Λ_c Physics at BESIII

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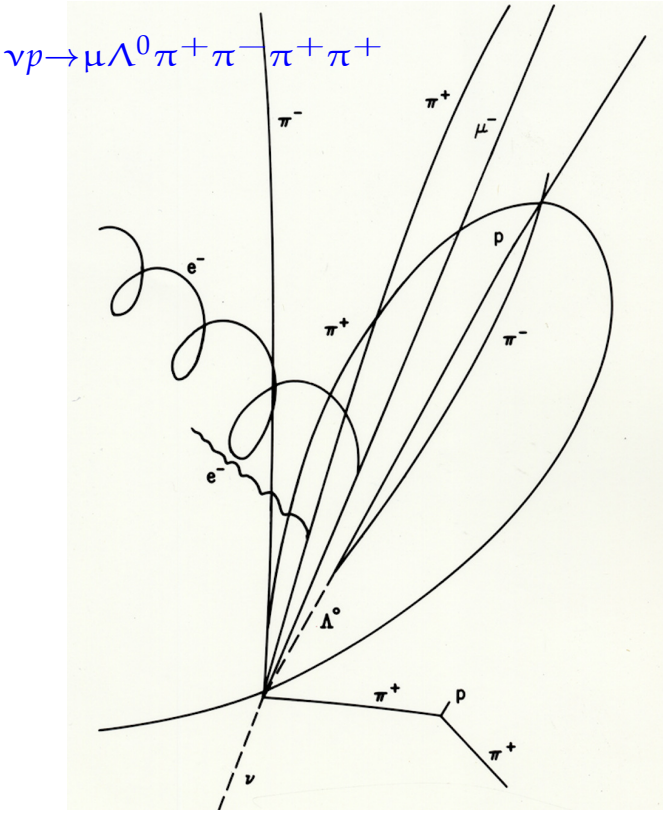
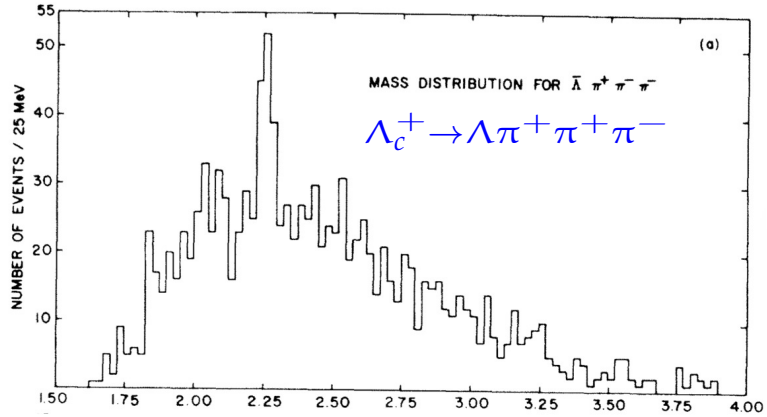
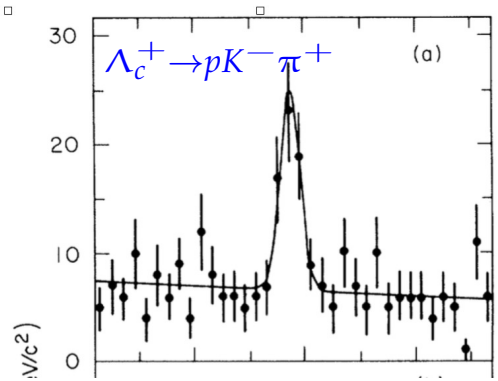
Outline

- Introduction
- The production of Λ_c
- Hadronic decays
- Semi-leptonic decays
- Inclusive decay
- Summary

The discovery of Λ_c^+





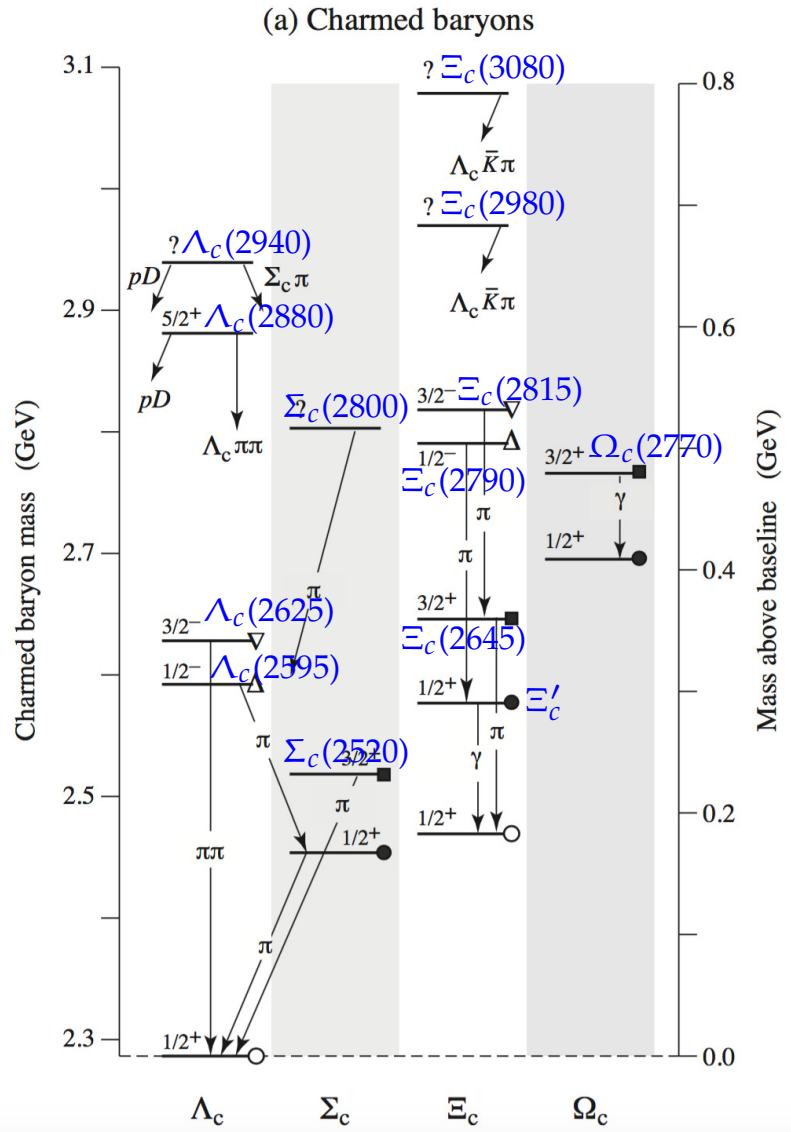


- First hint of charmed baryon $\Sigma_c^{++} \to \Lambda_c^+ \pi^+$ at BNL in 1975. PRL 34, 1125 (1975)
- The Λ_c^+ is firstly evidenced at Fermi Lab in 1976. PRL 37, 882 (1975)
- MarkII firstly established Λ_c^+ in 1980. PRL 44, 10 (1980)

