Λ_c^+ decays at BESIII

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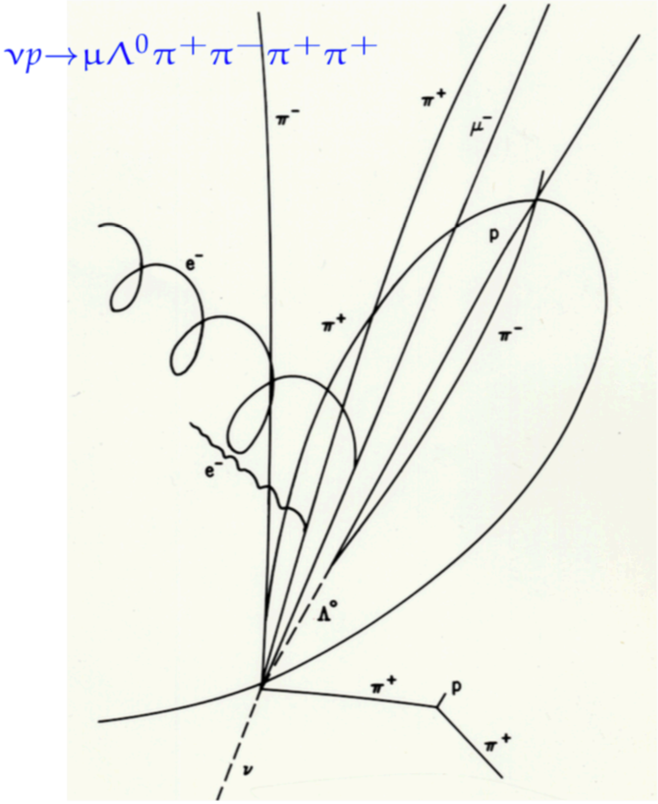
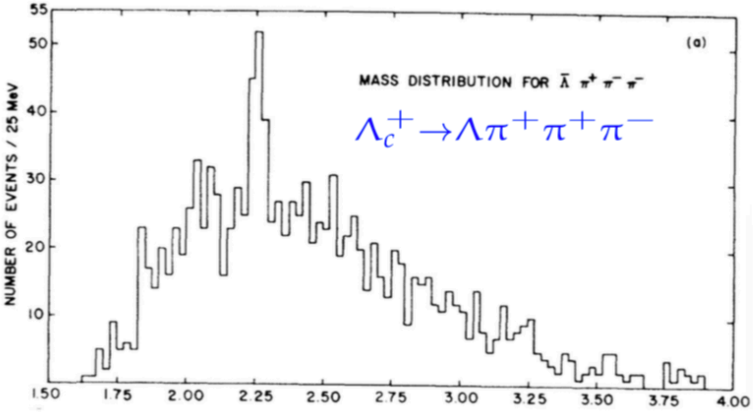
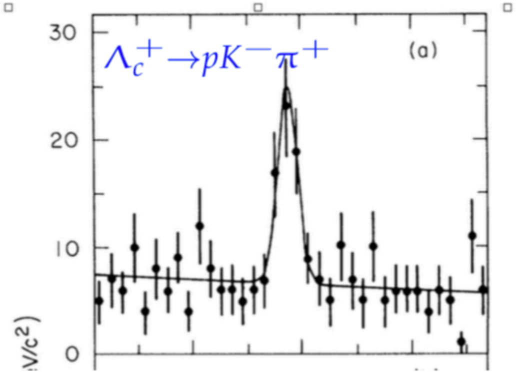
Outline

- Introduction to the lightest charm baryon Λ_c^+
- Λ_c^+ hadronic decays
- Λ_c^+ semi-leptonic decay $\Lambda_c^+ \rightarrow \Lambda l^+ \nu_l$
- Λ_c^+ inclusive decay $\Lambda_c^+ \rightarrow \Lambda + X$
- $\Lambda_c^+ \Lambda_c^-$ pair cross section measurement at threshold
- 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:

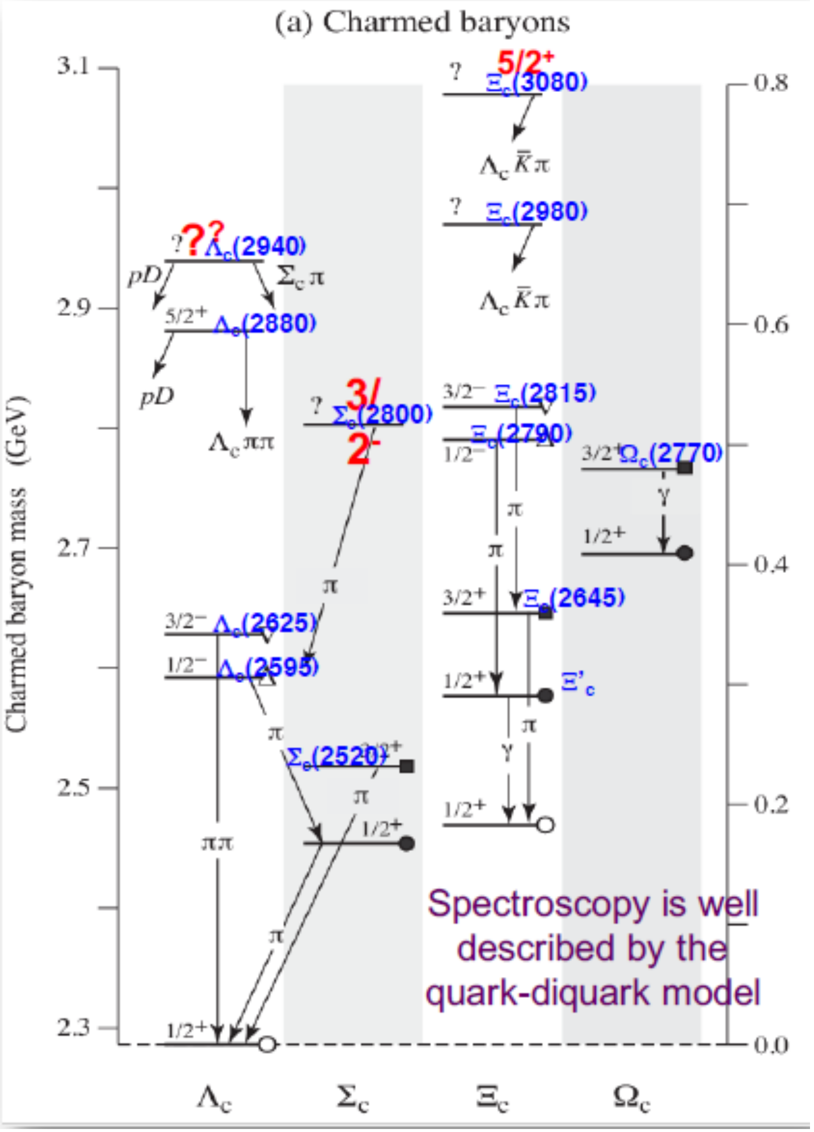
    $\Lambda_c^+, \Sigma_c, \Xi_c^{(\prime)}, \Omega_c$
  - ◆ Excited states are being explored
- **Doubly charmed baryons(Ξ_{cc}^{++}) observed recently.**
- **No observations of triply charmed baryons.**

✓ **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.**

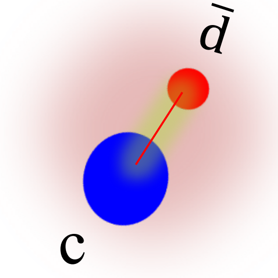


(a) Charmed baryons

Spectroscopy is well described by the quark-diquark model

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).**



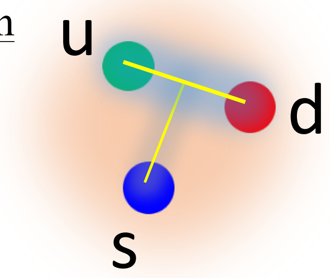
→ Charmed meson

($D^+[c\bar{d}]$)

$m_d << m_c$ →

quark + heavy quark

(q) (Q)

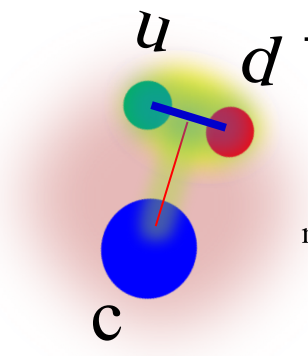


→ Strange baryons

(Λ[uds])

m_u, $m_d \approx m_s$ →

(qqq) uniform



→ Charmed baryon

(Λ_c[udc])

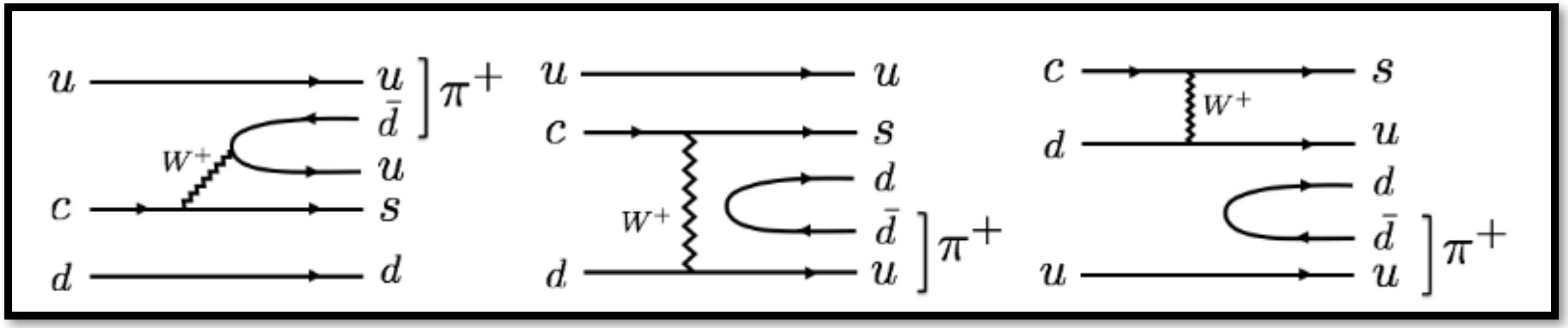
m_u, $m_d << m_c$ →

diquark + quark

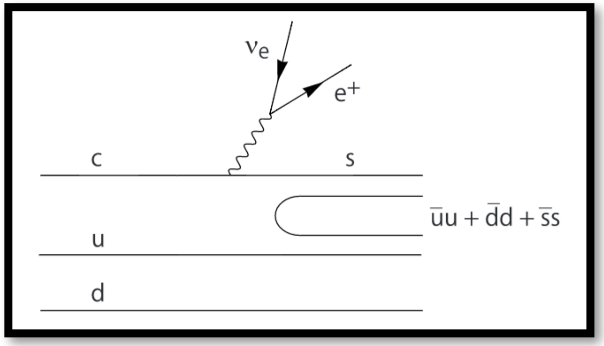
(qq) (Q)

