Λ_c physics at BESIII

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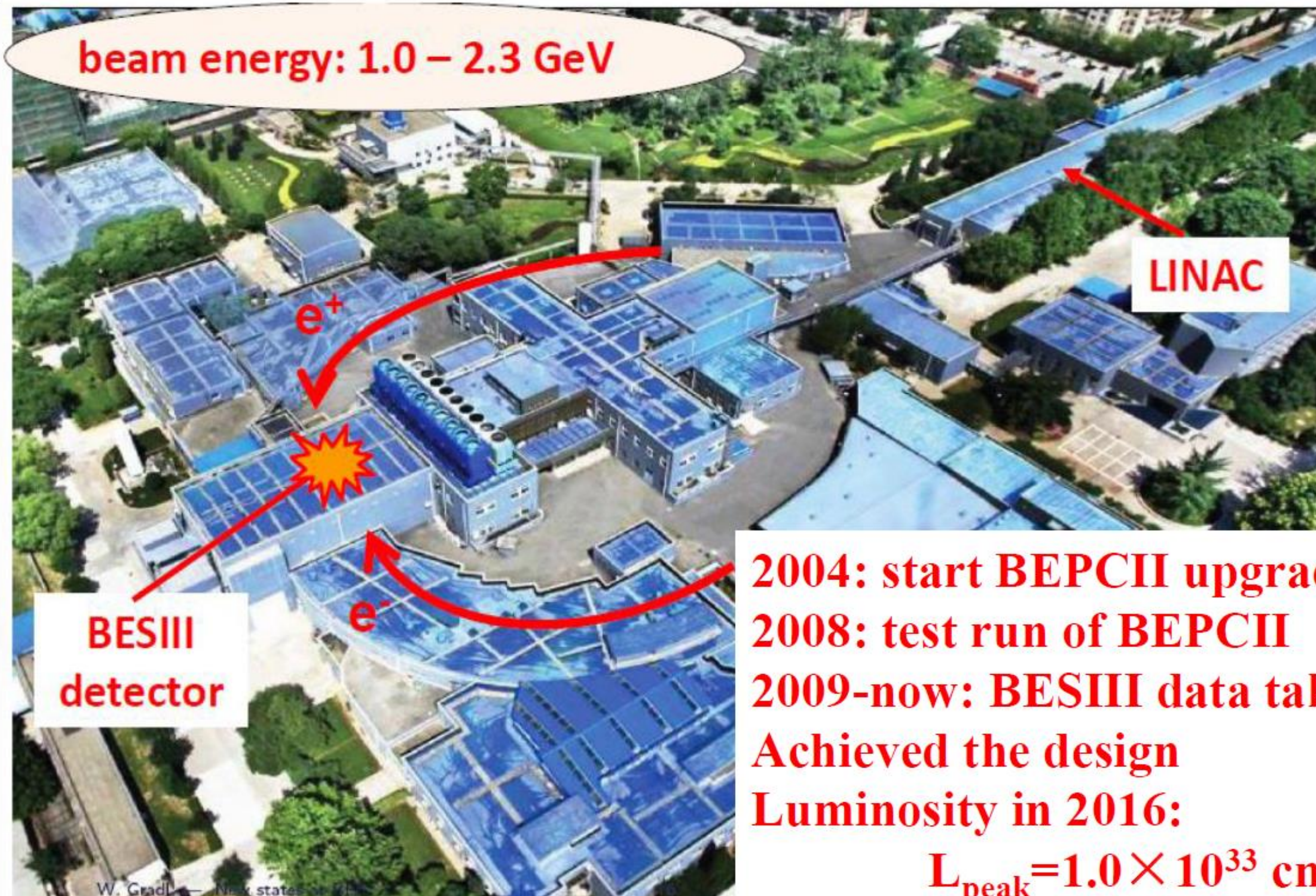
Hadron2017, Salamanca, Spain

Overview

- BEPCII and BESIII
- Physics of Λ_c
- BESIII Data Taken Near $\Lambda_c^+\bar{\Lambda}_c^-$ Threshold
- Analysis Method
  - Tagging Technique
  - ΔE and M_{BC}
- Λ_c Decays at BESIII
  - Λ_c hadronic decays
  - Λ_c semi-leptonic decays

Summary

Beijing Electron and Positron Collider(BEPCII)



