Charm baryons and Charmonium Production in e^+e^- collisions at Belle

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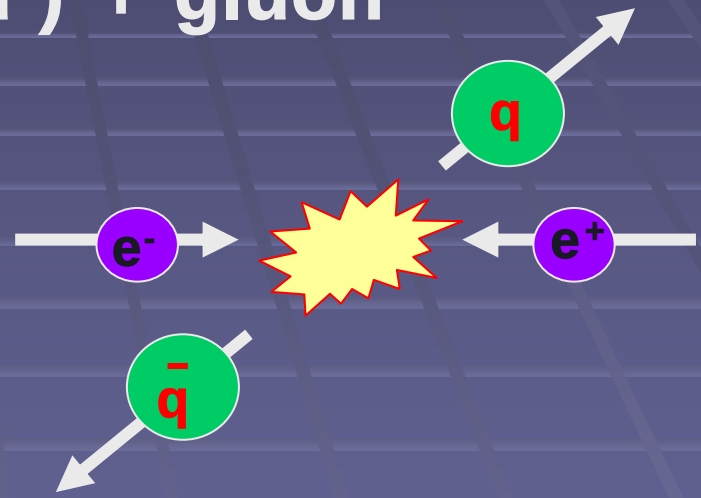
B-factory : E_{cm} ~10.58 GeV

$e^-e^+ \rightarrow \Upsilon(4s) \rightarrow B\bar{B}$ (~5.5x10^{+8} evts)

$b \rightarrow c\,(u) + W$

$b \rightarrow s\,(d) + \gamma / Z$; $b \rightarrow s\,(d)$ + gluon

$e^- e^+ \rightarrow q\bar{q}$						
u	$\bar{u}$	c	$\bar{c}$			2/3
d	$\bar{d}$	s	$\bar{s}$	b	$\bar{b}$	-1/3

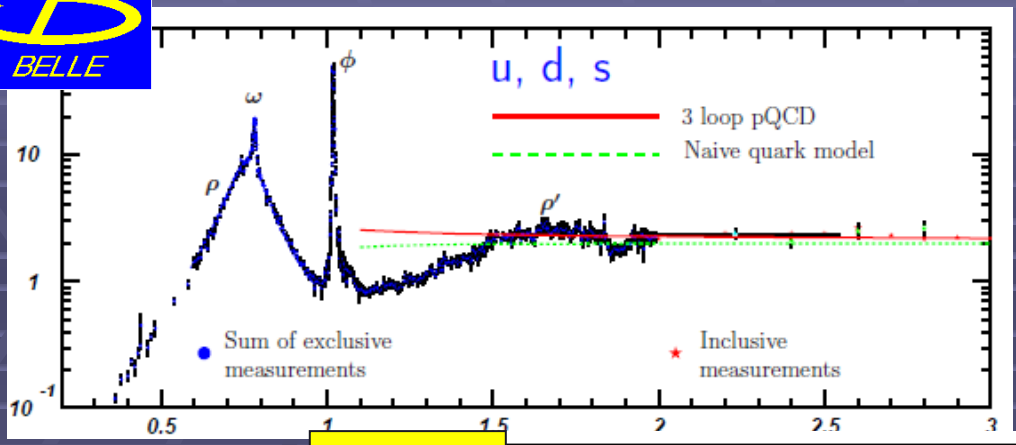


$e^+ e^- \rightarrow c\bar{c}$
at E_{cm} ~ 10 GeV

→ Charm baryon
Charmonium ($c\bar{c}$)
production

e^+e^- collisions

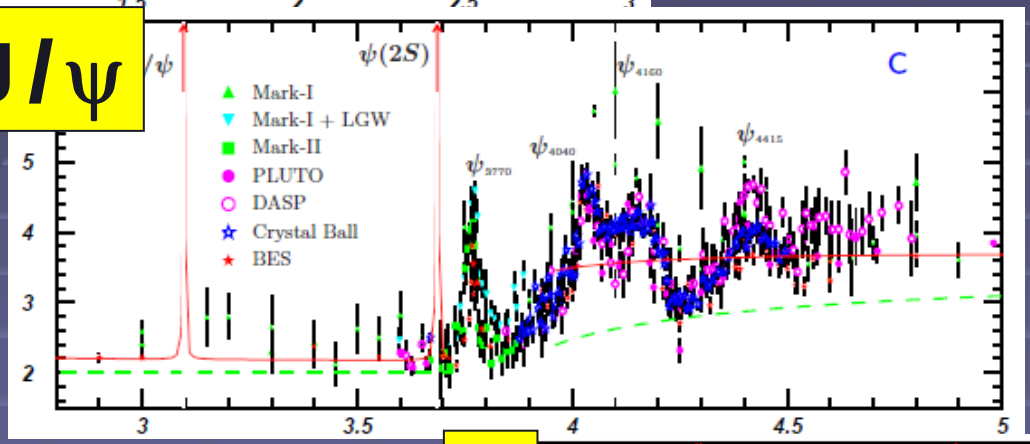
$R = \sigma_{hadron} / \sigma_{\mu\mu}$



charm

~3GeV

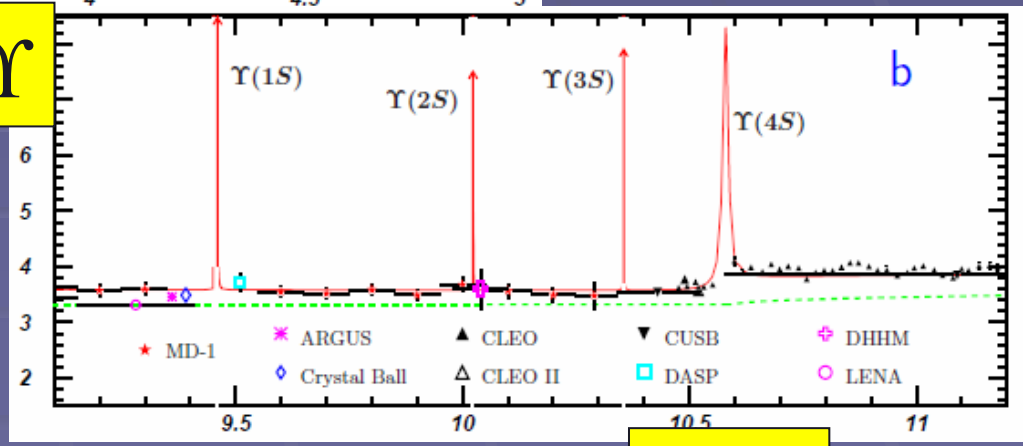
J/ψ



bottom

~10GeV

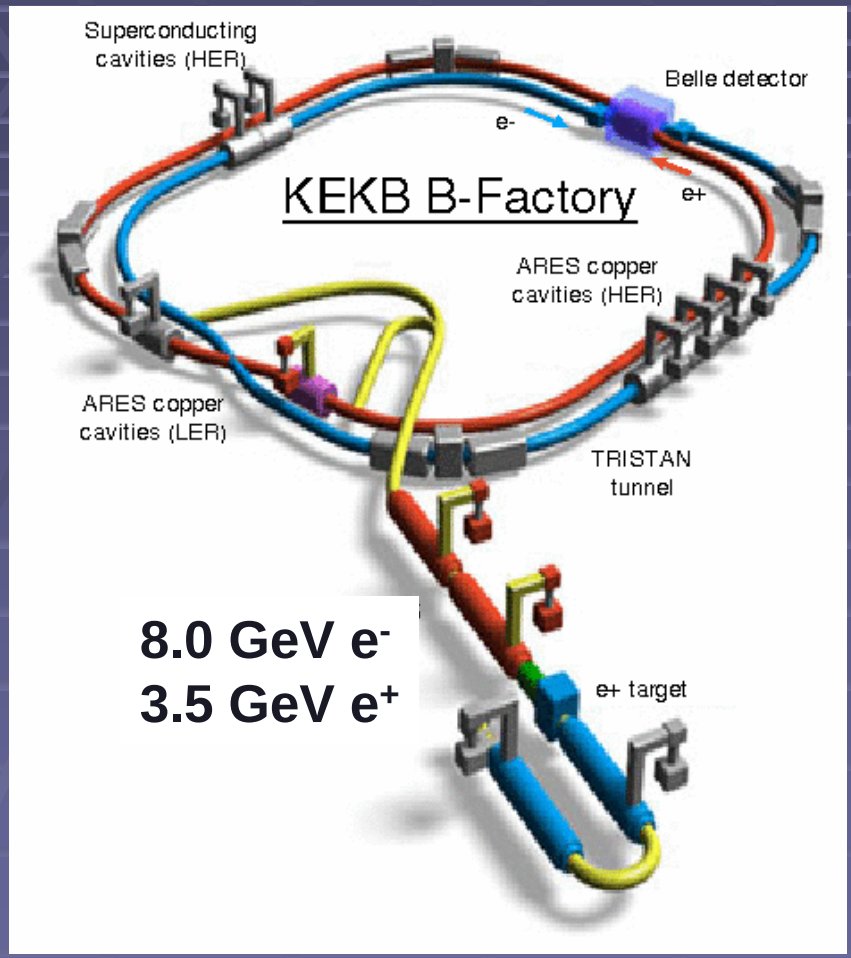
ϒ

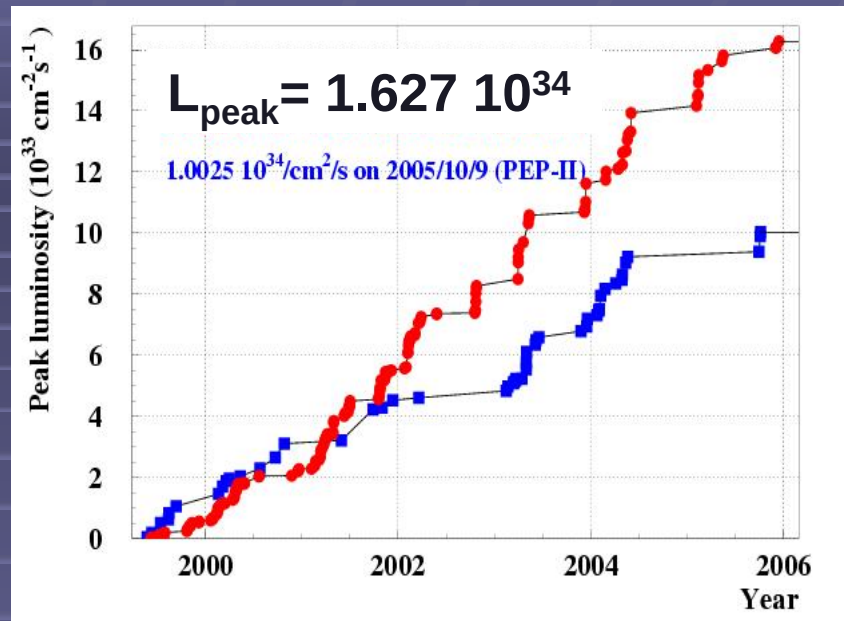


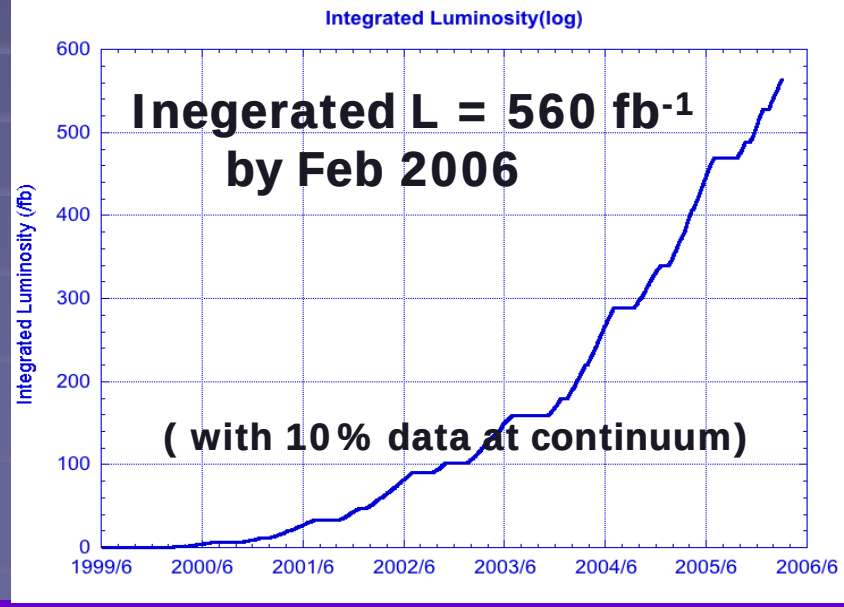
PDG2004

ϒ(4S)

