Study Λ_c^+ decay at BESIII

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Outline

- Introduction the lightest charm baryon Λ_c^+

- Λ_c^+ hadronic decays measured in BESIII
- Λ_c^+ inclusive decay $\Lambda_c^+ \rightarrow \Lambda$+X(preliminary)
- Λ_c^+ semi-leptonic decay $\Lambda_c^+ \rightarrow \Lambda l^+ \nu_l$

- Summary

The charmed baryon family

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

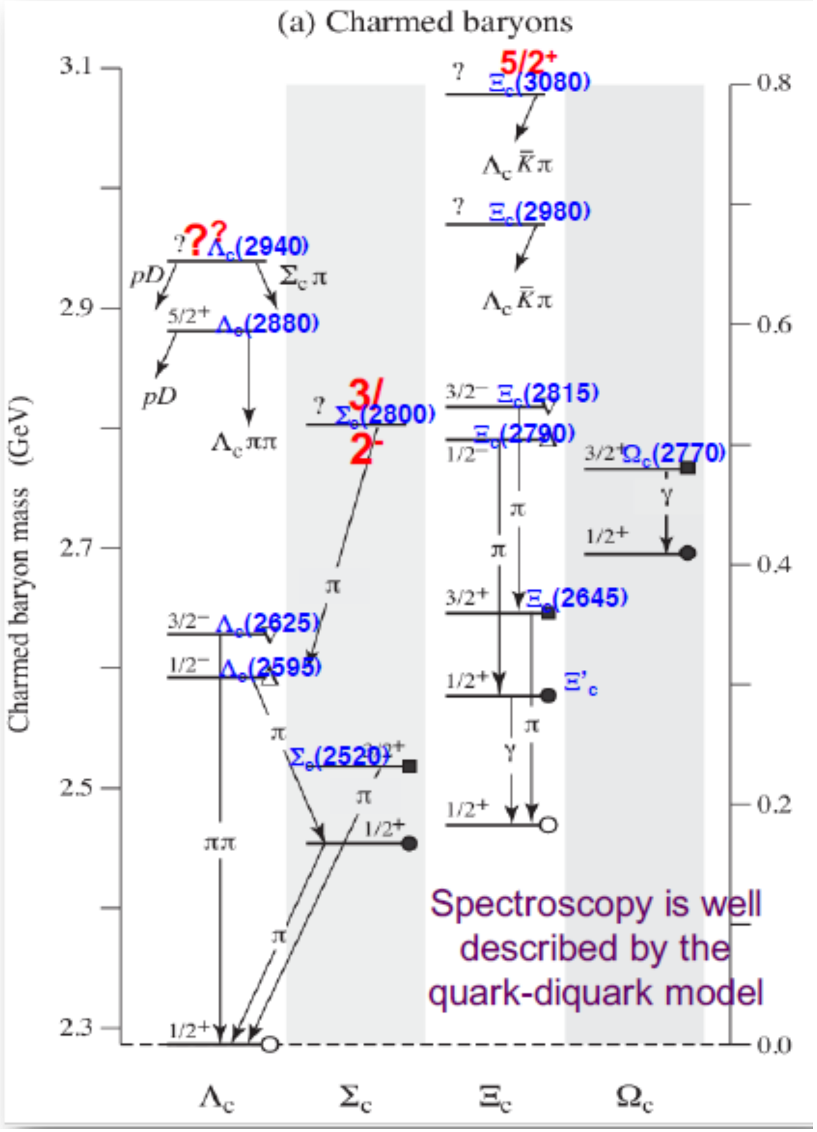
    $\Lambda_c^+, \Sigma_c, \Xi_c^{(\prime)}, \Omega_c$
  - ◆ Excited states are being explored
- **Doubly charmed baryons observed recently.**
- **No observations of triply charmed baryons**

✓ **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 $\Xi^- \pi^+(\pi^+)$.**

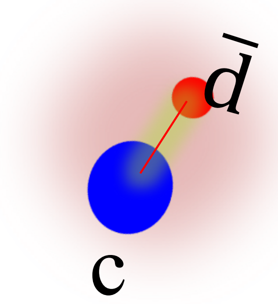
✓ **Ω_c:decay only weakly; no absolute BF measured.**



Spectroscopy is well described by the quark-diquark model

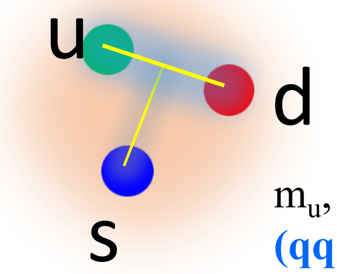
Λ_c^+:cornerstone of charmed baryon spectroscopy

- **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 dominatly to Λ_c .**
- **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).**



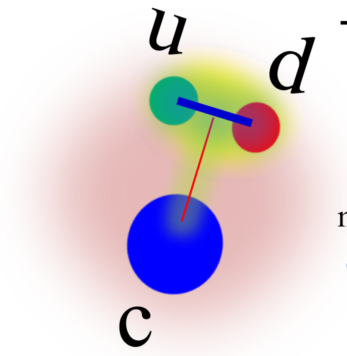
→ Charmed meson
($D^+[c\bar{d}]$)

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



→ Strange baryons
(Λ[uds])

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

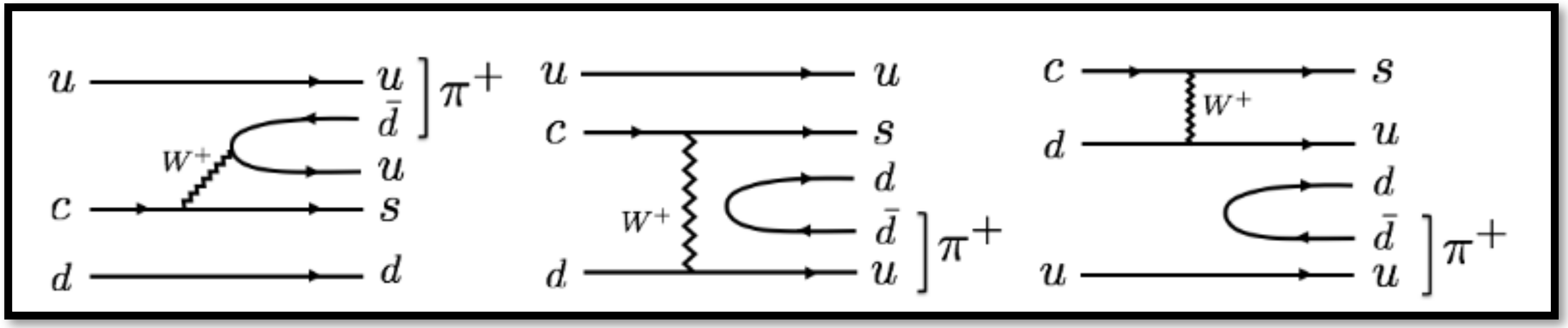


→ Charmed baryon
(Λ_c[udc])

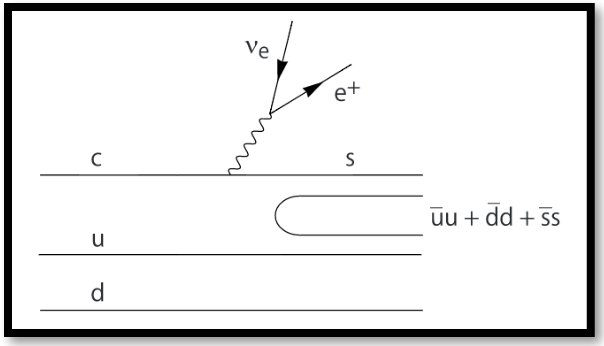
$m_u, m_d << m_c$ →
diquark + quark
(qq) (Q)

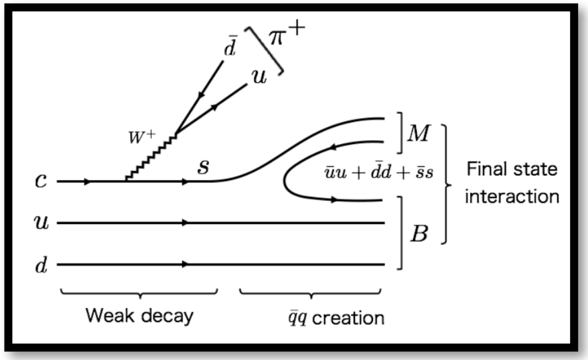
Λ_c^+ weak decays

- **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.**

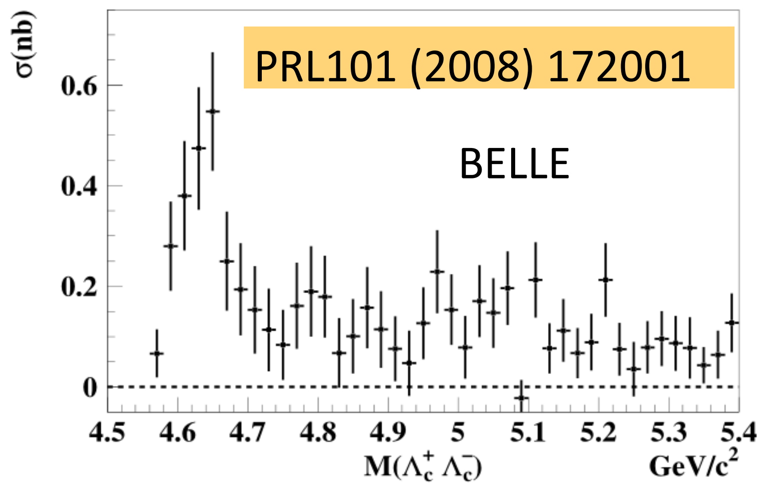


FIG. 4: The cross section for the exclusive process $e^+e^- \to \Lambda_c^+\Lambda_c^-$.

