New charm resonances

Tadeusz Lesiak

Institute of Nuclear Physics
Polish Academy of Sciences
Kraków, Poland

Representing the Belle collaboration

Results from:

8-th International Workshop on Heavy Quarks and Leptons (HQL2006)

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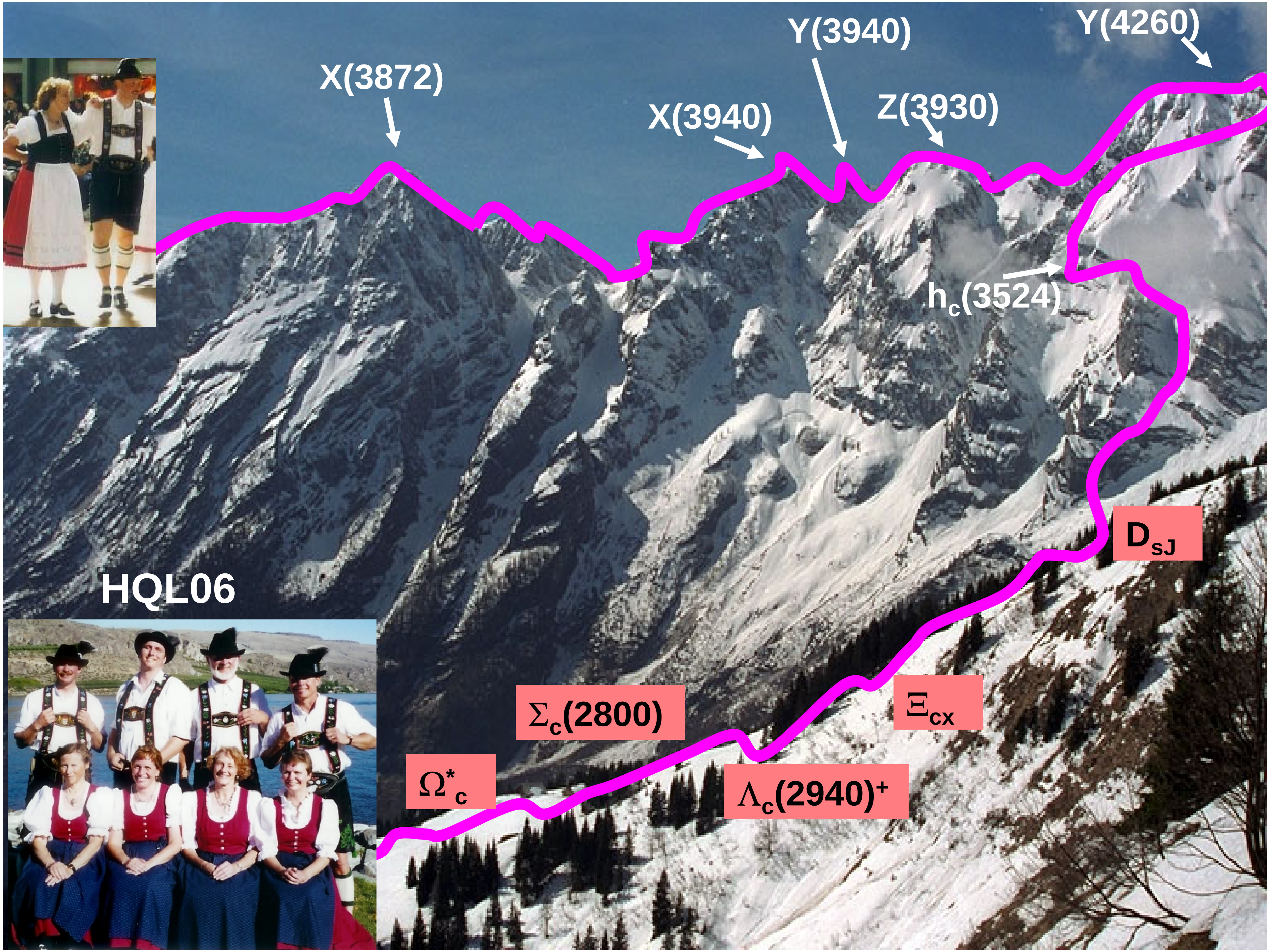
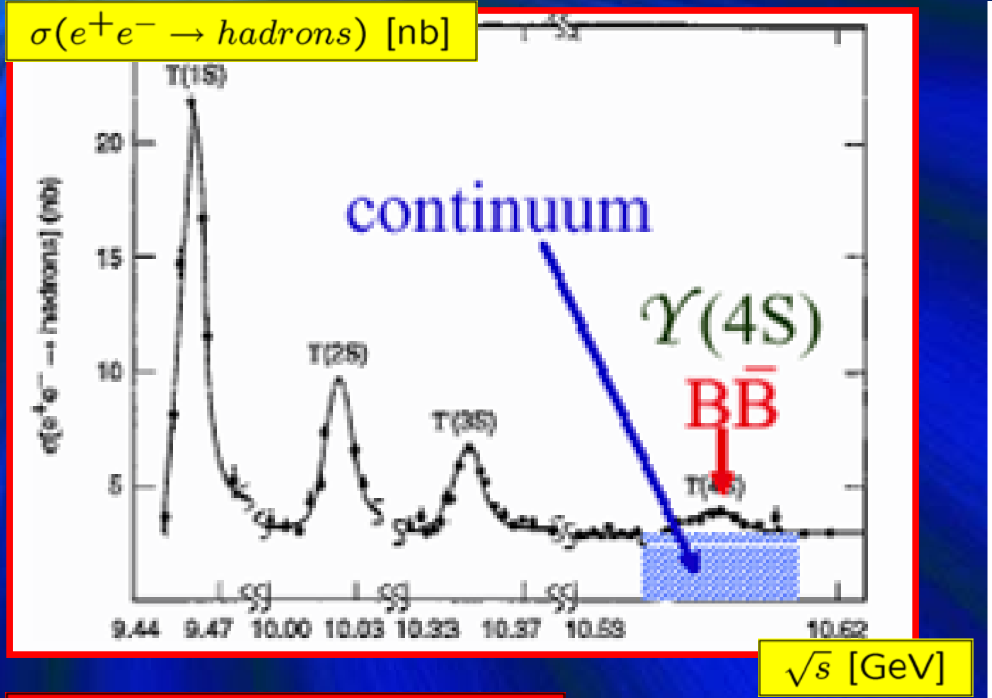
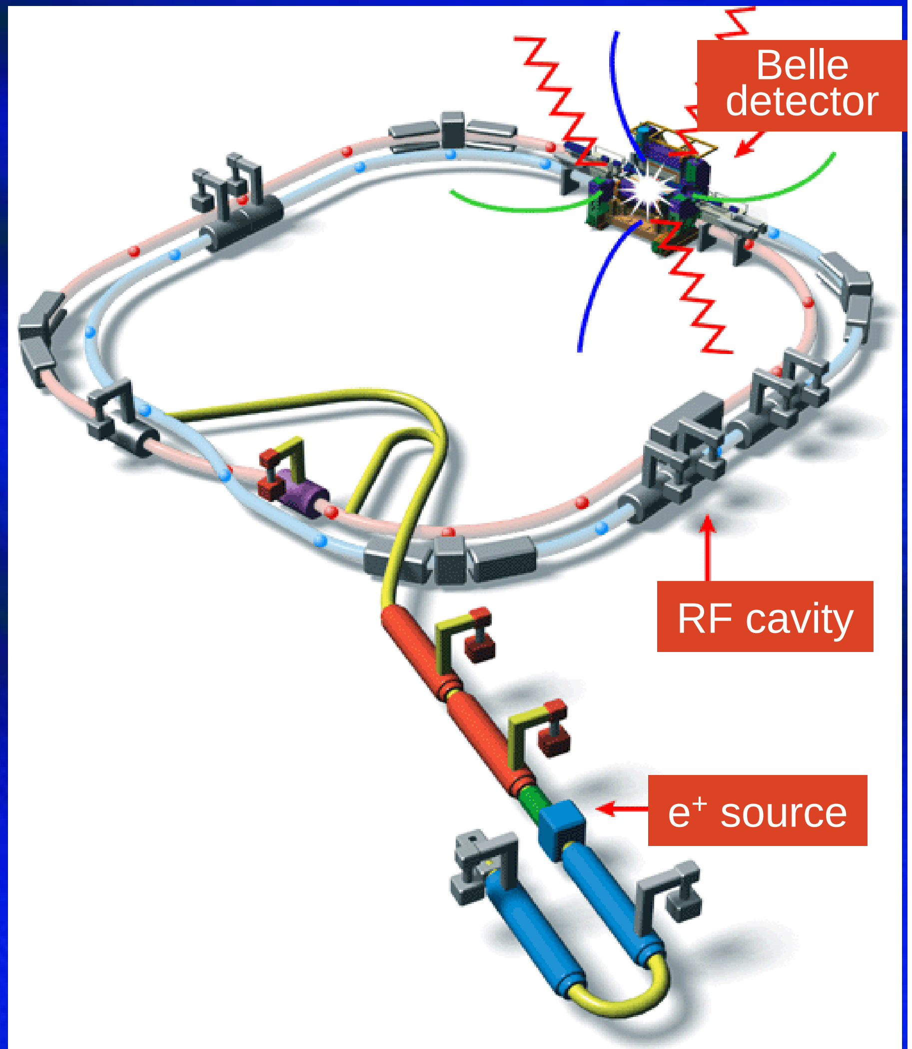

X(3872)
X(3940)
Y(3940)
Z(3930)
Y(4260)
h_c(3524)
HQL06
D_sJ
Σ_c(2800)
Ξ_cx
Ω*_c
Λ_c(2940)^+

B-factories in a nutshell

CESR: symmetric in beam energies
KEKB: 8 GeV (e^-) $\times$ 3.5 GeV (e^+)
PEP-II: 9 GeV(e^-) x 3.1 GeV (e^+)





$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$

$$e^+e^- \to q\bar{q}, \quad q = u, d, s, c$$

} different event topologies

$\sigma(b\bar{b}) \approx 1.1$ nb

$\sigma(c\bar{c}) \approx 1.3$ nb

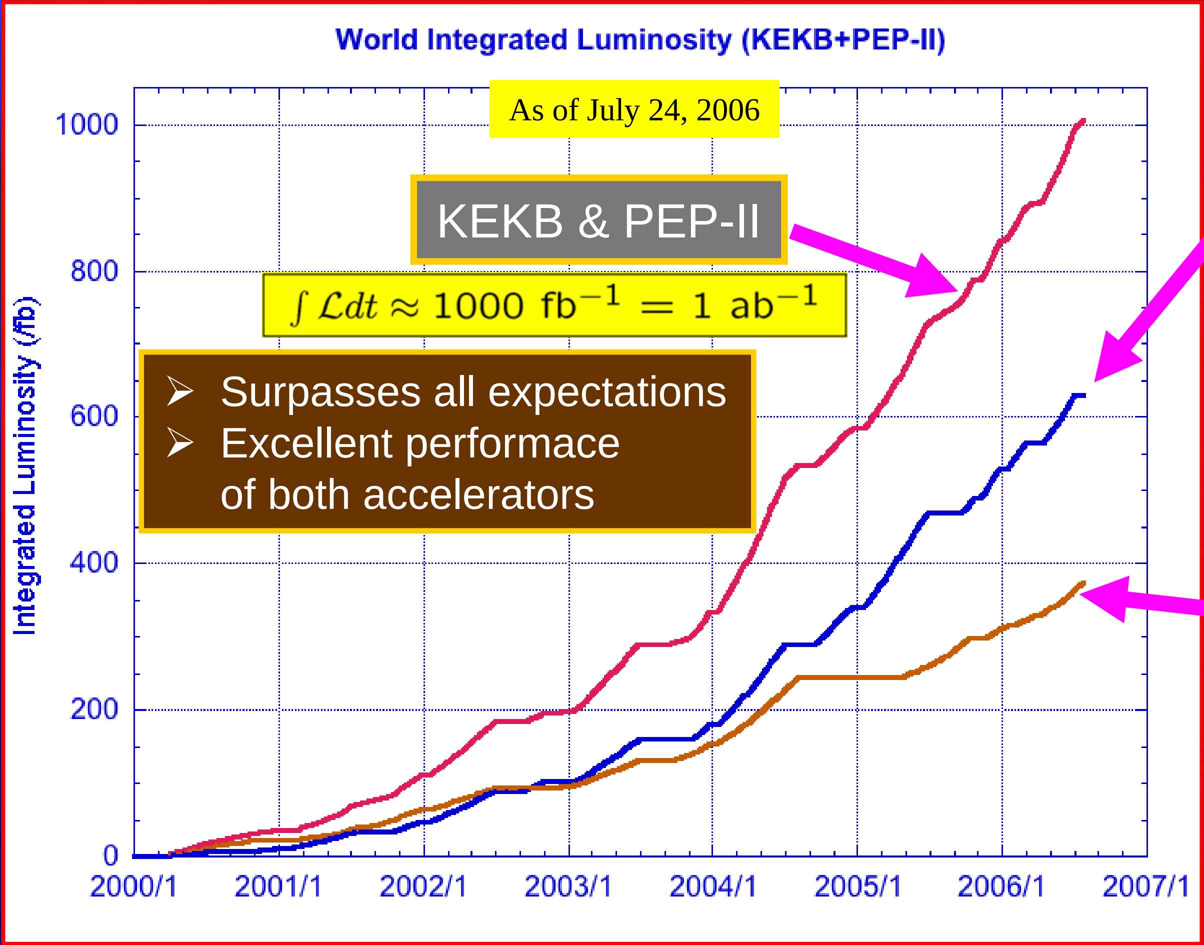
} Beauty AND charm factory

$\sigma(s\bar{s}) \approx 0.3$ nb | $\sigma(d\bar{d}) \approx 0.3$ nb | $\sigma(u\bar{u}) \approx 1.4$ nb

B-factories in a nutshell

CESR (CLEO): ~ 16 fb^{-1} at the Υ(4S) over 20 years
CESR-c (CLEO-c): work at the ψ(3770) peak since 2003

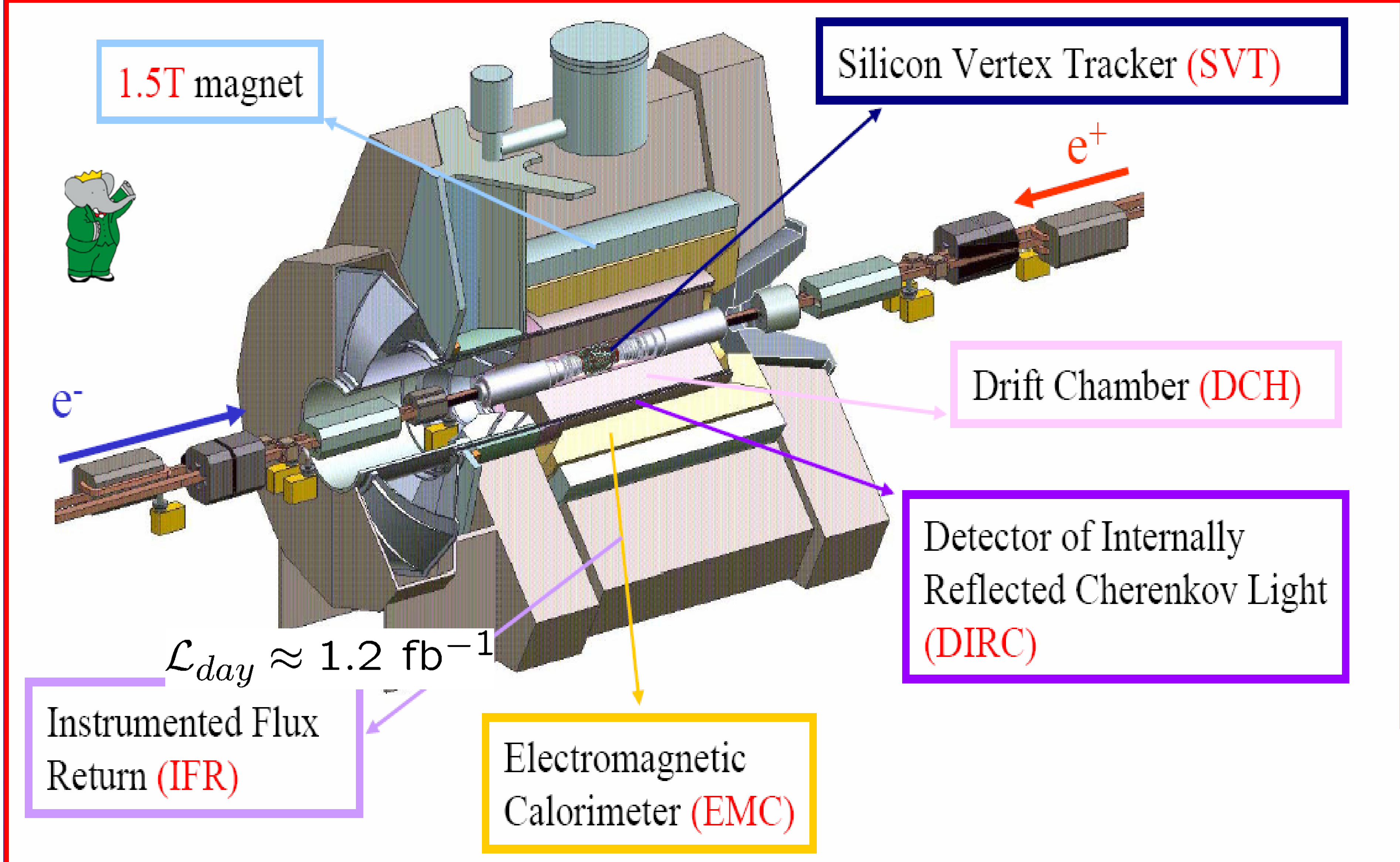
$\mathcal{L}_{peak} \approx 1.33 \times 10^{33}\ s^{-1}cm^{-2}$



