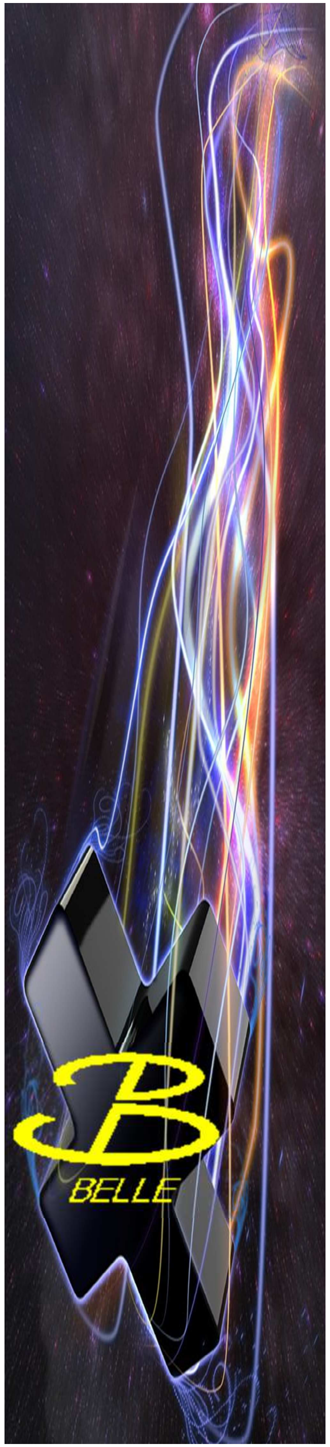
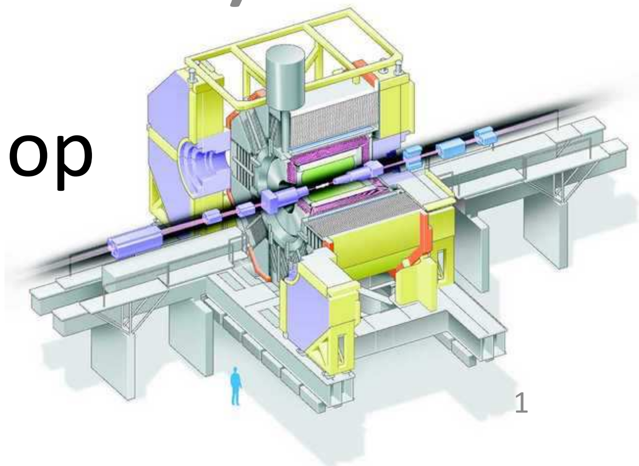


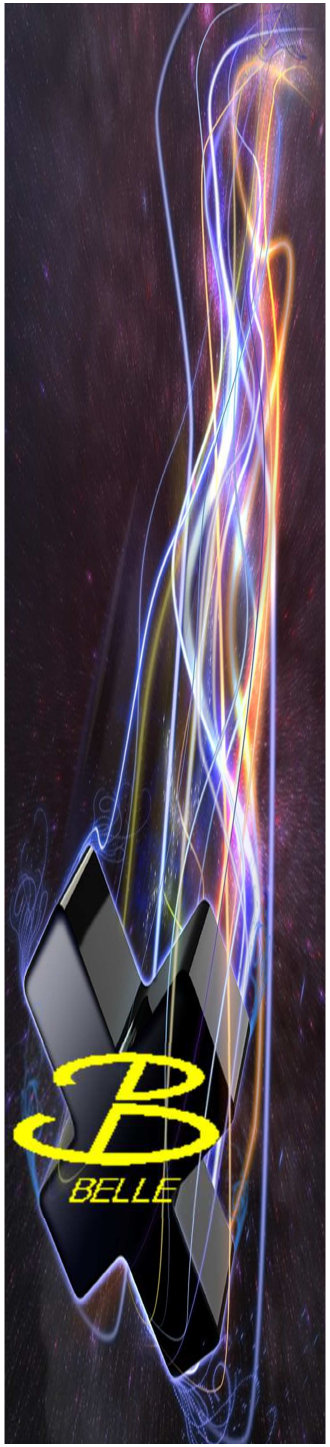
Conventional $c\bar{c}$ and ccq at Belle

Vishal Bhardwaj, NWU
(for Belle Collaboration)

QWG Workshop

22-26 April 2013

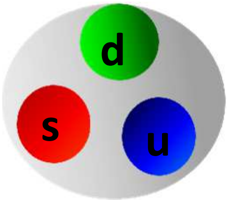




Outline

- η_c in $\gamma\gamma \rightarrow \eta'\pi^+\pi^-$
- Observation of *Ψ(4040)* and *Ψ(4160)* in $e^+e^- \rightarrow \gamma_{ISR} J/\Psi\eta$
- Evidence of *X(3823)*: missing Ψ_2
- Doubly charmed baryon search

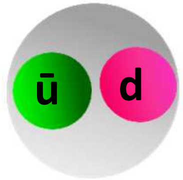
QCD : real particles are color singlet



Baryons are red-blue-green triplets

Λ=usd

Mesons are color-anticolor pairs

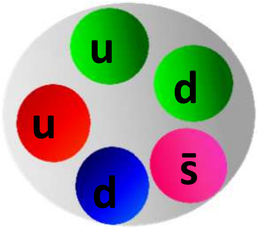


π=ūd

Other possible combinations of quarks and gluons :

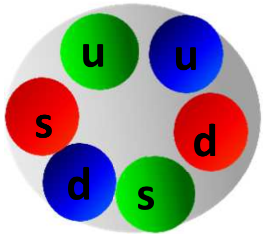
Pentaquark

S= +1
Baryon



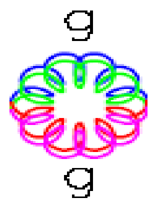
H di-Baryon

Tightly bound
6 quark state



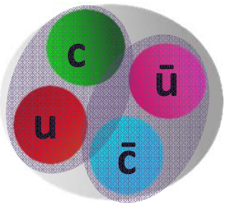
Glueball

Color-singlet multi-gluon bound state



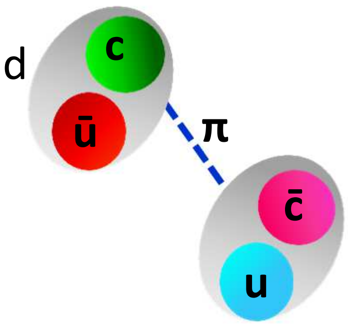
Tetraquark

Tightly bound
diquark &
anti-diquark

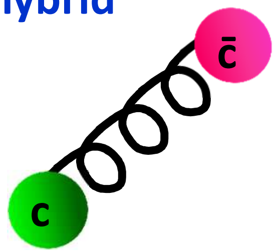


Molecule

loosely bound
meson-antimeson
"molecule"



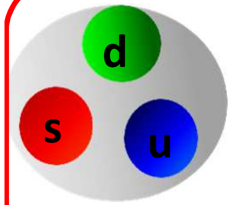
qq̄ -gluon hybrid mesons



artistic illustration

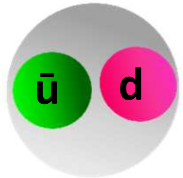
QCD : real particles are color singlet

Baryons are red-blue-green triplets



Λ=usd

Mesons are color-anticolor pairs

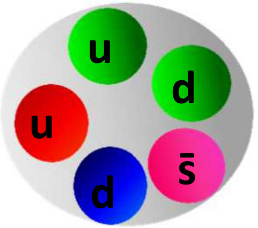


π=ūd

Other possible combinations of quarks and gluons :

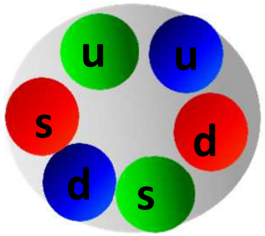
Pentaquark

S= +1 Baryon



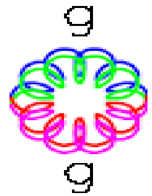
H di-Baryon

Tightly bound 6 quark state



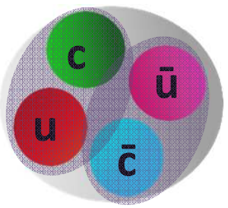
Glueball

Color-singlet multi-gluon bound state



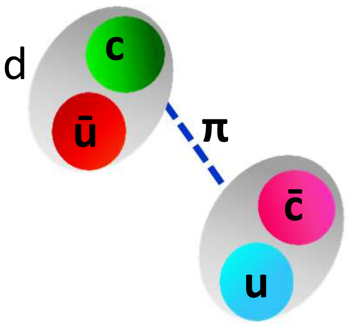
Tetraquark

Tightly bound diquark & anti-diquark

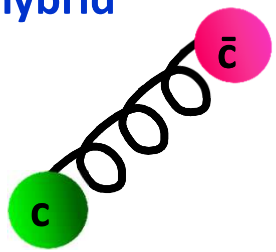


Molecule

loosely bound meson-antimeson "molecule"



qq̄ -gluon hybrid mesons



Covered by C.P. Shen on Monday

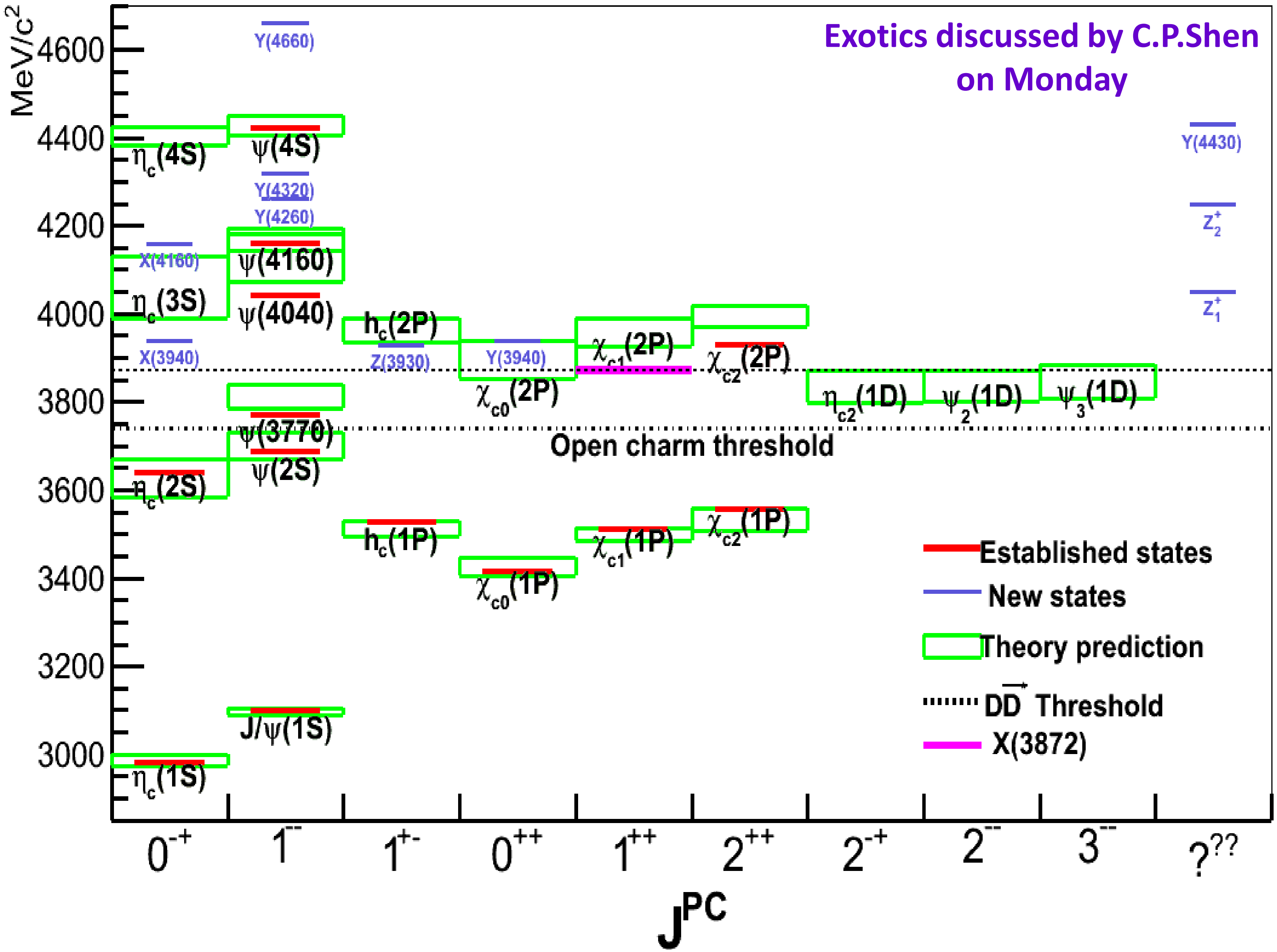
For exotic states in bottomonium, stay tune for Roman's talk on Friday

artistic illustration

Charmonium Spectroscopy

- Mass and width measurement of η_c in $\gamma\gamma \rightarrow \eta'\pi\pi$ **Belle, PRD 86,052002 (2012)**
- Observation of *Ψ(4040)* and *Ψ(4160)* in $J/\Psi\eta$ via *ISR* **Belle, PRD 87, 051101(R)(2013)**
- First evidence *of* $\Psi_2 \rightarrow \chi_{c1}\gamma$ ***arXiv:1304.3975***

$c\bar{c}$ spectrum



Previously measured η_c parameters

Experiment	Process	Mass, MeV/c^2	Width, MeV/c^2
E835 2001	$p\bar{p} \to \gamma\gamma$	$2984.1 \pm 2.1 \pm 1.0$	$20.4^{+7.7}_{-6.7} \pm 2.0$
BES 2003	$J/\Psi \to \gamma\eta_c$	$2977.5 \pm 1.0 \pm 1.2$	$17.0 \pm 3.7 \pm 7.4$
CLEO 2004	$\gamma\gamma \to K_s^0 K^+ \pi^-$	$2981.8 \pm 1.3 \pm 1.5$	$24.8 \pm 3.4 \pm 3.5$
Belle 2008	$\gamma\gamma \to hadrons$	$2986.1 \pm 1.0 \pm 2.5$	$28.1 \pm 3.2 \pm 2.2$
BaBar 2008	$B \to K\bar{K}\pi K^{(*)}$	$2985.8 \pm 1.5 \pm 3.1$	$36.3^{+3.7}_{-3.6} \pm 4.4$
Belle 2008	$\gamma\gamma \to K_s^0 K^+ \pi^-$	$2981.4 \pm 0.5 \pm 0.4$	$36.6 \pm 1.5 \pm 2.0$
BaBar 2010	$\gamma\gamma \to K_s^0 K^+ \pi^-$	$2982.5 \pm 0.4 \pm 1.4$	$32.2 \pm 1.1 \pm 1.3$
BaBar 2011	$\gamma\gamma \to K^- K^+ \pi^- \pi^+ \pi^0$	$2984.5 \pm 0.8 \pm 3.1$	$36.2 \pm 2.8 \pm 3.0$
Belle 2011	$B^\pm \to K^\pm (K_S^0 K^\pm \pi^\mp)$	$2985.4 \pm 1.5^{+0.5}_{-2.0}$	$35.1 \pm 3.1^{+1.0}_{-1.6}$
PDG	World average	2981.0±1.1	29.7±1.0

Largest
Smallest
Nearby

Some measurements are ~ 5MeV/c^2 (mass) or ~ 10 MeV/c^2 (width) away from the PDG average

η_c in $\gamma\gamma \to \eta' \pi^+ \pi^-$

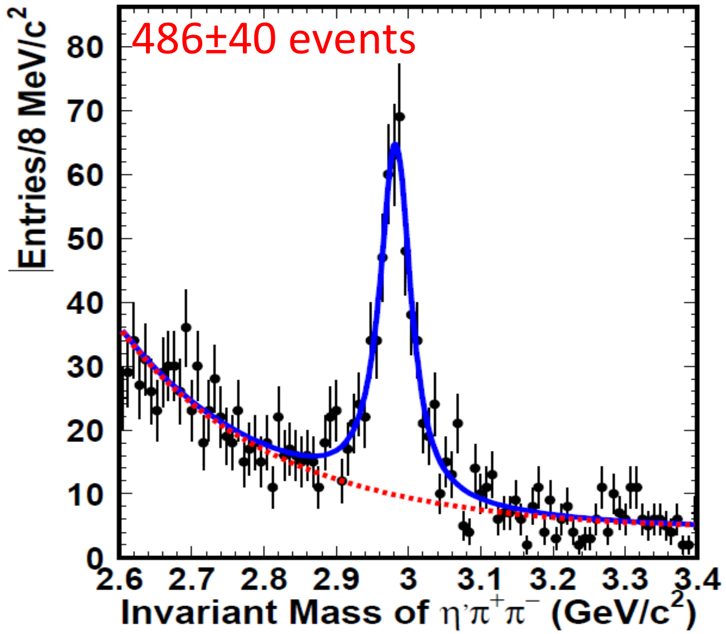
- Measurement of mass and width in $\eta_c \to \eta' \pi^+ \pi^-$ in $\gamma\gamma$ can provide useful information.
- No direct measurement of $\Gamma_{\gamma\gamma} \times \mathcal{B}$ for the decay $\eta_c \to \eta' \pi^+ \pi^-$ is available so far.

η_c in $\gamma\gamma \to \eta'\pi^+\pi^-$

Belle, PRD 86,052002 (2012)

No interference between η_c and non-resonant background is assumed.

Parameters	Belle	PDG
M, MeV/c²	2982.7±1.8±2.2	2981.0±1.1
Γ, MeV/c²	$37.8^{+5.8}_{-5.3}\pm2.8$	29.7±1.0
$\Gamma_{\gamma\gamma}\mathcal{B}$, eV/c²	$50.5^{+4.2}_{-4.1}\pm5.6$	143.1±60.1*
$\mathcal{B}$, %	0.87±0.20†	2.7±1.1



$\eta' \to \eta\pi^+\pi^-$

$\quad \hookrightarrow \gamma\gamma$

- Fit with interference is also tried.
- Results of mass and width of η_c are almost same.
- Possible difference has been added as a systematic uncertainty.
- Improvement in the branching fraction is striking.

