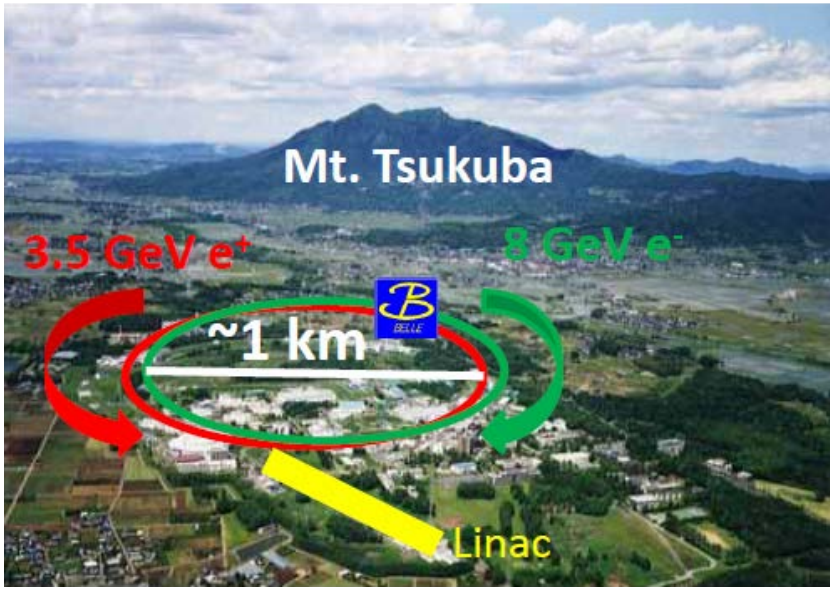
Recent highlights of heavy-flavor baryon physics from Belle

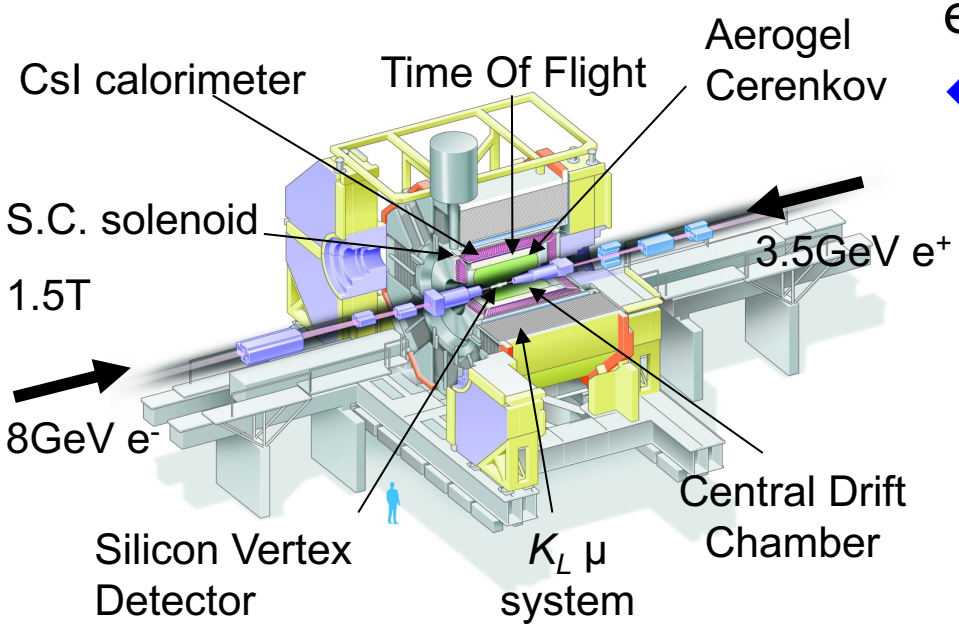
- Studies of excited Ξ_c
  - Mass and widths measurements of 5 excited Ξ_c states decaying into $\Xi_c\pi$
  - Higher excited Ξ_c decaying into ΛD
- Studies of Λ_c^+ decay modes
  - $\Lambda_c^+ \to p\phi\pi^0$ and $\Lambda_c^+ \to pK^-\pi^+\pi^0$
  - $\Lambda_c^+ \to pK^+\pi^-$
- Production cross sections of hyperons and charmed baryons

M. Niiyama (Kyoto U.)
for the Belle Collaboration

The Belle experiment

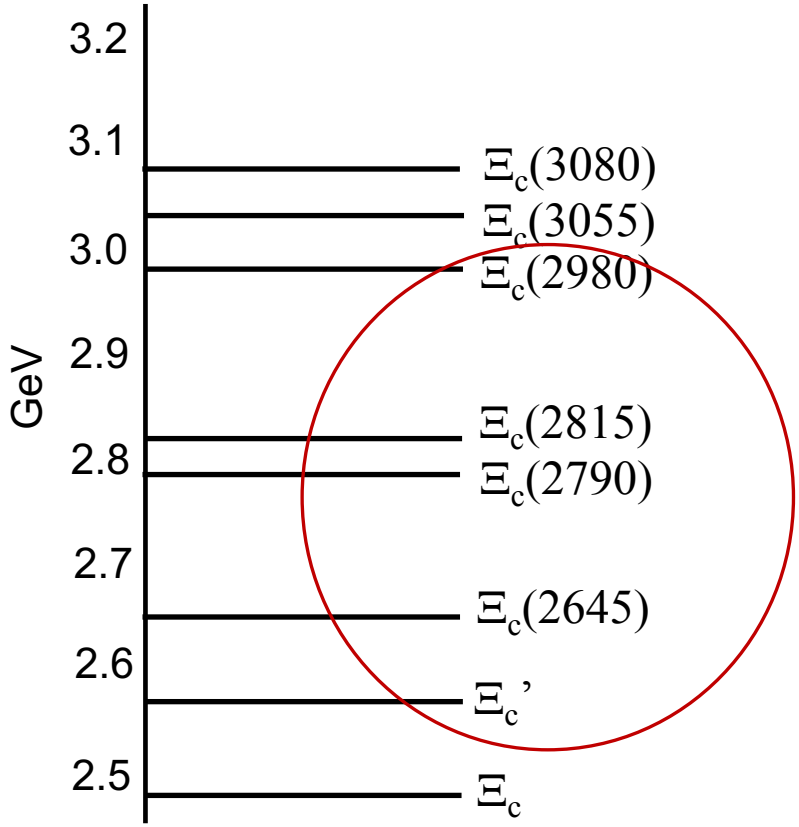


- Asymmetric energy e^+e^- collider
- General purpose detector
  - Detect charged particles and photons
  - Good momentum/vertex resolution
  - K/π separation up to 3.5 GeV/c
- Data at $\Upsilon(4S)$ and some other energies
- Integrated luminosity ~1 ab^{-1}



On resonance:	$\Upsilon(5S)$: 121 fb^{-1}
	$\Upsilon(4S)$: 711 fb^{-1}
	$\Upsilon(3S)$: 3 fb^{-1}
	$\Upsilon(2S)$: 25 fb^{-1}
	$\Upsilon(1S)$: 6 fb^{-1}
Off resonance/ scan:	~100 fb^{-1}

Mass and widths measurements of 5 excited Ξ_c states decaying into $\Xi_c\pi$



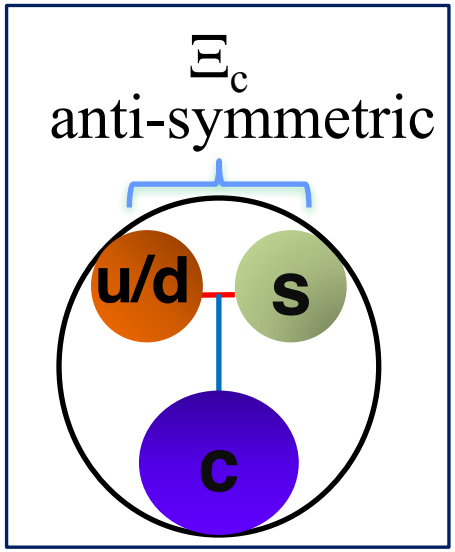
PRD 94, 052011(2016)

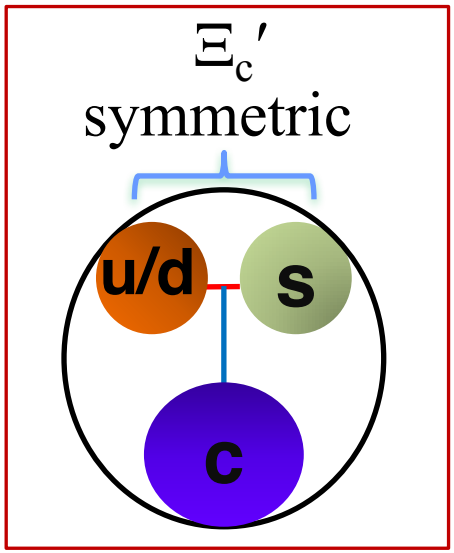
Study of excited Ξ_c states decaying into $\Xi_c\pi$

- Five isodoublets of excited Ξ_c [Ξ_c', $\Xi_c(2645)$, $\Xi_c(2790)$, $\Xi_c(2815)$, $\Xi_c(2980)$] are studied using 980/fb of Belle data.
- Previous measurements (CLEO, BaBar, Belle) were with low statistics. For widths, only upper limits were given for many states.
- Decays used in this analysis

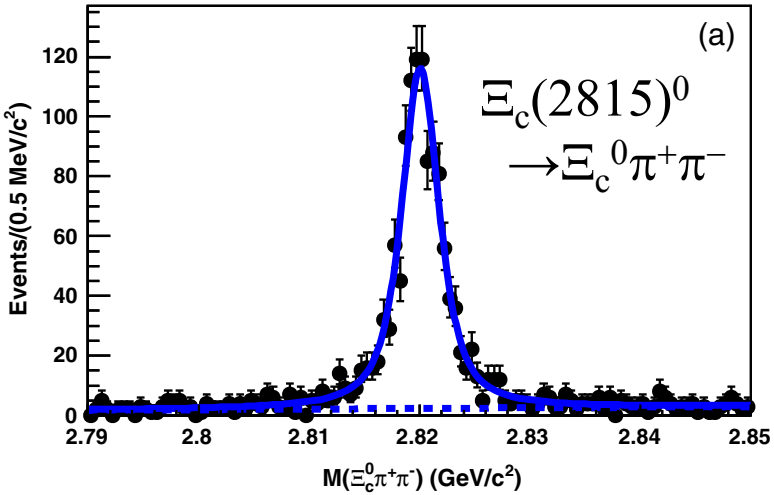
$$\Xi_c(2980) \to \Xi_c(2645)\pi \to \Xi_c\pi\pi$$
$$\Xi_c(2980) \to \Xi_c'\pi$$
$$\Xi_c(2815) \to \Xi_c(2645)\pi \to \Xi_c\pi\pi$$
$$\Xi_c(2815) \to \Xi_c'\pi$$
$$\Xi_c(2790) \to \Xi_c'\pi$$
$$\Xi_c' \to \Xi_c\gamma$$

