Charmed baryons results at Belle

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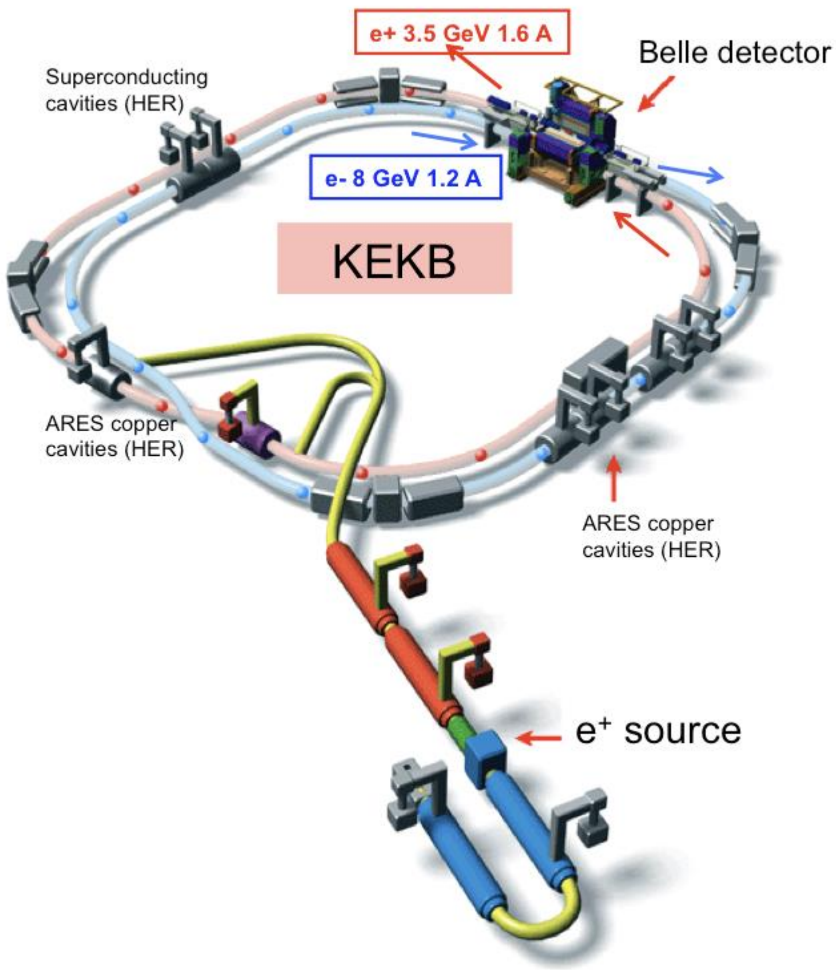
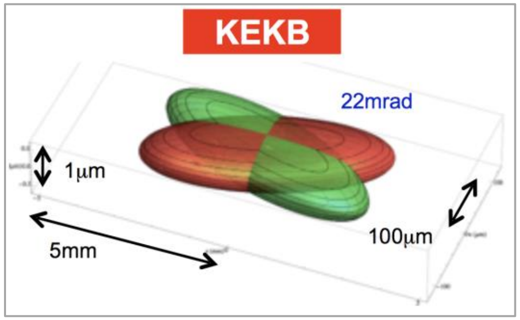
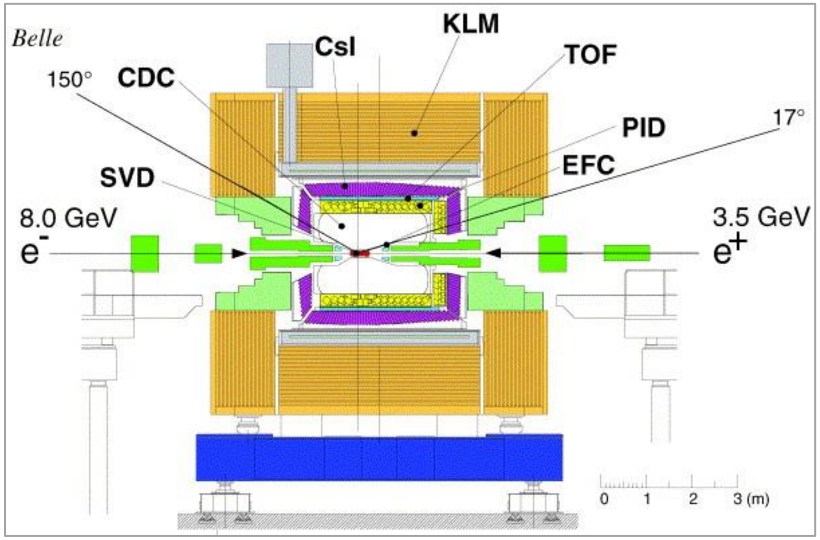
The 13th International Workshop on e^+e^- collisions from Phi to Psi

2022-08-15

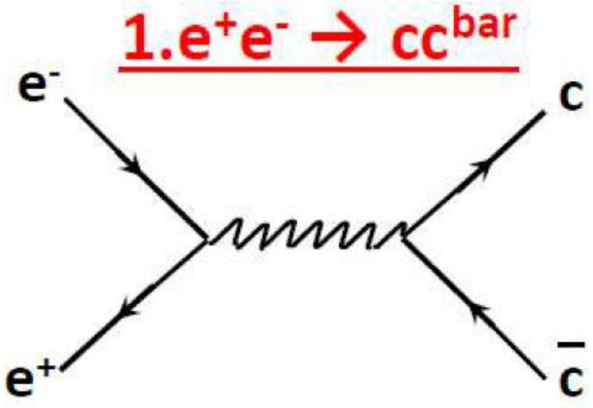
Belle experiment

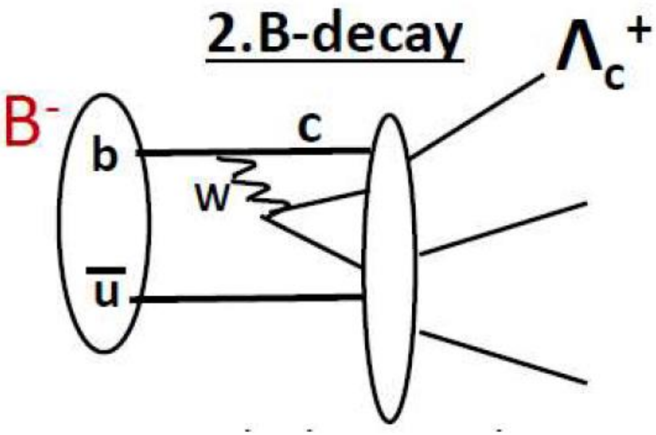






Charmed baryon production at B-factory

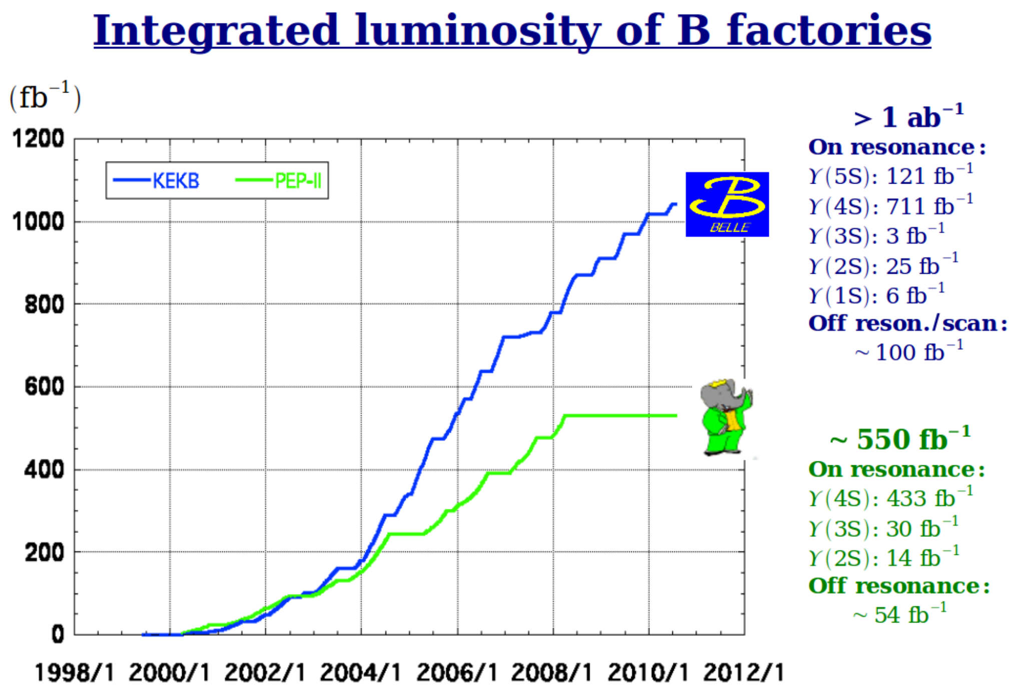




- B meson is efficiently produced via $\Upsilon(4S)$
- Once bottom is produced, it favorably decays into charm

Baryons produced via fragmentation

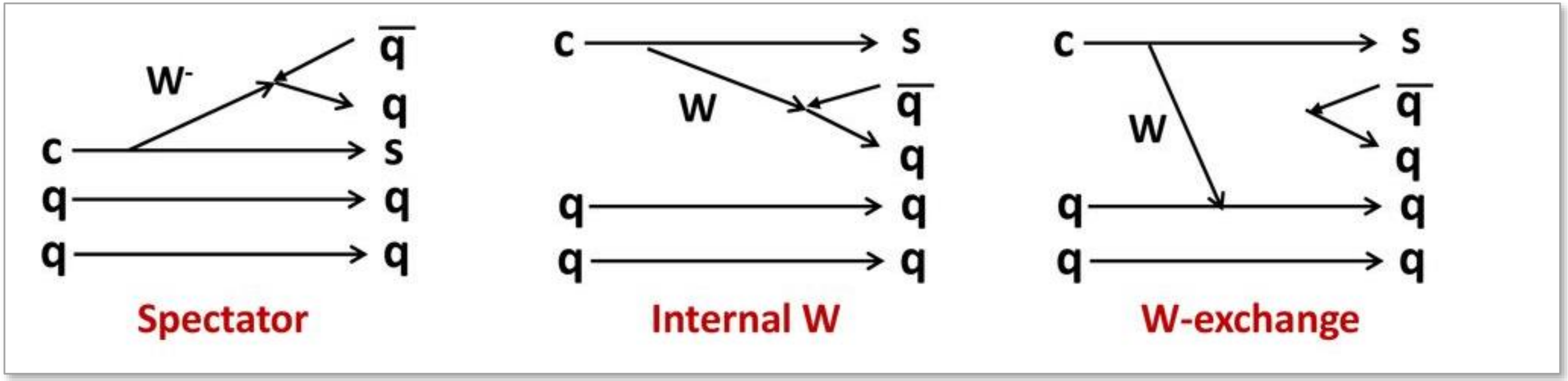
- Charmed baryons – rather direct
- Hyperons – later stage of fragmentation



Huge statistics

The charmed baryon physics

- The weak decay of charmed baryon is not understood well.
  - Three diagrams contribute to in the tree level, strength of each is not known
- Ground state charmed baryon is a good laboratory to study strange baryons as decay proceed via $c \to s$ transition.