2004: start BEPCII upgrade

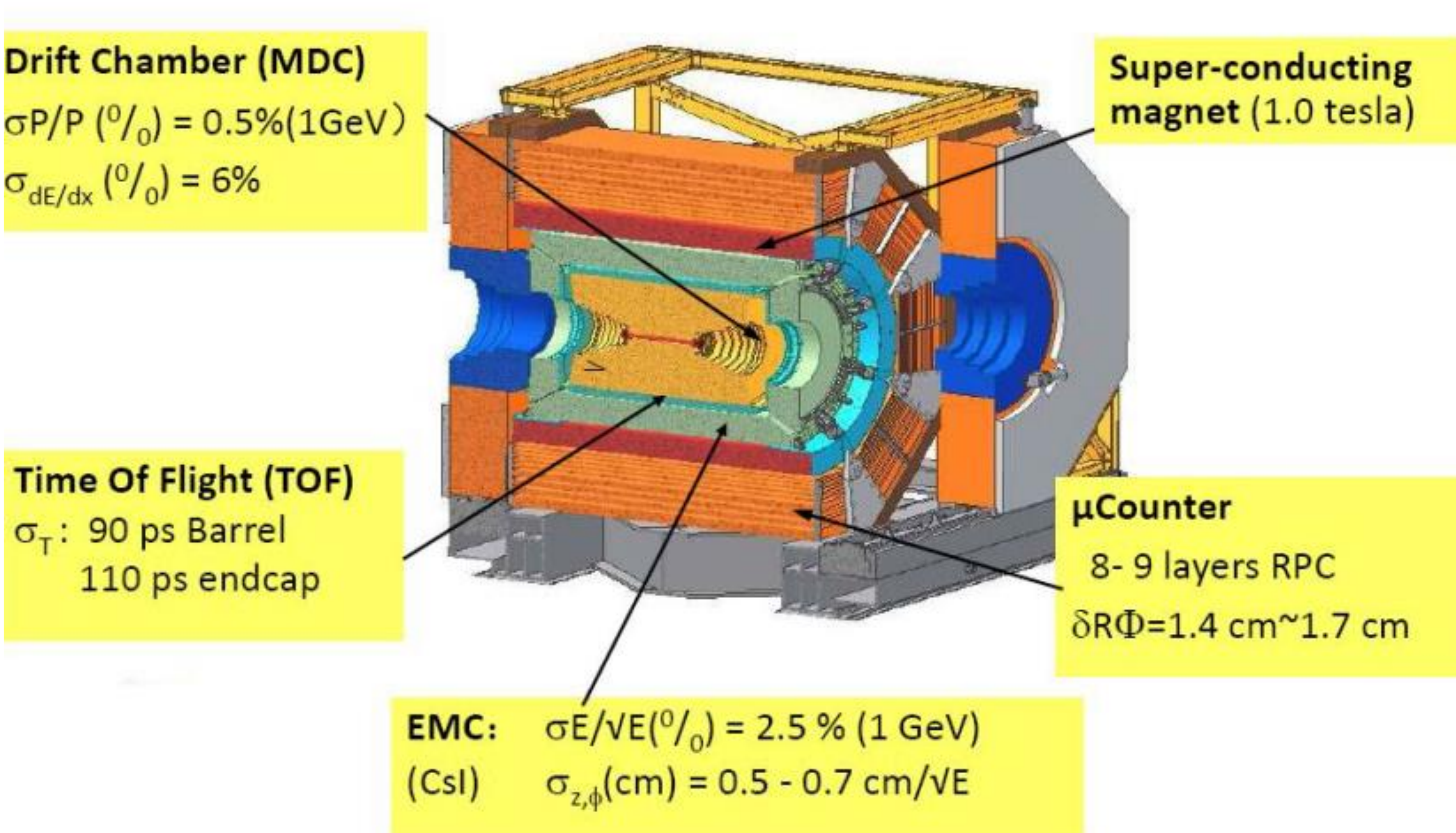
2008: test run of BEPCII

2009-now: BESIII data taking

Achieved the design Luminosity in 2016:

$$L_{peak}=1.0\times 10^{33}\ cm^{-2}s^{-1}$$

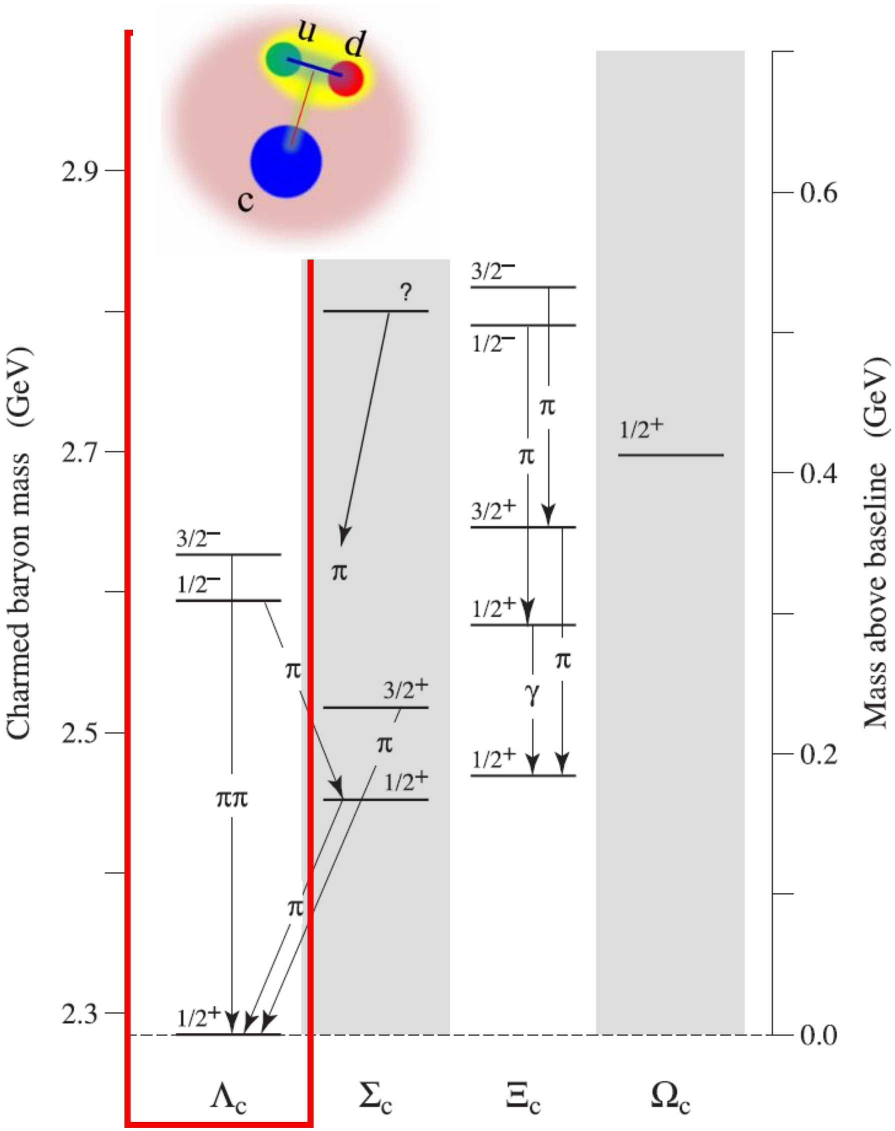
BESIII detector



The new BESIII detector is hermetic for neutral and charged particle with excellent resolution, PID and large coverage.