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 obtain the Λ_c^+ yields:
  - Single Tag(ST): Reconstruct only one of the Λ_c -pair.

    =>relative higher backgrounds

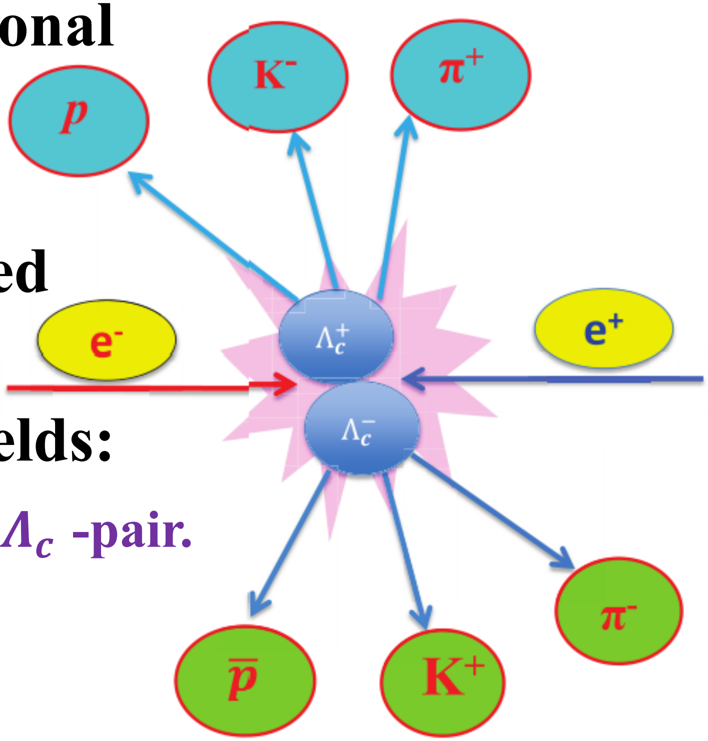
    =>Higher efficiencies

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

    =>Smaller backgrounds.

    =>Lower efficiencies.

    =>Systematic in tag side are most cancelled.

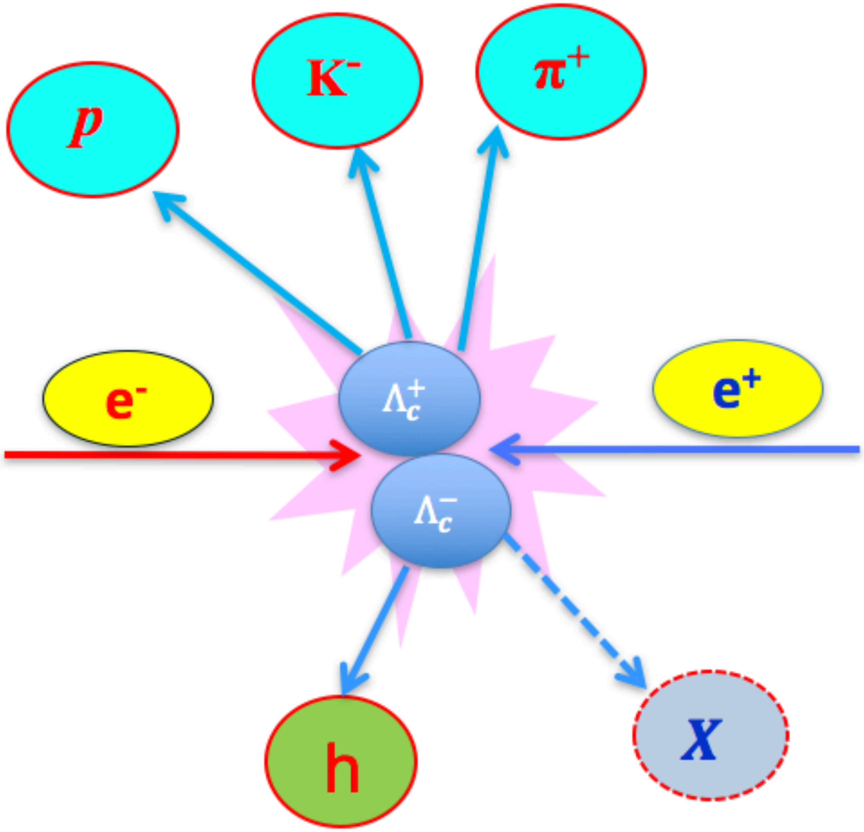


Few popular variables

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

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

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

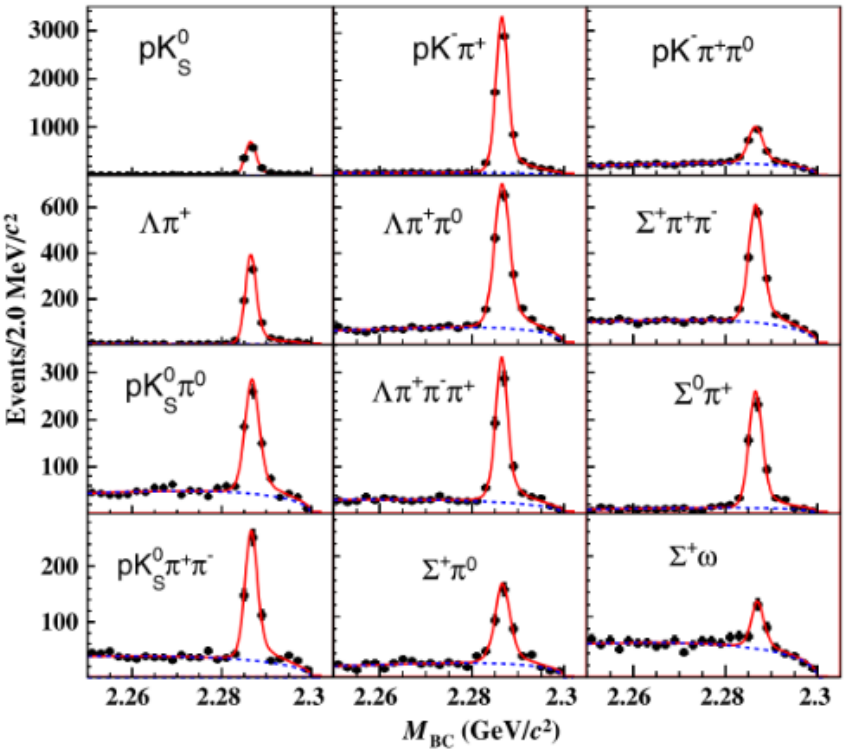


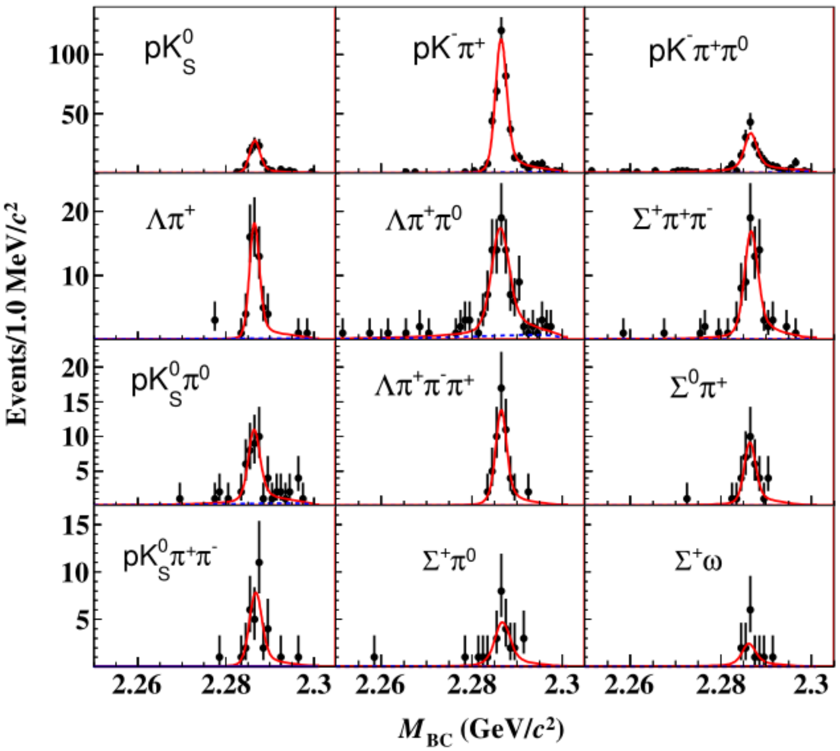
- $\hat{p}_{tag}$ is the direction of the momentum of the singly tagged Λ_c .
- $E_h(p_h)$ are the energy(momentum) of h which are measured in e^+e^- system.
- $m_{\Lambda_c^+}$ is the mass of the Λ_c^+ quoted from the PDG.