- Surpasses all expectations
- Excellent performace of both accelerators

Results presented below correspond to smaller data samples

B-factories in a nutshell

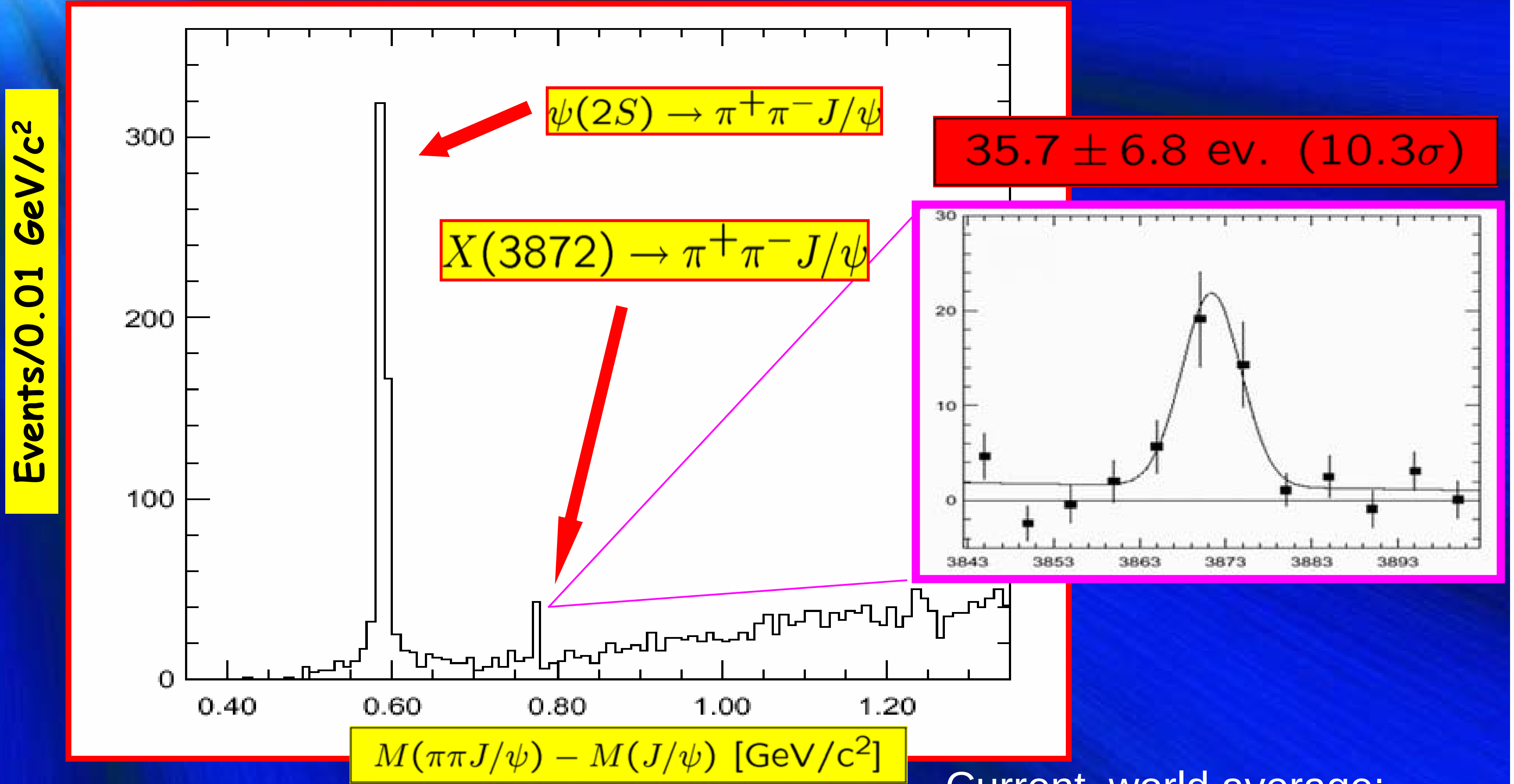


First observation of X(3872)

140 fb^{-1}

PRL 91, 262001 (2003)

- decays studied $B^- \to K^- \pi^+ \pi^- J/\psi$



35.7 ± 6.8 ev. (10.3σ)

First Belle measurement:

$M = 3872.0 \pm 0.6 \pm 0.5$ MeV

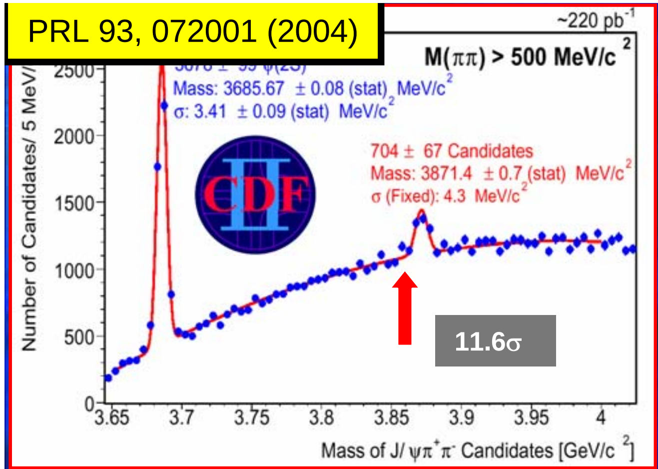
$\Gamma < 2.3$ MeV (90% CL)

Current world average:

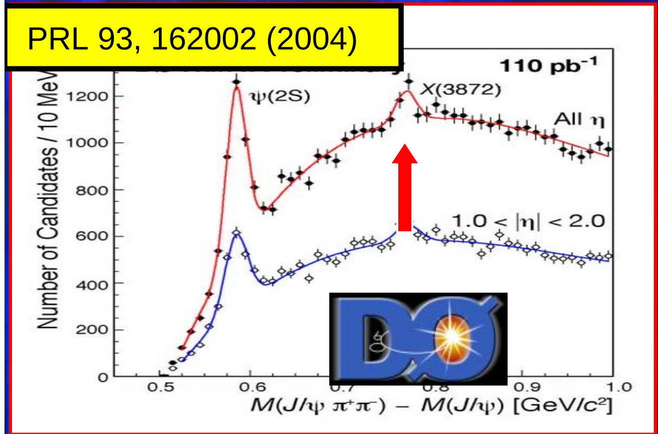
$M = 3871.2 \pm 0.5$ MeV/c^2

$\mathcal{B}(B \to KX) \times \mathcal{B}(X \to \pi^+\pi^- J/\psi) = (1.3 \pm 0.24 \pm 0.13) \times 10^{-5}$

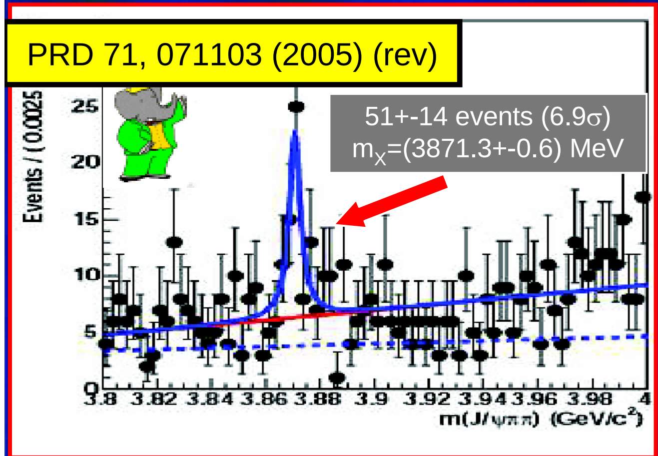
(Rapid) confirmation of X(3872)



PRL 93, 072001 (2004)

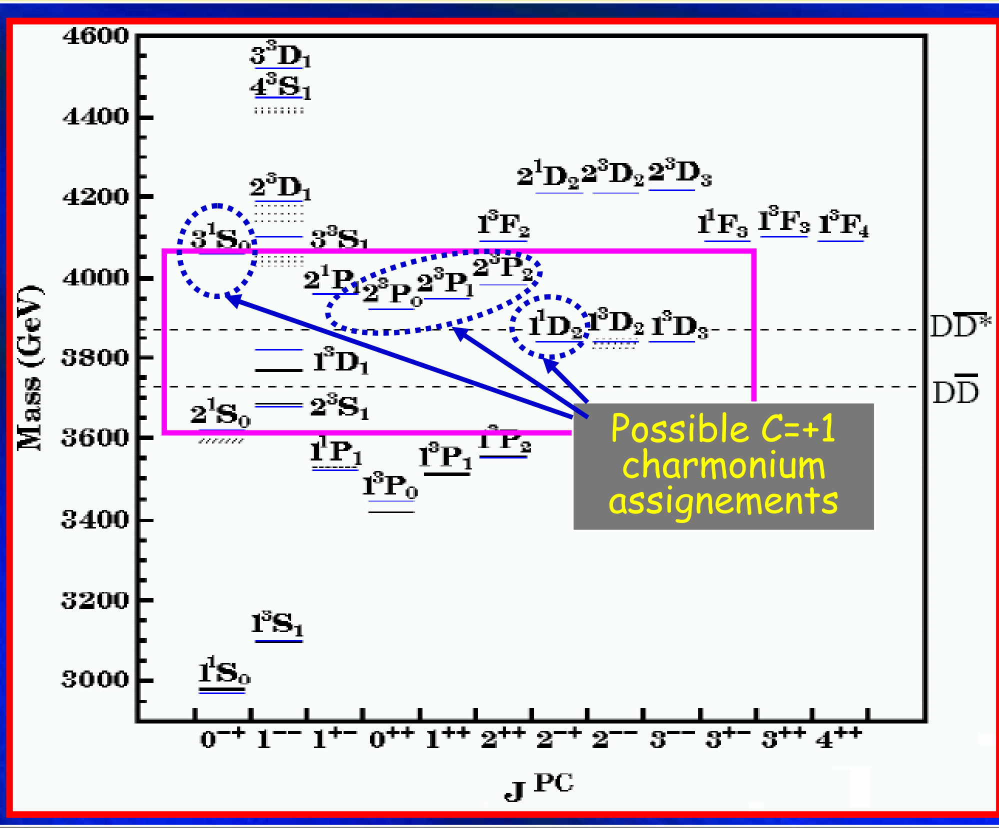


PRL 93, 162002 (2004)



PRD 71, 071103 (2005) (rev)

The existence of X(3872) – out of question However, X parameters (M, Γ and decay pattern) does not fit with any standard, vacant charmonium state

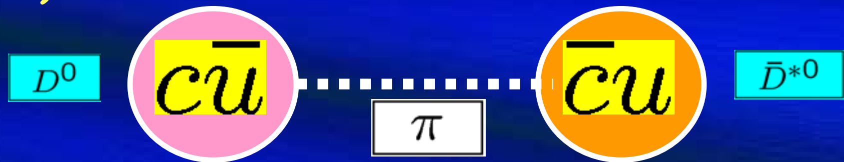


3^1S_0 (η_c'')	- mass far too high and width wrong: $\Gamma \approx$ 20MeV)
2^3P_0, 2^3P_2,	- cannot be that narrow as Γ < 2.3MeV; 2^3P_2=Z(3930)
2^3P_1	$\Gamma(\gamma J/\psi) \approx$ 40 (0.14 for X)
1^1D_2 (η_{c2})	$B(\pi^+\pi^- J/\psi)$ should be very small

Theoretical interpretation of X(3872)

M_X coincides with $M(D^0)+M(\bar{D}^{0*})$ = 3871.2+-1.0 MeV

❖ Deuson - a $D\bar{D}^*$ bound state (molecule)



- predicted $J^{PC} = 1^{++}$ (or 0^{-+})
- Wave function (S wave bound state):

$$(D^0\bar{D}^{*0} + \bar{D}^0 D^{*0})/\sqrt{2} \sim c\bar{c}u\bar{u}$$

- isospin violation (a substantial admixture of I=1)
- for C=+1 the decay to $\pi^+\pi^-$ J/ψ would proceed via an isovector ρ^0-J/ψ intermediate state

➔ prediction: $m(\pi\pi)$ peaked at high masses (as observed by Belle)

F.E.Close, P.R.Page PLB 578, 119 (2004)
N.A.Tornquist. PLB 590, 209 (2004)
E.S.Swanson, PLB 588, 189 (2004); ibid 598, 197 (2004)

❖ Tetraquark

L.Maiani et al., PRD 71, 014028 (2005)

- open charm diquark-antidiquark states $[c\bar{q}][\bar{c}q']$

❖ Hybrid $c\bar{c}$-gluon

B.A.Li, PLB 605, 306 (2005)

❖ Glueball with a $c\bar{c}$ admixture

K.K.Seth, PLB 612, 1 (2005)

❖ Cusp effect

D.Bugg, PLB 598, 8 (2004)

✓ try to find (other than $\pi^+\pi^- J/\psi$) decay modes

✓ determine the (J^{PC}) – angular distributions etc.

→ Both points discussed below

➔ more conclusive interpretation of X(3872)

Evidence for X(3872) → γ J/ψ

$B^- \to K^- \gamma J/\psi$

hep-ex/0505037

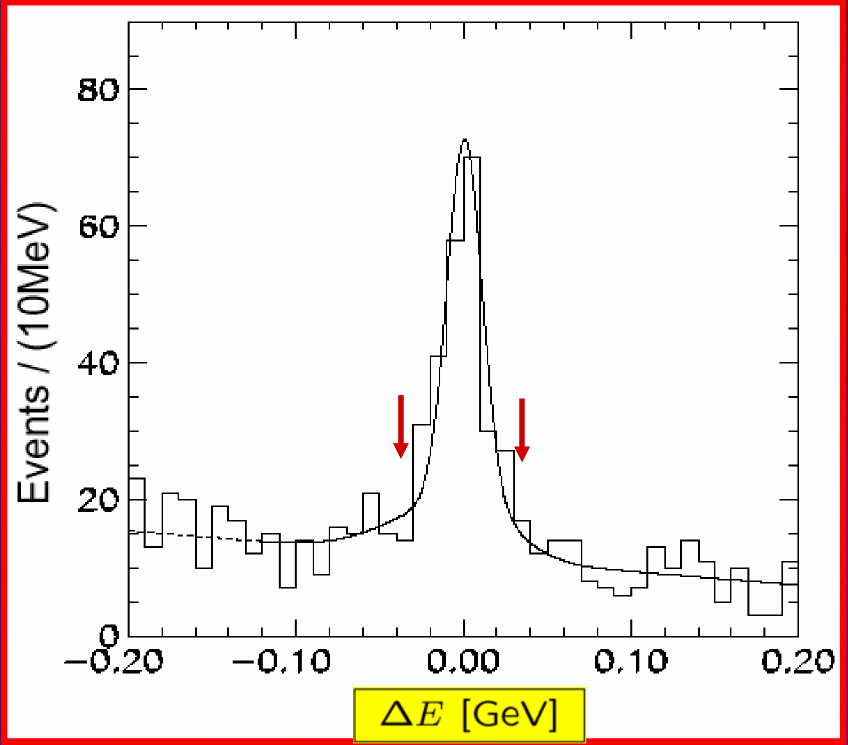
253 fb^{-1}

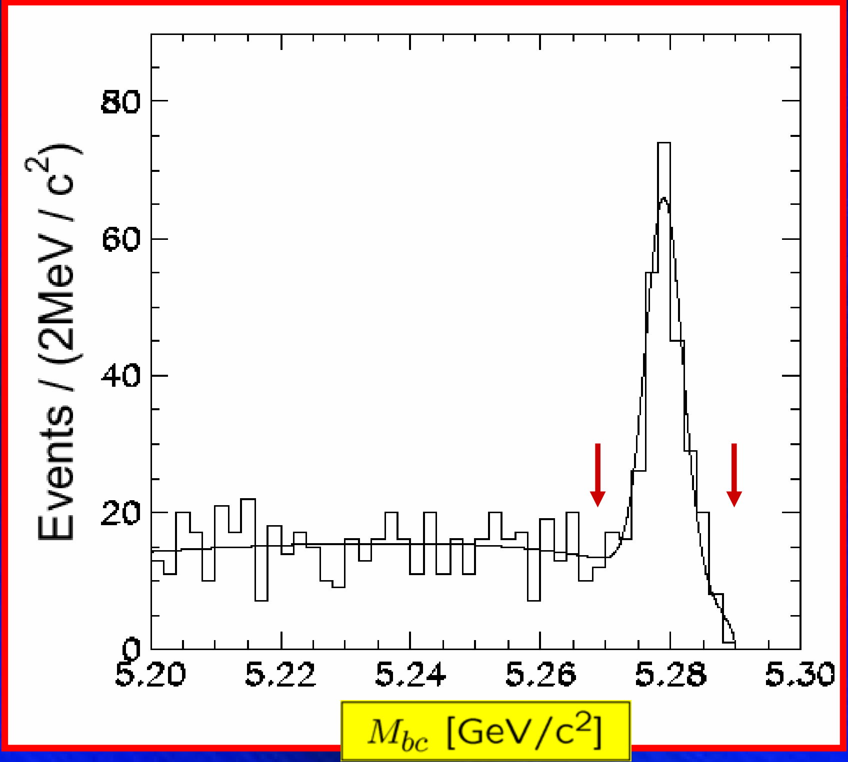
the energy difference:

$$\Delta E = E_B^{cms} - E_{beam}^{cms}$$

the beam-energy constrained mass:

$$M_{bc} = \sqrt{(E_{beam}^{cms})^2 - (p_B^{cms})^2}$$



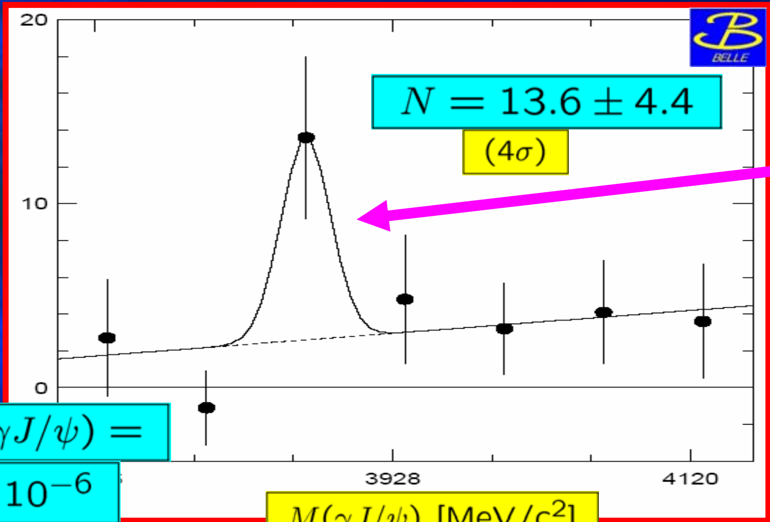


Inside of the *signal box* corresponding to the decay $B^- \to K^- \gamma\ J/\psi$
look at the $M(\gamma J/\psi)$

Evidence for X(3872) → γ J/ψ

The yield of B mesons

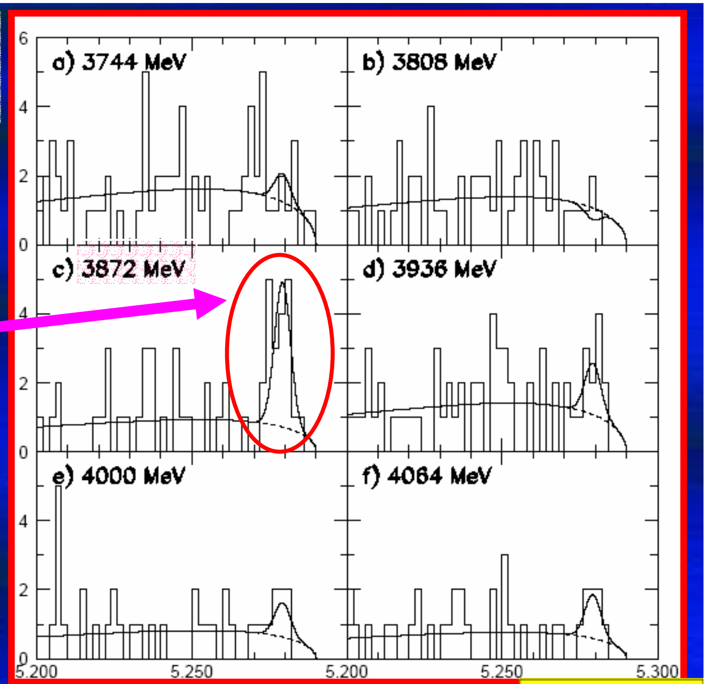
obtained from the fit to M_{bc} in bins of $M(\gamma J/\psi)$:



