Recent results on charmed baryon spectroscopy from Belle

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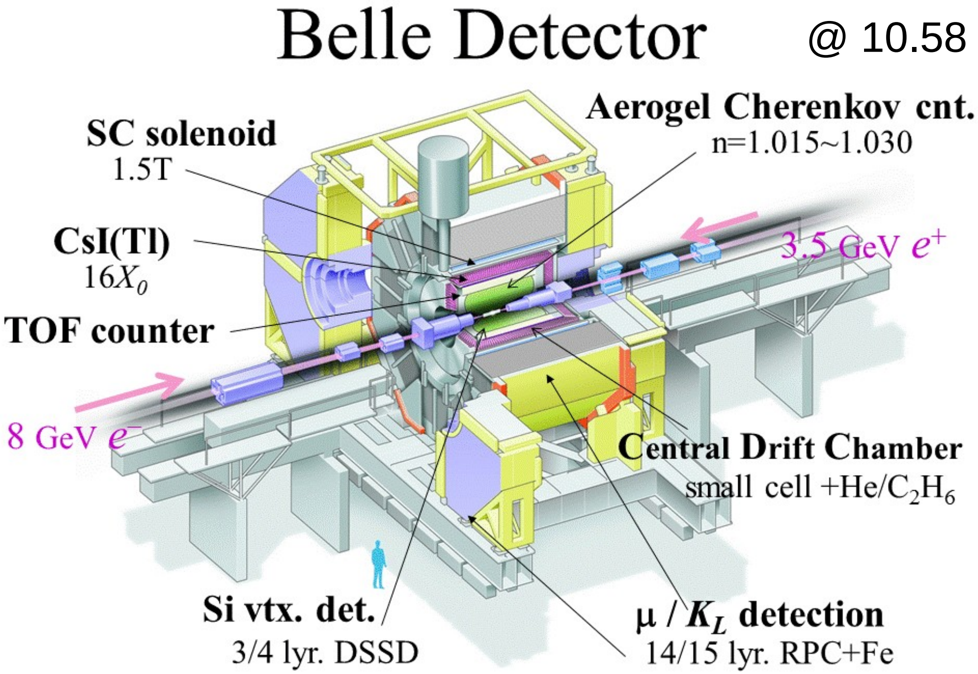
Outline

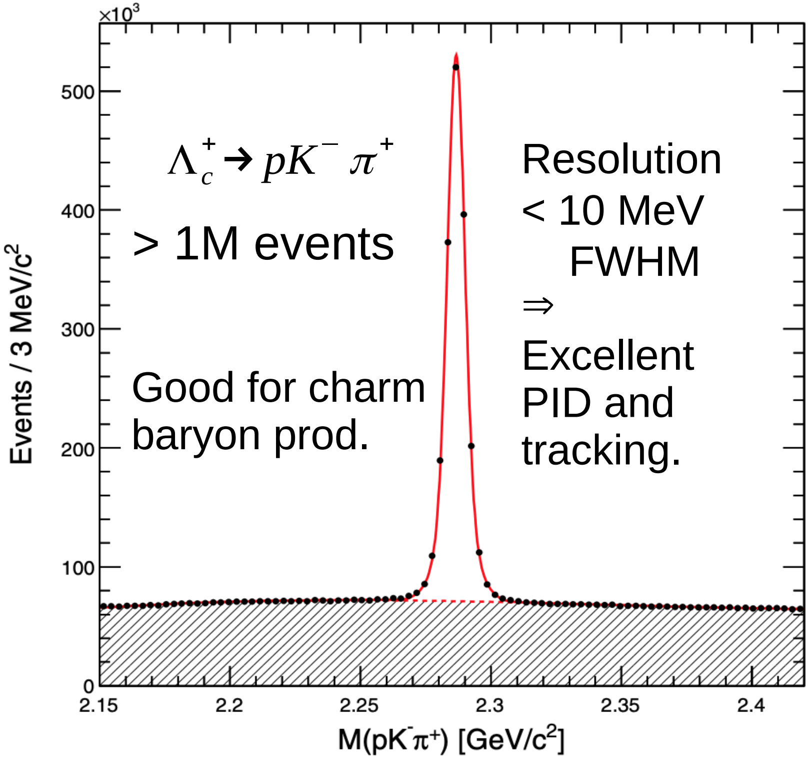
- Belle Detector and charmed baryon production.
- Spin and parity of $\Xi_c(2970)$. PRD 103, L111101 (2021)
- Radiative decays of $\Xi_c(2790/2815)$. PRD 102, 071103(R) (2020)
  - Precise mass and width measurements of $\Sigma_c(2455)^+$. arXiv:2107.05615 submitted to PRD

Belle Detector and charmed baryon production.



@ 10.58 GeV

$e^+e^- \to \Upsilon(4S): 1.1\,nb^{-1}$ $e^+e^- \to c\bar{c}: 1.3\,nb^{-1}$



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

> 1M events

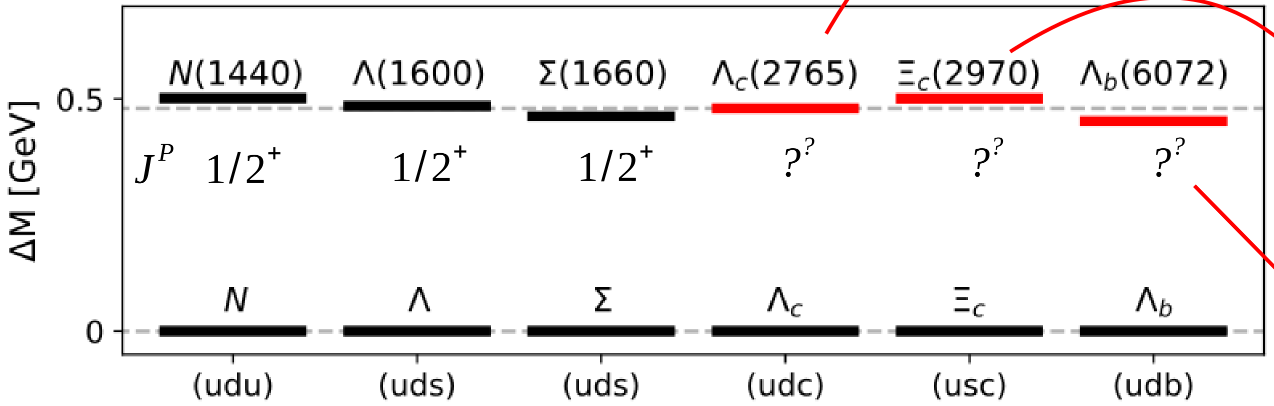
Good for charm baryon prod.

