \chi_{c2} \&\& D\bar{D})$  too small

# BaBar confirms $X(3872) \rightarrow J/\psi \gamma$



PRL102, 132001 (2009)  
(424 fb<sup>-1</sup>)

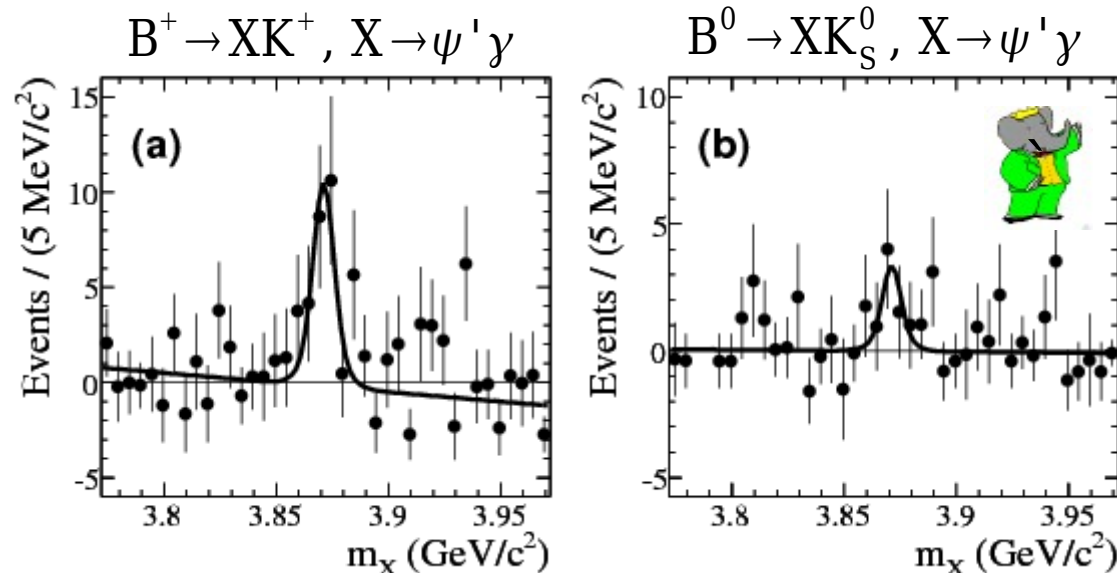
**confirmation from BaBar**

$$\text{BR}(B \rightarrow X(3872)K^+) \times \text{BR}(X(3872) \rightarrow J/\psi \gamma) = (2.8 \pm 0.8 \pm 0.1) \times 10^{-6}$$

$$\text{BR}(B \rightarrow X(3872)K^+) \times \text{BR}(X(3872) \rightarrow J/\psi \gamma) = (1.8 \pm 0.6 \pm 0.1) \times 10^{-6}$$



... and ...



Evidence for  $B^+ \rightarrow X(3872)(\rightarrow \psi' \gamma)K^+$   
 $N = 25.4 \pm 7.4$

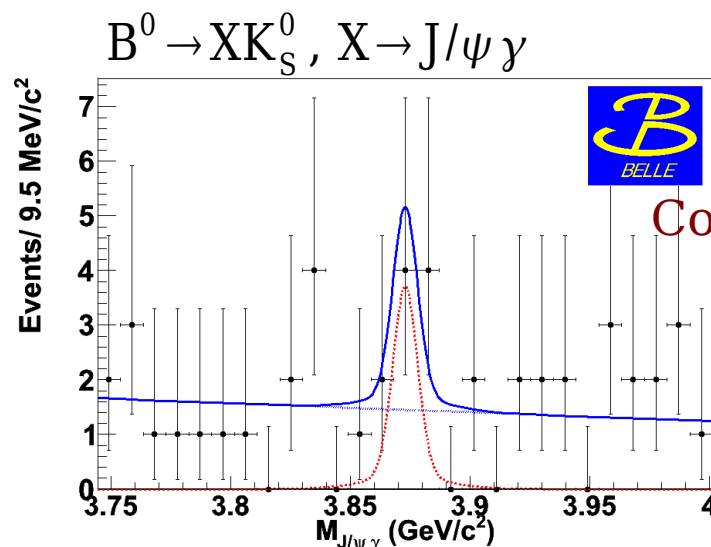
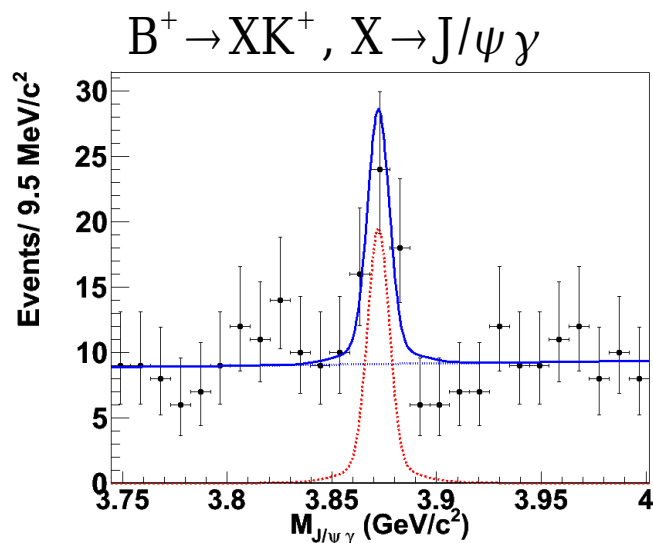
$$\frac{\text{BR}(X(3872) \rightarrow \psi' \gamma)}{\text{BR}(X(3872) \rightarrow J/\psi \gamma)} = 3.5 \pm 1.4$$

**inconsistent with a purely  $\bar{D}^0 D^{*0}$  molecular interpretation  
⇒ significant mixture with  $c\bar{c}$  component ?**



# X(3872) radiative decays (update)

preliminary shown at QWG7  
(711 fb<sup>-1</sup>)

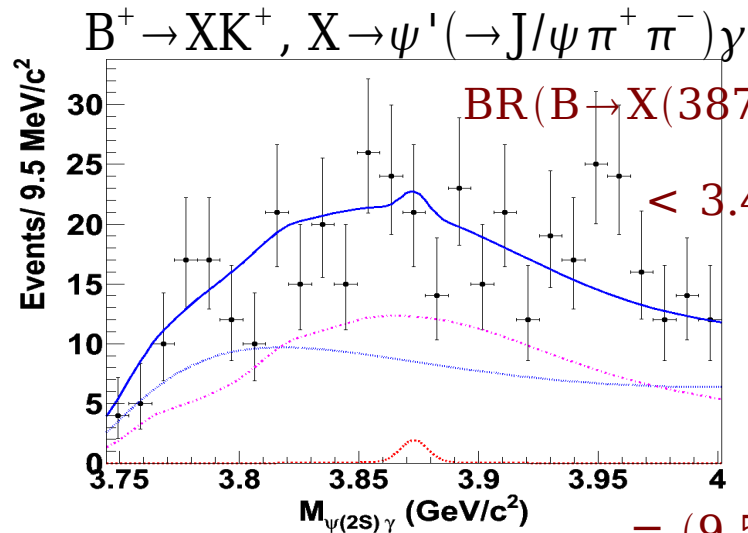
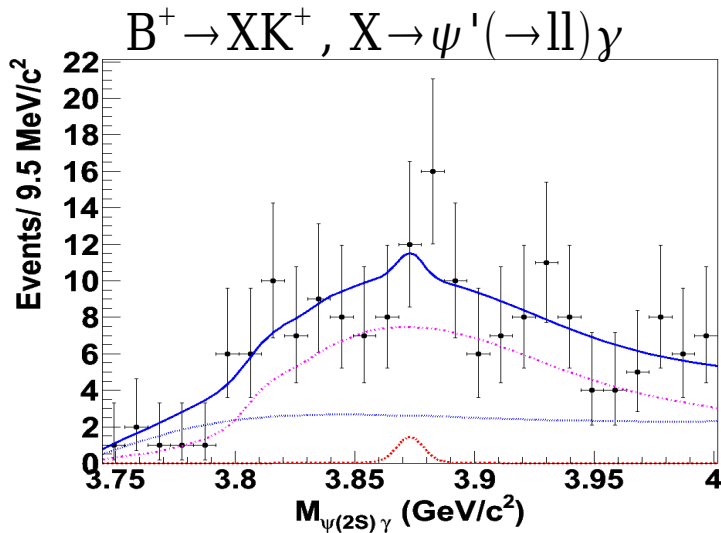


Consistent with our previous  
and BaBar results

$$\frac{\text{BR}(X \rightarrow J/\psi \gamma)}{\text{BR}(X \rightarrow J/\psi \pi^+ \pi^-)} = 0.22 \pm 0.05$$

... however ...

**No signal observed in  $X(3872) \rightarrow \psi' \gamma$  !!**

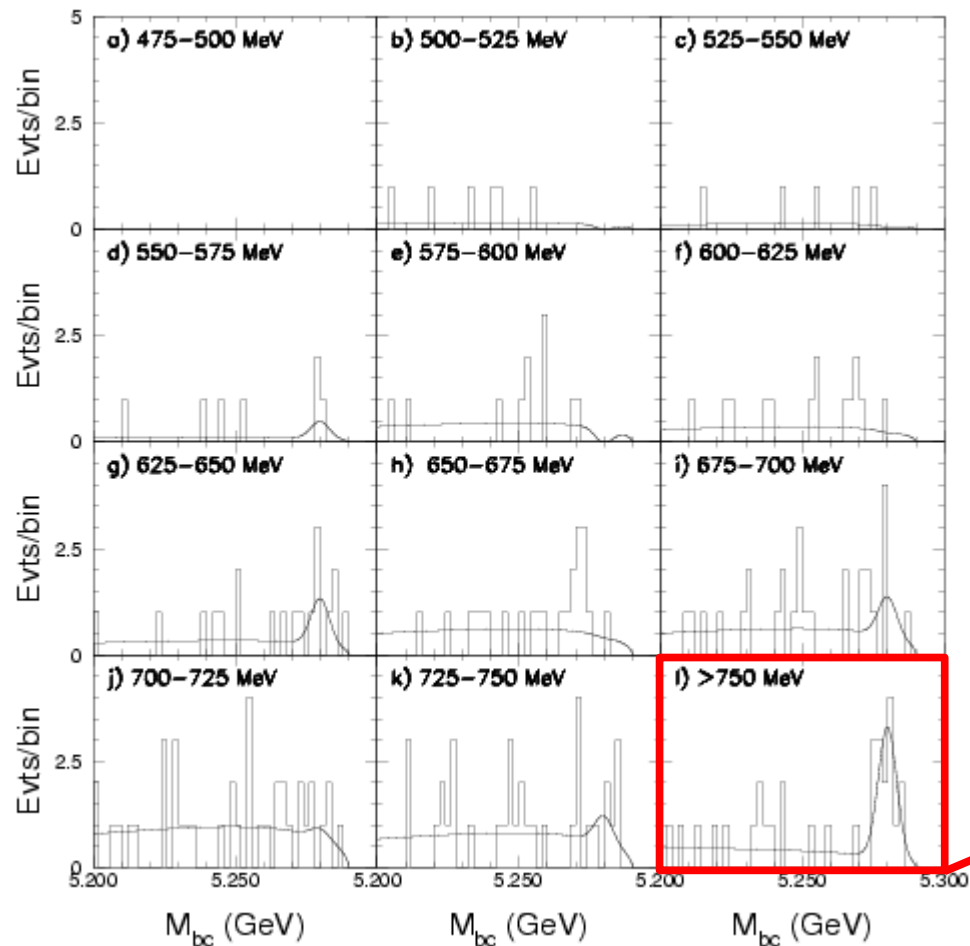


$$\text{BR}(B \rightarrow X(3872) K^+) \times \text{BR}(X(3872) \rightarrow \psi' \gamma)$$

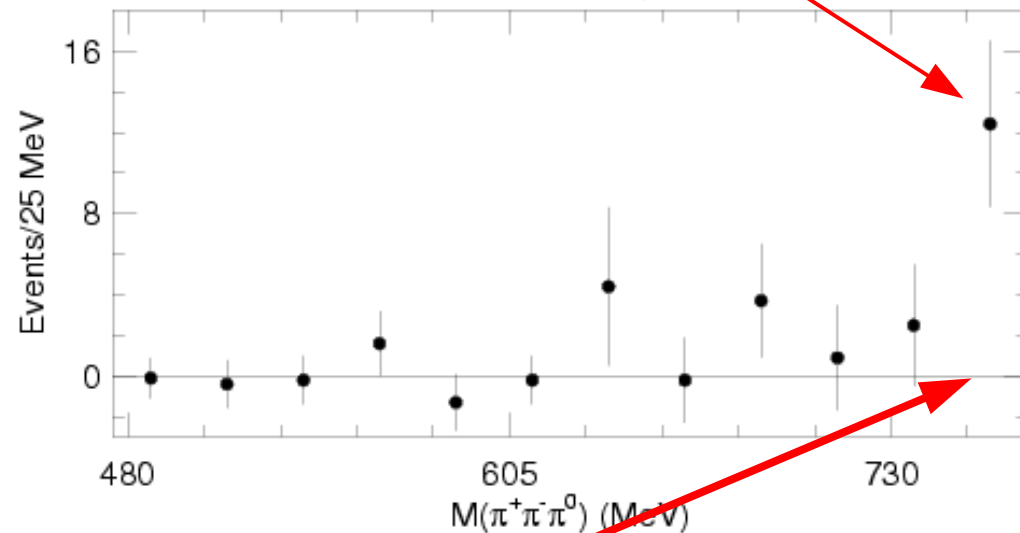
$$< 3.4 \times 10^{-6} \text{ @ 90\% CL}$$

$$= (9.5 \pm 2.7 \pm 0.6) \times 10^{-6} \text{ (BaBar)}$$

# Evidence for $X(3872) \rightarrow \pi^+ \pi^- \pi^0 J/\psi$ hep-ex/0505037 (256 fb<sup>-1</sup>)



**virtual  $\omega(782)$  ?**



$N = 12.1 \pm 4.1$   
Backgrounds =  $2.1 \pm 1.0$   
significance  $4.3\sigma$

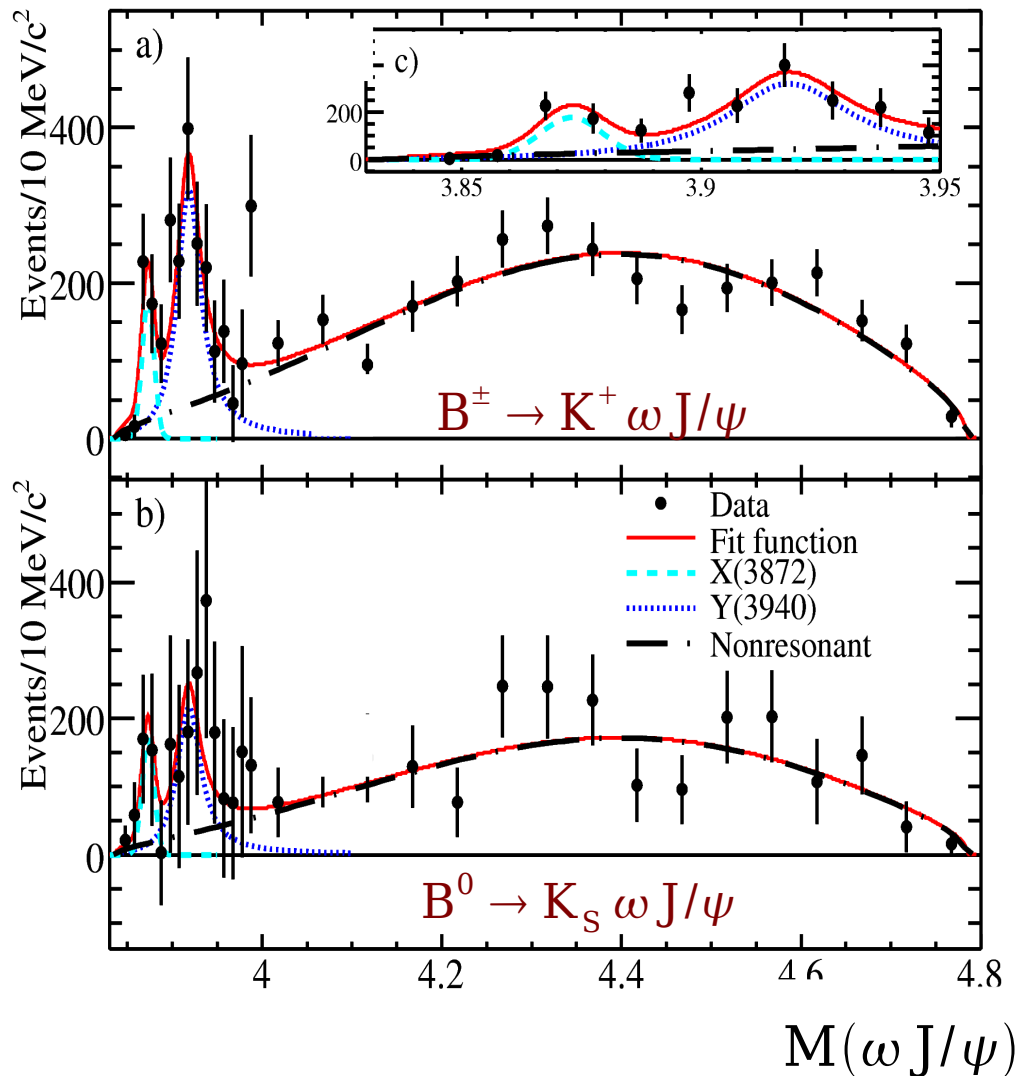
$$\frac{\text{BR}(X \rightarrow J/\psi \pi^+ \pi^- \pi^0)}{\text{BR}(X \rightarrow J/\psi \pi^+ \pi^-)} = 1.0 + 0.4 \pm 0.3$$

for  $M(\pi^+ \pi^- \pi^0) > 750 \text{ MeV}/c^2$

**Large isospin violation**

# BaBar confirms $X(3872) \rightarrow J/\psi \omega$

arXiv:1005.5190  
(426 fb<sup>-1</sup>)



