Λ_c^+ decays at BESIII

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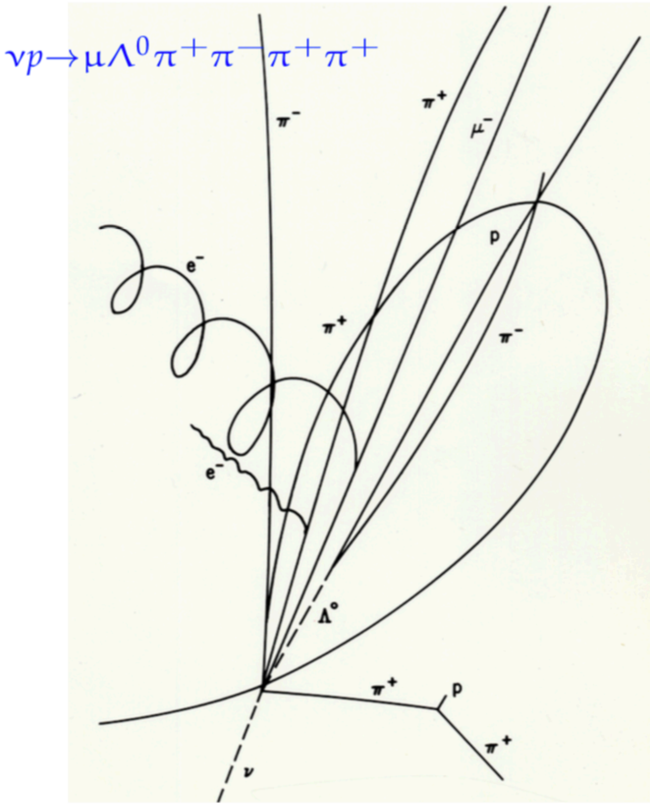
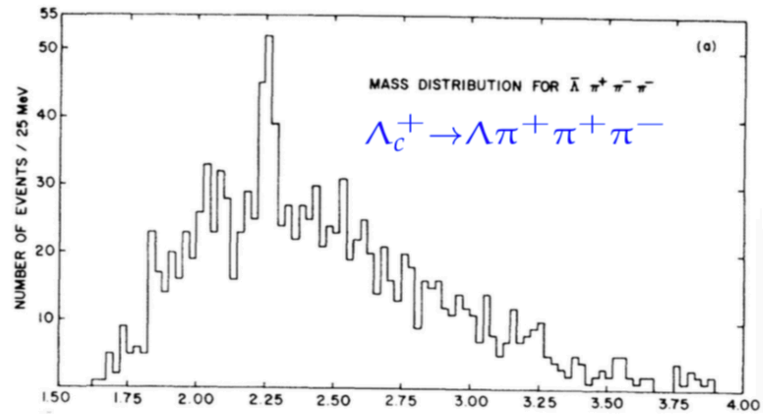
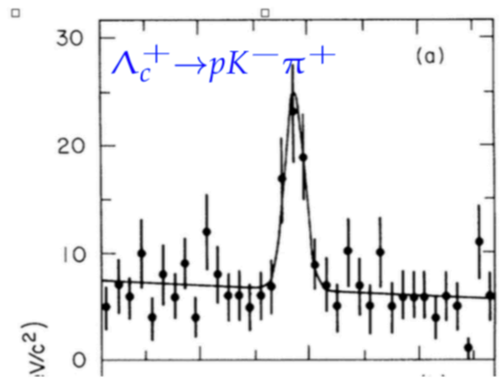
Outline

- Introduction to the lightest charm baryon Λ_c^+
- Λ_c^+ hadronic decays
- Prospect of next round data taking
- Summary

The discovery of Λ_c^+







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

The charmed baryon family

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

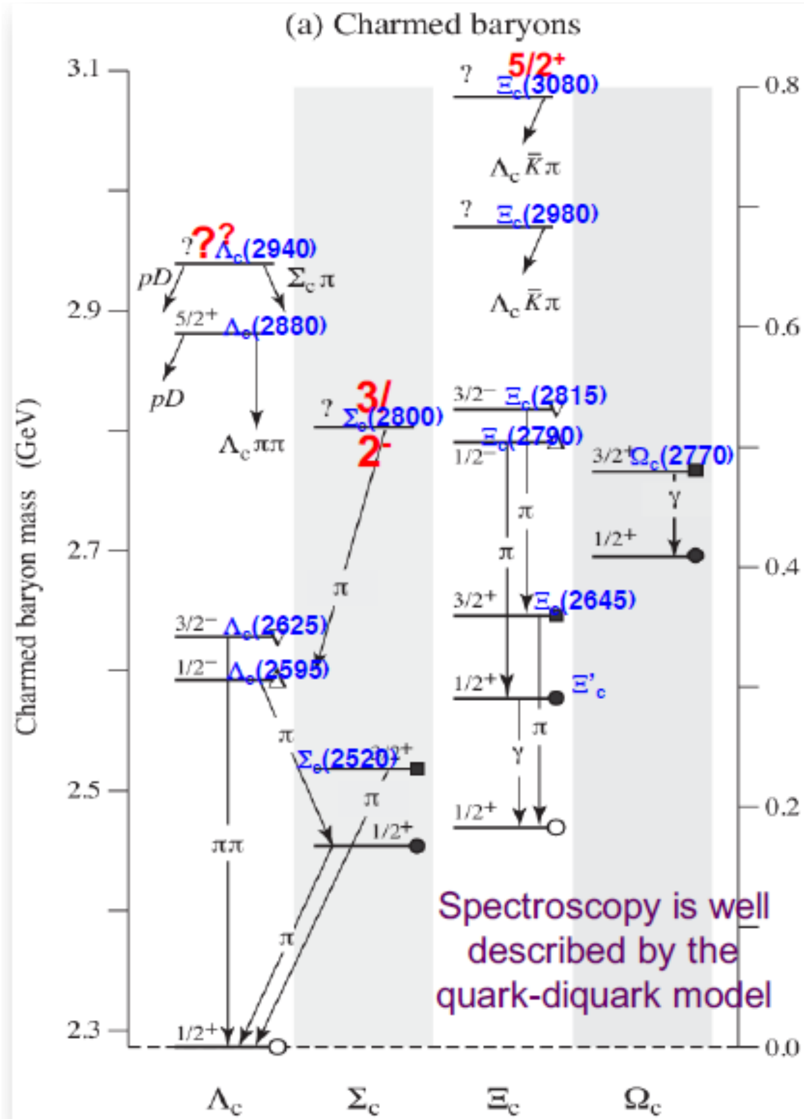
    Λ_c^+, Σ_c, Ξ_c , Ω_c
  - Excited states are being explored
- **Doubly charmed baryons(Ξ_{cc}^{++}) observed recently.**
- **No observations of triply charmed baryons.**

✓ **Λ_c^+ decay only weakly, many recent experimental progress since 2014.**

✓ **Σ_c: $B(\Sigma_c \to \Lambda_c^+ \pi)$~100%, $B(\Sigma_c \to \Lambda_c^+ \gamma)$?**

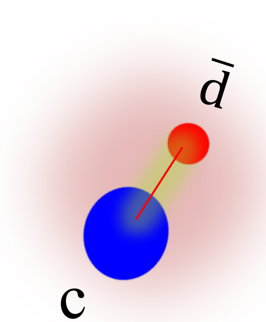
✓ **Ξ_c : decay only weakly; no absolute BF measured, most relative to $\Xi^- \pi^+(\pi^+)$.**

✓ **Ω_c:decay only weakly; no absolute BF measured.**



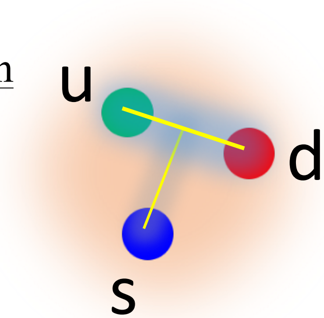
Λ_c^+:cornerstone of charmed baryon spectroscopy

- The lightest charmed baryon:2286.48MeV.
- 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 !
- 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).



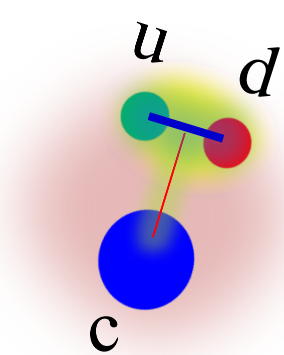
→ Charmed meson ($D^+[c\bar{d}]$)

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



→ Strange baryons (Λ[uds])

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

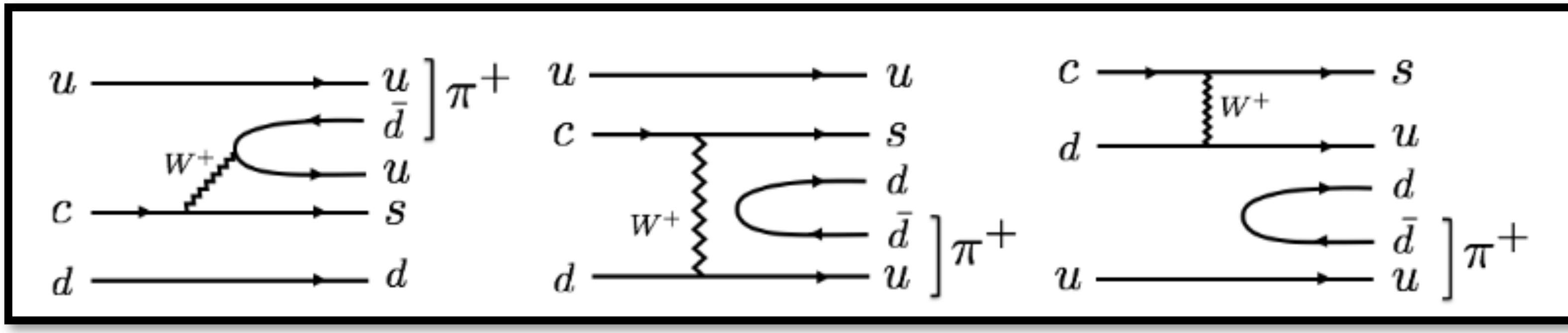


→ Charmed baryon (Λ_c[udc])

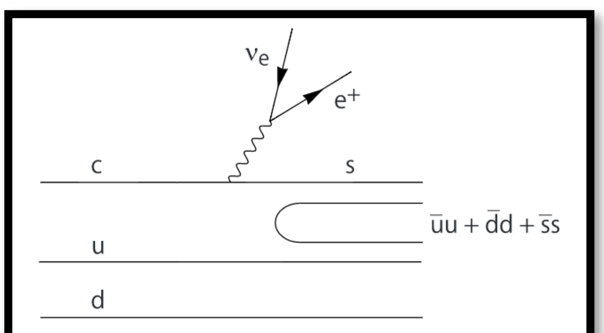
$m_u, m_d << m_c$ →
diquark + quark
(qq) (Q)

