Charmed baryon spectroscopy at Belle, Belle II

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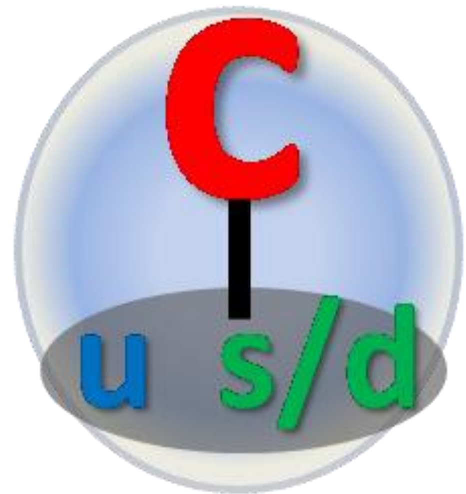
Physics of single charmed baryons

- Charm quark is heavy: (1500 MeV/c^2) > u,d,s quarks (300-500 MeV/c^2)
- spin-spin interaction $\propto 1/m_1 m_2$
- Di-quark correlation in light quarks? (more simple! New d.o.f!).

Nucleon

Every pair can not be distinguished.

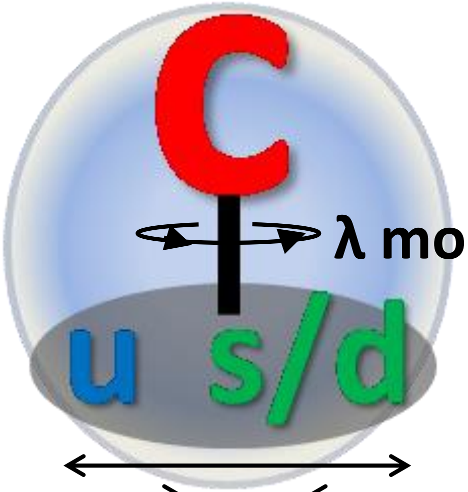
Charmed baryon



Light di-quark and charm quark?

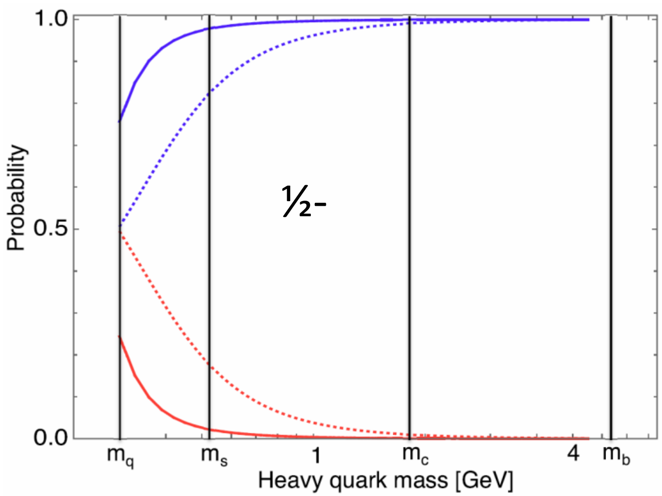
Excitation modes in the charmed baryons

- There are two kind of excitation modes.
  - λ mode: excitation between c quark and u-d di-quark.
  - ρ mode: excitation in the di-quarks.



$$\frac{h\omega_\rho}{h\omega_\lambda} = \sqrt{\frac{3m_Q}{2m_q + m_Q}} \sim= \sqrt{3}$$

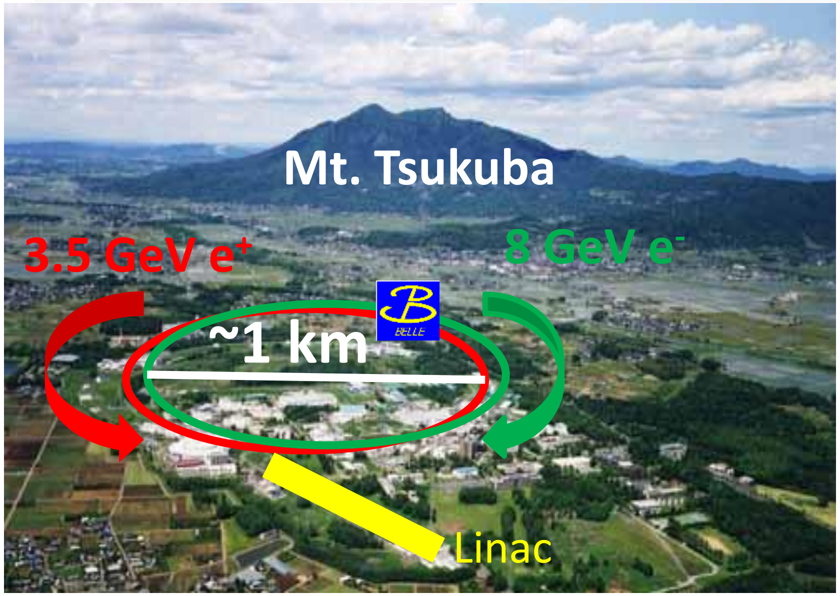
T. Yoshida et al. PRD 92, 114029 (2015)

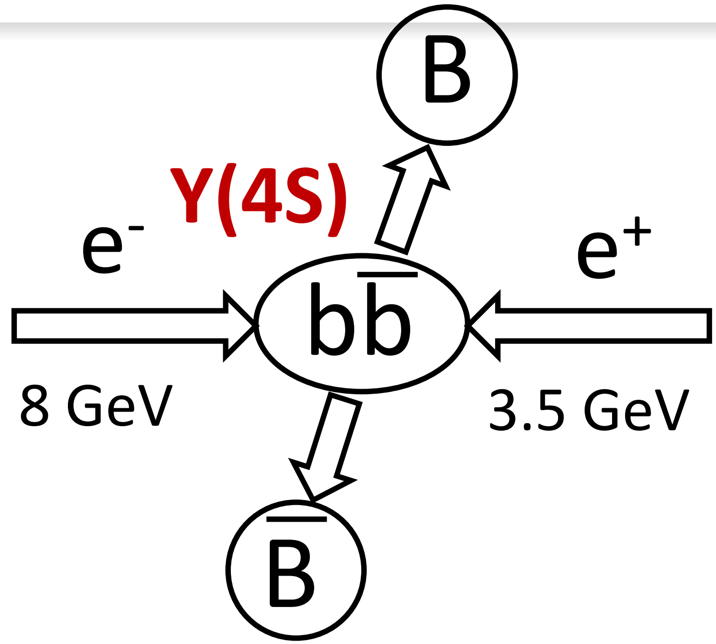


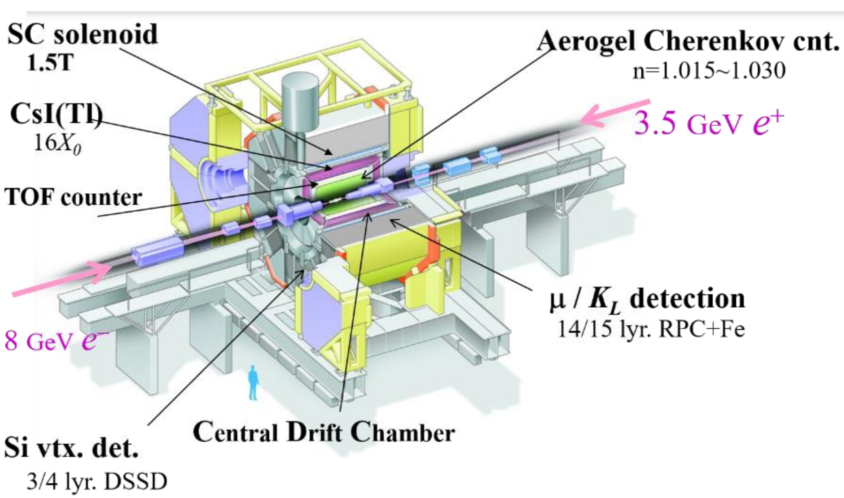
The fraction of λ mode for the 1st excited state.

- Di-quark picture is not confirmed yet.
- There should be two $1/2^-$ state, but not identified.
- Experimentally, discover charmed baryons, study the property and check global consistency with di-quark picture.

Belle experiment







- Asymmetric energy e^+e^- collider to test KM theory in B-meson decays.
- 7.7×10^8 BB^{bar} events are collected.
- Belle: General purpose detector.
- Hadron spectroscopy can be done, too.