- Belle has collected $\sim 1\ ab^{-1}\ e^{+}e^{-}$ data samples (mainly at $\Upsilon(4S)$).
  - $10^{9}\ e^{+}e^{-} \to c\bar{c}$ samples
  - $7.7 \times 10^{8}\ B\bar{B}$ samples
- Huge data sample enable to study various charmed baryons.

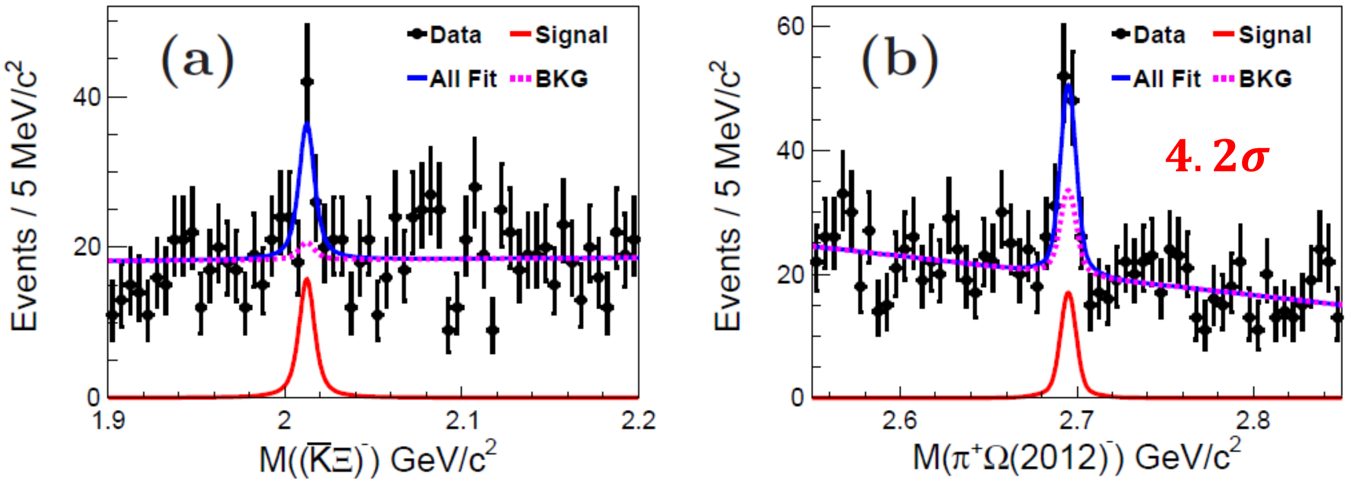
Charmed baryon resent results at Belle

Process	Reference	Physics Covered
$\Omega_c^0 \to \pi^+[\Omega(2012)^- \to \bar{K}\Xi]$	PRD 104, 052005 (2021)	Evidence: 4.2σ
$\Lambda_c^+ \to p\pi^0/p\eta$	PRD 103, 072004 (2021)	SCS decays
$\Lambda_c^+ \to p\omega$	PRD 104, 072008 (2021)	SCS decay, 3pi mode
$\Lambda_c^+ \to p\eta'$	JHEP 03, 090 (2022)	SCS decay, 5.4σ
$\Lambda_c^+ \to \eta\Lambda\pi^+$	PRD 103, 052005 (2021)	$\Lambda(1670), \Sigma(1385)^+$
$\Lambda_c^+ \to \Lambda h^+/\Sigma^0 h^+$	Belle note #625	Direct CPV search, Br, Acp
$\Lambda_c^+ \to \Sigma^+\pi^0/\Sigma^+\eta/\Lambda_c^+ \to \Sigma^+\eta'$	Belle note #626	Br, Acp
$\Lambda_c^+ \to \Sigma^+\gamma/\Xi_c^0 \to \Xi^0\gamma$	arXiv: 2206.12517	Weak radiative decays, UL
$\Xi_c^0 \to \Lambda K_S^0/\Sigma^0 K_S^0/\Sigma^+ K^-$	PRD 105, L011102 (2022)	Br, CF decays
$\Xi_c^0 \to \Xi^-\ell^+\nu_\ell$	PRL 127, 121803 (2021)	Br, Acp, LFU
$\Xi_c^0 \to \Lambda_c^+\pi^-$	arXiv: 2206.08527	Heavy-flavor-conserving decay
$\Omega_c^0 \to \Omega^-\ell^+\nu_\ell$	PRD 105, L091101 (2022)	Br, LFU
$\Sigma_c(2455)^+, \Sigma(2520)^+$	PRD 104, 052003 (2021)	mass and widths
$\Sigma_c(2455)^{0,++}\pi^\pm$	arXiv: 2206.08822	New excited charmed baryon, 4.2σ

Evidence for $\Omega_c^0 \to \pi^+[\Omega(2012)^- \to \bar{K}\Xi]$

- Searching for new production model is very important to understand the nature of $\Omega(2012)^-$
- A theoretical study of the $\Omega(2012)^-$ in the nonleptonic weak decays of $\Omega_c^0 \to \pi^+(\bar{K}\Xi)^-$ was reported [1]
- We do the search in both $K_S^0\Xi^-$ and $K^-\Xi^0$ final states

PRD 104, 052005 (2021)



Combined

$$= \frac{\mathcal{B}(\Omega_c^0 \to \pi^+\Omega(2012)^-) \times \mathcal{B}(\Omega(2012)^- \to (\bar{K}\Xi)^-)}{\mathcal{B}(\Omega_c^0 \to \pi^+\Omega^-)}$$

$$= \frac{N_{\rm sig.}^{\rm obs} \times \epsilon_{\pi^+\Omega^-}}{N_{\pi^+\Omega^-}^{\rm obs} \times (f_1 \times \epsilon_1 \times \mathcal{B}_1 + f_2 \times \epsilon_2 \times \mathcal{B}_2)}$$

$$= 0.220 \pm 0.059({\rm stat.}) \pm 0.035({\rm syst.}),$$

[1] PRD 102, 076009

Measurement of $\Lambda_c^+ \to p\pi^0/p\eta$

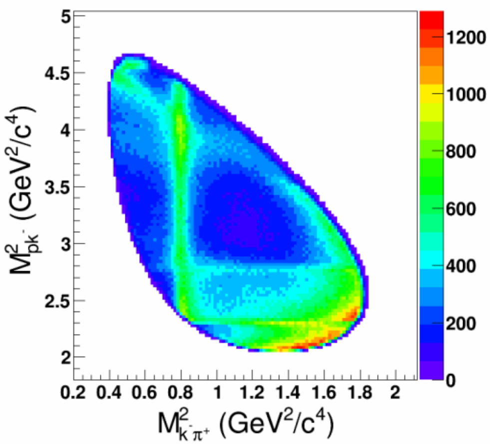
PRD 103, 052005 (2021)

A method of branching ratio with respect to Cabibbo-Favored decay $\boldsymbol{\Lambda_c^+ \to pK^-\pi^+}$ (reference mode) is applied to measure the branching fractions of signal decay.

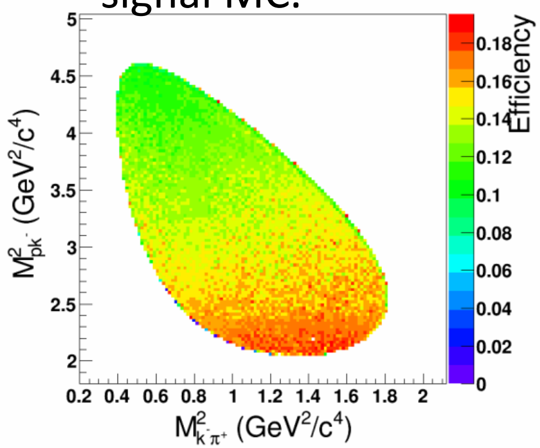
$$\frac{B(Signal)}{B(CF)} = \frac{N^{obs}(Signal)}{\epsilon^{MC}(Signal)} \times \frac{\epsilon^{MC}(CF)}{N^{obs}(CF)}$$

$\boldsymbol{\Lambda_c^+ \to pK^-\pi^+}$ efficiency estimation: Dalitz method.

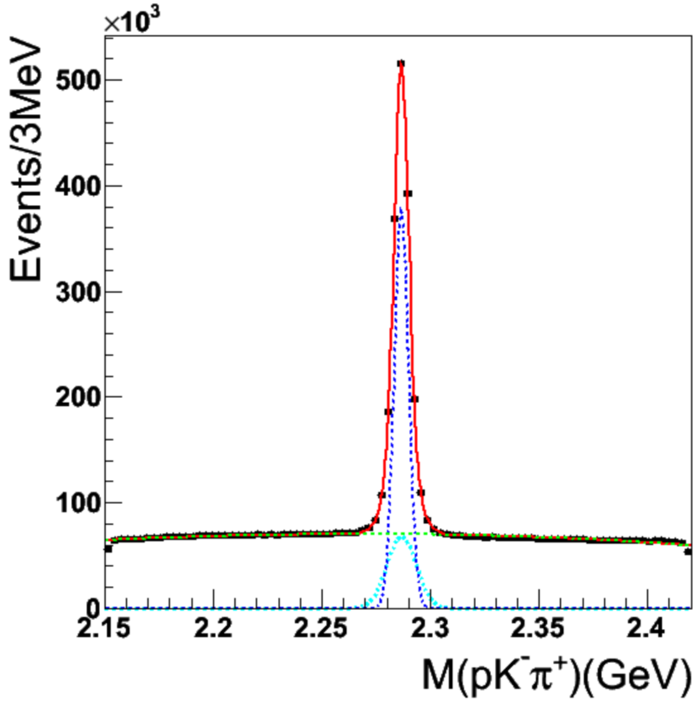
Data



Efficiency from signal MC.



