(Experimental) Overview on charm baryon (Λ_c^+) decays

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(On behalf of the BESIII collaboration)

Outline

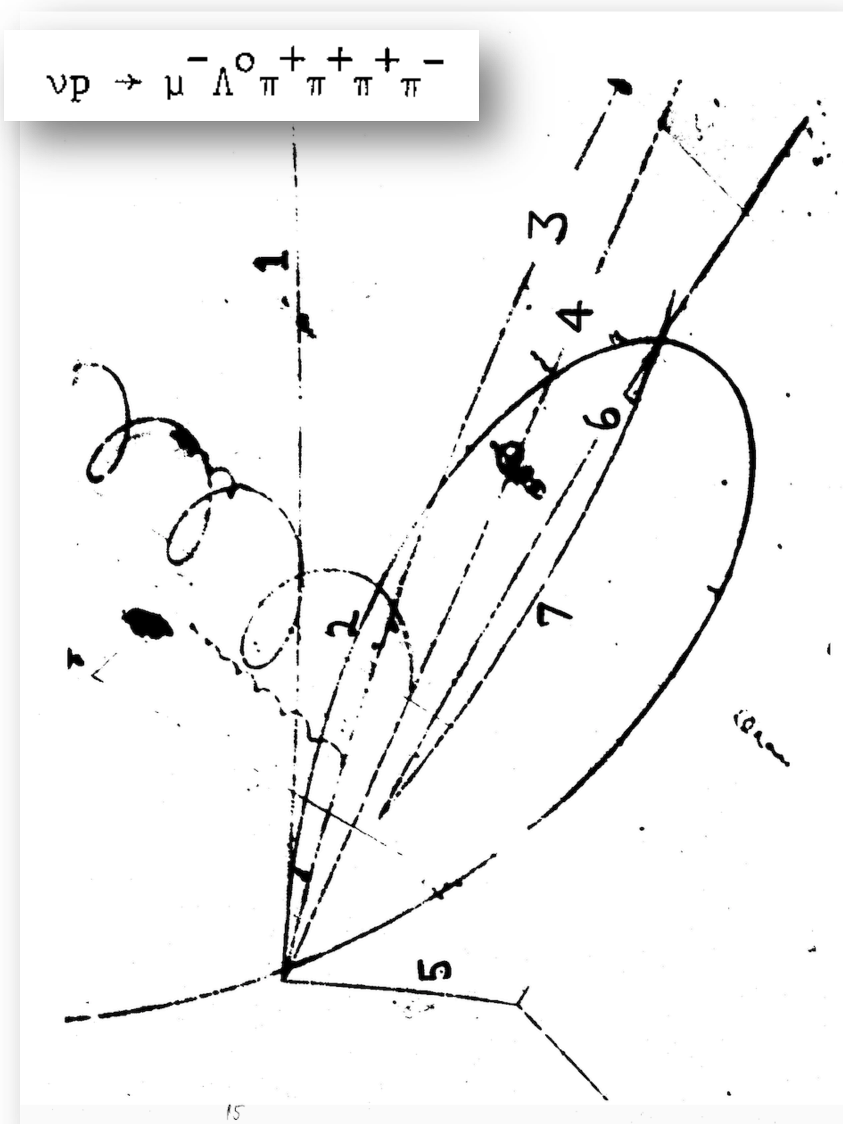
- History of charmed baryons
- The lightest *c*-ed baryon Λ_c^+
- Recent results on its decays

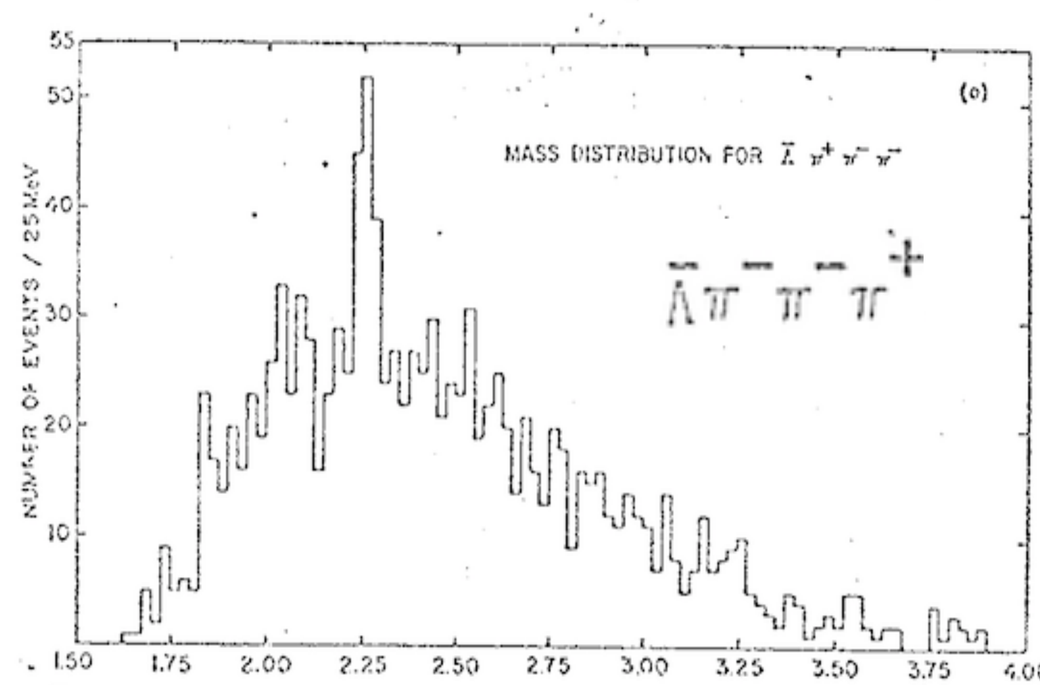
  (for the charmed baryon spectroscopy, one may refer to Alan & Paras's talks.)
- Summary and prospects

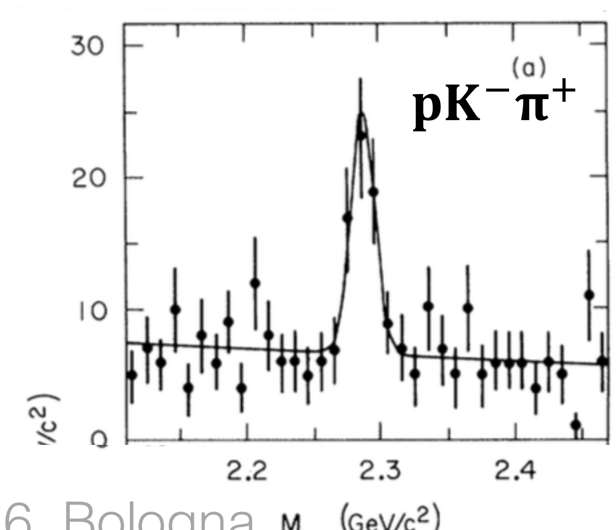
For more details, please join the parallel session:
Charm baryon decays *this afternoon.*

Discovery of the charmed heavy baryon

- Not exclusively clear about the first observation
- A number of experiments which published evidence for the charmed baryons beginning in 1975
  - ✓ First hint of charmed baryon $\Sigma_c^{++} \to \Lambda_c^+ \pi^+$ in BNL PRL34, 1125 (1975)
  - ✓ First evidence of Λ_c^+ at Fermi Lab PRL37, 882 (1976)
- The first well established state is the Λ_c^+ at MarkII PRL44, 10 (1980)







The charmed baryon family

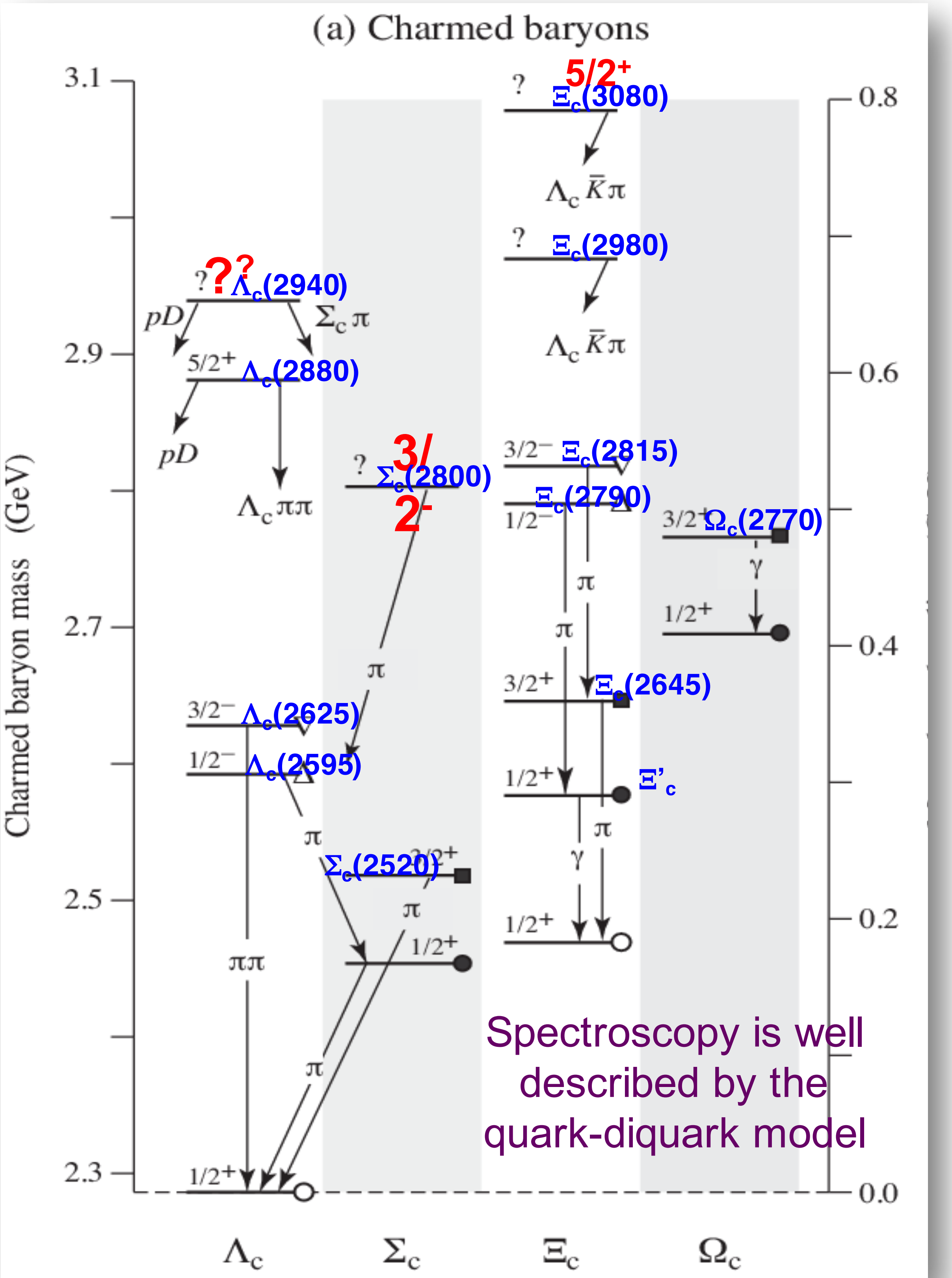
- **Singly charmed baryons**
  - ✓ Established ground states:
    Λ_c^+, Σ_c , $\Xi_c^{(\prime)}$, Ω_c
  - ✓ Excited states are being explored (see Alan's talk)
- **No observations of doubly or triply charmed baryons** (see Paras's talk)

➢ Λ_c^+: decay only weakly, **many recent experimental progress since 2014**

➢ Σ_c : $B(\Sigma_c \to \Lambda_c^+\pi)\sim 100\%$; $B(\Sigma_c \to \Lambda_c^+\gamma)$?