Physics of Λ_c

- The lightest and most common charmed baryon,
  → most of the charmed baryons will eventually decay into Λ_c.
  ☺ Important to know the decay properties of Λ_c.
- The golden mode, $\Lambda_c^+ \to pK^-\pi^+$, often used to normalize BFs.
  ☺ Very important to determine the absolute BF.
- Total known measured BF is ~ 60%.



BESIII Data Taken about Λ_c

- In 2014, BESIII collected Λ_c data with excellent performance near the pair-production threshold.

Energy (GeV)	Luminosity (pb^{-1})
4.5745	47.67
4.5800	8.545
4.5900	8.162
4.5995	566.9

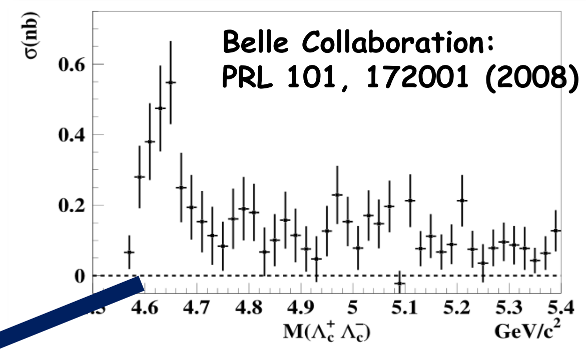


FIG. 4: The cross section for the exclusive process $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$.

Presented results use this sample

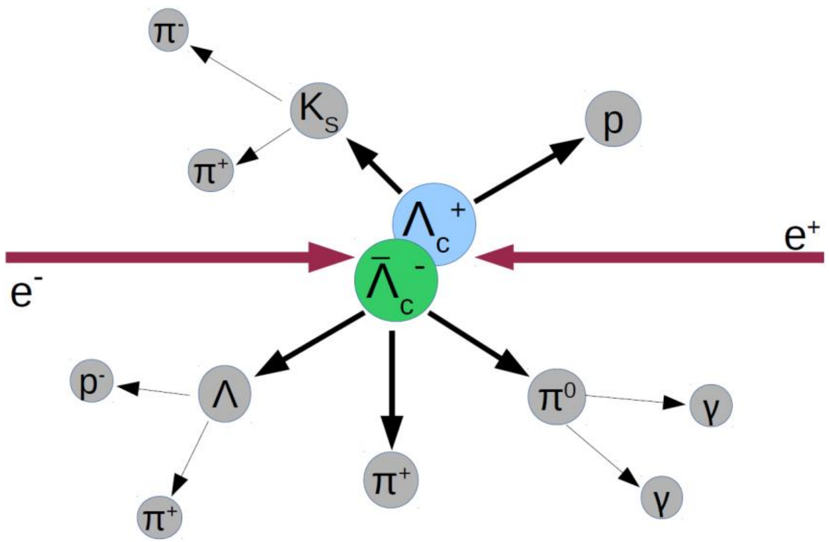
- Advantages of $\Lambda_c^+\bar{\Lambda}_c^-$ pair production near threshold:
  - Double Tag technique: access to absolute BFs and dynamics
  - With clean background
  - Most systematic uncertainties in tag side can be cancelled

Charm Production @ Mass Threshold

- Around E_{cm} ~ 4.6 GeV,

  Pair production:

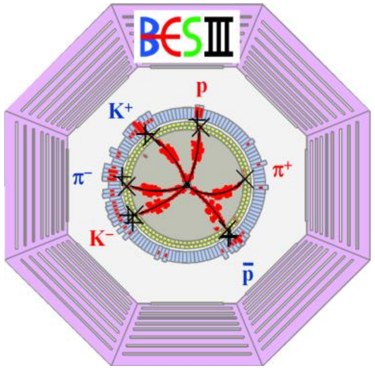
  $e^+e^- \rightarrow \gamma^* \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$



- Two ways to obtain the Λ_c yields:

  ✓ Single Tag (ST): Reconstruct only one of the Λ_c-pair.
  - ☺ Larger backgrounds
  - ☺ Higher efficiencies

  ✓ Double Tag (DT): Find both of them.
  - ☺ Smaller backgrounds
  - ☺ Lower efficiencies.



Analysis Method

- In ST studies frequently used variables:
  - ✓ Beam-Constrained Mass:

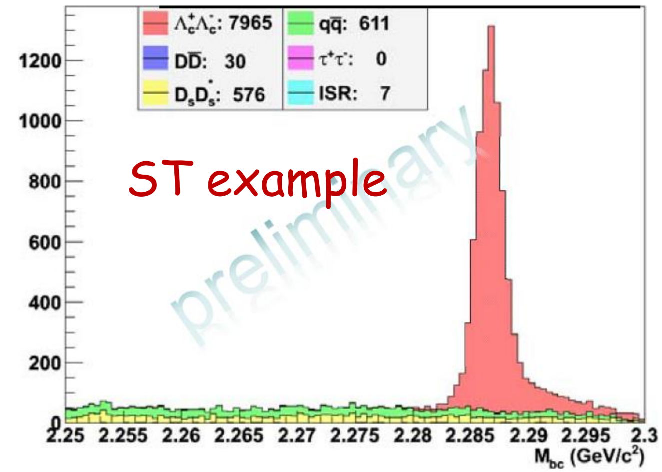
$$M_{\mathrm{BC}} = \sqrt{E_{\mathrm{beam}}^2/c^4 - p^2/c^2}$$

p is the reconstructed Λ_c 3-momentum

- Asymmetric shape due the ISR
- Resolution dominated by the energy spread of the beam (independently from the final states)

  - ✓ Energy Difference (ΔE)