"New hadrons" from B-factories

Hadron Type

Reaction

	Charmonium	Bottomonium	D, $D_{(s)}$	Charmed baryon	Hyperon
B-decay	$\eta_c(2S)$ $\psi_2(3823)$ X(3872) X(3915) $Z_c(4050)$ $Z_c(4250)$ $Z_c(4430)$ $Z_c(4200)$		$D^*_0(2400)$ $D_1(2430)$	$\Xi_c(2930)$	
Initial State Radiation	Y(4260) Z(3900) Y(4008) Y(4360) Y(4660)				
Double charmonium	X(3860) ≒ $\chi_{c0}(2P)$ X(3940) X(4160)				
Two photon	$\chi_{c2}(2P)$				
$e^+e^- \to cc^{bar}$			$D^*_{s0}(2317)$ $D_0(2550)$ $D_J^*(2600)$ $D_J(2740)$ $D_3^*(2750)$ $D^*_{s1}(2700)$ $D^*_{s1}(2860)$ $D_{sJ}(3040)$	$\Sigma_c(2800)$ $\Lambda_c(2940)$ $\Xi_c(2980)$ $\Xi_c(3080)$ $\Omega_c(2770)$ $\Xi_c(3055)$	
Y(nS) decay		$Z_b(10610)$ $Z_b(10650)$ $\eta_b(1S)$ $\eta_b(2S)$ $h_b(1P)$ $h_b(2P)$			$\Omega(2012)$

Belle
BaBar

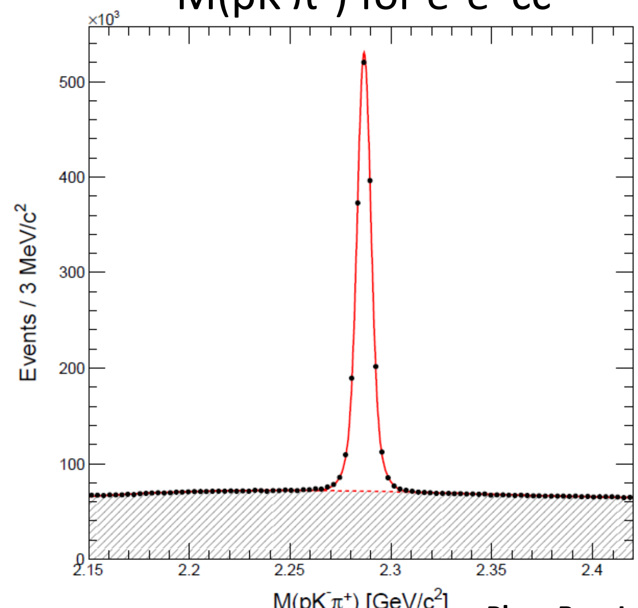
~ 40 new hadrons!
(Some states may be missed)

Charmed baryons production at B-factories

- Charmed baryons are produced mainly in
  - $e^+e^- \to c\bar{c}$ reaction
  - B-meson decays

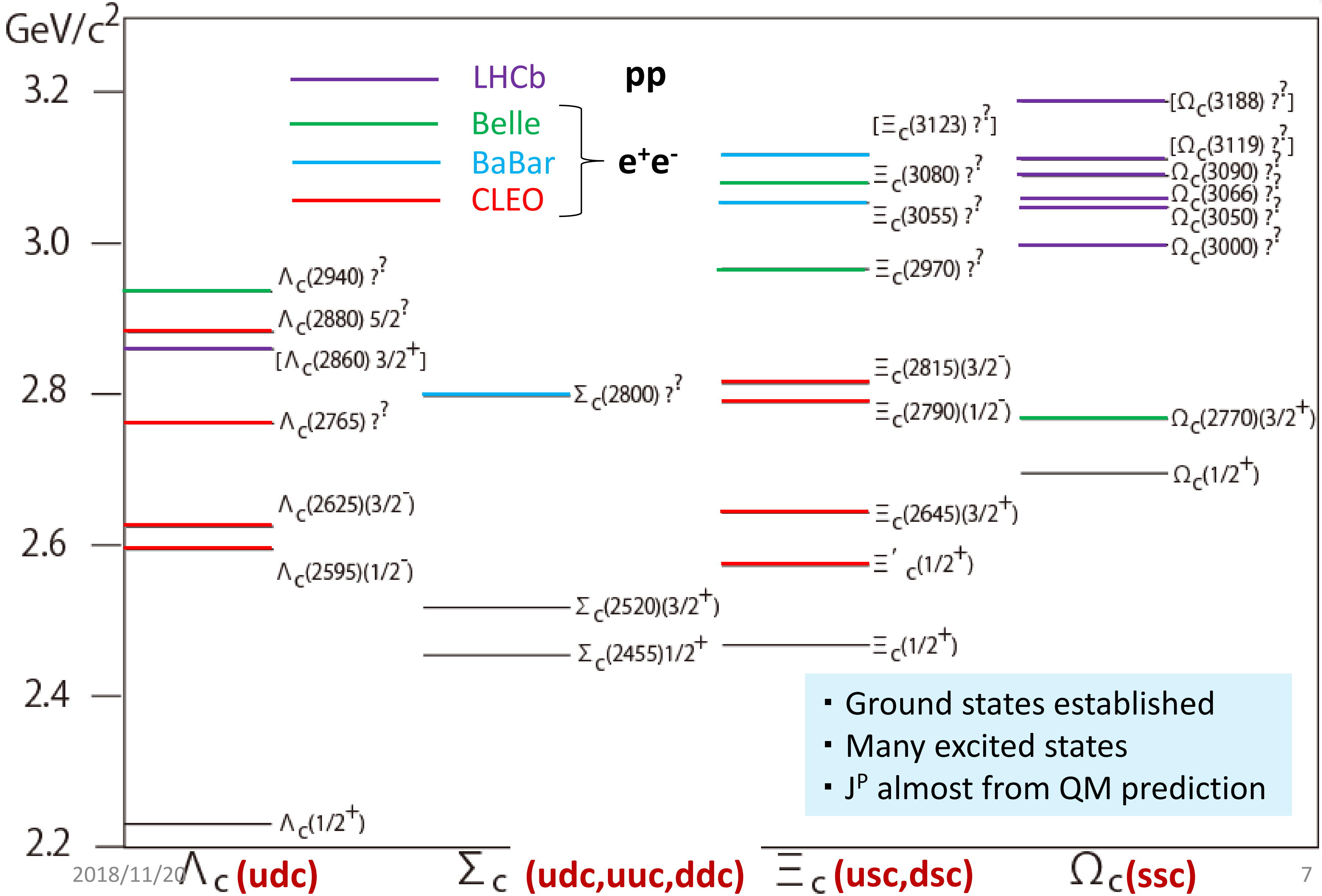
- ~1×10^9 $e^+e^- \to c\bar{c}$. More than 10^6 Λ_c^+ reconstructed exclusively from $pK^-\pi^+$.

$M(pK^-\pi^+)$ for e^+e^- $c\bar{c}$



Phys. Rev. Lett. 117, 011801

Observed charmed baryons



- Ground states established
- Many excited states
- J^P almost from QM prediction

What has been done so far?

(1): Discovery of new excited states

(2): Precise mass and width measurements

(3): Decay branching fraction

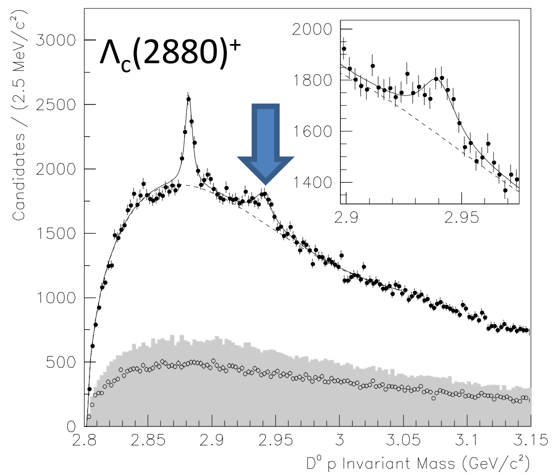
(4): Spin and parity

See more details in our review paper
"Open charm hadron spectroscopy at B-factories" 1810.03748
(submitted to Progress in Particle and Nuclear Physics)

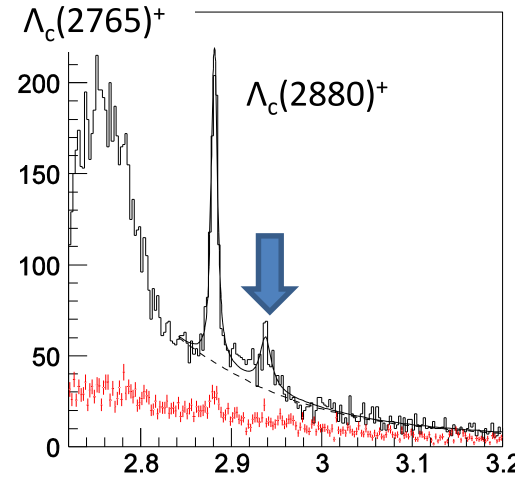
Observations

Discoveries: Λ_c^+ and Σ_c (udc,uuc,ddc)

