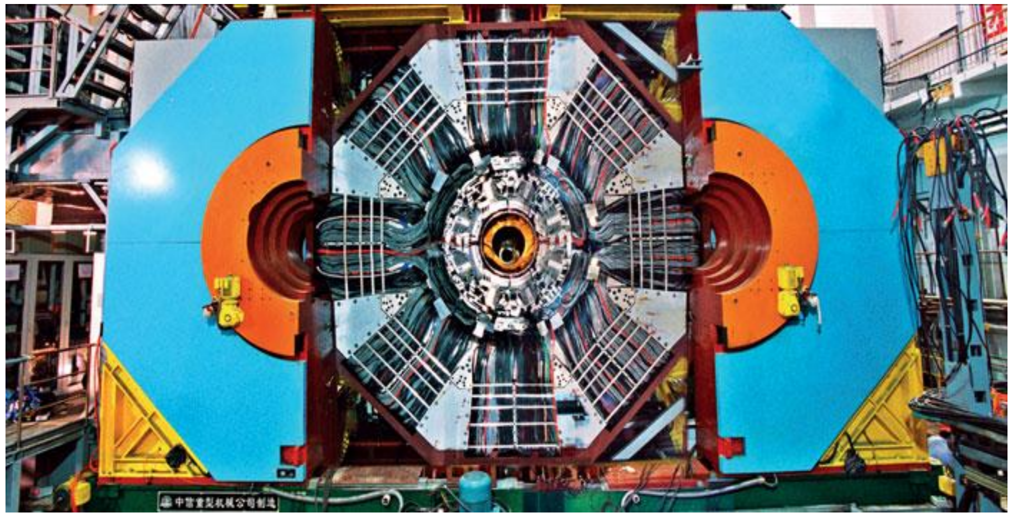
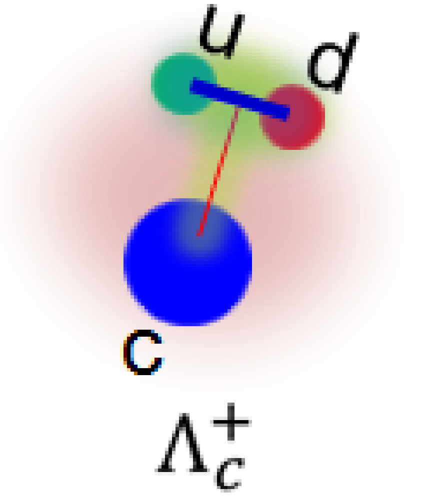
Physics achievements: Charmed baryon

Yangheng Zheng

for the Charmed baryon fans from

BIPT, IHEP, INFN/Frascati, LZU, NJU, SDU, UCAS, USTC…

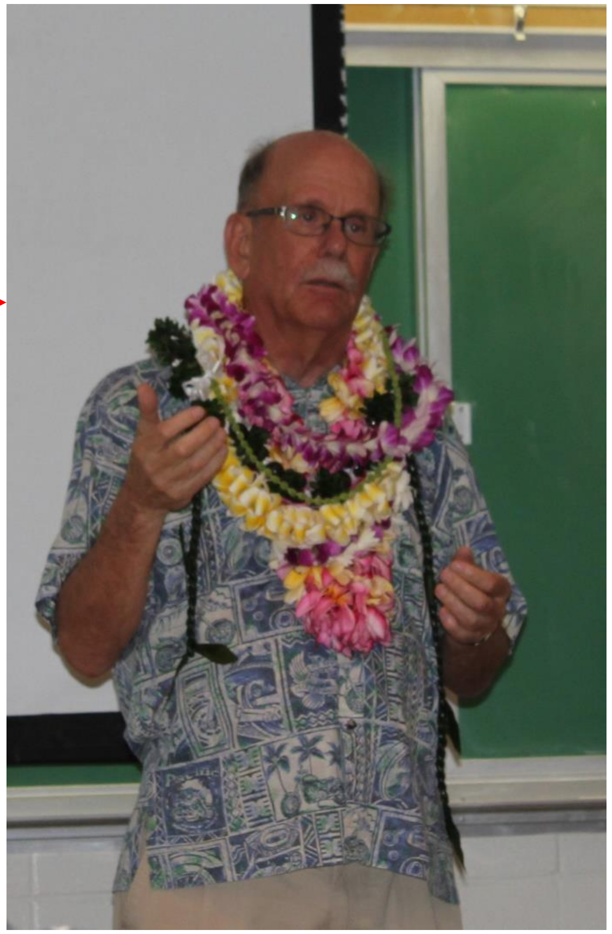




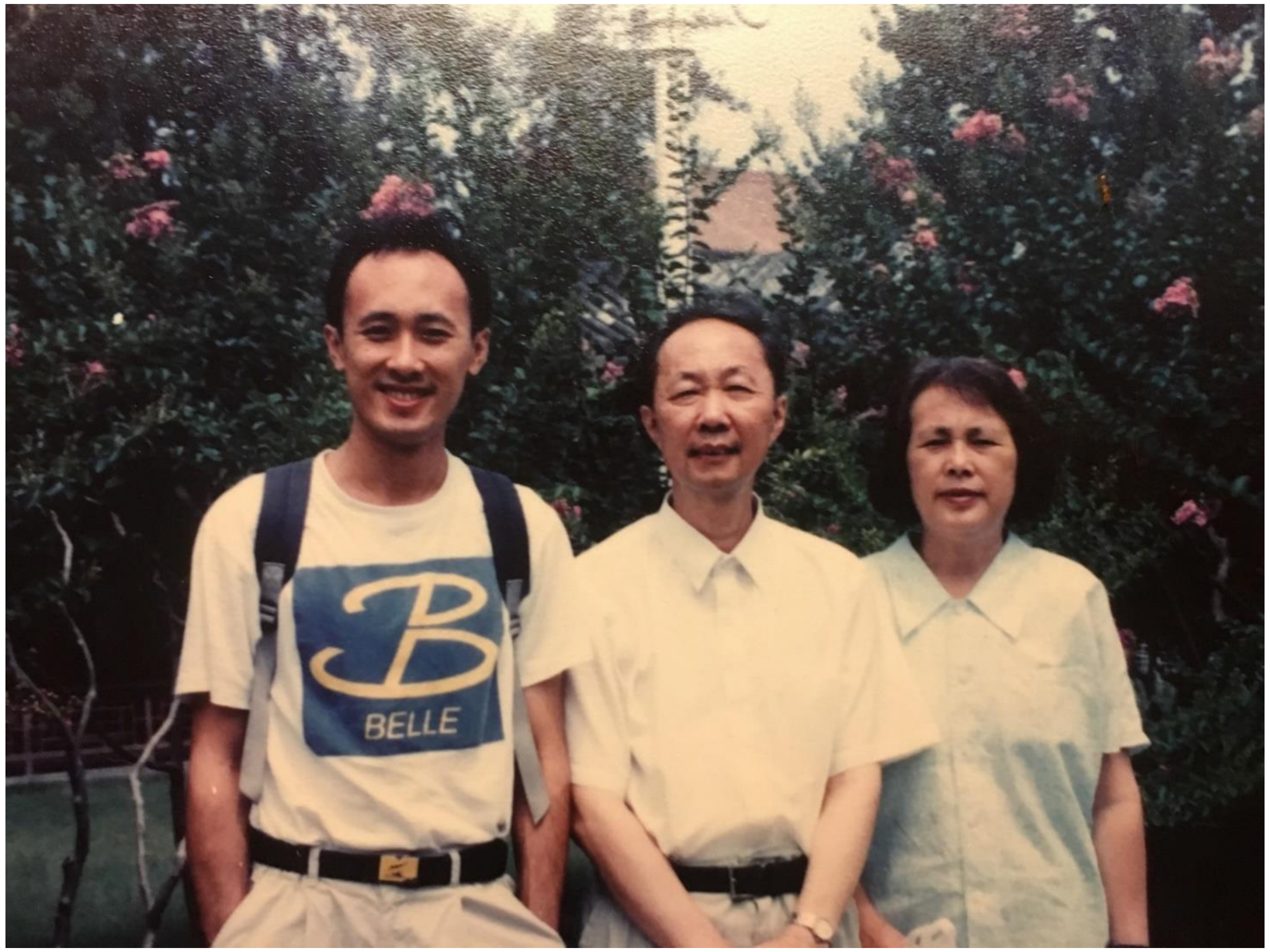
Symposium on 30 years of BES Physics, 6-Sep-2019, IHEP, Beijing