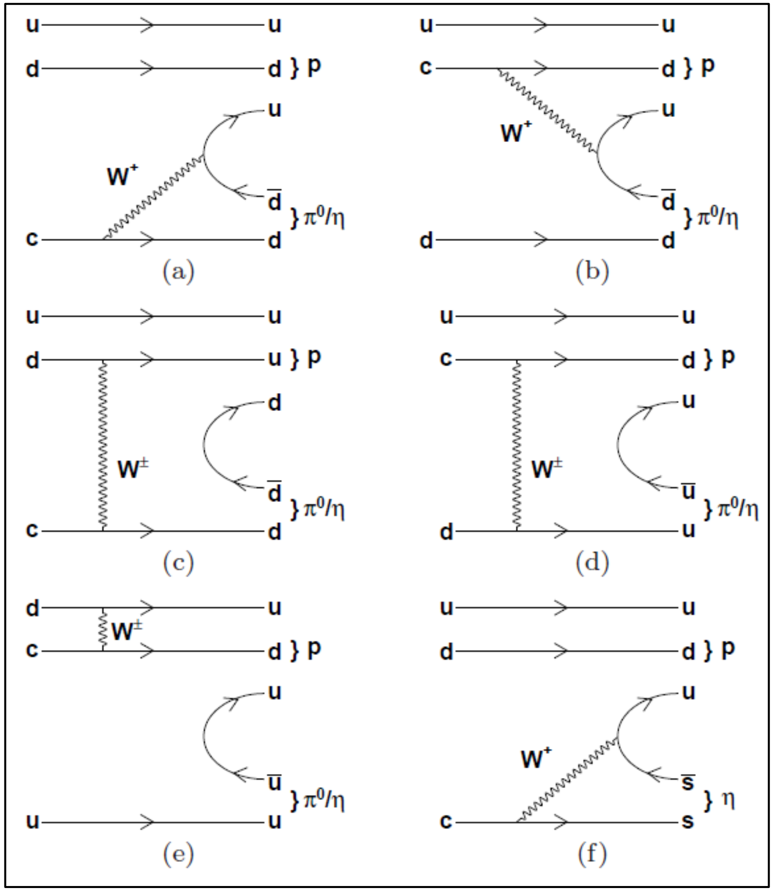
$$\boldsymbol{\varepsilon = \sum s_i \Big/ \sum_j (s_j/\varepsilon_j) = (14.06 \pm 0.01)\%.}$$



Fit to M($pK^-\pi^+$) from data using double Gaussian + second-order polynomial

Yield: **1476200 ± 1560**
χ^2/ndf=1.06

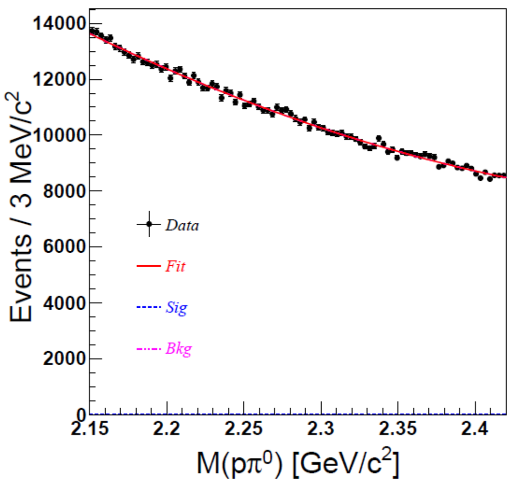
Measurement of $\Lambda_c^+ \to p\pi^0 / p\eta$

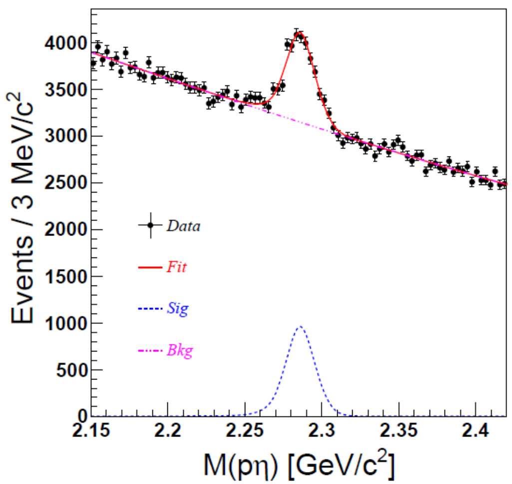


(a, b) Internal W emission
(c, d, e) W exchange
(f) Internal W emission

PRD 103, 072004 (2021)

- The W-boson exchange mechanism plays an important role in the decay of charmed baryons.
- Thus, measuring the branching fractions of these two Singly Cabibbo-Supressed decays will help elucidate the decay mechanism of charmed baryons.





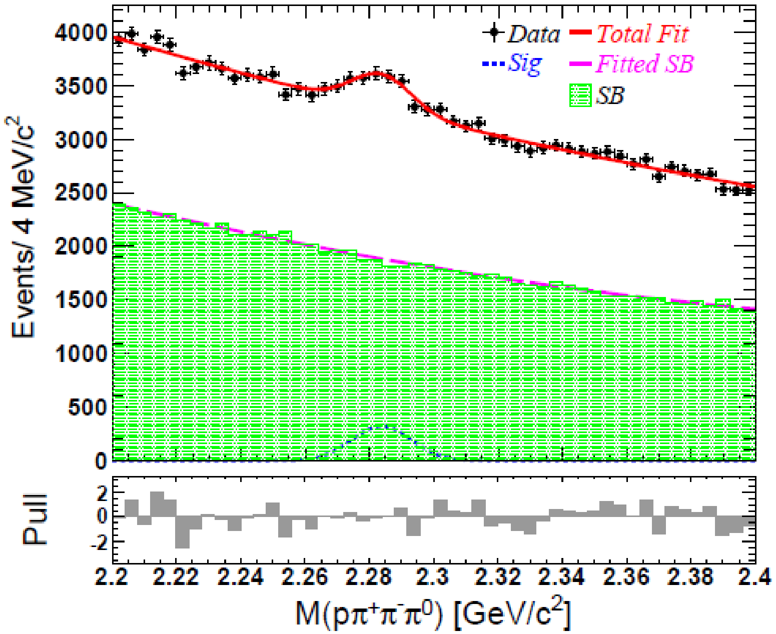
$Br(\Lambda_c^+ \to p\pi^0) < 8 \times 10^{-5}$ @ 90% C.L.
$Br(\Lambda_c^+ \to p\eta) = (1.42 \pm 0.05 \pm 0.11) \times 10^{-3}$

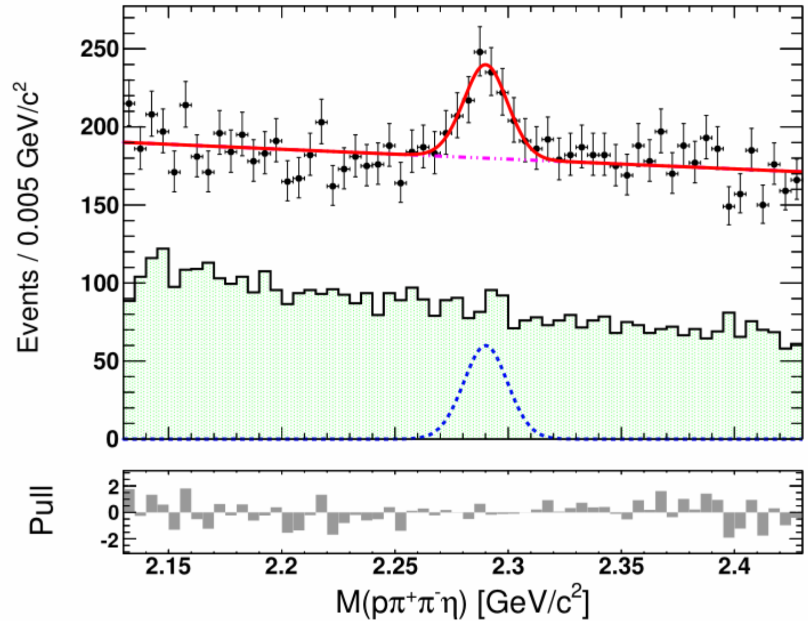
Observation of $\Lambda_c^+ \to p\omega$, $\Lambda_c^+ \to p\eta'$

- LHCb reported the first observation of a SCS decay $\Lambda_c^+ \to p\omega[\to \mu^+\mu^-]$, $\mathrm{Br}(\Lambda_c^+ \to p\omega) = (9.4 \pm 3.9) \times 10^{-4}$
- We perform same measurement by reconstructing $\omega \to \pi^+\pi^-\pi^0$ decay

PRD 104, 072008 (2021)

JHEP 03, 090 (2022)





$\mathrm{Br}(\Lambda_c^+ \to p\omega) = (8.27 \pm 0.75 \pm 0.62 \pm 0.42) \times 10^{-4}$

$\mathrm{Br}(\Lambda_c^+ \to p\eta') = (4.73 \pm 0.82 \pm 0.47 \pm 0.24) \times 10^{-4}$

- Most precise measurement
- Consistent with LCHb result

- First observation of Λ_c^+ in $\Lambda_c^+ \to p\eta'$
- Consistent with the $SU(3)_F$ calculation

Measurements of $\Lambda_c^+ \rightarrow \Lambda h^+, \Sigma^0 h^+ (h^+ = K, \pi)$

- SCS decays of charmed hadrons provide an ideal laboratory for studying CPV [1,2]
- The only observation of CPV in charm sector was made by LHCb $D^0 \rightarrow h^+ h^-$ [3]
- Direct CPV searches in two-body SCS:
  - No good theoretical predication, no experimental measurements

$$\begin{aligned} & A_{\rm raw}^{\rm corr}(\Lambda_c^+ \to \Lambda K^+) - A_{\rm raw}^{\rm corr}(\Lambda_c^+ \to \Lambda\pi^+) \\ = & A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda K^+) - A_{CP}^{\rm dir}(\Lambda_c^+ \to \Lambda\pi^+). \end{aligned}$$

$$A_{\rm raw} = \frac{N(\Lambda_c^+ \to f) - N(\overline{\Lambda}_c^- \to \overline{f})}{N(\Lambda_c^+ \to f) + N(\overline{\Lambda}_c^- \to \overline{f})}.$$

- We can also measure the decay asymmetry parameters

$$A_{CP}^{\alpha}(\text{total}) = \frac{\alpha_{\Lambda_c^+}\alpha_- - \alpha_{\overline{\Lambda}_c^-}\alpha_+}{\alpha_{\Lambda_c^+}\alpha_- + \alpha_{\overline{\Lambda}_c^-}\alpha_+},$$

$$\frac{dN}{d\cos\theta_\Lambda} \propto 1 + \alpha_{\Lambda_c^+}\alpha_- \cos\theta_\Lambda$$

$$A_{CP}^{\alpha}(\text{total}) = A_{CP}^{\alpha}(\Lambda \to p\pi^-)$$

$$\frac{dN}{d\cos\theta_{\Sigma^0} d\cos\theta_\Lambda} \propto 1 - \alpha_{\Lambda_c^+}\alpha_- \cos\theta_{\Sigma^0}\cos\theta_\Lambda$$

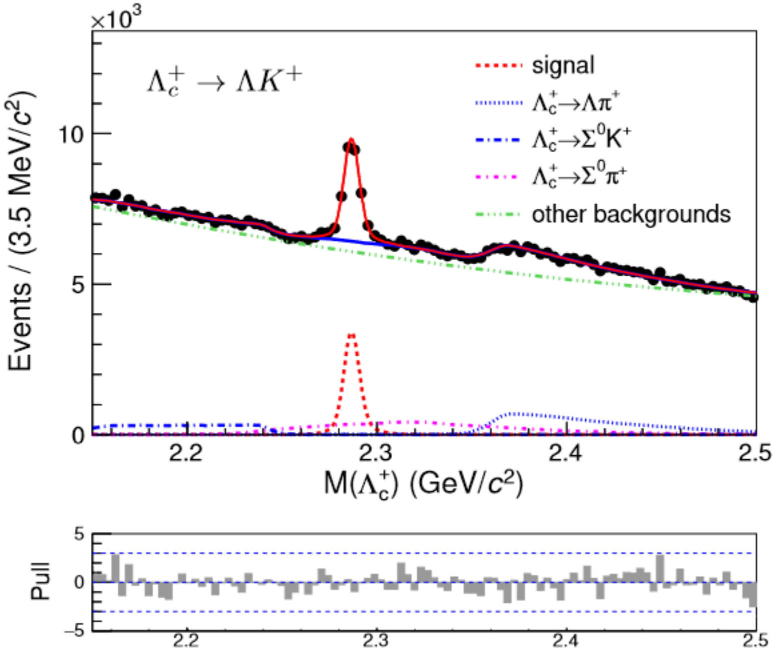
θ_Λ (θ_{Σ^0}) is the angle between the proton (Λ) momentum vector and the opposite of the Σ^0 (Λ_c^+) momentum vector in the Λ (Σ^0) rest frame; $\alpha_- = 0.7542 \pm 0.0022$ from world average value measured by BESIII.