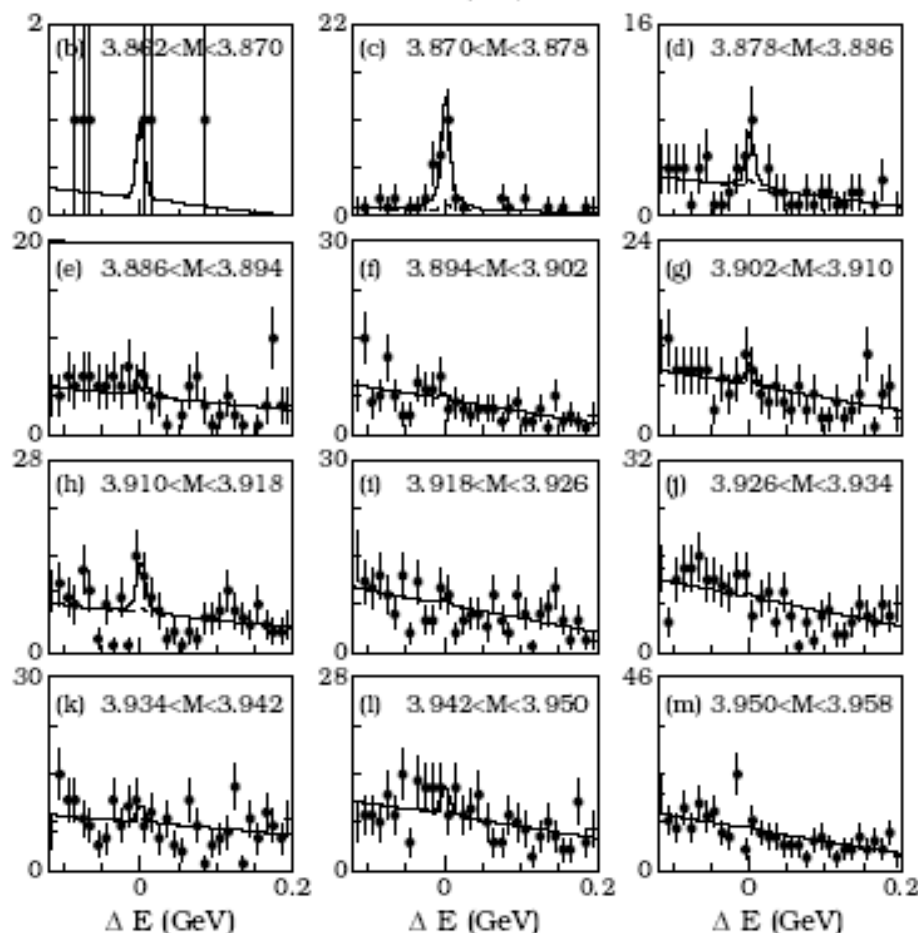
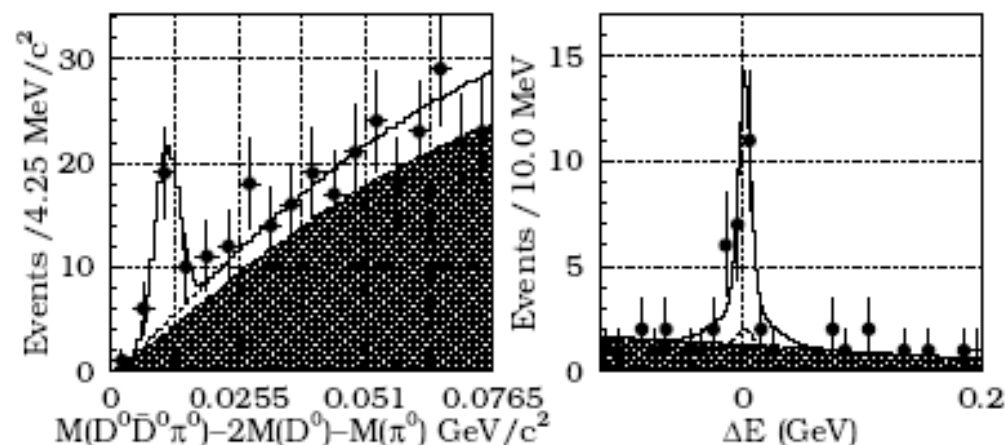
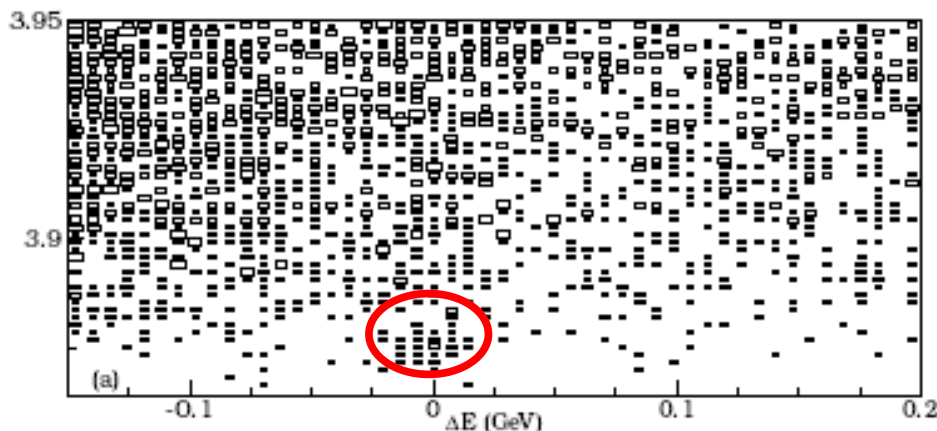
$$\frac{\text{BR}(X \rightarrow J/\psi \omega)}{\text{BR}(X \rightarrow J/\psi \pi^+ \pi^-)} = 0.8 \pm 0.3$$

⇒ Belle will update soon this analysis ( $\times 3$  data)

# threshold enhancement in $D^0\bar{D}^0\pi^0$

PRL97, 162002 (2006)

$\Sigma = 6.4\sigma$



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

$$\text{BR}(B \rightarrow XK) \times \text{BR}(X \rightarrow D^0\bar{D}^0\pi^0) = (1.27 \pm 0.31^{+0.22}_{-0.39}) \times 10^{-4}$$

$$\frac{\text{BR}(X \rightarrow D^0\bar{D}^0\pi^0)}{\text{BR}(X \rightarrow J/\psi \pi^+ \pi^-)} \sim 10$$

$X \rightarrow D^0\bar{D}^{*0}/D^0\bar{D}^0\pi^0$  expected to be strongly suppressed for  $J=2$

# ...and BaBar

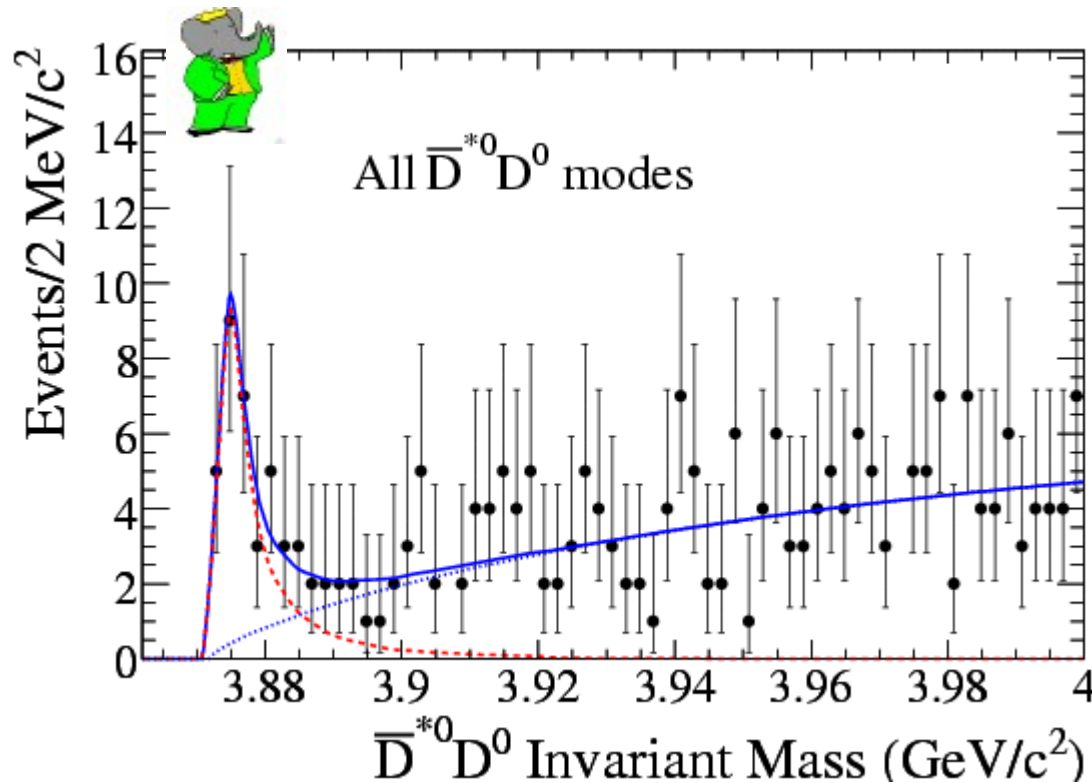
PRD77, 011102 (2008)

$$D^{*0} \rightarrow D^0 \pi^0, D^0 \gamma$$

$$\Sigma = 4.9\sigma$$

$$M = (3875.1^{+0.7}_{-0.5} \pm 0.5) \text{ MeV}/c^2$$

$$\Gamma = (3.0^{+1.9}_{-1.4} \pm 0.9) \text{ MeV}/c^2$$



$$\begin{aligned} \text{BR}(B^0 \rightarrow XK^0) \times \text{BR}(X \rightarrow \bar{D}^{*0} D^0) &= (2.22 \pm 1.05 \pm 0.42) \times 10^{-4} \\ \text{BR}(B^+ \rightarrow XK^+) \times \text{BR}(X \rightarrow \bar{D}^{*0} D^0) &= (1.67 \pm 0.36 \pm 0.47) \times 10^{-4} \end{aligned}$$

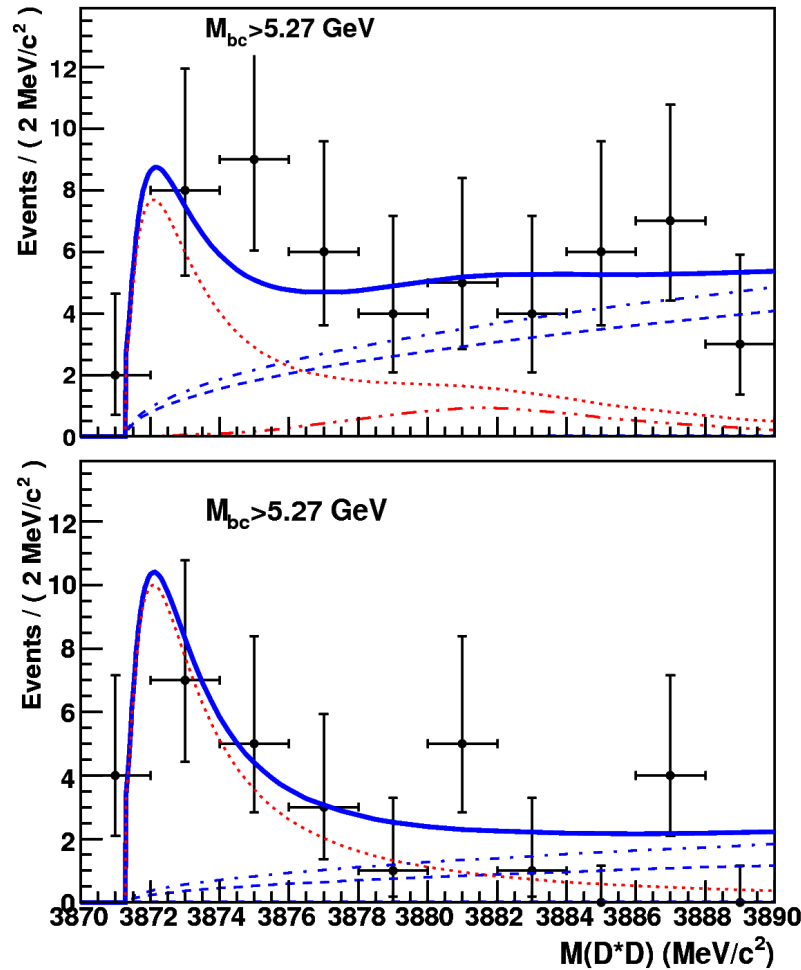
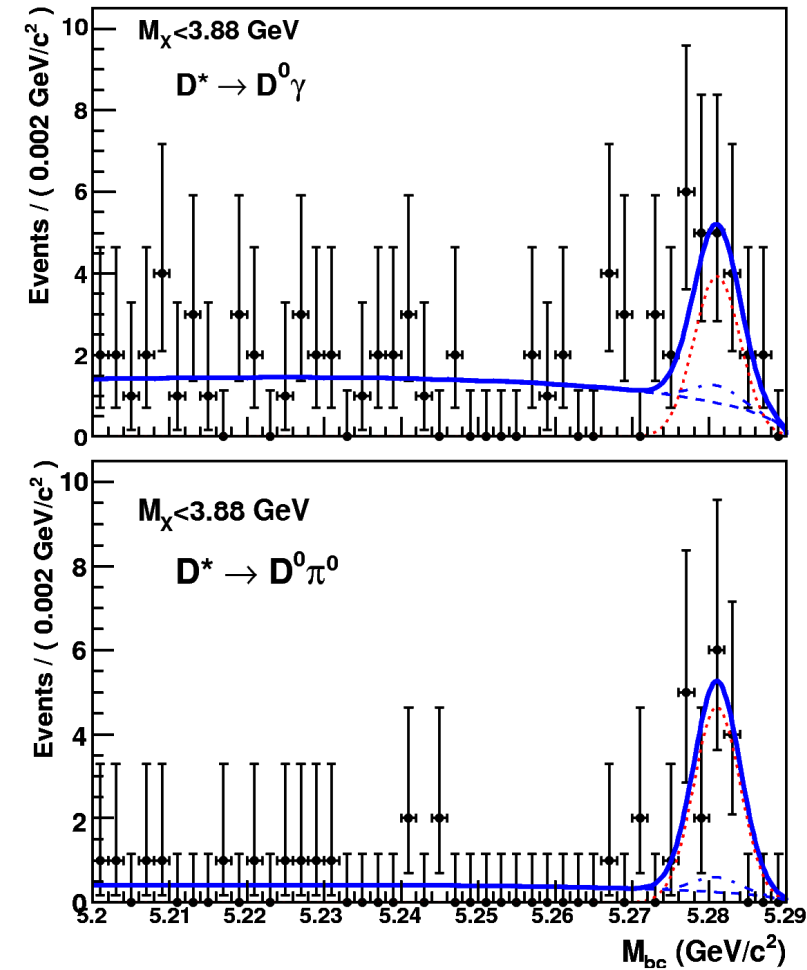
$M_X$  differs in  $D^0 \bar{D}^0 \pi^0$  and  $J/\psi \pi^+ \pi^-$  decays ?

Is it the same  $X(3872)$  or two different  $X$  states ?

# Most recent Belle analysis (with 605 fb<sup>-1</sup>)

PRD(RC)81, 031103 (2010)

## $D^{*0} \rightarrow D^0 \pi^0, D^0 \gamma$



$$N_S = 39.6^{+9.3}_{-8.1}$$

$$\Sigma = 8.0 \sigma$$

$$M = (3872.9^{+0.6+0.4}_{-0.4-0.5}) \text{ MeV}/c^2 \quad \Gamma(\text{BW}) = (3.9^{+2.8+0.2}_{-1.4-1.1}) \text{ MeV}/c^2$$

$$\text{BR}(B^0 \rightarrow XK) \times \text{BR}(X \rightarrow \bar{D}^{*0} D^0) = (0.80 \pm 0.20 \pm 0.10) \times 10^{-4}$$

## Summary for X(3872)

- narrow ( $\Gamma < 2.3 \text{ MeV}$  @ 90 %C.L.) and right at  $m_{D^0} + m_{D^{*0}}$   
 $M_X = (3871.46 \pm 0.37 \pm 0.07) \text{ MeV}$
- no mass splitting signature
- $C = +1$  well established,  $J^{PC} = 1^{++}$  seems likely
- first observation of  $B^0 \rightarrow X(3872) K^+ \pi^-$ , but  $K^+ \pi^-$  mostly non res.
- seen by Belle in  $D^0 \bar{D}^{*0}$ ,  $J/\psi \pi^+ \pi^-$ ,  $J/\psi \omega$ ,  $J/\psi \gamma$  **but not in  $\psi' \gamma$**
- recent  $D^0 \bar{D}^{*0}$  analysis:  
 $M_X = (3872.6_{-0.4}^{+0.5} \pm 0.4) \text{ MeV}$

→ no good charmonium candidate ?

so what is it ? tetraquark, molecule, ...?



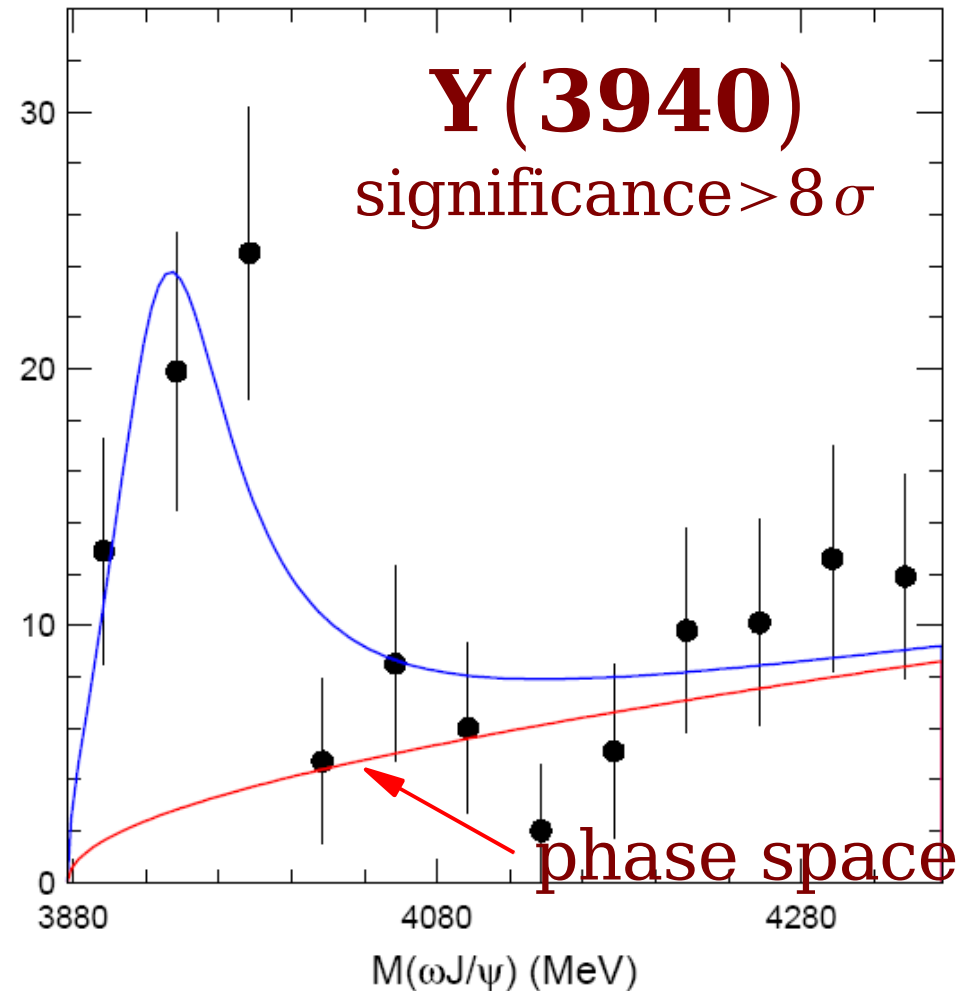
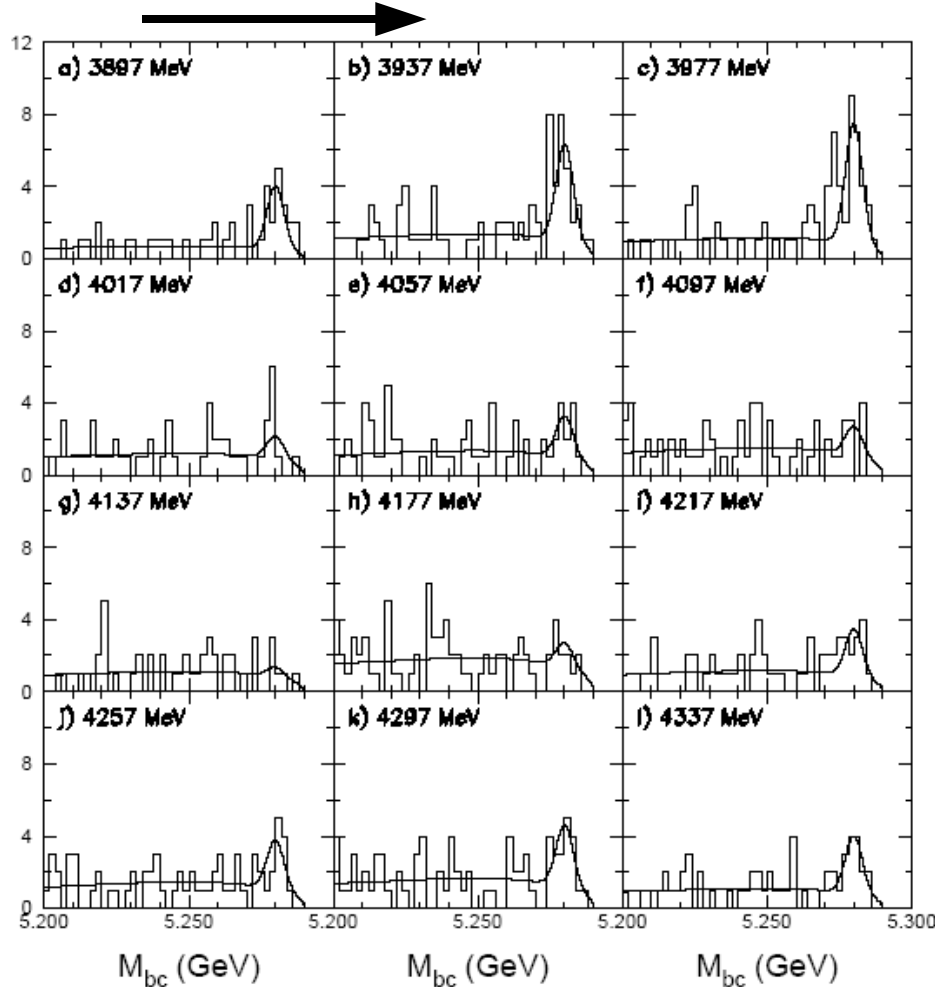
**Around 3940 MeV/c<sup>2</sup>**

# Another enhancement is found in $J/\psi \omega$ final state around threshold :



PRL94, 182002 (2005)  
(253fb<sup>-1</sup>)

$M_{bc}$  for  $B \rightarrow J/\psi \omega K$  in bins of  $M(J/\psi \omega)$



fit: threshold  $q^*(M)$  + S-wave BW

$$M = (3943 \pm 11 \pm 13) \text{ MeV}/c^2$$

$$\Gamma = (87 \pm 22 \pm 26) \text{ MeV}$$

- The mass is well above  $DD^{(*)}$  threshold and decay to  $J/\psi \omega$  should not be dominant if  $Y = \text{charmonium}$   
 → **no obvious charmonium meson assignment**

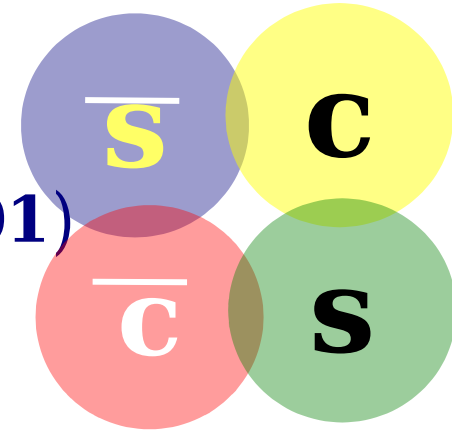
- another molecule ?