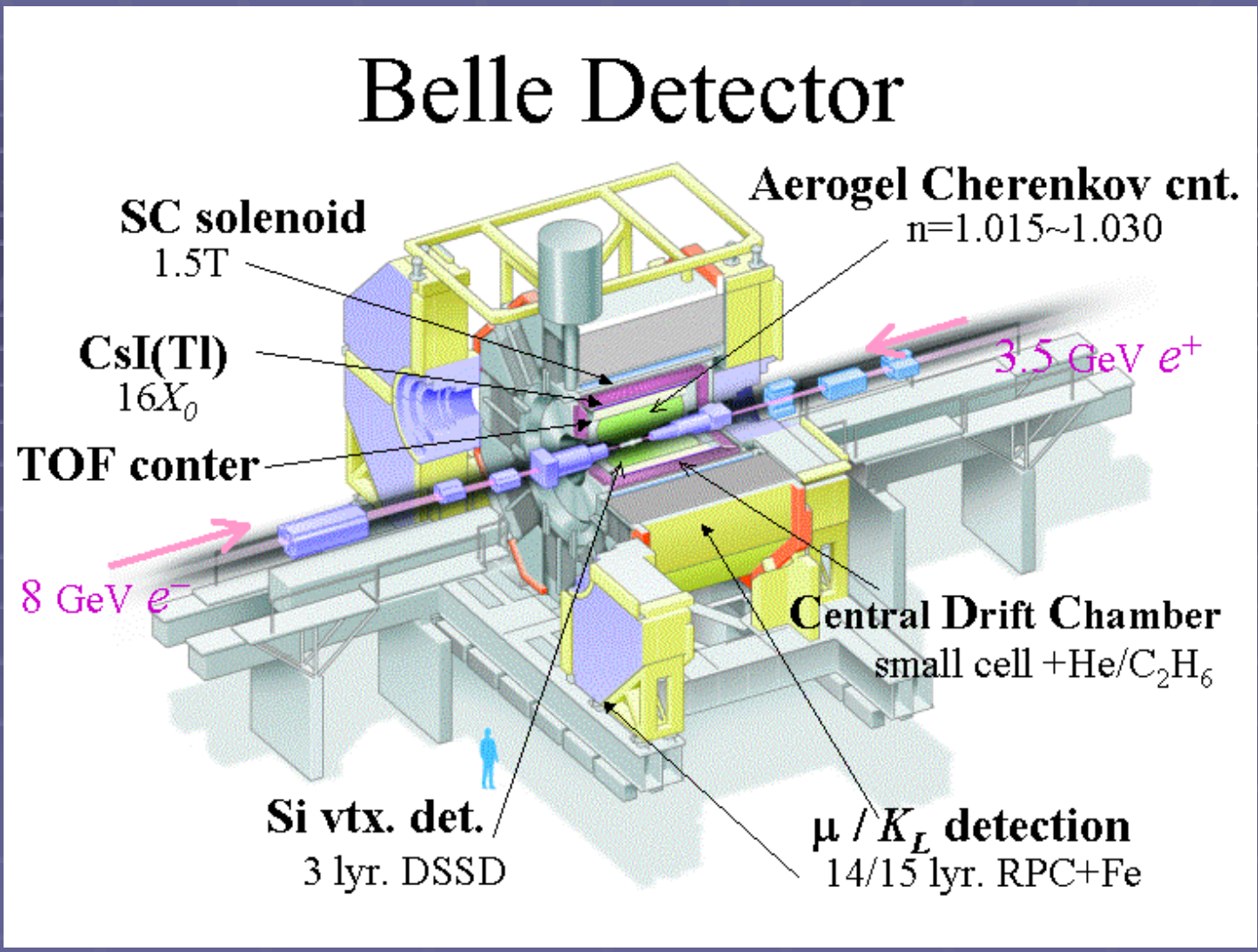
Excellent performance of KEKB







Belle Detector



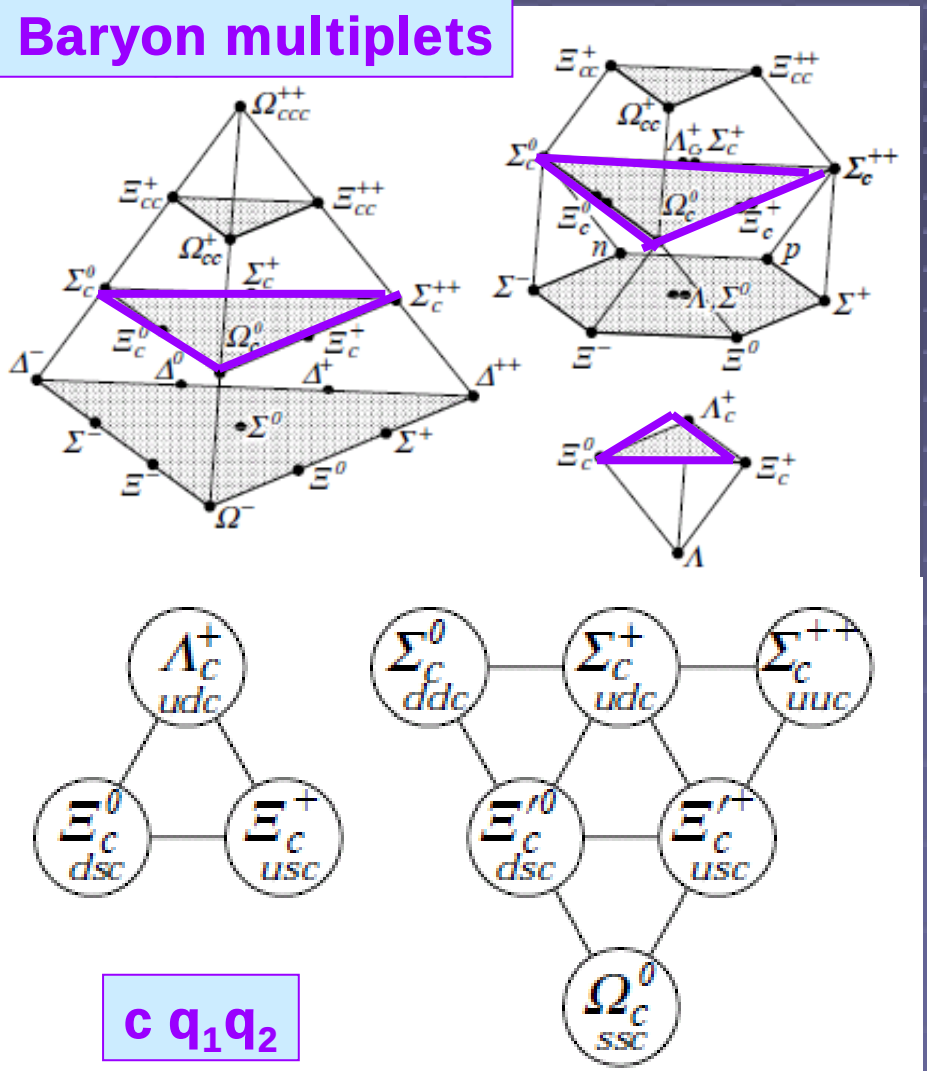
Tracking : SVD and CDC **1.5 Tesla field**

π / K / p : CDC dE/dx, ACC and TOF

e / μ : CsI-cal. and RPC+Fe

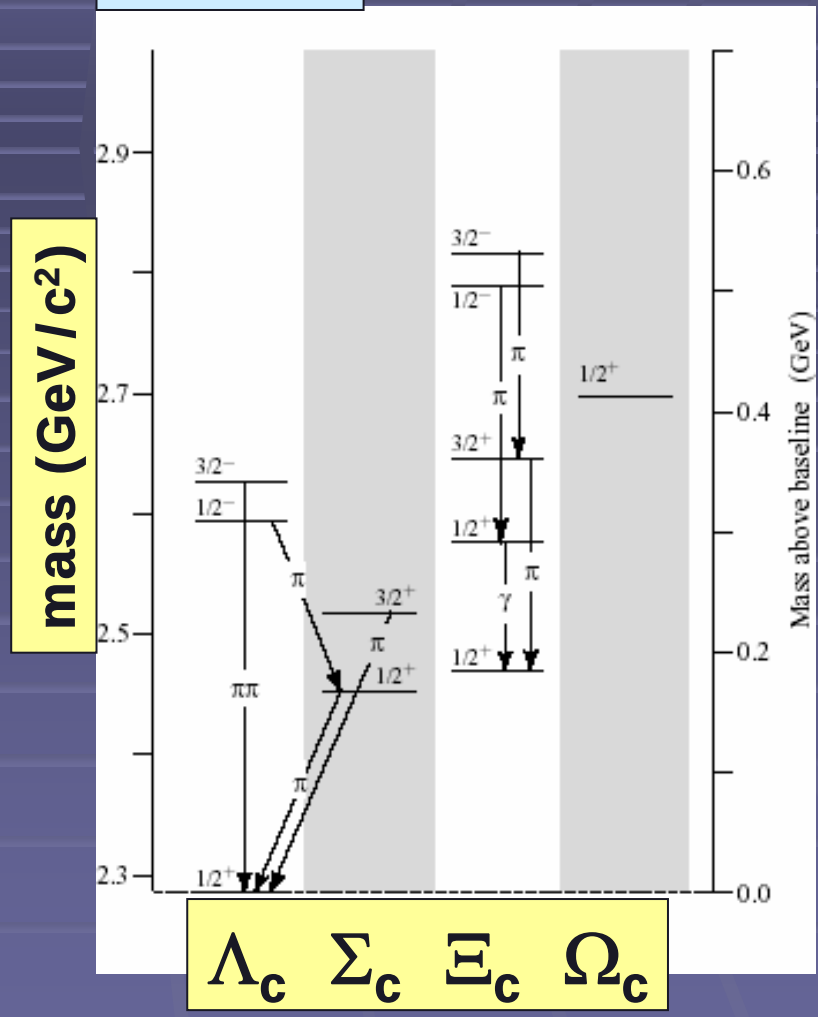
1. Charm baryons

Baryon multiplets



c $q_1 q_2$

PDG2004

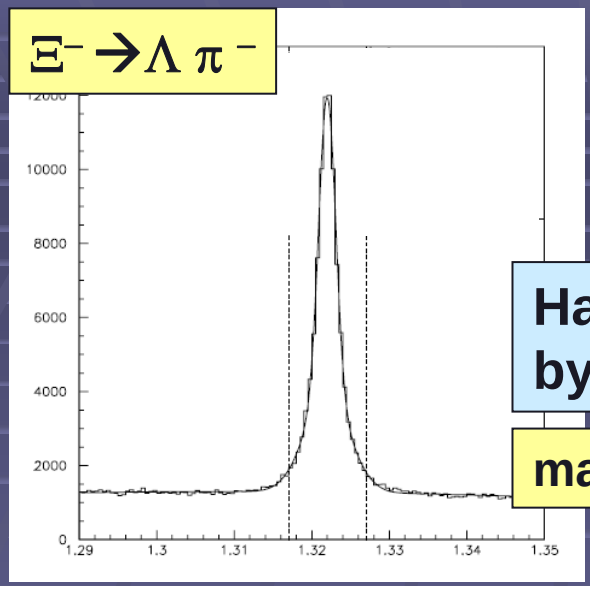


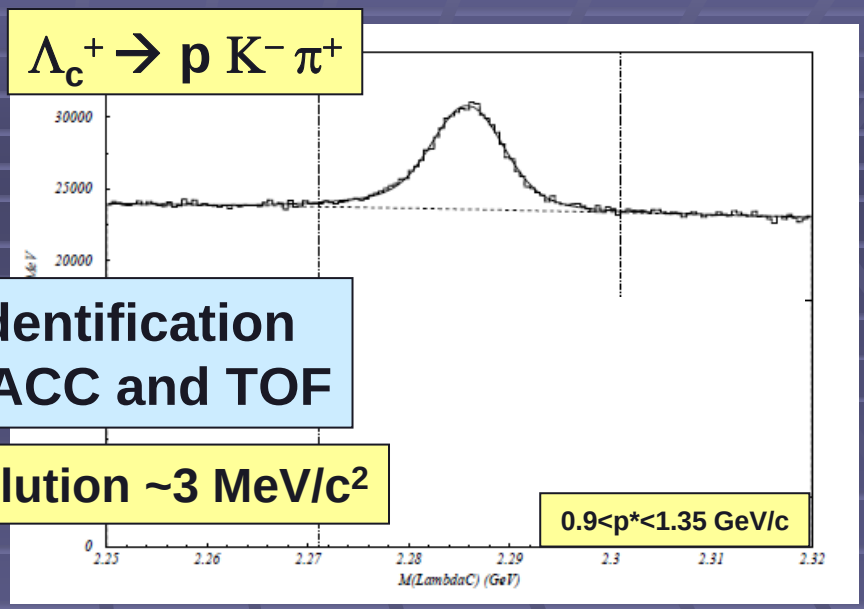
Λ_c Σ_c Ξ_c Ω_c

Spectrum is not known well.
Need more studies with larger samples.