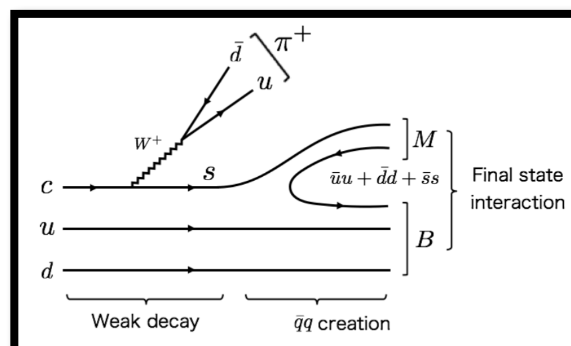
Λ_c^+ weak decays

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



- **The Λ_c weak decay acts as isospin filter**
  - For example, Oset suggests to study the Λ(1405) through $\Lambda_c \to \pi$ Λ(1405) and Λ(1405) e ν, which filters isospin I=0 from contamination of the I=1.
    [Phys. Rev. C 92, 055204 (2015), Phys. Rev. D 93, 014021 (2016)]





- **Exotic search in $\Lambda_c^+ \to \phi p \pi$ an analog to the Pc states in $\Lambda_b \to J/\psi p K^-$**

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!**
- **This is a marvelous achievement of BEPCII !**
- **~106×10[3] $\Lambda_c^+\Lambda_c^-$ pairs make sensitivity to 10^{-3}.**
- **First direct measurement on Λ_c^+ BFs at threshold.**
- **Collect more Λ_c^+ data are in the schedule.**

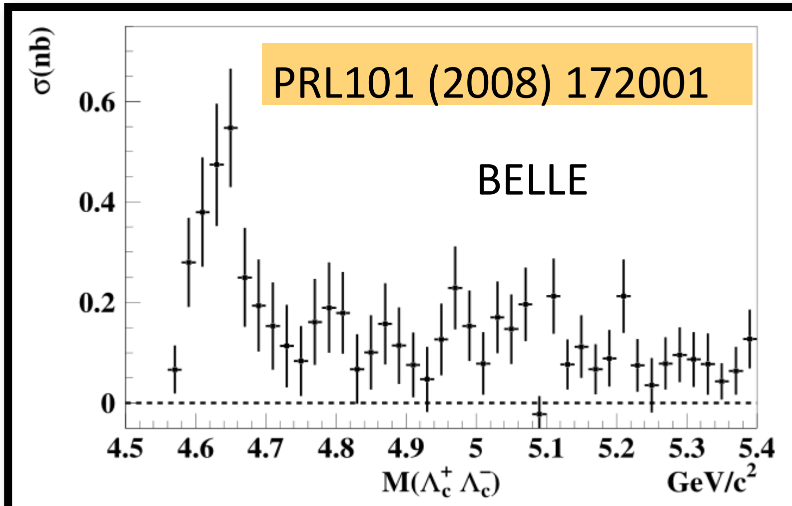


FIG. 4: The cross section for the exclusive process $e^+e^- \to \Lambda_c^+\Lambda_c^-$.

Energy(GeV)	lum.(pb^{-1})
4.575	~48
4.580	~8.5
4.590	~8.1
4.6	**~567**

Production near threshold and double tag technique

- E_{cms}-$2M_{\Lambda c}$=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): Reconstruct only one of the Λ_c -pair.

    =>relative higher backgrounds

    =>Higher efficiencies

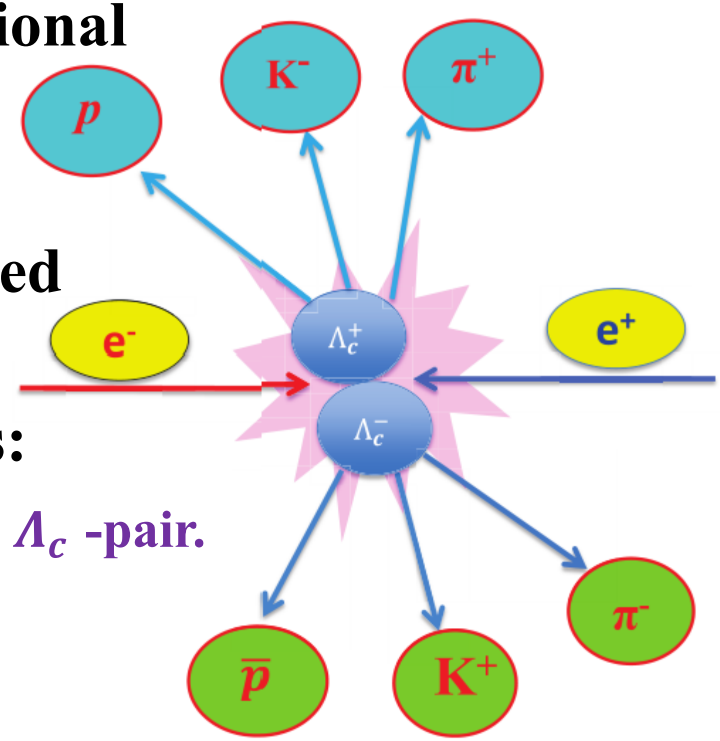
    =>Full reconstruction
  - Double Tag(DT): Find both of $\Lambda_c^+\Lambda_c^-$

    =>Smaller backgrounds.

    =>Missing technique.

    =>Lower efficiencies.

    =>Systematic in tag side are mostly cancelled.

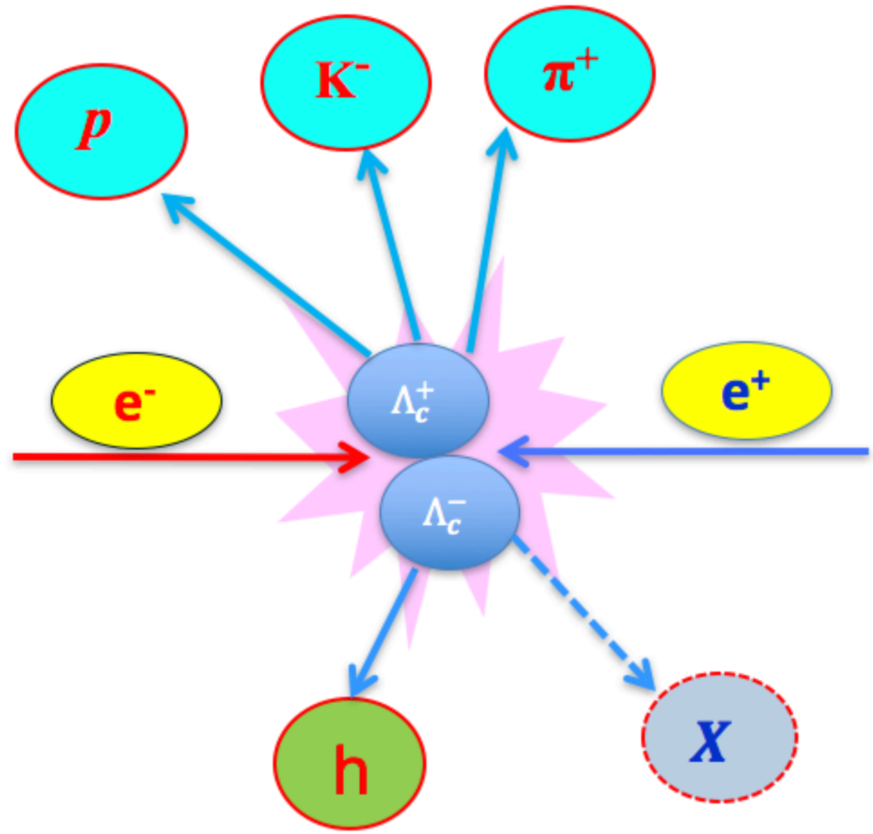


Several popular variables

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

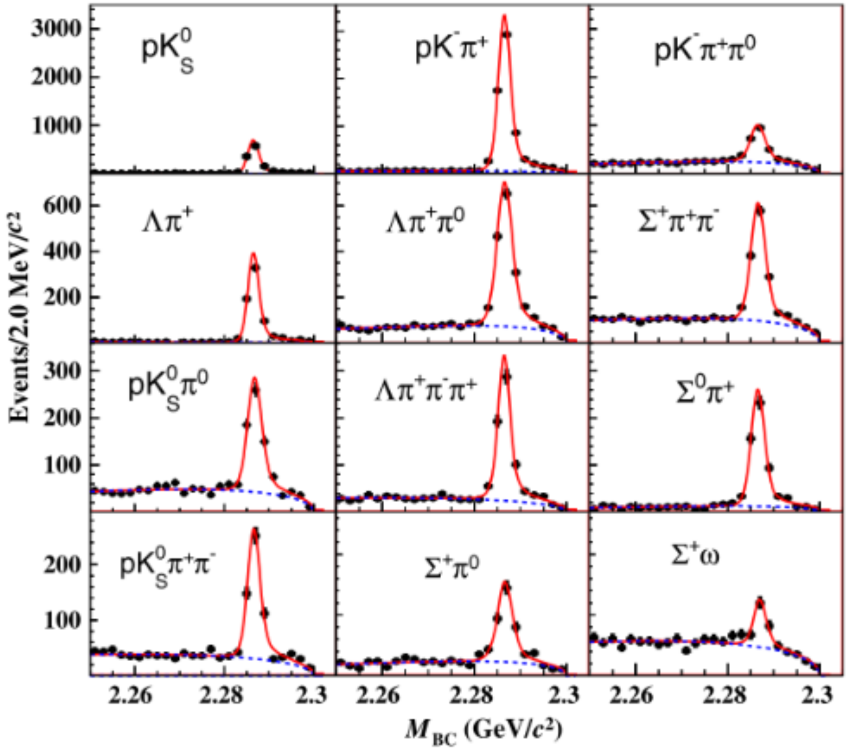
  $M_{BC} = \sqrt{E_{beam}^2 - |\vec{p}_{\Lambda c}|^2}$

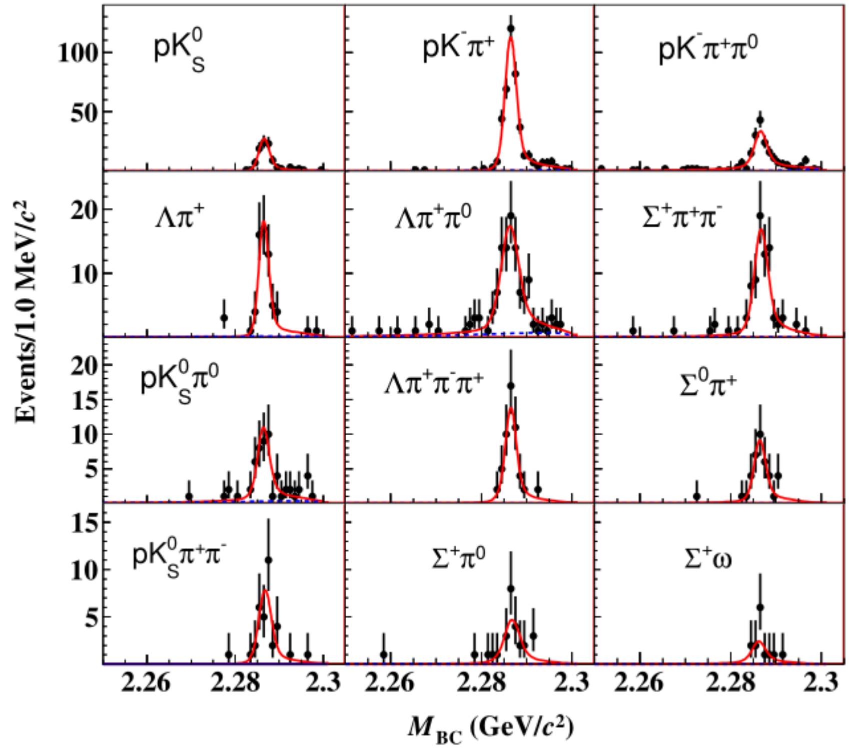
- $E_{miss} = E_{beam} - E_h$
- $\vec{p}_{miss} = \vec{p}_{\Lambda c} - \vec{p}_h$
- $\vec{p}_{\Lambda c} = -\hat{p}_{tag} \cdot \sqrt{E_{beam}^2 - m_{\Lambda c}^2}$
- $U_{miss} = E_{miss} - |\vec{p}_{miss}|$
- $M_{miss} = \sqrt{E_{miss}^2 - |\vec{p}_{miss}|^2}$