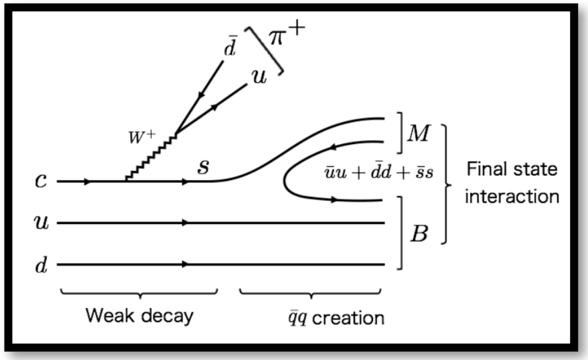
Λ_c^+ weak decays

- **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 $\Lambda_c \to \pi\ \Lambda(1405)$ 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.**

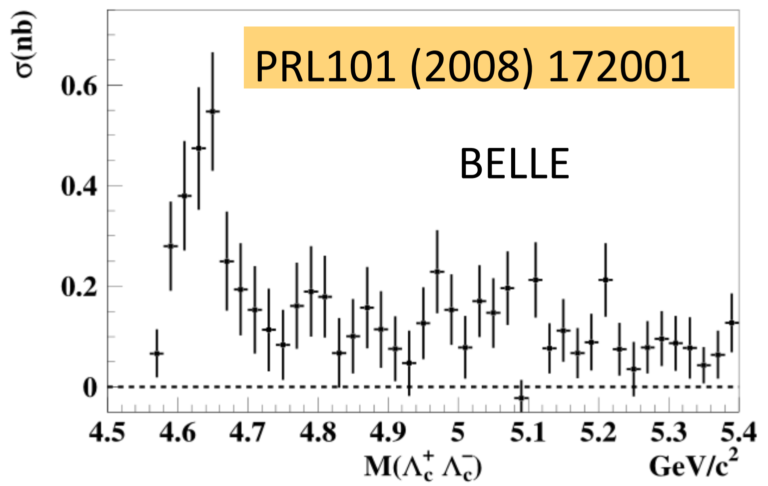


FIG. 4: The cross section for the exclusive process $e^+e^- \to \Lambda_c^+\Lambda_c^-$.

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

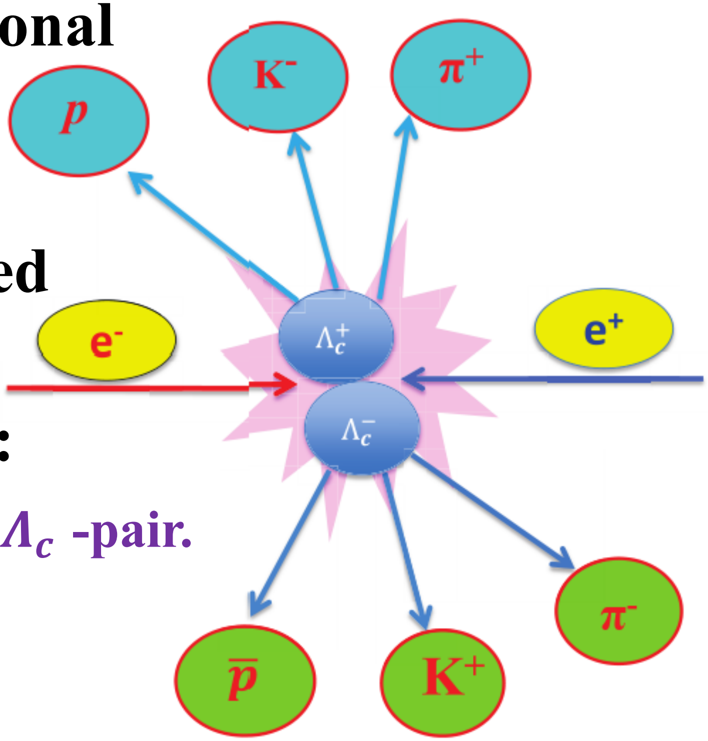
    =>Full reconstruction
  - Double Tag(DT): Find both of $\Lambda_c^+\Lambda_c^-$

    =>Smaller backgrounds.

    =>Missing technique.

    =>Lower efficiencies.

    =>Systematic in tag side are mostly cancelled.

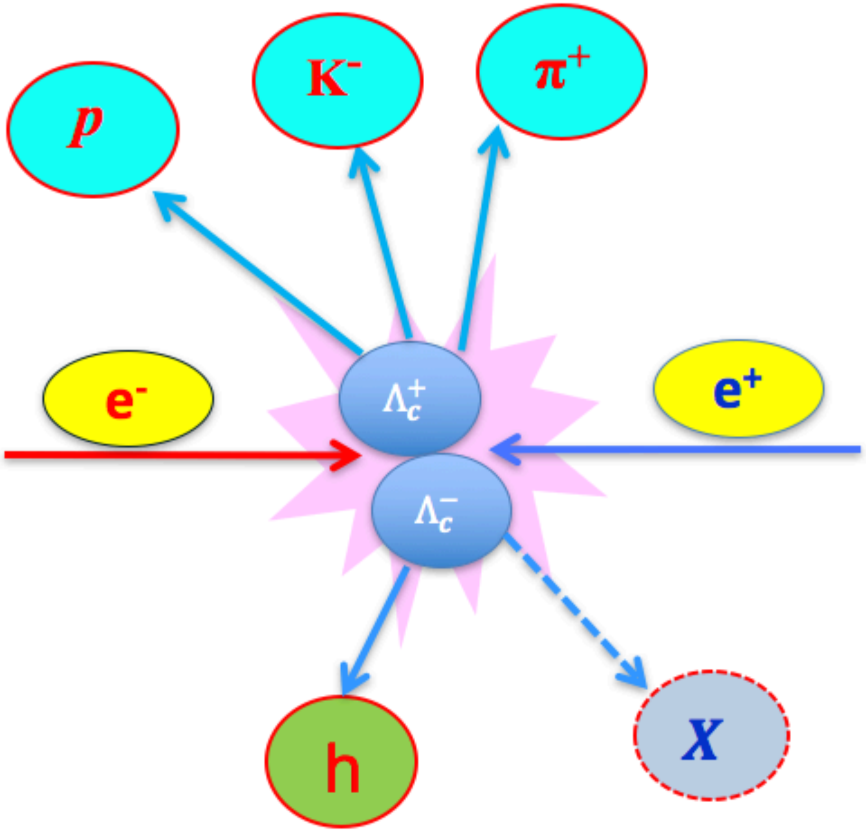


Several popular variables

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

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

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

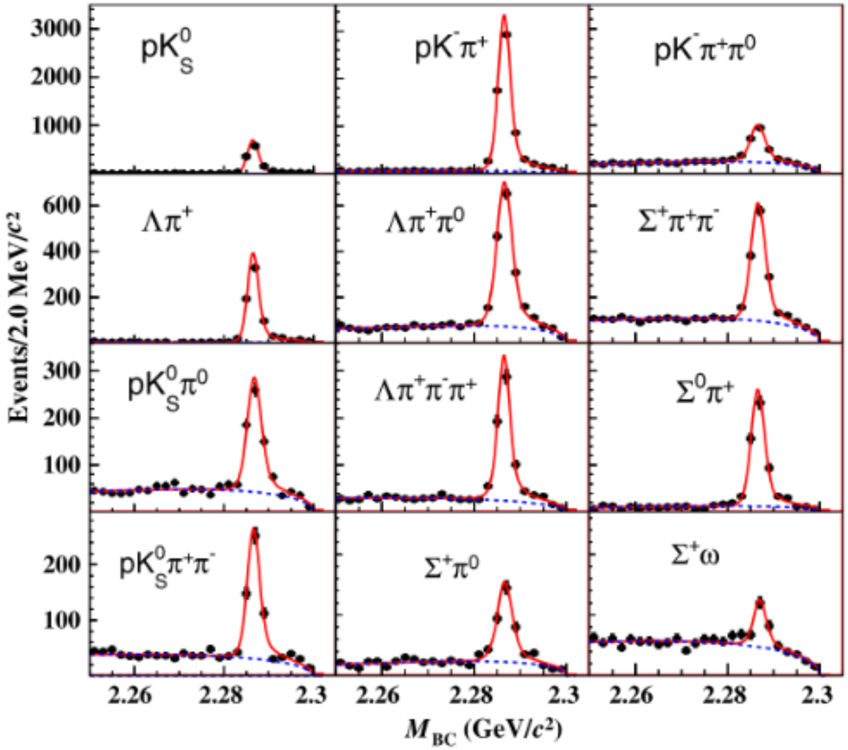


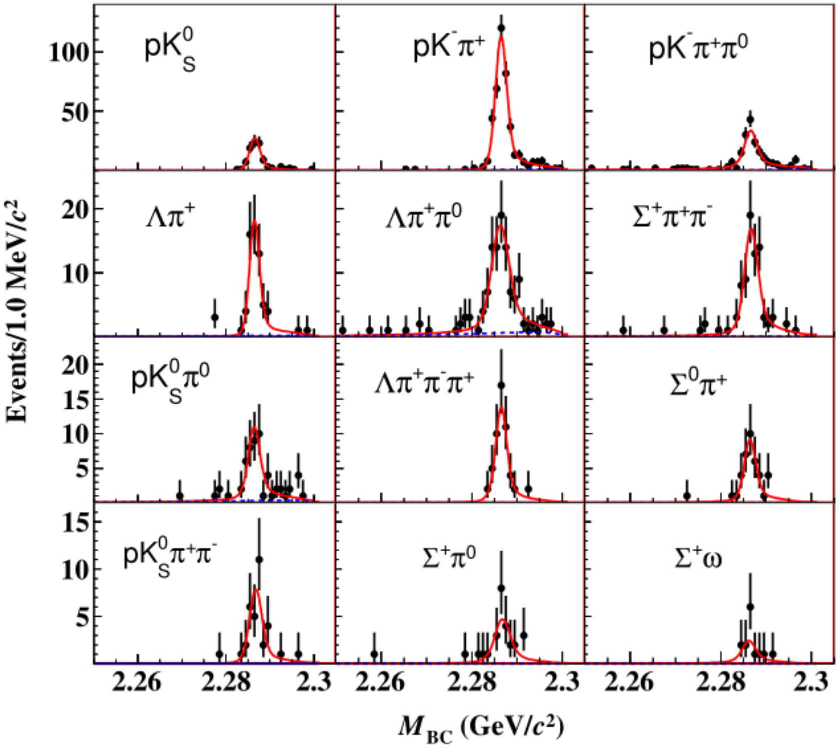
- $\hat{p}_{\mathrm{tag}}$ is the direction of the momentum of the singly tagged Λ_{c} .
- $E_{\mathrm{h}}(p_{\mathrm{h}})$ are the energy(momentum) of h which are measured in e^+e^- system.
- $m_{\Lambda_c^+}$ is the mass of the Λ_c^+ quoted from the PDG.

