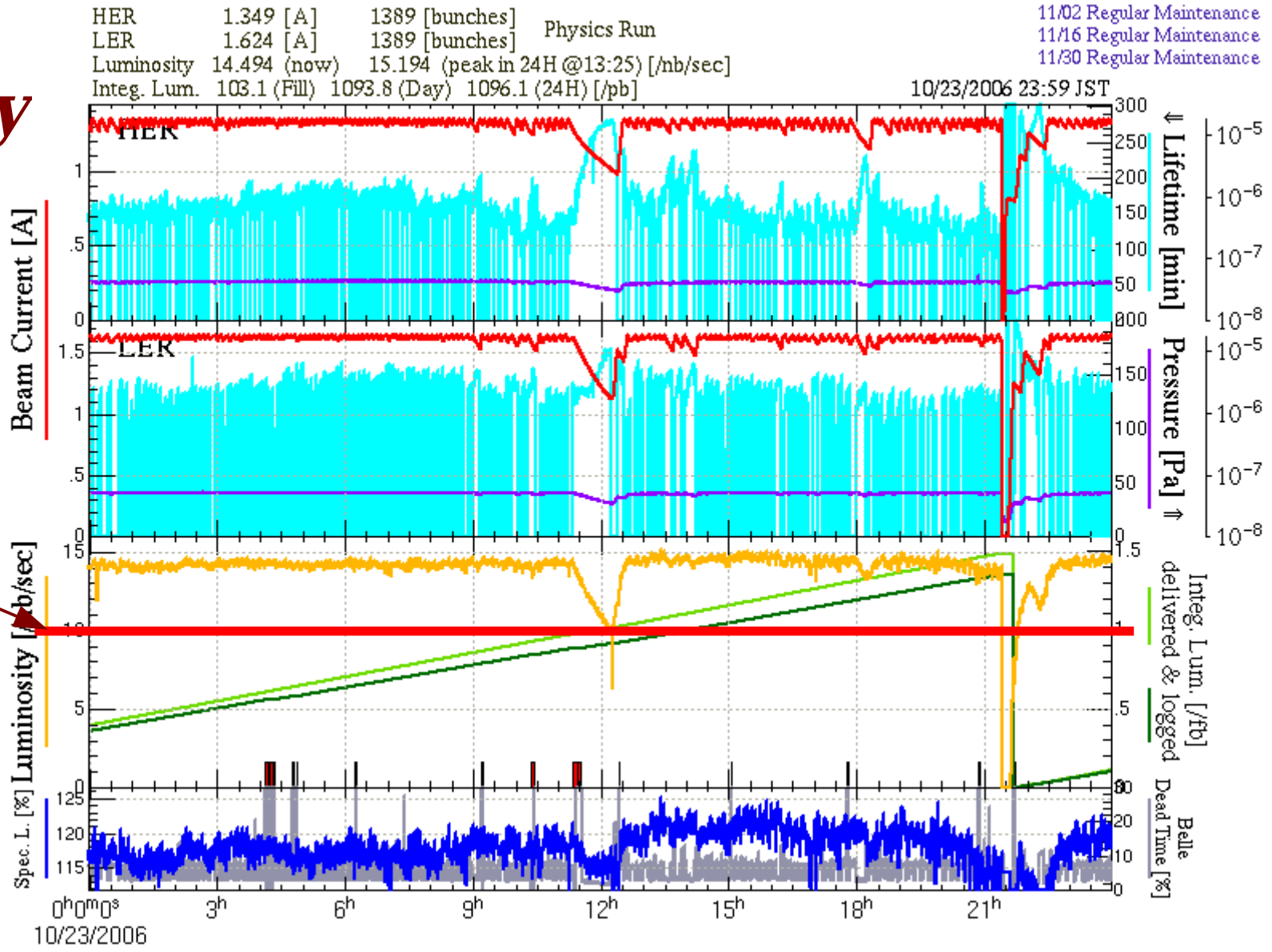
Study of charmonium (like) resonances at Belle

K.Trabelsi
KEK

$(c\bar{c})$ *states :* $X(3872)$, $Y(3940)$, $X(3940)$, $Z(3930)$...

Belle is a B–factory...

$>1\ fb^{-1}/day$

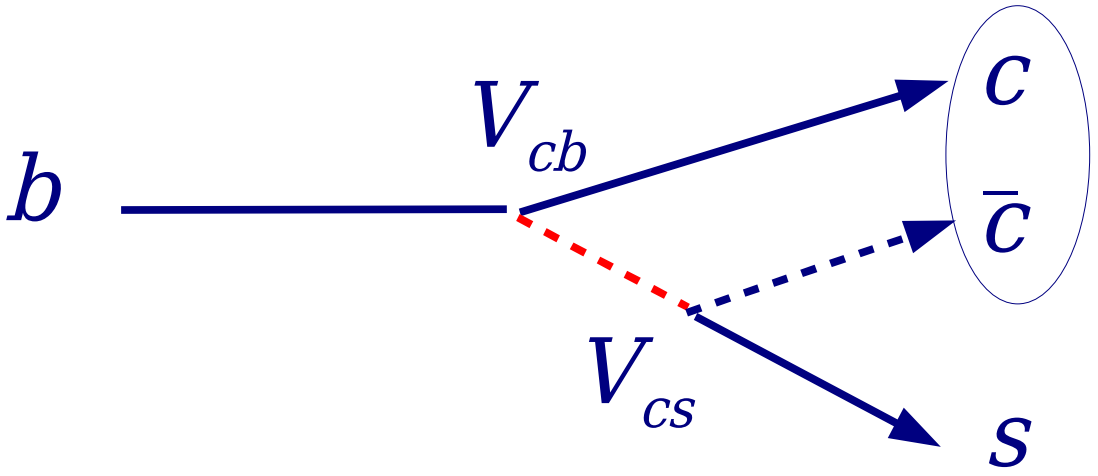


Design :
$10^{34}\ cm^{-2}\,s^{-1}$

$>600\ fb^{-1}$

...but also a $(c\bar{c})$ states–factory

$b \to c\bar{c}s$ *is a dominant process*



$J/\psi, \psi', \eta_c, \chi_{c1} \ldots$

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

B mesons are a good source for charm, charmonium and other $c\bar{c}$ *states*

An example : reconstruct $B \to K K_S K^- \pi^+$

PRL89, 102001 (2002)

Beam−constrained mass :

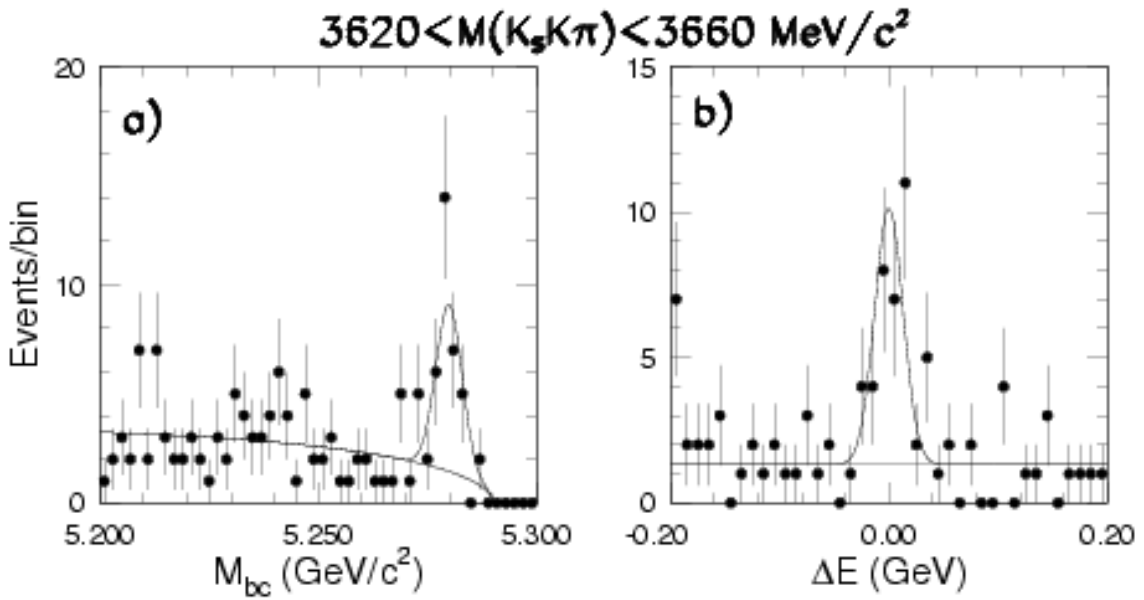
$$M_{bc} = \sqrt{(E_{CM}/2)^2 - (\sum \vec{p}_i)^2}$$

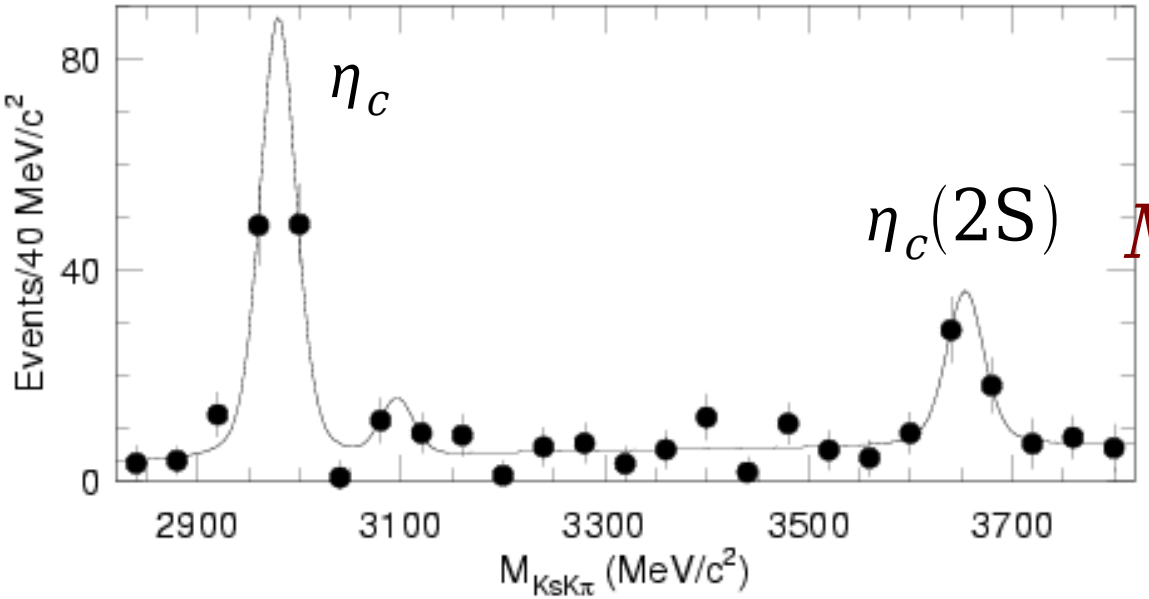
Energy difference :

$$\Delta E = \sum E_i - (E_{CM}/2)$$

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

$B \to K K_S K^- \pi^+$ to see $\eta_c(2S)$





significance$>6\sigma$

$M=3654\pm6\pm8$ *MeV*/c^2

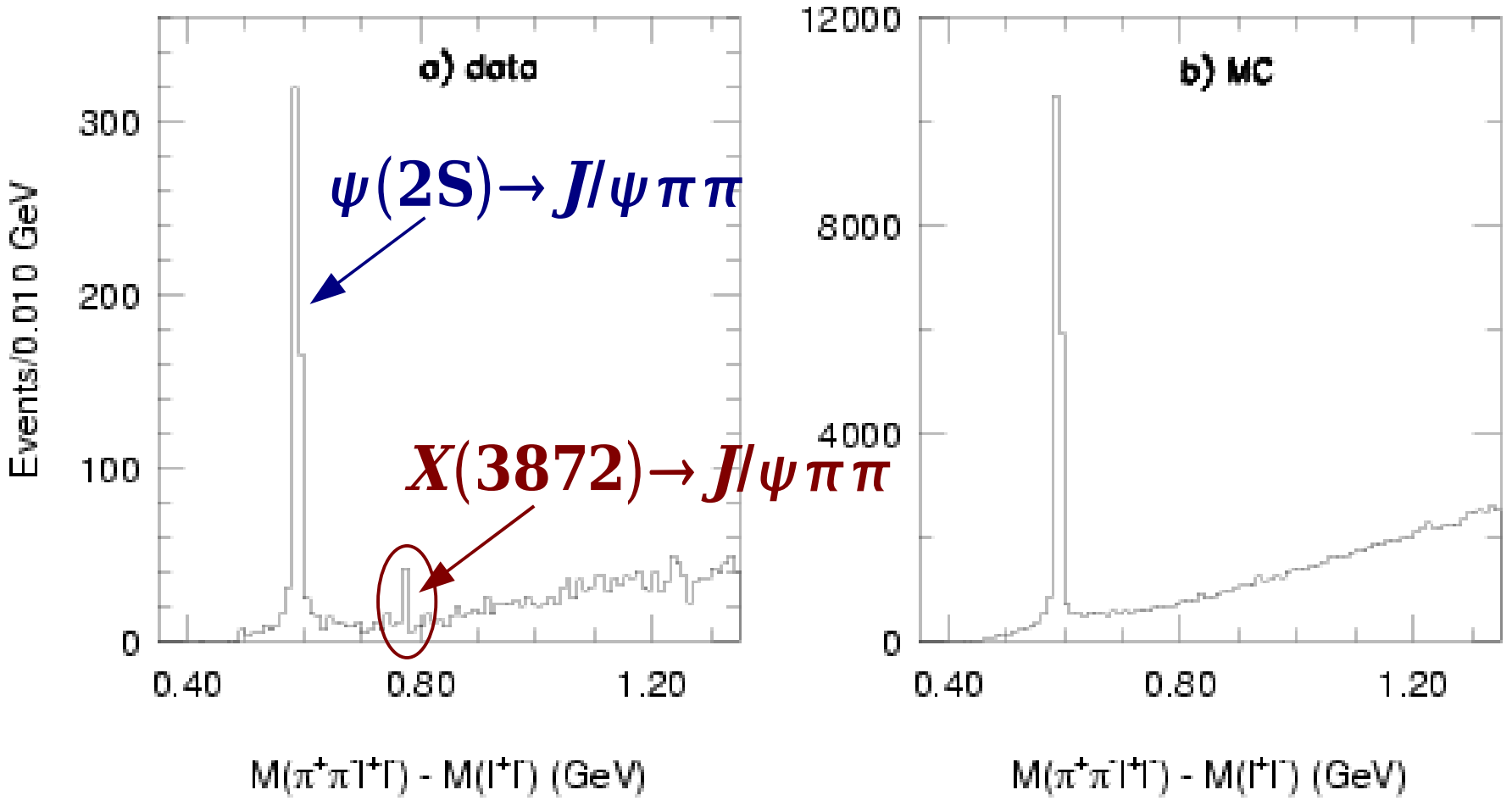
$\Gamma<55$ *MeV*/c^2

***PRL89*, 102001(2002)**

$X(3872)$ *observation*

S.−K.Choi, S.Olsen et al
PRL91, 262001(2003)

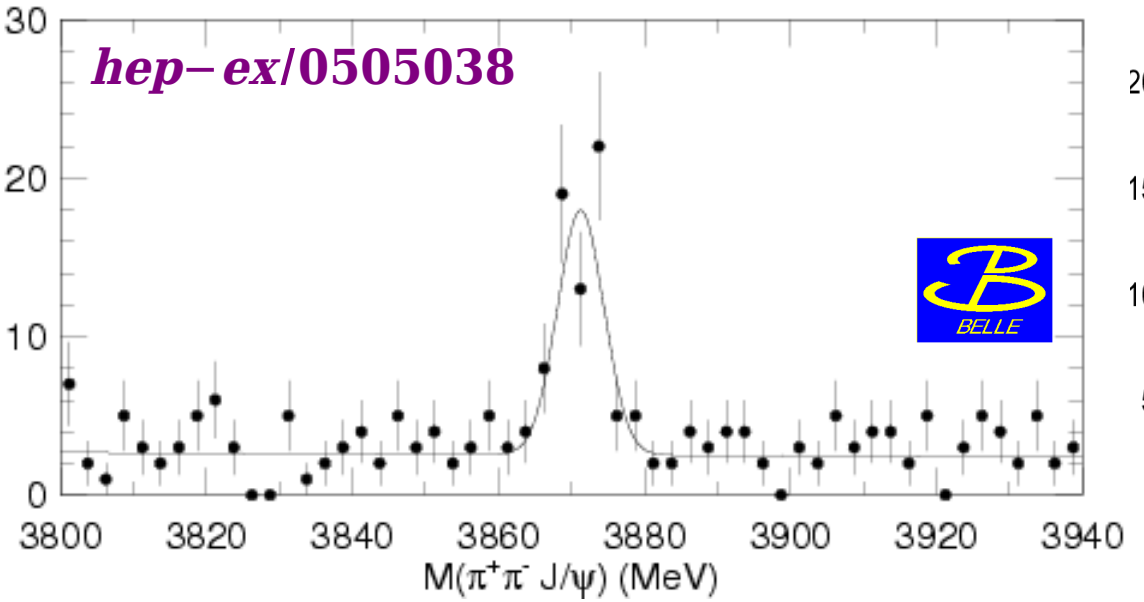
$B \to K \pi \pi J/\psi$ *using* $140\, fb^{-1}$

