Λ_c^+ physics at BESIII

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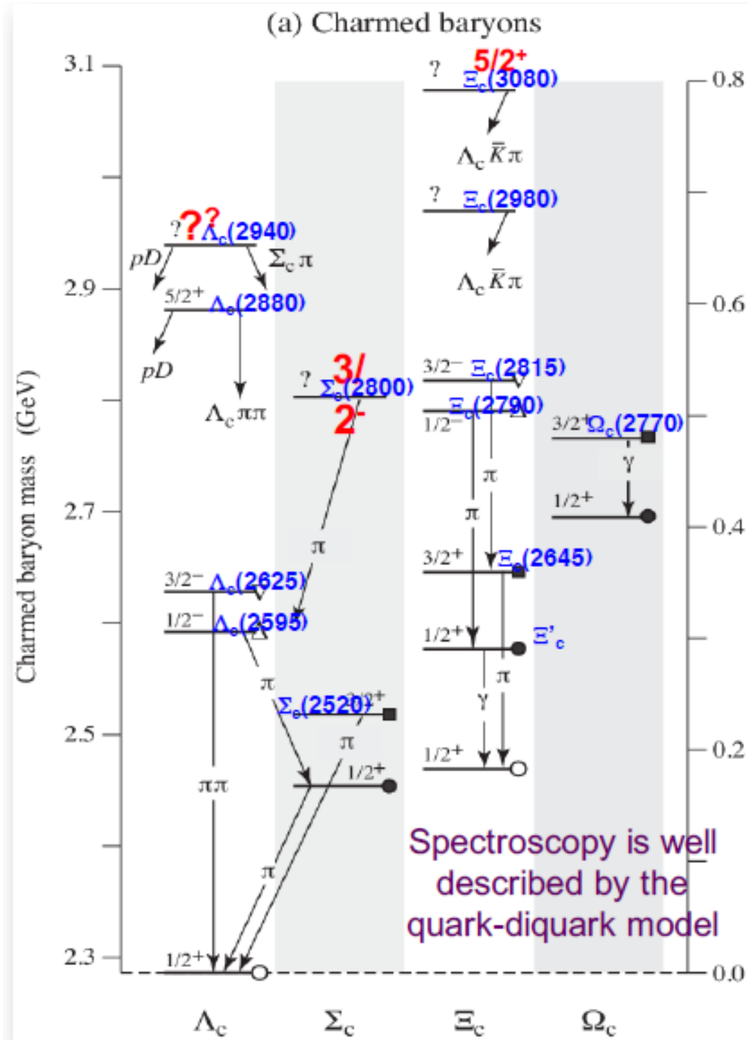
2018.12.15 @ LanZhou

Outline

- Introduction to 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($\Lambda_c^+ \to \Xi^{(*)0}K^+$) : PLB 783,200 (2018)
    - BF($\Lambda_c^+ \to \Sigma^+\boldsymbol{\eta}, \Sigma^+\boldsymbol{\eta}'$) : arXiv:1811,08028 new
  - 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($\boldsymbol{\Lambda_c^+ \to \Lambda}$X) : PRL 121, 062003(2018)
    - BF($\boldsymbol{\Lambda_c^+} \to e$X) : arXiv: 1805.09060(**PRL accepted**)
  - $\Lambda_c^+\Lambda_c^-$ pair cross section : PRL 120,132001(2018).
- Summary & prospect

Renaissance on the charmed heavy baryon

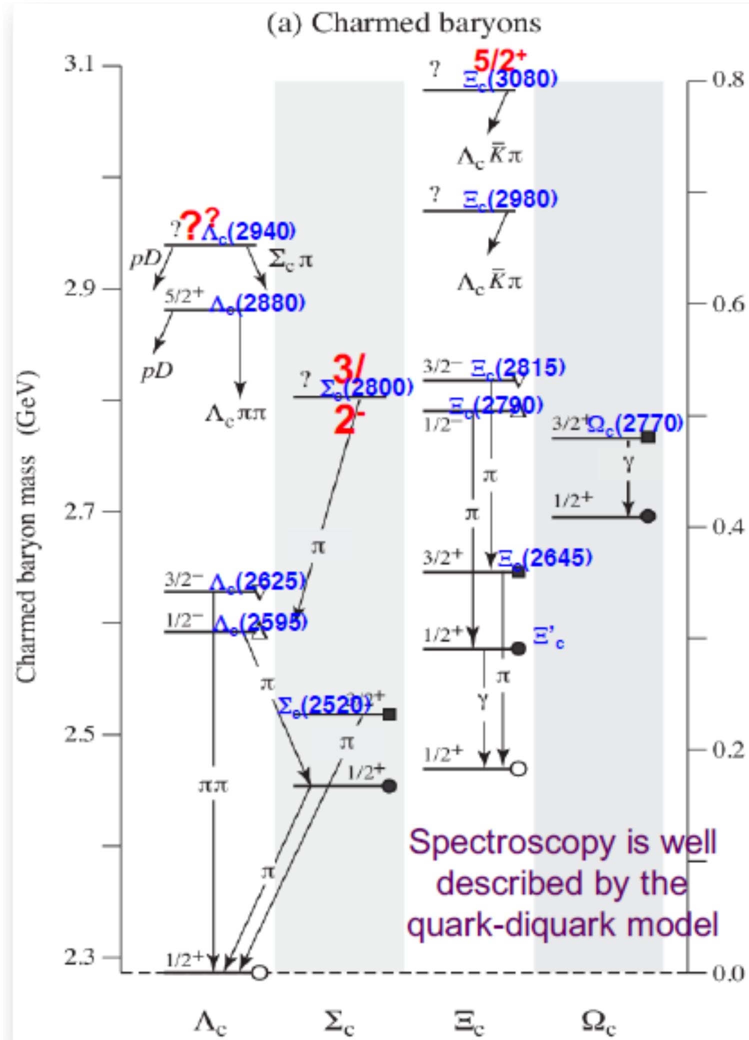
- **Before 2014, the charmed baryons have been produced and studied at many experiments, notably fixed-target experiments (such as FOCUS and SELEX) and e^+e^- B-factories (ARGUS, CLEO, BABAR, and BELLE).**
- **Large uncertainties in experiment=>Retarder development in theory.**
- **Afterwards, more extensive 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.**



The charmed baryon family

- **Singly charmed baryons**
  - Established ground states:

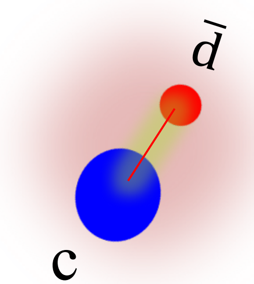
    Λ_c^+, Σ_c, $\Xi_c^{(\prime)}$, Ω_c
  - Excited states are being explored
- **Doubly charmed baryons(Ξ_{cc}^{++}) observed recently.**
- **No observations of triply charmed baryons.**



- ✓ **Λ_c^+ decay only weakly, many recent experimental progress since 2014.**
- ✓ **Σ_c: B($\Sigma_c \rightarrow \Lambda_c^+\pi$)~100%, B($\Sigma_c \rightarrow \Lambda_c^+\gamma$)?**
- ✓ **Ξ_c : decay only weakly; no absolute BF measured, most relative to Ξ^- $\pi^+(\pi^+)$.**
- ✓ **Ω_c:decay only weakly; no absolute BF measured.**

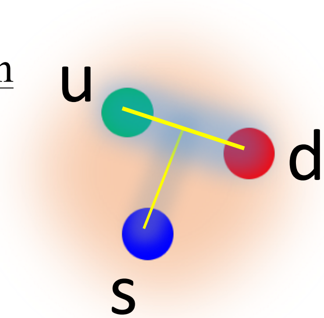
Λ_c^+: The lightest charmed baryon spectroscopy

- 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).



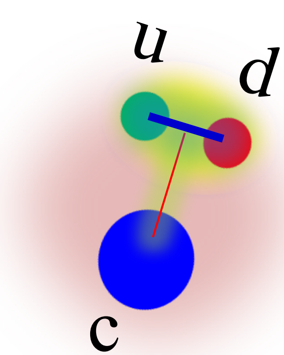
→ Charmed meson ($D^+[c\bar{d}]$)

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



→ Strange baryons ($\Lambda[uds]$)

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

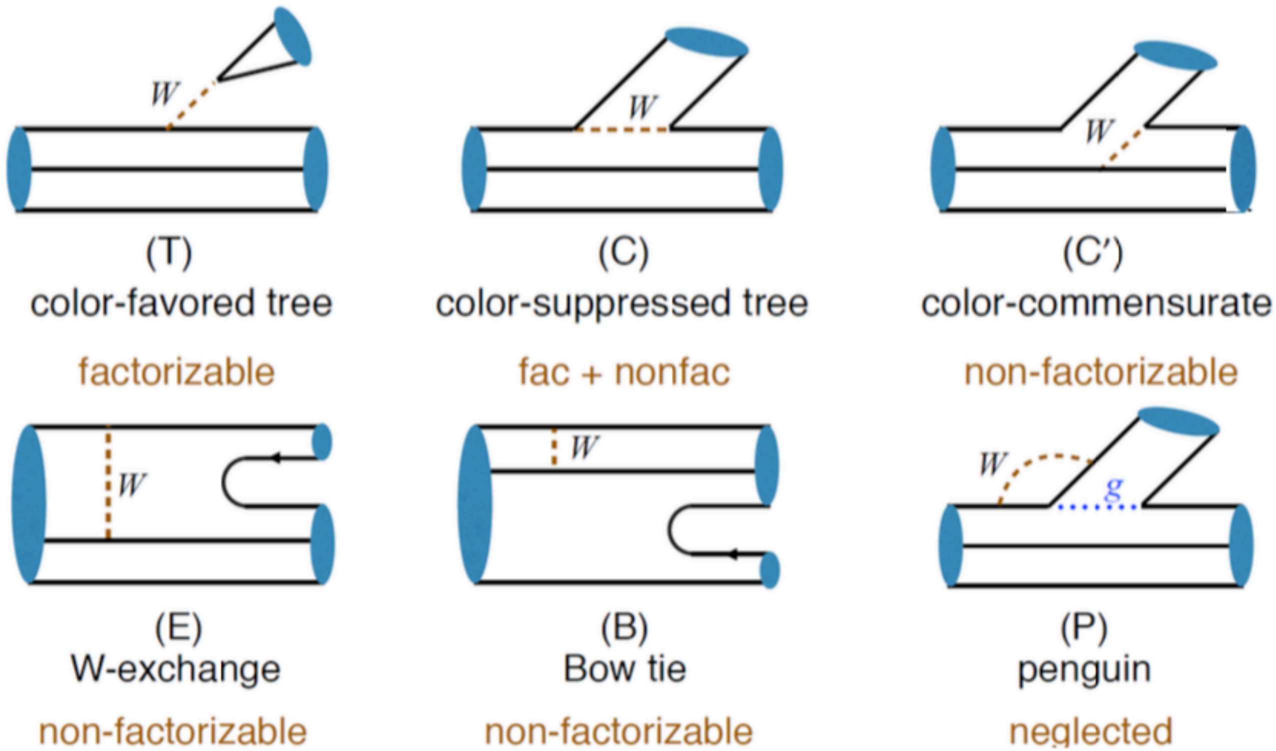


→ Charmed baryon ($\Lambda_c[udc]$)

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

Λ_c^+ weak decays

- **Contrary to charmed meson, W-exchange contribution is important.(No color suppress and helicity suppress)**



- **Phenomenology aim at explain data and predict important observables.**
- **Calculate what they can(HQET, factorization)+parametrize what they cannot + some non-perturbations extracted from data=> explain and predict.**

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: *<u>the most simple and straightforward.</u>***
- **~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.**

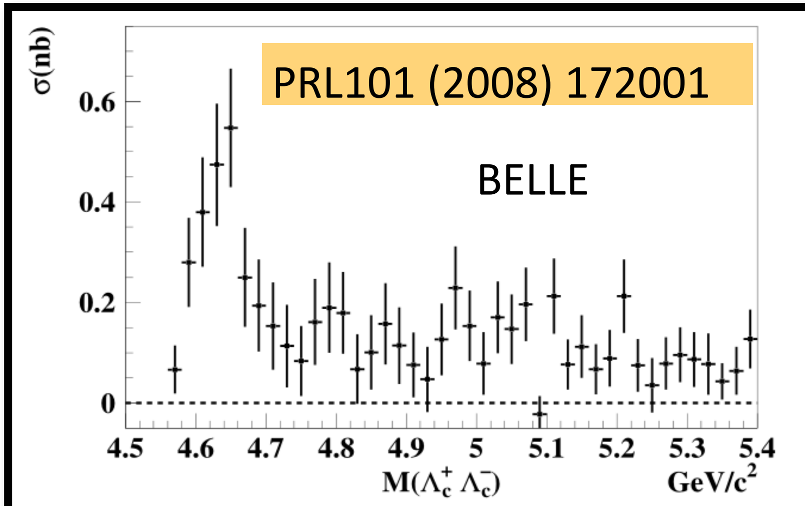


FIG. 4: The cross section for the exclusive process $e^+e^- \to \Lambda_c^+\Lambda_c^-$.