Resolution < 10 MeV FWHM $\Rightarrow$ Excellent PID and tracking.

Total int. lumnosity ~ 1 ab^{-1}
$\Rightarrow$ used in all three studies

$\Xi_c(2970)^+$ in baryon family

First excited $J^P = ½^+$ baryons



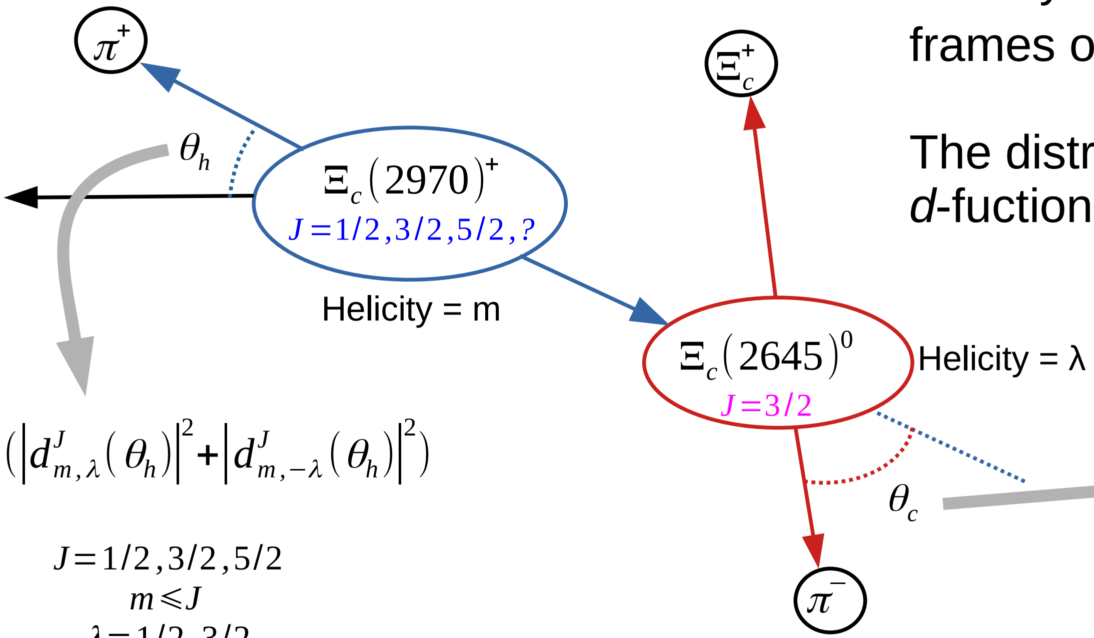
Not been pinned down.
Theory prediction only.

Nucl. Phys. Rev. 35, 1
Int J Theor Phys 59, 1129

Belle's work (this talk)
Phys. Rev. D 103, 111101

LHCb data suggest $½^+$ assignment.
- Arifi, Hosaka, Nagahiro, and Tanida
Phys. Rev. D 101, 111502

Angular Distribution of $\Xi_c(2970)^+ \rightarrow \Xi_c(2645)^0\pi^+$



$$\propto \rho_{mm}\left(\left|d^J_{m,\lambda}(\theta_h)\right|^2 + \left|d^J_{m,-\lambda}(\theta_h)\right|^2\right)$$

$$J=1/2,3/2,5/2$$
$$m \leqslant J$$
$$\lambda=1/2,3/2$$

$$\propto \left|d^{3/2}_{\lambda,1/2}(\theta_c)\right|^2 + \left|d^{3/2}_{\lambda,-1/2}(\theta_c)\right|^2$$

ρ_{mm}: Initial spin density of $\Xi_c(2970)^+$

Helicity angle θ_h and θ_c evaluated in rest frames of mother particle.

The distribution is related to Wigner's *d*-fuction.

Formula of angular distribution (θ_h and θ_c)

θ_h for $J \rightarrow 3/2(\Xi_c(2645)) + 0$

$$W_{\frac{1}{2}} = constant$$

$$W_{\frac{3}{2}} = \rho_{33}\left\{1 + T\left(\frac{3}{2}\cos^2\theta_h - \frac{1}{2}\right)\right\} + \rho_{11}\left\{1 + T\left(-\frac{3}{2}\cos^2\theta_h + \frac{1}{2}\right)\right\}$$

$$\begin{aligned} W_{\frac{5}{2}} = \frac{3}{32}[&\rho_{55}5\{(-\cos^4\theta_h - 2\cos^2\theta_h + 3) + T(-5\cos^4\theta_h + 6\cos^2\theta_h - 1)\} \\ &+ \rho_{33}\{(15\cos^4\theta_h - 10\cos^2\theta_h + 11) + T(75\cos^4\theta_h - 66\cos^2\theta_h + 7))\} \\ &+ \rho_{11}2\{(-5\cos^4\theta_h + 10\cos^2\theta_h + 3) + T(-25\cos^4\theta_h + 18\cos^2\theta_h - 1)\}] \end{aligned}$$

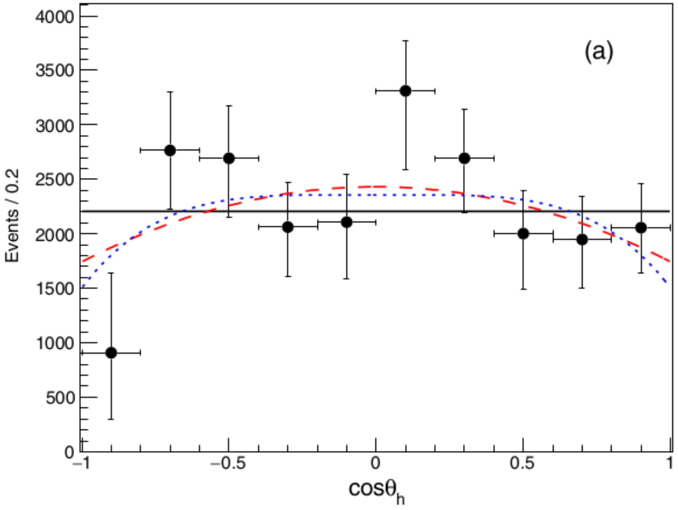
Relative fraction of 3/2 polarization in Ξc(2645)