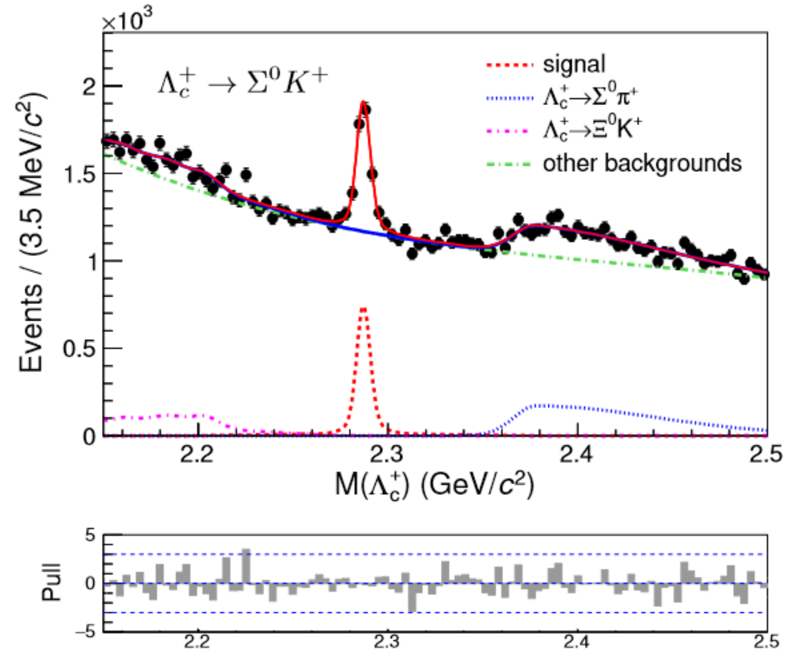
- And branching fractions

$$\frac{\mathcal{B}_{\rm sig}}{\mathcal{B}_{\rm ref}} = \frac{N_{\rm sig}/\varepsilon_{\rm sig}}{N_{\rm ref}/\varepsilon_{\rm ref}},$$

[1] PRD 86, 616 014023 (2012)
[2] PRD 85, 034036618 (2012)
[3] PRL 627 122, 211803 (2019)

Measurements of $\Lambda_c^+ \to \Lambda h^+, \Sigma^0 h^+ (h^+ = K, \pi)$





Direct CPV measurements:

$$A_{CP}^{dir}(\Lambda_c^+ \to \Lambda K^+) = (+2.1 \pm 2.6 \pm 0.1) \times 10^{-2}$$
$$A_{CP}^{dir}(\Lambda_c^+ \to \Sigma^0 K^+) = (+2.5 \pm 5.4 \pm 0.4) \times 10^{-2}$$

The first direct CP asymmetry measurement for SCS two-body decays of charmed baryons.

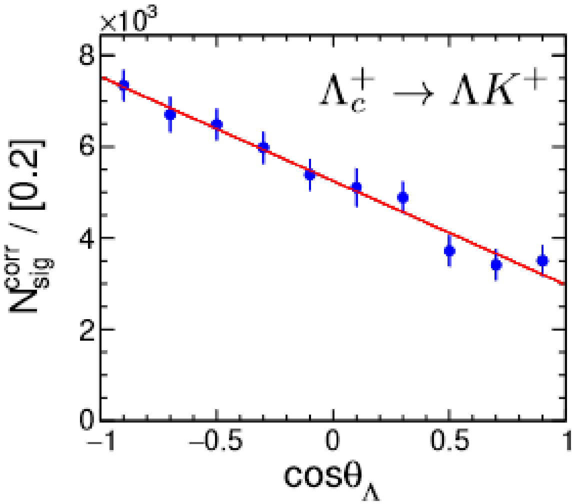
Branching fraction measurements:

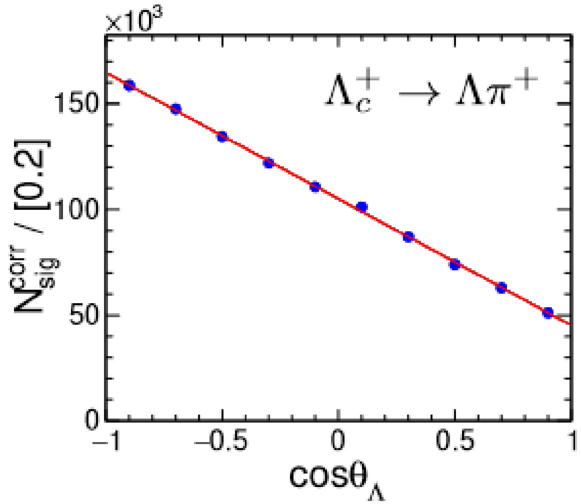
$$Br(\Lambda_c^+ \to \Lambda K^+) = (6.57 \pm 0.17 \pm 0.11 \pm 0.35) \times 10^{-4}$$
$$Br(\Lambda_c^+ \to \Sigma^0 K^+) = (3.58 \pm 0.19 \pm 0.06 \pm 0.19) \times 10^{-4}$$

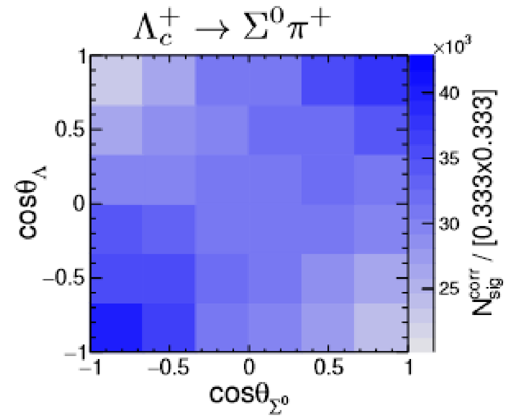
Significantly improved precision

Preliminary result

Measurements of $\Lambda_c^+ \to \Lambda h^+, \Sigma^0 h^+ (h^+ = K, \pi)$







Averaged decay asymmetry parameters:
- First measurements of K^+ modes
- Improved precision of π^+ modes

$$\begin{aligned} \alpha_{\rm avg}(\Lambda_c^+ \to \Lambda K^+) &= -0.585 \pm 0.049 \pm 0.018\,, \\ \alpha_{\rm avg}(\Lambda_c^+ \to \Lambda \pi^+) &= -0.755 \pm 0.005 \pm 0.003\,, \\ \alpha_{\rm avg}(\Lambda_c^+ \to \Sigma^0 K^+) &= -0.55 \pm 0.18 \pm 0.09\,, \\ \alpha_{\rm avg}(\Lambda_c^+ \to \Sigma^0 \pi^+) &= -0.463 \pm 0.016 \pm 0.008\,, \end{aligned}$$

α-induced CP asymmetry:
- First measurements of A_{CP}^{α} for SCS decays of charmed baryons

Channel	A_{CP}^{α}
$\Lambda_c^+ \to \Lambda K^+$	$-0.023 \pm 0.086 \pm 0.071$
$\Lambda_c^+ \to \Lambda \pi^+$	$+0.020 \pm 0.007 \pm 0.013$
$\Lambda_c^+ \to \Sigma^0 K^+$	$+0.08 \pm 0.35 \pm 0.14$
$\Lambda_c^+ \to \Sigma^0 \pi^+$	$-0.023 \pm 0.034 \pm 0.030$

Λ-hyperon CP violation:
- First measurement of hyperon CPV searches in CF charm decays.

$$A_{CP}^{\alpha} = +0.013 \pm 0.007 \pm 0.011$$

No evidence of baryon CPV is found

Preliminary result

Measurements of $\Lambda_c^+ \to \Sigma^+\pi^0, \Lambda_c^+ \to \Sigma^+\eta, \Lambda_c^+ \to \Sigma^+\eta'$

- Measure branching fractions and asymmetry parameters of charmed baryon weak decays: $B_c \to B + M$ (M is pseudoscalar or vector meson)

Decay	Körner [1]	Ivanov [2]	Żenczykowski [7]	Sharma [8]	Zou [10]	Geng [11]	Experiment [12]
$\Lambda_c^+ \to \Sigma^+\eta$	0.16	0.11	0.90	0.57	0.74	0.32±0.13	0.44±0.20
$\Lambda_c^+ \to \Sigma^+\eta'$	1.28	0.12	0.11	0.10	–	1.44±0.56	1.5±0.6
$\Lambda_c^+ \to \Sigma^+\pi^0$	0.70	0.43	0.39	−0.31	−0.76	−0.35±0.27	−0.55±0.11
$\Lambda_c^+ \to \Sigma^+\eta$	0.33	0.55	0.00	−0.91	−0.95	−0.40±0.47	–
$\Lambda_c^+ \to \Sigma^+\eta'$	−0.45	−0.05	−0.91	0.78	–	$1.00^{+0.00}_{-0.17}$	–

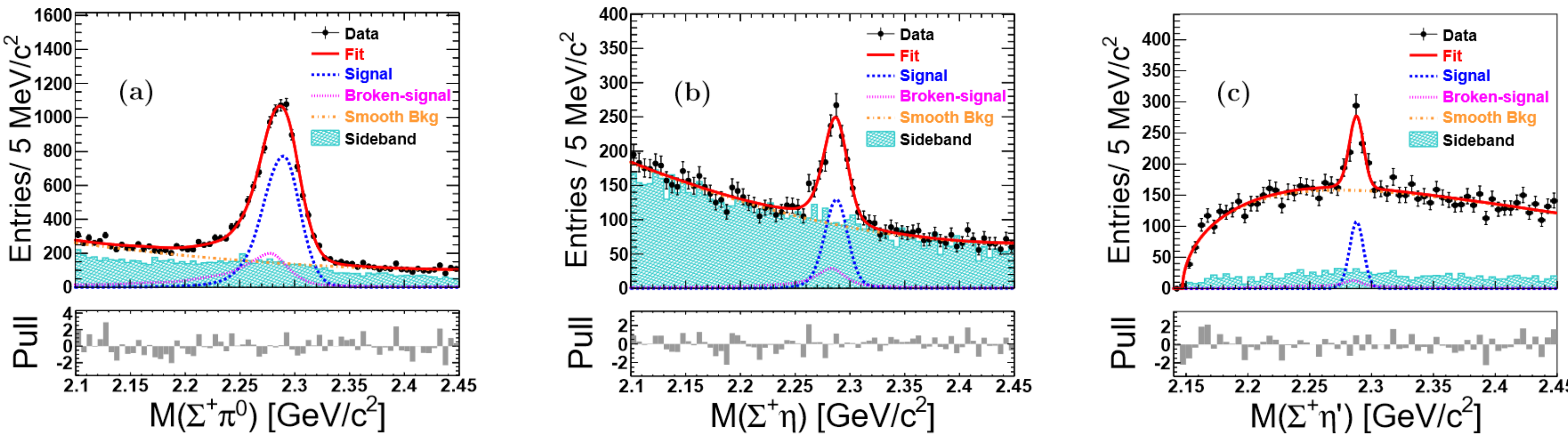
Branching fraction

Asymmetry parameter

- The rates of $\Lambda_c^+ \to \Sigma^+\eta$ and $\Lambda_c^+ \to \Sigma^+\eta'$ are naively comparable or the former is larger than the latter. However, the branching fraction of $\Lambda_c^+ \to \Sigma^+\eta'$ measured by BESIII was found to be larger than the $\Lambda_c^+ \to \Sigma^+\eta$ mode.

$$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta')}{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta)} = 3.5 \pm 2.1 \pm 0.4 .$$

- Compare the asymmetry parameters of $\Lambda_c^+ \to \Sigma^+\pi^0$ and $\Lambda_c^+ \to \Sigma^0\pi^+$ could test the isospin symmetry.