Measurements that I report today

- ◆ **Hadronic decay**
  - ☐ BF($\Lambda_c^+ \to pK^-\pi^+$) +11hadronic modes :PRL 116, 052001 (2016)
  - ☐ BF($\Lambda_c^+ \to nK_s\pi^+$) :PRL 118, 12001 (2017)
  - ☐ BF($\Lambda_c^+ \to pK^+K^-$, $p\pi^+\pi^-$) :PRL 117, 232002 (2016)
  - ☐ 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
- ◆ **Semi-leptonic decay**
  - ☐ BF($\boldsymbol{\Lambda}_c^+ \to \boldsymbol{\Lambda} e^+ \nu_e$) :PRL 115, 221805(2015)
  - ☐ BF($\boldsymbol{\Lambda}_c^+ \to \boldsymbol{\Lambda} \mu^+ \nu_\mu$) : PLB 767, 42 (2017)
- ◆ **Inclusive decay**
  - ☐ BF($\boldsymbol{\Lambda}_c^+ \to \boldsymbol{\Lambda} X$) : arXiv: 1803.05706
- ◆ **$\boldsymbol{\Lambda}_c^+ \boldsymbol{\Lambda}_c^-$ pair cross section measurement: PRL 120,132001(2018).**

Λ_c^+ reconstruction at BESIII





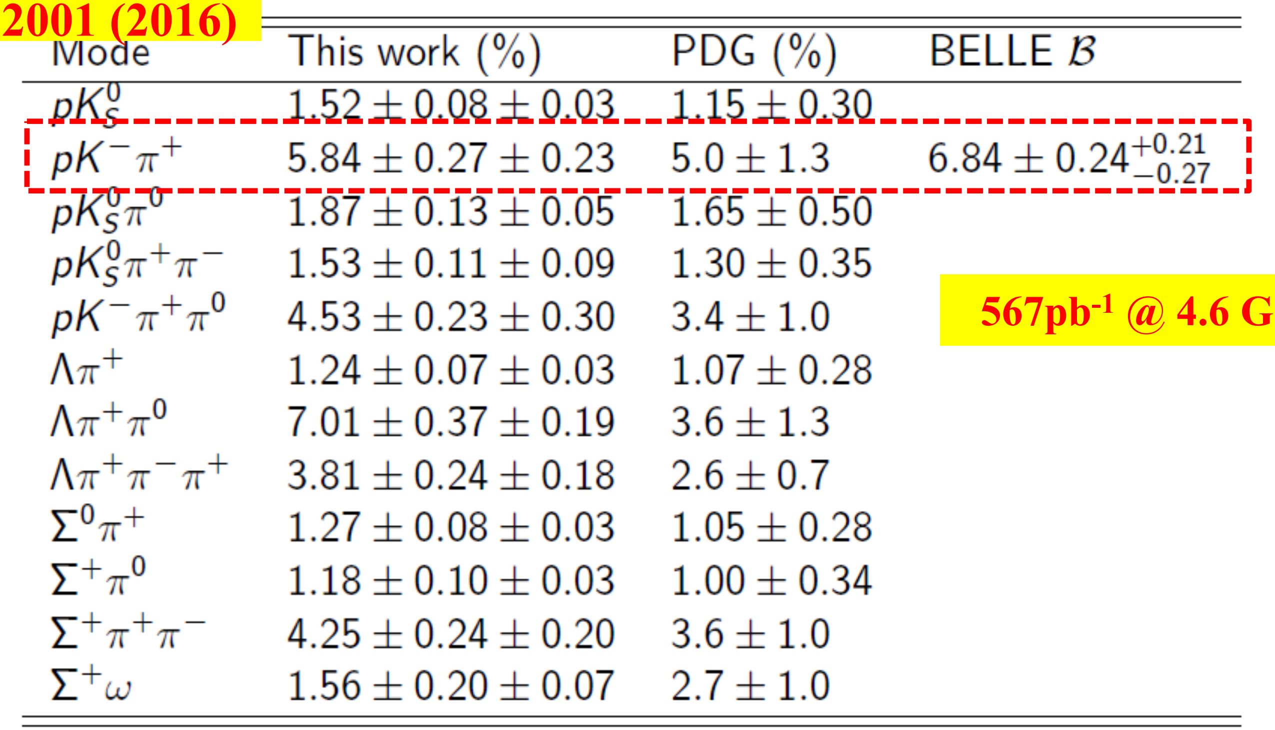
$$N_i^{\mathrm{ST}} = N_{\Lambda_c^+\bar{\Lambda}_c^-} \cdot \mathcal{B}_i \cdot \varepsilon_i^{\mathrm{ST}}$$

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

- **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	

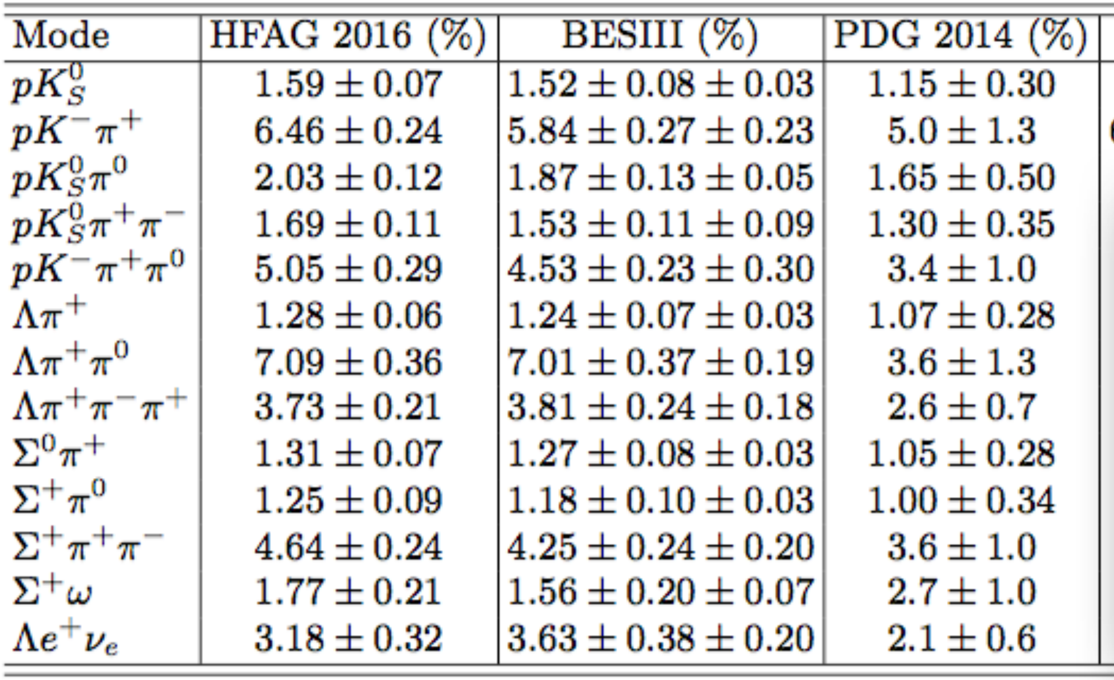
567pb^{-1} @ 4.6 GeV

- 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!
- $N_{\Lambda_c^+\Lambda_c^-}$ as a byproduct determined to be $(105.9 \pm 4.8 \pm 0.5) \times 10^3$

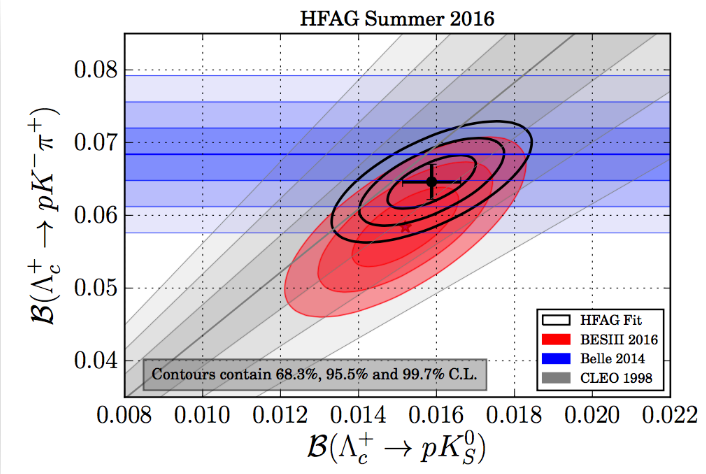
HFLAV Fit to world BF data

- 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^0_S	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	$6.84 \pm 0.24^{+0.21}_{-0.27}$
$pK^0_S\pi^0$	2.03 ± 0.12	$1.87 \pm 0.13 \pm 0.05$	1.65 ± 0.50	
$pK^0_S\pi^+\pi^-$	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	$B(K\pi)=(3.88\pm0.05)\%$	1.3%	$B(Kev)=(3.55\pm0.05)\%$	1.4%
D^+	$B(K\pi\pi)=(9.13\pm0.19)\%$	2.1%	$B(K^0ev)=(8.83\pm0.22)\%$	2.5%
D_s	$B(KKpi)=(5.39\pm0.21)\%$	3.9%	$B(\phi ev)=(2.49\pm0.14)\%$	5.6%
Λc	$B(pK\pi)=(5.0\pm1.3)\%$(PDG2014) $=(6.8\pm0.36)\%$ (BELLE) $=(5.84\pm0.35)\%$ (BESIII) $=(6.46\pm0.24)\%$ (HFAG)	26% 5.3% 6.0% 3.7%	$B(\Lambda ev)=(2.1\pm0.6)\%$(PDG2014) $=(3.63\pm0.43)\%$ (BESIII) $=(3.18\pm0.32)\%$ (HFAG)	29% 12% 10%

- The precisions of Λc decay rates is reaching to the level of charmed mesons!