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

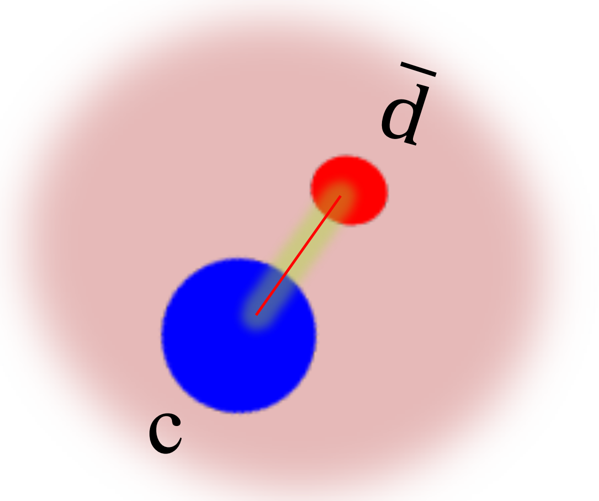
➢ Ω_c : decay only weakly; no absolute BF measured

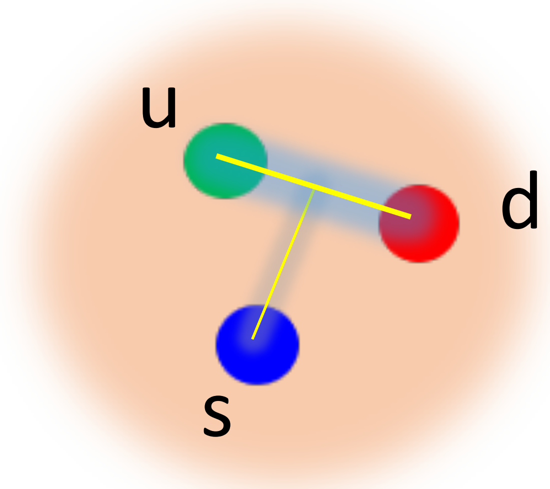


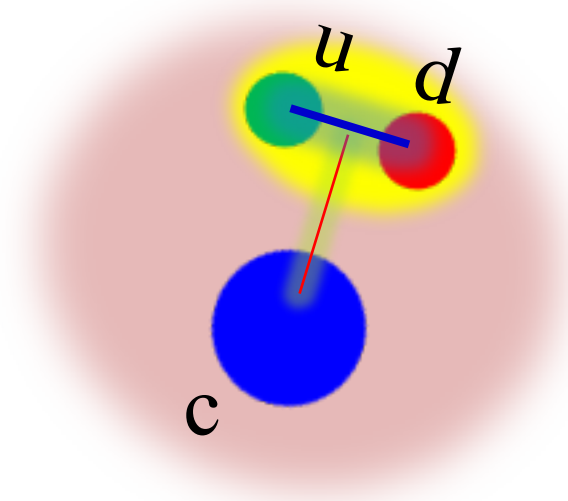
Quark model picture

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.*







→ Charmed meson ($D^+[c\bar{d}]$)
$m_d << m_c$ → **quark + heavy quark**
(q) (Q)

→ Strange baryons ($\Lambda[uds]$)
$m_u, m_d \approx m_s$ → **(qqq)** uniform

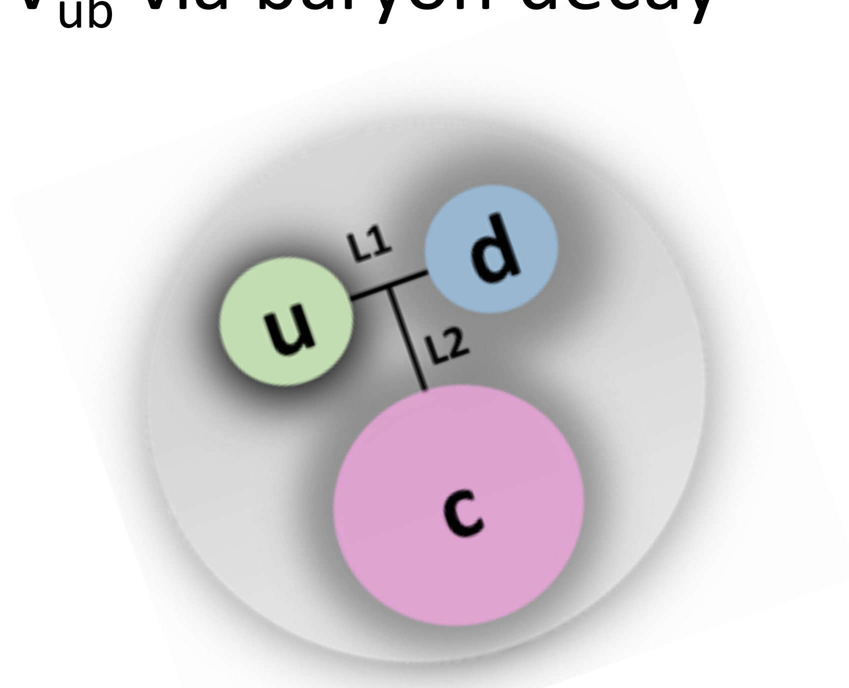
→ Charmed baryon ($\Lambda_c[udc]$)
$m_u, m_d << m_c$ → **diquark + quark**
(qq) (Q)

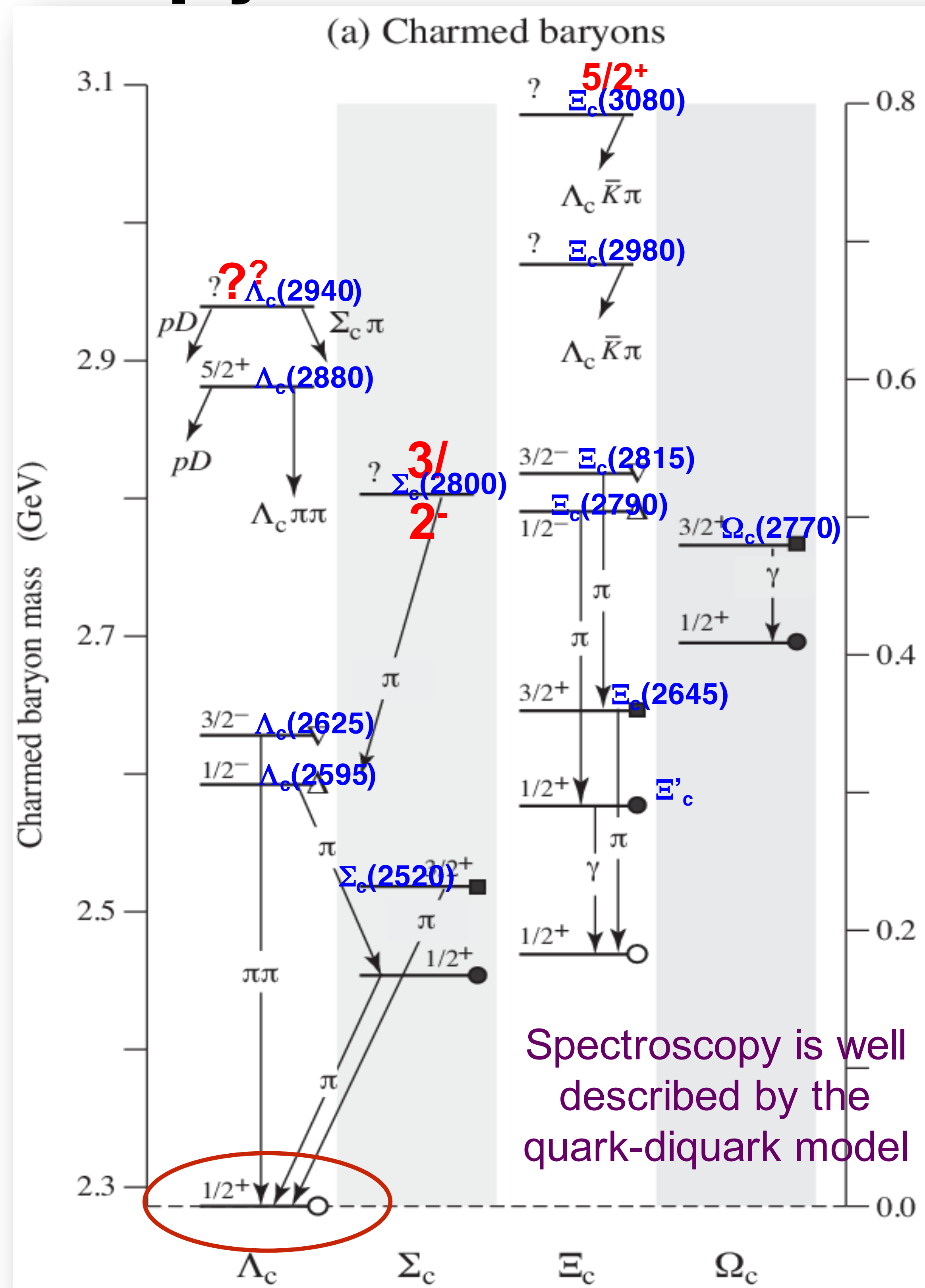
In some sense, more reliable prediction of heavy-light quark transition without dealing with light degrees of freedom that have net spin or isospin.

Λ_c^+ may provide complementary powerful test on internal dynamics to D/Ds does

Λ_c^+ : cornerstone of charmed baryon spectroscopy

- The lightest charmed baryon
- Most of the charmed baryons will eventually decay to Λc
- The Λc is one of important tagging hadrons in c-quark counting in the productions at high energy energies and Bottom baryon decays
- $B(\Lambda_c^+ \to pK^-\pi^+)$: dominant error for V_{ub} via baryon decay

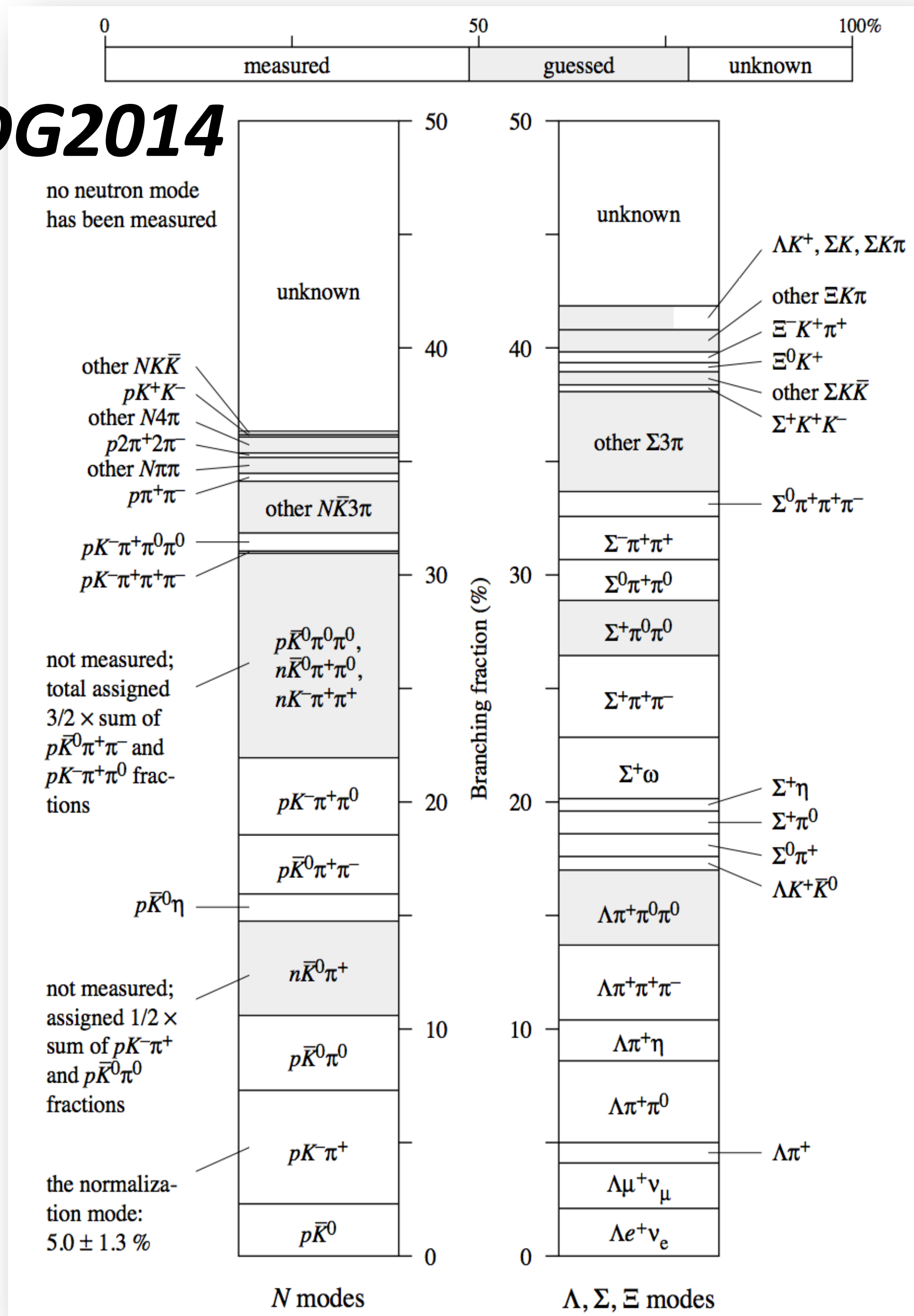




The Λ_c^+ decays

Since 1980's, the Λ_c^+ have been produced and studied at many experiments, notably fixed-target experiments (such as FOCUS and SELEX) and e^+e^- B-factories (ARGUS, CLEO, BABAR, and BELLE).