Measurements that I report today

- ☐ **Hadronic decay**
  - ☐ BF($\Lambda_c^+ \to pK^-\pi^+$) :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)
- ☐ **Inclusive decay**
  - ☐ BF($\boldsymbol{\Lambda}_c^+ \to \boldsymbol{\Lambda} X$) :Preliminary result
- ☐ **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)

Λ_c^+ reconstruction at BESIII





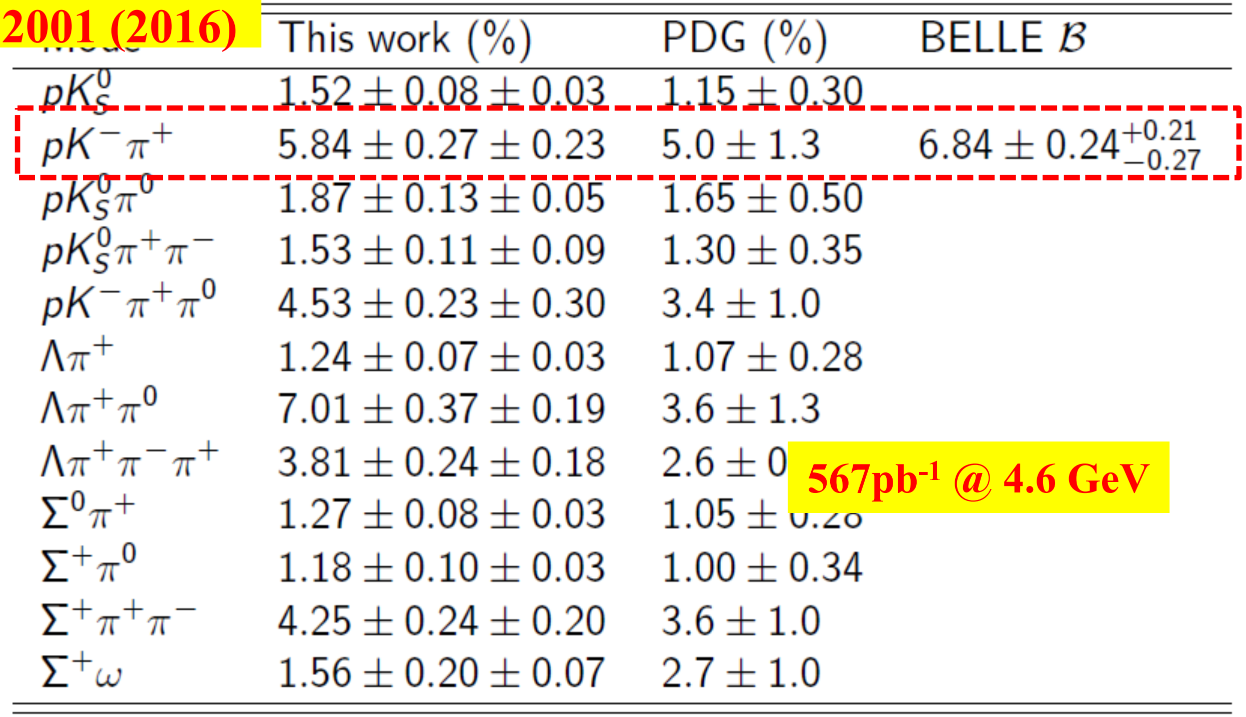
$$N_i^{\mathrm{ST}} = N_{\Lambda_c^+\bar{\Lambda}_c^-} \cdot \mathcal{B}_i \cdot \varepsilon_i^{\mathrm{ST}}$$

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

- **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	
$\Sigma^0\pi^+$	$1.27 \pm 0.08 \pm 0.03$	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	

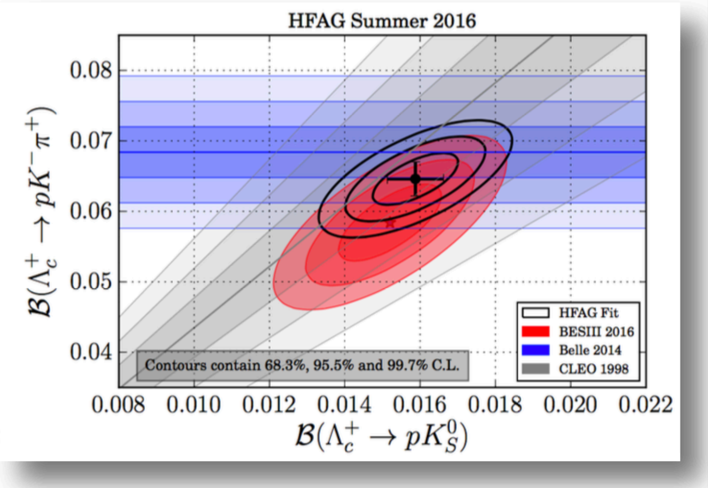
567pb^{-1} @ 4.6 GeV

- **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 ± 4.8 ± 0.5) × 10^3**

HFAG 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

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

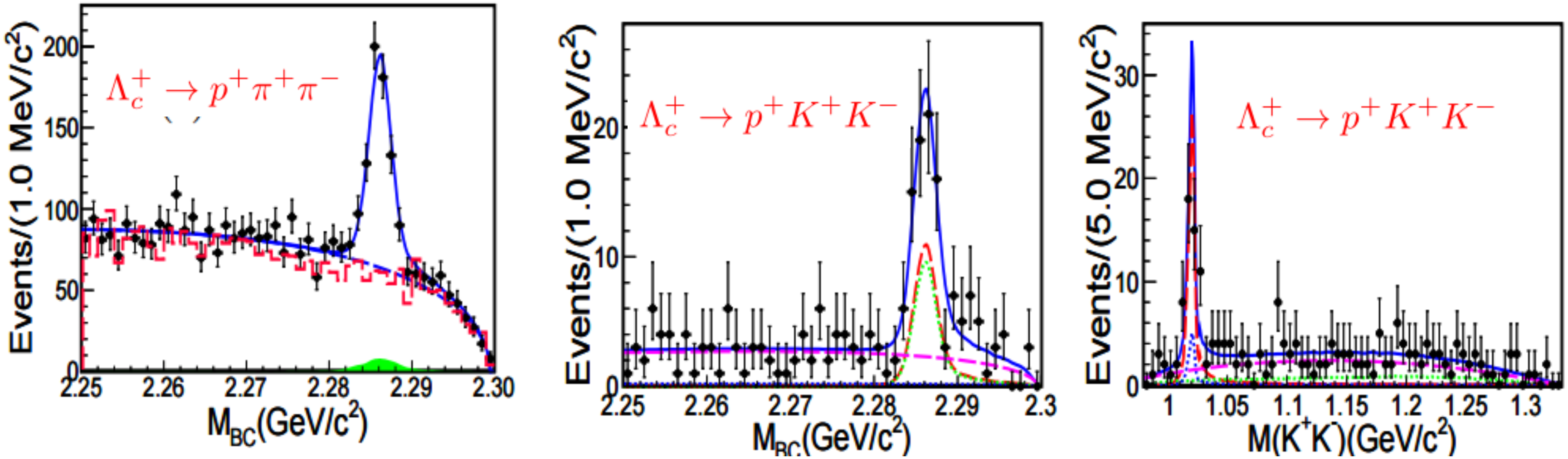
	Golden hadronic mode	δB/B	Golden SL mode	δB/B
D^0	B(Kπ)=(3.88±0.05)%	1.3%	B(Kev)=(3.55±0.05)%	1.4%
D^+	B(Kππ)=(9.13±0.19)%	2.1%	B(K^0ev)=(8.83±0.22)%	2.5%
D_s	B(KKpi)=(5.39±0.21)%	3.9%	B(ϕev)=(2.49±0.14)%	5.6%
Λc	B(pKπ)=(5.0±1.3)%(PDG2014) =(6.8±0.36)% (BELLE) =(5.84±0.35)% (BESIII) =(6.46±0.24)% (HFAG)	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!
- LHCb data will further constrain the HFAG 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