D^0p $\Lambda_c(2940)^+$ $\Sigma_c\pi$



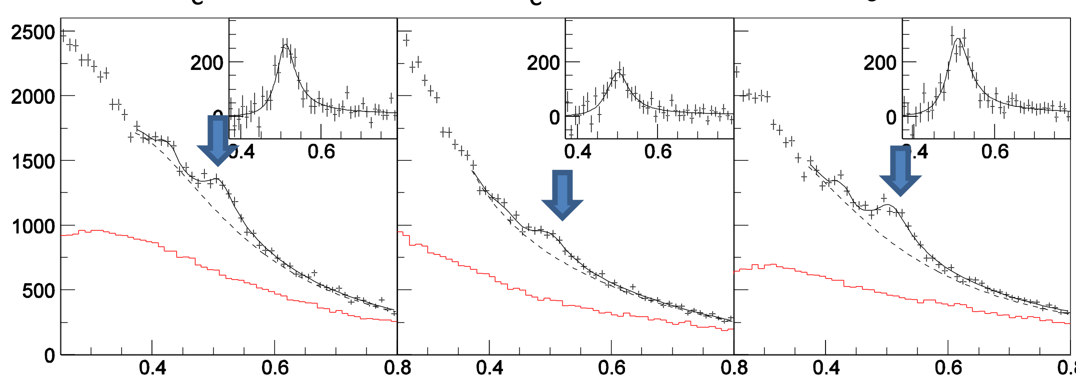
Phys. Rev. Lett. **98**, 012001



Phys. Rev. Lett. **98**, 262001

$\Sigma_c(2800) \rightarrow \Lambda_c^+\pi$

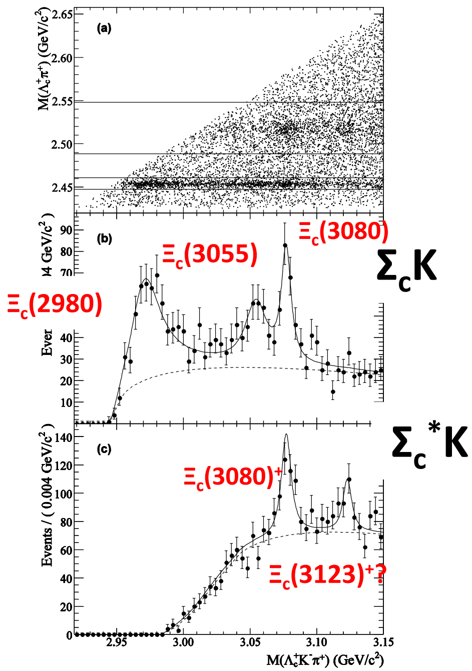
$\Lambda_c^+\pi^-$ $\Lambda_c^+\pi^0$ $\Lambda_c^+\pi^+$



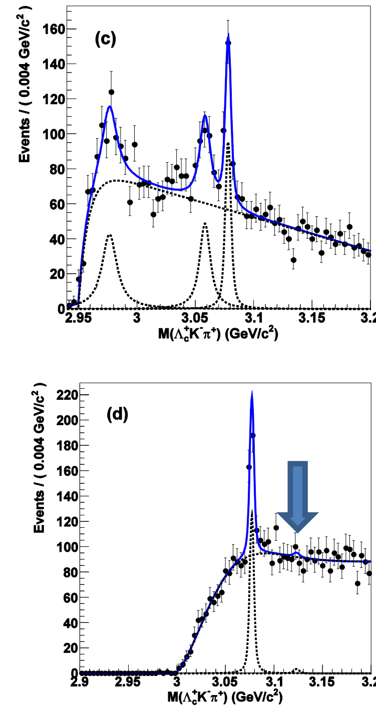
Phys. Rev. Lett. **94**, 122002

Discoveries: Ξ_c (usc,dsc)

Ξ_c(2980/3055/3080)→$\Sigma_c^{(*)}K^-$

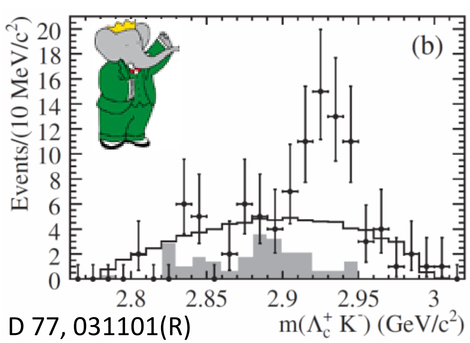


Phys. Rev. D 77, 012002

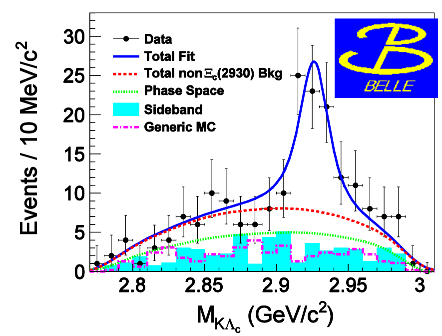


Phys. Rev. D **89**, 052003

B^-→Ξ_c(2930)Λ_c bar ,Ξ_c(2930)→$\Lambda_c^+K^-$



Phys. Rev. D 77, 031101(R)



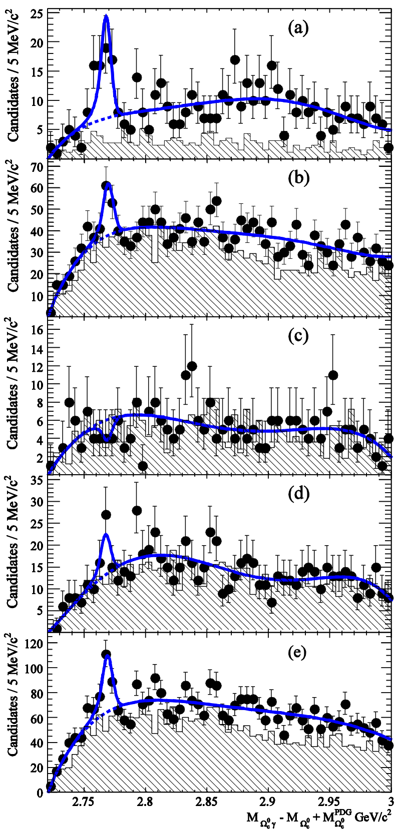
Phys. Rev. D **94**, 032002

First charmed baryon established in B-decay!

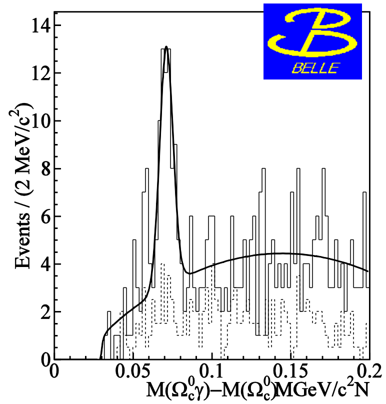
Eur. Phys. J. C 78, 252

Discoveries: Ω_c (ssc)

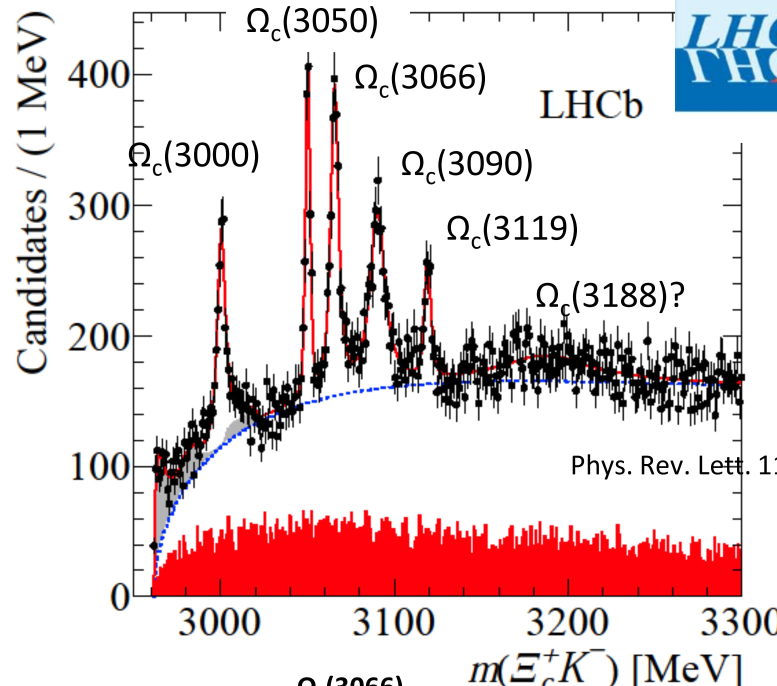
$\Omega_c(2770) \rightarrow \Omega_c \gamma$