- $M \sim 2m_{D_s}$

- not seen in  $Y \rightarrow \eta J/\psi$  (BaBar, PRL93, 041801)

- width too large

- no  $\pi$  exchange for  $D_s \bar{D}_s$



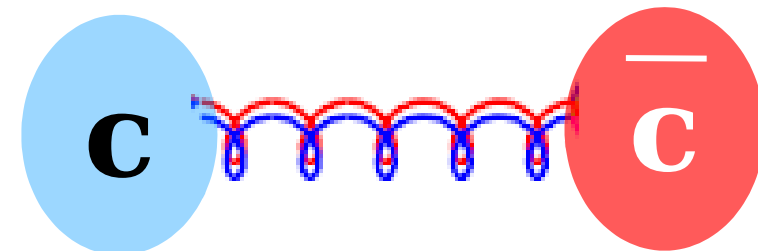
- $c\bar{c}$  gluon hybrid (Horn and Mandula, PRD 17898(1978))

- predicted by QCD

- decays to  $DD$  and  $DD^*$  are suppressed

- large (hadron +  $J/\psi$ ) widths predicted

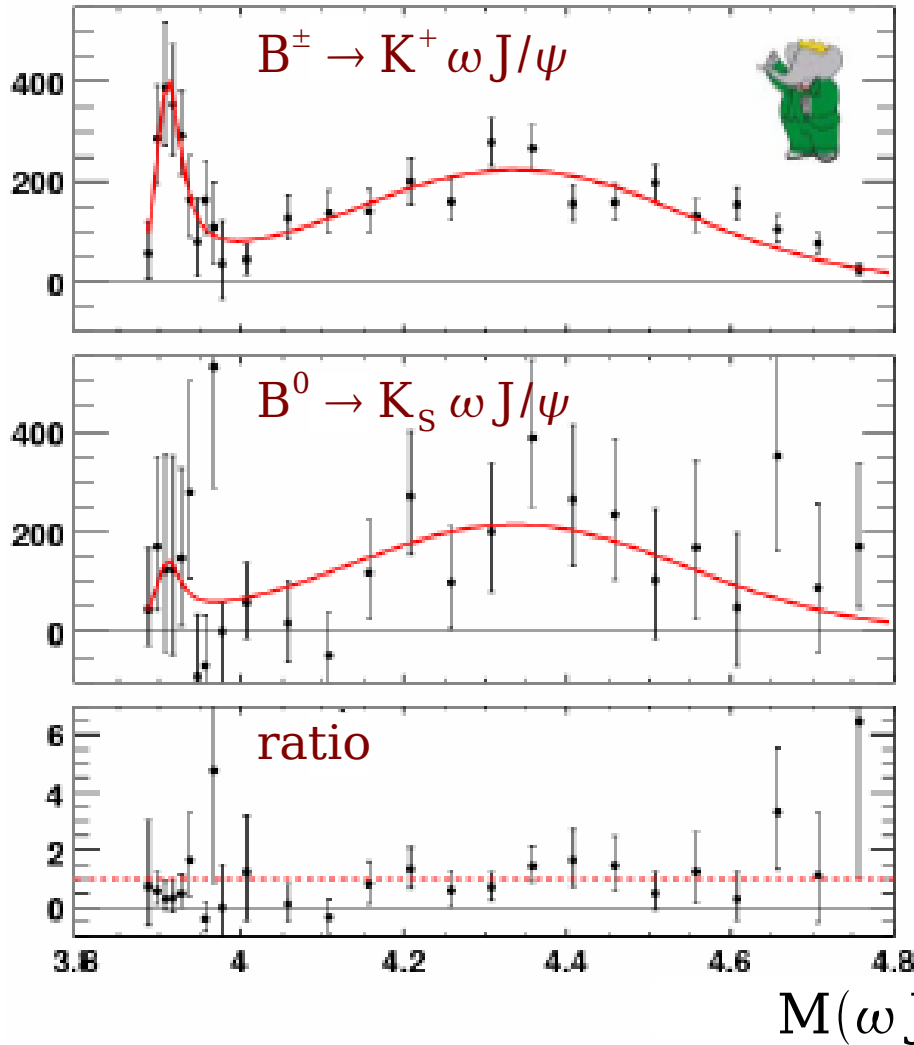
- but masses expected to be  $4.3 \sim 4.4 \text{ GeV}/c^2$



⇒ **least-believed of "XYZ" states...**

# Y(3940) confirmed by BaBar !

PRL101,082001(2008)  
(348 fb<sup>-1</sup>)



simultaneous  $B^+$  &  $B^0$  fit

Gaussian bkgd + S-wave BW signal

$$\text{BR}(B^+ \rightarrow YK^+, Y \rightarrow J/\psi \omega) = (4.9_{-0.9}^{+1.0} \pm 0.5) \times 10^{-5}$$

$$\text{BR}(B^+ \rightarrow YK^0, Y \rightarrow J/\psi \omega) = (1.3_{-1.1}^{+1.3} \pm 0.2) \times 10^{-5}$$

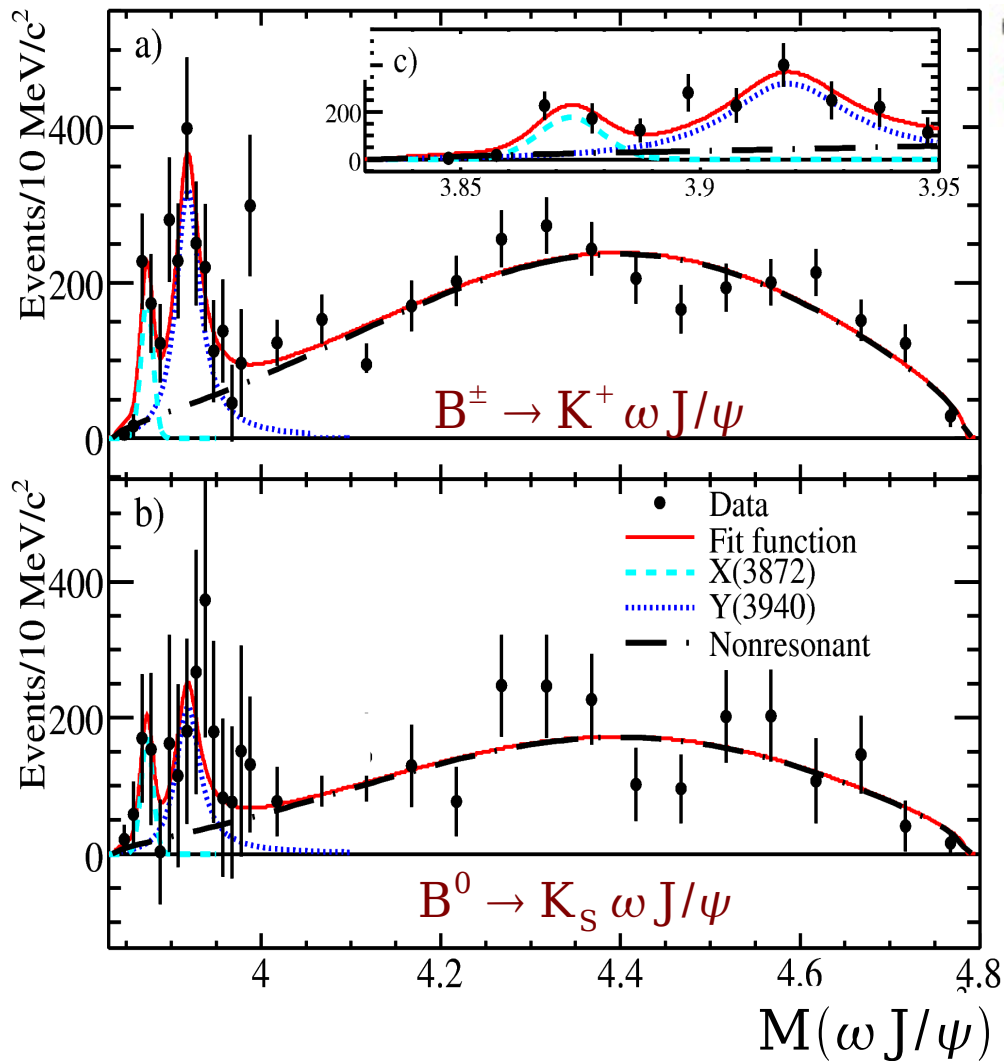
$$\mathbf{R_Y = BR_{B^0} / BR_{B^+} = 0.27_{-0.23}^{+0.28+0.04}} \\ (\sim 3 \sigma \text{ below isospin expectation})$$

$$\text{whereas } R_{\text{non res}} = 0.97_{-0.22}^{+0.23+0.03}$$

	$M$ (MeV)	$\Gamma$ (MeV)
Belle (253 fb <sup>-1</sup> )	$3943 \pm 11 \pm 13$	$87 \pm 22 \pm 26$
BaBar (348 fb <sup>-1</sup> )	$3914.6_{-3.4}^{+3.8} \pm 2.0$	$34_{-8}^{+12} \pm 5$

# Y(3940) confirmed by BaBar !

arXiv:1005.5190  
(426 fb<sup>-1</sup>)



simultaneous  $B^+$  &  $B^0$  fit

Gaussian bkgd + S-wave BW signal

$$\text{BR}(B^+ \rightarrow YK^+, Y \rightarrow J/\psi \omega) = (3.0^{+0.7+0.5}_{-0.6-0.3}) \times 10^{-5}$$

$$\text{BR}(B^+ \rightarrow YK^0, Y \rightarrow J/\psi \omega) = (2.1 \pm 0.9 \pm 0.3) \times 10^{-5}$$

$$\mathbf{R_Y = BR_{B^0} / BR_{B^+} = 0.7^{+0.4}_{-0.3} \pm 0.1}$$

(consistent with isospin expectation)

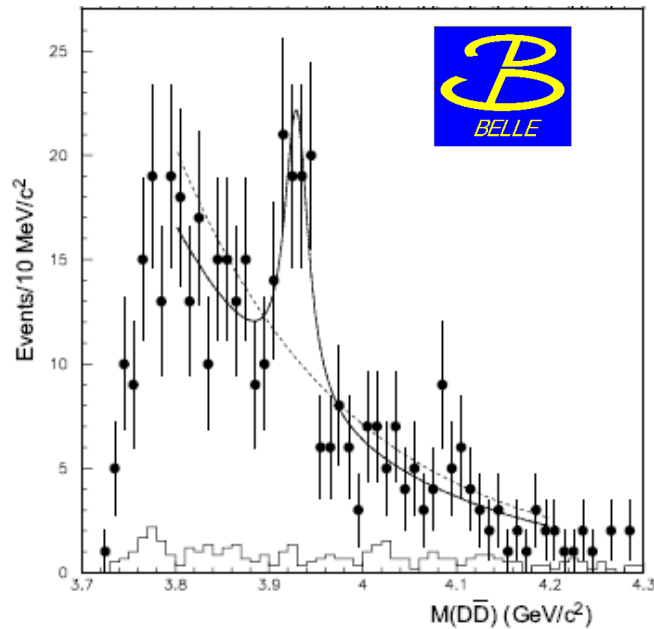
whereas  $R_{\text{non res}} = 0.7 \pm 0.1 \pm 0.1$

	M (MeV)	$\Gamma$ (MeV)
Belle (253 fb <sup>-1</sup> )	$3943 \pm 11 \pm 13$	$87 \pm 22 \pm 26$
BaBar (348 fb <sup>-1</sup> )	$3914.6^{+3.8}_{-3.4} \pm 2.0$	$34^{+12}_{-8} \pm 5$
BaBar (426 fb <sup>-1</sup> )	$3919.1^{+3.8}_{-3.4} \pm 2.0$	$31^{+10}_{-8} \pm 5$

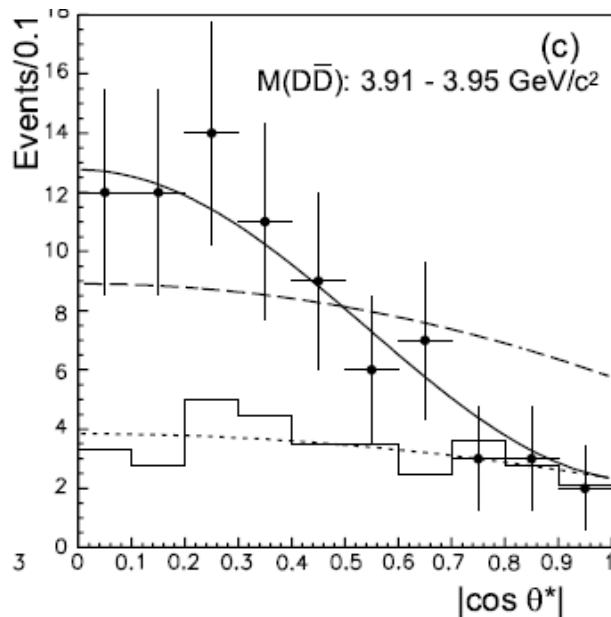
**Belle has 3 × more statistics, improved efficiency: will update soon !**

# $\gamma\gamma \rightarrow Z(3930) \rightarrow D\bar{D}$

PRL96, 082003 (2006)  
(395 fb<sup>-1</sup>)



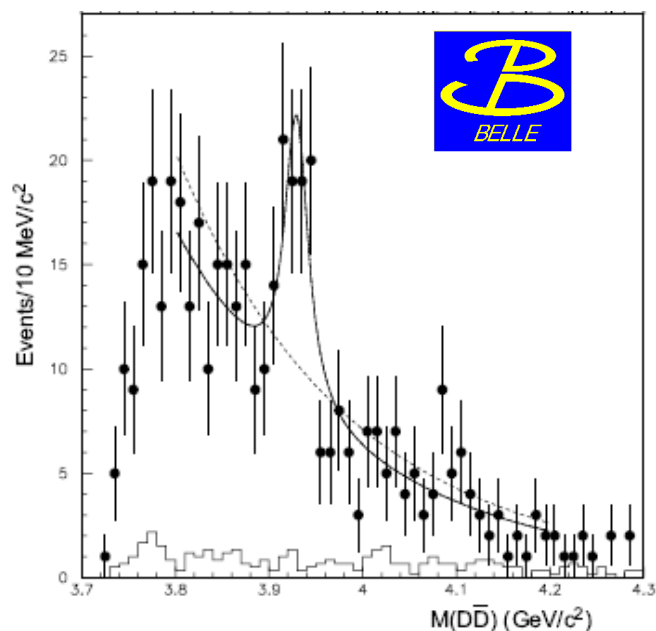
$$M = (3929 \pm 5 \pm 2) \text{ MeV}/c^2$$
$$\Gamma = (29 \pm 10 \pm 2) \text{ MeV}$$



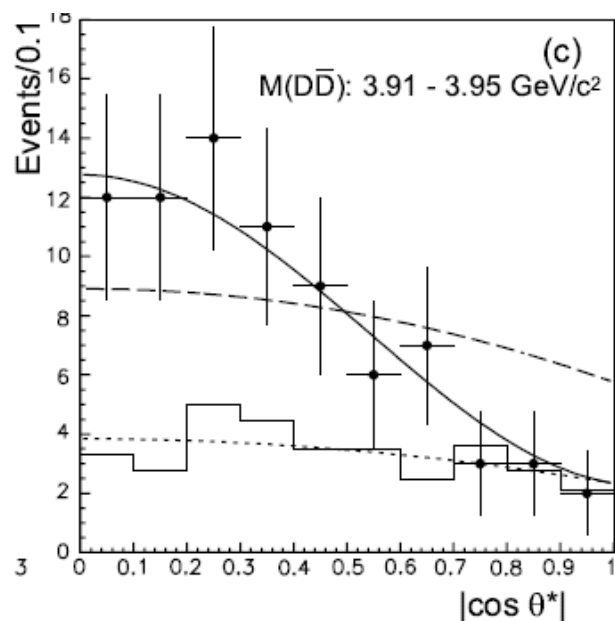
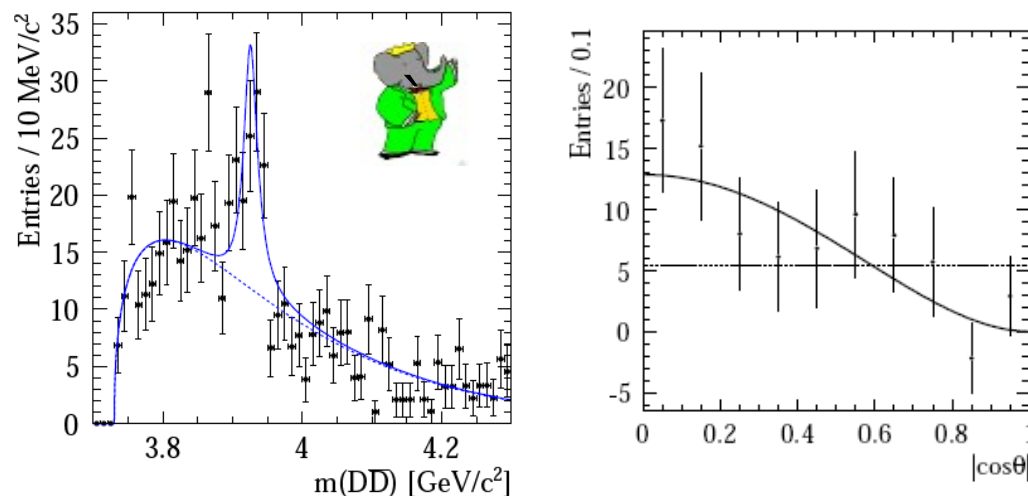
production angle distribution matches well  
the  $\sin^4 \theta^*$  behaviour expected for a J=2 meson

