Λ_c^+ physics at BESIII

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Outline

- The lightest charm baryon Λ_c^+
- BESIII results on its production and decays
  - Λ_c^+ hadronic decays
    - BF($\Lambda_c^+ \to pK^-\pi^+$) +11hadronic modes :PRL 116, 052001 (2016)
    - BF($\Lambda_c^+ \to pK^+K^-$, $p\pi^+\pi^-$) :PRL 117, 232002 (2016)
    - BF($\Lambda_c^+ \to nK_s\pi^+$) :PRL 118, 12001 (2017)
    - BF($\Lambda_c^+ \to p\eta$, $p\pi^0$) :PRD 95, 111102(R) (2017)
    - BF($\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$) :PLB 772, 388 (2017)
    - BF($\Lambda_c^+ \to \Xi^{(*)0}K^+$) : arXiv:1803.04299
  - Λ_c^+ semi-leptonic decay
    - BF($\Lambda_c^+ \to \Lambda e^+\nu_e$) :PRL 115, 221805(2015)
    - BF($\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$) : PLB 767, 42 (2017)
  - Λ_c^+ inclusive decay $\Lambda_c^+ \to \Lambda + X$
    - BF($\boldsymbol{\Lambda}_c^+ \to \boldsymbol{\Lambda}X$) : arXiv: 1803.05706
    - BF($\boldsymbol{\Lambda}_c^+ \to eX$) : arXiv: 1805.09060
  - $\Lambda_c^+\bar{\Lambda}_c^-$ pair cross section : PRL 120,132001(2018).
- Summary

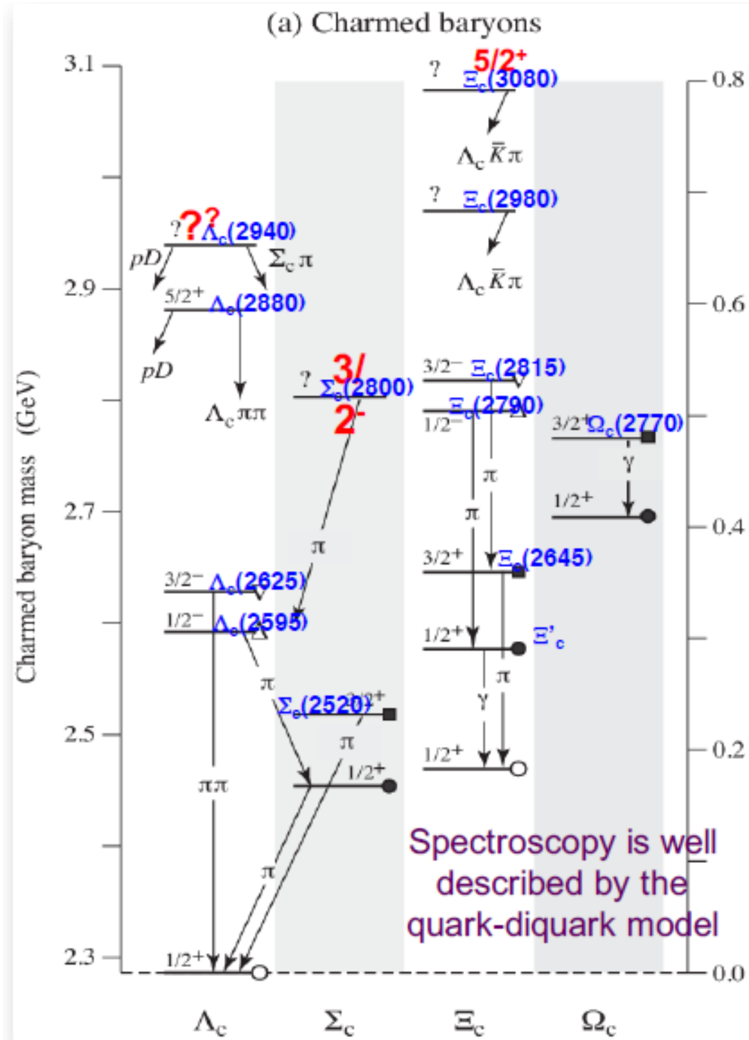
Renaissance on the charmed heavy baryon

- **Before 2014, the charmed baryons have been produced and studied at many experiments, notably fixed-target experiments (such as FOCUS and SELEX) and e^+e^- B-factories (ARGUS, CLEO, BABAR, and BELLE).**

- **Large uncertainties in experiment=>Retarder development in theory.**

- **Afterwards, more extensive measurements on charmed baryons are performed at BESIII, BELLE and LHCb.**
  - The absolute BF measurements at BESIII and BELLE.
  - The observation of the DCS mode $\Lambda_c^+ \to pK^+\pi^-$ at BELLE.
  - The observation of the doubly charmed baryon Ξ_{cc}^{++} at LHCb.

- **These experimental progresses have revoked the activities in the theoretical efforts.**



Λ_c^+: The lightest charmed baryon spectroscopy

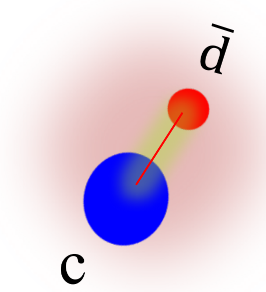
- Most of the charmed baryons will eventually decay to Λ_c^+.

- The Λ_c^+ is one of important tagging hadrons in c-quark counting in the productions at high energy experiment.

- Also important input to Λ_b (including Ξ_{cc}^{++}) physics as Λ_b decay preferentially to Λ_c . ==>Important input to B physics and V_{ub} calculations.

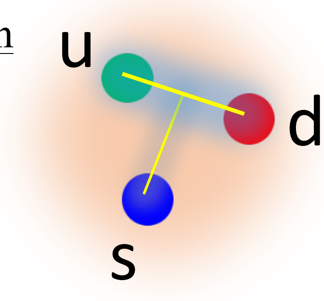
- Λ_c^+ may provide more powerful test on internal dynamics than D/Ds does !

- Naïve quark model picture: a heavy quark (*c*) with an unexcited spin-zero diquark (*u-d*). Diquark correlation is enhanced by weak Color Magnetic Interaction with a heavy quark(HQET).



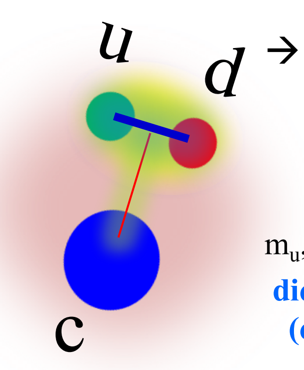
→ Charmed meson ($D^+[c\bar{d}]$)

$m_d << m_c$ →
quark + heavy quark
(q) (Q)



→ Strange baryons (Λ[uds])

$m_u, m_d \approx m_s$ →
(qqq) uniform



→ Charmed baryon (Λ_c[udc])

$m_u, m_d << m_c$ →
diquark + quark
(qq) (Q)

BESIII data taking @ $\Lambda_c^+\Lambda_c^-$ threshold

- **In 2014, BESIII took data above Λ_c pair threshold and run machine at 4.6GeV with excellent performance!**
- **Measurement using the threshold pair-productions via e^+e^- annihilations is unique: *the most simple and straightforward.***
- **~106×10[3] $\Lambda_c^+\Lambda_c^-$ pairs make sensitivity to 10^{-3}.**
- **First time to systematically study Λ_c^+ at threshold.**
- **Collect more Λ_c^+ data are in the schedule.**

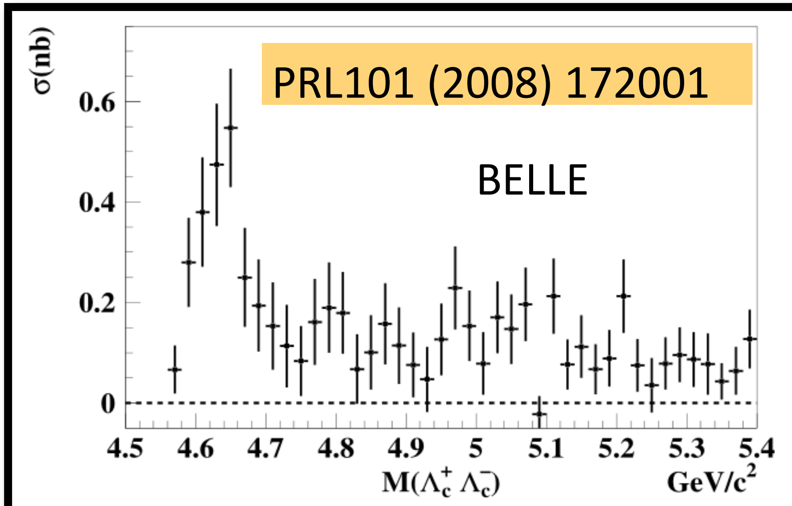


FIG. 4: The cross section for the exclusive process $e^+e^- \to \Lambda_c^+\Lambda_c^-$.