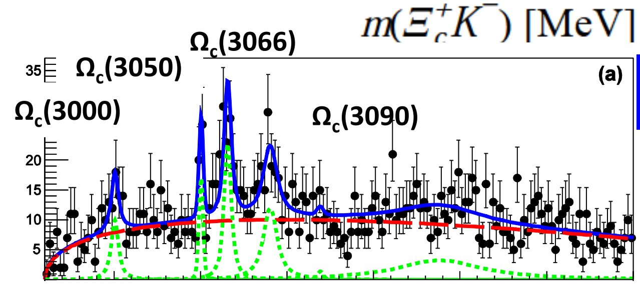
Phys. Rev. Lett. **97**, 232001



$\Xi_c^+ K^-$



Phys. Rev. Lett. 118, 182001

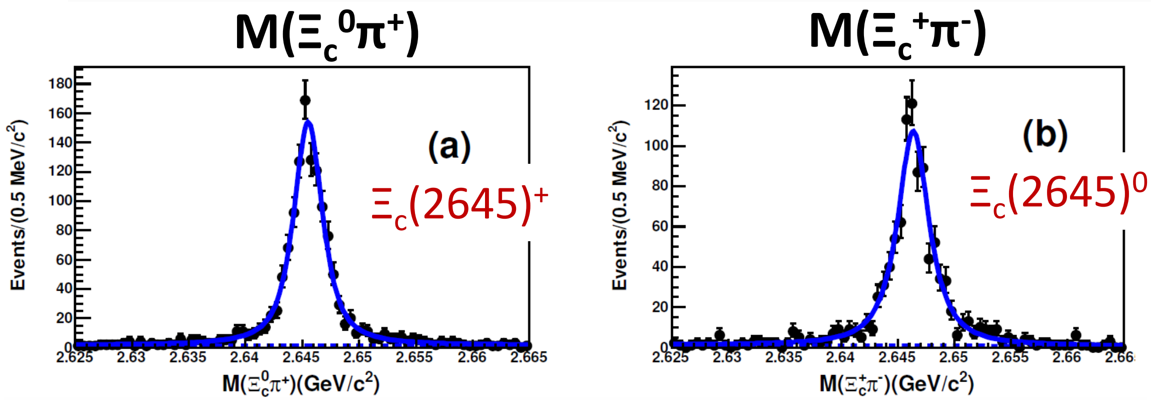


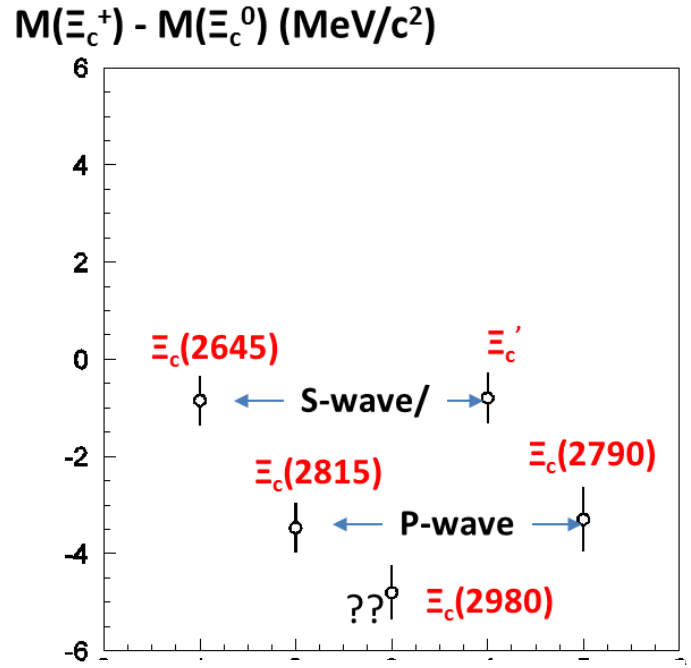
Phys. Rev. D 97, 051102

Precise mass determination

Isospin splitting

Phys. Rev. D 94, 052011





Phys. Rev. D **94**, 032002

Particle	$M(\Xi_c^+) - M(\Xi_c^0)$ (MeV/c^2)
$\Xi_c(2645)$	$-0.85 \pm 0.09 \pm 0.08 \pm 0.48$
$\Xi_c(2815))$	$-3.47 \pm 0.12 \pm 0.05 \pm 0.48$
$\Xi_c(2980))$	$-4.8 \pm 0.1 \pm 0.2 \pm 0.5$
$\Xi_c'^+$	$-0.8 \pm 0.1 \pm 0.1 \pm 0.5$
$\Xi_c(2790))$	$-3.3 \pm 0.4 \pm 0.1 \pm 0.5$

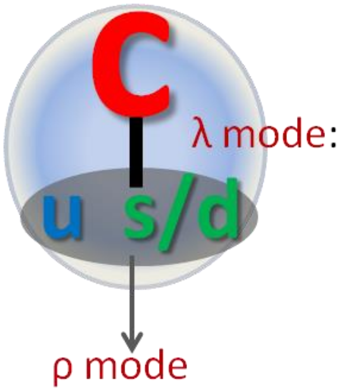
- Origin of Isospin splitting
  - up-down mass difference
  - Coulomb force

- Clear difference between S-wave P-wave states.
  Large charge radius → small coulomb repulsive force.

- Important: What we can say for $\Xi_c(2980)$???

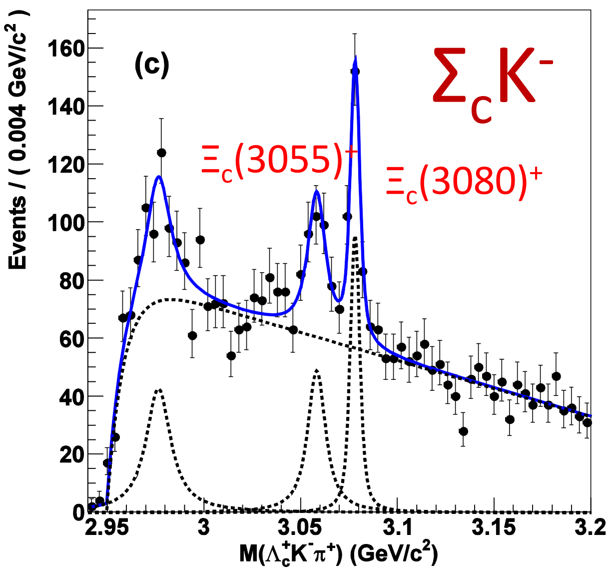
Decays

Decay branching ratio in various mode

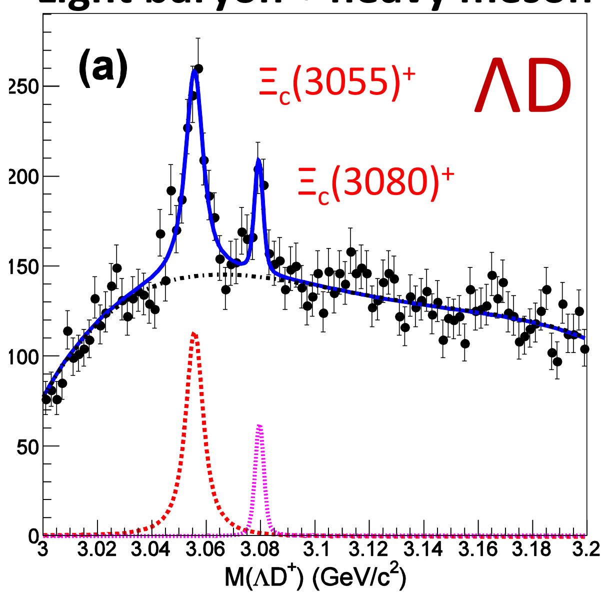


- Naively,
  λ mode excitation decays to (light baryon + heavy meson)
  ρ mode excitation decays to (heavy baryon + light meson)