θ_c in $\Xi_c(2645)(3/2^-) \rightarrow \Xi_c(1/2^+) + \pi(0^-)$

J^P of $\Xi_c(2970)^+$	Partial Wave	Expected Angular Distribution
$1/2^+$	P	$1 + 3\cos\theta_c^2$
$1/2^-$	D	$1 + 3\cos\theta_c^2$
$3/2^+$	P	$1 + 6\sin\theta_c^2$
$3/2^-$	S	1
$5/2^+$	P	$1 + (1/3)\cos\theta_c^2$
$5/2^-$	D	$1 + (15/4)\sin\theta_c^2$

J determination of $\Xi_c(2970)^+$

$\cos\theta_h$

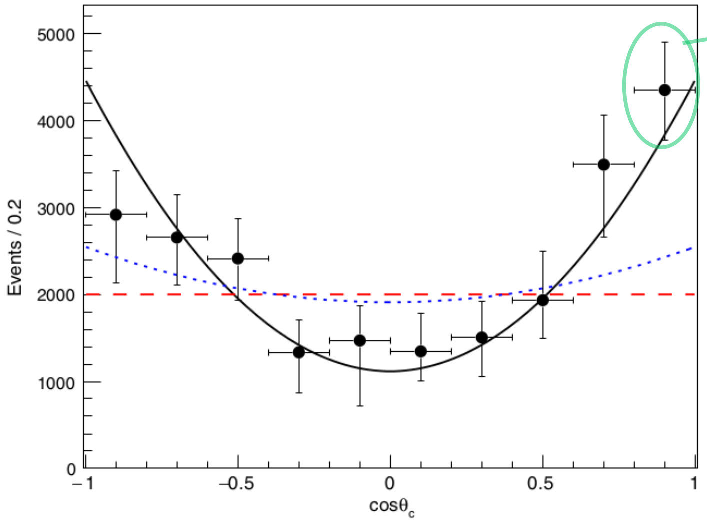


1/2

3/2

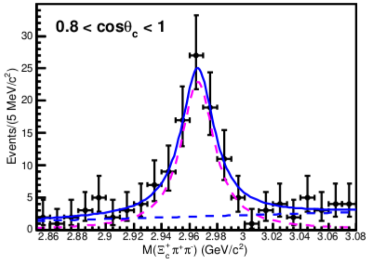
5/2

$\cos\theta_c$



$0.8<\cos\theta_c<1$

Yield=95±13
Eff.=2.46%
N=Yield/Eff.



Inconclusive in $\cos\theta_h$

Exclusion Level 0.8 (0.5)σ for 3/2 (5/2) hypothesis

Favors **J=1/2**
over 3/2 (5/2) at 5.1 (4.0)σ
- consistent with $\mathbf{1+3\cos^2\theta_c}$

Parity of $\Xi_c(2970)^+$

- HQS doublet with brown-muck (light component) spin j=1: J=3/2 ($\Xi_c(2645)^0$) and 1/2($\Xi_c'^0$)
- The decay rate ratio $R = \frac{\Gamma\left(\Xi_c(2970)^+ \to \Xi_c(2645)^0 \pi^+\right)}{\Gamma\left(\Xi_c(2970)^+ \to \Xi_c'^0 \pi^+\right)}$ is calculable:

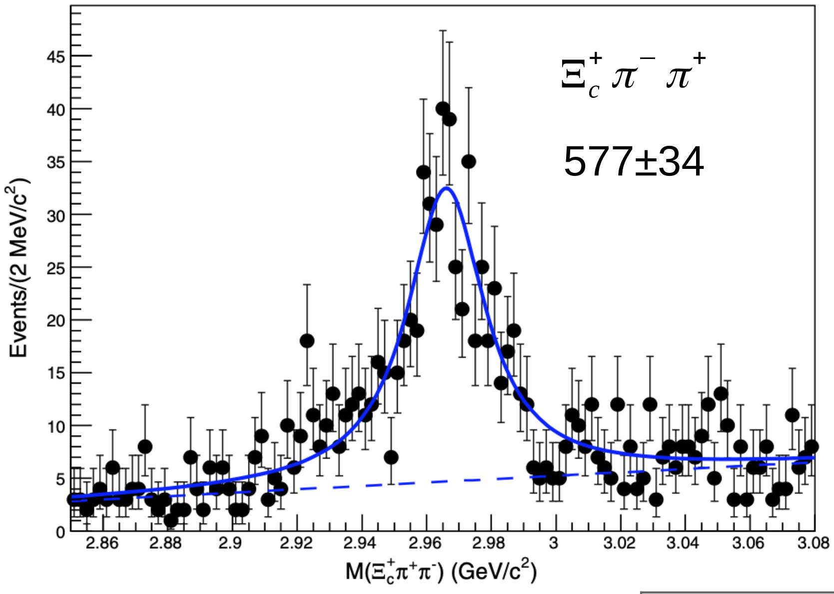
PRD 75 (2007) 014006

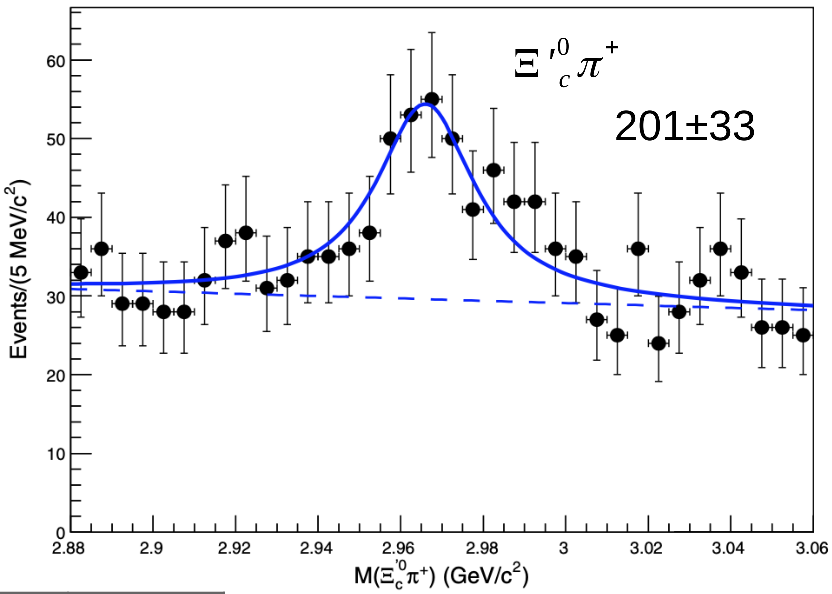
Parity	+	+	−	−
Brown-muck spin s_ℓ	0	1	0	1
R	1.06	0.26	0	$\ll 1$