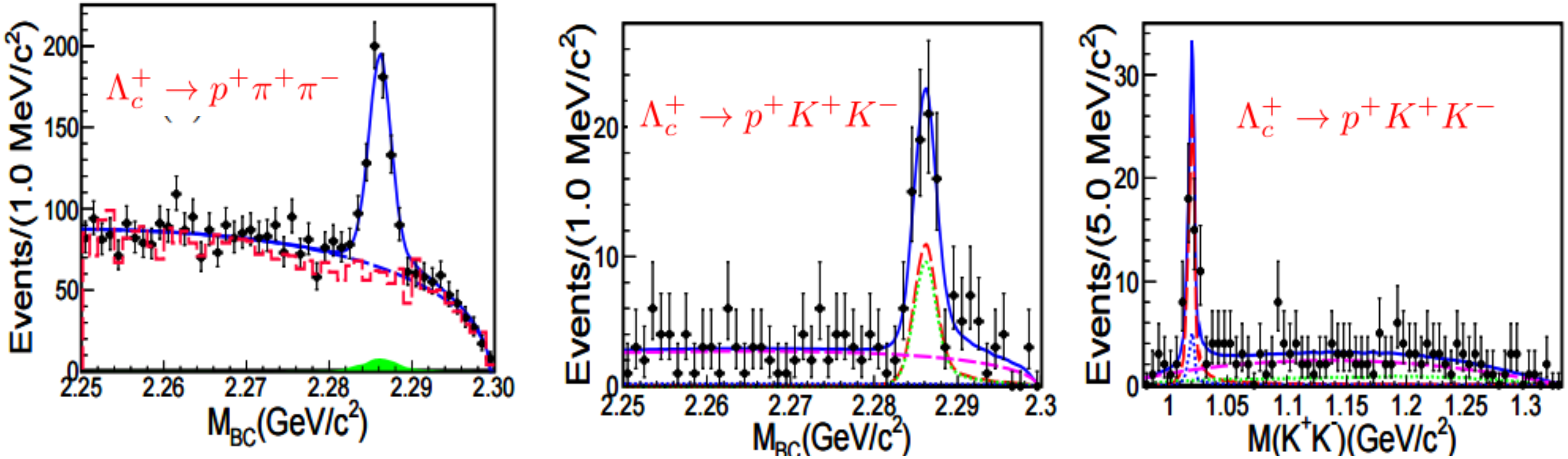
- More data input will further constrain the HFLAV fit.

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

]

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

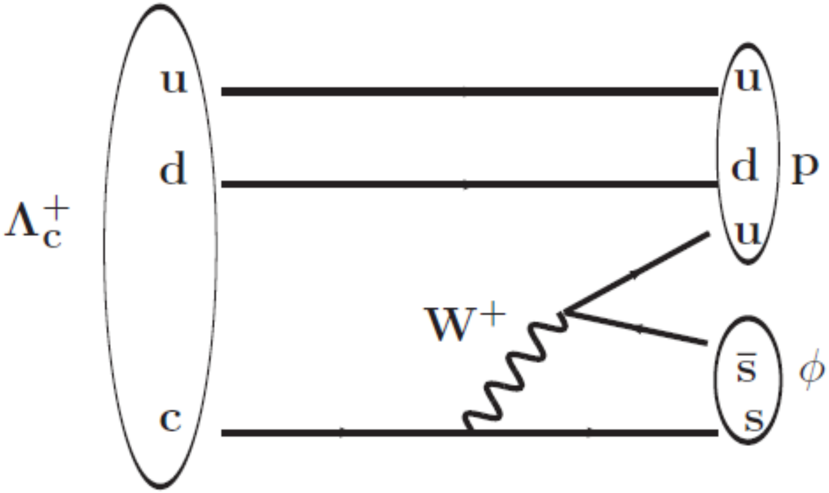
- **Charmed meson decays**

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

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

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

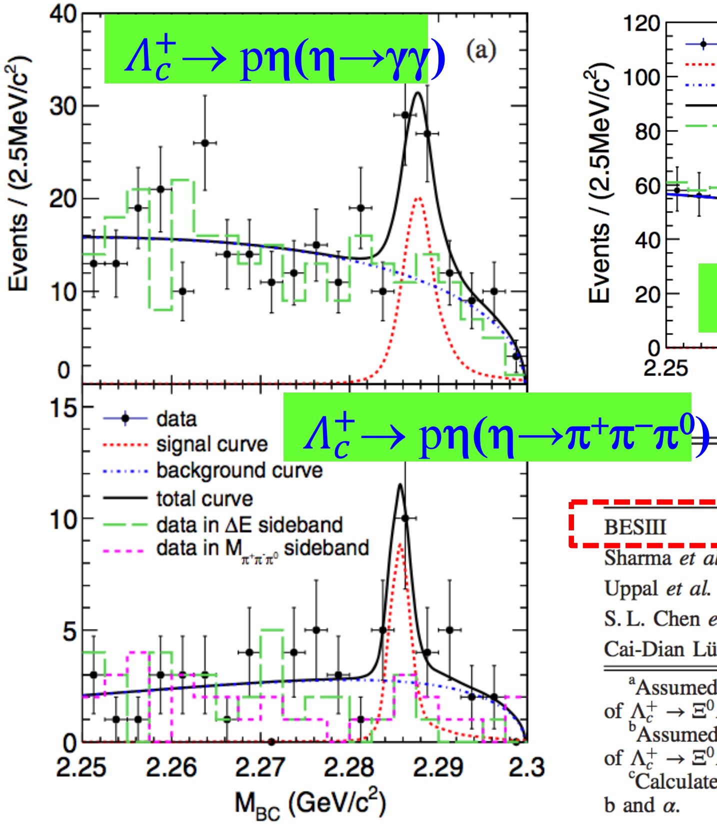
If $\chi_1 = \chi_2 = -1/N_c$, large-N_c factorization

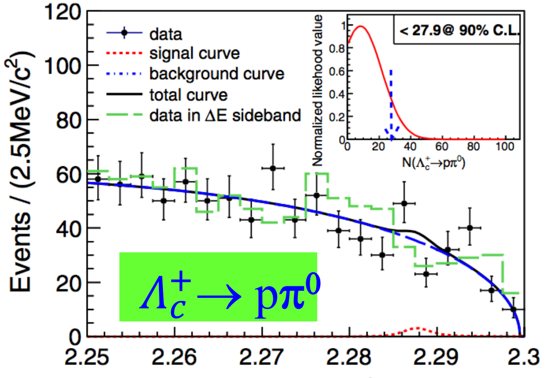


- $\Lambda_c^+ \to p\phi$ proceeds only through internal W-emission diagram.
- **Input BF ⇒ $|a_2|=0.70\pm0.07$, close to $c_2(m_c) \approx -0.59$(from theory)**
- **$1/N_c$ is also applicable to charmed baryon sector.**
- **BESIII measurement are consistent with previous measurement.**

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.

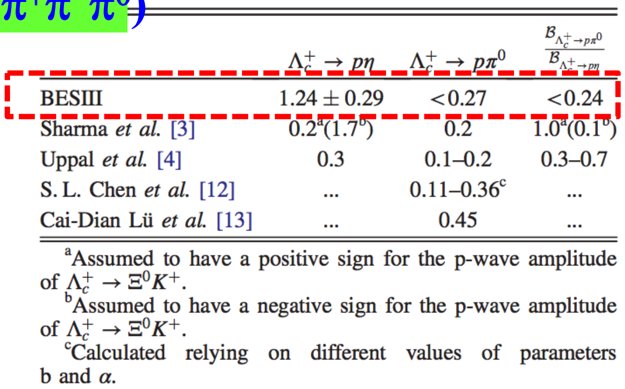




M_{BC} (GeV/c²)

PRD,111102(R) (2017)

- 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)