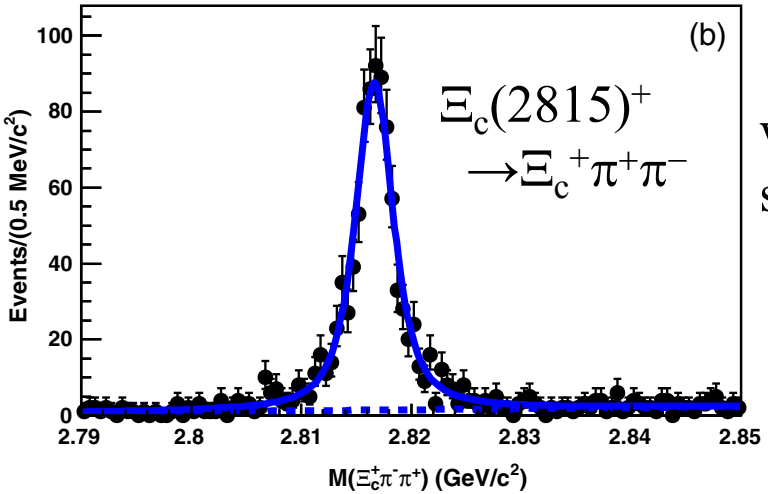
  - Ξ_c^+ and Ξ_c^0 are reconstructed from 10 and 7 decay modes





Invariant mass spectra of excited Ξ_c states





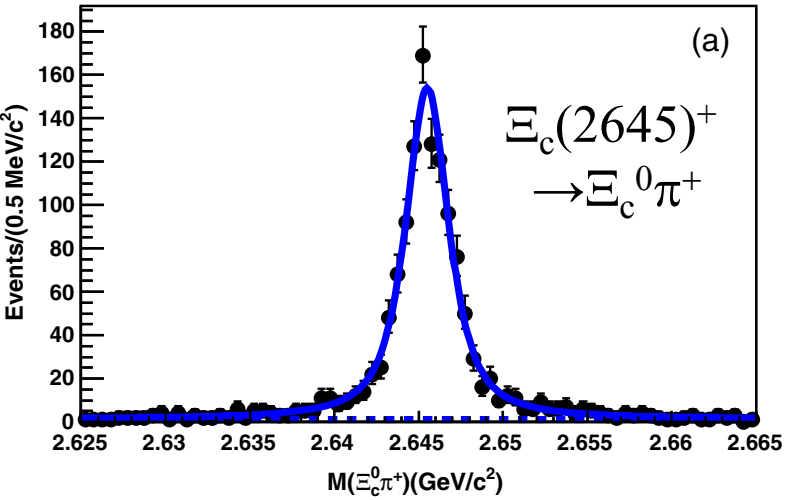
w/ $\Xi_c(2645)$ selection in $M(\Xi_c\pi)$

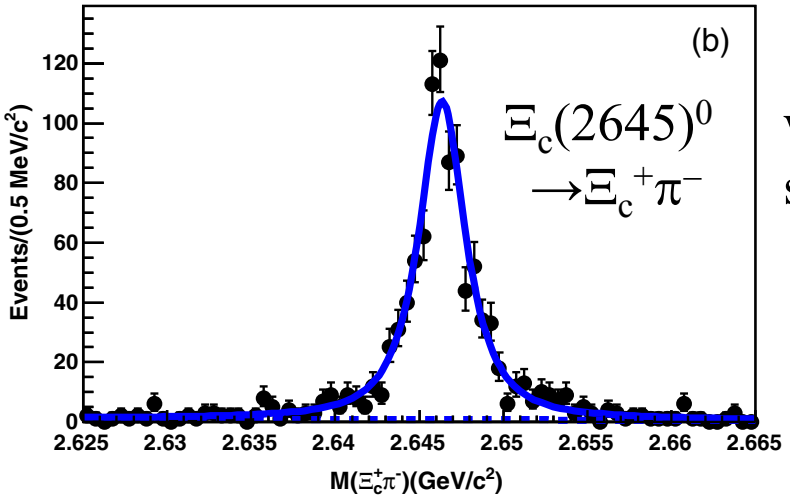
m=2820.20±0.08(stat.) MeV
Γ=2.54±0.18(stat.) MeV

m=2816.73±0.08(stat.) MeV
Γ=2.43±0.20(stat.) MeV

Masses and widths are determined from fit.
Fit functions are
Signal: Breit-Wigner convoluted with a double-Gaussian resolution functions
Background : polynomial functions

Invariant mass spectra of excited Ξ_c states

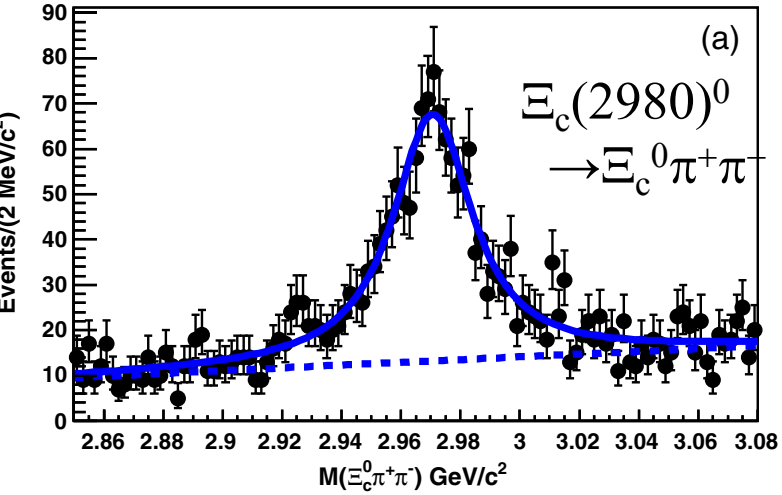


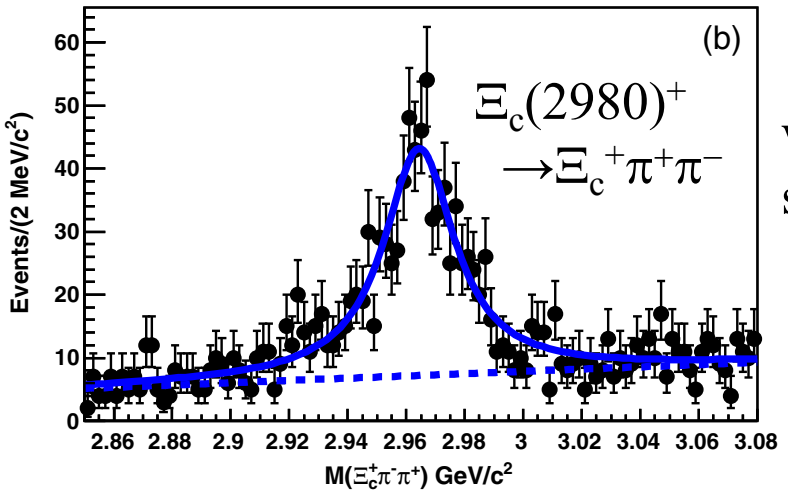


w/ $\Xi_c(2825)$ selection in $M(\Xi_c\pi\pi)$

m=2645.58±0.06(stat.) MeV
Γ=2.06±0.13(stat.) MeV

m=2646.43±0.07(stat.) MeV
Γ=2.35±0.18(stat.) MeV



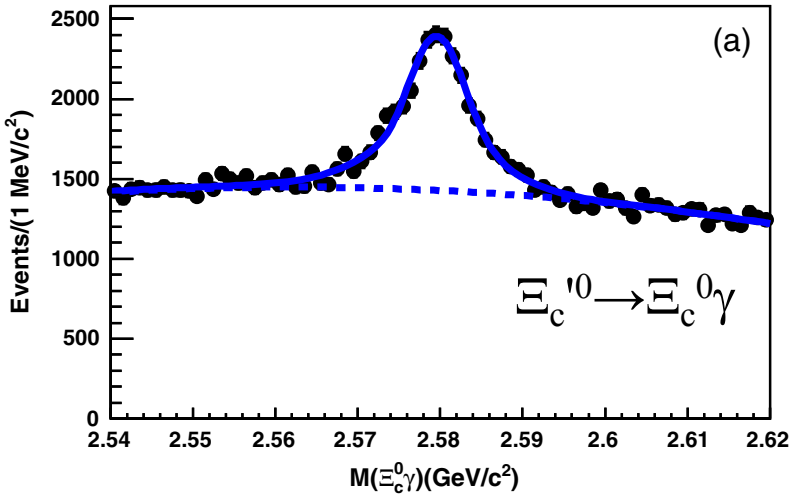


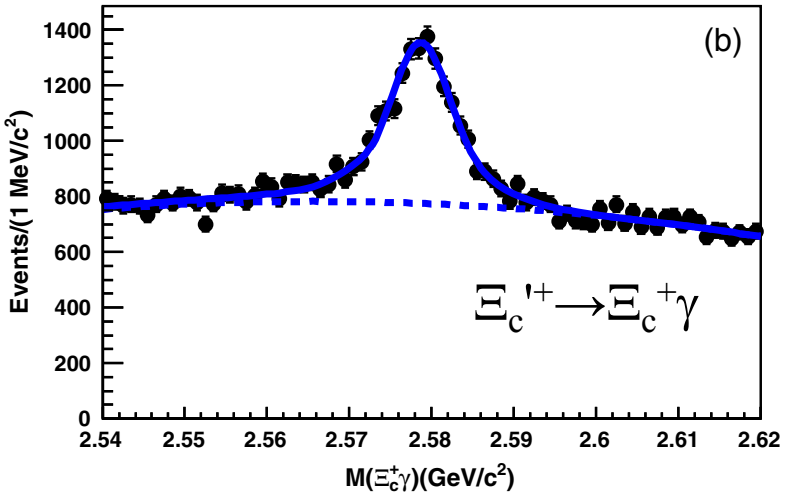
w/ $\Xi_c(2645)$ selection cut on $M(\Xi_c\pi)$

m=2970.8±0.7(stat.) MeV
Γ=30.3±2.3(stat.) MeV

m=2966.0±0.8(stat.) MeV
Γ=28.1±2.4(stat.) MeV

Reconstruction of Ξ_c' states

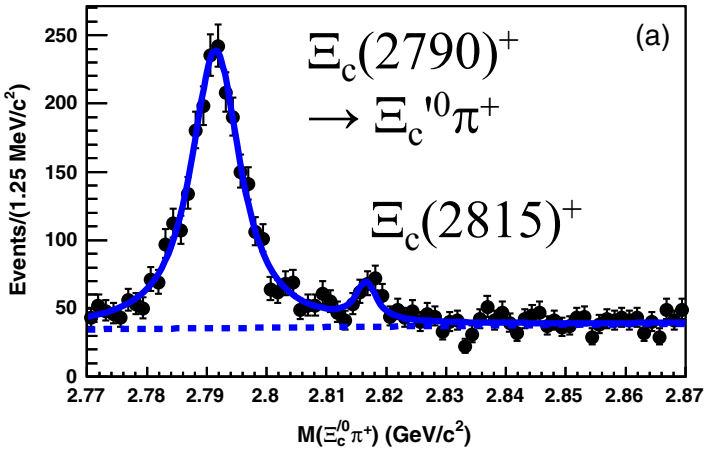


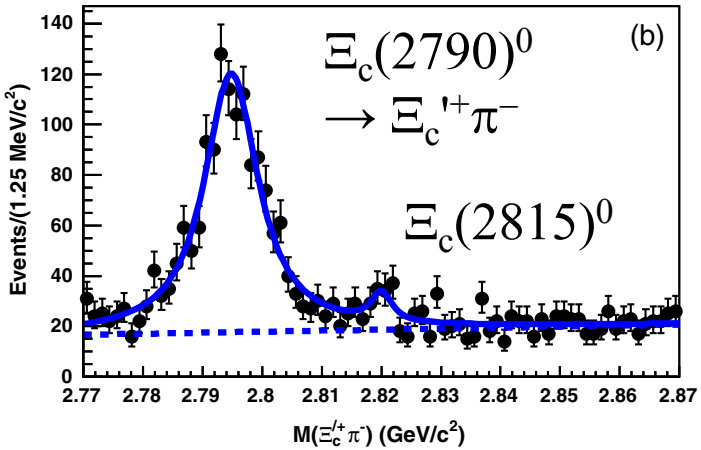


m=2579.2±0.1(stat.) MeV m=2578.4±0.1(stat.) MeV

Masses are determined from fit.
Fit functions are
  Signal: two ”crystal ball” functions with different resolution parameters that are fixed using MC
  Background : polynomial functions