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}-$2M_{\Lambda c}$=26MeV only!
- $\Lambda_c^+\Lambda_c^-$ produced in pairs with no additional accompany hadrons.
  - $e^+e^- \rightarrow \gamma^* \rightarrow \Lambda_c^+\Lambda_c^-$
- 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

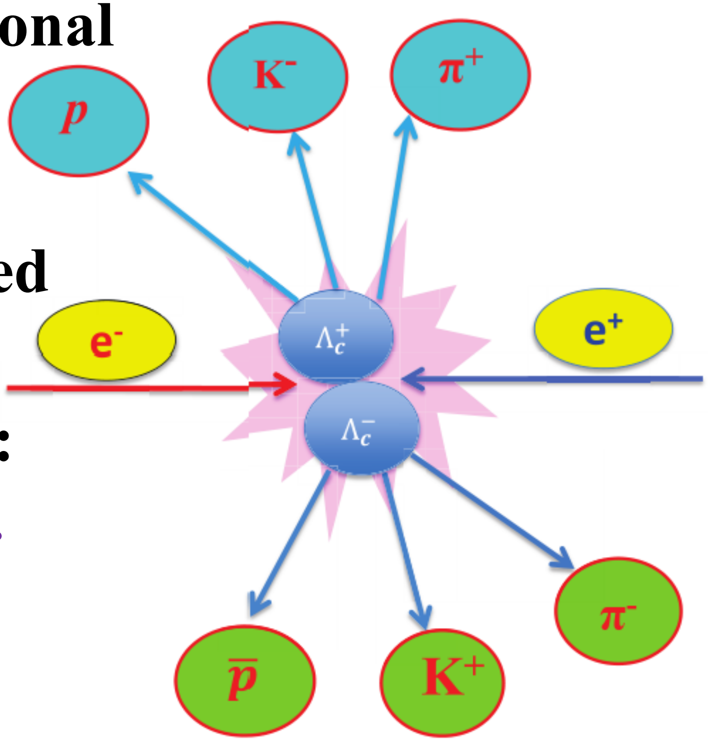
    =>Full reconstruction
  - Double Tag(DT): detec both of $\Lambda_c^+\Lambda_c^-$

    =>Smaller backgrounds.

    =>Missing technique.

    =>Lower efficiencies.

    =>Systematic in tag side are mostly cancelled.

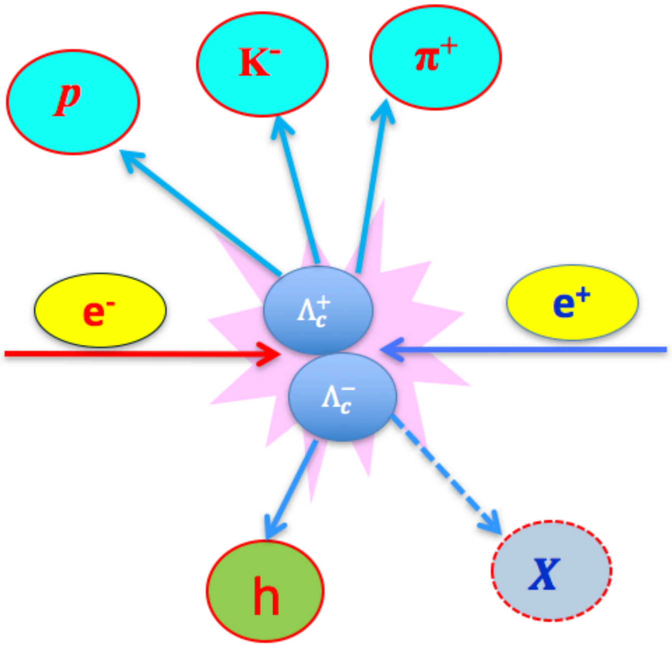


Several popular variables

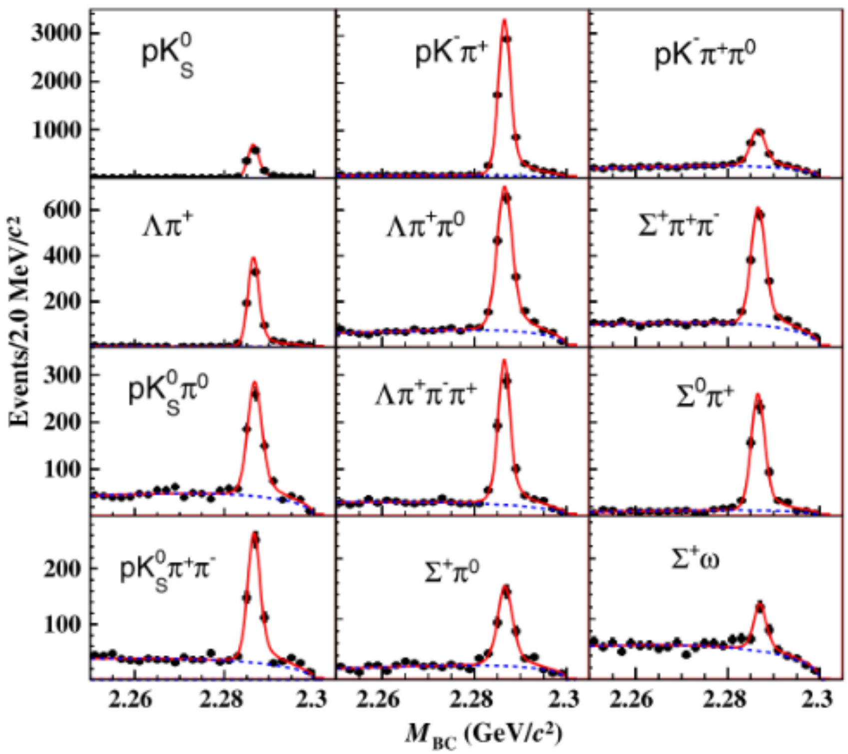
- $\Delta E = E_{\Lambda c} - E_{beam}$
- **Beam-Constrained-Mass;**

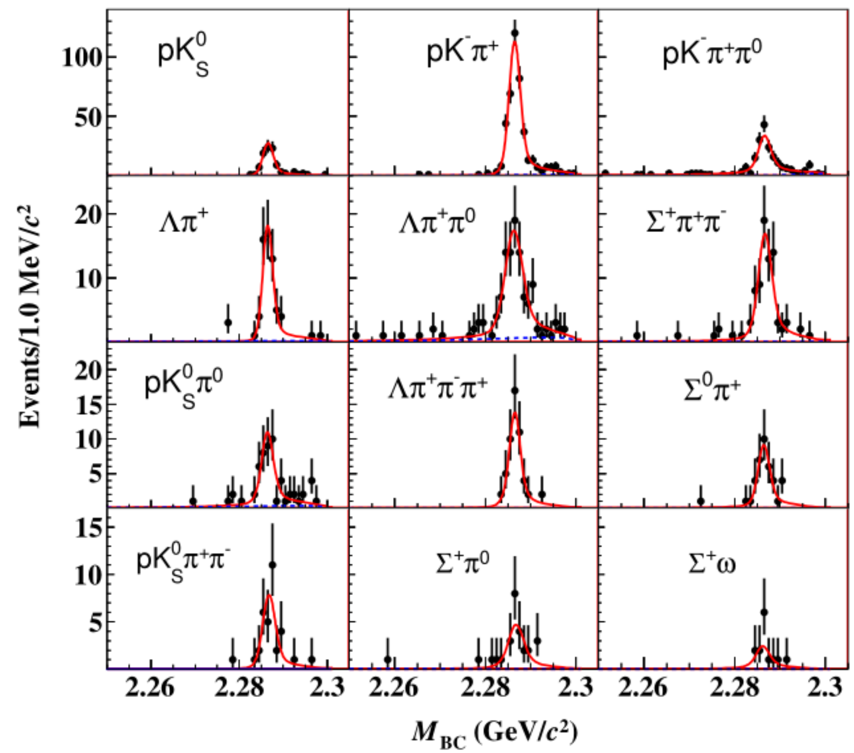
  $$M_{BC} = \sqrt{E_{beam}^2 - |\vec{p}_{\Lambda c}|^2}$$

- $E_{miss} = E_{beam} - E_h$
- $\vec{p}_{miss} = \vec{p}_{\Lambda c} - \vec{p}_h$
- $\vec{p}_{\Lambda c} = -\hat{p}_{tag} \cdot \sqrt{E_{beam}^2 - m_{\Lambda c}^2}$
- $U_{miss} = E_{miss} - |\vec{p}_{miss}|$
- $M_{miss} = \sqrt{E_{miss}^2 - |\vec{p}_{miss}|^2}$
  - $\hat{p}_{tag}$ 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





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

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

- **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

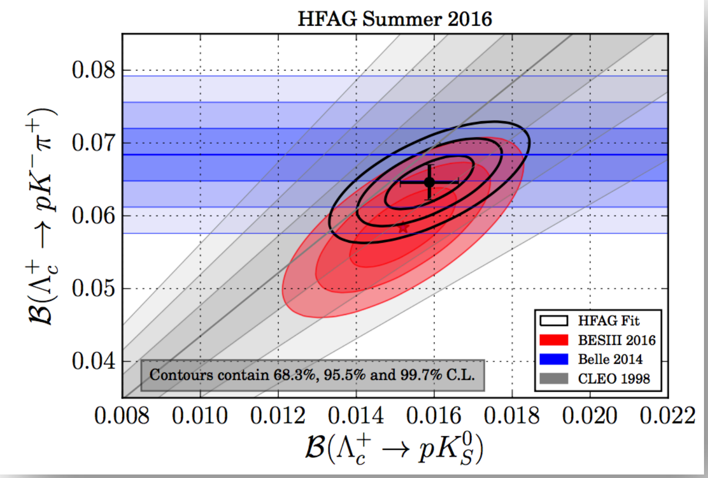
- **No absolute measurement (Model independently) on Λ_c^+ BFs at threshold after Λ_c^+ discovered(30 years ago).**
- **A least square global fit taking into account correlations over different modes are performed to improve the precision.**
- **The precision of B($pK^-\pi^+$) are comparable with Belle's**
- **The precisions of Λ_c decay rates is reaching to the level of charmed mesons!**
- **$N_{\Lambda_c^+\bar{\Lambda}_c^-}$ 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

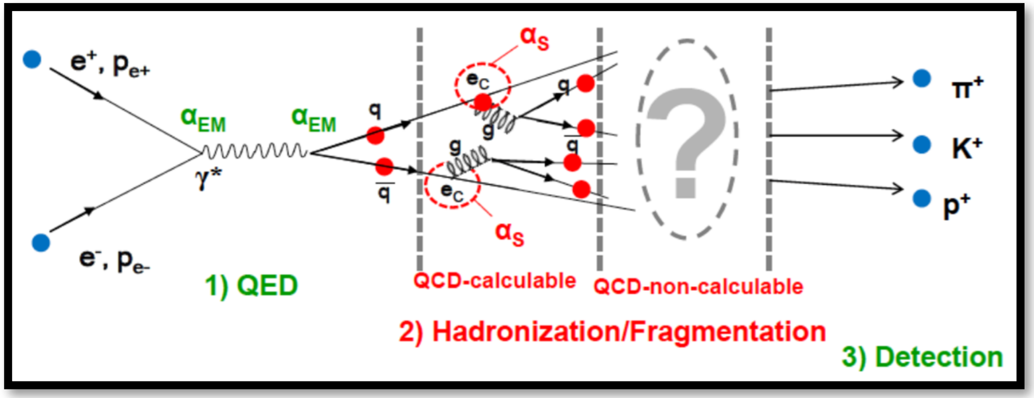
Important Input for b physics

- **stringent Fragmentation Function of b/c quark to baryon**
  - [Eur. Phys. J. C12, 225 (2000); Eur. Phys. J. C 16, 597 (2000); Phys. Rev. D 85, 032008 (2012), Phys. Rev.D 66, 091101 (2002).]
  - Fragmentation Function (FF) is an important probe in experiment to test and calibrate QCD theory.

PhysRevD.85.032008

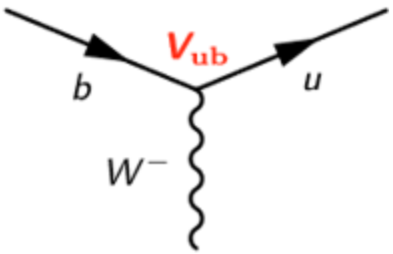
TABLE IV. Systematic uncertainties on the absolute scale of $f_{\Lambda_b}/(f_u + f_d)$.