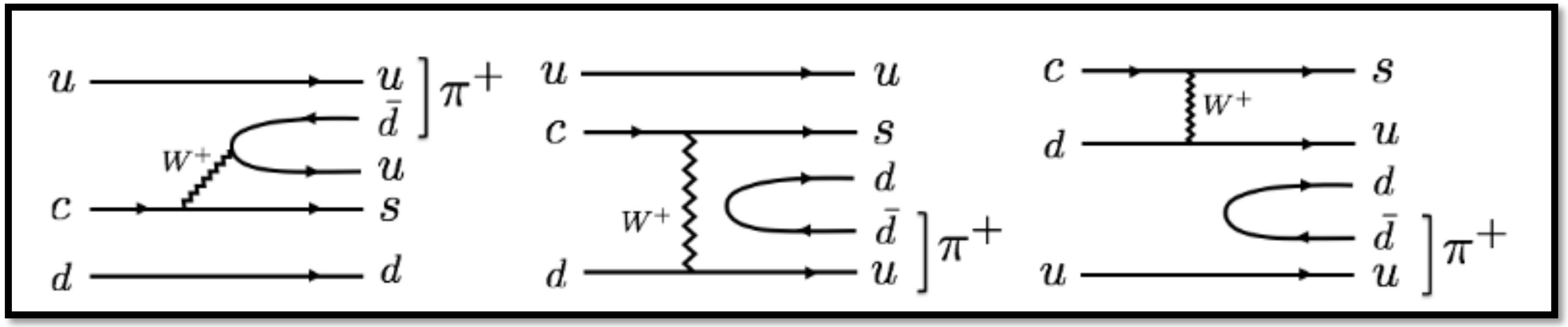
PDG2014



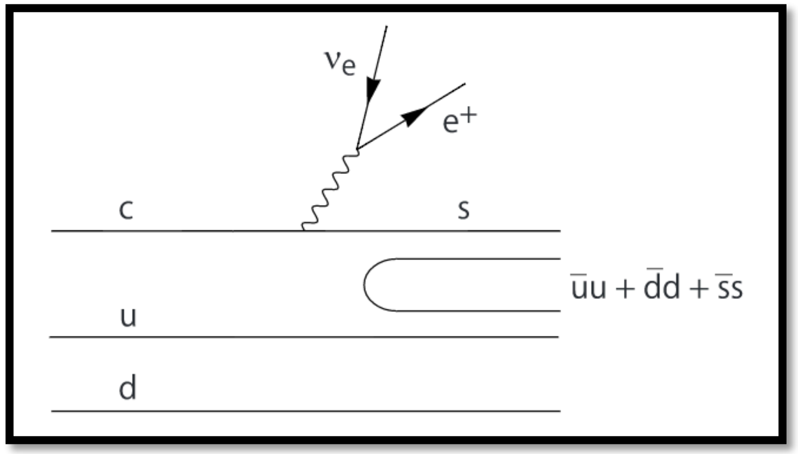
- Before 2014, absolute branching fractions (BF) of Λ_c^+ decays are still not well determined
  ➔ BFs of all measured decay modes are measured relative to $\Lambda_c^+ \to pK^-\pi^+$
- No completely model-independent measurements of $B(\Lambda_c^+ \to pK^-\pi^+)$: *uncertainties of BFs of Λ_c^+ decays are 25%~40% in PDG2014*
- The sum of measured BFs is only about 60%. Many missing channels, *esp.*, those leptonic or neutron-involved decays

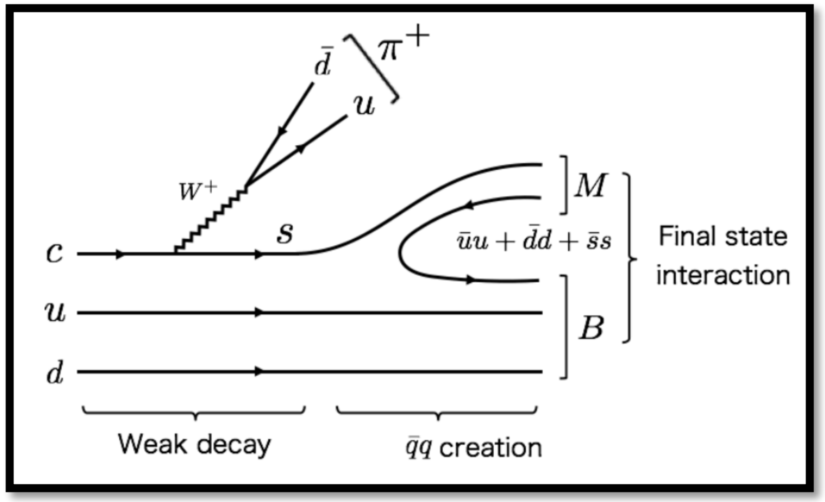
Λ_c^+ weak decays

- Contrary to charmed meson, W-exchange contribution is important



- The Λc weak decay acts as isospin filter
  - ✓ E.g., Oset suggests to study the Λ(1405) through Λc→πΛ(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 $\Lambda_c^+ \to \phi p \pi^0$:

  an analog to the Pc states in $\Lambda_b \to J/\psi p K^-$

BESIII threshold data set

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 BEPC!

available data set at BESIII

Energy(GeV)	lum.(1/pb)
4.575	~48
4.580	~8.5
4.590	~8.1
4.600	~567

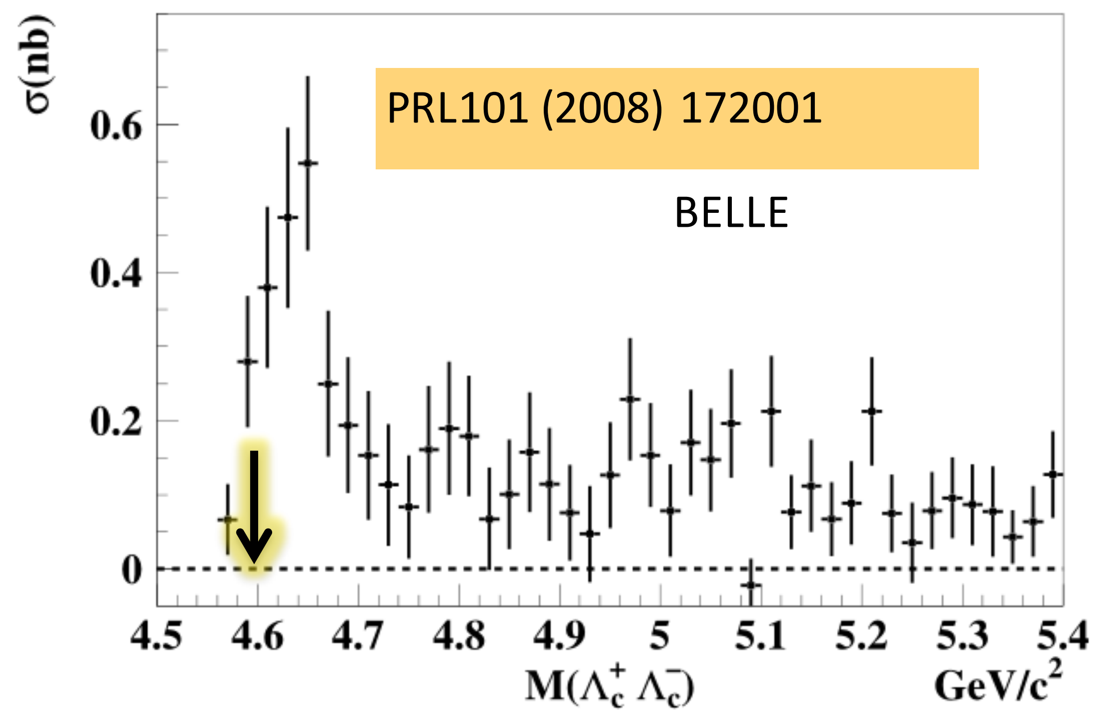


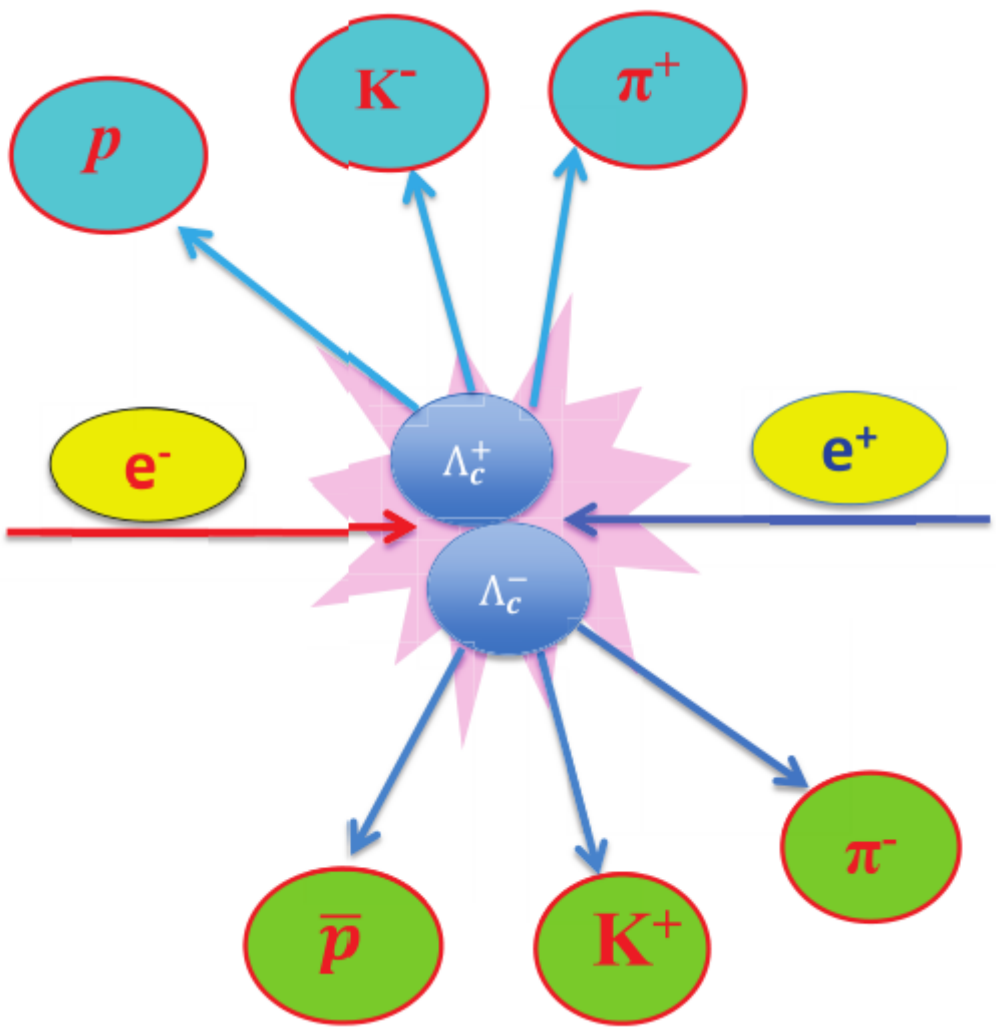
FIG. 4: The cross section for the exclusive process $e^+e^- \rightarrow \Lambda_c^+\Lambda_c^-$.

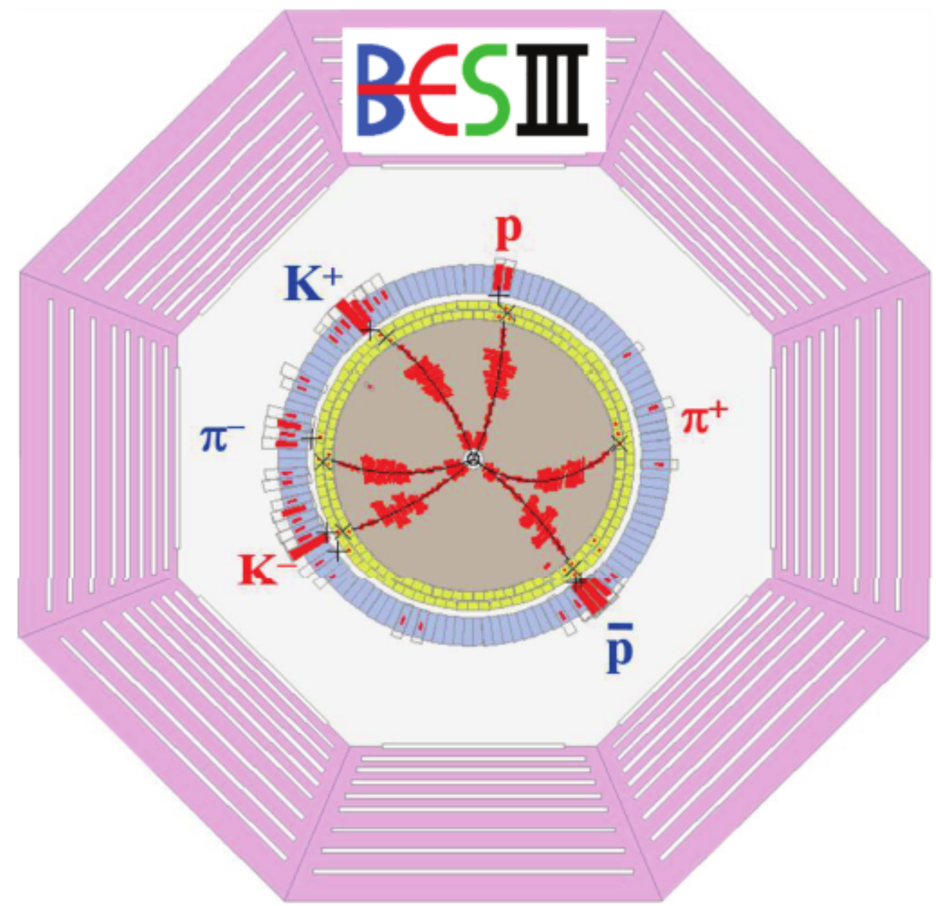
Measurement using the threshold pair-productions via e^+e^- annihilations is unique: *the most simple and straightforward*

First time to systematically study charmed baryon at threshold!