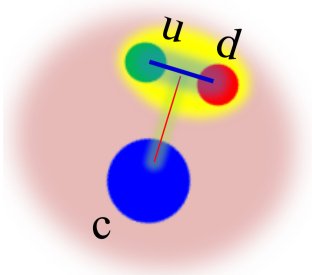
Charmed Baryon family

- Singly Charmed Baryons:
  - ground states:
    Λ_c^+, Σ_c, $\Xi_c^{(\prime)}$, Ω_c.
  - excited states
- No observation of doubly or triply charmed baryons

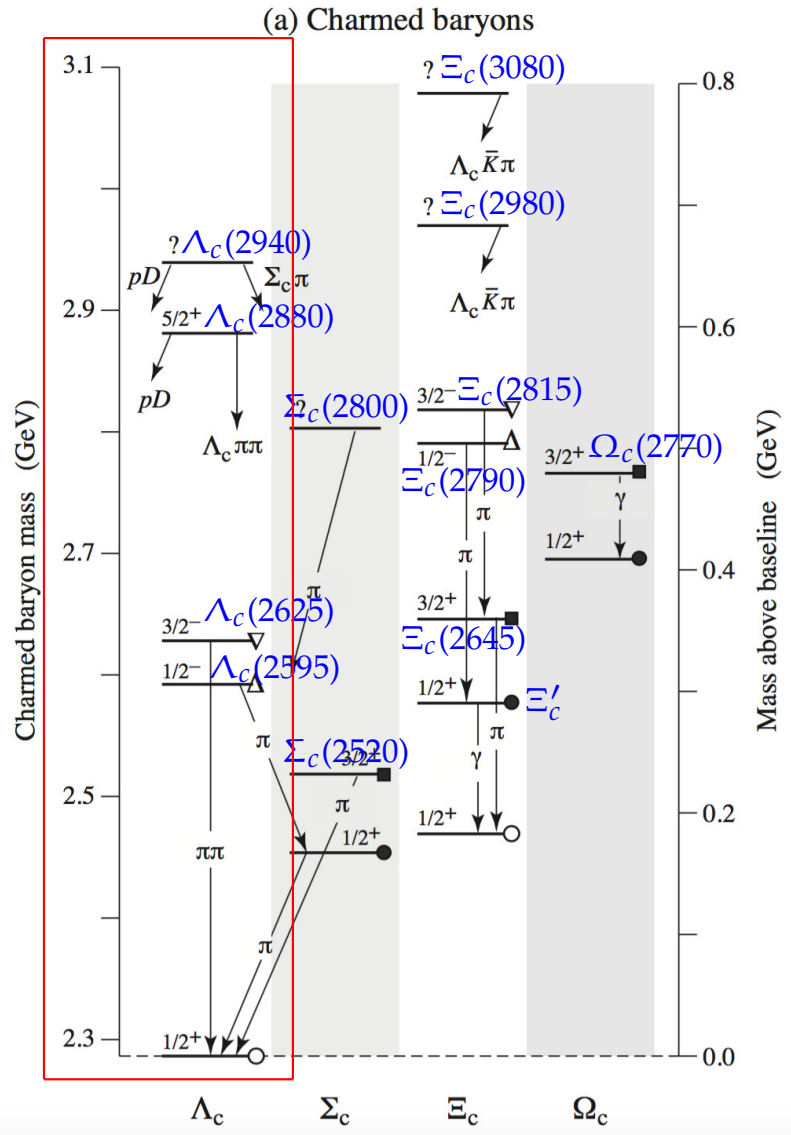
- Λ_c^+: decays only weakly
- Σ_c: B($\Sigma_c \to \Lambda_c^+ \pi$) ~100%
- Ξ_c: decays only weakly; no absolute BF measured, most are ratios relative to $\Xi^-\pi^+(\pi^+)$
- Ω_c: decays only weakly; no absolute BF measured