$N = 13.6 \pm 4.4$

(4σ)

$M(\gamma J/\psi)$ [MeV/c^2]



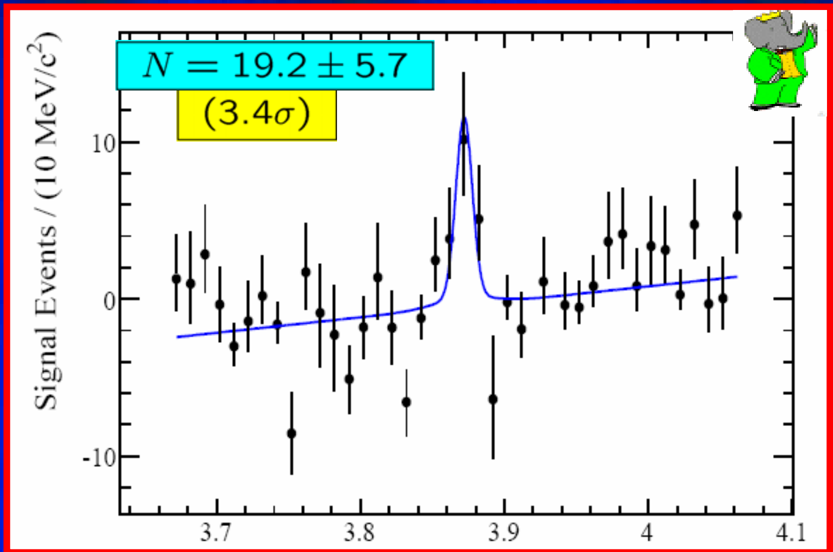
M_{bc} [GeV/c^2]

$\mathcal{B}(B \to KX) \times \mathcal{B}(X \to \gamma J/\psi) =$

$= (1.8 \pm 0.6 \pm 0.1) \times 10^{-6}$

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

Theory: 40 for the χ'_{c1} $^2 3P_1$ assignement



$N = 19.2 \pm 5.7$

(3.4σ)

$M(c\bar{c})$ [MeV/c^2]

260 fb^{-1}

hep-ex/0607050

$\mathcal{B}(B \to KX) \times \mathcal{B}(X \to \gamma J/\psi) =$

$= (3.3 \pm 1.0 \pm 0.3) \times 10^{-6}$

C(X(3872))=+1 unambiguosly established !

$c\bar{c}$ component in the X wave function

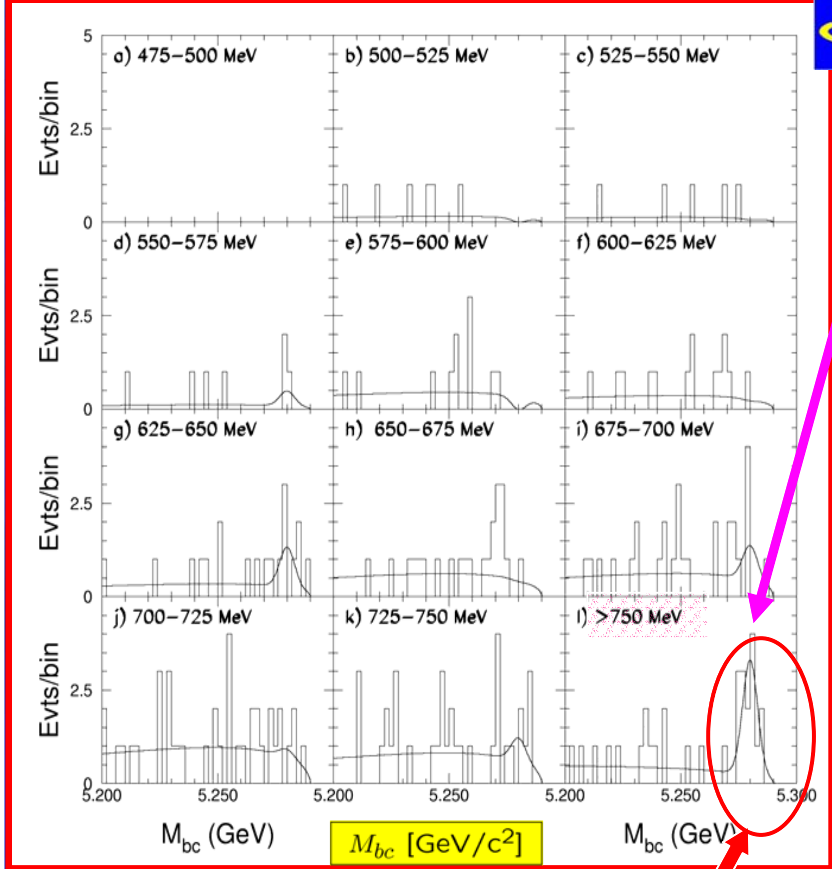
Evidence for X(3872) → $\pi^+\pi^-\pi^0$ J/ψ

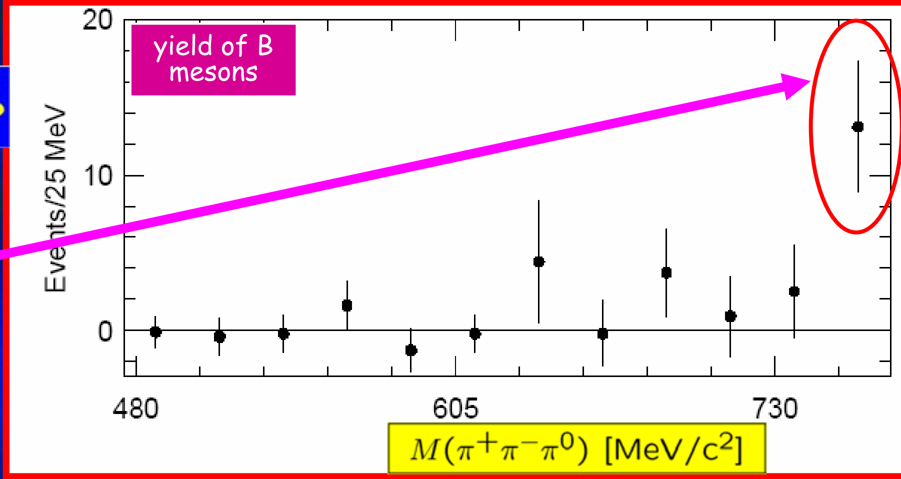
Signal of: $B^- \to K\pi^+\pi^-\pi^0 J/\psi$

hep-ex/0505037

253 fb^{-1}

→ fit M_{bc} in bins of $M(\pi^+\pi^-\pi^0)$:





12.4+-4.1 events (4.3σ)
for $M(\pi^+\pi^-\pi^0)$> 750 MeV

A virtual ω(782) (sub-threshold) decay X -> ω J/ψ ?
The kinematical limit for $M(\pi^+\pi^-\pi^0)$ is 7.5MeV below the ω mass (Γ(ω) = 8MeV)

Large (near max.) isospin violation:

$$\frac{\mathcal{B}(X\to\pi^+\pi^-\pi^0 J/\psi)}{\mathcal{B}(X\to\pi^+\pi^- J/\psi)} = 1.0 \pm 0.4 \pm 0.5$$

X(3872) = a mixture of I = 0 and I=1 state

➔ The substantial I=1 component

➔ there must be $u\bar{u}/d\bar{d}$ pairs in addition to $c\bar{c}$

Both X -> γ J/ψ and X -> $\pi^+\pi^-\pi^0$J/ψ support the DEUSON hypothesis

Spin-parity of X(3872)

hep-ex/0505038

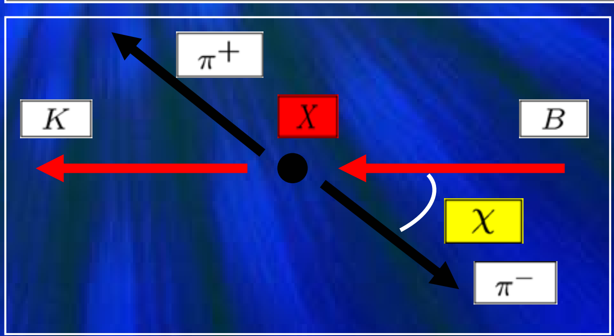
253 fb^{-1}

Studies of angular distributions of $X \to \pi^+\pi^- J/\psi$ according to

J.L.Rosner, Phys. Rev. D70 094023 (2004)
D.V.Bugg, Phys. Rev D71 016006 (2005)

→ tests of all relevant J^P assignments

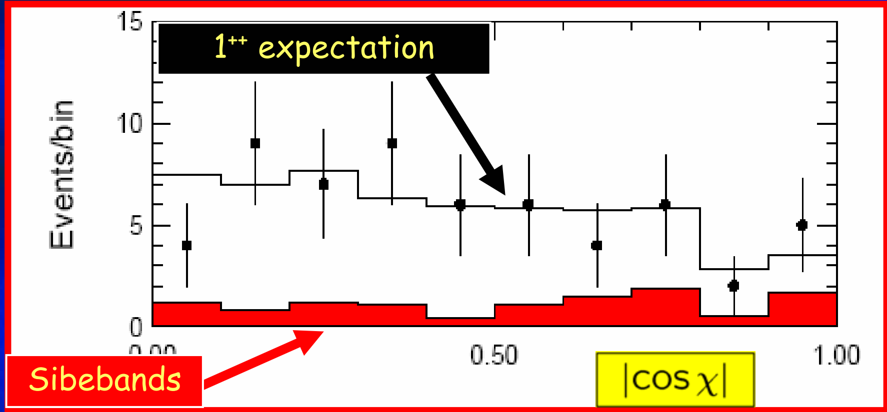
1^{++} clearly favoured;
2^{++} cannot be ruled out completely



1^{++}

$\propto \sin^2\chi$

$\chi^2/d.o.f. = 5/9$



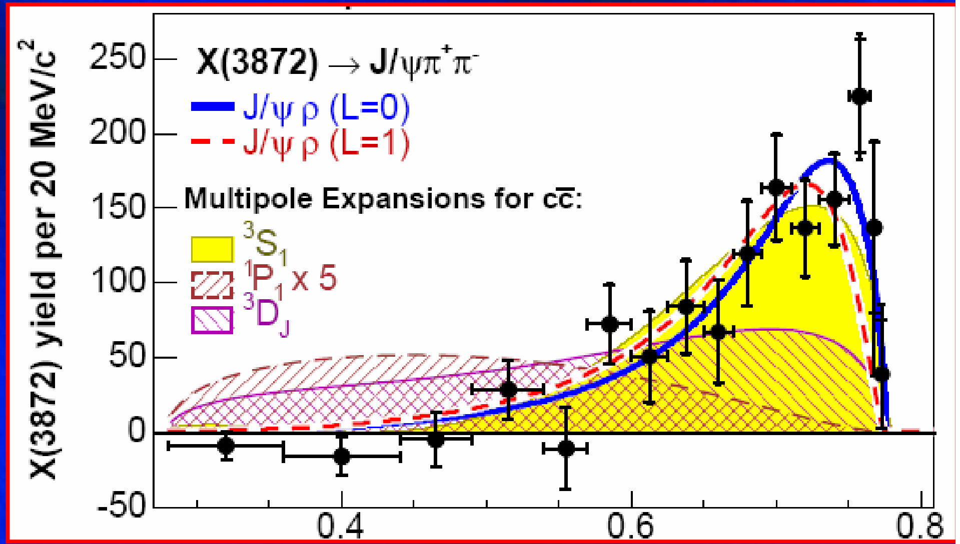
360 pb^{-1}

PRL 96, 102002 (2006)

Study of $M(\pi^+\pi^-)$:
the ρ dominance expected for C=+1;
cannot distinguish between 1^{++} and 2^{-+}
using high statistics (N(X)=3000 ev.);

hypothesis	3D χ^2 / 11 d.o.f.	χ^2 prob.
1^{++}	13.2	27.8%
2^{-+}	13.6	25.8%

(2^{-+} corresponds to L=1, η_{c2}, 1^1D_2)



Additional check:
look for the decay

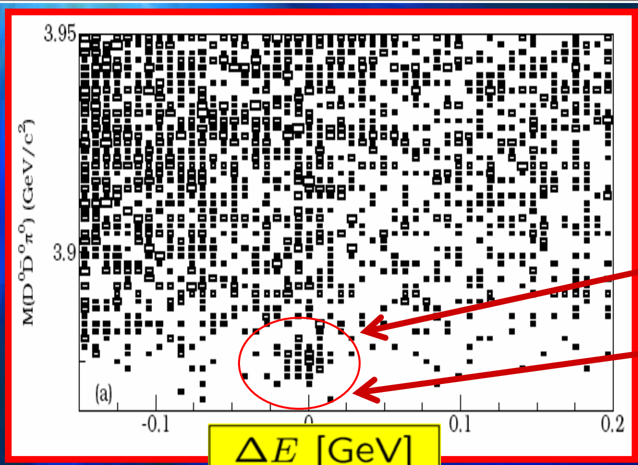
$X(3872) \to D^0\bar{D}^0\pi^0$

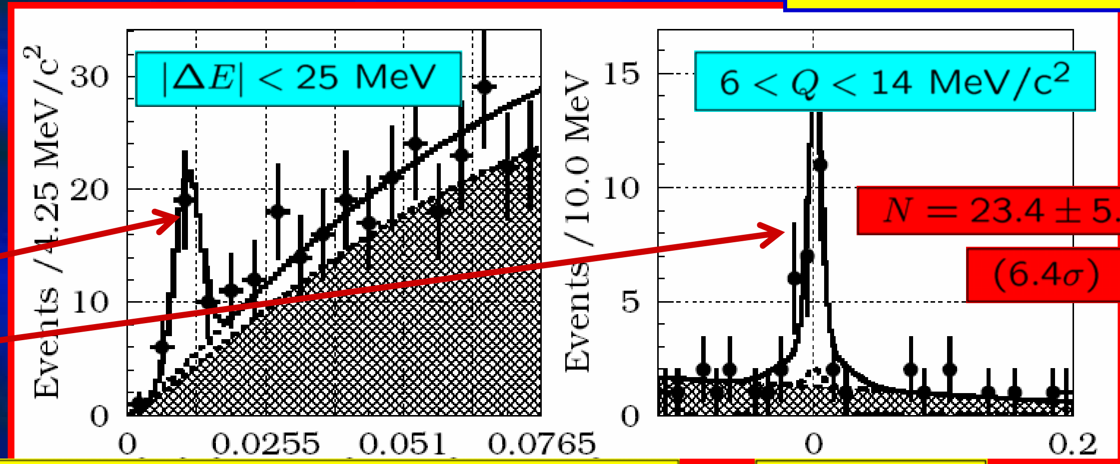
Evidence for $X(3872) \to D^0 \bar{D}^0 \pi^0$

414 fb^{-1}

hep-ex/0606055
Accepted by PRL

Observation of a near threshold enhancement in $B \to D^0 \bar{D}^0 \pi^0 K$





$M_X = 3875.2 \pm 0.7^{+0.3}_{-1.6} \pm 0.8$ MeV/c² (2σ higher than $M(X)_{PDG}$)

$\mathcal{B}(B \to D^0 \bar{D}^0 \pi^0 K) = (1.22 \pm 0.31^{+0.23}_{-0.30}) \times 10^{-4}$ ⇒ $10 \times \mathcal{B}(B \to KX) \times \mathcal{B}(X \to \pi^+\pi^- J/\psi)$

(dominant decay mode)

1^{++} or 2^{++} ?

- $2^+ \to 0^- \, 0^- \, 0^-$ requires at least one pair of final state particles to be in a D-wave
- The near threshold production of $D^0\bar{D}^0\pi^0$ would be suppressed by an l=2 centrifugal barrier

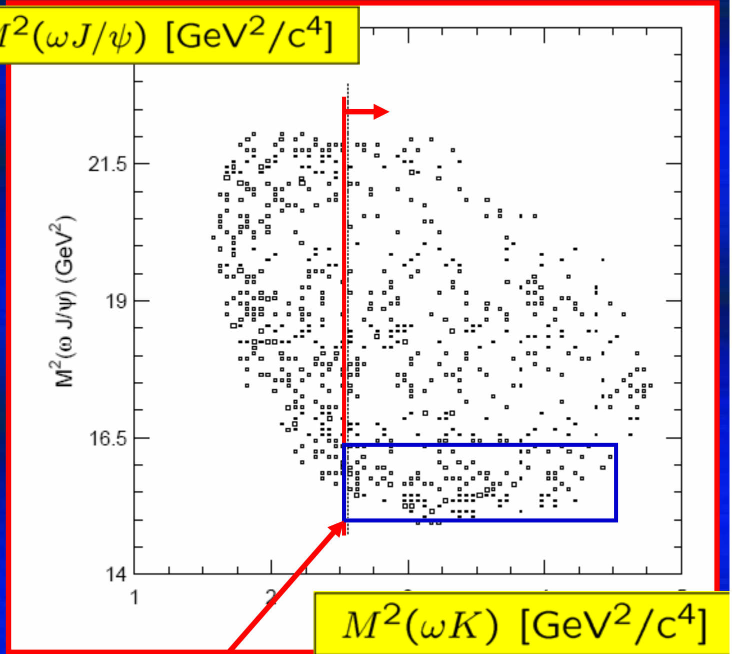
If the peak observed at 3875 MeV/c² is due to X(3872) → J=2 possibility unlikely

X(3872): $J^{PC} = 1^{++}$ strongly favoured (2^{++} and 2^{-+} cannot be discarded)

Observation of Y(3940)