Energy(GeV)	lum.(pb^{-1})
4.575	47.67
4.580	8.54
4.590	8.16
4.600	567.93

Production near threshold and tag technique

- E_{cms}-2$M_{\Lambda c}$=26MeV only!
- $\Lambda_c^+\Lambda_c^-$ produced in pairs with no additional accompany hadrons.
  - $e^+e^-\to\gamma^*\to\Lambda_c^+\Lambda_c^-$
- Clean backgrounds and well constrained kinematics.
- Typically, two ways to study Λ_c^+ decays:
  - Single Tag(ST): detect only one of the $\Lambda_c^+\Lambda_c^-$.

    =>Relative higher backgrounds

    =>Higher efficiencies

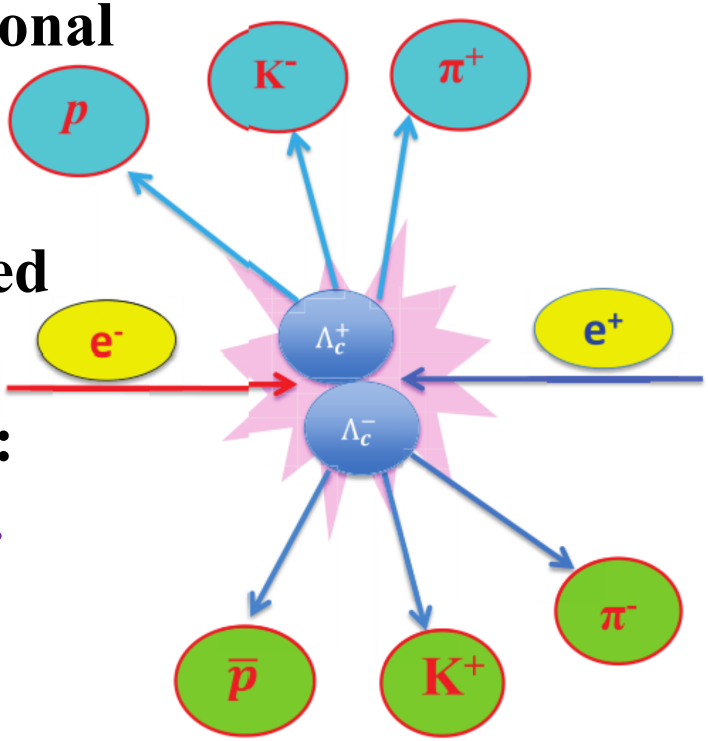
    =>Full reconstruction
  - Double Tag(DT): detec both of $\Lambda_c^+\Lambda_c^-$

    =>Smaller backgrounds.

    =>Missing technique.

    =>Lower efficiencies.

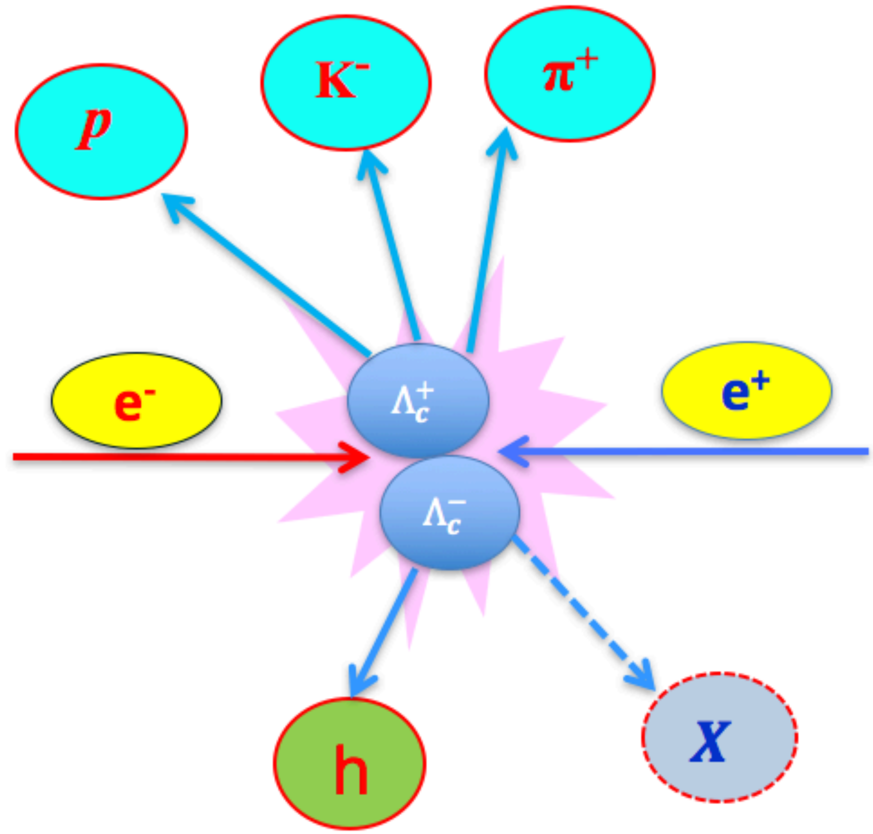
    =>Systematic in tag side are mostly cancelled.



Several popular variables

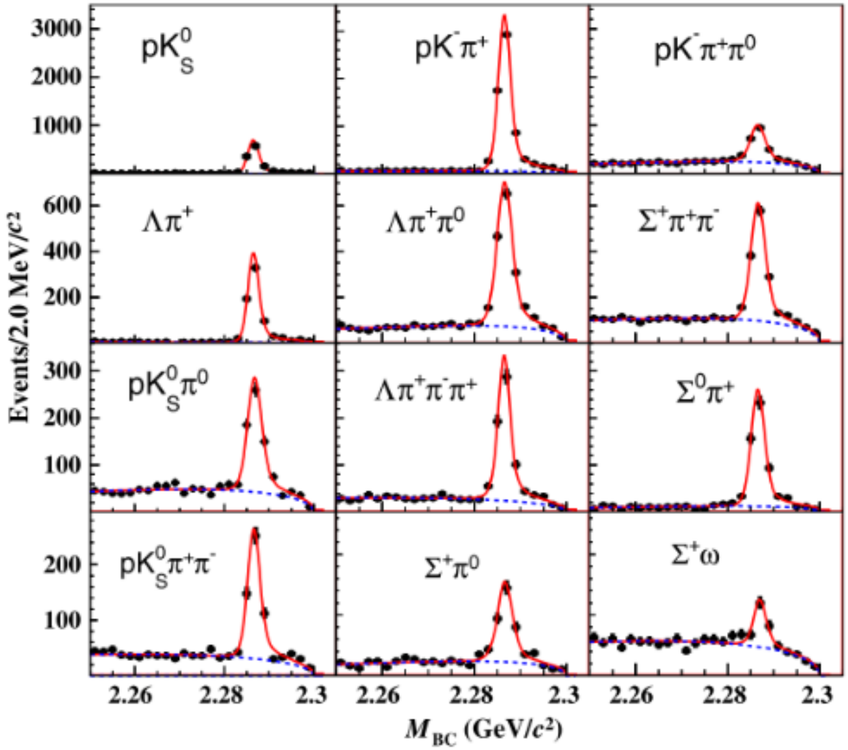
- $\Delta E = E_{\Lambda c} - E_{beam}$
- Beam-Constrained-Mass;

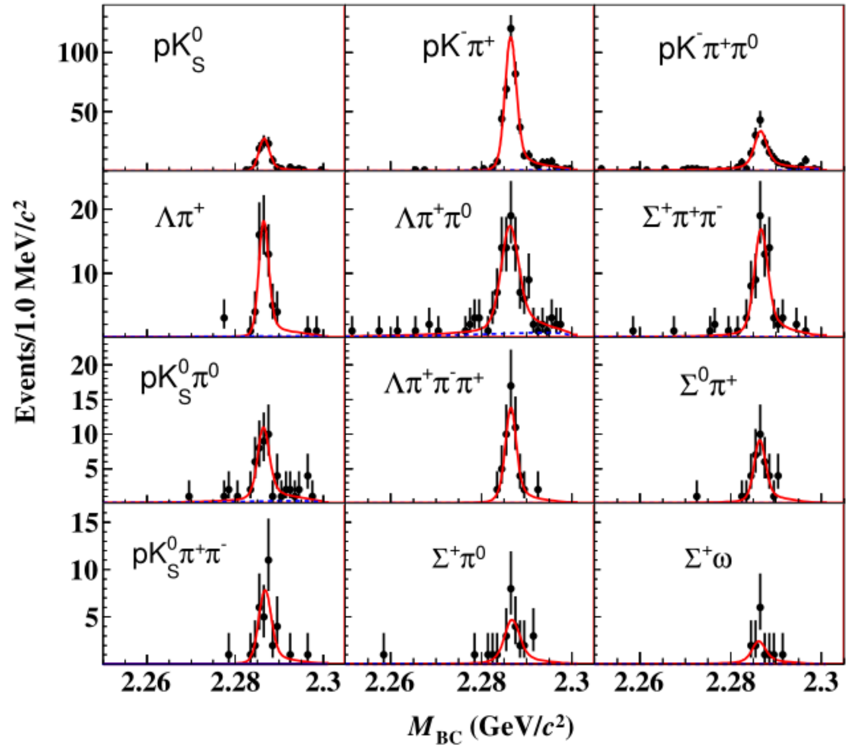
  $M_{BC} = \sqrt{E^2_{beam} - |\vec{p}_{\Lambda c}|^2}$



- $E_{miss} = E_{beam} - E_h$
- $\vec{p}_{miss} = \vec{p}_{\Lambda c} - \vec{p}_h$
- $\vec{p}_{\Lambda c} = -\vec{p}_{tag} \cdot \sqrt{E^2_{beam} - m^2_{\Lambda c}}$
- $U_{miss} = E_{miss} - |\vec{p}_{miss}|$
- $M_{miss} = \sqrt{E^2_{miss} - |\vec{p}_{miss}|^2}$
- $\hat{p}_{tag}$ is the direction of the momentum of the singly tagged Λ_c .
- $E_h(p_h)$ are the energy(momentum) of h which are measured in e^+e^- system.
- $m_{\Lambda_c^+}$ is the mass of the Λ_c^+ quoted from the PDG.