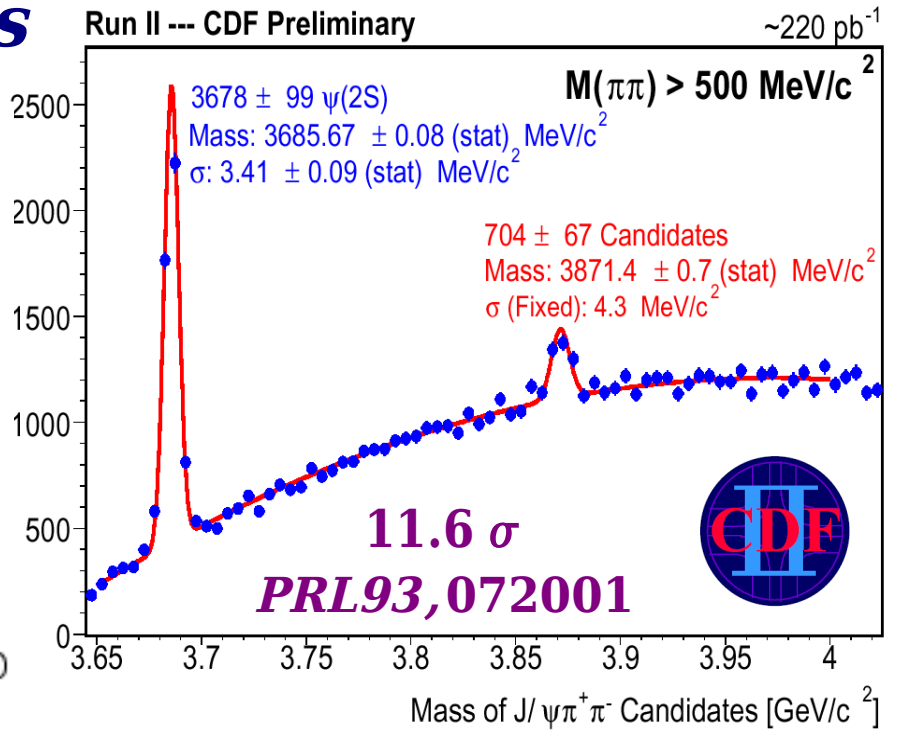


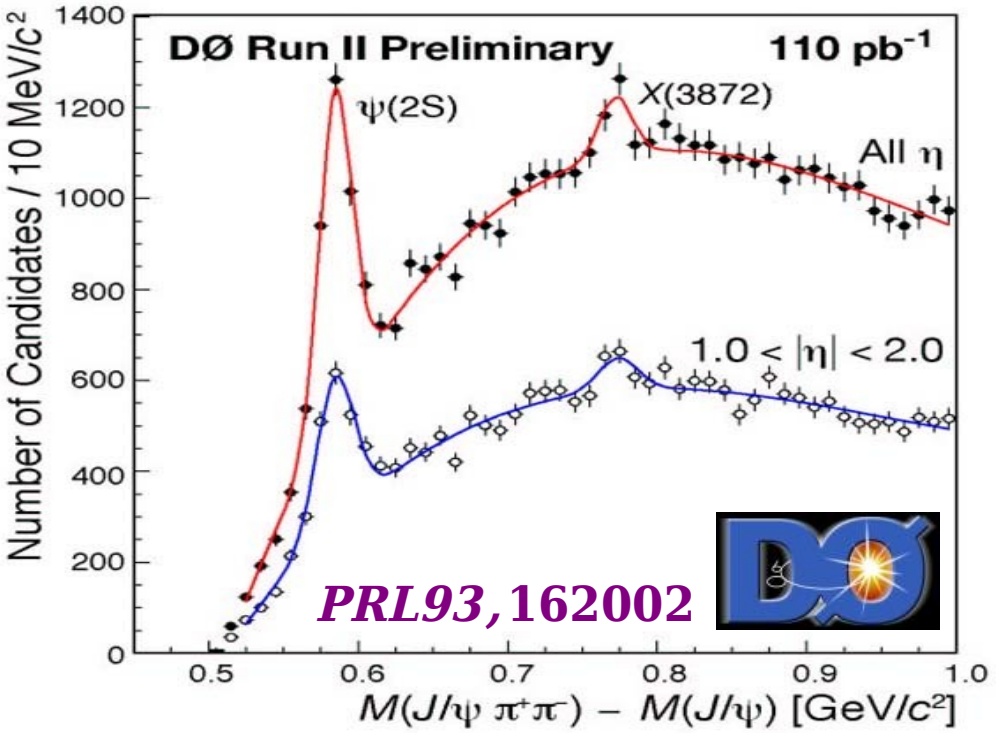
$N = 35.7 \pm 6.8$
significance 10.3σ

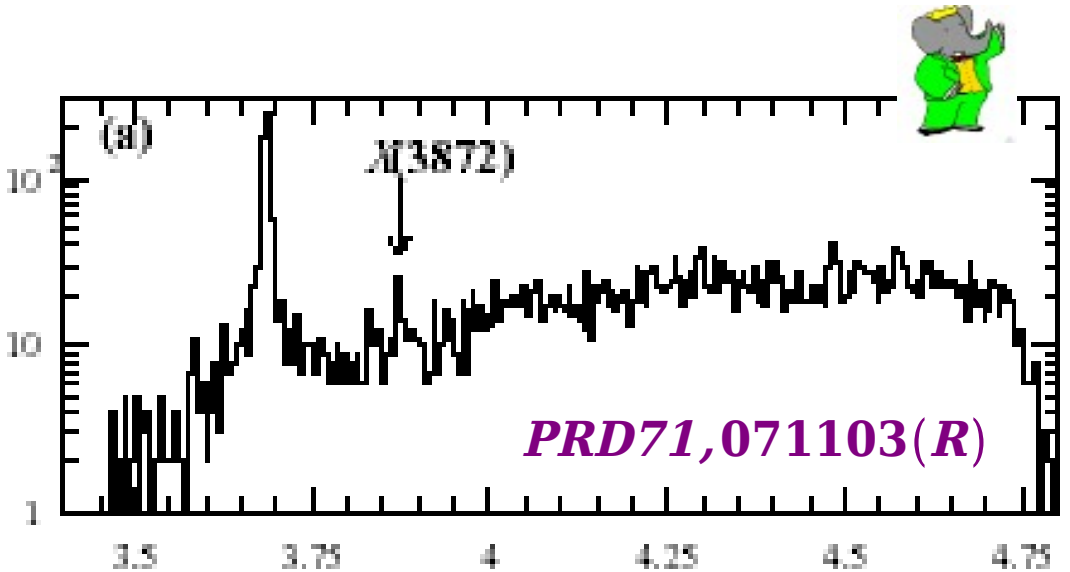
$(3872 \pm 0.6 \pm 0.5)\, MeV/c^2 \sim m_{D^0} + m_{D^{*0}}$
$\Gamma < 2.3\ MeV$

X(3872) *seen by* 4 *experiments*

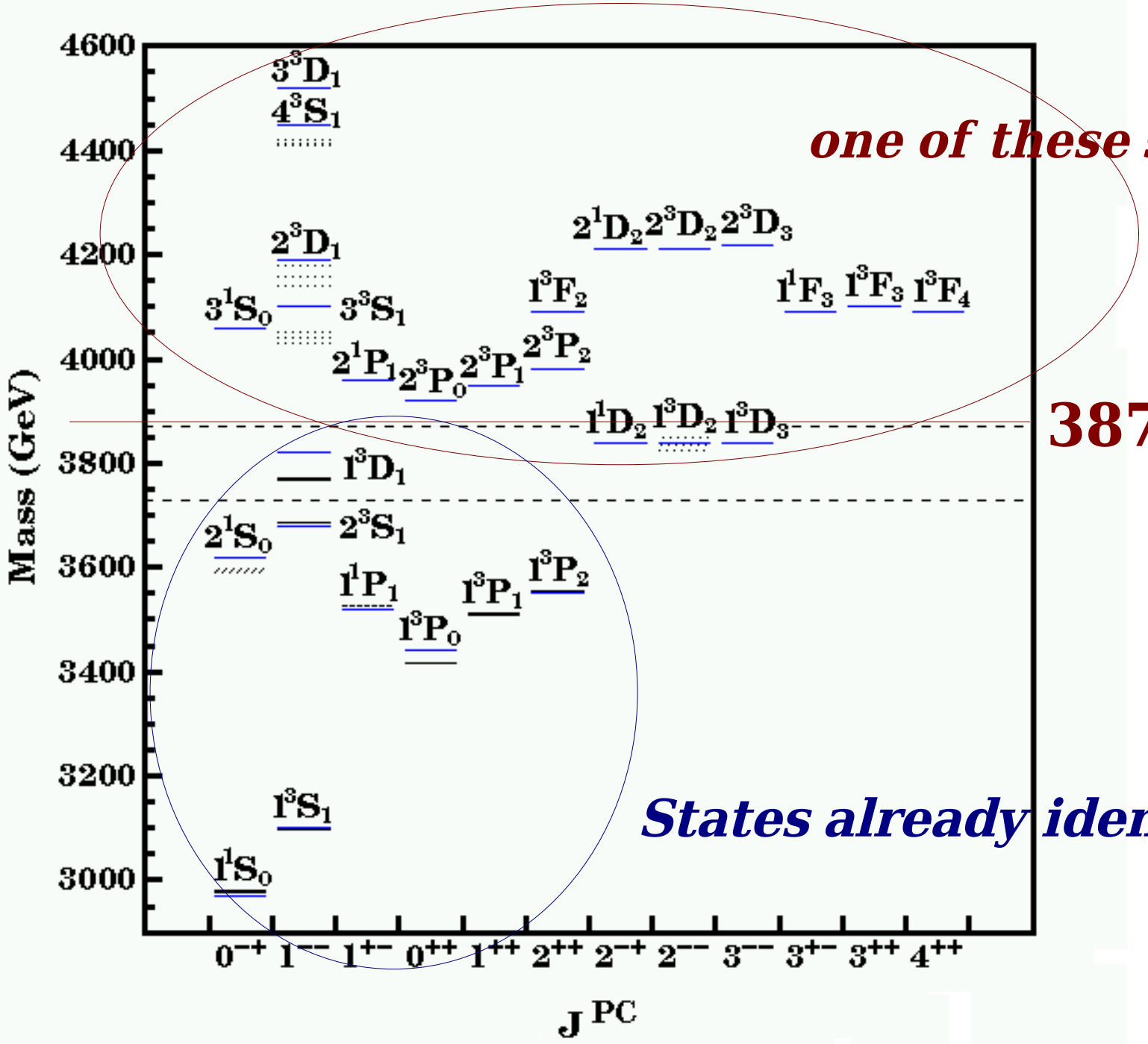








Is it a $c\bar{c}$ meson ?

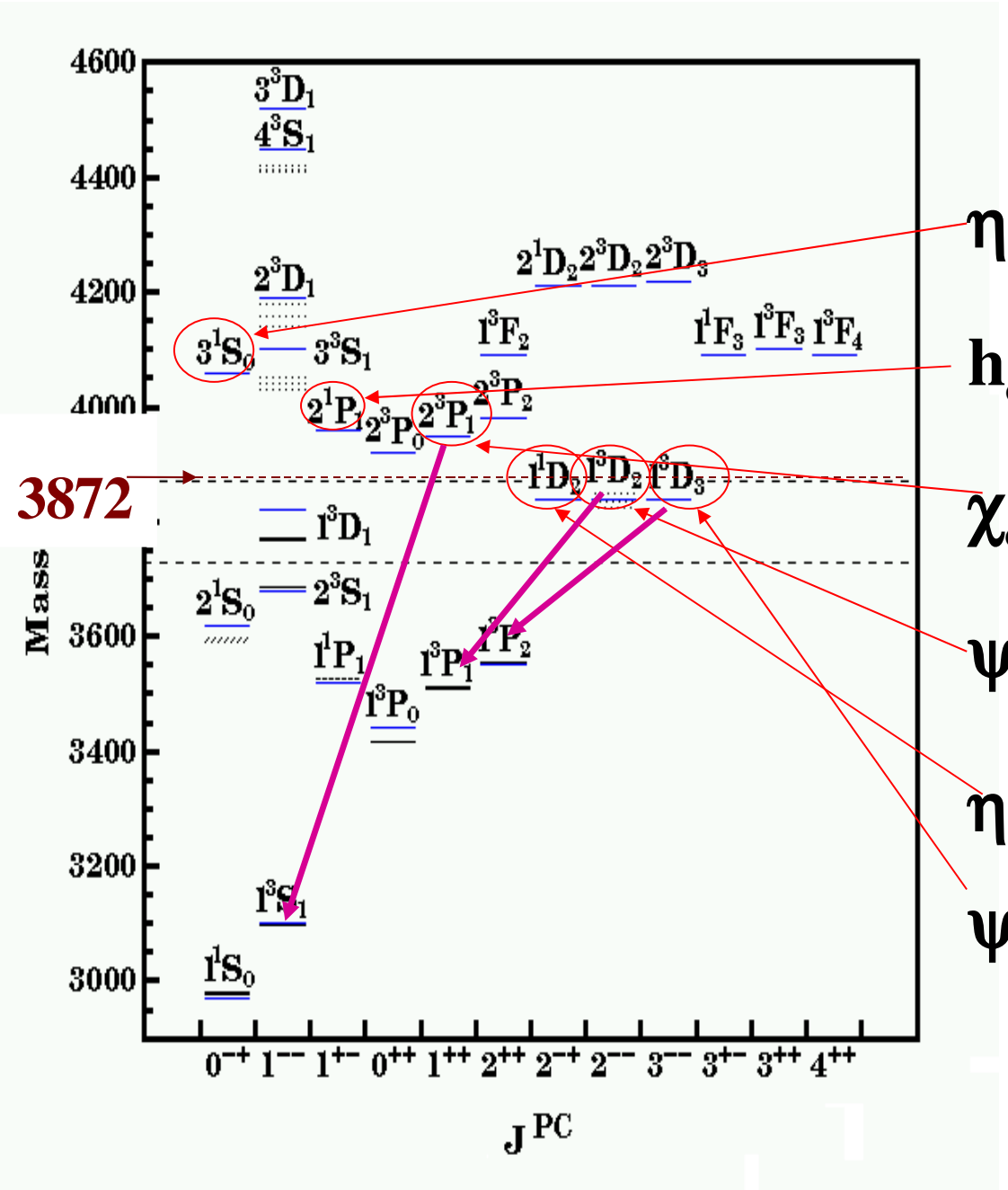


one of these states ?