Source	Error (%)
Bin-dependent errors	2.2
$\mathcal{B}(\Lambda_b^0 \to D^0 p X \mu^- \bar{\nu})$	2.0
Monte Carlo modelling	1.0
Backgrounds	3.0
Tracking efficiency	2.0
Γ_{sl}	2.0
Lifetime ratio	2.6
PID efficiency	2.5
Subtotal	6.3
$\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)$	26.0
Total	26.8



- **Now B($pK^-\pi^+$) are still dominated**

CKM matrix element V_{ub}



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}, \quad \frac{\sigma(V_{CKM})}{V_{CKM}}^{\text{PDG 2014}} \sim \begin{pmatrix} 0.02\% & 0.3\% & 12\% \\ 4\% & 2\% & 2\% \\ 7\% & 7\% & 3\% \end{pmatrix}$$

$$\underbrace{\frac{\mathcal{B}(\Lambda_b \to p\mu^-\nu_\mu)}{\mathcal{B}(\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu)}}_{\text{Measure this experimentally}} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \times \underbrace{\frac{G(\Lambda_b \to p\mu^-\nu_\mu)}{G(\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu)}}_{\text{Get this from theory}}$$

Nature Physics 11 (2015) 743

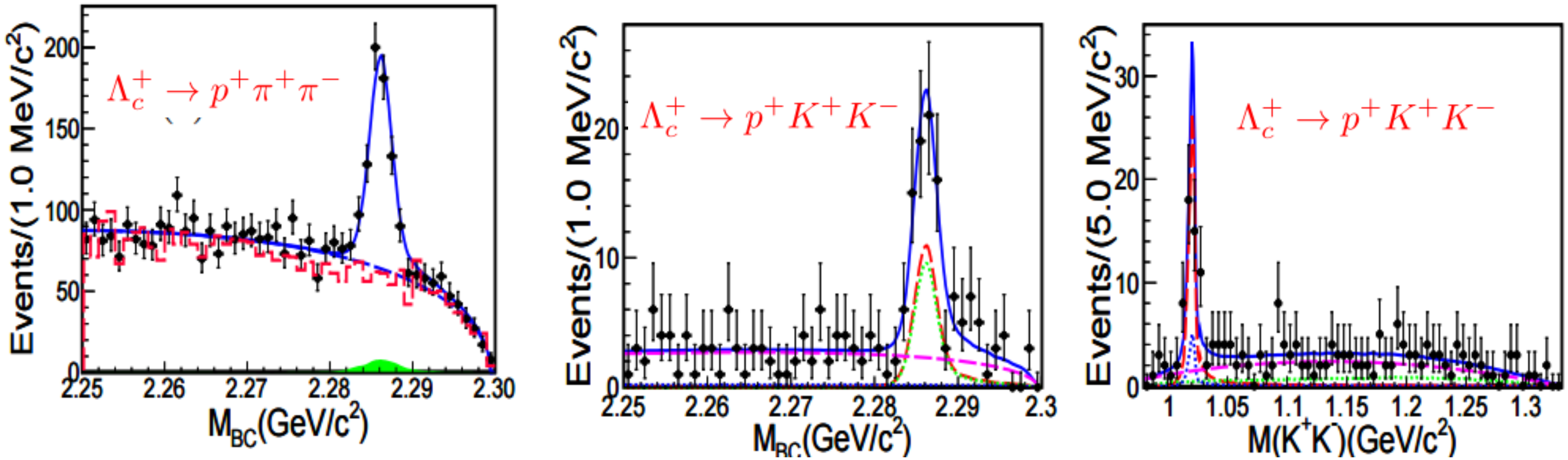
Source	Relative uncertainty (%)
$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$	$^{+4.7}_{-5.3}$
Trigger	[illegible]
Tracking	3.0
Λ_c^+ selection efficiency	3.0
$\Lambda_b^0 \to N^*\mu^-\overline{\nu}_\mu$ shapes	2.3
Λ_b^0 lifetime	1.5
Isolation	1.4
Form factor	1.0
Λ_b^0 kinematics	0.5
q^2 migration	0.4
PID	0.2
Total	$^{+7.8}_{-8.2}$

B($pK^-\pi^+$) are dominated systematic uncertainty

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 C 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)	$(5.47 \pm 1.30 \pm 0.41 \pm 0.33) \times 10^{-4}$	$(3.5 \pm 1.7) \times 10^{-4}$

$\Lambda_c^+ \to p\phi$: test large-N_c expansion

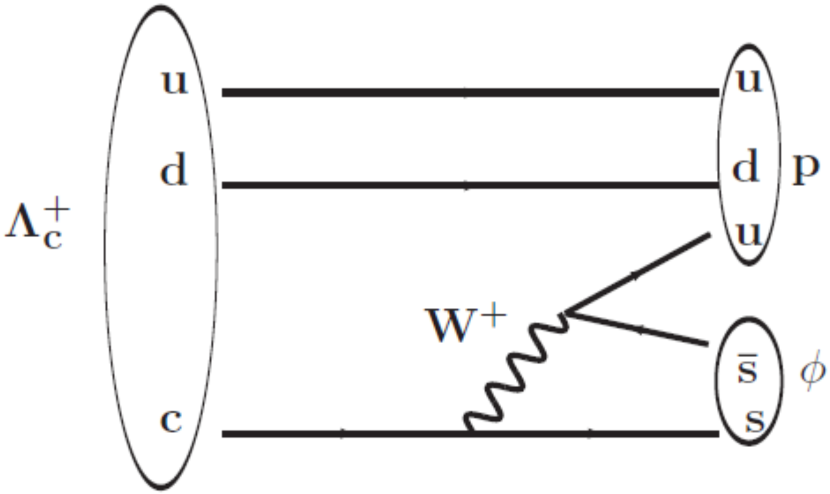
- **Charmed meson decays**

$$a_1 = c_1(\mu) + c_2(\mu)\,(1/N_c + \chi_1(\mu)),$$

$$a_2 = c_2(\mu) + c_1(\mu)\,(1/N_c + \chi_2(\mu)),$$

If $\chi_1 = \chi_2 = 0$, naïve factorization

If $\chi_1 = \chi_2 \approx -1/N_c$, large-$N_c$ factorization

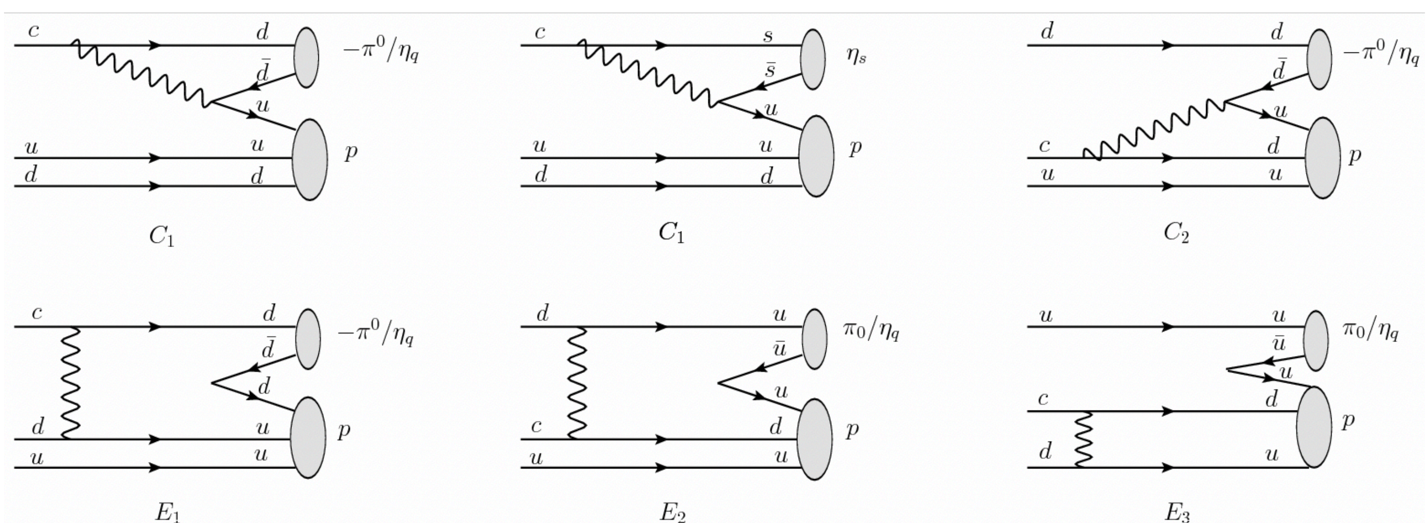


- $\Lambda_c^+ \to p\phi$ proceeds **only** through internal W-emission C diagram.
- **Input BF ⇒ $|a_2|$=0.45±0.03, Nc ≈7, close to $a_2(m_c)\approx$ -0.44(from theory)**
- **$1/N_c$ is also applicable to charmed baryon sector.**
- **BESIII measurement are consistent with previous measurement.**

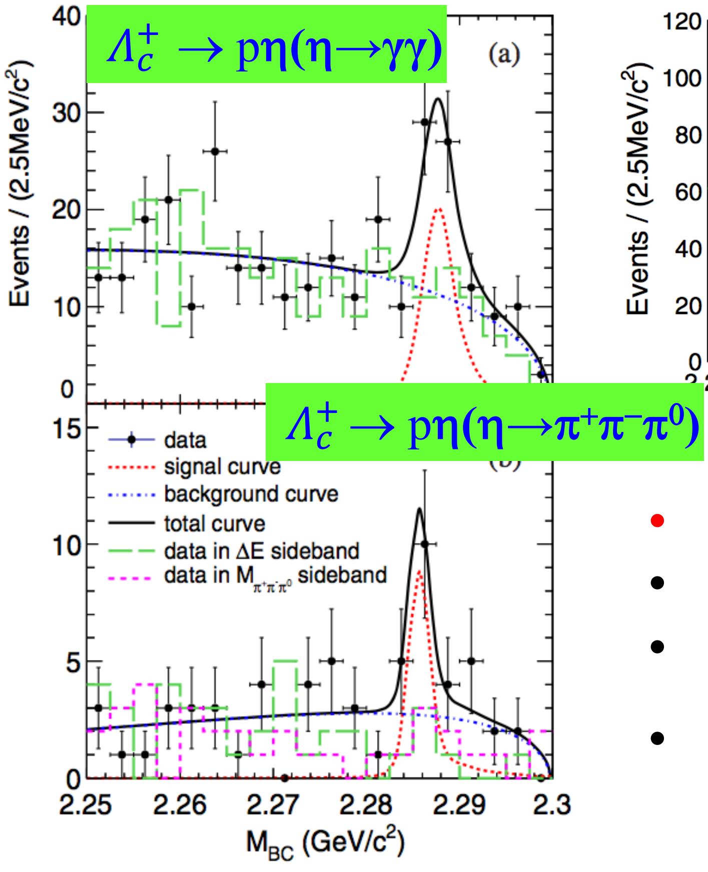
arXiv:1801.08625

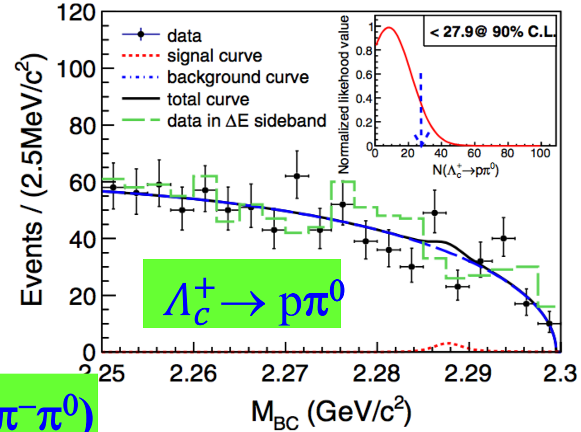
Singly Cabibbo-Suppressed Decays of $\Lambda_c^+ \to p\pi^0$ and $\Lambda_c^+ \to p\eta$

- 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
- $B(\Lambda_c^+ \to p\eta) = (1.24 \pm 0.28 \pm 0.10) \times 10^{-3}$
- No signal seen in $\Lambda_c^+ \to p\pi^0$, $B(\Lambda_c^+ \to p\pi^0) < 2.7 \times 10^{-4}$
- $\mathcal{B}(\Lambda_c^+ \to p\pi^0)/\mathcal{B}(\Lambda_c^+ \to p\eta) < 0.24$

PhysRevD.97.074028

(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

TABLE 2. The data of the $\mathbf{B}_c \to \mathbf{B}_n M$ decays.

Branching ratios	Data [4, 7]	Branching ratios	Data [4, 7]
$10^2\mathcal{B}(\Lambda_c^+ \to p\bar{K}^0)$	3.16 ± 0.16	$10^2\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta)$	0.70 ± 0.23
$10^2\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+)$	1.30 ± 0.07	$10^4\mathcal{B}(\Lambda_c^+ \to \Lambda K^+)$	6.1 ± 1.2
$10^2\mathcal{B}(\Lambda_c^+ \to \Sigma^+\pi^0)$	1.24 ± 0.10	$10^4\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)$	5.2 ± 0.8
$10^2\mathcal{B}(\Lambda_c^+ \to \Sigma^0\pi^+)$	1.29 ± 0.07	$10^4\mathcal{B}(\Lambda_c^+ \to p\eta)$	12.4 ± 3.0
$10^2\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)$	0.50 ± 0.12	$\mathcal{R} = \frac{\mathcal{B}(\Xi_c^0 \to \Lambda\bar{K}^0)}{\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)}$	0.420 ± 0.056

$10^4\mathcal{B}(\Lambda_c^+ \to p\pi^0) = 0.80 \pm 1.36$?