# $\gamma\gamma \rightarrow Z(3930) \rightarrow D\bar{D}$

PRL96, 082003 (2006)  
(395 fb<sup>-1</sup>)



PRD81, 092003 (2010)  
(384 fb<sup>-1</sup>)



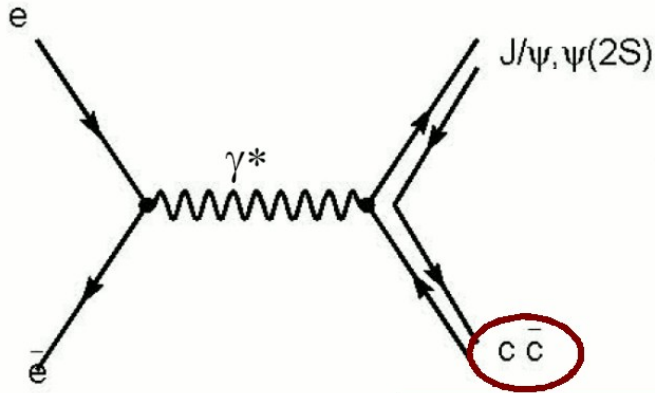
$M$ (MeV/c <sup>2</sup> )	$\Gamma$ (MeV)
$(3929 \pm 5 \pm 2)$	$(29 \pm 10 \pm 2)$
$(3926.7 \pm 2.7 \pm 1.1)$	$(21.3 \pm 6.8 \pm 3.6)$

$J=2$ , mass, width and  $\gamma\gamma$  production rate  
 $\Rightarrow$  match well to expectations for the  $2^3 P_2 (\chi_{c2}')$



# Double charmonium production

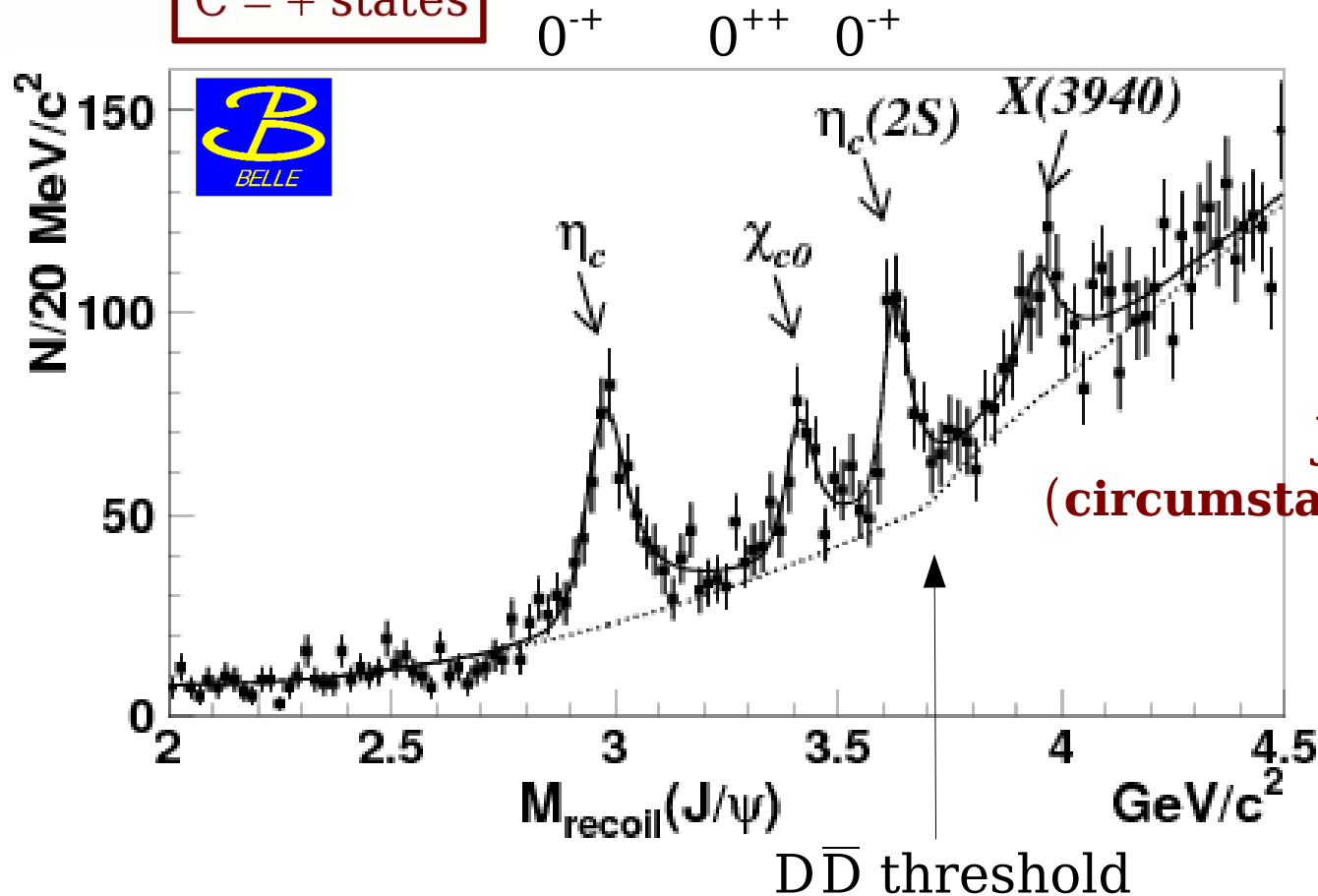
successful approach for producing  $C = (+)$  charmonia



$C = +$  states

$$M_{\text{recoil}}(J/\psi) = \sqrt{(E_{\text{CMS}} - E_{J/\psi}^*)^2 - p_{J/\psi}^{*2}}$$

PRL98, 082001 (2007)  
(357 fb $^{-1}$ )



$\Rightarrow X(3940)$

$J = 0 ?$

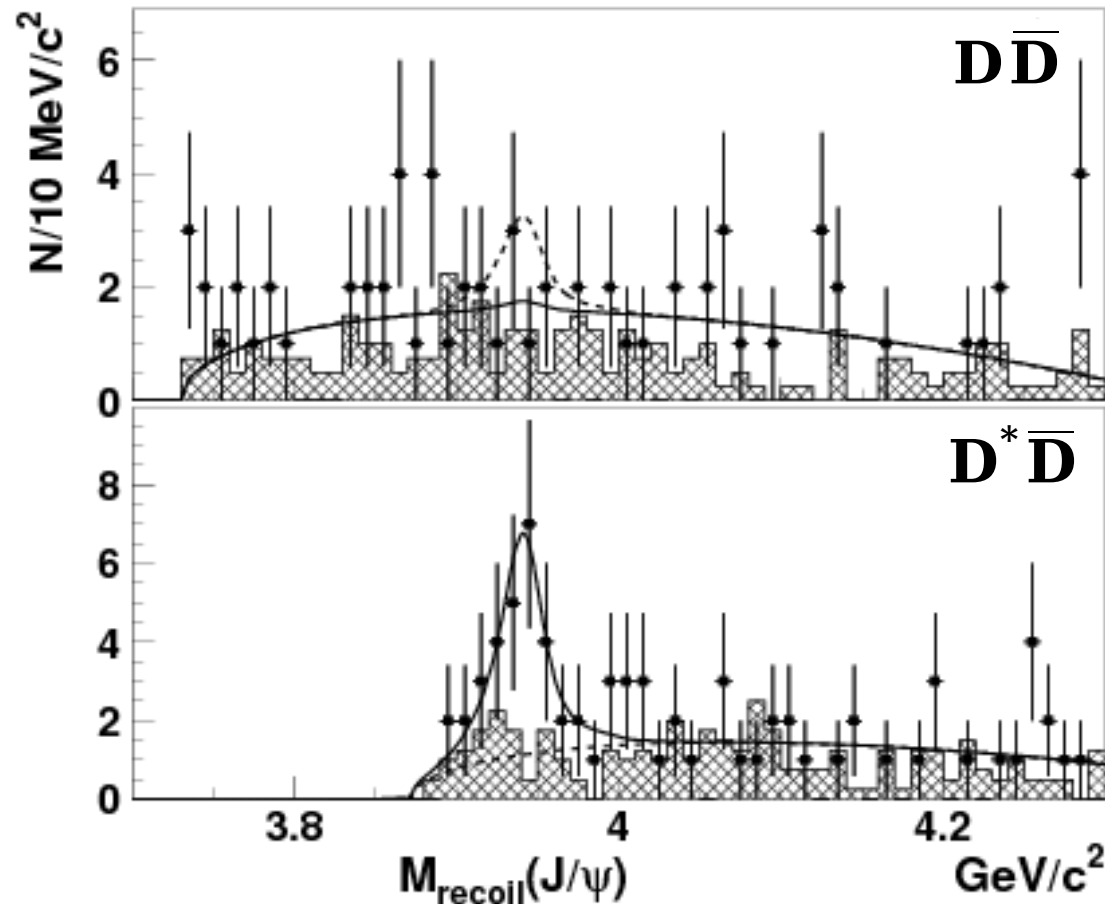
(circumstantial evidence ?)

# Double charmonium production



Search for  $X(3940) \rightarrow D\bar{D}, D^*\bar{D}, J/\psi\omega \dots$

PRL98, 082001 (2007)  
(357 fb<sup>-1</sup>)



in addition to fully rec.  $J/\psi$ ,  
one  $D$  (or  $\omega$ ) is reconstructed

**seen in  $D^*\bar{D}$  decay**

**not seen to decay to  $D\bar{D}$**   
[decay preferred for  $0^{++}$ , forbidden for  $0^{-+}$ ]

$\Rightarrow$  unfilled  $0^{-+}$  with closest  
expected mass:  $3^1 S_0 (\eta_c(3S))$   
...but potential model predicts:  
 $M = 4043 \text{ MeV}$  (or higher)

**not seen to decay to  $J/\psi\omega$**

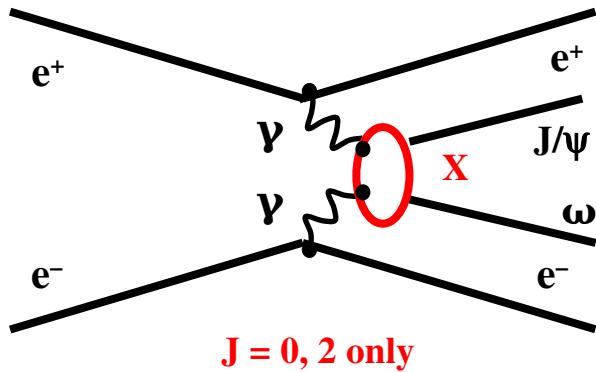
Confirmed later with larger sample (693 fb<sup>-1</sup>) [PRL100, 202001 (2008)]:

$$M = (3942_{-6}^{+7} \pm 6) \text{ MeV}/c^2$$

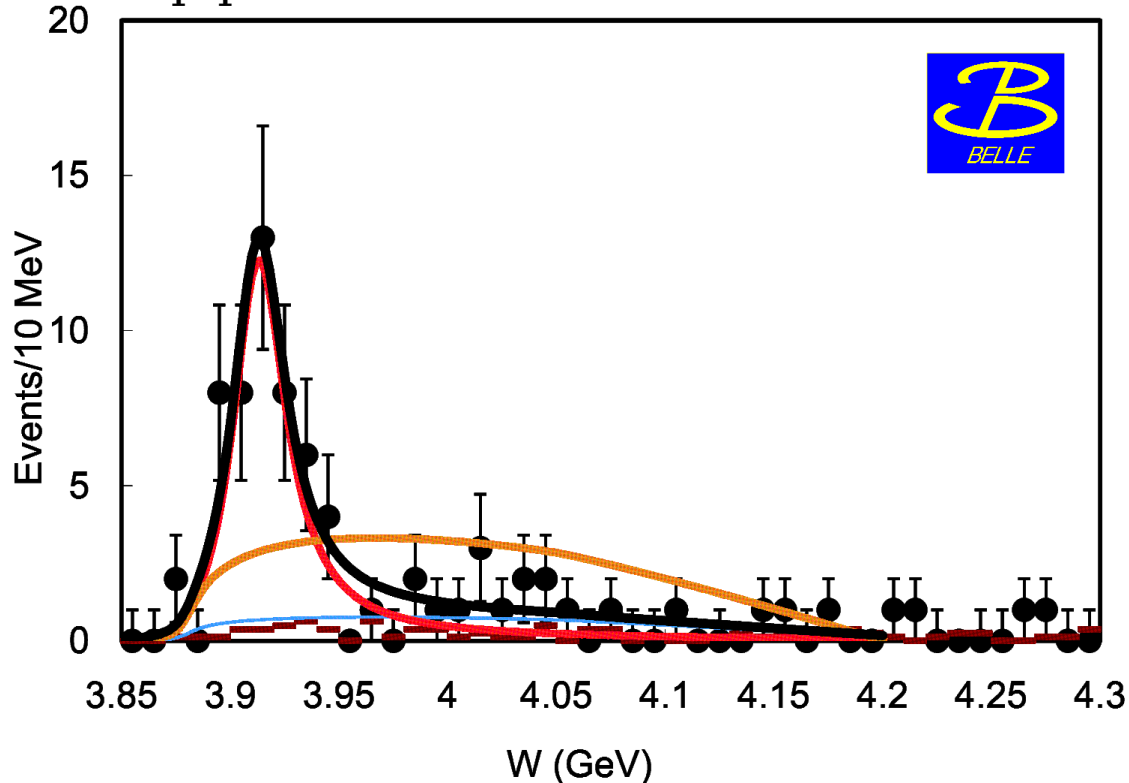
$$\Gamma = (37_{-15}^{+26} \pm 8) \text{ MeV}$$

# $\gamma\gamma \rightarrow X(3915) \rightarrow J/\psi \omega$

PRL104, 092001 (2010)  
(694 fb<sup>-1</sup>)



sharp peak near threshold and not much else...



$\Sigma = 7.1\sigma$

$$M = (3915 \pm 3 \pm 2) \text{ MeV}/c^2$$

$$\Gamma = (17 \pm 10 \pm 3) \text{ MeV}$$

$$\Gamma_{\gamma\gamma}(Y) \times \text{BR}(Y \rightarrow J/\psi \omega)$$

$$= (61 \pm 17 \pm 8) \text{ eV for } J^P = 0^+$$

$$= (18 \pm 5 \pm 2) \text{ eV for } J^P = 2^+$$

mass  $\sim 2\sigma$  away from Z(3930): two distinct peaks  
not different decay channels of same state

# 4 states around 3940 MeV: different states ?

	Name	Process	M (MeV/c <sup>2</sup> )	$\Gamma$ (MeV)
Belle (253 fb <sup>-1</sup> )	Y(3940)	B → J/ψ ω	3943 ± 11 ± 13	87 ± 22 ± 26
BaBar (426 fb <sup>-1</sup> )	Y(3940)	B → J/ψ ω	3919.1 <sup>+3.8</sup> <sub>-3.4</sub> ± 2.0	31 <sup>+10</sup> <sub>-8</sub> ± 5
Belle (694 fb <sup>-1</sup> )	X(3915)	2 γ → J/ψ ω	3915 ± 3 ± 2.0	17 ± 10 ± 5
Belle (694 fb <sup>-1</sup> )	X(3940)	e <sup>+</sup> e <sup>-</sup> → J/ψ D D <sup>*</sup>	3942 <sup>+7</sup> <sub>-6</sub> ± 6	37 <sup>+26</sup> <sub>-15</sub> ± 8
Belle (395 fb <sup>-1</sup> )	Z(3930)	2 γ → D D̄	3929 ± 5 ± 2	29 ± 10 ± 2
BaBar (384 fb <sup>-1</sup> )	Z(3930)	2 γ → D D̄	3926.7 ± 2.7 ± 1.1	21 ± 7 ± 4

**Q1: Y(3940) = X(3915) ?** same process, no disagreement mass/width in any case, difficulty with charmonium assignment

**Q2: Y(3940) = X(3940) ?**

Y(3940) not found in D<sup>\*0</sup> D̄<sup>0</sup> K

$$\frac{\text{BR}(Y(3940) \rightarrow \omega J/\psi)}{\text{BR}(Y(3940) \rightarrow D^{*0} \bar{D}^0)} > 0.71 \text{ @ } 90 \% \text{ C.L.}$$

X(3940) → J/ψ ω not found in 2 × charmonium prod

$$\frac{\text{BR}(X(3940) \rightarrow \omega J/\psi)}{\text{BR}(X(3940) \rightarrow D^{*0} \bar{D}^0)} < 0.58 \text{ @ } 90 \% \text{ C.L.}$$

⇒ **at least 3 states**

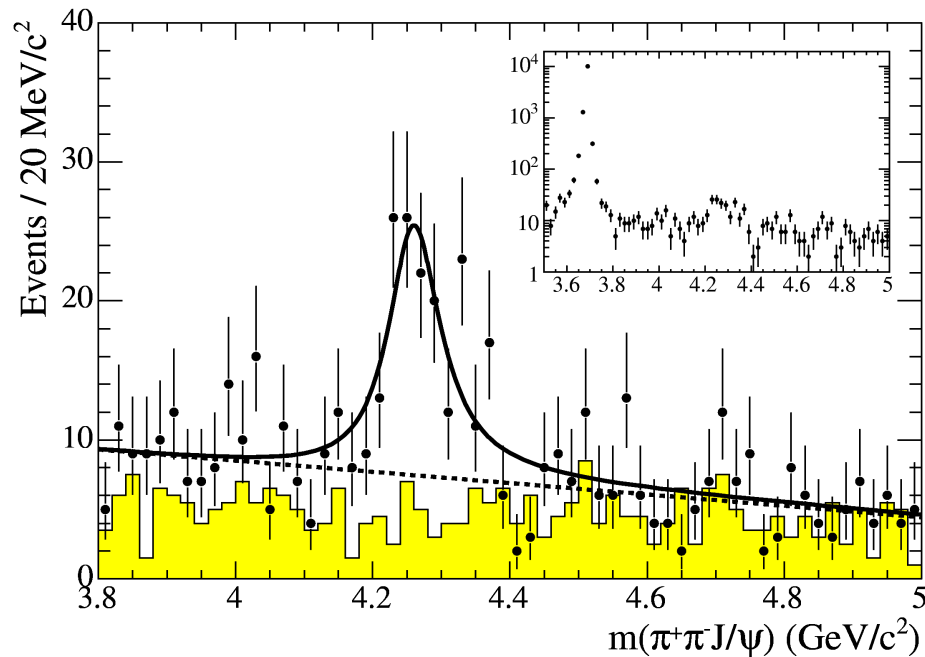
# The $Y(J^{PC} = 1^{--})$ family

# Y(4260): discovery in $e^+ e^- \rightarrow \gamma_{\text{ISR}} \pi^+ \pi^- J/\psi$

when running at  $\Upsilon(4S)$ :  $e^+ e^- \rightarrow \gamma_{\text{ISR}} X$ ,  $E_{\gamma_{\text{ISR}}} = 4 \sim 5 \text{ GeV}$

$e^+ e^-$  annihilation occurs in the energy region populated by charmonium states  
(comparable sensitivity to energy scan (Cleo-c, BES))

PRL95, 142001 (2005)  
( $233 \text{ fb}^{-1}$ )



...excess of  $125 \pm 23$  events  
centered  $\sim 4.26 \text{ GeV}/c^2$   
signifying the presence of one or more  
previously unobserved  $J^{\text{PC}} = 1^{--}$  states..