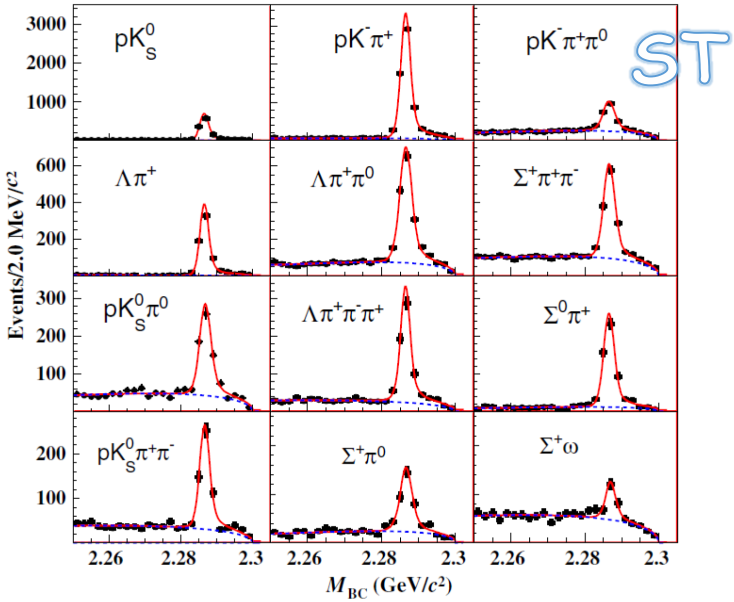
$$\Delta E = E - E_{\mathrm{beam}}$$

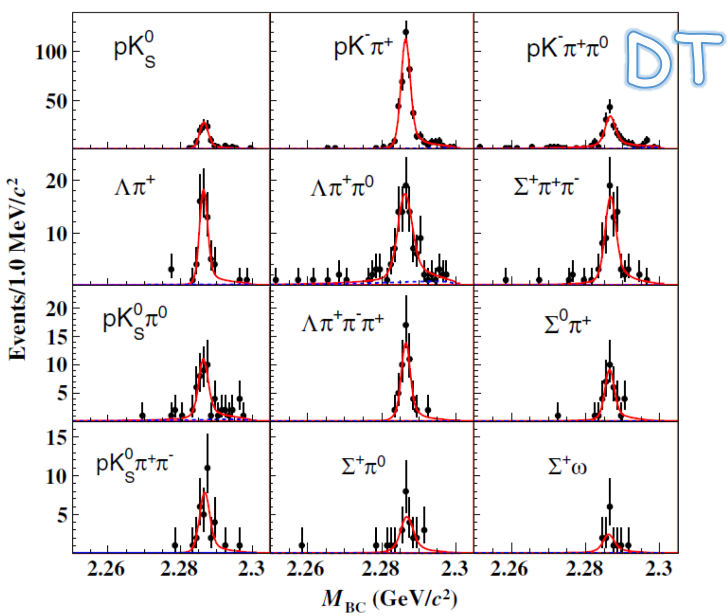


- In DT Studies:
  - ✓ U_{miss} (usually in semi-leptonic decay)

$$U_{\mathrm{miss}} = E_{\mathrm{miss}} - c|\vec{p}_{\mathrm{miss}}|$$

First direct measurement of Λ_c BF





$$N_j^{\mathrm{ST}} = N_{\Lambda_c^+\bar{\Lambda}_c^-}\mathcal{B}_j\varepsilon_j$$

$$N_{ij}^{\mathrm{DT}} = N_{\Lambda_c^+\bar{\Lambda}_c^-}\mathcal{B}_i\mathcal{B}_j\varepsilon_{ij}$$

- First **absolute BF measurement** of the Λ_c
- Very clean event environment!
- In the above DT case, summed over the 12 tag modes
- ***A least square global fit:*** Simultaneous fit to all the tag modes, while constraining the total $\Lambda_c^+\overline{\Lambda}_c^-$ pair number, taking into account the correlations.

First direct measurement of Λ_c BF

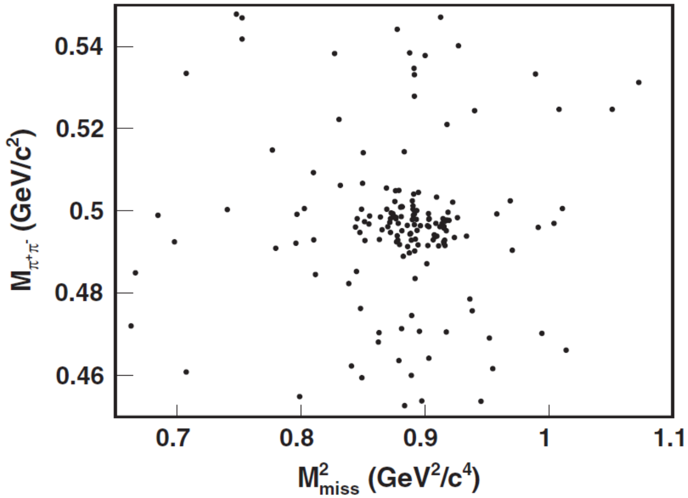
Mode	This work (%)	PDG (%)	BELLE $\mathcal{B}$
pK_S^0	$1.52 \pm 0.08 \pm 0.03$	1.15 ± 0.30	
$pK^-\pi^+$	$5.84 \pm 0.27 \pm 0.23$	5.0 ± 1.3	$6.84 \pm 0.24^{+0.21}_{-0.27}$
$pK_S^0\pi^0$	$1.87 \pm 0.13 \pm 0.05$	1.65 ± 0.50	
$pK_S^0\pi^+\pi^-$	$1.53 \pm 0.11 \pm 0.09$	1.30 ± 0.35	
$pK^-\pi^+\pi^0$	$4.53 \pm 0.23 \pm 0.30$	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	

PRL 116, 052001 (2016)

- BF for $pK^-\pi^+$ is consistent with PDG2014 within 2σ.
- The precision of absolute BFs of 12 modes are improved significantly.
- Also obtained $N_{\Lambda c\Lambda c} = (105.9 \pm 4.8 \pm 0.5) \times 10^3$