BRs of Cabibbo-allowed decays

channel	$10^3\mathrm{BR}_{th}$	$10^3\mathrm{BR}_{EX}$
$\Xi_c^0 \to \Sigma^+ K^-$	3.7 ± 0.6	-
$\Xi_c^0 \to \Sigma^0 \bar{K}^0$	1.0 ± 0.6	-
$\Xi_c^0 \to \Xi^0 \pi^0$	6.1 ± 1.1	-
$\Xi_c^0 \to \Xi^0 \eta$	3.1 ± 0.6	-
$\Xi_c^0 \to \Xi^- \pi^+$	20.3 ± 0.9	-
$\Xi_c^0 \to \Lambda^0 \bar{K}^0$	9.3 ± 0.9	-
$\Xi_c^+ \to \Sigma^+ \bar{K}^0$	2.1 ± 1.5	-
$\Xi_c^+ \to \Xi^0 \pi^+$	4.2 ± 1.9	
$\Lambda_c^+ \to \Sigma^+ \pi^0$	12.6 ± 2.1	12.4 ± 1.0
$\Lambda_c^+ \to \Sigma^+ \eta$	5.4 ± 1.0	7.0 ± 2.3
$\Lambda_c^+ \to \Sigma^0 \pi^+$	12.6 ± 2.1	12.9 ± 0.7
$\Lambda_c^+ \to \Xi^0 K^+$	5.9 ± 1.0	5.9 ± 1.0
$\Lambda_c^+ \to p \bar{K}^0$	31.3 ± 1.6	31.6 ± 1.6
$\Lambda_c^+ \to \Lambda^0 \pi^+$	13.1 ± 1.6	13.0 ± 0.7

BRs of Cabibbo-suppressed decays

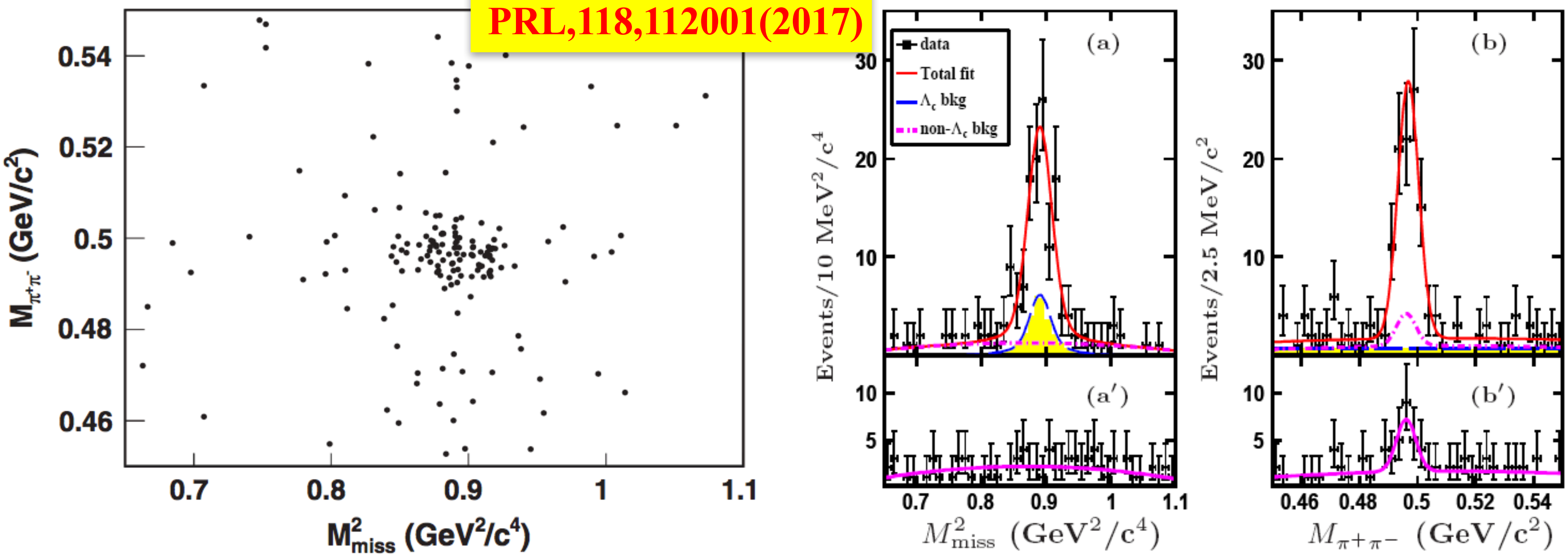
channel	$10^4\mathrm{BR}_{th}$	$10^4\mathrm{BR}_{EX}$
$\Xi_c^0 \to \Sigma^+ \pi^-$	2.2 ± 0.4	-
$\Xi_c^0 \to \Sigma^0 \pi^0$	2.8 ± 0.3	-
$\Xi_c^0 \to \Sigma^0 \eta$	1.0 ± 0.2	-
$\Xi_c^0 \to \Sigma^- \pi^+$	11.7 ± 0.5	-
$\Xi_c^0 \to \Xi^0 K^0$	6.2 ± 1.0	-
$\Xi_c^0 \to \Xi^- K^+$	9.8 ± 0.4	-
$\Xi_c^0 \to p K^-$	2.3 ± 0.4	-
$\Xi_c^0 \to n \bar{K}^0$	7.8 ± 1.3	-
$\Xi_c^0 \to \Lambda^0 \pi^0$	1.0 ± 0.3	-
$\Xi_c^0 \to \Lambda^0 \eta$	2.7 ± 0.3	-
$\Xi_c^+ \to \Sigma^+ \pi^0$	20.3 ± 2.0	-
$\Xi_c^+ \to \Sigma^+ \eta$	8.2 ± 1.9	-
$\Xi_c^+ \to \Sigma^0 \pi^+$	23.5 ± 2.3	-
$\Xi_c^+ \to \Xi^0 K^+$	9.8 ± 3.3	-
$\Xi_c^+ \to p \bar{K}^0$	29.2 ± 5.2	-
$\Xi_c^+ \to \Lambda^0 \pi^+$	5.1 ± 2.1	-
$\Lambda_c^+ \to \Sigma^+ K^0$	11.4 ± 2.0	-
$\Lambda_c^+ \to \Sigma^0 K^+$	5.7 ± 1.0	5.2 ± 0.8
$\Lambda_c^+ \to p \pi^0$	1.3 ± 0.7	0.8 ± 1.3
$\Lambda_c^+ \to p \eta$	13.0 ± 1.0	12.4 ± 3.0
$\Lambda_c^+ \to n \pi^+$	6.1 ± 2.0	-
$\Lambda_c^+ \to \Lambda^0 K^+$	6.4 ± 0.9	6.1 ± 1.2

From Chao-Qiang Geng' report at Wuhan

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

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

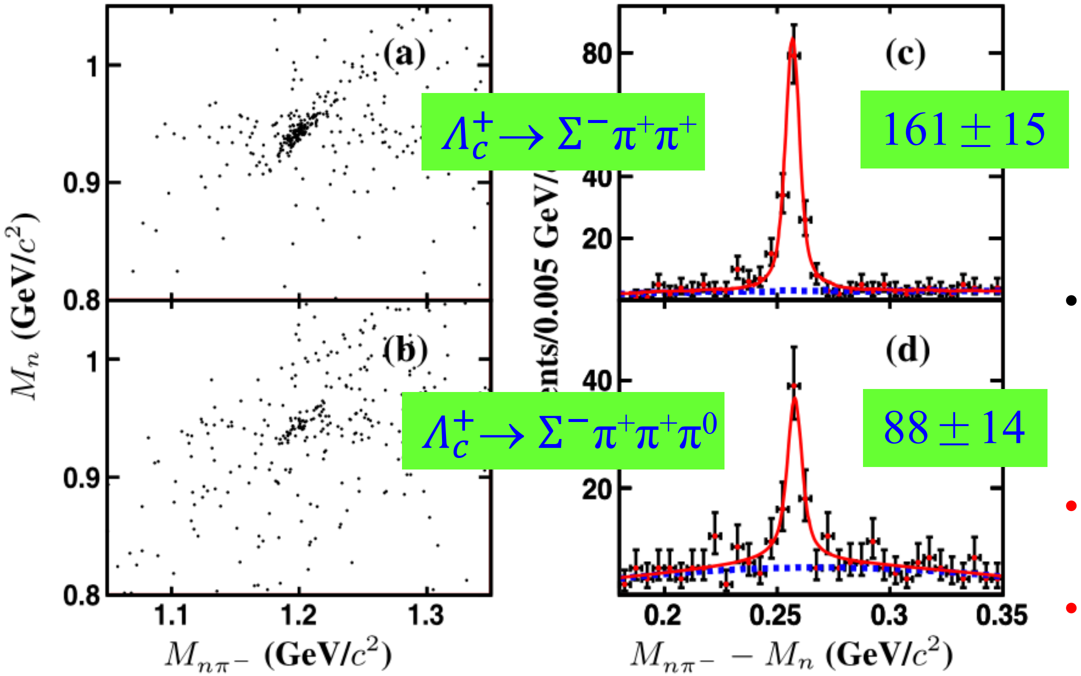
PRL,118,112001(2017)



- 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)

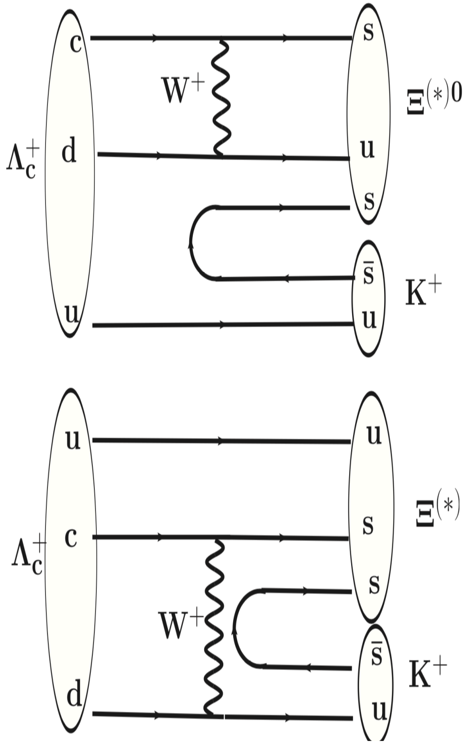
- **Λ_c^+ decay involving the neutron in the final state(missing technique). Less known in experiment.**
- **$B(\Lambda_c^+ \to \Sigma^- \pi^+ \pi^+ \pi^0) = (2.11 \pm 0.33 \pm 0.14)\%$**
- **$B(\Lambda_c^+ \to \Sigma^- \pi^+ \pi^+) = (1.81 \pm 0.17 \pm 0.09)\%$** more precise than old result $(2.3 \pm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

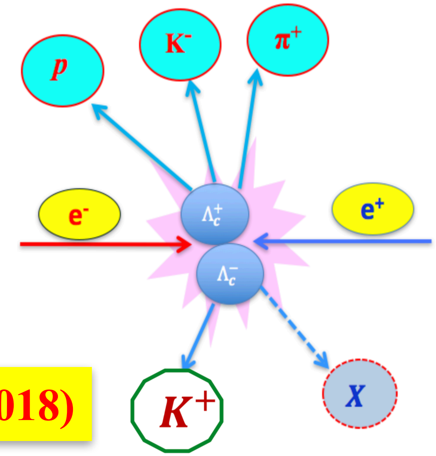


- **$\Lambda_c^+ \to \Xi^{0(*)} K^+$ decay only through W-exchange.**
- **W-exchange are non-factorable in theoretic calculation.**
- **Large cancellation both in S-wave and P-wave.**
- **This measurement helps in calibration of the W-exchange process in the charmed baryon sector.**
- **The previous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

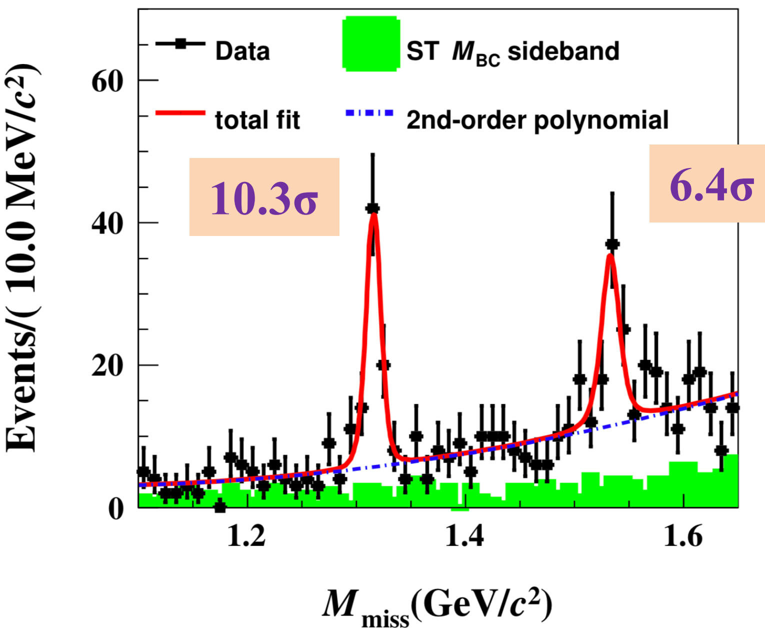


$$\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+) = (5.90\pm0.86\pm0.39)\times10^{-3}$$

$$\mathcal{B}(\Lambda_c^+ \to \Xi(1530)^0 K^+) = (5.02\pm0.99\pm0.31)\times10^{-3}$$

PLB 783,200 (2018)