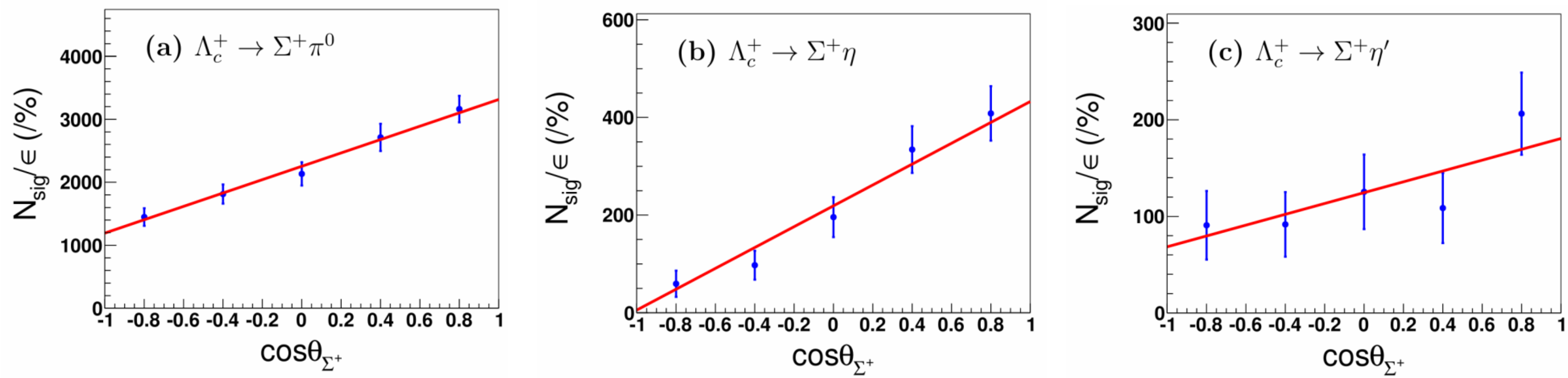
Measurements of $\Lambda_c^+ \to \Sigma^+\pi^0, \Lambda_c^+ \to \Sigma^+\eta, \Lambda_c^+ \to \Sigma^+\eta'$

$$Br(\Lambda_c^+ \to \Sigma^+\eta) = (3.14 \pm 0.35 \pm 0.11 \pm 0.25) \times 10^{-3}$$
$$Br(\Lambda_c^+ \to \Sigma^+\eta') = (4.16 \pm 0.75 \pm 0.21 \pm 0.33) \times 10^{-3}$$

Most precise results to date

$$\frac{\mathcal{B}_{\Lambda_c^+ \to \Sigma^+\eta'}}{\mathcal{B}_{\Lambda_c^+ \to \Sigma^+\eta}} = 1.34 \pm 0.28 \pm 0.06,$$

BESIII: $\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta')}{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta)} = 3.5 \pm 2.1 \pm 0.4\,.$



$\alpha_{\Sigma^+\pi^0} = -0.48 \pm 0.02 \pm 0.02$

Agrees with the world average value: -0.55 ± 0.11 in much improved precision.

Consistent with $\alpha_{\Sigma^0\pi^+} = -0.463 \pm 0.016 \pm 0.008$, no isospin symmetry broken.

$\alpha_{\Sigma^+\eta} = -0.99 \pm 0.03 \pm 0.05$ and $\alpha_{\Sigma^+\eta'} = -0.46 \pm 0.06 \pm 0.03$

Measured for the first time.

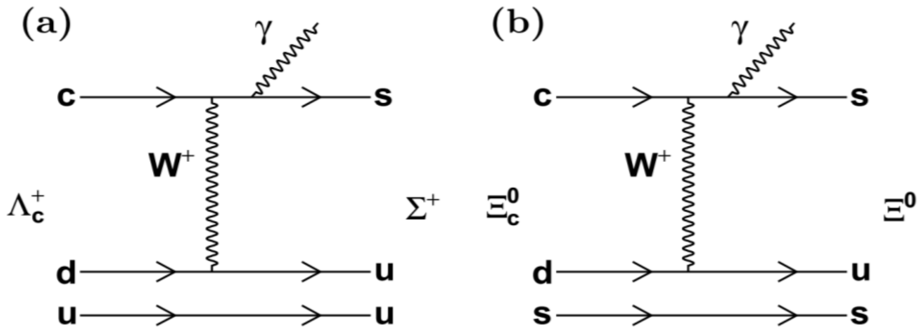
Preliminary result

First search for the weak radiative decays $\Lambda_c^+ \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$

arXiv:2206.12517

- Weak radiative decays of charmed hadrons are dominated by the long-range nonperturbative processes that can enhance the branching fractions up to 10^{-4}, whereas short-range interactions are predicted to yield rates at the level of 10^{-8}[1,2]

- At the CF level, there are two decay modes for the weak radiative decays of anti-triplet charmed baryons induced from $cd \to us + \gamma$, i.e., $\Lambda_c^+ \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$ decays.



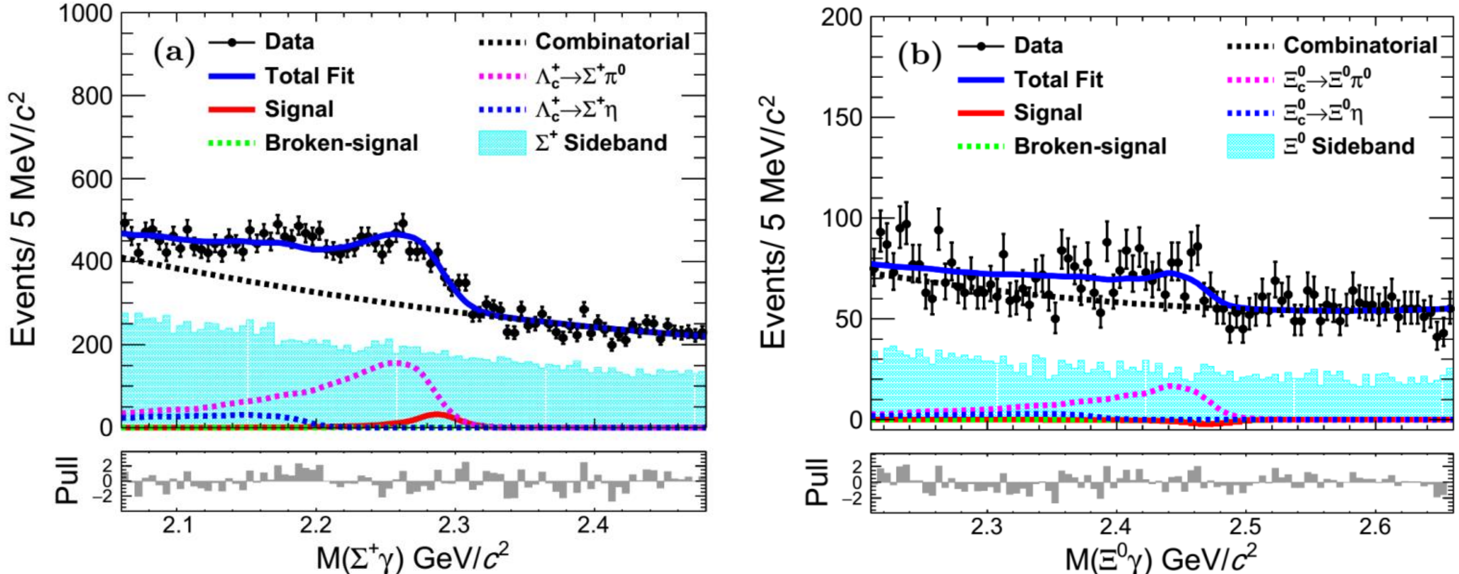
- The theoretical estimates of branching fractions cover ranges of $(4.5 - 29.1) \times 10^{-5}$ and $(3.0 - 19.5) \times 10^{-5}$ for $\Lambda_c^+ \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$ decays, respectively [3-6].

[1] PRD 52, 6383 (1995).
[2] PLB 382, 415 (1996).
[3] PRD 28, 2176 (1983).
[4] PRD 47, 2858 (1993).
[5] PRD 51, 1199 (1995).
[6] arXiv:2109.01216.

First search for the weak radiative decays $\Lambda_c^+ \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$

arXiv:2206.12517

- There are no evident $\Lambda_c^+ \to \Sigma^+\gamma$ or $\Xi_c^0 \to \Xi^0\gamma$ signals. The signal significance of $\Lambda_c^+ \to \Sigma^+\gamma$ decay is only 2.2σ, after considering the systematic uncertainty.



- Taking $\Lambda_c^+ \to pK^-\pi^+$ and $\Xi_c^0 \to \Xi^-\pi^+$ as normalization channels, the upper limits at 90% confidence level (C.L.) on the ratios of branching fractions are

$$\frac{\mathrm{Br}(\Lambda_c^+\to\Sigma^+\gamma)}{\mathrm{Br}(\Lambda_c^+\to pK^-\pi^+)} < 3.99\times10^{-3}$$

$$\frac{\mathrm{Br}(\Xi_c^0\to\Xi^0\gamma)}{\mathrm{Br}(\Xi_c^0\to\Xi^-\pi^+)} < 1.15\times10^{-2}$$

- The upper limits at 90% C.L. on the absolute branching fractions are determine:

$$\mathrm{Br}(\Lambda_c^+ \to \Sigma^+\gamma) < 2.55\times10^{-4}$$

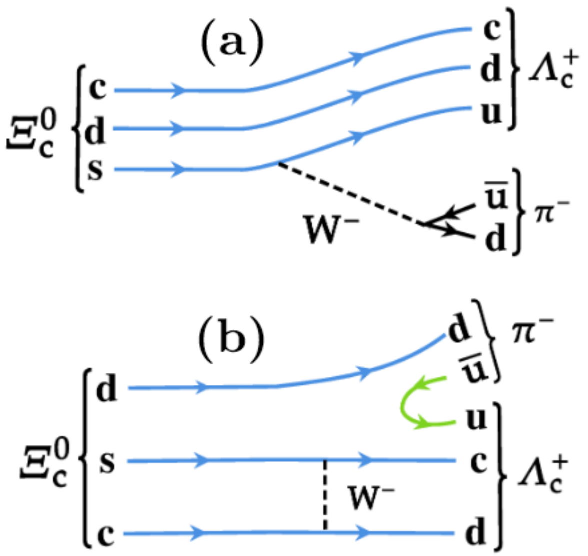
$$\mathrm{Br}\left(\Xi_c^0 \to \Xi^0\gamma\right) < 1.73\times10^{-4}$$