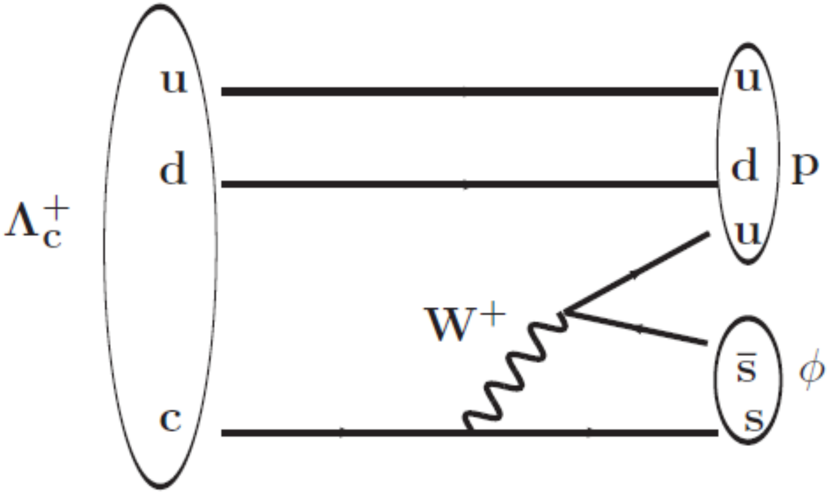
- **Charmed meson decays**

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

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

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

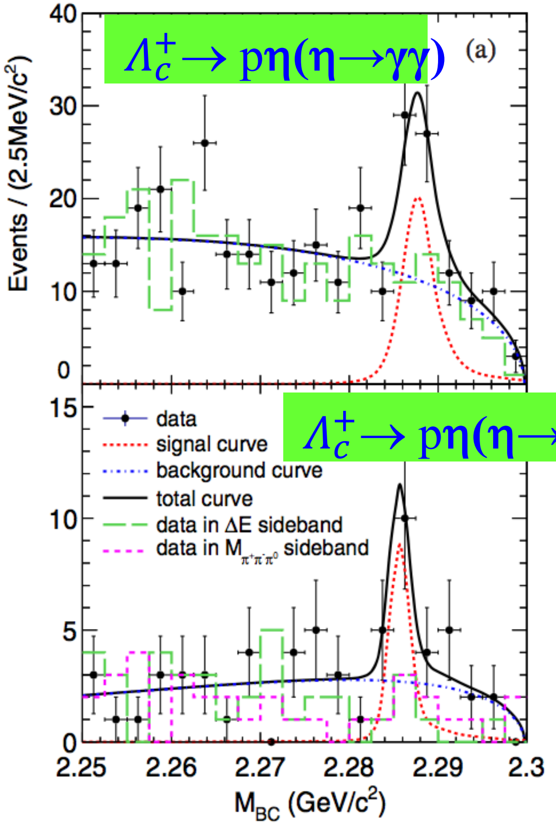
  If $\chi_1 = \chi_2 = -1/N_c$, large-N_c factorization

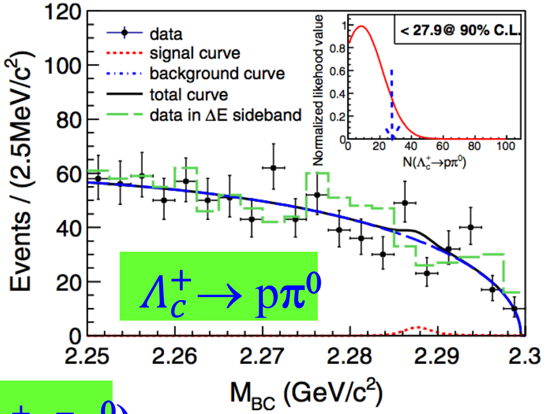


- $\Lambda_c^+ \to p\phi$ proceeds only through internal W-emission diagram.
- **Input BF ⇒ $|a_2|$=0.70±0.07, close to $c_2(m_c) \approx$ -0.59(from theory)**
- **$1/N_c$ is also applicable to charmed baryon sector.**
- **BESIII measurement are consistent with previous measurement.**

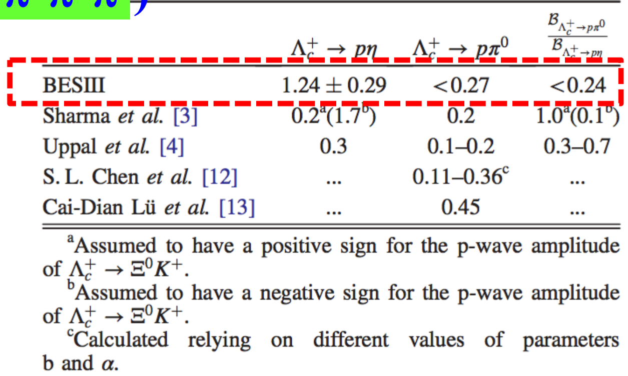
Singly Cabibbo-Suppressed Decays of $\Lambda_c^+ \to p\pi^0$ and $\Lambda_c^+ \to p\eta$

- $B(\Lambda_c^+ \to p\eta) >> B(\Lambda_c^+ \to p\pi^0)$ **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.





PRD,111102(R) (2017)

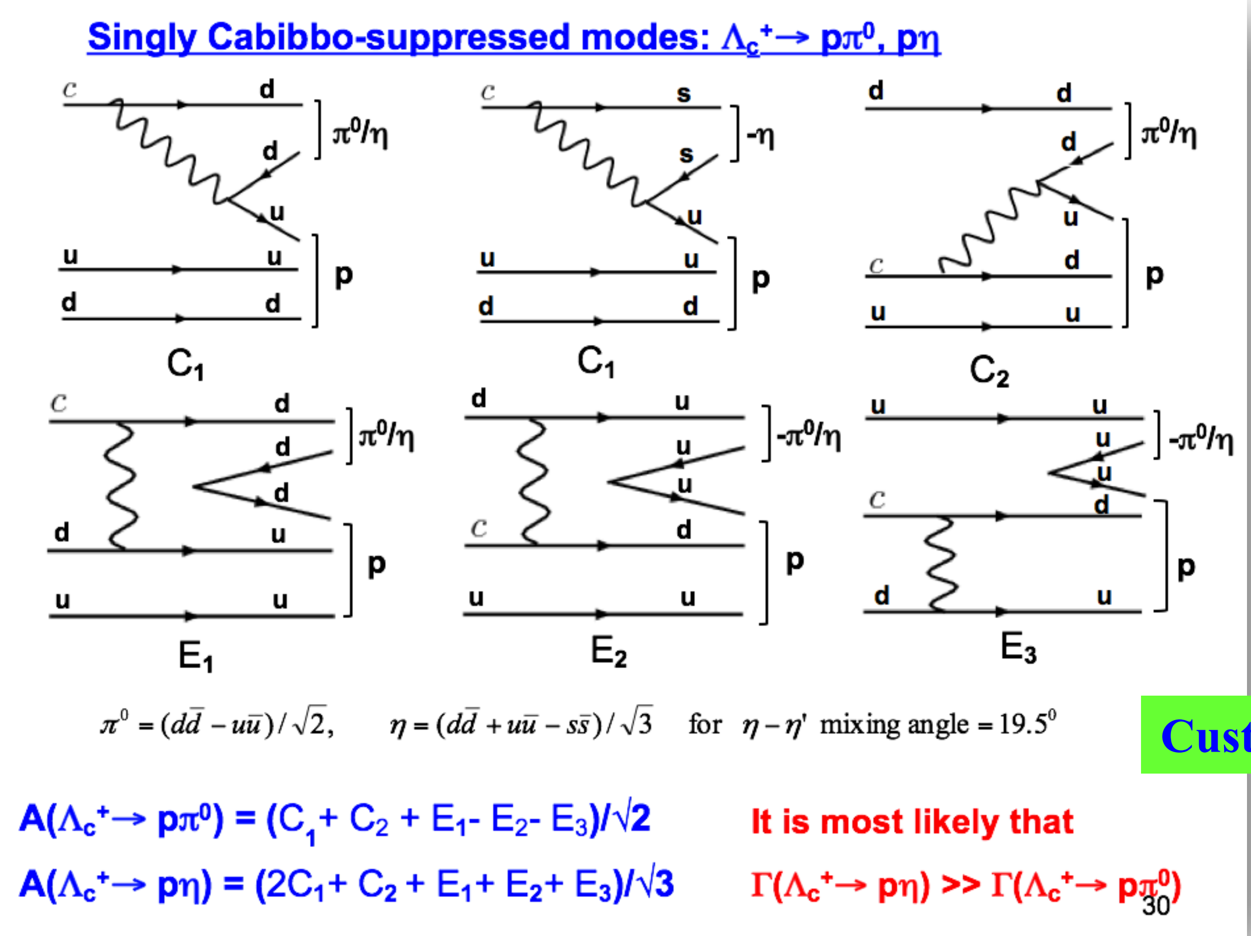


	$\Lambda_c^+ \to p\eta$	$\Lambda_c^+ \to p\pi^0$	$\frac{\mathcal{B}_{\Lambda_c^+ \to p\pi^0}}{\mathcal{B}_{\Lambda_c^+ \to p\eta}}$
BESIII	1.24 ± 0.29	<0.27	<0.24
Sharma *et al.* [3]	$0.2^a(1.7^b)$	0.2	$1.0^a(0.1^b)$
Uppal *et al.* [4]	0.3	0.1–0.2	0.3–0.7
S. L. Chen *et al.* [12]	...	$0.11–0.36^c$	...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