Λ_c^+ reconstruction at BESIII





$$N_i^{\rm ST} = N_{\Lambda_c^+\bar{\Lambda}_c^-} \cdot \mathcal{B}_i \cdot \varepsilon_i^{\rm ST}$$

$$N_{-j}^{\rm DT} = N_{\Lambda_c^+\bar{\Lambda}_c^-} \cdot \sum_i \mathcal{B}_i \cdot \mathcal{B}_j \cdot \varepsilon_{-j}^{\rm DT}.$$

- **The BFs are extracted via the double-tag technique.**
- **BF is determined independent of $N_{\Lambda_c^+\Lambda_c^-}$ and the systematic due to the reconstruction of ST side to be canceled.**
- **~15400 ST yields and ~1000 DT yields**

Results of 12 Λ_c^+ hadronic decay BFs

PRL 116, 052001 (2016)

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	

567pb^{-1} @ 4.6 GeV

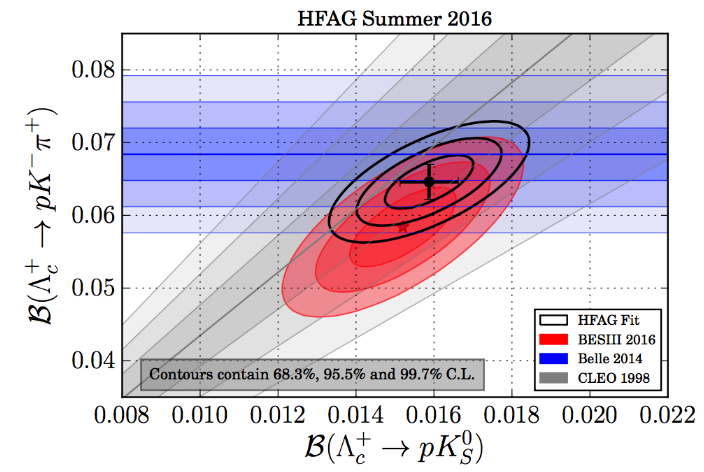
- **No absolute measurement (Model independently) on Λ_c^+ BFs at threshold after Λ_c^+ discovered(30 years ago).**
- **A least square global fit taking into account correlations over different modes are performed to improve the precision.**
- **The precision of B(p$K^-\pi^+$) are comparable with Belle's**
- **The precisions of Λ_c decay rates is reaching to the level of charmed mesons!**
- **$N_{\Lambda_c^+\Lambda_c^-}$ as a byproduct determined to be $(105.9 \pm 4.8 \pm 0.5) \times 10^3$**

HFLAV Fit to world BF data

- A fitter to constrain the 12 hadronic BFs and 1 SL BF, based on all the existing experimental data
- Correlated systematics are fully taken into account

Eur. Phys. J. C77, 895 (2017)

Mode	HFAG 2016 (%)	BESIII (%)	PDG 2014 (%)	BELLE (%)
pK_S^0	1.59 ± 0.07	$1.52 \pm 0.08 \pm 0.03$	1.15 ± 0.30	
$pK^-\pi^+$	6.46 ± 0.24	$5.84 \pm 0.27 \pm 0.23$	5.0 ± 1.3	$6.84 \pm 0.24^{+0.21}_{-0.27}$
$pK_S^0\pi^0$	2.03 ± 0.12	$1.87 \pm 0.13 \pm 0.05$	1.65 ± 0.50	
$pK_S^0\pi^+\pi^-$	1.69 ± 0.11	$1.53 \pm 0.11 \pm 0.09$	1.30 ± 0.35	
$pK^-\pi^+\pi^0$	5.05 ± 0.29	$4.53 \pm 0.23 \pm 0.30$	3.4 ± 1.0	
$\Lambda\pi^+$	1.28 ± 0.06	$1.24 \pm 0.07 \pm 0.03$	1.07 ± 0.28	
$\Lambda\pi^+\pi^0$	7.09 ± 0.36	$7.01 \pm 0.37 \pm 0.19$	3.6 ± 1.3	
$\Lambda\pi^+\pi^-\pi^+$	3.73 ± 0.21	$3.81 \pm 0.24 \pm 0.18$	2.6 ± 0.7	
$\Sigma^0\pi^+$	1.31 ± 0.07	$1.27 \pm 0.08 \pm 0.03$	1.05 ± 0.28	
$\Sigma^+\pi^0$	1.25 ± 0.09	$1.18 \pm 0.10 \pm 0.03$	1.00 ± 0.34	
$\Sigma^+\pi^+\pi^-$	4.64 ± 0.24	$4.25 \pm 0.24 \pm 0.20$	3.6 ± 1.0	
$\Sigma^+\omega$	1.77 ± 0.21	$1.56 \pm 0.20 \pm 0.07$	2.7 ± 1.0	
$\Lambda e^+\nu_e$	3.18 ± 0.32	$3.63 \pm 0.38 \pm 0.20$	2.1 ± 0.6	



- The least overall χ^2/ndf=30.0/23=1.3
- Precise $B(pK^-\pi^+)$ is useful for constrain V_{ub} determined via baryonic mode

Experimental precision reaches of the charmed hadrons

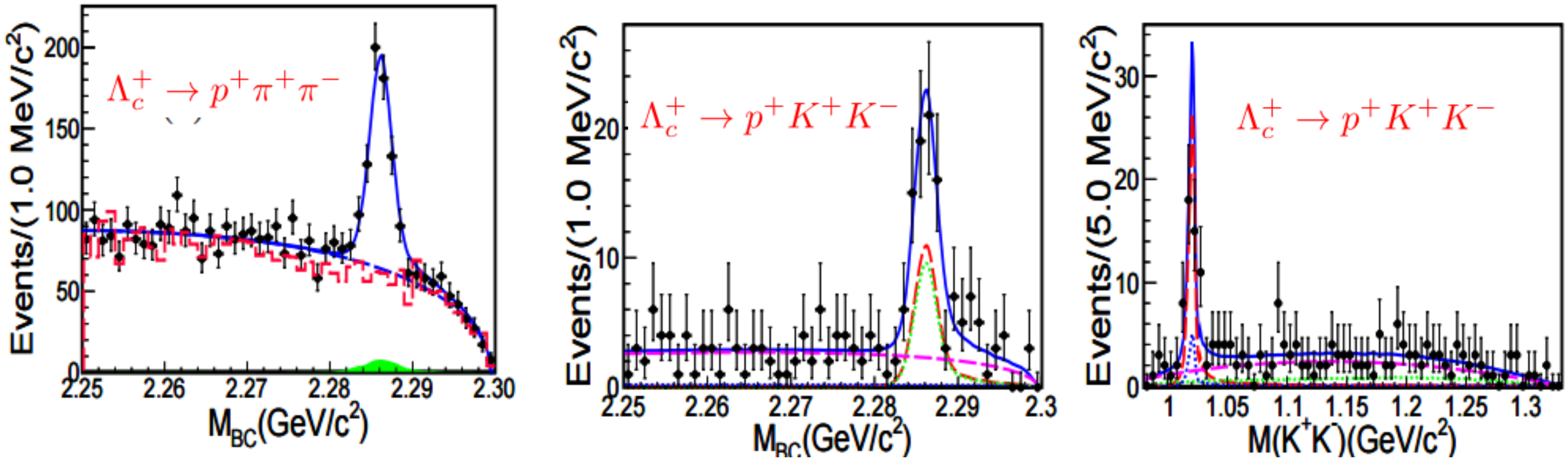
	Golden hadronic mode	δB/B	Golden SL mode	δB/B
D^0	B(Kπ)=(3.88 ± 0.05)%	1.3%	B(Keν)=(3.55 ± 0.05)%	1.4%
D^+	B(Kππ)=(9.13 ± 0.19)%	2.1%	B(K^0eν)=(8.83 ± 0.22)%	2.5%
D_s	B(KKpi)=(5.39 ± 0.21)%	3.9%	B(ϕeν)=(2.49 ± 0.14)%	5.6%
Λc	B(pKπ)=(5.0 ± 1.3)%(PDG2014) =(6.8 ± 0.36)% (BELLE) =(5.84 ± 0.35)% (BESIII) =(6.46 ± 0.24)% (HFAG)	26% 5.3% 6.0% 3.7%	B(Λeν)=(2.1 ± 0.6)%(PDG2014) =(3.63 ± 0.43)% (BESIII) =(3.18 ± 0.32)% (HFAG)	29% 12% 10%