Single Tag (ST) and Double Tag (DT) method at Threshold

The absolute BF can be obtained by the ratio of DT yields to ST yields.





$$\mathcal{B}_i = \frac{N_{ij}^{\mathrm{DT}}}{N_j^{\mathrm{ST}}} \frac{\varepsilon_j}{\varepsilon_{ij}}$$

Specialties of current ongoing experiments

BESIII

- Threshold production & two body process
- Clean background
- Absolute meas. with many systematics cancel out
- Missing-mass technique: neutron, neutrino …
- Good photon resolution: Σ, Ξ, π^0, …

Belle & Babar LHCb

- Large statistics
- High background
- Good PID and vertexing
- Complex production environment
- Good hadron-ID and μ-ID
- Good photon resolution in electron machines

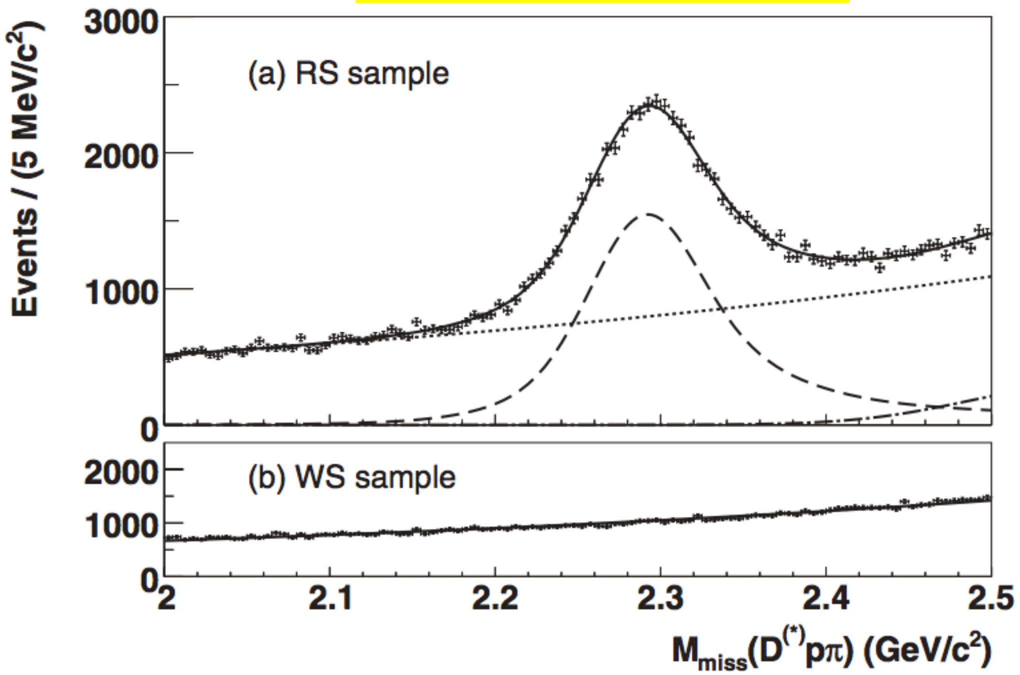
They are complementary!

Belle's first model-independent measurement of $B(\Lambda_c^+ \to pK^-\pi^+)$

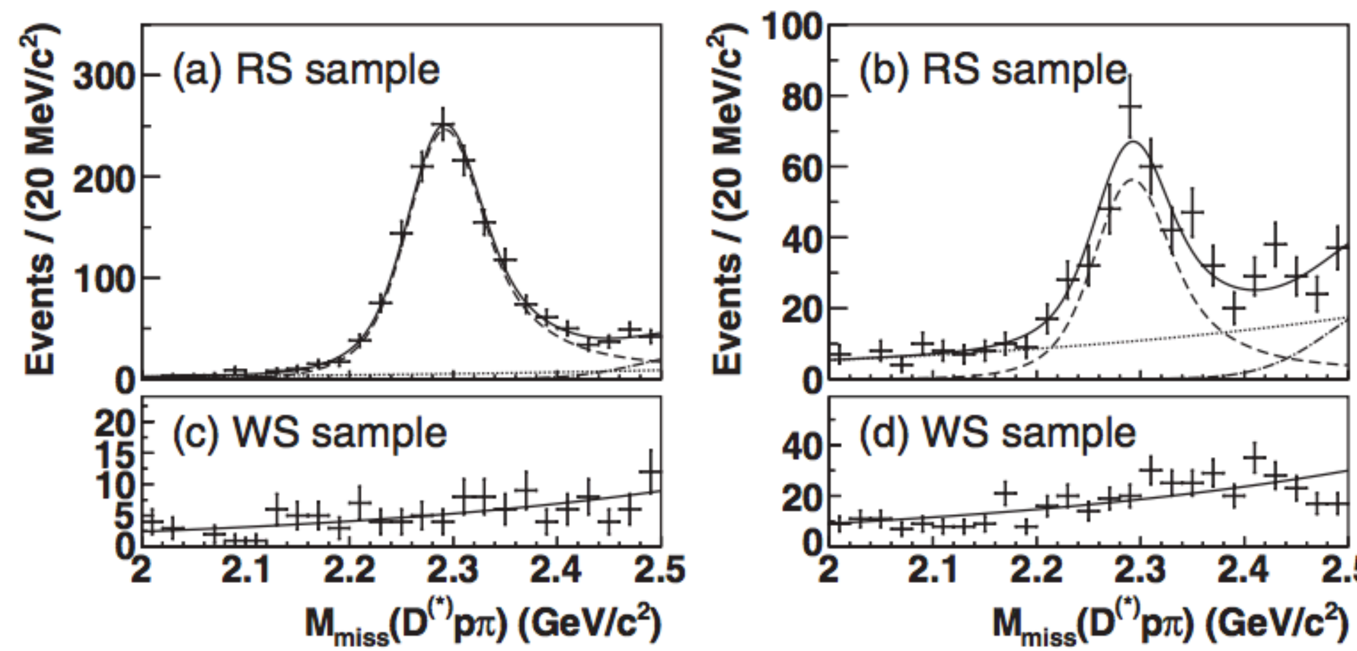
PRL 113, 042002 (2014)

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



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

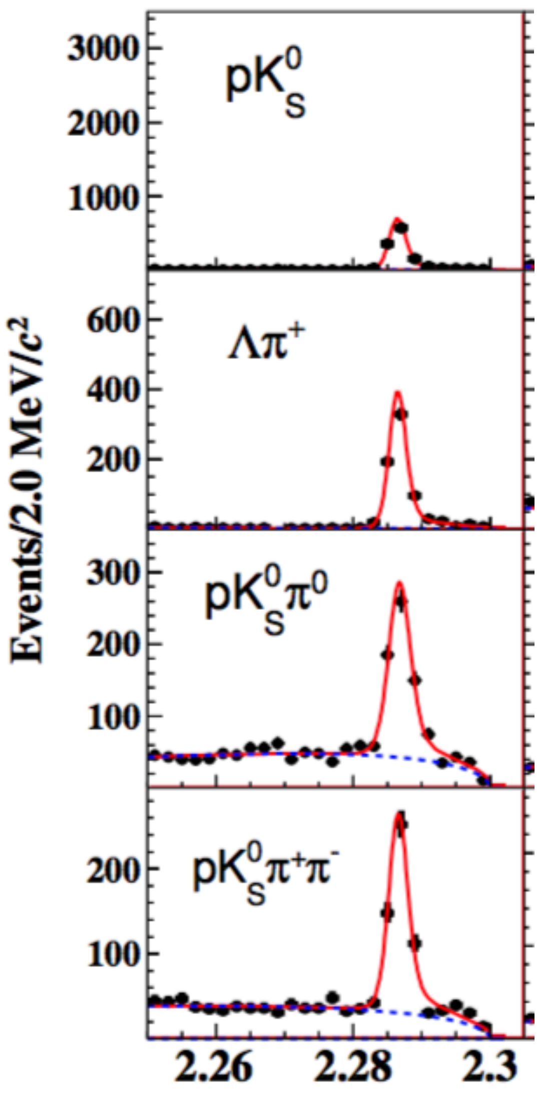
precision reaches to 4.7%:

significant improvement from old world average (~25%)

Absolute BFs for 12 $\Lambda_c^\pm$ CF hadronic decays

PRL 116, 052001 (2016)

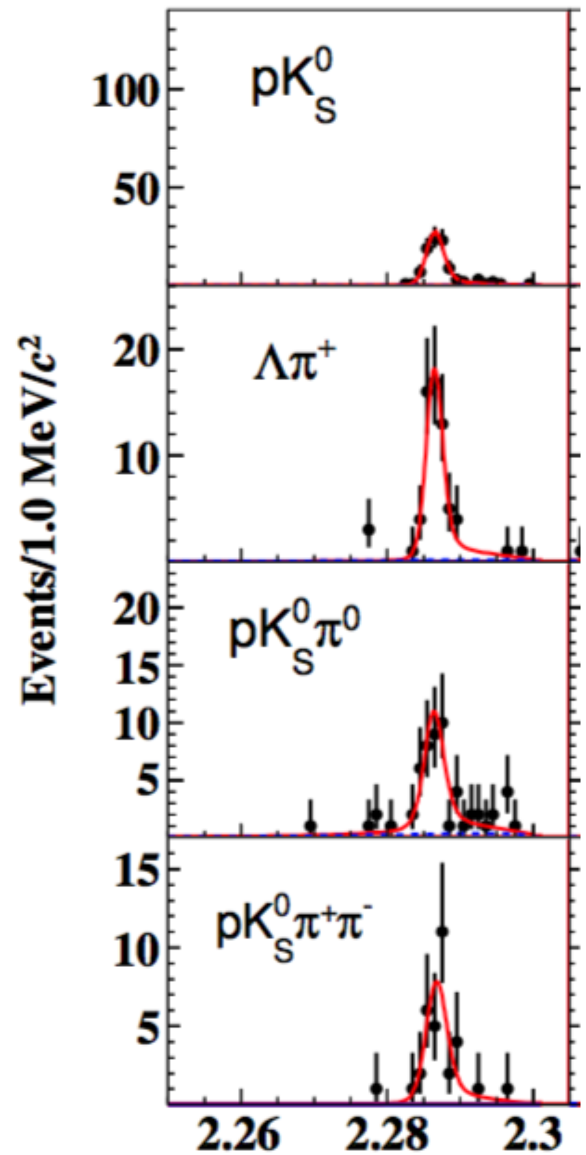
We define an optimal invariant mass: $M_{\rm BC}c^2 \equiv \sqrt{E_{\rm beam}^2 - p^2c^2}$,



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

ST yields

modes	N_i^{ST}
pK_S	1243 ± 37
$pK^-\pi^+$	6308 ± 88
$pK_S\pi^0$	558 ± 33
$pK_S\pi^+\pi^-$	454 ± 28
$pK^-\pi^+\pi^0$	1849 ± 71
$\Lambda\pi^+$	706 ± 27
$\Lambda\pi^+\pi^0$	1497 ± 52
$\Lambda\pi^+\pi^-\pi^+$	609 ± 31
$\Sigma^0\pi^+$	586 ± 32
$\Sigma^+\pi^0$	271 ± 25
$\Sigma^+\pi^+\pi^-$	836 ± 43
$\Sigma^+\omega$	157 ± 22



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

DT yields

Decay modes	N_{-j}^{DT}
pK_S	89 ± 10
$pK^-\pi^+$	390 ± 21
$pK_S\pi^0$	40 ± 7
$pK_S\pi^+\pi^-$	29 ± 6
$pK^-\pi^+\pi^0$	148 ± 14
$\Lambda\pi^+$	59 ± 8
$\Lambda\pi^+\pi^0$	89 ± 11
$\Lambda\pi^+\pi^-\pi^+$	53 ± 7
$\Sigma^0\pi^+$	39 ± 6
$\Sigma^+\pi^0$	20 ± 5
$\Sigma^+\pi^+\pi^-$	56 ± 8
$\Sigma^+\omega$	13 ± 3

Very clean backgrounds!

Results of 12 hadronic BFs

a least square global fitter: simultaneous fit to all the modes and constrain to the total number of $\Lambda_c^\pm$ pairs.