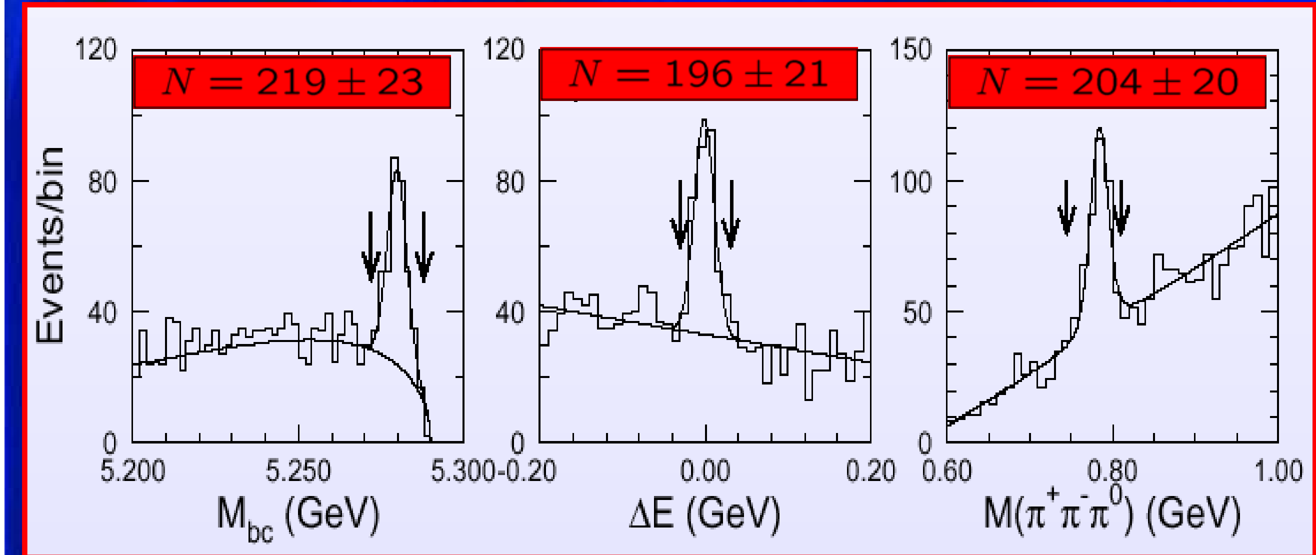
PRL 94, 182002 (2005) **253 fb^{-1}**

- **decays studied: B→ $K\pi^+\pi^-\pi^0$ J/ψ**
- **Observation of B→ J/ψ ω K, ω→ $\pi^+\pi^-\pi^0$**
- **M(ωK) > 1.6 GeV**
  (removal of strange resonances like K^*→ωK, $K_X = K_1(1270)$, $K_1(1400)$, $K_2^*(1430)$…)



➢SIGNAL REGIONS:

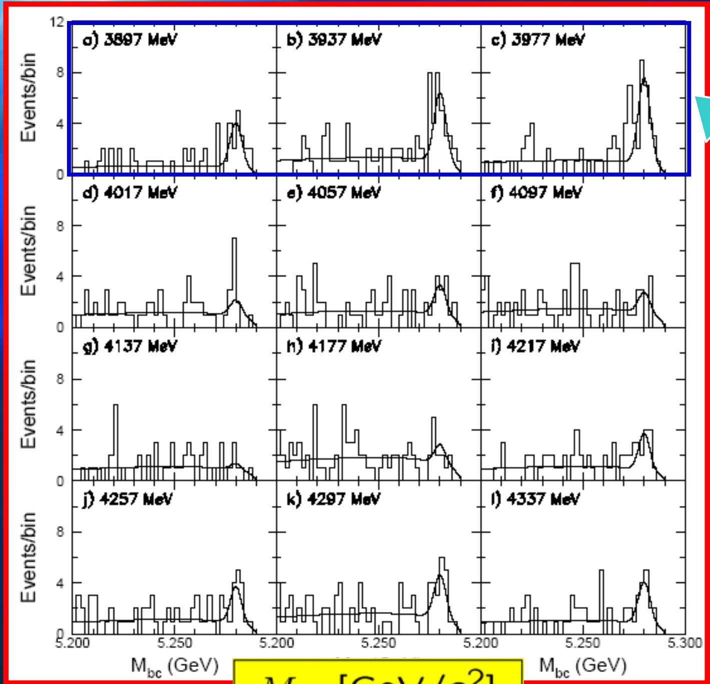
$5.2725 < M_{bc} < 5.2875$ GeV/c²
$|\Delta E| < 0.03$ GeV
$0.760 < M(\pi^+\pi^-\pi^0) < 0.805$ GeV/c²



Next slide →

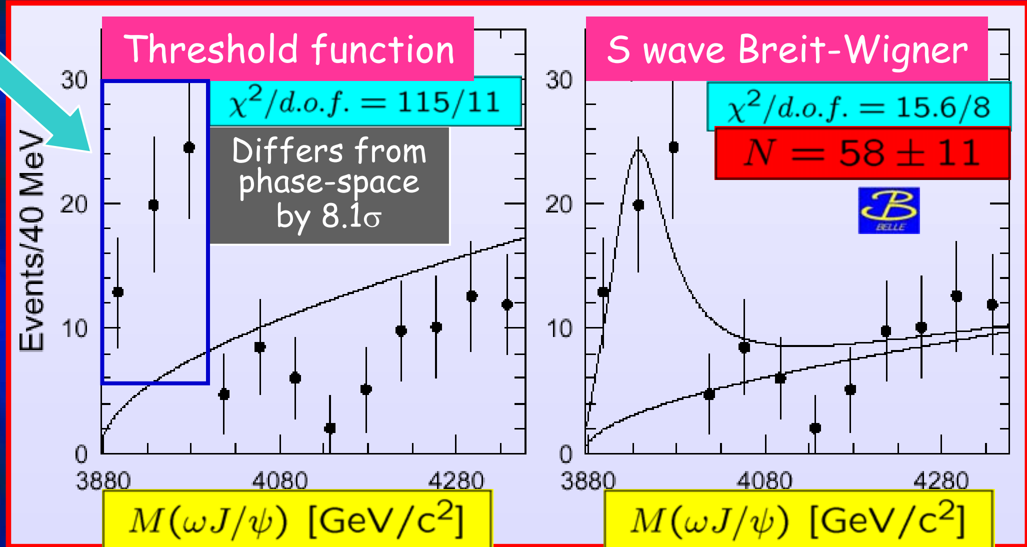
Observation of Y(3940)

$M(\omega K) > 1.6$ GeV



M_{bc} [GeV/c^2]

Fit the (Δ E,M_{bc}) distribution in bins of $M(J/\psi\ \omega)$



$M_Y = 3943 \pm 11 \pm 13$ MeV/c^2

$\Gamma_Y = 87 \pm 22 \pm 26$ MeV

Conventional charmonium χ'_{cJ}

$\chi'_{b1,2}$ observed in $\omega Y(1S)$

- then $B(\chi'_{cJ}K) < B(\chi_{cJ}K) \sim 4\times 10^{-4}$, →
- Belle result implies: $B(Y \to J/\psi\omega) \approx 20\%$
  - very unusual for a conventional ($c\bar{c}$) above the open charm threshold
- Should predominantly decay to $D^*\bar{D}^*$ – not observed yet

$c\bar{c}$-g hybrid

- (+) mass above $D\bar{D}^{(*)}$ threshold but no decay to $D\bar{D}^{(*)}$ — F.Close, S.Godfrey, PLB 574, 210 (2003)
- (+) Large $B(Y \to J/\psi\ X)$ — F.Close, PLB 432, 369 (1995)
- (+) partial width consistent with Lattice QCD predictions for $c\bar{c}g$ — X.Liao, T.Manke, hep-lat/0210030, (2002)
- (-) expected mass: (4.3-4.5) GeV/c^2 — C.Banner et al., PRD56, 7039, (1997)

Interpretation: a χ_{c1} (2^3P_1) or a $c\bar{c}$-gluon hybrid meson

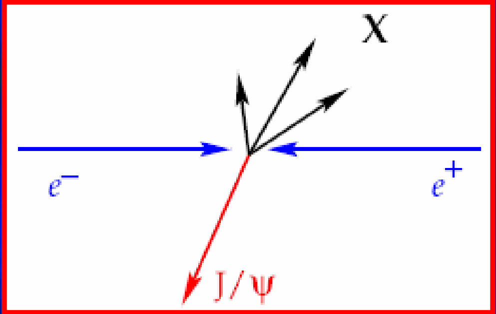
Observation of X(3940)

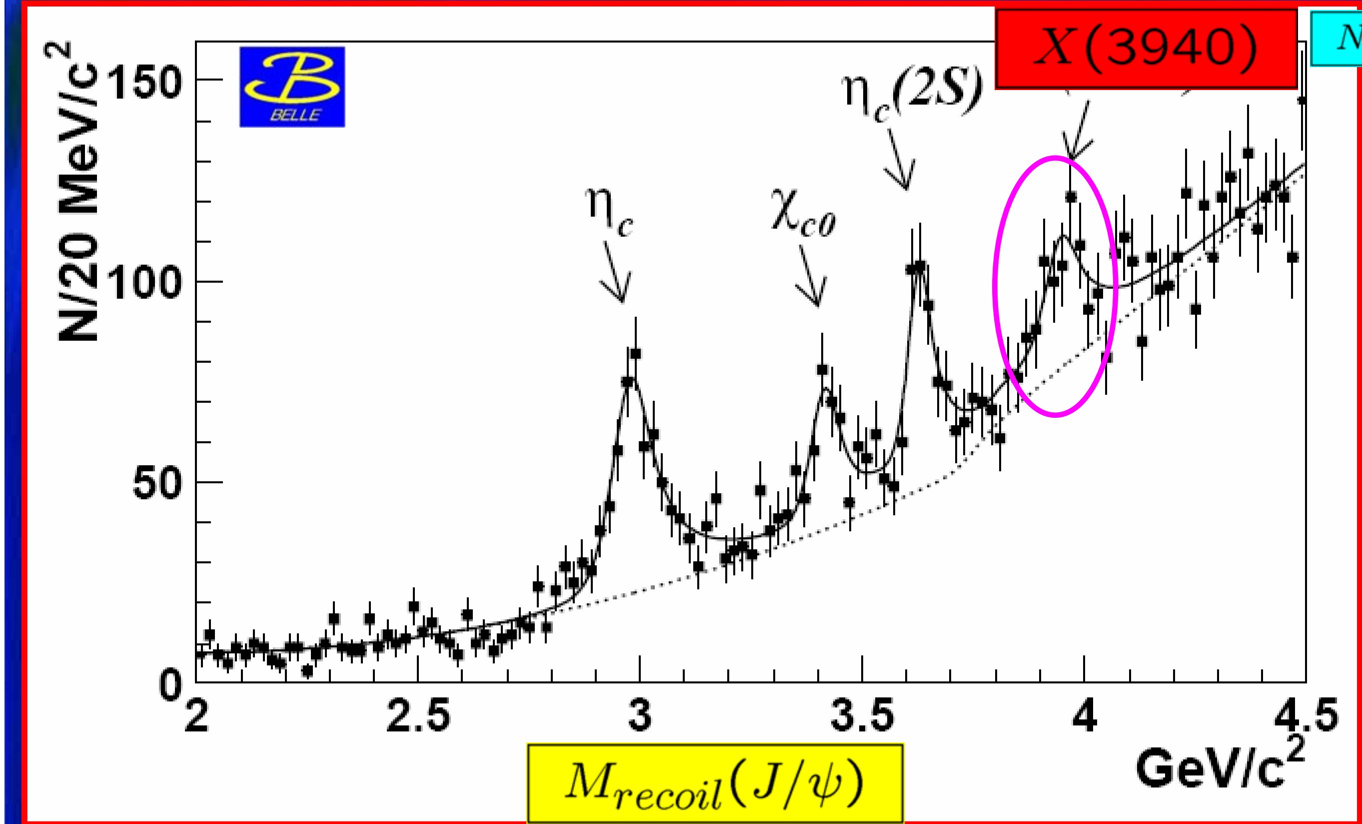
357 fb^{-1}

hep-ex/0507019, subm. to PRL

- a new charmonium state observed by Belle in the process: $e^+e^- \to c\bar{c}c\bar{c} \to J/\psi X(3940))$
- The signal seen in the J/ψ recoil mass

$$M_{recoil}(J/\psi) = \sqrt{(E_{CMS} - E^*_{J/\psi})^2 - p^{*2}_{J/\psi}}$$





$N(X(3940)) = 266 \pm 63$

- M(X) > $D\bar{D}^{(*)}$ →

Does X(3940) decay into $D\bar{D}^{(*)}$?

Observation of X(3940)

Select the D (D^0, D^+) and
look at the $M_{recoil}(J/\psi)$ after the kinematical constraint: $M_{recoil}(J/\psi D) \to M(D^{(*)})$

→ improves resolution on $M_{recoil}(J/\psi)$ by a factor of 2.5 ($\sigma(M_{recoil}(J/\psi)) \approx 10$ MeV/c^2)

$X(3940) \to D\bar{D}$

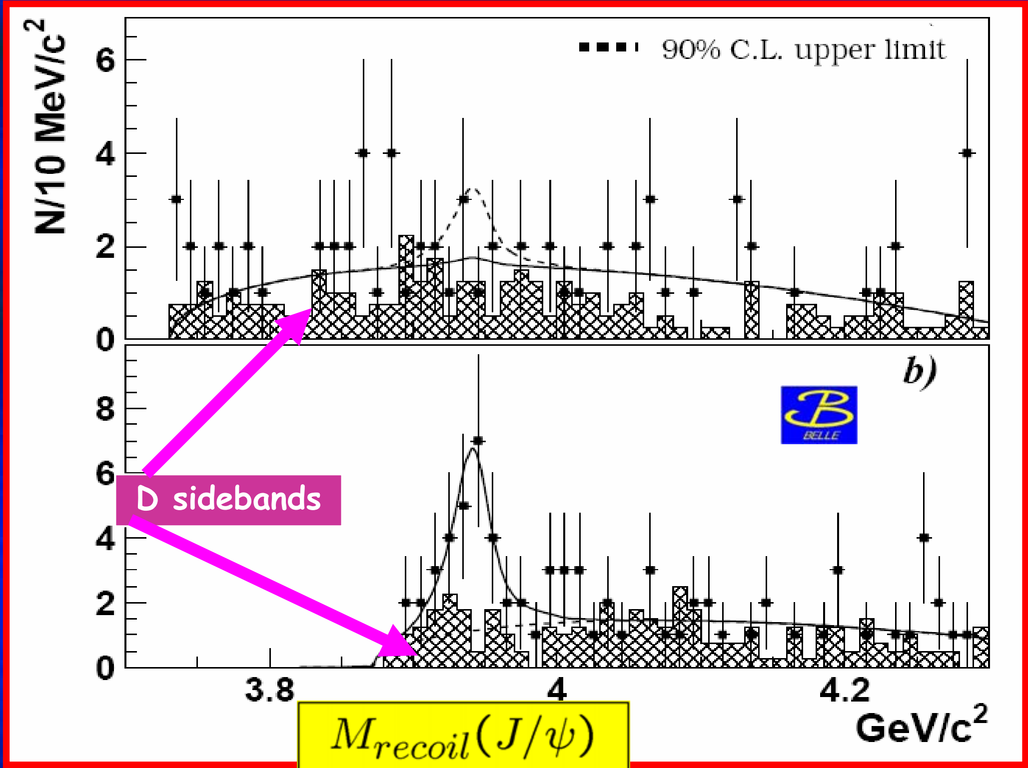
$N = 0.2^{+4.4}_{-3.5} \quad (< 8.1)$

$\mathcal{B} < 41\%$ (90% C.L.)

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

$N = 24.5 \pm 6.9 \quad (5\sigma)$

$\mathcal{B} = (96^{+45}_{-32} \pm 22)\%$



$M_X = 3943 \pm 6 \pm 6$ MeV/c^2

$\Gamma_X < 52$ MeV (90% C.L) $(15.4 \pm 10.1$ MeV)

- **No evidence for for X(3940)→ $J/\psi\omega$** $\quad \mathcal{B} < 41\%$ (90% C.L.)

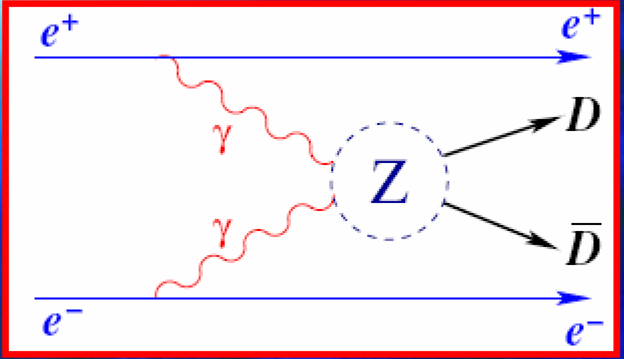
X(3940)=Y(3940) unlikely

Possible interpretation X(3940) = $\eta_c(3S) = \eta_c''$

Observation of χ'_{c2}=Z(3930)

395 fb^{-1}

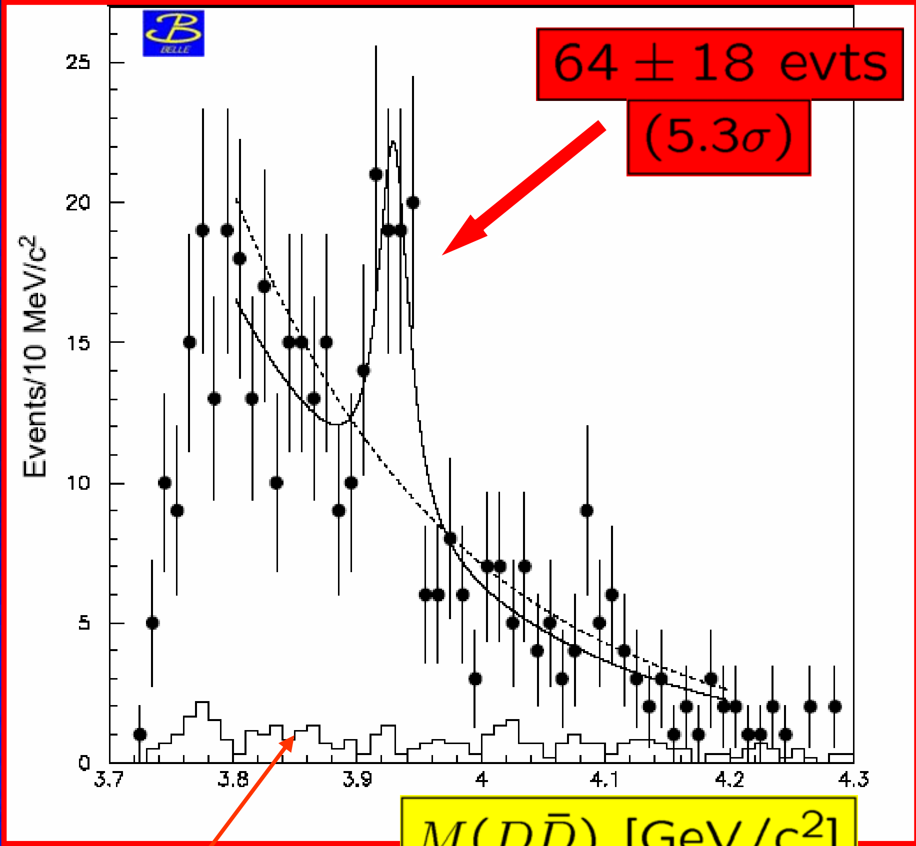
PRL 96, 082003 (2006)



$$\gamma\gamma \to Z(3930) \to D\bar{D}$$

- zero-tag two-photon processes
- $D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^-\pi^+$; $D^+ \to K^-\pi^+\pi^+$
- $P_t(DD) < 0.05$ GeV/c