- $\hat{p}_{tag}$ 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(p$K^-\pi^+$) are comparable with Belle's**
- **The precisions of Λ_c decay rates is reaching to the level of charmed mesons!**
- **$N_{\Lambda_c^+\bar{\Lambda}_c^-}$ as a byproduct determined to be $(105.9 \pm 4.8 \pm 0.5) \times 10^3$**

历史上对Λ_c^+ →pKπ分支比的测量

- **ARGUS 和 CLEO 1988-1996年进行的测量**

$$B(\overline{B} \to \Lambda_c^+ X) \cdot B(\Lambda_c^+ \to pK^-\pi^+) = (0.30 \pm 0.12 \pm 0.06)\% \quad (0.273 \pm 0.051 \pm 0.039)\%$$

$$B(\Lambda_c^+ \to pK^-\pi^+) = (4.14 \pm 0.91)\%$$

$$\sigma(e^+e^- \to \Lambda_c^+ X) \cdot B(\Lambda_c^+ \to \Lambda \ell^+ \nu_\ell) = (4.15 \pm 1.03 \pm 1.18) \text{ pb and } (4.77 \pm 0.25 \pm 0.66) \text{ pb.}$$

$$\sigma(e^+e^- \to \Lambda_c^+ X) \cdot B(\Lambda_c^+ \to pK^-\pi^+) = (11.2 \pm 1.3) \text{ pb}$$

$$R \equiv B(\Lambda_c^+ \to pK^-\pi^+)/B(\Lambda_c^+ \to \Lambda \ell^+ \nu_\ell) = 2.40 \pm 0.43$$

$$B(\Lambda_c^+ \to pK^-\pi^+) = R f F \frac{\Gamma(D \to X \ell^+ \nu_\ell)}{1 + |V_{cd}/V_{cs}|^2} \cdot \tau(\Lambda_c^+) = (7.3 \pm 1.4 \pm 2.2)\%.$$

平均=> B(Λ_c^+ →pKπ)=(5.0±1.3)% (PDG2000)

- **2000年CLEO B(Λ_c^+ →pKπ)=(5.0±1.3)%** $\overline{D}\,\overline{p}\,\Lambda_c^+$

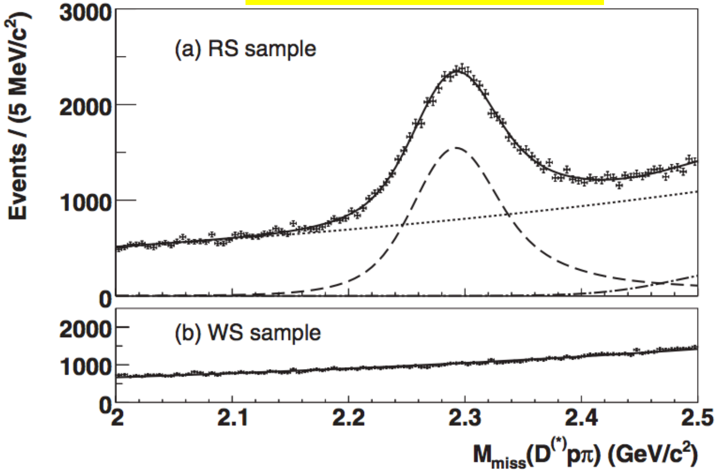
- **均为模型依赖的测量**

First precise measurement of $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$

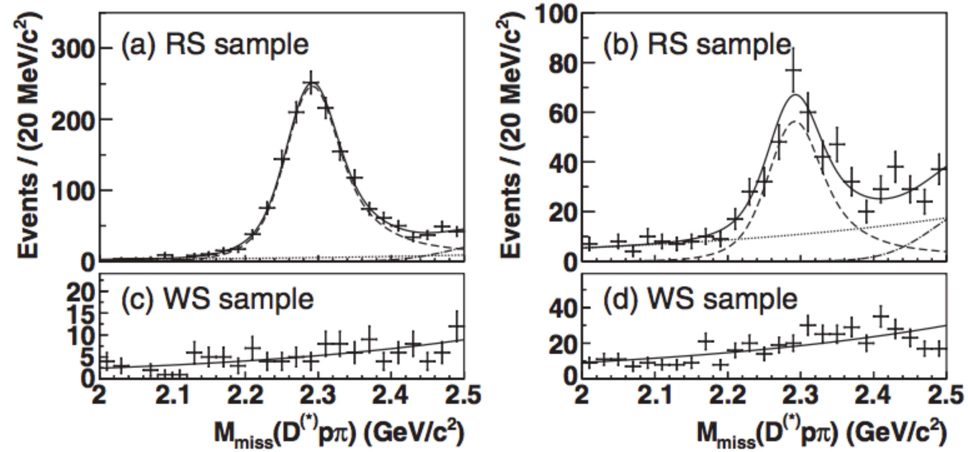
PRL 113, 042002 (2014)

The number of Λc baryons is determined by reconstructing the recoiling $D^{(*)-}\bar{p}\pi^+$ system in events of the type $e^+e^- \to D^{(*)-}\bar{p}\pi^+\Lambda_c^+$

Missing Λ_c^+



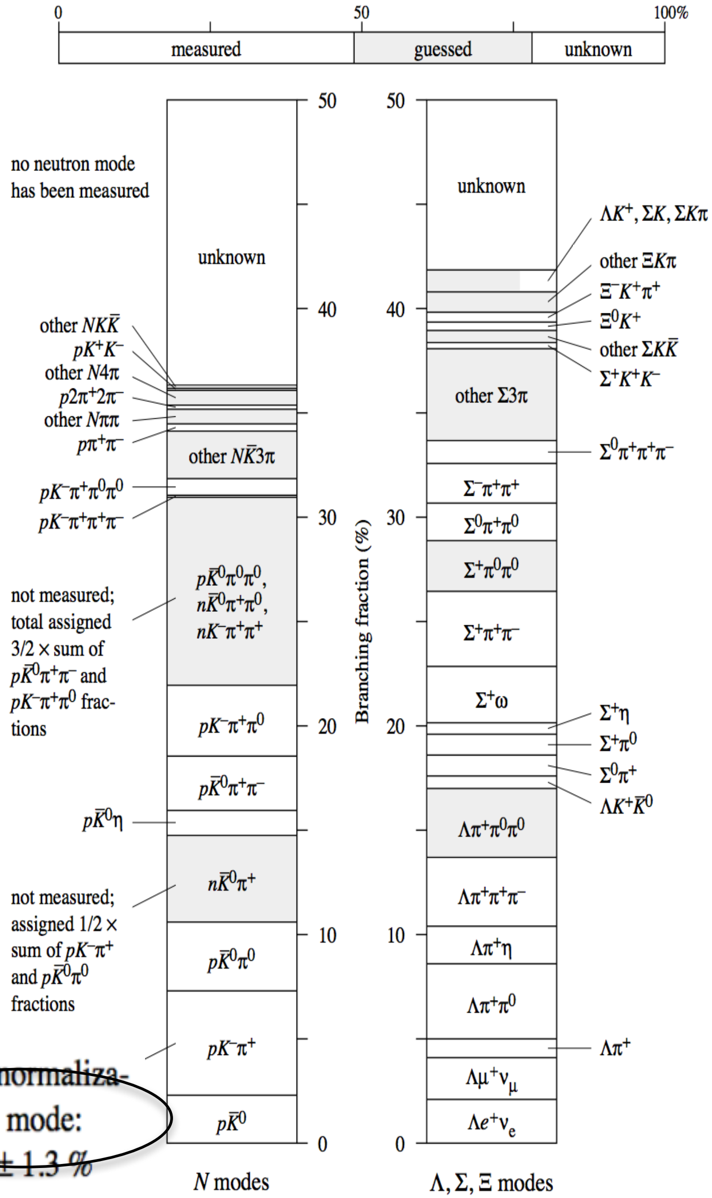
Tagging $\Lambda_c^+ \to pK^-\pi^+$

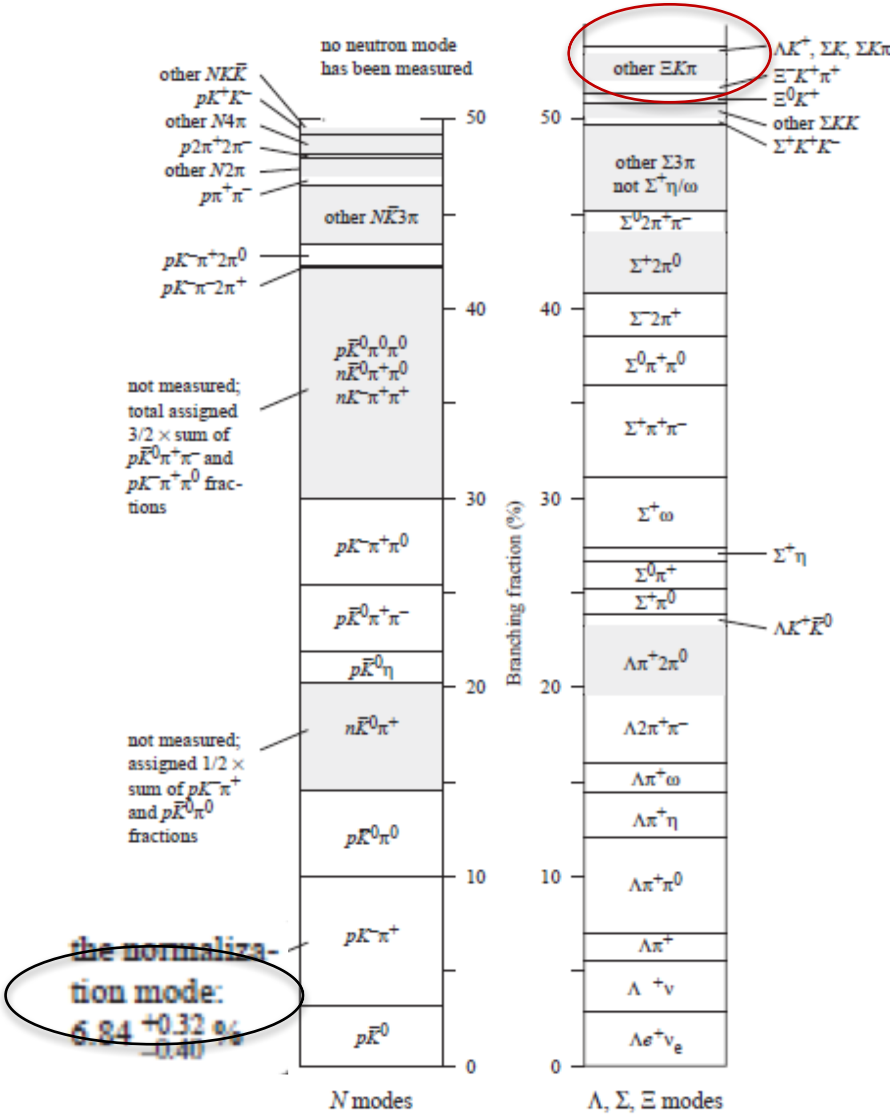


$$\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = \frac{N(\Lambda_c^+ \to pK^-\pi^+)}{N_{\rm inc}^{\Lambda_c} f_{\rm bias}\,\varepsilon(\Lambda_c^+ \to pK^-\pi^+)} = (6.84 \pm 0.24^{+0.21}_{-0.27})\%$$

PDG2014

Total BF overflows after taking into account BEELE's $B(\Lambda_c^+ \to pK^-\pi^+)$?