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	

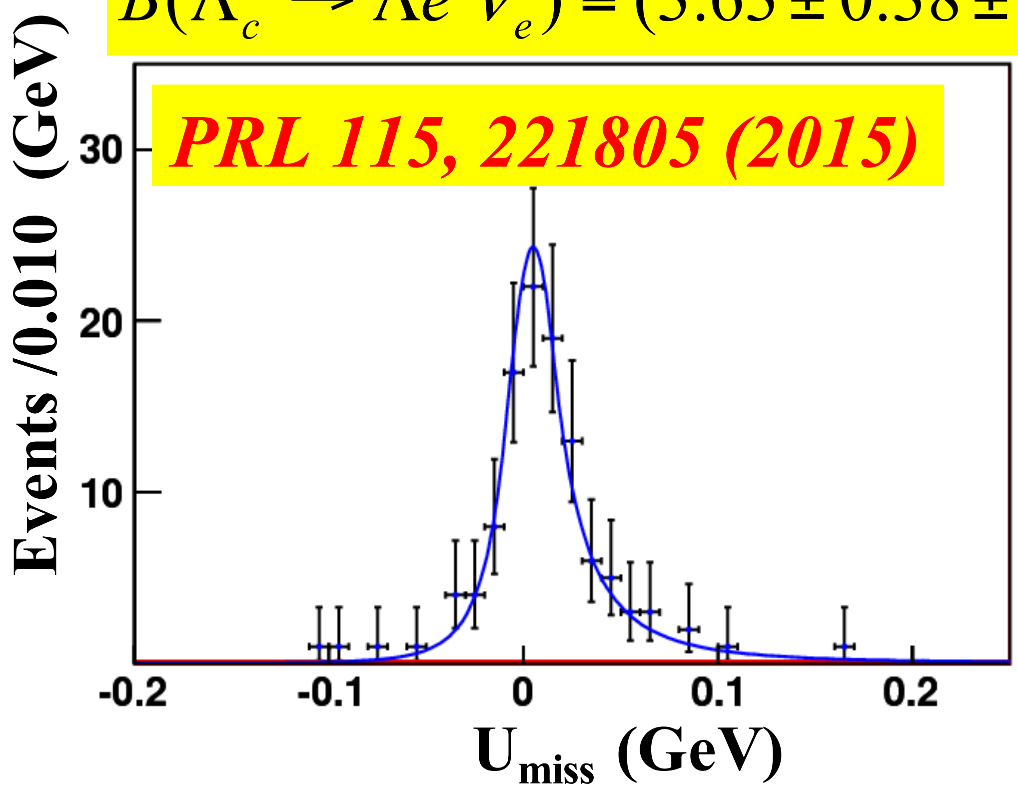
- ✓ **$B(pK^-\pi^+)$: BESIII precision comparable with Belle's**
- ✓ **BESIII $B(pK^-\pi^+)$ is compatible with BELLE's with 2σ**
- ✓ **Improved precisions of the other 11 modes significantly**

Absolute BFs for semi-leptonic (SL) $\Lambda_c^+ \to \Lambda l^+ \nu$

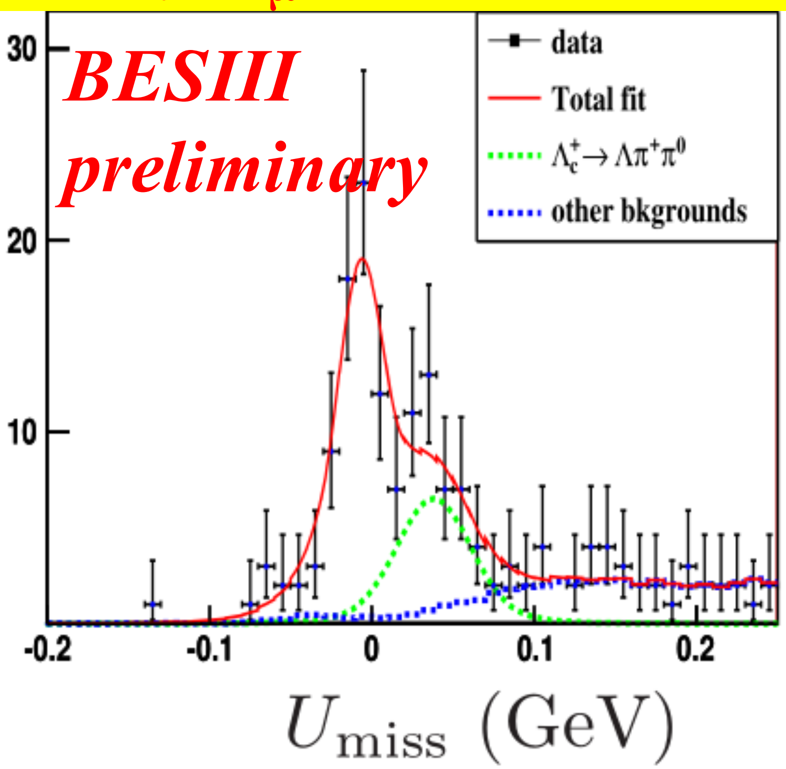
- No absolute measurements yet
  - ✓ $B(\Lambda_c^+ \to \Lambda e^+ \nu)$: poor precision in PDG2014 (2.1±0.6)%
  - ✓ $B(\Lambda_c^+ \to \Lambda \mu^+ \nu)$: no measurement
- BESIII uses the DT method and missing-mass technique at threshold:
  11 ST modes are used, except $\Sigma^+\omega$
- **An optimized missing mass:** $U_{\rm miss} = E_{\rm miss} - c|\vec{p}_{\rm miss}|$
  which takes into account beam energy constrain.

$B(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.63 \pm 0.38 \pm 0.20)\%$

PRL 115, 221805 (2015)



$B[\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu] = (3.49 \pm 0.46 \pm 0.26)\%$



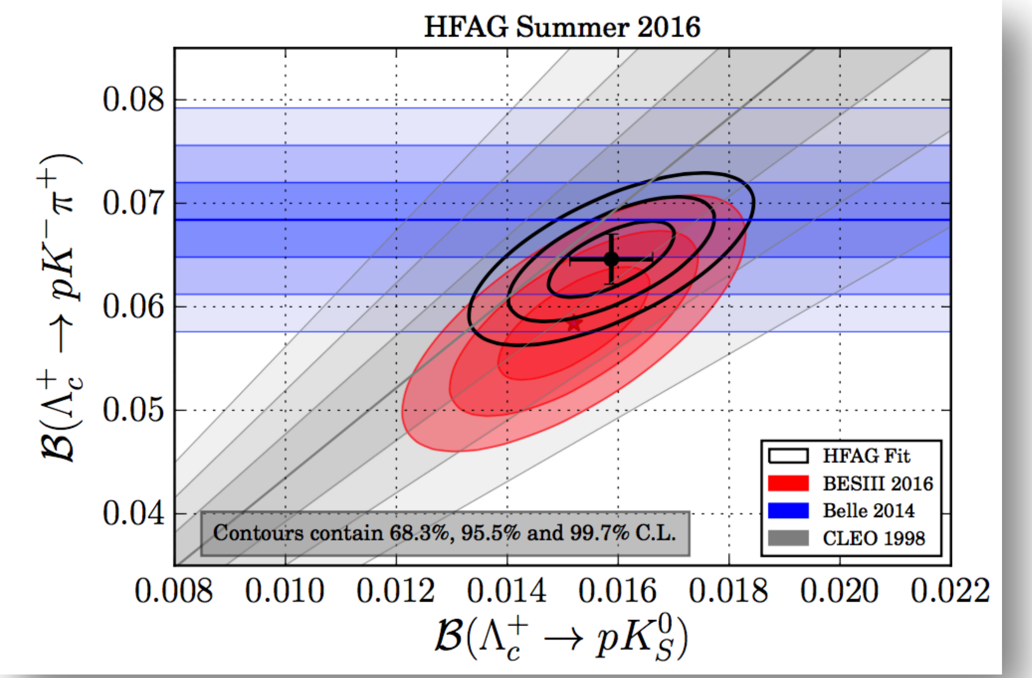
$\Gamma[\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu]/\Gamma[\Lambda_c^+ \to \Lambda e^+ \nu_e] = 0.96 \pm 0.16 \pm 0.04$ **(preliminary)**

Also See Gang's plenary talk

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_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

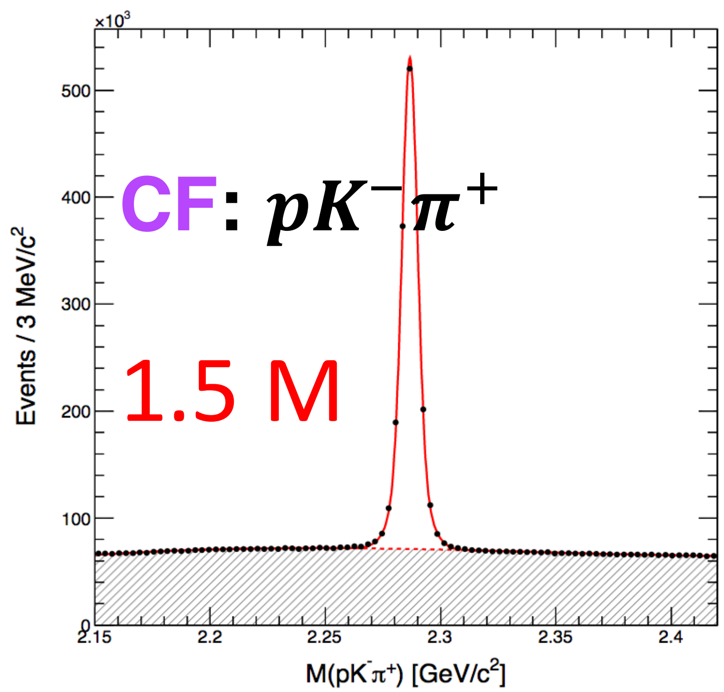
	Golden hadronic mode	δB/B	Golden SL mode	δB/B
D^0	B(Kπ)=(3.88±0.05)%	1.3%	B(Kev)=(3.55±0.05)%	1.4%
D^+	B(Kππ)=(9.13±0.19)%	2.1%	B(K^0ev)=(8.83±0.22)%	2.5%
D_s	B(KKpi)=(5.39±0.21)%	3.9%	B(φev)=(2.49±0.14)%	5.6%
Λc	B(pKπ)=(5.0±1.3)%(PDG2014) =(6.8±0.36)% (BELLE) =(5.84±0.35)% (BESIII) =(6.46±0.24)% (HFAG)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

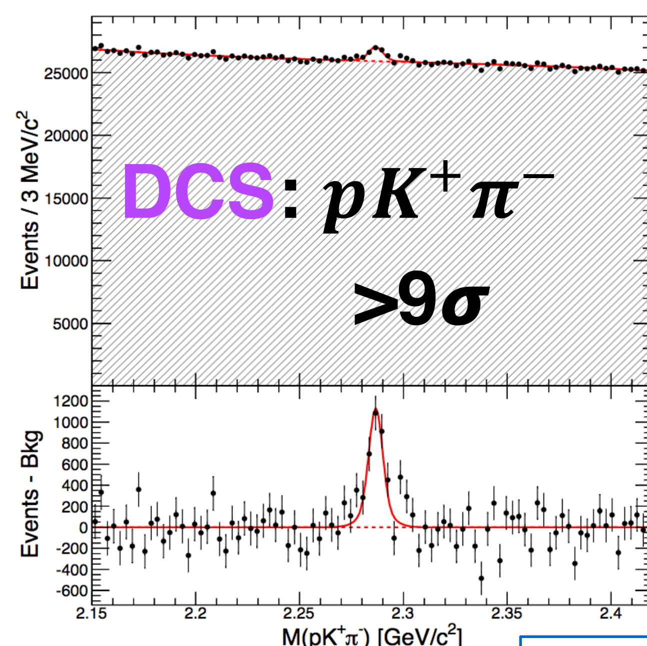
- The precisions of Λc decay rates is reaching to the level of charmed mesons!
- LHCb data will further constrain the HFAG fit
- However, search for more unknown modes are important

Observation of doubly Cabibbo suppress decay $\Lambda_c^+ \to pK^+\pi^-$

PRL117, 011801 (2016)

- Important to constraining models of W-exchange diagram and in the study of flavor SU(3) symmetry
- DCS decays of charmed baryons have not yet been observed: $\mathrm{B}(\Lambda_c^+ \to pK^+\pi^-)$<0.46% by FOCUS *PLB624, 166(2005)*





3587±380 signals

$$\frac{\mathrm{B}(\Lambda_c^+ \to pK^+\pi^-)}{\mathrm{B}(\Lambda_c^+ \to pK^-\pi^+)} = (2.35 \pm 0.27 \pm 0.21)\%$$

$$=(0.82 \pm 0.12)\tan^4\theta_c$$

➔ $\mathrm{B}(\Lambda_c^+ \to pK^+\pi^-) = \left(1.61 \pm 0.23^{+0.07}_{-0.08}\right)\times 10^{-4}$

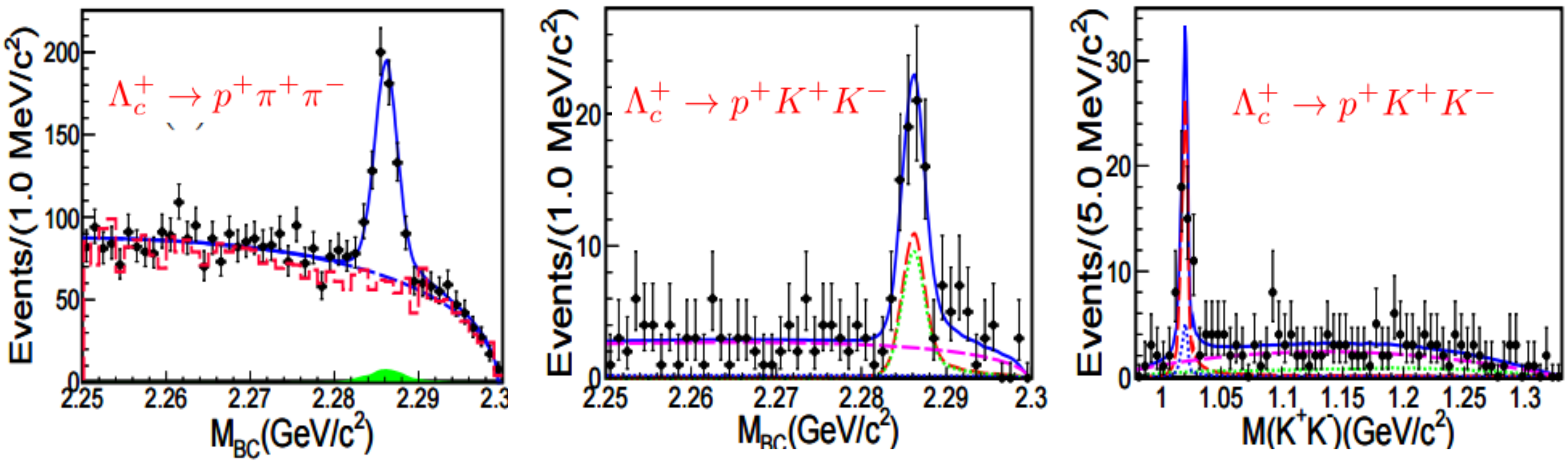
- no W-exchange contribution?
- effect of resonance contributions of Λ* or Δ?