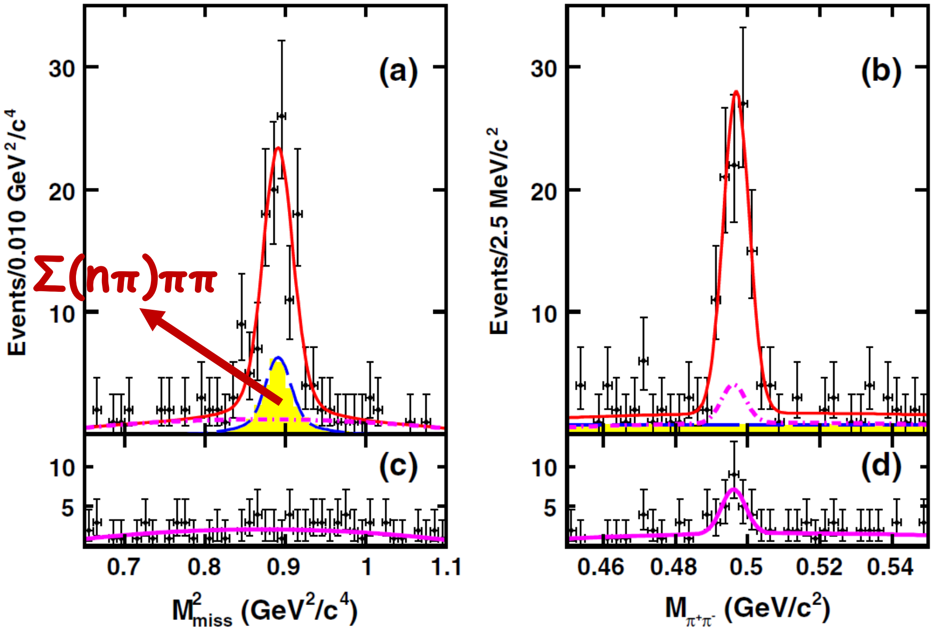
Observation of $\Lambda_c^+ \to nK_s\pi^+$

- First direct measurement in a final state involving a neutron
- Test if Isospin symmetry holds in charmed baryon decay (after it fails in charmed meson)



First Observation!

Simultaneous 2D fit



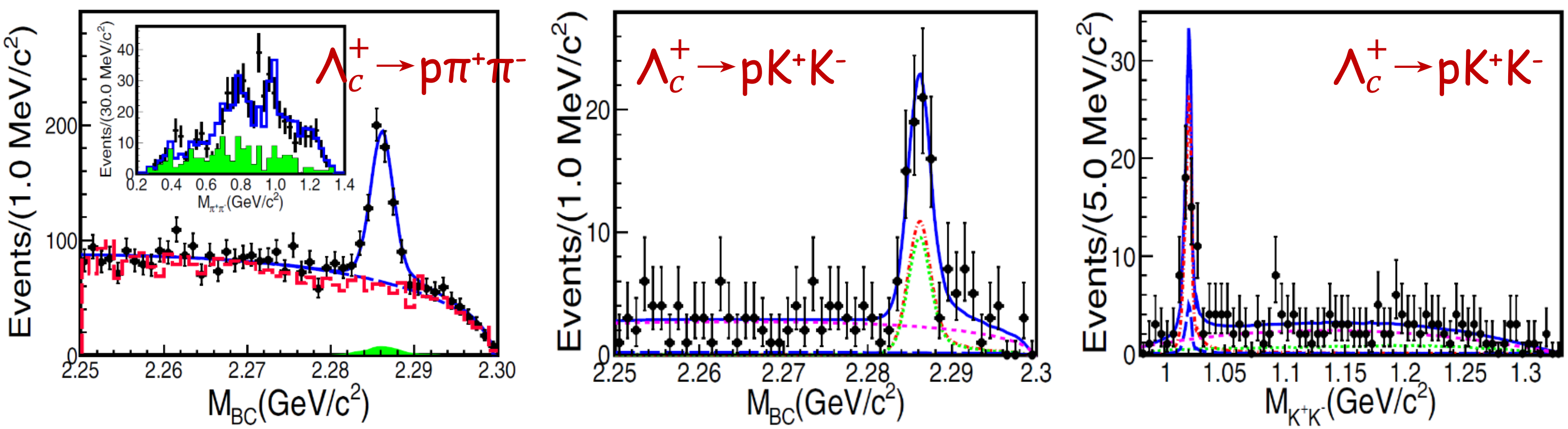
$$\mathcal{B}(\Lambda_c^+ \to nK_S^0\pi^+) = (1.82\pm0.23\pm0.11)\%$$

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

PRL 118, 112001 (2017)

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

- ST method relative BF w.r.t. the $pK\pi$ mode
- First observation of Singly Cabibbo Suppressed (SCS) decay $\Lambda_c^+ \to p\pi^+\pi^-$
- Improved measurements on the SCS decays, $\Lambda_c^+ \to p\Phi$ and $\Lambda_c^+ \to pK^+K^-{}_{\text{non-}\Phi}$