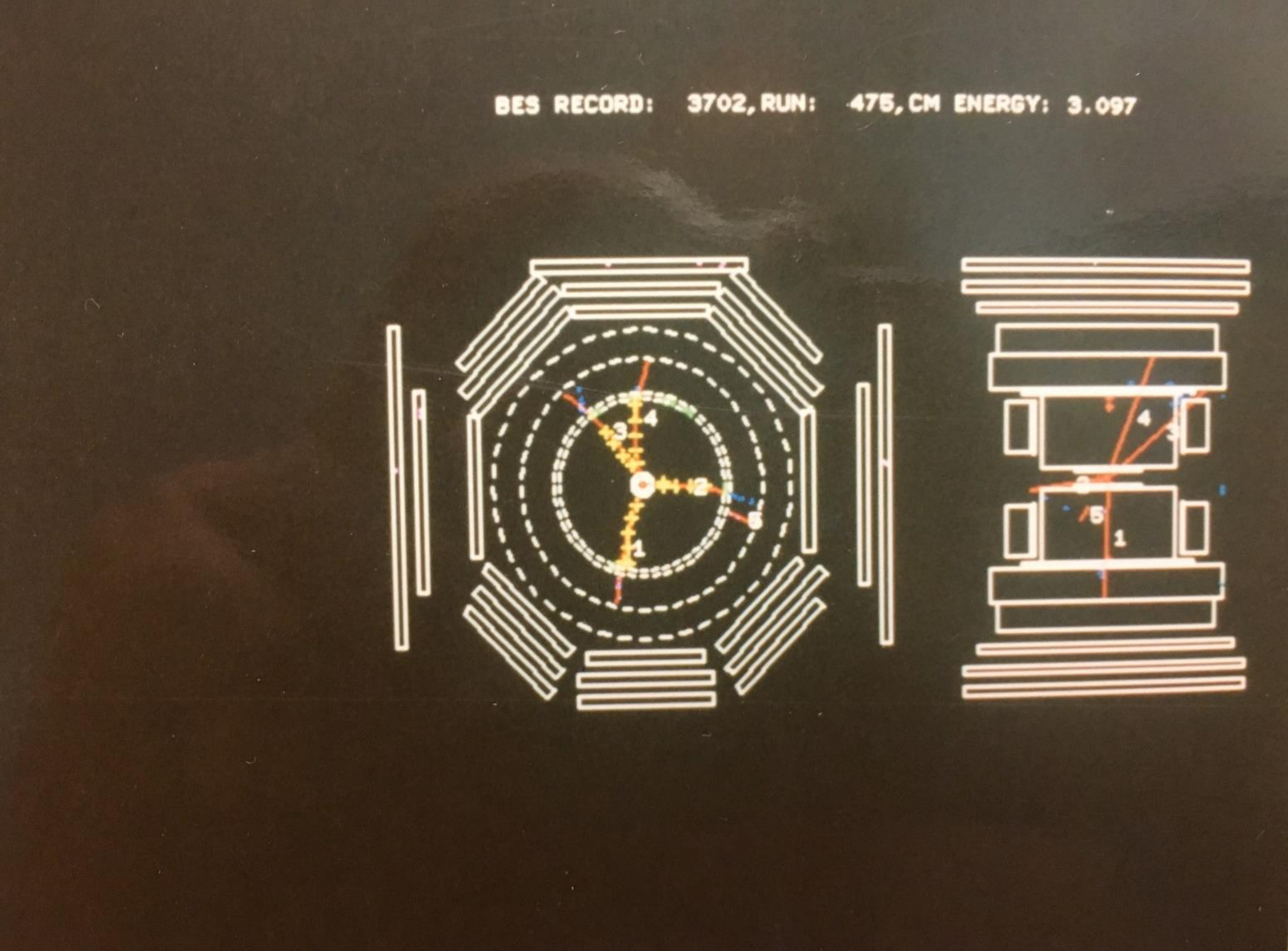
Few BES facts about me

- I grew up in the IHEP campus and I am still living in this campus.
- During BESII time, I was a UH-Belle student supervised by Steve Olsen.



- I met Prof. Joe Izen, Prof. Walter Toki in KEK, Japan
- I met a lot of Chinese BES members in Hawaii: Zhengguo, Xiaoyan, Yuanbo, Rongguang, Xiao, Benwei, Yunyong,
- My first contribution to BES: took shifts for drilling holes on MDCIII Endcap of BESII at Hawaii in 1999.




BES RECORD: 3702, RUN: 475, CM ENERGY: 3.097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Outline

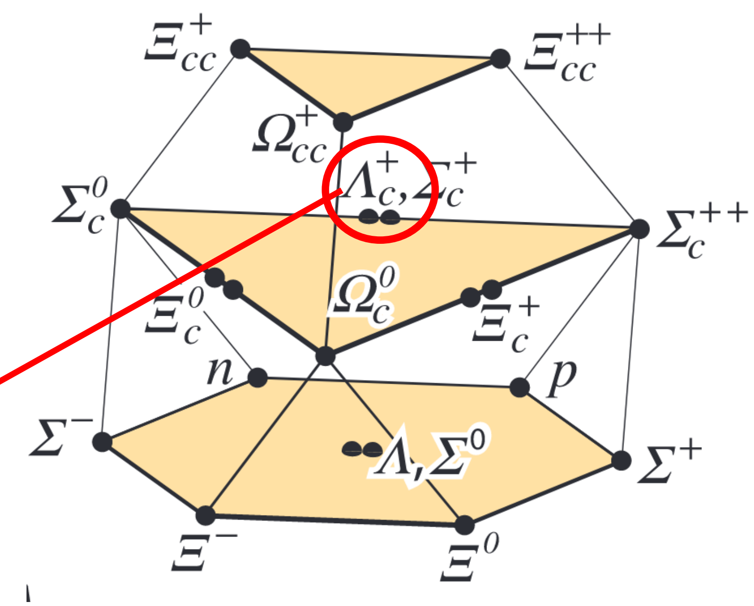
- Introduction
- Some highlight results on Λ_c decays at BESIII (567 pb^{-1} @4.6GeV)
- Data taking plan & Prospects
- Summary

Charm facilities

- Hadron colliders (huge cross-section ⇒ statistics overwhelming, energy boost)
  - Tevetron (CDF)
  - LHC (LHCb)
- e^+e^- Colliders (more kinematic constrains, clean environment, ~100% trigger efficiency)
  - B-factories (BaBar, Belle/Belle-II)
    - Energy boost for Charm hadrons
    - High luminosity + ISR
  - Threshold production (CLEOc, BESIII)
    - Only Charmed hadron pairs, no extra CM Energy for pions
    - Lots of systematic uncertainties cancellation while applying double tag technique ⇒ absolute BF (model independent)
    - Quantum Correlations (QC) and CP-tagging are unique

Introduction of Charmed Baryons

- Before BESIII, the charmed baryons (Λ_c^+, Σ_c, $\Xi_c^{(\prime)}$, Ω_c) have been produced and studied at many experiments (such as FOCUS, SELEX, ARGUS, CLEO, BABAR, and BELLE).
- Lightest charmed baryon Λ_c
  - First observed in Fermilab (PRL37, 882 (1976));confirmed by SLAC (PRL44, 10 (1980))
- Experimental status of Λ_c before 2014
  - Nearly all BFs are measured relative to $\Lambda_c^+ \to$ pKπ mode.
  - No model independent measurements of BF($\Lambda_c^+ \to$pKπ)
  - Large uncertainties in experiment $\Rightarrow$ Retarded development of theory



PDG2014

Λ_c^+ DECAY MODES

Nearly all branching fractions of the Λ_c^+ are measured relative to the $pK^-\pi^+$ mode, but there are no model-independent measurements of this branching fraction. We explain how we arrive at our value of B($\Lambda_c^+ \to pK^-\pi^+$) in a Note at the beginning of the branching-ratio measurements, below. When this branching fraction is eventually well determined, all the other branching fractions will slide up or down proportionally as the true value differs from the value we use here.

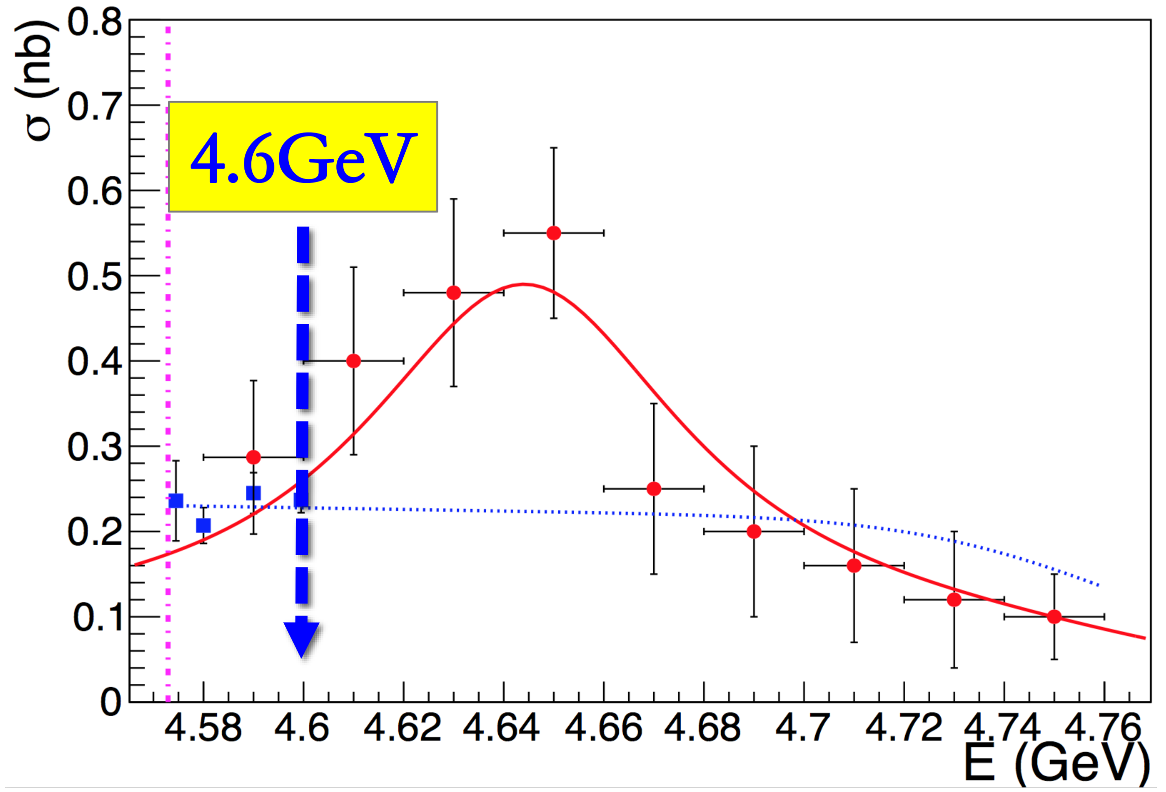
	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Hadronic modes with a p: $S = -1$ final states			
Γ_1	$p\overline{K}^0$		(2.3 ± 0.6) %	
Γ_2	$pK^-\pi^+$	[a]	(5.0 ± 1.3) %	
Γ_3	$p\overline{K}^*(892)^0$	[b]	(1.6 ± 0.5) %	
Γ_4	$\Delta(1232)^{++}K^-$		(8.6 ± 3.0) $\times 10^{-3}$	
Γ_5	$\Lambda(1520)\pi^+$	[b]	(1.8 ± 0.6) %	
Γ_6	$pK^-\pi^+$ nonresonant		(2.8 ± 0.8) %	