$$M = (4259 \pm 8_{-6}^{+2}) \text{ MeV}/c^2$$

$$\Gamma = (88 \pm 23_{-4}^{+6}) \text{ MeV}$$

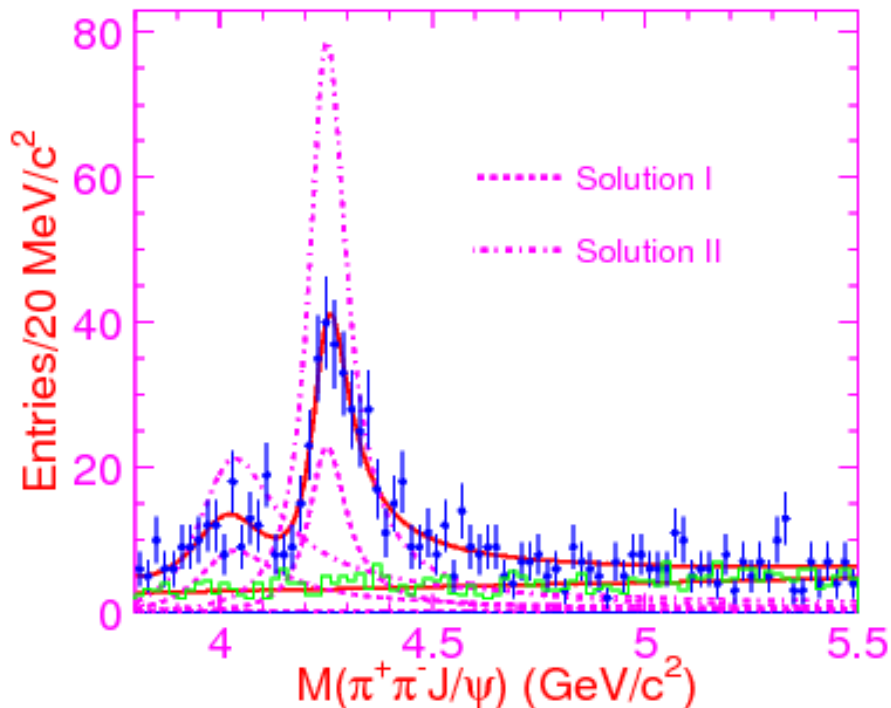
$$\Gamma_{e^+e^-} \times \text{BR}(Y(4260) \rightarrow \pi^+ \pi^- J/\psi) = (5.5 \pm 1.0_{-0.7}^{+0.8}) \text{ eV}/c^2$$

# Y(4260): discovery in $e^+ e^- \rightarrow \gamma_{\text{ISR}} \pi^+ \pi^- J/\psi$

(also confirmed by Cleo)

2 BW with interference  
two solutions: different peak cross-sections

PRL99, 182004 (2007)  
(548 fb<sup>-1</sup>)



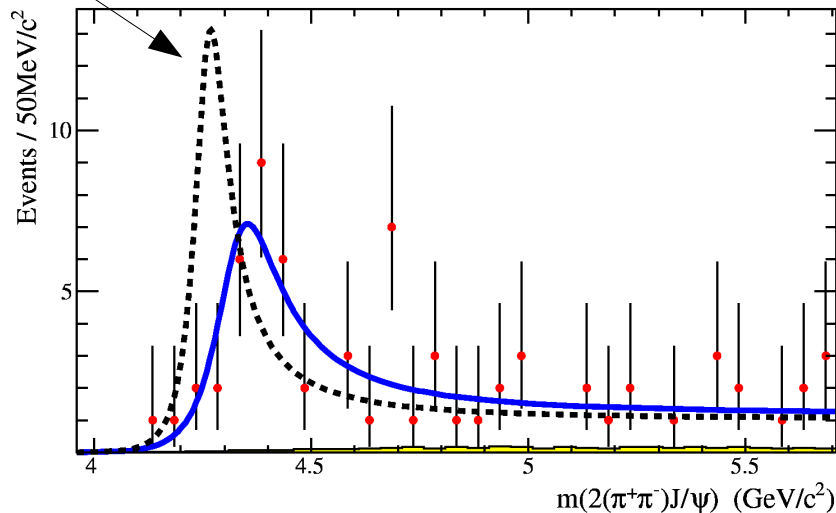
Parameters	Solution I	Solution II
$M(R1)$	$4008 \pm 40^{+114}_{-28}$	
$\Gamma_{\text{tot}}(R1)$	$226 \pm 44 \pm 87$	
$\mathcal{B} \cdot \Gamma_{e^+e^-}(R1)$	$5.0 \pm 1.4^{+6.1}_{-0.9}$	$12.4 \pm 2.4^{+14.8}_{-1.1}$
$M(R2)$	$4247 \pm 12^{+17}_{-32}$	
$\Gamma_{\text{tot}}(R2)$	$108 \pm 19 \pm 10$	
$\mathcal{B} \cdot \Gamma_{e^+e^-}(R2)$	$6.0 \pm 1.2^{+4.7}_{-0.5}$	$20.6 \pm 2.3^{+9.1}_{-1.7}$
$\phi$	$12 \pm 29^{+7}_{-98}$	$-111 \pm 7^{+28}_{-31}$

# more Y discovered in $e^+ e^- \rightarrow \gamma_{\text{ISR}} \pi^+ \pi^- \psi(2S)$

PRL98, 212001 (2007)  
(298 fb<sup>-1</sup>)



fit with Y(4260)

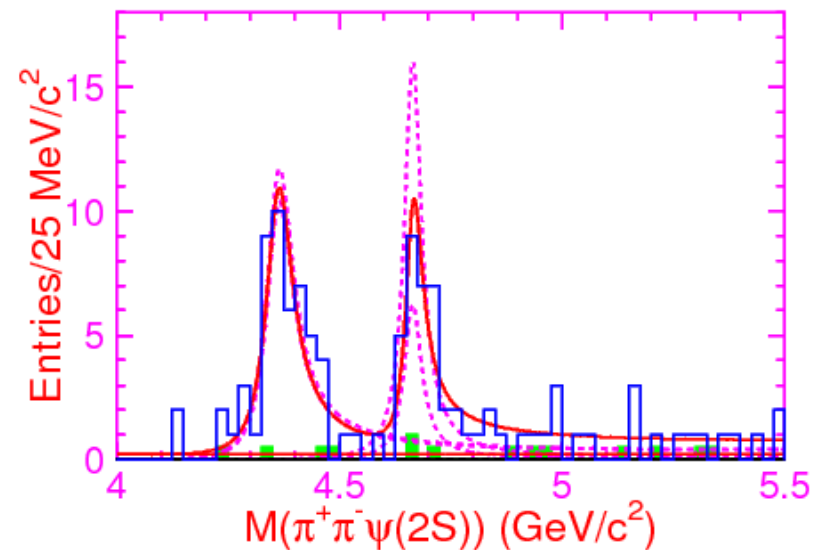


...a fit to the mass spectrum  
with a single resonance yields...

$$M = (4324 \pm 24) \text{ MeV}/c^2$$

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

PRL99, 142002 (2007)  
(673 fb<sup>-1</sup>)



Parameters	Solution I	Solution II
$M(Y(4360))$	$4361 \pm 9 \pm 9$	
$\Gamma_{\text{tot}}(Y(4360))$	$74 \pm 15 \pm 10$	
$\mathcal{B} \cdot \Gamma_{e^+e^-}(Y(4360))$	$10.4 \pm 1.7 \pm 1.5$	$11.8 \pm 1.8 \pm 1.4$
$M(Y(4660))$	$4664 \pm 11 \pm 5$	
$\Gamma_{\text{tot}}(Y(4660))$	$48 \pm 15 \pm 3$	
$\mathcal{B} \cdot \Gamma_{e^+e^-}(Y(4660))$	$3.0 \pm 0.9 \pm 0.3$	$7.6 \pm 1.8 \pm 0.8$
$\phi$	$39 \pm 30 \pm 22$	$-79 \pm 17 \pm 20$

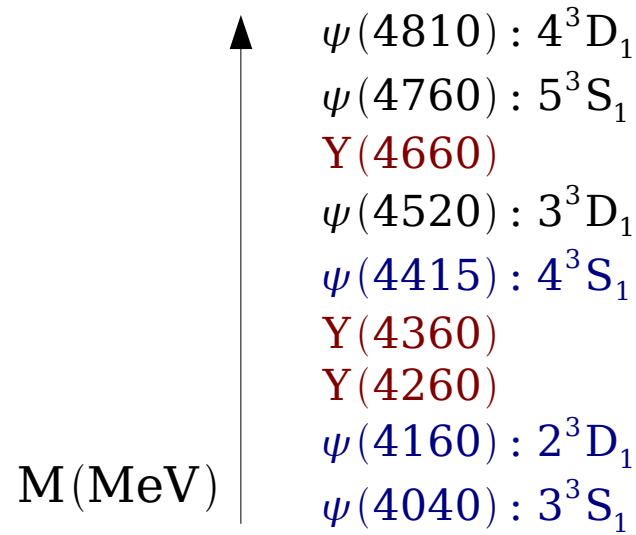
⇒ both structures differ from those in  $J/\psi \pi^+ \pi^-$

Can Y(4008) ?, Y(4260), Y(4360), Y(4660) be charmonium states ?



# Can these be charmonium states ?

⇒ Only one unassigned  $1^{--}$  charmonium in this mass region  
no room for all 3 (4?) peaks



⇒ **most popular theoretical explanation:  $c\bar{c}$ -gluon hybrids**

⇒ absence of any corresponding peaking features in the total cross-section for  $e^+e^-$  annihilation into hadrons at the same energy

Y(4260)

Ratio	UL, 90% CL
$\mathcal{B}(D\bar{D})/\mathcal{B}(\pi^+\pi^-J/\psi)$	$< 1$
$\mathcal{B}(D^*\bar{D})/\mathcal{B}(\pi^+\pi^-J/\psi)$	$< 34$
$\mathcal{B}(D^*\bar{D}^*)/\mathcal{B}(\pi^+\pi^-J/\psi)$	$< 40$

For the  $\psi(3770)$ :  $\mathcal{B}(D\bar{D})/\mathcal{B}(\pi^+\pi^-J/\psi) = 440$  !

# Can these be charmonium hybrids ?

- The lightest hybrid is expected by LQCD around 4.2 GeV
  - relevant open-charm threshold for these hybrids are  $M_{D^{**}} + M_D$
- $\Rightarrow$  search for exclusive  $e^+ e^- \rightarrow D \bar{D} \pi, D^* \bar{D} \pi$  via ISR

## $D \bar{D} \pi$

see strong signal  $\psi(4415) \rightarrow D \bar{D}_2^*(2460)$  but no  $Y(4260) \rightarrow D_0(2400) \bar{D}$

## $D^* \bar{D} \pi$

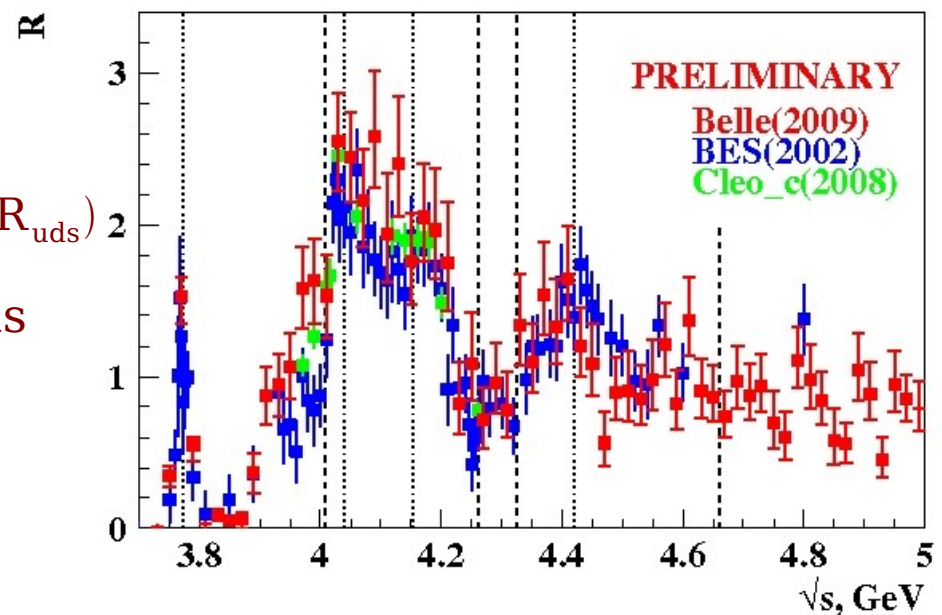
UL at 90% CL	Y(4260)	Y(4350)	Y(4660)
$BR(X \rightarrow D^0 D^{*-} \pi^+) / BR(X \rightarrow \pi^+ \pi^- J/\psi)$	9		
$BR(X \rightarrow D^0 D^{*-} \pi^+) / BR(X \rightarrow \pi^+ \pi^- \psi(2S))$		8	10

Sum of all contributions

$DD, DD^*, D^* D^*, DD\pi, DD^* \pi, \Lambda_c \Lambda_c$

saturates  $R (= \sigma(e^+ e^- \rightarrow \text{hadrons}) / \sigma(e^+ e^- \rightarrow \mu^+ \mu^-) - R_{uds})$

only small room for unaccounted contributions



## **The charged Z states**

# Z(4430): study of $B \rightarrow K \pi^+ \psi'$ with $548\text{fb}^{-1}$

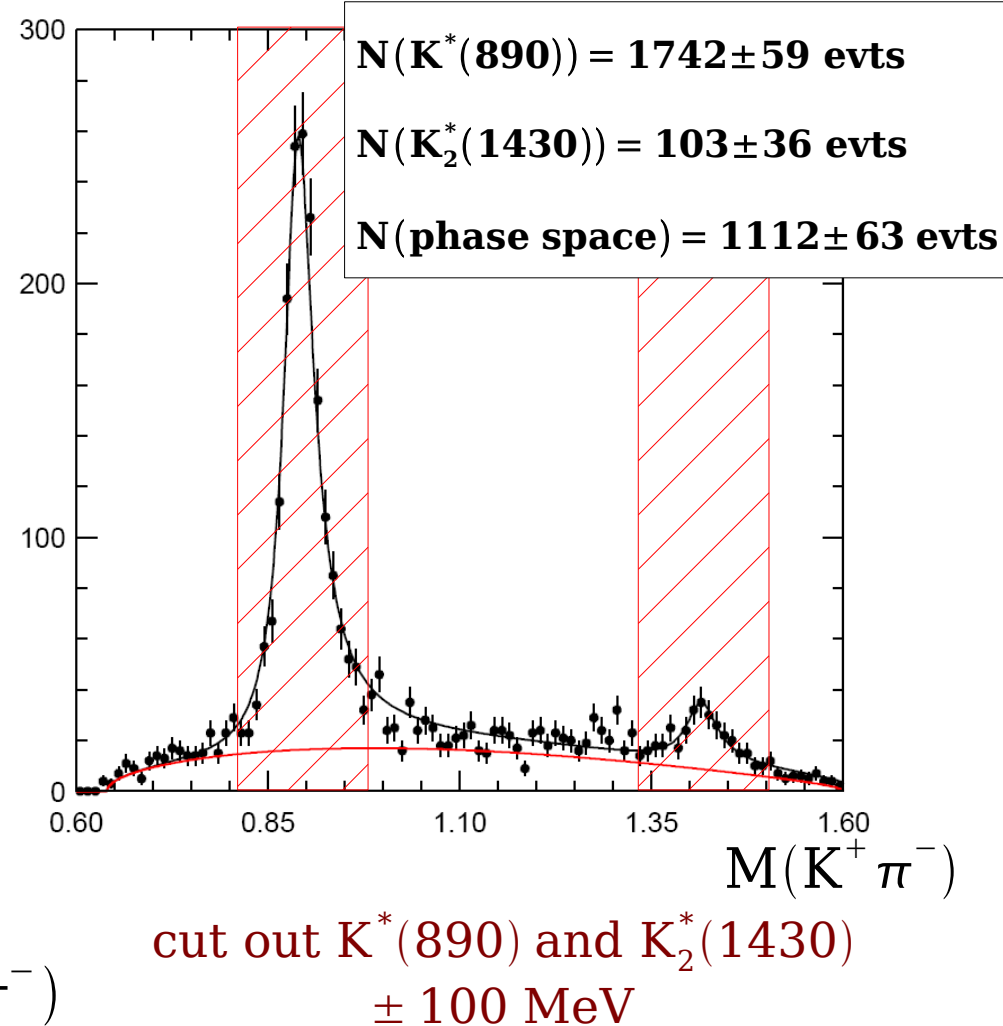
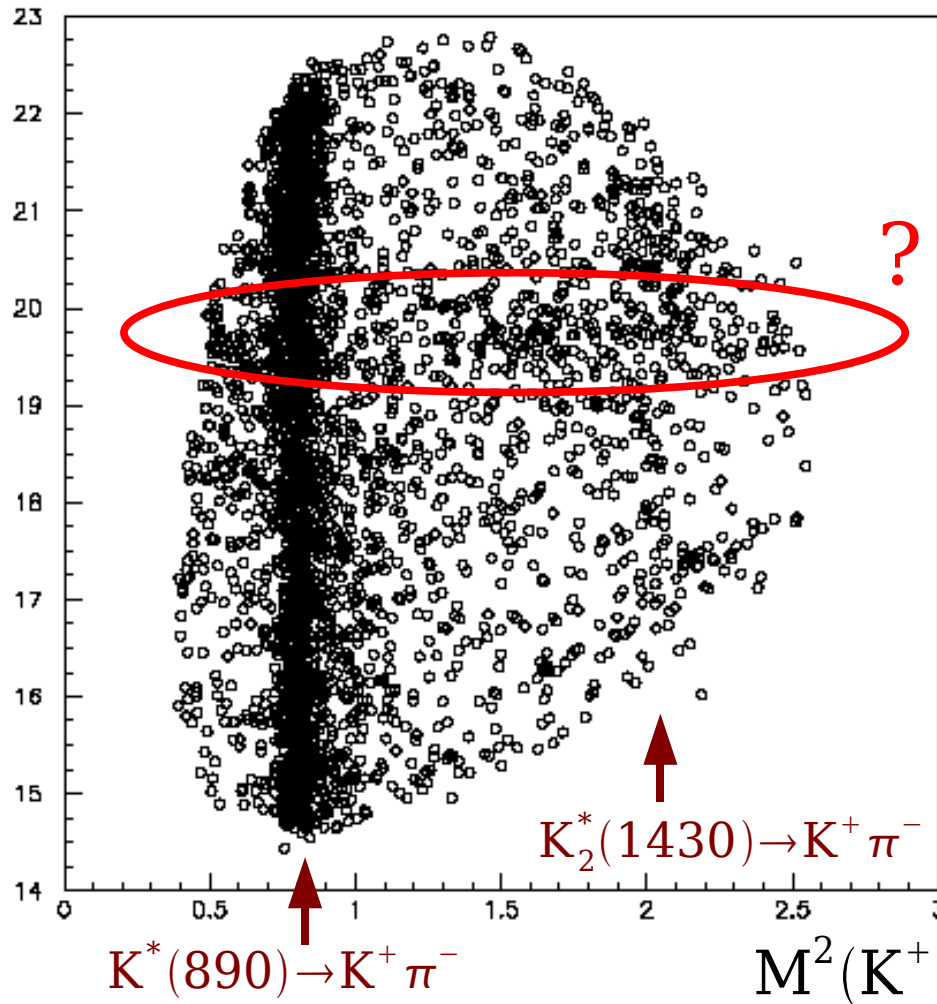
arXiv:0708.1790 [hep-ex]  
PRL 100, 142001 (2007)

$$\psi' \rightarrow e^+ e^-, \mu^+ \mu^-$$

$$\psi' \rightarrow \pi^+ \pi^- J/\psi, J/\psi \rightarrow e^+ e^-, \mu^+ \mu^-$$