3872 *MeV*

States already identified

No obvious $c\bar{c}$ assignment



η_c” M too low and Γ too small

h_c’ angular dist’n rules out 1^{+-}

χ_{c1}’ $\Gamma(\gamma J/\psi)$ way too small

ψ_2 $\Gamma(\gamma\chi_{c1})$ too small; $M(\pi^+\pi^-)$ wrong

η_{c2} $\pi\pi\,\eta_c$ should dominate

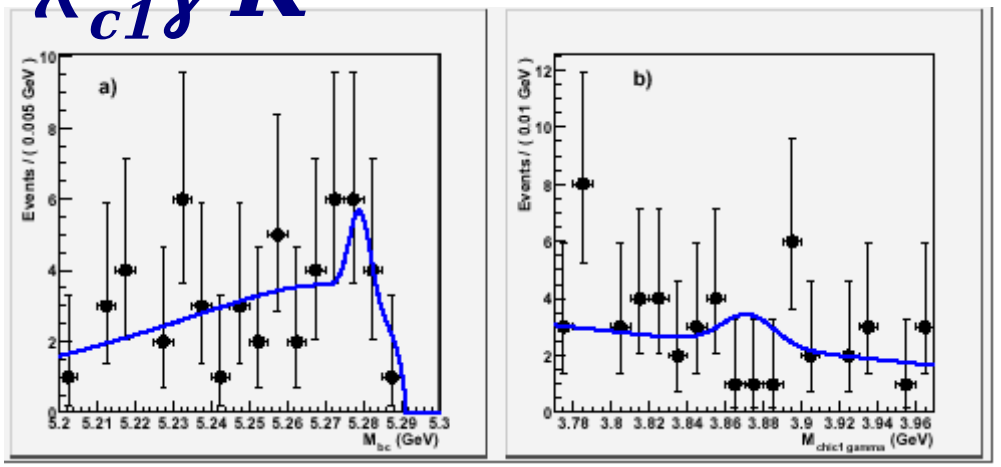
ψ_3 $\Gamma(\gamma\chi_{c2}$ & $D\bar{D})$ too small

hep−ex/0407033

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

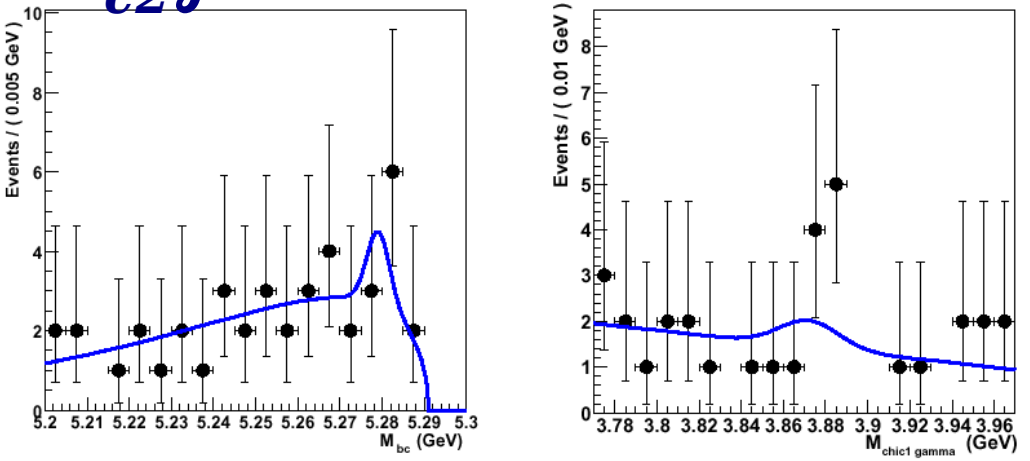
The radiative decays to $\chi_{cJ}\gamma$ expected to be large for some charmonium states... but not found

$\chi_{c1}\gamma K$



M_{bc} ΔE

$\chi_{c2}\gamma K$



M_{bc} ΔE

$B(X \to \chi_{c1}\gamma)/B(X \to J\psi\pi^+\pi^-) < 0.9$ *at* 90 % *CL* $X \equiv \psi_2$ *expect* > 2.5

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

J^{PC} possibilities (for $J \leq 2$)

0^{--} *exotic* violates parity	0^{-+} (η_c'')	0^{++} DD allowed (χ_{c0}')	0^{+-} *exotic* DD allowed
1^{--} DD allowed ($\psi(3S)$)	1^{-+} *exotic* DD allowed	1^{++} (χ_{c1}')	1^{+-} (h_c')
2^{--} (ψ_2)	2^{-+} (η_{c2})	2^{++} DD allowed (χ_{c2}')	2^{+-} *exotic* DD allowed

J^{PC} possibilities

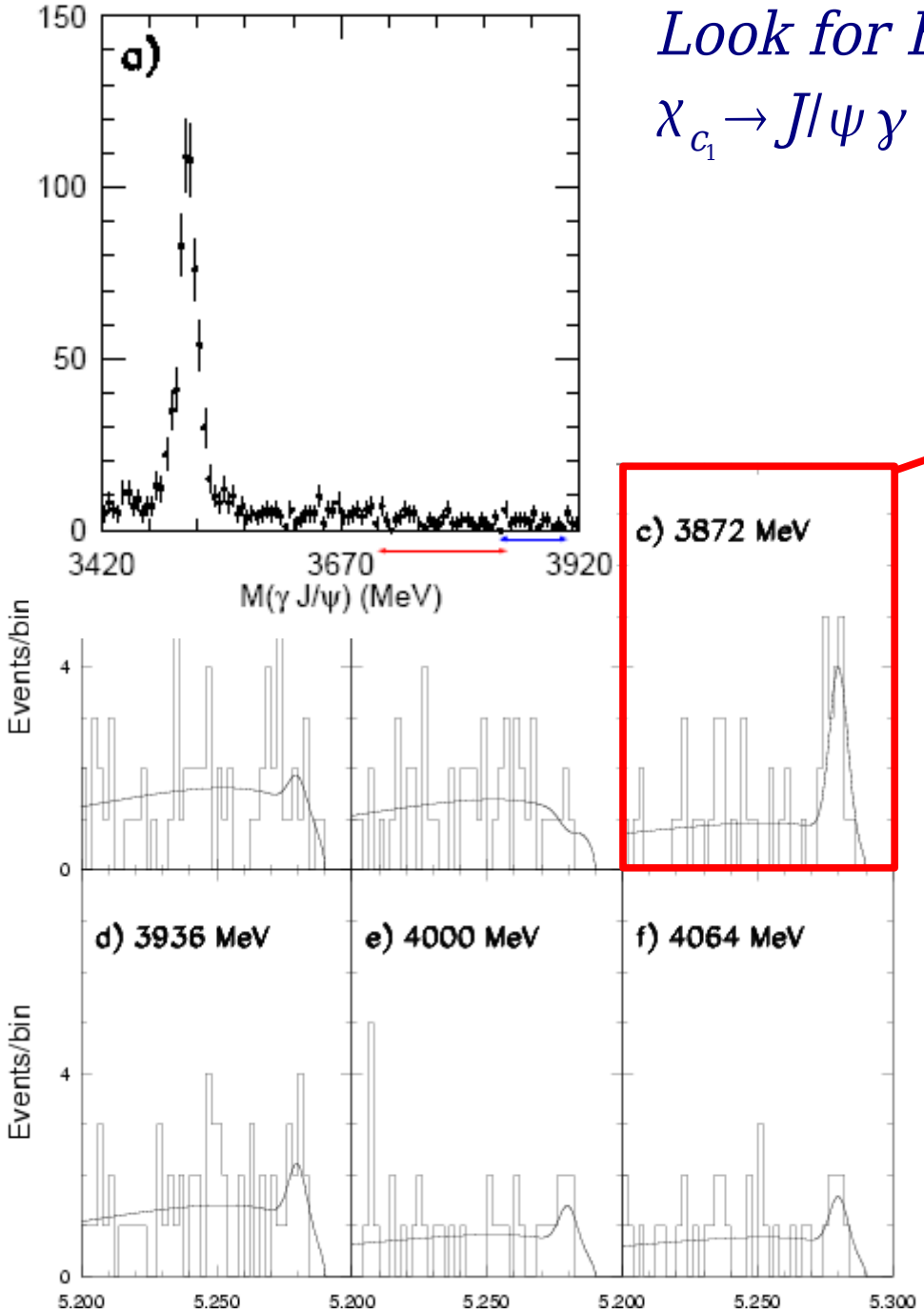
0^{--} ruled out; $J^P=0^+,1^-$ & 2^+ unlikely

0^{--} *exotic* violates parity	0^{-+} (η_c'')	0^{++} DD allowed (χ_{c0}')	0^{+-} *exotic* DD allowed
1^{--} DD allowed ($\psi(3S)$)	1^{-+} *exotic* DD allowed	1^{++} (χ_{c1}')	1^{+-} (h_c')
2^{--} (ψ_2)	2^{-+} (η_{c2})	2^{++} DD allowed (χ_{c2}')	2^{+-} *exotic* DD allowed

Areas of investigation to assign J^{PC}

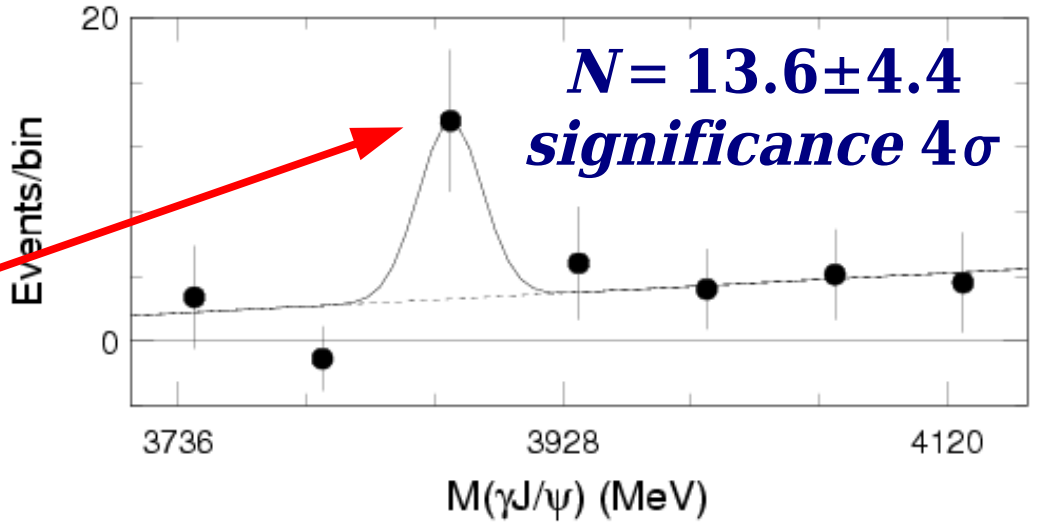
- ***Search of other modes (radiative decays...)***
- ***Angular correlations in $X \to \pi\pi J/\psi$ decays***
- ***Fits to the $M(\pi\pi)$ distribution***
- ***Search for $X \to D^0 \bar{D}^0 \pi^0$***

Evidence for $X(3872) \to J/\psi\gamma$ $hep-ex/0505037$ $(256\, fb^{-1})$



Look for $B \to XK$ *where* $X \to J/\psi\gamma$ *and* $K = K^{+}, K_S$

$\chi_{c_1} \to J/\psi\gamma$ *as calibration mode*



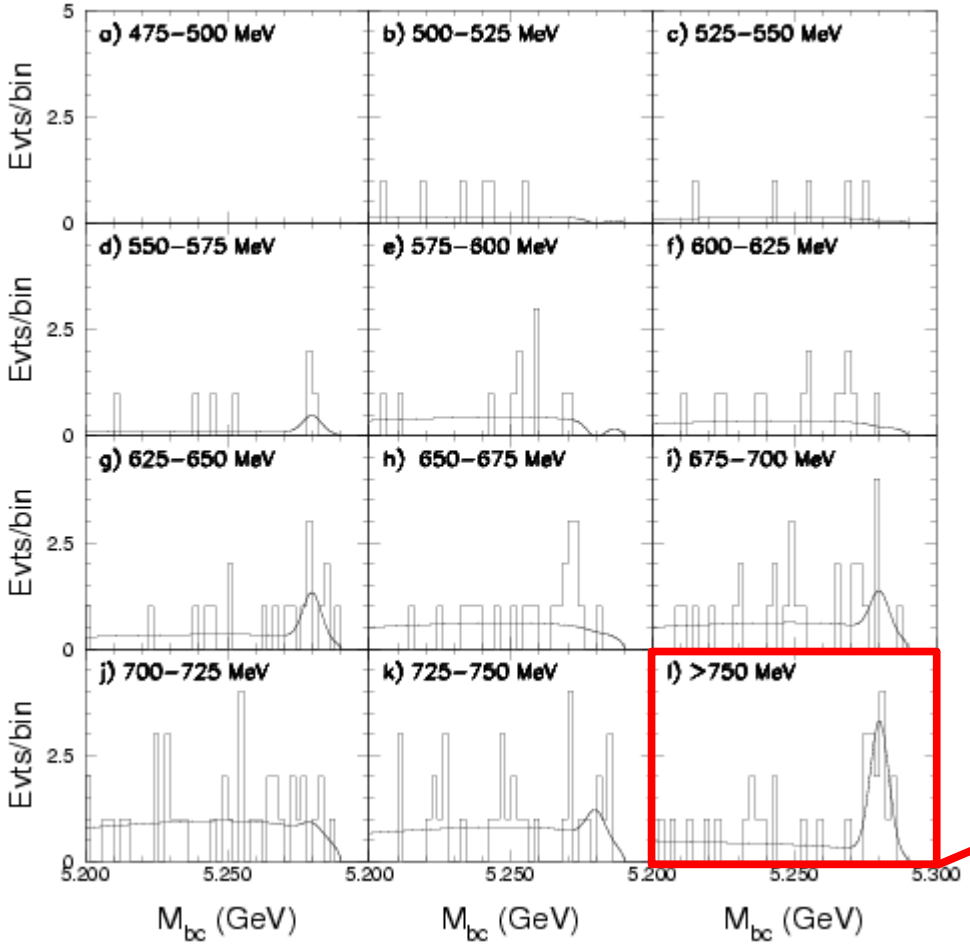
$$\frac{\Gamma(X \to J/\psi\gamma)}{\Gamma(X \to J/\psi\pi^{+}\pi^{-})} = 0.14 \pm 0.05$$

BaBar $(PRD74\,(2006)\,071101)$

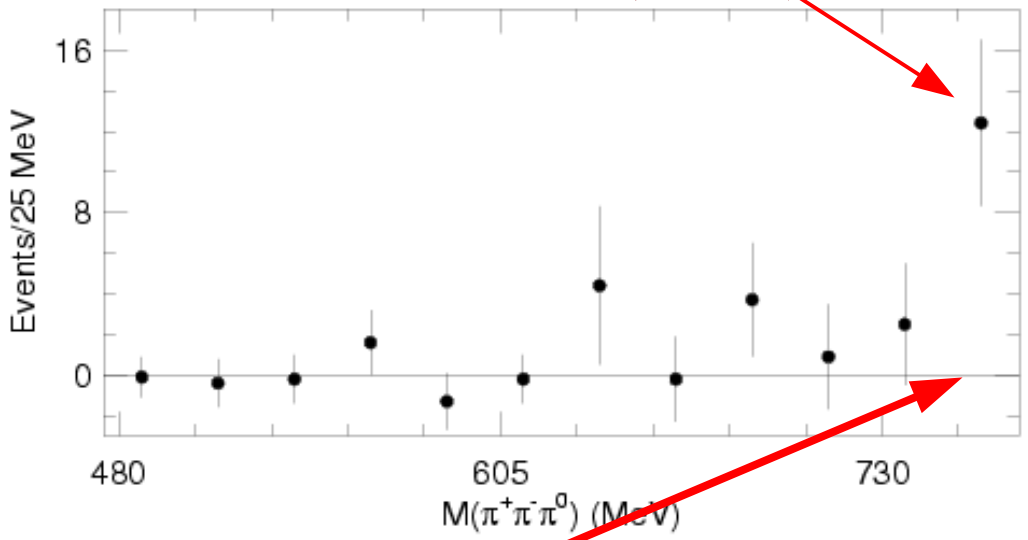
evidence with $3.4\,\sigma$

***C*=+1 established**

Evidence for $X(3872) \to \pi\pi\pi^0 J/\psi$ *hep−ex/0505037* ($256\ fb^{-1}$)



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



$N = 12.1 \pm 4.1$

Backgrounds $= 2.1 \pm 1.0$

significance $4.3\,\sigma$

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

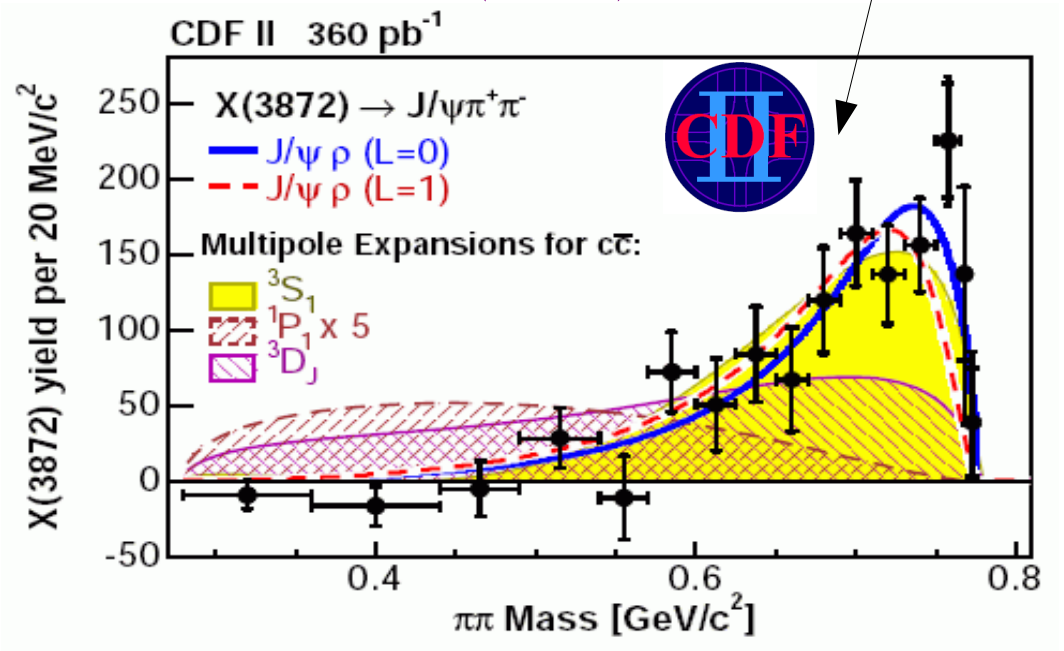
for $M(\pi^+\pi^-\pi^0) > 750\ MeV/c^2$

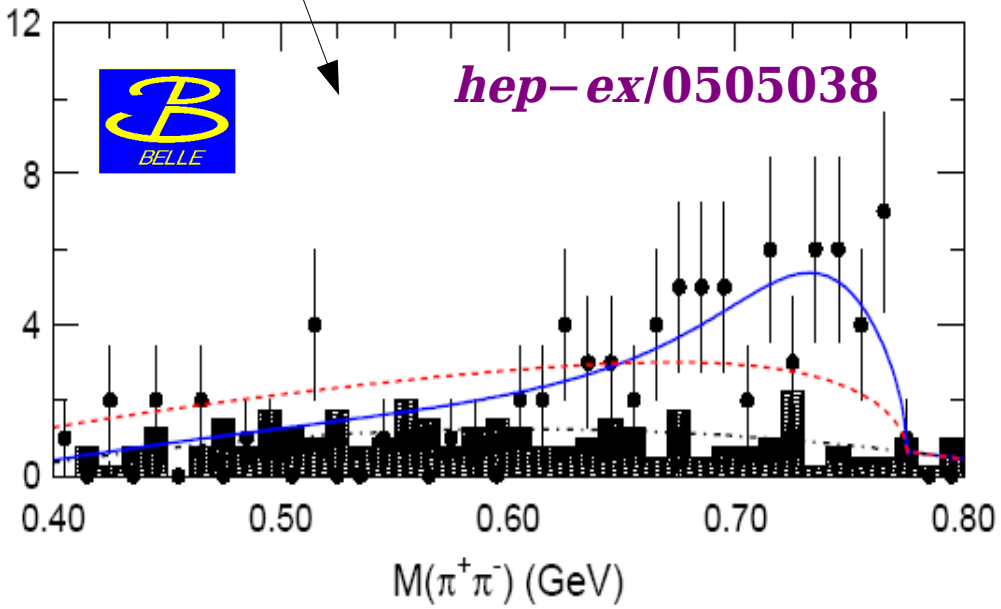
Large isospin violation

C=+1 established

- $X \to J/\psi\,\gamma$ is only allowed for $C=+1$
- same for J/ψ ''ω''
- $M(\pi\pi)$ for $X \to \pi^+\pi^-\,J/\psi$ looks like a ρ