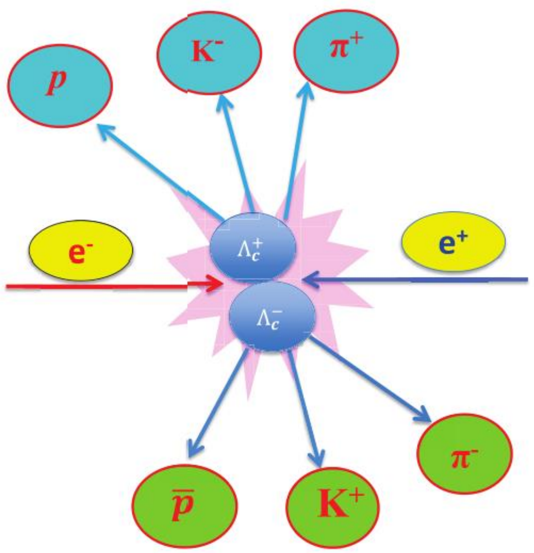
Renaissance on the charmed baryon

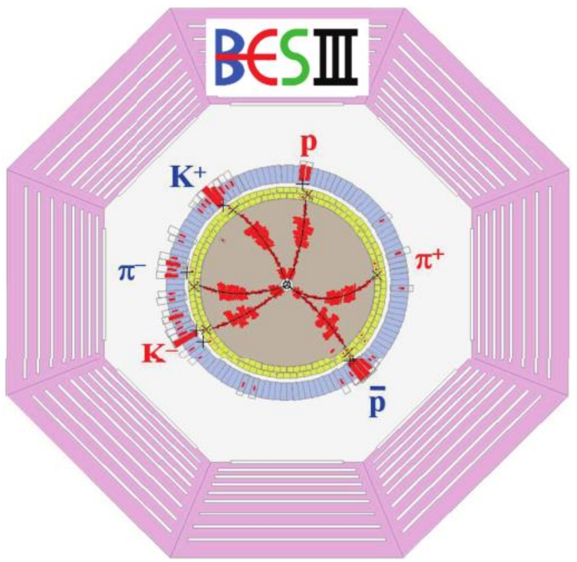
- After 2014, more extensive measurements on charmed baryons are performed at the BESIII, BELLE and LHCb
  - The absolute BF measurements at BESIII and BELLE
  - The observation of the DCS mode $\Lambda_c^+ \to pK^+\pi^-$ at BELLE
  - The observation of the cc-d baryon Ξ_{cc}^{++} at LHCb
  - New lifetime hierarchy of charmed baryons reported by LHCb
- These experimental progresses have revoked the activities in the theoretical efforts

BESIII data taking @ $\Lambda_c^+\bar{\Lambda}_c^-$ threshold

- In 2014, BESIII took data above $\Lambda_c^+\bar{\Lambda}_c^-$ pair threshold (**35 days: 567 pb^{-1}@4.6GeV**) with excellent performance!
- Measurement using the threshold pair-productions via e^+e^- annihilations is unique: the most simple and straightforward.
- ~106 × 10^3 $\Lambda_c^+\bar{\Lambda}_c^-$ pairs make sensitivity to 10^{-3}.
- First time to systematically study Λ_c at threshold.

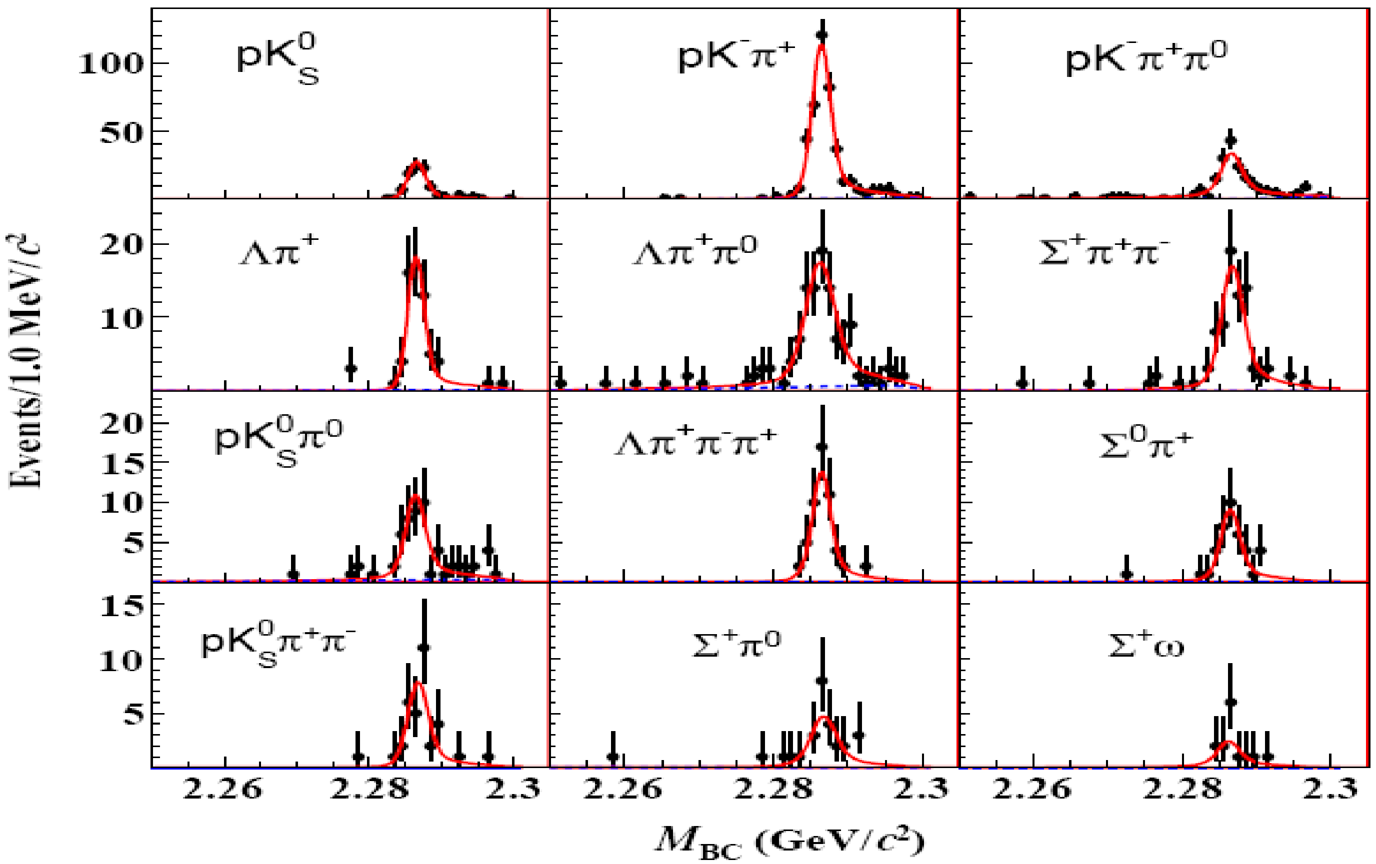






Absolute BFs of Λ_c^+ hadronic decays

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	

- **The absolute BF can be obtained by the ratio of double tag yields to single tag yields.**
- **A global least square fit to 12 hadronic modes**
- **First direct measurement on Λ_c BFs at threshold**
- ***BF*($pK^-\pi^+$): BESIII precision comparable with Belle's**
- **Improved precisions of the other 11 modes significantly**

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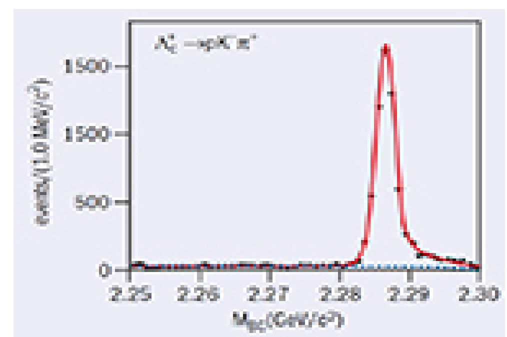
Mar 18, 2016