See Kiyoshi's talk

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

arXiv:1608.00407 submitted to PRL

- **Sensitive to nonfactorizable contributions from W-exchange diagrams**
- **ST method: $\Lambda_c^+ \to pK^-\pi^+$ as ref. mode**



Decay modes	$\mathcal{B}_{mode}/\mathcal{B}_{ref.}$ (this work)	$\mathcal{B}_{mode}/\mathcal{B}_{ref.}$ ([28])
$\Lambda_c^+ \to p\pi^+\pi^-$	$(6.70 \pm 0.48 \pm 0.25) \times 10^{-2}$	–
$\Lambda_c^+ \to p\phi$	$(1.81 \pm 0.33 \pm 0.13) \times 10^{-2}$	$0.015 \pm 0.002 \pm 0.002$
$\Lambda_c^+ \to pK^+K^-$ (non-ϕ)	$(9.36 \pm 2.22 \pm 0.71) \times 10^{-3}$	$0.007 \pm 0.002 \pm 0.002$
–	$\mathcal{B}_{mode}$	$\mathcal{B}$(PDG)
$\Lambda_c^+ \to p\pi^+\pi^-$	$(3.91 \pm 0.28 \pm 0.15 \pm 0.24) \times 10^{-3}$	$(3.5 \pm 2.0) \times 10^{-3}$
$\Lambda_c^+ \to p\phi$	$(1.06 \pm 0.19 \pm 0.08 \pm 0.06) \times 10^{-3}$	$(8.2 \pm 2.7) \times 10^{-4}$
$\Lambda_c^+ \to pK^+K^-$ (non-ϕ)	$(5.47 \pm 1.30 \pm 0.41 \pm 0.33) \times 10^{-4}$	$(3.5 \pm 1.7) \times 10^{-4}$

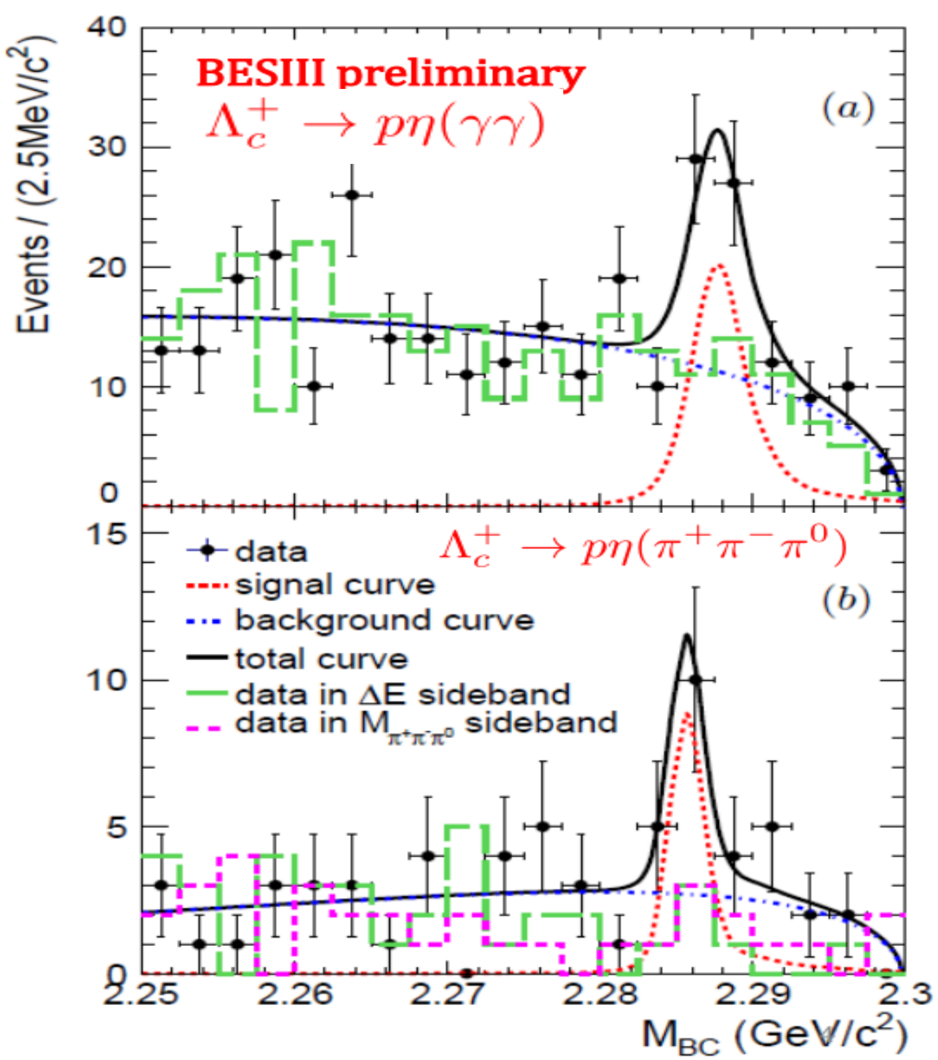
first observation ($\Lambda_c^+ \to p\pi^+\pi^-$)

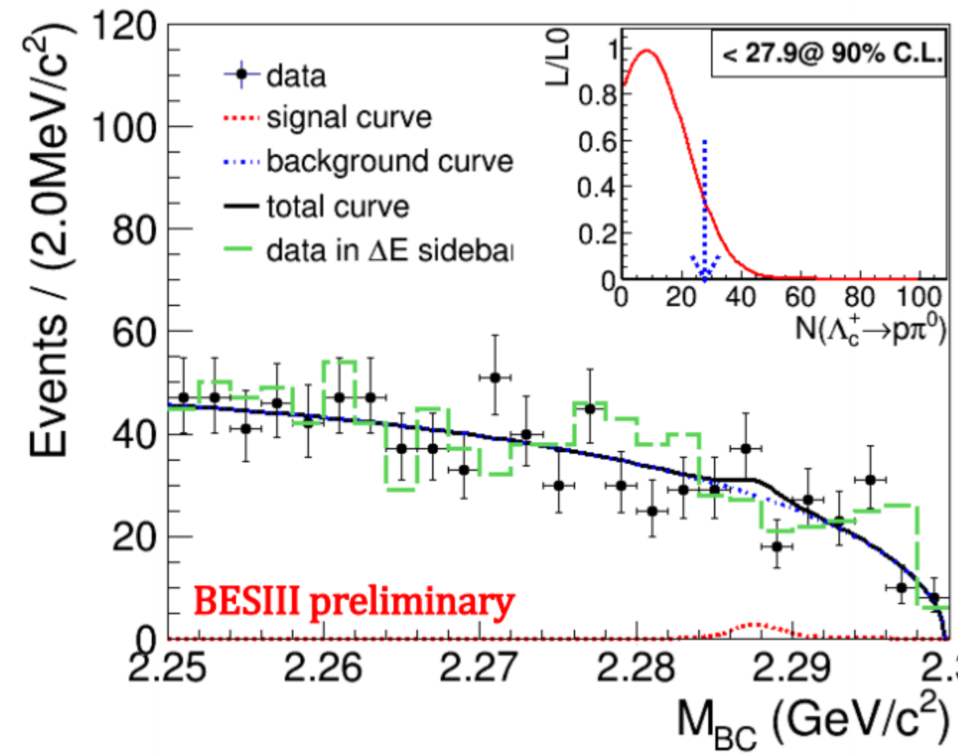
improved precision ($\Lambda_c^+ \to p\phi$, $\Lambda_c^+ \to pK^+K^-$ (non-ϕ))

See Binlong's talk

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

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





$$B = \frac{N^{obs}}{2 \cdot N_{\Lambda_c^+ \overline{\Lambda}_c^-} \cdot \varepsilon \cdot B_{int}}$$

- BESIII preliminary results:
  $B(\Lambda_c^+ \to p\eta) = (1.24 \pm 0.28 \pm 0.10) \times 10^{-3}$;
  $B(\Lambda_c^+ \to p\pi^0) < 2.7 \times 10^{-4}$;
  $B(\Lambda_c^+ \to p\pi^0)/B(\Lambda_c^+ \to p\eta) < 0.24$
- First evidence for $\Lambda_c^+ \to p\eta$ with 4.2σ