***PRL*96, 102002 (2006)**



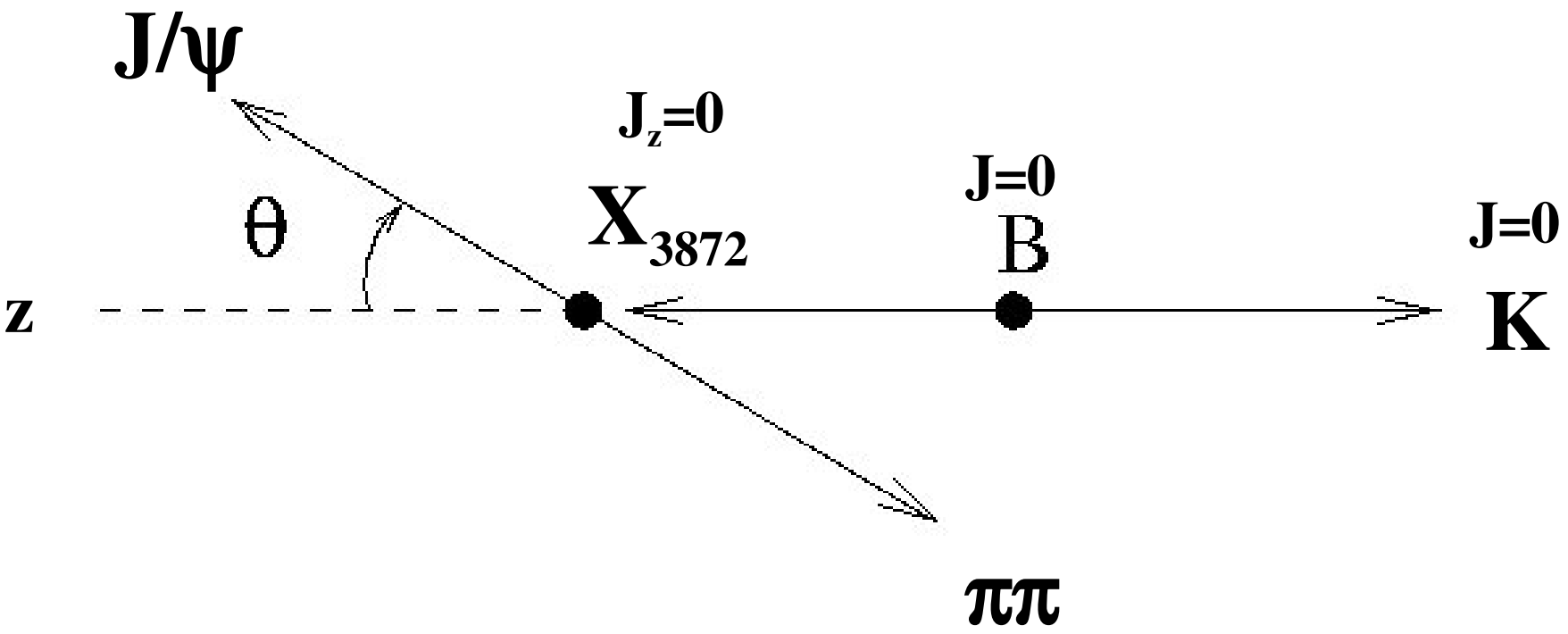


J^{PC} possibilities
(C=-1 ruled out)

0^{--} *exotic* Violates parity	0^{-+} (η_c'')	0^{++} DD allowed (χ_{c0}')	0^{+-} *exotic* DD allowed
1^{--} DD allowed ($\psi(3S)$)	1^{-+} *exotic* DD allowed	1^{++} (χ_{c1}')	1^{+-} (h_c')
2^{--} (ψ_2)	2^{-+} (η_{c2})	2^{++} DD allowed (χ_{c2}')	2^{+-} *exotic* DD allowed

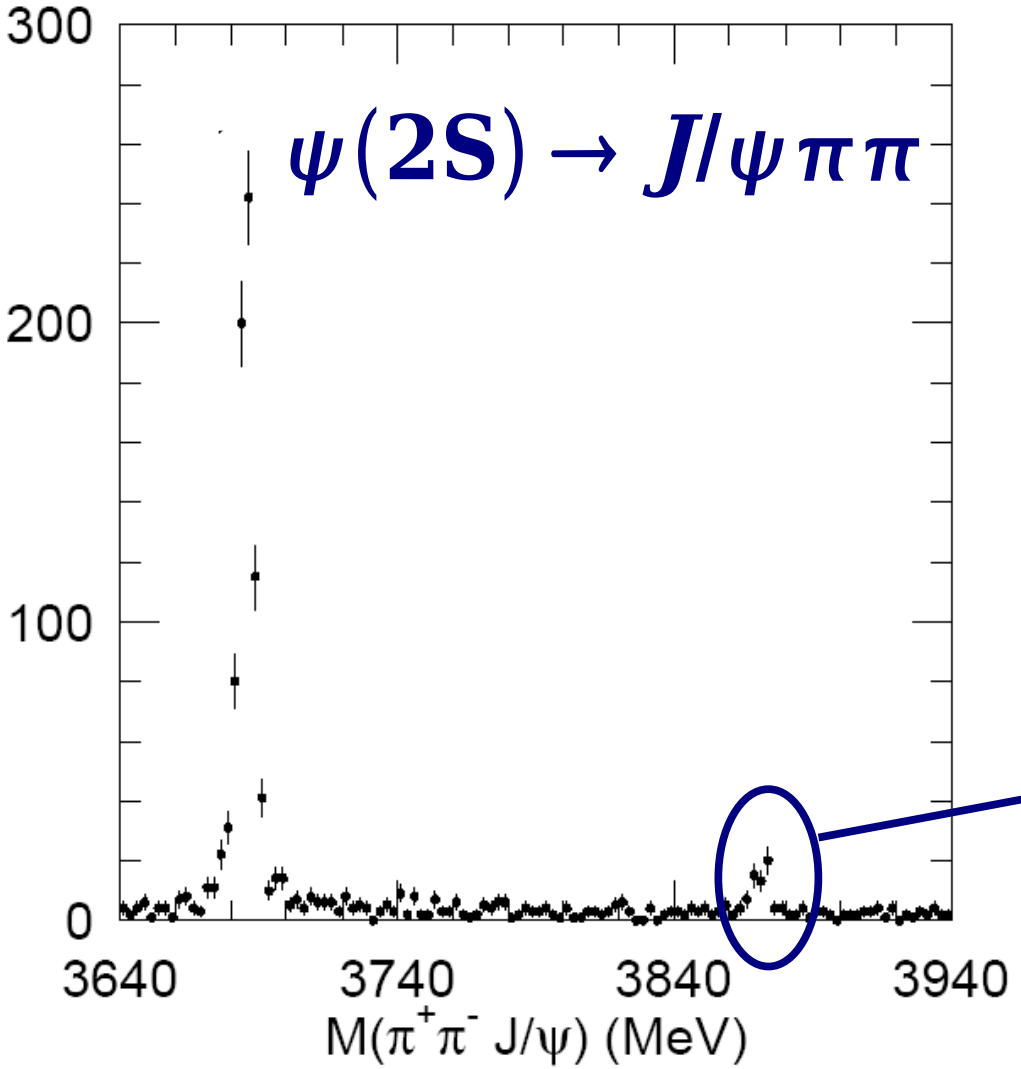
Angular Correlations

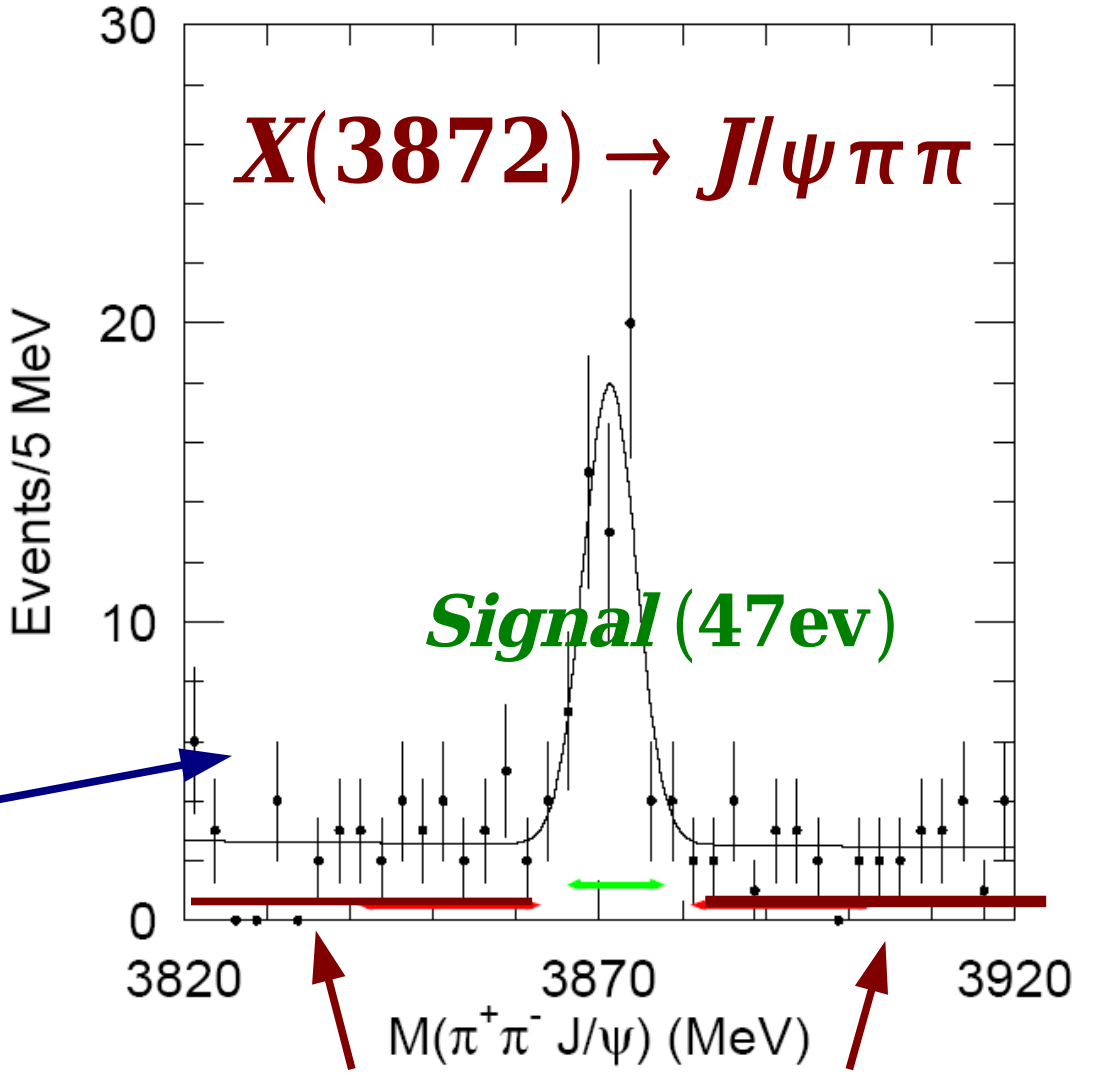
Rosner (***PRD*** **70 094023**)
Bugg (***PRD*** **71 016006**)
Suzuki , Pakvasa (***PLB*** **57967**)



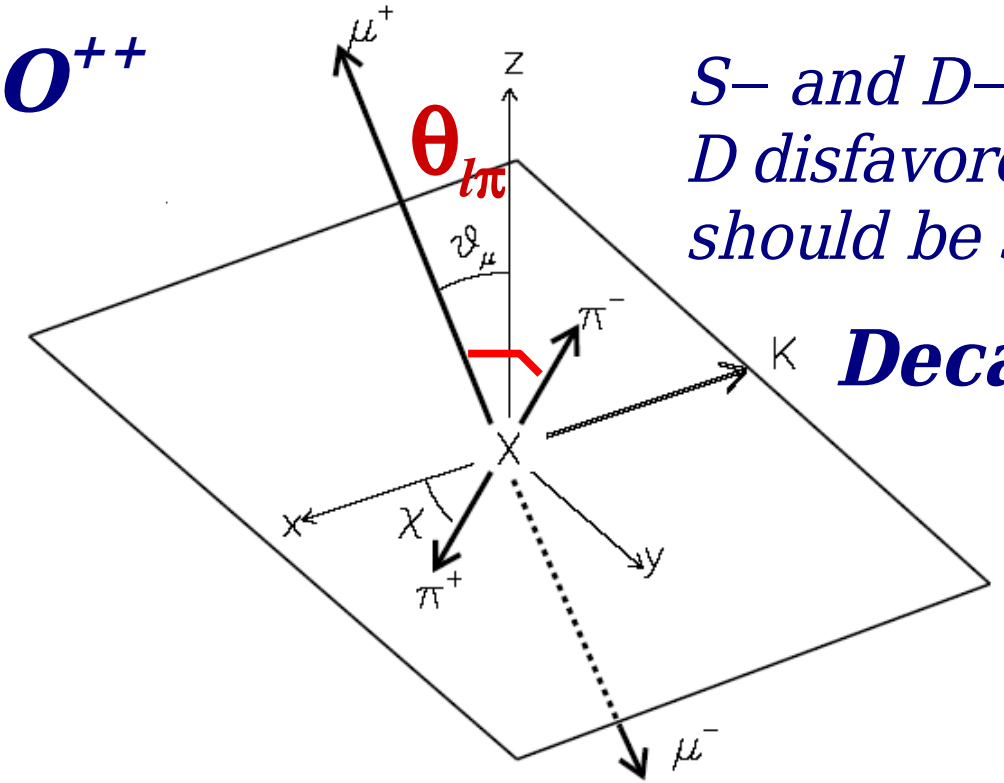
Use 256 fb^{-1} (275 *M* $B\bar{B}$ *pairs*)

hep−ex/0505038





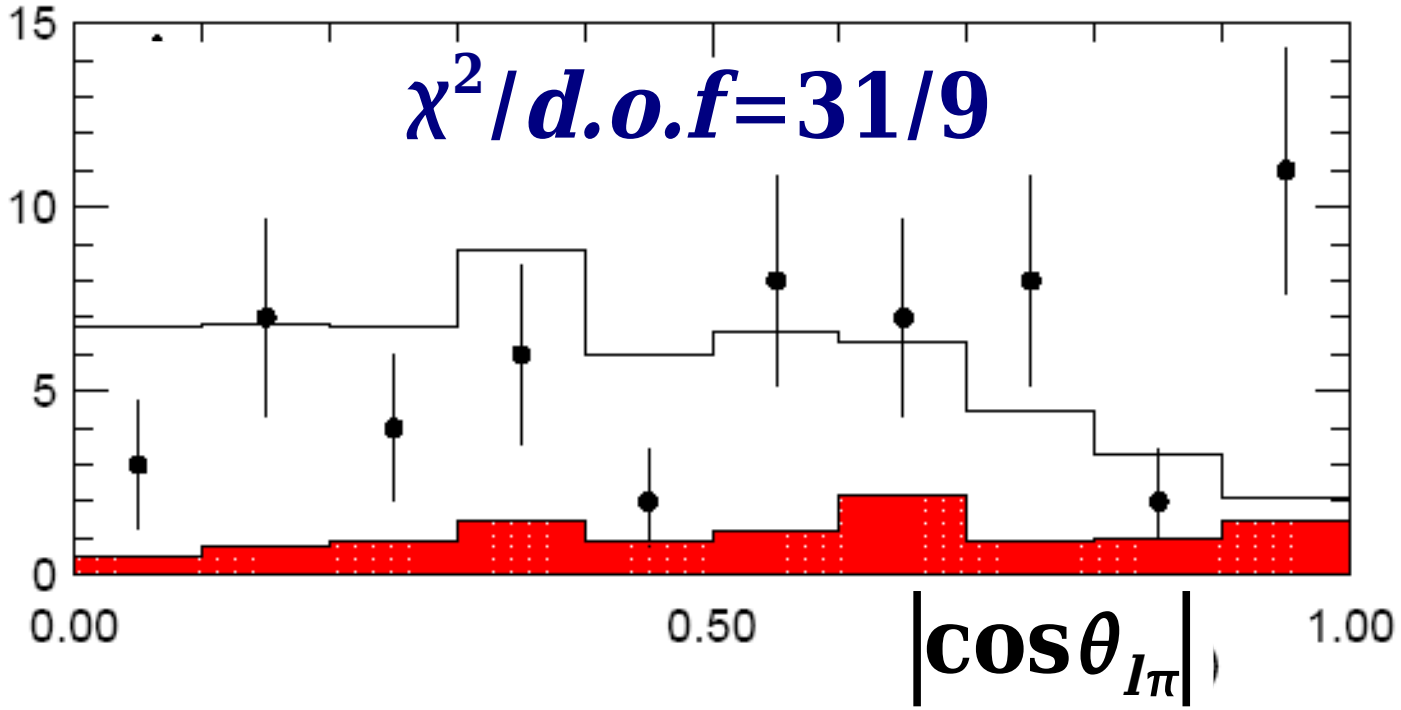
$J^{PC}=O^{++}$



S– and D– waves possible but D disfavored by $M(\pi\pi)$ and should be suppressed by phase space