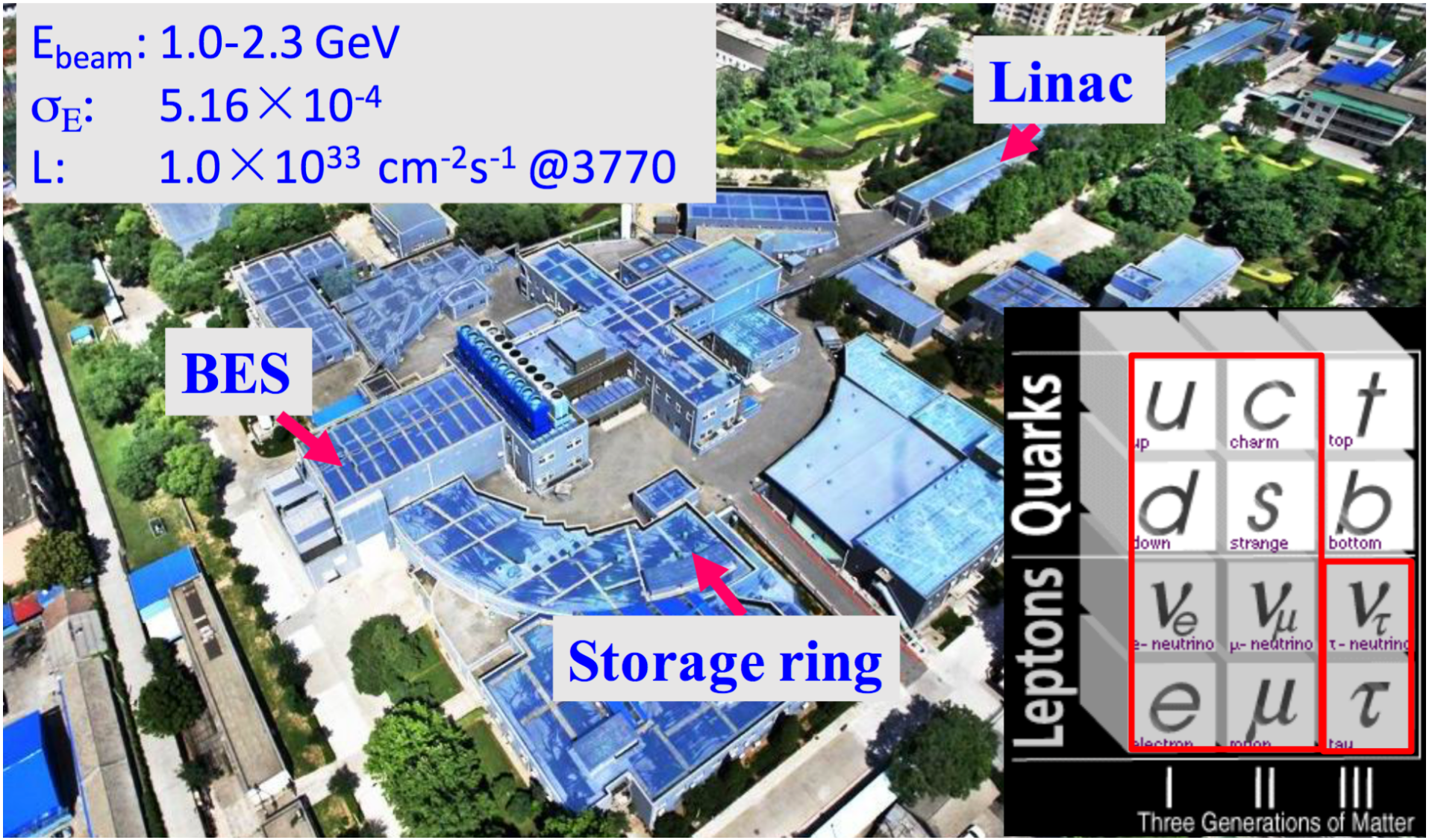


Λ_c^+: cornerstone of charmed baryon spectroscopy



- Quark component: a heavy quark (c) with an unexcited spin-zero di-quark (ud)
- The lightest charmed baryon: $m_{\Lambda_c} = 2286.48$ MeV
- Most of the charmed baryon will eventually decay to Λ_c
- The Λ_c is one of the important tagging hadrons in c-quark counting in the productions at high energies.
- B($\Lambda_c^+ \to pK^-\pi^+$): dominant error for V_{ub} via Λ_b decay

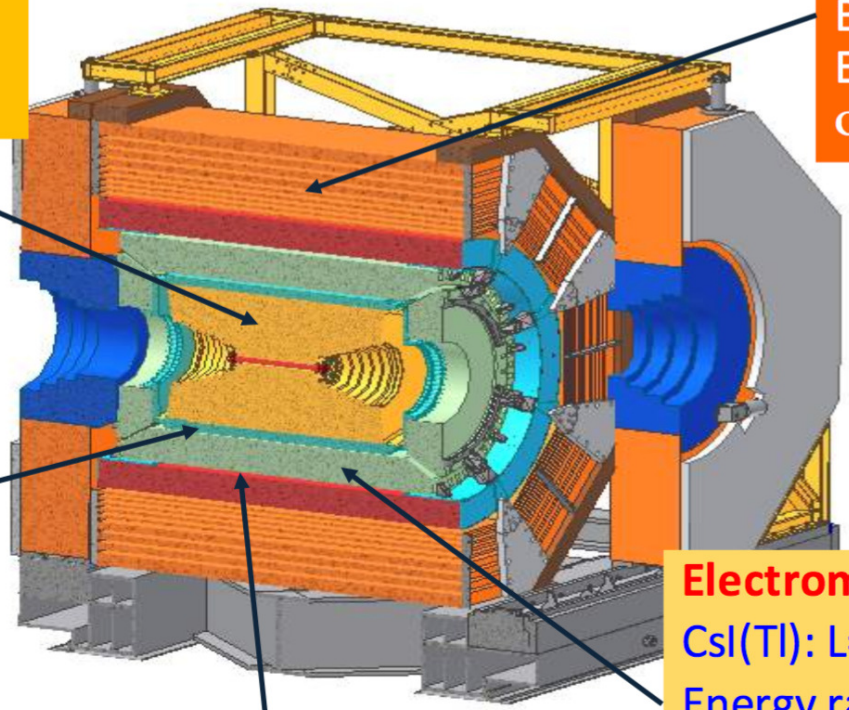




BEPC = Beijing Electron Positron Collider

Main Drift Chamber
Small cell, 43 layer
σ_{xy}=130 μm, dE/dx~6%
σ_p/p = 0.5% at 1 GeV

Muon Counter
Resistive plate chamber
Barrel: 9 layers
Endcaps: 8 layers
$\sigma_{spatial}$: 1.48 cm



Time Of Flight
Plastic scintillator
σ_T(barrel): 80 ps
σ_T(endcap): 110 ps
70 ps with MRPC ETOF