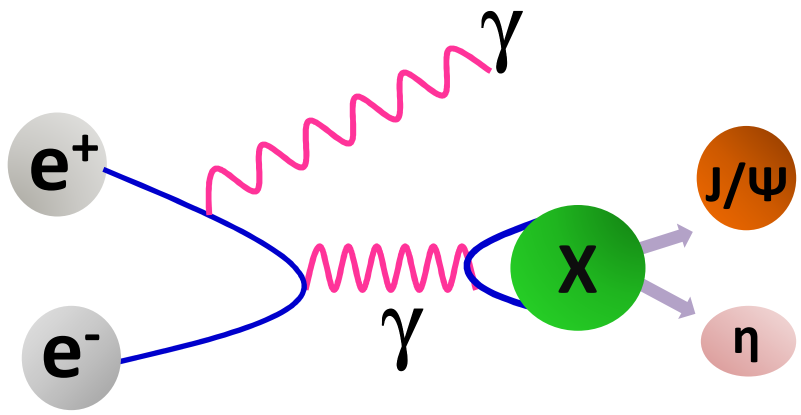
*Using indirect measurement, $\Gamma_{\gamma\gamma}$ and $\mathcal{B}(\eta_c \to \eta'\pi^+\pi^-)$ measured separately.

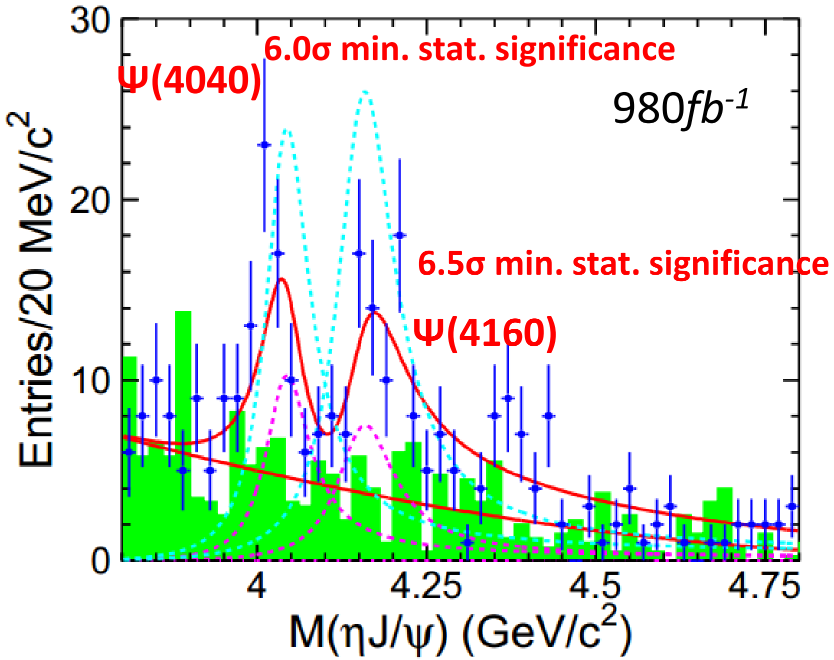
†$\Gamma_{\gamma\gamma}$ is determined using $\Gamma_{\gamma\gamma}\Gamma_{K\bar{K}\pi}/\Gamma_{total}$ and $\Gamma_{K\bar{K}\pi}/\Gamma_{total}$

$e^+e^- \rightarrow \gamma_{ISR} J/\Psi\eta$ process

Belle, PRD 87, 051101(R)(2013)

- Many *Y*-particles have been found in $J/\Psi\pi^+\pi^-$ and $\Psi'\pi^+\pi^-$ modes.
- $J/\Psi\eta$ mode has not yet been visited.



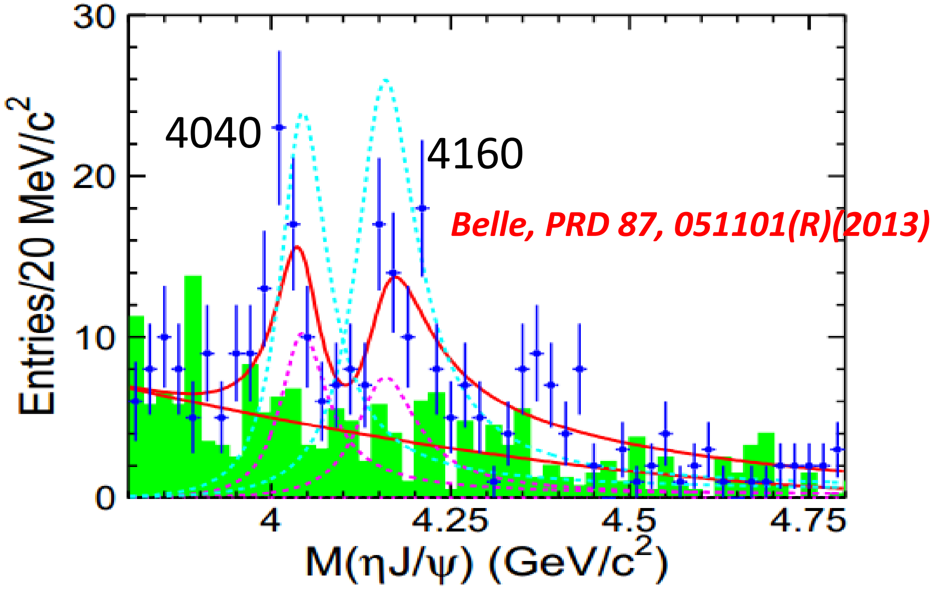


Parameters	Solution I	Solution II
$M_{\Psi(4040)}$ (MeV)	4039 (fixed)	
$\Gamma_{\Psi(4040)}$ (MeV)	80 (fixed)	
$B.\Gamma^{\psi(4040)}_{e+e-}$ (eV)	4.8±0.9±1.4	11.2±1.3±1.9
$M_{\Psi(4160)}$ (MeV)	4153 (fixed)	
$\Gamma_{\Psi(4160)}$ (MeV)	103 (fixed)	
$B.\Gamma^{\psi(4160)}_{e+e-}$ (eV)	4.0±0.8±1.4	13.8±1.3±2.0
ϕ	336±12±14	251±4±7

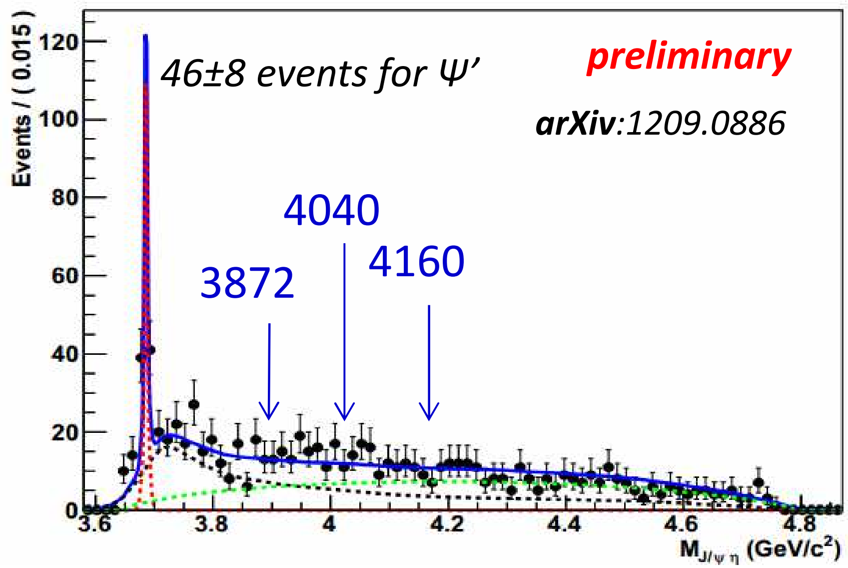
- First time *Ψ(4040)* and *Ψ(4160)* have been observed to decay into $J/\Psi\eta$
- Their dominant decay modes are known to be $D\bar{D}$, $D^*\bar{D}$, $D^*\bar{D}^*$, $D^0D^*\pi$ as seen at BaBar. CLEO and Belle.
- No evidence for the *Y(4260), Y (4360), Ψ(4415) or Y(4660)* in the $J/\Psi\eta$ final states.

Comparing with $B \rightarrow J/\Psi \eta K$ decay

$e^+e^- \rightarrow \gamma_{ISR} J/\Psi \eta$



$B^+ \rightarrow J/\Psi \eta K^+$



- No *Ψ(4040)* or *Ψ(4160)* in *J/Ψη* seen in *B→J/ΨηK* study

- Assuming that $\mathcal{B}$*(B→Ψ(4040* or *4160)K)* = $\mathcal{B}$*(B→Ψ'K),* expected signal yield is 5~20 events for *Ψ(4040 or 4160)* in my own estimation*.
- In *B* decay, peak(s) may not become apparent considering their natural width.
- Thus both results seem to be not contradicting with each other.

*Taking Γ_{ee} ~ 0.8keV from PDG

$\mathcal{B}$*(Ψ'→J/Ψη)* = 3.6±0.1%[PDG]

$\mathcal{B}$(*Ψ(4040)→J/Ψη*) ~ 0.6 % or 1.4 % and $\mathcal{B}$(*Ψ(4160)→J/Ψη*) ~ 0.5 % or 1.7 %

$B \rightarrow \chi_{c1}\gamma K$ and $B \rightarrow \chi_{c2}\gamma K$

- $\chi_{c1}\gamma$ and $\chi_{c2}\gamma$: suitable final state to look for either *X(3872)*'s C-odd partner or unseen charmonium.
- ***"B decay"*** is the proper process for such purpose.
- Theory predicts $^3D_2$ $c\bar{c}$ state to lie around ~3810-3840 MeV/c^2 mass and be narrow.

  Partial width, $\Gamma(\Psi_2 \rightarrow \chi_{c1}\gamma)$ = 260 keV.
- Along with this, there should be $^3D_3$ $c\bar{c}$ state lying around ~ 3830-3880 MeV/c^2 mass and will decay into $\chi_{c2}\gamma$.

  Partial width, $\Gamma(\Psi_3 \rightarrow \chi_{c2}\gamma)$ = 286 keV.

S. Godfrey & N. Isgur, PRD 32, 189 (1985)
E. Eichten et al., PRL 89,162002 (2002), PRD 69, 094019 (2004)

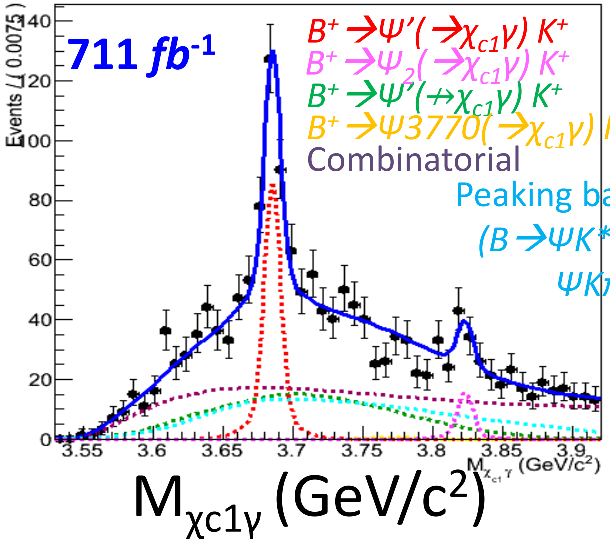
✓ With current statistics, we expect to find some hint of Ψ_2 and Ψ_3.

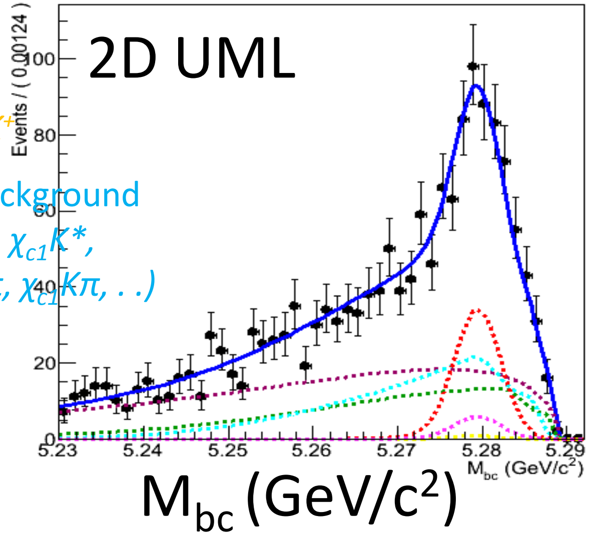
Search for new exotic states in $\chi_{c1}\gamma$ and $\chi_{c2}\gamma$ by scanning $M_{\chi c1,c2\gamma}$ (mass distribution) for narrow peak.

arXiv:1304.3975

New state @ 3823

$B^{\pm} \rightarrow \chi_{c1}\gamma K^{\pm}$





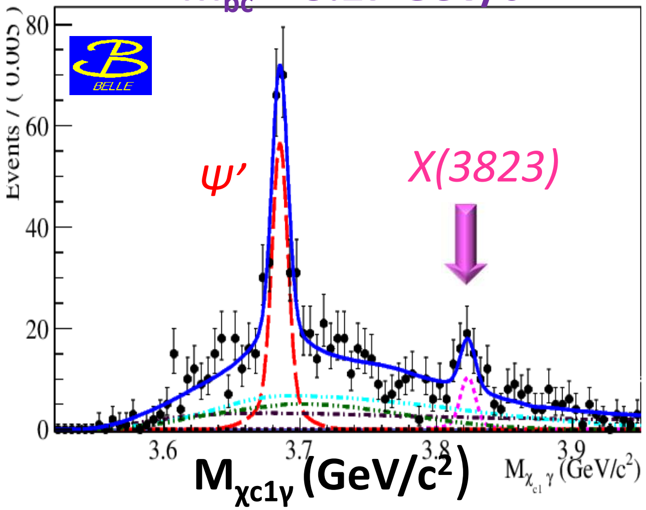
Clear evidence of a peak at 3823MeV/c^2

Yield: 3.8σ (syst. Included)
33.2±9.7 events

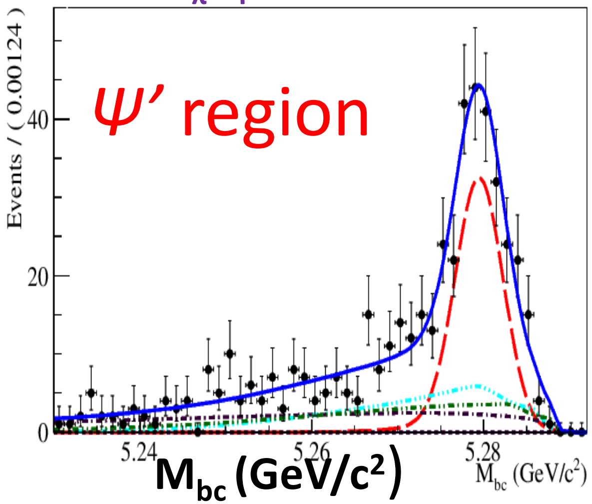
Γ = 1.7±5.5 MeV if fitted, poor sensitivity

Projection in signal region

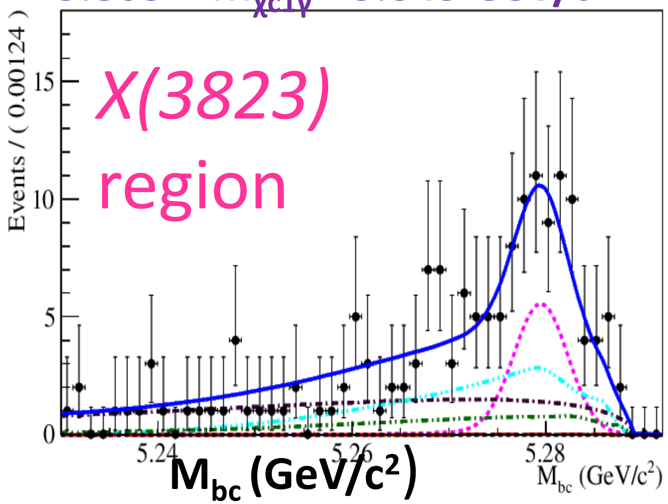
M_{bc} > 5.27 GeV/c^2



3.66 < $M_{\chi c1\gamma}$ <3.708 GeV/c^2

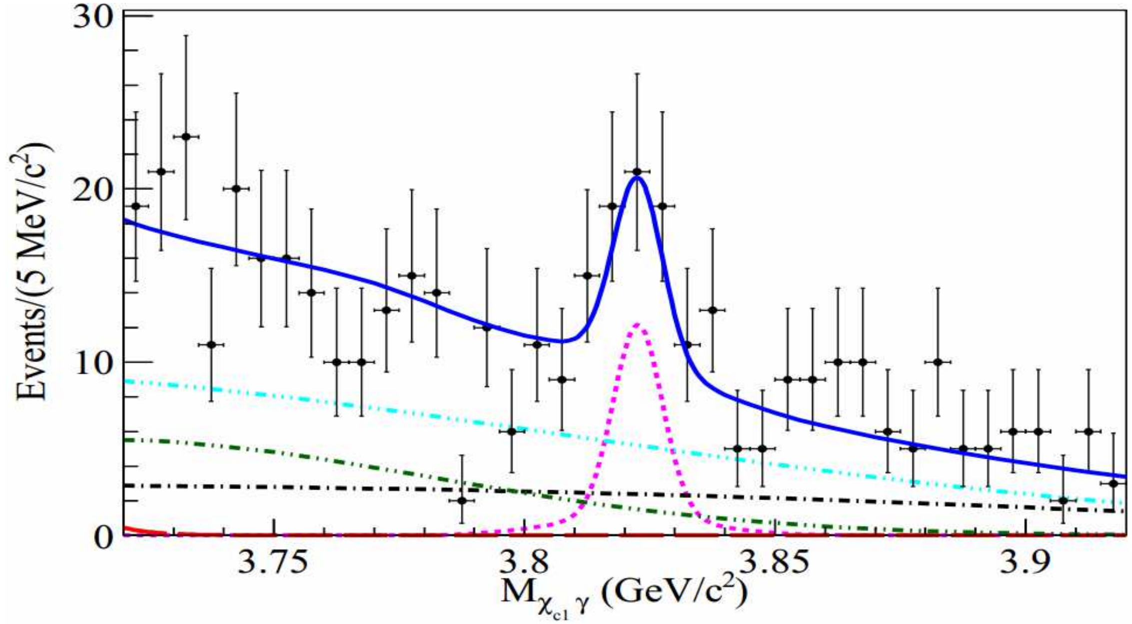


3.805 < $M_{\chi c1\gamma}$ <3.845 GeV/c^2



arXiv:1304.3975

Measuring its properties



Simultaneous fit to $B^+ \to X(3823)K^+$ and $B^0 \to X(3823)K_S^0$

Mean : 3823.1 ± 1.8 (stat)± 0.7(syst) MeV/c²

Γ : 1.7 ± 5.5 (stat) MeV/c²
(Γ< 24 MeV @ 90% UL)*

**** Using frequentist method***

Statistics not sufficient for width estimation and angular analysis.