Invariant mass spectra of excited Ξ_c states

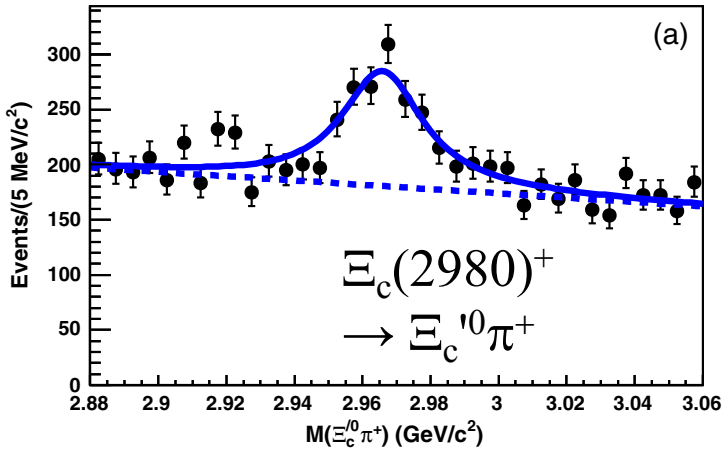


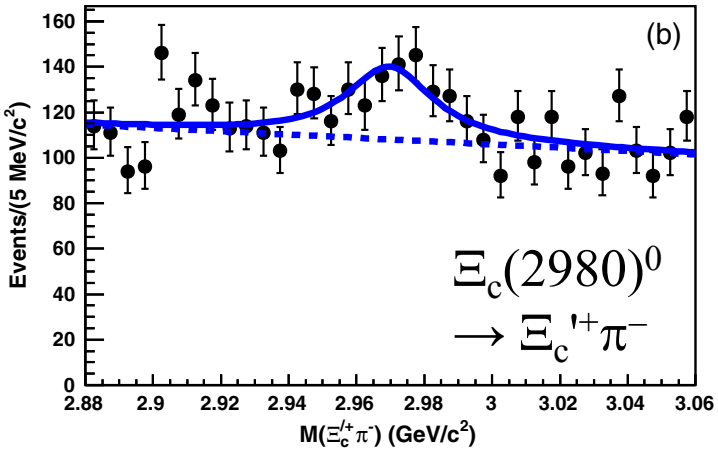


m=2791.6±0.2(stat.) MeV
Γ=8.9±0.6(stat.) MeV

m=2794.9±0.3(stat.) MeV
Γ=10.0±0.7(stat.) MeV

Signal: Breit-Wigner convoluted with a double-Gaussian resolution functions
Background : polynomial functions





First observation in $\Xi_c'\pi$ decay.

Results

Particle	Yield	Mass	Width
$\Xi_c(2645)^+$	1260 ± 40	$2645.58 \pm 0.06 \pm 0.07^{+0.28}_{-0.40}$	$2.06 \pm 0.13 \pm 0.13$
PDG		2645.9 ± 0.5	$2.6 \pm 0.2 \pm 0.4$
$\Xi_c(2645)^0$	975 ± 36	$2646.43 \pm 0.07 \pm 0.07^{+0.28}_{-0.40}$	$2.35 \pm 0.18 \pm 0.13$
PDG		2645.9 ± 0.5	< 5.5
$\Xi_c(2815)^+$	941 ± 35	$2816.73 \pm 0.08 \pm 0.06^{+0.28}_{-0.40}$	$2.43 \pm 0.20 \pm 0.17$
PDG		2816.6 ± 0.9	< 3.5
$\Xi_c(2815)^0$	1258 ± 40	$2820.20 \pm 0.08 \pm 0.07^{+0.28}_{-0.40}$	$2.54 \pm 0.18 \pm 0.17$
PDG		2819.6 ± 1.2	< 6.5
$\Xi_c(2980)^+$	916 ± 55	$2966.0 \pm 0.8 \pm 0.2^{+0.3}_{-0.4}$	$28.1 \pm 2.4^{+1.0}_{-5.0}$
PDG		2970.7 ± 2.2	17.9 ± 3.5
$\Xi_c(2980)^0$	1443 ± 75	$2970.8 \pm 0.7 \pm 0.2^{+0.3}_{-0.4}$	$30.3 \pm 2.3^{+1.0}_{-1.8}$
PDG		$2968.0 \pm 2.6 \pm 0.5$	20 ± 7
$\Xi_c'^+$	7055 ± 211	$2578.4 \pm 0.1 \pm 0.4^{+0.3}_{-0.4}$	
PDG		2575.6 ± 3.0	
$\Xi_c'^0$	11560 ± 276	$2579.2 \pm 0.1 \pm 0.4^{+0.3}_{-0.4}$	
PDG		2577.9 ± 2.9	
$\Xi_c(2790)^+$	2231 ± 103	$2791.6 \pm 0.2 \pm 0.1 \pm 0.4^{+0.3}_{-0.4}$	$8.9 \pm 0.6 \pm 0.8$
PDG		2789.8 ± 3.2	< 15
$\Xi_c(2790)^0$	1241 ± 72	$2794.9 \pm 0.3 \pm 0.1 \pm 0.4^{+0.3}_{-0.4}$	$10.0 \pm 0.7 \pm 0.8$
PDG		2791.9 ± 3.3	< 12

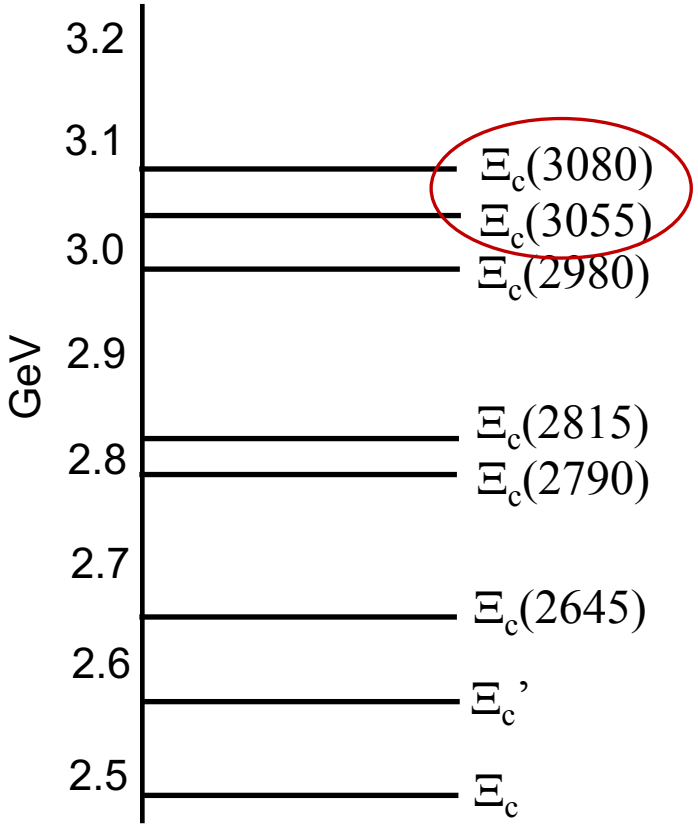
- Masses: ~1order improvement of precision
- Widths: 5 first measurements ($\Xi_c(2645)^0$, $\Xi_c(2815)^+$, $\Xi_c(2815)^0$, $\Xi_c(2790)^+$, $\Xi_c(2790)^0$)

Measurement of the isospin splitting consistent with non-relativistic quark model. [B. Silvestre-Brac et.al. J.phys G 29, 2685, (2003)]

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

Excited Ξ_c states in ΛD

PRD94, 032002 (2016)



Excited Ξ_c states in ΛD

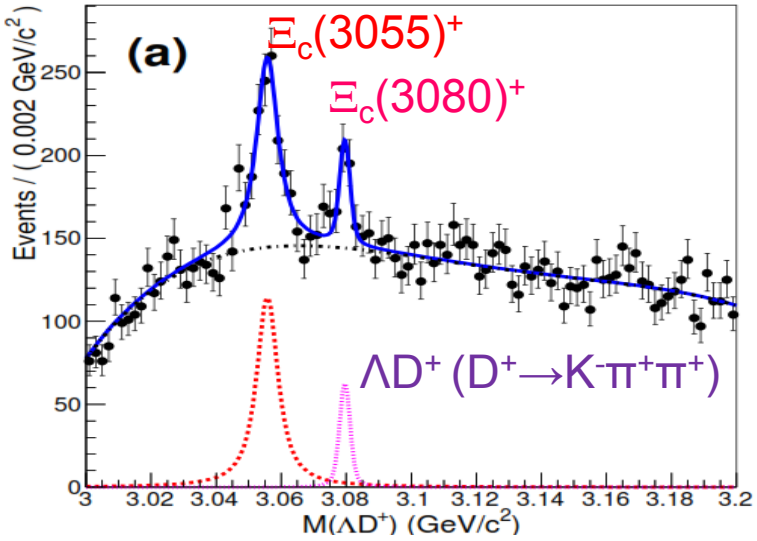
- Relative branching fractions (BF) of $\Sigma_c K$ and ΛD decays reveal the internal structure of Ξ_c states.
  - Chiral quark model: $\Xi_c(3055)$, $\Xi_c(3080)$ as D-wave and S-wave excitation in N=2 (radial) states. Small coupling to ΛD. PRD86,034024(2012)

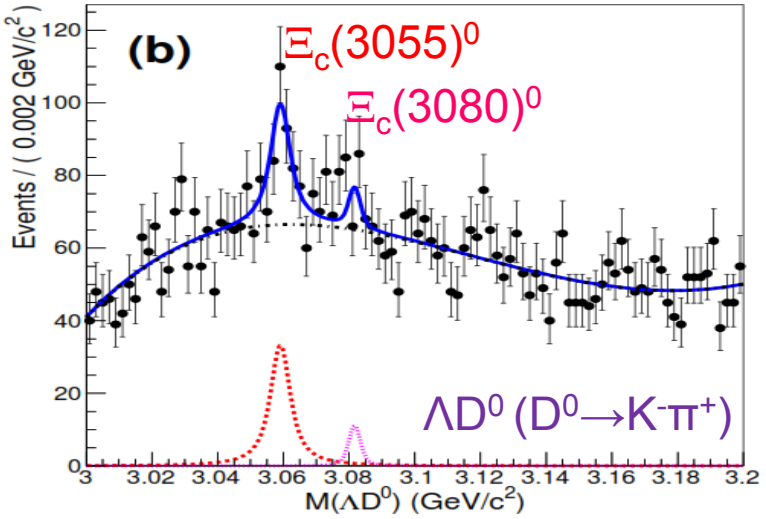
- Relative BFs ($\Lambda D / \Sigma_c K$) for $\Xi_c(3055)$, $\Xi_c(3080)$ are studied using 980/fb of Belle data.
- Relative BF ($\Sigma_c^* K / \Sigma_c K$) for $\Xi_c(3080)$ is also studied.
- $D^{+/0}$ mesons are reconstructed in
  - $D^+ \to K^-\pi^+\pi^+$
  - $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^+\pi^-$, $D^0 \to K^-\pi^+\pi^0$