Ξ^-, Ξ_c^- and Λ_c^+ mass reconstruction

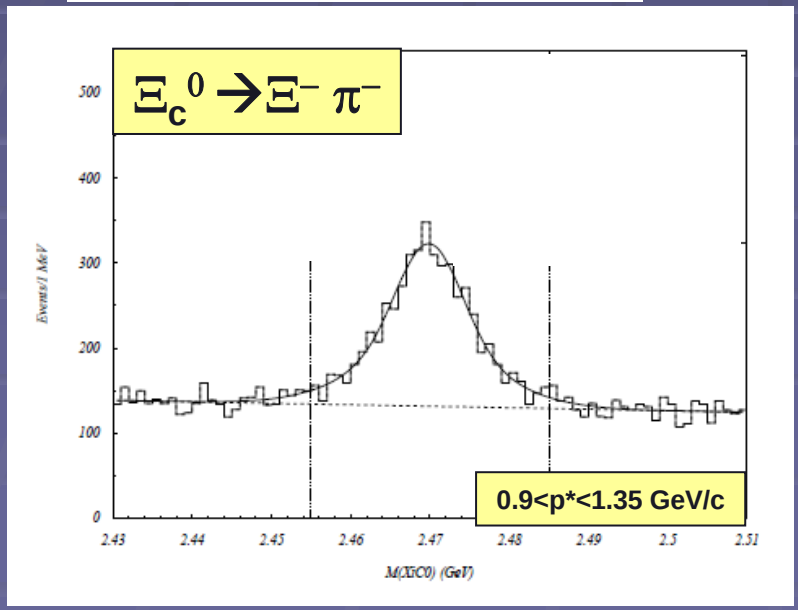
Data

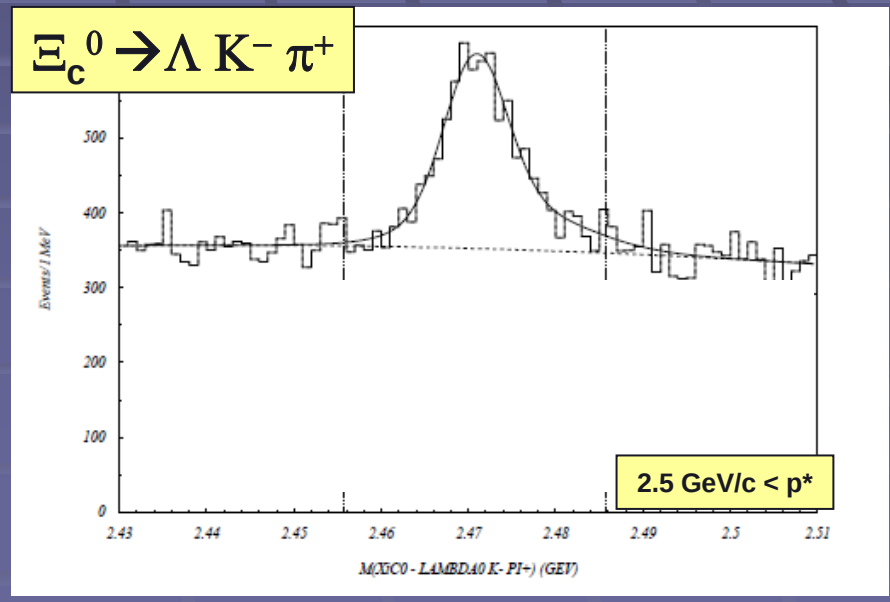




Hadron identification by CDC, ACC and TOF

mass resolution ~3 MeV/c²



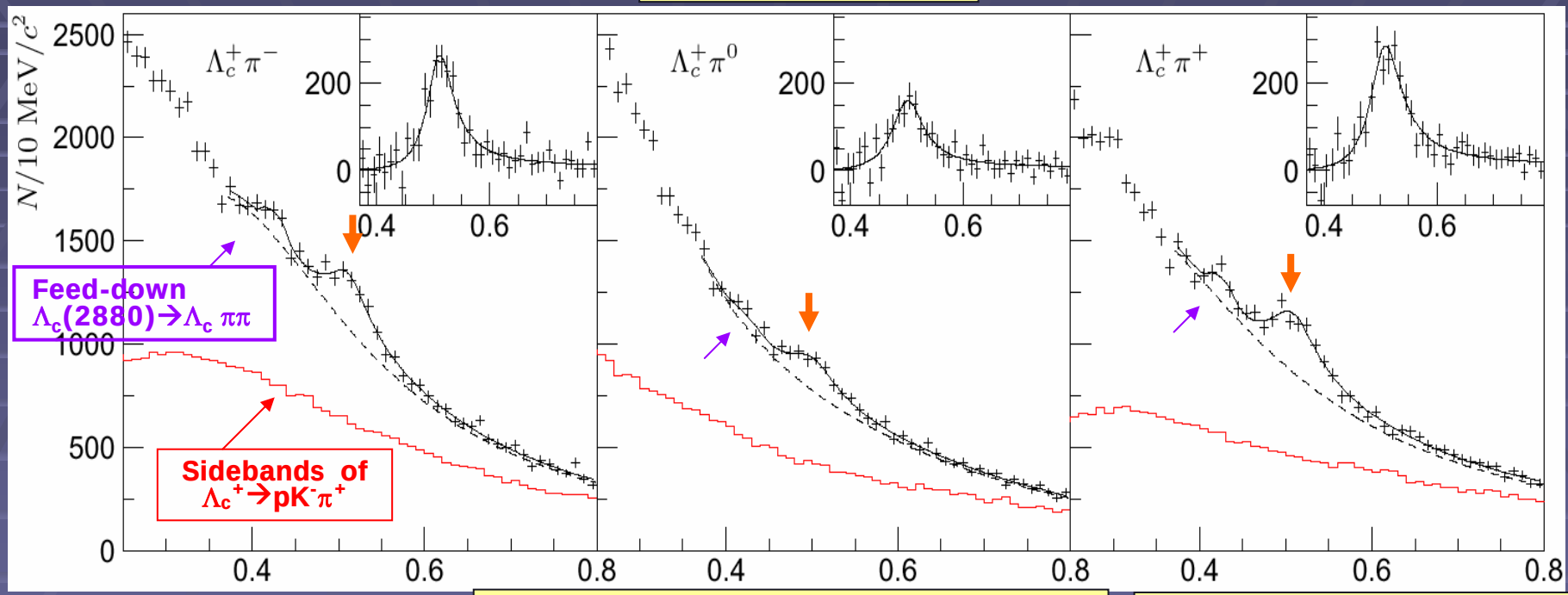


(1) Observation of isotriplet $\Sigma_c(2800)$

$\Sigma_c^0(2800), \Sigma_c^+(2800), \Sigma_c^{++}(2800) \rightarrow \Lambda_c^+ \pi$

$\Lambda_c^+ \rightarrow p K^- \pi^+$

PRL 94, 122002 (2005)
281 fb^{-1}



$\Delta M = M(\Lambda_c^+\pi) - M(\Lambda_c^+)$ GeV/c^2

Large data sample

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 :

Σ_{c2} **member of**

$J^P = 3/2^-$ **isotriplet**

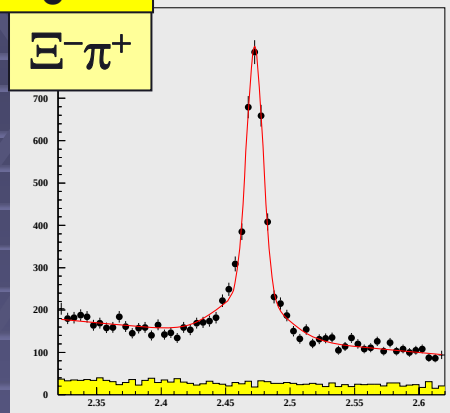
PRL86,4490(2001) CLEO 14fb-1
$\Lambda_c(2880) \rightarrow \Sigma_c(2455)\,\pi \rightarrow \Lambda_c^+\pi^+\pi^-$
M = (2881)±1±2 MeV
Γ< 8 MeV @90%CL

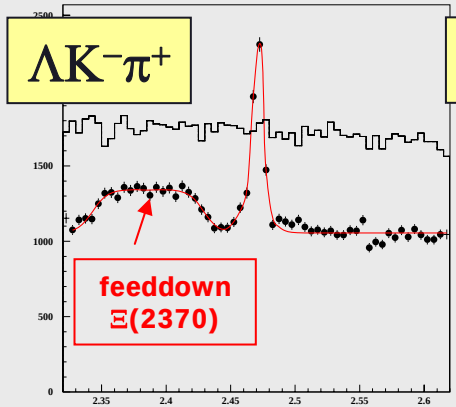
(2) Ξ_c^0 and Ξ_c^+

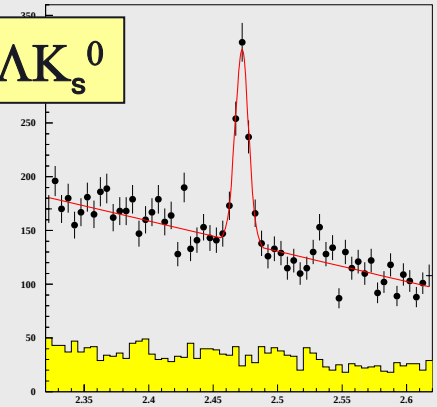
$\Xi_c(2470)$ $\frac{1}{2}^+$ Ground state

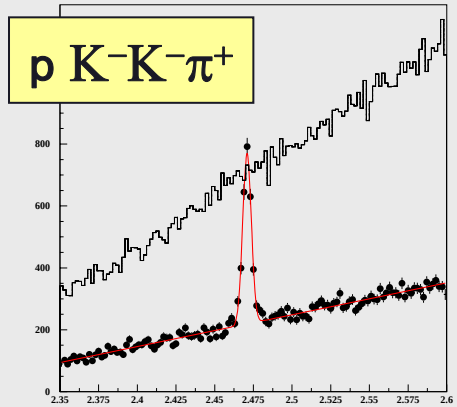
PLB605(2005)237 140fb^{-1}

Ξ_c^0 :







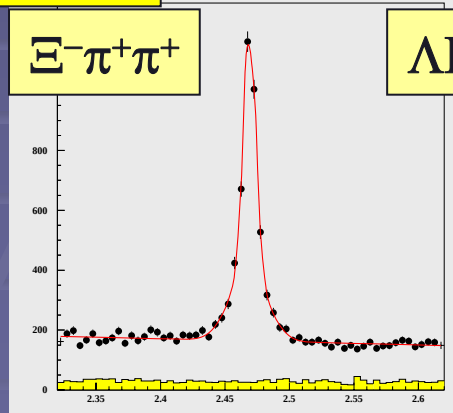


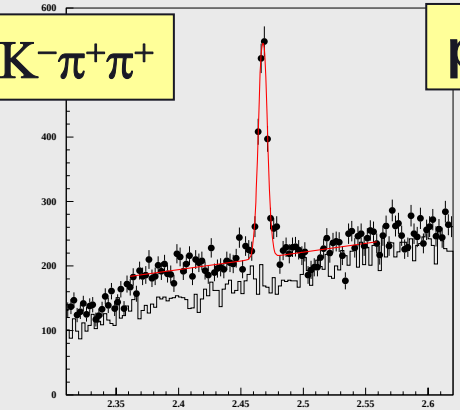
Wrong-sign combinations

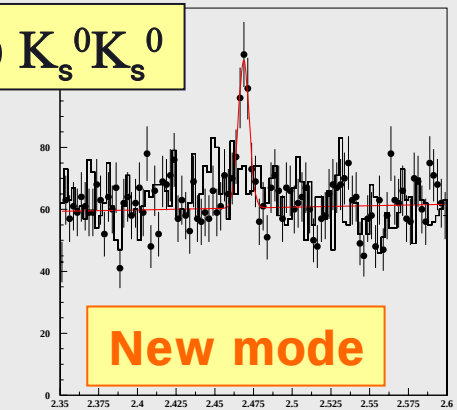
Sidebands of K^0_s -> $\pi^+\pi^-$

Wrong-sign combinations

Ξ_c^+ :







Wrong-sign combinations

Sidebands of K^0_s -> $\pi^+\pi^-$

Clear signals in various modes with large data samples.

Ξ_c^0 and Ξ_c^+

PLB 605, 237 (2005)
140 fb^{-1}

Decay mode	# of events	mass [MeV/c^2]
$\Xi_c^0 \to \Xi^-\pi^+$	2979 ± 211	$2471.3 \pm 0.5 \pm 0.8$
$\Xi_c^0 \to \Lambda K^-\pi^+$	3268 ± 276	$2470.0 \pm 0.6 \pm 0.7$
$\Xi_c^0 \to \Lambda K_S^0$	465 ± 37	$2472.2 \pm 0.5 \pm 0.5$
$\Xi_c^0 \to pK^-K^-\pi^+$	1908 ± 62	$2470.9 \pm 0.1 \pm 0.2$
$\Xi_c^+ \to \Xi^-\pi^+\pi^+$	3605 ± 279	$2468.6 \pm 0.4 \pm 0.5$
$\Xi_c^+ \to \Lambda K^-\pi^+\pi^+$	1177 ± 55	$2467.6 \pm 0.2 \pm 0.5$
$\Xi_c^+ \to pK_S^0K_S^0$	168 ± 27	$2468.6 \pm 0.7 \pm 0.9$

Precise measurements :
Mass in various modes
Branching fractions

with >x10 larger samples

$$m_{\Xi_c^0} = (2471.0 \pm 0.3(stat \oplus syst)^{+0.2}_{-1.4})\ \mathrm{MeV/c^2}$$

$$m_{\Xi_c^+} = (2468.1 \pm 0.4(stat \oplus syst)^{+0.2}_{-1.4})\ \mathrm{MeV/c^2}$$

syst. err due to mass scale bias

$$m_{\Xi_c^0} - m_{\Xi_c^+} = (2.9 \pm 0.5)\ \mathrm{MeV/c^2}$$

PDG:

2471.8 ± 1.4

2466.3 ± 1.4

5.5 ± 1.4

Branching ratios

$$\frac{\Gamma(\Xi_c^+ \to \Lambda K^-\pi^+\pi^+)}{\Gamma(\Xi_c^+ \to \Xi^-\pi^+\pi^+)} = 0.32 \pm 0.03 \pm 0.02,$$

$$\frac{\Gamma(\Xi_c^+ \to pK_S^0K_S^0)}{\Gamma(\Xi_c^+ \to \Xi^-\pi^+\pi^+)} = 0.087 \pm 0.016 \pm 0.014,$$

$$\frac{\Gamma(\Xi_c^0 \to \Lambda K^-\pi^+)}{\Gamma(\Xi_c^0 \to \Xi^-\pi^+)} = 1.07 \pm 0.12 \pm 0.07,$$

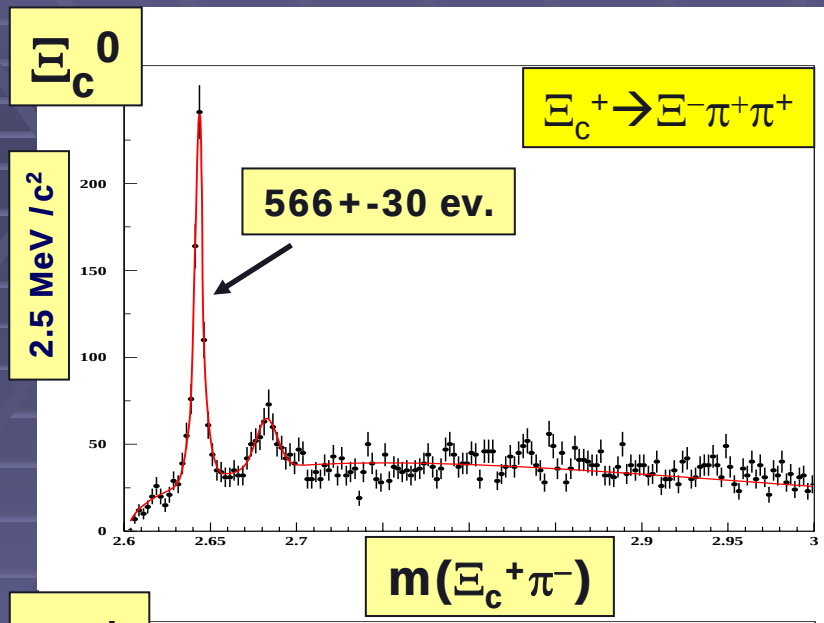
$$\frac{\Gamma(\Xi_c^0 \to \Lambda K_S^0)}{\Gamma(\Xi_c^0 \to \Xi^-\pi^+)} = 0.21 \pm 0.02 \pm 0.02,$$