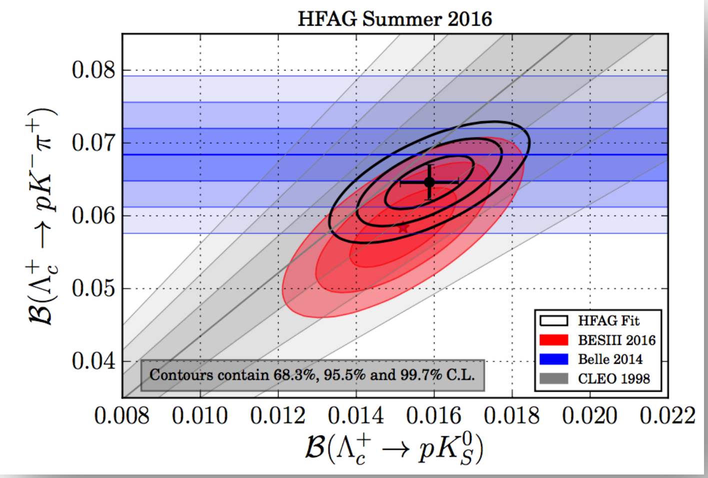


HFLAV Fit to world BF data

- 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(Kev)=(3.55±0.05)%	1.4%
D^+	B(Kππ)=(9.13±0.19)%	2.1%	B(K^0ev)=(8.83±0.22)%	2.5%
D_s	B(KKpi)=(5.39±0.21)%	3.9%	B(ϕev)=(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(Λev)=(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

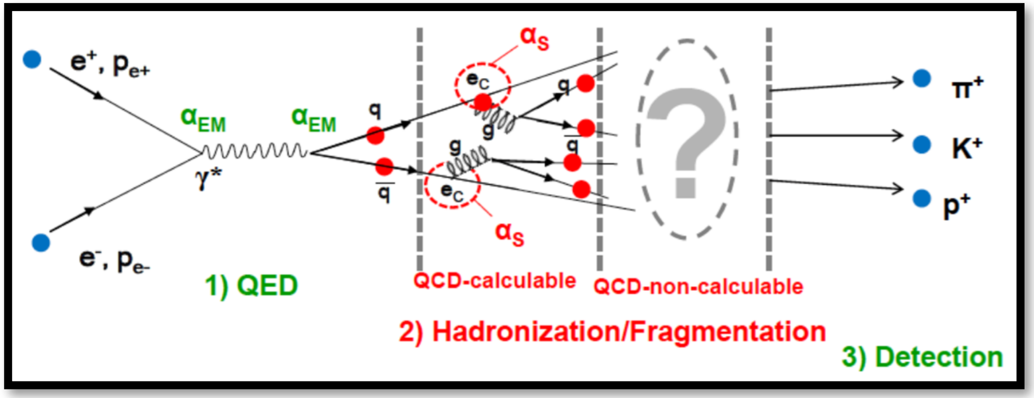
Important Input for b physics

- **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

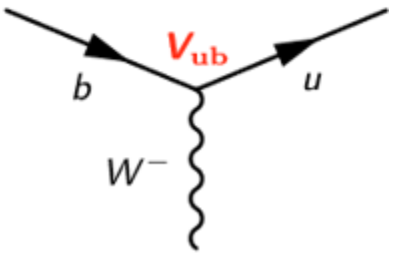
TABLE IV. Systematic uncertainties on the absolute scale of $f_{\Lambda_b}/(f_u + f_d)$.

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
$\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$	26.0
Total	26.8



- **Now B($pK^-\pi^+$) are still dominated (6%)**
- **X5 data=> small than 3%**

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

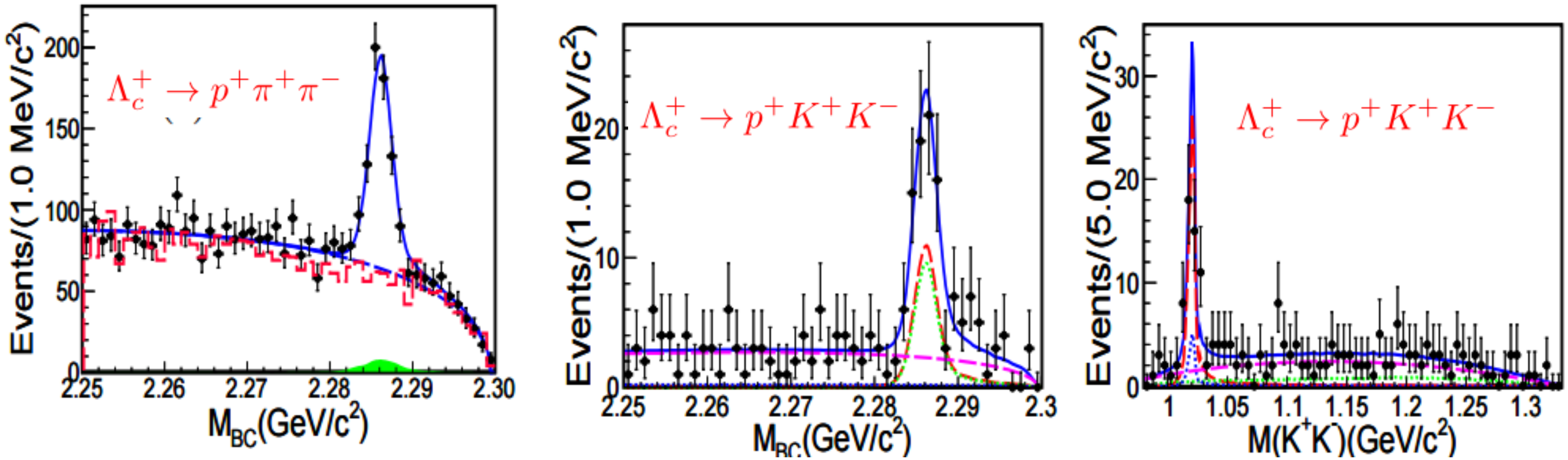
Source	Relative uncertainty (%)
$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$	$^{+4.7}_{-5.3}$
Trigger	[illegible]
Tracking	3.0
Λ_c^+ selection efficiency	3.0
$\Lambda_b^0 \to N^*\mu^-\overline{\nu}_\mu$ shapes	2.3
Λ_b^0 lifetime	1.5
Isolation	1.4
Form factor	1.0
Λ_b^0 kinematics	0.5
q^2 migration	0.4
PID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

- **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**

PRL117,232002(2016)

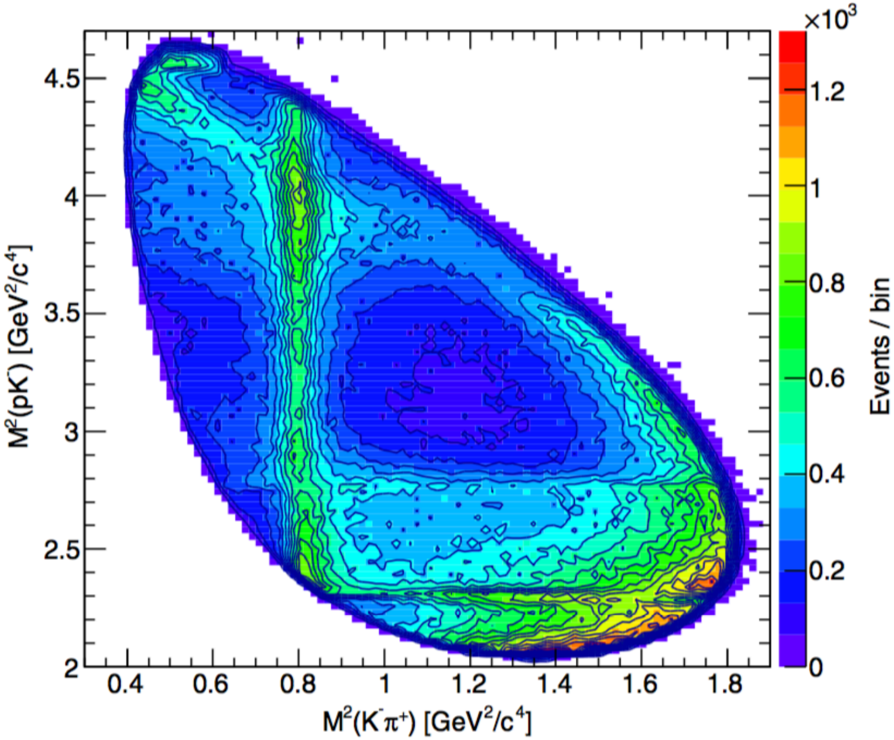


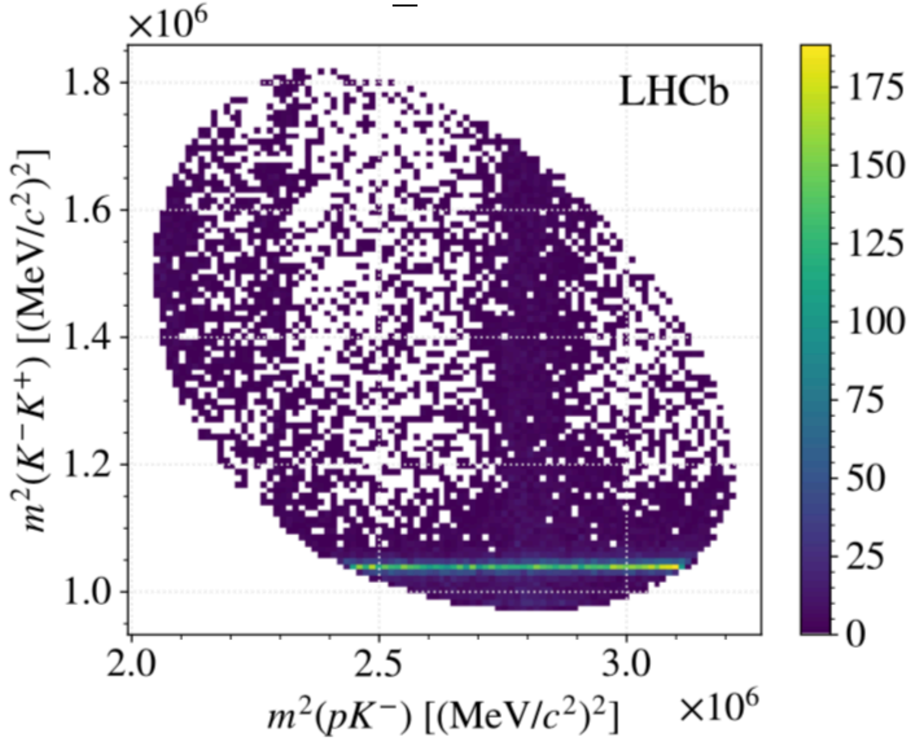
Decay modes	$\mathcal{B}_{mode}/\mathcal{B}_{ref}$ (This work)	$\mathcal{B}_{mode}/\mathcal{B}_{ref}$ (PDG average)
$\Lambda_c^+ \to p\pi^+\pi^-$	$(6.70 \pm 0.48 \pm 0.25) \times 10^{-2}$	$(6.9 \pm 3.6) \times 10^{-2}$
$\Lambda_c^+ \to p\phi$	$(1.81 \pm 0.33 \pm 0.13) \times 10^{-2}$	$(1.64 \pm 0.32)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