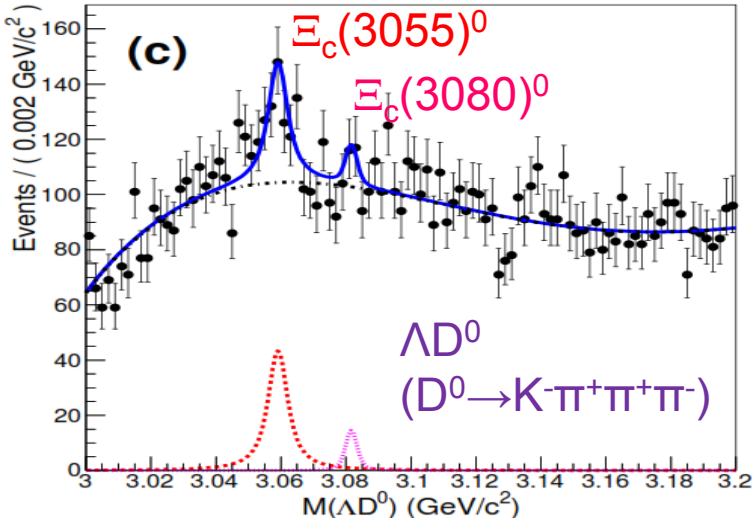
Observation of excited Ξ_c decay to ΛD

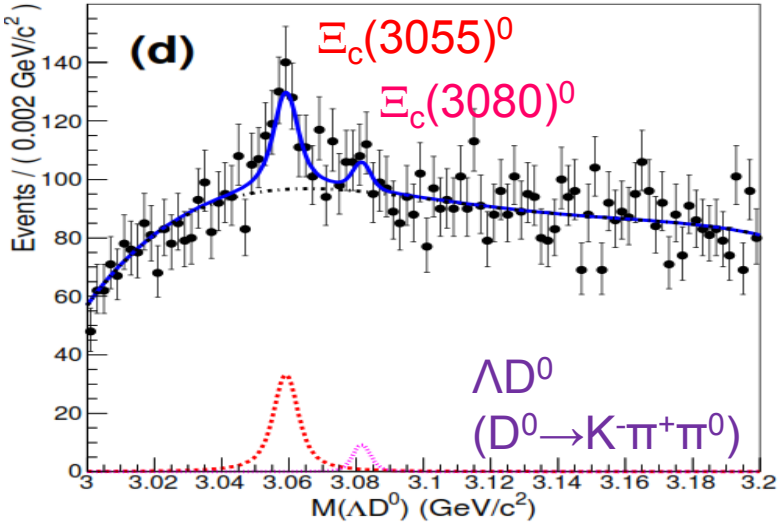
980fb^{-1}

PRD 94, 032002 (2016)







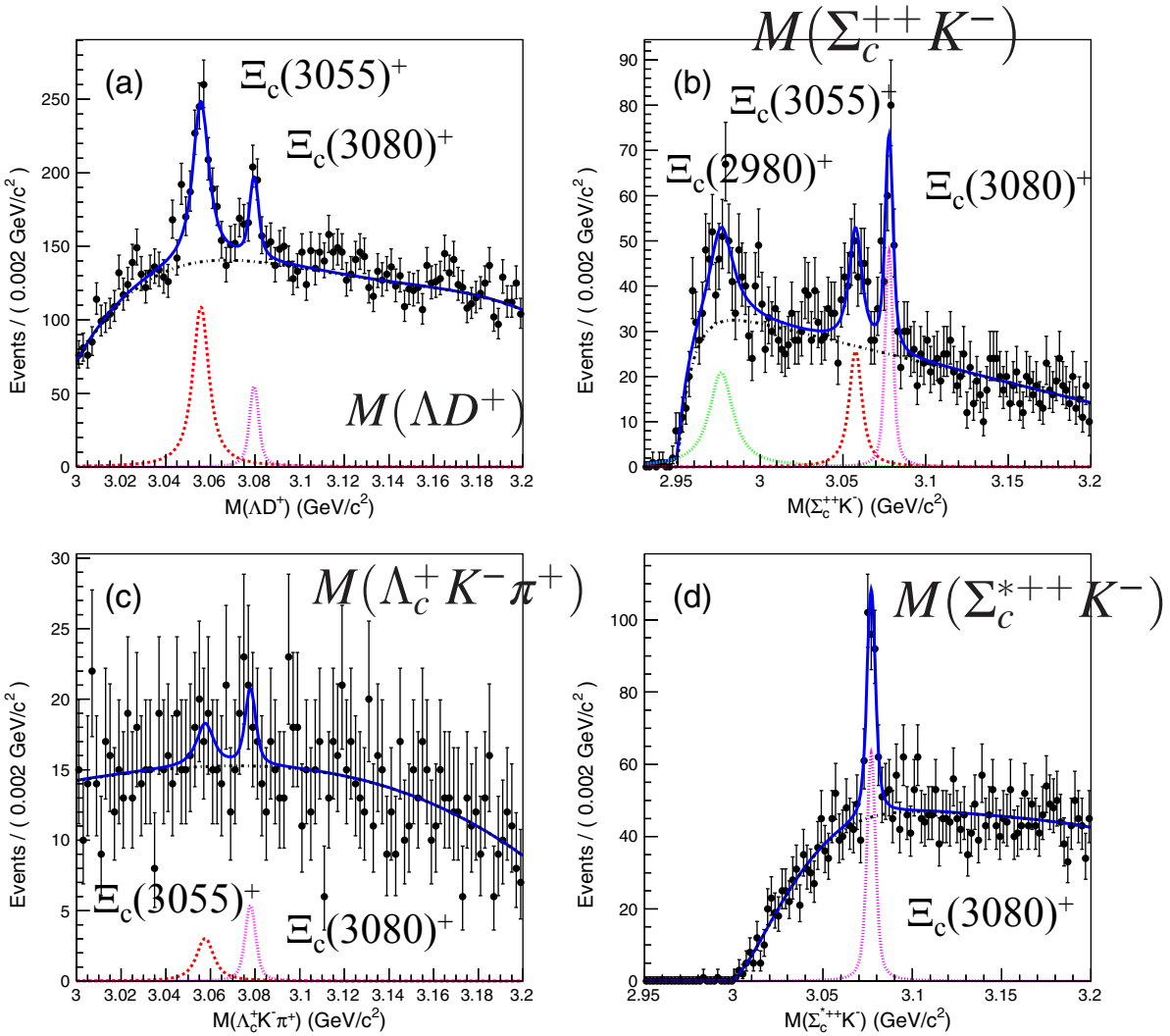


- Discovery of $\Xi_c(3055)^+ \to \Lambda D^+$ with 11.7σ and evidence for $\Xi_c(3080)^+ \to \Lambda D^+$ with 4.8σ
- Discovery of isosin partner $\Xi_c(3055)^0 \to \Lambda D^0$ with 8.6σ

Combined analysis of ΛD and $\Sigma_c K$ modes

- Simultaneous fit b/w m(ΛD), m($\Sigma_c^{++}K^-$), m($\Sigma_c^{*++}K^-$) , m($\Lambda_c^+K^-\pi^+$) with common width.

Resonance	Width (MeV)
$\Xi_c(3055)^+$	$7.8 \pm 1.2 \pm 1.5$
$\Xi_c(3080)^+$	$3.0 \pm 0.7 \pm 0.4$



Σ_c^{++} sideband region

Observation of excited Ξ_c decay to ΛD

980fb^{-1}

PRD 94, 032002 (2016)

First discovery of $\Xi_c(3055)^0$, we measure its mass and width

- $M(\Xi_c(3055)^0) = 3059.0 \pm 0.5 \pm 0.6$ MeV/c^2
- $\Gamma(\Xi_c(3055)^0) = 6.4 \pm 2.1 \pm 1.1$ MeV

State	BR(ΛD^+)/BR($\Sigma_c^{++}K^-$)	BR($\Sigma^*{}_c^{++}K^-$)/BR($\Sigma_c^{++}K^-$)
$\Xi_c(3055)^+$	$5.09 \pm 1.01 \pm 0.76$	
$\Xi_c(3080)^+$	$1.29 \pm 0.30 \pm 0.15$	$1.07 \pm 0.27 \pm 0.01$

The chiral quark model has been used to identify $\Xi_c(3055)$ as *D*-wave excitation in N=2 shell, and predict

PRD86,034024 (2012)

	$\Sigma_c\bar{K}$	$\Xi_c^*(2645)\pi$	$\Xi_c'\pi$	$\Sigma_c^*\bar{K}$	$D\Lambda$	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

Further identifies *$\Xi_c(3080)$* as an *S*-wave excitation mode in N=2 shell and predicts that its decay into *ΛD* is forbidden.

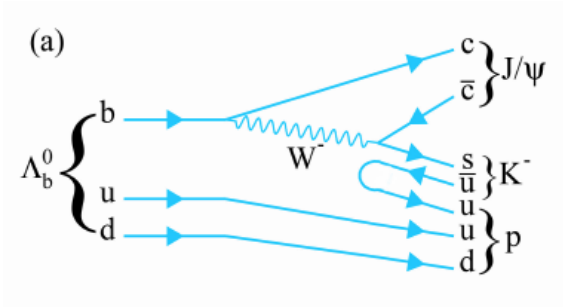
- Belle results contradicts some theory results.
- Crucial input to understand the nature of excited Ξ_c baryons.

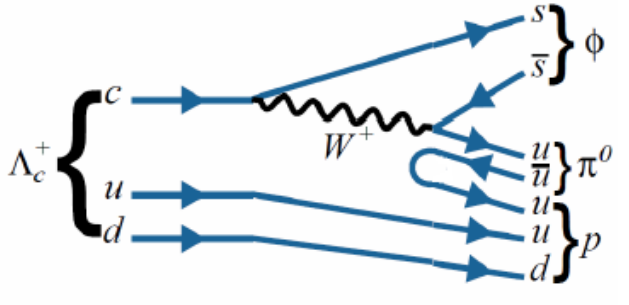
Study of $\Lambda_c^+ \to p\phi\pi^0$ and $\Lambda_c^+ \to pK^-\pi^+\pi^0$ decay with a search for pentaquark state

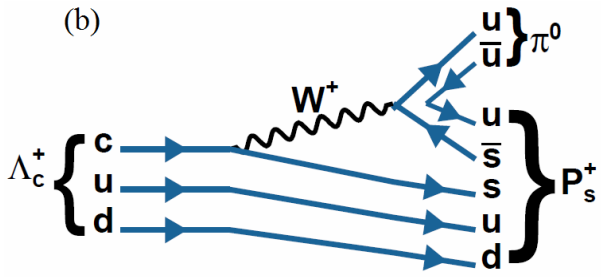
arXiv:1707.00089 [hep-ex]
accepted by PRD

Search for pentaquark state in $\Lambda_c^+ \to p\phi\pi^0$ decay

- LHCb's hidden-charm pentaquark (P_c^+) discovery in $J/\psi p$ of $\Lambda_b^0 \to J/\psi p K^-$
- Strange analog state (P_s^+) may appear in ϕp of $\Lambda_c^+ \to \phi p \pi^0$ assuming production mechanism is flavor independent
  - V. Kopeliovich, arxiv:1510.05958 [hep-ph], R. F. Lebed, PRD92, 114030
  - Cabibbo-suppressed decay
- LEPS & CLAS observed a bump at $\sqrt{s}$~2.2 GeV in ϕ photoproduction
  - PRL95, 182001, PRC89 055208, PRC90 019901
- This analysis used 916/fb of data collected at and near $\Upsilon(4S)$ and $\Upsilon(5S)$
- In addition, the precise measurement of branching fraction of Cabibbo favored decay $\Lambda_c^+ \to p\pi^+ K^- \pi^0$ is presented