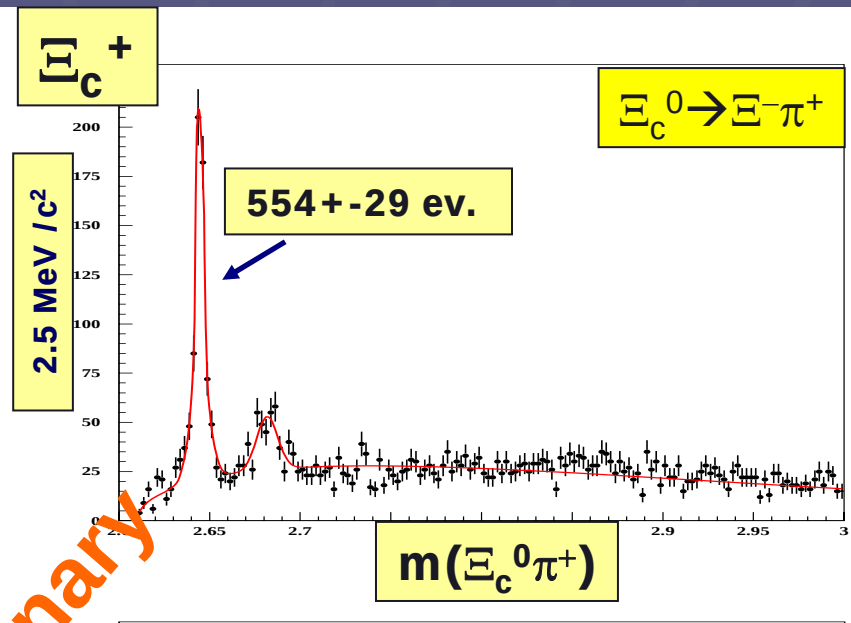
$$\frac{\Gamma(\Xi_c^0 \to pK^-K^-\pi^+)}{\Gamma(\Xi_c^0 \to \Xi^-\pi^+)} = 0.33 \pm 0.03 \pm 0.03.$$

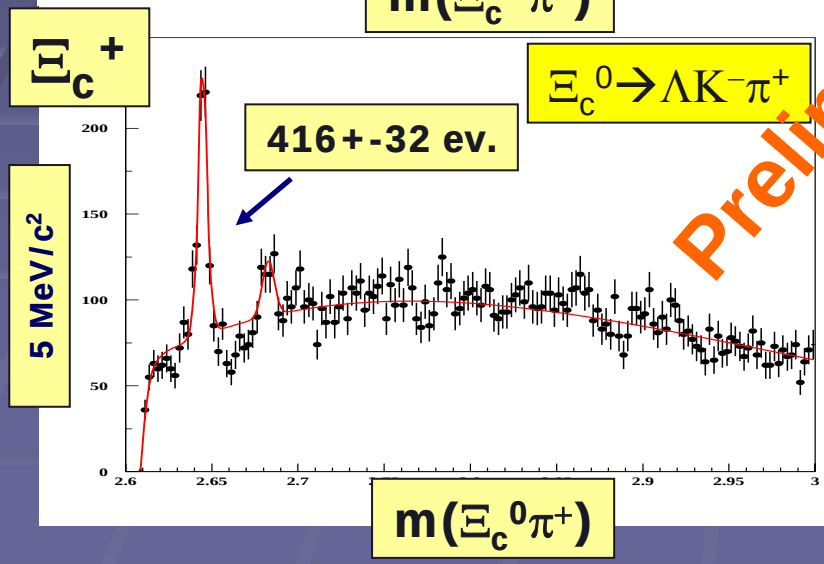
(3) $\Xi_c(2645)$ mass

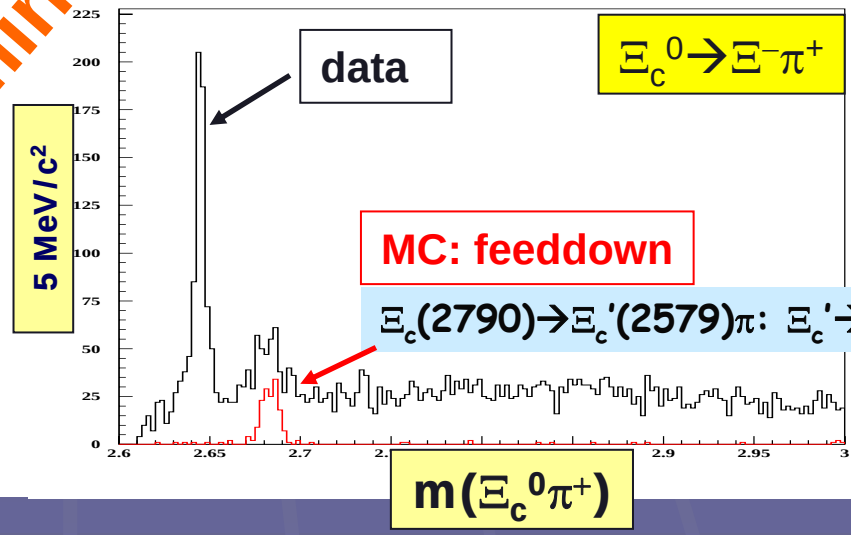
Ξ_c $3/2^+$

357 fb^{-1}









Preliminary

Ξc(2645) mass

Ξ_c 3/2⁺

Preliminary

Ξ_c decay mode	# of events	mass [MeV/c^2]
$\Xi_c^+ \to \Xi^-\pi^+\pi^+$	566 ± 30	$2643.1 \pm 0.2(stat) \pm 0.5(syst)$
$\Xi_c^0 \to \Xi^-\pi^+$	554 ± 29	$2644.7 \pm 0.2(stat) \pm 0.5(syst)$
$\Xi_c^0 \to \Lambda K^-\pi^+$	416 ± 32	$2644.7 \pm 0.3(stat) \pm 0.6(syst)$

PDG:

$m_{\Xi_c(2645)^+} = (2644.7 \pm 0.4 \pm 0.4)$ MeV/c^2 2647.4 ± 2.0

$m_{\Xi_c(2645)^0} = (2643.1 \pm 0.6 \pm 0.4)$ MeV/c^2 2644.5 ± 1.8

syst. Err including mass scale bias

$m_{\Xi_c(2645)^+} - m_{\Xi_c(2645)^0} = (1.6 \pm 0.7)$ MeV/c^2 2.9 ± 2.7

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

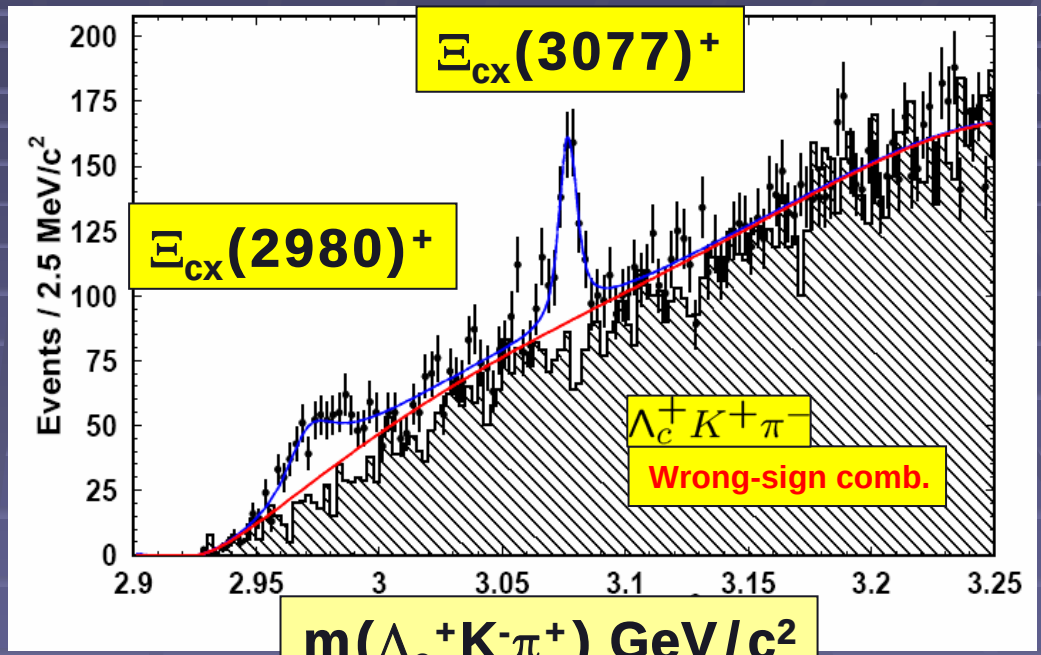
Initially, searching for the SELEX $\Xi_{cc}(3519)^+$ state ($\Lambda_c^+ K^- \pi^+$)

462 fb^{-1}

charm strange baryons

$\Xi_c(csu)^+ \rightarrow \Lambda_c^+ K^- \pi^+$
→ c and s quarks are carried away by different final state particles

Preliminary

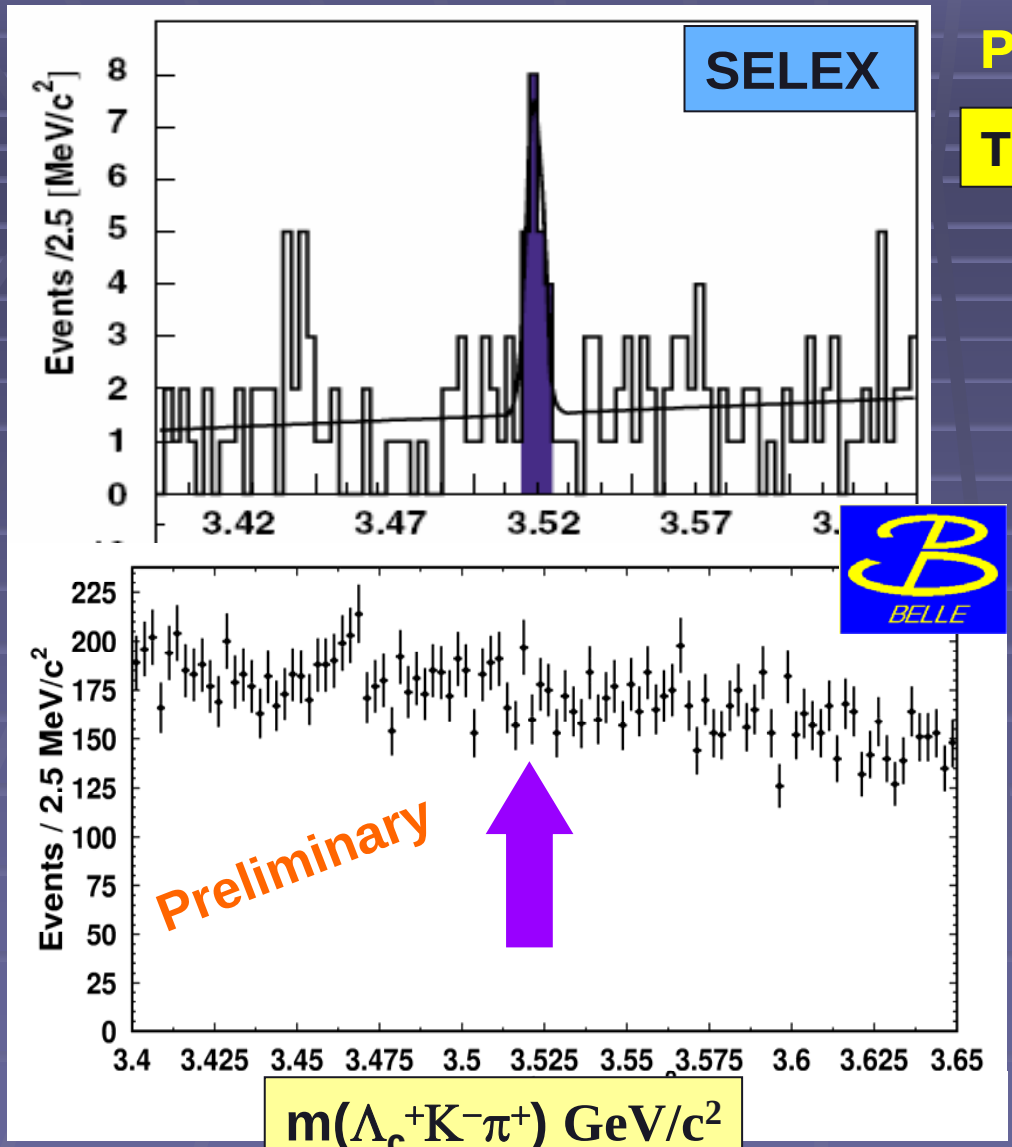


Background: threshold function w/3rd order poly

New State	Mass, (MeV/c^2)	Width, (MeV/c^2)	Yield, (events)	Significance, (σ)
$\Xi_{cx}(2980)^+$	$2978.5 \pm 2.1 \pm 2.0$	$43.5 \pm 7.5 \pm 7.0$	405.3 ± 50.7	6.3
$\Xi_{cx}(3077)^+$	$3076.7 \pm 0.9 \pm 0.5$	$6.2 \pm 1.2 \pm 0.8$	326.0 ± 39.6	9.7

Reflections e.g. $\Lambda_c(2593)^+$, $\Lambda_c(2625)^+$, $\Lambda_c(2765)^+$, $\Lambda_c(2880)^+ \rightarrow \Lambda_c^+ \pi^+ \pi^-$

Search for the SELEX signal



PRL 89, 112001 (2002)

The doubly charmed baryon

$\Xi_{cc}(3519)^+ \rightarrow \Lambda_c K^- \pi^+$
15.9 evts excess
3519 ± 1 MeV/c^2