BESIII makes first direct measurement of the Λ_c at threshold

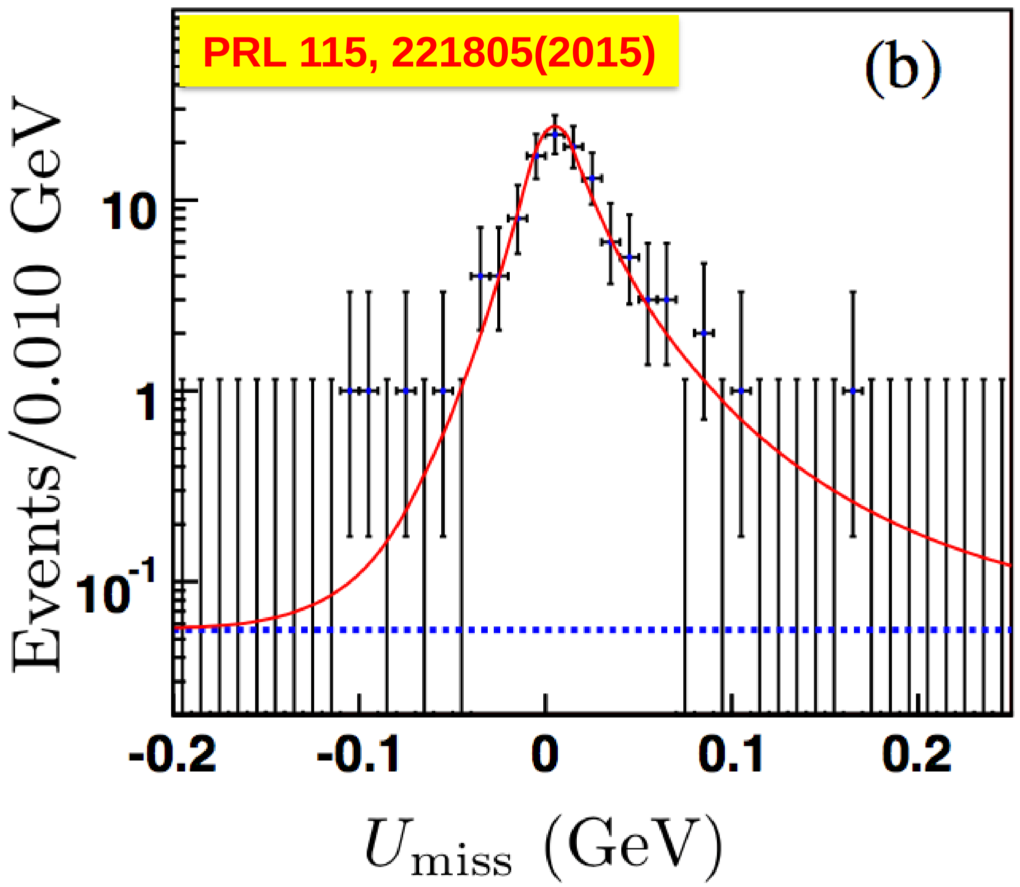


Beam-constrained mass distribution

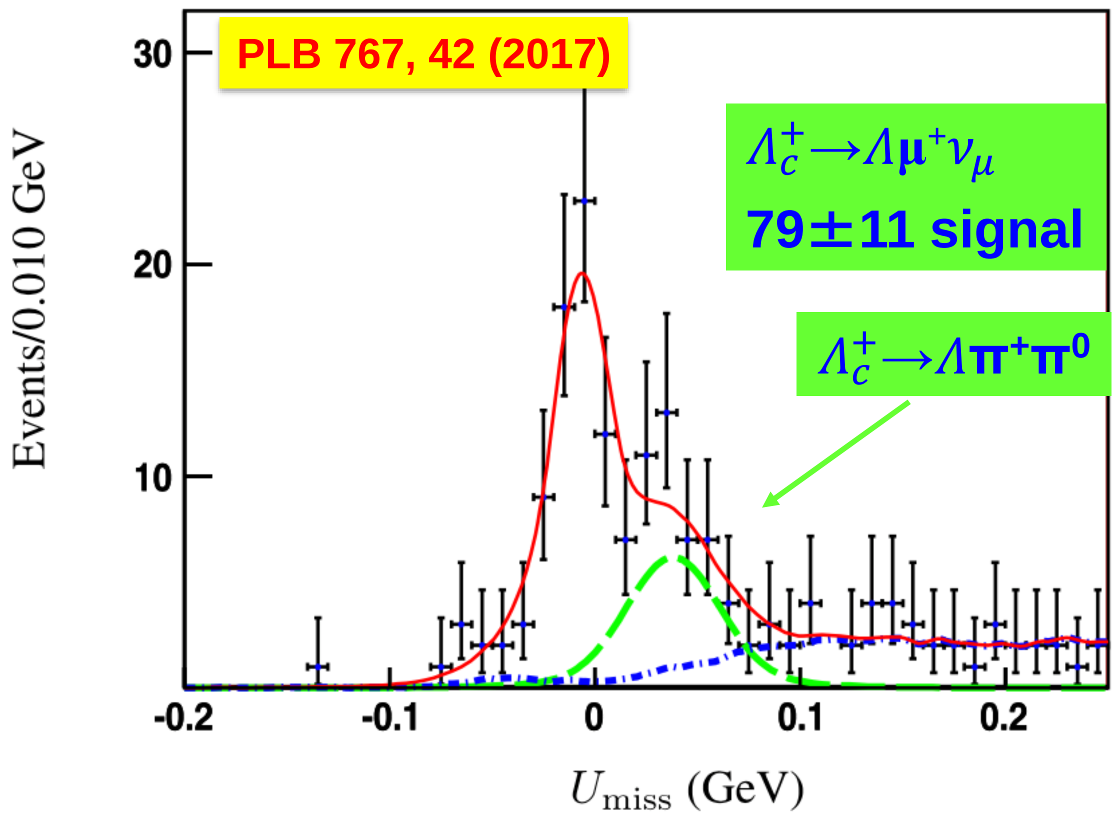
The charmed baryon, Λ_c, was first observed at Fermilab in 1976. Now, 40 years later, the Beijing Spectrometer (BESIII) experiment at the Beijing Electron-Positron Collider II (BEPCII) has measured the absolute branching fraction of $\Lambda^+_c \rightarrow pK^-\pi^+$ at threshold for the first time.

Because the decays of the Λ^+_c to hadrons proceed only through the weak interaction, their branching fractions are key probes for understanding weak interactions inside of a baryon. In particular, precise measurements of the decays of the Λ^+_c will provide important information on the final-state strong interaction in the charm sector, thereby improving the understanding of quantum chromodynamics in the non-perturbative energy region. In addition, because most of the

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



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



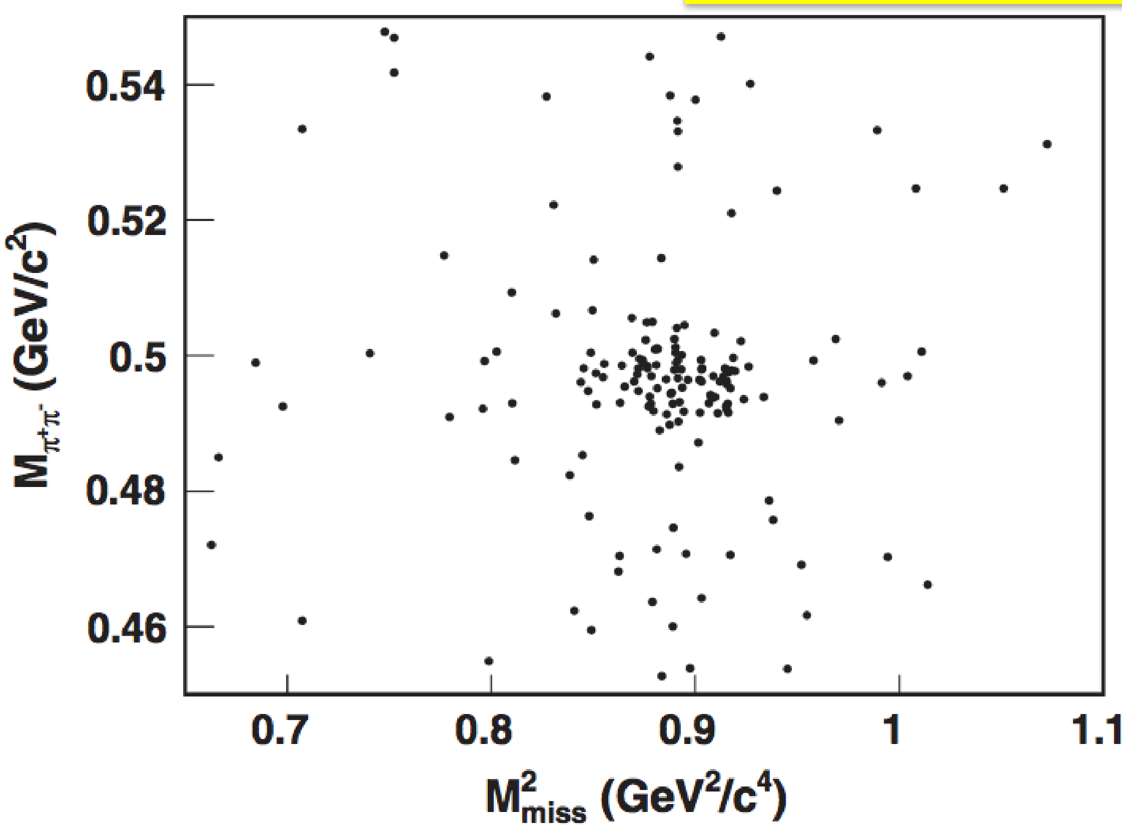
B[$\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu$]=(3.49±0.46±0.27)%

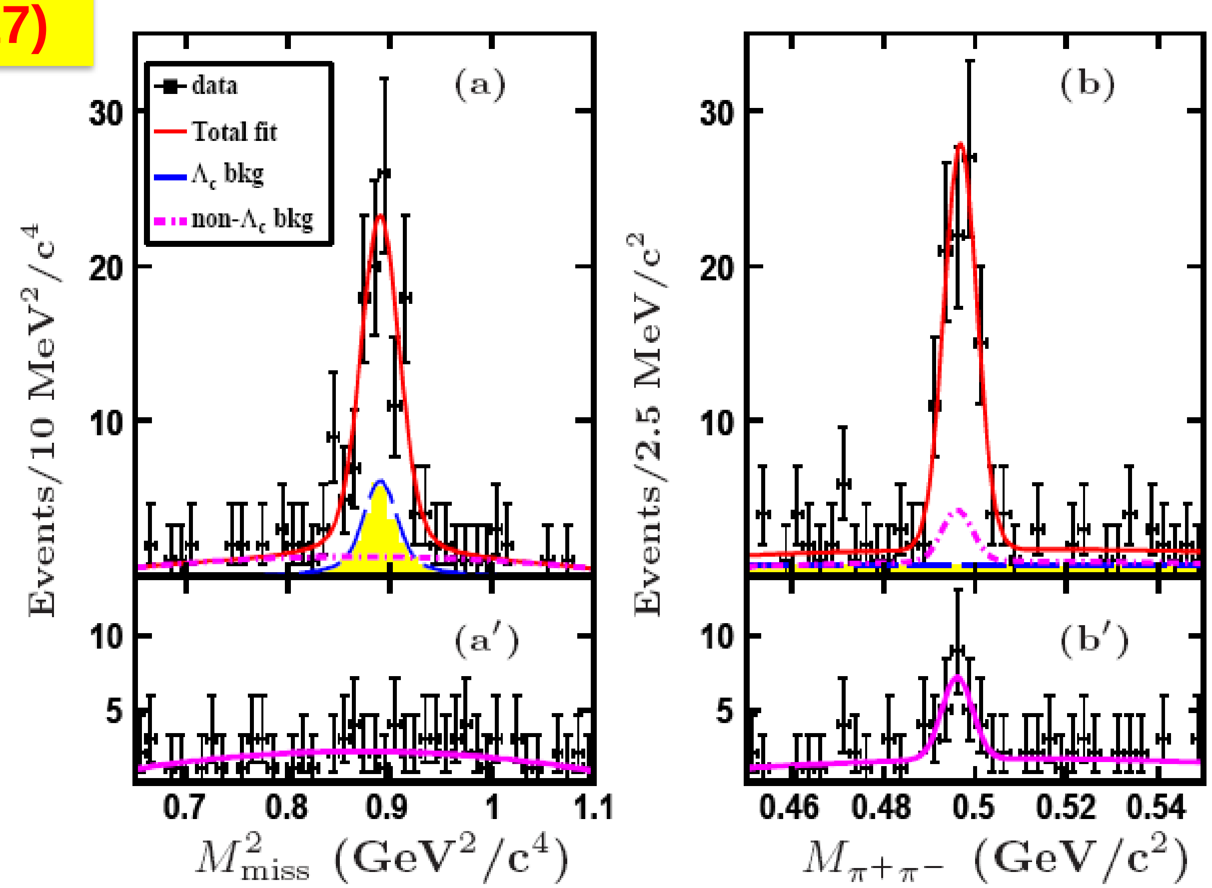
- **First absolute measurement of the semi-leptonic decay (Statistics limited)**
- **Important input for implementing and calibrating the Lattice QCD calculations**
- **Best precision to date: twofold improvement**
- $\Gamma[\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu]/\Gamma[\Lambda_c^+ \to \Lambda e^+ \nu_e]$= 0.96±0.16±0.04 ⇒ **compatible with unity**