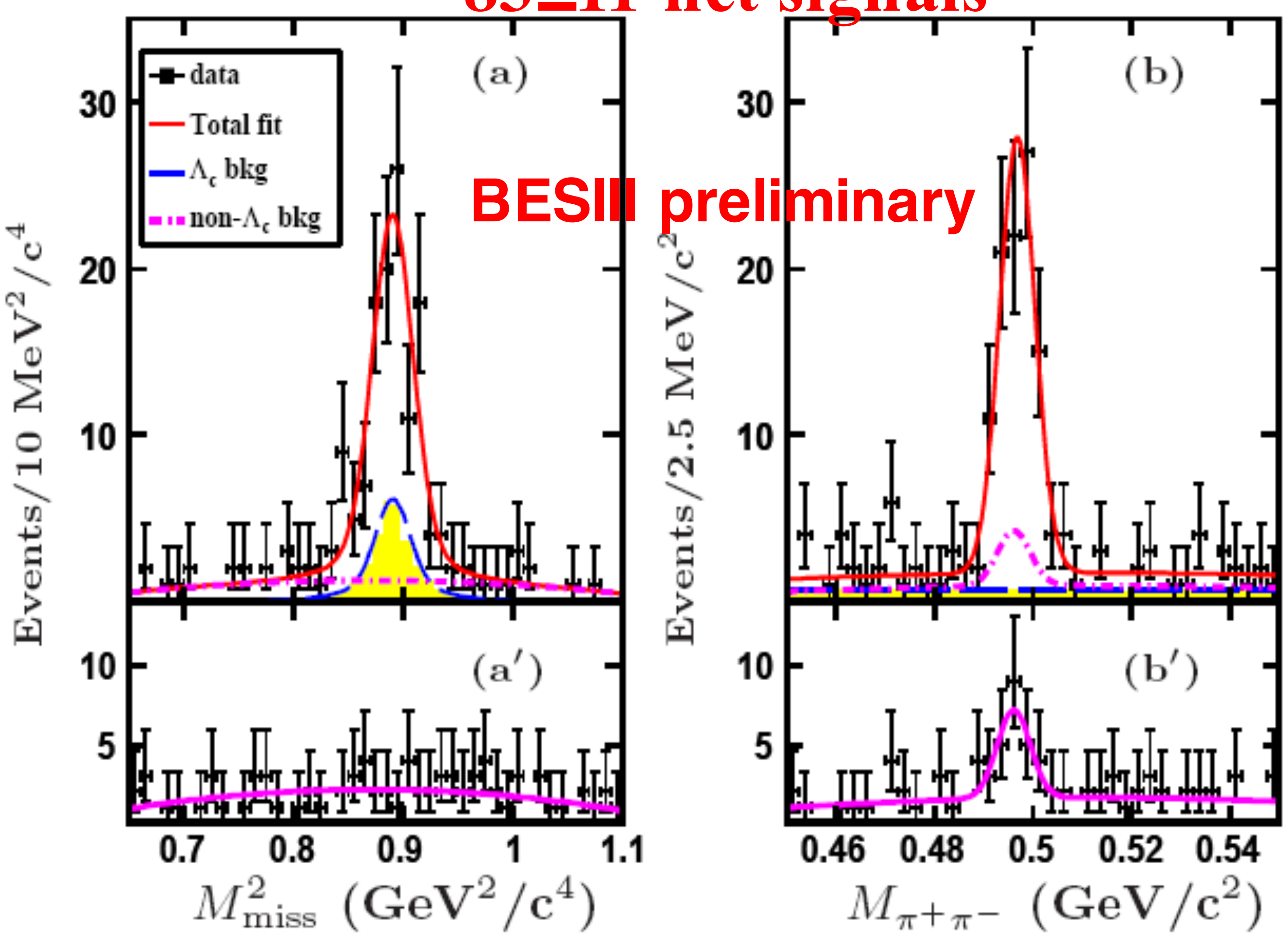
See Binlong's talk

Measurements of channels involving a neutron

See Binlong's talk

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

83±11 net signals



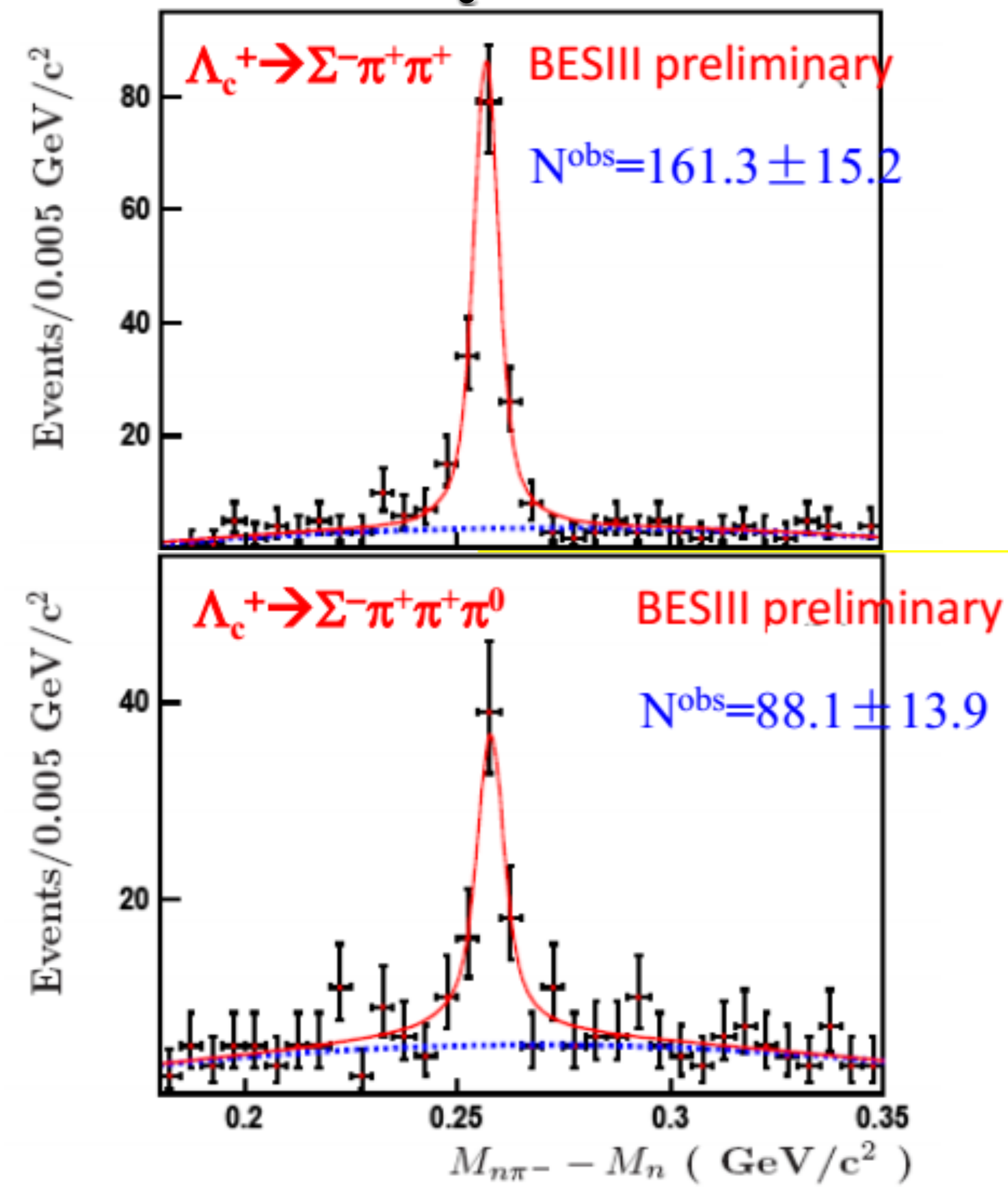
$B[\Lambda_c^+ \to nK_S^0\pi^+]=(1.82\pm0.23\pm0.11)\%$

$B[\Lambda_c^+ \to nK^0\pi^+]/B[\Lambda_c^+ \to pK^-\pi^+]=0.62\pm0.09$

$B[\Lambda_c^+ \to nK^0\pi^+]/B[\Lambda_c^+ \to pK^0\pi^0]=0.97\pm0.16$

to test final state interactions and isospin asymmetry in the charmed baryon sector [PRD93, 056008 (2016)]

Observation of a large-rate channel $\Lambda_c^+ \to \Sigma^- \pi^+\pi^+\pi^0$



- $B(\Lambda_c \to \Sigma^-\pi^+\pi^+) = (1.81\pm0.17)\%$, [more precise than old result $(2.3\pm0.4)\%$]
- $B(\Lambda_c \to \Sigma^-\pi^+\pi^+\pi^0) = (2.11\pm0.33)\%$

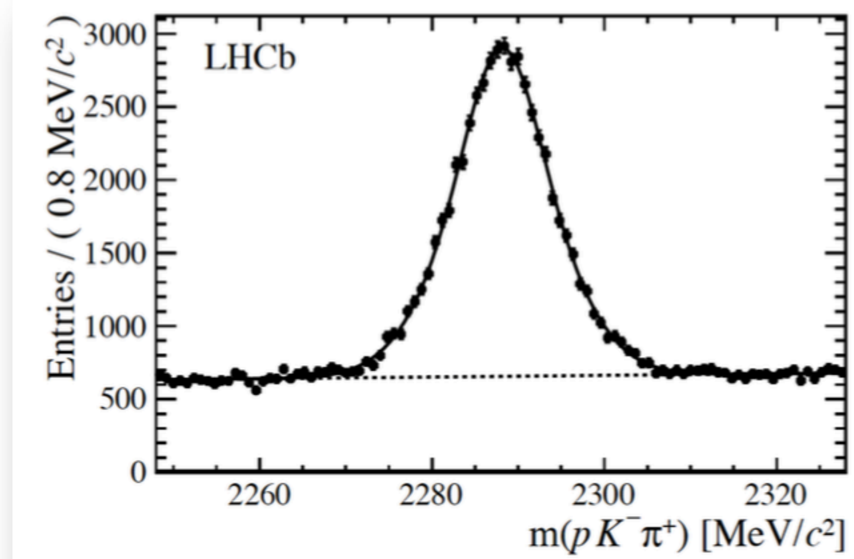
More efforts in the coming years

- 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
- Establishment of absolute BFs for Ξ_c and Ω_c decays at BELLE and LHCb ?

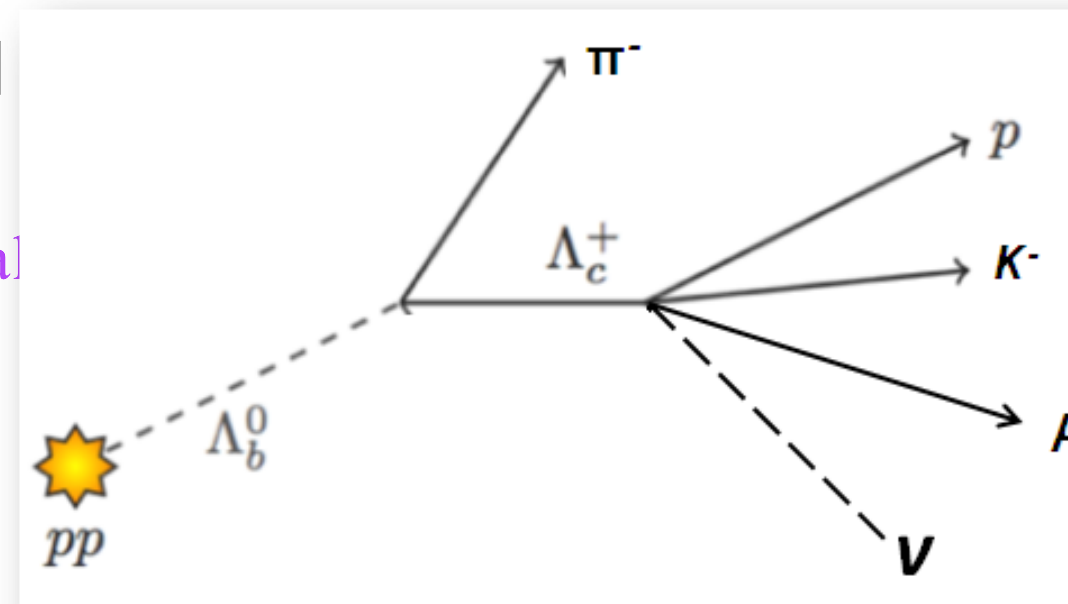
Many more outputs are expected in the coming future years.

Potentials @LHCb

- Huge Λc production at LHCb: ~100μb
- Prompt charm: using exclusive reconstruction
- Secondary charm from *b*-hadron decays with inclusive *b* triggers
- $\Lambda_c^+ \to pK^-\pi^+$ CF yields: 0.8M in 0.65/fb (~20% of Run I data)
- CS samples O(10^5) in Run I:
  BF measurement and CPV
- DCS $\Lambda_c^+ \to pK^+\pi^-$ can be measured with best precision
- Potential to set up the SL modes $pK^-\mu^+\nu$ and $p\pi^-\mu^+\nu$
  ➔ size of this BF is critical to understand the internal dynamics of Λc
- Search for CS SL mode: $p\pi^-\mu^+\nu$
- amplitude analysis of Λc➔$\Lambda\mu^+\nu$, to extract form factors
  ➔ input to theoretical calculation
- Rare decays: $p\mu^+\mu^-$, 3μ, $p\mu^+\mu^+$, …



30 pb^{-1} of $\Lambda_c^+ \to pK\pi$
~5% of the 2011 data sample
JHEP **1312** 90 (2013)



tag in secondary Λ_b/Σ_c decays

Summary

- In recent two years, experimental activities on Λ_c^+ are reviving, esp. at BESIII & Belle (& LHCb)
- Threshold data at BESIII opens a new door to direct measurements of the decays → **precise study of Λc decays**
  - BESIII has published several world-best results based on 567/pb data
  - More efforts on hadronic decays w/ $n/\Sigma/\Xi$ particles & semi-leptonic decays
  - Potential to take a larger data set for thorough exploration of Λ_c decays:
- LHCb/BELLE has large Λc yields → **large potential of best precisions**
  - Search for a second SL decay: $pK^- l^+\nu$, $p\pi^- l^+\nu$ …
  - Precise determination of phh' and DCS $pK^+\pi^-$ (and associate CPV)
  - Hadronic weak decay asymmetry and CPV test: $\Lambda\pi^+$, ΛK^+, $p\phi$
  - Rare decays: LFV, FCNC, …
- BESIII and B factories will be complementary in Λc decays and provide the precise measurements in the future several years.
- Research on absolute BFs for Ξ_c and Ω_c decays at BELLE and LHCb

Thank you!
谢谢！

BESIII negates many old predictions and stimulate new calculation on SL mode

BF's (%) of Λ_c^+ semileptonic decays

		$\Lambda_c^+ \to \Lambda^0 e^+ \nu_e$	$\Lambda_c^+ \to n e^+ \nu_e$
	Expt	**2.9±0.5 (PDG2015)** **3.63±0.43 (BESIII)** (-0.86±0.04)	
NRQM	Perez-Marcial et al. ('89)	3.0 (1.0) 2.2 (0.7)	
NRQM	Singleton ('91)	2.0	
NRQM	Cheng, Tseng ('96)	1.4	
RQM	Ivanov et al. ('97)	1.4 (-0.812)	0.26
LFQM	Luo ('98)	1.4	
QSR	Dosch et al. ('98)	3.0±0.9	
QSR	Marques de Carvalho et al.('99)	2.6±0.4 (-1)	
NRQM	Pervin et al. ('05)	4.1 (HONR) 4.7 (HOSR)	0.20 (HONR) 0.27 (HOSR)
QSR	Liu, Huang, Wang ('09)	3.0±0.3 (CZ) 2.0±0.3 (Ioffe)	
CQM	Gutsche et al. ('14)		0.20
CQM	Gutsche et al. ('16)	2.78	