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



Z(3930) matches predictions for the unobserved yet radially excited states $\chi_{c0}(2P)$ (χ'_{c0}) and $\chi_{c2}(2P)$ (χ'_{c2}):

- ✓Masses in the range 3.9-4 GeV
- ✓(above $D\bar{D}$ and around $D\bar{D}^*$ thresholds)
- ✓χ'_{cJ} -> $D\bar{D}^{(*)}$ should be dominant

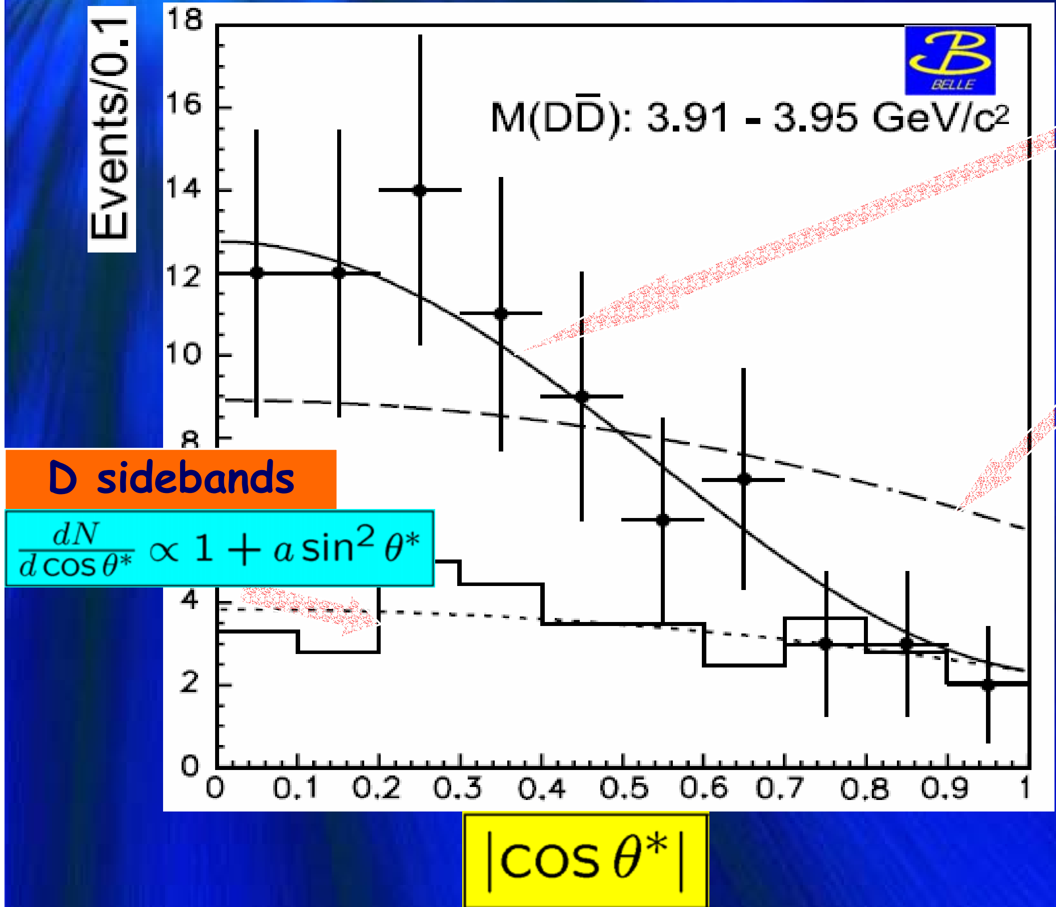
(S.Godfrey, N.Isgur, PRD 32, 189, (1985)
E.J.Eichten, K.Lane, C.Quigg, PRD 69 094019 (2004))

(among charmonia, radial excitation states known only for the ψ (^{3}**3**S_1) and η_c ($^1S_0$))

Observation of χ'_{c2}=Z(3930)

Z=χ'_{cJ}, J = 0,2 ? ➔ look at angular distributions (efficiency corrected)

θ^* - angle of a D meson relative to the beam axis in the $\gamma\gamma$ c.m. frame



$J = 2$ $\quad \frac{dN}{d\cos\theta^*} \propto \sin^4\theta^*$

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

$J = 0$ flat

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

J=2 hypothesis clearly favoured

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

Consistent with expectations for χ'_{c2}

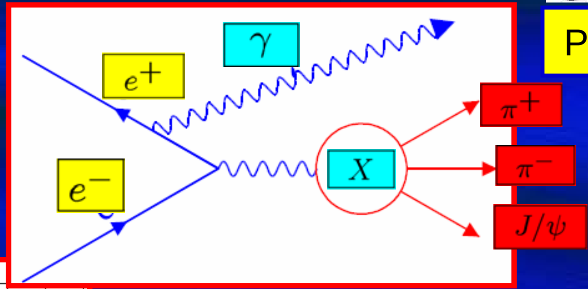
All properties of Z(3930): mass, angular distributions and $\Gamma_{\gamma\gamma}$(Z)× Br(Z→DD̄) are consistent with expectations for χ'_{c2} (2^{++} 2^3P_2) charmonium state

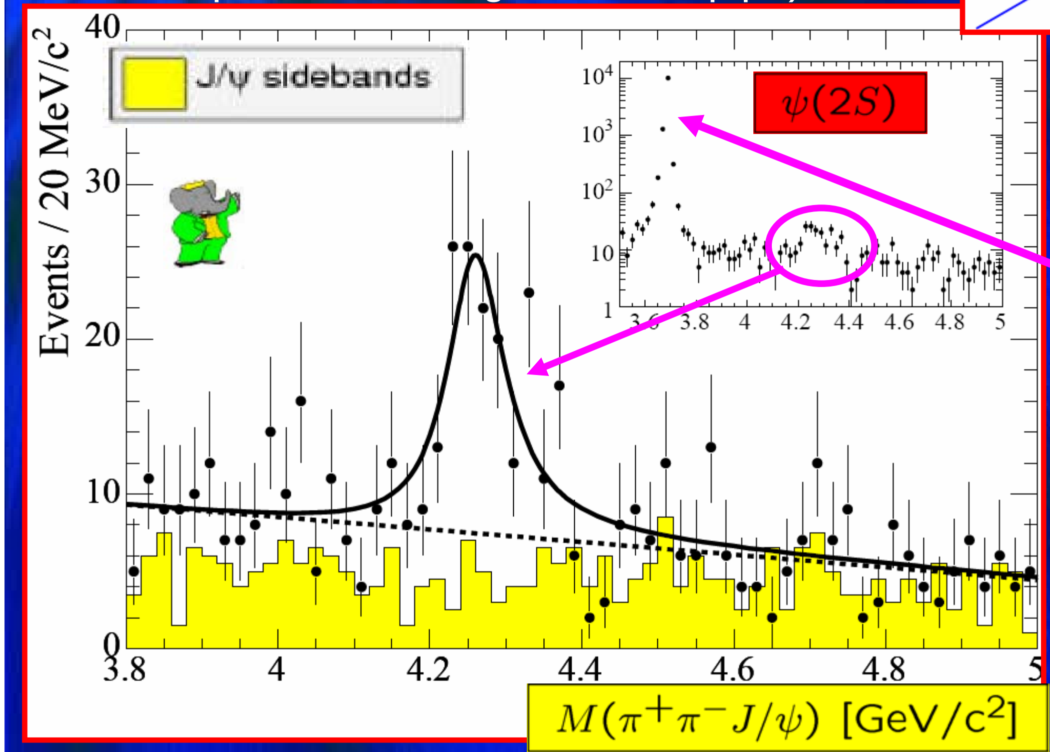
Observation of Y(4260)

$233\ fb^{-1}$

PRL 95, 142001 (2005)

- **observed in ISR events**
  $e^+e^- \to \gamma_{ISR}\pi^+\pi^- J/\psi$ → $J^{PC} = 1^{--}$
- detection of γ_{ISR} is not required (most of them are produced along the beam pipe)





Signatures:

- small mass recoiling against the $\pi^+\pi^- J/\psi$
- low missing transverse momentum

$e^+e^- \to \psi(2S)\gamma$ provides a reference

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

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

$$\Gamma^Y_{e^+e^-} \times \mathcal{B}(Y(4260) \to \pi^+\pi^- J/\psi) = (5.5 \pm 1.0^{+0.8}_{-0.7})\ \mathrm{eV}$$

- **confirmed by CLEO and Belle BUT**

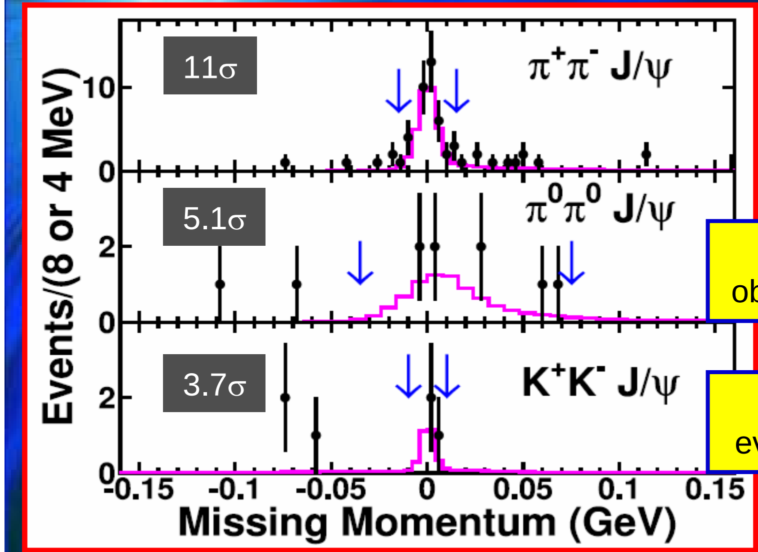
Measurements of mass and width of Y(4260) are marginally consistent

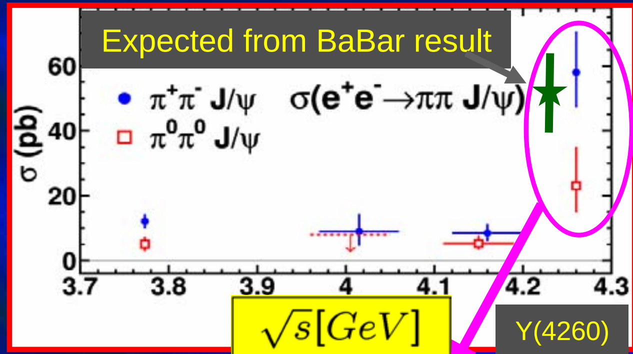
ISR $\pi^+\pi^- J/\psi$	BaBar	CLEO-III	Belle (Preliminary)
Yield	125 ± 23 (>8σ)	$14.1^{+5.2}_{-4.2}$ (4.9σ)	165 ± 24 (>7σ)
Mass(MeV/c²)	$4259 \pm 8^{+2}_{-6}$	$4283^{+17}_{-16} \pm 4$	$4295 \pm 10^{+11}_{-5}$
Width(MeV)	$88 \pm 23^{+6}_{-4}$	$70^{+40}_{-25} \pm 5$	$133 \pm 26^{+13}_{-6}$

PRL 96, 162003 (2006)

CLEO

Observation of Y(4260)





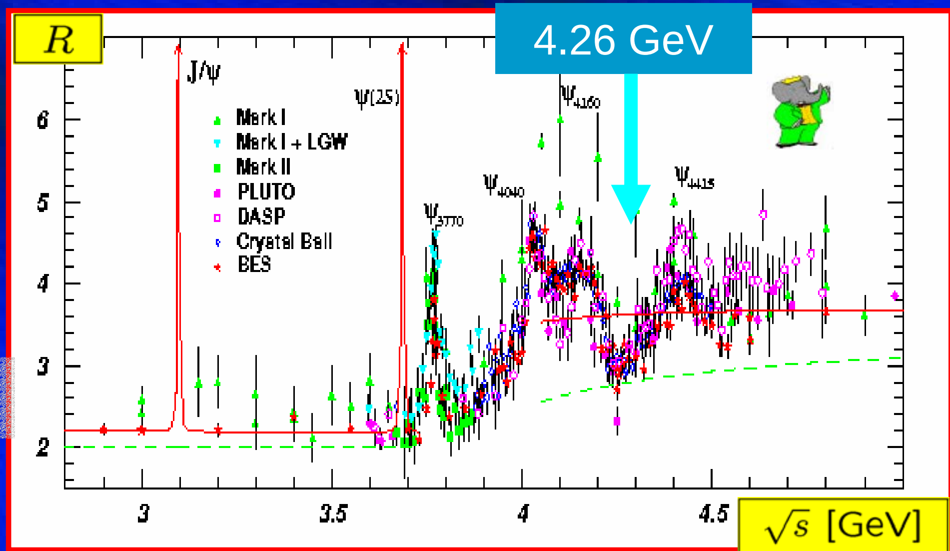
$\frac{\mathcal{B}(Y\to\pi^0\pi^0 J/\psi)}{\mathcal{B}(Y\to\pi^+\pi^- J/\psi)} \approx 0.5$ ➔ $I_Y = 0$

➢ disfavours some exotic interpretations: $\chi_{cJ}\rho$ molecule, baryonium, glueball

- ➢ Y(4260) located at a dip in e^+e^-→hadrons)
- ➢ Why has not been observed before?
- ➢ BaBar: $\sigma(e^+e^-\to\pi\pi J/\psi)\approx$ 50pb at 4.26 GeV
- ➢ ➔ R-0.05 << $\delta\sigma(e^+e^- \to$ hadrons)

hep-ex/0608018 | 548 fb^{-1}

Similar dip around 4.26 GeV/c^2 in $M(D^{*+}D^{*-})$



Conventional interpretation: Y(4260)=ψ(4S);

the dip in R is due to the interference with ψ(3S); the latter must have a large coupling to $\pi^+\pi^-$ J/ψ

Possible exotic interpretations:

- ➢ Hybrid meson
- ➢ tetraquark

can be tested by studying Y decays to open charm (difficult task!)

Observation of Y(4260)

BaBar-CONF-06/33
SLAC-PUB-11983

289 fb^{-1}

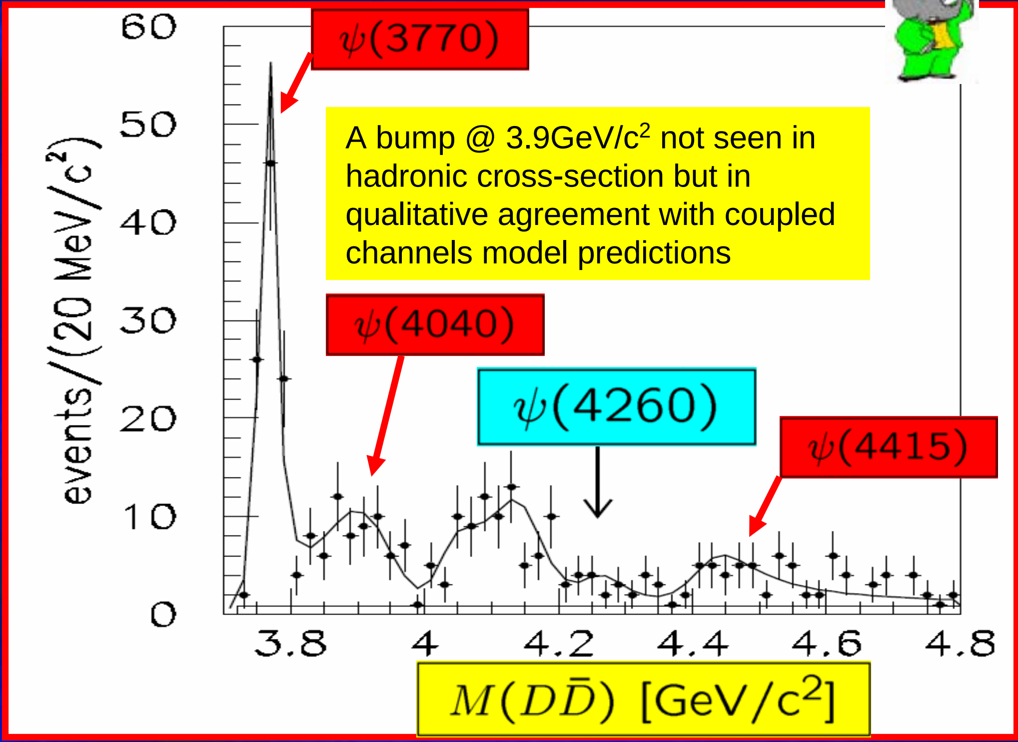
- Study of exclusive production of $D\bar{D}$ system through ISR radiation
- $D^0 \rightarrow K^-\pi^+(\pi^0)$, $D^+ \rightarrow K^-\pi^+\pi^+$

No evidence for Y(4260) → $D\bar{D}$

$$\frac{\mathcal{B}(Y(4260)\rightarrow D\bar{D})}{\mathcal{B}(Y(4260)\rightarrow\pi^+\pi^- J/\psi)} < 7.6 \text{ (90\% C.L.)}$$

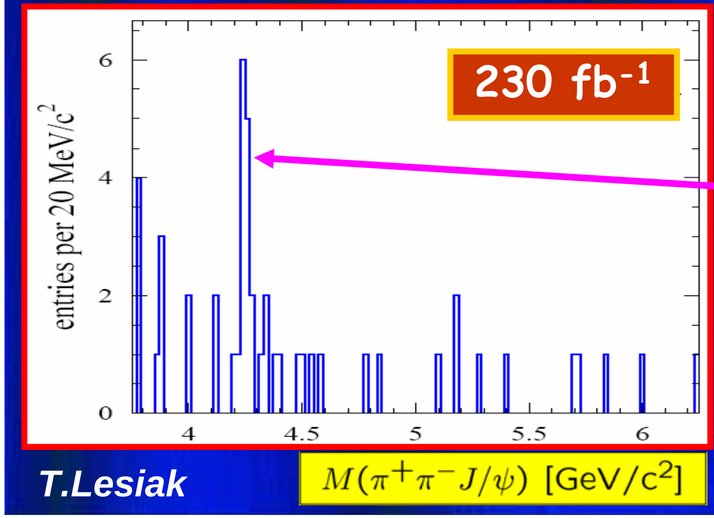
order of magnitude smaller than the value measured for the $\psi(3770)$

→ against a conventional interpretation of Y



BABAR-CONF-06/03, SLAC-PUB-11971

- Study of $e^+e^- \rightarrow (J/\psi\pi^+\pi^-)\gamma_{ISR}$ and $e^+e^- \rightarrow (J/\psi\gamma\gamma)\gamma_{ISR}$