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

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

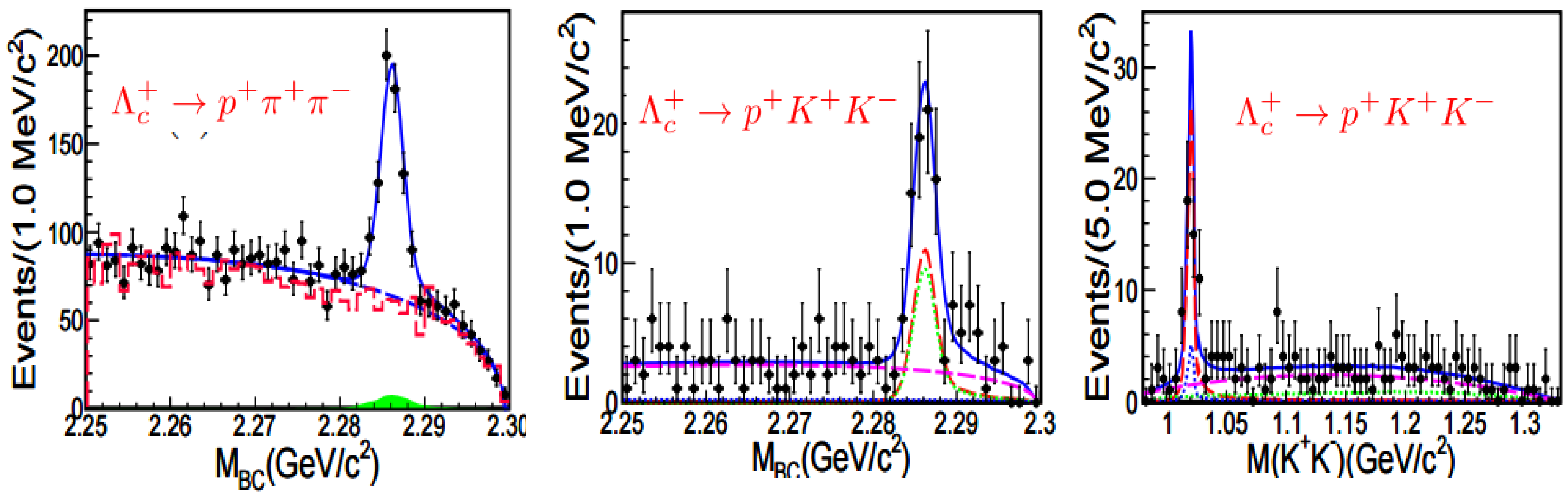
PRL,118,112001(2017)

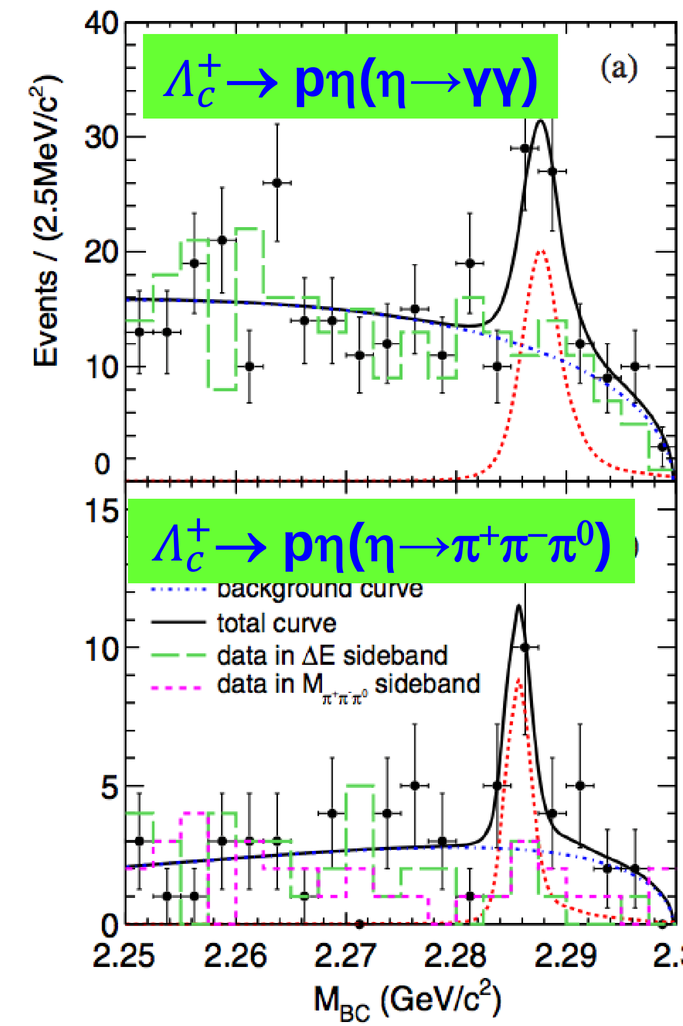




- Peaking background from $\Lambda_c^+ \rightarrow \Sigma^+ (\rightarrow n\pi^+)\ \pi^+\pi^-$
- 2-D fitting extract 83 ± 11 net signals => $B[\Lambda_c^+ \rightarrow nK_s^0\pi^+] = (1.82 \pm 0.23 \pm 0.11)\%$
- $B[\Lambda_c^+ \rightarrow nK^0\pi^+]/B[\Lambda_c^+ \rightarrow pK^-\pi^+] = 0.62 \pm 0.09$; $B[\Lambda_c^+ \rightarrow nK^0\pi^+]/B[\Lambda_c^+ \rightarrow pK^0\pi^0] = 0.97 \pm 0.16$
- A test of final state interactions and isospin symmetry in the charmed baryon sector. [PRD93, 056008 (2016)]

Singly Cabibbo-Suppressed Decays





Decay modes	$\mathcal{B}_{\text{mode}}/\mathcal{B}_{\text{ref}}$ (This work)	$\mathcal{B}_{\text{mode}}/\mathcal{B}_{\text{ref}}$ (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)	$(9.36 \pm 2.22 \pm 0.71) \times 10^{-3}$	$(7 \pm 2 \pm 2) \times 10^{-3}$
–	$\mathcal{B}_{\text{mode}}$ (This work)	$\mathcal{B}_{\text{mode}}$ (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)	$(5.47 \pm 1.30 \pm 0.41 \pm 0.33) \times 10^{-4}$	$(3.5 \pm 1.7) \times 10^{-4}$

- **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 Color-suppressed tree diagrams**
- **First evidence for $\Lambda_c^+\to p\eta$ with 4.2σ**

BF precisions improved significantly

PDG2014

$\Gamma(p\overline{K}^0\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_7/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.66±0.05±0.07	774	ALAM	98	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(p\overline{K}^0\eta)/\Gamma(pK^-\pi^+)$ — Γ_8/Γ_2

Unseen decay modes of the η are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.25±0.04±0.04	57	AMMAR	95	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(p\overline{K}^0\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_9/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.51±0.06 OUR AVERAGE					
0.52±0.04±0.05	985	ALAM	98	CLE2	$e^+e^- \approx \Upsilon(4S)$
0.43±0.12±0.04	83	AVERY	91	CLEO	e^+e^- 10.5 GeV
0.98±0.36±0.08	12	BARLAG	90D	NA32	π^- 230 GeV

$\Gamma(pK^-\pi^+\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_{10}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.67±0.04±0.11	2606	ALAM	98	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(pK^*(892)^-\pi^+)/\Gamma(p\overline{K}^0\pi^+\pi^-)$ — Γ_{11}/Γ_9

Unseen decay modes of the $K^*(892)^-$ are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.44±0.14	17	ALEEV	94	BIS2	nN 20–70 GeV

$\Gamma(p(K^-\pi^+)_{\text{nonresonant}}\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_{12}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.73±0.12±0.05	67	BOZEK	93	NA32	π^- Cu 230 GeV

PDG2019

$\Gamma(pK^0_S\pi^0)/\Gamma_{\text{total}}$ — Γ_7/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.96±0.13 OUR FIT	Error includes scale factor of 1.1.				
1.87±0.13±0.05	558	ABLIKIM	16	BES3	$e^+e^- \to \Lambda_c\overline{\Lambda}_c$, 4.599 GeV

$\Gamma(pK^0_S\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_7/Γ_2

Measurements given as a $\overline{K}^0$ ratio have been divided by 2 to convert to a K^0_S ratio.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.314±0.018 OUR FIT					
0.33 ±0.03 ±0.04	774	ALAM	98	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(nK^0_S\pi^+)/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.82±0.23±0.11	83	ABLIKIM	17H	BES3	e^+e^- at 4.6 GeV

$\Gamma(p\overline{K}^0\eta)/\Gamma(pK^-\pi^+)$ — Γ_9/Γ_2

Unseen decay modes of the η are included.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.25±0.04±0.04	57	AMMAR	95	CLE2	$e^+e^- \approx \Upsilon(4S)$

$\Gamma(pK^0_S\pi^+\pi^-)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.59±0.12 OUR FIT	Error includes scale factor of 1.2.				
1.53±0.11±0.09	485	ABLIKIM	16	BES3	$e^+e^- \to \Lambda_c\overline{\Lambda}_c$, 4.599 GeV