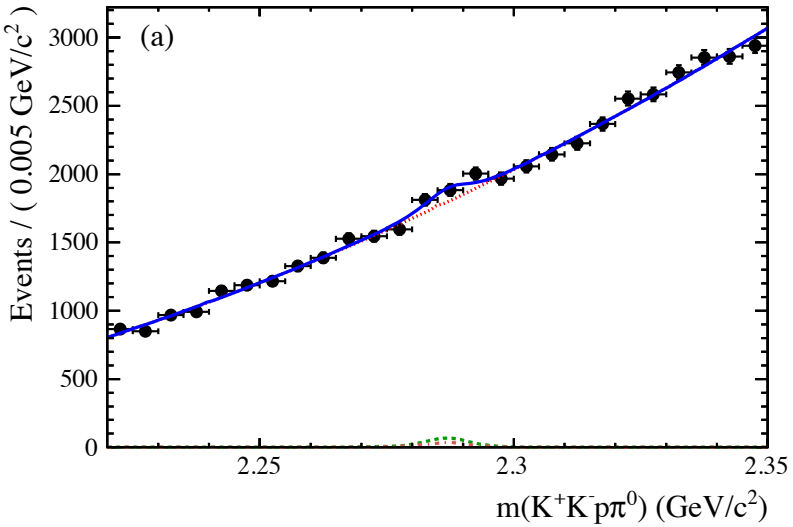


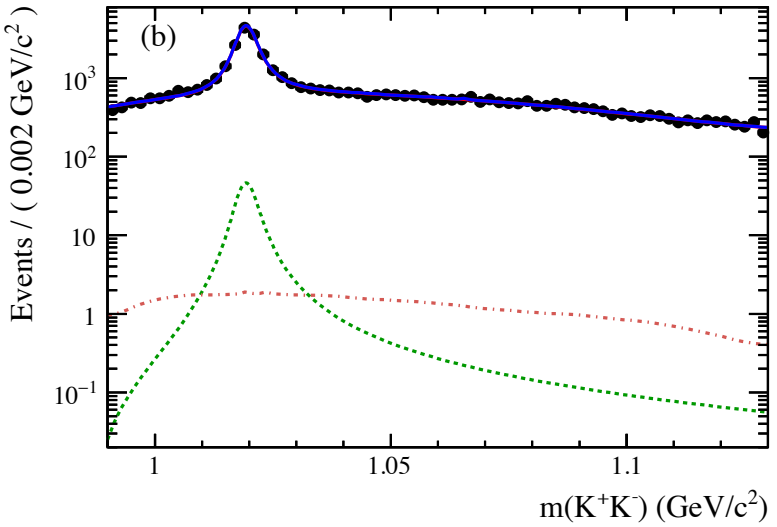


Analysis of $\Lambda_c^+ \to p\phi\pi^0$ decay

- Exclude events of M($p\pi^0$) within 10 MeV of mass of Σ^+
- Two dimensional fit is performed to $pK^+K^-\pi^0$ and K^+K^- invariant masses in order to extract the Λ_c^+ signal yield
  - 148.4±61.8 for $\Lambda_c^+ \to p\phi\pi^0$
  - 75.9±84.8 for $\Lambda_c^+ \to pK^+K^-\pi^0$

$$\mathcal{B}(\Lambda_c^+ \to \phi p\pi^0) < 15.3 \times 10^{-5},$$
$$\mathcal{B}(\Lambda_c^+ \to K^+K^- p\pi^0)_{\rm NR} < 6.3 \times 10^{-5},$$

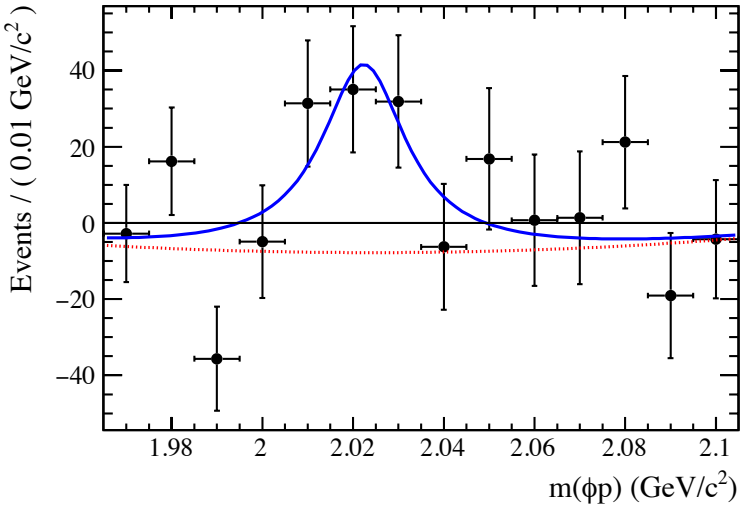




Search for a pentaquark state and branching fraction of $\Lambda_c^+ \to pK^-\pi^+\pi^0$

- Select $\Lambda_c^+ \to pK^+K^-\pi^0$ candidates in which M(K^+K^-) is within 20 MeV of the mass of ϕ
  - 77.6±28.1 evens

$$\mathcal{B}(\Lambda_c^+ \to P_s^+\pi^0) \times \mathcal{B}(P_s^+ \to \phi p) \; < \; 8.3 \times 10^{-5}$$



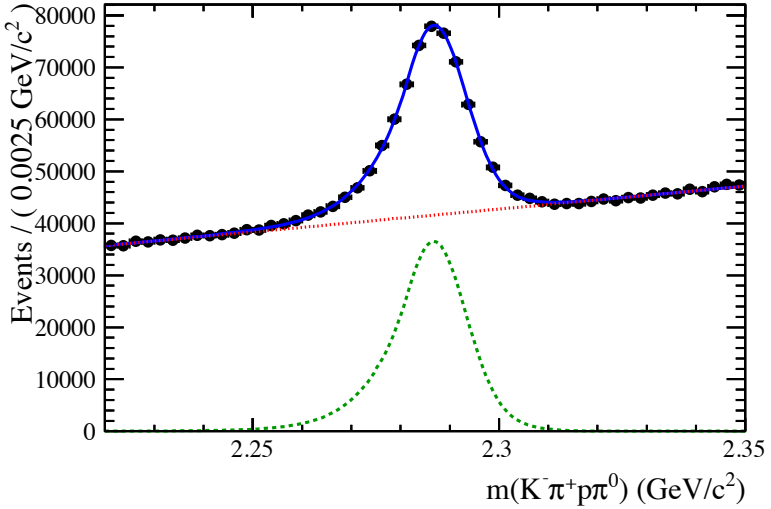
- Fit to M($pK^-\pi^+\pi^0$) spectrum
  - Two crystal ball functions with a common mean for signal, and a linear function for background

$$\mathcal{B}(\Lambda_c^+ \to K^-\pi^+p\pi^0) = (4.42 \pm 0.05 \pm 0.12 \pm 0.16)\%$$

  - World best measurement,

consistent with BESIII (PRL116, 052001)

$$\mathcal{B}(\Lambda_c^+ \to K^-\pi^+p\pi^0) = (4.53 \pm 0.23 \pm 0.30)\%$$

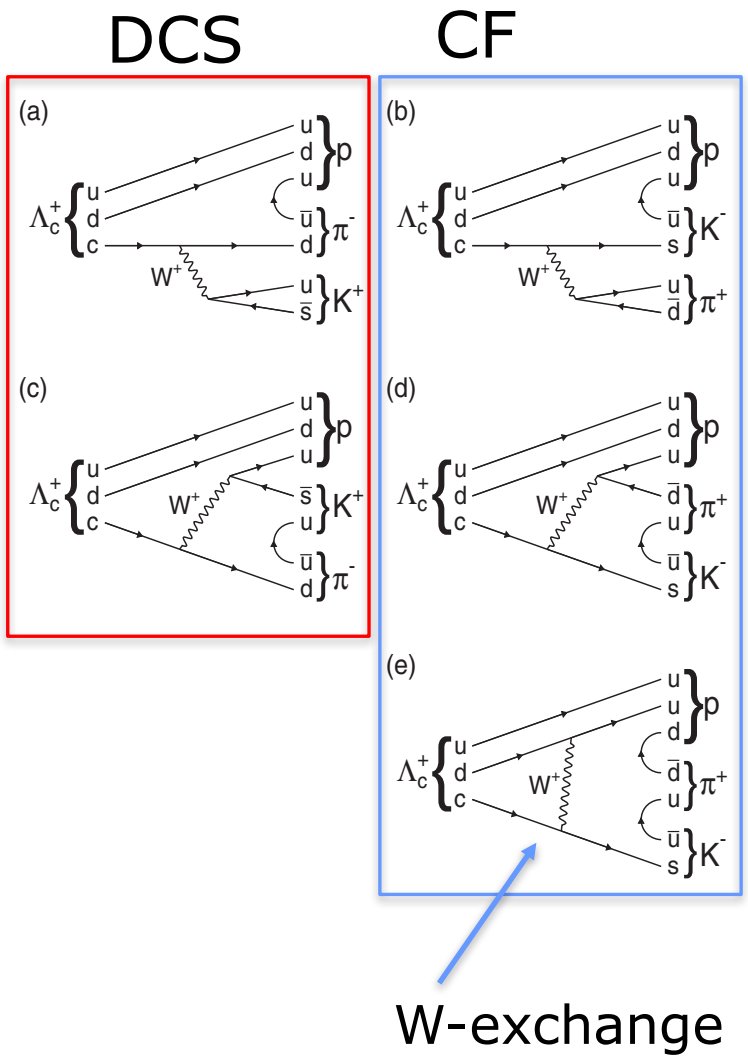


$\Lambda_c^+ \to pK^+\pi^-$, doubly Cabibbo-suppressed (DCS) decay of Λ_c

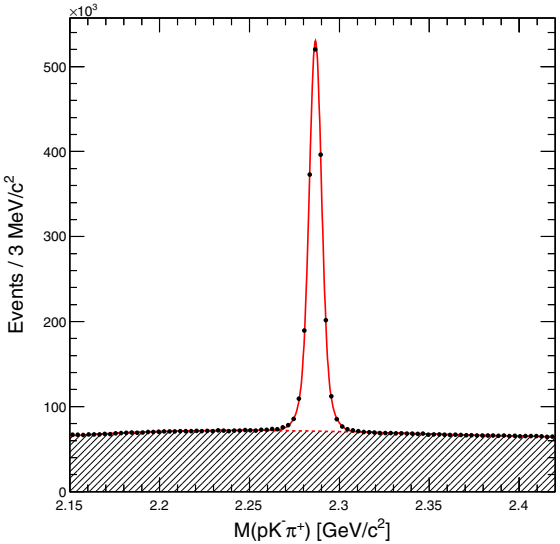
PRL117, 011801 (2016)

Doubly Cabibbo-suppressed decay of Λ_c

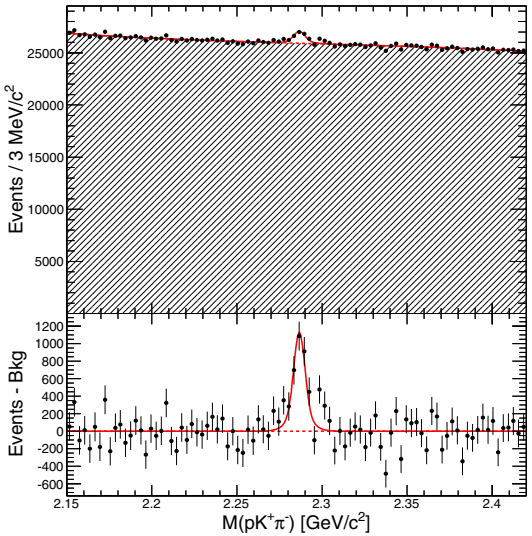
- Doubly Cabibbo-suppressed (DCS) decays seen in charm mesons, but not previously in baryons.
  Naïve expectation: $\frac{\mathcal{B}(DCS)}{\mathcal{B}(CF)} = tan^4\,\theta_c = 0.285\%$
  Since W-exchange diagram is absent in DCS decay, $\frac{\mathcal{B}(DCS)}{\mathcal{B}(CF)}$ may be smaller than the naïve expectation.
- This analysis uses 980/fb of data collected at and near $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S), \Upsilon(4S)$ and $\Upsilon(5S)$ resonances.