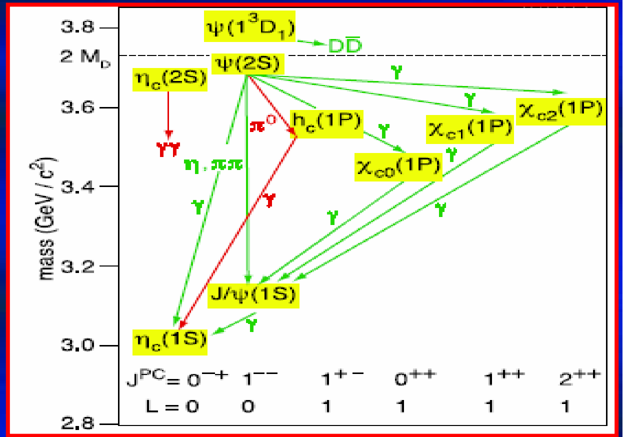
- The ISR photon IS DETECTED (reduction of background; improvement of signal/background ratio)
- The signal of Y(4260) → $\pi^+\pi^- J/\psi$ (consistent with previous BaBar's result, corresponding to undetected γ_{ISR})
- No sign of Y(4260) → $J/\psi\eta$, $J/\psi\pi^0$, $\chi_{c2}\gamma$
- Two candidates of Y(4260) → $\chi_{c1}\gamma$

Observation of $h_c(^1P_1)$

CLEO III & CLEO-c | PRL 95, 102003 (2005) | $3.1\times 10^6\ \psi(2S)$

$\psi(2S) \to \pi^0 h_c, \quad h_c \to \gamma\eta_c$

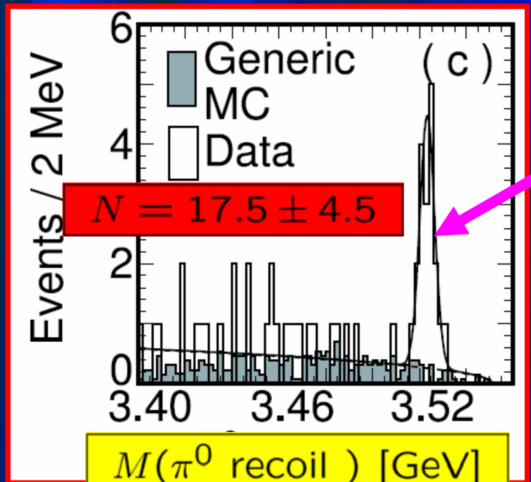
Observation of an enhancement in the π^0 recoil mass



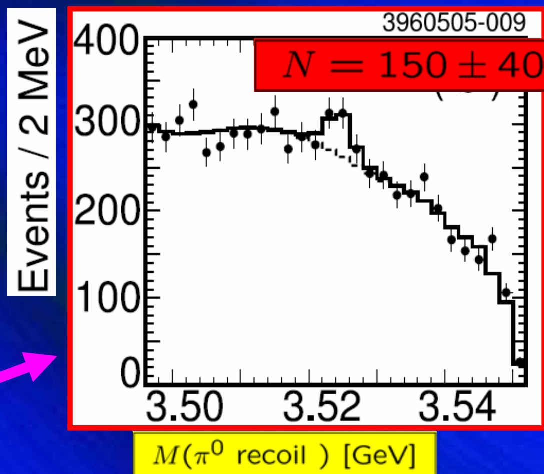
1. EXCLUSIVE reconstruction of the η_c (10% of η_c decays):

$\eta_c \to K^0_{S(L)}K^\pm\pi^\mp, \quad K^+K^-\pi^+\pi^- \quad \pi^+\pi^-\pi^+\pi^-$

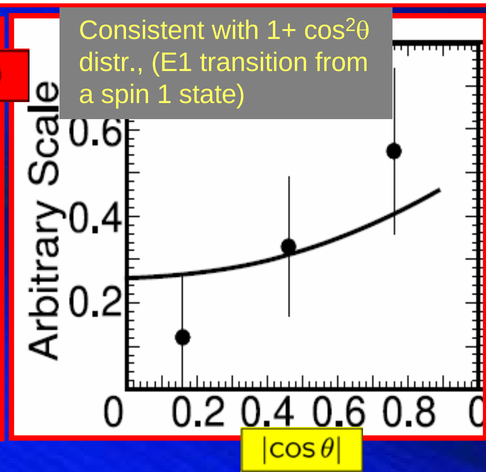
$\eta_c \to K^+K^-\pi^0, \quad \pi^+\pi^-\eta(\to\gamma\gamma,\ \pi^+\pi^-\pi^0)$



2. INCLUSIVE η_c



5σ



$M(h_c) = (3524.4 \pm 0.6 \pm 0.4)$ MeV

Theory: 3518 MeV

T.Barnes,S.Godfrey,E.Swanson, hep-ph/0505002

$\chi_{cog} = \frac{1}{9}(\chi_{c0} + 3\chi_{c1} + 5\chi_{c2}) = 3525.36 \pm 0.06$ MeV

1st measurement of the hyperfine splitting in the P wave:

$\Delta M_{h_f}(<M(^3P_J)> - M(^1P_1)) = +1.0 \pm 0.6 \pm 0.4$ MeV

Expectation: max a few MeV

➡ **Test of spin dependence and spatial behaviour of the $Q\bar{Q}$ force**

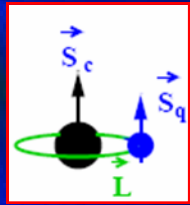
$c\bar{s}$ spectroscopy:

- framework: HQS based potential models

S.Godfrey, N.Isgur, PRD 32, 189 (1985)

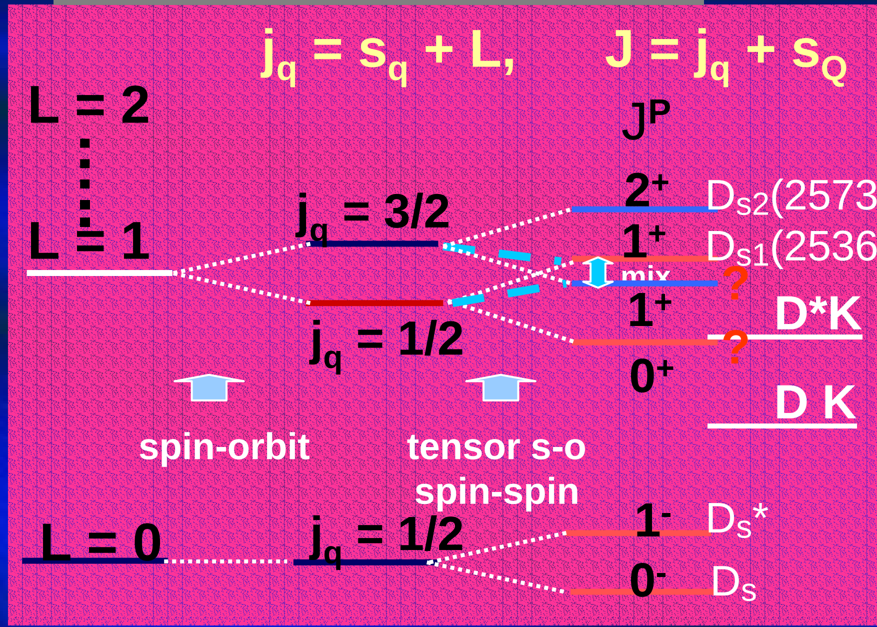
M.Di Pierro, E.Eichten PRD 64, 114004 (2001)

- L=1: two doublets $j_q=1/2$: 0^+, 1^+ ; $j_q=3/2$: 1^+, 2^+



- All four states above M(D)+M(K)
- $\Gamma(j_q=3/2) << \Gamma(j_q=1/2)$
- Experimental observation of the $J_q=3/2$ doublet:
  - $D_{s1}(2536)$ (1^+) Argus 1989
  - $D_{s2}(2573)$ (2^+) Cleo 1994

Theoretical expectations



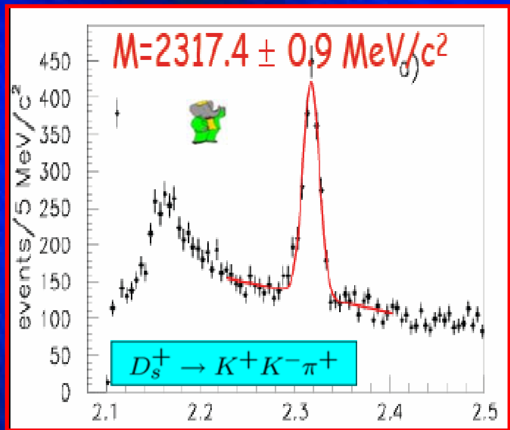
- j=1/2 doublet wide → not seen until 2003? ⟷

Golden year of $c\bar{s}$ spectroscopy

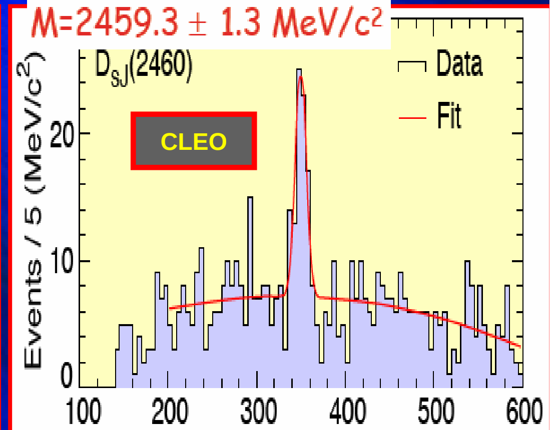
- $D_{sJ}(2317) \rightarrow D_s\,\pi^0$ — PRL 90, 242001 (2003)
- CLEO $D_{sJ}(2460) \rightarrow D_s^*\,\pi^0$ — PRD 68, 032002 (2003)

} $e^+e^- \rightarrow c\bar{c}$

- confirms both, also in B decays — PRL 92, 012002 (2004)



$M(D_s\pi^0)$ [GeV/c²]



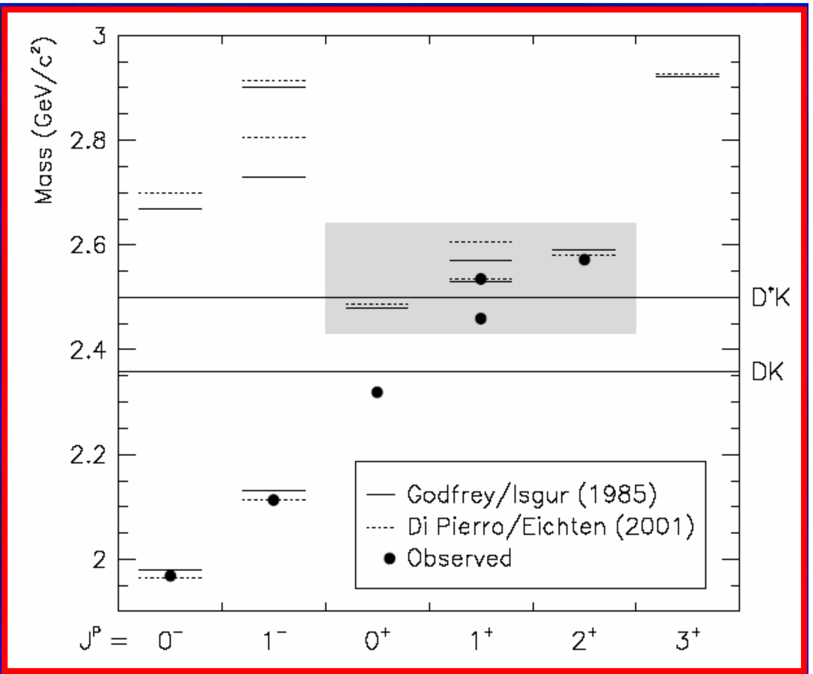
$M(D_s\gamma\pi^0) - M(D_s\gamma)$ [MeV/c²]

$c\bar{s}$ spectroscopy:

$M(D_{sJ}(2317)^{\pm}) = 2317.3 \pm 0.4 \pm 0.8$ MeV/c^2 — $\Gamma < 4.6$ MeV

$M(D_{sJ}(2460)^{\pm}) = 2458.0 \pm 1.0 \pm 1.0$ MeV/c^2 — $\Gamma < 5.5$ MeV

PDG 2006



- Masses below D$^{(*)}$K thresholds
- Isospin-violation in the decay

→Very narrow

- Other decay modes:

Rules out spin zero

$D_{sJ}(2460) \rightarrow D_s \gamma$, $D_{sJ}(2460) \rightarrow D_s \pi^+ \pi^-$

$\frac{\Gamma(D_s^+ \gamma)}{\Gamma(D_s^{*+} \pi^0)} = 0.31 \pm 0.06$ $\frac{\Gamma(D_s^+ \pi^+ \pi^-)}{\Gamma(D_s^{*+} \pi^0)} = 0.14 \pm 0.04 \pm 0.02$ PDG 2006

- Are they the, eagerly and long awaited, 0^+ and 1^+ ($c\bar{s}$) states or something exotic ?

❖ DK molecule — T.Barnes, F.Close, H.Lipkin, PRD 68, 054006 (2003); A.Szczepaniak, PLB 567, 23 (2003)

❖ Chiral doublers — M.Nowak, M.Rho, I.Zahed, PRD 48, 4370 (1993); W.Bardeen, C.Hill PRD 49, 409 (1994)

❖ Spin-orbit & tensor forces — B.Cahn, J.Jackson, PRD 68, 037502 (2003)

❖ $q\bar{q}$ + $q\bar{q}q\bar{q}$ mixing — T.Browder, S.Pakvasa, A.Petrov, PLB 578, 365 (2004)

❖ $q\bar{q}$ mixing with DK$^{(*)}$ — D.Hwang, D-W.Kim, PLB 601, 137 (2004)

$B \to D_{sJ}\bar{D}^{(*)}$ decays

$b \to c\bar{c}s$ tree-level transitions

First observation

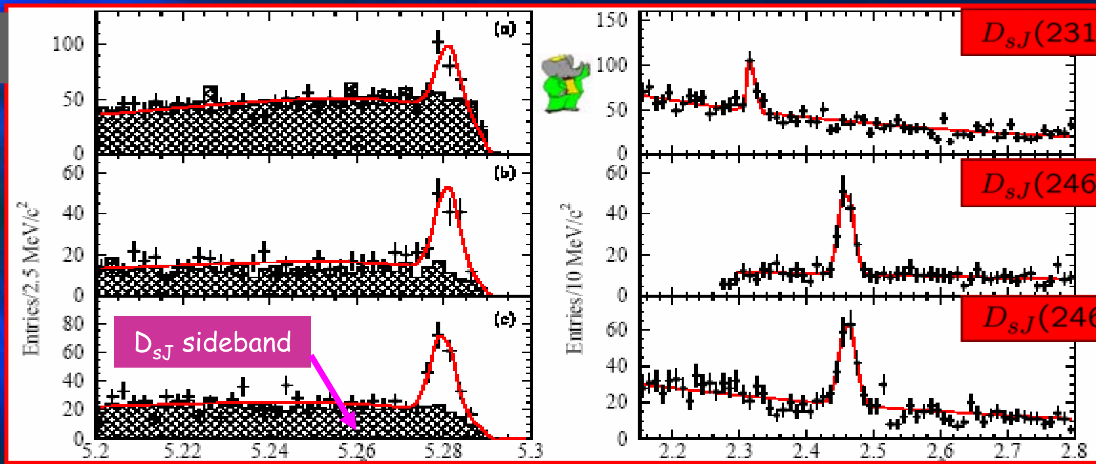
PRL 91, 262002 (2003)

Belle-CONF-0461 (2004)

253 fb^{-1}

113 fb^{-1}

PRL 93, 181801 (2004)



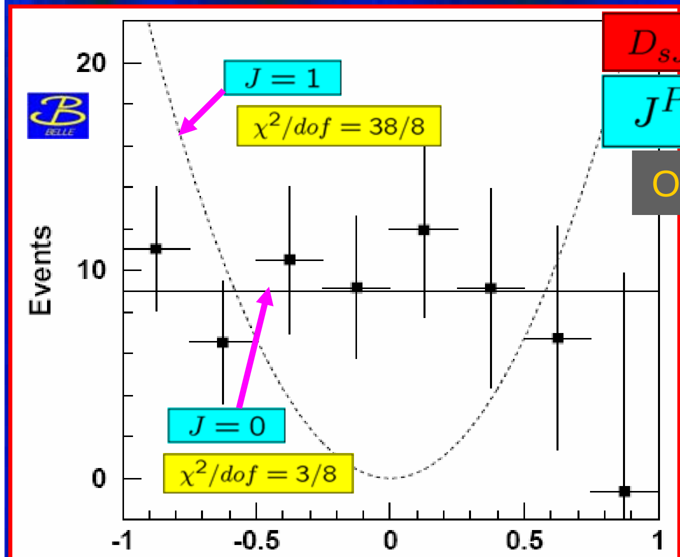
M_{bc} [GeVc²] $M(D_{sJ})$ [GeV/c²]

Surprise:

$$\frac{\mathcal{B}(B\to\bar{D}D_{sJ}^{(*)})}{\mathcal{B}(B\to\bar{D}D_s^{(*)})} \approx \frac{10^{-4}}{10^{-2}} \approx 10^{-2}$$

Spin-parity of D_{sJ}

$\theta_{D_s\pi}$, $\theta_{D_s\gamma}$ – angles between the D_{sJ} momentum in the B rest frame and the D_s momentum in the D_{sJ} rest frame



$\cos\theta_{D_s\pi}$

$D_{sJ}(2317) \to D_s\pi^0$

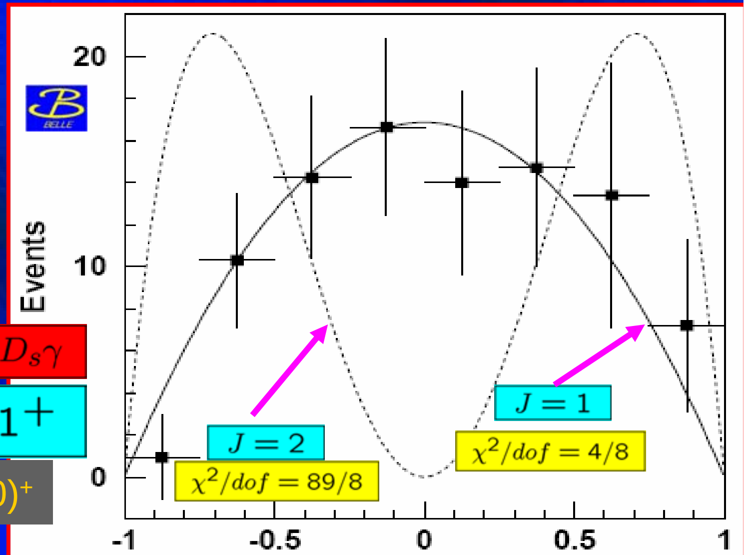
$J^P(D_{sJ}(2317)) = 0^+$

Official name: $D^*_{s0}(2317)^+$

$D_{sJ}(2460) \to D_s\gamma$

$J^P(D_{sJ}(2460)) = 1^+$

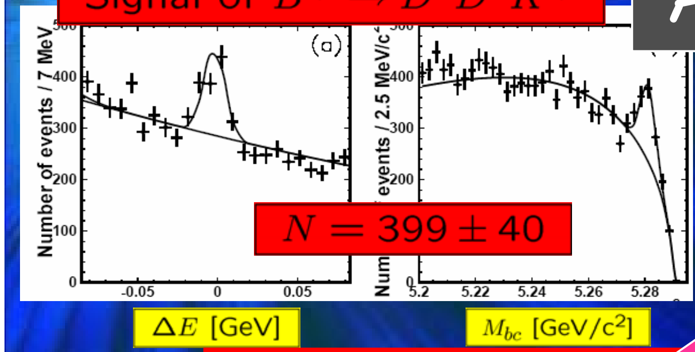
Official name: $D_{s1}(2460)^+$



$\cos\theta_{D_s\gamma}$

A new D_{sJ} in $B^+ \to D^0 \bar{D}^0 K^+$ decays ?