Heavy baryon + light meson



Light baryon + heavy meson



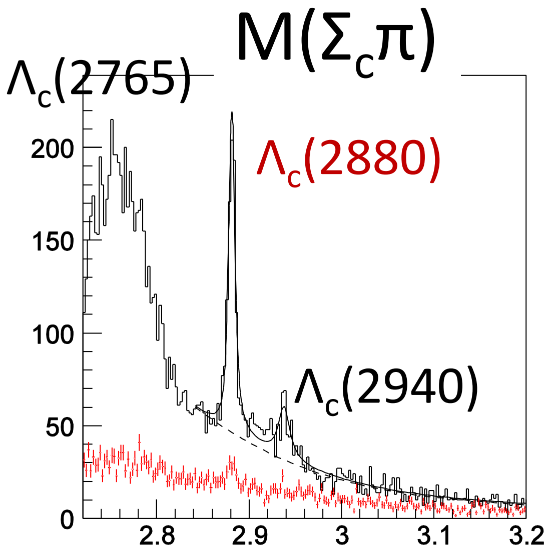
- $\Xi_c(3055)^+$
  $Br(\Lambda D^+)/Br(\Sigma_c^{++}K^-) = 5.09 \pm 1.01 \pm 0.76$
- $\Xi_c(3080)^+$
  $Br(\Lambda D^+)/Br(\Sigma_c^{++}K^-) = 1.29 \pm 0.30 \pm 0.15$

Phys. Rev. D **94**, 032002

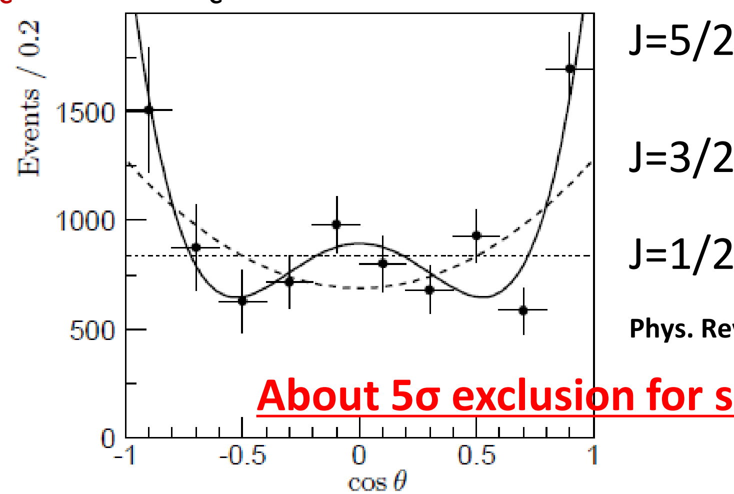
Combining absolute branching fraction by E50,
decay width can be determined precisely!

Spin/parity

$\Lambda_c(2880)$ J^P determination



$\Lambda_c^+(2880)$ $\Sigma_c\pi$ decay angular distribution



Phys. Rev. Lett. 98, 262001

About 5σ exclusion for spin 1/2, 3/2

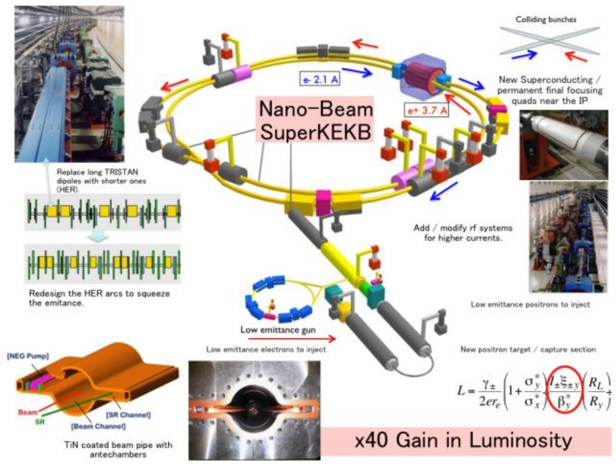
The decay angular distribution for spin 5/2.

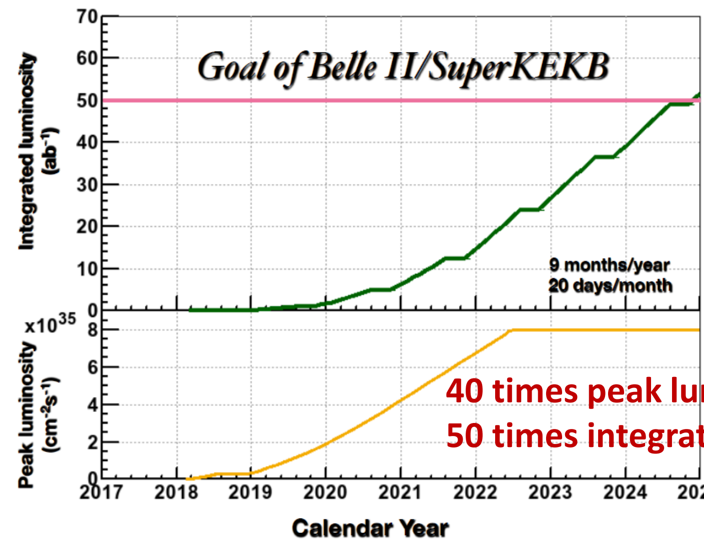
$$W_{5/2} = \frac{3}{8}[\rho_{55}2(5\cos^4\theta - 2\cos^2\theta + 1) + \rho_{33}(-15\cos^4\theta + 14\cos^2\theta + 1) + \rho_{11}5(1-\cos^2\theta)^2]$$

- There is a difficulty for 1/2 state.
- Decay angular distribution depends on helicity fraction (ρ_{ii}).
  Difficult to predict ρ_{ii} in $e^+e^- \to c\bar{c}$ production.
- If a charm baryon is not polarized (ρ_{ii} have same value), angular distribution becomes flat.
  → It is difficult to distinguish spin 1/2 and no polarization.

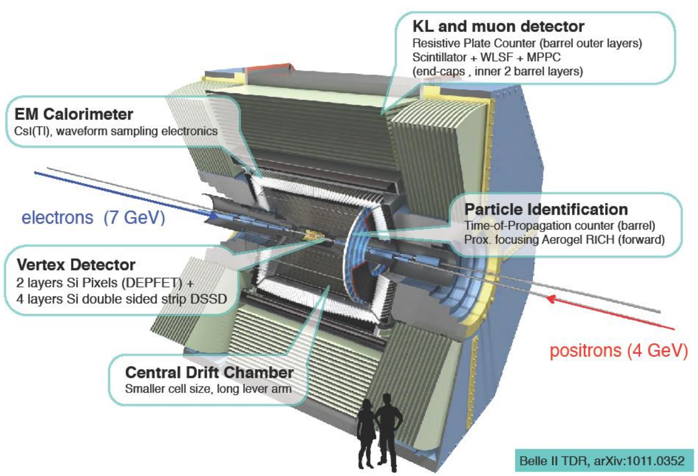
Belle→Belle II

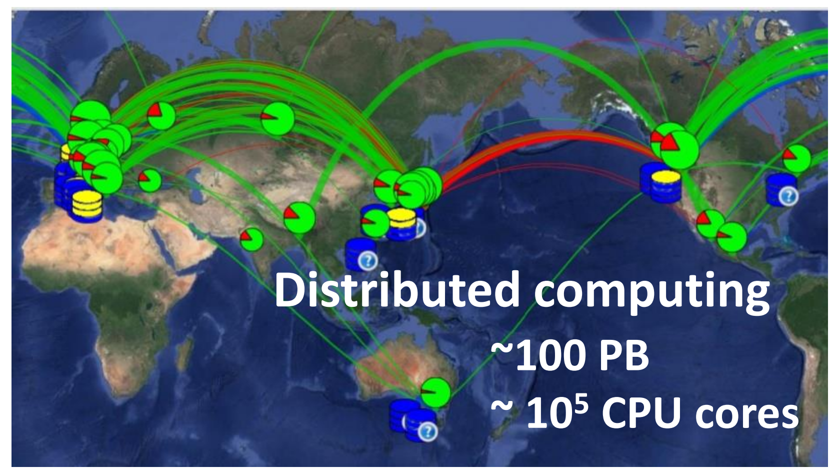
Aim to find physics beyond the Standard Model



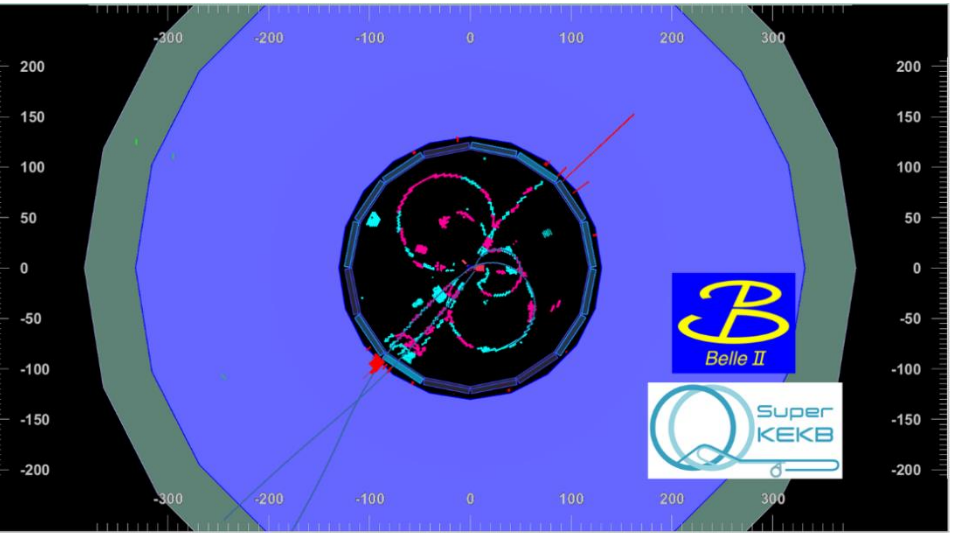


40 times peak luminosity.
50 times integrated luminosity.