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



$\Lambda_c^+ \to \Sigma^+\eta, \Sigma^+\eta'$

1811.08028

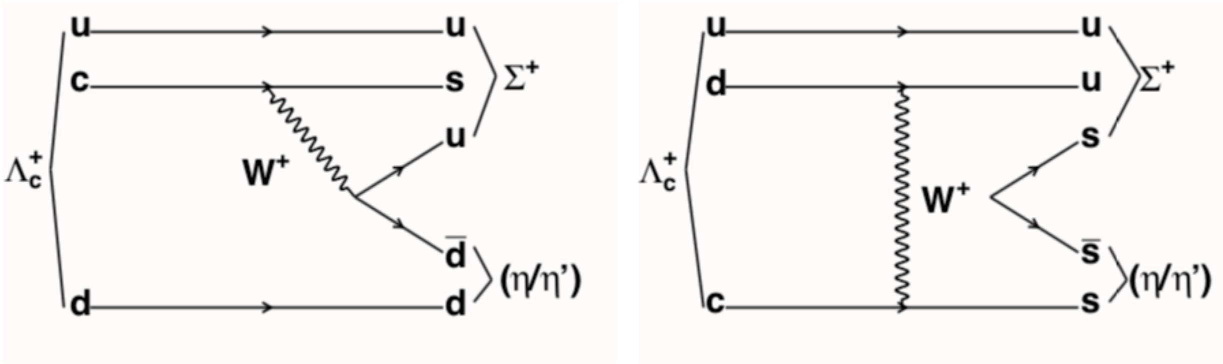
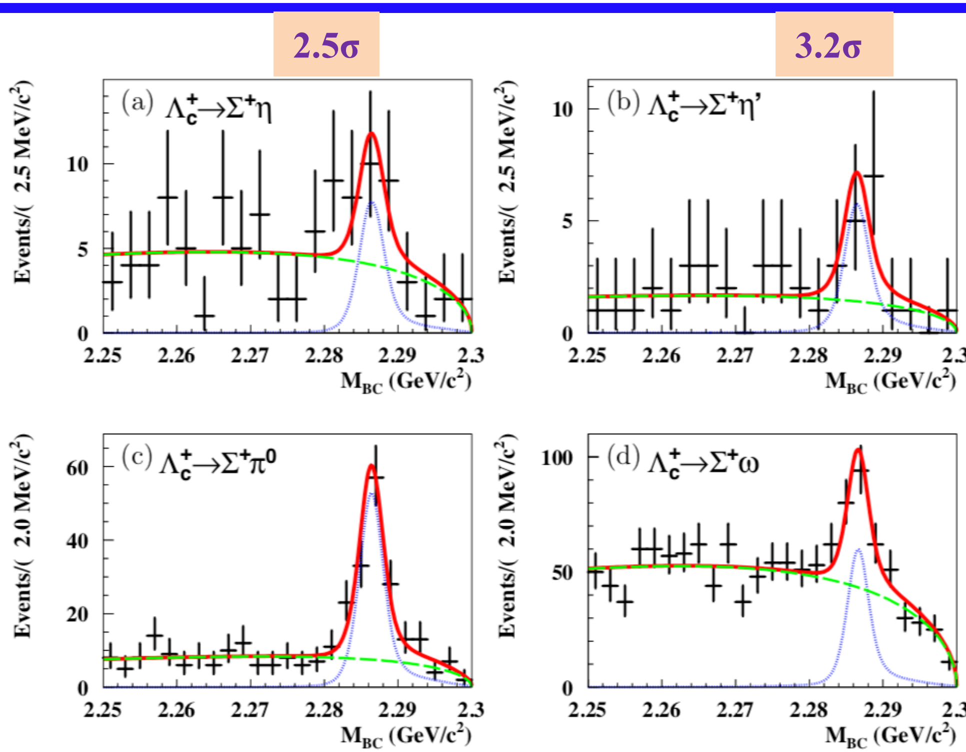


Figure 1. Representative tree level diagrams of decays of $\Lambda_c^+ \to \Sigma^+\eta$ and $\Lambda_c^+ \to \Sigma^+\eta'$.

- **Decay through internal W-emission and W-exchange.**
- **Both are non-factorable in theoretic calculation.**
- **Large variations in theory: $B(\Lambda_c^+ \to \Sigma^+\eta)$ =(0.11-0.94)%, $B(\Lambda_c^+ \to \Sigma^+\eta')$ =(0.1-1.28)%**
- **$\Lambda_c^+ \to \Sigma^+\eta$ is measured by CLEO with BF=(0.70±0.23)% (~33% uncertainty)**
- **$\Lambda_c^+ \to \Sigma^+\eta'$ is not observed yet.**

$\Lambda_c^+ \to \Sigma^+\eta\,,\Sigma^+\eta'$

1811.08028



$$R_{ac} = \frac{\mathcal{B}(a)}{\mathcal{B}(c)} = \frac{N_a\varepsilon_c\mathcal{B}(\pi^0\to\gamma\gamma)}{N_c\varepsilon_a\mathcal{B}(\eta\to\gamma\gamma)}$$

$$R_{bd} = \frac{\mathcal{B}(b)}{\mathcal{B}(d)} = \frac{N_b\varepsilon_d\mathcal{B}(\omega\to\pi^+\pi^-\pi^0)\mathcal{B}(\pi^0\to\gamma\gamma)}{N_d\varepsilon_b\mathcal{B}(\eta'\to\pi^+\pi^-\eta)\mathcal{B}(\eta\to\gamma\gamma)}$$

Decay mode	N_i	ε_i (%)
(a) $\Lambda_c^+ \to \Sigma^+\eta$	14.6 ± 6.6	7.80
(b) $\Lambda_c^+ \to \Sigma^+\eta'$	13.0 ± 4.8	4.61
(c) $\Lambda_c^+ \to \Sigma^+\pi^0$	122.4 ± 14.5	8.98
(d) $\Lambda_c^+ \to \Sigma^+\omega$	135.4 ± 20.4	7.83

$$\frac{\mathcal{B}(\Lambda_c^+\to\Sigma^+\eta)}{\mathcal{B}(\Lambda_c^+\to\Sigma^+\pi^0)} = 0.35\pm0.16\pm0.03 \qquad \frac{\mathcal{B}(\Lambda_c^+\to\Sigma^+\eta)}{\mathcal{B}(\Lambda_c^+\to\Sigma^+\pi^0)} < 0.58$$

$$\frac{\mathcal{B}(\Lambda_c^+\to\Sigma^+\eta')}{\mathcal{B}(\Lambda_c^+\to\Sigma^+\omega)} = 0.86\pm0.34\pm0.07 \qquad \frac{\mathcal{B}(\Lambda_c^+\to\Sigma^+\eta')}{\mathcal{B}(\Lambda_c^+\to\Sigma^+\omega)} < 1.2$$

$$\frac{\mathcal{B}(\Lambda_c^+\to\Sigma^+\eta')}{\mathcal{B}(\Lambda_c^+\to\Sigma^+\eta)} = 3.5\pm2.1\pm0.4$$

- **$\Lambda_c^+ \to \Sigma^+\eta$ is smaller than CLEO but still compatible within uncertainty.**
- **$\Lambda_c^+ \to \Sigma^+\eta'$ is measured for first time.**
- **Our measurement contradict with most theoretical calculations.**

Decay mode	Körner [5]	Sharma [3]	Zenczykowski [4]	Ivanov [6]	CLEO [12]	This work
$\Lambda_c^+ \to \Sigma^+\eta$	0.16	0.57	0.94	0.11	0.70±0.23	0.41±0.20 (<0.68)
$\Lambda_c^+ \to \Sigma^+\eta'$	1.28	0.10	0.12	0.12	-	1.34±0.57 (<1.9)

TABLE 2. The data of the $\mathbf{B}_c \to \mathbf{B}_n M$ decays.

Branching ratios	Data [4, 7]	Branching ratios	Data [4, 7]
$10^2\mathcal{B}(\Lambda_c^+ \to p\bar{K}^0)$	3.16 ± 0.16	$10^2\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta)$	0.70 ± 0.23
$10^2\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+)$	1.30 ± 0.07	$10^4\mathcal{B}(\Lambda_c^+ \to \Lambda K^+)$	6.1 ± 1.2
$10^2\mathcal{B}(\Lambda_c^+ \to \Sigma^+\pi^0)$	1.24 ± 0.10	$10^4\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)$	5.2 ± 0.8
$10^2\mathcal{B}(\Lambda_c^+ \to \Sigma^0\pi^+)$	1.29 ± 0.07	$10^4\mathcal{B}(\Lambda_c^+ \to p\eta)$	12.4 ± 3.0
$10^2\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)$	0.50 ± 0.12	$\mathcal{R} = \frac{\mathcal{B}(\Xi_c^0 \to \Lambda\bar{K}^0)}{\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)}$	0.420 ± 0.056

$10^4\mathcal{B}(\Lambda_c^+ \to p\pi^0) = 0.80 \pm 1.36$

BRs of Cabibbo-allowed decays

channel	$10^3\mathrm{BR}_{th}$	$10^3\mathrm{BR}_{EX}$
$\Xi_c^0 \to \Sigma^+ K^-$	3.7 ± 0.6	-
$\Xi_c^0 \to \Sigma^0 \bar{K}^0$	1.0 ± 0.6	-
$\Xi_c^0 \to \Xi^0 \pi^0$	6.1 ± 1.1	-
$\Xi_c^0 \to \Xi^0 \eta$	3.1 ± 0.6	-
$\Xi_c^0 \to \Xi^- \pi^+$	20.3 ± 0.9	-
$\Xi_c^0 \to \Lambda^0 \bar{K}^0$	9.3 ± 0.9	-
$\Xi_c^+ \to \Sigma^+ \bar{K}^0$	2.1 ± 1.5	-
$\Xi_c^+ \to \Xi^0 \pi^+$	4.2 ± 1.9	
$\Lambda_c^+ \to \Sigma^+ \pi^0$	12.6 ± 2.1	12.4 ± 1.0
$\Lambda_c^+ \to \Sigma^+ \eta$	5.4 ± 1.0	7.0 ± 2.3
$\Lambda_c^+ \to \Sigma^0 \pi^+$	12.6 ± 2.1	12.9 ± 0.7
$\Lambda_c^+ \to \Xi^0 K^+$	5.9 ± 1.0	5.9 ± 1.0
$\Lambda_c^+ \to p\bar{K}^0$	31.3 ± 1.6	31.6 ± 1.6
$\Lambda_c^+ \to \Lambda^0 \pi^+$	13.1 ± 1.6	13.0 ± 0.7

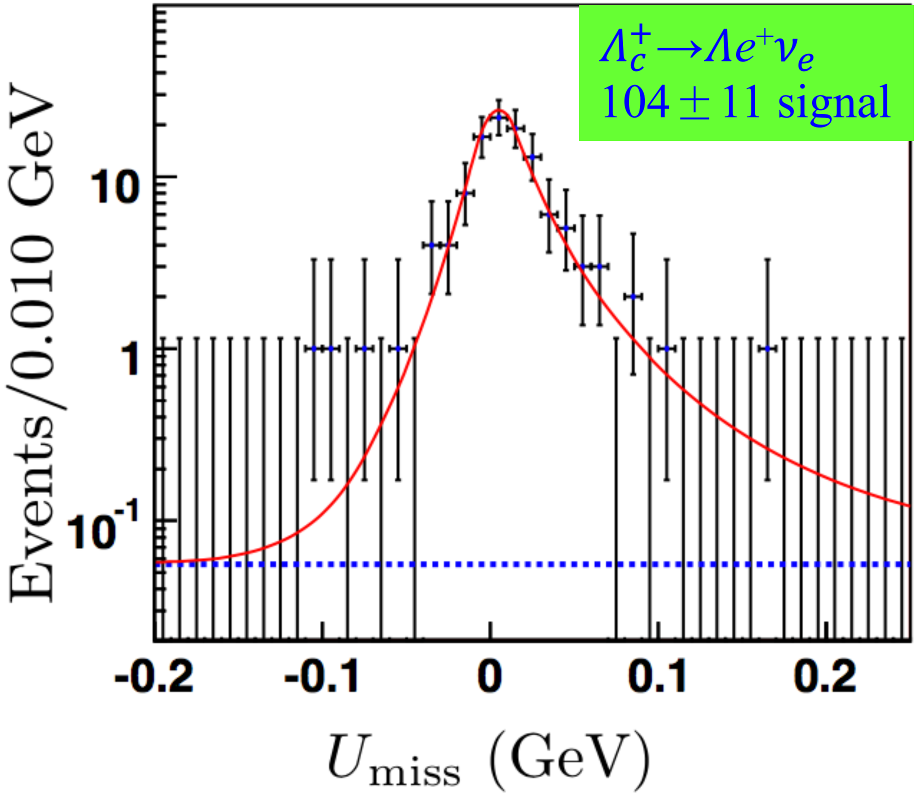
BRs of Cabibbo-suppressed decays

channel	$10^4\mathrm{BR}_{th}$	$10^4\mathrm{BR}_{EX}$
$\Xi_c^0 \to \Sigma^+ \pi^-$	2.2 ± 0.4	-
$\Xi_c^0 \to \Sigma^0 \pi^0$	2.8 ± 0.3	-
$\Xi_c^0 \to \Sigma^0 \eta$	1.0 ± 0.2	-
$\Xi_c^0 \to \Sigma^- \pi^+$	11.7 ± 0.5	-
$\Xi_c^0 \to \Xi^0 K^0$	6.2 ± 1.0	-
$\Xi_c^0 \to \Xi^- K^+$	9.8 ± 0.4	-
$\Xi_c^0 \to pK^-$	2.3 ± 0.4	-
$\Xi_c^0 \to n\bar{K}^0$	7.8 ± 1.3	-
$\Xi_c^0 \to \Lambda^0 \pi^0$	1.0 ± 0.3	-
$\Xi_c^0 \to \Lambda^0 \eta$	2.7 ± 0.3	-
$\Xi_c^+ \to \Sigma^+ \pi^0$	20.3 ± 2.0	-
$\Xi_c^+ \to \Sigma^+ \eta$	8.2 ± 1.9	-
$\Xi_c^+ \to \Sigma^0 \pi^+$	23.5 ± 2.3	-
$\Xi_c^+ \to \Xi^0 K^+$	9.8 ± 3.3	-
$\Xi_c^+ \to p\bar{K}^0$	29.2 ± 5.2	-
$\Xi_c^+ \to \Lambda^0 \pi^+$	5.1 ± 2.1	-
$\Lambda_c^+ \to \Sigma^+ K^0$	11.4 ± 2.0	-
$\Lambda_c^+ \to \Sigma^0 K^+$	5.7 ± 1.0	5.2 ± 0.8
$\Lambda_c^+ \to p\pi^0$	1.3 ± 0.7	0.8 ± 1.3
$\Lambda_c^+ \to p\eta$	13.0 ± 1.0	12.4 ± 3.0
$\Lambda_c^+ \to n\pi^+$	6.1 ± 2.0	-
$\Lambda_c^+ \to \Lambda^0 K^+$	6.4 ± 0.9	6.1 ± 1.2

From Chao-Qiang Geng' report at Wuhan

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

PRL 115, 221805(2015)