Along with this $B \to (\chi_{c2}\gamma)$ K study is also performed
No significant peak is observed and we measured U.L. on $\mathcal{B}(B \to X(3823)K).\mathcal{B}(X(3823) \to \chi_{c2}\gamma))$

$$\frac{\Gamma(X(3823)\to\chi_{c2}\gamma)}{\Gamma(X(3823)\to\chi_{c1}\gamma)} < \mathbf{0.41} \text{ (@ 90\% CL)}$$

Let's see if this state can be interpreted as one of the unseen charmonia.

arXiv:1304.3975

Interpretation of *X(3823)* as Ψ_2

TABLE III: Charmonium spectrum, including the influence of open-charm channels. All masses are in MeV. The penultimate column holds an estimate of the spin splitting due to tensor and spin-orbit forces in a single-channel potential model. The last column gives the spin splitting induced by communication with open-charm states, for an initially unsplit multiplet.

State	Mass	Centroid	Splitting (Potential)	Splitting (Induced)
1^1S_0	$2\,979.9^a$	$3\,067.6^b$	−90.5	+2.8
1^3S_1	$3\,096.9^a$		+30.2	−0.9
1^3P_0	$3\,415.3^a$	$3\,525.3^c$	-114.9^e	+5.9
1^3P_1	$3\,510.5^a$		-11.6^e	−2.0
1^1P_1	3 525.3		$+1.5^e$	+0.5
1^3P_2	$3\,556.2^a$		-31.9^e	−0.3
2^1S_0	$3\,637.7^a$	$3\,673.9^b$	−50.4	+15.7
2^3S_1	$3\,686.0^a$		+16.8	−5.2
1^3D_1	$3\,769.9^{ab}$		−40	−39.9
1^3D_2	3 830.6	$(3\,815)^d$	0	−2.7
1^1D_2	3 838.0		0	+4.2
1^3D_3	3 868.3		+20	+19.0
2^3P_0	3 931.9	$3\,968^d$	−90	+10
2^3P_1	4 007.5		−8	+28.4
2^1P_1	3 968.0		0	−11.9
2^3P_2	3 966.5		+25	−33.1

S. Godfrey & N. Isgur, PRD 32, 189 (1985)
E. Eichten et al., PRL 89,162002 (2002),
PRD 69, 094019 (2004)

Three states with similar mass (predicted): $^3D_2$, $^1D_2$, $^3D_3$

- $^1D_2$ excluded due to C conservation in EM decays.
- $^3D_3$ doesn't have E1 transition to $\chi_{c1}\gamma$
- $^3D_2$ seems to be appropriate

- Ψ_2 below $D\bar{D}^*$ threshold: expected to have narrow decay width of 300-400 keV
- $\Psi_2 \to DD$ is forbidden due to parity
- Mostly decaying into $\chi_{c1}\gamma$.

- ✓ The observed peak (@3823) has not been seen in $D\bar{D}$ ($^3D_2 \nrightarrow DD$ is expected).
- ✓ $\frac{\Gamma(X(3823)\to\chi_{c2}\gamma)}{\Gamma(X(3823)\to\chi_{c1}\gamma)}$ <0.41 (@ 90% CL) , Expected $\frac{\Gamma(\Psi_2\to\chi_{c2}\gamma)}{\Gamma(\Psi_2\to\chi_{c1}\gamma)}$ ~ 0.2 (model dependent)

PRL 89, 162002 (2002); PRD 67, 014027 (2003)

If we assume, $\mathcal{B}(\Psi_2\to\chi_{c1}\gamma) = 0.64$ PRD 55, 4001 (1997), PLB 395, 107 (1997)

$$\frac{BR(B\to\Psi_2 K)}{BR(B\to\Psi' K)} \sim 0.02$$

Factorization penalty similar to the one observed in $B\to\chi_{c2}K$

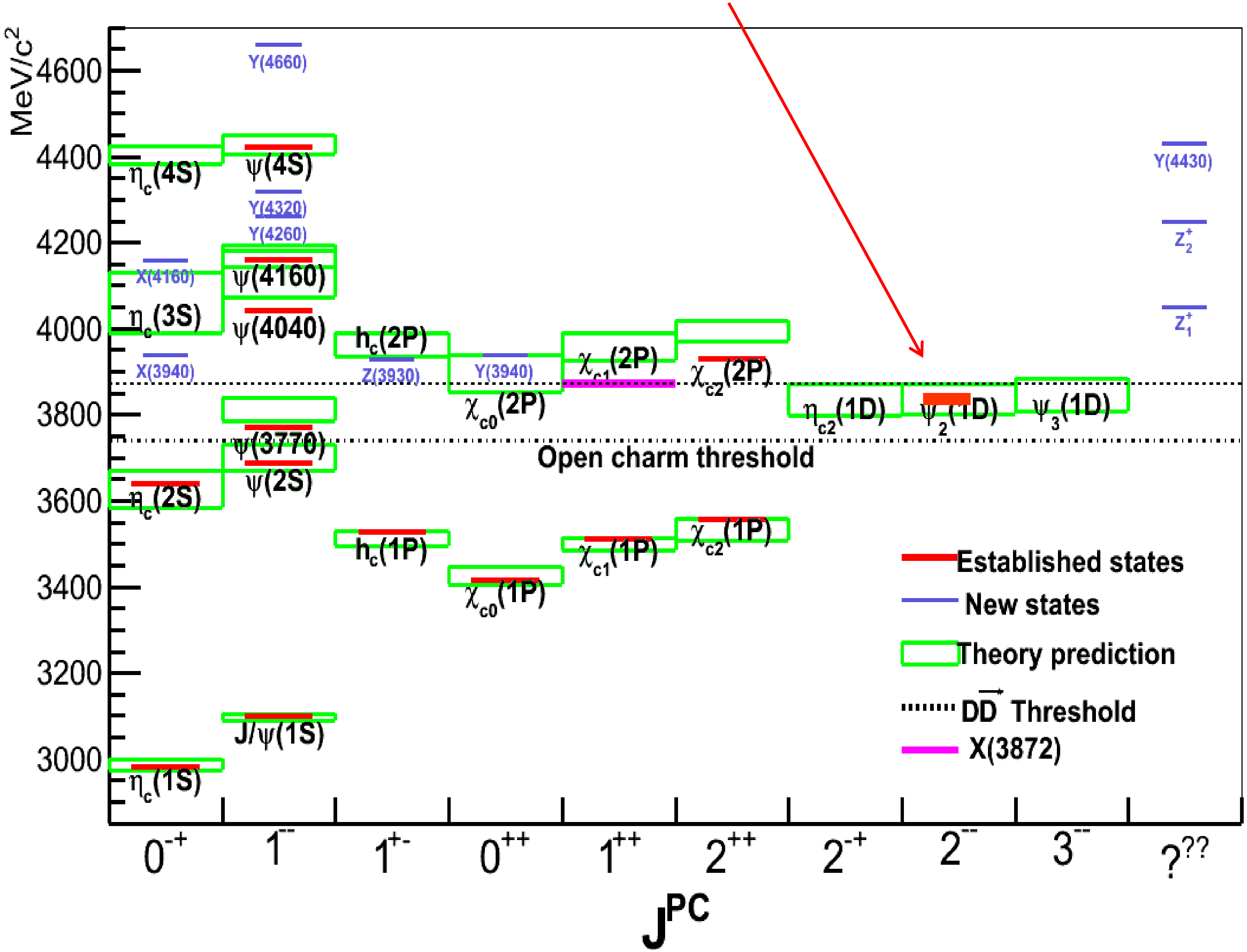
$$\frac{BR(B\to\chi_{c2} K)}{BR(B\to\chi_{c1} K)} = 0.022\pm0.007$$

Belle, PRL 107, 091803 (2011)

- ✓ Suppression w.r.t. to $J^{PC}=1^{--}$, similar to the observed suppression of $J^{PC}=2^{++}$ w.r.t. $J^{PC}=1^{++}$.

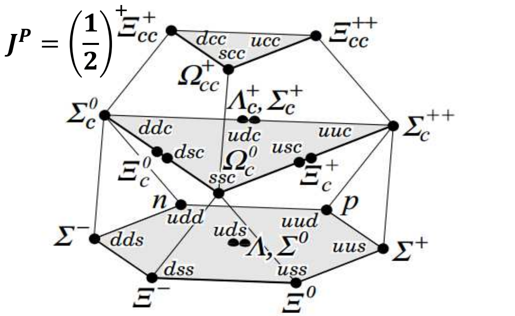
$X(3823)$ seems to be the missing Ψ_2 from the charmonium spectrum .

New member added



Search For
Doubly Charmed Baryon

Doubly charmed Baryon (Ξ_{cc}^{+})

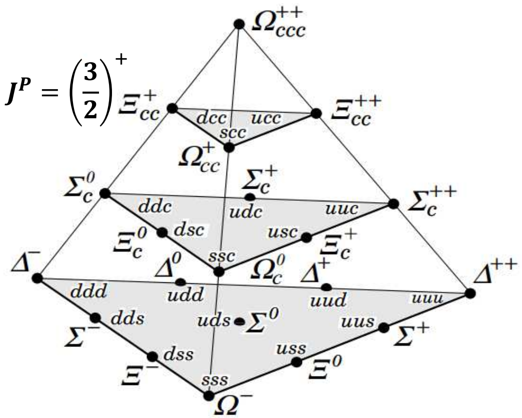


Doubly charmed states combine two extreme regimes inside them:

i) Slow relative motion of two heavy quark, as in charmonium

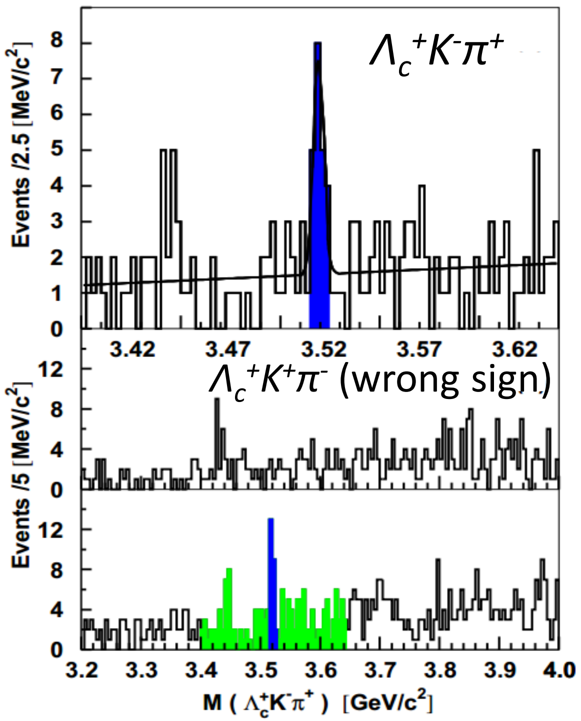
ii) Fast motion of light quark.

Doubly charmed baryons provide a new window for understanding the structure of all baryons



- **Lightest doubly-charmed baryons can exist with either quark content ccu, Ξ_{cc}^{++} or ccd, Ξ_{cc}^{+}.**
- **Models generally predict mass range of 3.52-3.66 for J^P=1/2$^+$ ground state and 3.636-3.66 GeV for J^P=3/2$^+$ excited state.**

SELEX, PRL 89, 112001 (2002)
SELEX. PLB 628. 18 (2005)



- SELEX observed statistically compelling high mass states near 3.6 GeV/c^2
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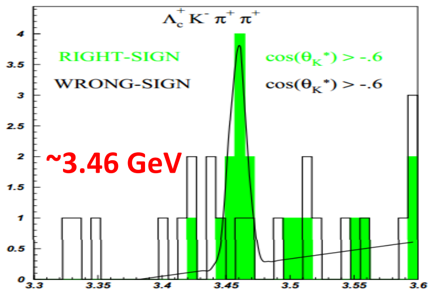

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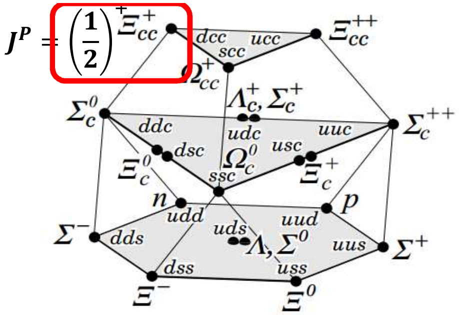
Doubly charmed Baryon (Ξ_{cc}^{+})



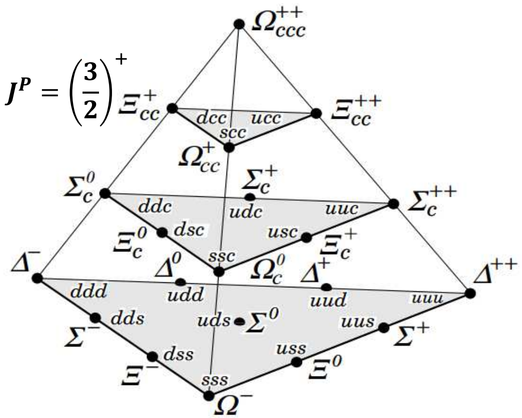
Doubly charmed states combine two extreme regimes inside them:

i) Slow relative motion of two heavy quark, as in charmonium

ii) Fast motion of light quark.

Doubly charmed baryons provide a new window for understanding the structure of all baryons

- **Lightest doubly-charmed baryons can exist with either quark content ccu, Ξ_{cc}^{++} or ccd, Ξ_{cc}^{+}.**
- **Models generally predict mass range of 3.52-3.66 for $J^P=1/2^+$ ground state and 3.636-3.66 GeV for $J^P=3/2^+$ excited state.**



SELEX, PRL 89, 112001 (2002)

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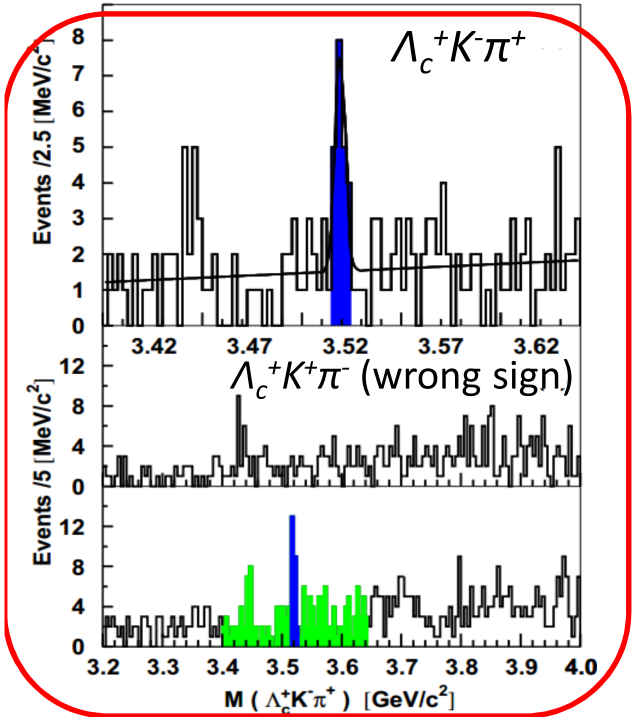

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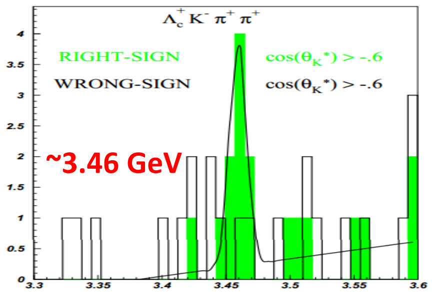

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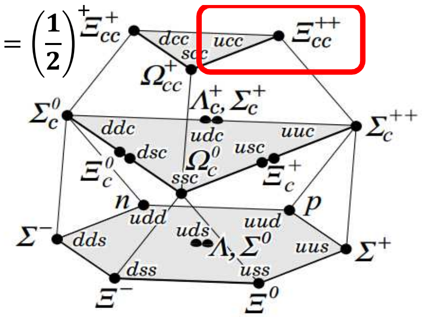