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

$\pi^0 = (d\bar{d} - u\bar{u})/\sqrt{2}, \quad \eta = (d\bar{d} + u\bar{u} - s\bar{s})/\sqrt{3}$ 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

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

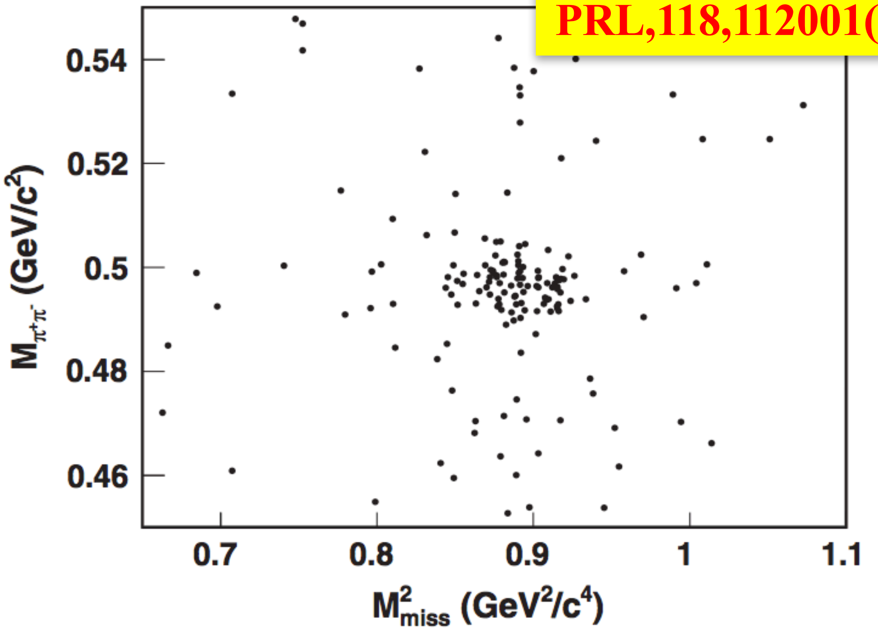
Custody by H-Y Cheng

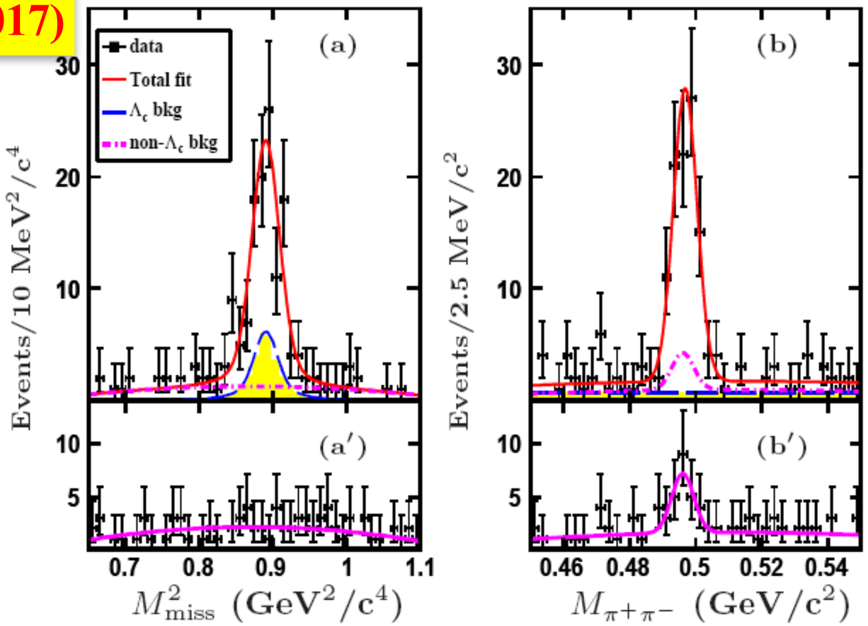
- More precise comparison of the two BFs are desired to explore the interference of different non-factorizable diagrams
- BESIII Preliminary result support the theoretic prediction.

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

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

PRL,118,112001(2017)

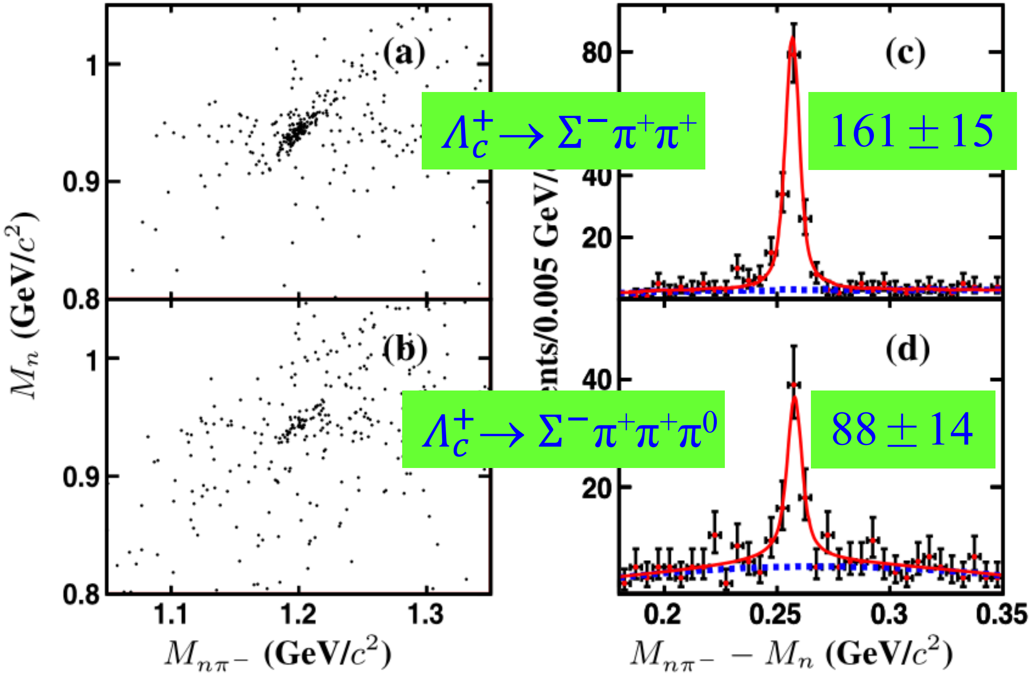




- Peaking background from $\Lambda_c^+ \rightarrow \Sigma^+ (\rightarrow n\pi^+) \pi^+\pi^-$
- **2-D fitting extract 83 ± 11 net signals**
- **$B[\Lambda_c^+ \rightarrow nK_S^0\pi^+] = (1.82 \pm 0.23 \pm 0.11)\%$**
- **$B[\Lambda_c^+ \rightarrow nK^0\pi^+]/B[\Lambda_c^+ \rightarrow pK^-\pi^+] = 0.62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



PLB 772, 388 (2017)

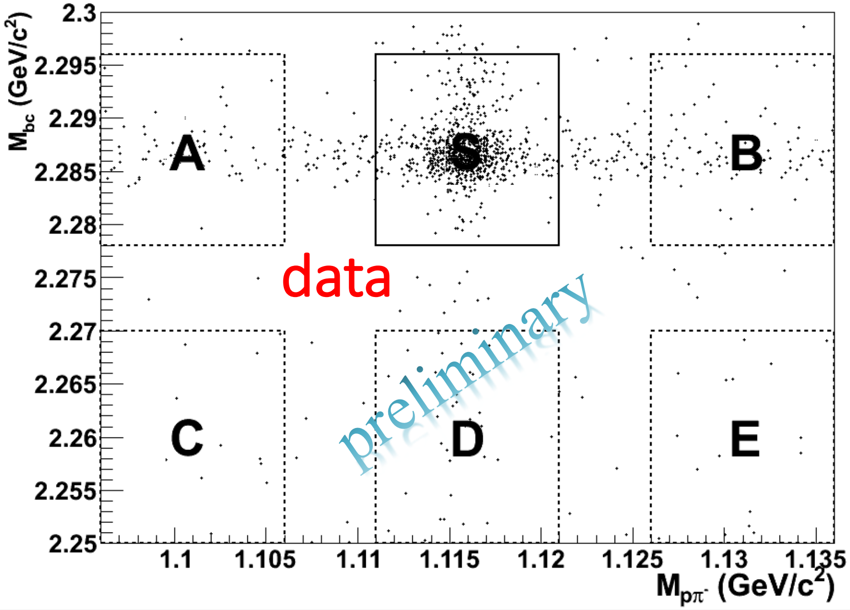
- **Λ_c^+ decay involving the neutron in the final state(missing technique).**
- **B($\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$) = (2.11±0.33±0.14)%**
- **B($\Lambda_c \to \Sigma^-\pi^+\pi^+$) = (1.81±0.17 ±0.09)%** more precise than old result (2.3 ± 0.4)%