$$K = K^\pm \text{ or } K_S^0$$

$$M^2(\pi^+ \psi')$$

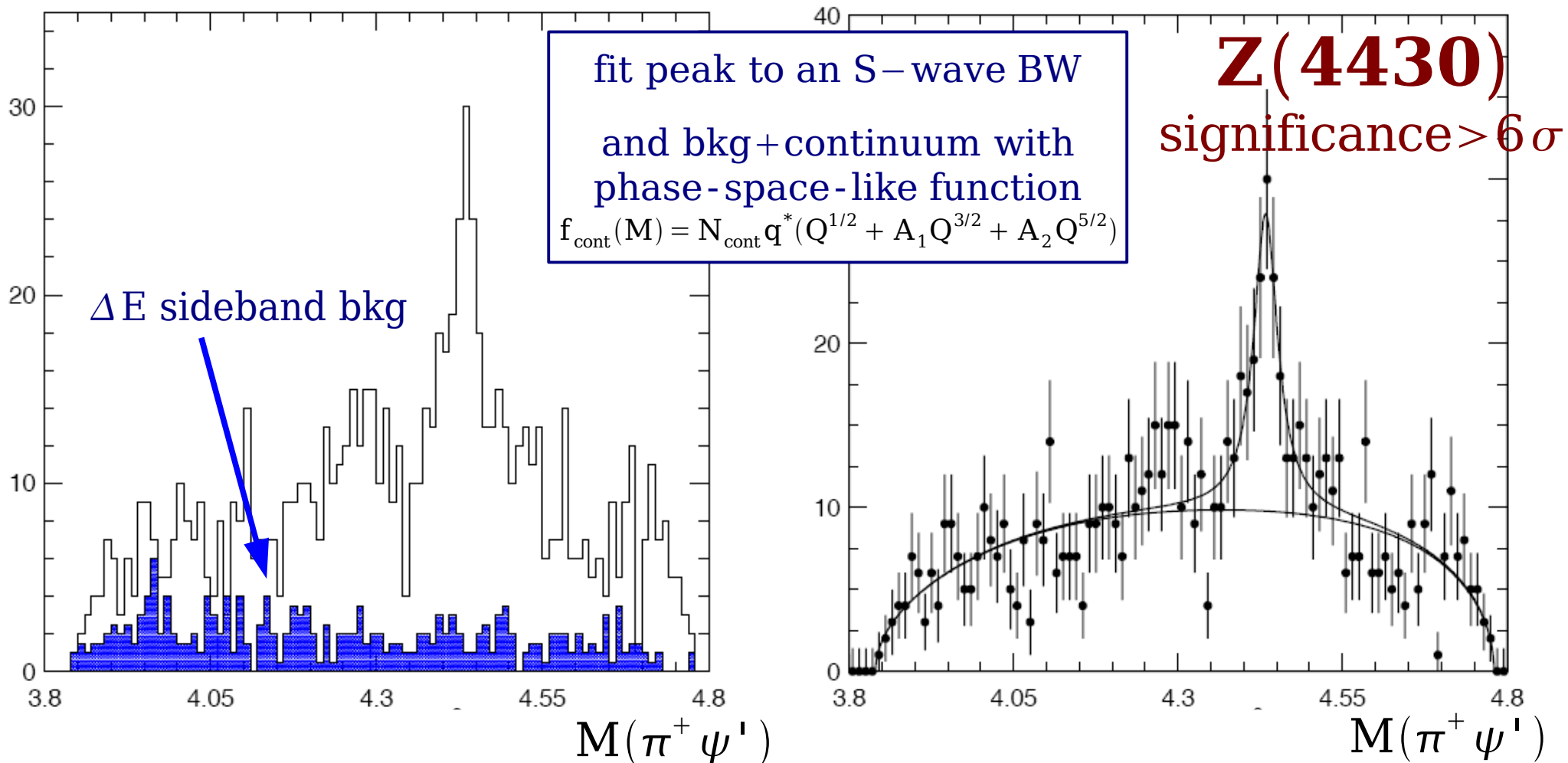


# After $K^*$ veto, $M(\pi^+ \psi')$ ...

PRL 100, 142001 (2007)

$$M = (4433 \pm 4 \pm 2) \text{ MeV}$$

$$\Gamma = (45^{+18+30}_{-13-13}) \text{ MeV}$$



$$\text{BR}(\bar{B}^0 \rightarrow K^- Z^+(4430)) \times \text{BR}(Z^+(4430) \rightarrow \pi^+ \psi') = (4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$$

# Compare data subsamples

Significant signals @  $\sim 4433$  MeV in all subsets



Subset	Signal events	Mass (GeV)	Width (GeV)	signif. ( $\sigma$ )	constr. yield ( $\Gamma = 0.045\text{GeV}$ )
$\psi' \rightarrow \pi^+\pi^- J/\psi$ (*)	$50.2 \pm 14.9$	$4.435 \pm 0.004$	$0.026^{+0.013}_{-0.008}$	4.5	$64.1 \pm 14.6$
$\psi' \rightarrow \ell^+\ell^-$	$93.4 \pm 29.4$	$4.435 \pm 0.010$	$0.094^{+0.042}_{-0.030}$	4.7	$58.6 \pm 13.4$
$J/\psi(\psi') \rightarrow e^+e^-$	$46.4 \pm 16.0$	$4.430 \pm 0.009$	$0.056^{+0.028}_{-0.020}$	3.5	$41.2 \pm 11.6$
$J/\psi(\psi') \rightarrow \mu^+\mu^-$ (**)	$73.4 \pm 22.6$	$4.434 \pm 0.004$	$0.038^{+0.023}_{-0.013}$	5.2	$80.3 \pm 16.2$
$\pi^-\psi'$	$109.8 \pm 35.8$	$4.437 \pm 0.008$	$0.081 \pm 0.030$	5.0	$73.3 \pm 15.5$
$\pi^+\psi'$	$41.4 \pm 13.7$	$4.430 \pm 0.004$	$0.025 \pm 0.012$	4.0	$53.7 \pm 13.5$
$K^\pm\pi^\mp\psi'$ (***)	$105.7 \pm 26.3$	$4.434 \pm 0.005$	$0.048^{+0.019}_{-0.014}$	6.0	$102.4 \pm 18.1$
$K_S\pi^\mp\psi'$	$19.1 \pm 8.0$	$4.430 \pm 0.009$	0.048-fixed	2.0	$18.5 \pm 8.1$
vary $K^*$ veto (****)	$207.9 \pm 49.4$	$4.437 \pm 0.005$	$0.063^{+0.024}_{-0.017}$	7.1	$169.8 \pm 25.6$

(\*) MC-determined acceptance ratio of  $\pi^+\pi^- J/\psi/\ell^+\ell^-$  is 1.23

(\*\*) expected  $e^+e^-/\mu^+\mu^-$  acceptance ratio of 0.61

(\*\*\*)  $K_S/K^+$  acceptance ratio is 0.19

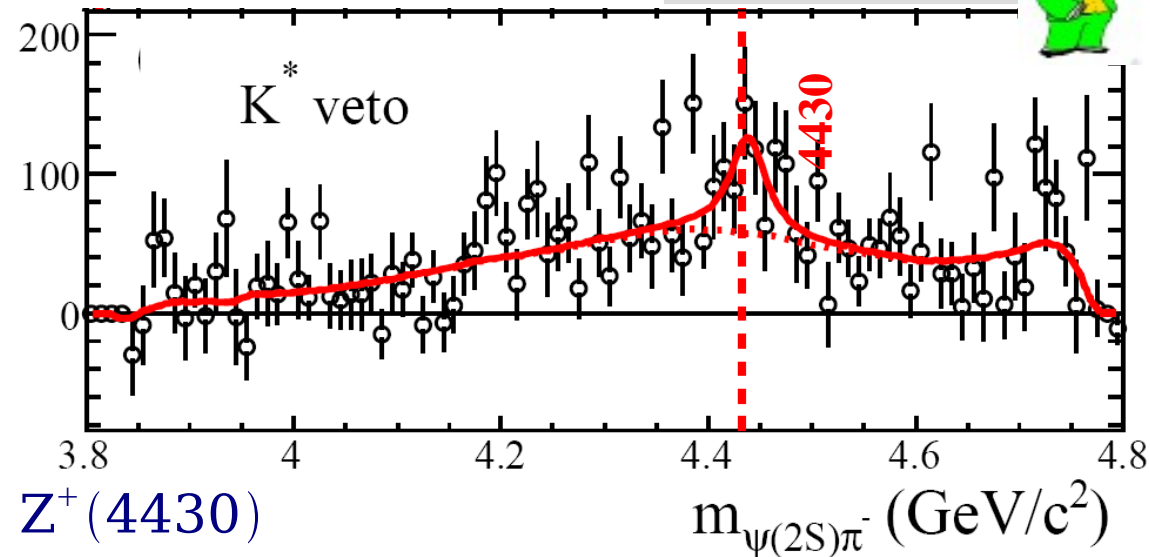
(\*\*\*\*)  $|M(K\pi) - m_{K^*(890)}| \geq 0.05$  GeV

# BaBar's search for Z(4430)

PRD79:112001 (2009)



performed detailed analysis  
of the  $K\pi^-$  system, corrected  
for efficiency, included S, P  
and D waves



⇒ no conclusive evidence for the  $Z^+(4430)$

$BR(\bar{B}^0 \rightarrow K^- Z^+) \times BR(Z^+ \rightarrow \pi^+ \psi')$   $< 3.1 \times 10^{-5}$  @ 95% C.L.

## Belle's analysis using Dalitz fit

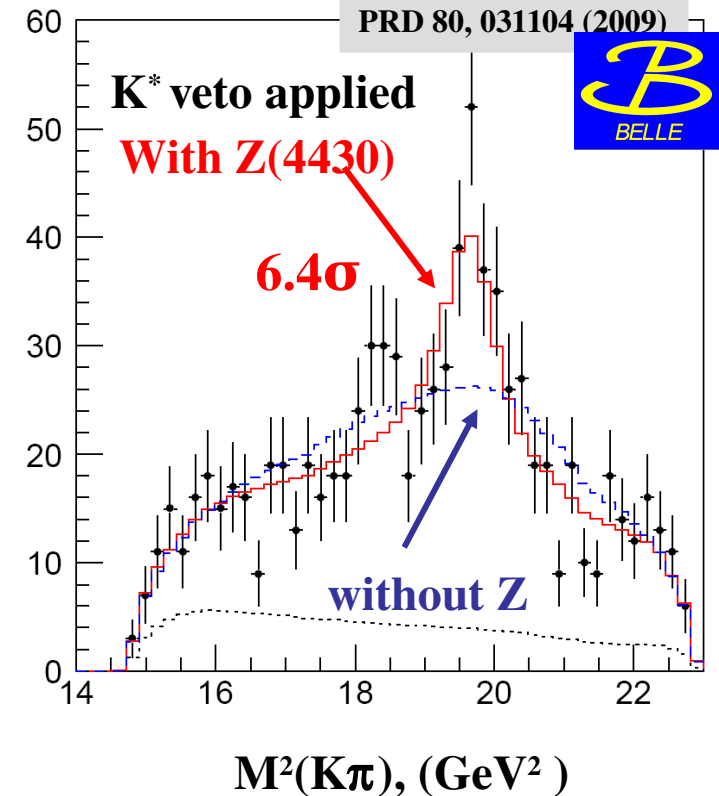
Fit  $B^0 \rightarrow \psi(2S)\pi^+ K^-$  amplitude by  
coherent sum of RBW contributions

- all known  $K\pi$  resonances
- all known  $K\pi$  resonances + Z

$$M = (4443^{+15}_{-12} {}^{+17}_{-13}) \text{ MeV}$$

$$\Gamma = (109^{+86}_{-43} {}^{+57}_{-52}) \text{ MeV}$$

$$BR(\bar{B}^0 \rightarrow K^- Z^+) \times BR(Z^+ \rightarrow \pi^+ \psi') = (3.2^{+1.8}_{-0.9} {}^{+5.3}_{-1.6}) \times 10^{-5}$$

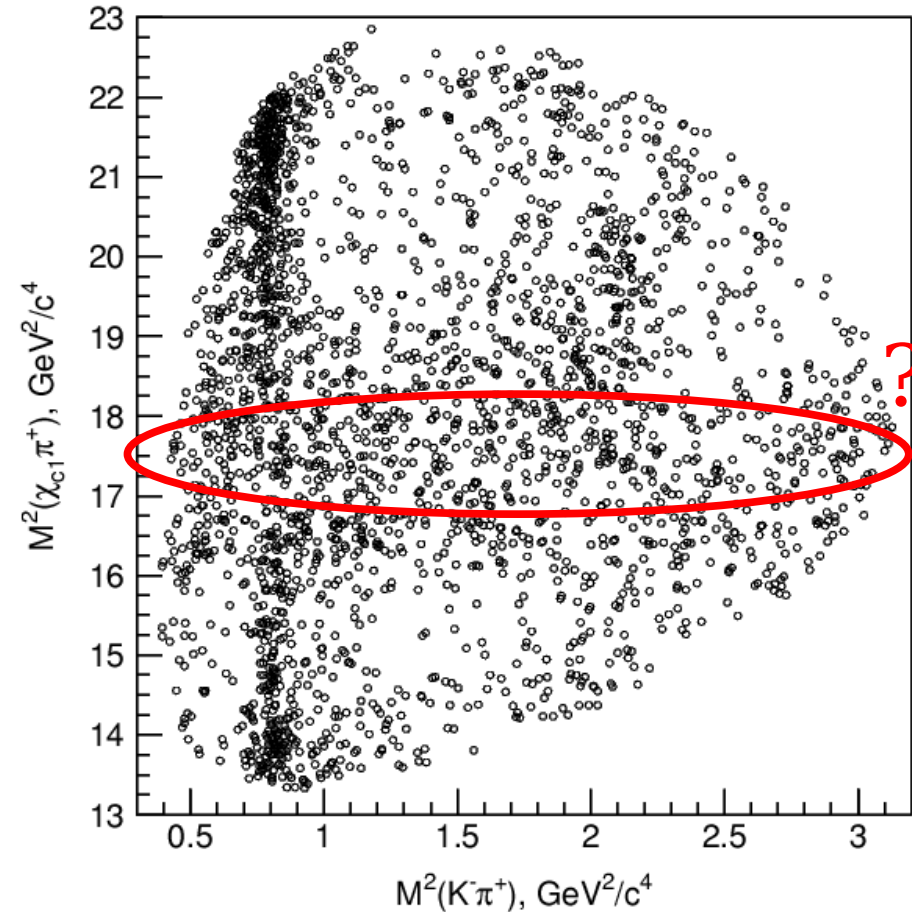




# $\bar{B}^0 \rightarrow K^- \pi^+ \chi_{c1}$

PRD80, 031104 (2009)

- $605 \text{ fb}^{-1} : 657 \times 10^6 \text{ B}\bar{\text{B}}$
- recon  $\bar{B}^0 \rightarrow K^- \pi^+ \chi_{c1} + \text{c.c.}$   
 $\chi_{c1} \rightarrow \gamma J/\psi$   
 $J/\psi \rightarrow l^+ l^- = e^+ e^-, \mu^+ \mu^-$   
mass-constrained fit to both
- selection:  
 $M_{bc} \in [5275, 5287] \text{ MeV}, |\Delta E| < 12 \text{ MeV}$   
 $\Delta E$  sidebands for bkgd estimation  
constrained fit to  $m_B$   
 $\epsilon = (20.0 \pm 1.4)\%$   
 $2125 \pm 56 \pm 42$  candidates
- Dalitz ( $M^2(K^- \pi^+), M^2(\chi_{c1} \pi^+)$ )  
vertical band for  $K^*(892)^+ \chi_{c1}$   
horizontal band  $M^2(\chi_{c1} \pi^+) \simeq 17 \text{ GeV}^2$
- isobar model:  $\pi^+ \chi_{c1}$  exotic resonance + known  $K^- \pi^+$   
( $\kappa, K^*(892), K^*(1410), K_0^*(1430), K_2^*(1430), K^*(1680), K_3^*(1780)$ )

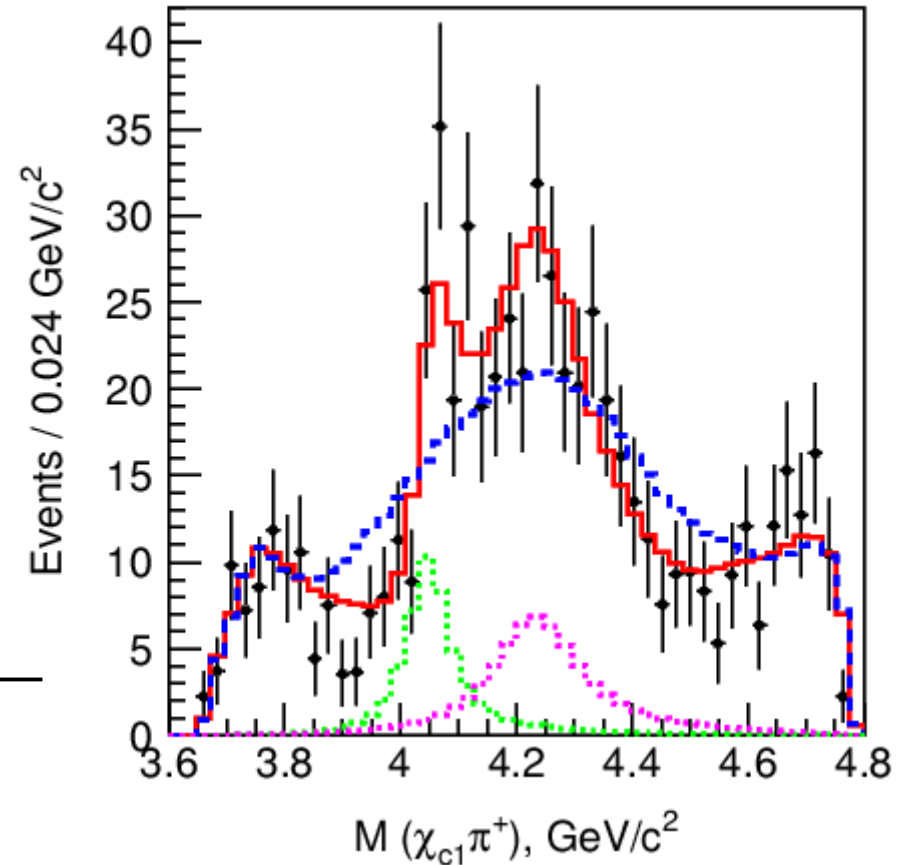




# $\bar{B}^0 \rightarrow K^- \pi^+ \chi_{c1}$ summary of Dalitz analysis

PRD80, 031104 (2009)

- very poor fit using known states
- exotic  $Z^+ \rightarrow \pi^+ \chi_{c1}$  needed
- $> 6\sigma$  even under speculative changes to the fitting model
- two terms preferred at  $> 5\sigma$



	$Z_1^+$	$Z_2^+$
M (MeV)	$4051 \pm 14^{+20}_{-41}$	$4248^{+44+180}_{-29-35}$
$\Gamma$ (MeV)	$82^{+21+47}_{-17-22}$	$177^{+54+316}_{-39-61}$
$B_{\bar{B}^0} \times B_{Z^+} (\times 10^{-5})$	$(3.1^{+1.5+3.7}_{-0.9-1.7})$	$(4.0^{+2.3+19.7}_{-0.9-0.5})$

$Z_1^+, Z_2^+$  join  $Z(4430)^+$  as candidate hidden-charm exotics

Many new  $c\bar{c}$ -like states decaying to  $c\bar{c}X$  rather than to open charm were unexpectedly found

From some there is no place in  $c\bar{c}$  spectrum

Table I Summary of the Charmonium-like  $XYZ$  states.