Suppressed due to D-wave of $\Xi_c(2645)^0\pi^+$

Determination of Parity and s_l

Results of BR





s_l (P=+)	0	1
R	1.06	0.26

Favors

$$R = \frac{\Gamma\left(\Xi_c(2970)^+ \to \Xi_c(2645)^0 \pi^+\right)}{\Gamma\left(\Xi_c(2970)^+ \to \Xi_c'^0 \pi^+\right)} = 1.67 \pm 0.29^{+0.18}_{-0.09} \pm 0.25$$

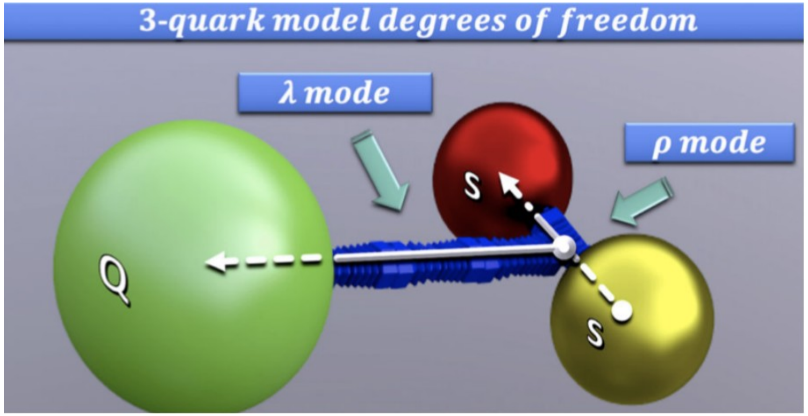
Due to isospin assumption in sub-BF calculation for $\Xi_c^{+/0}$

Final conclusion: $J^P(s_l) = 1/2^+(0)$

PRD 103, L111101 (2021)

Electromagnetic (EM) transitions of charm baryons

- EM transitions of charmed baryons are observed only for strong decay forbidden states: $\Xi'_c \rightarrow \Xi_c\gamma$ and $\Omega_c(2770) \rightarrow \Omega_c\gamma$.
- Theoretical predictions of observable partial width (~300 keV) for decays from $\Xi_c(2790)$ and $\Xi_c(2815)$ to $\Xi_c\gamma$ (3-10 % level of BR).
- Input of EM decay measurements is crucial for interpretation of λ-ρ modes and theoretical modeling.

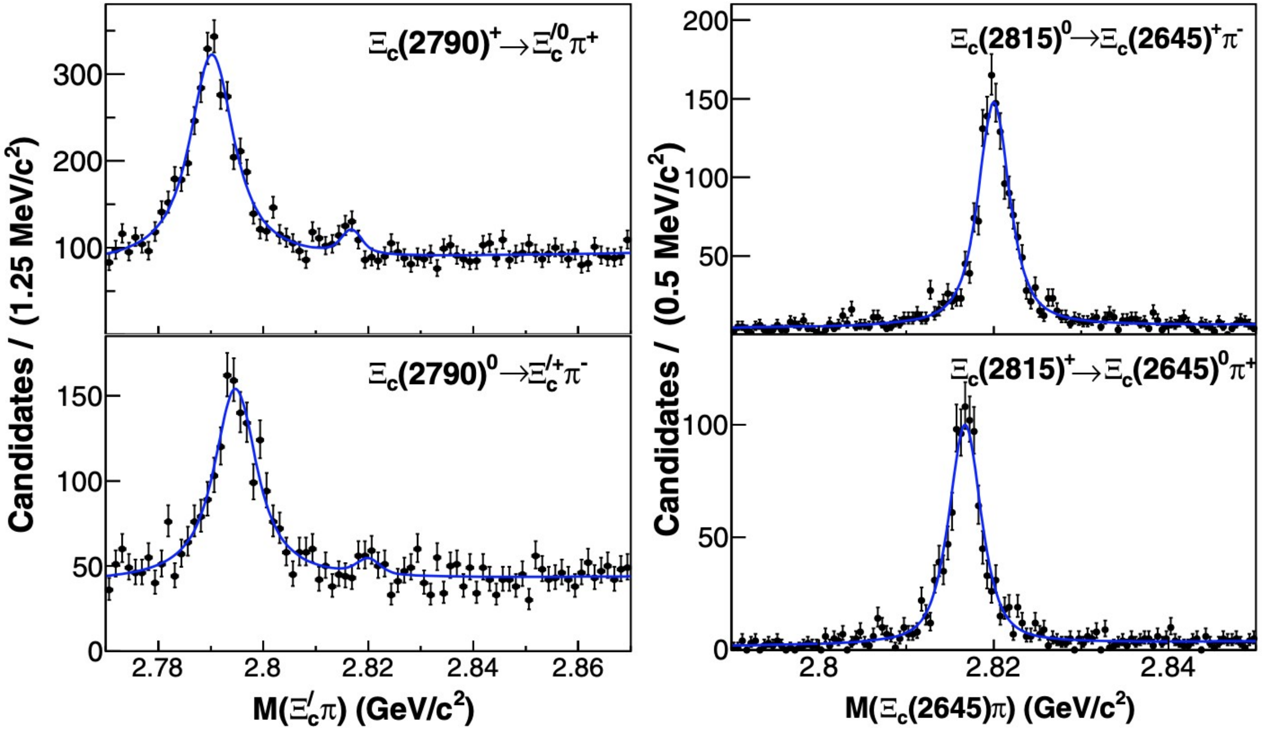


Mode	WYZZ [14] λ excitation	WYZZ [14] ρ excitation	WYZZ [14] ρ excitation	Actual total width [3]
$\Xi_c(2790)^+ \rightarrow \Xi_c^+\gamma$	4.65	1.39	0.79	$8900 \pm 600 \pm 800$
$\Xi_c(2790)^0 \rightarrow \Xi_c^0\gamma$	263	5.57	3.00	$10000 \pm 700 \pm 800$
$\Xi_c(2815)^+ \rightarrow \Xi_c^+\gamma$	2.8	1.88	2.81	$2430 \pm 200 \pm 170$
$\Xi_c(2815)^0 \rightarrow \Xi_c^0\gamma$	292	7.50	11.2	$2540 \pm 180 \pm 170$

$\Xi_c(2790)$ & $\Xi_c(2815)$

Typically interpreted as an HQS doublet with orbital L=1 (λ-mode), with expected J^P = $1/2^-$ and $3/2^-$.

Clearly seen in hadronic modes at Belle.



$\Xi_c(2790)$ & $\Xi_c(2815)$ results

10 and 7 decay channels for Ξ_c^0 and Ξ_c^+ reconstruction.