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

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

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

- **Large rate, but also with large uncertainty…**



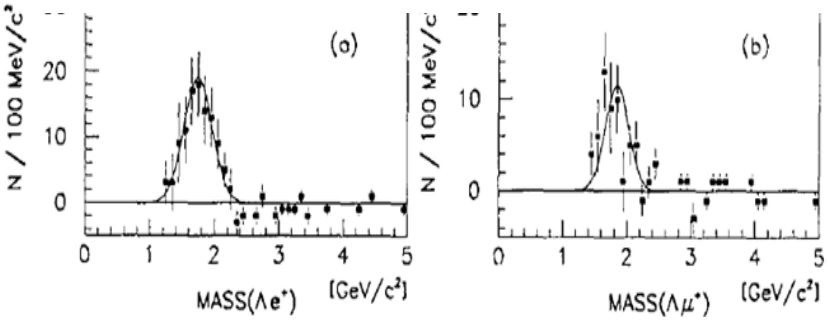
$$\mathcal{A}_{\rm CP} = \frac{\mathcal{B}(\Lambda_c^+ \to \Lambda + X) - \mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X)}{\mathcal{B}(\Lambda_c^+ \to \Lambda + X) + \mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X)}.$$

Decay mode	Branching fraction(%)	$\mathcal{A}_{\rm CP}$
$\Lambda_c^+ \to \Lambda + X$	$38.02 \pm 3.24 \pm 0.61$	$0.02 \pm 0.06 \pm 0.01$
$\bar{\Lambda}_c^- \to \bar{\Lambda} + X$	$36.70 \pm 3.04 \pm 0.59$	

- **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 $p - |cos\theta|$**
- **The number of observed $\Lambda_C^+ \to \Lambda + X$ events is 706 ± 29, the weighted efficiency is $(26.1 \pm 0.9)\%$.**
- **$\mathcal{B}(\Lambda_C^+ \to \Lambda + X) = (36.98 \pm 2.18)\%$**

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

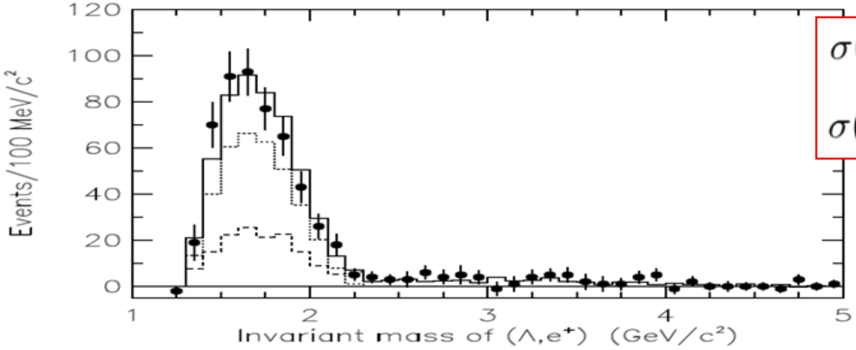


$$\sigma(e^+e^- \to \Lambda_c^+ X) \cdot \mathrm{BR}(\Lambda_c^+ \to \Lambda e^+ X) = 4.20 \pm 1.28 \pm 0.71 \text{ pb}$$

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

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

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



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

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

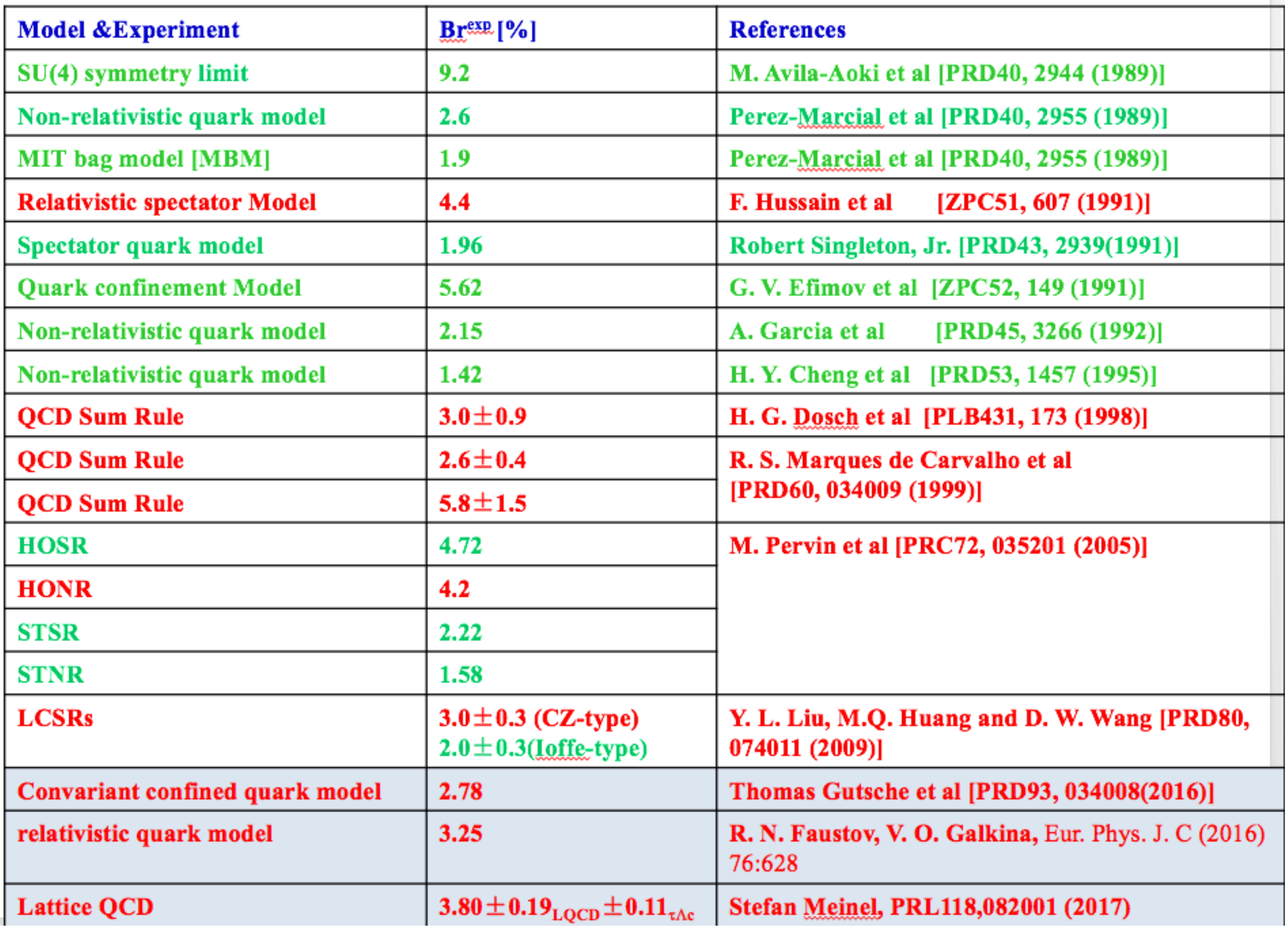
Phys. Lett. B 323, 219 (1994).

- 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!