Analysis of $\Lambda_c^+ \to pK^+\pi^-$, DCS decay



1.45M events in Cabibbo favored (CF) decay



3587±380 events

After subtraction of $\Lambda_c^+ \to \Lambda K^+ \to p\pi^- K^+$, we observe 3379±380±78 DCS events with a significance > 9σ!

$$\frac{\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (2.35 \pm 0.27 \pm 0.21) \times 10^{-3}$$
$$= (0.82 \pm 0.12)\, tan^4\, \theta_c$$

Absolute branching fraction

$$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-) = (1.61 \pm 0.23^{+0.07}_{-0.08}) \times 10^{-4}$$

(First observation)

After subtracting the contribution $\Lambda^*(1520)$ and Δ isobar intermediates, which only contribute to CF decay, the revised ratio

$$\frac{\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (1.10 \pm 0.17)\, tan^4\, \theta_c$$

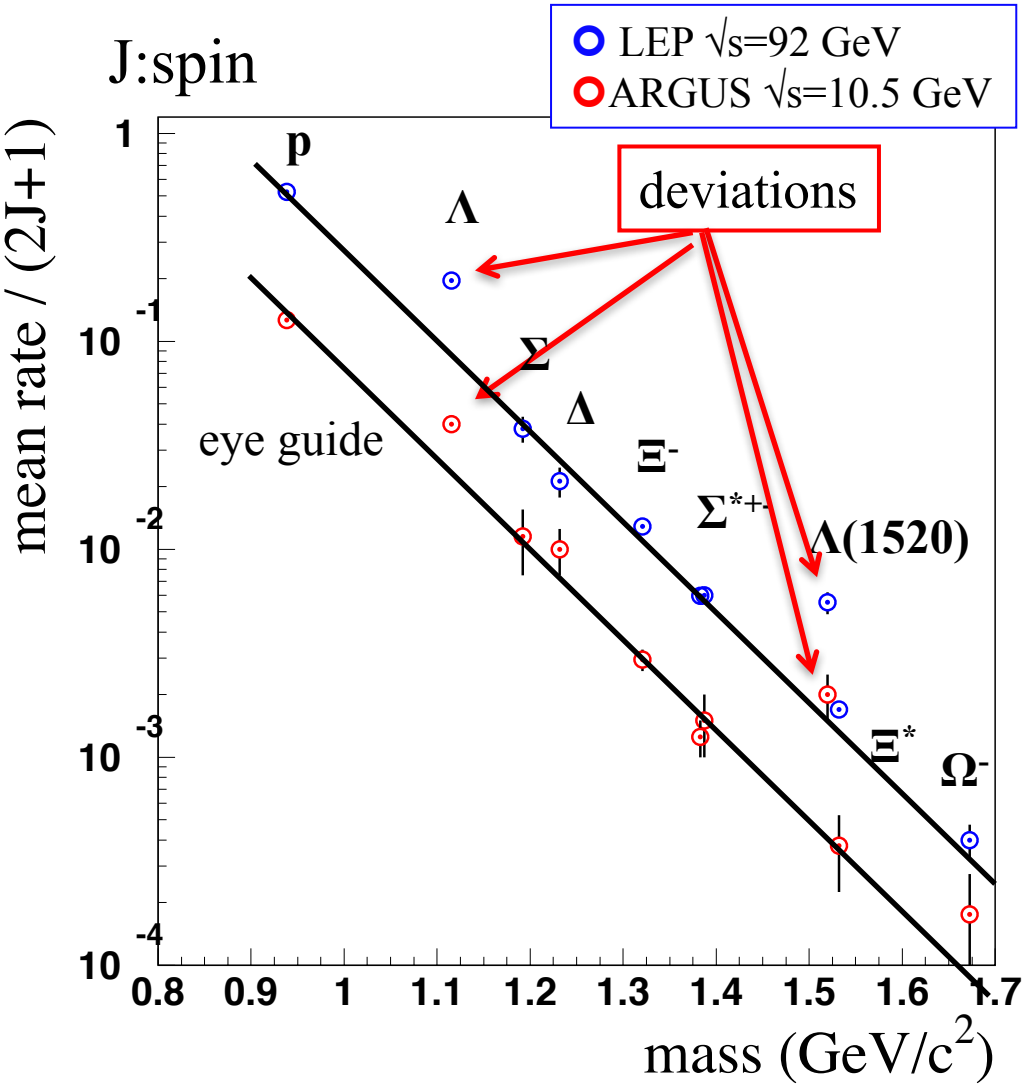
compatible with naïve expectation: no large W-exchange contribution in CF decay.

Production cross sections of hyperons and charmed baryons

arXiv:1706.06791 [hep-ex]
submitted to PRD

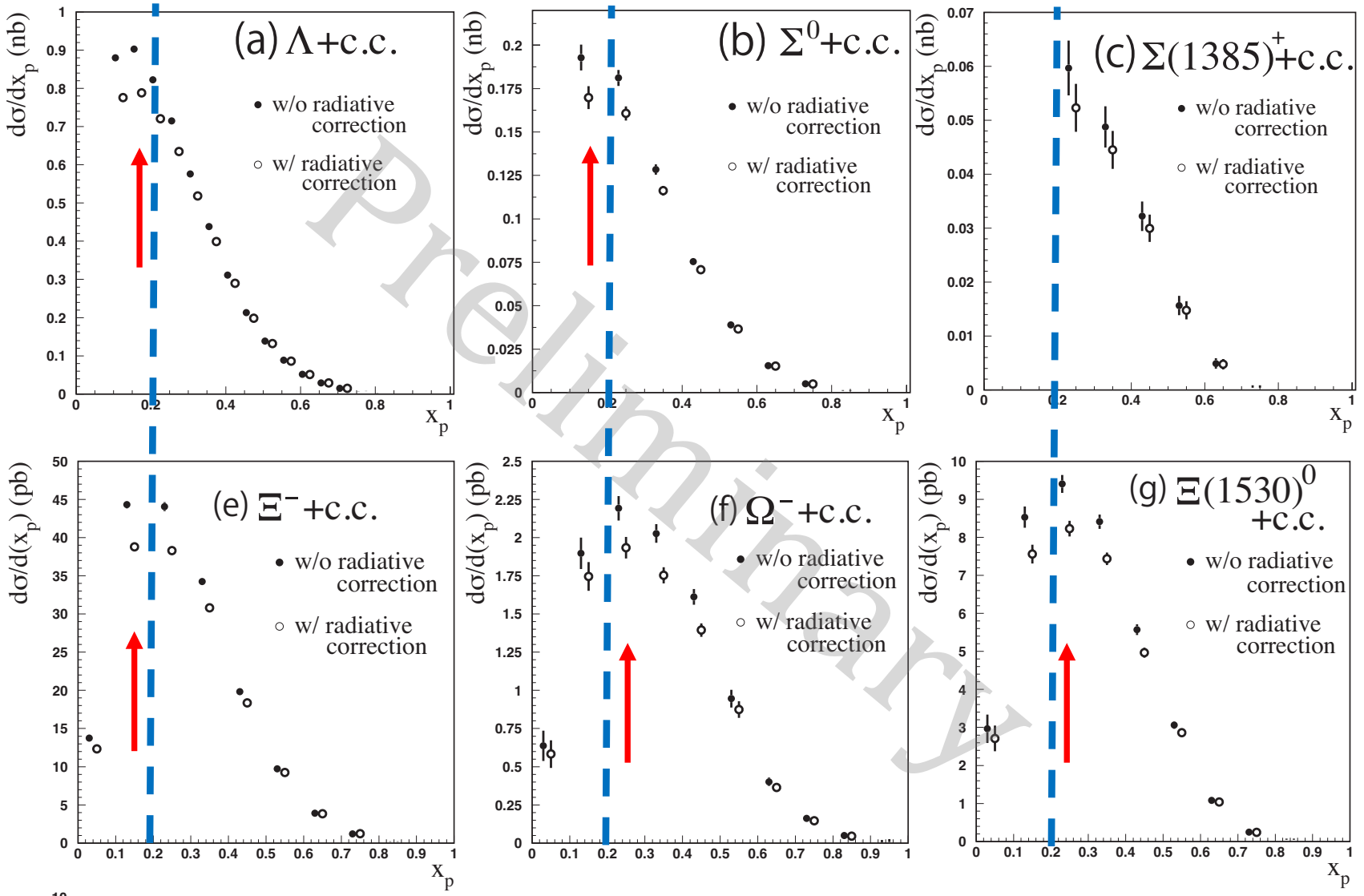
Baryon production rates in e^+e^- collision

- $\sigma/(2J+1) \propto \exp(\alpha m)$
- Higher rates for Λ and $\Lambda(1520)$ in ARGUS and LEP.
- J=0, light (ud) diquark in Λ?
  - R.L. Jaffe, Phys.Rept.409,1 (2005)
  - A. Selem, F. Wilczek, hep-ph/0602128
- Issues
  - Feed down is not subtracted.
  - Large error in ARGUS results.
  - How about charmed baryons?
  - Study at Belle!