PRD 102, 071103(R) (2020)

Clear signal for neutral channel, but not charged.

$$\frac{\mathcal{B}(\Xi_c(2815)^0 \to \Xi_c^0 \gamma)}{\mathcal{B}(\Xi_c(2815)^0 \to \Xi_c(2645)^+ \pi^- \to \Xi_c^0 \pi^+ \pi^-)} = 0.45 \pm 0.05 \pm 0.03$$

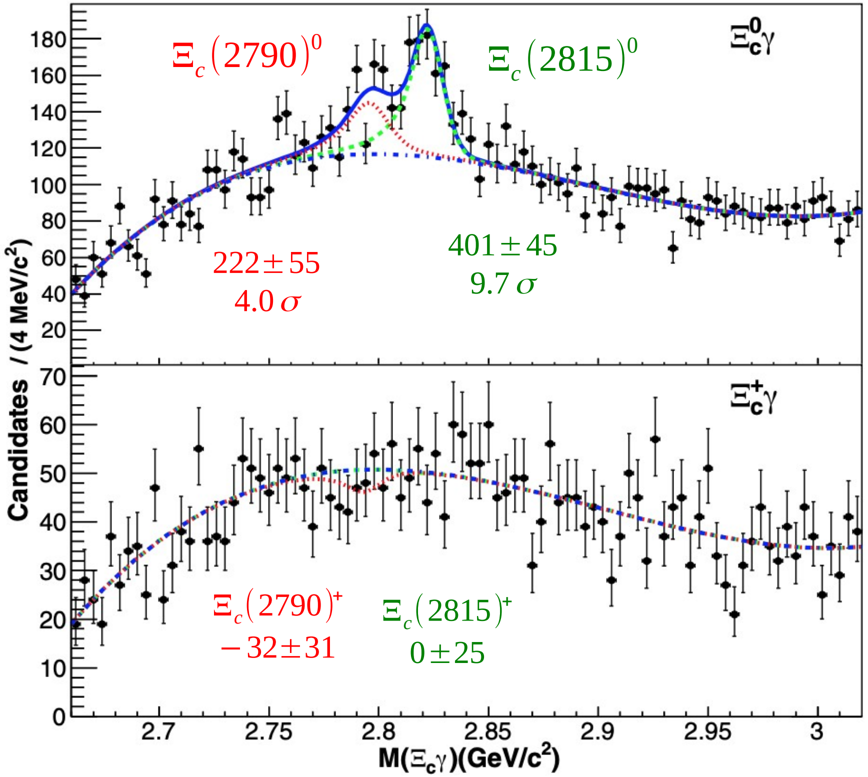
$$\frac{\mathcal{B}(\Xi_c(2790)^0 \to \Xi_c^0 \gamma)}{\mathcal{B}(\Xi_c(2790)^0 \to \Xi_c'^+ \pi^- \to \Xi_c^+ \gamma \pi^-)} = 0.13 \pm 0.03 \pm 0.02$$

$$\Gamma(\Xi_c(2815)^0 \to \Xi_c^0 \gamma) = 320 \pm 45^{+45}_{-80}\ \text{keV}$$

$$\Gamma(\Xi_c(2790)^0 \to \Xi_c^0 \gamma) \sim 800\ \text{keV}\ (\text{uncertainty} \sim 40\%)$$

$$\Gamma(\Xi_c(2815)^+ \to \Xi_c^+ \gamma) < 80\ \text{keV}$$

$$\Gamma(\Xi_c(2790)^+ \to \Xi_c^+ \gamma) < 350\ \text{keV}$$



Consistent with orbital excitation interpretation.

Phys.Rev. D 96, 116016 (2017)

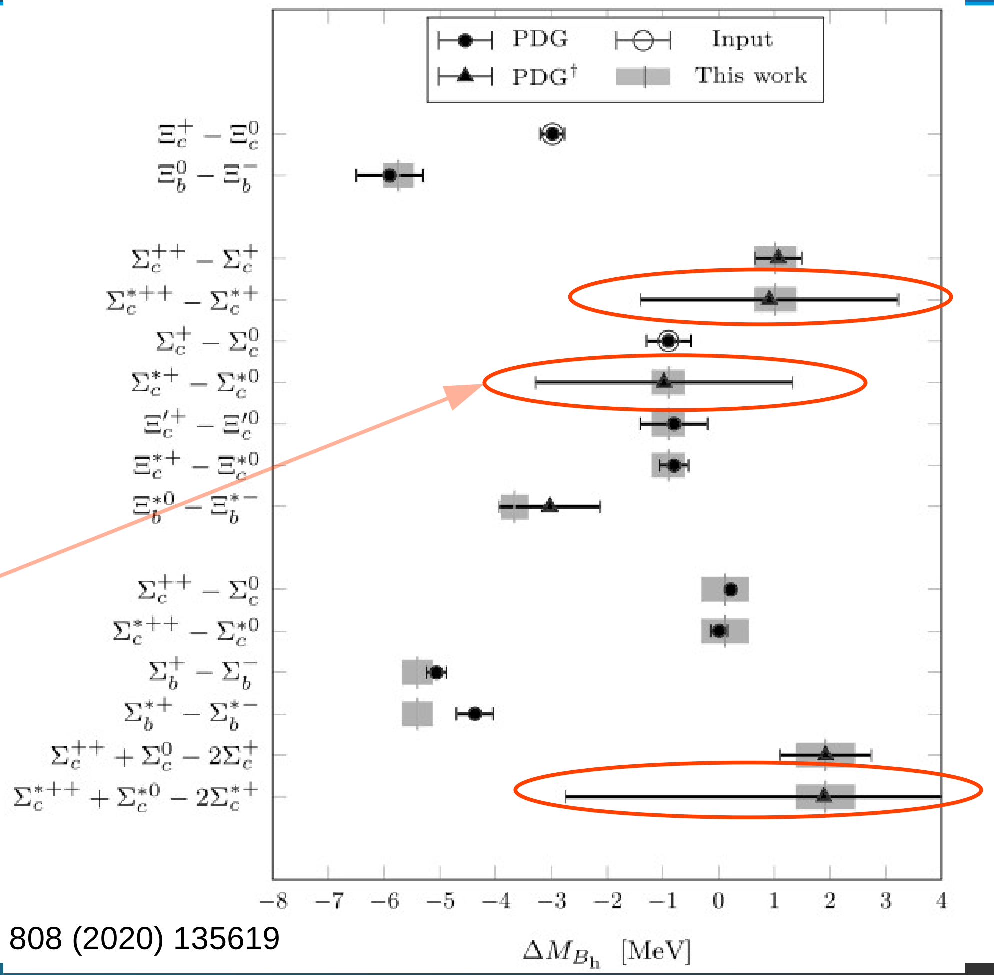
Masses and Widths of $\Sigma_c^+(2455/2520)$

$\Sigma_c(2455)$: isotriplet with $I(J^P) = 1\ (1/2\ +)$
$\Sigma_c(2520)$: isotriplet with $I(J^P) = 1\ (3/2\ +)$

- Σ_c^{++} and Σ_c^0 were measured well through $\Lambda_c\pi^{+/-}$ decay.
- Neutral π^0 in $\Sigma_c(2455/2520)^+$ decay limits experimental precision.
- Only width limits for $\Sigma_c(2455/2520)^+$ before.