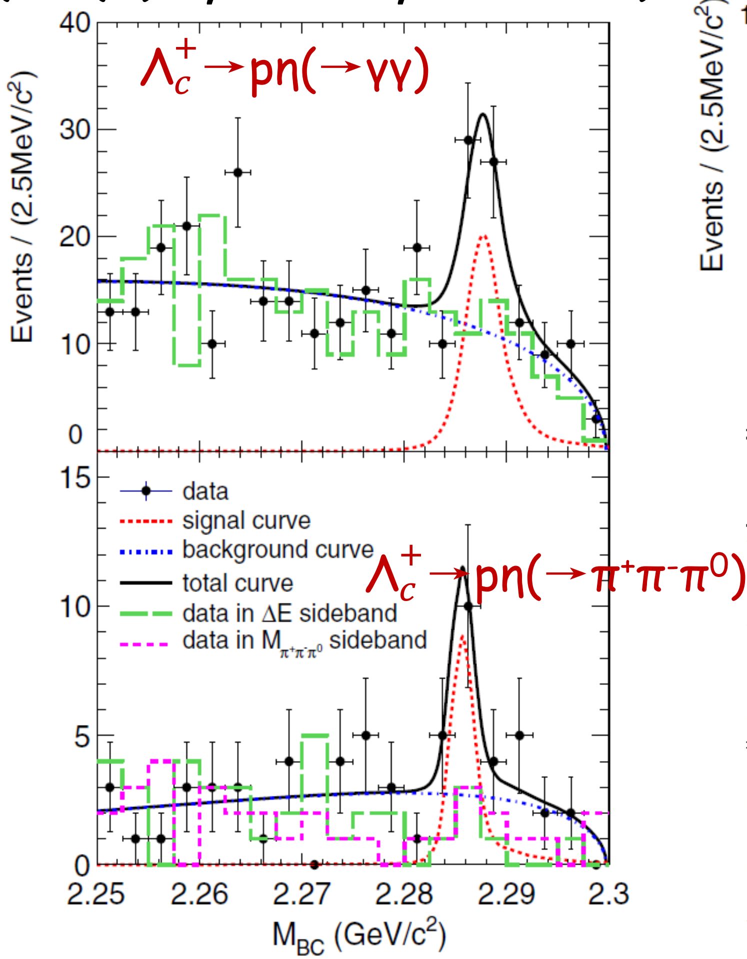


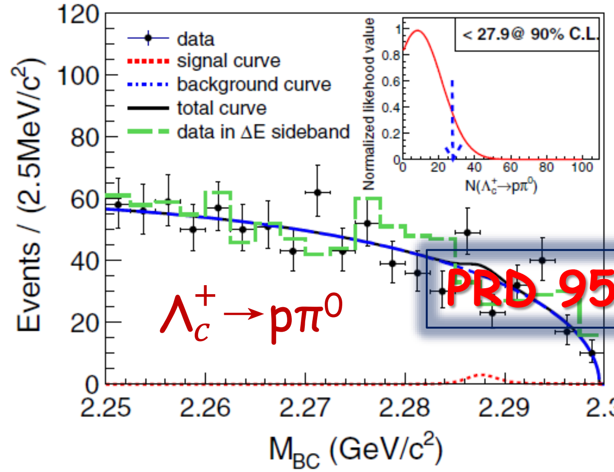
Decay modes	$\mathcal{B}_{\text{mode}}/\mathcal{B}_{\text{ref}}$ (This work)	$\mathcal{B}_{\text{mode}}/\mathcal{B}_{\text{ref}}$ (PDG average)
$\Lambda_c^+ \to p\pi^+\pi^-$	$(6.70 \pm 0.48 \pm 0.25) \times 10^{-2}$	$(6.9 \pm 3.6) \times 10^{-2}$
$\Lambda_c^+ \to p\phi$	$(1.81 \pm 0.33 \pm 0.13) \times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

PRL 117, 232002 (2016)

$\Lambda_c^+ \to p\eta$ and $p\pi^0$

- First evidence of the SCS decay, $\Lambda_c^+ \to p\eta$ (4.2σ stat. significance)
- No signals seen in $\Lambda_c^+ \to p\pi^0$
- Predicted BFs vary under different theoretical models (SU(3) symmetry and FSI)





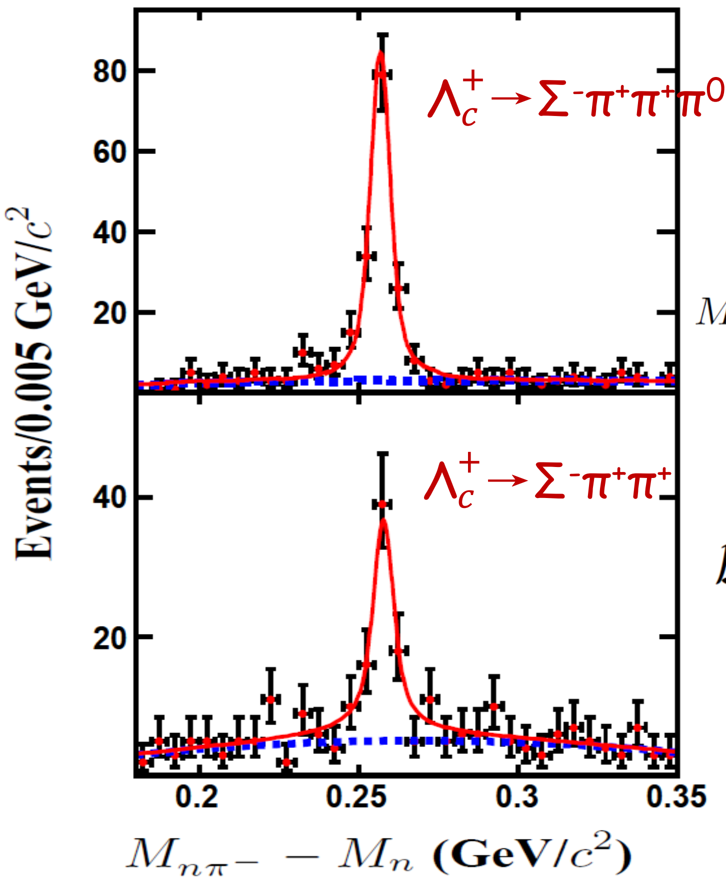
PRD 95, 111102(R) (2017)

	$\Lambda_c^+ \to p\eta$	$\Lambda_c^+ \to p\pi^0$	$\frac{\mathcal{B}_{\Lambda_c^+ \to p\pi^0}}{\mathcal{B}_{\Lambda_c^+ \to p\eta}}$
BESIII	1.24 ± 0.29	<0.27	<0.24
Sharma *et al.* [3]	0.2[a](1.7[b])	0.2	1.0[a](0.1[b])
Uppal *et al.* [4]	0.3	0.1–0.2	0.3–0.7
S. L. Chen *et al.* [12]	...	0.11–0.36[c]	...
Cai-Dian Lü *et al.* [13]	...	0.45	...