Decay amplitude $\propto (\vec{\epsilon}_{J/\psi}.\vec{\epsilon}_{\rho})$

$$\frac{dN}{d(\cos\theta_{l\pi})} \propto \sin^2\theta_{l\pi}$$

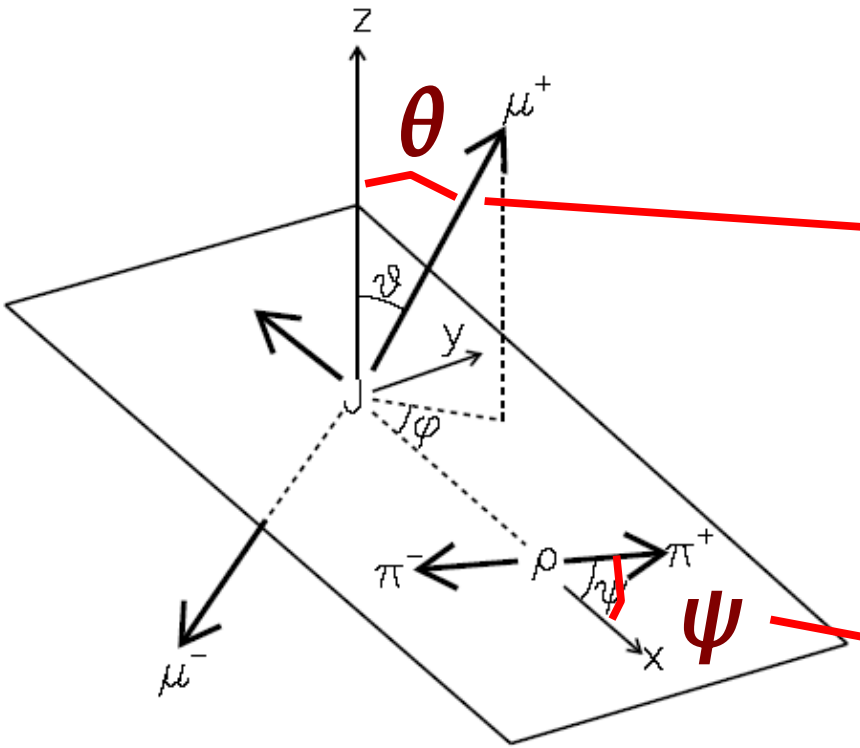


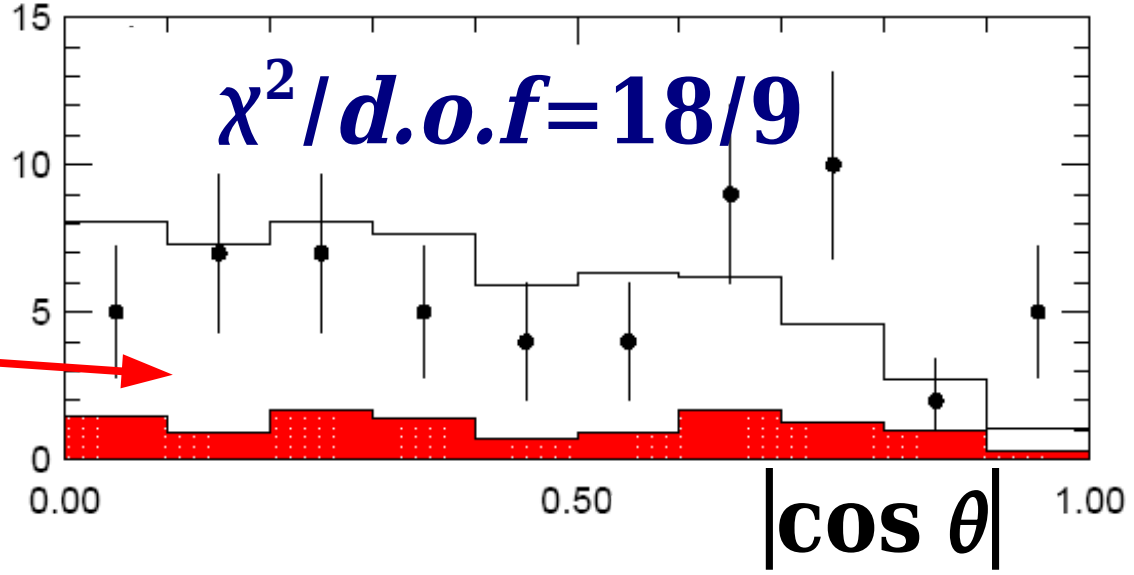
disfavours 0^{++}

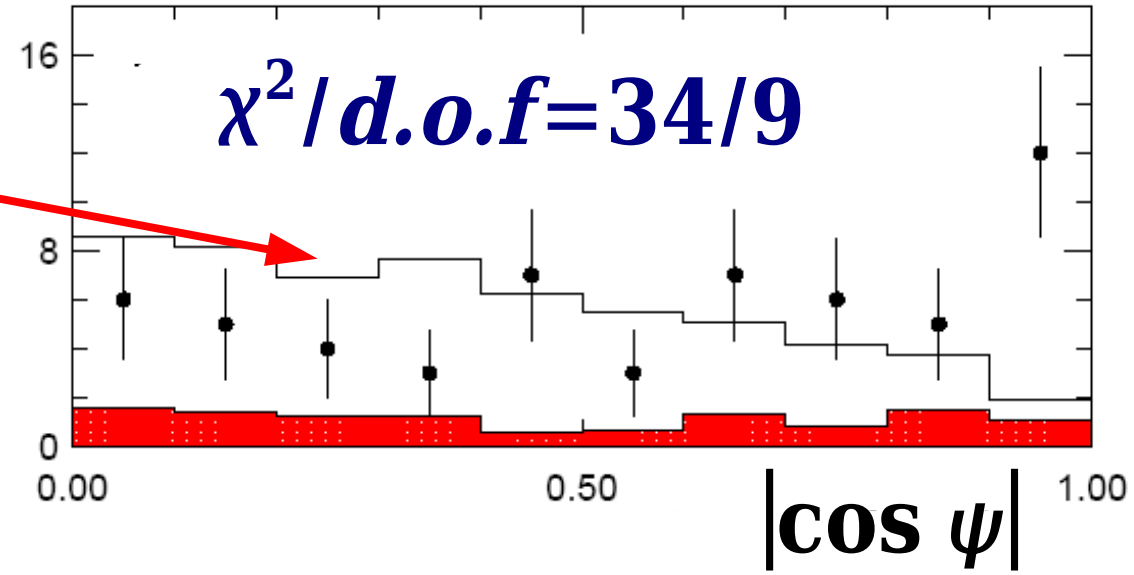
$J^{PC}=O^{-+}$

$$\text{Decay amplitude} \propto \vec{p}_{J/\psi}.(\vec{\epsilon}_{J/\psi}\times\vec{\epsilon}_{\rho})$$

$$\frac{d^2N}{d(\cos\theta)\,d(\cos\psi)} \propto \sin^2\theta\sin^2\psi$$







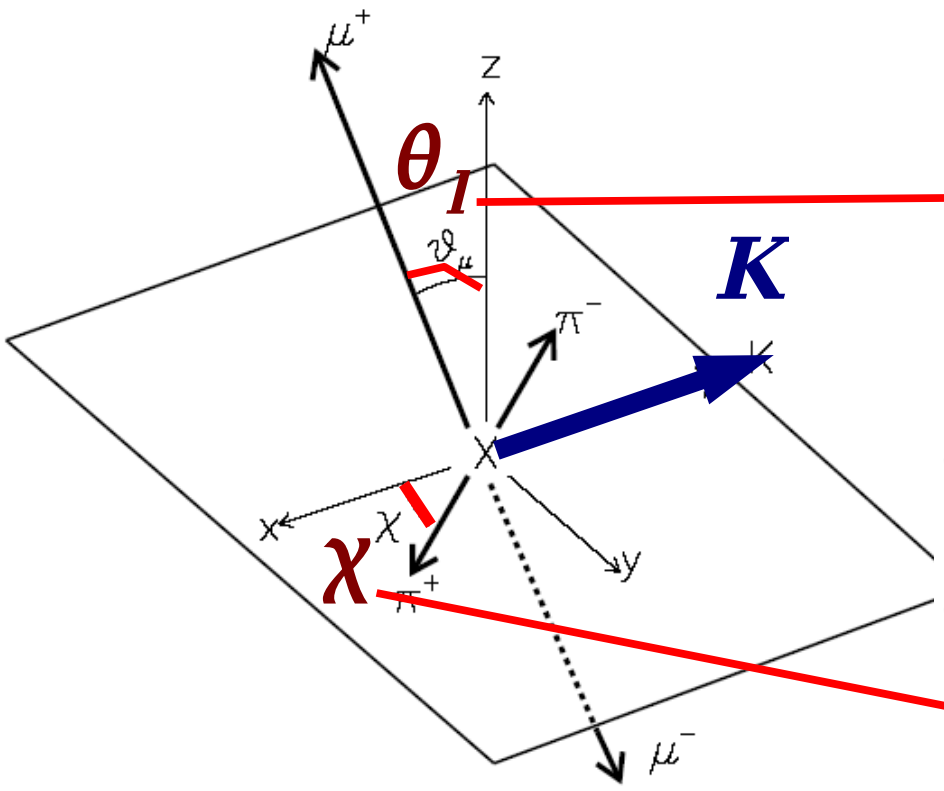
disfavours 0^{-+}

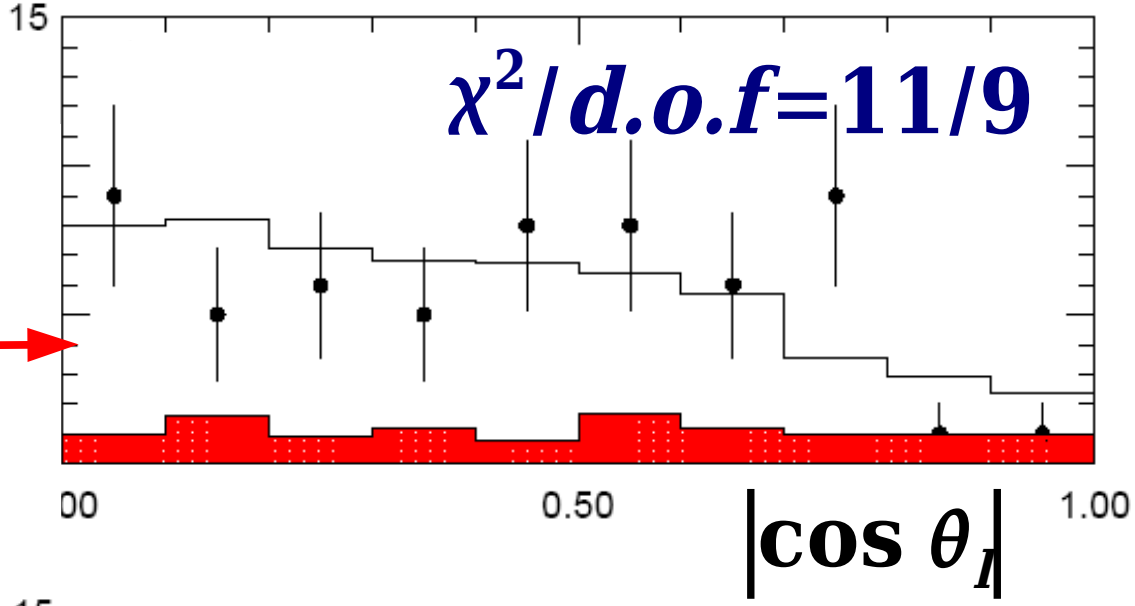
$J^{PC}=1^{++}$

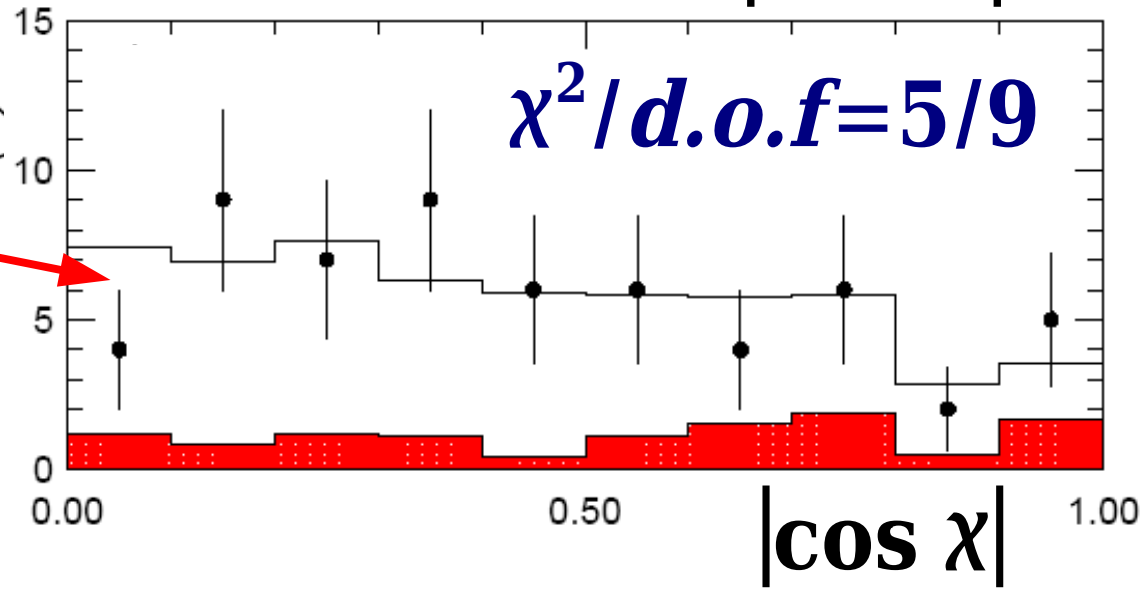
S– and D– waves allowed

Decay amplitude $\propto \vec{\epsilon}_X \times \vec{\epsilon}_{J/\psi} \times \vec{\epsilon}_\rho$

$$\frac{d^2N}{d(\cos\theta_l)\,d(\cos\chi)} \propto \sin^2\theta_l \sin^2\chi$$





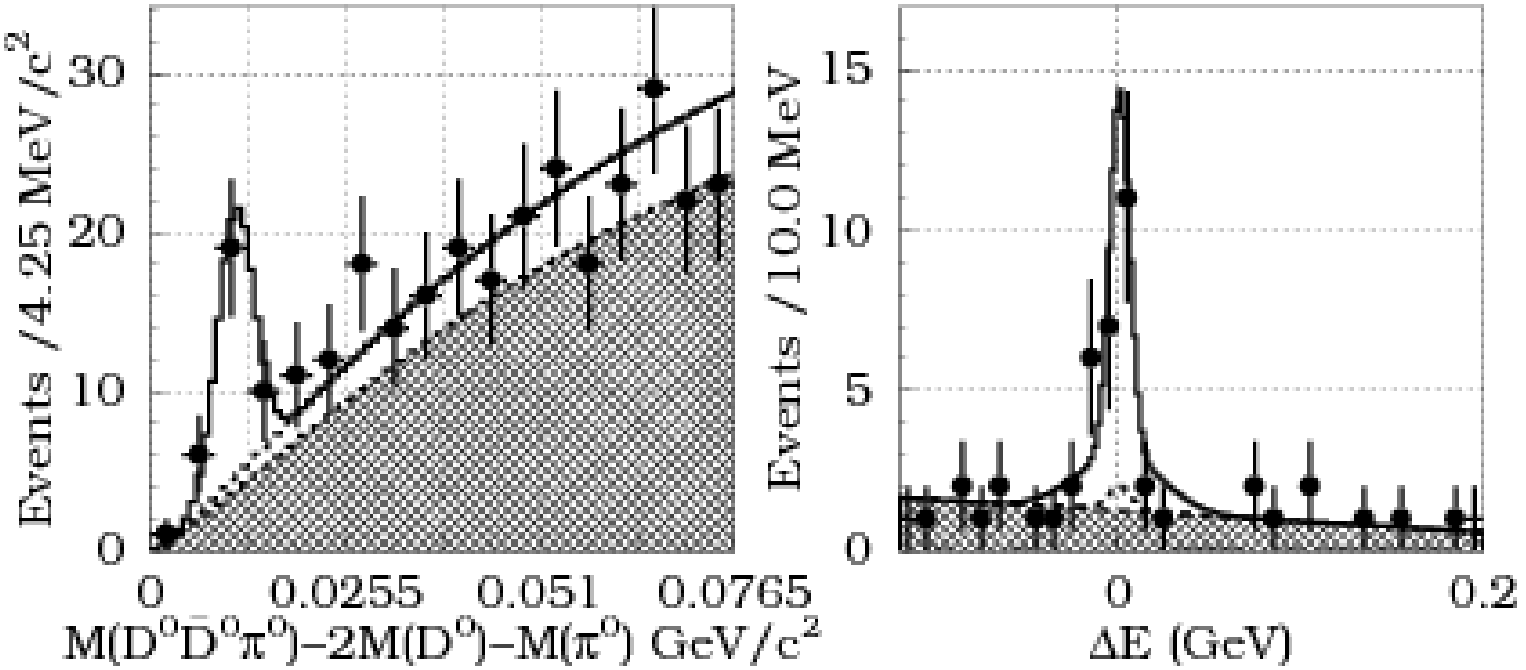


J^{PC} possibilities
(0^{-+} & 0^{++} ruled out)