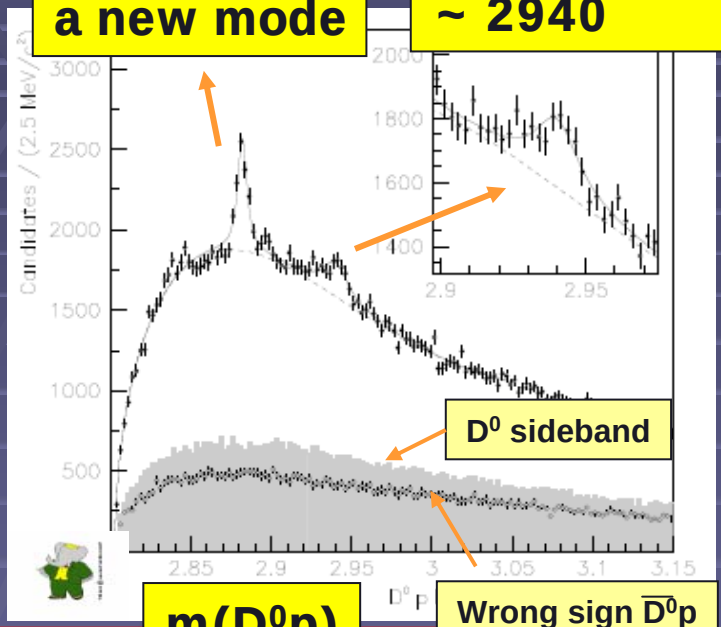
No evidence found

(5) Resonances in D^0 p

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

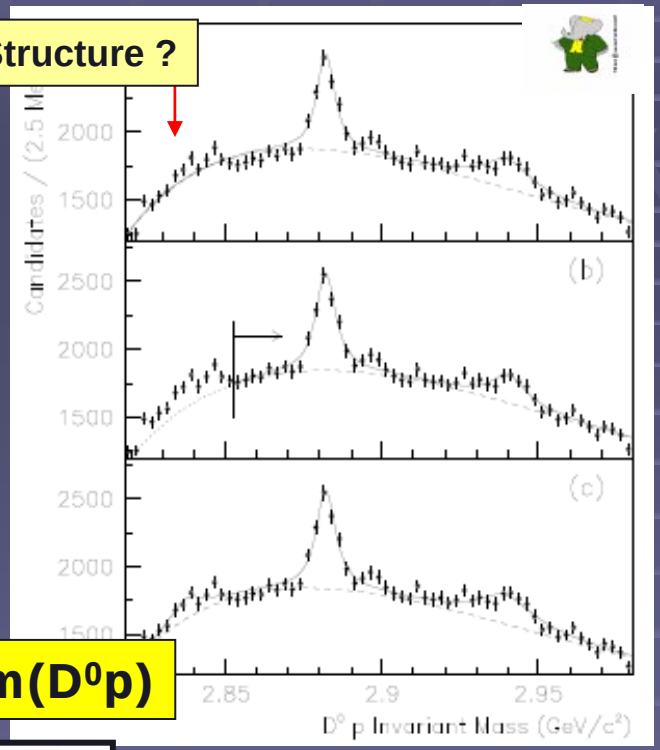
$\Lambda_c(2880)^+$ a new mode

New state ? ~ 2940

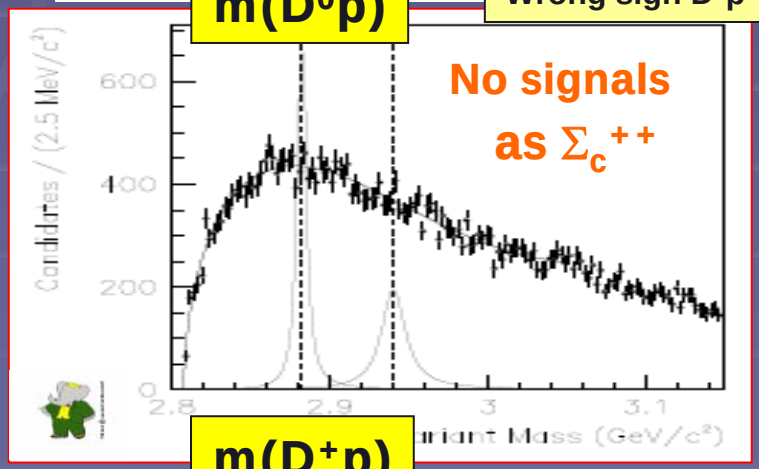


m(D^0p)

Structure ?



m(D^0p)



m(D^+p)

Charm meson + baryon

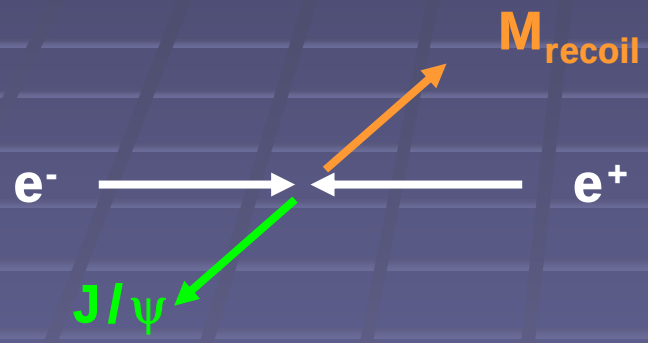
a new mode for $\Lambda_c(2880)^+$
M = 2881.9±0.1±0.5 MeV/c²
Γ = 5.8±1.5±1.1 MeV/c²

$\Lambda_c(2940)^+$
M = 2939.8±1.3±1.0 MeV/c²
Γ = 17.5±5.2±5.9 MeV/c²

2. Double charmonium production in e+e- collisions

Observation of $e^+e^- \rightarrow J/\psi\, X(3940)$
$X(3940) \rightarrow D^* D$

hep-ex/0507019
357 fb-1



Recoil Mass

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

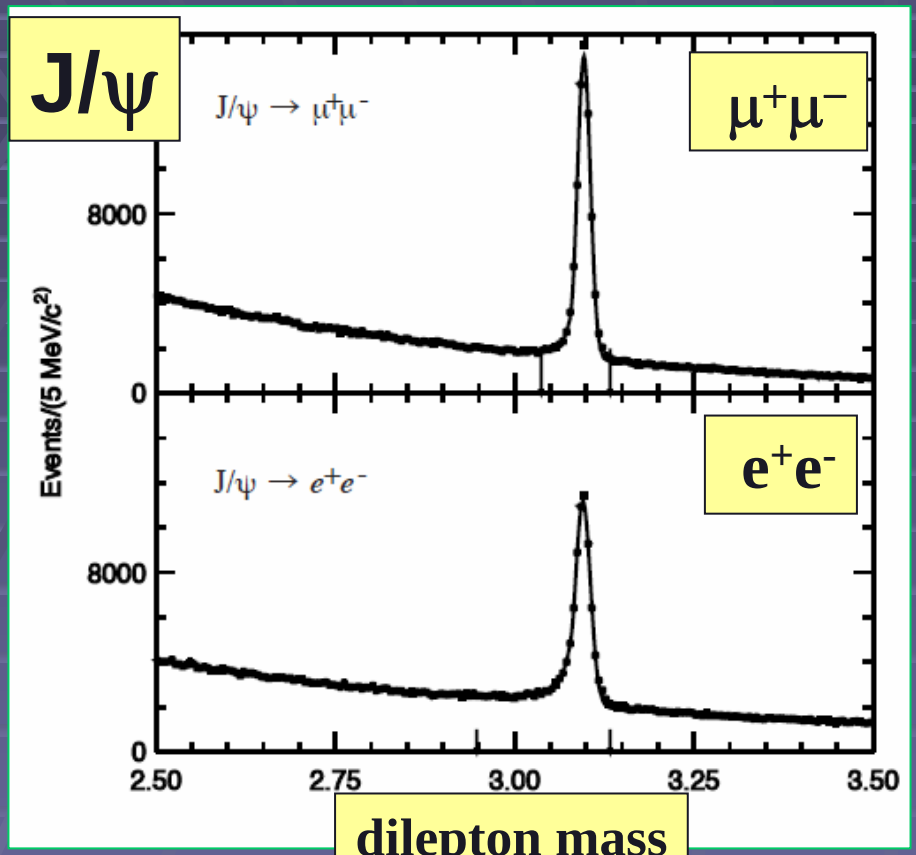
cf. PRL89 (2002) 142001 46 fb^{-1}
PRD80 (2004) 1550(R) 140 fb^{-1}

$Z(3930) \rightarrow D\bar{D}$ in $\gamma\gamma$ fusion : χ'_{c2} $2\,^3P_2$

Spin determination 0 or 2

PRL96, 082003(2006)
395 fb^{-1}

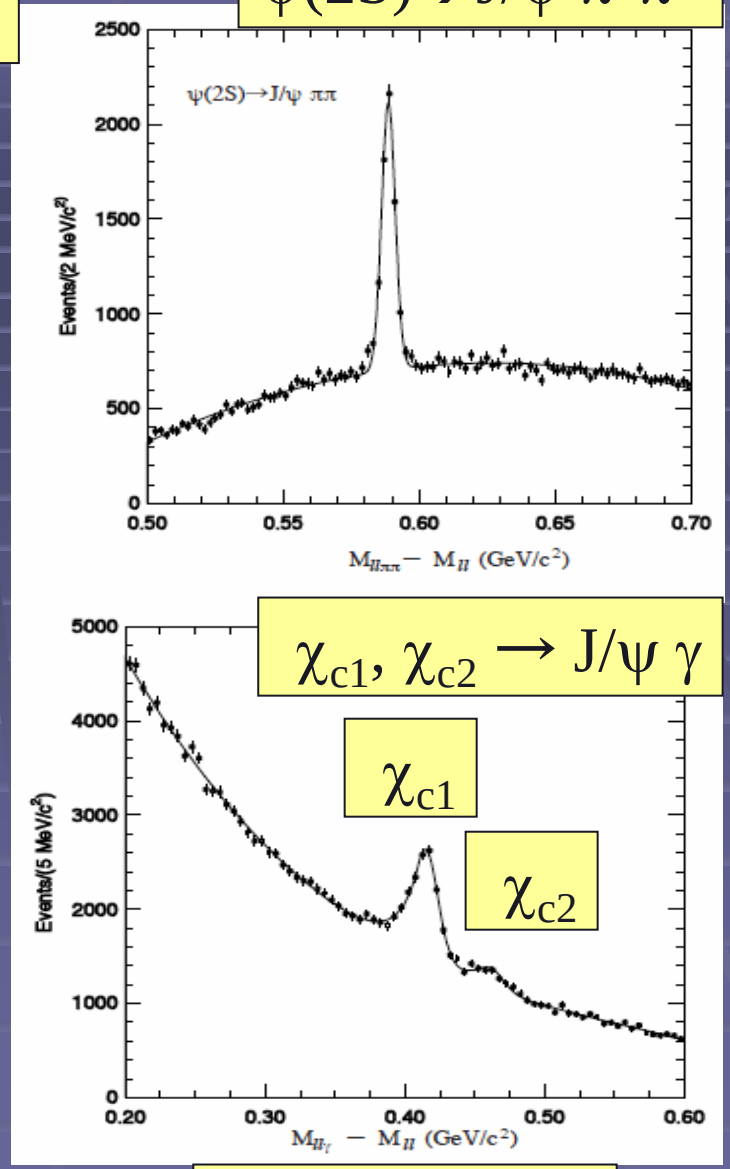
Charmonium signals



photons from e+ / e- included

J/ψ mass window : ±30MeV

ψ(2S)→J/ψ π⁺π⁻

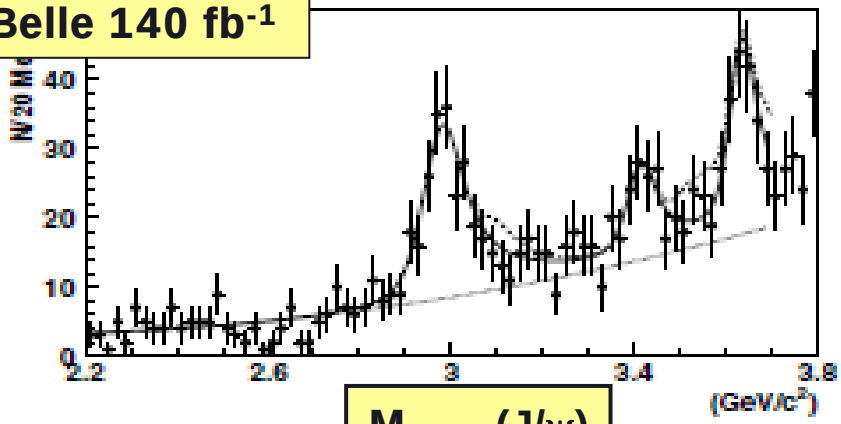


Double charmonium production in e+e- collision

Recoil mass M_{recoil} (J/ψ) distribution

PRD70, 071102(2004)

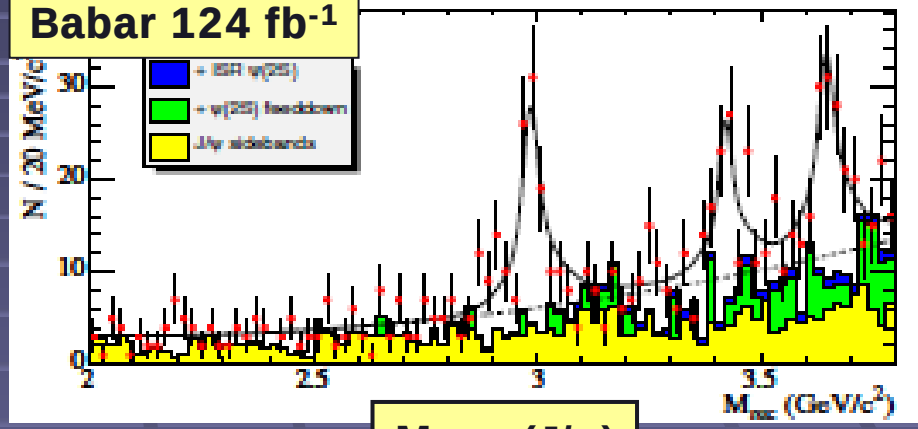
Belle 140 fb^{-1}



M_{recoil} (J/ψ)

PRD72, 031101(2005)

Babar 124 fb^{-1}



M_{recoil} (J/ψ)

TABLE III. Comparison of cross sections ($\sigma \times \mathcal{B}_{>2}$ in fb) with Belle's results [14], and with theoretical expectations that do not include the $\mathcal{B}_{>2}$ factor.