Inclusive differential cross sections, hyperons

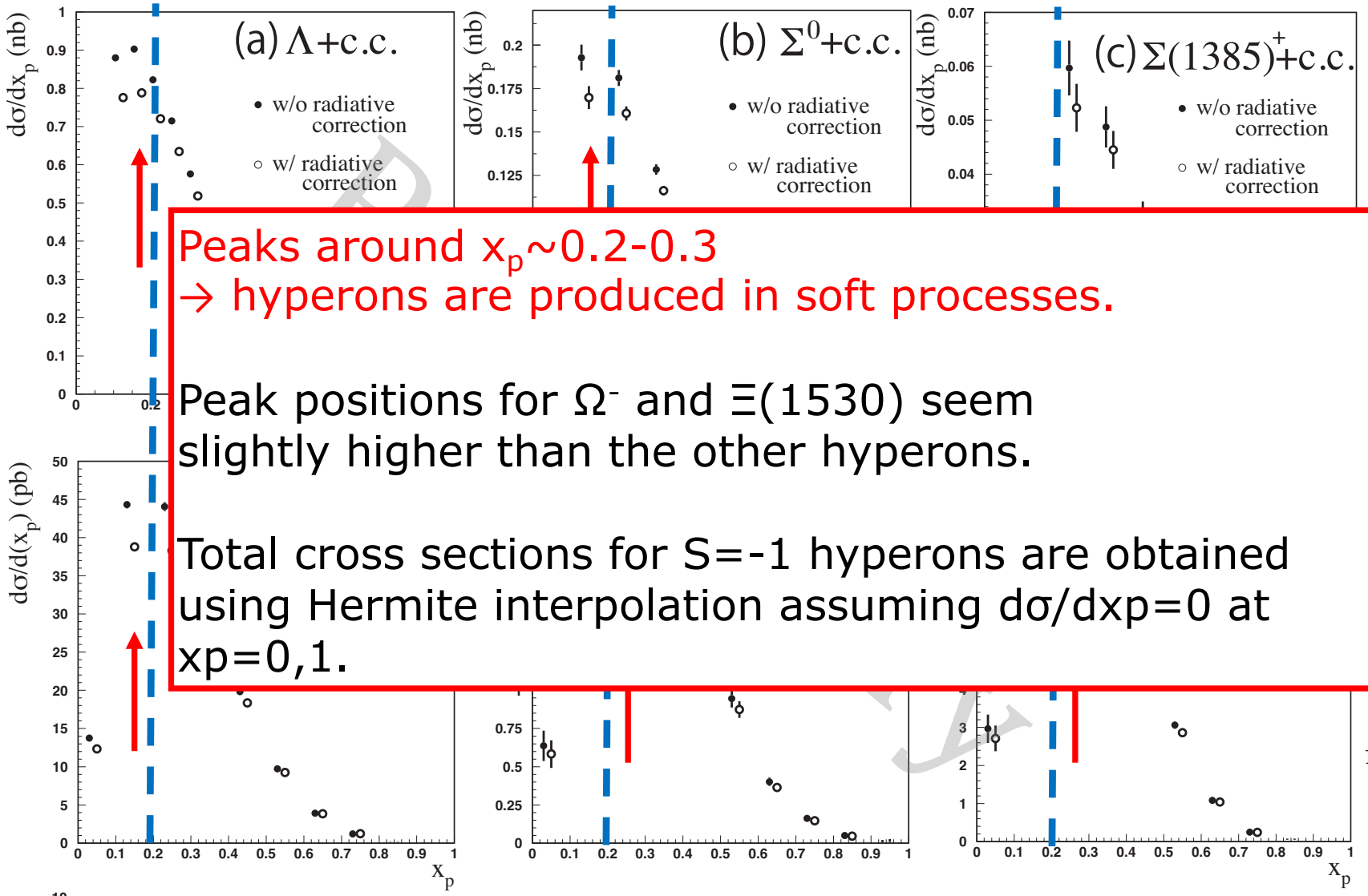
"Inclusive" cross sections (including feed-down) are obtained as a function of hadron scaled momentum (x_p). $x_p = p/\sqrt{s/4 - M^2}$ (M, p : mass and CM momentum)



Error bar represent statistical fluctuation.

Inclusive differential cross sections, hyperons

"Inclusive" cross sections (including feed-down) are obtained as a function of hadron scaled momentum (x_p). $x_p = p/\sqrt{s/4 - M^2}$ (M, p : mass and CM momentum)



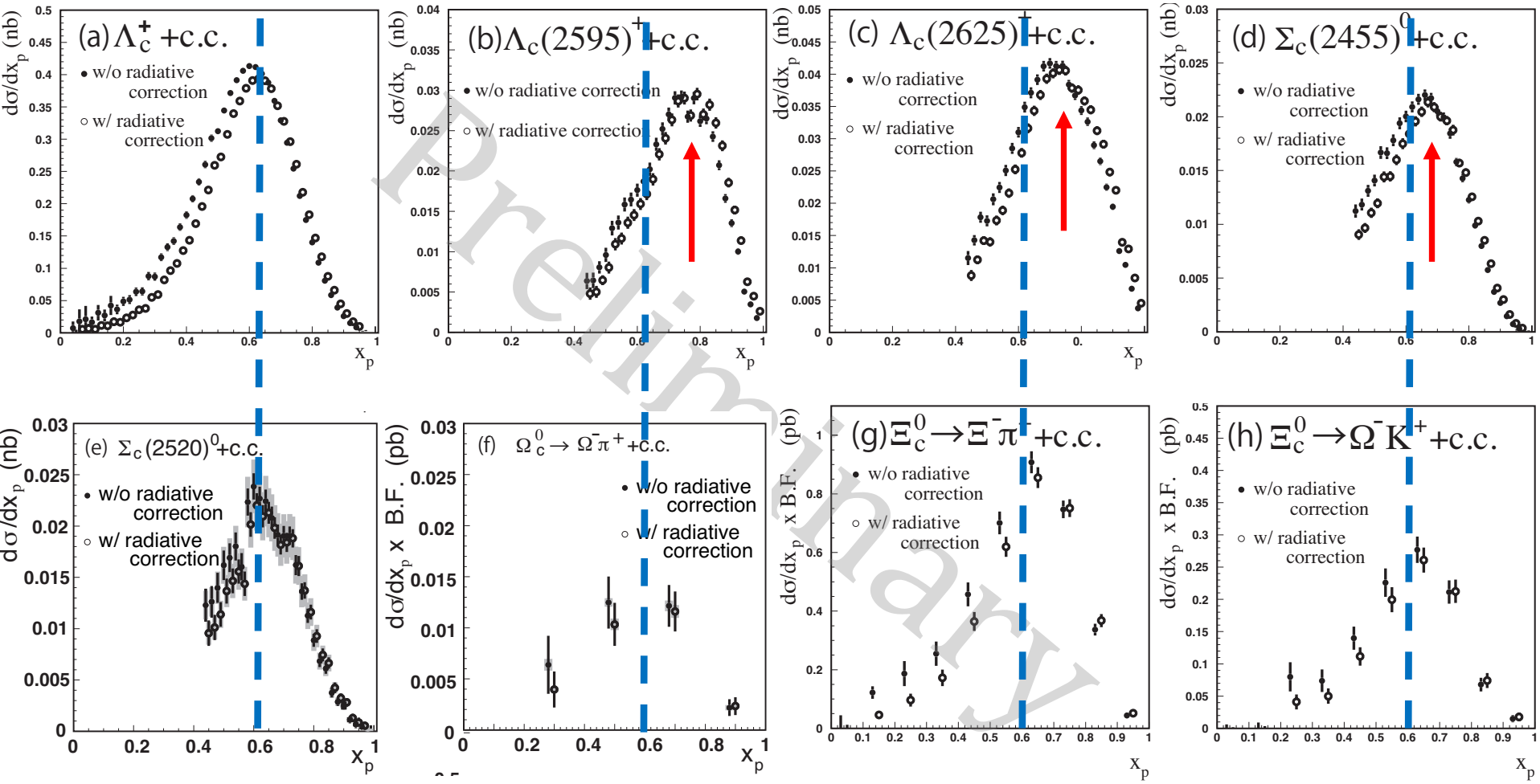
Peaks around x_p~0.2-0.3
→ hyperons are produced in soft processes.

Peak positions for Ω^- and $\Xi(1530)$ seem slightly higher than the other hyperons.

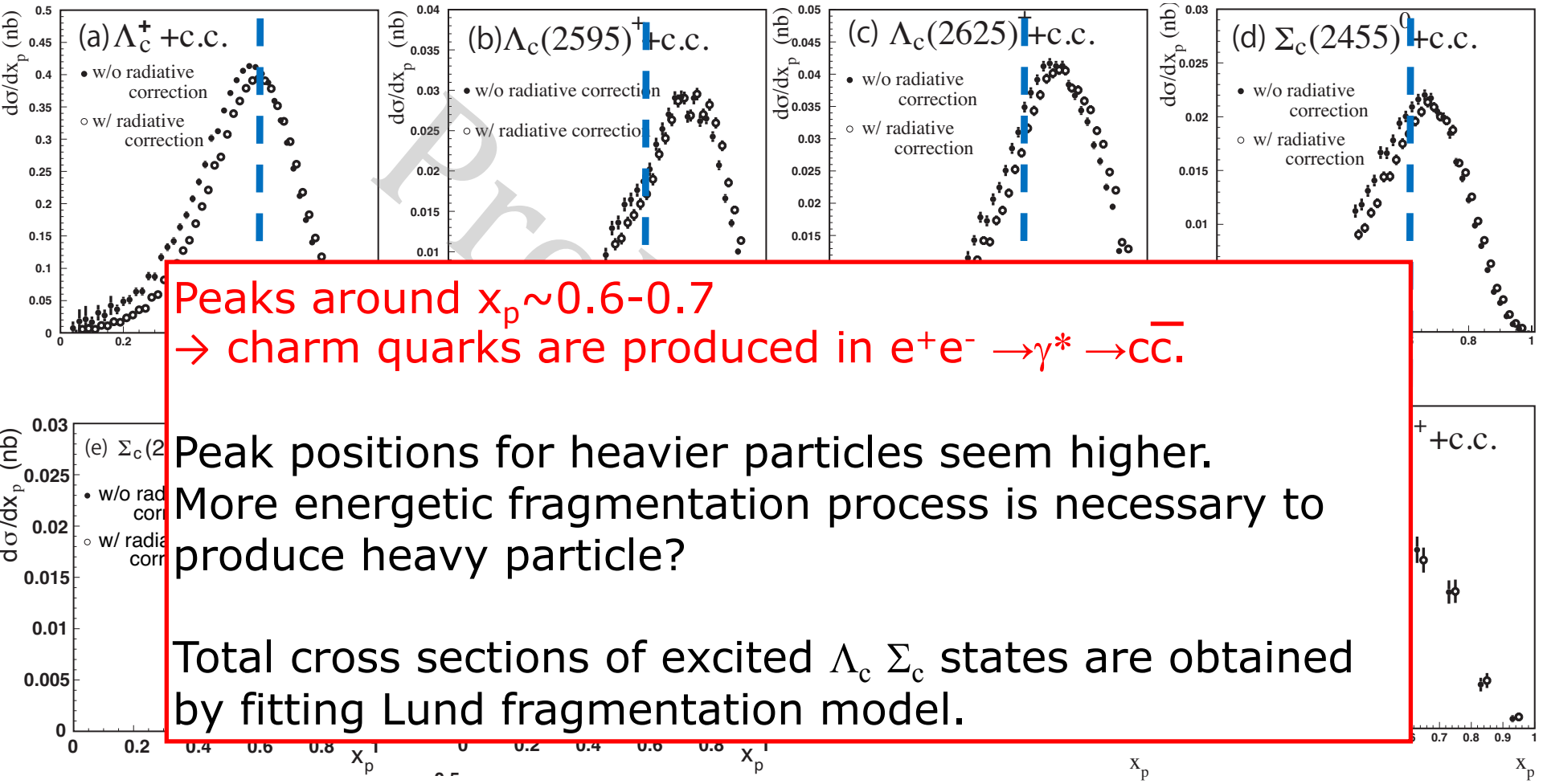
Total cross sections for S=-1 hyperons are obtained using Hermite interpolation assuming dσ/dxp=0 at xp=0,1.

Error bar represent statistical fluctuation.