SC Magnet 1.0T

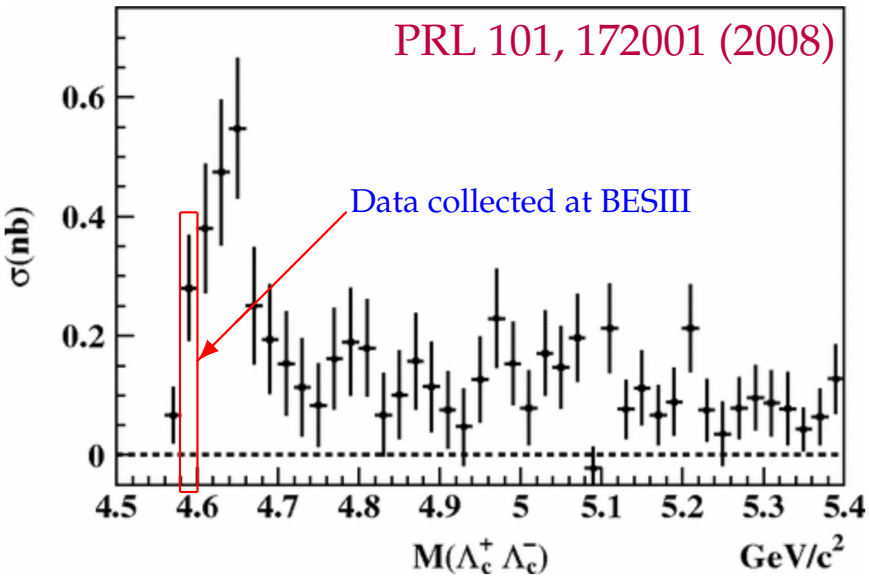
Electromagnetic Calorimeter
CsI(Tl): L=28 cm (15X_0)
Energy range: 0.02-2GeV
Barrel σ_E 2.5%, σ_l 6mm
Endcap σ_E 5.0%, σ_l 9mm

BESIII = Beijing Spectrometer III

Data sets of Λ_c^+ at BESIII

Data sample:

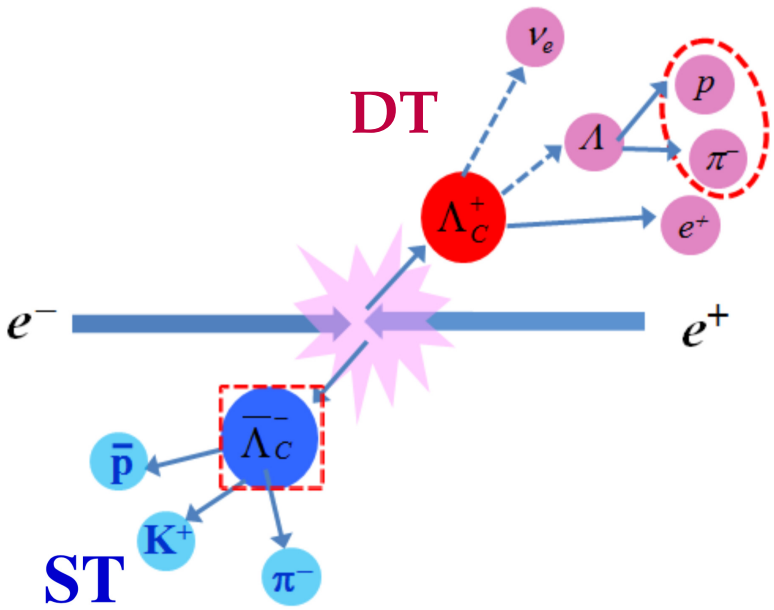
$\sqrt{s}$ (GeV)	$\mathcal{L}_{int}$ (pb^{-1})
4.5745	47.67
4.580	8.545
4.590	8.162
4.5995	566.9



- At $\sqrt{s} = 4.5995$ GeV, the hadronic, semi-leptonic and inclusive decays of Λ_c^+ can be measured directly
- The samples make precise measurement of the Born cross section line-shape of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ near threshold possible
- At $\sqrt{s} = 4.5745$ and 4.5995 GeV, the polar angular distribution of Λ_c can be studied and the $|G_E|/|G_M|$ ratios can be extracted

These samples enable systematical study of the Λ_c^+ for the first time

Single Tag (ST) and Double Tag (DT) method



- Single Tag:
  - $\Delta E = E - E_{\text{beam}}$
  - $M_{BC}c^2 = \sqrt{E_{\text{beam}}^2 - |\overrightarrow{p}|^2}$
- Double Tag:
  - $U_{\text{miss}} = E_{\text{miss}} - c|\overrightarrow{p}_{\text{miss}}|$
- Branching Fraction (BF):
  - $\mathcal{B}_i = \frac{N_{ij}^{DT}}{N_j^{ST}} \frac{\varepsilon_j}{\varepsilon_{ij}}$

- Only two body process near threshold and clean background
- Many systematics canceled in directly measurement of BF
- Neutron and neutrino can be traced with missing mass technique

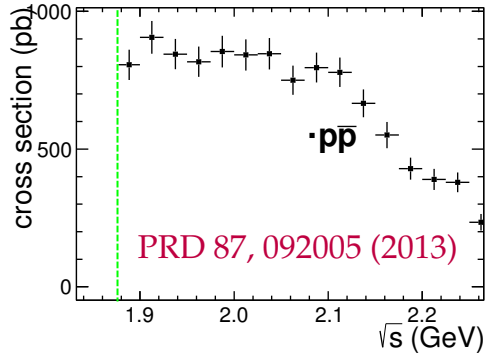
The production of Λ_c^+

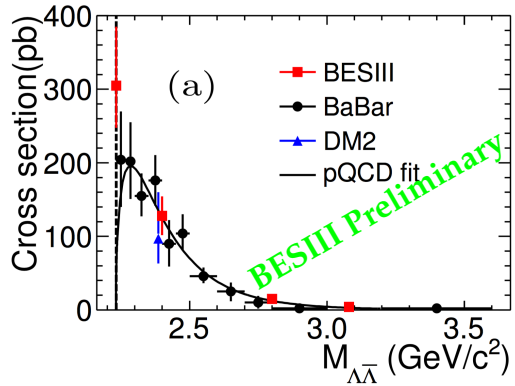
The Born cross section of the reaction $e^+e^- \to \gamma^* \to B\bar{B}$ can be parameterized in terms of electromagnetic form factors:

$$\sigma_{B\bar{B}}(q) = \frac{4\pi\alpha^2 C\beta}{3q^2}[|G_M(q)|^2 + \frac{1}{2\tau}|G_E(q)|^2]$$

- Baryon velocity $\beta = \sqrt{1 - 4m_B^2c^4/q^2}$, $\tau = q^2/(4m_B^2c^4)$
- For charged B, the Coulomb factor C will results in a non-zero cross section at threshold