$J/\psi\ c\bar{c}$	η_c (1S)	χ_{c0}	η_c (2S)
BABAR	$17.6 \pm 2.8^{+1.5}_{-2.1}$	$10.3 \pm 2.5^{+1.4}_{-1.8}$	$16.4 \pm 3.7^{+2.4}_{-3.0}$
Belle [14]	$25.6 \pm 2.8 \pm 3.4$	$6.4 \pm 1.7 \pm 1.0$	$16.5 \pm 3.0 \pm 2.4$
NRQCD [6]	2.31 ± 1.09	2.28 ± 1.03	0.96 ± 0.45
NRQCD [4]	5.5	6.9	3.7

Large cross sections for double charmonium production
>> NRQCD prediction
not well described by theory.

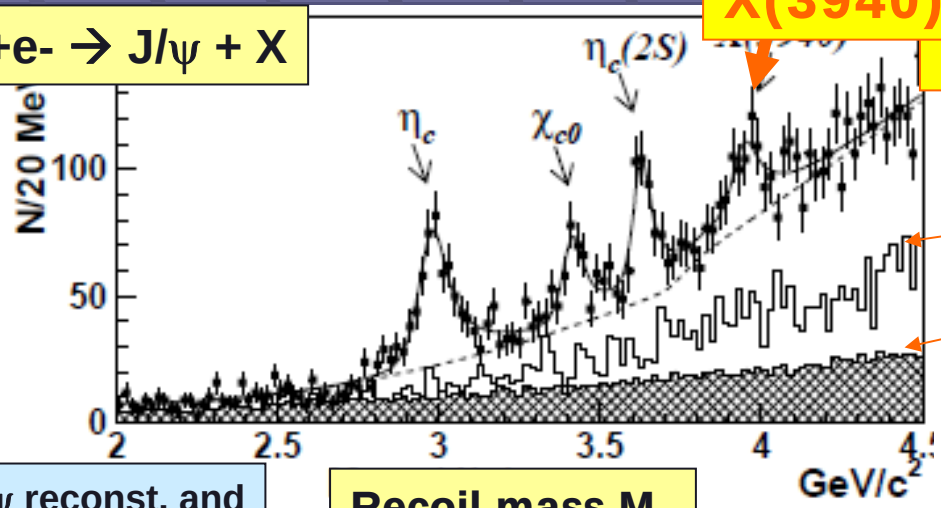
(1) Double charmonium production

X(3940)

above DD threshold

hep-ex/0507019
with 357 fb-1

e+e- → J/ψ + X



Feeddown from ψ(2S)→J/ψ X

J/ψ sideband

P*(J/ψ)>2.0GeV/c
to remove B signal bkgd

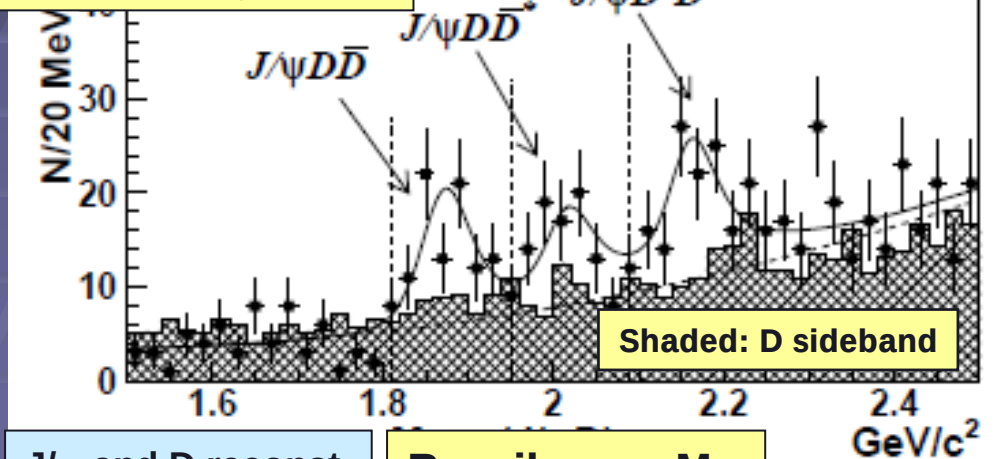
J/ψ reconst. and see M_{recoil} (J/ψ)

Recoil mass M_X

$(c\bar{c})_{res}$	N	M [GeV/c^2]	N_σ
η_c	501 ± 44	2.970 ± 0.005	15.3
χ_{c0}	230 ± 40	3.406 ± 0.007	6.3
$\eta_c(2S)$	311 ± 42	3.626 ± 0.005	8.1
$X(3940)$	266 ± 63	3.936 ± 0.014	5.0

e+e- → J/ψ D + X

D-mass region



Shaded: D sideband

J/ψ and D reconst.
$D^{(*)}$ as M_{recoil} (J/ψD)

Recoil mass M_X

MC res. 30MeV

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

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

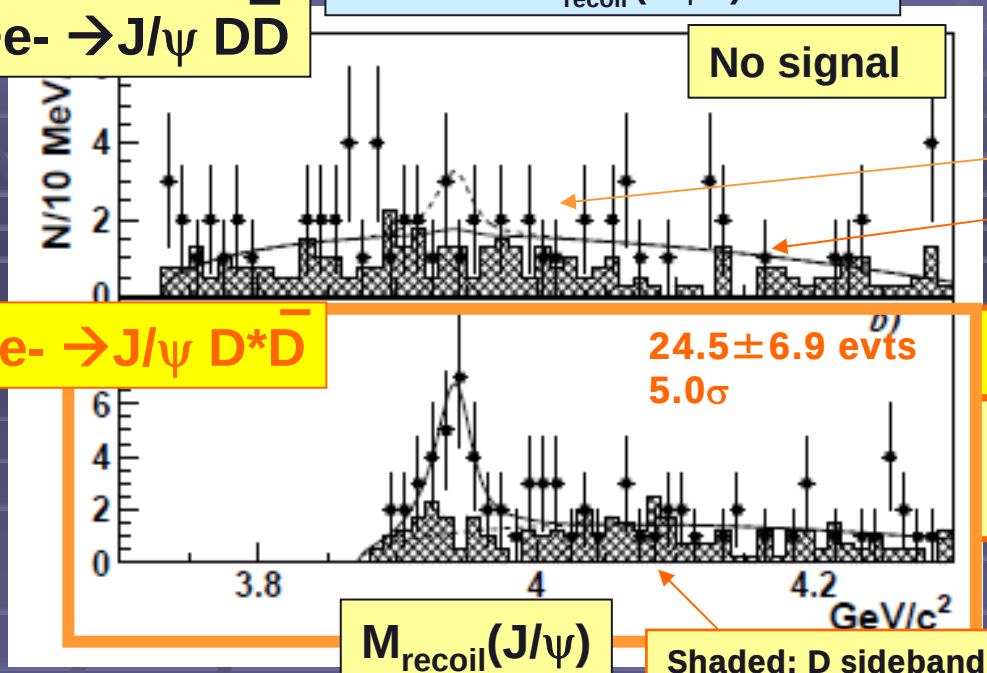
D mass window ±15MeV

hep-ex/0507019

357 fb^{-1}

e+e- →J/ψ $D\bar{D}$

constrain M_{recoil} (J/ψD) to D(*)



X (3940)→ D* D

M 3.943±0.006

Γ 15.4±10.1 MeV/c²

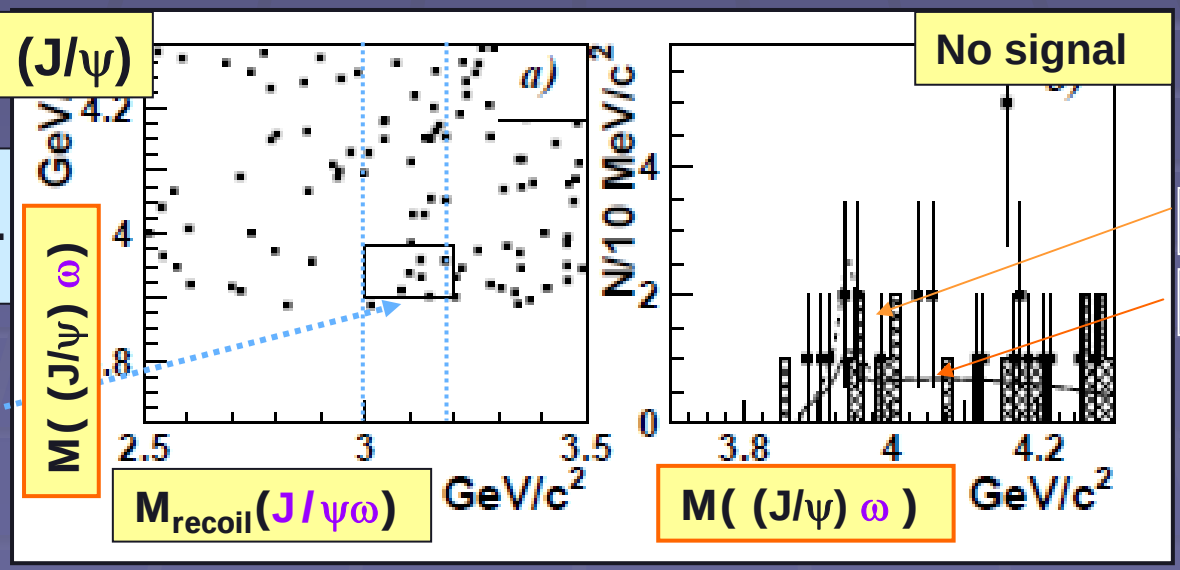
e+e- →J/ψ ω (J/ψ)

Event selection

J/ψ and ω reconst.