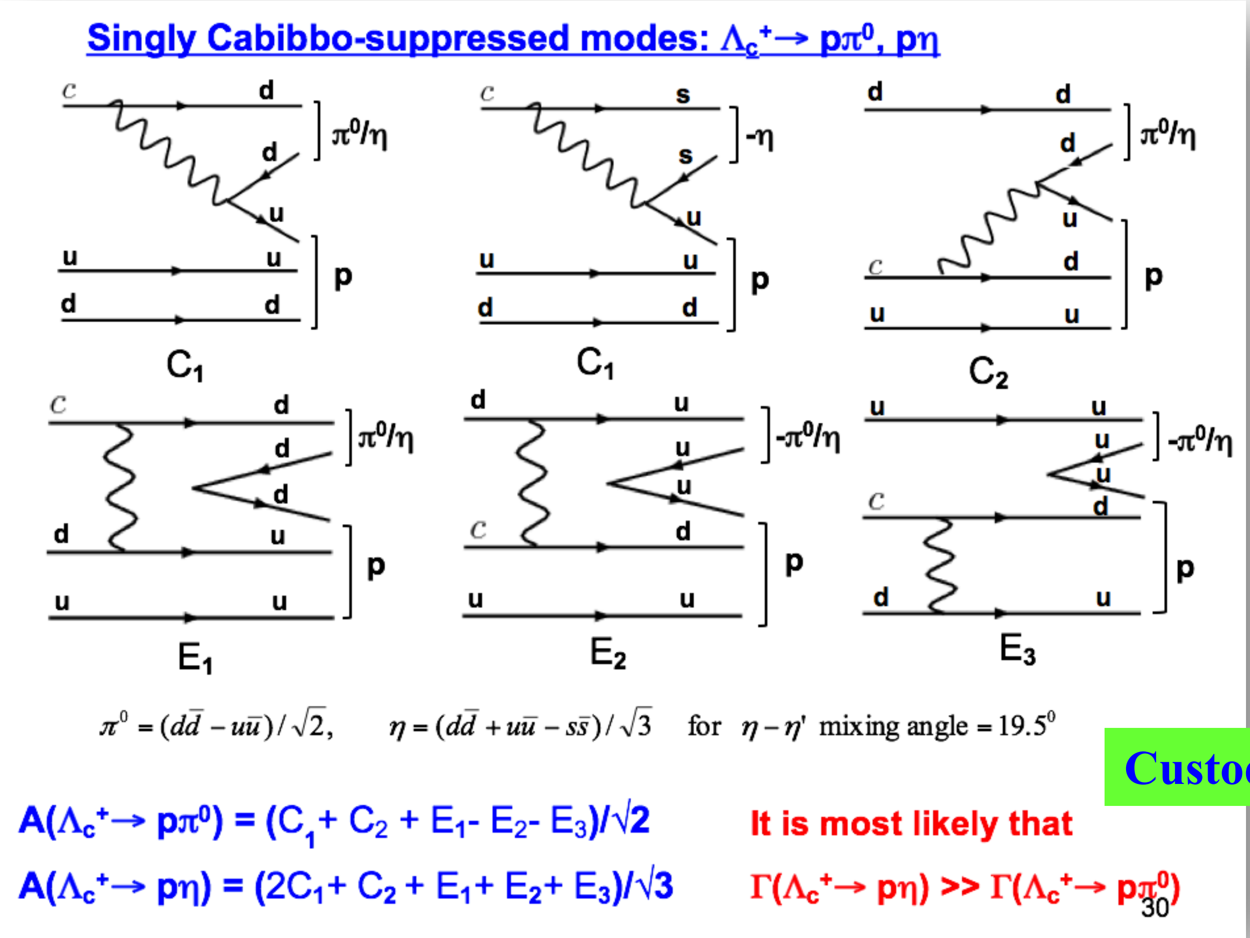
	$\Lambda_c^+ \to p\eta$	$\Lambda_c^+ \to p\pi^0$	$\frac{\mathcal{B}_{\Lambda_c^+\to p\pi^0}}{\mathcal{B}_{\Lambda_c^+\to p\eta}}$
BESIII	1.24 ± 0.29	<0.27	<0.24
Sharma *et al.* [3]	$0.2^a(1.7^b)$	0.2	$1.0^a(0.1^b)$
Uppal *et al.* [4]	0.3	0.1–0.2	0.3–0.7
S. L. Chen *et al.* [12]	...	$0.11–0.36^c$	...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

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



Singly Cabibbo-suppressed modes: $\Lambda_c^+ \to p\pi^0$, $p\eta$

$\pi^0 = (d\bar{d} - u\bar{u})/\sqrt{2}$, $\eta = (d\bar{d} + u\bar{u} - s\bar{s})/\sqrt{3}$ for $\eta - \eta'$ mixing angle $= 19.5^0$

$A(\Lambda_c^+ \to p\pi^0) = (C_1 + C_2 + E_1 - E_2 - E_3)/\sqrt{2}$

$A(\Lambda_c^+ \to p\eta) = (2C_1 + C_2 + E_1 + E_2 + E_3)/\sqrt{3}$

It is most likely that

$\Gamma(\Lambda_c^+ \to p\eta) >> \Gamma(\Lambda_c^+ \to p\pi^0)$

30

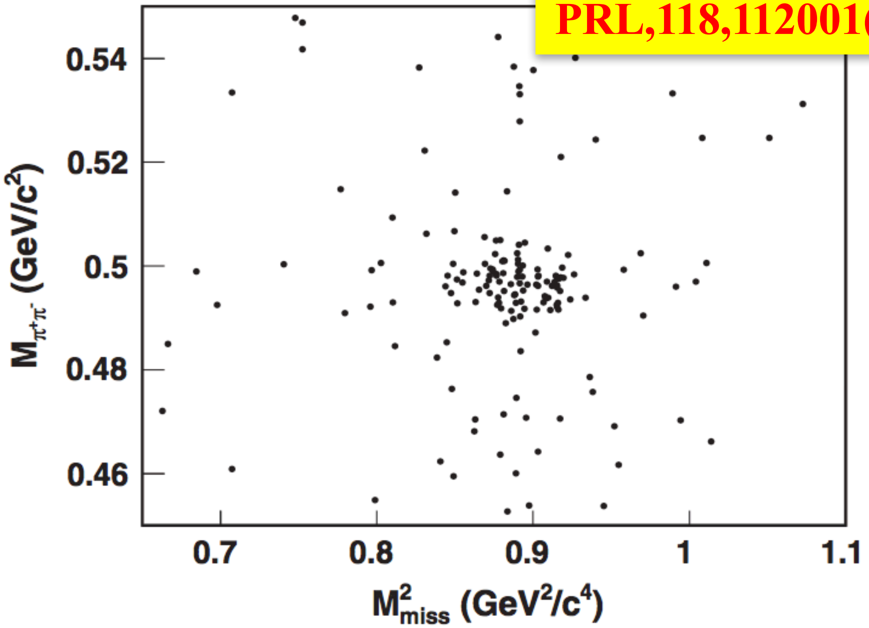
Custody by H-Y Cheng

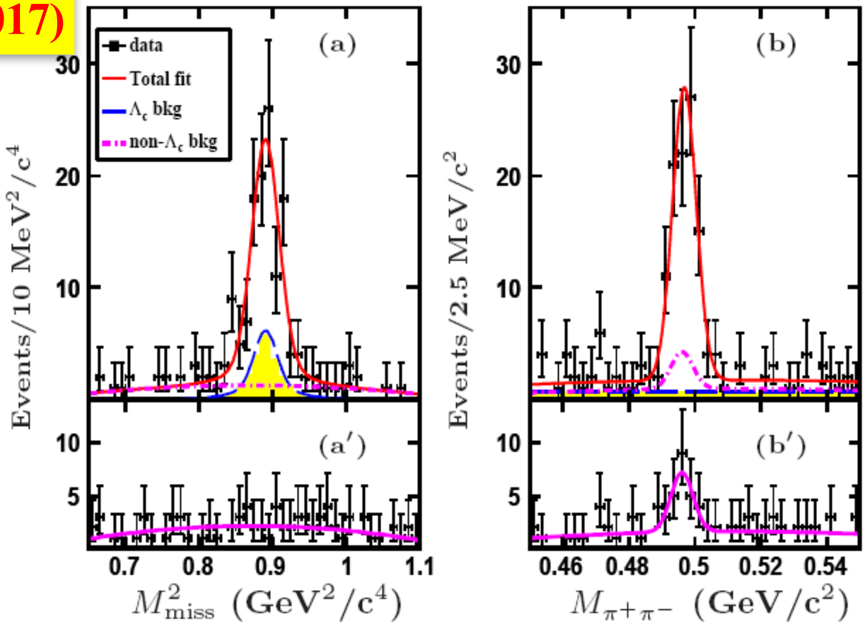
- More precise comparison of the two BFs are desired to explore the interference of different non-factorizable diagrams
- BESIII result support the theoretic prediction.

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

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

PRL,118,112001(2017)

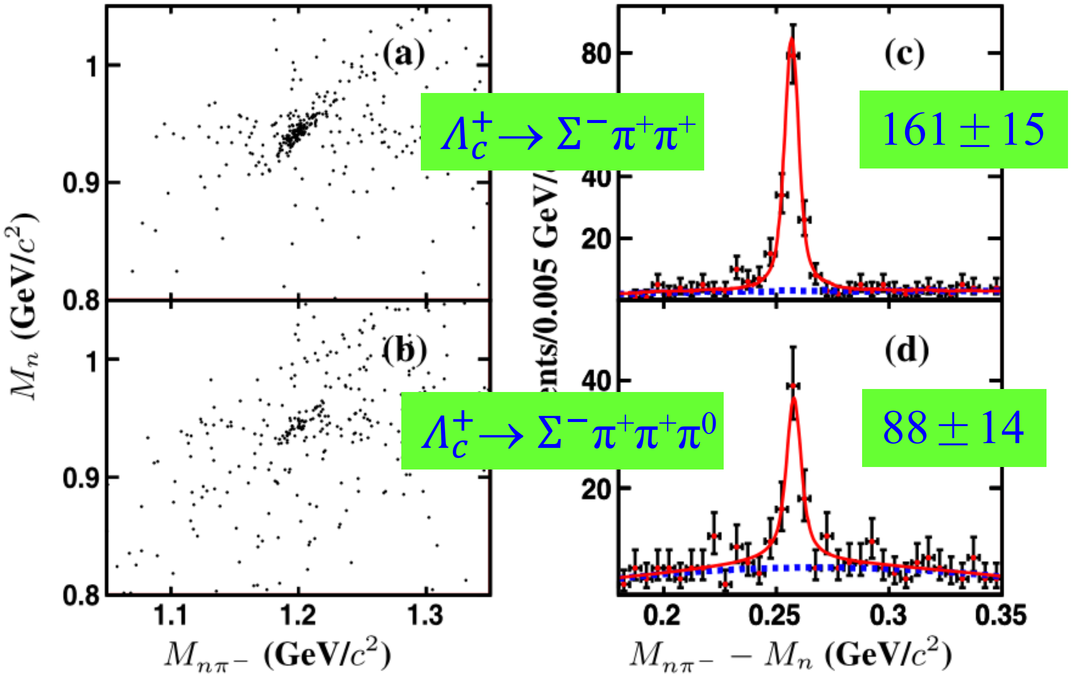




- Peaking background from $\Lambda_c^+ \rightarrow \Sigma^+ (\rightarrow n\pi^+) \pi^+\pi^-$
- **2-D fitting extract 83 ± 11 net signals**
- **$B[\Lambda_c^+ \rightarrow nK_S^0\pi^+] = (1.82 \pm 0.23 \pm 0.11)\%$**
- **$B[\Lambda_c^+ \rightarrow nK^0\pi^+]/B[\Lambda_c^+ \rightarrow pK^-\pi^+] = 0.62 \pm 0.09$; $B[\Lambda_c^+ \rightarrow nK^0\pi^+]/B[\Lambda_c^+ \rightarrow pK^0\pi^0] = 0.97 \pm 0.16$**
- **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)**



$\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$

161 ± 15

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

88 ± 14

PLB 772, 388 (2017)