From S.Godfrey (arXiv:0910.3409)

state	$M$ (MeV)	$\Gamma$ (MeV)	$J^{PC}$	Seen In	Observed by:	Comments
$Y_s(2175)$	$2175 \pm 8$	$58 \pm 26$	$1^{--}$	$(e^+e^-)_{ISR}, J/\psi \rightarrow Y_s(2175) \rightarrow \phi f_0(980)$	BaBar, BESII, Belle	
$X(3872)$	$3871.4 \pm 0.6$	$< 2.3$	$1^{++}$	$B \rightarrow KX(3872) \rightarrow \pi^+\pi^- J/\psi, \gamma J/\psi, D\bar{D}^*$	Belle, CDF, D0, BaBar	Molecule?
$X(3915)$	$3914 \pm 4$	$28^{+12}_{-14}$	$?^{++}$	$\gamma\gamma \rightarrow \omega J/\psi$	Belle	
$Z(3930)$	$3929 \pm 5$	$29 \pm 10$	$2^{++}$	$\gamma\gamma \rightarrow Z(3940) \rightarrow D\bar{D}$	Belle	$2^3P_2(c\bar{c})$
$X(3940)$	$3942 \pm 9$	$37 \pm 17$	$0^{?+}$	$e^+e^- \rightarrow J/\psi X(3940) \rightarrow D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$ )	Belle	$3^1S_0(c\bar{c})?$
$Y(3940)$	$3943 \pm 17$	$87 \pm 34$	$?^{?+}$	$B \rightarrow KY(3940) \rightarrow \omega J/\psi$ (not $D\bar{D}^*$ )	Belle, BaBar	$2^3P_1(c\bar{c})?$
$Y(4008)$	$4008^{+82}_{-49}$	$226^{+97}_{-80}$	$1^{--}$	$(e^+e^-)_{ISR} \rightarrow Y(4008) \rightarrow \pi^+\pi^- J/\psi$	Belle	
$Y(4140)$	$4143 \pm 3.1$	$11.7^{+9.1}_{-6.2}$	$?^?$	$B \rightarrow KY(4140) \rightarrow J/\psi\phi$	CDF	
$X(4160)$	$4156 \pm 29$	$139^{+113}_{-65}$	$0^{?+}$	$e^+e^- \rightarrow J/\psi X(4160) \rightarrow D^*\bar{D}^*$ (not $D\bar{D}$ )	Belle	
$Y(4260)$	$4264 \pm 12$	$83 \pm 22$	$1^{--}$	$(e^+e^-)_{ISR} \rightarrow Y(4260) \rightarrow \pi^+\pi^- J/\psi$	BaBar, CLEO, Belle	Hybrid?
$Y(4350)$	$4324 \pm 24$	$172 \pm 33$	$1^{--}$	$(e^+e^-)_{ISR} \rightarrow Y(4350) \rightarrow \pi^+\pi^- \psi'$	BaBar	
$Y(4350)$	$4361 \pm 13$	$74 \pm 18$	$1^{--}$	$(e^+e^-)_{ISR} \rightarrow Y(4350) \rightarrow \pi^+\pi^- \psi'$	Belle	
$Y(4630)$	$4634^{+9.4}_{-10.6}$	$92^{+41}_{-32}$	$1^{--}$	$(e^+e^-)_{ISR} \rightarrow Y(4630) \rightarrow \Lambda_c^+ \Lambda_c^-$	Belle	
$Y(4660)$	$4664 \pm 12$	$48 \pm 15$	$1^{--}$	$(e^+e^-)_{ISR} \rightarrow Y(4660) \rightarrow \pi^+\pi^- \psi'$	Belle	
$Z_1(4050)$	$4051^{+24}_{-23}$	$82^{+51}_{-29}$	$?$	$B \rightarrow KZ_1^\pm(4050) \rightarrow \pi^\pm \chi_{c1}$	Belle	
$Z_2(4250)$	$4248^{+185}_{-45}$	$177^{+320}_{-72}$	$?$	$B \rightarrow KZ_2^\pm(4250) \rightarrow \pi^\pm \chi_{c1}$	Belle	
$Z(4430)$	$4433 \pm 5$	$45^{+35}_{-18}$	$?$	$B \rightarrow KZ^\pm(4430) \rightarrow \pi^\pm \psi'$	Belle	
$Y_b(10890)$	$10,890 \pm 3$	$55 \pm 9$	$1^{--}$	$e^+e^- \rightarrow Y_b \rightarrow \pi^+\pi^- \Upsilon(1, 2, 3S)$	Belle	

## **X(3872)**

- narrow and right at  $m_{D^0} + m_{D^{*0}}$
- seen in  $D^0 \bar{D}^0 \pi^0$ ,  $J/\psi \pi^+ \pi^-$ ,  $J/\psi \omega$ ,  $J/\psi \gamma$ , not seen in  $\psi(2S) \gamma$
- $C = +1$  well established,  $J^{PC} = 1^{++}$  seems likely

⇒ no charmonium candidate, so what is it ? tetraquark, molecule, ... ?

## **Y(3940)**

- seen in  $J/\psi \omega$  ⇒ no obvious charmonium assignment,  $c\bar{c}$ -gluon hybrid ?

## **Y( $J^{PC}=1^{--}$ )**

- seen in  $J/\psi \pi^+ \pi^-$ ,  $\psi(2S) \pi^+ \pi^-$  ⇒ no obvious assignment

## **Z(4430), $Z_1$ , $Z_2$**

- significant  $\pi^+ \psi'(\chi_{c1})$  invariant mass peak (in  $B \rightarrow K \pi^+ \psi'(\chi_{c1})$  decays)
- not produced by interference effects in  $K\pi$  system

⇒ non-zero charge: not  $c\bar{c}$  or hybrid

→ **need more experimental inputs**

(updates, precise measurements ( $J^{PC}$  for Z), new decays...)

→ **...and suggestions from theorists !**



# $B^0 \rightarrow X(3872) K^+ \pi^-$

Motivation:

Charmonium modes

$\Gamma_{143}$	$\eta_c K^0$	$(9.9 \pm 1.9) \times 10^{-4}$	
$\Gamma_{144}$	$\eta_c K^*(892)^0$	$(1.6 \pm 0.7) \times 10^{-3}$	
$\Gamma_{145}$	$J/\psi(1S) K^0$	$(8.72 \pm 0.33) \times 10^{-4}$	
$\Gamma_{146}$	$J/\psi(1S) K^+ \pi^-$	$(1.2 \pm 0.6) \times 10^{-3}$	
$\Gamma_{147}$	$J/\psi(1S) K^*(892)^0$	$(1.33 \pm 0.06) \times 10^{-3}$	
$\Gamma_{169}$	$\psi(2S) K^0$	$(6.2 \pm 0.6) \times 10^{-4}$	
$\Gamma_{170}$	$\psi(2S) K^+ \pi^-$	$< 1 \times 10^{-3}$	CL=90%
$\Gamma_{171}$	$\psi(2S) K^*(892)^0$	$(7.2 \pm 0.8) \times 10^{-4}$	
$\Gamma_{176}$	$\chi_{c1}(1P) K^0$	$(3.9 \pm 0.4) \times 10^{-4}$	
$\Gamma_{177}$	$\chi_{c1}(1P) K^*(892)^0$	$(3.2 \pm 0.6) \times 10^{-4}$	
<hr/>			
$\Gamma_{149}$	$J/\psi(1S) K^+$	$(1.007 \pm 0.035) \times 10^{-3}$	
$\Gamma_{163}$	$J/\psi(1S) K^*(892)^+$	$(1.41 \pm 0.08) \times 10^{-3}$	
$\Gamma_{175}$	$\psi(2S) K^+$	$(6.48 \pm 0.35) \times 10^{-4}$	
$\Gamma_{176}$	$\psi(2S) K^*(892)^+$	$(6.7 \pm 1.4) \times 10^{-4}$	S=1.3
$\Gamma_{187}$	$\chi_{c1}(1P) K^+$	$(4.9 \pm 0.5) \times 10^{-4}$	S=1.5
$\Gamma_{188}$	$\chi_{c1}(1P) K^*(892)^+$	$(3.6 \pm 0.9) \times 10^{-4}$	

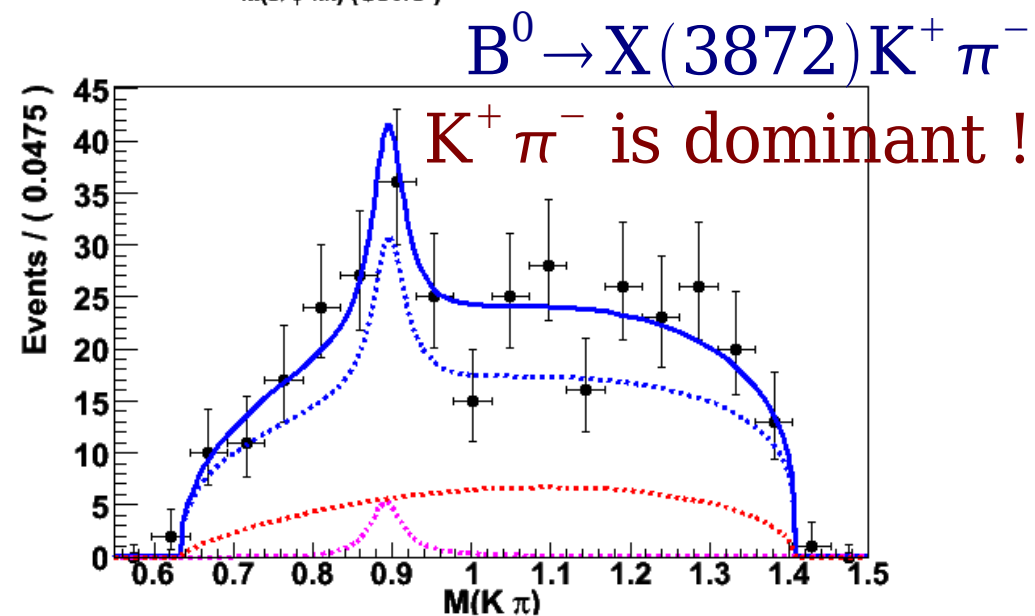
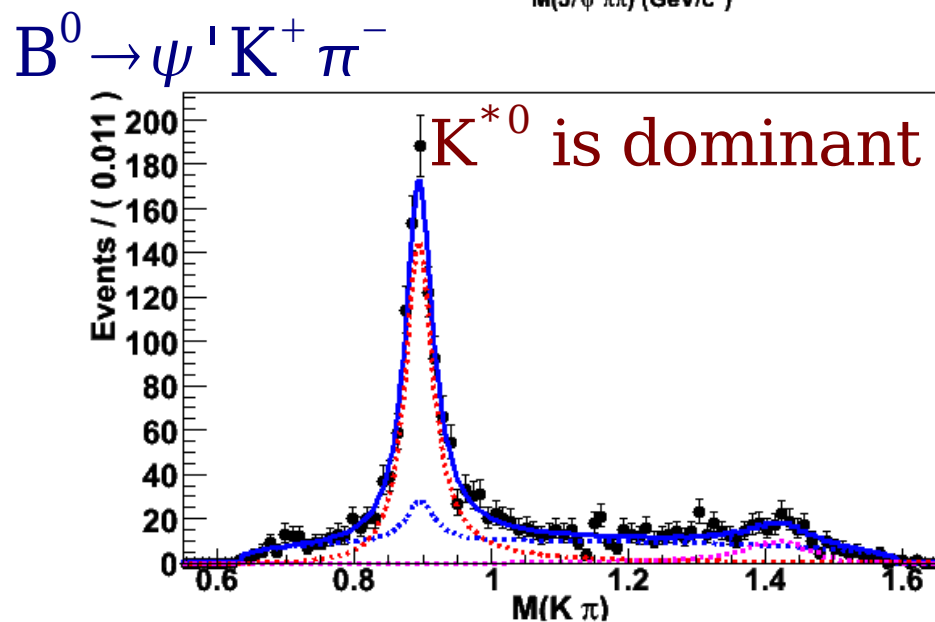
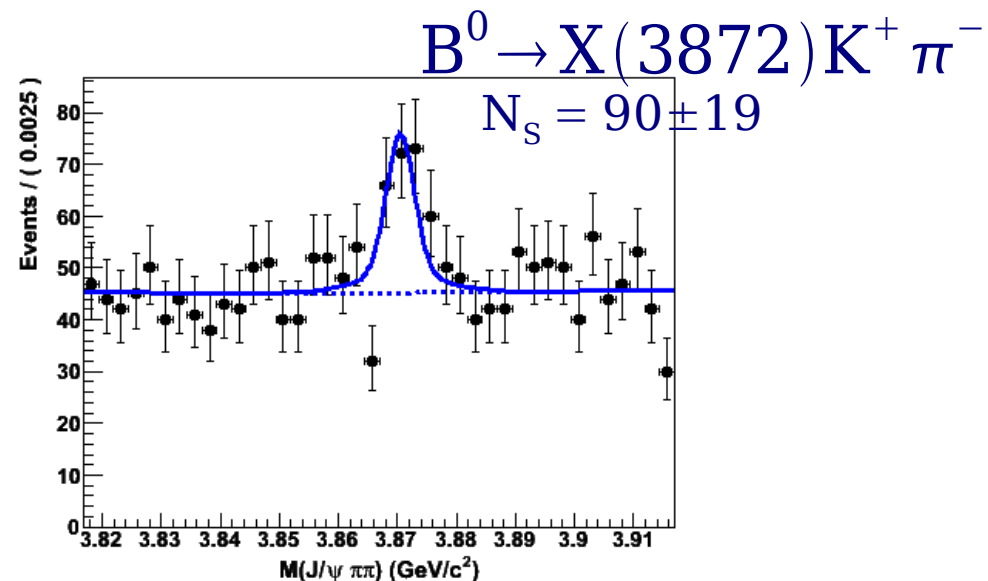
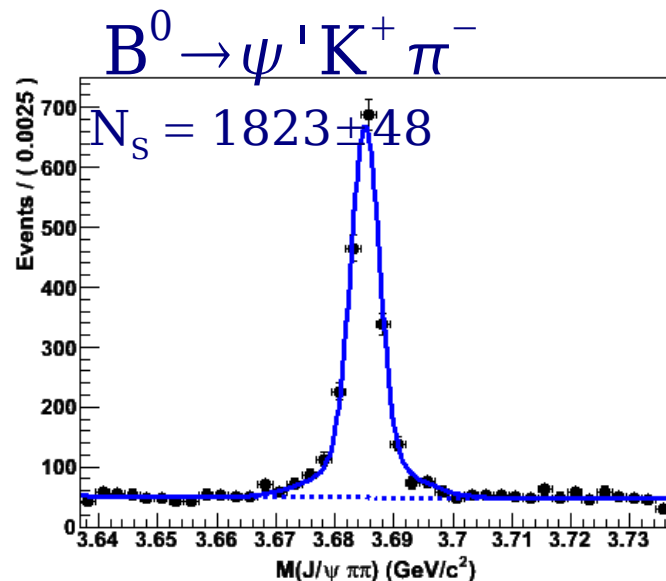
$$BR(J/\psi K^0) \sim BR(J/\psi K^+) \sim BR(J/\psi K^{*0}) \sim BR(J/\psi K^{*+})$$

$$BR(\psi(2S) K^0) \sim BR(\psi(2S) K^+) \sim BR(\psi(2S) K^{*0}) \sim BR(\psi(2S) K^{*+})$$

$$BR(\chi_{c1} K^0) \sim BR(\chi_{c1} K^+) \sim BR(\chi_{c1} K^{*0}) \sim BR(\chi_{c1} K^{*+})$$

# $B^0 \rightarrow X(3872) K^+ \pi^-$

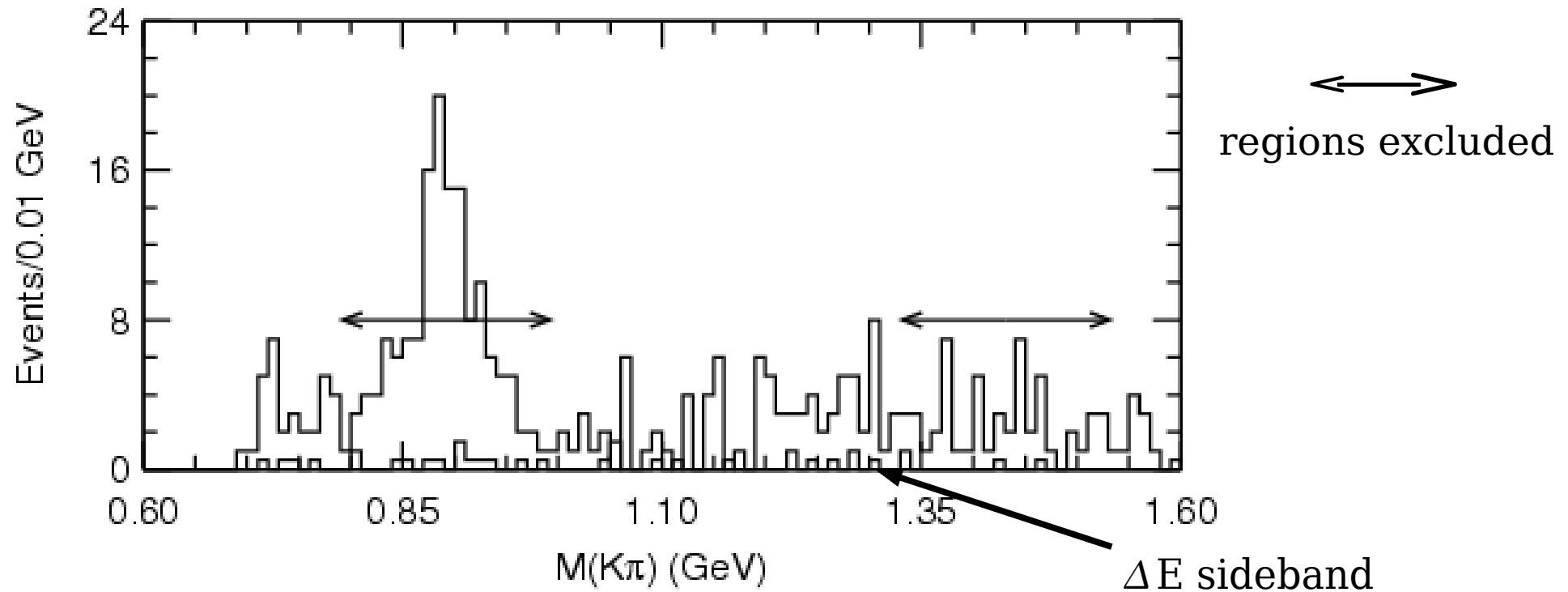
BELLE-CONF-0849  
NEW RESULTS !



$$\text{BR}(B^0 \rightarrow X(3872)(K^+ \pi^-)_{\text{NR}}) \times \text{BR}(X \rightarrow J/\psi \pi^+ \pi^-) = (8.1 \pm 2.0^{+1.1}_{-1.4}) \times 10^{-6}$$

$$\text{BR}(B^0 \rightarrow X(3872) K^{*0}) \times \text{BR}(X \rightarrow J/\psi \pi^+ \pi^-) < 3.4 \times 10^{-6} \text{ (90\% C.L.)}$$

$M(K\pi)$  for events within  $\pm 0.03$  GeV of the 4.43 GeV peak



→ no dramatic features are evident (aside  $K^*(890)$  evts vetoed)

# $\overline{B}^0 \rightarrow K^- \pi^+ \chi_{c1}$

arXiv:0806.4098 [hep-ex]  
submitted to PRD

- integration over angular quantities  
 $\cos\theta_{\chi_{c1}}, \phi_{\chi_{c1}}, \cos\theta_{J/\psi}, \phi_{J/\psi}$ :

efficiency almost uniform...

distributions studied as cross-check after the fit

- binned likelihood fit  
(small bins: fully-contained subset of  $400 \times 400$ )