- The precisions of Λc decay rates is reaching to the level of charmed mesons!
- More data input will further constrain the HFLAV fit.
- However, search for more unknown modes are important

Singly Cabibbo-Suppressed Decays of $\Lambda_c^+ \to p\pi^+\pi^-$ and $\Lambda_c^+ \to pK^+K^-$

PRL117,232002(2016)

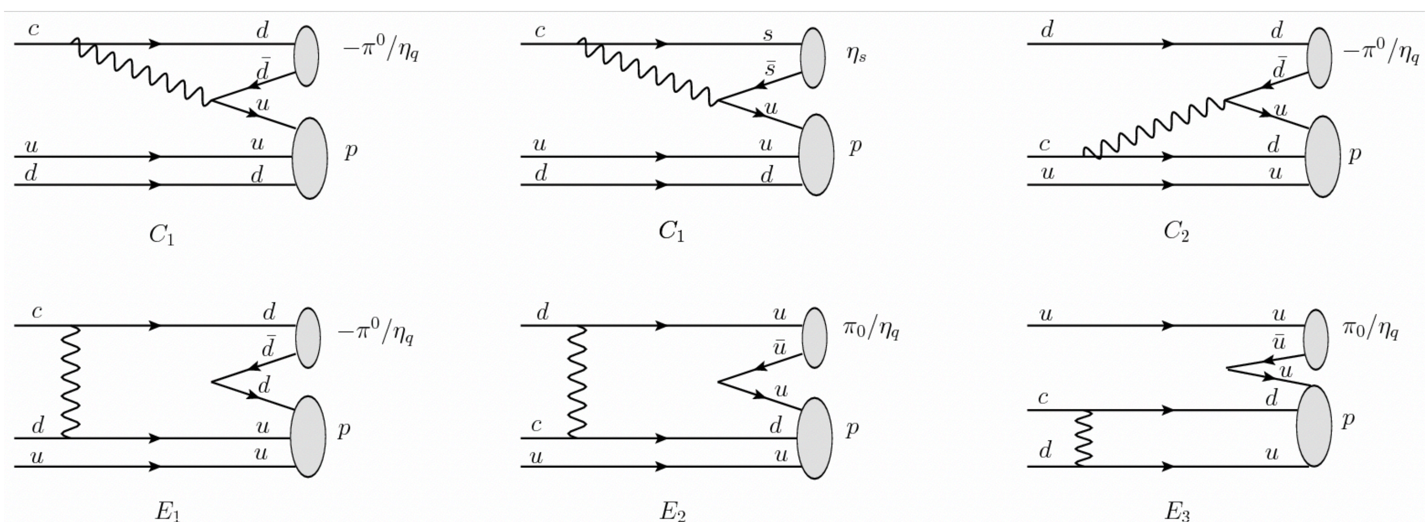
- **ST method:** $\Lambda_c^+ \to pK^-\pi^+$ as ref. mode
- **First observation of SCS decay of $\Lambda_c^+ \to p\pi^+\pi^-$**
- **Improved measurement on the SCS decays $\Lambda_c^+ \to pK^+K^-$**
- **$\Lambda_c^+ \to p\phi$ are sensitive to non-factorable contributions from W-exchange diagrams**



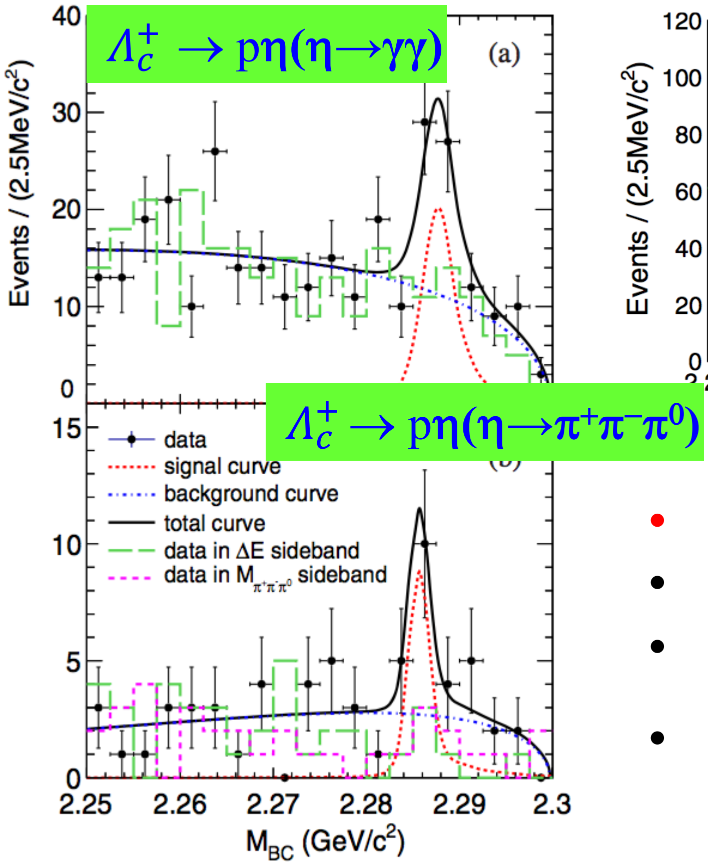
Decay modes	$\mathcal{B}_{mode}/\mathcal{B}_{ref}$ (This work)	$\mathcal{B}_{mode}/\mathcal{B}_{ref}$ (PDG average)
$\Lambda_c^+ \to p\pi^+\pi^-$	$(6.70 \pm 0.48 \pm 0.25) \times 10^{-2}$	$(6.9 \pm 3.6) \times 10^{-2}$
$\Lambda_c^+ \to p\phi$	$(1.81 \pm 0.33 \pm 0.13) \times 10^{-2}$	$(1.64 \pm 0.32)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

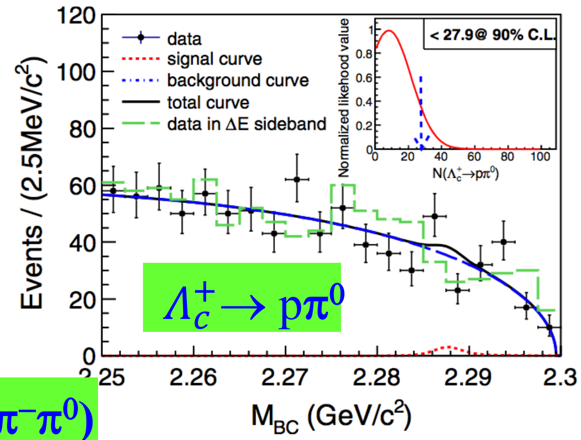
Singly Cabibbo-Suppressed Decays of $\Lambda_c^+ \to p\pi^0$ and $\Lambda_c^+ \to p\eta$

- These modes have not been measured before.
- Predicted BFs vary under different theoretical models(SU(3) symmetry and FSI)
- $B(\Lambda_c^+ \to p\eta) >> B(\Lambda_c^+ \to p\pi^0)$ in the SU(3) flavor symmetry generated by u,d and s
- Nonfactorizable terms contribute constructively to pη and destructively to $p\pi^0$
- Their relative size is essential to understand the interference of different non factorizable diagrams.



SCS Decays of $\Lambda_c^+\to p\pi^0$ and $\Lambda_c^+\to p\eta$





PRD,111102(R) (2017)

ST method

- First evidence for $\Lambda_c^+\to p\eta$ with 4.2σ
- $B(\Lambda_c^+\to p\eta)=(1.24\pm0.28\pm0.10)\times10^{-3}$
- No signal seen in $\Lambda_c^+\to p\pi^0$, $B(\Lambda_c^+\to p\pi^0)<2.7\times10^{-4}$
- $\mathcal{B}(\Lambda_c^+ \to p\pi^0)/\mathcal{B}(\Lambda_c^+ \to p\eta) < 0.24$