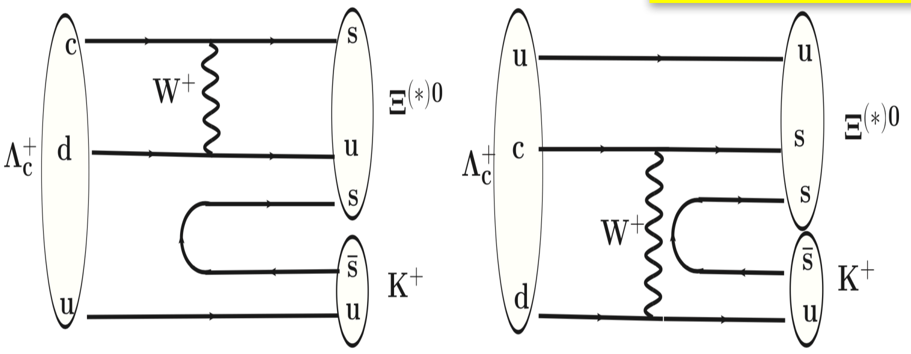
- **Λ_c^+ decay involving the neutron in the final state(missing technique).**
- **$B(\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0) = (2.11 \pm 0.33 \pm 0.14)\%$**
- **$B(\Lambda_c^+ \to \Sigma^-\pi^+\pi^+) = (1.81 \pm 0.17 \pm 0.09)\%$**
  more precise than old result $(2.3 \pm 0.4)\%$

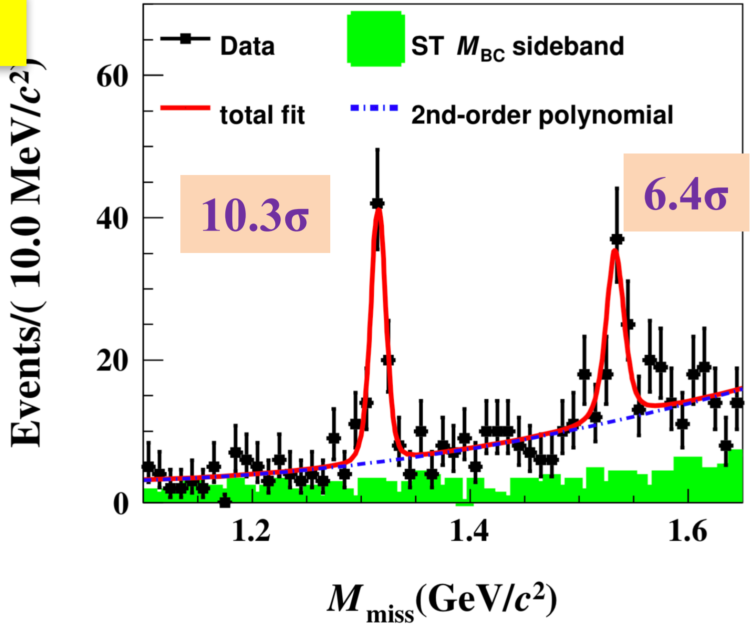
$$M_{n\pi^-} = \sqrt{(E_{\text{beam}} - E_{\pi^+\pi^+(\pi^0)})^2 - |\vec{p}_{\Lambda_c^+} - \vec{p}_{\pi^+\pi^+(\pi^0)}|^2}$$

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

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.

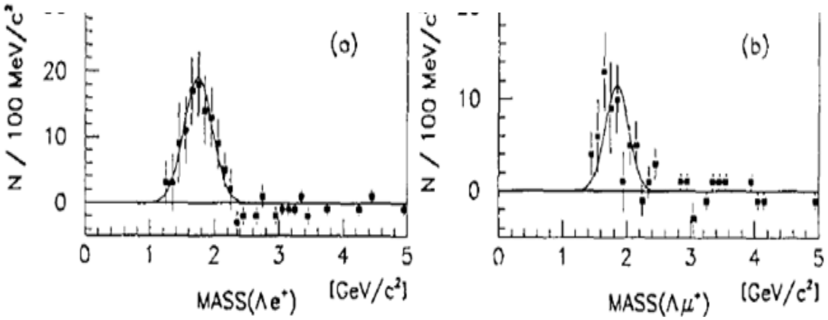
Decay	Measured $\frac{\mathcal{B}(\Lambda_c^+\to\Xi^{(*)0}K^+)}{\mathcal{B}(\Lambda_c^+\to pK^-\pi^+)}$	Predicted $\mathcal{B}(\Lambda_c^+\to\Xi^{(*)0}K^+)$
Ξ^0K^+	$(7.8\pm1.8)\%$ [18] $(5.0\pm1.2)\times10^{-3}$	2.6×10^{-3} [4] 3.6×10^{-3} [6] 3.1×10^{-3} [10] 1.0×10^{-3} [14] 1.3×10^{-3} [15]
$\Xi^{*0}K^+$	$(5.3\pm1.9)\%$ [18] $(9.3\pm3.2)\%$ [19, 20] $(4.0\pm1.0)\times10^{-3}$	5.0×10^{-3} [4] 0.8×10^{-3} [16] 0.6×10^{-3} [17]

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

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

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

- In 1991, ARGUS reported the first measurement of $\Lambda_c^+ \to \Lambda l^+ \nu_l$ with 477 pb^{-1} $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(4S)$ data

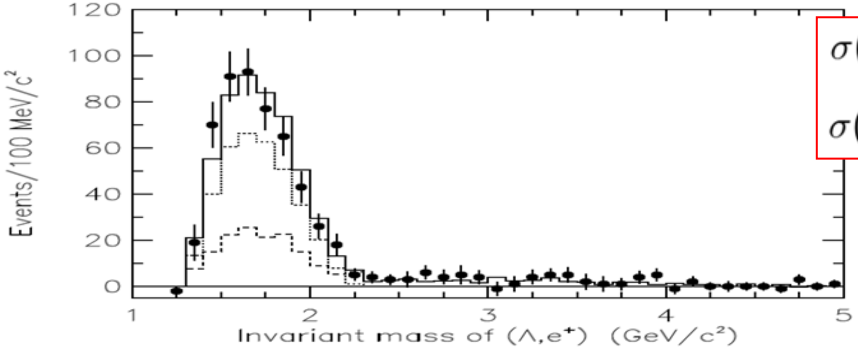


$$\sigma(e^+e^- \to \Lambda_c^+ X) \cdot \mathrm{BR}(\Lambda_c^+ \to \Lambda e^+ X) = 4.20 \pm 1.28 \pm 0.71 \text{ pb}$$

$$\sigma(e^+e^- \to \Lambda_c^+ X) \cdot \mathrm{BR}(\Lambda_c^+ \to \Lambda \mu^+ X) = 3.91 \pm 2.02 \pm 0.90 \text{ pb}$$

Phys. Lett. B 269, 234 (1991).

- In 1994, CLEO performed same measurement with 1.6 fb^{-1} $\Upsilon(4S)$ data



$$\sigma(e^+e^- \to \Lambda_c^+ X) \cdot \mathrm{BR}(\Lambda_c^+ \to \Lambda e^+ X) = 4.87 \pm 0.28 \pm 0.69 \text{ pb}$$

$$\sigma(e^+e^- \to \Lambda_c^+ X) \cdot \mathrm{BR}(\Lambda_c^+ \to \Lambda \mu^+ X) = 4.43 \pm 0.51 \pm 0.64 \text{ pb}$$

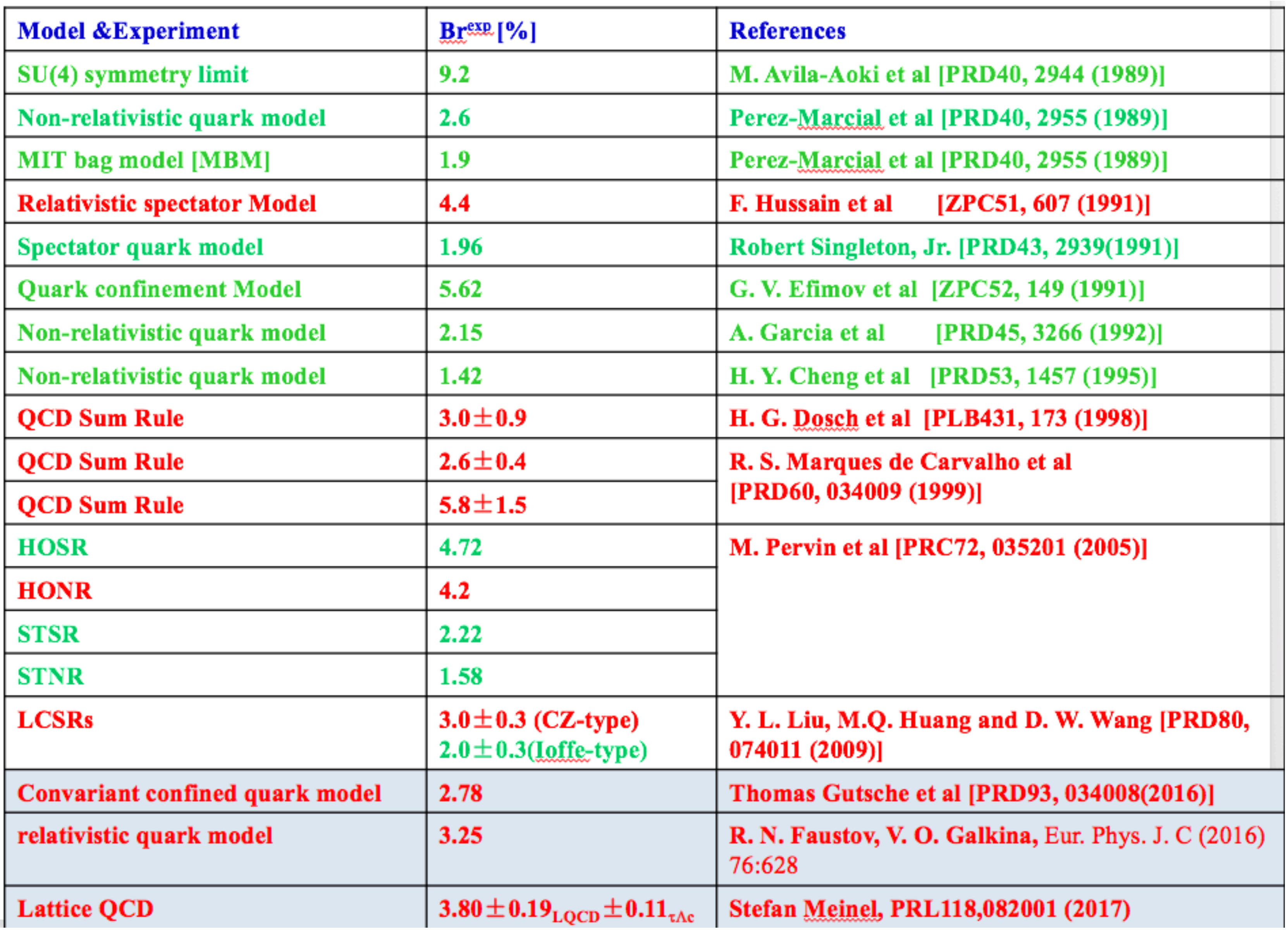
Phys. Lett. B 323, 219 (1994).