- $F(s_x, s_y) = S(s_x, s_y) \times \epsilon(s_x, s_y) + B(s_x, s_y)$

bkgd  $B(s_x, s_y)$  from  $\Delta E$  sidebands

efficiency  $\epsilon(s_x, s_y)$  from MC; both smoothed

- isobar model:  $\pi^+ \chi_{c1}$  exotic resonance + known  $K^- \pi^+$

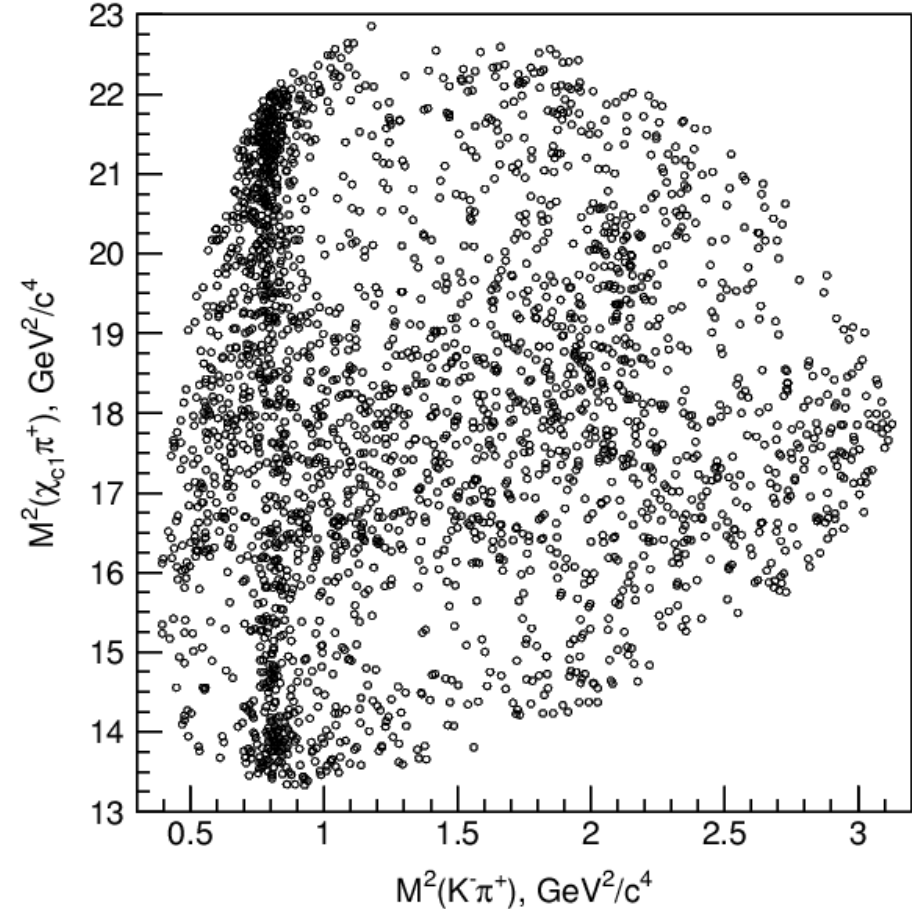
$(\kappa, K^*(892), K^*(1410), K_0^*(1430), K_2^*(1430), K^*(1680), K_3^*(1780))$

Blatt-Weisskopf form factors

energy-dependent widths

angular terms from helicity formalism

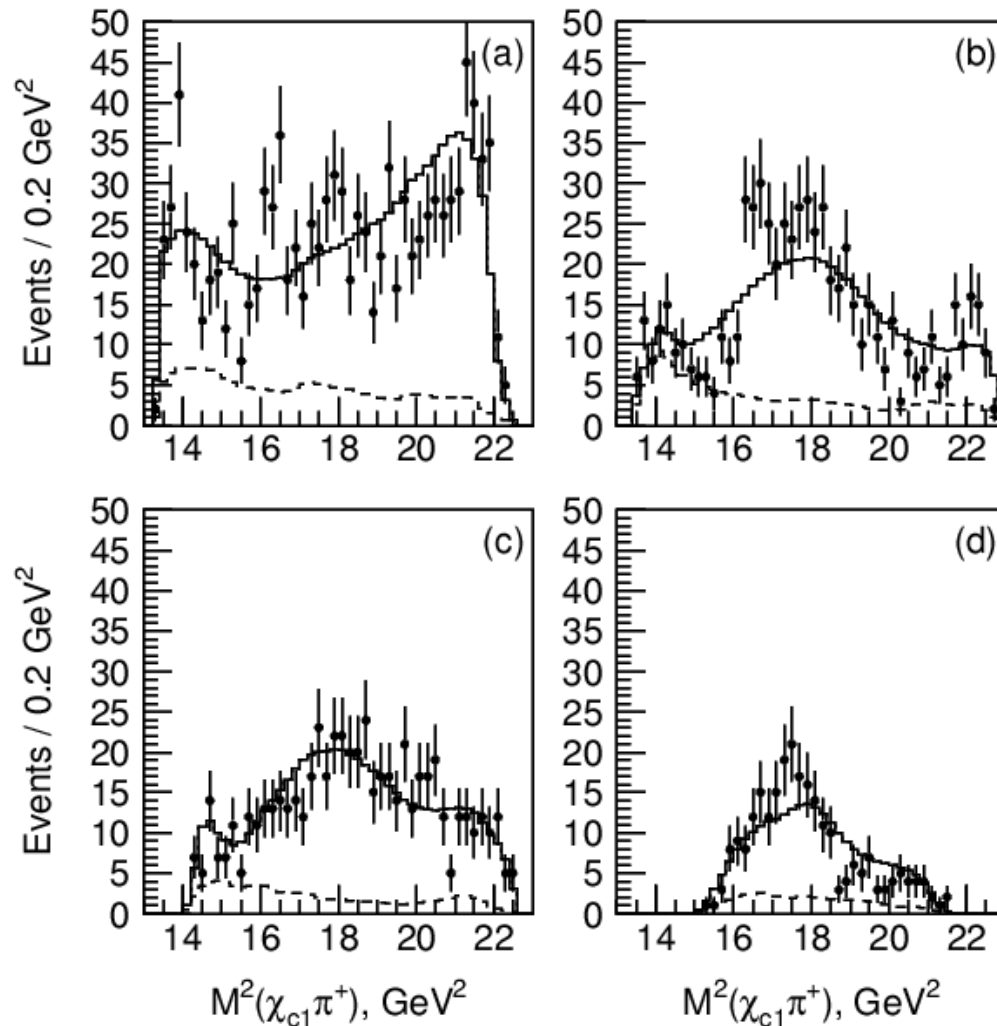
$(m_i, \Gamma_i)$  fixed to PDG averages



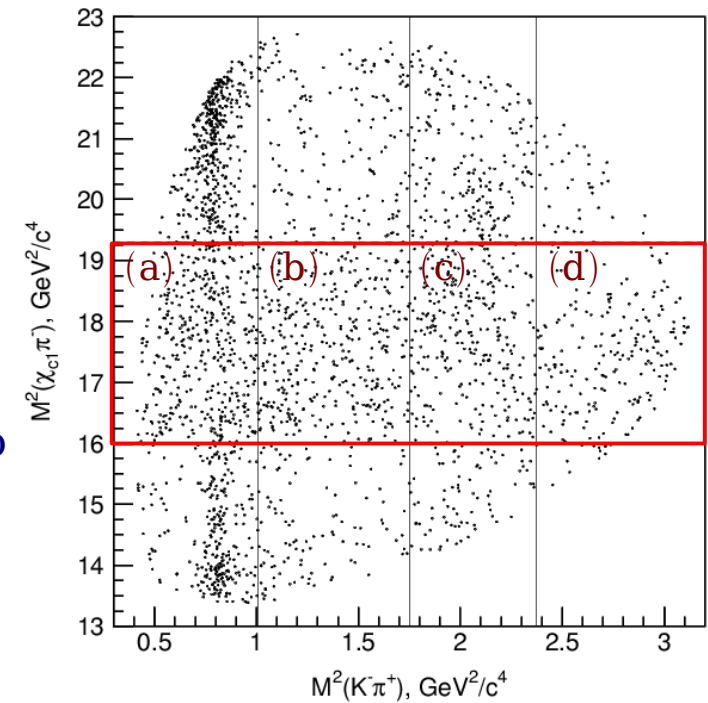


# $\bar{B}^0 \rightarrow K^- \pi^+ \chi_{c1}$ fit with known $K^*$ states

arXiv:0806.4098 [hep-ex]



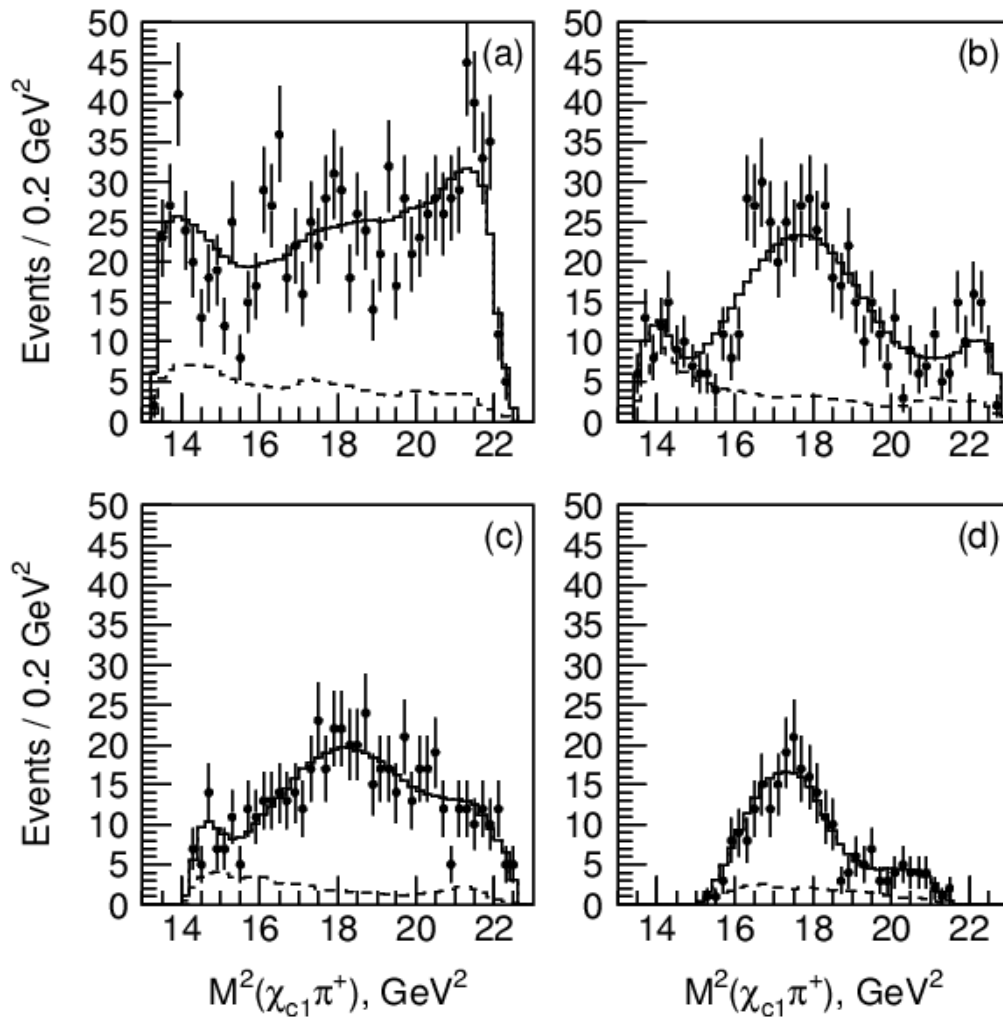
projections to  
Dalitz slices



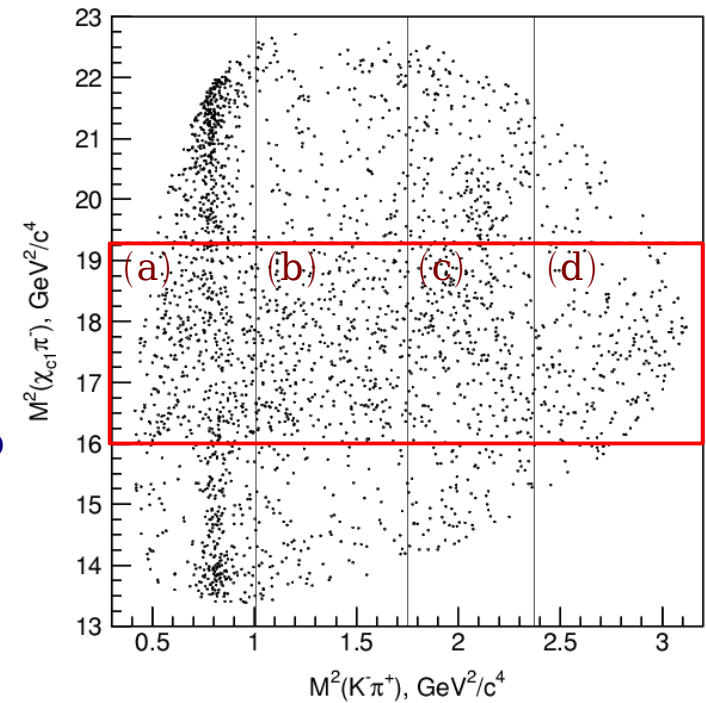
- very poor fit quality; unresolved:  
M ~ 4150 MeV enhancement
- only 1 of 4 slices plausible

# $\bar{B}^0 \rightarrow K^- \pi^+ \chi_{c1}$ known $K^* + K_2^*, \chi_{c1} K$ NR

arXiv:0806.4098 [hep-ex]



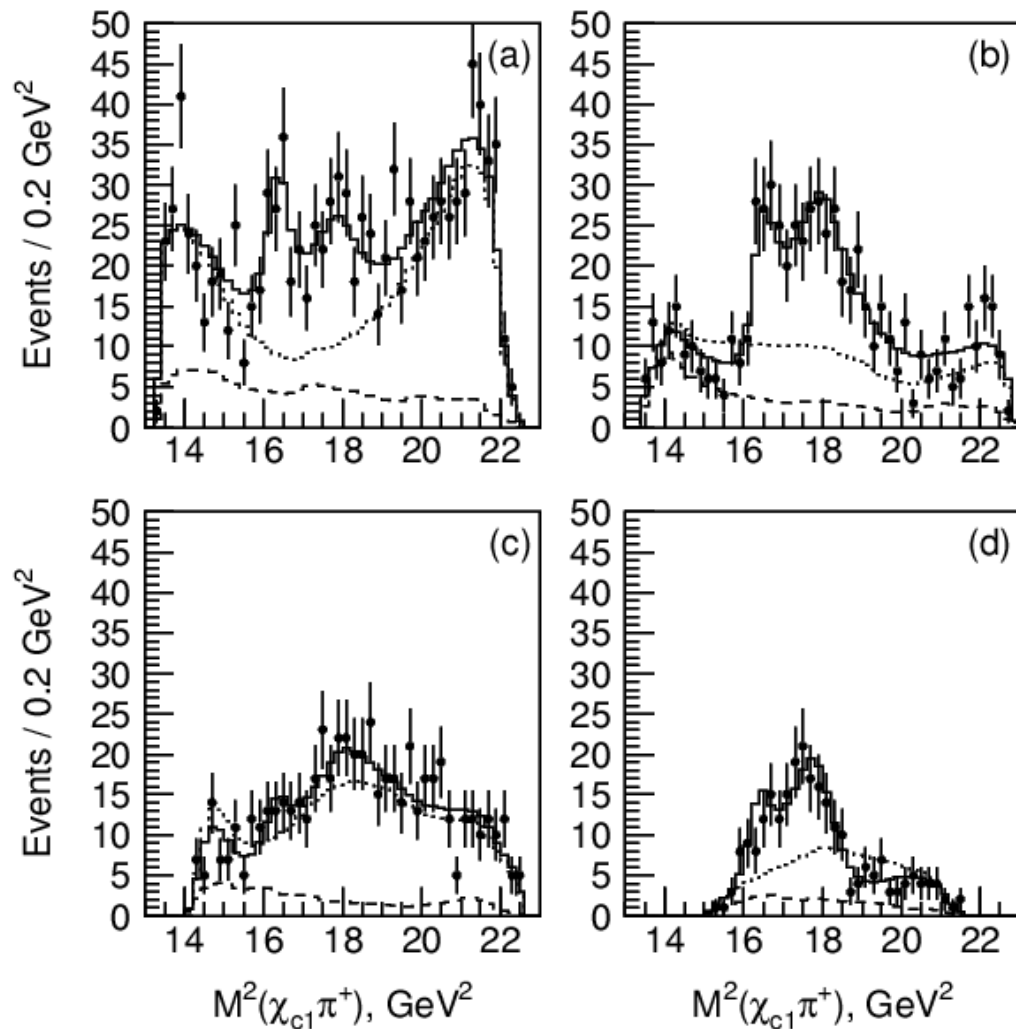
projections to  
Dalitz slices



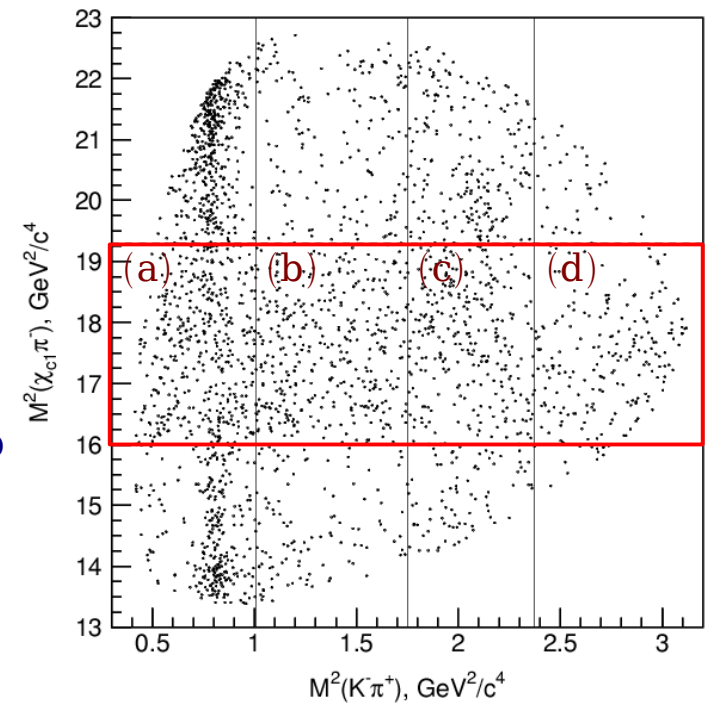
- improvements:
  - 2 of 4 slices  $\approx$  OK
- peak still poorly matched

# $\overline{B}^0 \rightarrow K^- \pi^+ \chi_{c1}$ with two $Z^+ \rightarrow \pi^+ \chi_{c1}$ terms

arXiv:0806.4098 [hep-ex]



projections to  
Dalitz slices



- two-vs-one Z favoured:  
matches peak fine structure  
> 5 $\sigma$  improvement
- good total fit quality: 40% C.L.

$\overline{\text{B}}^0 \rightarrow \text{K}^- \pi^+ \chi_{c1}$  fit contributions

arXiv:0806.4098 [hep-ex]

Contribution	One $Z^+$		Two $Z^+$	
	Fit fraction	Signif.	Fit fraction	Signif.
$Z_{(1)}^+$	$(33.1^{+8.7}_{-5.8})\%$	$10.7\,\sigma$	$(8.0^{+3.8}_{-2.2})\%$	$5.7\,\sigma$
$Z_2^+$	—	—	$(10.4^{+6.1}_{-2.3})\%$	$5.7\,\sigma$
$\kappa$	$(1.9 \pm 1.8)\%$	$2.1\,\sigma$	$(3.6 \pm 2.6)\%$	$3.5\,\sigma$
$K^*(892)$	$(28.5 \pm 2.1)\%$	$10.6\,\sigma$	$(30.1 \pm 2.3)\%$	$9.8\,\sigma$
$K^*(1410)$	$(3.6 \pm 4.4)\%$	$1.3\,\sigma$	$(4.4 \pm 4.3)\%$	$2.0\,\sigma$
$K_0^*(1430)$	$(22.4 \pm 5.8)\%$	$3.4\,\sigma$	$(18.6 \pm 5.0)\%$	$4.5\,\sigma$
$K_2^*(1430)$	$(8.4 \pm 2.7)\%$	$5.2\,\sigma$	$(6.1 \pm 2.9)\%$	$5.4\,\sigma$
$K^*(1680)$	$(5.2 \pm 3.7)\%$	$2.2\,\sigma$	$(4.4 \pm 3.1)\%$	$2.4\,\sigma$
$K_3^*(1780)$	$(7.4 \pm 3.0)\%$	$3.6\,\sigma$	$(7.2 \pm 2.9)\%$	$3.8\,\sigma$
	110.5%		92.8%	