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

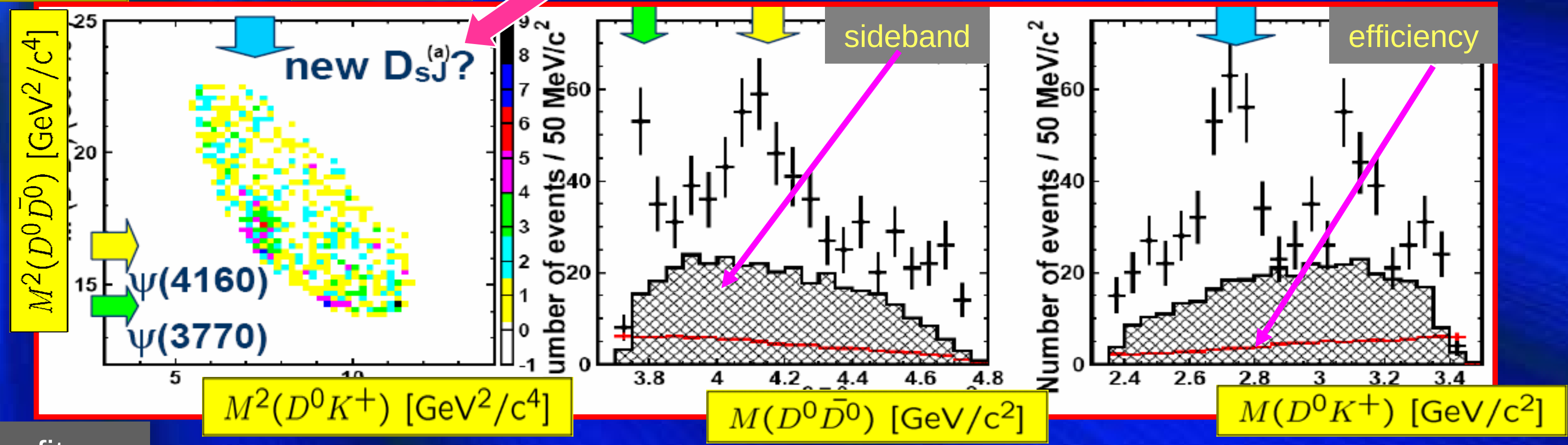


hep-ex/0608031

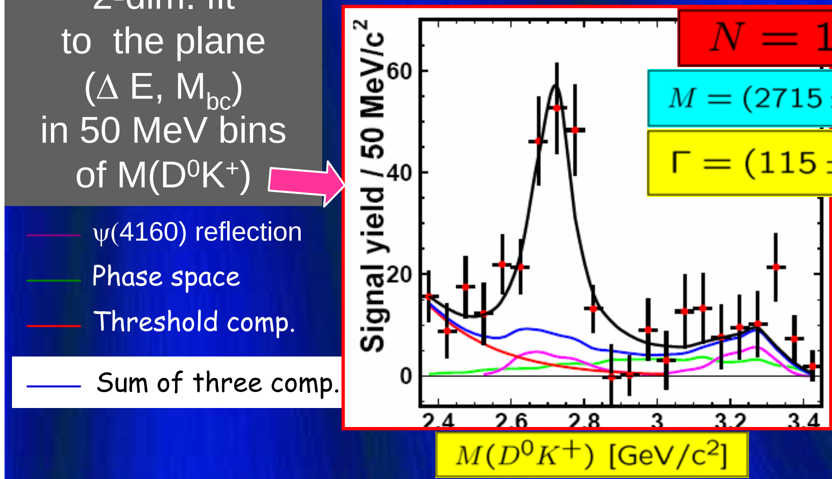
414 fb^{-1}

$$\mathcal{B}(B^+ \to D^0 \bar{D}^0 K^+) = (13.1 \pm 1.3^{+1.7}_{-2.7}) \times 10^{-4}$$

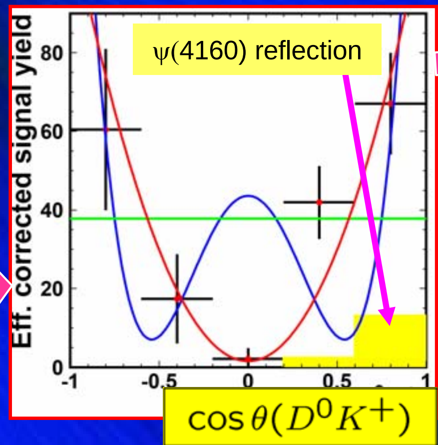
Dalitz plot $M(D^0\bar{D}^0)$ vs $M(D^0K)$ differs from 3-body phase space



2-dim. fit
to the plane
(Δ E, M_{bc})
in 50 MeV bins
of $M(D^0K^+)$



Spin	χ^2/dof
J=0	185/5
J=1	7/5
J=2	250/5



$J^P = 1^-$

($c\bar{s}$) radial excitation 2^3S_1 of $D_s^*(2112)$
or
chiral doubler to the 1^+ state $D_{s1}(2536)$

angle between the K momentum in the DK rest frame and the DK momentum in the B rest frame

A new D_{sJ} (→DK) at 2.86 GeV/c^2

240 fb^{-1}

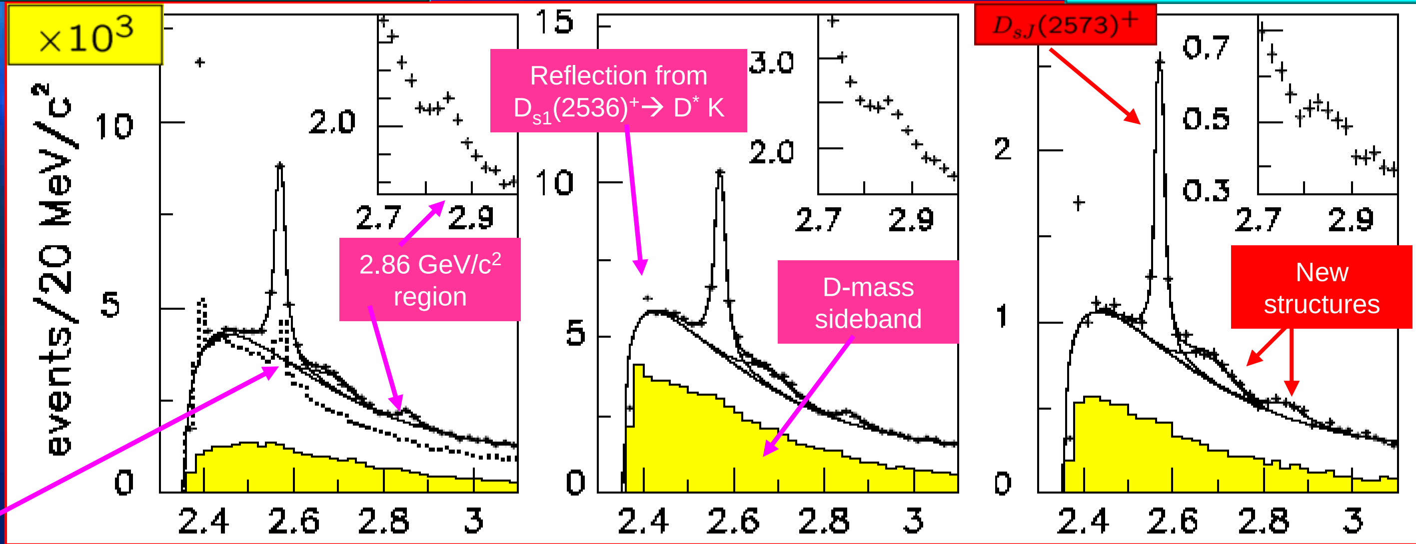
hep-ex/0607082

Processes studied:

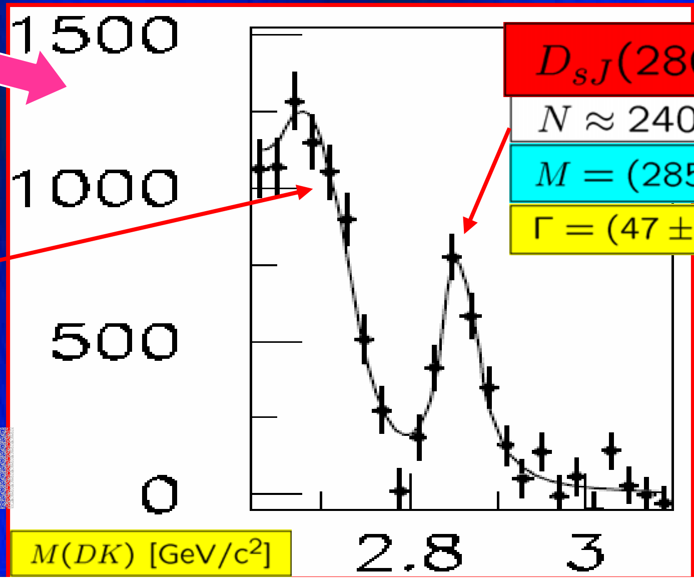
$e^+e^- \to D^0 K^+ X, D^0 \to K^- \pi^+$

$e^+e^- \to D^0 K^+ X, D^0 \to K^- \pi^+ \pi^0$

$e^+e^- \to D^+ K^0_s X, D^+ \to K^- \pi^+ \pi^+$



Background subtracted sum of all three channels:



$X(2690)^+$

$M = (2688 \pm 4 \pm 3)$ MeV/c^2

$\Gamma = (112 \pm 7 \pm 36)$ MeV

coincides with the Belle state (from the previous slide) ???

Needs more study

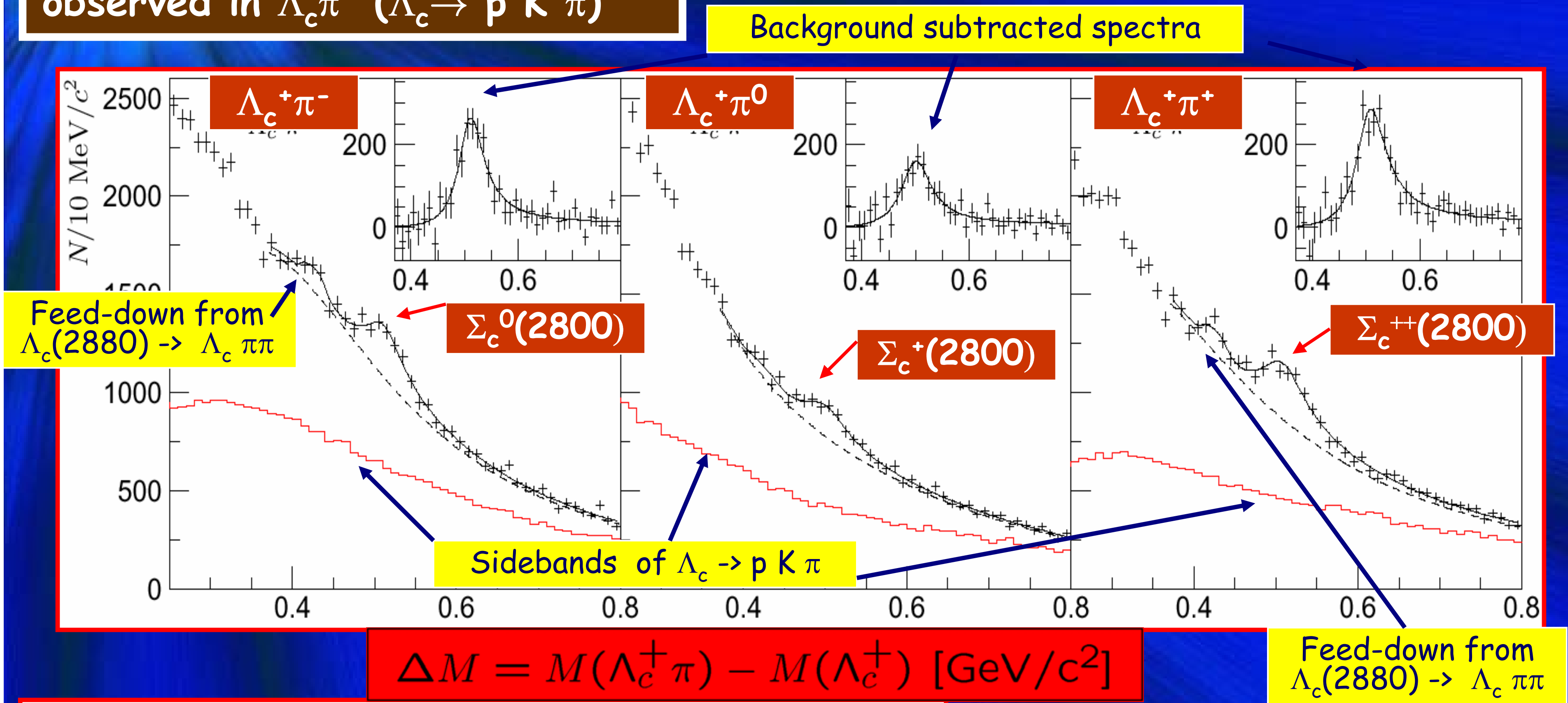
A radial excitation of $D^*_{s0}(2317)$?

Observation of isotriplet $\Sigma_c(2800)$

$\Sigma_c^0(2800)$, $\Sigma_c^+(2800)$, $\Sigma_c^{++}(2800)$ observed in $\Lambda_c\pi$ ($\Lambda_c \to p K \pi$)

PRL 94, 122002 (2005)

281 fb^{-1}



State	Yield $/10^3$	ΔM, MeV$/c^2$	Γ, MeV
$\Sigma_c(2800)^0$	$2.24^{+0.79+1.03}_{-0.55-0.50}$	$515.4^{+3.2+2.1}_{-3.1-6.0}$	61^{+18+22}_{-13-13}
$\Sigma_c(2800)^+$	$1.54^{+1.05+1.40}_{-0.57-0.88}$	$505.4^{+5.8+12.4}_{-4.6-\ 2.0}$	62^{+37+52}_{-23-38}
$\Sigma_c(2800)^{++}$	$2.81^{+0.82+0.71}_{-0.60-0.49}$	$514.5^{+3.4+2.8}_{-3.1-4.9}$	75^{+18+12}_{-13-11}

Interpretation:

as the Σ_{c2}
– members of the
$J^P=3/2^-$ isospin triplet

Observation of $\Lambda_c(2940)^+$

hep-ex/0603052 | 287 fb^{-1}

- BaBar: a new baryon seen in the D^0 p final state (also the $\Lambda_c(2880) \to$ p D^0 is being observed for the first time)

- CLEO: PRL 86 4479, (2001)
  First observation of $\Lambda^+_c(2880) \to \Lambda_c^+\pi^-\pi^+$

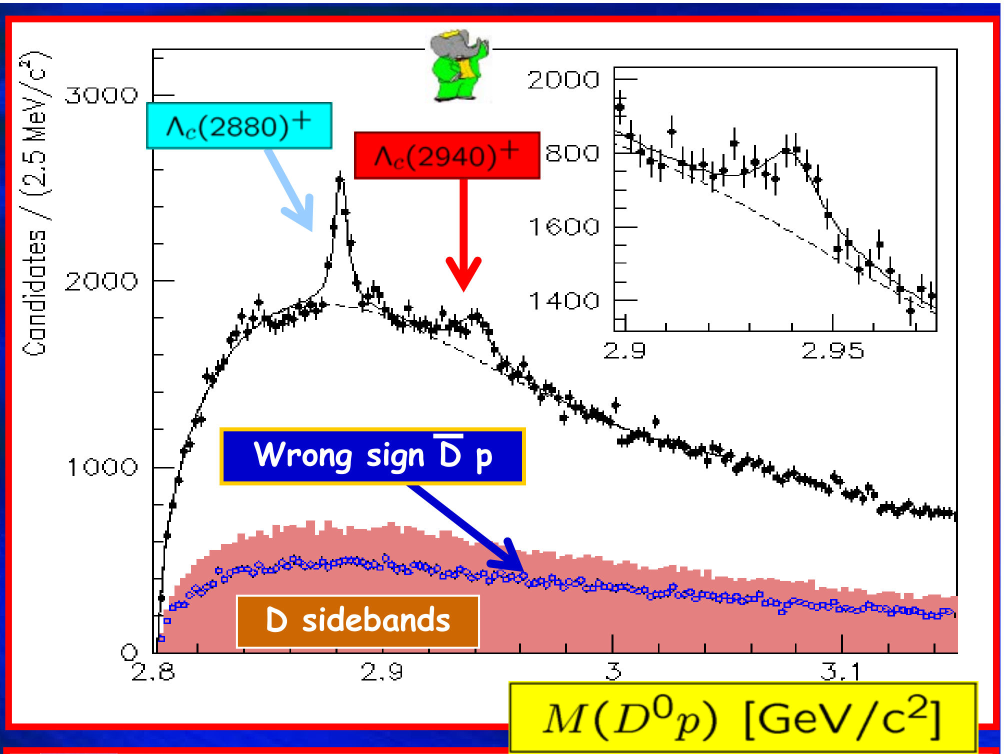
hep-ex/0608043 | 553 fb^{-1}

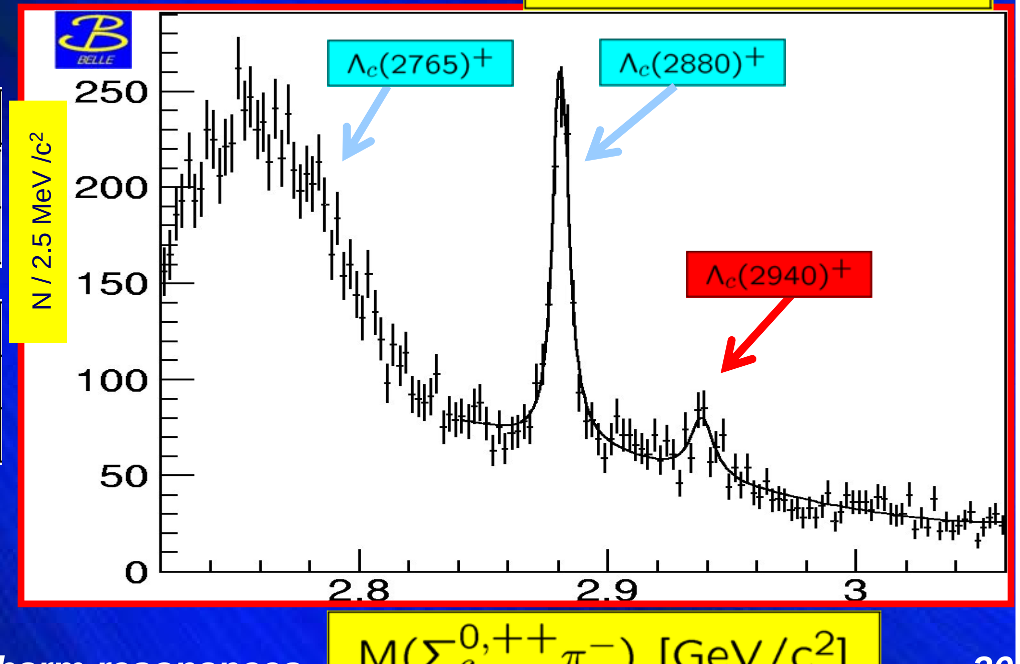
- Belle: confirmation ($\Sigma_c\pi$ final state)