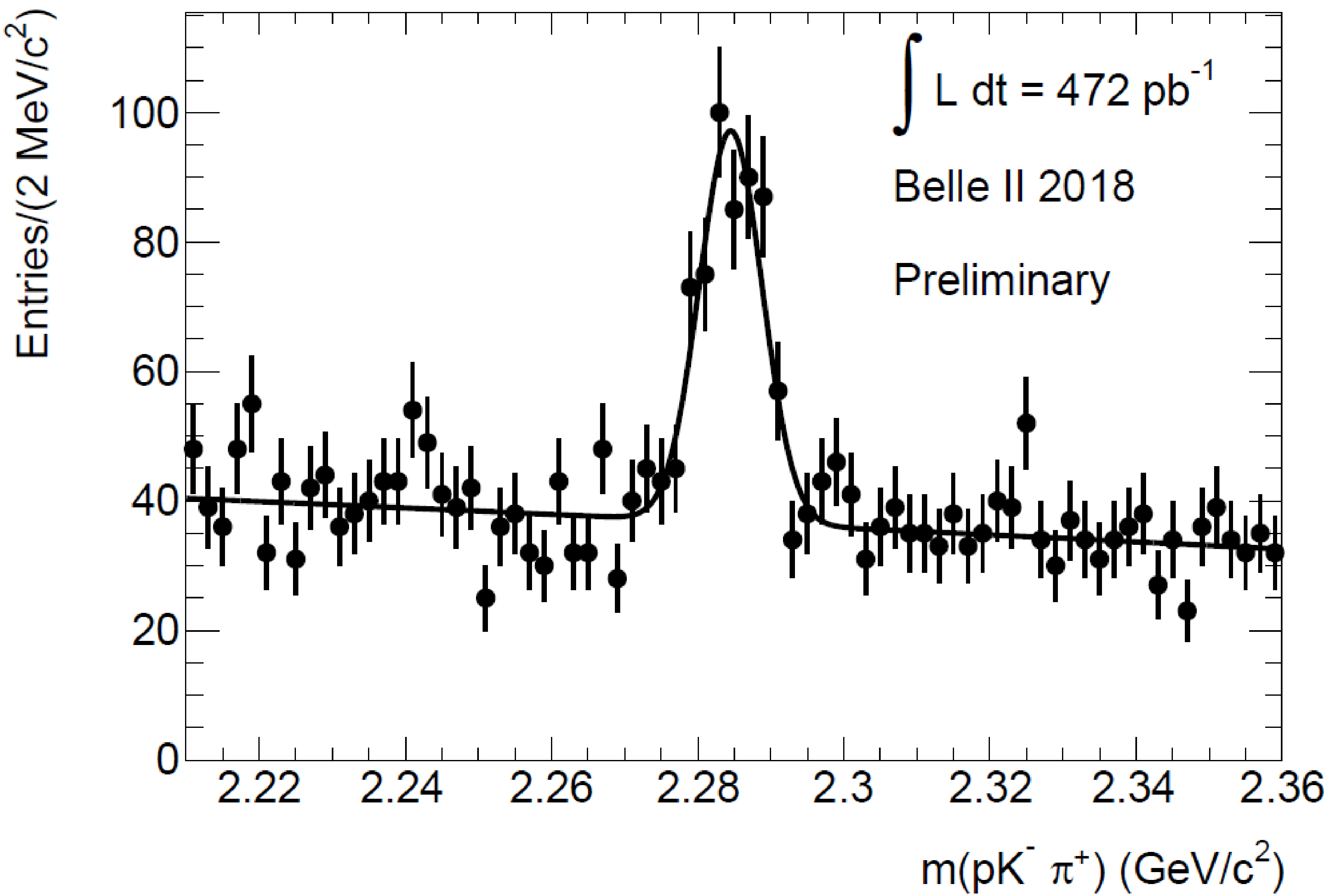




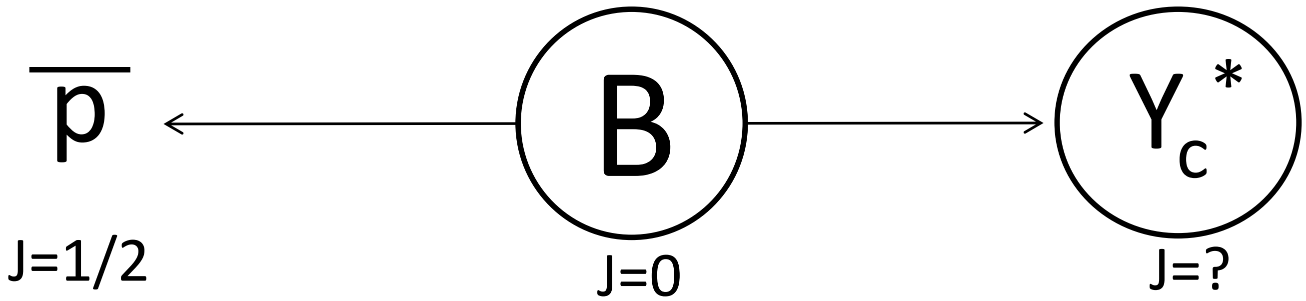
First collision!



“Rediscovery” of Λ_c^+ !



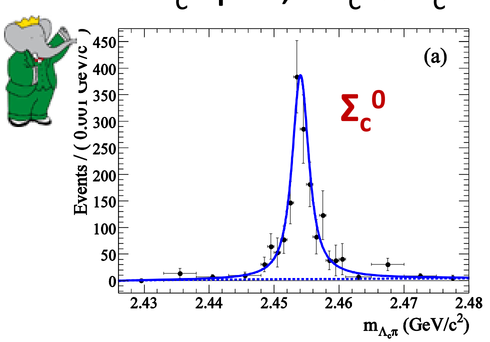
Spin prospect at Belle II



- B meson two body decay constraints helicity to be 1/2
- Not enough statistics for higher excited state at Belle

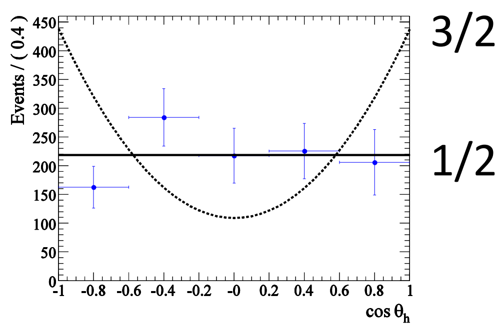
Example

$B \to \Sigma_c^0\, p^{bar}$, $\Sigma_c \to \Lambda_c^+\pi^-$



10.1103/PhysRevD.78.112003

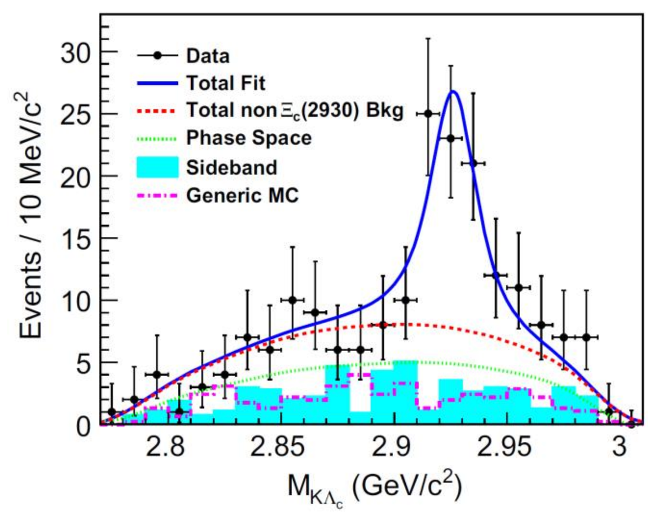
$\Lambda_c^+\pi^-$ angular distribution



S=1/2, exclude 3/2 by ~4σ

Higher excited states observed!