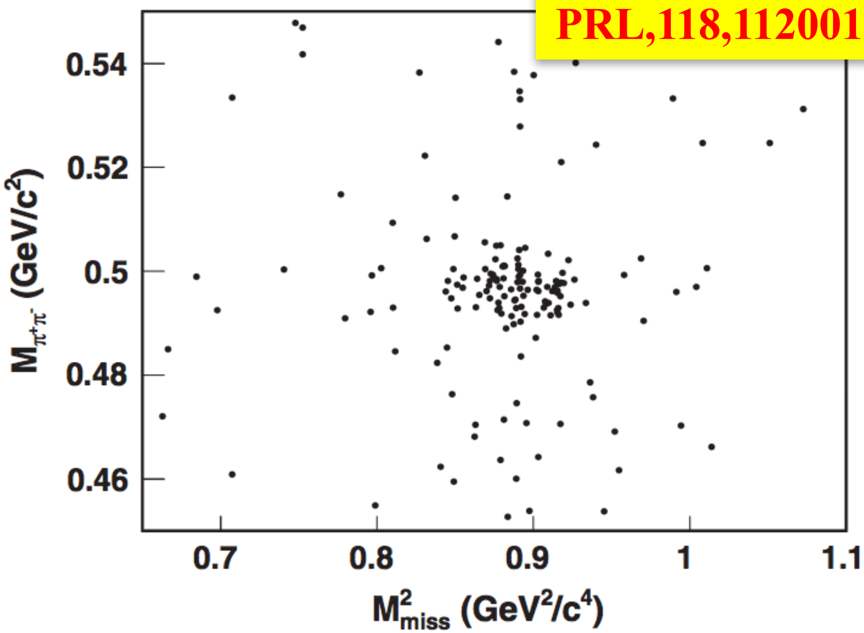
arXiv:1801.08625

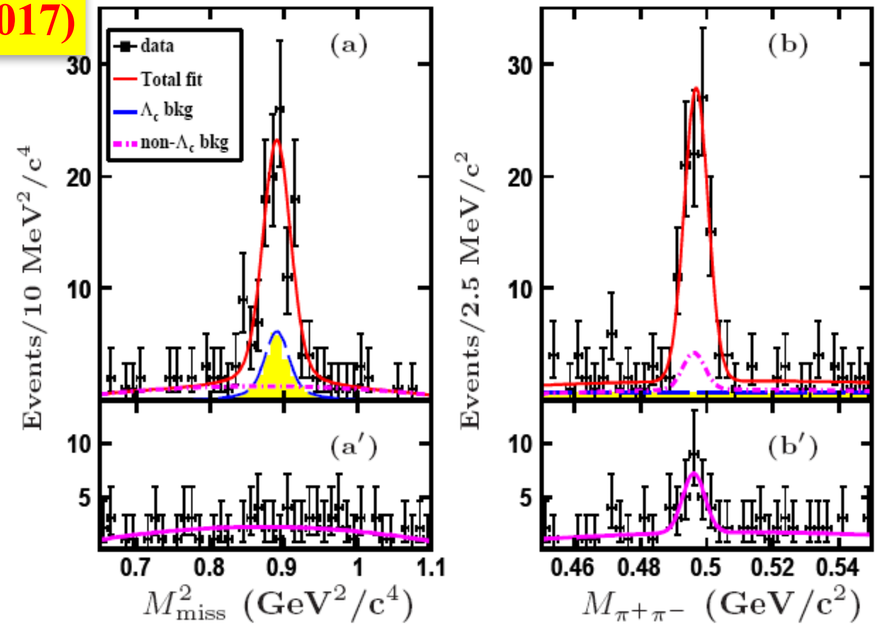
(10^{-3})	Sharma *et al.* SU(3)	Uppal *et al.* QM	Chen *et al.* Fac.	Lu *et al.* SU(3)	Geng *et al.* SU(3)	Cheng *et al.* C.A.	Expt [7, 19]
$\Lambda_c^+\to p\pi^0$	0.2	0.1-0.2	0.11-0.36	0.48	0.56 ± 0.15	0.08	<0.27
$\Lambda_c^+\to p\eta$	$0.2^a(1.7)^b$	0.3			1.24 ± 0.41	1.28	1.24 ± 0.29

Observation of $\Lambda_c^+ \to nK_S^0\pi^+$

- **First direct measurement of Λ_c^+ decay involving the neutron in the final state.**

PRL,118,112001(2017)

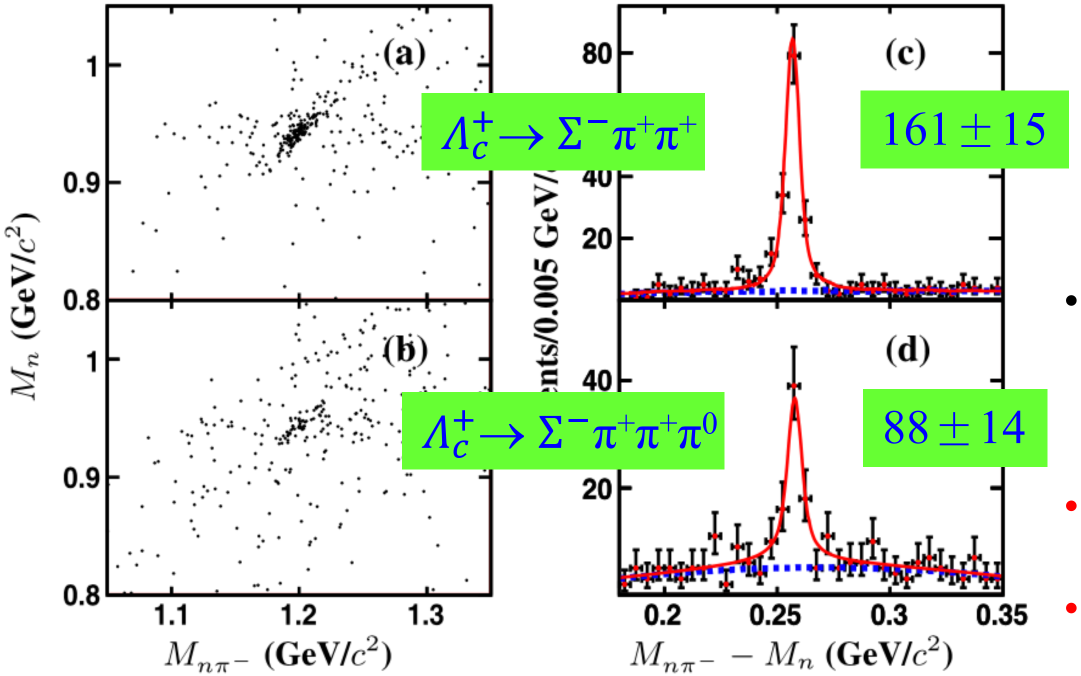




- Peaking background from $\Lambda_c^+ \to \Sigma^+ (\to n\pi^+) \pi^+\pi^-$
- **2-D fitting extract 83 ± 11 net signals => B[$\Lambda_c^+ \to nK_S^0\pi^+$]=(1.82±0.23±0.11)%**
- **B[$\Lambda_c^+ \to nK^0\pi^+$]/B[$\Lambda_c^+ \to pK^-\pi^+$]=0.62±0.09; B[$\Lambda_c^+ \to nK^0\pi^+$]/B[$\Lambda_c^+ \to pK^0\pi^0$]=0.97±0.16**
- **A test of final state interactions and isospin symmetry in the charmed baryon sector.** [PRD93, 056008 (2016)]

Study of $\Lambda_c^+ \to \Sigma^- \pi^+ \pi^+ (\pi^0)$

- **First observation** of a large-rate forgotten channel $\Lambda_c^+ \to \Sigma^- \pi^+ \pi^+ \pi^0$ (CF decay)



PLB 772, 388 (2017)

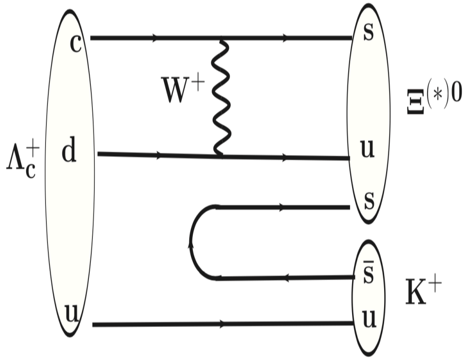
- **Λ_c^+ decay involving the neutron in the final state(missing technique). Less known in experiment.**
- **$B(\Lambda_c^+ \to \Sigma^- \pi^+ \pi^+ \pi^0) = (2.11 \pm 0.33 \pm 0.14)\%$**
- **$B(\Lambda_c^+ \to \Sigma^- \pi^+ \pi^+) = (1.81 \pm 0.17 \pm 0.09)\%$** more precise than old result $(2.3 \pm 0.4)\%$
- **$B[\Lambda_c^+ \to \Sigma^- \pi^+ \pi^+]/B[\Lambda_c^+ \to \Sigma^+ \pi^+ \pi^-]$ $=0.42 \pm 0.05 \pm 0.02$ better precision than rhe previous ratio $0.53 \pm 0.15 \pm 0.07$**

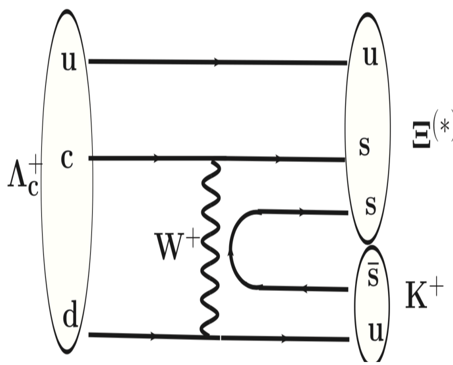
Constrained variables:

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

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

W-exchange-only process $\Lambda_c^+ \to \Xi^{(*)0} K^+$



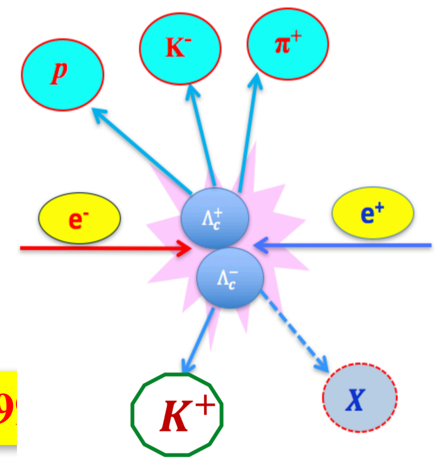


- **$\Lambda_c^+ \to \Xi^{0(*)} K^+$ decay only through W-exchange.**
- **W-exchange are non-factorable in theoretic calculation.**
- **Large cancellation both in S-wave and P-wave.**
- **This measurement helps in calibration of the W-exchange process in the charmed baryon sector.**
- **The previous measurements have poor precision.**

Decay	Measured $\frac{\mathcal{B}(\Lambda_c^+ \to \Xi^{(*)0} K^+)}{\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)}$	Measured $\mathcal{B}(\Lambda_c^+ \to \Xi^{(*)0} K^+)$	Predicted $\mathcal{B}(\Lambda_c^+ \to \Xi^{(*)0} K^+)$
$\Xi^0 K^+$	$(7.8 \pm 1.8)\%$ [18] **CLEO**	$(5.0 \pm 1.2) \times 10^{-3}$ [24]	2.6×10^{-3} [4] 3.6×10^{-3} [6] 3.1×10^{-3} [10] 1.0×10^{-3} [14] 1.3×10^{-3} [15]
$\Xi^{*0} K^+$	$(5.3 \pm 1.9)\%$ [18] **CLEO** $(9.3 \pm 3.2)\%$ [19, 2 **ARGUS**	$(4.0 \pm 1.0) \times 10^{-3}$ [24, 20]	5.0×10^{-3} [4] 0.8×10^{-3} [16] 0.6×10^{-3} [17]

W-exchange-only process $\Lambda_c^+ \to \Xi^{(*)0} K^+$

- **Double tag and missing $\Xi^{0(*)}$ to increase the detection efficiency.**
- **Low backgrounds because the anti-strangeness of K^+**

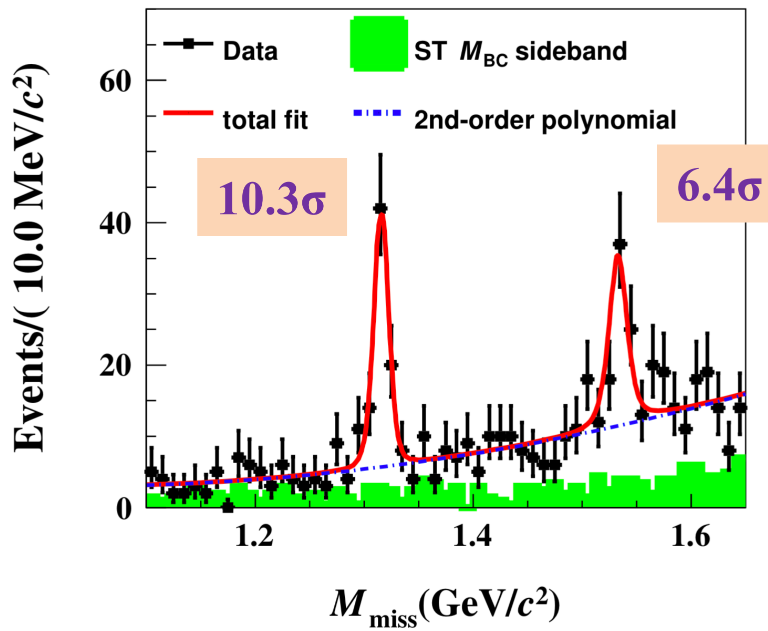


$$\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+) = (5.90 \pm 0.86 \pm 0.39) \times 10^{-3}$$

$$\mathcal{B}(\Lambda_c^+ \to \Xi(1530)^0 K^+) = (5.02 \pm 0.99 \pm 0.31) \times 10^{-3}$$

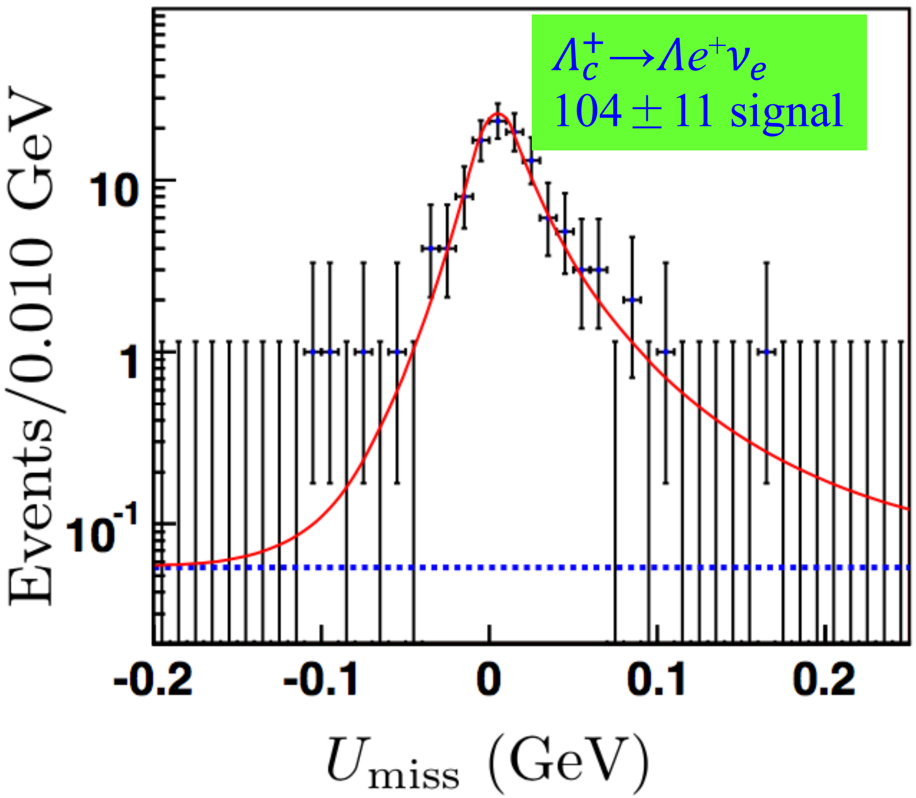
arXiv:1803.0429

- **First absolute measurement, using world largest on-threshold data at $\sqrt{s}$=4.6GeV**
- **Improved precision**
- **No model can accommodate the both rates**



Absolute BF for $\Lambda_c^+ \to \Lambda l^+ \nu_l$

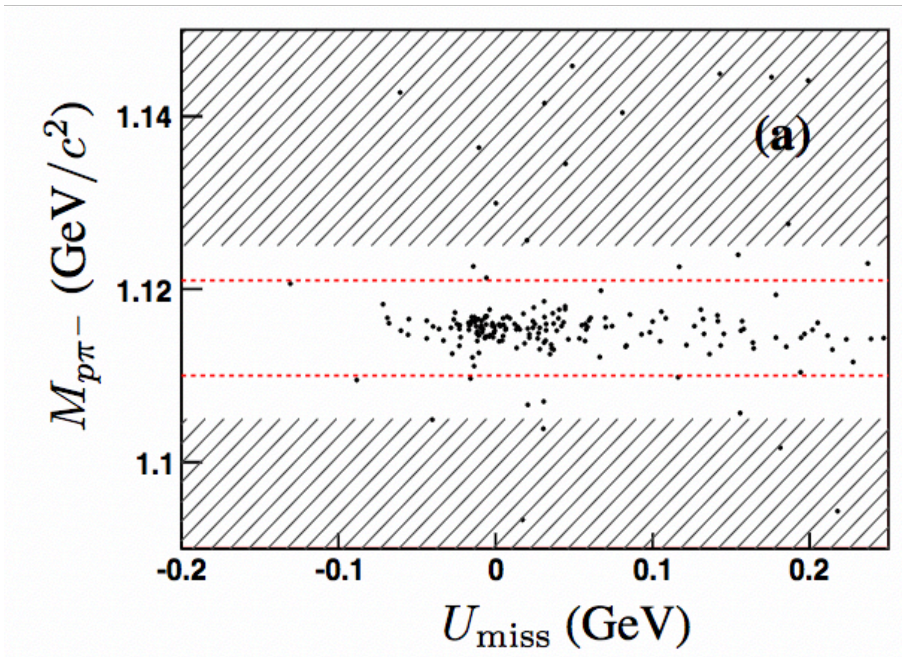
PRL 115, 221805(2015)