$\Gamma(pK^0_S\pi^+\pi^-)/\Gamma(pK^-\pi^+)$ — Γ_{10}/Γ_2

Measurements given as a $\overline{K}^0$ ratio have been divided by 2 to convert to a K^0_S ratio.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.255±0.015 OUR FIT	Error includes scale factor of 1.1.				
0.257±0.031 OUR AVERAGE					
0.26 ±0.02 ±0.03	985	ALAM	98	CLE2	$e^+e^- \approx \Upsilon(4S)$
0.22 ±0.06 ±0.02	83	AVERY	91	CLEO	e^+e^- 10.5 GeV
0.49 ±0.18 ±0.04	12	BARLAG	90D	NA32	π^- 230 GeV

$\Gamma(pK^-\pi^+\pi^0)/\Gamma_{\text{total}}$ — Γ_{11}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
4.42±0.31 OUR FIT	Error includes scale factor of 1.5.				
4.53±0.23±0.30	1849	ABLIKIM	16	BES3	$e^+e^- \to \Lambda_c\overline{\Lambda}_c$, 4.599 GeV

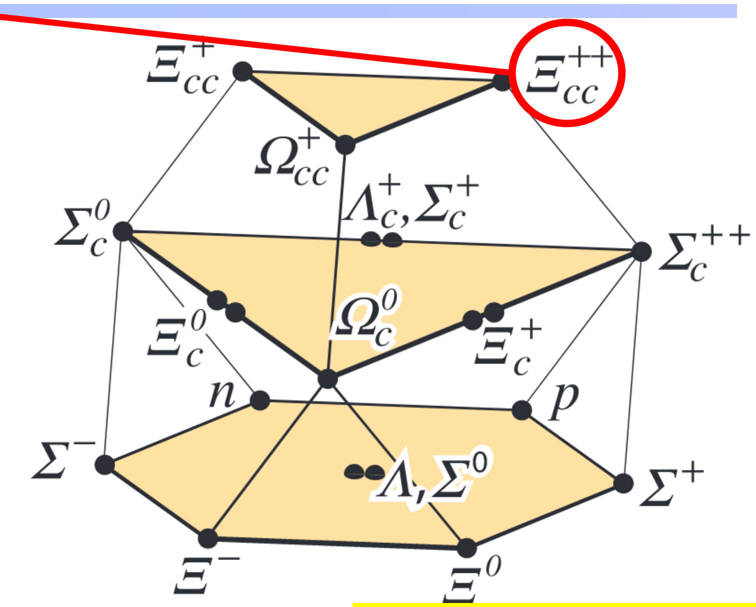
$\Gamma(pK^-\pi^+\pi^0)/\Gamma(pK^-\pi^+)$ — Γ_{11}/Γ_2

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT

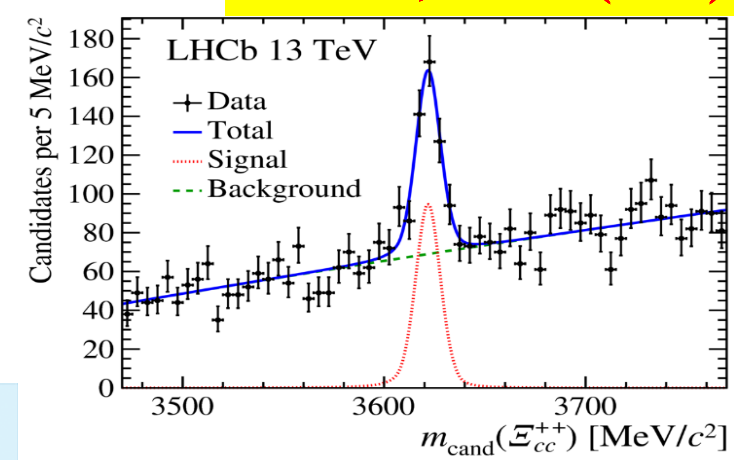
- BFs of many Λ_c decays: improved significantly
- BF($\Lambda_c^+ \to pK\pi$): model dependent ⇒ model independent
- New decay channels observed: i.e. Λ_c^+ decay involving the neutron in the final state; more SCS decays

Contributions to Ξ_{cc}^{++} observation

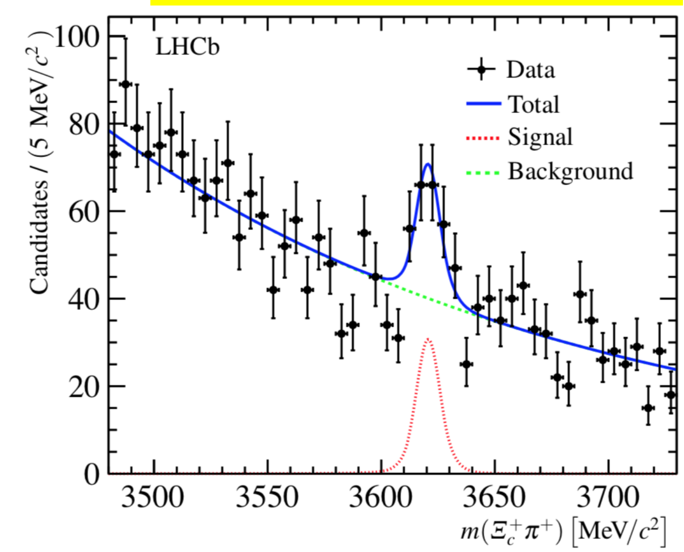
- **LHCb observed Ξ_{cc}^{++} from $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$ decays**
- **Credits from theorists**
  - $\tau(\Xi_{cc}^{++}) \approx 3\,\tau(\Xi_{cc}^{+})$ **(Chang, Li, Wang, Karliner, et al.)**
  - **"Discovery channels of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$ was predicted: benefited from BESIII Λ_c^+ measurements " (Yu, Lu, Wang, Li et al, '17)**



PRL 119, 112001 (2017)



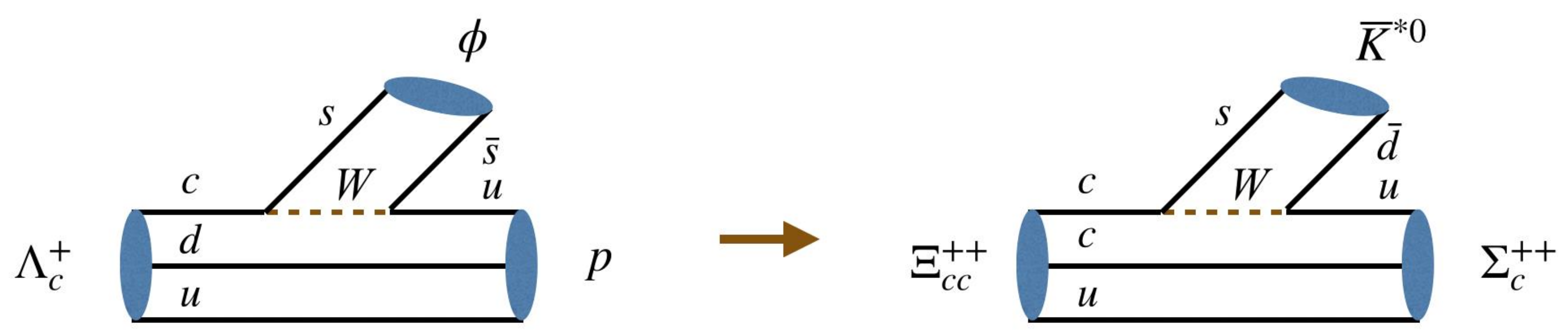
PRL 121, 162002 (2018)



A theoretical Frame for Charmed hadrons

- **Topological diagrams + Symmetries + Experimental inputs $\Rightarrow$ to understand the decaying dynamics, predicting double-charm baryon decays, CPV, etc. (predictive power)**
  - Λ_c^+ **branching fractions used for global analysis**

  $\Rightarrow$ $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ **and** $\Xi_c^+ \pi^+$ **are large enough for observation.**



$Br(\Lambda_c^+ \to p\phi)/|V_{us}|^2$ = 2 % $\rightarrow$ $Br\left(\Xi_{cc}^{++} \to \Sigma_c^{++}\overline{K}^{*0}\right)$ = O(%)

$\downarrow$

$\Xi_{cc}^{++} \to \Lambda_c^+ \pi^+ K^- \pi^+$

Large enough for observation

Λ_c^+ BFs from BESIII $\Rightarrow$ Stronger predictive power

Physics outputs on the Λ_c^+

- **35 days data taking $\Rightarrow$ Published 17 papers (7 PRLs)**
- **This is just a beginning; more will be coming.**

Hadronic decay

$\Lambda_c^+ \to pK^-\pi^+$ + 11 CF hadronic modes	PRL 116, 052001 (2016)
$\Lambda_c^+ \to pK^+K^-$, $p\pi^+\pi^-$	PRL 117, 232002 (2016)
$\Lambda_c^+ \to nK_S\pi^+$	PRL 118, 12001 (2017)
$\Lambda_c^+ \to p\eta$, $p\pi^0$	PRD 95, 111102(R) (2017)
$\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$	PLB 772, 388 (2017)
$\Lambda_c^+ \to \Xi^{0(*)}K^+$	PLB783, 200 (2018)
$\Lambda_c^+ \to \Lambda\eta\pi^+$	PRD99, 032010 (2019)
Λ	CPC43, 083002 (2019)

Sen

New gateway to charmed baryon for BESIII

One of the highlight BESIII results!