[a] Assumed to have a positive sign for the p-wave amplitude of $\Lambda_c^+ \to \Xi^0 K^+$.
[b] Assumed to have a negative sign for the p-wave amplitude of $\Lambda_c^+ \to \Xi^0 K^+$.
[c] Calculated relying on different values of parameters b and α.

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

- First observation of CF decay, $\Lambda_c^+ \rightarrow \Sigma^-\pi^+\pi^+\pi^0$
- Improved BF on $\Lambda_c^+ \rightarrow \Sigma^-\pi^+\pi^+$
- $\Sigma^- \rightarrow n\pi^-$ is reconstructed.



Fit to $M_{n\pi^-} - M_n$ to extract the signal yield

$$M_{n\pi^-} = \sqrt{(E_{\rm beam} - E_{\pi^+\pi^+(\pi^0)})^2 - |\vec{p}_{\Lambda_c^+} - \vec{p}_{\pi^+\pi^+(\pi^0)}|^2}$$

$$M_n = \sqrt{(E_{\rm beam} - E_{\pi^+\pi^+\pi^-(\pi^0)})^2 - |\vec{p}_{\Lambda_c^+} - \vec{p}_{\pi^+\pi^+\pi^-(\pi^0)}|^2}$$

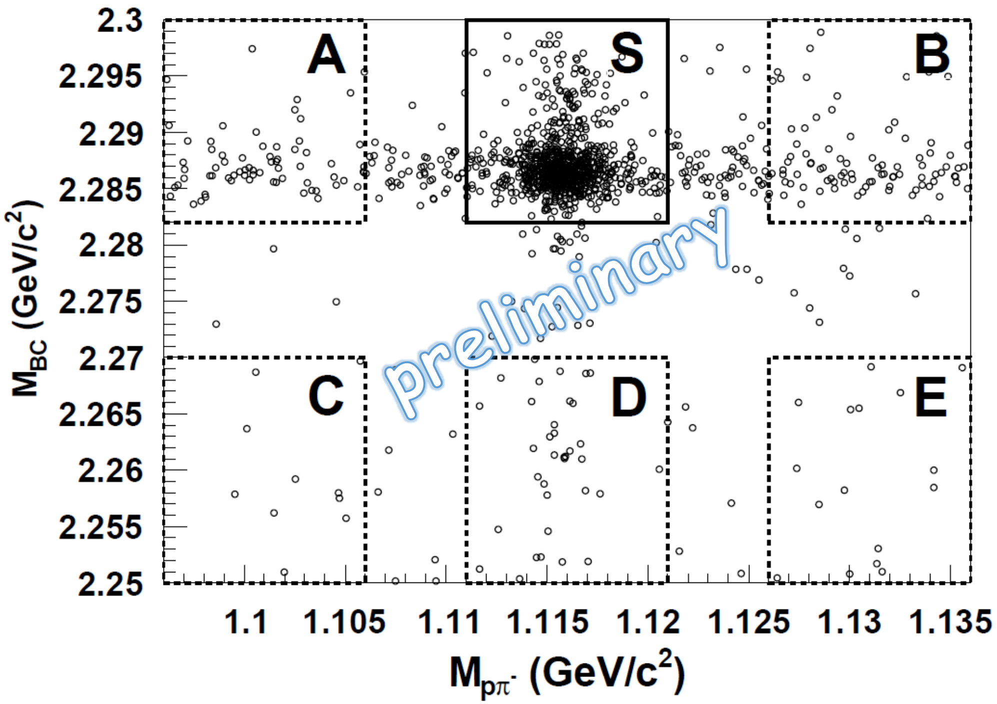
$$\mathcal{B}(\Lambda_c^+ \rightarrow \Sigma^-\pi^+\pi^+\pi^0) = (2.11 \pm 0.33 \pm 0.14)\%$$

$$\mathcal{B}(\Lambda_c^+ \rightarrow \Sigma^-\pi^+\pi^+) = (1.81 \pm 0.17 \pm 0.09)\%$$

PLB 772, 388 (2017)

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

- Currently PDG: BF($\Lambda_c^+ \to \Lambda$+X) = (35$\pm$11)%
  - Large rate, but also with large uncertainty…
- DT method: ST with pKπ and pK$_S$
- Extract yields from 2D distributions in bins of $p_{p\pi}$ and |cosθ| where θ is the polar angle w.r.t. the beam pipe.



☺ BF($\Lambda_c^+ \to \Lambda$+X) = (36.98$\pm$2.18)%

☺ *Also look for:*

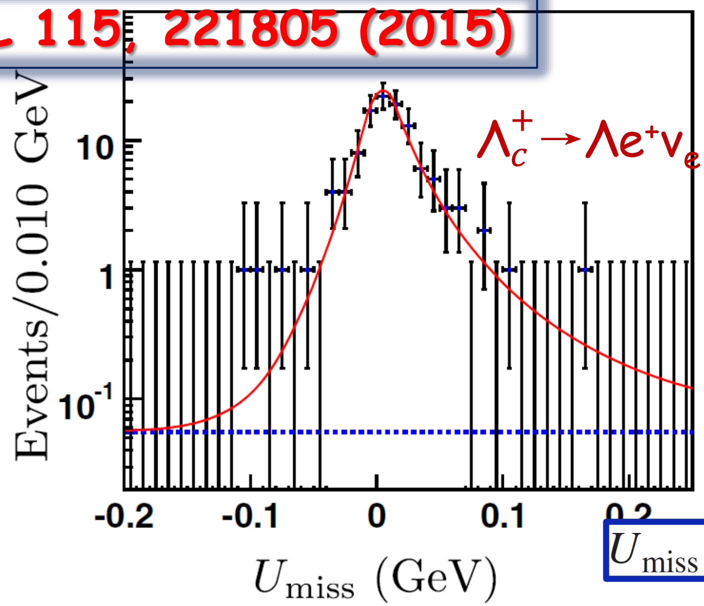
$$\mathcal{A}_{\mathrm{CP}} \equiv \frac{\mathcal{B}(\Lambda_c^+ \to \Lambda + X) - \mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X)}{\mathcal{B}(\Lambda_c^+ \to \Lambda + X) + \mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X)}$$