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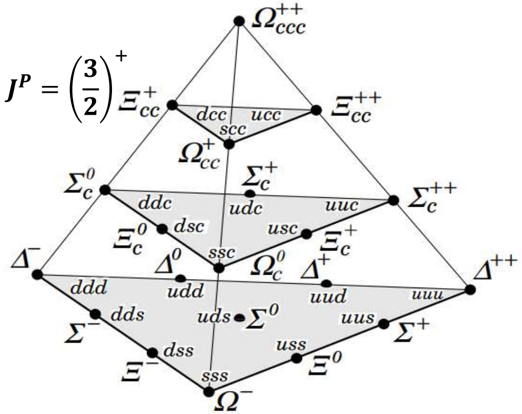

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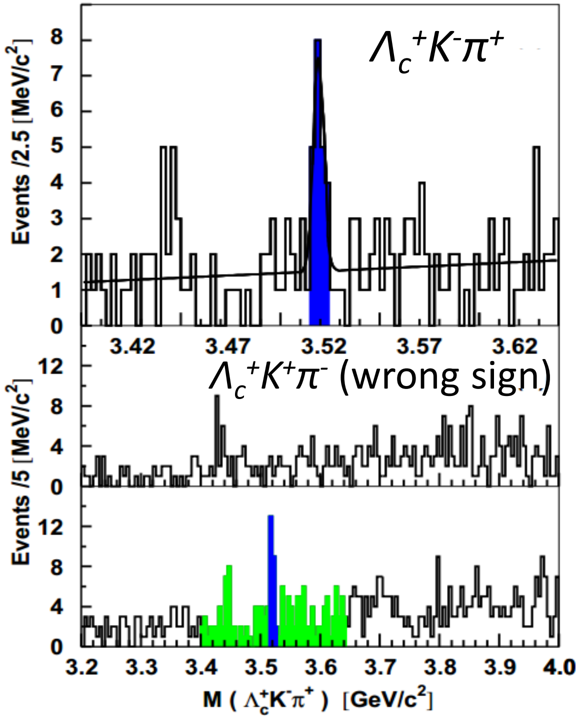

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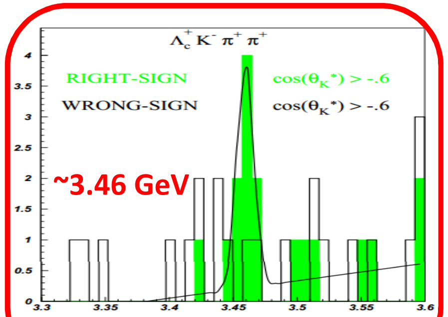

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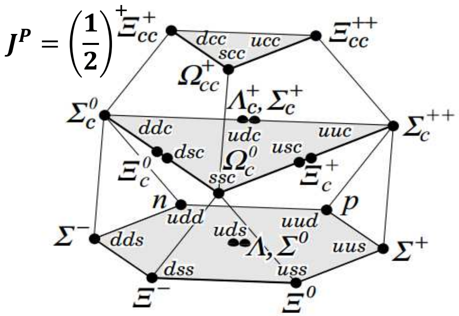

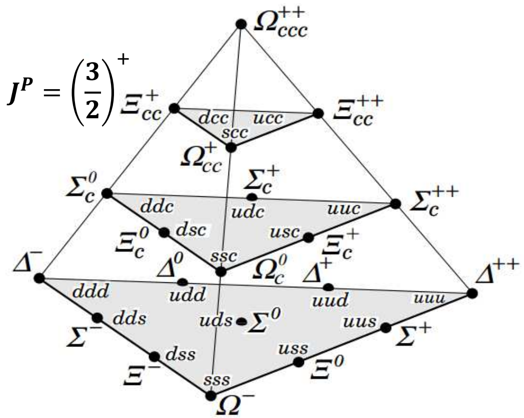

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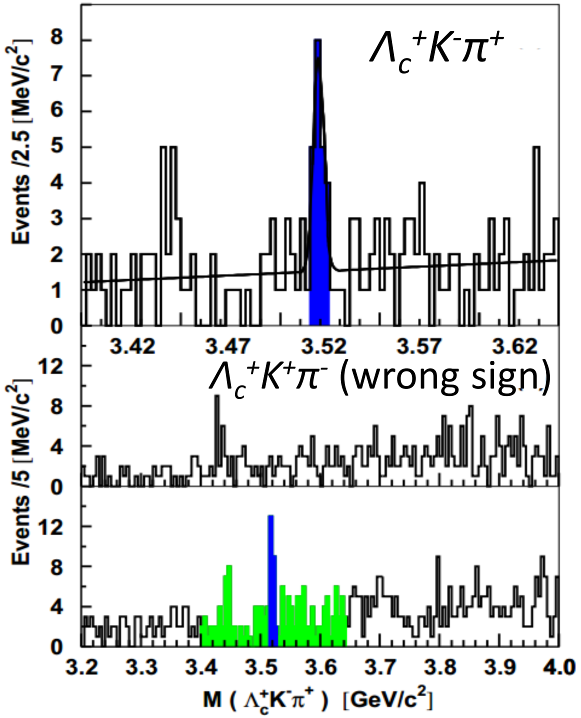

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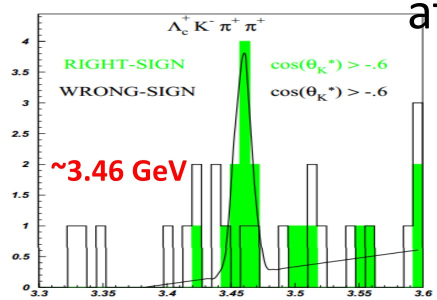
Production cross-section for $e^+e^- \rightarrow \Xi_{cc} X$ at B factories : 3 fb to 230 fb



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

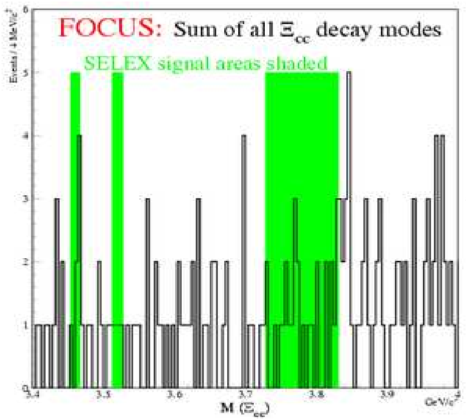
PLB 332, 411(1994);
Phys. Atom. Nucl, 65, 1537 (2002
PLB 568 568 (2003)

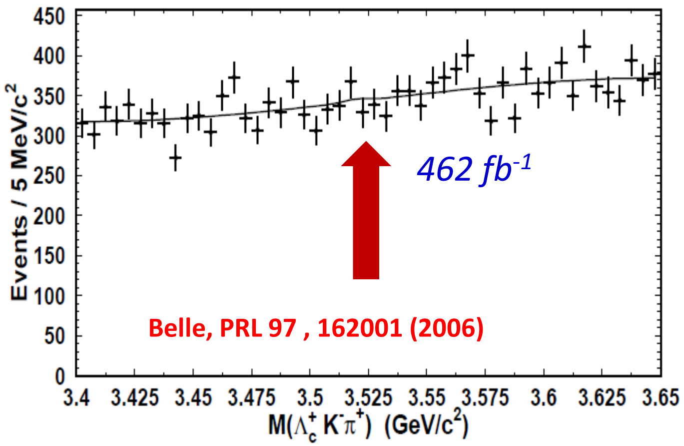
We should perform confirmation at B factories !

Searches in other experiments

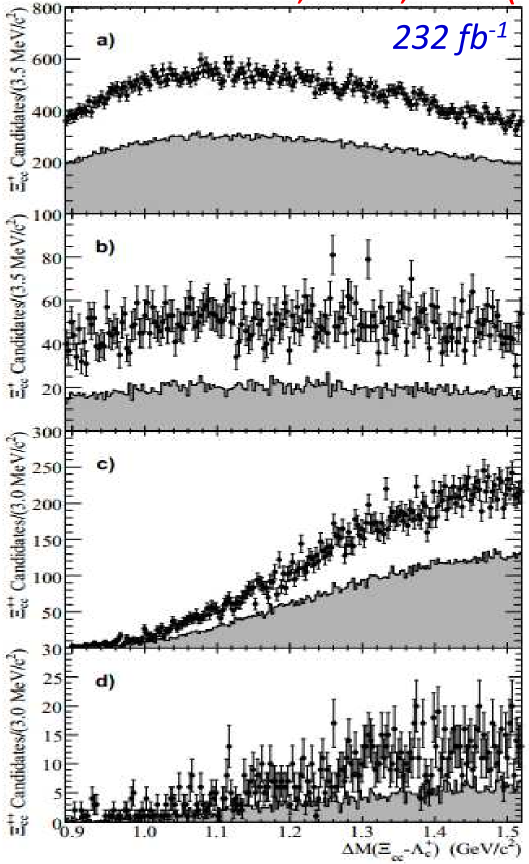
In order to establish Ξ_{cc} state, confirmation at other experiment necessary.

FOCUS, NPB proc. 115, 33(2003)





BaBar, PRD 74 , 011103 (2006)



Experiment	Limit on $R_{\Xi cc+/\Lambda c+}$	Kinematic cuts
BaBar	6.9×10^{-4} @95% CL	
BaBar	2.7×10^{-4} @95% CL	p*> 2.3 GeV/c
Belle	1.5×10^{-4} @90% CL	p*> 2.5 GeV/c
Focus	2.3×10^{-3} @95% CL	

- SELEX results have not been confirmed by FOCUS, Belle and BaBar.
- Belle doubled the data statistics with improved reconstruction.
- We revisit this topic with an effort to have additional final states.

Search for $\Xi_{cc}^{+(+)}$

980fb^{-1} data is used in this search.
Previous study uses $pK^-\pi^+$ to reconstruct Λ_c^+ and only $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$.

$\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$
$\to \Xi_c^0 \pi^+$ NEW

NEW
$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$
$\to \Xi_c^0 \pi^+ \pi^+$

$\Lambda_c^+ \to pK^-\pi^+$
$\to p K_S^0$ NEW

NEW
$\Xi_c^0 \to \Xi^- \pi^+$
$\to \Lambda K^- \pi^+$
$\to pK^- K^- \pi^+$

$\Lambda \to p\pi^-$
$K_S^0 \to \pi^-\pi^+$

$\Lambda_c^+ \to pK_S$ mode helps in increasing statistics by 20%.

Inclusion of $\Xi_c^0 \to \Lambda K^- \pi^+$ and $pK^-K^-\pi$, increase statistics by 80% for Ξ_{cc}^+

To reduce background X_p>0.5 is required , where $X_p = p_{cm}/p_{max}$; $p_{max} = \mathrm{sqrt}(E_{cm}^2 - M_{\Xi cc}^2)$

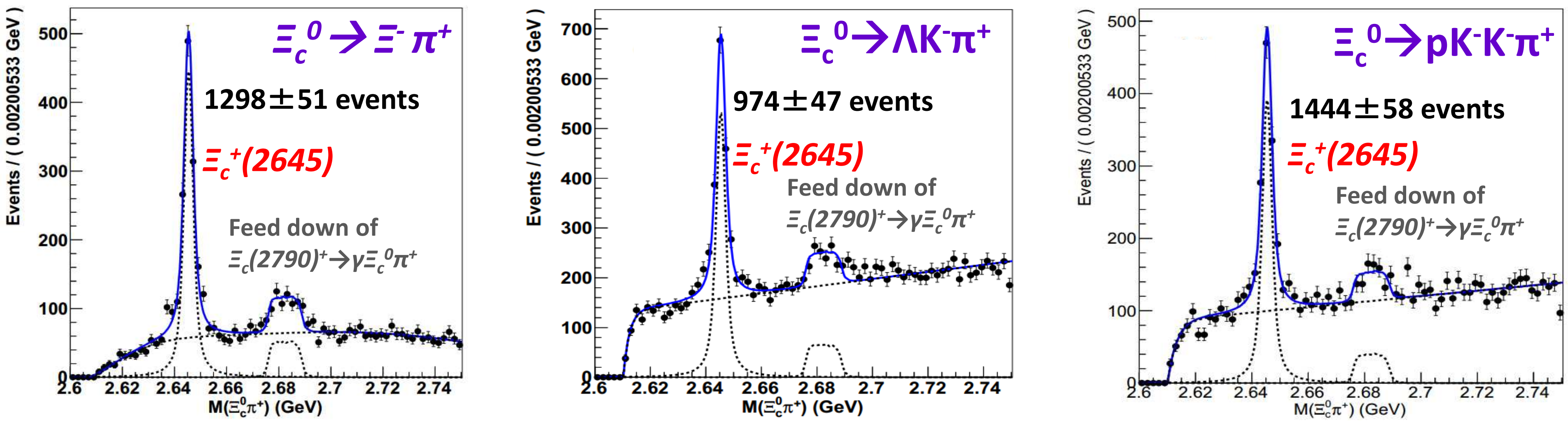
$\Xi_c^0\pi^+$ is a strong decay mode of $\Xi_c^+(2645)$ ($J^P=3/2^+$) as well as weak decay of Ξ_{cc}^+

$\Xi_c^+(2645) \to \Xi_c^0\pi^+$ is used as calibration sample for Ξ_{cc}

preliminary

Landmark state, $\Xi_c^+(2645)$

Signal PDF: Gaussian convoluted BW (σ = 1.05 MeV from MC)



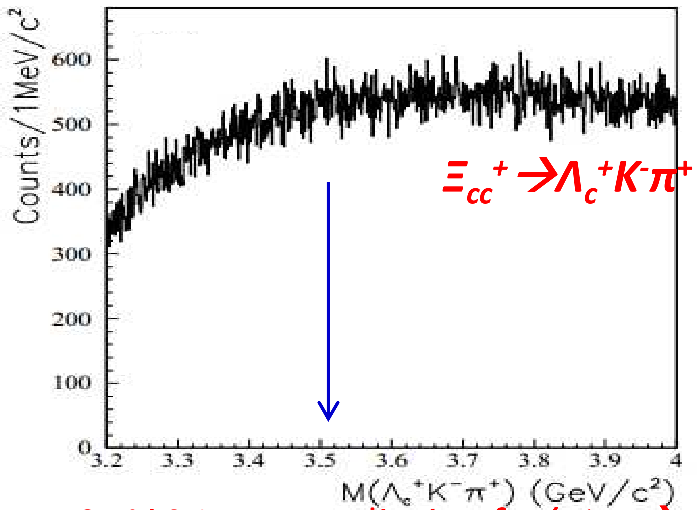
Submode→	$\Xi_c^0 \to \Xi^- \pi^+$	$\Xi_c^0 \to \Lambda K^- \pi^+$	$\Xi_c^0 \to p K^- K^- \pi^+$	Simultaneous fit	PDG
Mass(GeV/c²)	2645.4±0.1	2645.3±0.1	2645.5±0.1	2645.4±0.1**(stat only)**	2645.9±0.6
Width(GeV/c²)	2.9±0.3	2.6±0.3	2.5±0.3	2.6±0.2±0.4	<3.1

- All sub modes give consistent Mass and width of $\Xi_c^+(2645)$.
- Systematics come from : BG shape, fitting region, ensemble study and difference of data and MC resolution .

First precise measurement of the width of $\Xi_c^+(2645)$
Accuracy of the mass is also significantly improved.

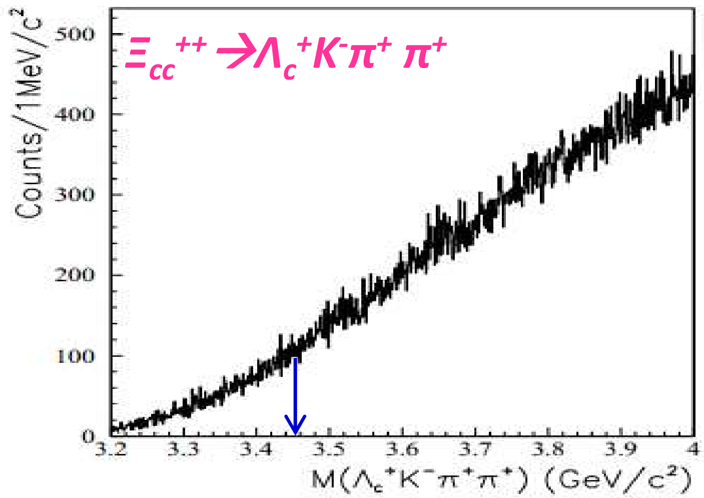
preliminary

Search for $\Xi_{cc}^{+(+)}$



Arrow shows the mass claimed by SELEX

Expected mass resolution: 2.0-3.5 MeV/c^2 depending upon the mass



95%C.L. upper limit of $\sigma(e^+e^- \rightarrow \Xi_{cc}X) \times \mathcal{B}(\Xi_{cc}^+ \rightarrow \Lambda_c K^- \pi^+)$ < 4.6-20.5 fb

95%C.L. upper limit of $\sigma(e^+e^- \rightarrow \Xi_{cc}X) \times \mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c K^- \pi^+ \pi^+)$ < 2.5-26.0 fb

preliminary

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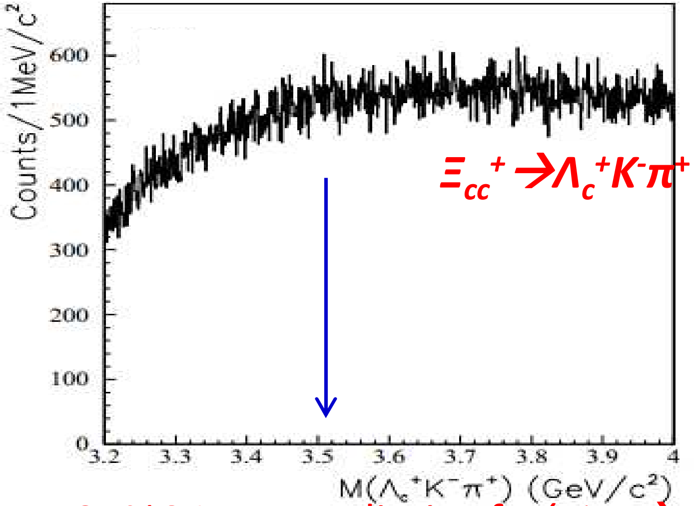