0^{--} *exotic* violates parity	0^{-+} (η_c")	0^{++} DD allowed (χ_{c0}')	0^{+-} *exotic* DD allowed
1^{--} DD allowed ($\psi(3S)$)	1^{-+} *exotic* DD allowed	1^{++} (χ_{c1}')	1^{+-} (h_c')
2^{--} (ψ_2)	2^{-+} (η_{c2})	2^{++} DD allowed (χ_{c2}')	2^{+-} *exotic* DD allowed

$B \to K D^0 \bar{D}^0 \pi^0$

PRL 97, 162002 (2006)



23.4 ± 5.6 *signal evts* *significance* $= 6.4\sigma$

$$B(B \to D^0 \bar{D}^0 \pi^0 K) = (1.22 \pm 0.31^{+0.23}_{-0.30}) \times 10^{-4}$$

$$M = (3875.2 \pm 0.7^{+0.3}_{-1.6} \pm 0.8)\ MeV/c^2$$

2^{++} *from three pseudoscalars*

$\to$ *at least one combination in D− wave*

$\to$ *production should be suppressed*

if this enhancement is $X(3872)$, 2^{++} *is unlikely*

1^{++} $c\bar{c}$ state ? (χ'_{c1})

- *Mass is* 100MeV *off*
- $\chi'_{c1} \to J/\psi\,\rho$ *not allowed by isospin*

...but $B(X(3872) \to \pi^+\pi^- J/\psi) > 4.3\,\%$
BaBar, Moriond QCD 2005

- *Expect* $\dfrac{\Gamma(\chi'_{c1} \to \gamma J/\psi)}{\Gamma(\chi'_{c1} \to \pi\pi J/\psi)} \sim 40$

Godfrey and Barnes, PRD69, 054008(2004)

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

χ'_{c1} *component is small* $(<$ *few %)$

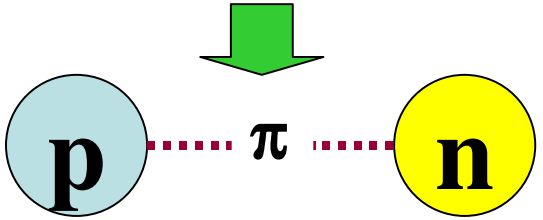
$\bar{D}^0 D^{*0}$ bound state (deuson)?

Voloshin & Okun JETP Lett 23, 333 (1976)
Bander et al PRL 36, 695(1976)
DeRujula et al PRL 38, 317 (1977)
Manohar & Wise, NP B339, 17 (1993)
Tornqvist, Z Phys C61, 525(1994)

Tornqvist
hep-ph/0308277

deuteron:

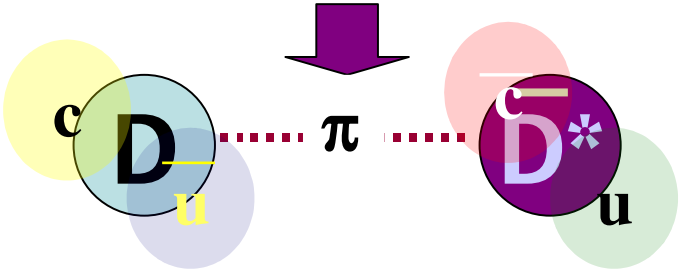
attractive nuclear force



2 loosely bound qqq color singlets with $M_d = m_p + m_n - \varepsilon$

deuson:

attractive force??



2 loosely bound $q\bar{q}$ color singlets with $M = m_{D^+} m_{D^*} - \delta$

$X(3872) = D^0 \bar{D}^{*0}$ bound state ?

- $M \sim m_{D^0} + m_{D^{*0}}$
- $J^{PC} = 1^{++}$ is favored

  Swanson PLB588, 189 (2004)
  Tornqvist PLB590, 209 (2004)
- Maximal isospin violation is natural (and was predicted)

  Swanson PLB588, 189 (2004)
- $\Gamma(X \to \gamma J/\psi) < \Gamma(X \to \pi\pi J/\psi)$ was predicted

  Swanson PLB598, 197 (2004)

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

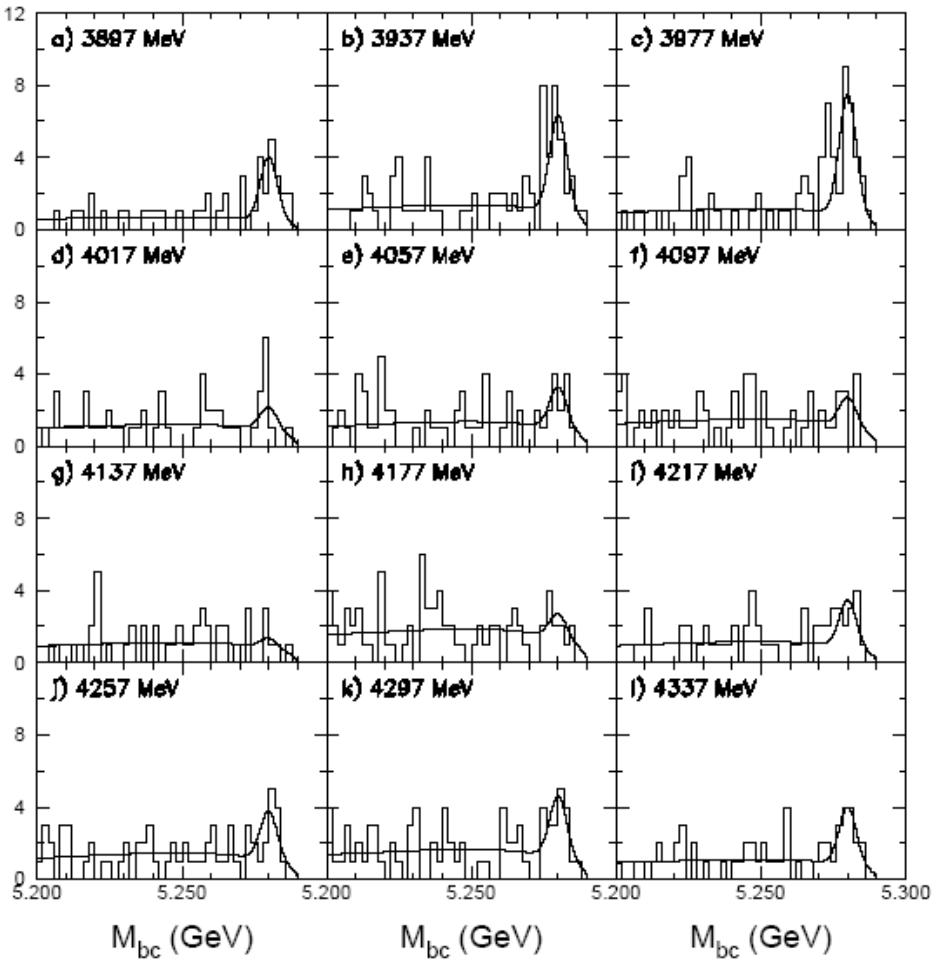
PRL94, 182002 (2005)

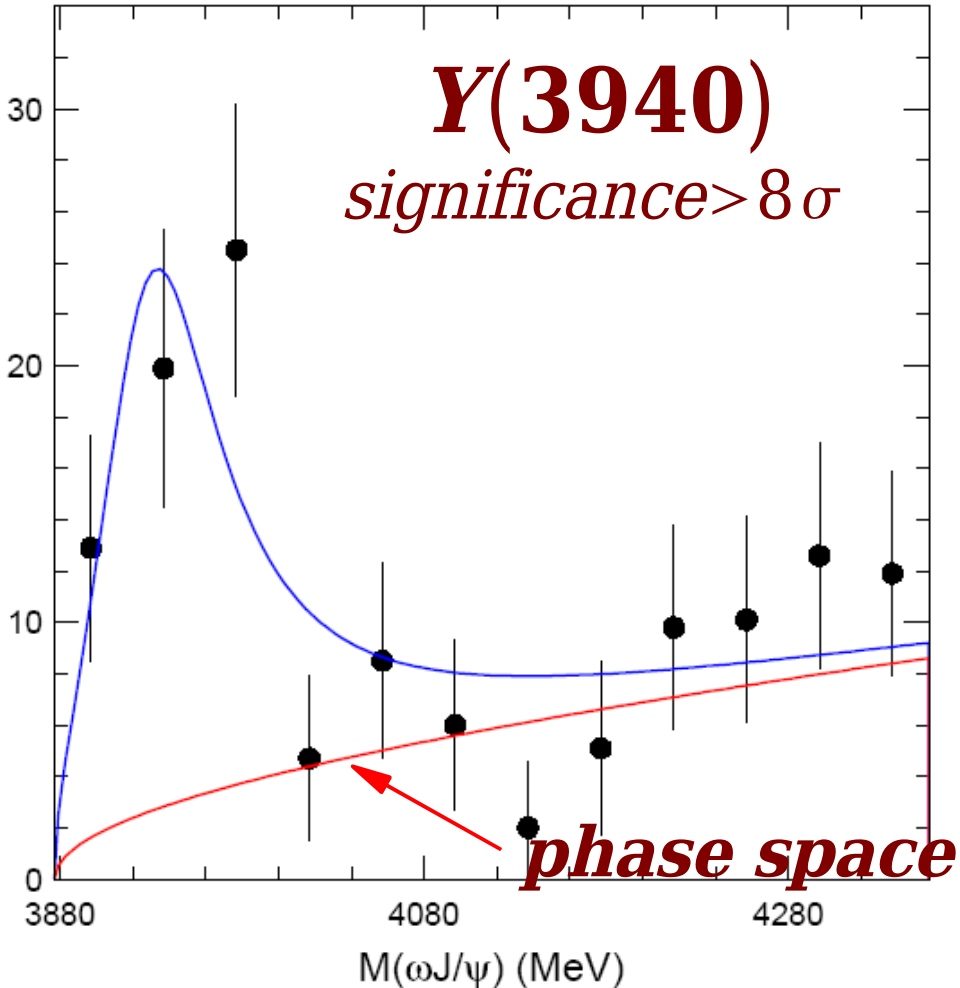
$M = (3940 \pm 11)\ MeV/c^2$

$\Gamma = (92 \pm 24)\ MeV$

high $M(K\omega)$ cut to reject K^* decays

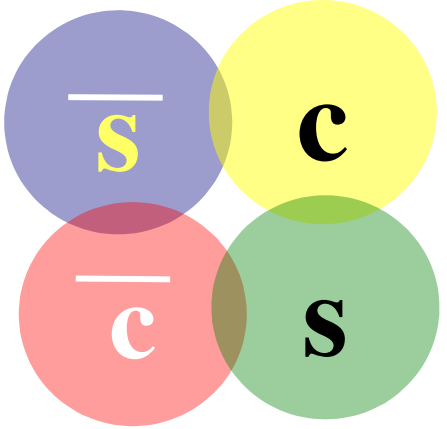
M_{bc} for $B \to J/\psi\omega K$ in bins of $M(J/\psi\omega)$



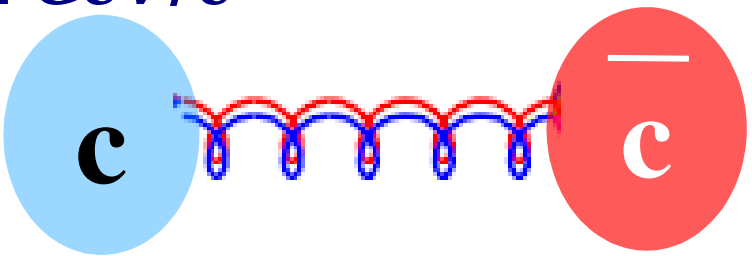


- *The mass is well above $DD^{(*)}$ threshold and decay to $J/\psi\,\omega$ should not be dominant if Y=charmonium*
  - → ***no obvious charmonium meson assignment***

- *another molecule ?*
  - → ***M~ $2m_{D_s}$***
  - → ***not seen in $Y\to\eta\,J/\psi$ (BaBar, PRL93, 041801)***
  - → ***width too large***
  - → ***no π exchange for $D_s\bar{D}_s$***



- *$c\bar{c}$ gluon hybrid (Horn and Mandula, PRD17898(1978))*
  - → ***predicted by QCD***
  - → ***decays to DD and DD^* are suppressed***
  - → ***large (hadron+J/ψ) widths predicted***
  - → ***but masses expected to be 4.3~4.4 GeV/c^2***



Double charmonium $e^+e^- \to J/\psi\, c\bar{c}$ *PRL89,142001(2002)*

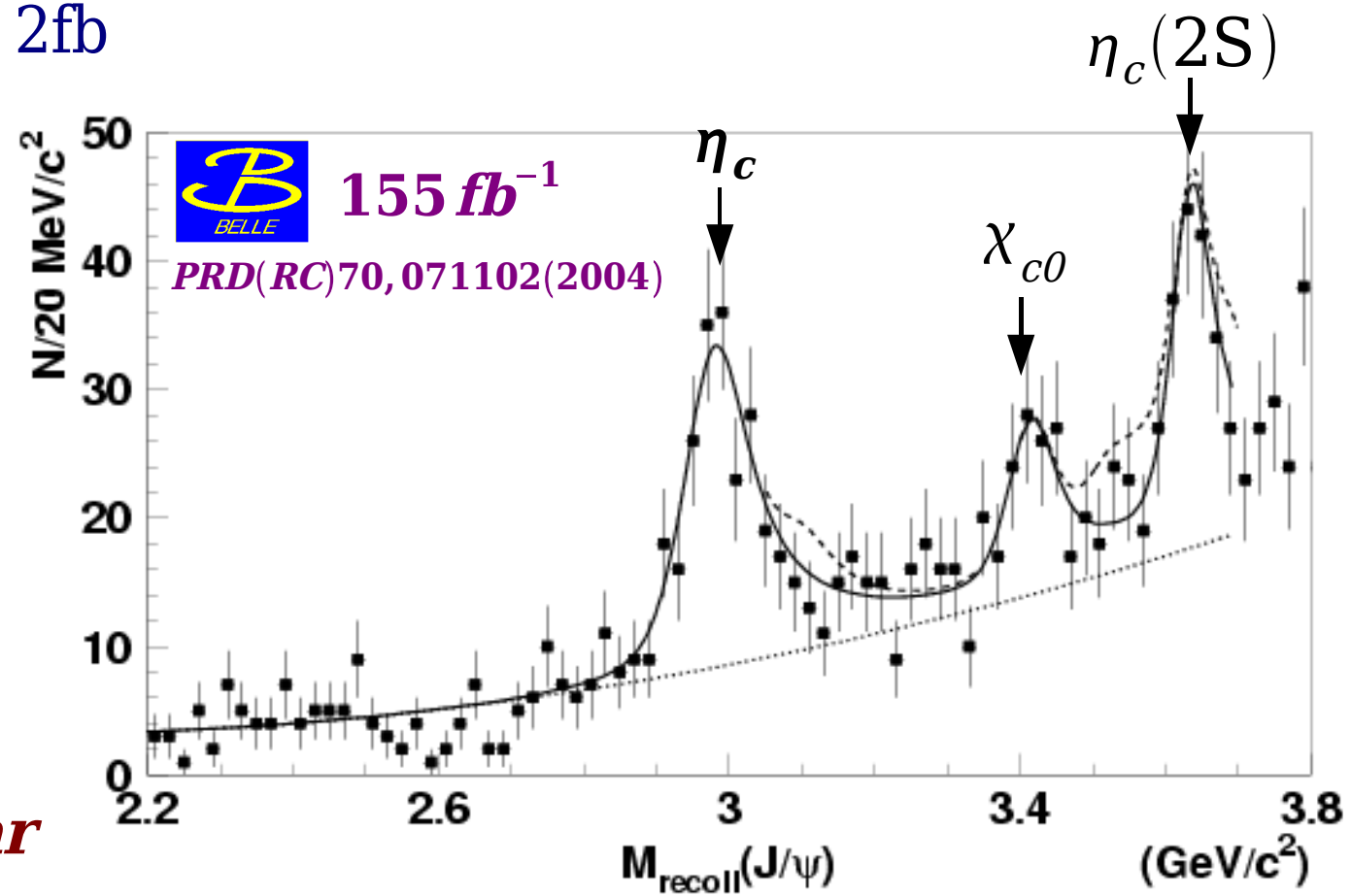
PRD(RC)70,071102(2004)