$\Lambda_c^+ \to \Lambda e^+\nu_e$	
$\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$	PLB 767, 42 (2017)

Inclusive decay

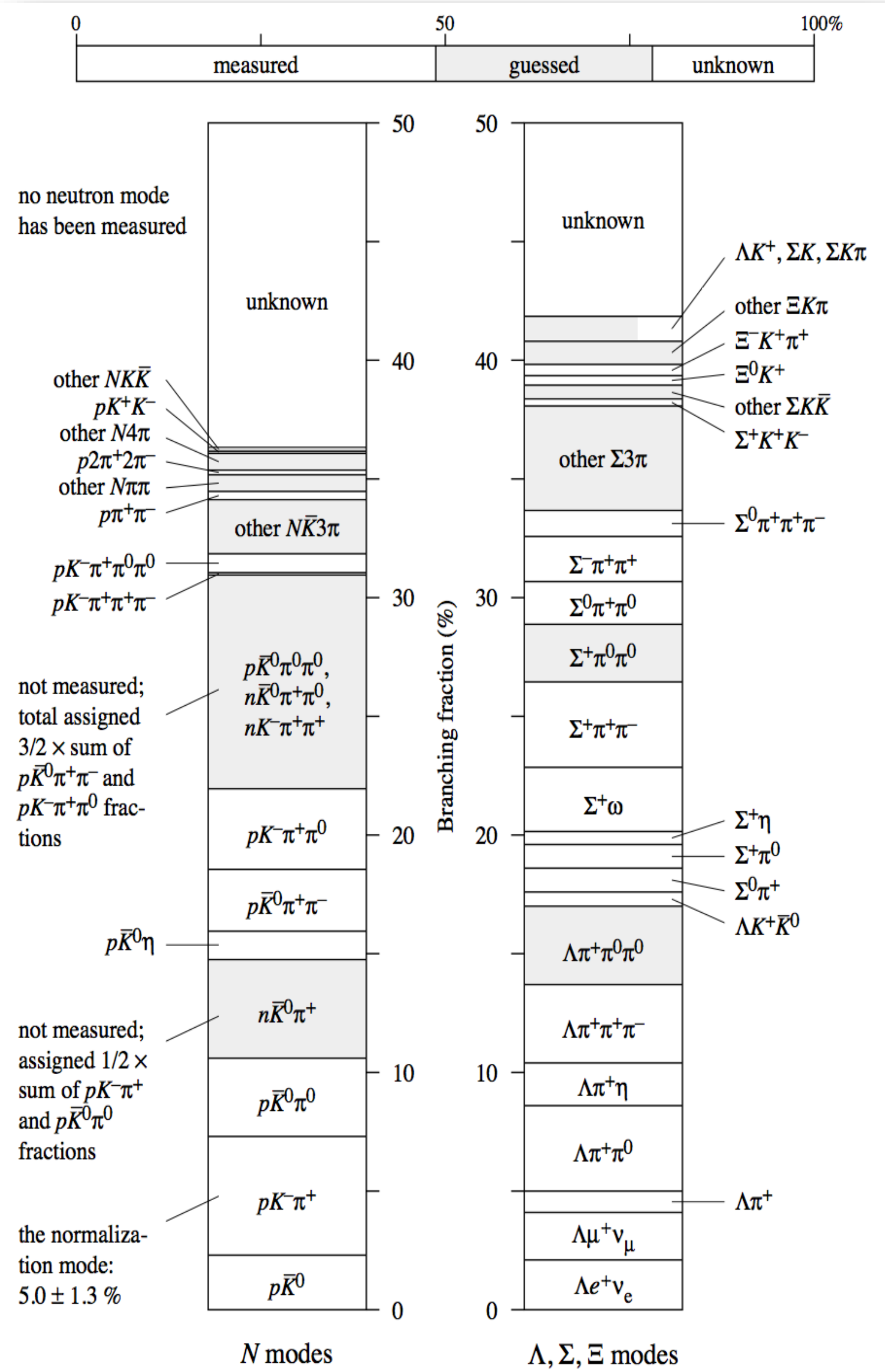
$\Lambda_c^+ \to \Lambda X$	PRL121, 062003 (2018)
$\Lambda_c^+ \to e^+X$	PRL 121 251801(2018)

Production

$\Lambda_c^+\bar{\Lambda}_c^-$ cross section	PRL 120,132001(2018)

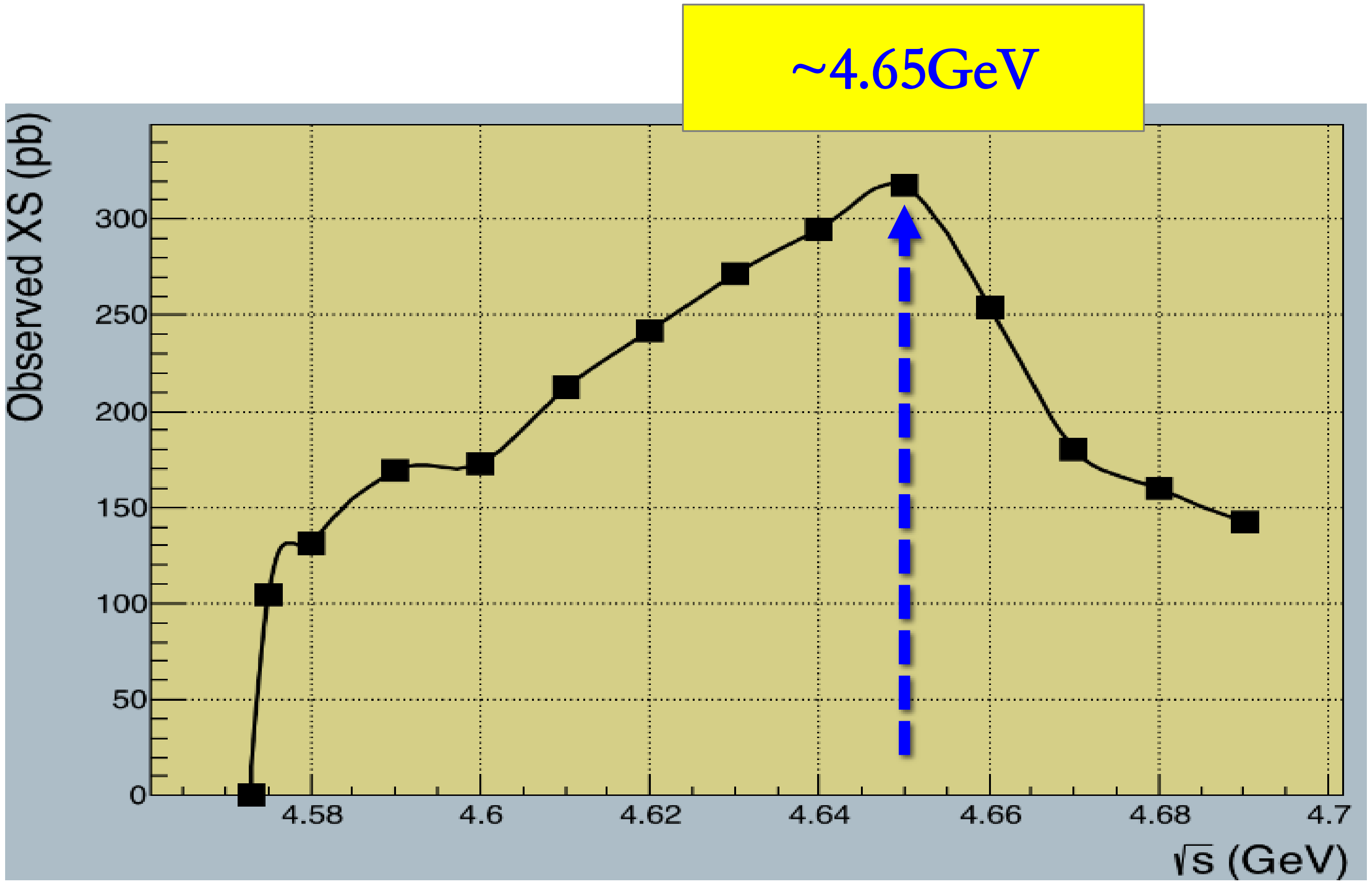
Yet unknowns

- Many of the following modes are not measured (~40%)
  - most of the semileptonic (SL) modes
  - the singly Cabibbo-Suppressed (CS) and doubly CS hadronic modes
  - the neutron- and K_L-involved channels
- Amplitude analysis of the three- and four-body decays
  - important to study the excited hyperons
  - to study the decay types of $B\left(\frac{1}{2}^{+}\right)V$ and $B(\frac{3}{2}^{+})P$
  - not much have been done yet



Approved data taking between 4.6~4.7 GeV in 2020

- We will accumulate at least 10~20x more Λ_c pairs (1~2 M)
- Irreplaceable sample to systematically refresh the whole Λ_c knowledge and impact relevant theoretical and experimental studies



BEPCII beam energy upgrade

- **Two steps of maximum beam energy (BE) upgrade**
  - **Step 1: upgrade on the power cooling system in the summer of 2018**
    $\Rightarrow$ BE up to 4.7 GeV
    (Done! Many thanks to BEPCII team!)
  - **Step 2: R&D of a new ISPB magnet by 2020**
    $\Rightarrow$ BE up to 4.9 GeV $\Rightarrow e^+e^- \to \Lambda_c^+\bar{\Sigma}_c^-$ at 4.74 GeV (or $\Sigma_c^+\bar{\Sigma}_c^-$ around 4.91 GeV?)

Abundant topics with more data

- **Precise studies of the Λ_c^+ decays**
  precision test on the strong and weak interactions
  - **BFs of CF modes: Stat. Err. < Sys. Err.**
  - **to explore as-yet-unmeasured channels**
    - **most of Cabibbo-suppressed (CS) modes are not measured both in semi-leptonic and hadronic decays**
  - **to understand full picture of intermediate structures (sufficient for PWA: exotics, Hyperons…)**
  - **to study weak radiative decay $\Lambda_c^+ \to \gamma\Sigma^+$:$10^{-4}$ ~10^{-5}**
  - **to search for rare decays:**
    FCNC $\Lambda_c^+ \to p l^+ l^-$: 10^{-5} ~ 10^{-6}; LNV $\Lambda_c^+ \to pe\mu$: 10^{-5} ~ 10^{-6}
- **Form factors and polarization of the Λ_c^+**
  - **Improved measurement on this unique channel to understand dynamics near threshold**

Impacts on Λ_c decay data

D_s^+ BRANCHING RATIOS

A number of older, now obsolete results have been omitted. They may be found in earlier editions.

Inclusive modes

$\Gamma(e^+ \text{semileptonic})/\Gamma_{total}$ Γ_1/Γ

This is the purely e^+ semileptonic branching fraction: the e^+ fraction from τ^+ decays has been subtracted off. The sum of our (non-τ) exclusive fractions — an $e^+\nu_e$ with an η, η', ϕ, K^0, or K^{*0} — is 5.99 ± 0.31 %.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
6.52±0.39±0.15	536 ± 29	[1] ASNER	10	CLEO	e^+e^- at 3774 MeV

[1] Using the D_s^+ and D^0 lifetimes, ASNER 10 finds that the ratio of the D_s^+ and D^0 semileptonic widths is 0.828 ± 0.051 ± 0.025.