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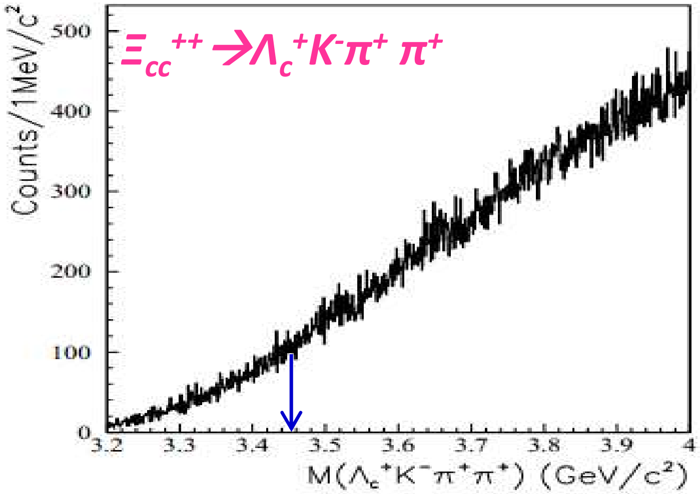

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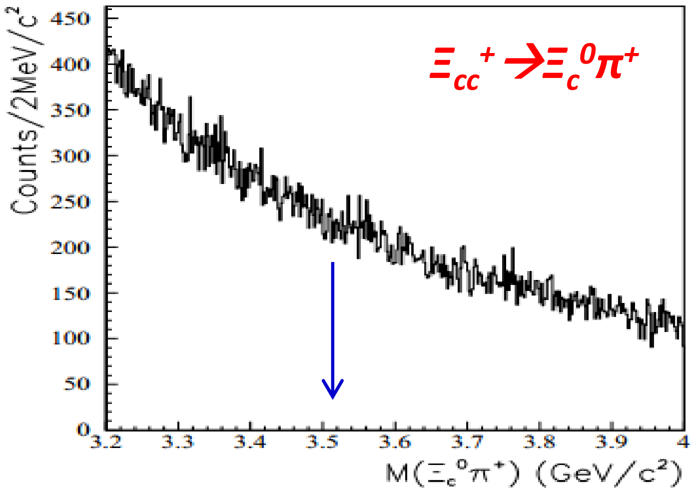
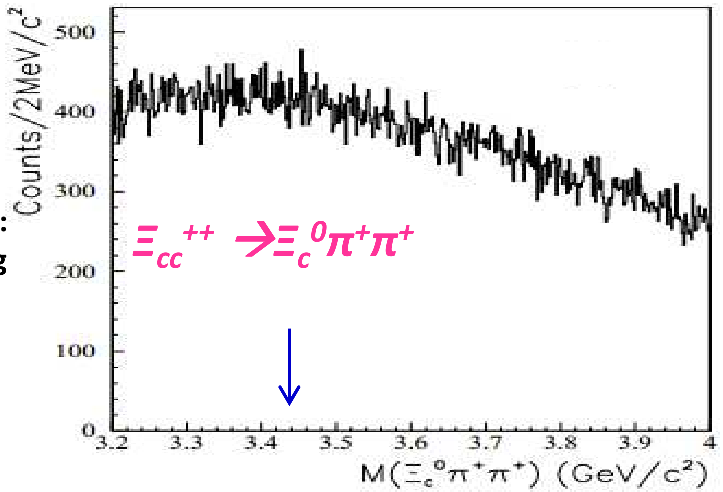


Expected mass resolution: 2.7-4.2 MeV/c² depending upon the mass



95%C.L. upper limit of $\sigma(e^+e^- \rightarrow \Xi_{cc}X) \times \mathcal{B}(\Xi_{cc}^{+} \rightarrow \Xi_c^0 \pi^+) \times \mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+)$ < 0.76-0.26 fb

95%C.L. upper limit of $\sigma(e^+e^- \rightarrow \Xi_{cc}X) \times \mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c^0 \pi^+ \pi^+) \times \mathcal{B}(\Xi_c^0 \rightarrow \Xi^- \pi^+)$ < 0.094-0.36 fb

- No significant signal is seen

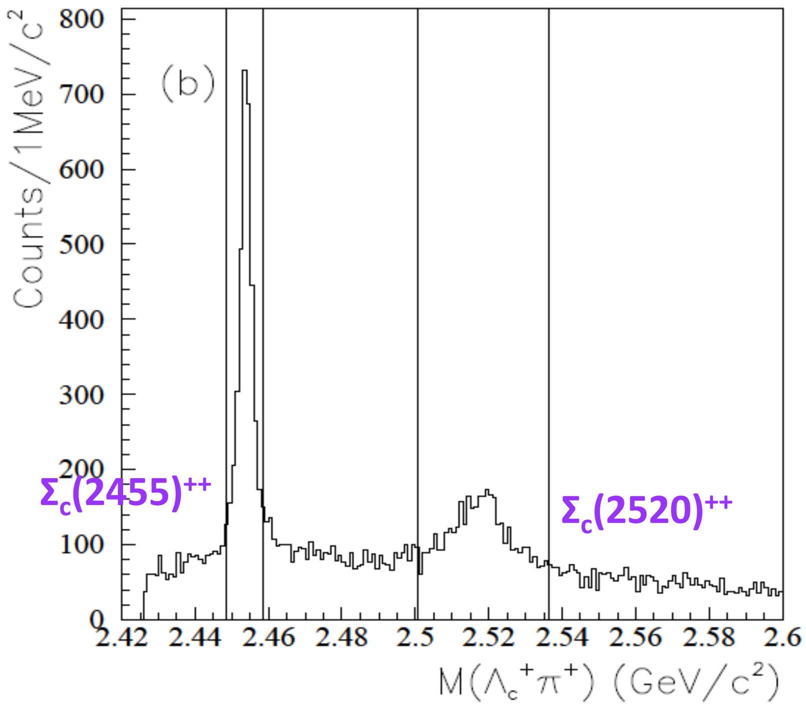
Excited Ξ_c^+ in $\Lambda_c^+ K \pi^+$

Along with confirming Belle's $\Xi_c^+(2980)$ and $\Xi_c^+(3080)$, BaBar also found two excited states:

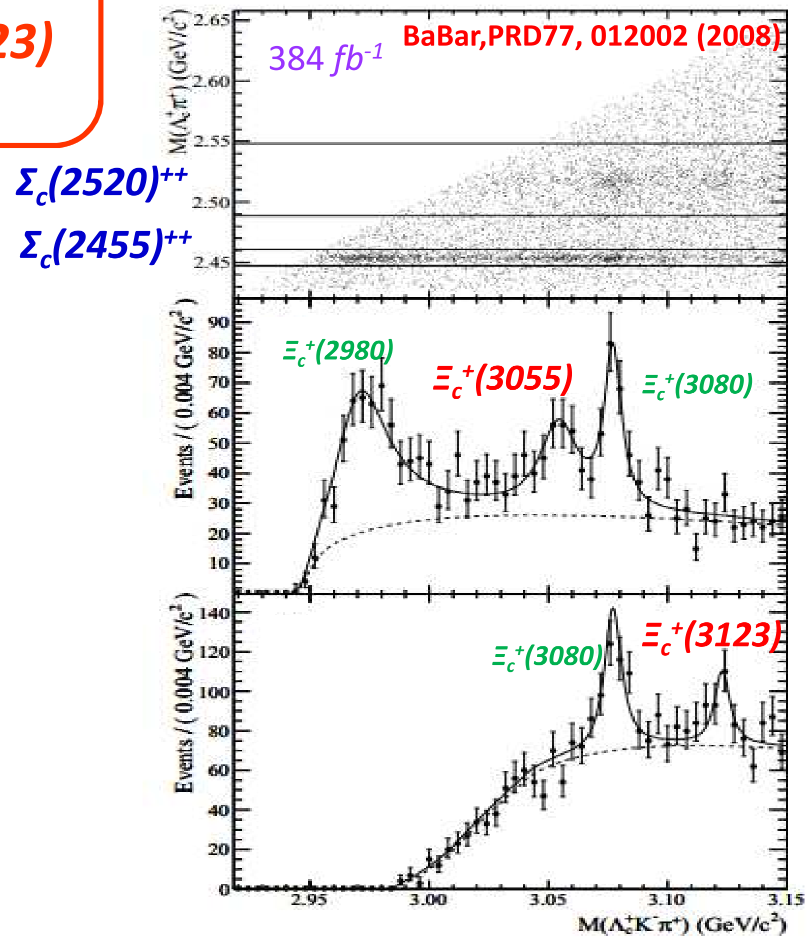
$\Xi_c^+(3055)$ and $\Xi_c^+(3123)$

Still awaiting confirmation by other experiment

$x_P > 0.7$ (similar to BaBar's cut on p^*>2.9 GeV/c)

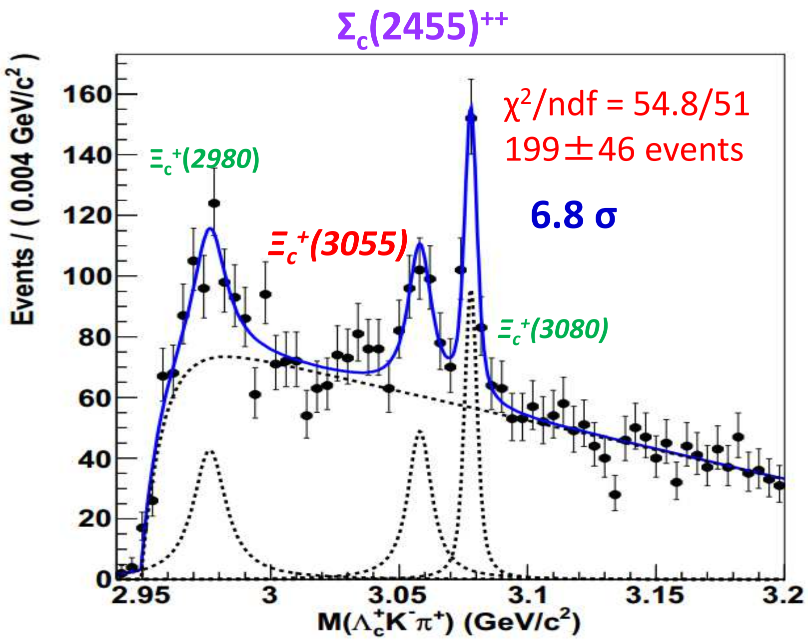


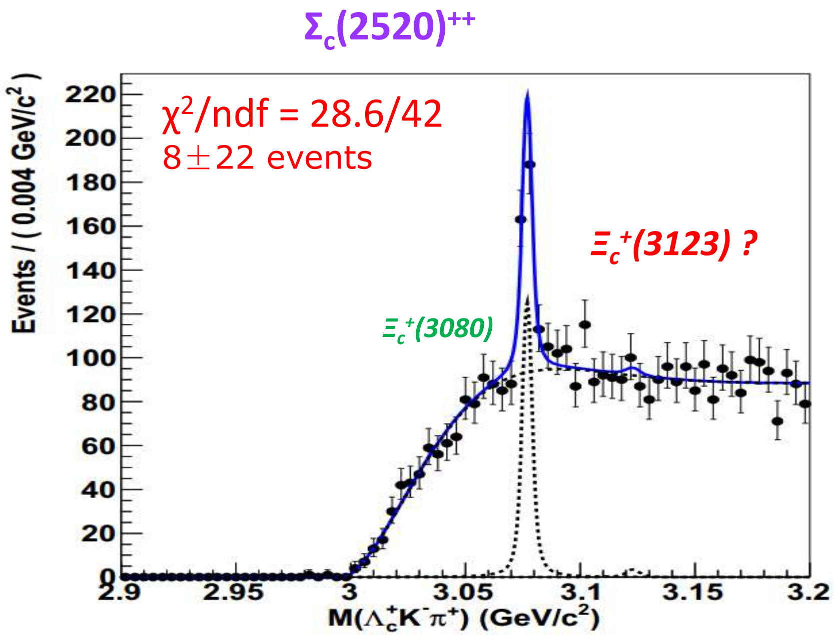
$|M(\Lambda_c \pi^+)-M_{\Sigma c(2445)+}| < 5$ MeV/c^2
$|M(\Lambda_c \pi^+)-M_{\Sigma c(2520)+}| < 18$ MeV/c^2



preliminary

$\Xi_c^+(3055)$ and $\Xi_c^+(3123)$; seen or unseen ?





	Yield	Belle results (MeV/c^2)		World Averages (MeV/c^2)	
		Mass	Width	Mass	Width
$\Xi_c(2980)^+$	244±39	2974.9±1.5±0.4	14.8±2.5±1.0	2971.4±3.3	26±7
$\Xi_c(3055)^+$	199±46	3058.1±1.0±0.5	9.7±3.4±1.0	3054.2±1.2±0.5	17±6±11
$\Xi_c(3080)^+$	185±31	3077.9±0.4±0.1	3.2±1.3±0.3	3077.0±0.4	5.8±1.0

Belle confirmed $\Xi_c(3055)^+$ but could not see $\Xi_c(3123)^+$

$\sigma \times \mathcal{B}(\Lambda_c^+ \rightarrow pK^-\pi^+)$ of $\Xi_c^+(3123)$ < 0.17 fb@ 95% C.L. [1.6±0.6±0.2 fb by BaBar]

Summary

First observation of $\gamma\gamma \rightarrow \eta'\pi^+\pi^-$

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Measure mass, width of η_c and first measurement of $\Gamma_{\gamma\gamma}\mathcal{B}$

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$e^+e^- \rightarrow \gamma_{ISR} J/\Psi\eta$

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First time $\Psi(4040)$ and $\Psi(4160)$ have been observed to decay to final states not involving charm meson pairs

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- Consistent mass and decay mode with theory prediction.

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Search for $\Xi_{cc}^{+(+)}$

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Search for $\Xi_{cc}^{+(+)}$ → No significant signal is observed

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Search for $\Xi_{cc}^{+(+)}$

→

No significant signal is observed

- Confirmation of $\Xi_c^+(3055)$ with 6.8σ significance
- No evidence for $\Xi_c^+(3123)$

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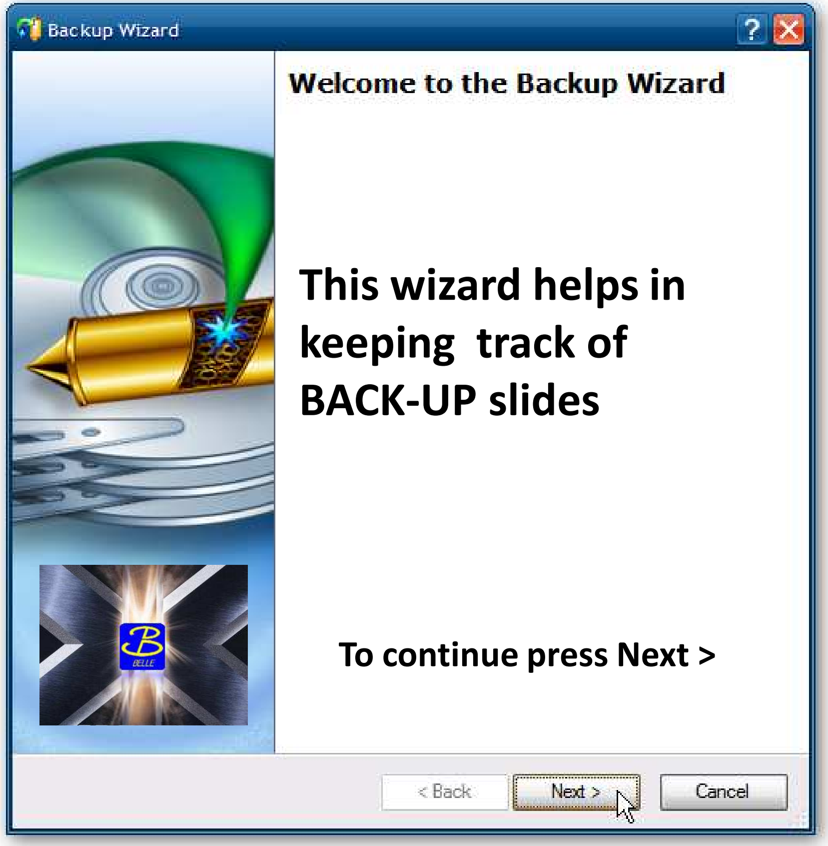
Belle is still actively solving questions about heavy flavor hadrons

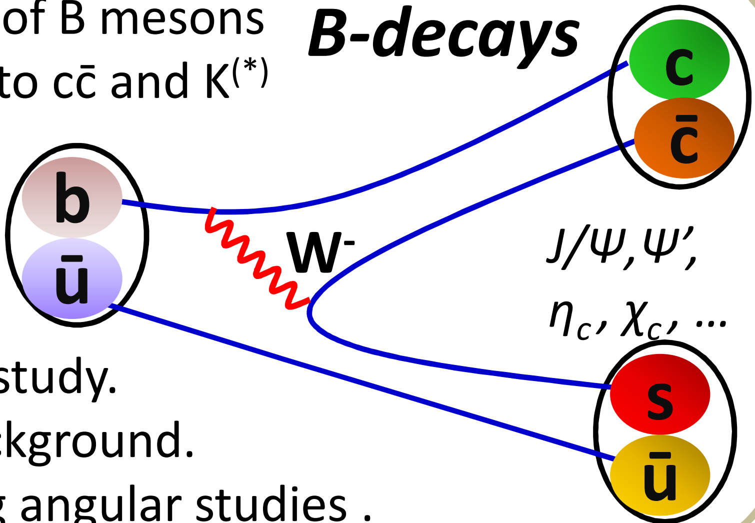
Thank you


Backup Wizard
Welcome to the Backup Wizard
This wizard helps in keeping track of BACK-UP slides
To continue press Next >
< Back
Next >
Cancel

Production of $c\bar{c}$ (-like) *@ B-factories*

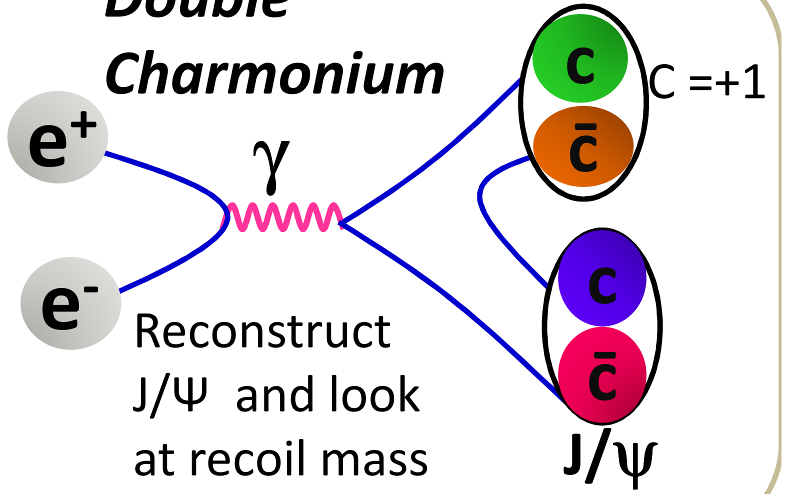
B-decays

A few % of B mesons decay into $c\bar{c}$ and $K^{(*)}$



Easy to study.
Low background.
J^{PC} using angular studies .