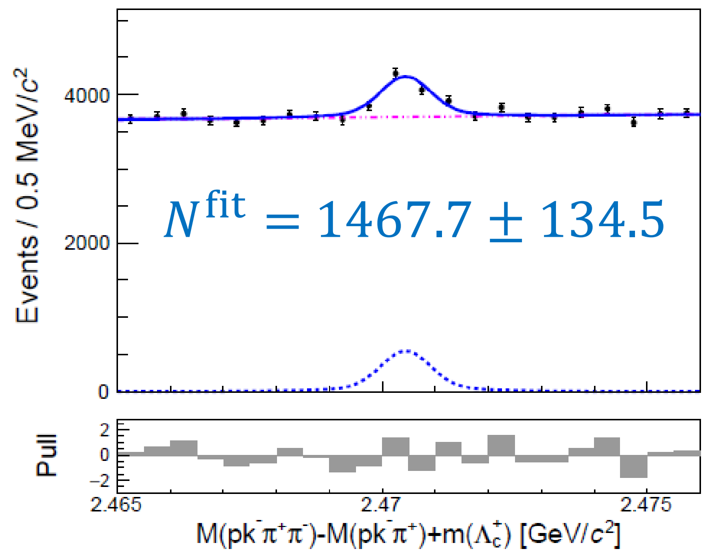
Measurements of $Br(\Xi_c^0 \to \Lambda_c^+ \pi^-)$

arXiv:2206.08527

- The heavy-flavor-conserving nonleptonic decays in charmed baryons containing both an *s* and a *c* quark, that proceeds via the decay of the s quark, i.e. $\Xi_c^0 \to \Lambda_c^+ \pi^-$.

- The decay width of $\Xi_c^0 \to \Lambda_c^+ \pi^-$ is based on the size of the *s* quark decay amplitude of $s \to u(\bar{u}d)$ and the weak scattering amplitude $cs \to dc$.





$$Br(\Xi_c^0 \to \Lambda_c^+ \pi^-) = (6.8 \pm 0.6 \pm 0.6 \pm 2.0) \times 10^{-3}$$

- The result is consistent with previous measurement by LHCb experiment and recent theoretical calculation, and larger than the previous theoretical predictions.

Measurements of $\Omega_c^0 \to \Omega^- l^+ \nu$ and $\Xi_c^0 \to \Xi^- l^+ \nu$

Semi-leptonic decays of charmed baryons:

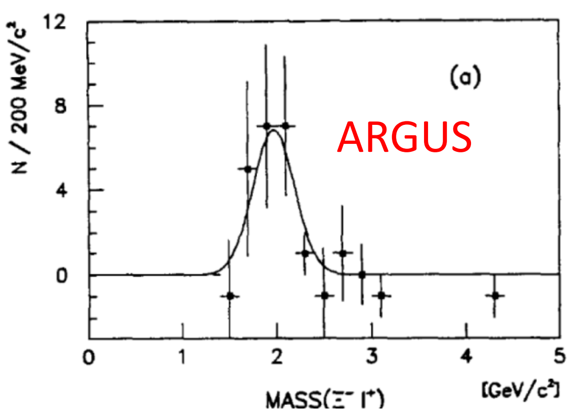
- Ideal test of QCD in transition region of (non-)perturbative.
- The cleanest processes among charm decays
- Test lepton flavor universality (LFU).

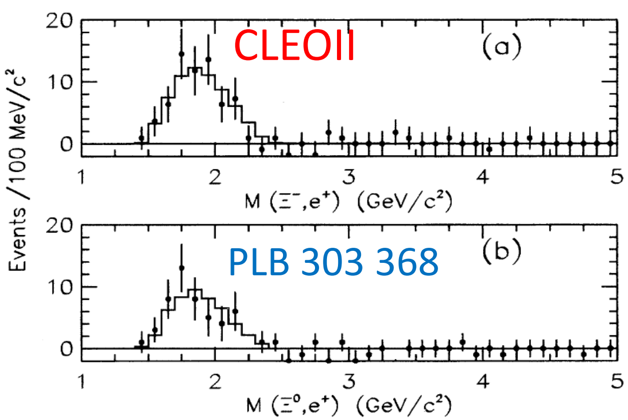
Experimentally:

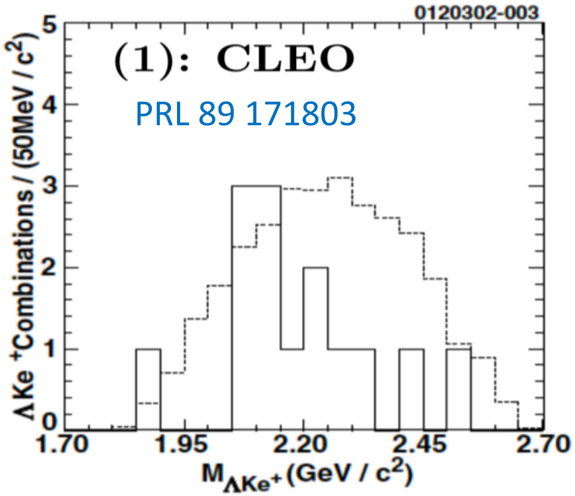
- BESIII measured the $\mathcal{B}(\Lambda_c^+ \to \Lambda l^+ \nu)$
- ARGUS and CLEOII measured $\mathcal{B}(\Xi_c \to \Xi\, l^+ \nu)$
- CLEO measured $\mathcal{B}(\Omega_c^0 \to \Omega^- e^+ \nu)$

} **large uncertainty**

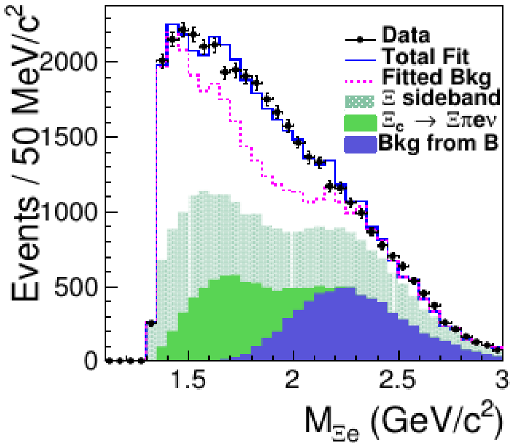
$\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.6 \pm 0.4)\%$ PRL 115, 221805(2015)
$\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_e) = (3.5 \pm 0.4)\%$ PLB 767, 42 (2017)

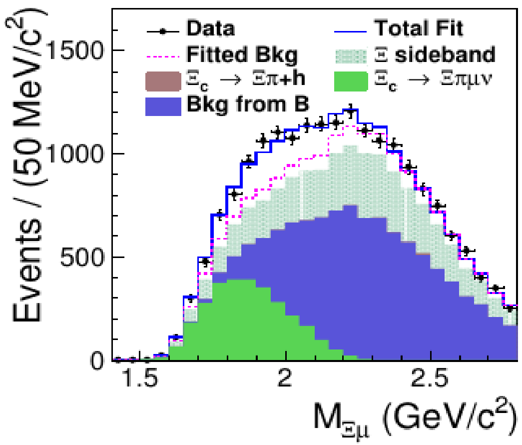






Measurements of $\Omega_c^0 \to \Omega^- l^+ \nu$ and $\Xi_c^0 \to \Xi^- l^+ \nu$





Data-driven method for bkg

- Mis-selected ℓ^+
- Wrongly constructed Ξ
- $\Xi_c \to \Xi\pi\ell^+\nu_\ell$
- $\Xi_c \to \Xi\pi + h$
- B decay

PRL 127, 121803 (2021)

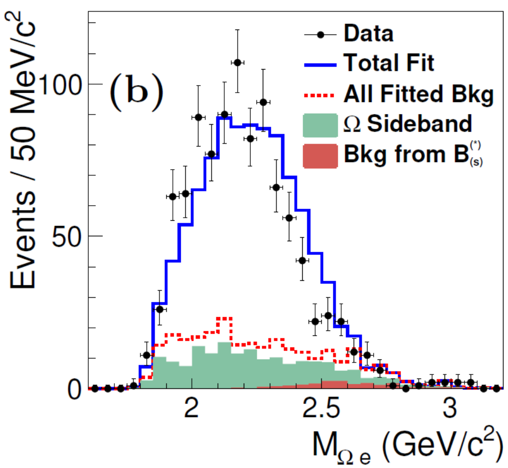
$\mathcal{Br}(\Xi_c^0 \to \Xi^- e^+\nu_e) = (1.31 \pm 0.39)\%$

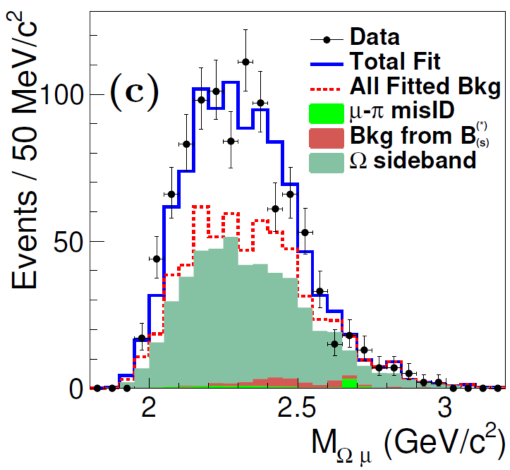
$\mathcal{Br}(\Xi_c^0 \to \Xi^- \mu^+\nu_\mu) = (1.27 \pm 0.39)\%$

Previous: $(2.34 \pm 1.59)\%$

Consistent with LFU

PRD 105, L091101 (2022)





$$\frac{\mathcal{B}(\Omega_c^0 \to \Omega^- e^+ \nu)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)} = 1.98 \pm 0.15$$

$$\frac{\mathcal{B}(\Omega_c^0 \to \Omega^- \mu^+ \nu)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)} = 1.94 \pm 0.21$$

Previous: 2.4 ± 1.2

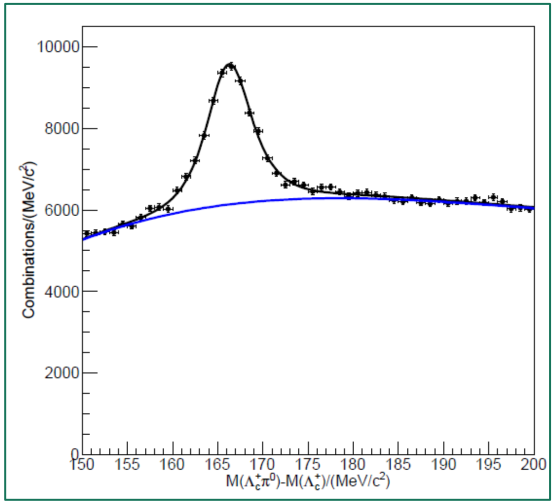
Consistent with LFU

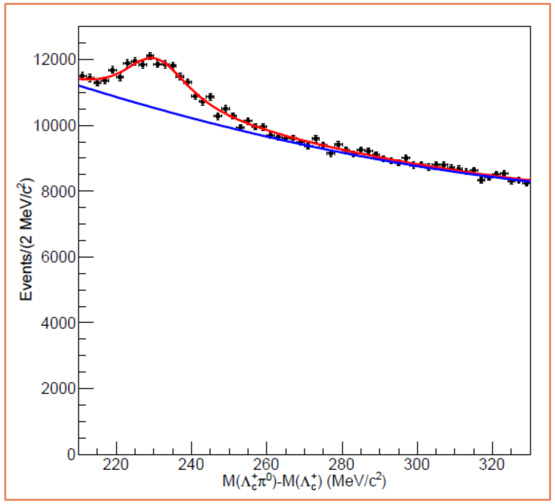
Measurement of the masses and widths of the $\Sigma_c(2455)^+$ and $\Sigma_c(2520)^+$ baryons

PRD 104, 052003 (2021)

- The doubly-charged and neutral Σ_c states are well studied.
- However, there is comparatively little experimental information on the singly-charged Σ_c^+ states due to π^0 transition.
- Good tests of models of isospin mass splittings, most mass models predict Σ_c^+ states have masses a little lower than doubly-charged and neutral analogs.