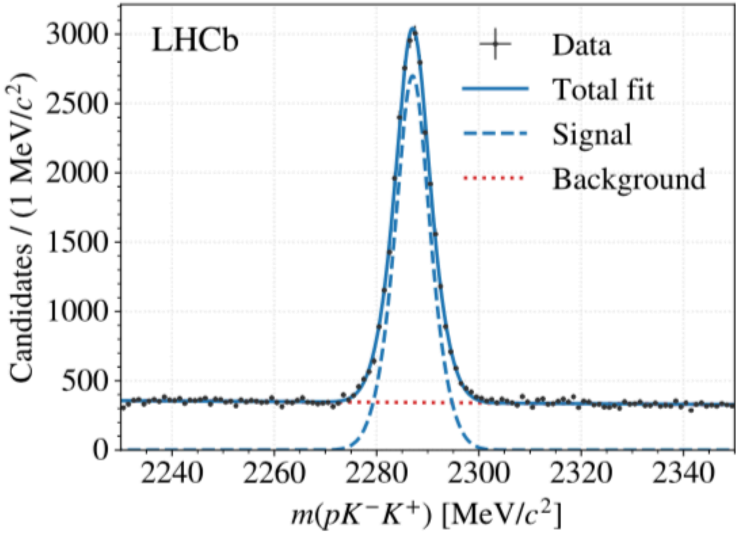
LHCb_JHEP03(2018)043

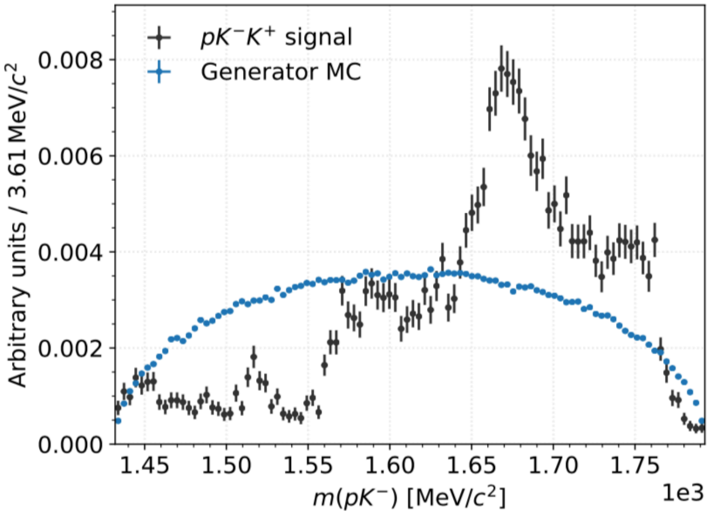
Belle_PhysRevLett.117.011801

arXiv_1712.07051

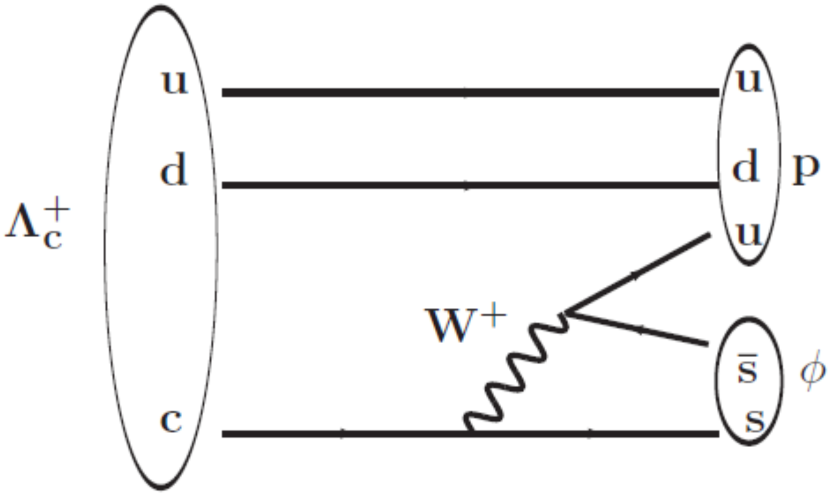








$\Lambda_c^+ \rightarrow p\phi$: test large-$N_c$ expansion



- **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

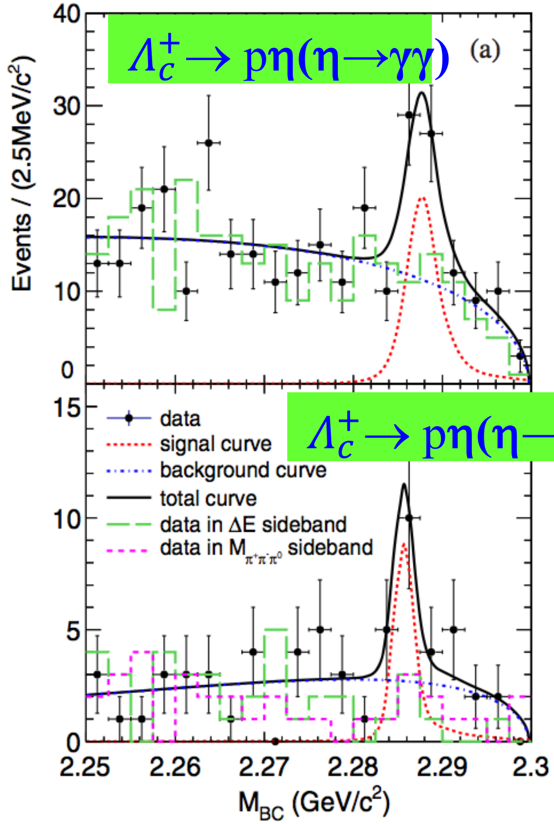
  If $\chi_1 = \chi_2 \approx -1/N_c$, large-$N_c$ factorization

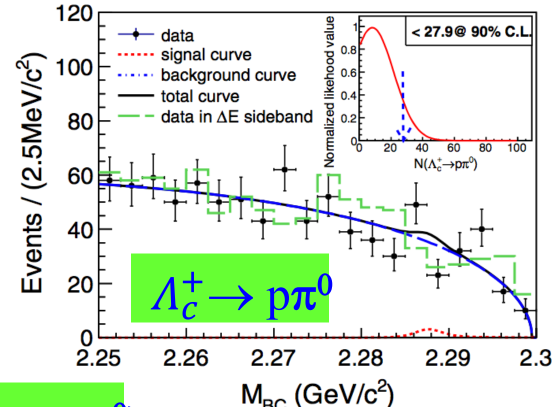
- $\Lambda_c^+ \rightarrow p\phi$ proceeds **only** through internal W-emission diagram.
- **Input BF $\Rightarrow$ $|a_2|=0.45\pm0.03$, Nc $\approx$7, close to $a_2(m_c) \approx -0.44$(from theory)**

  arXiv:1801.08625
- **$1/N_c$ is also applicable to charmed baryon sector.**
- **BESIII measurement are consistent with previous measurement.**

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

- $B(\Lambda_c^+ \to p\eta) >> B(\Lambda_c^+ \to p\pi^0)$ **in the SU(3) flavor symmetry generated by u,d and s**
- Their relative size is essential to understand the interference of different non factorizable diagrams.





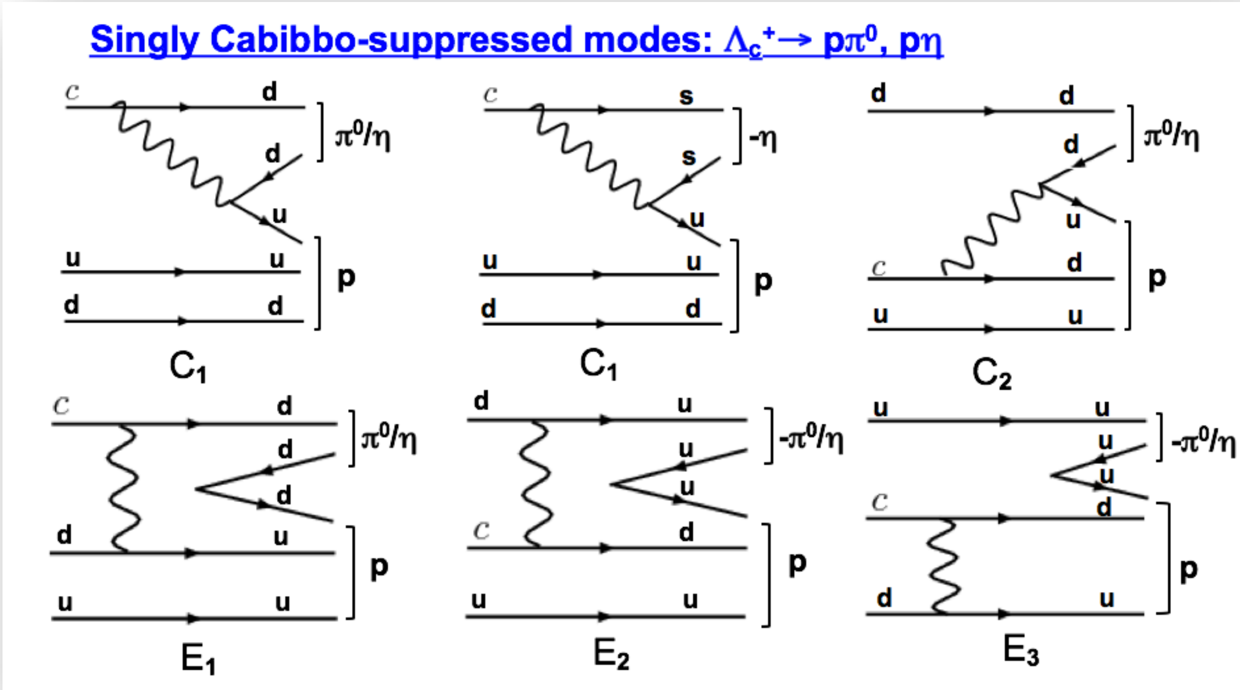
PRD,111102(R) (2017)

	$\Lambda_c^+ \to p\eta$	$\Lambda_c^+ \to p\pi^0$	$\frac{\mathcal{B}_{\Lambda_c^+ \to p\pi^0}}{\mathcal{B}_{\Lambda_c^+ \to p\eta}}$
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.