☺ A_{CP} = +0.02$\pm$0.06

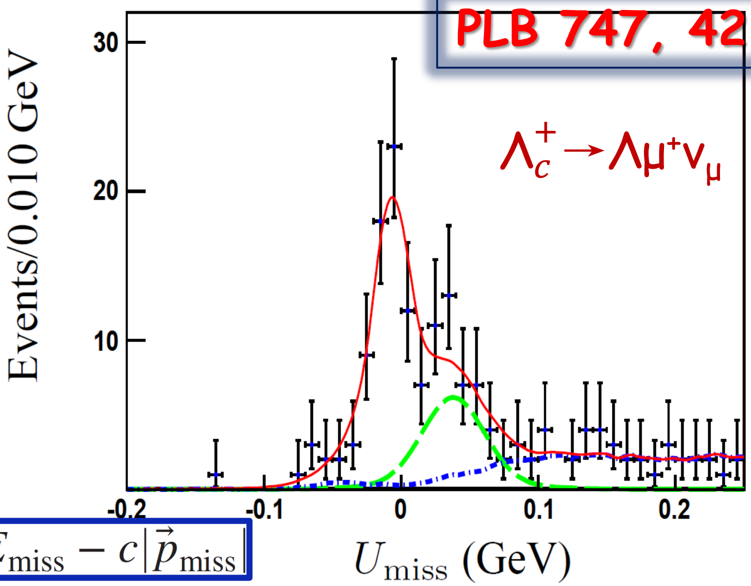
$\Lambda_c^+ \to \Lambda l^+ \nu_l$

- $\Lambda_c^+ \to \Lambda l^+ \nu_l$ is a $c \to s l^+ \nu_l$ dominated process
- First absolute BF of semi-leptonic mode
- First measurement of its muonic mode!
- Useful for calibrating the Lattice-QCD calculations

PRL 115, 221805 (2015)



PLB 747, 42 (2017)



$$U_{\rm miss} = E_{\rm miss} - c|\vec{p}_{\rm miss}|$$

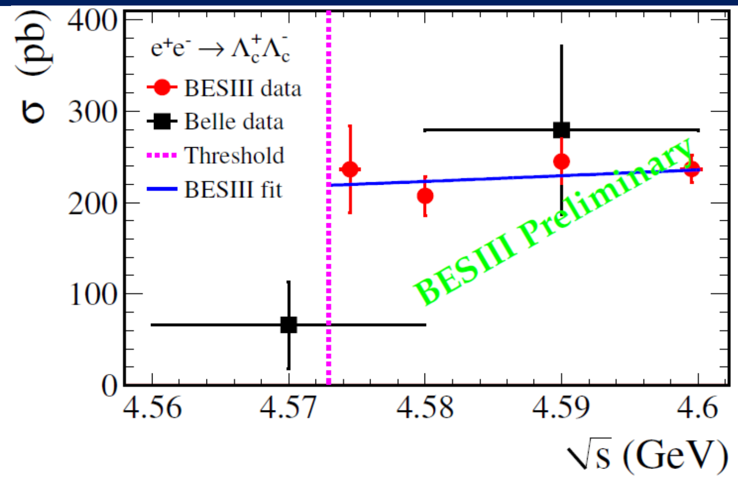
$$\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.63 \pm 0.38 \pm 0.20)\%$$

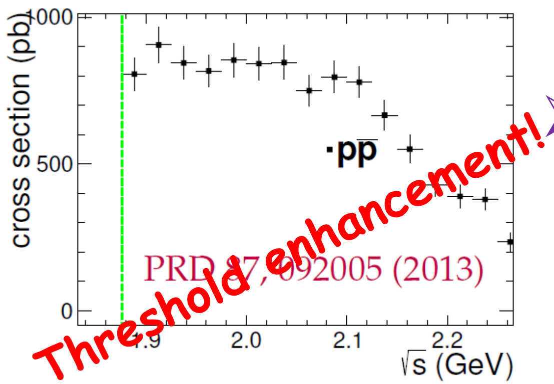
$$\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu) = (3.49 \pm 0.46(\rm stat) \pm 0.27(\rm syst))\%$$

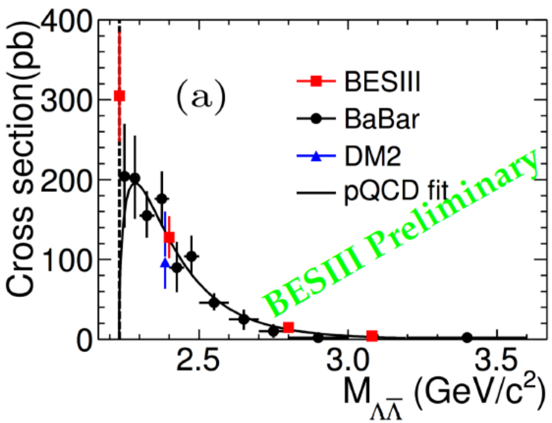
$$\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu)/\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)$$
$$= 0.96 \pm 0.16(\rm stat) \pm 0.04(\rm syst)$$

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

$\sqrt{s}$ (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	$237 \pm 3 \pm 15$







- The Born Cross Section of $e^+e^- \to \gamma^* \to B\bar{B}$ 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 Baryon, the Coulomb factor C will results in a non-zero cross section at threshold.

- Coulomb enhanced factor in $e^+e^- \to \gamma^* \to \Lambda_c^+\bar{\Lambda}_c^-$?

Summary

- BESIII took a data set of 567 pb^{-1} and improved various Λ_c BFs significantly
- Measured some new decay modes
- Continue to study on precise measurement of Λ_c decays by the near-threshold data

More potentials

- A larger data set
  - BESIII will keep collecting data in the next ~ decade
  - The current plan is to accumulate 1M Λ_c in total

Thank you!