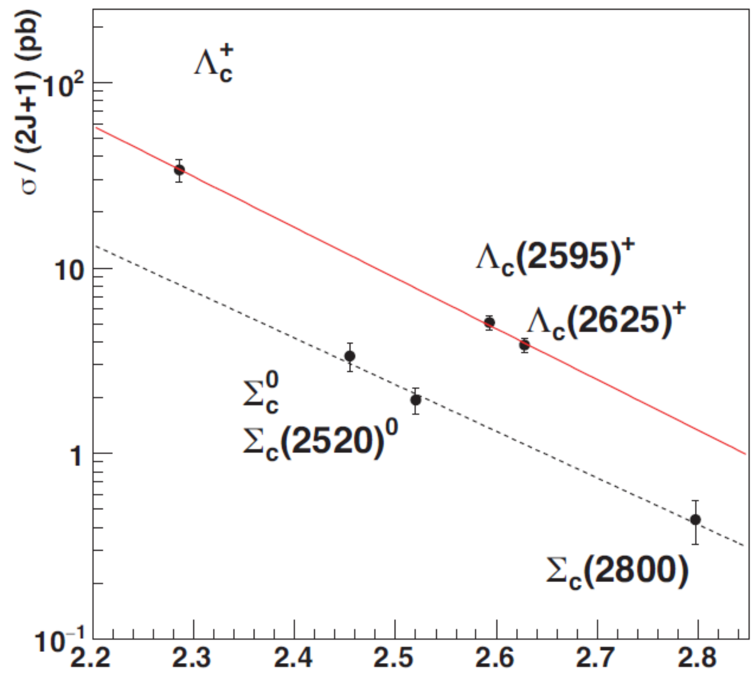
$B \to \Xi_c(2930)\Lambda_c$, $\Xi_c(2930) \to K\Lambda_c$



Eur. Phys. J. C (2018) 78: 252.

Discovery of new excited states

Phys. Rev. D **97**, 072005



- Cross section decrease with mass by exponential curve (~1/2 with 100 MeV increase)

- CLEO reached discovery of $\Lambda_c^+(2880)$.
  B-factories reached $\Lambda_c(2940)^+$, $\Xi_c(3080)$, $\Omega_c(3119)^+$
  - ~200 MeV higher sensitivity.

- We may have another 2-300 MeV sensitivity at Belle II, right?

- ρ mode, Roper, and higher excited states.

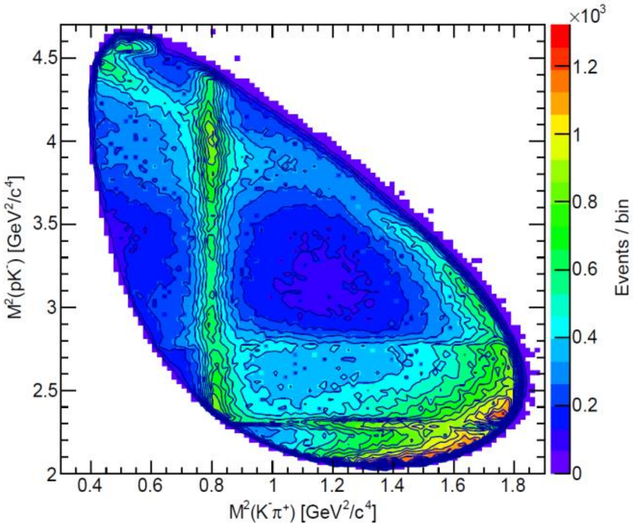
Charm baryon as a strange factory

- Ground state charm baryons proceed via c→s transition.
  → Good laboratory to study baryons including strange quarks.

- There are couple of examples on these analysis recently from Belle.

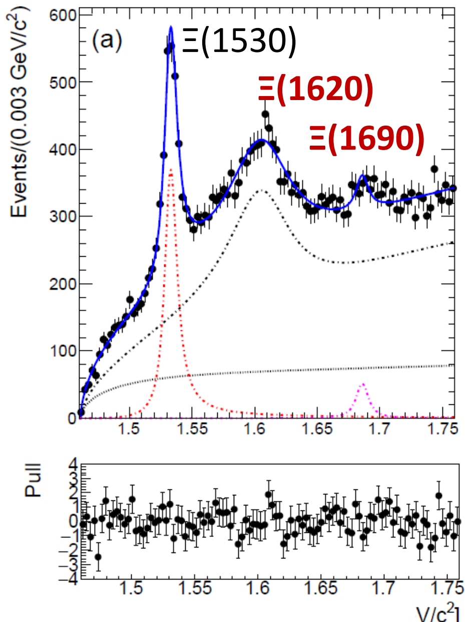
- Rare process, Ω_c decays, etc should be available at Belle II.

$\Lambda_c^+ \to pK^-\pi^+$



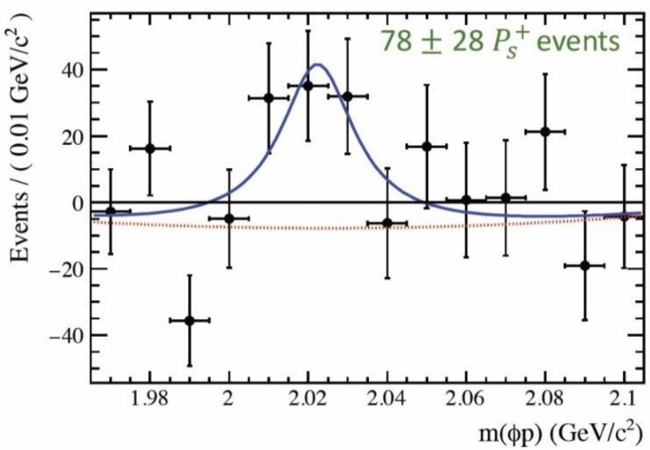
Phys. Rev. Lett. 117, 011801

$\Xi_c^+ \to \Xi^*\pi$, $\Xi^* \to \Xi^-\pi$



arXiv:1810.06181

$\Lambda_c^+ \to P_s\pi^0$, $P_s \to \phi p$ (only 2σ)



Phys. Rev. D 96, 051102(R)

Summary

- Charmed baryons spectroscopy by Belle
  - Discovery
  - Mass and width
  - Spin parity
  - Decay
  - Weak decay

- Belle II has started!
  - Spin determination using B-decay
  - Discovery of new hadrons, decays.

- Stay tuned for new results for Belle II (and also Belle).

Backup

Comparison with chiral quark model

- Ξ_c(3055) is $^2D_{\lambda\lambda}(3/2^+)$ or $^2D_{\rho\rho}(3/2^+)$ concerning mass. (Phys. Rev. D 86, 034024)

Partial width (MeV)

	$\Sigma_c\bar{K}$	$\Xi_c^*(2645)\pi$	$\Xi_c'\pi$	$\Sigma_c^*\bar{K}$	$D\Lambda$	total
$\|\Xi_c\,{}^2D_{\lambda\lambda}(3/2^+)\rangle$	2.3	0.5	1.0	0.1	0.1	4.0
$\|\Xi_c\,{}^2D_{\rho\rho}(3/2^+)\rangle$	5.6	0.8	3.3	0.3	-	10.0

ΛD is predicted to be suppressed..

- Ξ_c(3080) is $^2S_{\rho\rho}$. Decay into ΛD is predicted to be suppressed.

- I hope theorists IN this room are interested in this.