- First evidence for $\Lambda_c^+ \to p\eta$ with 4.2σ
- No signal seen in $\Lambda_c^+ \to p\pi^0$
- Predicted BFs vary under different theoretical modes(SU(3) symmetry and FSI)

$B(\Lambda_c^+ \to p\pi^0)$ v.s. $B(\Lambda_c^+ \to p\eta)$



arXiv:1801.08625

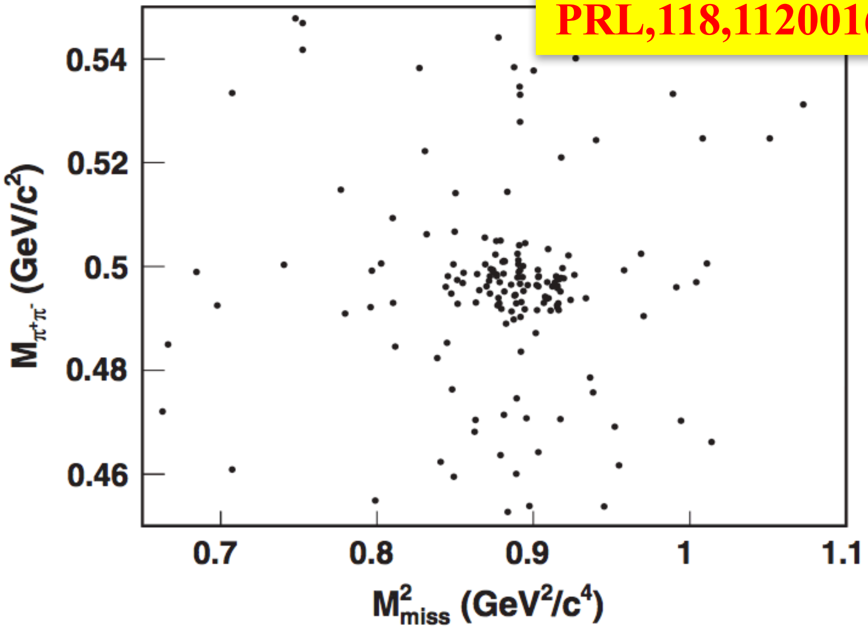
	Sharma et al. [24]	Uppal et al. [41]	Chen et al. [42]	Lu et al. [25]	Geng et al. [26]	H-Y Cheng	Expt [7, 19]
$\Lambda_c^+ \to p\pi^0$	0.2	0.1-0.2	0.11-0.36	0.48	0.56 ± 0.15	0.08	< 0.27
$\Lambda_c^+ \to p\eta$	$0.2^a(1.7)^b$	0.3			1.24 ± 0.41	1.28	1.24 ± 0.29

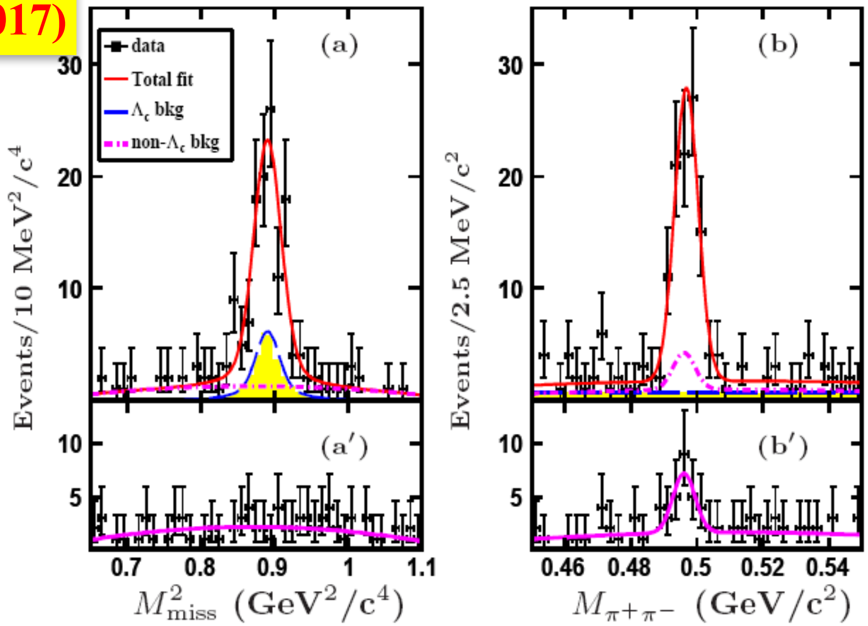
- Large constructive(destructive) interference between the factorizable and nonfactorizable amplitudes for both S- and P-waves.
- More precise comparison of the two BFs are desired to explore the interference of different non-factorizable diagrams
- BESIII result support the theoretic prediction.

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)

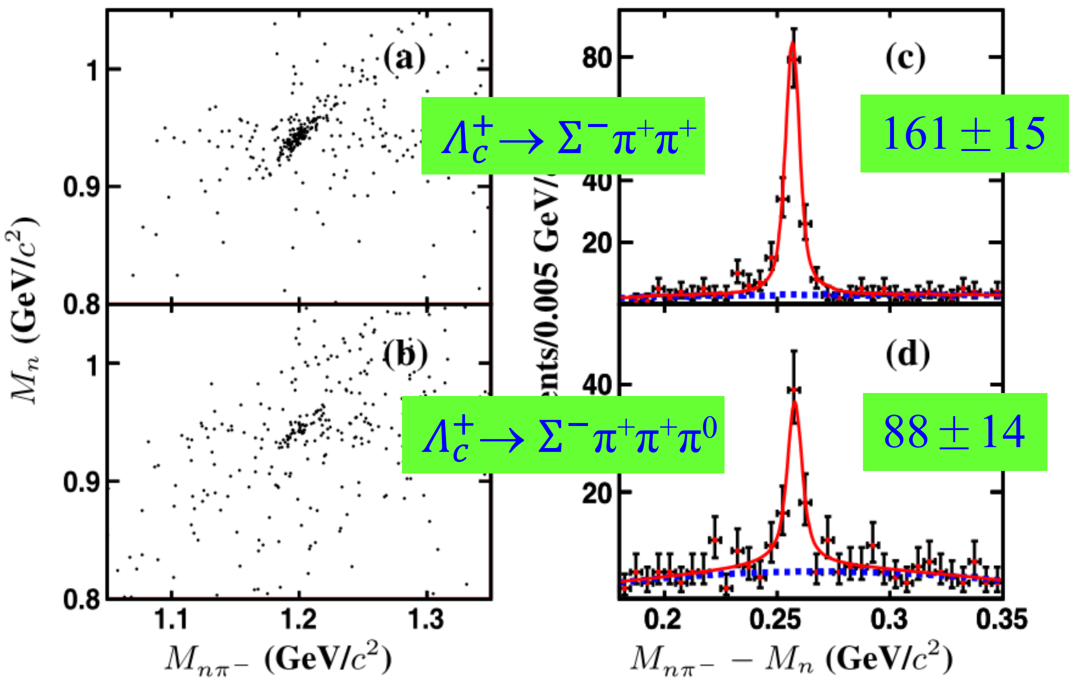




- Peaking background from $\Lambda_c^+ \to \Sigma^+ (\to n\pi^+)\ \pi^+\pi^-$
- **2-D fitting extract 83 ± 11 net signals**
- **$B[\Lambda_c^+ \to nK_S^0\pi^+]=(1.82\pm0.23\pm0.11)\%$**
- **$B[\Lambda_c^+ \to nK^0\pi^+]/B[\Lambda_c^+ \to pK^-\pi^+]=0.62\pm0.09$; $B[\Lambda_c^+ \to nK^0\pi^+]/B[\Lambda_c^+ \to pK^0\pi^0]=0.97\pm0.16$**
- **A test of final state interactions and isospin symmetry in the charmed baryon sector.** [PRD93, 056008 (2016)]

Observation 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).**
- ***$B(\Lambda_c^+ \to \Sigma^- \pi^+ \pi^+ \pi^0) = (2.11 \pm 0.33 \pm 0.14)\%$***
- ***$B(\Lambda_c^+ \to \Sigma^- \pi^+ \pi^+) = (1.81 \pm 0.17 \pm 0.09)\%$***

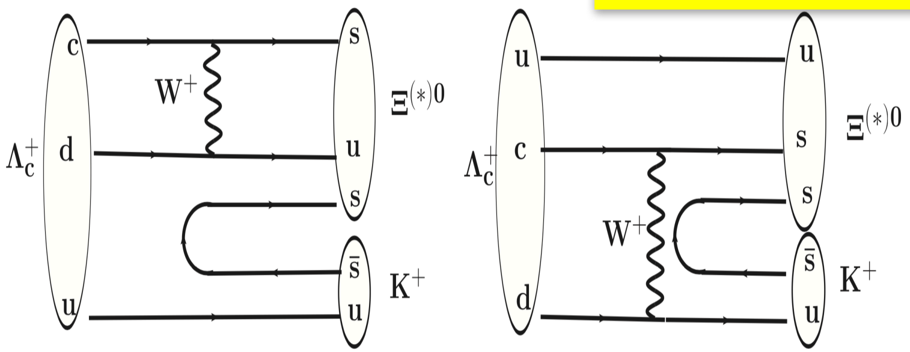
  more precise than old result $(2.3 \pm 0.4)\%$

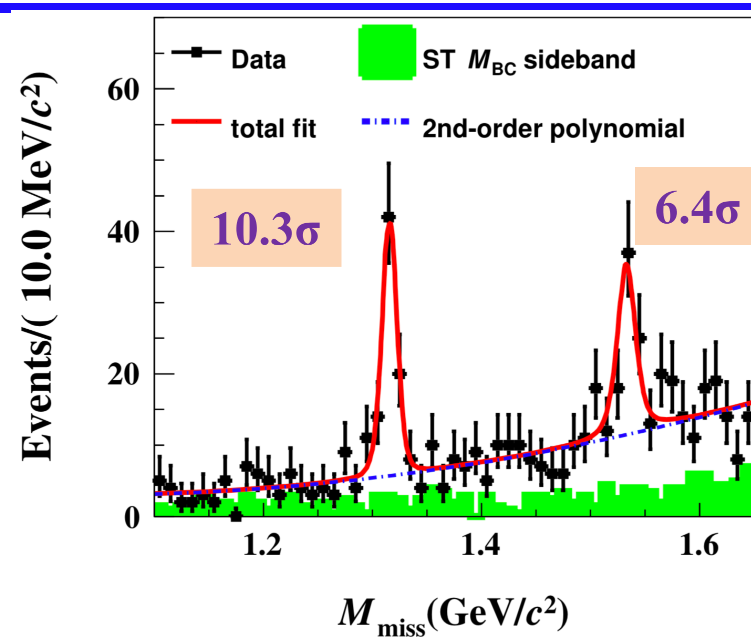
$$M_{n\pi^-} = \sqrt{(E_{\text{beam}} - E_{\pi^+\pi^+(\pi^0)})^2 - |\vec{p}_{\Lambda_c^+} - \vec{p}_{\pi^+\pi^+(\pi^0)}|^2}$$

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

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

arXiv:1803.04299





- **$\Lambda_c^+ \to \Xi^{0(*)} K^+$ decay only through W-exchange.**
- **W-exchange are non-factorable in theoretic calculation.**
- **Large cancellation both in S-wave and P-wave.**

- **First absolute measurement, using world largest on-threshold data at $\sqrt{s}$=4.6GeV**
- **Excited states in higher side is more interesting and will be confirmed by next round data taking.**

Decay	Measured $\frac{\mathcal{B}(\Lambda_c^+ \to \Xi^{(*)0} K^+)}{\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)}$	Predicted $\mathcal{B}(\Lambda_c^+ \to \Xi^{(*)0} K^+)$
$\Xi^0 K^+$	$(7.8 \pm 1.8)\%$ [18] $(5.0 \pm 1.2)\times 10^{-3}$	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] $(9.3 \pm 3.2)\%$ [19, 20] $(4.0 \pm 1.0)\times 10^{-3}$	5.0×10^{-3} [4] 0.8×10^{-3} [16] 0.6×10^{-3} [17]

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

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

More Λ_c data set ?