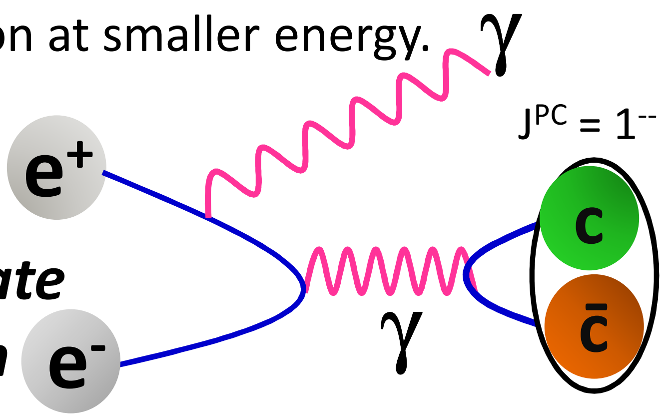
Double Charmonium



Reconstruct J/Ψ and look at recoil mass

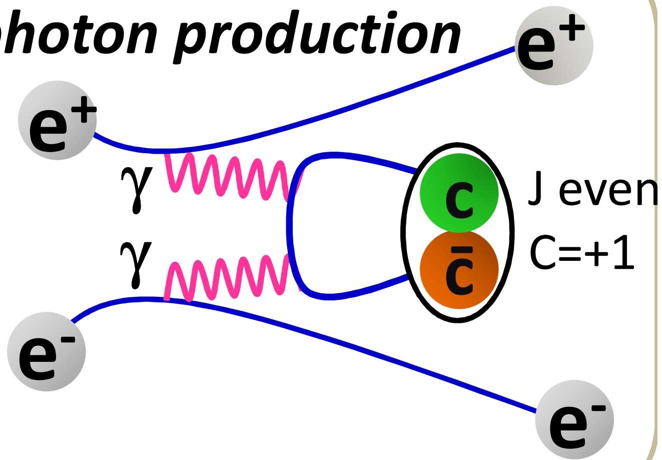
Initial state radiation

Annihilation at smaller energy.



Two photon production

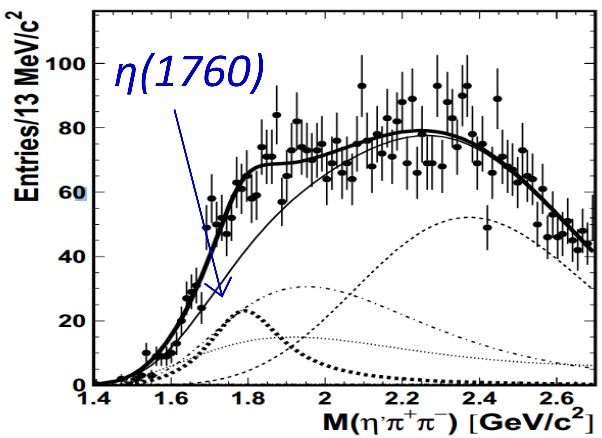
$c\bar{c}$ states produced without additional hadrons.



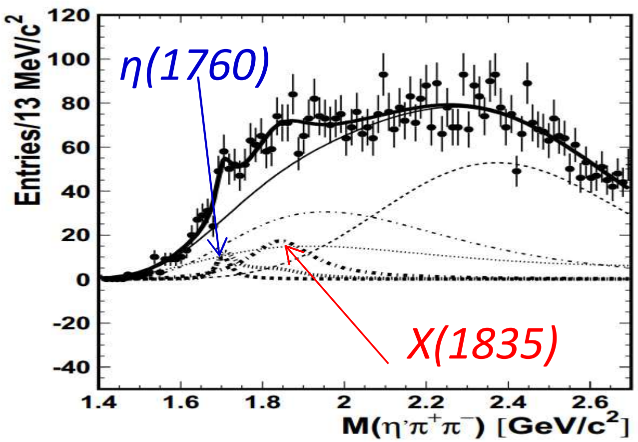
605 fb^{-1} $M_{\eta'\pi+\pi-}$ in low mass region

Belle, PRD 86,052002 (2012)

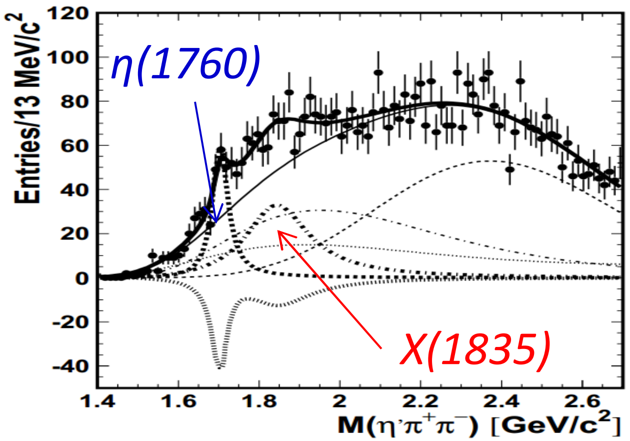
We also search for light hadrons : η(1760) and X(1835).
Both are not well known and two photon process can help in identifying their nature.



Only η(1760) is used for fitting



Constructive interference



Destructive interference

Assumption that both η(1760) and X(1835) has J^{PC} of 0^{-+}

No interference between resonant and non-resonant is taken into account.

It has also been suggested that data can also be well described by using broad $J^{PC}=0^{-+}$ peaking in mass 2250-2300 and X(1835), without η(1760) **D.V.Bugg, Phys. Rev. D86 114006(2012)**

Parameter	One resonance	Two interfering resonances		Reference
		Solution I	Solution II	
		$X(1835)$		
M, MeV/c^2		1836.5 (fixed)		$1836.5 \pm 3.0^{+5.6}_{-2.1}$ [6]
Γ, MeV/c^2		190 (fixed)		$190 \pm 9^{+38}_{-36}$ [6]
Y		$332^{+140}_{-122} \pm 73$	$632^{+224}_{-231} \pm 139$	
Y_{90}		< 650	< 1490	
$\Gamma_{\gamma\gamma}\mathcal{B}$, eV/$c^2$		$18.2^{+7.7}_{-6.7} \pm 4.0$	$35^{+12}_{-13} \pm 8$	
$(\Gamma_{\gamma\gamma}\mathcal{B})_{90}$ eV/c^2		< 35.6	< 83	
S, σ		2.8		
		$\eta(1760)$		
M, MeV/c^2	$1768^{+24}_{-25} \pm 10$	$1703^{+12}_{-11} \pm 1.8$		1756 ± 9 [1]
Γ, MeV/c^2	$224^{+62}_{-56} \pm 25$	$42^{+36}_{-22} \pm 15$		96 ± 70 [1]
Y	$465^{+131}_{-124} \pm 60$	$52^{+35}_{-20} \pm 15$	$315^{+223}_{-165} \pm 88$	
$\Gamma_{\gamma\gamma}\mathcal{B}$, eV/$c^2$	$28.2^{+7.9}_{-7.5} \pm 3.7$	$3.0^{+2.0}_{-1.2} \pm 0.8$	$18^{+13}_{-10} \pm 5$	
S, σ	4.7	4.1		
ϕ		$(287^{+42}_{-51})^\circ$	$(139^{+19}_{-9})^\circ$	

Interference with Non-resonant component

Belle, PRD 86,052002 (2012)

Non-resonant into two component :

a) Interfere with resonant (NR1)
b) Don't interfere with resonant part (NR2)

α_{NR} = n1/(n1+n2)

Two solutions for interference

Mass = 2982.7 MeV/c^2 for α_{NR} = 0.01%

= 2983.0 MeV/c^2 for α_{NR} = 100%

Γ = 36.4 MeV/c^2

If for α_{NR} = 100%,

with destructive interference , Yield = 854±59 events with ϕ_1 = $(-92\pm15)^o$

with constructive interference, Yield = 264±22events with ϕ_2 = $(91\pm8)^o$

With no interference :

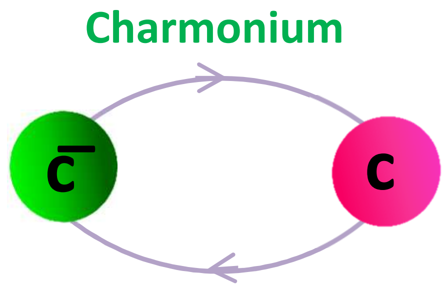
Mass = 2982.7±1.8±2.2 MeV/c^2

Γ = $37.8^{+5.8}_{-5.3}\pm2.8$ MeV/c^2

Yield = 486±40 events

Experiment	*Mass, MeV/c^2*	*Γ, MeV/c^2*
Belle ***PLB 706,139(2011)***	$2985.4 \pm 1.5^{+0.5}_{-2.0}$	$35.1 \pm 3.1^{+1.0}_{-1.6}$
BES ***PRL 108,222002(2012)***	*2984.3±0.6±0.6*	*32.0±1.2±1.0*

Charmonium



Bound state of c and c̄
Spin : ½ and ½ = 0,1
Orbital angular momentum: L =0,1,2,...
Parity (P) = $(-1)^{L+1}$
Charge Conjugation (C) = $(-1)^{L+S}$
Total Spin : $\vec{J} = \vec{L} + \vec{S}$

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

(Cornell potential)

Quark model quantum numbers

L=0, S=0 : J=0	**$J^{PC}=0^{-+}$**
L=0, S=1 : J=1	**$J^{PC}=1^{--}$**
L=1, S=0 : J=1	**$J^{PC}=1^{+-}$**
L=1, S=1 : J=0,1,2	**$J^{PC} = 0^{++}\ 1^{++}\ 2^{++}$**
L=2, S=0 : J=1	**$J^{PC}=\ 2^{-+}$**
L=2, S=1 : J=1,2,3	**$J^{PC}=1^{--}\ 2^{--}\ 3^{--}$**

and so on..

Spectrum based on this, with spin-orbital, spin-spin and tensor term.

Exotic quantum numbers
0^{+-}, 0^{--}, 1^{-+}, 2^{+-} and so on..

States not easily accommodated, candidates for exotic nature.

TABLE I: Thresholds for decay into open charm.

Channel	Threshold Energy (MeV)
$D^0\bar{D}^0$	3729.4
D^+D^-	3738.8
$D^0\bar{D}^{*0}$ or $D^{*0}\bar{D}^0$	3871.5
$D^{\pm}D^{*\mp}$	3879.5
$D_s^+D_s^-$	3936.2
$D^{*0}\bar{D}^{*0}$	4013.6
$D^{*+}D^{*-}$	4020.2
$D_s^+\bar{D}_s^{*-}$ or $D_s^{*+}\bar{D}_s^-$	4080.0
$D_s^{*+}D_s^{*-}$	4223.8

TABLE V: Calculated and observed rates for E1 radiative transitions among charmonium levels. *Values in italics* result if the influence of open-charm channels is not included.

Transition (γ energy in MeV)	Partial width (keV) Computed	Measured
$1^3D_1(3770) \to \chi_{c2}\,\gamma(208)$	*3.2* $\to$ 3.9	
$1^3D_1(3770) \to \chi_{c1}\,\gamma(251)$	*183* $\to$ 59	
$1^3D_1(3770) \to \chi_{c0}\,\gamma(338)$	*254* $\to$ 225	
$1^3D_1(3815) \to \chi_{c2}\,\gamma(250)$	*5.5* $\to$ 6.8	
$1^3D_1(3815) \to \chi_{c1}\,\gamma(293)$	*128* $\to$ 120	
$1^3D_1(3815) \to \chi_{c0}\,\gamma(379)$	*344* $\to$ 371	
$1^3D_2(3815) \to \chi_{c2}\,\gamma(251)$	*50* $\to$ 40	
$1^3D_2(3815) \to \chi_{c1}\,\gamma(293)$	*230* $\to$ 191	
$1^3D_2(3831) \to \chi_{c2}\,\gamma(266)$	*59* $\to$ 45	
$1^3D_2(3831) \to \chi_{c1}\,\gamma(308)$	*264* $\to$ 212	
$1^3D_2(3872) \to \chi_{c2}\,\gamma(303)$	*85* $\to$ 45	
$1^3D_2(3872) \to \chi_{c1}\,\gamma(344)$	*362* $\to$ 207	
$1^3D_3(3815) \to \chi_{c2}\,\gamma(251)$	*199* $\to$ 179	
$1^3D_3(3868) \to \chi_{c2}\,\gamma(303)$	*329* $\to$ 286	
$1^3D_3(3872) \to \chi_{c2}\,\gamma(304)$	*341* $\to$ 299	

TABLE III: Charmonium spectrum, including the influence of open-charm channels. All masses are in MeV. The penultimate column holds an estimate of the spin splitting due to tensor and spin-orbit forces in a single-channel potential model. The last column gives the spin splitting induced by communication with open-charm states, for an initially unsplit multiplet.

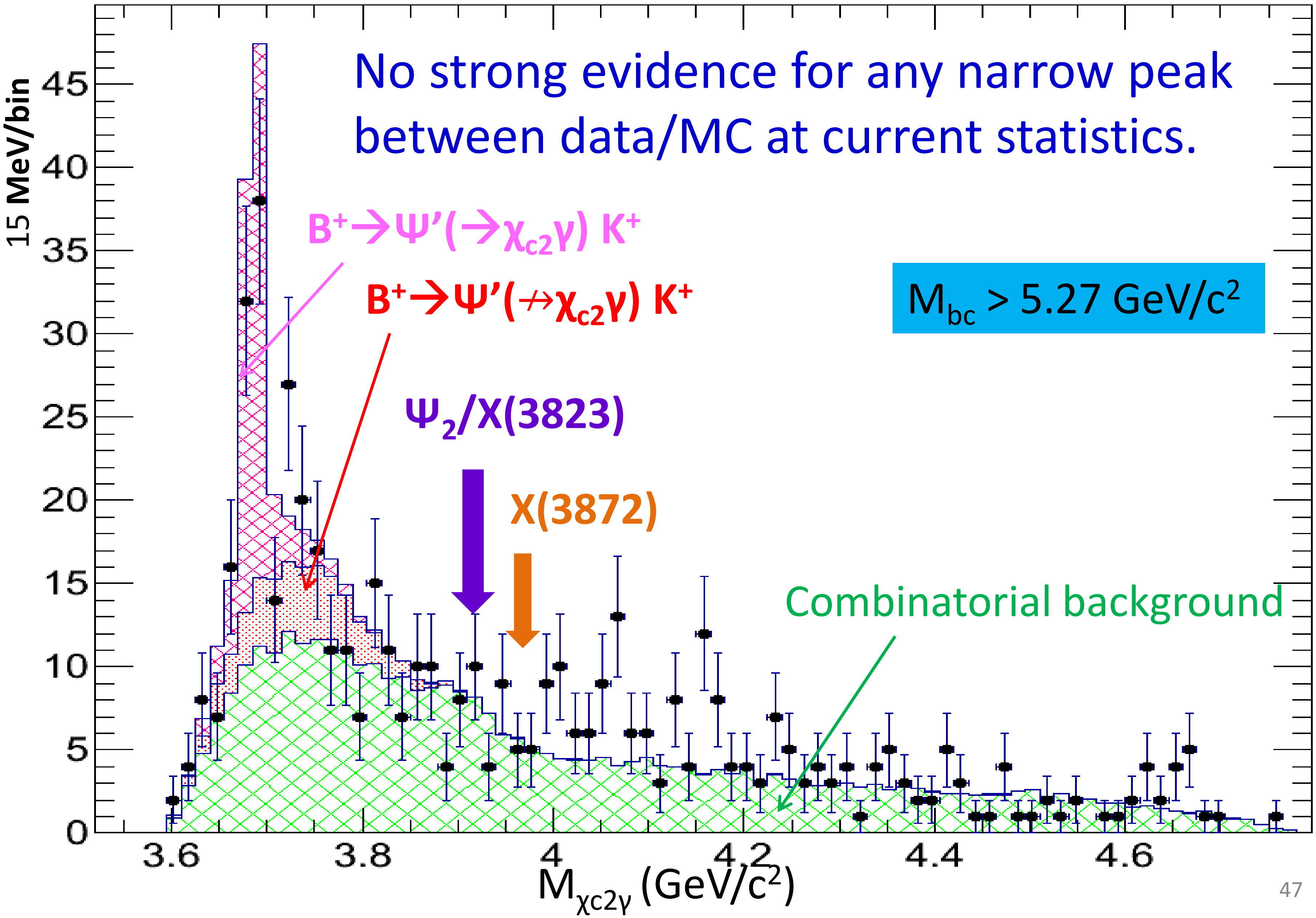
State	Mass	Centroid	Splitting (Potential)	Splitting (Induced)
1^1S_0	$2\,979.9^a$	$3\,067.6^b$	-90.5	$+2.8$
1^3S_1	$3\,096.9^a$		$+30.2$	-0.9
1^3P_0	$3\,415.3^a$	$3\,525.3^c$	-114.9^e	$+5.9$
1^3P_1	$3\,510.5^a$		-11.6^e	-2.0
1^1P_1	$3\,525.3$		$+1.5^e$	$+0.5$
1^3P_2	$3\,556.2^a$		-31.9^e	-0.3
2^1S_0	$3\,637.7^a$	$3\,673.9^b$	-50.4	$+15.7$
2^3S_1	$3\,686.0^a$		$+16.8$	-5.2
1^3D_1	$3\,769.9^{ab}$	$(3\,815)^d$	-40	-39.9
1^3D_2	$3\,830.6$		0	-2.7
1^1D_2	$3\,838.0$		0	$+4.2$
1^3D_3	$3\,868.3$		$+20$	$+19.0$
2^3P_0	$3\,931.9$	$3\,968^d$	-90	$+10$
2^3P_1	$4\,007.5$		-8	$+28.4$
2^1P_1	$3\,968.0$		0	-11.9
2^3P_2	$3\,966.5$		$+25$	-33.1