BaBar	Yield	Mass, MeV/c^2	Width, MeV
$\Lambda_c(2880)^+$	2800 ± 190	$2881.9 \pm 0.1 \pm 0.5$	$5.8 \pm 1.5 \pm 1.1$
$\Lambda_c(2940)^+$	2280 ± 310	$2939.8 \pm 1.3 \pm 1.0$	$17.5 \pm 5.2 \pm 5.9$

Belle	Yield	Mass, MeV/c^2	Width, MeV
$\Lambda_c(2880)^+$	$880 \pm 50 \pm 40$	$2881.2 \pm 0.2^{+0.4}_{-0.3}$	$5.5^{+0.7}_{-0.3} \pm 0.4$
$\Lambda_c(2940)^+$	$210^{+70+100}_{-40-60}$	$2937.9 \pm 1.0^{+1.8}_{-0.4}$	$10 \pm 4 \pm 5$

- **Mass and width measurements consistent: BaBar vs Belle**
- **Belle favours $J^P=5/2^+$**

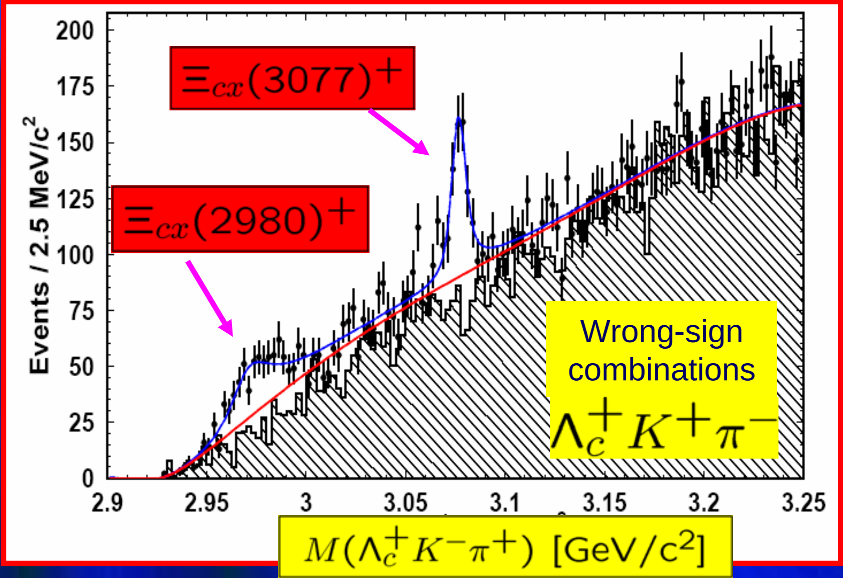




Observation of $\Xi_{cx}(2980)^+$ and $\Xi_{cx}(3077)^+$

First observation (Belle)

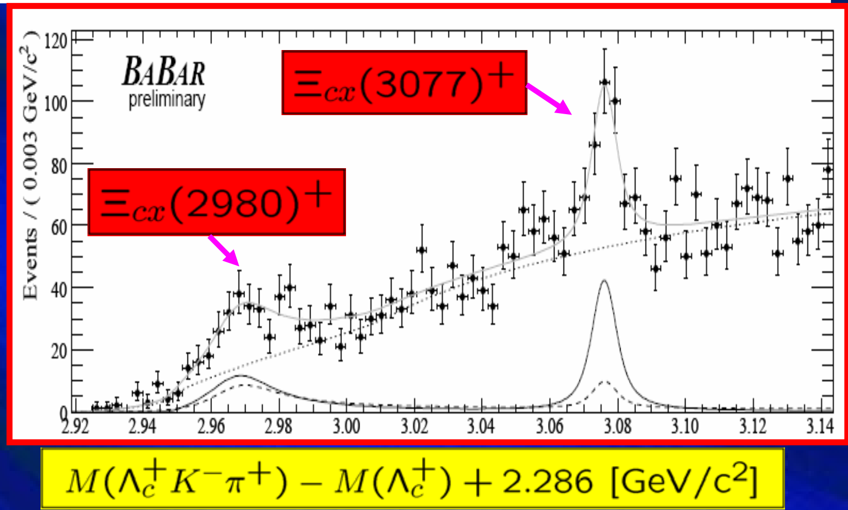
462 fb^{-1} hep-ex/0606051, accepted by PRL



Confirmation (BaBar)

316 fb^{-1} BABAR-CONF-06/01, subm. to PRL

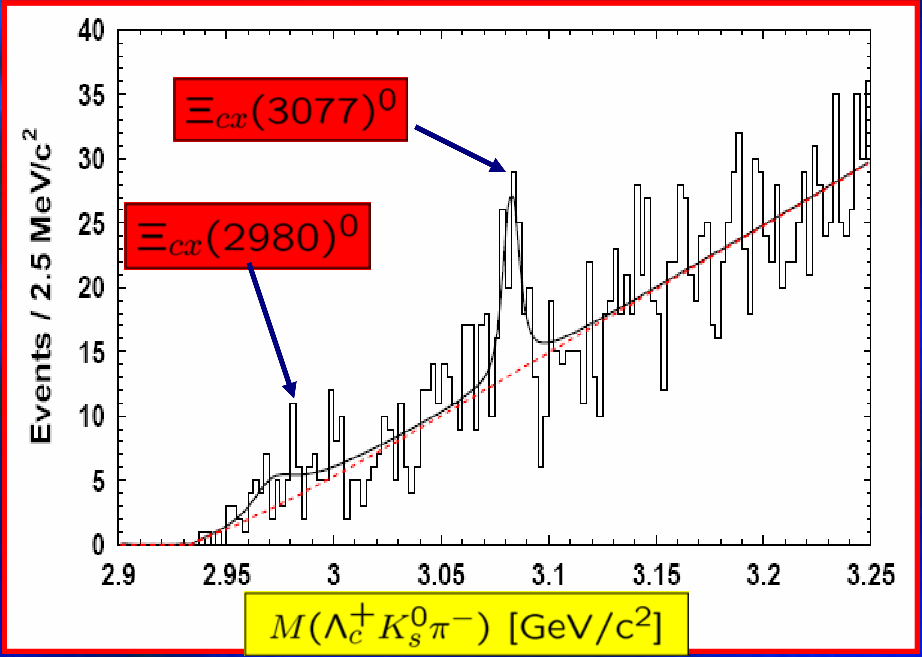
AND evidence for $\Xi_{cx} \to \Sigma_c(2455)^{++} (\to \Lambda_c^+ \pi^+) K^-$



	Mass (MeV/c^2)	Width (MeV)	Yield (Events)	Significance
BABAR $\Xi_c(2980)^+$	$2967.1 \pm 1.9 \pm 1.0$	$23.6 \pm 2.8 \pm 1.3$	$284 \pm 45 \pm 46$	$7.0\,\sigma$
Belle $\Xi_c(2980)^+$	$2978.5 \pm 2.1 \pm 2.0$	$43.5 \pm 7.5 \pm 7.0$	405 ± 51	$6.3\,\sigma$
BABAR $\Xi_c(3077)^+$	$3076.4 \pm 0.7 \pm 0.3$	$6.2 \pm 1.6 \pm 0.5$	$204 \pm 35 \pm 12$	$8.6\,\sigma$
Belle $\Xi_c(3077)^+$	$3076.7 \pm 0.9 \pm 0.5$	$6.2 \pm 1.2 \pm 0.8$	326 ± 40	$9.7\,\sigma$

M and Γ: good ($\Xi_{cx}(3077)$) and marginal ($\Xi_{cx}(2980)$) consistency Belle vs BaBar

Observation of $\Xi_{cx}(3077)^0$



hep-ex/0606051,
Accepted by PRL

462 fb^{-1}

New State	Mass (MeV/c^2)	Width (MeV/c^2)	Yield (events)	Significance (σ)
$\Xi_{cx}(2980)^0$	$2977.1 \pm 8.8 \pm 3.5$	43.5 (fixed)	42.3 ± 23.8	2.0
$\Xi_{cx}(3077)^0$	$3082.8 \pm 1.8 \pm 1.5$	$5.2 \pm 3.1 \pm 1.8$	67.1 ± 19.9	5.1

Observation of isospin partner(s) makes even more plausible:

interpretation of the Ξ_{cx}(2980) and Ξ_{cx}(3077) as excited charmed strange baryons Ξ_c

Ξ_{cx}(csu) → $\Lambda_c K\pi$ ➔ c and s quarks are carried away by different final state particles

Looking for doubly charmed baryons Ξ_{cc}^{+} and Ξ_{cc}^{++}

SELEX

Evidence for the Ξ_{cc}^{+} in the decay modes: $\Lambda_c^+ K^- \pi^+$ PRL 89, 112001 (2002); $p D^+ K^-$ PLB 628, 18 (2005)

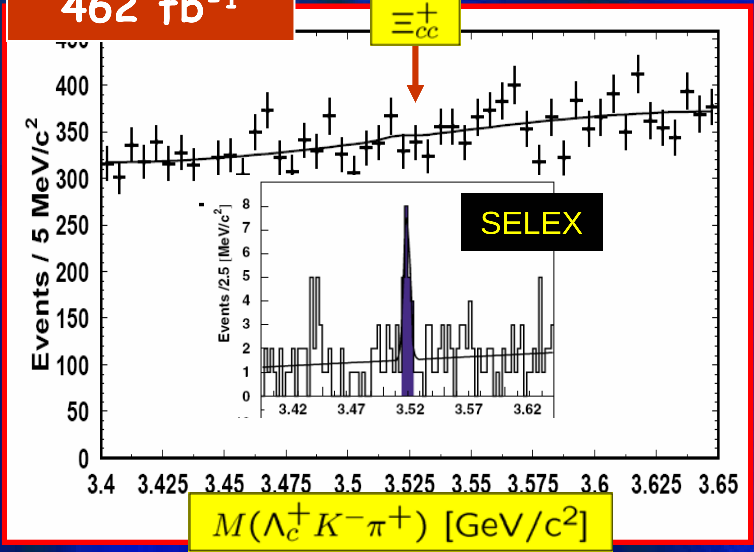
Evidence for the $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$: ICHEP02

$M(\Xi_{cc}^{+}) = 3518.7 \pm 1.7$ [MeV/c²]

$M(\Xi_{cc}^{++}) \approx 3460$ [MeV/c²]

Both states NOT confirmed by FOCUS, in spite of much more abundant sample of Λ_c's

hep-ex/0606051, accepted by PRL



$\frac{\sigma(\Xi_{cc}(3520)^+) \times \mathcal{B}}{\sigma(\Lambda_c^+)} < 1.5 \times 10^{-4}$ (90% C.L.)

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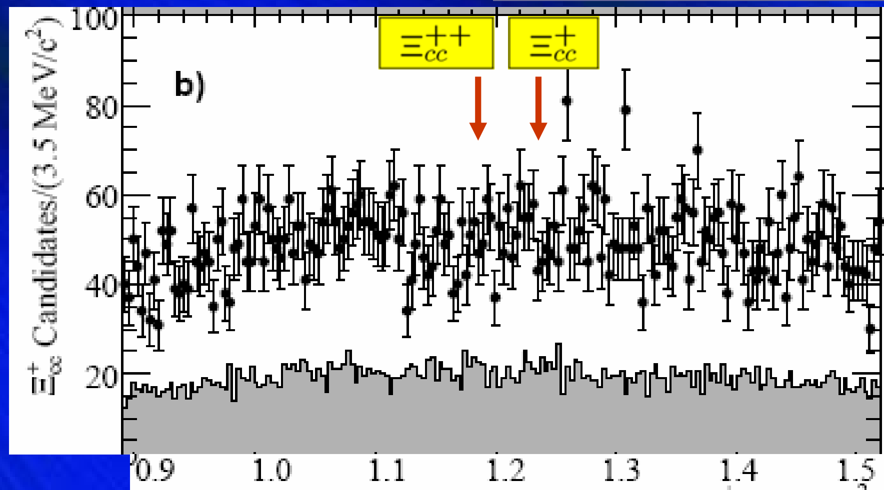
316 fb^{-1}

More extensive search:

$\Xi_{cc}^{+} \rightarrow \Lambda_c^+ K^- \pi^+$

$\Xi_{cc}^{+} \rightarrow \Xi_c^0 \pi^+$, $\Xi_c^0 \rightarrow \Xi^- \pi^+$

$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$



$\frac{\sigma(\Xi_{cc}(3520)^+) \times \mathcal{B}}{\sigma(\Lambda_c^+)} < 2.7 \times 10^{-4}$ (90% C.L.)

$\frac{\sigma(\Xi_{cc}(3460)^{++}) \times \mathcal{B}}{\sigma(\Lambda_c^+)} < 4.0 \times 10^{-4}$ (90% C.L.)

BaBar & Belle: no evidence for Ξ_{cc}^{+}

BaBar: no evidence for Ξ_{cc}^{++}

Observation of Ω_c^{*0}

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Ω_c^{*0} (css) $J^P = \frac{3}{2}+$

$\Omega_c^* \to \Omega_c\gamma$

the last single-charm baryon with zero orbital angular momentum, not observed so far

$N(\Omega_c^*) = 105 \pm 21 \pm 6$ 5.2σ

$\Delta M = M(\Omega_c^{*0}) - M(\Omega_c^0)$

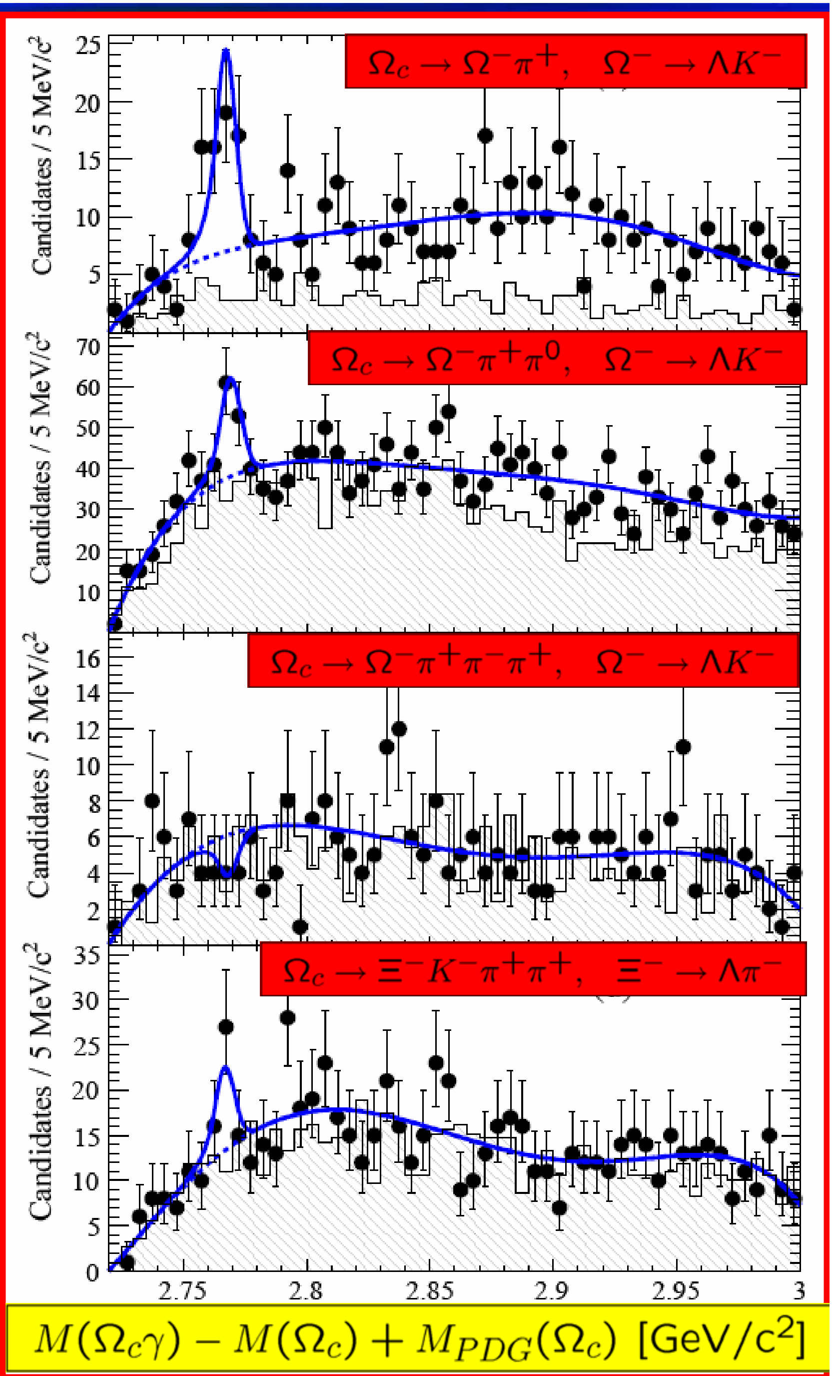
$\Delta M = (70.8 \pm 1.0 \pm 1.1)$ MeV/c^2

Theoretical expectations span the range 50-100 MeV/c^2

$R = \frac{\sigma(e^+e^- \to \Omega_c^* X)}{\sigma(e^+e^- \to \Omega_c X)}$, $x_P(\Omega_c^{(*)}) > 0.5$

$R = 1.01 \pm 0.23 \pm 0.11$

Ω_c^{*0} observed in agreement with expectations



Summary

- The renaissance of charm spectroscopy at B-factories
- Several new states observed (both mesons and baryons): X(3872), X(3940), Y(3940), Z (3930), Y(4260) …
  → a by-product provided important results
- Theoretical studies reinvigorated (231 answers to the query „new charm particle” in the CERN document server for the period 2003-2006)
- Still much work to be done:
- Experiment: more detailed and extensive studies of new particles
- Theory: more precise estimates & new ideas
- I hope that B-factories will deliver new charming discoveries soon