A combined data taking proposal of studying Λ_c^+

Proposal of precise study of the charmed baryon Λ_c^+ decays

Hai-Bo Li, Peirong Li, Lei Li, Xiao-Rui Lyu, Haiping Peng, Yangheng Zheng

Analyticity Violation in $e^+e^- \to \Lambda_c \bar{\Lambda}_c$?
A request for
additional integrated luminosity at threshold

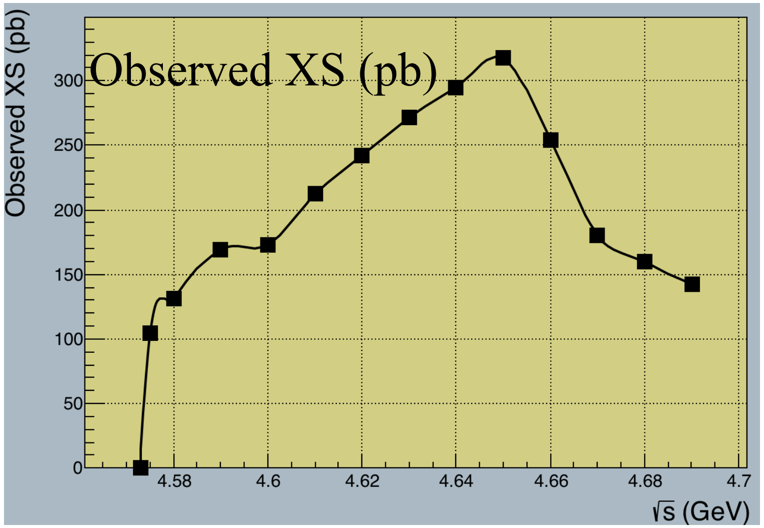
Rinaldo Baldini, Marco Maggiora, Guangshun Huang, RongGang Ping, Weimin Song, Weiping Wang, Liang Yan, Zhengguo Zhao, Xiaorong Zhou, Kai Zhu,
and the BESIII Italian Collaboration Team

BESIII collaboration meeting at SJTU 2015.6.14

We propose one year dedicated data taking at Λ_c threshold

Our proposal

- **A one-year data taking of 3fb^{-1} above Λ_c^+ pair mass threshold: >= 4.6 GeV**
- **This corresponds to 5~10 times of the number of Λ_c^+ pairs in existing data**



Energy (MeV)	**Observed XS (pb)**	**Requested Lum. (pb^{-1})**	**Days**	**Λ_c pairs (K)**	**Times of current data set**
4600	172 ± 3	3000	180	510	5.1
4610	210	3000	180	630	6.3
4620	245	3000	180	735	7.3
4630	270	3000	180	810	8.1
4640	**320**	**3000**	**180**	**960**	**9.6**

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

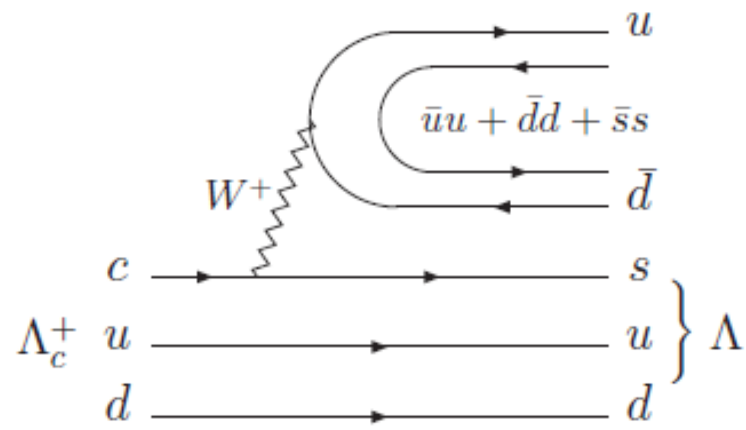
Eur.Phys.J. C76 (2016) no.9, 496

The $a_0(980)$ and $\Lambda(1670)$ in the $\Lambda_c^+ \to \pi^+\eta\Lambda$ decay

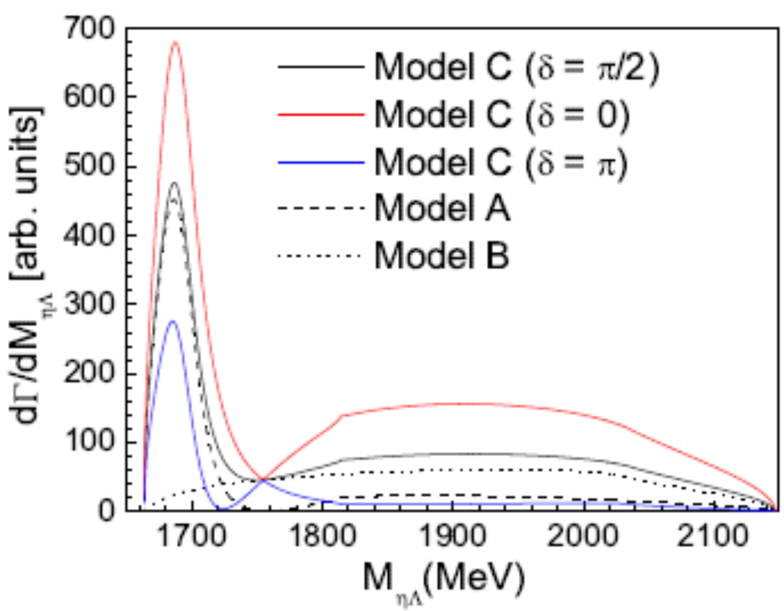
Ju-Jun Xie[1,2] and Li-Sheng Geng[3,2,*]
[1]Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[2]State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China
[3]School of Physics and Nuclear Energy Engineering and International Research Center for Nuclei and Particles in the Cosmos, Beihang University, Beijing 100191, China
(Dated: April 14, 2016)

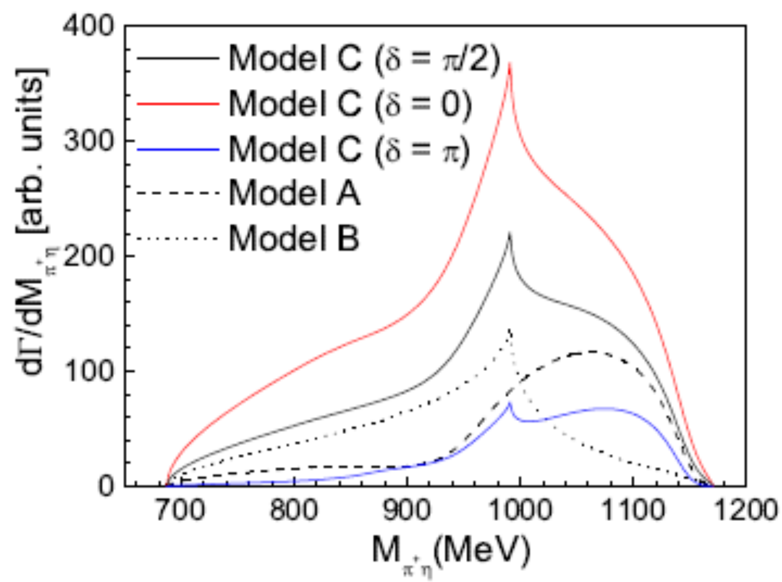
We propose to study the $a_0(980)$ and the $\Lambda(1670)$ resonances in the $\Lambda_c^+ \to \pi^+\eta\Lambda$ decay via the final state interactions of the $\pi^+\eta$ and $\eta\Lambda$ pairs. The weak interaction part proceeds through the c quark decay process: $c(ud) \to (s + u + \bar{d})(ud)$, while the hadronization part takes place in two different mechanisms. In the first mechanism, the sud cluster picks up a $q\bar{q}$ pair from the vacuum to form the $\eta\Lambda$ meson-baryon pair while the $u\bar{d}$ pair from the weak decay hadronizes into a π^+. In the second, the sud cluster turns into a Λ, while the $u\bar{d}$ pair from the c decay picks up a $q\bar{q}$ pair and hadronizes into a meson-meson pair ($\pi\eta$ or $K\bar{K}$). Because the final $\pi^+\eta$ and $\eta\Lambda$ states are in pure isospin $I = 1$ and $I = 0$ combinations, the $\Lambda_c^+ \to \pi^+\eta\Lambda$ decay can be an ideal process to study the $a_0(980)$ and $\Lambda(1670)$ resonances. Describing the final state interaction in the chiral unitary approach, we find that the $\pi^+\eta$ and $\eta\Lambda$ invariant mass distributions, up to an arbitrary normalization, show clear cusp and peak structures, which can be associated with the $a_0(980)$ and $\Lambda(1670)$ resonances, respectively. The proposed mechanism can provide valuable information on the nature of these resonances and can in principle be test by facilities such as BEPCII.