S. Godfrey & N. Isgur, PRD 32, 189 (1985)
E. Eichten et al., PRL 89,162002 (2002), PRD 69, 094019 (2004)

711 fb^{-1}

$M_{\chi c2\gamma}$ distribution

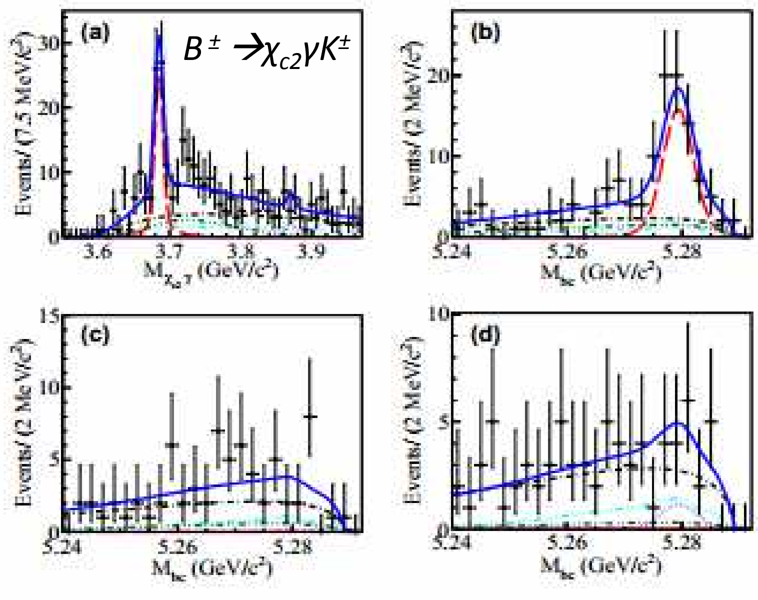
$B^{\pm} \rightarrow \chi_{c2}\gamma K^{\pm}$

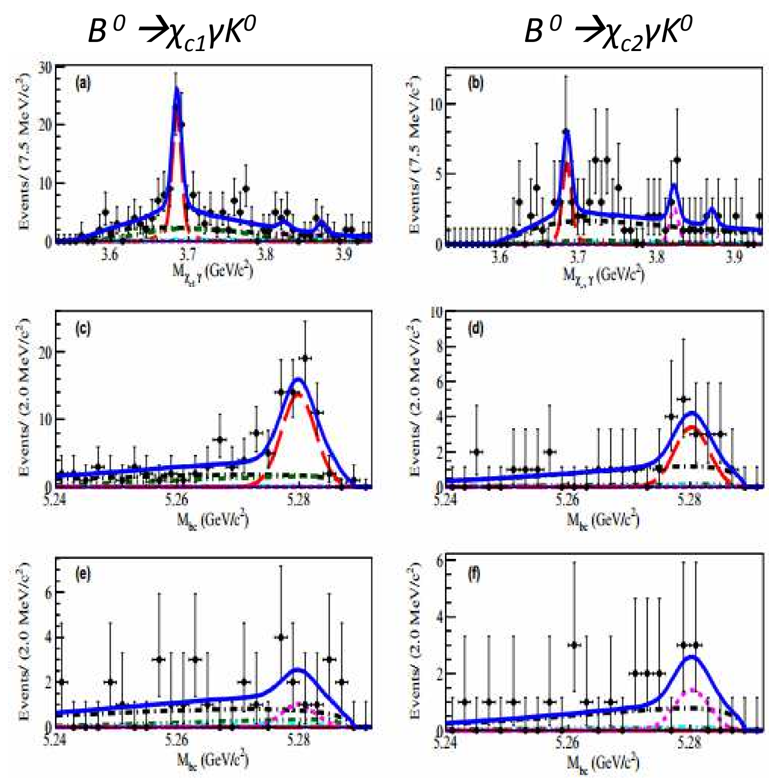


arXiv:1304.3975

Table summarized the results

Decay	Yield (Y)	$\mathcal{S}(\sigma)$	$\epsilon(\%)$	Branching fraction
$B^{\pm} \to \psi'(\to \chi_{cJ}\gamma)K^{\pm}$				$\mathcal{B}(10^{-4})$
χ_{c1}	193.2 ± 19.2	14.8	8.6	$7.7 \pm 0.8 \pm 0.9$
χ_{c2}	59.1 ± 8.4	7.8	6.0	$6.3 \pm 0.9 \pm 0.6$
$B^{0} \to \psi'(\to \chi_{cJ}\gamma)K^{0}$				
χ_{c1}	50.3 ± 7.3	7.2	5.1	$6.8 \pm 1.0 \pm 0.7$
χ_{c2}	12.9 ± 4.4	2.9	3.5	$4.7 \pm 1.6 \pm 0.8$
$B^{\pm} \to X(3823)(\to \chi_{cJ}\gamma)K^{\pm}$				$\mathcal{B}(10^{-6})$
χ_{c1}	33.2 ± 9.7	3.8	10.9	$9.7 \pm 2.8 \pm 1.1$
χ_{c2}	0.3 ± 3.9	0.1	8.8	< 3.6
$B^{0} \to X(3823)(\to \chi_{cJ}\gamma)K^{0}$				
χ_{c1}	3.9 ± 3.4	1.2	6.0	< 9.9
χ_{c2}	5.3 ± 2.9	2.4	5.0	< 22.8
$B^{\pm} \to X(3872)(\to \chi_{cJ}\gamma)K^{\pm}$				
χ_{c1}	-0.9 ± 5.1		11.1	< 1.9
χ_{c2}	4.7 ± 4.4	1.3	9.3	< 6.7
$B^{0} \to X(3872)(\to \chi_{cJ}\gamma)K^{0}$				
χ_{c1}	4.6 ± 3.0	1.6	6.2	< 9.6
χ_{c2}	2.3 ± 2.2	1.1	5.2	< 12.2





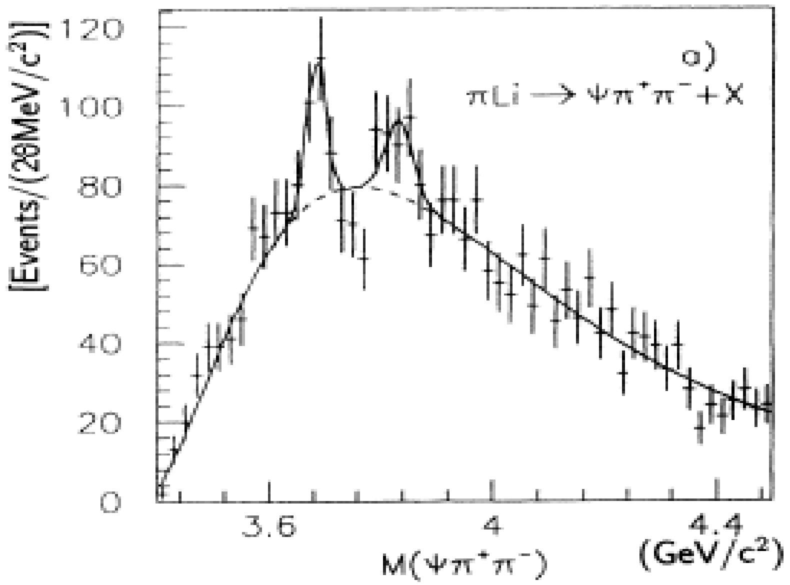
E705 Collaboration

Belle Mass
3.823 GeV/c²

Looking at ψ’, here 3.836 peaks looks prominent ???

A search has been made in 300 GeV/c $\pi^{\pm}$- and proton-Li interactions for production of states that decay into J/ψ or ψ' plus one or two pions. A 2.5σ enhancement in the $J/\psi\,\pi^0$ spectrum, possibly the recently reported ${}^1P_1$ state of charmonium, is observed at a mass of 3.527 GeV/c^2. In the J/ψ plus two pion mass spectrum, we report, together with the expected $\psi' \to J/\psi\,\pi^+\pi^-$, the tentative observation of a structure at a mass of 3.836 GeV/c^2. No enhancements are seen in the $J/\psi\,\pi^{\pm}\pi^{\pm}$, $J/\psi\,\pi^{\pm}\pi^0$, $J/\psi\,\pi^{\pm}$, or $\psi'\,\pi^{\pm}$ mass spectra.

PhysRevD.50.4258



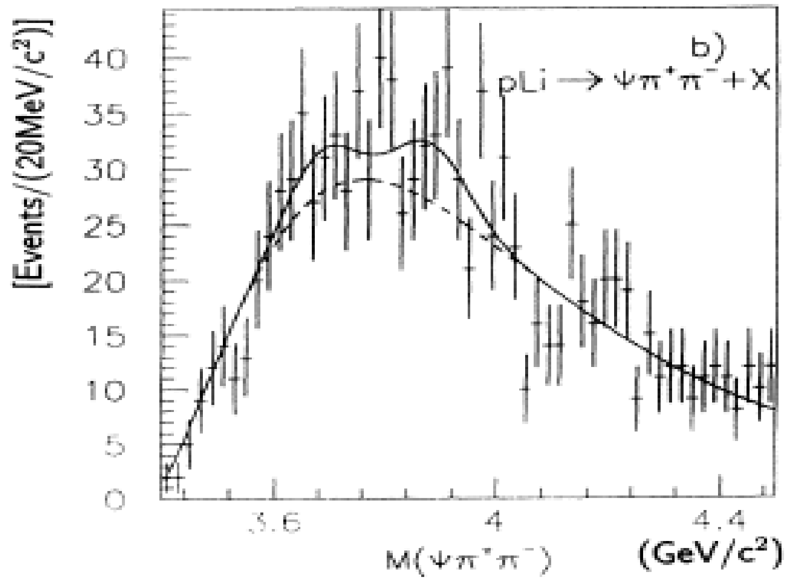
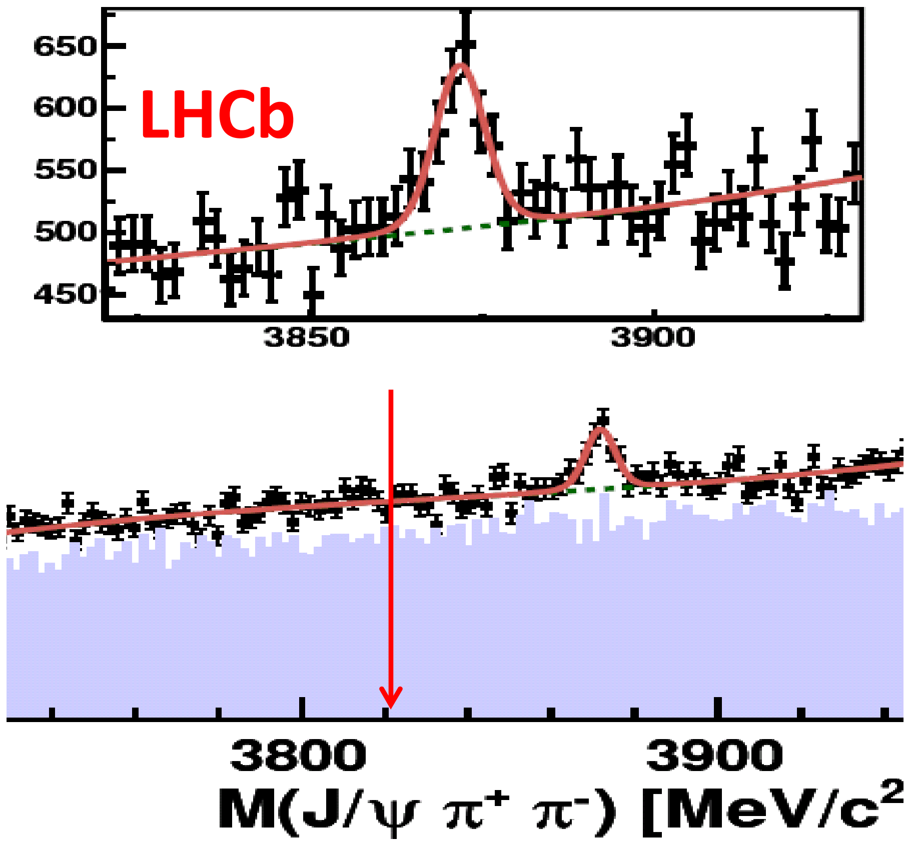
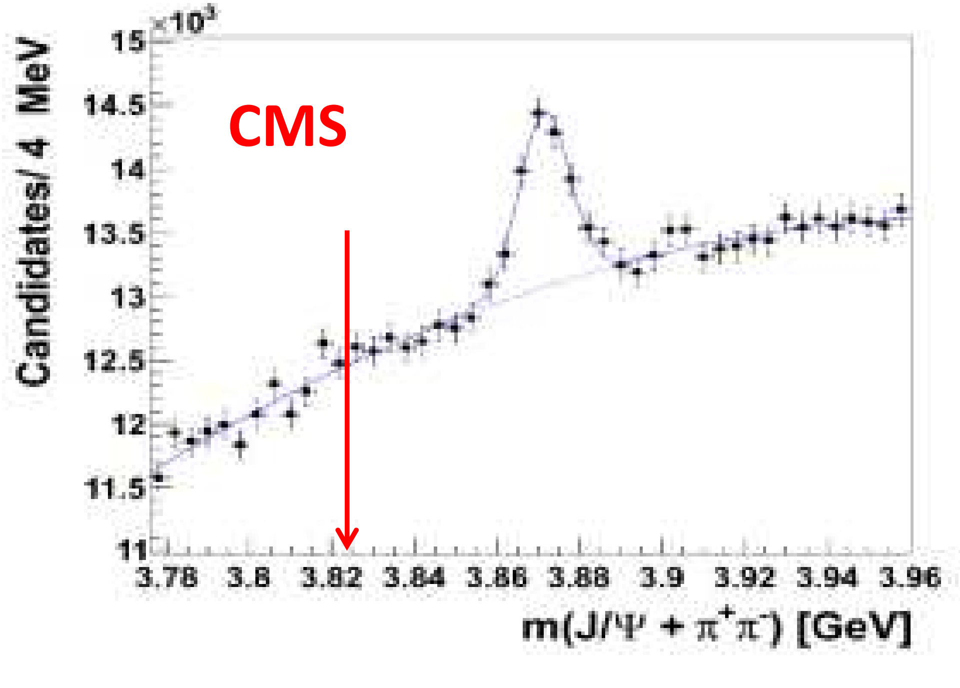
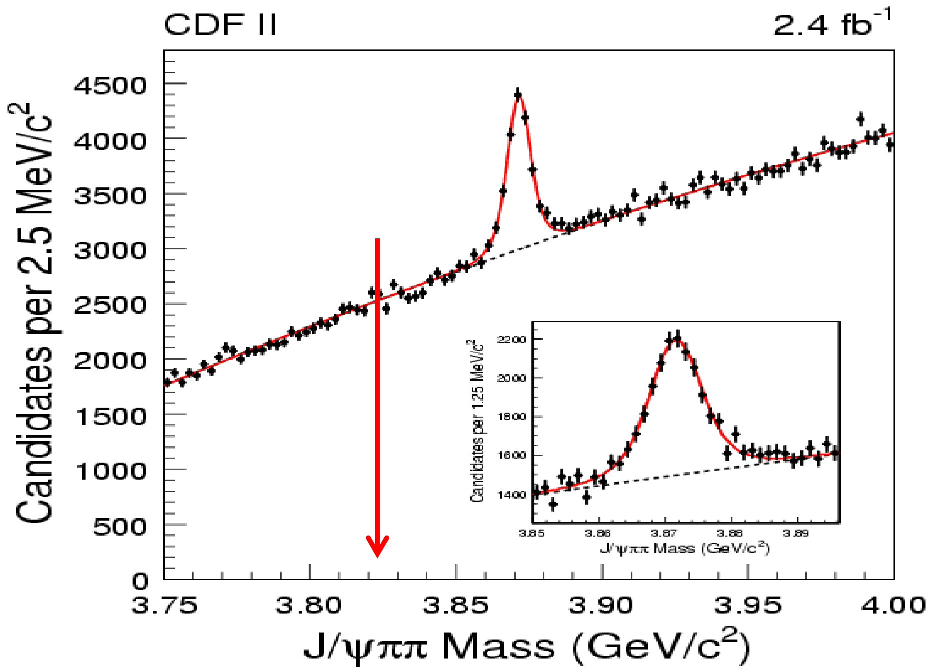


FIG. 6. $J/\psi\,\pi^+\pi^-$ mass spectra from 300 GeV/$c\,\pi^{\pm}$Li interactions; (b) $J/\psi\,\pi^+\pi^-$ mass spectrum from 300 GeV/c proton Li interactions.