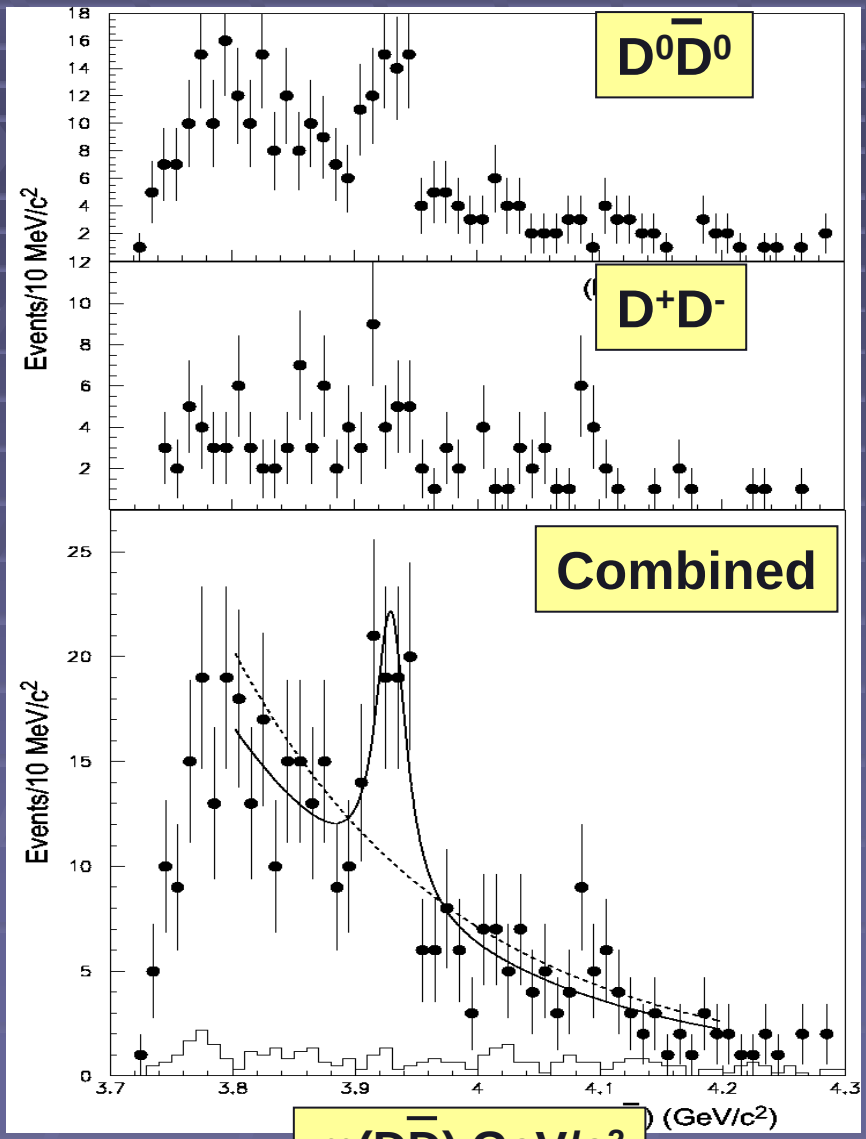
ω-mass: ±20MeV

(J/ψ) :±100MeV



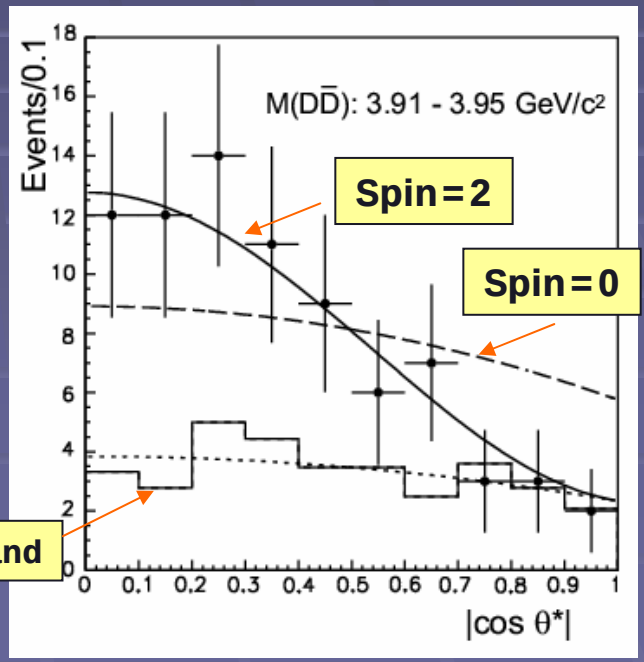
(2) $\gamma\gamma \rightarrow D\bar{D}$

PRL96, 082003(2006)
395 fb^{-1}

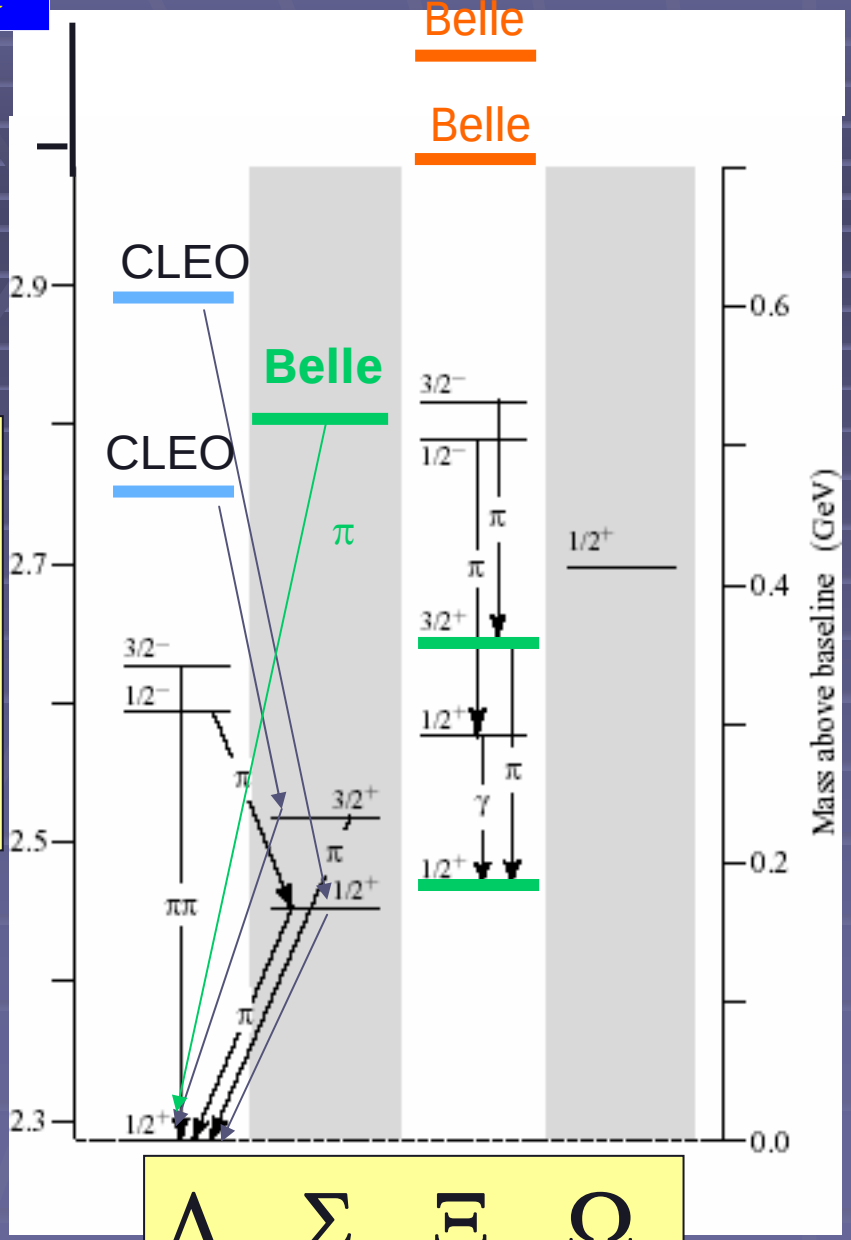


Z(3930)
M = 3929 ± 5 ± 2 MeVc^2
Γ = 29 ± 10 ± 2 MeV/c^2
Yield = 64 ± 18 events
Stat. Sig. 5.3σ

χ'_{c2} : 2 $^3P_2$ charmonium



Charm baryons



Summary1

Belle

$\Xi_{cx}(3077)$

$\Xi_{cx}(2980)$

Charm strange baryon

Babar

$?(2940) \rightarrow D^0p$

$\Lambda_c^+(2880) \rightarrow D^0p$

Charm meson + p

$\Sigma_c(2800)$

New isotriplet

$3/2^-$

$\Xi_c(2645)$

$3/2^+$

Precise measurements of mass and branching ratios in various modes

$\Xi_c(2470)$

$1/2^+$

Published / submitted / preliminary

$\Lambda_c(2880)/\Lambda_c(2765)$ into $\Lambda_c^+\pi^+\pi^-$
PRL86,4490(2001) 14fb^{-1}

CLEO

Charmonium production in e^+e^- collision

Large cross sections for double charmonium production >> NRQCD prediction : not well described by theory.

(Belle, Babar)

Observation of $e^+e^- \rightarrow J/\psi\ X(3940)$
$X(3940) \rightarrow D^* \bar{D}$
no evidence in $D\bar{D}$ and $J/\psi\ \omega$
$\neq$ Y(3940) in $B \rightarrow K\ Y(3940)$, $Y(3940) \rightarrow J/\psi\ \omega$

$Z(3930) \rightarrow D\bar{D}$ in $\gamma\gamma$ fusion : χ'_{c2} $2\ ^3P_2$

Published / submitted / preliminary

Backup slides

Charmonium (like) states

states	decay	Mass MeV/c^2	Γ MeV/c^2	process	Ref.
Y(3940)	$J/\psi\ \omega$	3943 ± 11	87 ± 22	$B \rightarrow K\ \omega\ J/\psi$	Belle(1)
X(3940)	$D\ \bar{D}^*$	3936 ± 14	39 ± 26	$e^+e^- \rightarrow J/\psi\ DD^*$, J/ψ X	This
Z(3930)	$D\ \bar{D}$ $\chi'_{c2}(2^3P_2)$	3929 ± 5	29 ± 10	$\gamma\gamma \rightarrow D\ \bar{D}$	Belle(3)
Y(4260)	$J/\psi\pi^+\pi^-$	~4260	~90	$e^+e^- \rightarrow \gamma_{ISR}\ J/\psi\ \pi^+\ \pi^-$	Babar(2)

1. Belle: PRL94,182002(2005)
2. Babar: PRL95,142001(2005)
3. Belle: PRL96, 082003(2006)

Double charmonium production in e+e- collision

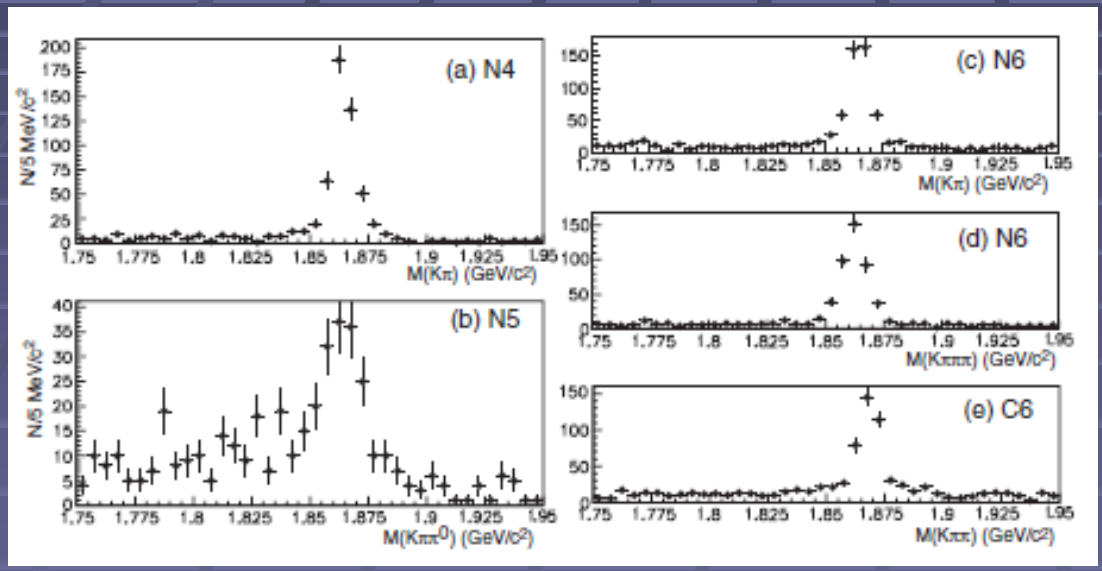
Belle : PRL89,142001(2002), PRD70,071102(R)(2004)
Babar : PRL92,142002(2004), PRD72,031101(R)(2005)

PRL96, 082003(2006)

395 fb^{-1}

D signal selection in $\gamma\gamma \rightarrow D\,D$ analysis

Clear D signals



$$\gamma\gamma \rightarrow D^0\bar{D}^0,\ D^0 \rightarrow K^-\pi^+,\ \bar{D}^0 \rightarrow K^+\pi^- \quad \text{(N4)},$$

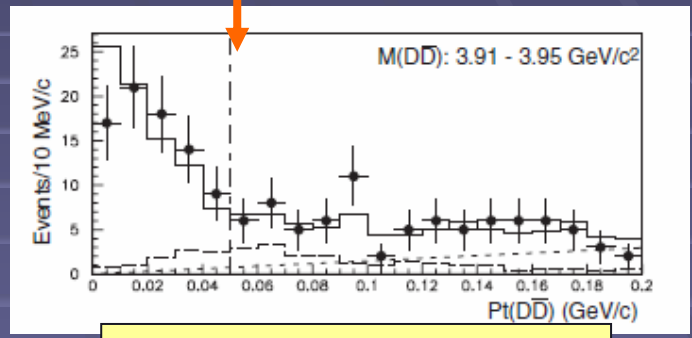
$$\gamma\gamma \rightarrow D^0\bar{D}^0,\ D^0 \rightarrow K^-\pi^+,\ \bar{D}^0 \rightarrow K^+\pi^-\pi^0 \quad \text{(N5)},$$

$$\gamma\gamma \rightarrow D^0\bar{D}^0,\ D^0 \rightarrow K^-\pi^+,\ \bar{D}^0 \rightarrow K^+\pi^-\pi^+\pi^- \quad \text{(N6)},$$

$$\gamma\gamma \rightarrow D^+D^-,\ D^+ \rightarrow K^-\pi^+\pi^+,\ D^- \rightarrow K^+\pi^-\pi^- \text{(C6)}.$$