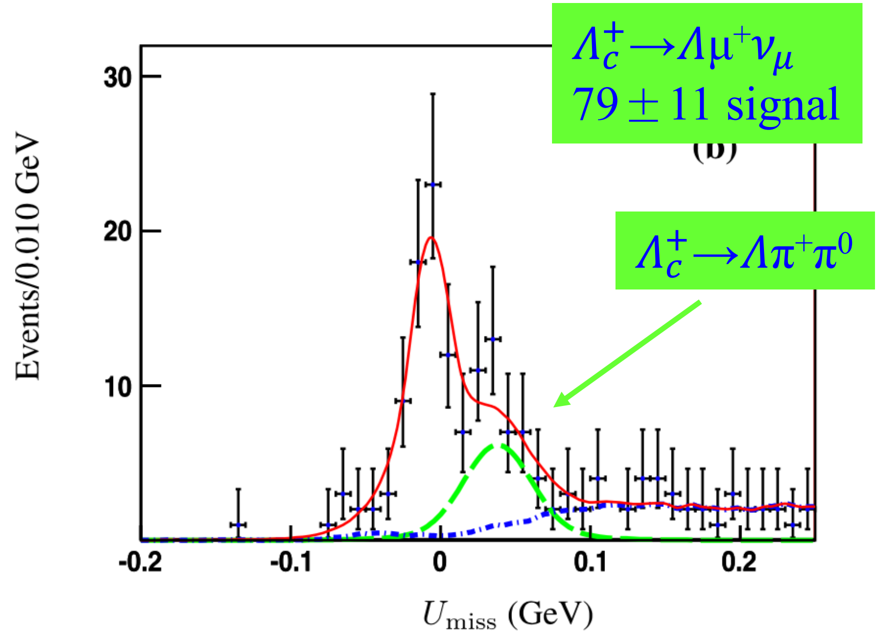


$B[\Lambda_c^+ \to \Lambda e^+ \nu_e] = (3.36 \pm 0.38 \pm 0.20)\%$

- **Benchmark channel via the CF transition $c \to s l^+ \nu_l$**
- **BESIII measured the electronic mode $\Lambda_c^+ \to \Lambda e^+ \nu_e$ by missing the neutrino.**
- **Provides stringent test for nonperturbative aspects of the theory of strong interaction.**
- **Important input for implementing and calibrating the LQCD calculations.**

Study on $\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu$





- **Double tag and missing neutrino.**
- **Peaking backgrounds from muon-pion mis-ID**

PLB 767, 42 (2017)

- **B[$\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu$]=(3.49±0.46±0.27)%**
  =>improved precision,
  =>first absolute measurements.

- **$\Gamma[\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu]/\Gamma[\Lambda_c^+ \to \Lambda e^+ \nu_e]$= 0.96 ± 0.16 ± 0.04**
  =>compatible with unity

$\Lambda_c \to \Lambda l^+ \nu_l$ Form Factors and Decay Rates from Lattice QCD with Physical Quark Masses

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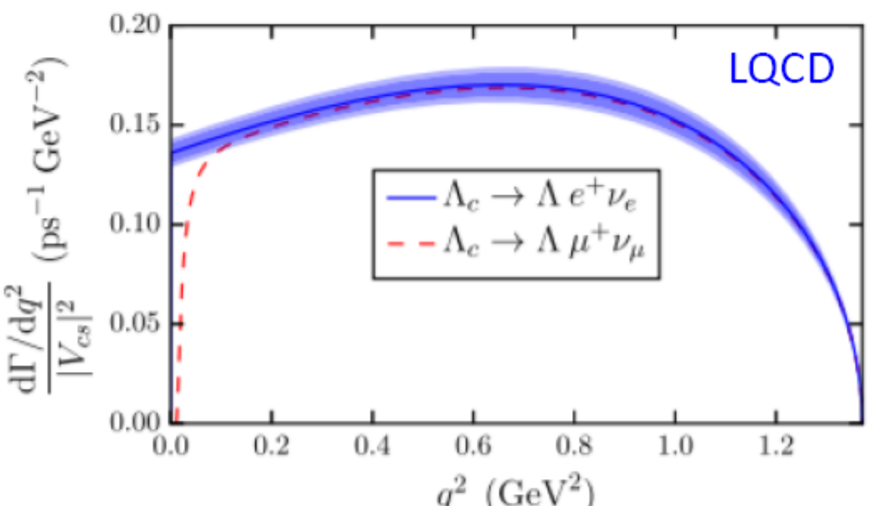
PRL118(2017)082001

- Input the measured BFs from BESIII

$$\mathcal{B}(\Lambda_c \to \Lambda \ell^+ \nu_\ell) = \begin{cases} 0.0363(38)(20), & \ell = e, \\ 0.0349(46)(27), & \ell = \mu. \end{cases}$$

- The first LQCD calculations on BFs and form factors

$$\mathcal{B}(\Lambda_c \to \Lambda \ell^+ \nu_\ell) = \begin{cases} 0.0380(19)_{\rm LQCD}(11)_{\tau_{\Lambda_c}}, & \ell = e, \\ 0.0369(19)_{\rm LQCD}(11)_{\tau_{\Lambda_c}}, & \ell = \mu, \end{cases}$$



✓ The first determination of $|V_{cs}|$ based on BFs of $\Lambda_c^+ \to \Lambda l^+ \nu_l$ measured by BESIII

$$|V_{cs}| = \begin{cases} 0.951(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(56)_{\mathcal{B}} & \ell = e, \\ 0.947(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(72)_{\mathcal{B}} & \ell = \mu, \\ 0.949(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(49)_{\mathcal{B}} & \ell = e, \mu, \end{cases}$$

$\Lambda_c^+ \to \Lambda l^+ \nu_l$ BF is the largest error source.

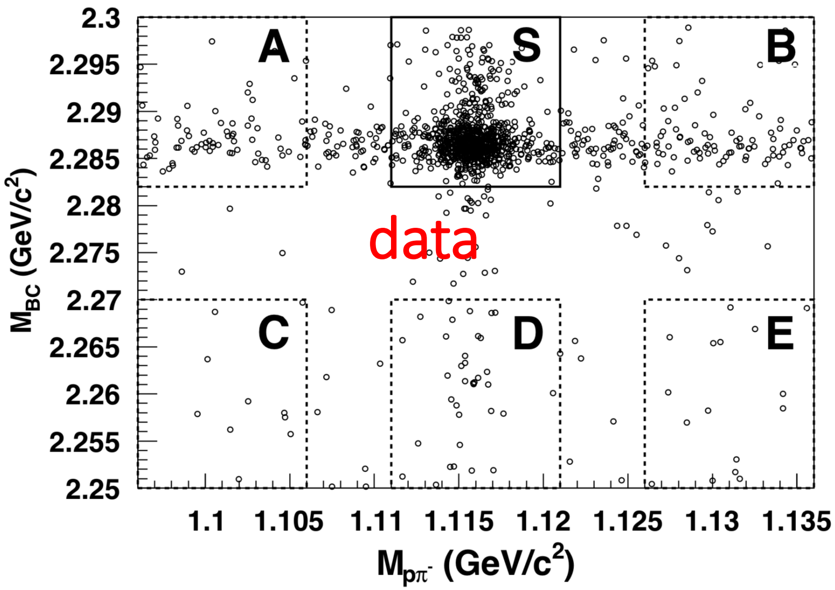
The inclusive channel $\Lambda_c^+ \to \Lambda + X$

- The inclusive process mediated by the *c*-*s* transition.
- Essential input in the calculation of the Λ_c^+ life time.
- Useful in understanding the heavier charmed baryons, esp. the less known double- or triple-charm baryons.
- Current PDG: BF($\Lambda_c^+ \to \Lambda$+X)=(35±11)% with large uncertainty.
- The sum of know exclusive modes only accounts for (24.5±2.1)% => need better understanding of the gap between exclusive and inclusive rates.
- Comparison with K+X will shed light on the Λ_c^+ internal dynamics.
- Search for the CPV by measuring the asymmetry.

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

The inclusive channel $\Lambda_c^+ \to \Lambda + X$

arXiv:1803.05706



$$N^{\rm sig} = N^{\rm S} - \frac{N^{\rm A} + N^{\rm B}}{2} - f \cdot (N^{\rm D} - \frac{N^{\rm C} + N^{\rm E}}{2})$$

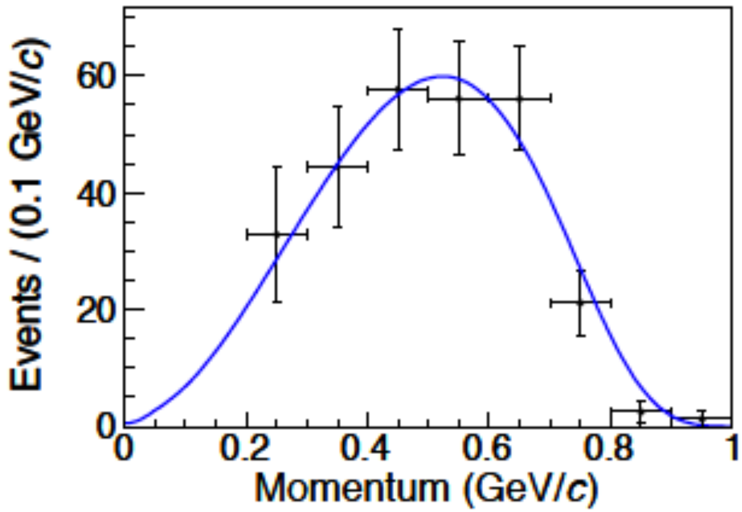
- **In the ST modes of $\Lambda_c^+ \to pK^-\pi^+$ and pK_S^0, to measure the probability of find a Λ in the final states.**
- **Extract yields from 2D distributions in bins of $p-|cos\theta|$**
- **Data-driven 2D efficiency correction using several Λ control samples.**
- $\mathcal{B}(\Lambda_c^+ \to \Lambda + X) = (38.2^{+2.8}_{-2.2} \pm 0.8)\%$
  (excl. rate $(24.5 \pm 2.1)\%$ observed, indicates ~1/3 BFs are unknown)
- $A_{cp} = (2.1^{+7.0}_{-6.6} \pm 1.4)\%$
  (No CPV is observed.)