- $e^+e^- \to p\bar{p}$: an enhancement and wide-range plateau in the line-shape
- $e^+e^- \to \Lambda\bar{\Lambda}$: non-zero cross section near threshold
- It can be anticipate that Λ_c^+ has a similar behaviour with proton
- Belle collaboration has measured the cross section of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ using ISR technique PRL 101, 172001 (2008)

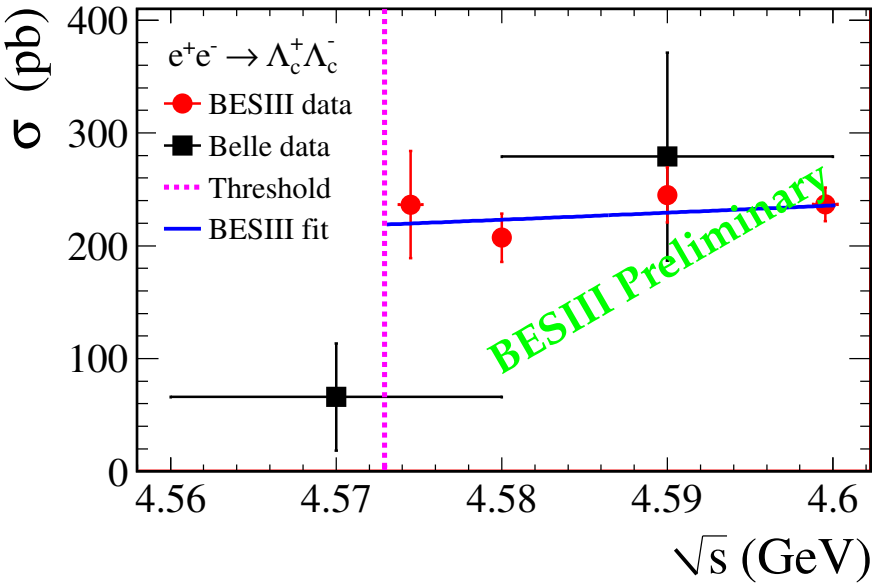




Cross section of $e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^-$ near threshold

BESIII preliminary results:

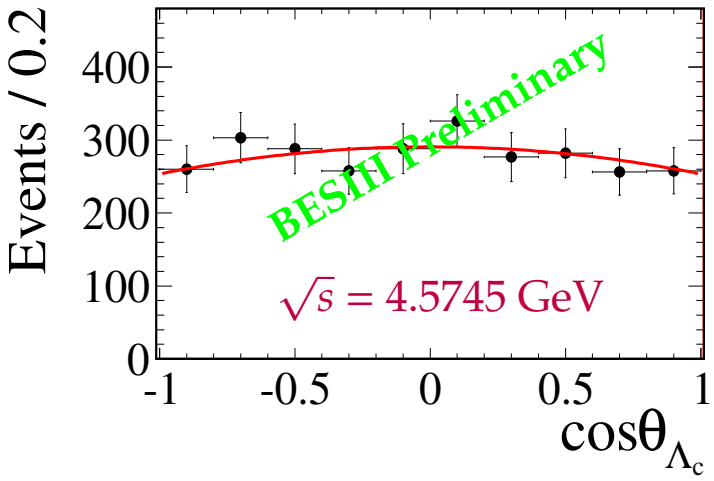
$\sqrt{s}$ (GeV)	σ (pb)
4.5745	$236 \pm 11 \pm 46$
4.580	$207 \pm 17 \pm 13$
4.590	$245 \pm 19 \pm 16$
4.5995	$237 \pm 3 \pm 15$

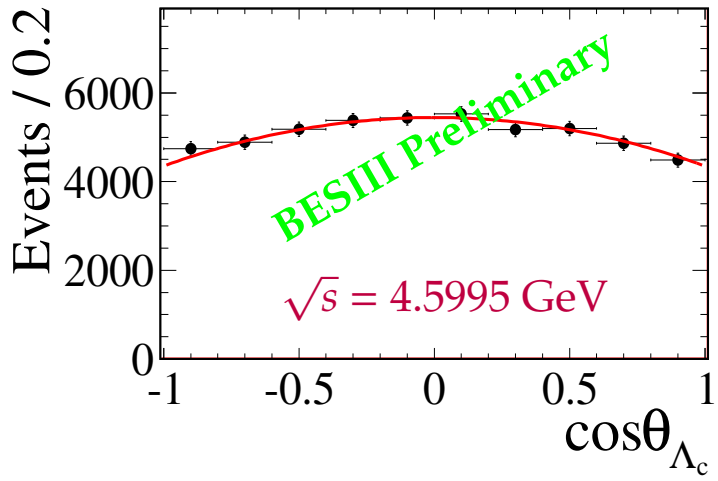


- 10 hadronic decays of Λ_c are employed
- Single Tag method (ΔE & M_{BC}) is used
- Λ_c^+ and $\bar{\Lambda}_c^-$ are reconstructed independently
- Total cross sections are obtained from weighted average

- **The cross sections are measured with unprecedented precision**
- **Enhanced cross section of reaction $e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^-$ near threshold is discerned for the first time**
- **The Coulomb enhanced factor?**

Scattering angular distribution of Λ_c





- Studied at 4.5745 and 4.5995 GeV only
- The bin-by-bin efficiency correction is applied on the total yields
- Combined the corrected yields from Λ_c^+ and $\bar{\Lambda}_c^-$ bins
- The χ^2 fit on the angular distribution with shape $1 + \alpha_{\Lambda_c} \cos^2\theta$