Exp. error dominated by

precision of $\Sigma_c(2520)^+$ mass.



Physics Letters B 808 (2020) 135619

Calibration of gamma momentum

Precise gamma measurement is crucial to reduce systematic uncertainty.

Calibrate MC for ECL gamma measurement using control samples in real data:

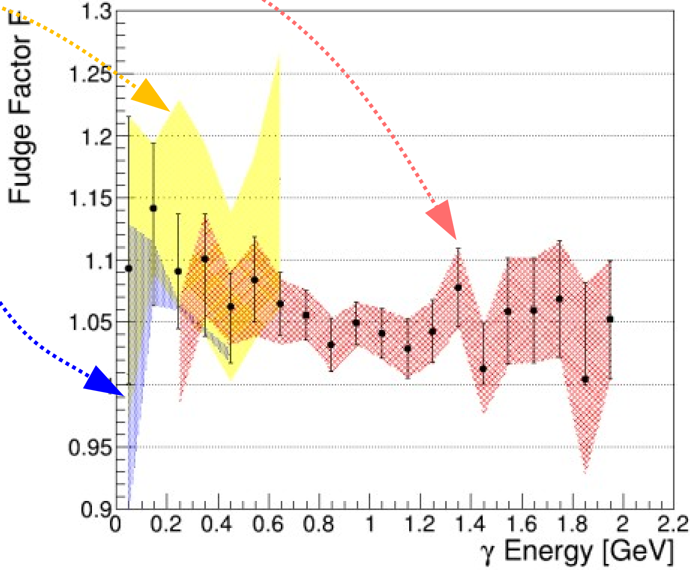
$D^{0*} \to D^0 \gamma$; $\eta \to \gamma\gamma$; $\pi^0 \to \gamma\gamma$

Asymmetry of γ energy < 5%

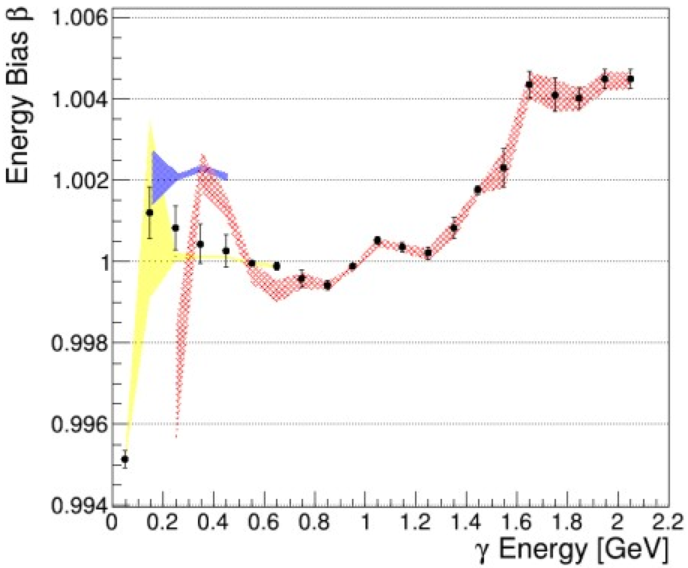
- After calibration, D^{*+} - D^+ mass difference's central value and width used in systematic error evaluation.

$$\vec{P}_s = (\vec{P}_0 + (\vec{P}_r - \vec{P}_0)\cdot F_{res})\cdot F_{en}$$

Resolution fudge factor



Global energy scale



Results of M and Γ for $\Sigma_c^+(2455/2520)$

arXiv:2107.05615, submitted to PRD

$$M(\Sigma_c(2455)^+) - M(\Lambda_c^+) = 166.17 \pm 0.05^{+0.16}_{-0.07}\ \mathrm{MeV}/c^2$$

$$\Gamma(\Sigma_C(2455)^+) = 2.3 \pm 0.3 \pm 0.3\ \mathrm{MeV}/c^2$$

$$M(\Sigma_c(2520)^+) - M(\Lambda_c^+) = 230.9 \pm 0.5^{+0.5}_{-0.1}\ \mathrm{MeV}/c^2$$

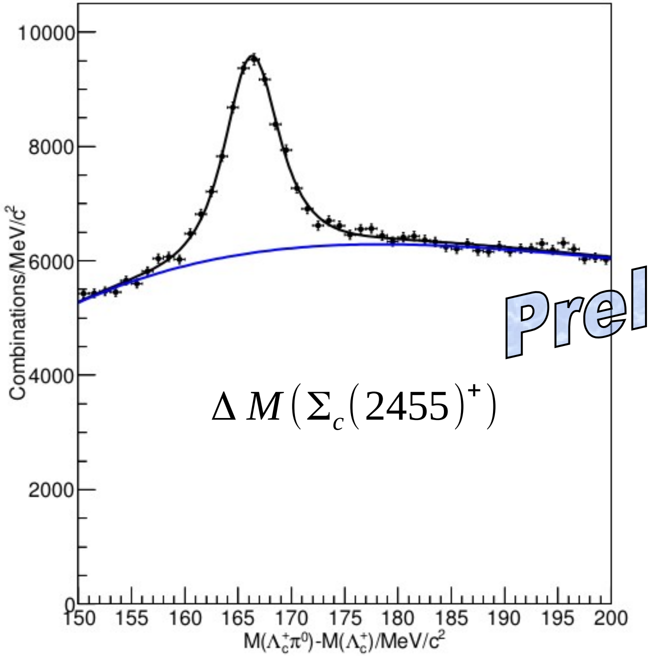
$$\Gamma(\Sigma_C(2520)^+) = 17.2^{+2.3\ +3.1}_{-2.1\ -0.7}\ \mathrm{MeV}/c^2$$