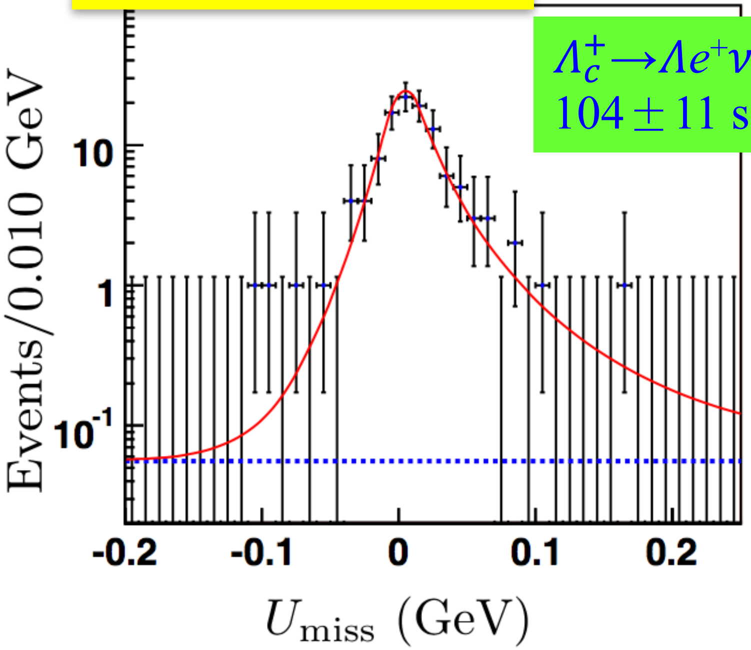
Theoretical calculations on the BF $\Lambda_c^+ \rightarrow \Lambda l^+ \nu_l$



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)**

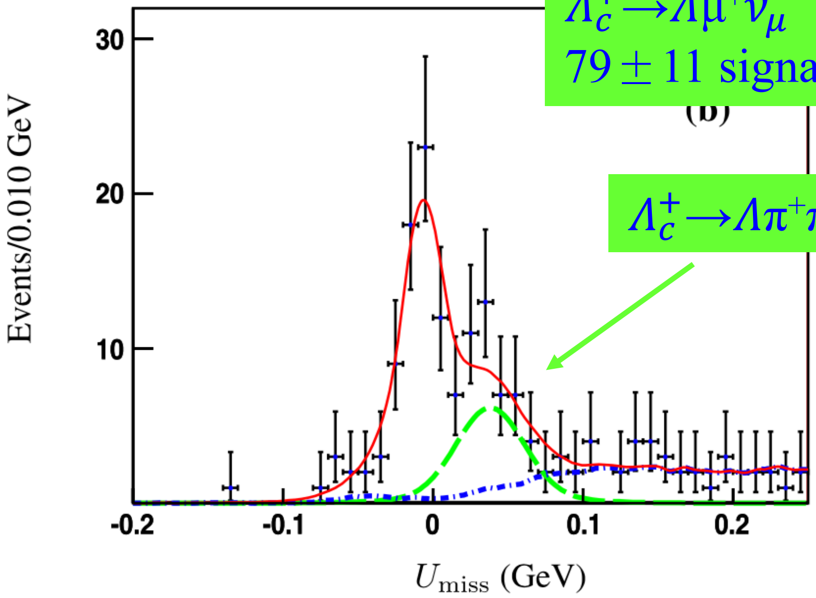
Absolute BFs for semi-leptonic $\Lambda_c^+ \to \Lambda l^+ \nu_l$

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 $c \to s l^+ \nu_l$**
- **First absolute BF measurement.** (input for determining $|V_{cs}|$)
- **First measurement of its muonic mode**
- **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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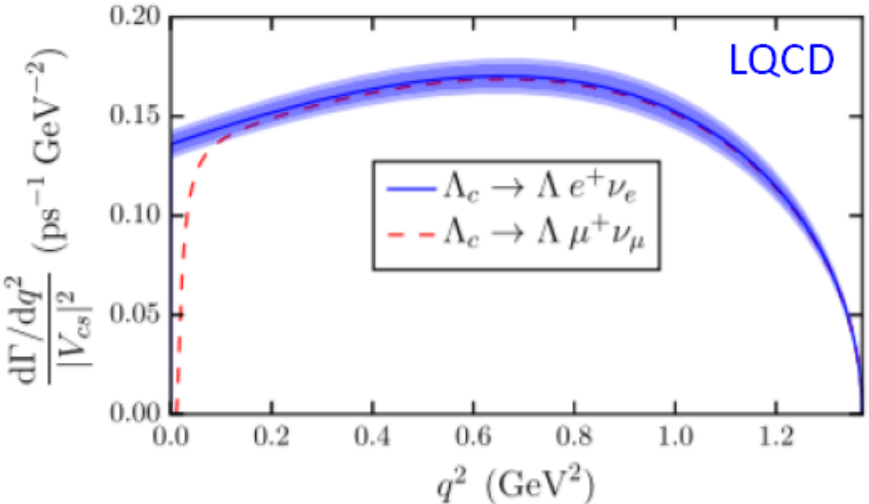
PRL118(2017)082001

☐ 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 dominate the calculation.

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

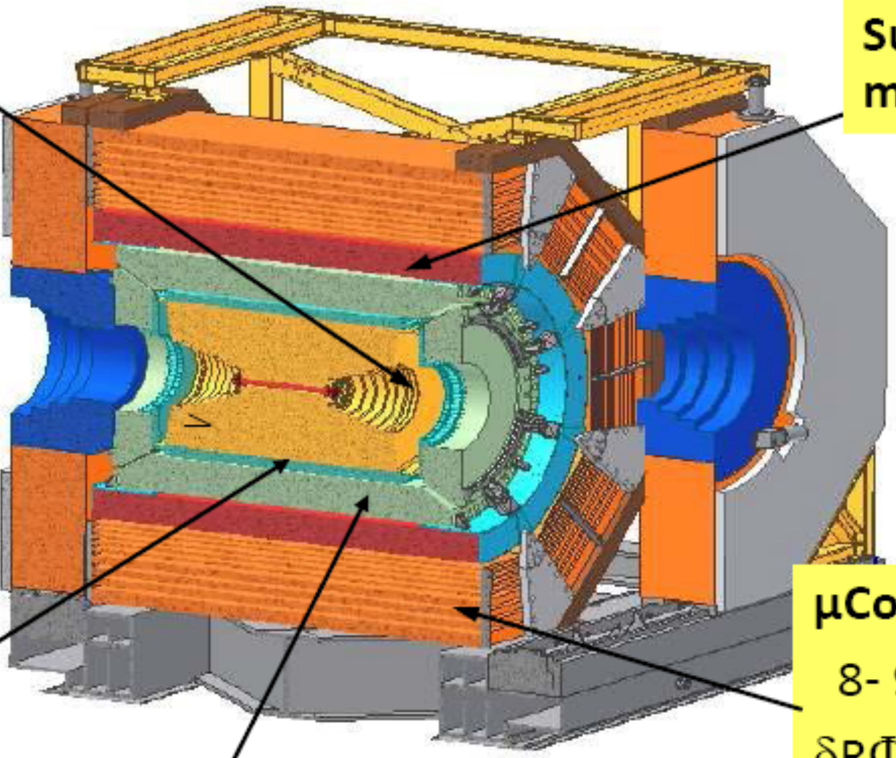
- **A larger data set could help to improve our knowledge on Λ_c^+ decays. BESIII will keep collecting Λ_c^+ data (~1M in total).**

- **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 Slides

BESIII Detector



Drift Chamber (MDC)

$\sigma P/P\ (^0/_0) = 0.5\%$(1GeV)

$\sigma_{dE/dx}\ (^0/_0) = 6\%$

Super-conducting magnet (1.0 tesla)

Time Of Flight (TOF)

σ_T: 90 ps Barrel

110 ps endcap

μCounter

8- 9 layers RPC

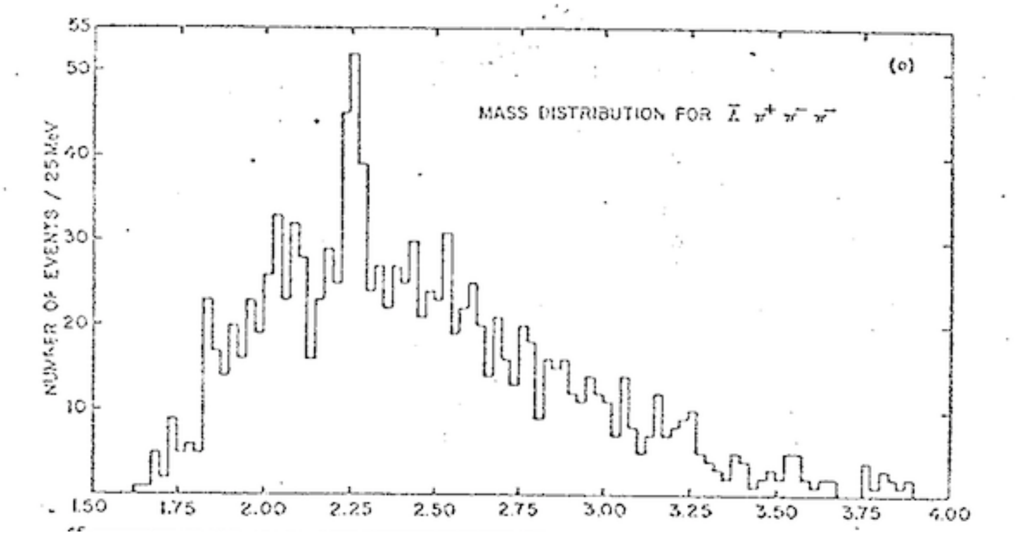
$\delta R\Phi$=1.4 cm~1.7 cm

EMC: $\sigma E/\sqrt{E}(^0/_0) = 2.5\ \%$ (1 GeV)