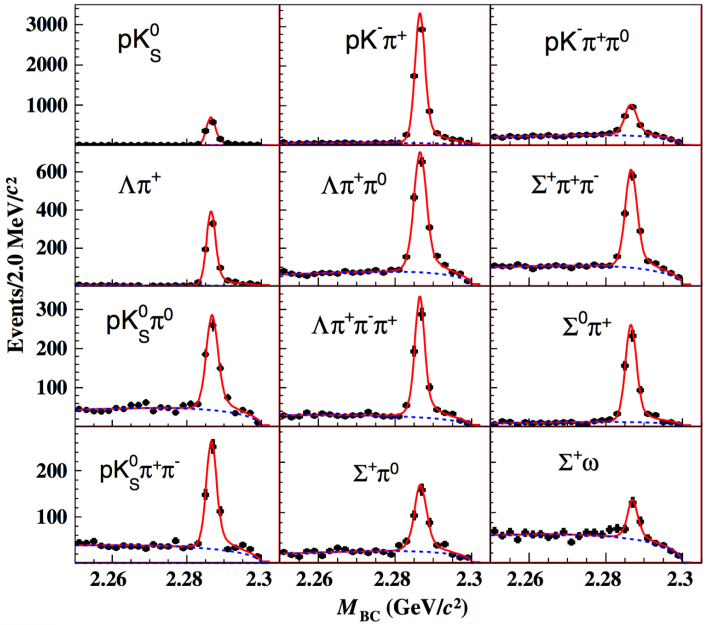
BESIII preliminary results:

$\sqrt{s}$ (MeV)	α_{Λ_c}	$\lvert G_E/G_M \rvert$
4.5745	$-0.13 \pm 0.12 \pm 0.08$	$1.14 \pm 0.14 \pm 0.07$
4.5995	$-0.20 \pm 0.04 \pm 0.02$	$1.23 \pm 0.05 \pm 0.03$

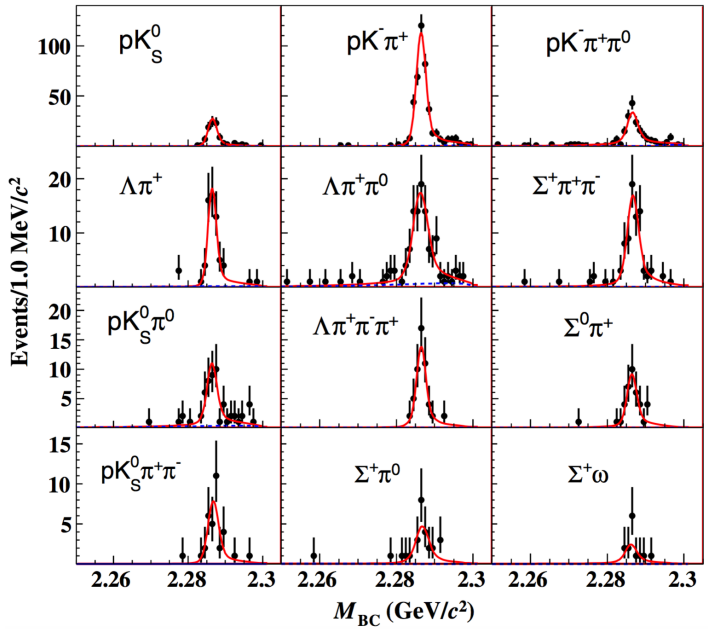
- **This is the first time that the $\lvert G_E/G_M \rvert$ ratios of Λ_c are measured near threshold**

BF of Cabibbo-Favored Hadronic decays of Λ_c

ST events:



DT events:



PRL 116, 052001 (2016)

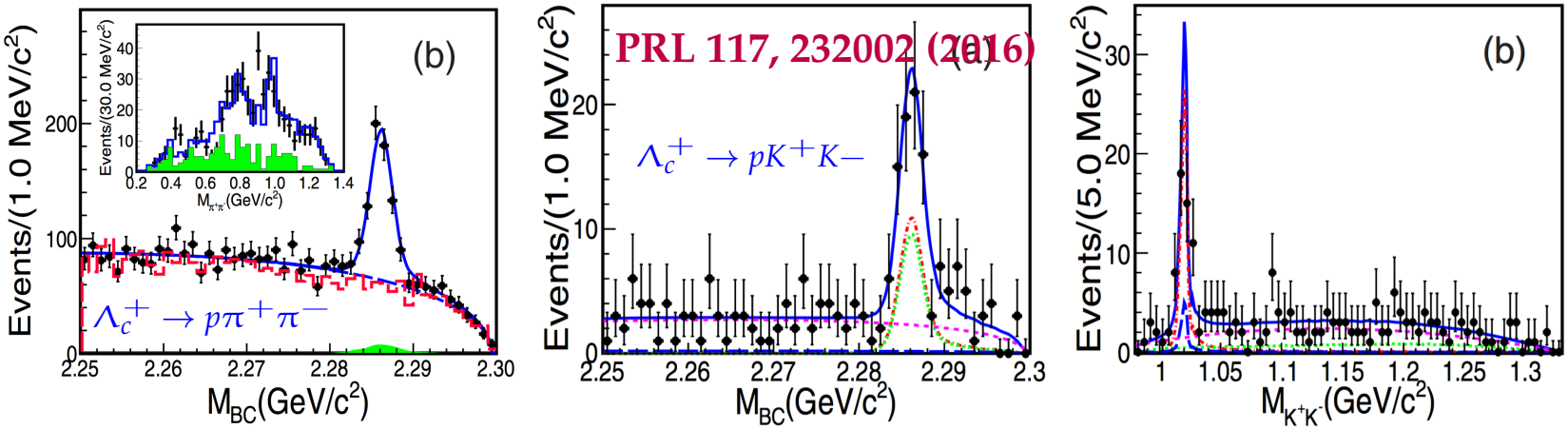
- $N_j^{ST} = N_{Tot.} \mathcal{B}_j \varepsilon_j$
- $N_{ij}^{DT} = N_{Tot.} \mathcal{B}_i \mathcal{B}_j \varepsilon_{ij}$
- $\mathcal{B}_i = \frac{N_{ij}^{DT}}{N_j^{ST}} \frac{\varepsilon_j}{\varepsilon_{ij}}$