Study of J/ψ recoil mass spectrum : $M_{recoil}=\sqrt{(E_{CM}-E^*_{J/\psi})^2-p^{*2}_{J/\psi}}$

Large rate for process of the type $e^+e^- \to J/\psi\,\eta_c$:

$\sigma(e^+e^- \to J/\psi\,\eta_c)\times B(\eta_c \to >2\,charged)=25.6\pm2.8\pm3.4\,fb$

NRQCD prediction ~ 2fb



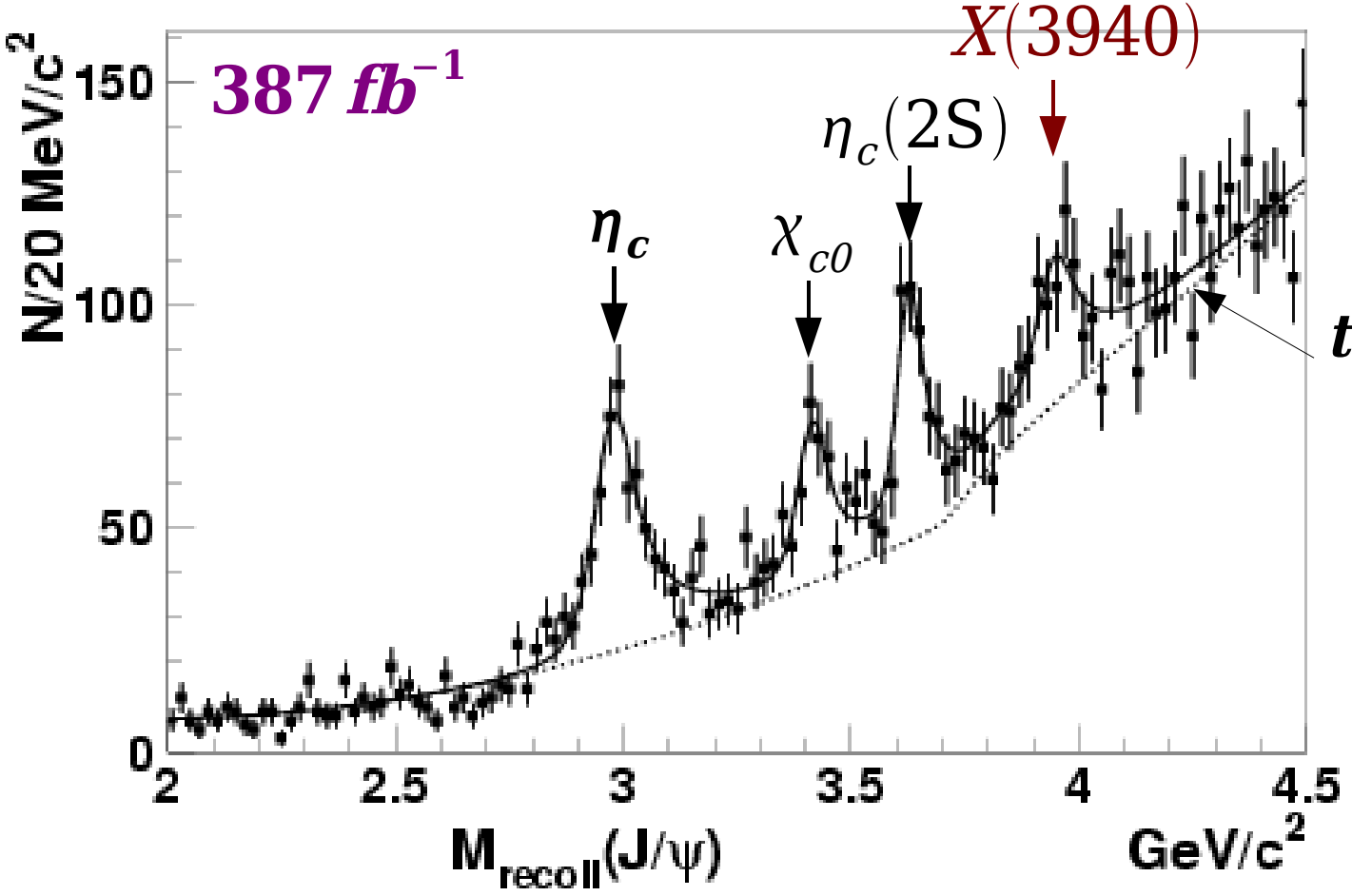
Confirmed by BaBar

hep−ex/0506062

Observation of X(3940) in double $c\bar{c}$ production

hep−ex/0507019
submitted to PRL

$N = 266 \pm 63$ *cand*
significance 5σ



threshold function
$e^+ e^- \to J/\psi D^{(*)} \bar{D}^{(*)}$

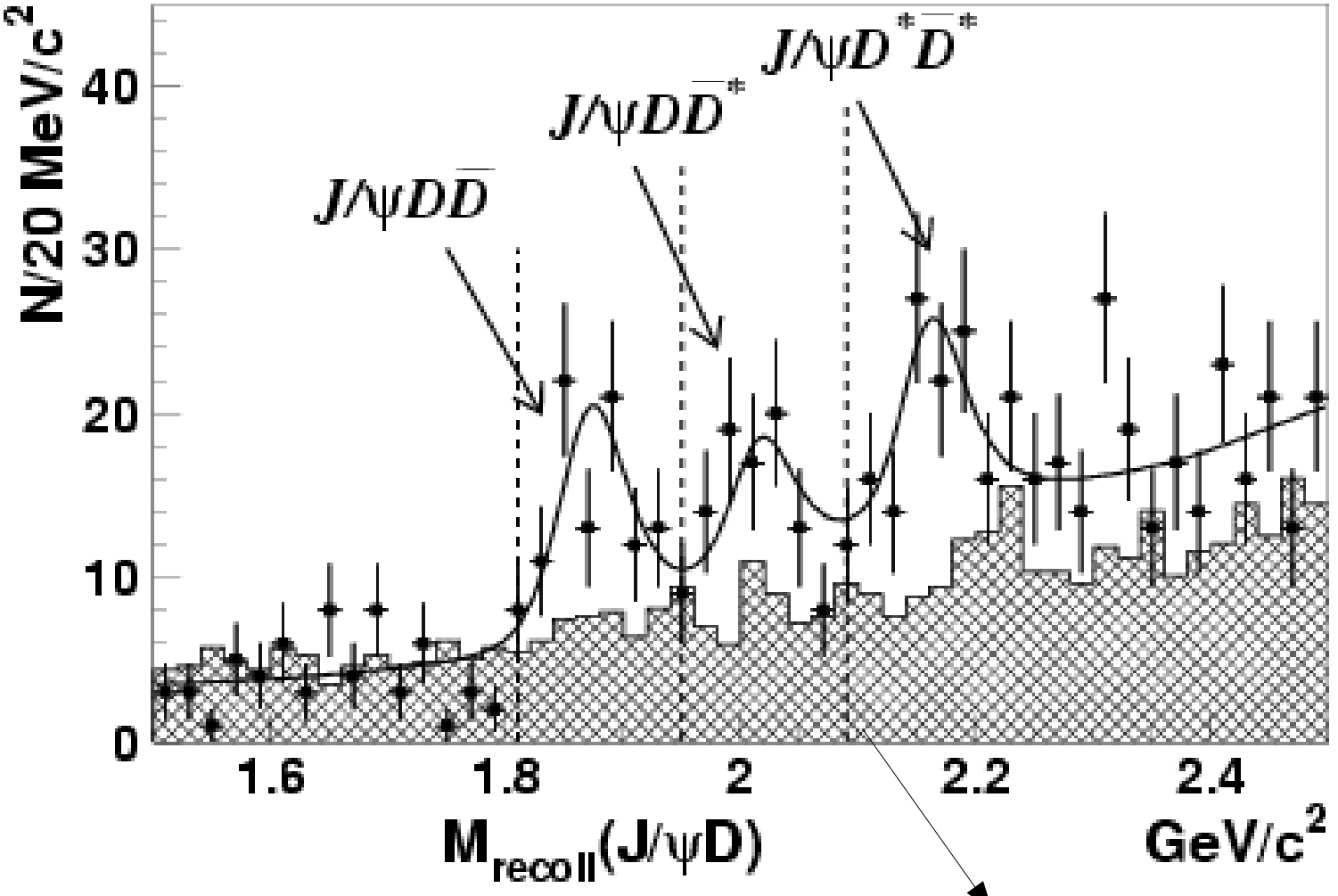
$M(X(3940)) = (3936 \pm 14)$ *MeV*$/c^2$
$\Gamma(X(3940)) = 39 \pm 26$ *MeV*

$M(\eta_c(2S)) = 3626 \pm 5 \pm 6$ *MeV*$/c^2$

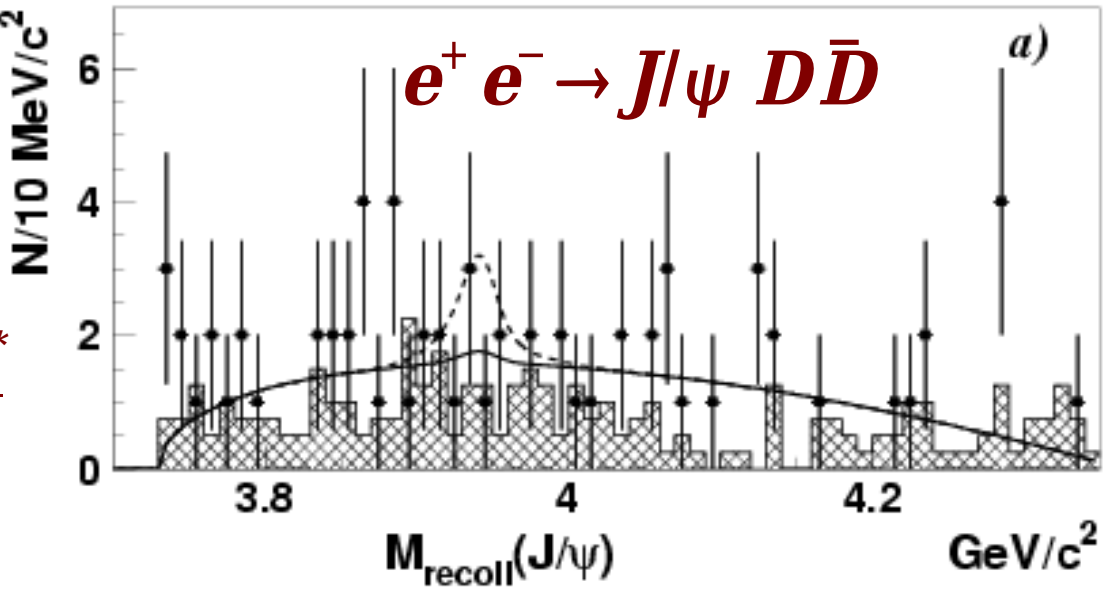
$X(3940)$ *decay modes ?*

Reconstruct D and look for $(J/\psi D)$ *recoil mass*

Clear evidence for $e^+ e^- \to J/\psi D\bar{D}^{(*)}$ *process*



Then we select events from the region of $M_{recoil}(J/\psi D)$ around D and D^* masses



observation of $X(3940) \to D\bar{D}^*$

$N = 24.5 \pm 6.9$

significance 5σ

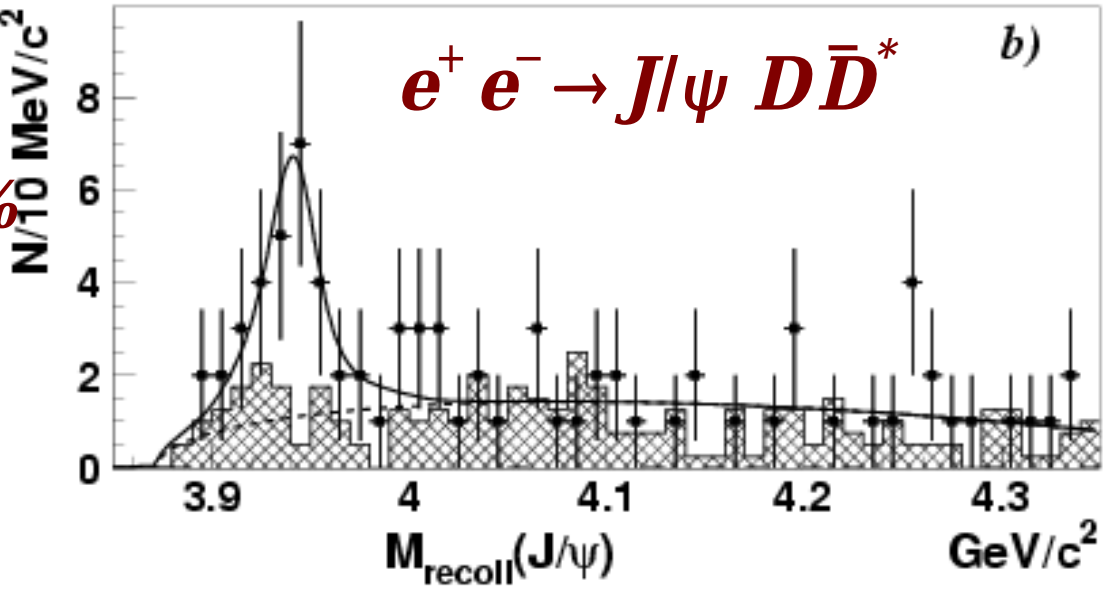
$M = 3943 \pm 6 \pm 6$ *MeV*/c^2

$\Gamma = 15.4 \pm 10.1$ *MeV*

$B(X(3940) \to D^*\bar{D}) = (96^{+45}_{-32} \pm 22)\,\%$

$B(X(3940) \to D\bar{D}) < 41\,\%$

$B(X(3940) \to J/\psi\omega) < 26\,\%$



$X(3940) = Y(3940)$ *?*

→ *no,* $X(3940) \to J/\psi\omega$ *not seen and width different !!*

$\eta_c(3S)$ *?? but mass ~*

Observation of a new state Z(3930) in γγ collisions

PRL 96, 082003 (2006)

No radially excited χ_{cJ} states yet found

(only ψ's $(3S_1)$ and one η_c $(1S_0)$)

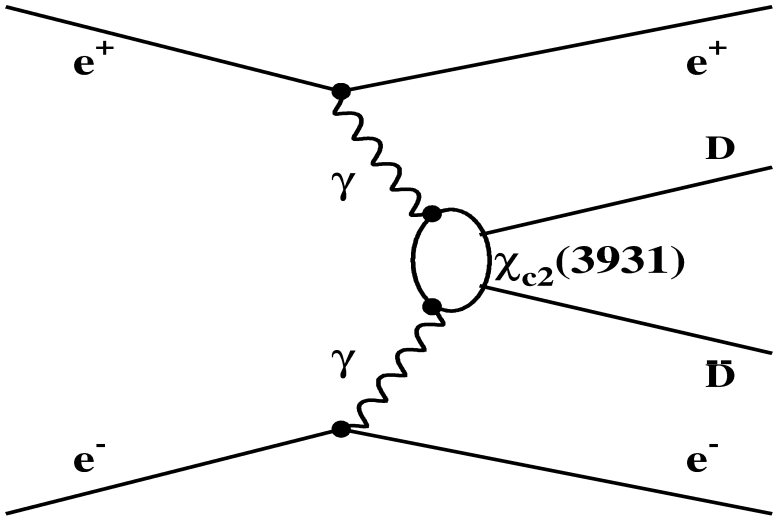
First radially excited χ_{cJ} states predicted in the range $[3.9-4.0]$ GeV

(above $D\bar{D}$ threshold)