α in parentheses

(..) with SU(6) spin-flavor suppression

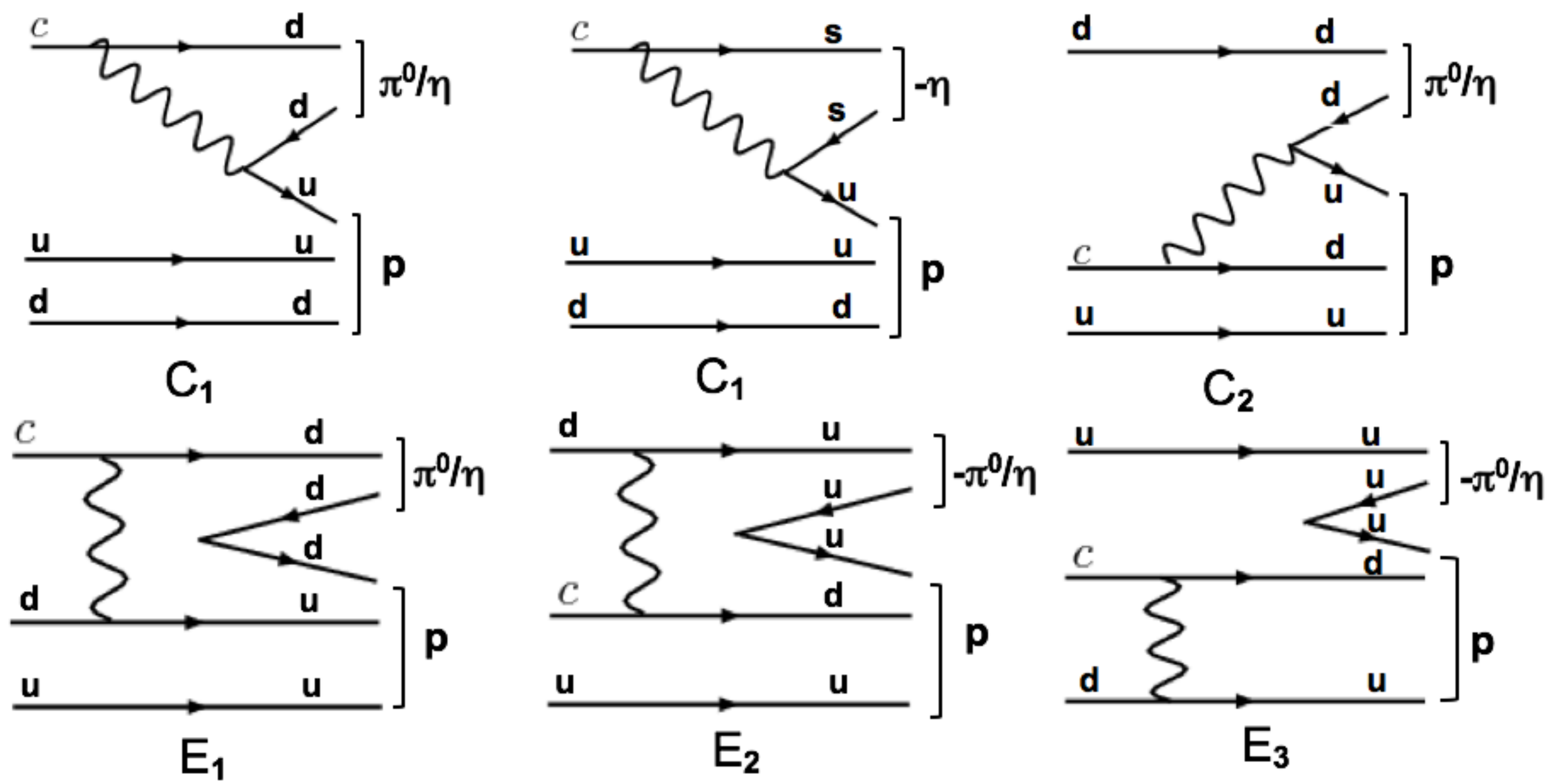
first absolute measurement of SL

Custody by H-Y Cheng

BESIII

$B(\Lambda_c^+ \to p\pi^0)$ 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 $= 19.5^0$

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

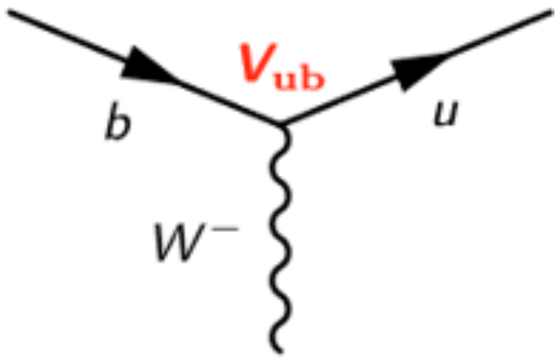
$A(\Lambda_c^+ \to p\eta) = (2C_1 + C_2 + E_1 + E_2 + E_3)/\sqrt{3}$

It is most likely that

$\Gamma(\Lambda_c^+ \to p\eta) >> \Gamma(\Lambda_c^+ \to p\pi^0)$ 30

Custody by H-Y Cheng

CKM matrix element V_{ub}



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

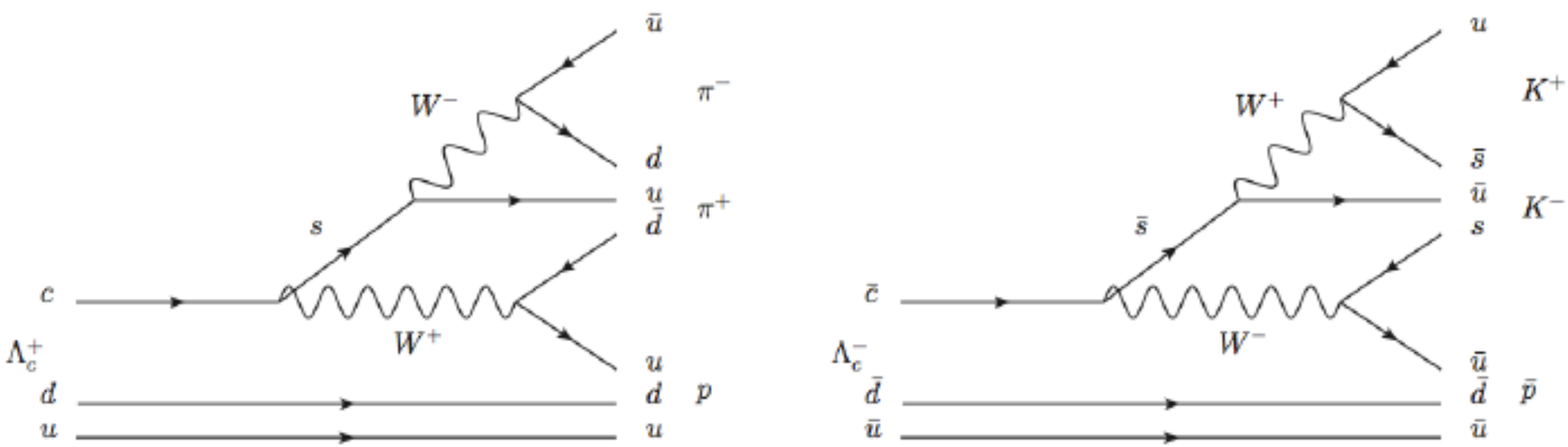
$$\underbrace{\frac{\mathcal{B}(\Lambda_b \to p\mu^-\nu_\mu)}{\mathcal{B}(\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu)}}_{\text{Measure this experimentally}} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \times \underbrace{\frac{G(\Lambda_b \to p\mu^-\nu_\mu)}{G(\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu)}}_{\text{Get this from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

Nature Physics 11 (2015) 743

Source	Relative uncertainty (%)
$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$	$^{+4.7}_{-5.3}$
Trigger	
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

CPV in CS and DCS processes



- Production and detector asymmetries mostly cancelled by taking difference:

$$\Delta A_{CP}^{\Lambda_c} = A_{Raw}^{\Lambda_c}(K) - A_{Raw}^{\Lambda_c}(\pi) \approx A_{CP}^{\Lambda_c}(K) - A_{CP}^{\Lambda_c}(\pi)$$

- In SCS modes should be close to zero in SM: $\mathcal{O}(10^{-4})$

- CPV in DCS - SM even smaller CP asymmetry than SCS - possible window to NP?
- Examine local assymetries in "Dalitz" plot, e.g. Miranda method (Phys.Rev.D80 (2009) 096006) - local asymmetries stronger than global.

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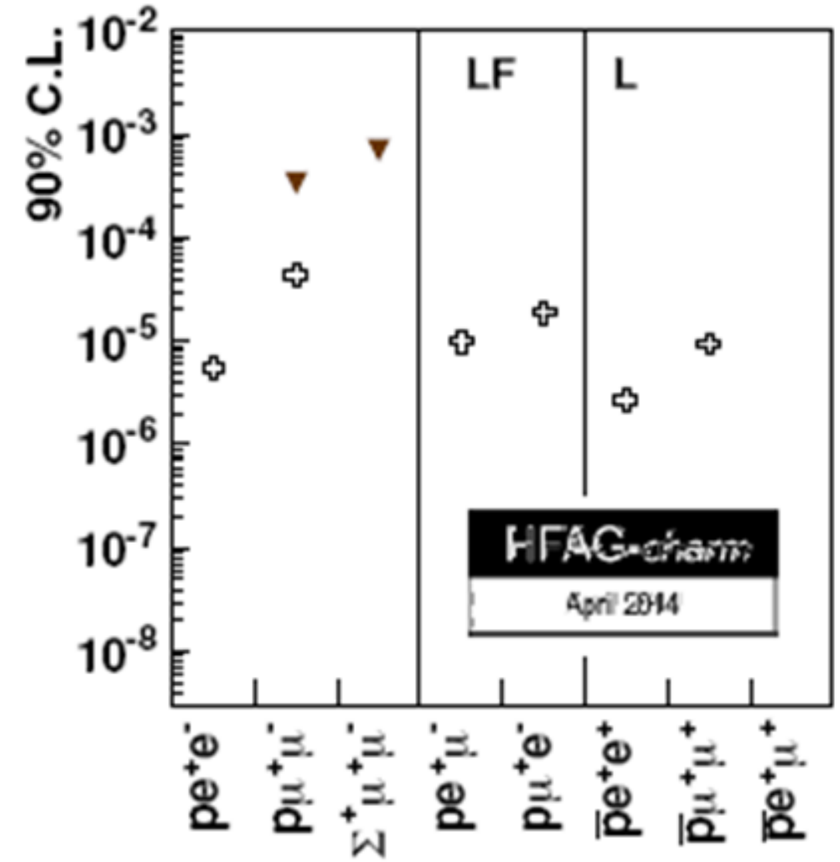
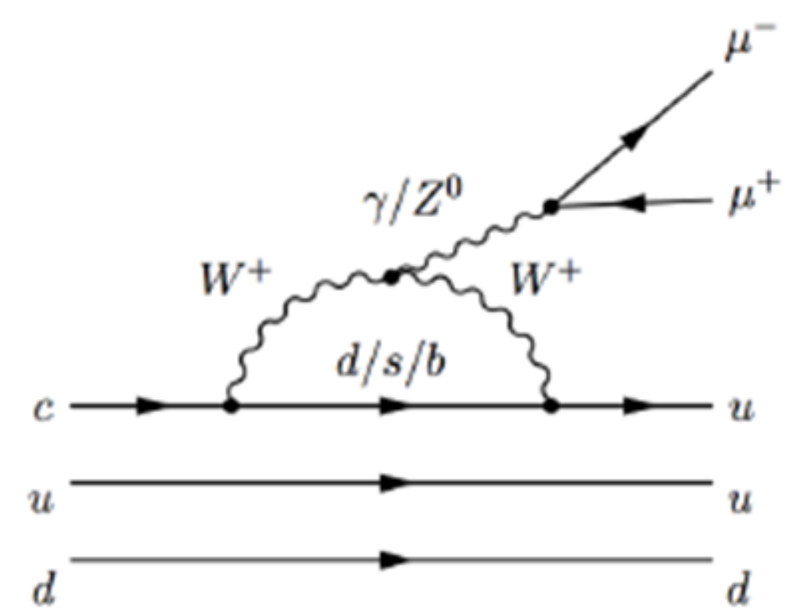
Rare decays

- LHCb published $\tau \to 3\mu$ and $\tau \to p\mu\mu$ searches Phys.Lett.B724(2013), JHEP 02 (2015) 121
- First direct experimental limits on $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^+\mu^-$
- Analogous channels for Λ_c:

$$\tau \to 3\mu \text{ (LFV)} \; : \Lambda_c \to 3\mu \; (|B-L| = 0)$$
$$\tau^+ \to p\mu^-\mu^+ \; (|B-L| = 0) \; : \Lambda_c^+ \to p\mu^-\mu^+ \text{ (FCNC)}$$
$$\tau^+ \to \bar{p}\mu^+\mu^+ \; (|B-L| = 0) \; : \Lambda_c^+ \to \bar{p}\mu^+\mu^+ \; (|B-L| = 0)$$



- Current limits at 90% CL:
  - $\mathcal{B}(\Lambda_c^+ \to p\mu^-\mu+) < 4.4 \times 10^{-5}$
    $\mathcal{B}(\Lambda_c^+ \to \bar{p}\mu^+\mu^+ < 9.4 \times 10^{-6}$
    Babar - Phys. Rev. D84 (2011) 072006
  - $\mathcal{B}(\Lambda_c^+ \to 3\mu)$ - no constraints.
- LHCb should probe $\Lambda_c^+ \to p\mu^-\mu^+$ to $\mathcal{O}(10^{-7})$ with current dataset.
- After Run II down to $\mathcal{O}(10^{-8})$



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