Interestingly Ψ_2 is not seen in $J/\Psi\pi\pi$ in other experiments.

PDG2012

$\eta_c(1S)$ WIDTH

References   History since 1990

VALUE (MeV)	CL%	EVTS		DOCUMENT ID		TECN	COMMENT
29.7±1.0	OUR FIT						
29.7±2.1	OUR AVERAGE						Error includes scale factor of 2.0. See the ideogram.
36.2±2.8±3.0		11k		DEL-AMO-SAN...	11M	BABR	$\gamma\gamma \to K^+ K^- \pi^+ \pi^- \pi^0$
$35.1\pm3.1^{+1.0}_{-1.6}$		920	1	VINOKUROVA	11	BELL	$B^\pm \to K^\pm (K^0_S K^\pm \pi^\mp)$
31.7±1.2±0.8		14k	2	LEES	10	BABR	$10.6\ e^+ e^- \to e^+ e^- K^0_S K^\pm \pi^\mp$
$36.3^{+3.7}_{-3.6}\pm4.4$		921±32		AUBERT	08AB	BABR	$B \to \eta_c(1S) K^{(*)} \to K \overline{K} \pi K^{(*)}$
28.1±3.2±2.2		7.5k		UEHARA	08	BELL	$\gamma\gamma \to \eta_c \to$ hadrons
$48^{+8}_{-7}\pm5$		195		WU	06	BELL	$B^+ \to p \overline{p} K^+$
40±19±5		20		WU	06	BELL	$B^+ \to \Lambda \overline{\Lambda} K^+$
24.8±3.4±3.5		592		ASNER	04	CLEO	$\gamma\gamma \to \eta_c' \to K^0_S K^\pm \pi^\mp$
$20.4^{+7.7}_{-6.7}\pm2.0$		190		AMBROGIANI	03	E835	$\overline{p} p \to \eta_c \to \gamma\gamma$
17.0±3.7±7.4			3	BAI	03	BES	$J/\psi \to \gamma \eta_c$
11.0±8.1±4.1			4	BAI	00F	BES	$J/\psi \to \gamma \eta_c$ and $\psi(2S) \to \gamma \eta_c$
$23.9^{+12.6}_{-7.1}$				ARMSTRONG	95F	E760	$\overline{p} p \to \gamma\gamma$
$7.0^{+7.5}_{-7.0}$		12		BAGLIN	87B	SPEC	$\overline{p} p \to \gamma\gamma$
$10.1^{+33.0}_{-8.2}$		23	5	BALTRUSAITI...	86	MRK3	$J/\psi \to \gamma p \overline{p}$
11.5±4.5				GAISER	86	CBAL	$J/\psi \to \gamma X$, $\psi(2S) \to \gamma X$

U.L. on $\sigma(e^+e^- \rightarrow \Xi_{cc}^{+(+)} X)$

Assuming $BR(\Xi_{cc}^{+(+)} \rightarrow \Lambda_c^+ K^- \pi^+(\pi^+))$, $BR(\Xi_{cc}^{+(+)} \rightarrow \Xi_c^0 \pi^+(\pi^+))$ and $BR(\Xi_c^0 \rightarrow \Xi^- \pi^+)$ to be 5% *

$\sigma(e^+e^- \rightarrow \Xi_{cc}^{+} X) <$ 92.0-410.0 fb
$\sigma(e^+e^- \rightarrow \Xi_{cc}^{++} X) <$ 50.0-520.0 fb

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

$\sigma(e^+e^- \rightarrow \Xi_{cc}^{+} X) <$ 30.4-104.0 fb
$\sigma(e^+e^- \rightarrow \Xi_{cc}^{++} X) <$ 37.6-144.0 fb

for $\Xi_{cc}^{+(+)} \rightarrow \Xi_c^0 \pi^+(\pi^+)$

Theory predicts production cross-section for $e^+e^- \rightarrow \Xi_{cc} X$ at *B* factories :3-230 fb

PLB 332, 411(1994);
Phys. Atom. Nucl, 65, 1537 (2002)
PLB 568 568 (2003)

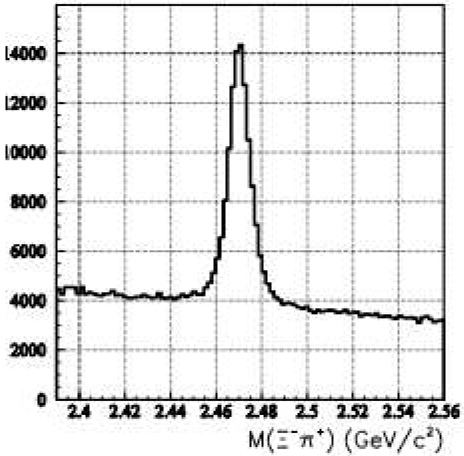
Result is comparable with some of the theoretical model.

* Similar to $B(\Lambda_c^+ \rightarrow pK^-\pi^+)$ decay

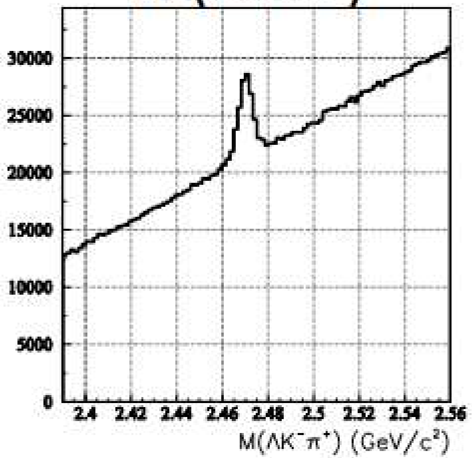
Taken from Y. Kato (Belle), JPS talk March 2013

Reconstruction of Ξ_c^0

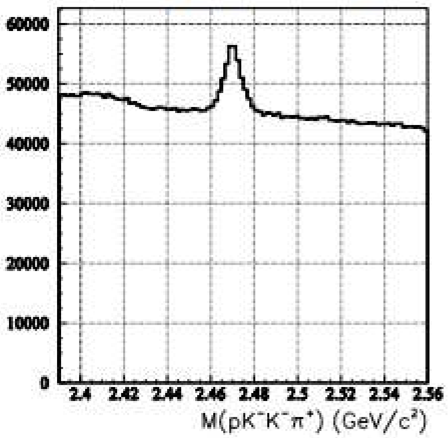
$M(\Xi^-\pi^+)$



$M(\Lambda K^-\pi^+)$



$M(pK^-K^-\pi^+)$



- Previous study by BaBar use $\Xi^-\pi^+$ only.
- Yield is comparable for 3 modes.
- S/N largely depends on the decay mode.

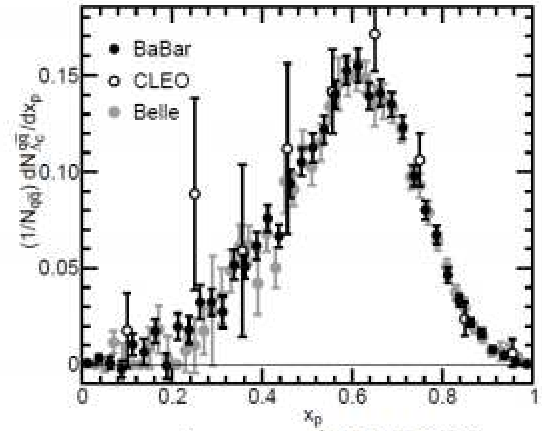
→Simultaneous fitting with fixing signal yield gives better sensitivity.
However, no measurement on branching ratio.

Taken from Y. Kato (Belle), JPS talk March 2013

Signal MC

Ξ_{cc} momentum is expected to be lower than Λ_c^+ momentum because 4 charm, anti-charm quarks are produced and kinetic energy available is small.

Use measured momentum of Λ_c^+



hep-ex/0609004
$d\sigma/dX_p$ measurment
for inclusive Λ_c^+ production
by Belle/Babar/CLEO

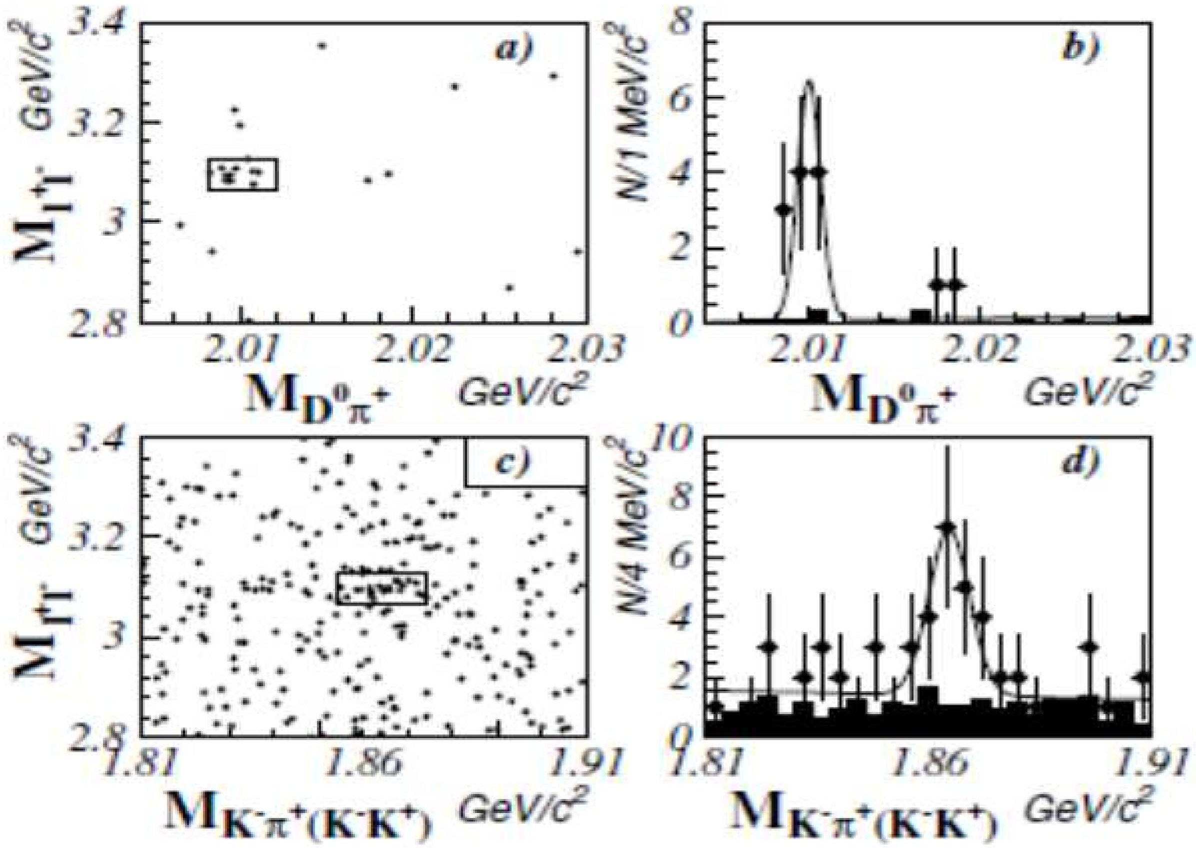
$X_p = p_{cm}/p_{max}$
$p_{max} = \mathrm{sqrt}(E_{cm}{}^2 - M_{\Lambda c}{}^2)$
P_{max} is ~4.7 GeV/c

Assume the same $d\sigma/dXp$ and change $M_{\Lambda c} \rightarrow M_{\Xi cc}$
P_{max} ~ 3.9 GeV/c ($M_{\Xi cc}$=3.52 GeV/c^2)

8

Taken from Y. Kato (Belle), JPS talk
March 2013

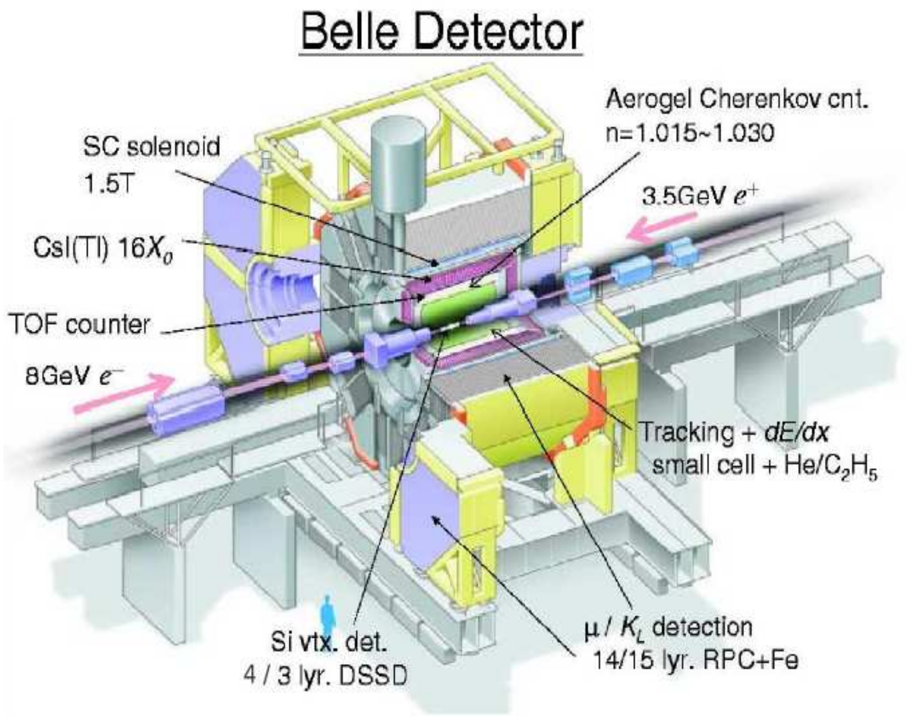
▪ $e^+e^- \rightarrow J/\psi + c\bar{c}$ by Belle

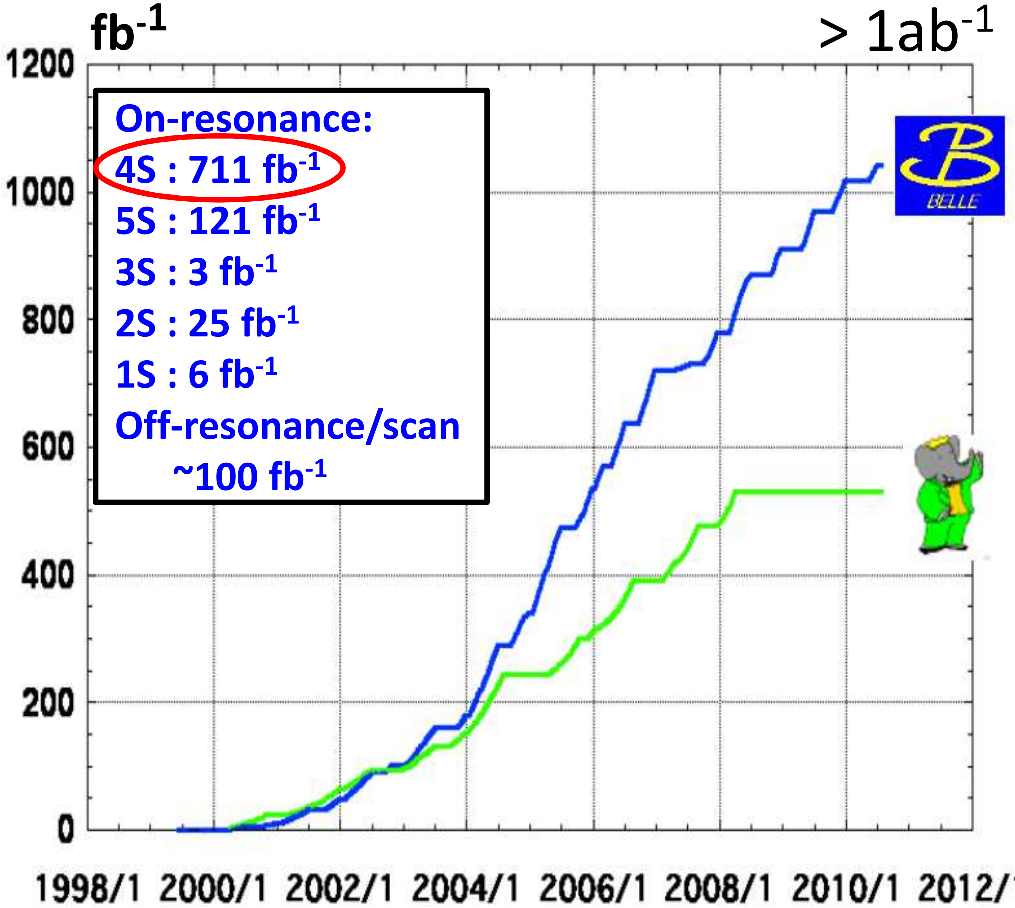


$$\sigma(J/\psi + c\bar{c}) = 0.87^{+0.21}_{-0.19} \pm 0.17\,pb \Leftrightarrow 0.006 - 0.012\,pb$$

Prediction of cross section for Ξ_{cc} 100-200 fb
→might be much larger.

$c\bar{c}$ (-like) states at Belle





General purpose detector, build to test Standard Model mechanism for CP violation in B decays to charmonium ($B^0 \rightarrow J/\Psi, \Psi', \chi_{c1} K^0$). arXiv:1201.4643v1 accepted in PRL

Contribution to charmonium (-like) states:

$\eta_c(2S)$, X(3872), Y(3940), Z(3930), X(3940),X(3915), Y(4260), Y(4660), $Z(4430)^+$, $Z_1(4050)^+$, $Z_2(4250)^+$ …