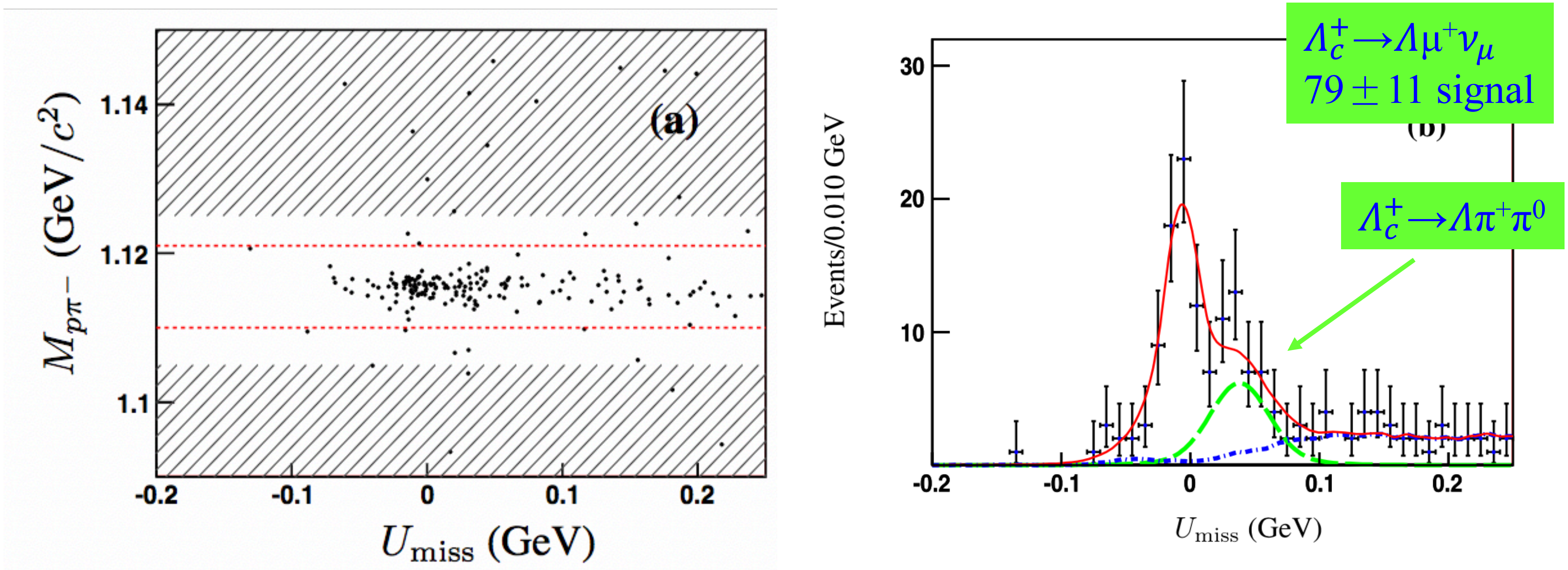


$B[\Lambda_c^+ \to \Lambda e^+ \nu_e]$=(3.36±0.38±0.20)%

- **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.**

$\Lambda_c^+ \to n e^+ \nu_e$ is very urgent in theory.

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.

- $\Gamma[\Lambda_c^+ \to \Lambda\mu^+\nu_\mu]/\Gamma[\Lambda_c^+ \to \Lambda e^+\nu_e] = 0.96 \pm 0.16 \pm 0.04$
  =>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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(Received 1 December 2016; published 21 February 2017)

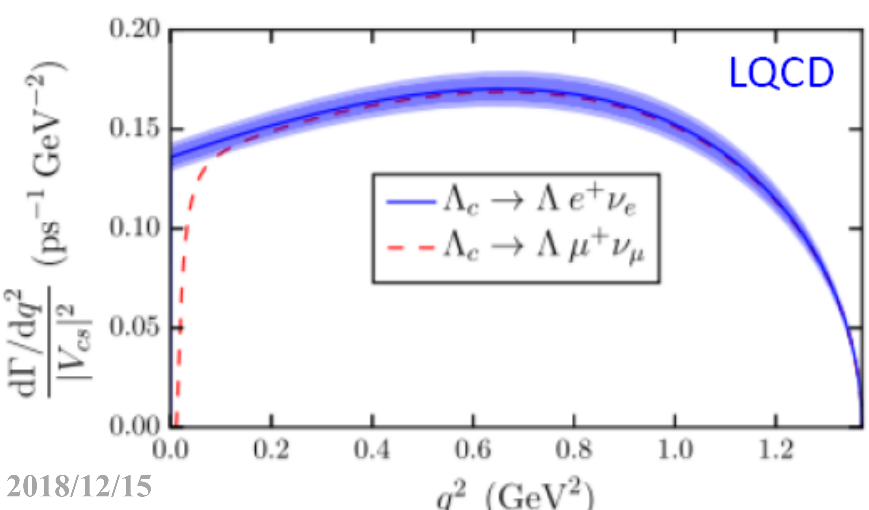
PRL118(2017)082001

- 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.

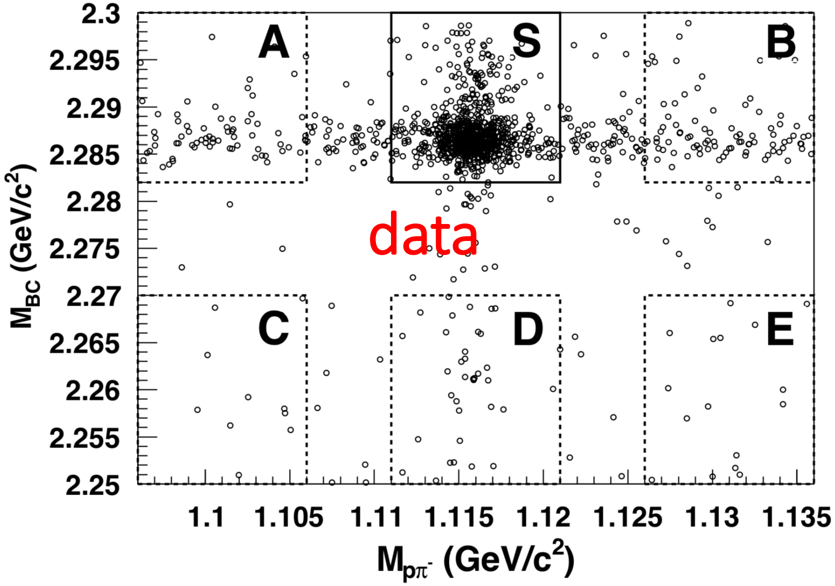
The inclusive channel $\Lambda_c^+ \to \Lambda + X$

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

PRL 121, 062003(2018)



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

- **Comparison with K+X will shed light on the internal dynamics**

- **In the ST modes of $\Lambda_c^+ \to pK^-p^+$ 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)

- $A_{cp} = (2.1^{+7.0}_{-6.6} \pm 1.4)\%$

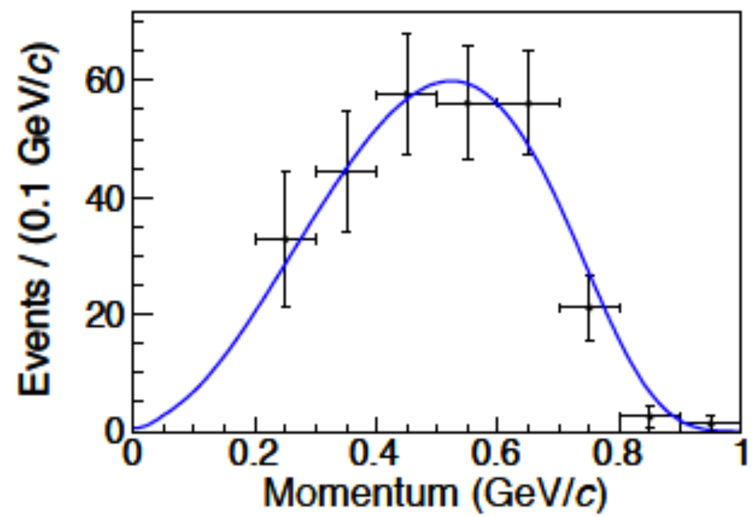
(No CPV is observed.)

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

- **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**

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

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

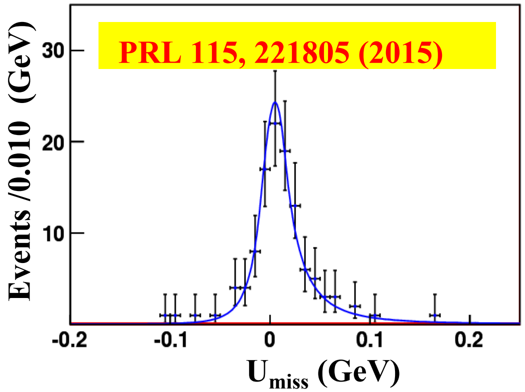


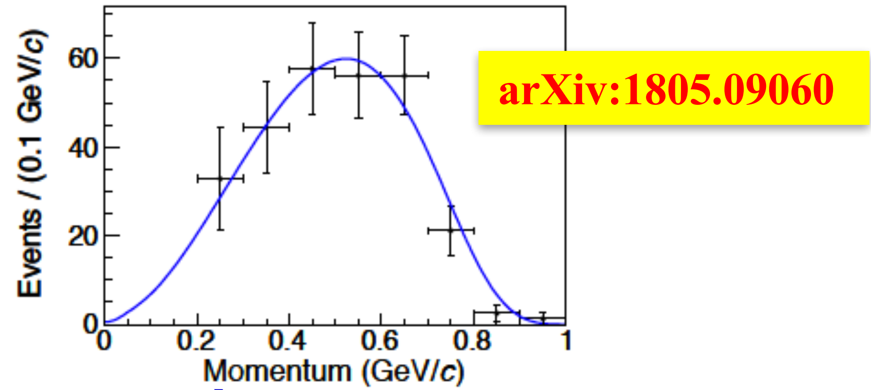
- **The $\Lambda l^+ \nu_l$ dominate the l^++X =>$\mathcal{B}$ ($pKl^+\nu_l$)~10^{-3}.**

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

Why $\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e$ are dominated?

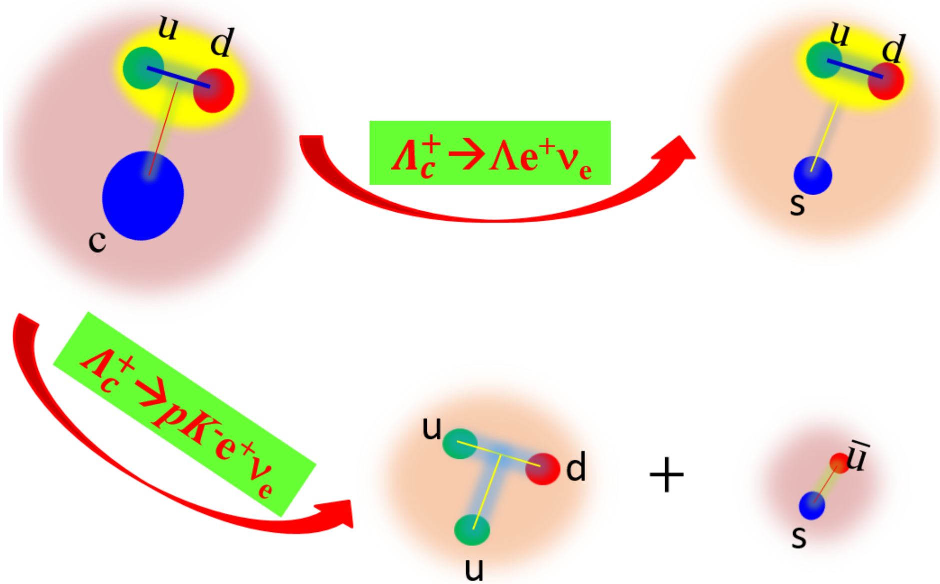




$B[\Lambda_c^+ \rightarrow \Lambda e^+ v]=(3.63\pm0.38\pm0.20)\%$

$B[\Lambda_c^+ \rightarrow e^+ + X]=(4.31\pm0.4)\%$

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

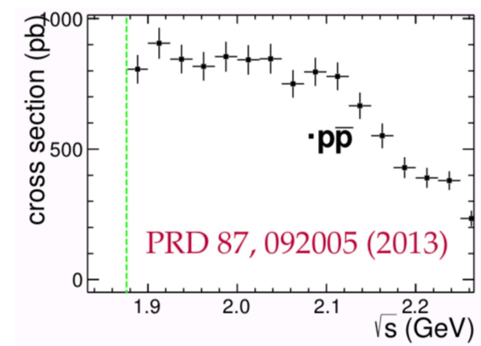


The cross-section of baryon pair

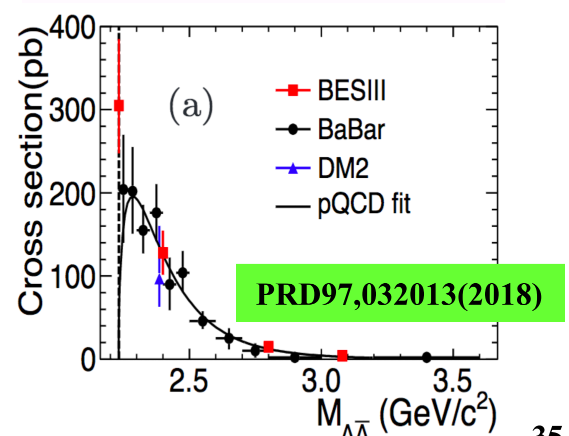
The Born cross section of the reaction $e^+e^- \to \gamma^* \to B\bar{B}$ can be parameterized in terms of electromagnetic form factors:

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

- 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

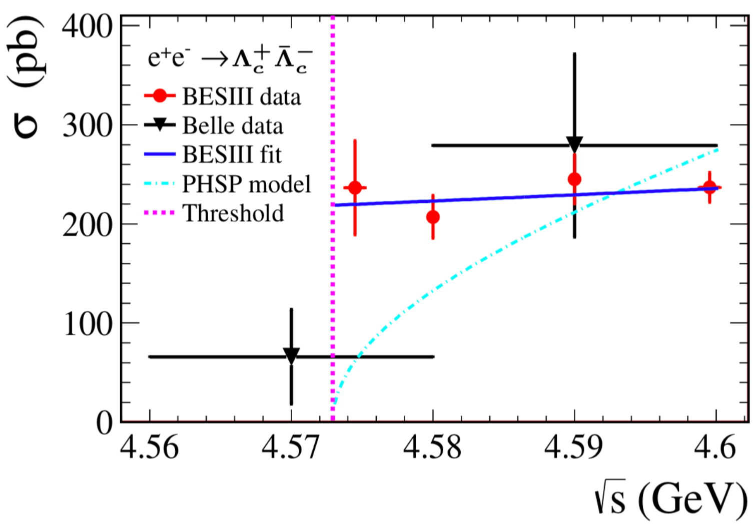


- $e^+e^- \to p\bar{p}$: an enhancement and wide-range plateau in the line-shape
- $e^+e^- \to \Lambda\bar{\Lambda}$: non-zero cross section near threshold
- It can be anticipate that Λ_c^+ has a similar behaviour with proton
- Belle collaboration has measured the cross section of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$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



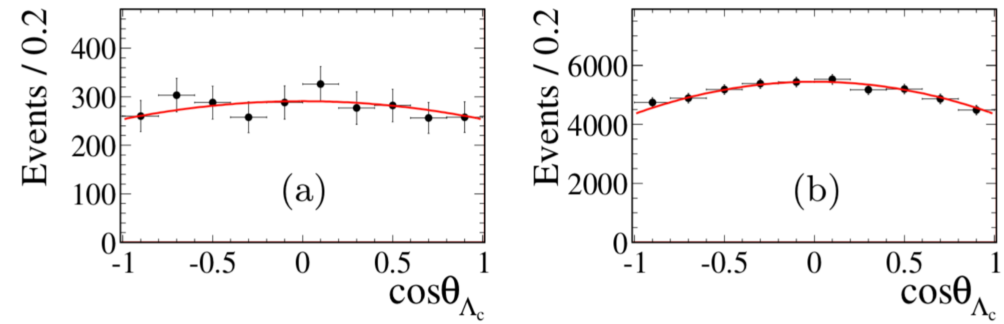


FIG. 3. Angular distribution after efficiency correction and results of the fit to data at $\sqrt{s} = 4574.5$ MeV (a) and 4599.5 MeV (b).

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

- 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	$-0.20 \pm 0.04 \pm 0.02$	$1.23 \pm 0.05 \pm 0.03$

Other efforts from experimental side

- $\Lambda_c^+ \to \Lambda\pi^+\eta$

- Weak decay asymmetries of $\Lambda_c^+ \to pK_s^0, \Lambda\pi^+, \Sigma^+\pi^0 and\ \Sigma^0\pi^+$

- Inclusive measurement of $\Lambda_c^+ \to K_s^0X, KX$

- **$\Lambda_c^+ \to ne^+\nu_e$ is under investigate even very challenging.**

Summary

- **Threshold data at BESIII opens a new door to direct measurements of the decays →precise study of Λ_c decays**
  - kinematics does not allow additional particle produced along with the $\Lambda_c^+\Lambda_c^-$ pair
  - fully reconstruct the pairs and take their yield ratios to measure the BFs:
  - low backgrounds and high detection efficiency

- **Era of precision study of the Λ_c decays:**
  - provide more data for theorists to develop more reliable models
  - precise measurement of the W-exchange and W-internal-emission only process: to test the quark-diquark configuration
    important to understand the non-factorizable contribution
  - explore as-yet-unmeasured channels and understand full picture of intermediate structures

- **We are proposing to take a larger data set;**
  a golden opportunity to thoroughly improve our knowledge on Λc decays

Prospect Charm Baryons data sample at BESIII

Energy	physics highlight	Current data # of events or integrated luminosity	Expected final data # of events or integrated luminosity
1.8 - 2.0 GeV	R values cross-sections	N/A	Scan: 3 energy points
2.0 - 3.1 GeV	R values cross-sections	Scan: 20 energy points	No requirement
J/ψ peak	Light Hadron & Glueball Charmonium decay	5.0 billion	10.0 billion
$\psi(3686)$ peak	Light hadron& Glueball Charmonium decay	0.5 billion	3.0 billion
$\psi(3770)$ peak	$D^0/D^{\pm}$ decays Form-factor/CKM decay constant	2.9 fb^{-1}	20.0 fb^{-1}
3.8 - 4.6 GeV	R value XYZ/Open charm	Scan: 105 energy points	No requirement
4.180 GeV	D_s decay XYZ/Open charm	3.1 fb^{-1}	6.0 fb^{-1}
4.0 - 4.6 GeV	XYZ/Open charm Higher charmonia cross-sections	Scan: 12.0 fb^{-1}	Scan: 30.0 fb^{-1} 10 MeV step/0.5 fb^{-1}/point 30 energy points
4.60 GeV	Λ_c/XYZ	0.56 fb^{-1}	1.0 fb^{-1}
4.64 GeV	Λ_c/XYZ	N/A	5.0 fb^{-1}
4.65 GeV	Λ_c/XYZ	N/A	0.2 fb^{-1}
4.70 GeV	Λ_c/XYZ	N/A	0.65 fb^{-1}
4.80 GeV	Λ_c/XYZ	N/A	1.0 fb^{-1}
4.90 GeV	Λ_c/XYZ	N/A	1.3 fb^{-1}
$\Sigma_c^+\bar{\Lambda}_c^-$ 4.74 GeV	Charm Baryons	N/A	1.0 fb^{-1}
$\Sigma_c\bar{\Sigma}_c$ 4.91 GeV	Charm Baryons	N/A	1.0 fb^{-1}
$\Xi_c\bar{\Xi}_c$ 4.95 GeV	Charm Baryons	N/A	1.0 fb^{-1}

Precision Prospects（1）

Push the precisions to the level of those of D/Ds mesons.

Hadronic decays

- PWA analysis of hadronic decays: hadron spectroscopy
- studies of the modes involving $n/\Sigma/\Xi$ particles
- more Cabbibo-suppressed modes, esp. W-exchange only process

SL decays :

- so far, only $\Lambda e^+\nu_e$ mode is measured; How about $pK^- e^+\nu_e$?
- many more SL modes can be established

	golden mode	δB/B	SL	δB/B
D0	B(Kpi)=(3.88±0.05)%	1.3%	B(K e ν)=(3.55±0.05)%	1.4%
D+	B(Kpipi)=(9.13±0.19)%	2.1%	B(K0 e ν)=(8.83±0.22)%	2.5%
Ds	B(Kkpi)=(5.39±0.21)%	3.9%	B(phi e ν)=(2.49±0.14)%	5.6%
Λc	B(pKpi)=(5.0±1.3)% (PDG2014) =(6.8±0.36)% (BELLE) =(5.84±0.35)% (BESIII) **=(5.84±0.18)% (new BESIII)**	26% 5.3% 6.0% **3.0%**	B(Λeν)=(2.1±0.6)%(PDG2014) =(3.63±0.43)% (BESIII) **=(3.63±0.20)% (new BESIII)**	29% 12% **5.4%**

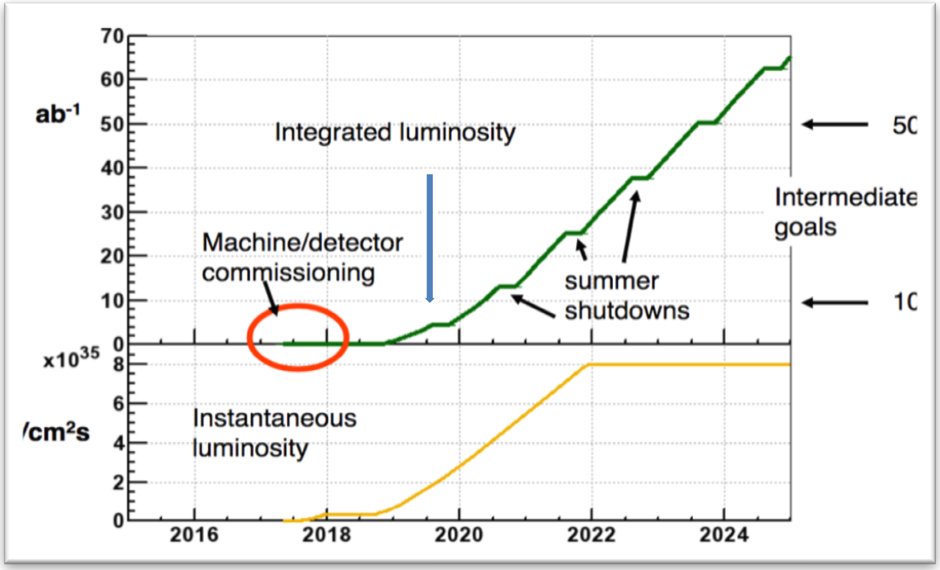
Precision Prospects（2）

- Prospects with the proposed new Λ_c^+ data set
  - ✓ precise measurement of the W-exchange and W-internal-emission only process: to test the quark-diquark configuration *important to understand the non-factorizable contribution*
  - ✓ establishment of more SL and neutron modes: $nl\upsilon$, $pKl\upsilon$, …
  - ✓ search for more decay modes unexplored yet in experiment

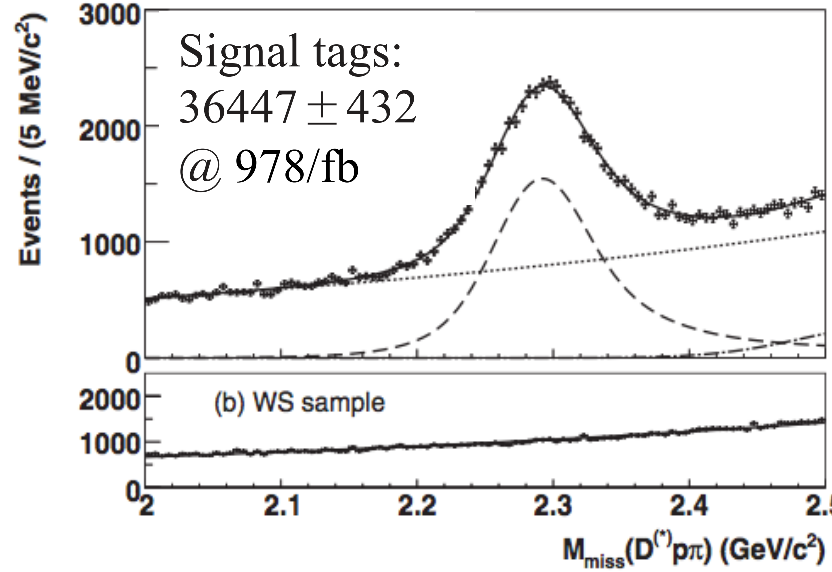
A good chance for BESIII to systematically enhance our knowledge on Λ_c^+ decays (to the level of D/D$_s$ mesons)

- Better understanding of baryonic structure
- many new observations
- refresh the precisions in old data

Competition from Belle & BelleII



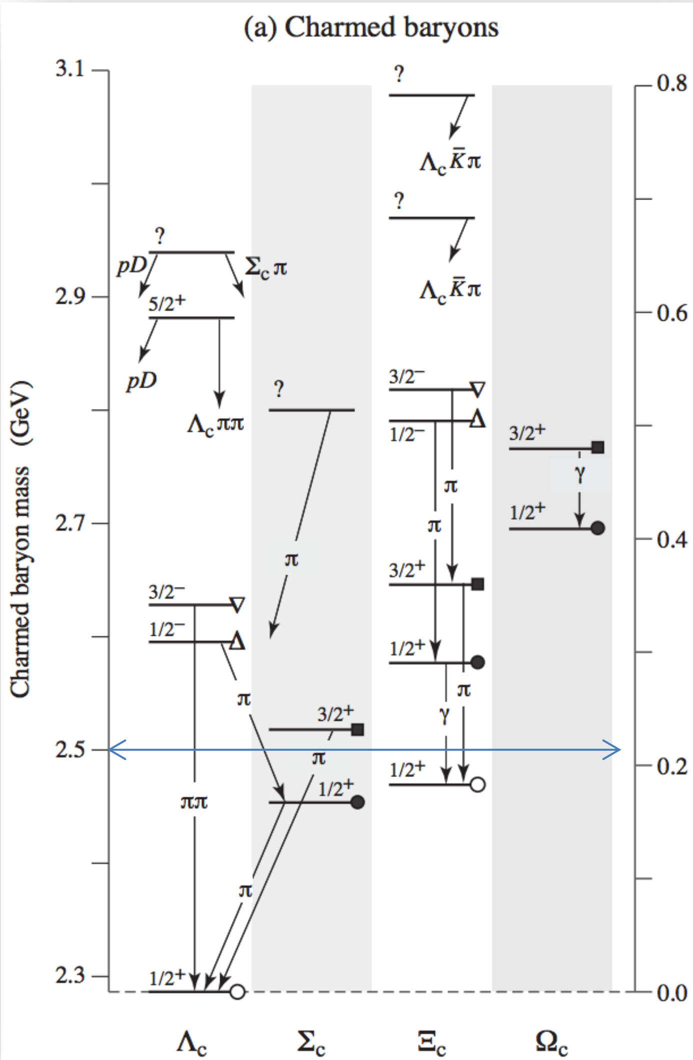
Belle, PRL113, 042002 (2014)