PACS numbers: 13.75.Jz, 14.20.-c, 11.30.Rd



new $\Lambda^*(1670)3/2^-$ → $\Lambda\eta$ with width of 1.5 MeV
[us]{ds} $\bar{s}$

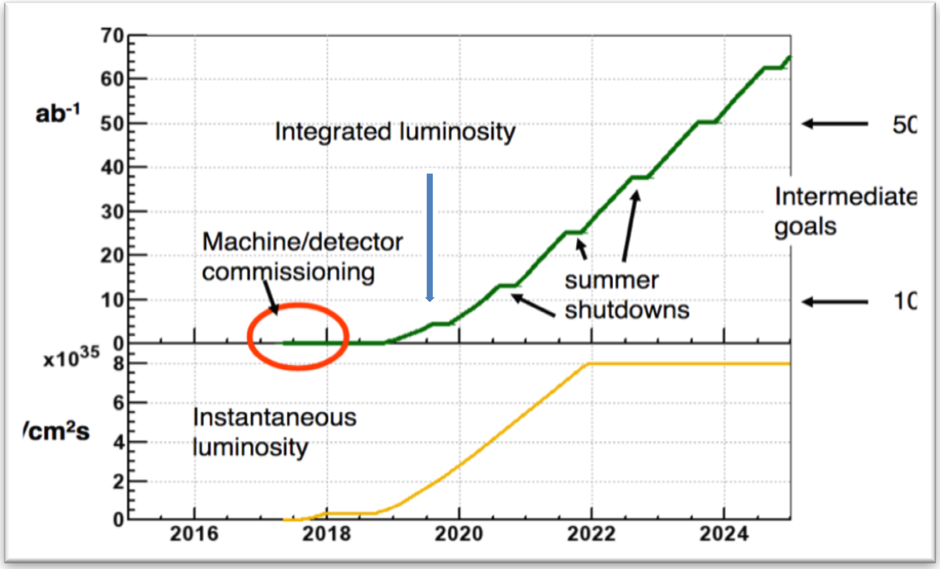


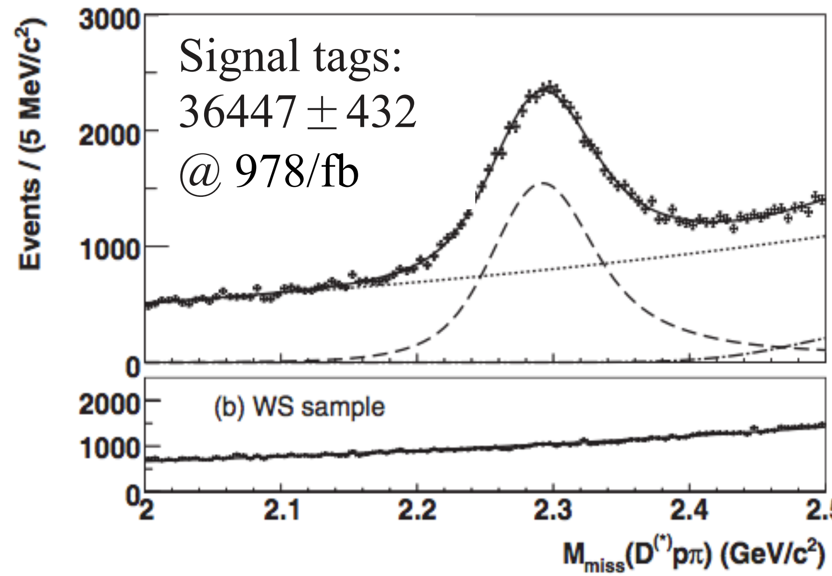


BESIII present data only see some **Hint, more data is needed!!**

Competition from Belle & BelleII

Belle, PRL113, 042002 (2014)

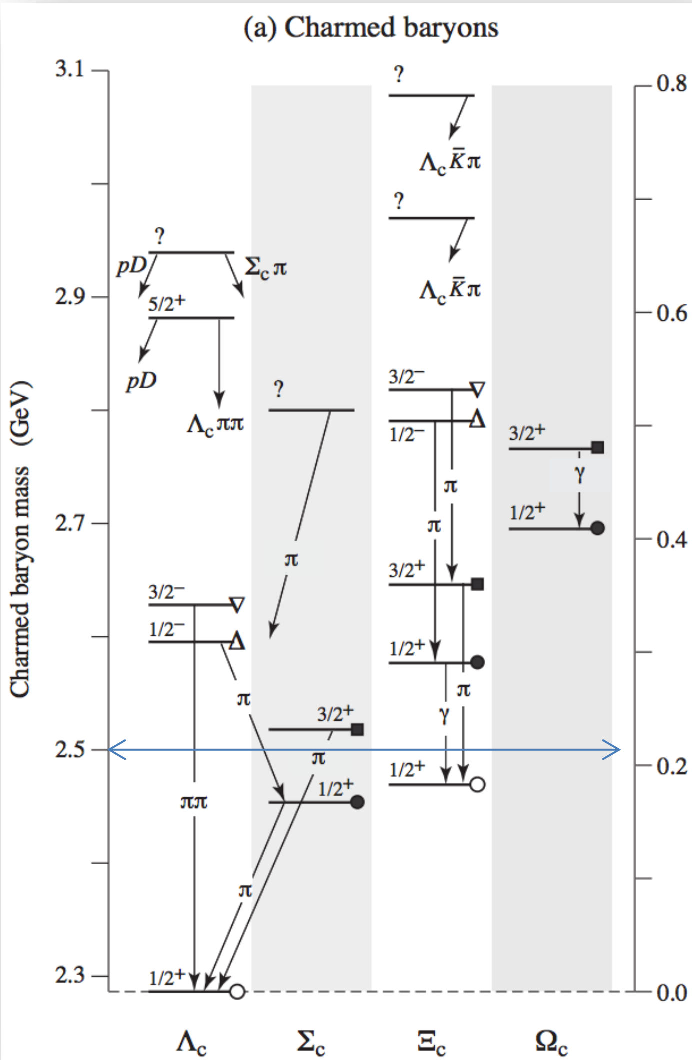


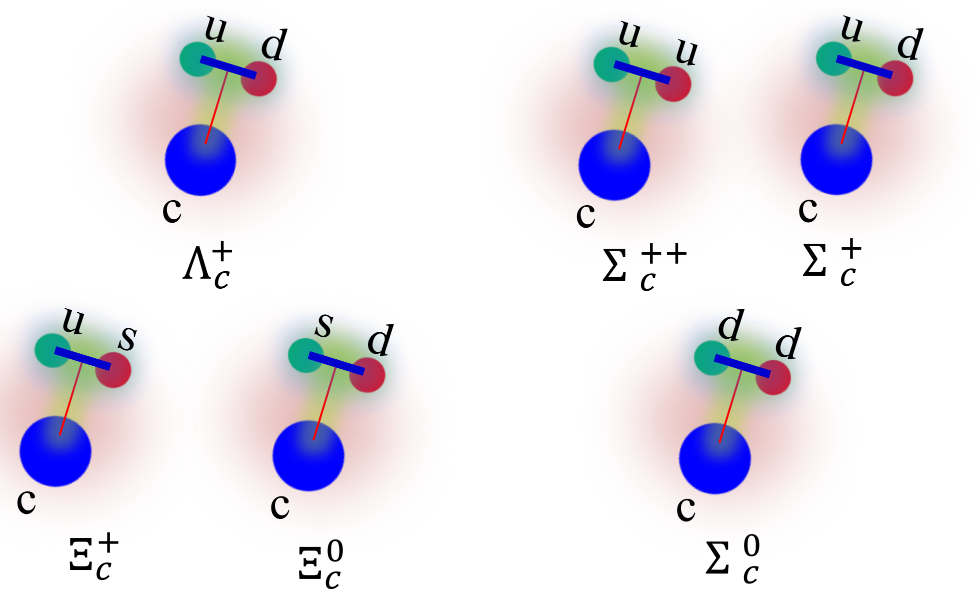


- Belle tags ~36K Λ_c^+, while BESIII now tags 15K Λ_c^+ (567/pb@4.6GeV)
- By middle of 2019, Belle-II will have 5/ab data, 5x of BELLE data;
  ➔ 180K Λ_c^+ tagging; 12x BESIII data
- We shall have 10x more Λ_c^+ pairs before Belle-II begins data taking at the end of 2018
- Many precise measurements 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	$\Sigma(138$[illegible]	[illegible]
Γ_7	$\Sigma^+K^-\pi^+$	[illegible]
Γ_8	$\Sigma^+\overline{K}^*$ [illegible]	[illegible]
Γ_9	$\Sigma^0K^-2\pi$[illegible]	[illegible]
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}	$\Xi^0e^+\nu_e$	$2.3^{+0.7}_{-0.8}$
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[illegible] $=-2$) 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
[illegible]	[illegible]	[illegible]28
Γ_8	$\Xi^-\pi^+$	**DEFINEDAS1**
Γ_9	$\Xi^-\pi^+\pi^+\pi^-$	3.3 ± 1.4
Γ_{10}	Ω^-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}	Ξ^-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) (RQM)	Xu, Kamal ('92) (Pole)	Cheng, Tseng ('93) (Pole)	Ivanov et al. ('98) (RQM)	Żenczykowski ('94) (Pole)	Sharma, Verma ('99) (Pole)	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

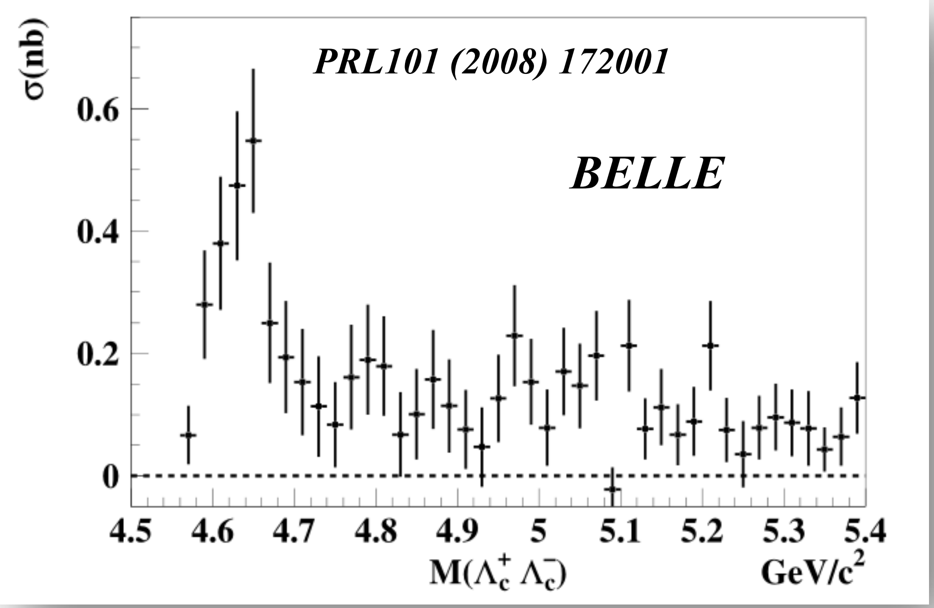
|→ NRQM ←| RQM LFQM QSR QSR

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 $10^{10}\ s^{-1}$

Other interesting charm topics above 4.6GeV

- $\Lambda_c^+\overline{\Lambda}_c^-$ **line shapes to understand Y(4630)**



- **Threshold effect of charged** $\Xi_c^+\overline{\Xi}_c^-$ **and neutral** $\Xi_c^0\overline{\Xi}_c^0$ **pairs**
- **Production of excited states of** $D_{(s)}$**, such as** $D_1(2420)$**,** $D_2(2460)$**,** $D_{s0}(2317)$**,** $D_{s1}(2460)$**,** $D_{s1}(2536)$**, and** $D_{s2}(2573)$
  - ✓ potentials to establish the absolute BFs of their decays
  - ✓ potentials to precisely measure their masses and widths

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