Mode	This work (%)	PDG (%)
pK_S^0	$1.52 \pm 0.08 \pm 0.03$	1.15 ± 0.30
$pK^-\pi^+$	$5.84 \pm 0.27 \pm 0.23$	5.0 ± 1.3
$pK_S^0\pi^0$	$1.87 \pm 0.13 \pm 0.05$	1.65 ± 0.50
$pK_S^0\pi^+\pi^-$	$1.53 \pm 0.11 \pm 0.09$	1.30 ± 0.35
$pK^-\pi^+\pi^0$	$4.53 \pm 0.23 \pm 0.30$	3.4 ± 1.0
$\Lambda\pi^+$	$1.24 \pm 0.07 \pm 0.03$	1.07 ± 0.28
$\Lambda\pi^+\pi^0$	$7.01 \pm 0.37 \pm 0.19$	3.6 ± 1.3
$\Lambda\pi^+\pi^-\pi^+$	$3.81 \pm 0.24 \pm 0.18$	2.6 ± 0.7
$\Sigma^0\pi^+$	$1.27 \pm 0.08 \pm 0.03$	1.05 ± 0.28
$\Sigma^+\pi^0$	$1.18 \pm 0.10 \pm 0.03$	1.00 ± 0.34
$\Sigma^+\pi^+\pi^-$	$4.25 \pm 0.24 \pm 0.20$	3.6 ± 1.0
$\Sigma^+\omega$	$1.56 \pm 0.20 \pm 0.07$	2.7 ± 1.0

- **The first direct measurement of the Λ_c^+ near the threshold**
- BF of $pK^-\pi^+$ is consistent with the measurement of Belle
- Precisions of the other 11 modes improved significantly

$\Lambda_c^+ \to pK^+K^-$ and $\Lambda_c^+ \to p\pi^+\pi^-$

- Sensitive to nonfactorizable contributions from W-exchange diagrams
- $\Lambda_c^+ \to p\phi$ is particular interest due to only internal W-emission diagrams



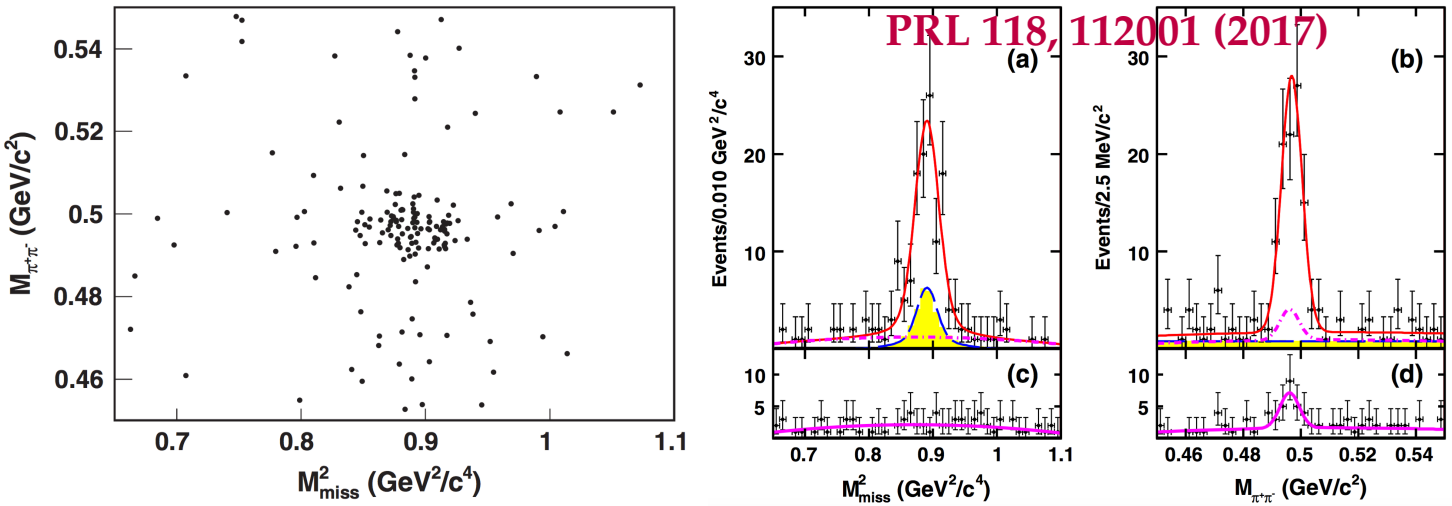
Decay modes	$\mathcal{B}_{\rm mode}/\mathcal{B}_{\rm ref}$ (This work)	$\mathcal{B}_{\rm mode}/\mathcal{B}_{\rm ref}$ (PDG average)
$\Lambda_c^+ \to p\pi^+\pi^-$	$(6.70 \pm 0.48 \pm 0.25) \times 10^{-2}$	$(6.9 \pm 3.6) \times 10^{-2}$
$\Lambda_c^+ \to p\phi$	$(1.81 \pm 0.33 \pm 0.13) \times 10^{-2}$	$(1.64 \pm 0.32) \times 10^{-2}$
$\Lambda_c^+ \to pK^+K^-$ (non-ϕ)	$(9.36 \pm 2.22 \pm 0.71) \times 10^{-3}$	$(7 \pm 2 \pm 2) \times 10^{-3}$
–	$\mathcal{B}_{\rm mode}$ (This work)	$\mathcal{B}_{\rm mode}$ (PDG average)
$\Lambda_c^+ \to p\pi^+\pi^-$	$(3.91 \pm 0.28 \pm 0.15 \pm 0.24) \times 10^{-3}$	$(3.5 \pm 2.0) \times 10^{-3}$
$\Lambda_c^+ \to p\phi$	$(1.06 \pm 0.19 \pm 0.08 \pm 0.06) \times 10^{-3}$	$(8.2 \pm 2.7) \times 10^{-4}$
$\Lambda_c^+ \to pK^+K^-$ (non-ϕ)	$(5.47 \pm 1.30 \pm 0.41 \pm 0.33) \times 10^{-4}$	$(3.5 \pm 1.7) \times 10^{-4}$

- Single tag method is used
- Using the decay $pK^-\pi^+$ as the reference mode

First observation of the SCS decays of $\Lambda_c^+ \to p\pi^+\pi^-$
Improved precision of decays $\Lambda_c^+ \to pK^+K^-$(non-ϕ) and $\Lambda_c^+ \to p\phi$

$\Lambda_c^+ \to n K_S^0 \pi^+$

- A precision test for the isospin symmetry and final states interaction
- DT method: $M^2_{miss} \equiv E^2_{miss}/c^4 - |\vec{p}_{miss}|^2/c^2$