- Based on above two measurements , PDG extracts BF for $\Lambda_c^+ \to \Lambda l^+ \nu_l$ with $\tau(\Lambda_c^+)$ and the assumption of form factors

$\Lambda \ell^+ \nu_\ell$	[r]	(2.8 ± 0.4) %
$\Lambda e^+ \nu_e$		(2.9 ± 0.5) %
$\Lambda \mu^+ \nu_\mu$		(2.7 ± 0.6) %

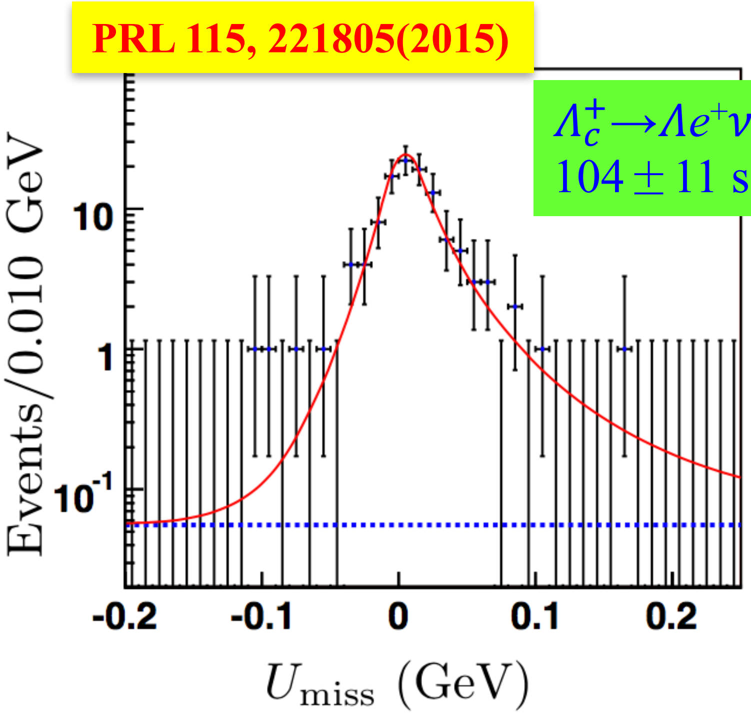
Not a direct measurement!

Theoretical calculations on the BF $\Lambda_c^+ \to \Lambda l^+ \nu_l$



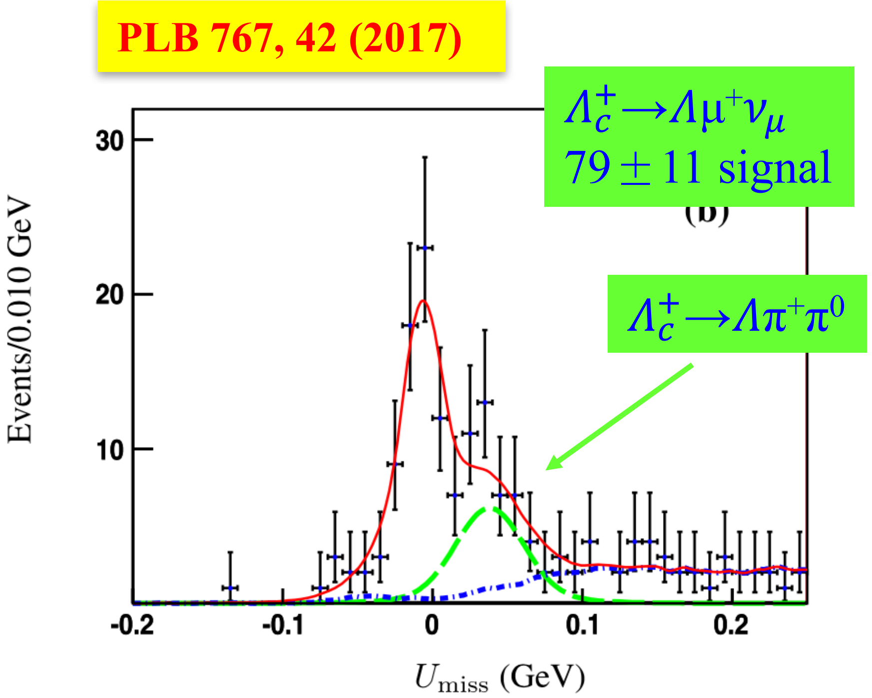
Model &Experiment	Br^{exp} [%]	References
SU(4) symmetry limit	9.2	M. Avila-Aoki et al [PRD40, 2944 (1989)]
Non-relativistic quark model	2.6	Perez-Marcial et al [PRD40, 2955 (1989)]
MIT bag model [MBM]	1.9	Perez-Marcial et al [PRD40, 2955 (1989)]
Relativistic spectator Model	4.4	F. Hussain et al [ZPC51, 607 (1991)]
Spectator quark model	1.96	Robert Singleton, Jr. [PRD43, 2939(1991)]
Quark confinement Model	5.62	G. V. Efimov et al [ZPC52, 149 (1991)]
Non-relativistic quark model	2.15	A. Garcia et al [PRD45, 3266 (1992)]
Non-relativistic quark model	1.42	H. Y. Cheng et al [PRD53, 1457 (1995)]
QCD Sum Rule	3.0 ± 0.9	H. G. Dosch et al [PLB431, 173 (1998)]
QCD Sum Rule	2.6 ± 0.4	R. S. Marques de Carvalho et al [PRD60, 034009 (1999)]
QCD Sum Rule	5.8 ± 1.5	
HOSR	4.72	M. Pervin et al [PRC72, 035201 (2005)]
HONR	4.2	
STSR	2.22	
STNR	1.58	
LCSRs	3.0 ± 0.3 (CZ-type) 2.0 ± 0.3(Ioffe-type)	Y. L. Liu, M.Q. Huang and D. W. Wang [PRD80, 074011 (2009)]
Convariant confined quark model	2.78	Thomas Gutsche et al [PRD93, 034008(2016)]
relativistic quark model	3.25	R. N. Faustov, V. O. Galkina, Eur. Phys. J. C (2016) 76:628
Lattice QCD	$3.80 \pm 0.19_{LQCD} \pm 0.11_{\tau\Lambda c}$	Stefan Meinel, PRL118,082001 (2017)

Absolute BFs for semi-leptonic $\Lambda_c^+ \to \Lambda l^+ \nu_l$



PRL 115, 221805(2015)

$\Lambda_c^+ \to \Lambda e^+ \nu_e$
104 ± 11 signal



PLB 767, 42 (2017)

$\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu$
79 ± 11 signal

$\Lambda_c^+ \to \Lambda \pi^+ \pi^0$

- **Large rate via the CF transition $c \to s l^+ \nu_l$**
- **$\Lambda_c^+ \to \Lambda l^+ \nu$ is a benchmark for other semileptonic decays of Λ_c^+.**
- **Provides stringent test for nonperturbative aspects of the theory of strong interaction.**
- **Key ingredient in calibrating LQCD calculations.**
- **Provides important input for calibrating the LQCD calculations.**

- **$B[\Lambda_c^+ \to \Lambda e^+ \nu_e] = (3.36 \pm 0.38 \pm 0.20)\%$**
- **$B[\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu] = (3.49 \pm 0.46 \pm 0.27)\%$**
- **$\Gamma[\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu] / \Gamma[\Lambda_c^+ \to \Lambda e^+ \nu_e] =$ $0.96 \pm 0.16 \pm 0.04$**

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

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(Received 1 December 2016; published 21 February 2017)