$\Lambda_c^+ \to e^+ \nu_e + X$

- **Current PDG: BF($\Lambda_c^+ \to e$+X)=(4.5±1.7)%.**
- **Large rate, but also with large uncertainty**
- **Tagged with $\Lambda_c^+ \to pK^-\pi^+$ and pK_S^0**

=> $\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e) = (3.95 \pm 0.34 \pm 0.09)\%$

=> $\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)}{\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e)} = (91.9 \pm 12.5 \pm 5.4)\%$



- **The $\Lambda l^+ \nu_l$ dominate the l^++X =>$\mathcal{B}$ ($pKl^+\nu_l$)~10^{-3}.**

Result	$\Lambda_c^+ \to X e^+ \nu_e$	$\frac{\Gamma(\Lambda_c^+ \to X e^+ \nu_e)}{\bar{\Gamma}(D \to X e^+ \nu_e)}$
BESIII	3.95 ± 0.35	1.26 ± 0.12
MARK II [7]	4.5 ± 1.7	1.44 ± 0.54
Effective-quark Method [9, 10]		1.67
Heavy-quark Expansion [11]		1.2

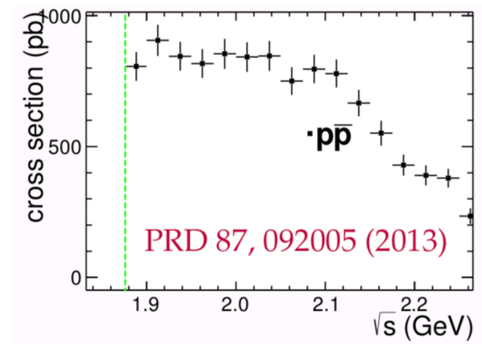
arXiv:1805.09060

The cross-section of baryon pair

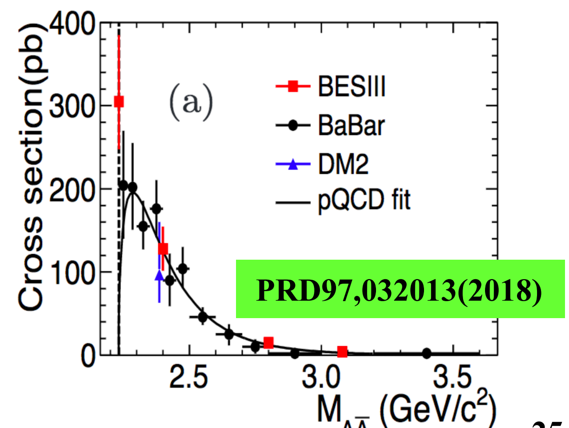
The Born cross section of the reaction $e^+e^- \to \gamma^* \to B\bar{B}$ can be parameterized in terms of electromagnetic form factors:

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

- 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

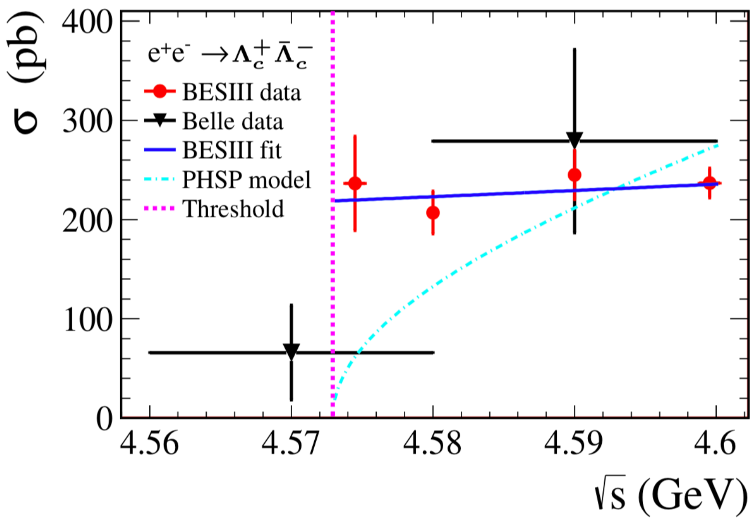


- $e^+e^- \to p\bar{p}$: an enhancement and wide-range plateau in the line-shape
- $e^+e^- \to \Lambda\bar{\Lambda}$: non-zero cross section near threshold
- It can be anticipate that Λ_c^+ has a similar behaviour with proton
- Belle collaboration has measured the cross section of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$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



Cross-section and EMFF of $e^+e^- \to \Lambda_c^+\Lambda_c^-$ near threshold

Phys. Rev. Lett. 120, 132001 (2018).



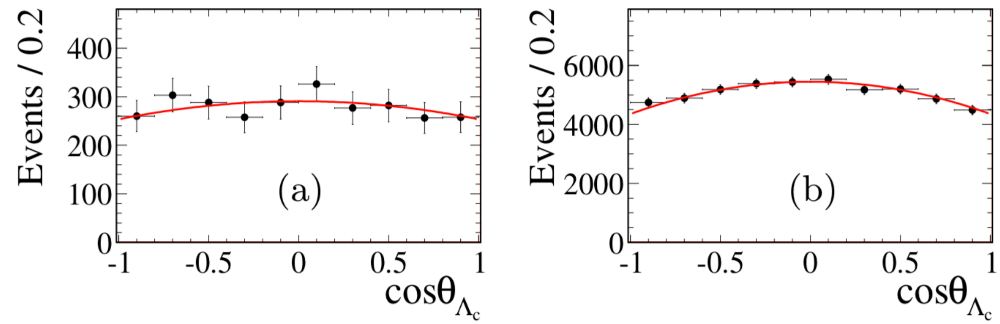


FIG. 3. Angular distribution after efficiency correction and results of the fit to data at $\sqrt{s} = 4574.5$ MeV (a) and 4599.5 MeV (b).

$$|G_E/G_M|^2(1-\beta^2) = (1-\alpha_{\Lambda_c})/(1+\alpha_{\Lambda_c}).$$

- **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?**

- **One of the most basic observables that intimately related to the internal structure of the nucleon.**
- **One of the most challenging questions in contemporary physics is why and how quarks are confined into hadrons.**
- **The electromagnetic form factors (EMFFs) have been a powerful tool in understanding the structure of nucleons.**

$\sqrt{s}$ (MeV)	α_{Λ_c}	$\lvert G_E/G_M \rvert$
4574.5	$-0.13 \pm 0.12 \pm 0.08$	$1.14 \pm 0.14 \pm 0.07$
4599.5	$-0.20 \pm 0.04 \pm 0.02$	$1.23 \pm 0.05 \pm 0.03$

More efforts in the coming years

- BEPCII increase of the maximum energy funded:
  4.6 GeV → 4.7 GeV (~2018 summer) → 4.9 GeV (~2020)
- Era of precision study of the Λ_c decays at BESIII
  to provide more data for theorists to develop more reliable models
  - hadronic decays:
    to explore as-yet-unmeasured channels and understand full picture of intermediate structures
  - more semi-leptonic decays: $\Sigma\pi l^+\nu$, $pK^- l^+\nu$, $p\pi^- l^+\nu$, ...
    understand internal dynamics
  - CPV in charmed baryon:
    BP and BV decay asymmetry, charge-dependent rate of SCS ph^+h^-
  - Rare decays: LFV, BNV, FCNC
- Establishment of absolute BFs for Ξ_c and Ω_c decays?

Many more results are expected in the coming future years.

Summary

- **In recent several years, experimental activities on Λ_c^+ are reviving, esp. at BESIII, Belle &LHCb.**

- **Threshold data at BESIII opens a new door to direct measurements of the decays ➔precise study of Λ_c decays**
  - BESIII has published several world-best results bashed on 567pb^{-1} data.
  - More efforts on hadronic decays with n/Σ/Ξ particles and semi-leptonic decays.
  - Potential to take a large data set for thorough exploration of Λ_c decays

- **BESIII and B factories will be complementary in Λ_c^+ decays and provide the precise measurements in the future several years.**

- **Possibility of studying on the absolute BFs for Ξ_c and Ω_c**