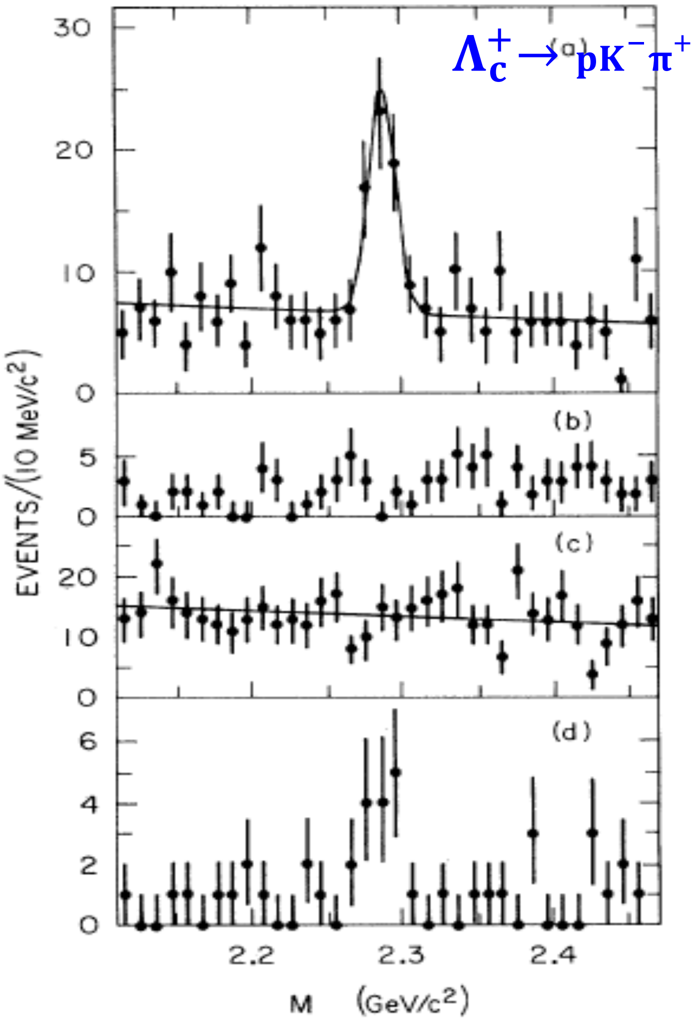
(CsI) $\sigma_{z,\phi}$(cm) = 0.5 - 0.7 cm/$\sqrt{E}$

Discovery of the lightest heavy baryon

- **First evidence of Λ_c^+ at Fermi Lab in 1976** **PRL37, 882 (1976)**
- **Λ_c^+ established in MarkII in 1980** **PRL44, 10 (1980)**

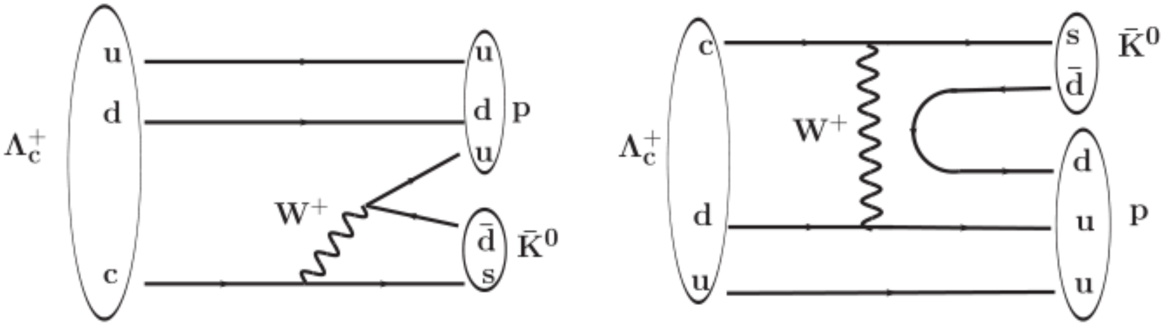


Invariant mass distribution



$\Lambda_c^+ \rightarrow pK^-\pi^+$

Λ_c^+ weak decays: W-exchange



- **Experimental measurement of $B(\Lambda_c^+ \rightarrow p\overline{K^0})$ are not consistent with theoretically factorization approach at tree level.**

- **Contrary to charmed meson, W-exchange contribution is important（NO CS and HS）**

- **W-exchange are non-factorizable. There contribution can be only determined by experiment measurement.**

- **Search for process happened only through W-exchange process to extract their contribution are key to factorization approach**

$$\Lambda_c^+ \to \Xi^0 K^+, \Xi^{*0} K^+, \Delta^{++} K^-, \Sigma^+ K^+ K^-$$

粲重子衰变中的理论焦点

- 不可因子化的作用（部分C图和W交换图）与可因子化部分相比并不低甚至比可因子化部分更主导

- W-diagram (W-exchange) only process:
  - $\mathbf{\Lambda_c^+} \to \Sigma^+\phi, \Xi^0 K^+, \Delta^{++}K^-$
- C-diagram (Internal W-emission) only process:
  - $\mathbf{\Lambda_c^+} \to p\phi$
- They provide clean and unique inputs to the amplitudes of the non-factorizable diagrams, which are not calculable in theory
- However, their experimental measurements are limited in precision

理论上对两体过程的计算

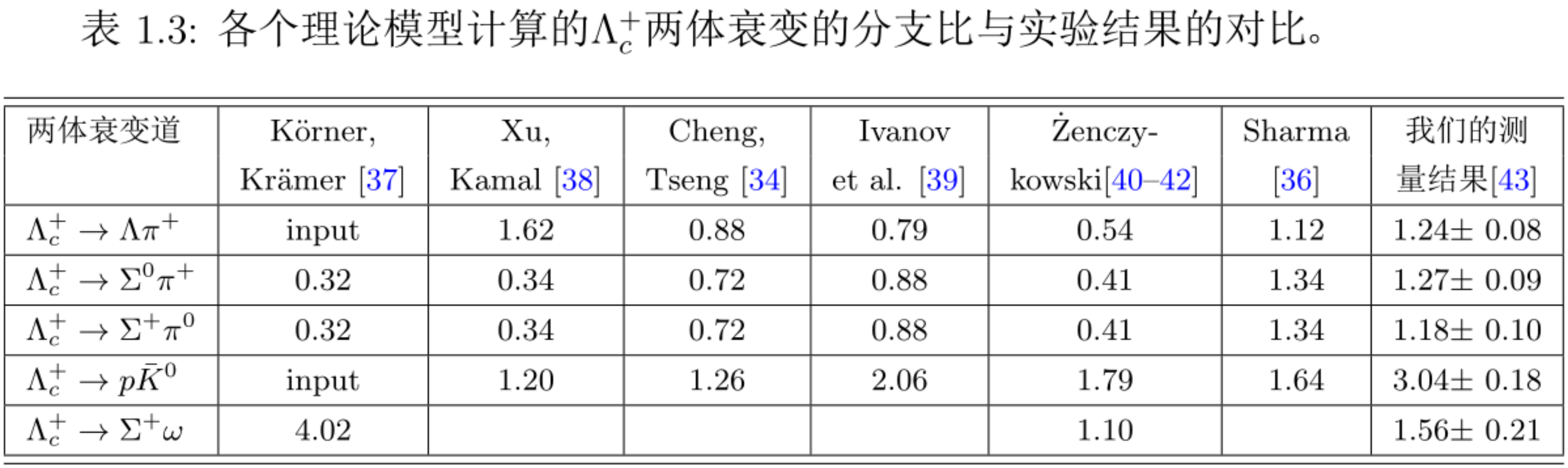


表 1.3: 各个理论模型计算的Λ_c^+两体衰变的分支比与实验结果的对比。

两体衰变道	Körner, Krämer [37]	Xu, Kamal [38]	Cheng, Tseng [34]	Ivanov et al. [39]	Żenczy-kowski[40–42]	Sharma [36]	我们的测量结果[43]
$\Lambda_c^+ \to \Lambda\pi^+$	input	1.62	0.88	0.79	0.54	1.12	1.24± 0.08
$\Lambda_c^+ \to \Sigma^0\pi^+$	0.32	0.34	0.72	0.88	0.41	1.34	1.27± 0.09
$\Lambda_c^+ \to \Sigma^+\pi^0$	0.32	0.34	0.72	0.88	0.41	1.34	1.18± 0.10
$\Lambda_c^+ \to p\bar{K}^0$	input	1.20	1.26	2.06	1.79	1.64	3.04± 0.18
$\Lambda_c^+ \to \Sigma^+\omega$	4.02				1.10		1.56± 0.21