- Reconstruct Σ_c^+ baryons from $\Lambda_c^+\pi^0$ decays. Fits performed to limited-range subsets





$\Sigma_c(2455)^+$:
- $\Delta(M) = 166.17 \pm 0.05^{+0.16}_{-0.07}$ MeV
- $\Gamma = 2.3 \pm 0.3 \pm 0.3$ MeV

$\Sigma_c(2520)^+$:
- $\Delta(M) = 230.9 \pm 0.5^{+0.5}_{-0.1}$ MeV
- $\Gamma = 17.2^{+2.3+3.1}_{-2.1-0.7}$ MeV

First non-zero measurements of the intrinsic widths.
No deviation from the expectations of their isospin partners

Evidence of a new Λ_c^+ excited state

arXiv: 2206.08822

- Charmed baryons are good platform to study related theories such as HQET.
- High mass excited states are still not well understood.
- Most of Λ_c^+ excited states decay (via Σ_c) to $\Lambda_c^+\pi\pi$ final states

Experimentally

$\overline{\mathrm{B}}^{\mathbf{0}} \to \boldsymbol{\Lambda_c \pi\pi\bar{p}}$ is a promising channel to study

- Low background contributions
- High branching fraction $\sim 10^{-4}$
- Large $B\bar{B}$ sample: 772×10^6

B^0 Decay Modes

Γ_{500}	$\overline{\Lambda}_c^- p\pi^+\pi^-$ (nonresonant)	$(5.5 \pm 1.0) \times 10^{-4}$
Γ_{501}	$\overline{\Sigma}_c(2520)^{--} p\pi^+$	$(1.02 \pm 0.18) \times 10^{-4}$
Γ_{502}	$\overline{\Sigma}_c(2520)^0 p\pi^-$	$< 3.1 \times 10^{-5}$
Γ_{503}	$\overline{\Sigma}_c(2455)^0 p\pi^-$	$(1.08 \pm 0.16) \times 10^{-4}$

$\Lambda_c(2880)^+$ Decay Modes

Γ_1	$\Lambda_c^+\pi^+\pi^-$

$\Lambda_c(2595)^+$ Decay Modes

Γ_1	$\Lambda_c^+\pi^+\pi^-$

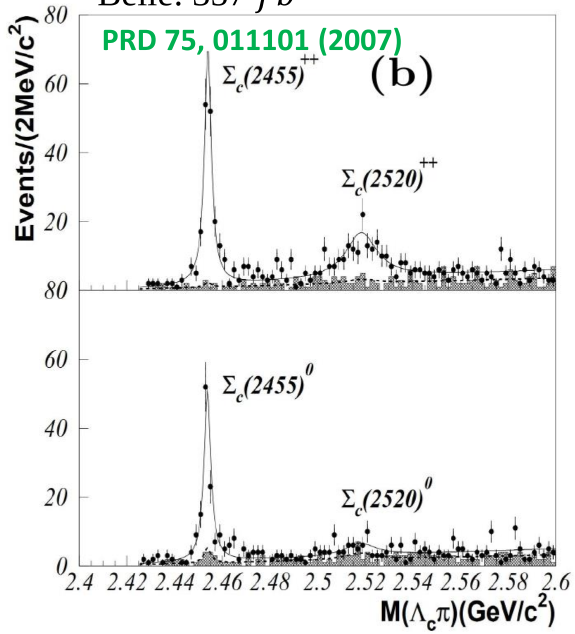
$\Lambda_c(2625)^+$ Decay Modes

Γ_1	$\Lambda_c^+\pi^+\pi^-$

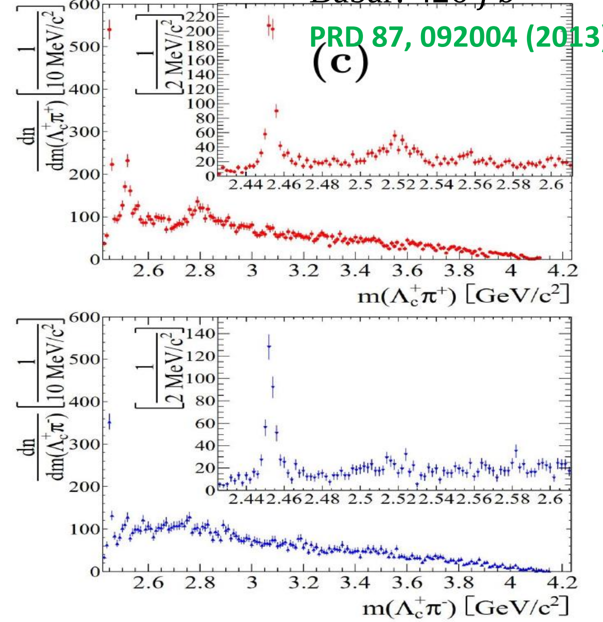
$\Lambda_c(2940)^+$ Decay Modes

Γ_1	pD^0
Γ_2	$\Sigma_c(2455)^{0,++}\pi^\pm$

Belle: 357 fb^{-1}



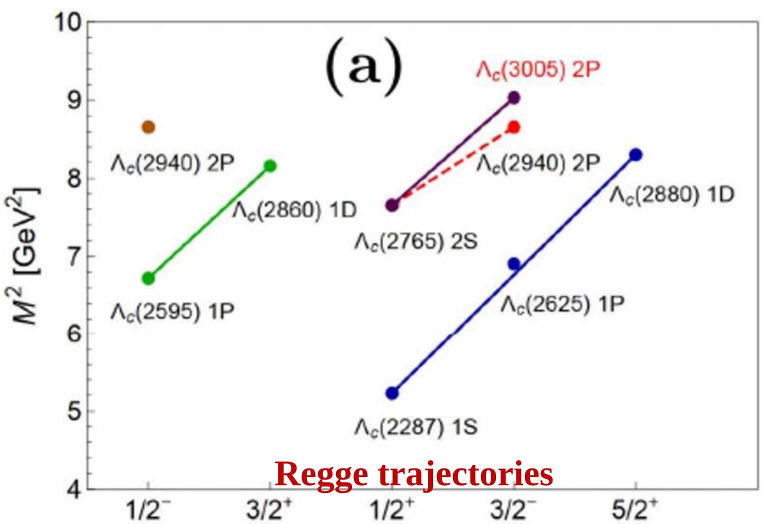
Babar: 426 fb^{-1}



Evidence of a new Λ_c^+ excited state

arXiv: 2206.08822

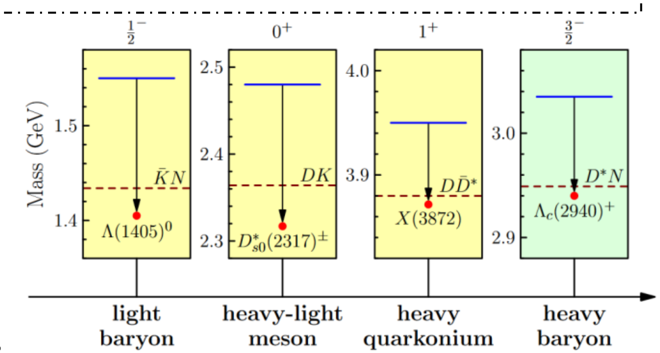
- $\boldsymbol{\Lambda_c(2940) \to \Sigma_c(2455)\pi}$ is the current highest mass Λ_c excited state
- LHCb result prefers $J^P = \frac{3}{2}^-$, but doesn't exclude other values [JHEP 05, 030 (2017)].
- The mass of $\boldsymbol{\Lambda_c(2940)}$ is lower than predication of contradictory quark model.



Int J Theor Phys 59, 1129 (2020)

State	J^P	Present	[9]	[10]	[11]	[16]	[20]	[21]	PDG [1]
$2P$	$\frac{1}{2}^-$	2.978	3.017	2.983	2.989	2.890		2.980	
$2P$	$\frac{3}{2}^-$	2.970	3.034	3.005	3.000	2.917		3.004	$2.9396^{+0.0014}_{-0.0015}$

[9]. Phys. Lett. B 659, 612 (2008).
[10]. Phys. Rev. D 84, 014025 (2011).
[11]. Phys. Rev. D 91, 054034 (2015).
[16]. Phys. Rev. D 92, 114029 (2015).
[21]. Eur. Phys. J. C 77, 154 (2017).