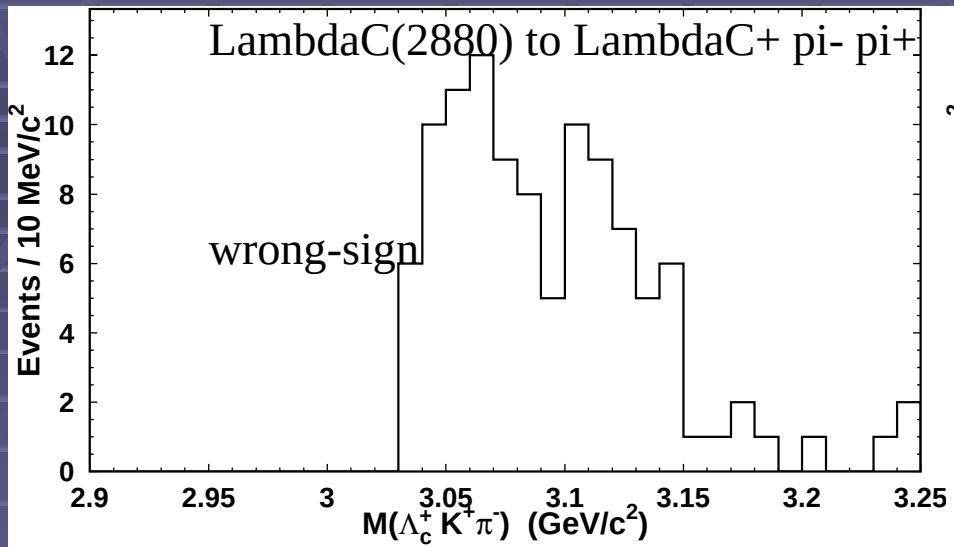
$\gamma\gamma$ selection

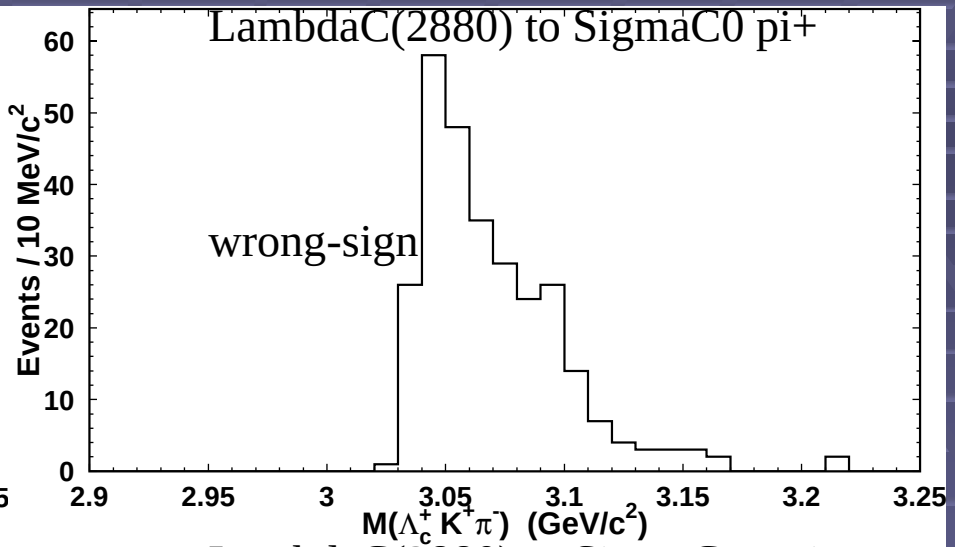
$P_t(DD) < 0.05$GeV/c

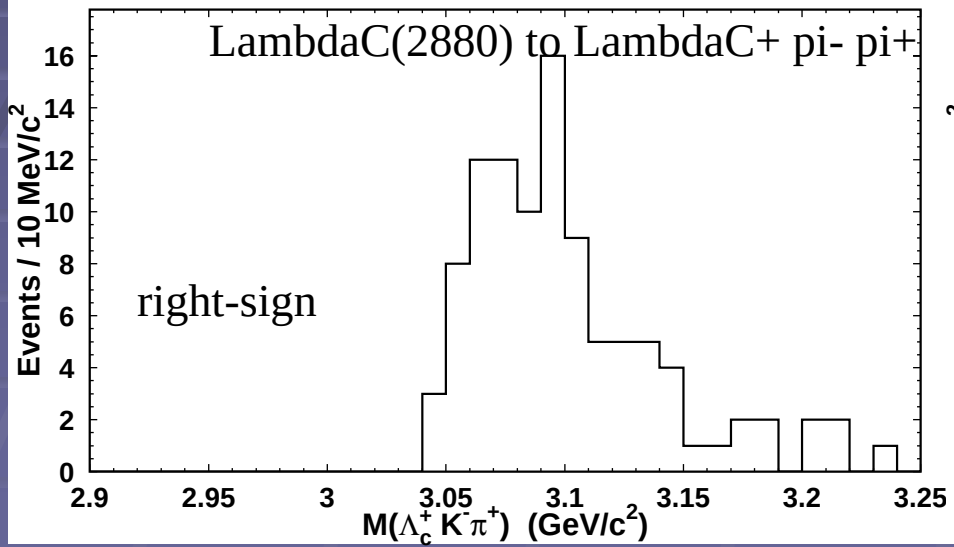


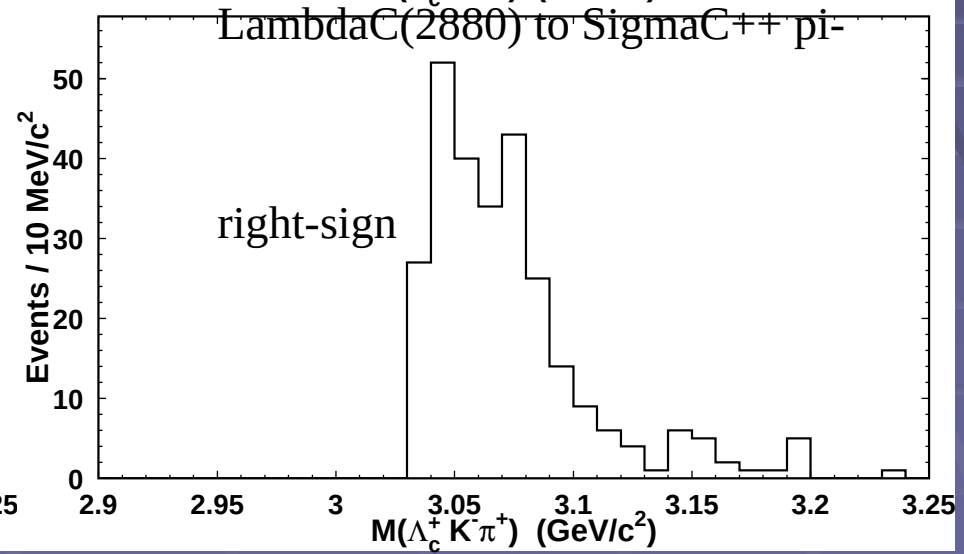
$P_t(DD)$ distribution

MC : feeddown of $\Lambda_c(2880) \rightarrow \Sigma_c(2455)\pi$ to $m(\Lambda_c^+ K^- \pi^+)$



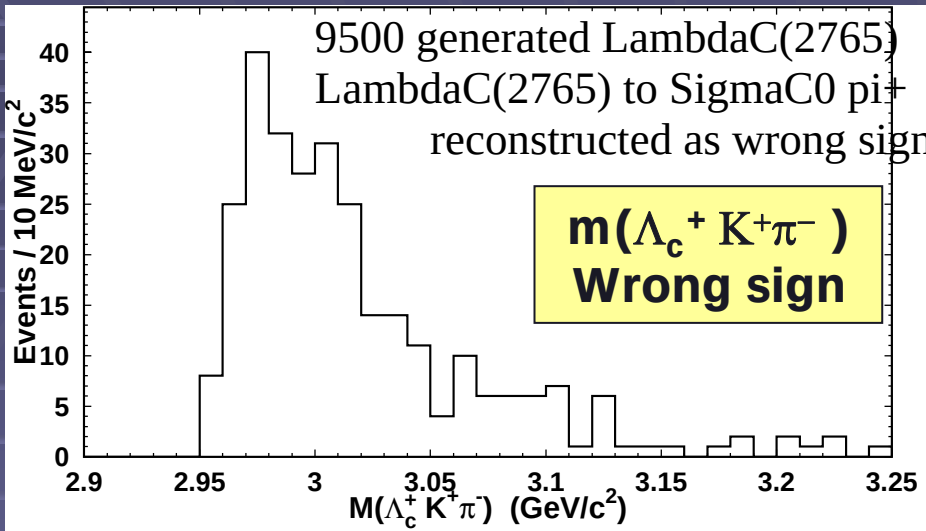


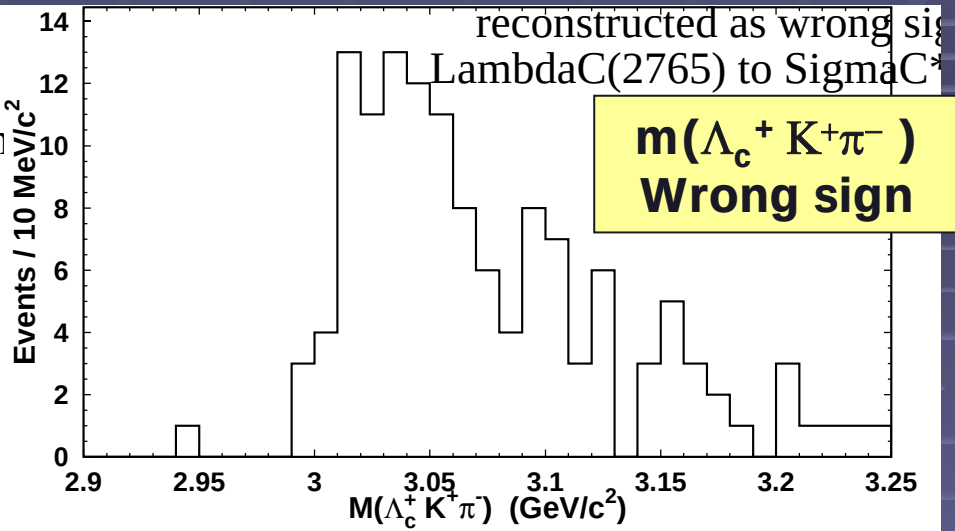


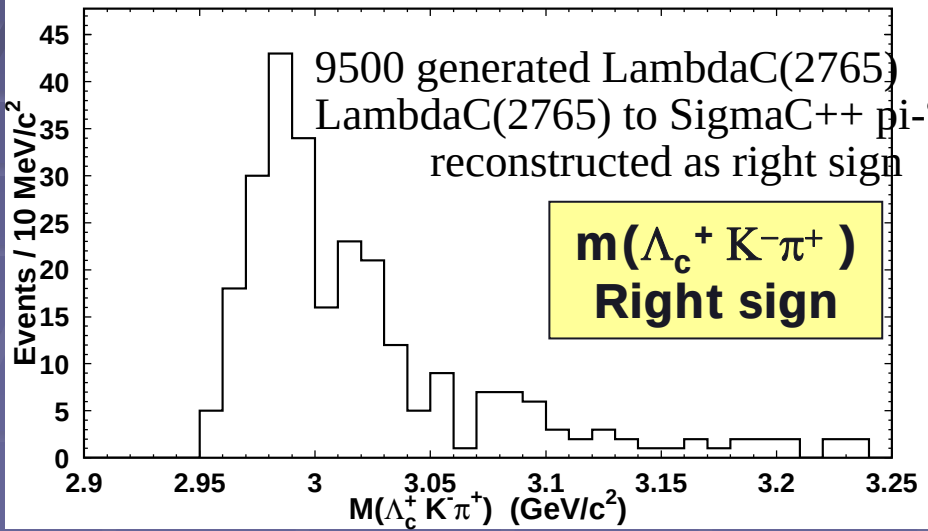


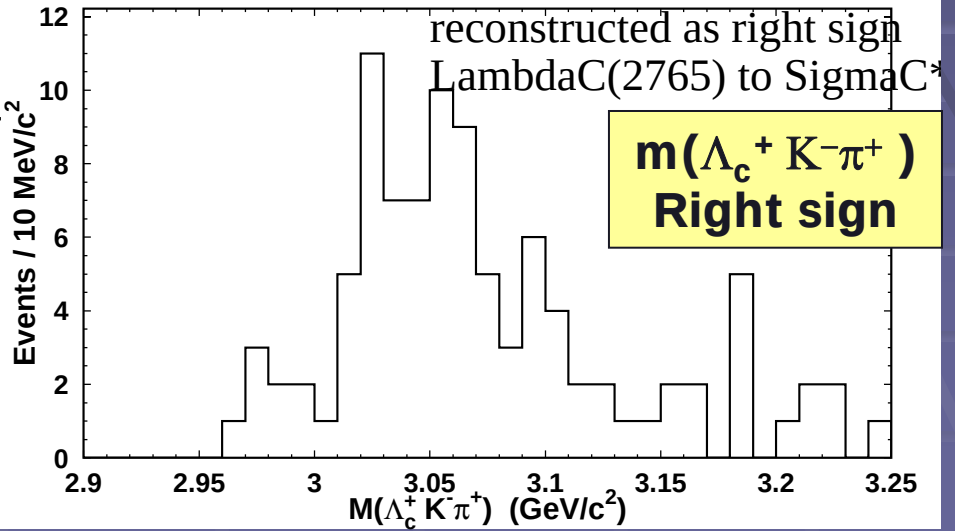
MC : feeddown of $\Lambda_c(2765) \rightarrow \Sigma_c(2455)^0\pi^+$, $\Sigma_c(2455)^0 \rightarrow \Lambda_c^+\pi^-$

and $\Lambda_c(2765) \rightarrow \Sigma_c(2455)^{++}\pi^-$, $\Sigma_c(2455)^{++} \rightarrow \Lambda_c^+\pi^+$

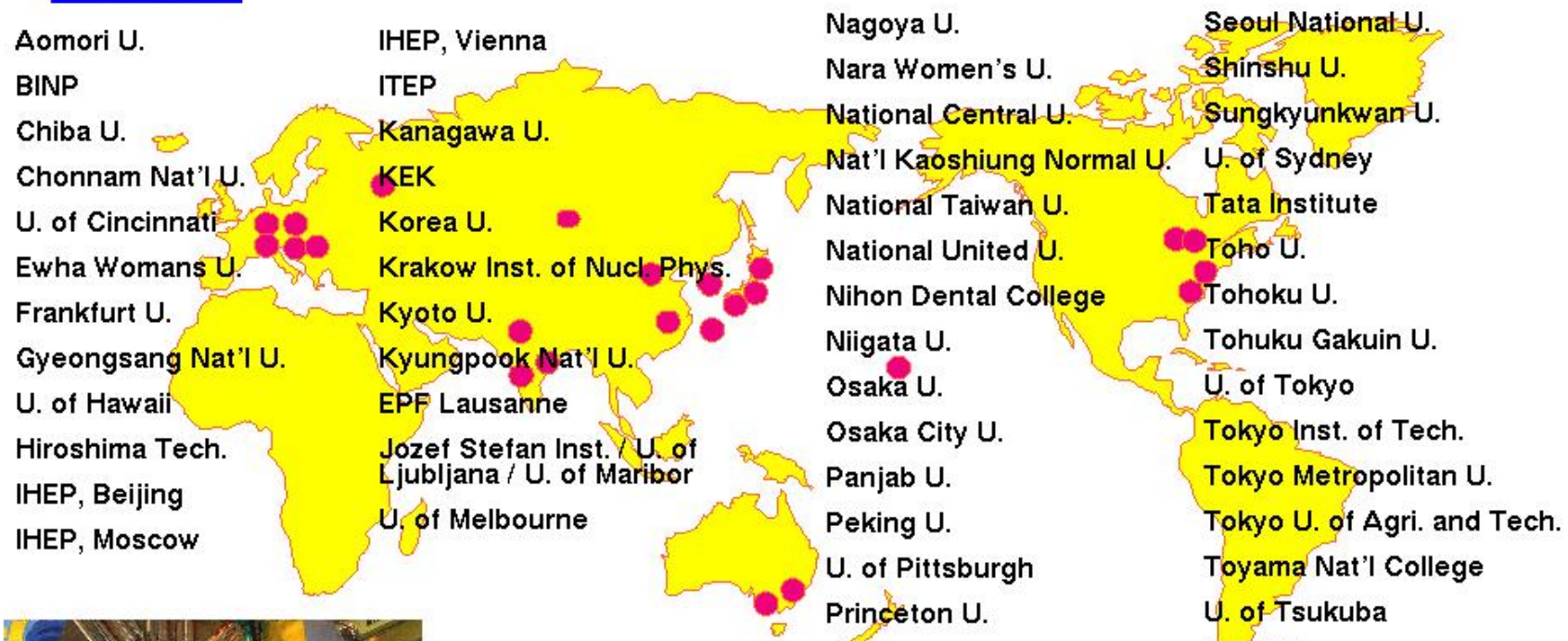








International Collaboration: Belle



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13 countries, 57 institutes, ~400 collaborators