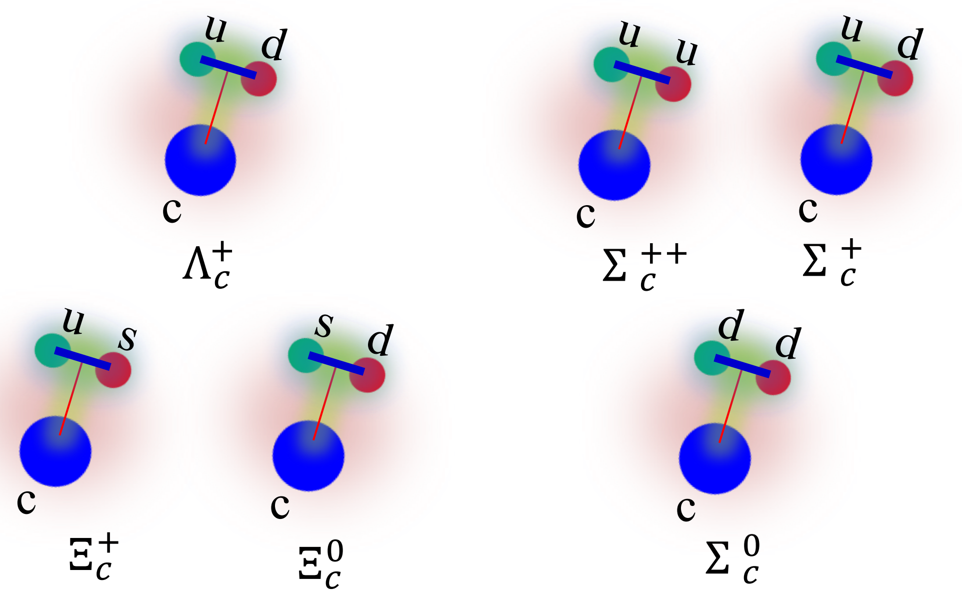


- Belle tags ~36K Λ_c^+, while BESIII now tags 15K Λ_c^+ (567/pb@4.6GeV)
- By middle of 2019, Belle-II will have 5/ab data, 5x of BELLE data;
  ➔ 180K Λ_c^+ tagging; 12x BESIII data
- We shall have 10x more Λ_c^+ pairs ASAP
- Many precise measurements at BESIII will reach to the level of systematic dominated
  ➔ BESIII has advantages on backgrounds and systematics

Energies go up to 5GeV

The charmed baryon spectroscopies





If BEPCII can access energies up to 5GeV, we can study the Λ_c, Σ_c and Ξ_c at threshold.

- Study on the isospin triplet Σ_c
- First absolute measurements of Ξ_c decays

Partiale Width of decay of Σ_c^+

(MeV)

Decay	Expt. [3]	HHChPT [10]	Tawfiq et al. [25]	Ivanov et al. [26]	Huang et al. [27]	Albertus et al. [28]
$\Sigma_c^{++} \to \Lambda_c^+ \pi^+$	$1.89^{+0.09}_{-0.18}$	input	1.51 ± 0.17	2.85 ± 0.19	2.5	2.41 ± 0.07
$\Sigma_c^{+} \to \Lambda_c^+ \pi^0$	< 4.6	$2.3^{+0.1}_{-0.2}$	1.56 ± 0.17	3.63 ± 0.27	3.2	2.79 ± 0.08
$\Sigma_c^{0} \to \Lambda_c^+ \pi^-$	$1.83^{+0.11}_{-0.19}$	$1.9^{+0.1}_{-0.2}$	1.44 ± 0.16	2.65 ± 0.19	2.4	2.37 ± 0.07
$\Sigma_c(2520)^{++} \to \Lambda_c^+ \pi^+$	$14.8^{+0.3}_{-0.4}$	$14.5^{+0.5}_{-0.8}$	11.77 ± 1.27	21.99 ± 0.87	8.2	17.52 ± 0.75
$\Sigma_c(2520)^{+} \to \Lambda_c^+ \pi^0$	< 17	$15.2^{+0.6}_{-1.3}$			8.6	17.31 ± 0.74
$\Sigma_c(2520)^{0} \to \Lambda_c^+ \pi^-$	$15.3^{+0.4}_{-0.5}$	$14.7^{+0.6}_{-1.2}$	11.37 ± 1.22	21.21 ± 0.81	8.2	16.90 ± 0.72

- Precise determination of $\Gamma(\Sigma_c^+ \to \Lambda_c^+ \pi^0)$ can be used for for testing heavy quark symmetry and chiral symmetry *Wise; Yan et al.; Burdman, Donoghue ('92)*
- measurements of Σ_c^+ & $\Sigma_c(2520)$ widths by Belle [PRD89, 091102 (2014)]: $\Gamma(\Sigma_c^+ \to \Lambda_c^+ \pi^0)$ is not easy for Belle; BESIII has potential to improve it.

BESIII will search for the EM decay

Decay	HHChPT +QM	Ivanov et al.	Bañuls et al.	Tawfiq et al.	Dey et al.	Majethiya et al.	Fayyazuddin et al.	Aliev et al.
$\Sigma_c^+ \to \Lambda_c^+ \gamma$	88	60.7 ± 1.5		87	98.7	$60.1 - 85.6$	89.0	

(keV)

Ξ_c (usc): 3-star particle in PDG

No absolute branching fractions have been measured/calculated

Ξ_c^+: relative to the decay of $\Xi^- 2\pi^+$

	Mode	Fraction (Γ_i/Γ)
No absolute branching fractions have been measured.The following are branching to $\Xi^-\pi^+$ .Cabibbo-favored ($S=-2$) decays — relative to $\Xi^-\pi^+$		
Γ_1	$p2K_S^0$	0.087 ± 0.021
Γ_2	$\Lambda\overline{K}^0\pi^+$	
Γ_3	$\Sigma(1385)^+\overline{K}^0$	1.0 ± 0.5
Γ_4	$\Lambda K^- 2\pi^+$	0.323 ± 0.033
Γ_5	$\Lambda\overline{K}^*(892)^0\pi^+$	< 0.16
Γ_6	$\Sigma(138$	
Γ_7	$\Sigma^+K^-\pi^+$	
Γ_8	$\Sigma^+\overline{K}^*$	
Γ_9	$\Sigma^0K^-2\pi$	
Γ_{10}	$\Xi^0\pi^+$	0.55 ± 0.16
Γ_{11}	$\Xi^- 2\pi^+$	DEFINEDAS1
Γ_{12}	$\Xi(1530)^0\pi^+$	< 0.10
Γ_{13}	$\Xi^0\pi^+\pi^0$	2.3 ± 0.7
Γ_{14}	$\Xi^0\pi^- 2\pi^+$	1.7 ± 0.5
Γ_{15}	$\Xi^0 e^+\nu_e$	$2.3^{+0.7}_{-0.8}$
Γ_{16}	$\Omega^- K^+\pi^+$	0.07 ± 0.04
Cabibbo-suppressed decays — relative to $\Xi^-\pi^+$		
Γ_{17}	$pK^-\pi^+$	0.21 ± 0.04
Γ_{18}	$p\overline{K}^*(892)^0$	0.116 ± 0.030
Γ_{19}	$\Sigma^+\pi^+\pi^-$	0.48 ± 0.20
Γ_{20}	$\Sigma^- 2\pi^+$	0.18 ± 0.09
Γ_{21}	$\Sigma^+K^+K^-$	0.15 ± 0.06

Ξ_c^0: relative to the decay of $\Xi^-\pi^+$

	Mode	Fraction (Γ_i/Γ)
No absolute branching fractions have been measured.The following are bran = -2) decays — relative to $\Xi^-\pi^+$		
Γ_1	$pK^-K^-\pi^+$	0.34 ± 0.04
Γ_2	$pK^-\overline{K}^*(892)^0$	0.21 ± 0.05
Γ_3	$pK^-K^-\pi^+$ (no $\overline{K}^{*0}$)	0.21 ± 0.04
		28
Γ_8	$\Xi^-\pi^+$	DEFINEDAS1
Γ_9	$\Xi^-\pi^+\pi^+\pi^-$	3.3 ± 1.4
Γ_{10}	$\Omega^- K^+$	0.297 ± 0.024
Γ_{11}	$\Xi^- e^+\nu_e$	3.1 ± 1.1
Γ_{12}	$\Xi^-\ell^+$ anything	1.0 ± 0.5
Cabibbo-suppressed decays — relative to $\Xi^-\pi^+$		
Γ_{13}	$\Xi^- K^+$	0.028 ± 0.006
Γ_{14}	ΛK^+K^- (no ϕ)	0.029 ± 0.007
Γ_{15}	$\Lambda\phi$	0.034 ± 0.007

Very limited knowledge on their decays
We have opportunity to firstly fill up the decay tables

Most of the Ξ_c weak decays to BP are missing in experiment.

BFs of Cabibbo-allowed decays

RQM Pole Pole RQM Pole Pole (in units of %)

Decay	Körner, Krämer ('92)	Xu, Kamal ('92)	Cheng, Tseng ('93)	Ivanov et al. ('98)	Żenczykowski ('94)	Sharma, Verma ('99)	Expt.
$\Xi_c^+ \to \Sigma^+ \bar{K}^0$	6.45	0.44	0.84	3.08	1.56	0.04	
$\Xi_c^+ \to \Xi^0 \pi^+$	3.54	3.36	3.93	4.40	1.59	0.53	0.55 ± 0.16^a
$\Xi_c^0 \to \Lambda \bar{K}^0$	0.12	0.37	0.27	0.42	0.35	0.54	seen
$\Xi_c^0 \to \Sigma^0 \bar{K}^0$	1.18	0.11	0.13	0.20	0.11	0.07	
$\Xi_c^0 \to \Sigma^+ K^-$	0.12	0.12		0.27	0.36	0.12	
$\Xi_c^0 \to \Xi^0 \pi^0$	0.03	0.56	0.28	0.04	0.69	0.87	
$\Xi_c^0 \to \Xi^0 \eta$	0.24			0.28	0.01	0.22	
$\Xi_c^0 \to \Xi^0 \eta'$	0.85			0.31	0.09	0.06	
$\Xi_c^0 \to \Xi^- \pi^+$	1.04	1.74	1.25	1.22	0.61	2.46	seen
$\Omega_c^0 \to \Xi^0 \bar{K}^0$	1.21		0.09	0.02			

Most of the Ξ_c weak decay asymmetries are missing in experiment.

Decay asymmetry α for Cabibbo-allowed decays

Longitudinal pol. of daughter baryon from unpol. parent baryon

⇒ information on the relative sign between s- and p-waves

Decay	Körner, Krämer ('92)	Xu, Kamal ('92)	Cheng, Tseng ('93)	Ivanov et al. ('98)	Żenczykowski ('94)	Sharma, Verma ('99)	Expt.
$\Xi_c^+ \to \Sigma^+ \bar{K}^0$	-1.0	0.24	-0.09	-0.99	1.00	0.54	
$\Xi_c^+ \to \Xi^0 \pi^+$	-0.78	-0.81	-0.77	-1.0	1.00	-0.27	
$\Xi_c^0 \to \Lambda \bar{K}^0$	-0.76	1.0	-0.73	-0.75	-0.29	-0.79	
$\Xi_c^0 \to \Sigma^0 \bar{K}^0$	-0.96	-0.99	-0.59	-0.55	-0.50	0.48	
$\Xi_c^0 \to \Sigma^+ K^-$	0	0		0	0	0	
$\Xi_c^0 \to \Xi^0 \pi^0$	0.92	0.92	-0.54	0.94	0.21	-0.80	
$\Xi_c^0 \to \Xi^0 \eta$	-0.92			-1.0	-0.04	0.21	
$\Xi_c^0 \to \Xi^0 \eta'$	-0.38			-0.32	-1.00	0.80	
$\Xi_c^0 \to \Xi^- \pi^+$	-0.38	-0.38	-0.99	-0.84	-0.79	-0.97	-0.6 ± 0.4
$\Omega_c^0 \to \Xi^0 \bar{K}^0$	0.51		-0.93	-0.81			

Charm-flavor-conserving weak decays

■ Light quarks undergo weak transitions, while c quark behaves as a "spectator"
e.g. $\Xi_c \to \Lambda_c \pi$. Can be studied using HHChPT.

$Br(\Xi_c^0 \to \Lambda_c^+ \pi^-) = 2.9\times10^{-4}$

$Br(\Xi_c^+ \to \Lambda_c^+ \pi^0) = 6.7\times10^{-4}$

$s \to W^- u$

can be firstly explored at BESIII

Cheng, Cheung, Lin, Lin, Yan, Yu ('92)

Semileptonic decays

|→ NRQM ←| RQM LFQM QSR QSR

Process	Pérez-Marcial et al. [85]	Singleton [86]	Cheng, Tseng [81]	Ivanov et al. [87]	Luo [88]	Marques de Carvalho et al. [89]	Huang, Wang [90]	Expt. [3]
$\Xi_c^0 \to \Xi^- e^+ \nu_e$	18.1 (12.5)	8.5	7.4	8.16	9.7			seen
$\Xi_c^+ \to \Xi^0 e^+ \nu_e$	18.4 (12.7)	8.5	7.4	8.16	9.7			seen

in units of 10^{10} s^{-1}

Thanks