***S.Godfrey and N.Isgur, PRD32,* 189 (1985)**

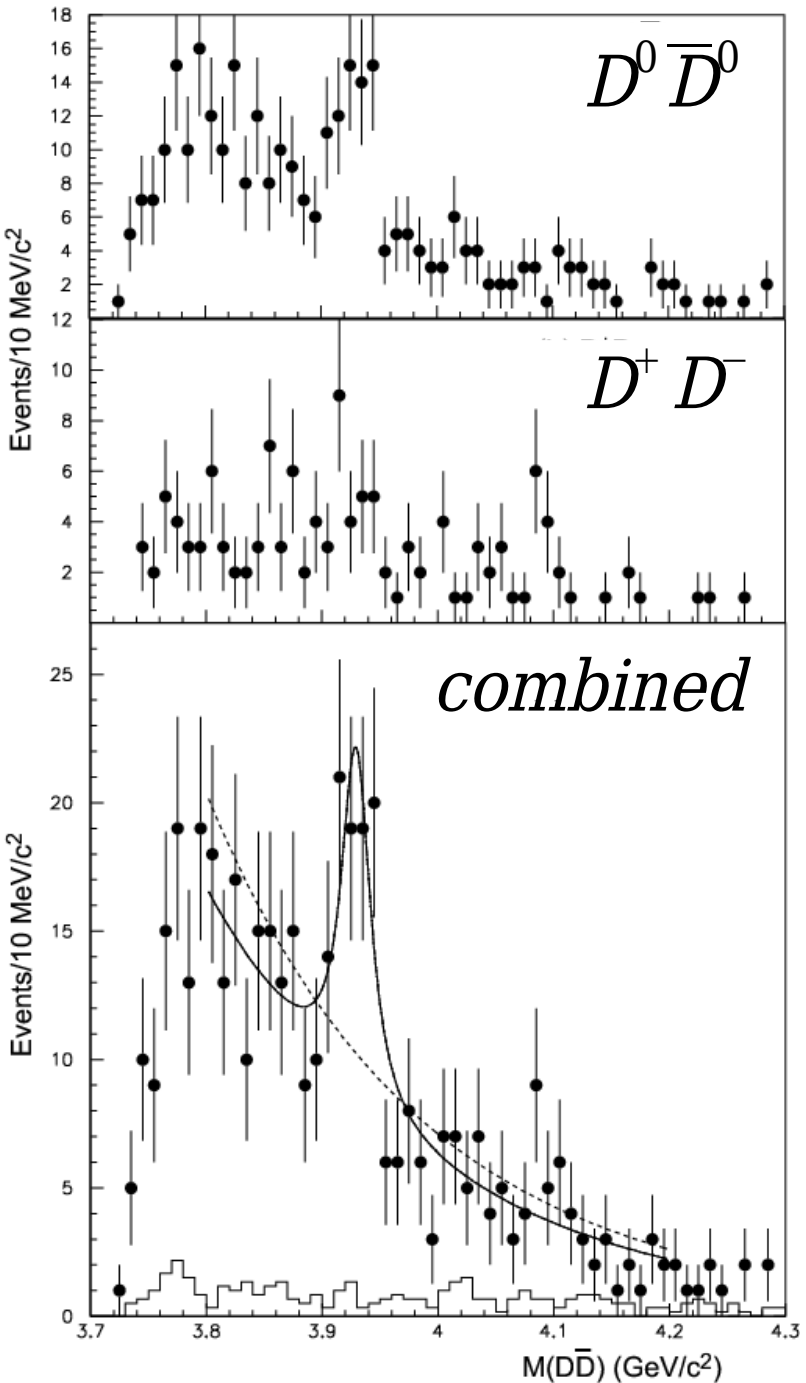
***E.Eichten, K.Lane and C.Quigg, PRD69,* 094019 (2006)**

χ'_{c0} and χ'_{c2} are expected to decay primarly into $D\bar{D}$



Observation of a new state Z(3930) in γγ collisions

Look at DD mass distribution in γγ events ($P_t(DD)<50\,MeV/c$)



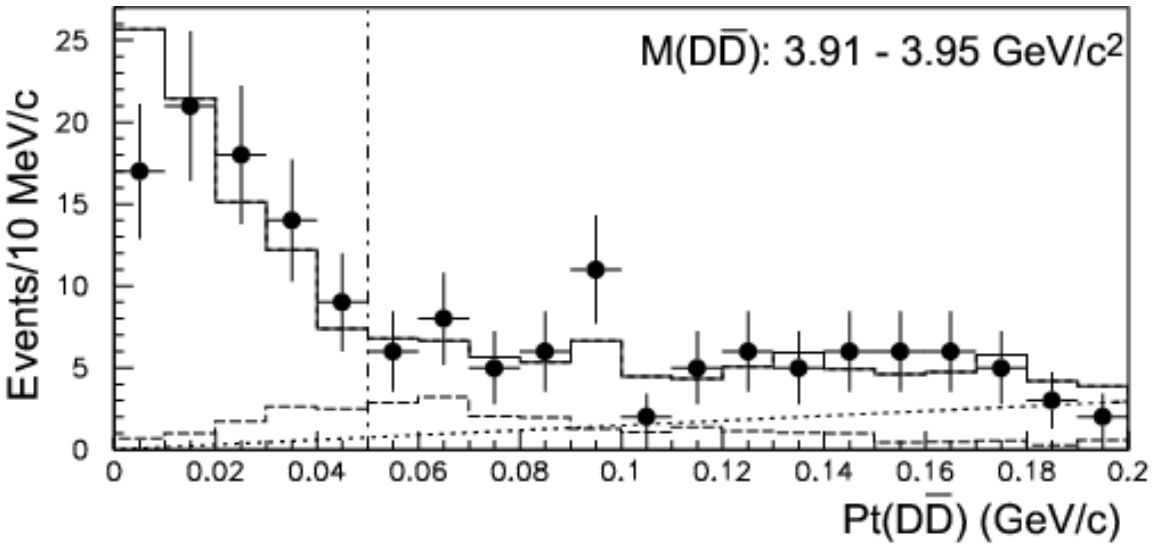
clear peak at M_{DD} ~ 3.930 GeV/c^2

$N = 64 \pm 18$

***significance* 5.3σ**

$M = 3929 \pm 5 \pm 2\ MeV/c^2$

$\Gamma = 29 \pm 10 \pm 2\ MeV$

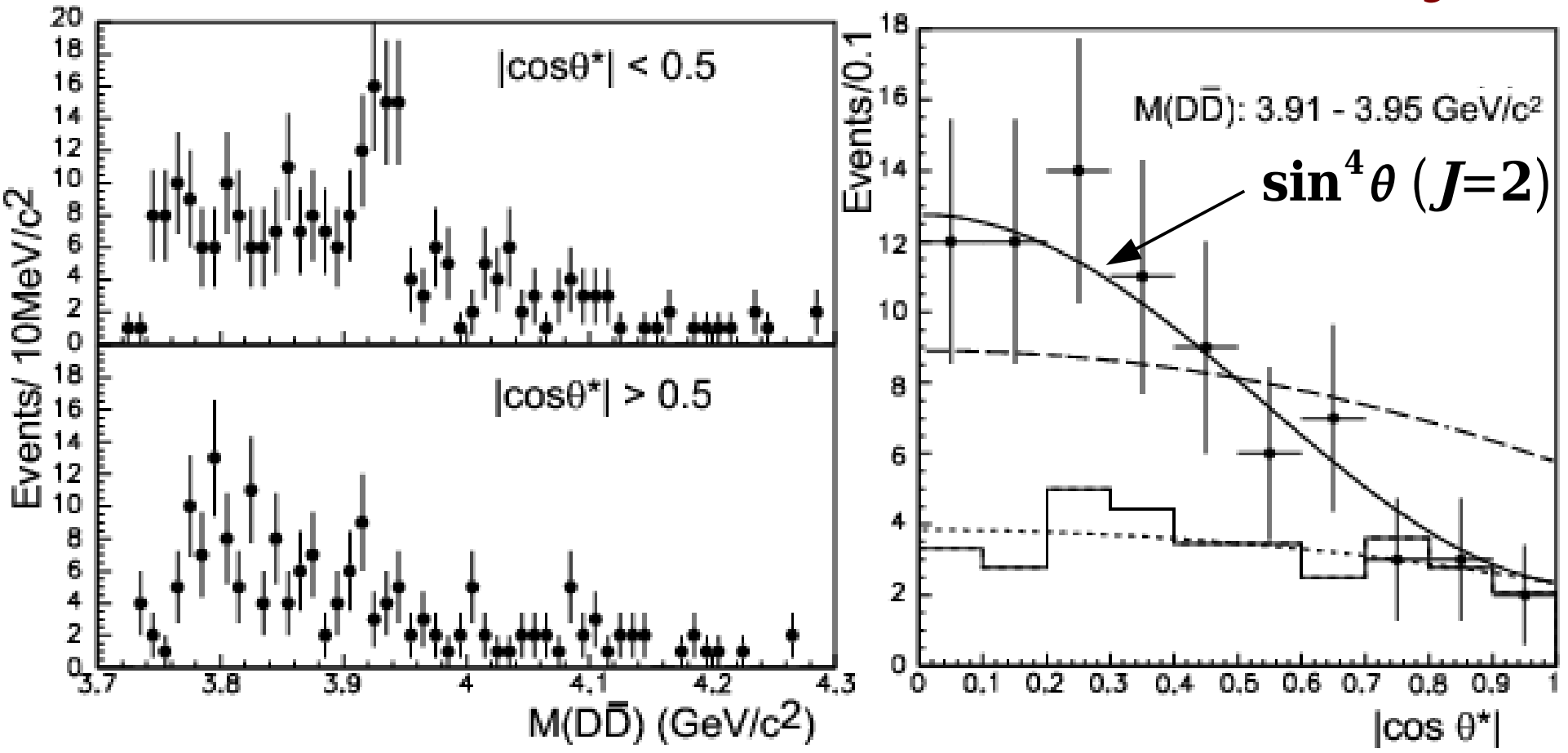


Check helicity of the $Z(3930)$: θ^*

(angle of a D relative to beam axis in the $\gamma\gamma$ cm frame)

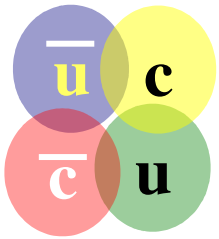
$\chi^2/d.o.f = 23.4/9$ for $J=0$

$\chi^2/d.o.f = 1.9/9$ for $J=2$



$\Gamma_{\gamma\gamma} \times Br(Z(3930) \to D\bar{D}) = (0.18 \pm 0.05 \pm 0.03)\, keV$

Properties of $Z(3930)$ consistent with expectations from χ'_{c2}



New Particles found by Belle

X(3872)

1^{++} *is a good candidate*

$c\bar{c}$ *charmonium component is small* $(<$ *few %)*

properties consistent with a $D^0 \bar{D}^{*0}$ *bound state*

Y(3940)

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

$4-$*quark state seems unlikely*

$c\bar{c}-$*gluon hybrid ?*

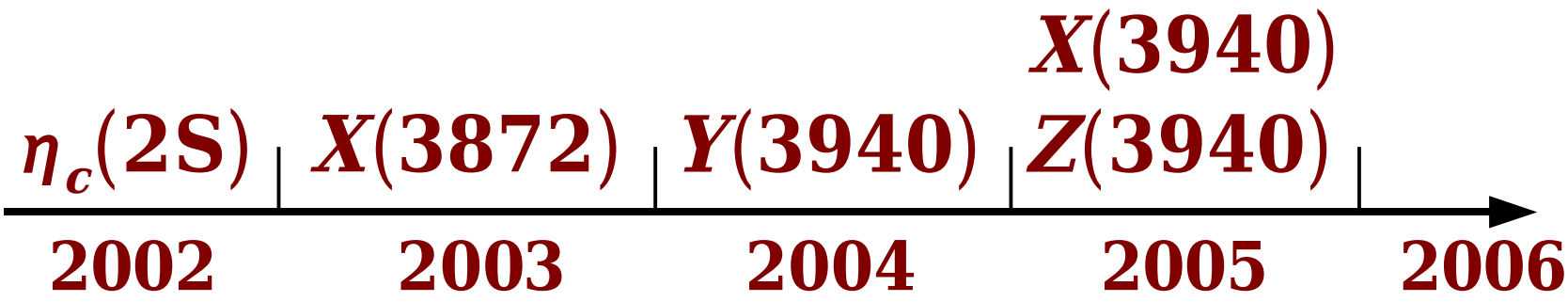
X(3940)

new charmonium in $e^+ e^- \to J/\psi\,(c\bar{c})$ *:* $\eta_c(3S)$ *??*

Z(3930)

χ'_{c2} *candidate in* $\gamma\gamma \to D\bar{D}$ *production*

New Particles found by Belle



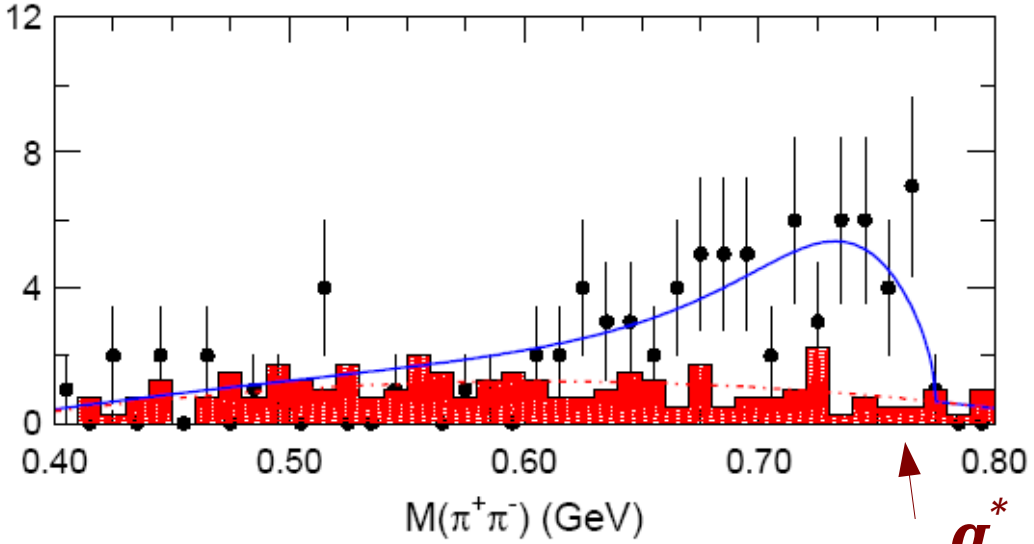
(New Particles–factory ?!)

$M(\pi\pi)$ can distinguish $\rho - J/\psi$ S– and P–waves

For $C = +1$

S– wave

$\chi^2/d.o.f = 43/39$ ($CL = 28\,\%$)

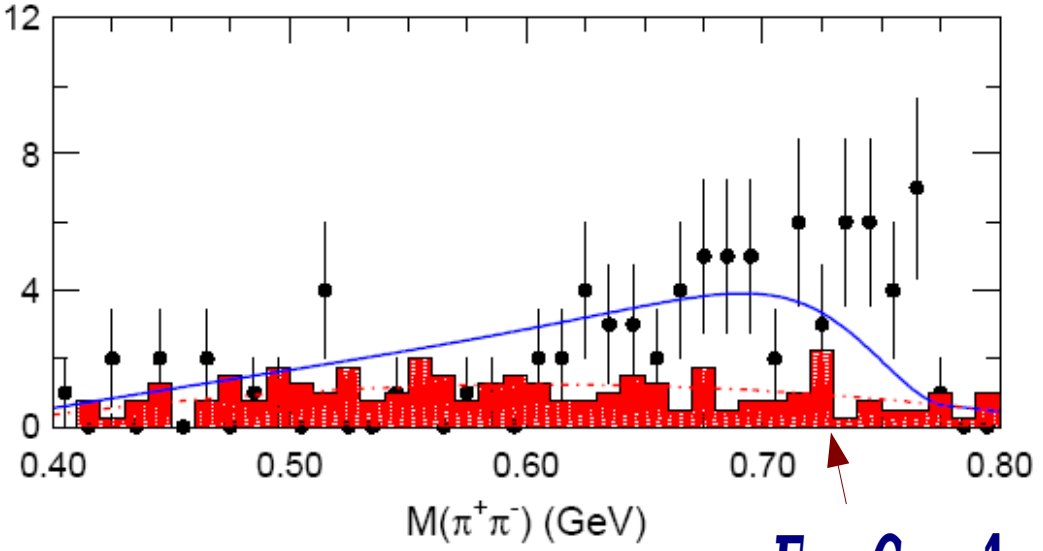


q^* roll–off

$M(\pi\pi) \propto (q^*_{J/\psi})^{2l+1}$

P– wave

$\chi^2/d.o.f = 71/39$ ($CL = 0.1\,\%$)



For $C=+1$

Shape of $M(\pi\pi)$ distribution near the kinematic limit favors S– wave

Possible J^{PC} values
(J^{-+} ruled out)

0^{--} *exotic* violates parity	0^{-+} (η_c")	0^{++} DD allowed (χ_{c0}')	0^{+-} *exotic* DD allowed
1^{--} DD allowed ($\psi(3S)$)	1^{-+} *exotic* DD allowed	**1^{++}** (χ_{c1}')	1^{+-} (h_c')
2^{--} (ψ_2)	2^{-+} (η_{c2})	**2^{++}** DD allowed (χ_{c2}')	2^{+-} *exotic* DD allowed