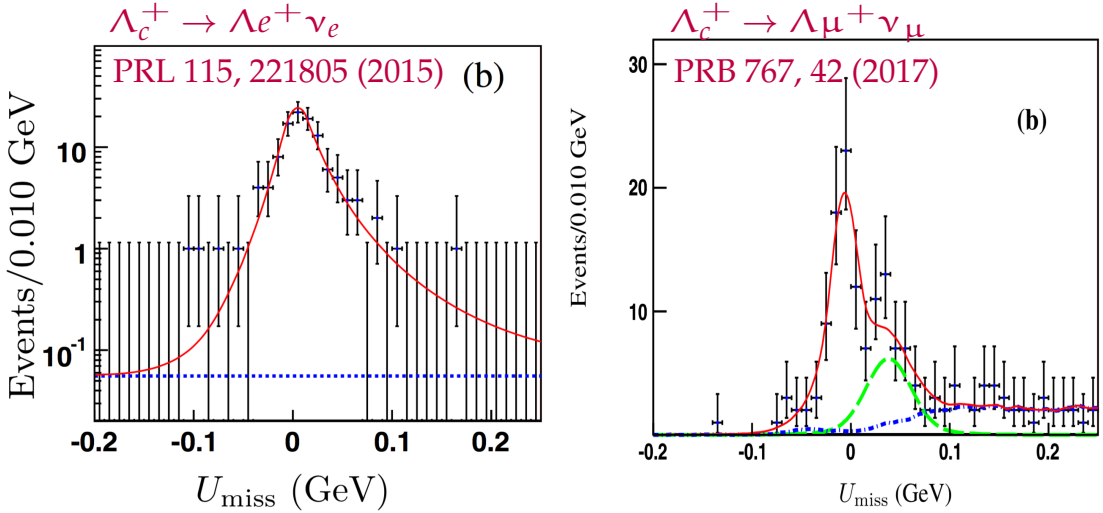


- $\mathcal{B}(\Lambda_c^+ \to n K_S^0 \pi^+) = (1.82 \pm 0.23 \pm 0.11)\%$
- $\mathcal{B}(\Lambda_c^+ \to n \bar{K}^0 \pi^+)/\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+) = 0.62 \pm 0.09$
- $\mathcal{B}(\Lambda_c^+ \to n \bar{K}^0 \pi^+)/\mathcal{B}(\Lambda_c^+ \to p \bar{K}^0 \pi^0) = 0.97 \pm 0.16$

The first direct measurement of the Λ_c^+ decay involving the neutron in the final state

$\Lambda_c^+ \to \Lambda e^+ \nu_e$ and $\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu$

- A stringent test for nonperturbative aspects of strong interaction theory
- The key ingredient in calibrating Lattice QCD calculations
- There is no absolute measurement of Λ_c^+ semi-leptonic decay yet
- Mutually confirm and test the leptonic university



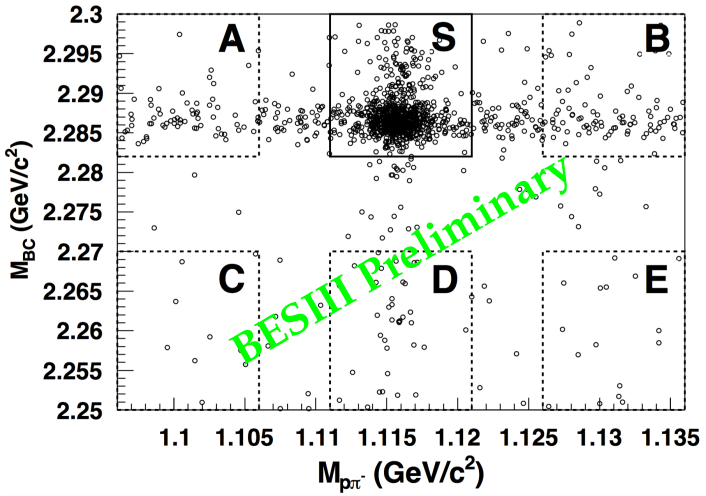
- DT method is used, 11 modes are tagged
- missing mass technique at threshold
- $U_{\rm miss} = E_{\rm miss} - c|\overrightarrow{p}_{\rm miss}|$

- $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.63 \pm 0.38 \pm 0.20)\%$
- $\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu) = (3.49 \pm 0.46 \pm 0.27)\%$
- $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)/\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu) = 0.96 \pm 0.16 \pm 0.04$

The first direct measurement of the semi-leptonic decay of Λ_c^+

$\Lambda_c^+ \to \Lambda + X$

- This decay is mediated by $c \to s$ and dominates the lifetime of Λ_c^+
- Help to understand the quark structure and decay dynamics of Λ_c^+
- Provide an essential input for decays of b-flavored hadrons



- DT method is used, modes $\bar{p}K^+\pi^-$ and $\bar{p}K_S^0$ are singly tagged.
- $\mathcal{A}_{cp} \equiv \frac{\mathcal{B}(\Lambda_c^+ \to \Lambda + X) - \mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X)}{\mathcal{B}(\Lambda_c^+ \to \Lambda + X) - \mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X)}$

The preliminary results:

$$\mathcal{B}(\Lambda_c^+ \to \Lambda + X) = (38.2^{+2.8}_{-2.2} \pm 0.6)\% \text{ and } \mathcal{A}_{cp} = (2.1^{+7.0}_{-6.6} \pm 1.1)\%$$

- Total known exclusive BFs of $\Lambda_c^+ \to \Lambda + X$ is $(24.5 \pm 2.1)\%$. This indicates many unknown decay modes
- No CP violation is observed in current precision

Summary

- Based on the large data sample collected near threshold, BESIII can systematically study the physics of Λ_c^+
- The production behaviour of Λ_c^+ is studied from Born cross section and scattering angle distribution
- Absolute BFs of Λ_c^+ are measured directly at BESIII, including hadronic and semi-leptonic decays
- Fruitful results of Λ_c^+ decays are achieved at BESIII, which are important to understand the property of Λ_c^+

Thanks for your attention!