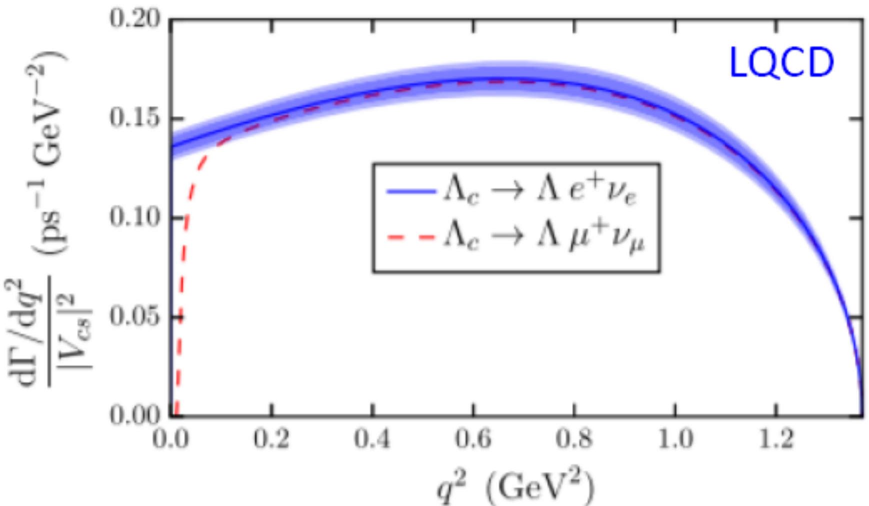
PRL118(2017)082001

☐ 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

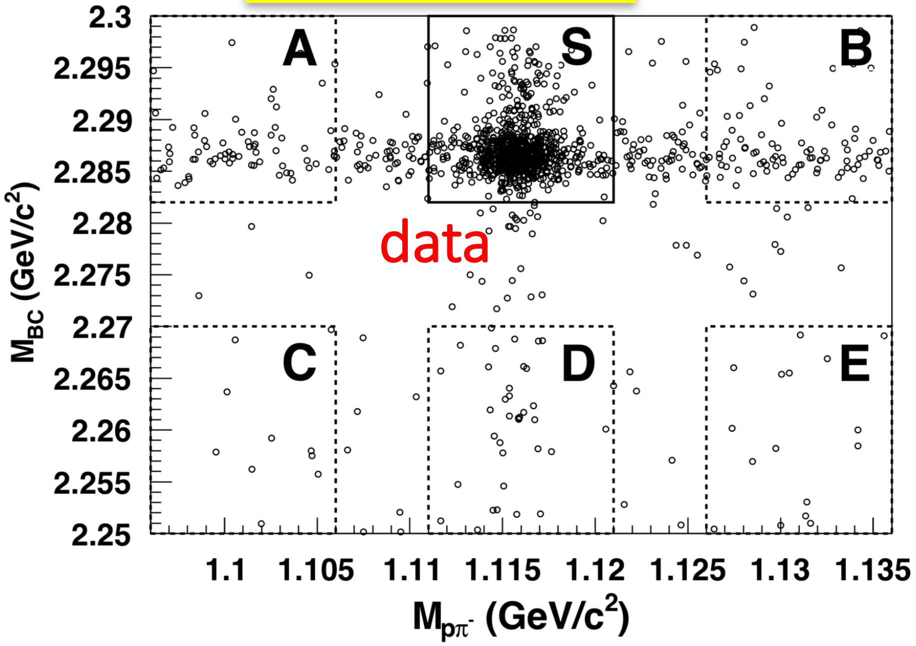
$$|V_{cs}| = \begin{cases} 0.951(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(56)_{\mathcal{B}} & \ell = e, \\ 0.947(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(72)_{\mathcal{B}} & \ell = \mu, \\ 0.949(24)_{\rm LQCD}(14)_{\tau_{\Lambda_c}}(49)_{\mathcal{B}} & \ell = e, \mu, \end{cases}$$

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

$\Lambda_c^+ \rightarrow \Lambda + \mathrm{X}$

Large rate, but also with large uncertainty

arXiv:1803.05706



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

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

- **Curent PDG: BF($\Lambda_c^+ \to \Lambda$+X)=(35±11)%**
- **Double tag method: Tagged with $\Lambda_c^+ \to pK^-\pi^+$ and pK_S^0**
- **Extract yields from 2D distributions in bins of p−$|\cos\theta|$**
- **$\mathcal{B}(\Lambda_c^+ \to \Lambda + X) = \left(38.2^{+2.8}_{-2.2} \pm 0.8\right)\%$**

  (only $(24.5 \pm 2.1)\%$ observed in PDG which indicates more unknown decay channels)
- **$A_{cp} = \left(2.1^{+7.0}_{-6.6} \pm 1.4\right)\%$**

  (No CPV is observed.)
- **Comparison with K+X will shed light on the Λ_c^+ internal dynamics.**
- **The $\Lambda l^+\nu_l$ dominate the l^++X , $\mathcal{B}$ ($pKl^+\nu_l$)~10^{-3}.**

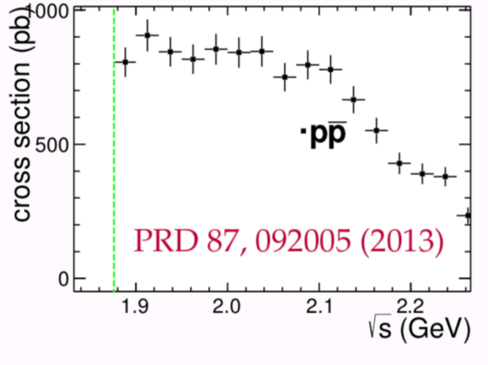
The cross-section of baryon pair

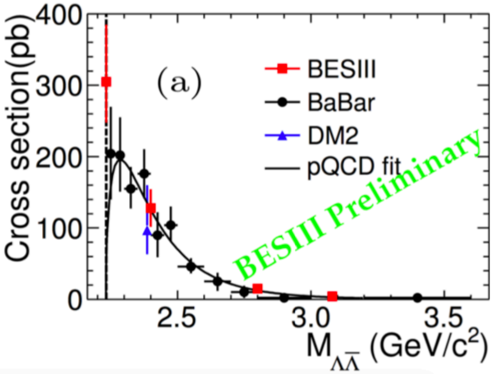
The Born cross section of the reaction $e^+e^- \to \gamma^* \to B\bar{B}$ can be parameterized in terms of electromagnetic form factors:

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

- 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

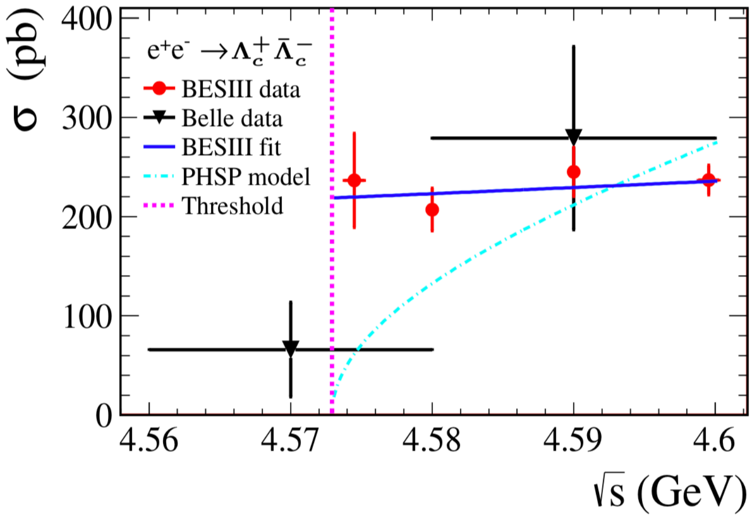
- $e^+e^- \to p\bar{p}$: an enhancement and wide-range plateau in the line-shape
- $e^+e^- \to \Lambda\bar{\Lambda}$: non-zero cross section near threshold
- It can be anticipate that Λ_c^+ has a similar behaviour with proton
- Belle collaboration has measured the cross section of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$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



- **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?**

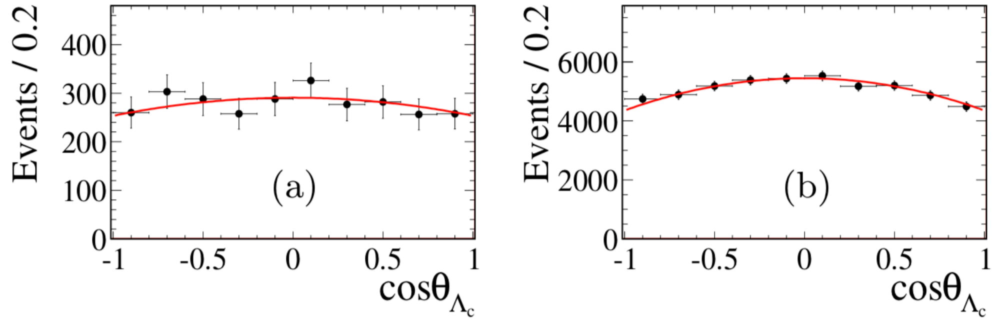


FIG. 3. Angular distribution after efficiency correction and results of the fit to data at $\sqrt{s} = 4574.5$ MeV (a) and 4599.5 MeV (b).

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

- **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}	$\|G_E/G_M\|$
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

- Era of precision study of the Λ_c decays: BESIII/LHCb/BELLE
  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

Many more outputs are expected in the coming future years.

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

- **A larger data set could help to improve our knowledge on Λ_c^+ decays. BESIII will keep collecting Λ_c^+ data (~1M in total).**

- **Many Λ_c^+ related topics in BESIII are in progress(other hadronic/semi-leptonic/rare decays).**

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

BackUp

Λ_c 衰变展望

BEPCII能否**挑战**质心系能量为**4.6 GeV**的**极限**? (**HIEPA**没有问题)

如果采集现有 Λ_c样本20倍的数据

- □ 分波分析 ⇒ 三体衰变末态的中间共振结构
- □ 测量更多包含中微子末态的衰变: nlν, Λ*lν, ΣXlν …
- □ Λ_c^+的自旋宇称测量
- □ $\Lambda_c^+ \to pK_S$, pK_L CP破坏研究 （中性K系统的CP破坏）
- □ 衰变不对称参数α的测量 ⇐ $\Lambda_c^+ \to$ BP/BV （$\frac{dW}{d\cos\theta} = \frac{1}{2}(1 + \alpha_{\Lambda c}\alpha_B \cos\theta)$）
- □ Λ_c^+的稀有衰变敏感度估计
  - □ 辐射衰变 $\Lambda_c^+ \to \gamma\Sigma^+$: $10^{-4} \sim 10^{-5}$
  - □ 味道改变中性流$\Lambda_c^+ \to pl^+l^-$: $10^{-5} \sim 10^{-6}$
  - □ 轻子数破坏 $\Lambda_c^+ \to pe\mu$: $10^{-5} \sim 10^{-6}$

目前的数据

567 pb^{-1} @4.6GeV

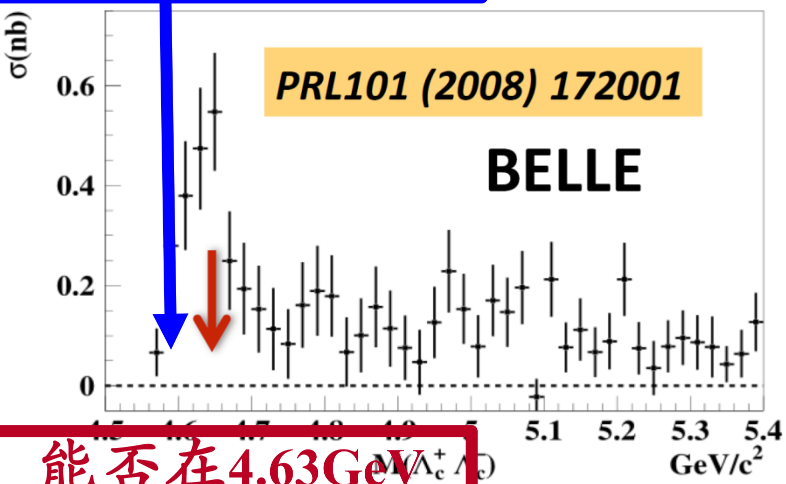


FIG. 4: The cross section for the exclusive process $e^+e^- \to \Lambda_c^+\Lambda_c^-$.

能否在4.63GeV峰上采集数据?

20倍现有数据：$10fb^{-1}$

在超级τ-粲工厂上只需要几天!