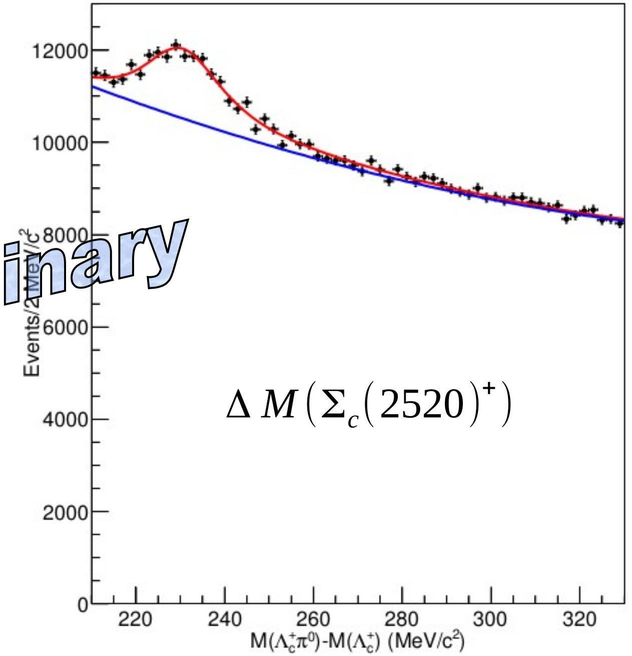
Mass and Width consistent with:
Phys. Lett. B 808 135619 ;
Phys. Rev. D 92, 074014.

Mass relationship is same:
(Phys. Rev. D. 12 2077)

$$M(\Sigma_c^{++}) + M(\Sigma_c^0) - 2M(\Sigma_c^+) = 2.48^{+0.17}_{-0.34}\ (2.2^{+1.0}_{-1.4})\ \mathrm{MeV}/c^2$$

for 2455(2520) triplets

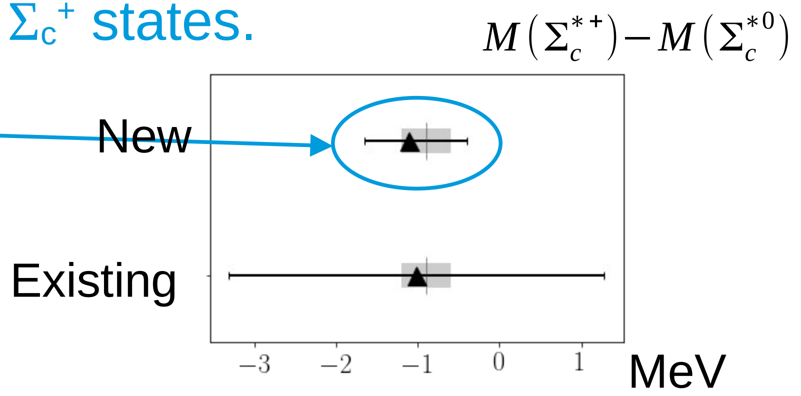




Critical for study of $\Lambda_c(2593)^+$, which is close to $\Sigma_c^+(2455)\pi^0$ threshold.

Summary

- J^P of $\Xi_c(2970)^+$
  - Angular distribution ⇨ J=1/2; Decay BRs ⇨ P=+, s_l=0
- Radiative decays of $\Xi_c(2790)$ and $\Xi_c(2815)$
  - Strong transition for neutral modes ⇨ L=1
- Mass and Width measurement of $\Sigma_c^+(2455/2520)$
  - First determination of widths of two Σ_c^+ states.
  - Precise mass of $\Sigma_c^{(*)+}$



BACKUP

Branching fractions of $\Xi_c^{+(0)}$

$$R = \frac{\mathcal{B}(\Xi_c(2970)^+ \to \Xi_c(2645)^0 \pi^+)}{\mathcal{B}(\Xi_c(2970)^+ \to \Xi_c'^0 \pi^+)}$$

$$R = \frac{N^*}{\mathcal{E}^* \times \mathcal{B}^+} \Big/ \frac{N'}{\sum_i \mathcal{E}_i' \times \mathcal{B}_i^0}$$

$$= \frac{N^*}{\mathcal{E}^* \times \frac{N(\Xi_c^+)}{\epsilon^+}} \Big/ \frac{N'}{\sum_i \mathcal{E}_i' \times \frac{N(\Xi_c^0)_i}{\epsilon_i^0}}$$

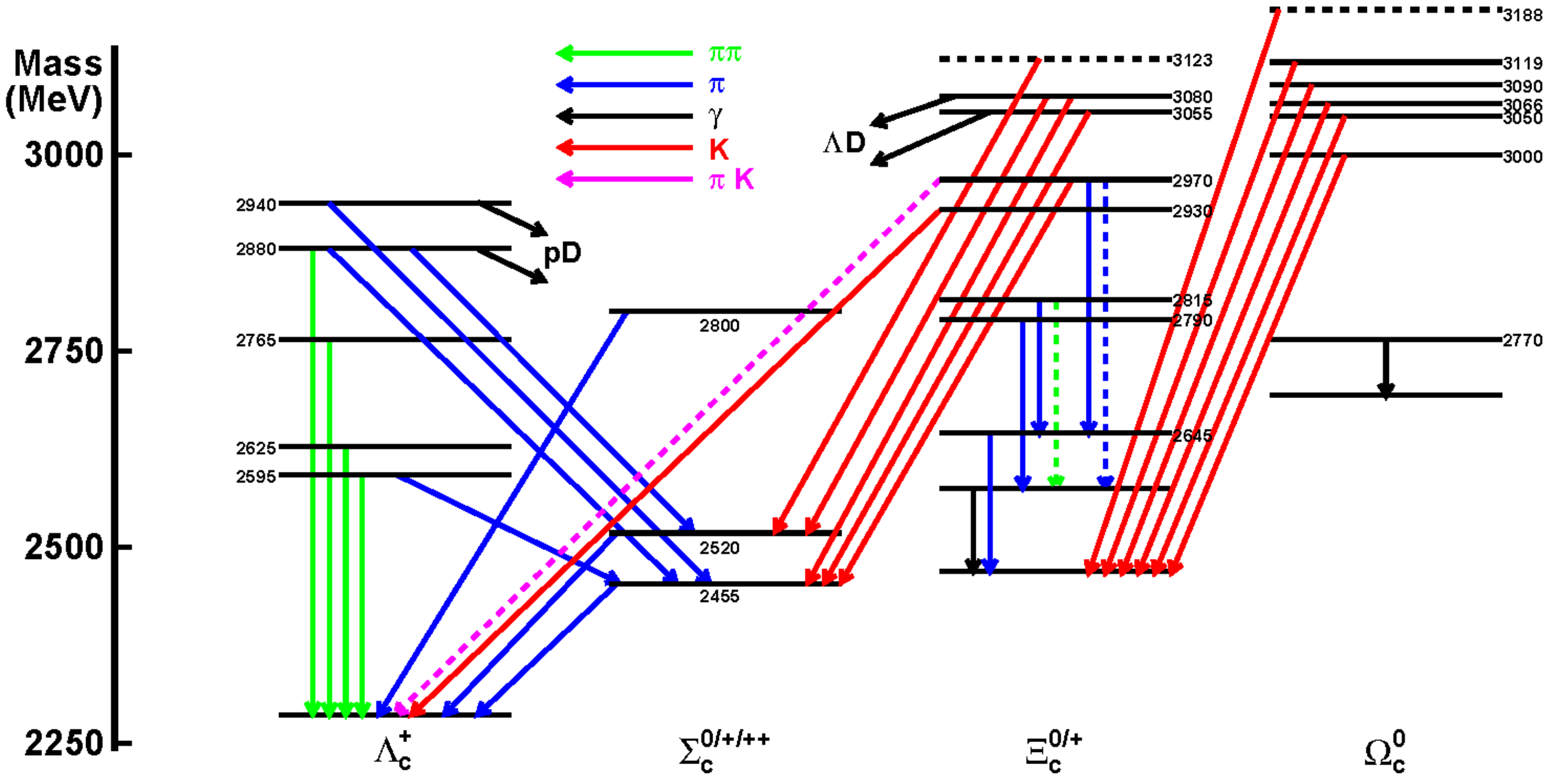
BF of $\Xi_c^{+(0)}$:

$$\mathcal{B}_i^{+(0)} = \frac{N(\Xi_c^{+(0)})_i}{\mathcal{L} \times \sigma_{\Xi_c} \times \epsilon_i^{+(0)}}$$

- Assumed to be same for Ξ_c^+ and Ξ_c^+
- Checked with Σ_c in real data.

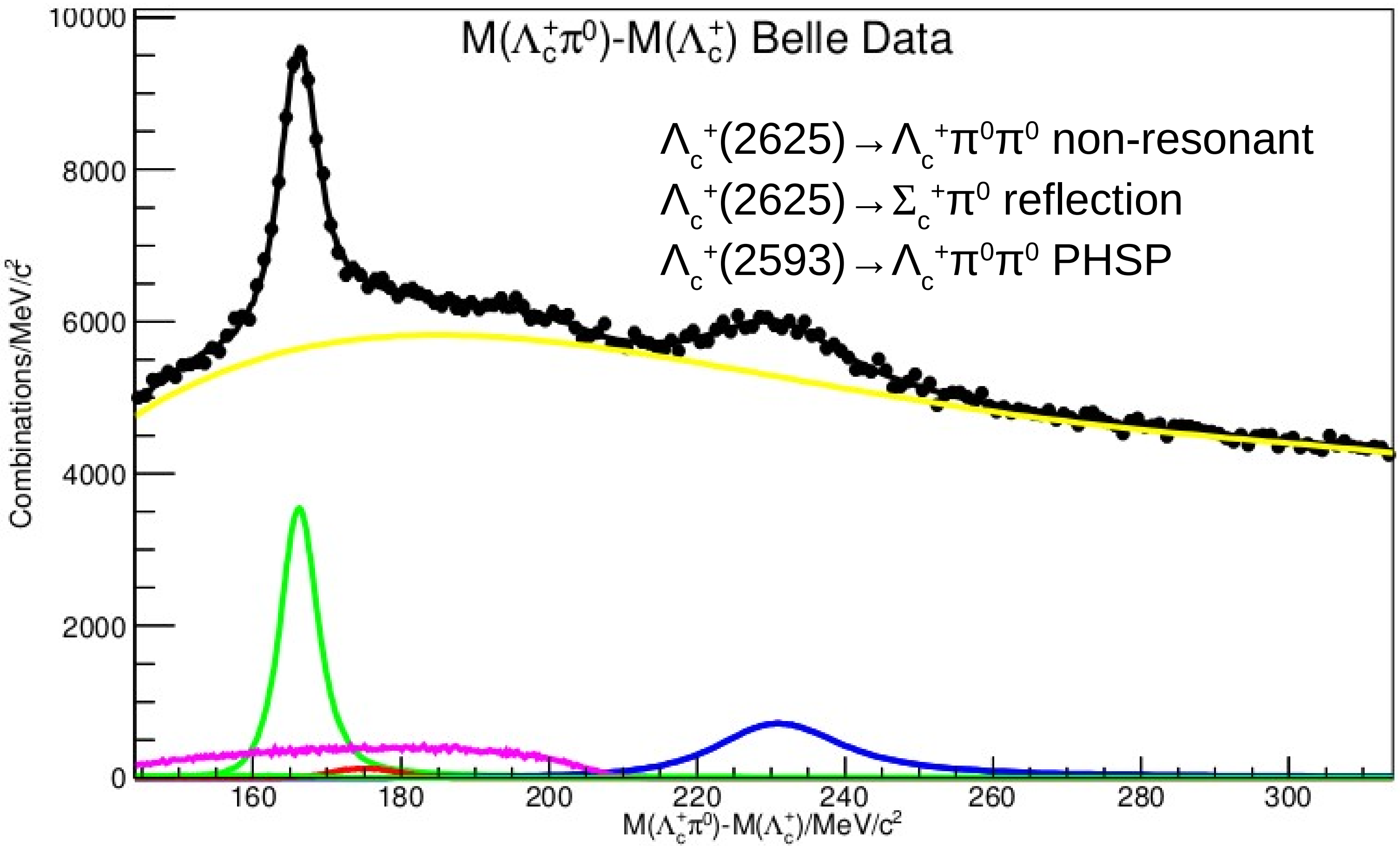
Transitions of charmed baryons

HFLAV



Only $\Xi_c' \to \Xi_c \gamma$ and $\Omega_c(2770) \to \Omega_c \gamma$ for electromagnetic decays.

$M(\Lambda_c^+\pi^0)$-$M(\Lambda_c^+)$



$\Lambda_c^+(2625) \to \Lambda_c^+\pi^0\pi^0$ non-resonant
$\Lambda_c^+(2625) \to \Sigma_c^+\pi^0$ reflection
$\Lambda_c^+(2593) \to \Lambda_c^+\pi^0\pi^0$ PHSP