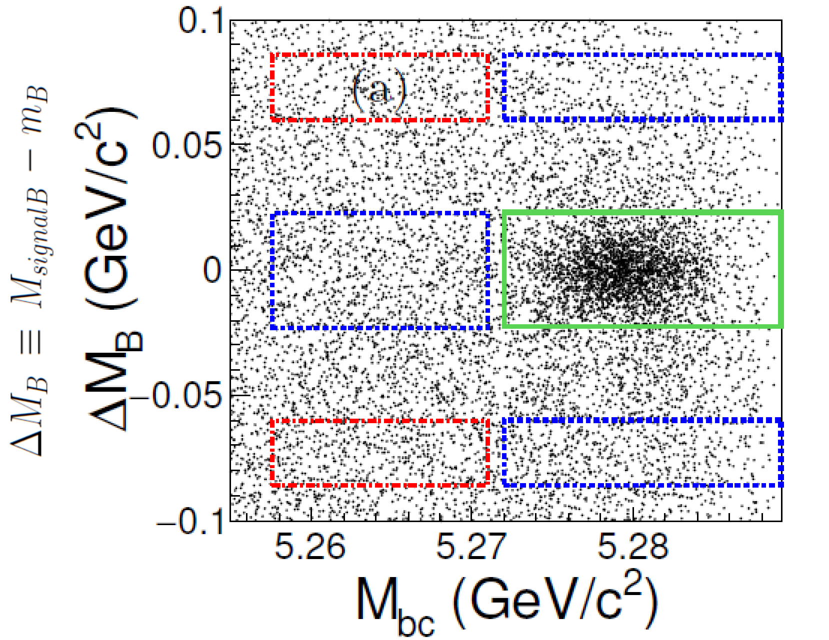


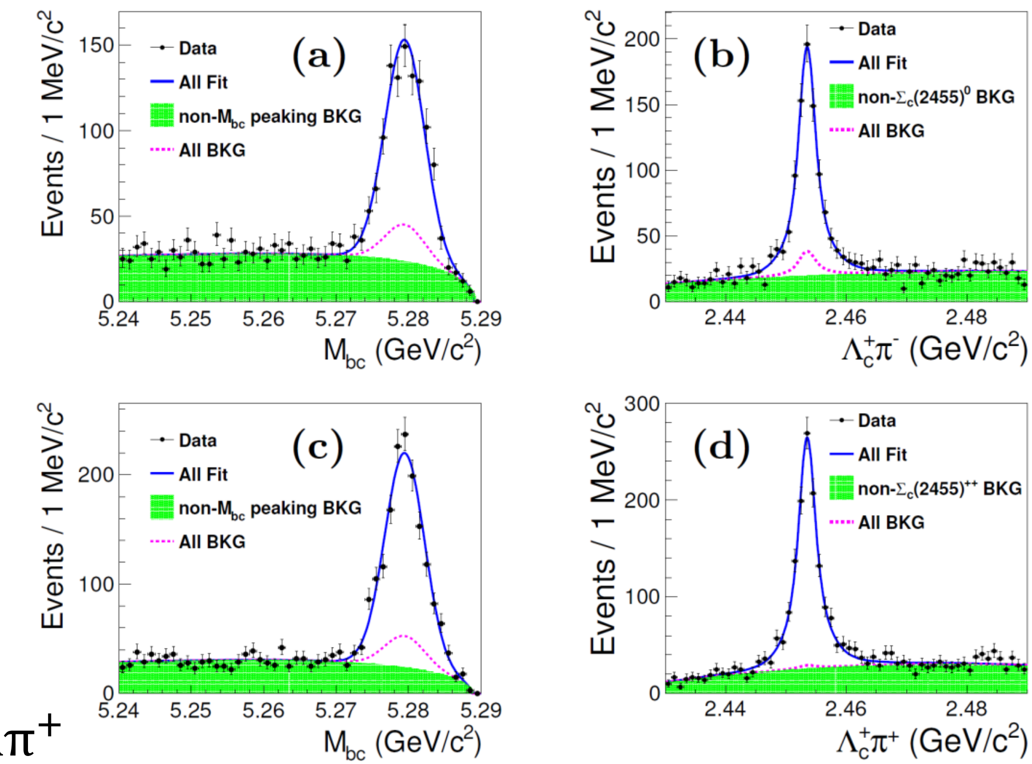
Theoretically:

- $\Lambda_c(2940)$ has $J^P = \frac{1}{2}^-$, belongs to another Regge trajectories
  - Search for $\Lambda_c(3005)$
- $\Lambda_c(2940)$ has D*N contribution is similar to $(1405), D_s(2317), X(3872)$,
  - $\Lambda_c\left(\frac{1}{2}^-, 2P\right)$ has reversed mass which is larger than $\Lambda_c\left(\frac{3}{2}^-, 2P\right)$

Evidence of a new Λ_c^+ excited state

arXiv: 2206.08822





Reconstruct Λ_c^+ via $pK^-\pi^+$, pK_S, and $\Lambda\pi^+$

Significant signal of $\overline{B}^0 \to \Sigma_c(2455)\pi\bar{p}$

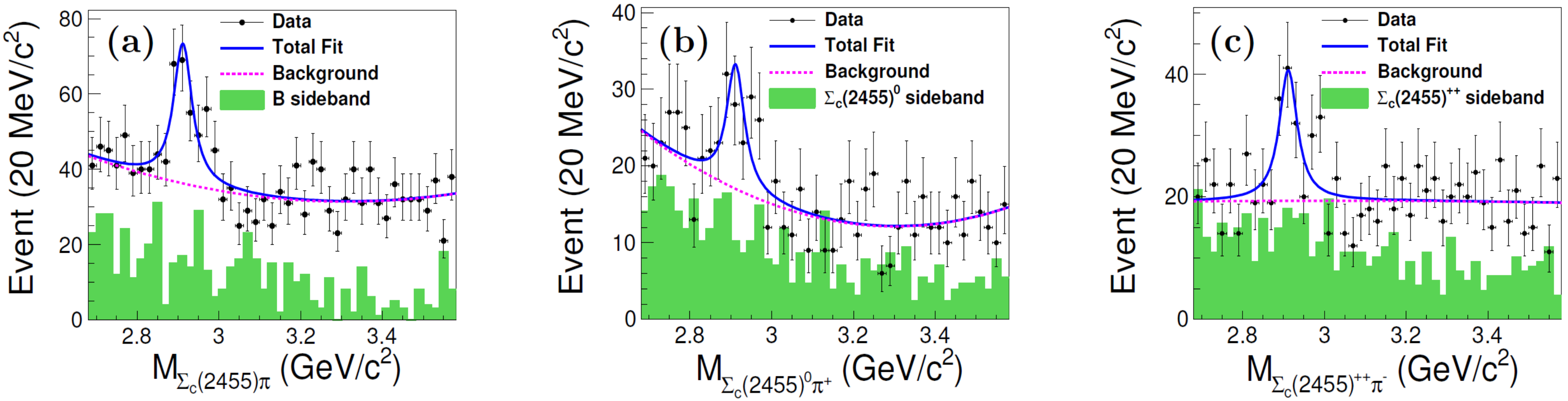
Measured branching fraction consistent with previous study at improved precision

B decay mode	yield	Br(10^{-4})	PDG (10^{-4})
$\Sigma_c(2455)^0\pi\bar{p}$	767 ± 44	$1.09 \pm 0.06 \pm 0.07$	1.08 ± 0.16
$\Sigma_c(2455)^{++}\pi\bar{p}$	1213 ± 73	$1.84 \pm 0.11 \pm 0.12$	1.88 ± 0.24

Evidence of a new Λ_c^+ excited state

arXiv: 2206.08822

Search for excited $\boldsymbol{\Lambda_c}$ states



- A resonant structure in $\Sigma_c(2455)\pi$ invariant mass spectra, the mass and width are measured to be:

  $m = (2913.8 \pm 5.6 + 3.7)$ MeV/c^2, $\Gamma = (51.8 \pm 20.0 \pm 18.8)$ MeV

- The significance in the most conservative case is 4.2σ
- The J^p prefers to be $\frac{1}{2}^-$, $\Lambda_c\left(\frac{1}{2}^-, 2P\right)$, thus name it $\Lambda_c(2910)$
- Need further efforts from both experimental and theoretical sides to understand $\Lambda_c(2910)$ and $\Lambda_c(2940)$

Summary

- Although Belle has stopped data taking for >10 years ago, we are still producing exciting results.
- The Belle II experiment at SuperKEKB aims to find New Physics beyond the SM with ultimate precision measurement (a few %, typically) of heavy flavor decays.
- Belle II started data taking on 25 March 2019 with its full detector and is performing as expected and obtained early physics results.
- Belle II can achieve lots of important results on baryons and charmed baryons near future.

Thanks!

Measurements of $\Omega_c^0 \to \Omega^- l^+ \nu$ and $\Xi_c^0 \to \Xi^- l^+ \nu$

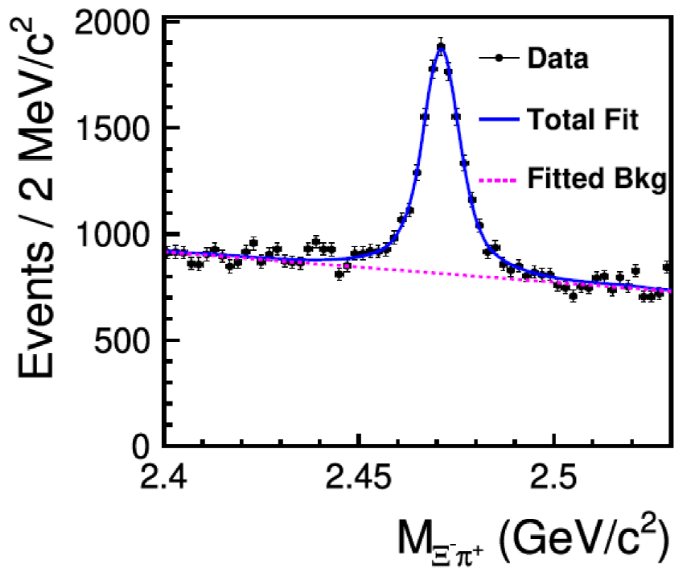
PRL 127, 121803 (2021)

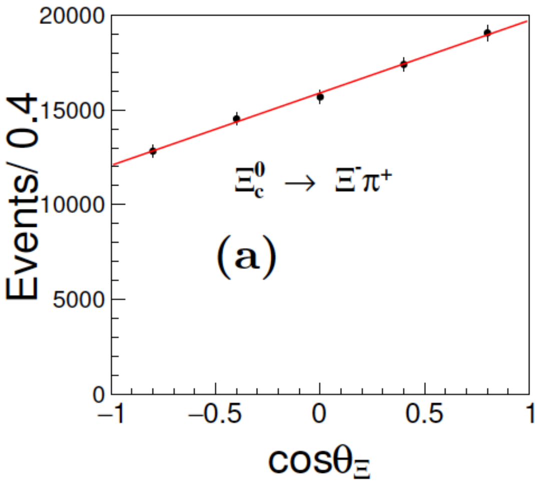
$\mathcal{A}_{cp}$ of $\Xi_c^0 \to \Xi^- \pi^+$: search for CP violation in charmed baryons section

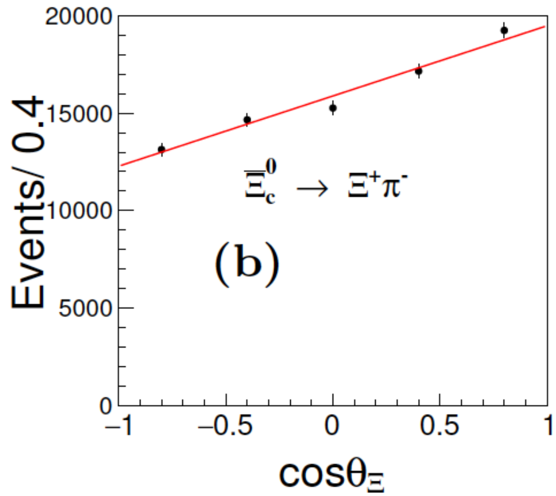
$$\frac{dN}{d\cos\theta_\Xi} \propto 1 + \alpha_{\Xi^-\pi^+}\alpha_{\Xi^-}\cos\theta_\Xi$$

θ_Ξ: angle between the $\vec{p}_\Lambda$ and $-\vec{p}_{\Xi_c^0}$ in the Ξ^- rest frame

$$\mathcal{A}_{CP} = (\alpha_{\Xi^-\pi^+} + \alpha_{\bar{\Xi}^+\pi^-})/(\alpha_{\Xi^-\pi^+} - \alpha_{\bar{\Xi}^+\pi^-})$$







$$\alpha_{\Xi^-\pi^+} = -0.60 \pm 0.045$$
$$\alpha_{\Xi^+\pi^-} = 0.58 \pm 0.045$$
$$\mathcal{A}_{cp} = 0.015 \pm 0.056$$

Previous: -0.60 ± 0.4