Inclusive differential cross sections, charmed baryons



Inclusive differential cross sections, charmed baryons



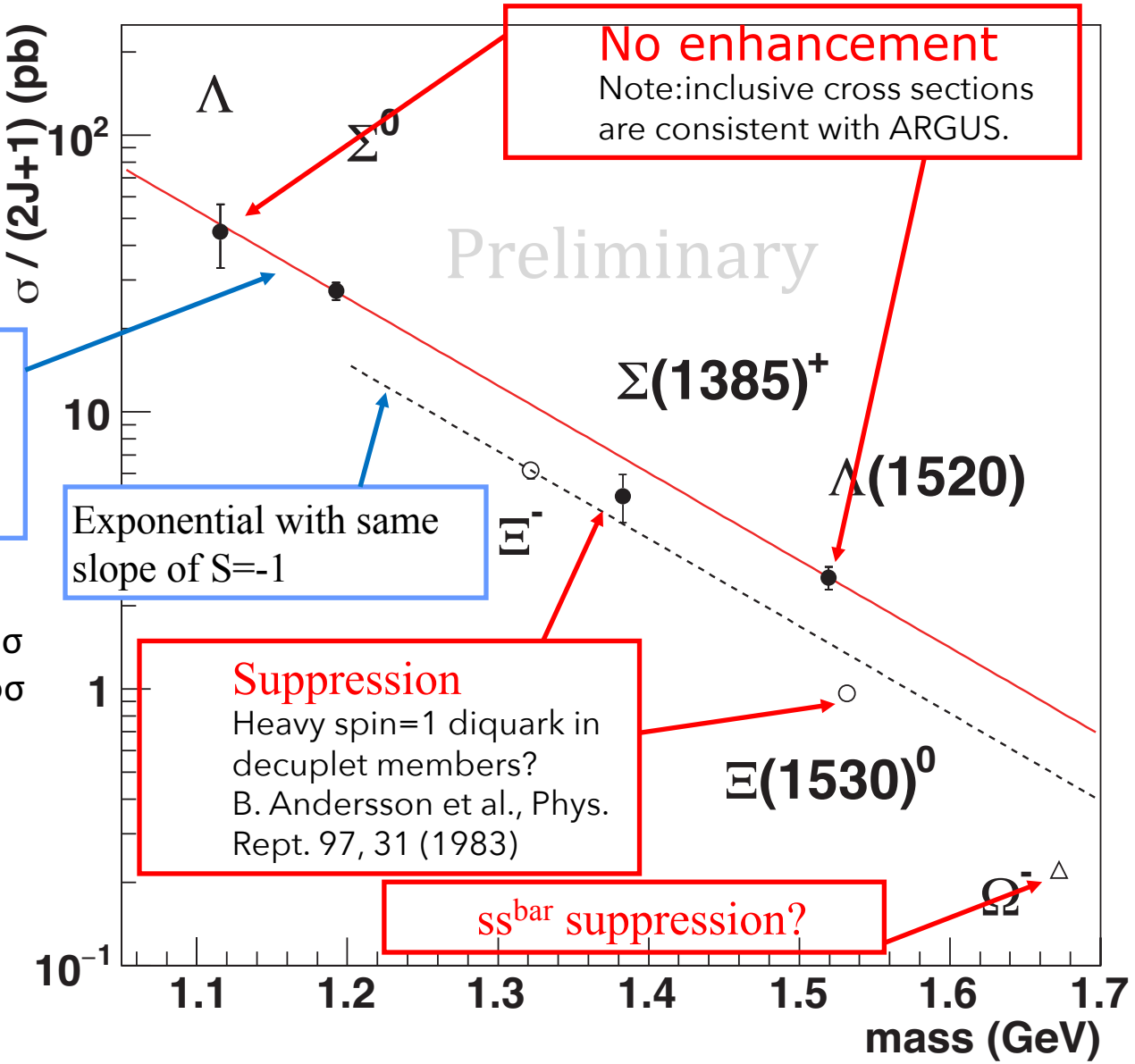
Peaks around x_p~0.6-0.7
→ charm quarks are produced in $e^+e^- \rightarrow \gamma^* \rightarrow c\bar{c}$.

Peak positions for heavier particles seem higher.
More energetic fragmentation process is necessary to produce heavy particle?

Total cross sections of excited Λ_c Σ_c states are obtained by fitting Lund fragmentation model.

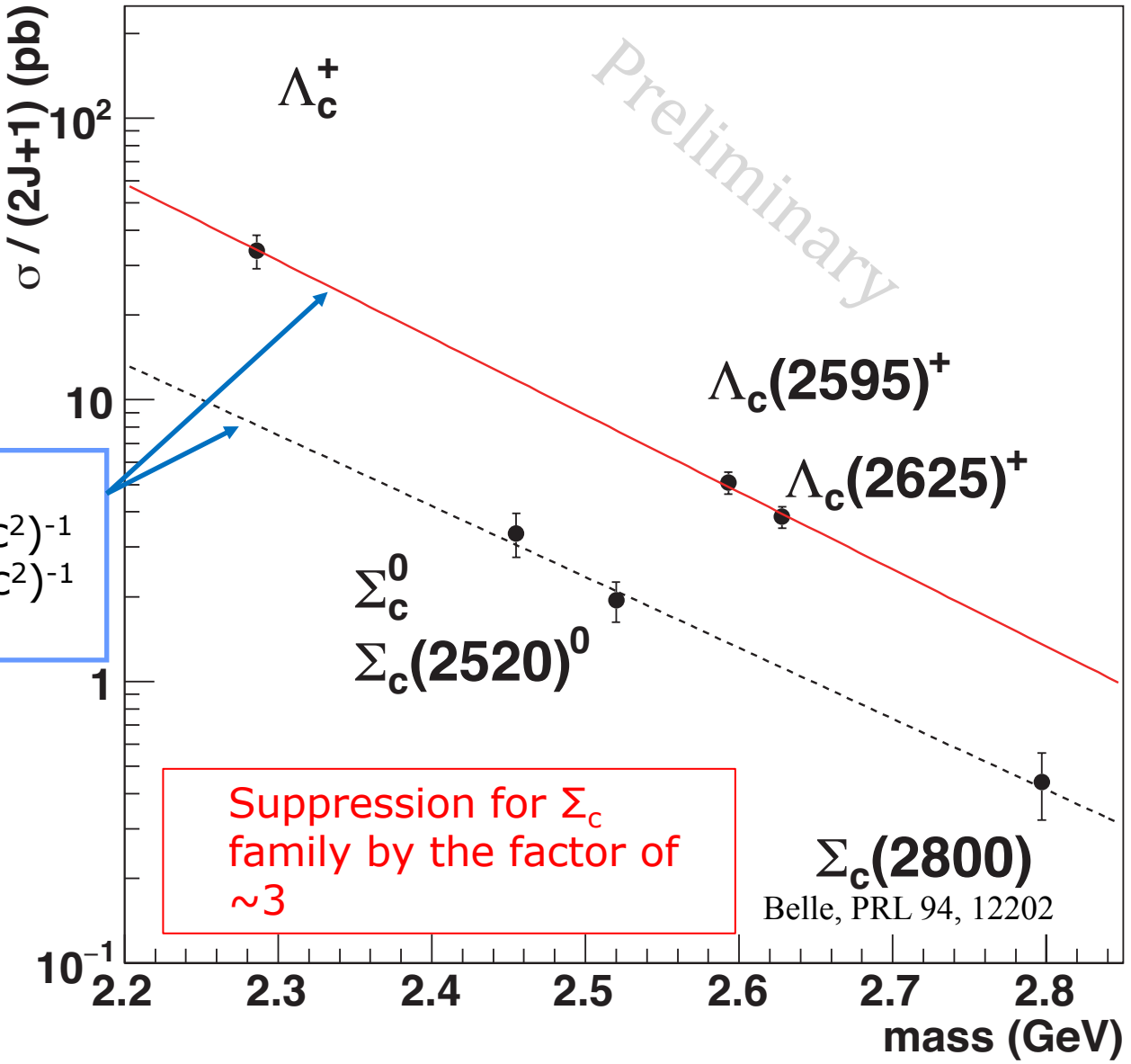
Results for hyperons

Feed-down subtracted



- Suppression
- Σ(1385) : 33% with 2.3σ
- Ξ(1530) : 22% with 4.6σ

Results of charmed baryons



Slope parameters
Λ_c : -6.3± 0.5 $(GeV/c^2)^{-1}$
Σ_c : -5.8± 1.0 $(GeV/c^2)^{-1}$
consistent

Suppression for Σ_c family by the factor of ~3

Discussion

- Assuming that a c-quark picks up a diquark from vacuum,
  - Schwinger-like "tunnel effect" of diquark and anti-diquark

$$\sigma \propto \exp(-\pi\mu^2/\kappa)$$

μ: diquark mass
κ: gluonic string tension

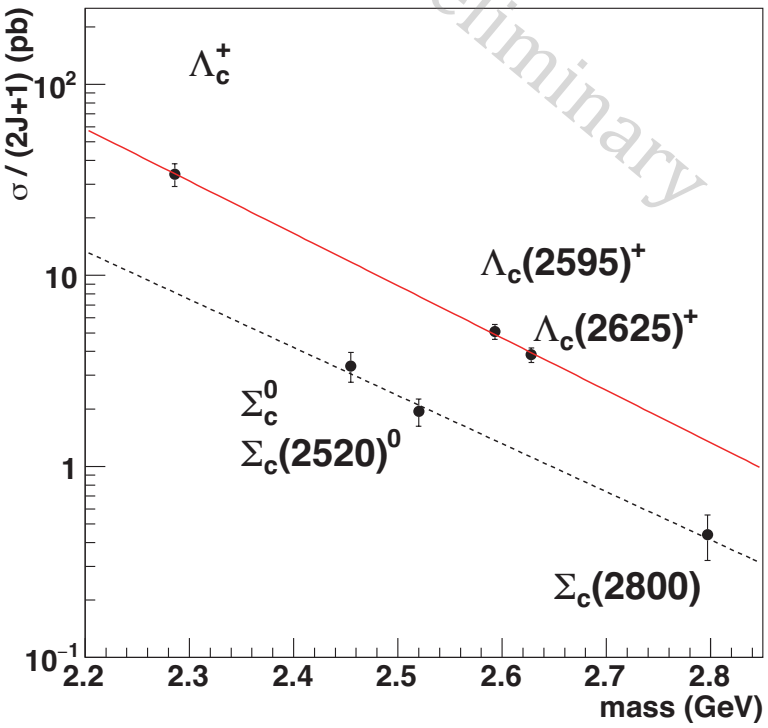
B. Andersson et al., Phys. Scripta. 32, 574 (198

- $\sigma(\Sigma_c)/\sigma(\Lambda_c) = 0.27 \pm 0.07$
  - Λ_c: spin-0 diquark, Σ_c: spin-1 diquark,
  - mass difference of spin-1 and 0 diquarks

$$m(ud_1)^2 - m(ud_0)^2 = (8.2 \pm 0.8) \times 10^4 \ (\mathrm{MeV}/c^2)^2$$

ref. $490^2 - 420^2 = 6.4 \times 10^4 \ (\mathrm{MeV}/c^2)^2$

B. Andersson et al., Phys. Rept. 97, 31 (1983)



- Slightly higher than reference but consistent with the spin-1/0 diquark mass difference!

Summary

- Mass and widths of 5 excited Ξ_c states decaying into $\Xi_c\pi$
  - Masses: ~1order improvement of precision
  - Widths: 5 first measurements ($\Xi_c(2645)^0$, $\Xi_c(2815)^+$, $\Xi_c(2815)^0$, $\Xi_c(2790)^+$, $\Xi_c(2790)^0$)
- Higher excited Ξ_c decaying into ΛD
  - Relative BFs (ΛD / $\Sigma_c K$) for $\Xi_c(3055)$, $\Xi_c(3080)$
  - Relative BF ($\Sigma_c^* K$ / $\Sigma_c K$) for $\Xi_c(3080)$
  - Mass and width of $\Xi_c(3055)^0$
- Studies of Λ_c^+ decay modes
  - Upper limit on $\Lambda_c^+ \to p\phi\pi^0$ and P_s
  - Precise measurement of B.F. of $\Lambda_c^+ \to pK^-\pi^+\pi^0$
  - First observation of DCS decay of $\Lambda_c^+ \to pK^+\pi^-$
- Production cross sections of hyperons and charmed baryons
  - Suppression for Σ_c baryons, indicating diquark structure in charmed baryons