"New hadrons" from B-factories

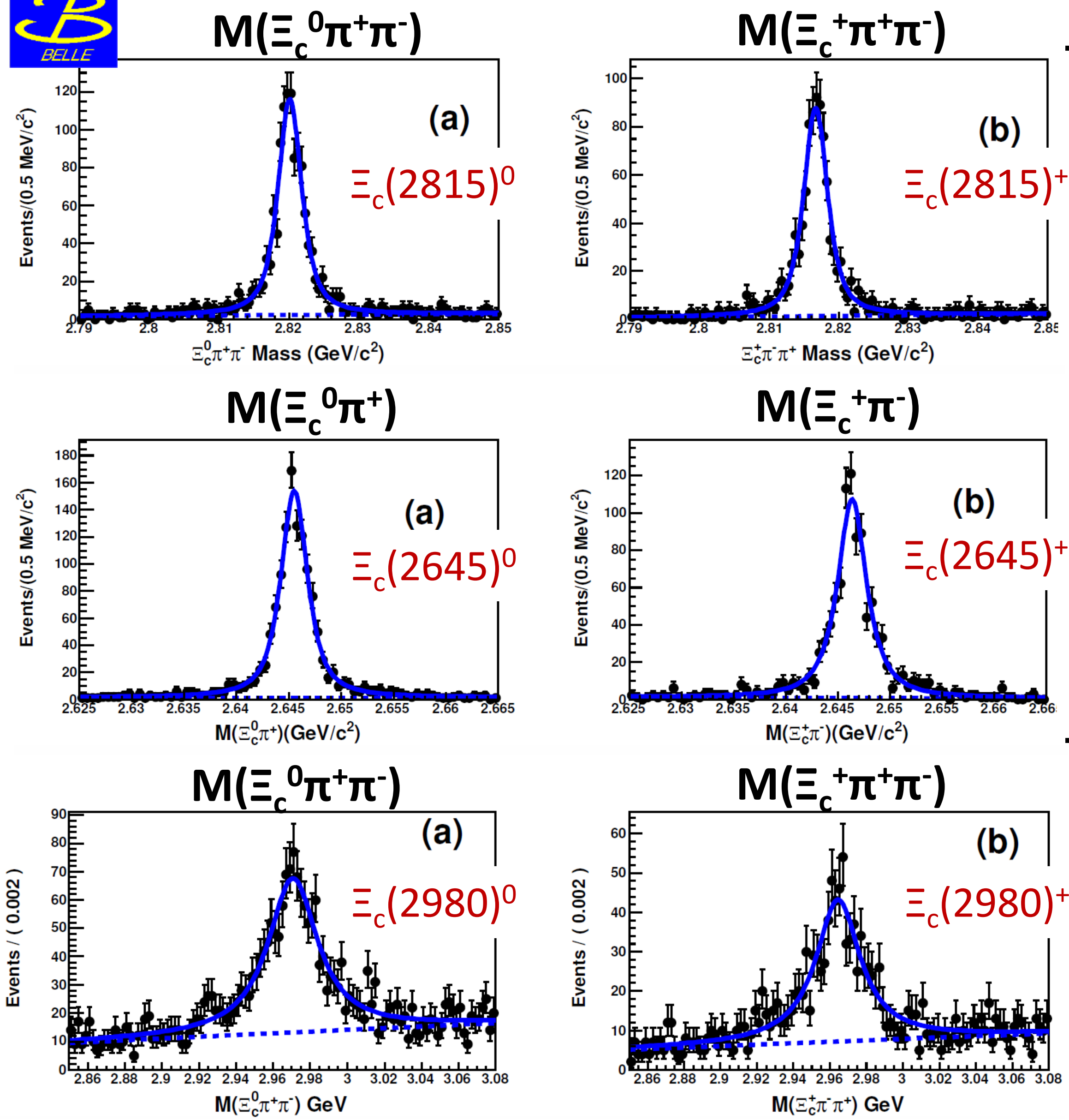
Hadron Type

Reaction

	Charmonium (like) = cc^{bar}	$D_{(s)}$ = cu^{bar}, cs^{bar}	Charmed baryon = cud, cus, css,…	Bottomonium = bb^{bar}
B-decay	$\eta_c(2S)$ X(3872) X(3915) $Z_c(4050)$ $Z_c(4250)$ $Z_c(4430)$ $Z_c(4200)$	$D^*_0(2400)$ $D_1(2430)$ $D^*_{s1}(2700)$	$\Xi_c(2930)$	Belle BaBar
Initial State Radiation	Y(4260) Z(3900) Y(4008) Y(4360) Y(4660)			
Double charmonium	X(3940) X(4160)			
Two photon	$\chi_{c2}(2P)$			
$e^+e^- \rightarrow cc^{bar}$		$D_0(2550)$ $D_J^*(2600)$ $D_J^*(2640)$ $D_J(2750)$ $D_{s0}(2317)$ $D_{sJ}(2860)$ $D_{sJ}(3040)$	$\Sigma_c(2800)$ $\Lambda_c(2940)$ $\Xi_c(2980)$ $\Xi_c(3080)$ $\Omega_c(2770)$ $\Xi_c(3055)$	
Y(5S) decay				$Z_b(10610)$ $Z_b(10650)$ $h_b(1P)$,$h_b(2P)$ $\eta_b(1S)$,$\eta_b(2S)$

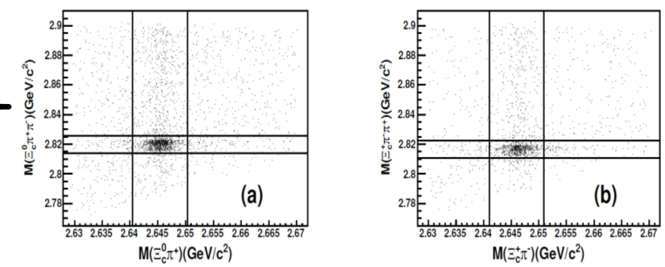
~ 40 new hadrons!
(Some states may be missed)

Excited Ξ_c mass splitting



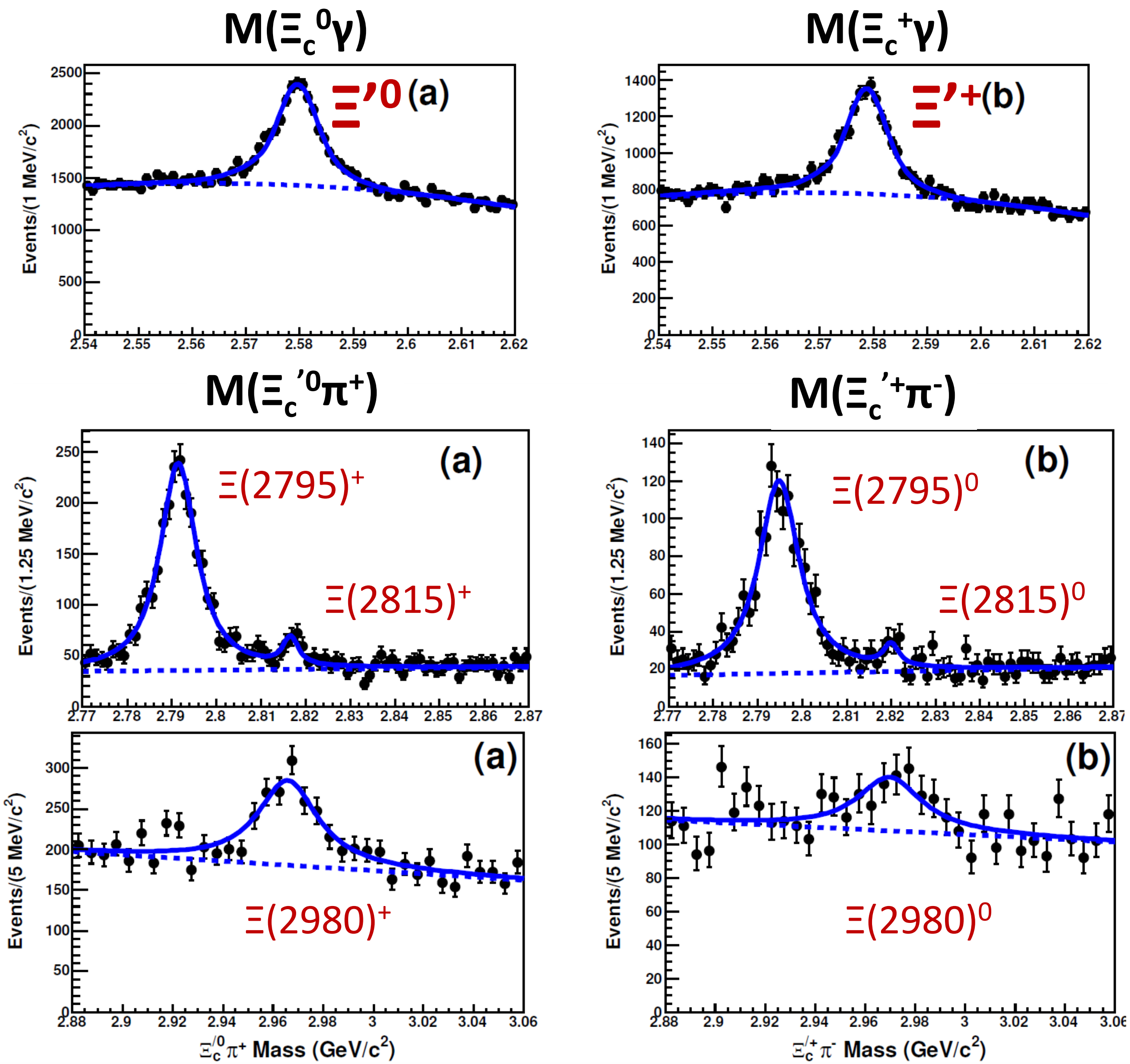
Reduce background using decay chain

$\Xi_c(2815) \rightarrow \Xi_c(2645)\pi \rightarrow \Xi_c\pi\pi$



Phys. Rev. D 94, 052011

Ξ_c excited states decaying to $\Xi_c'\pi$



First observations for
$\Xi_c(2815) \to \Xi_c'\pi$
$\Xi_c(2980) \to \Xi_c'\pi$

Phys. Rev. D 94, 052011