$\Gamma(\pi^+ \text{anything})/\Gamma_{total}$ Γ_2/Γ

Events with two π^+'s count twice, etc. But π^+'s from $K_S^0 \to \pi^+\pi^-$ are not included.

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
119.3±1.2±0.7	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(\pi^- \text{anything})/\Gamma_{total}$ Γ_3/Γ

Events with two π^-'s count twice, etc. But π^-'s from $K_S^0 \to \pi^+\pi^-$ are not included.

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
43.2±0.9±0.3	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(\pi^0 \text{ anything})/\Gamma_{total}$ Γ_4/Γ

Events with two π^0's count twice, etc. But π^0's from $K_S^0 \to \pi^0\pi^0$ are not included.

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
123.4±3.8±5.3	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(K^- \text{anything})/\Gamma_{total}$ Γ_5/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
18.7±0.5±0.2	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(K^+ \text{anything})/\Gamma_{total}$ Γ_6/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
28.9±0.6±0.3	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(K_S^0 \text{ anything})/\Gamma_{total}$ Γ_7/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
19.0±1.0±0.4	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(\eta \text{ anything})/\Gamma_{total}$ Γ_8/Γ

This ratio includes η particles from η' decays.

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
29.9±2.2±1.7		DOBBS	09	CLEO	e^+e^- at 4170 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
23.5±3.1±2.0	674 ± 91	HUANG	06B	CLEO	See DOBBS 09

$\Gamma(\omega \text{ anything})/\Gamma_{total}$ Γ_9/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
6.1±1.4±0.3	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(\eta' \text{ anything})/\Gamma_{total}$ Γ_{10}/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
10.3±1.4 OUR AVERAGE		Error includes scale factor of 1.1.			
8.8±1.8±0.5	68	ABLIKIM	15Z	BES3	482 pb^{-1}, 4009 MeV
11.7±1.7±0.7		DOBBS	09	CLEO	e^+e^- at 4170 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
8.7±1.9±0.8	68	HUANG	06B	CLEO	See DOBBS 09

$\Gamma(f_0(980) \text{ anything}, f_0 \to \pi^+\pi^-)/\Gamma_{total}$ Γ_{11}/Γ

VALUE (units 10^{-2})	CL%	DOCUMENT ID		TECN	COMMENT
<1.3	90	DOBBS	09	CLEO	e^+e^- at 4170 MeV

$\Gamma(\phi \text{ anything})/\Gamma_{total}$ Γ_{12}/Γ

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN	COMMENT
15.7±0.8±0.6		DOBBS	09	CLEO	e^+e^- at 4170 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
16.1±1.2±1.1	398 ± 27	HUANG	06B	CLEO	See DOBBS 09

$\Gamma(K^+K^- \text{anything})/\Gamma_{total}$ Γ_{13}/Γ

VALUE (units 10^{-2})	DOCUMENT ID		TECN	COMMENT
15.8±0.6±0.3	DOBBS	09	CLEO	e^+e^- at 4170 MeV

CLEOc dominants the D_s BF measurements. (Sys. Err. Dominates CF modes. Many SCS&DCS modes observed.)

Baryon Particle Listings

Λ_c^+

$\Gamma(\Lambda\pi^+)/\Gamma(pK^-\pi^+)$ Γ_{28}/Γ_2

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.208±0.009 OUR FIT			Error includes scale factor of 1.2.			
0.204±0.019 OUR AVERAGE						
0.217±0.013±0.020		750	LINK	05F	FOCS	γ nucleus, $\overline{E}_\gamma \approx$ 180 GeV
0.18 ±0.03 ±0.04			ALBRECHT	92	ARG	$e^+e^- \approx$ 10.4 GeV
0.18 ±0.03 ±0.03		87	AVERY	91	CLEO	e^+e^- 10.5 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.33	90		ANJOS	90	E691	γBe 70–260 GeV
<0.16	90		ALBRECHT	88C	ARG	e^+e^- 10 GeV

$\Gamma(\Lambda\pi^+\pi^0)/\Gamma_{total}$ Γ_{29}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
7.0 ±0.4 OUR FIT		Error includes scale factor of 1.1.			
7.01±0.37±0.19	1497	ABLIKIM	16	BES3	$e^+e^- \to \Lambda_c\overline{\Lambda}_c$, 4.599 GeV

$\Gamma(\Lambda\pi^+\pi^0)/\Gamma(pK^-\pi^+)$ Γ_{29}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.13±0.06 OUR FIT		Error includes scale factor of 1.1.			
0.73±0.09±0.16	464	AVERY	94	CLE2	$e^+e^- \approx \Upsilon(3S), \Upsilon(4S)$

$\Gamma(\Lambda\rho^+)/\Gamma(pK^-\pi^+)$ Γ_{30}/Γ_2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.95	95	AVERY	94	CLE2	$e^+e^- \approx \Upsilon(3S), \Upsilon(4S)$

$\Gamma(\Lambda\pi^-2\pi^+)/\Gamma_{total}$ Γ_{31}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
3.61±0.29 OUR FIT		Error includes scale factor of 1.3.			
3.81±0.24±0.18	609	ABLIKIM	16	BES3	$e^+e^- \to \Lambda_c\overline{\Lambda}_c$, 4.599 GeV

$\Gamma(\Lambda\pi^-2\pi^+)/\Gamma(pK^-\pi^+)$ Γ_{31}/Γ_2

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.58 ±0.05 OUR FIT		Error includes scale factor of 2.0.			
0.522±0.032 OUR AVERAGE					
0.508±0.024±0.024	1356	LINK	05F	FOCS	γ nucleus, $\overline{E}_\gamma \approx$ 180 GeV
0.65 ±0.11 ±0.12	289	AVERY	91	CLEO	e^+e^- 10.5 GeV
0.82 ±0.29 ±0.27	44	ANJOS	90	E691	γBe 70–260 GeV
0.94 ±0.41 ±0.13	10	BARLAG	90D	NA32	π^- 230 GeV
0.61 ±0.16 ±0.04	105	ALBRECHT	88C	ARG	e^+e^- 10 GeV

$\Gamma(\Sigma(1385)^+\pi^+\pi^-, \Sigma^{*+} \to \Lambda\pi^+)/\Gamma(\Lambda\pi^-2\pi^+)$ Γ_{32}/Γ_{31}

VALUE	DOCUMENT ID		TECN	COMMENT
0.28±0.10±0.08	LINK	05F	FOCS	γ nucleus, $\overline{E}_\gamma \approx$ 180 GeV

$\Gamma(\Sigma(1385)^-2\pi^+, \Sigma^{*-} \to \Lambda\pi^-)/\Gamma(\Lambda\pi^-2\pi^+)$ Γ_{33}/Γ_{31}

VALUE	DOCUMENT ID		TECN	COMMENT
0.21±0.03±0.02	LINK	05F	FOCS	γ nucleus, $\overline{E}_\gamma \approx$ 180 GeV

$\Gamma(\Lambda\pi^+\rho^0)/\Gamma(\Lambda\pi^-2\pi^+)$ Γ_{34}/Γ_{31}

VALUE	DOCUMENT ID		TECN	COMMENT
0.40±0.12±0.12	LINK	05F	FOCS	γ nucleus, $\overline{E}_\gamma \approx$ 180 GeV

$\Gamma(\Sigma(1385)^+\rho^0, \Sigma^{*+} \to \Lambda\pi^+)/\Gamma(\Lambda\pi^-2\pi^+)$ Γ_{35}/Γ_{31}

VALUE	DOCUMENT ID		TECN	COMMENT
0.14±0.09±0.07	LINK	05F	FOCS	γ nucleus, $\overline{E}_\gamma \approx$ 180 GeV

$\Gamma(\Lambda\pi^-2\pi^+ \text{nonresonant})/\Gamma(\Lambda\pi^-2\pi^+)$ Γ_{36}/Γ_{31}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.3	90	LINK	05F	FOCS	γ nucleus, $\overline{E}_\gamma \approx$ 180 GeV

Can BESIII dominate Λ_c ?

Summary

- BEPCII/BESIII is capable to reach the energy at 4.6 GeV
  - A new territory has never been explored in direct production
- 35 days data @4.6 GeV (567/pb) $\Rightarrow$ Highlight & productive physics outputs of Λ_c decays
- BEPCII is ready for the energy up to 4.7 GeV (will reach 4.9 GeV by 2020)
- A larger data set (10x - 20x more data) for thorough exploration of Λ_c decays are coming.
  - BESIII's opportunity to firstly map out the full picture of Λc decay patterns.
  - Strong impact on non-pQCD framework development
  - The outcomes are expected to become one of the landmarks of BESIII experiment.

Backups

Experimental precision reaches

	Favored mode	Typical two-body mode	Semi-leptonic mode
D0	$B(K^-\pi^+)=(3.89\pm0.04)\%(1.0\%)$	$B(K_s\pi^0)=(1.19\pm0.04)\%(3.4\%)$	$B(K^-e\nu)=(3.53\pm0.03)\%(0.8\%)$
D+	$B(K^-\pi^+\pi^+)=(8.98\pm0.28)\%(3.1\%)$	$B(K_s\pi^+)=(1.47\pm0.08)\%(5.4\%)$	$B(K_se\nu)=(4.41\pm0.07)\%(1.5\%)$
Ds	$B(K^-K^+\pi^+)=(5.45\pm0.17)\%(3.8\%)$	$B(K_sK^+)=(1.40\pm0.05)\%(3.6\%)$	$B(\phi e\nu)=(2.39\pm0.23)\%(9.6\%)$
Λ_c	$B(K^-p^+\pi^+)=$ PDG2014: $(5.0\pm1.3)\%$ (26%) PDG2017(w/ BESIII): $(6.35\pm0.33)\%(5.2\%)$	$B(K_sp^+)=$ PDG2014: $(5.0\pm1.3)\%$ (26%) BESIII: $(1.52\pm0.08)\%(5.6\%)$	$B(\Lambda e\nu)=$ PDG2014: $(2.1\pm0.6)\%$ (29%) BESIII: $(3.63\pm0.43)\%$ (12%)
	2M Λ_c (<2%) (syst. dominant)	2M Λ_c (<2%) (syst. dominant)	2M Λ_c (3%) (stat. dominant)

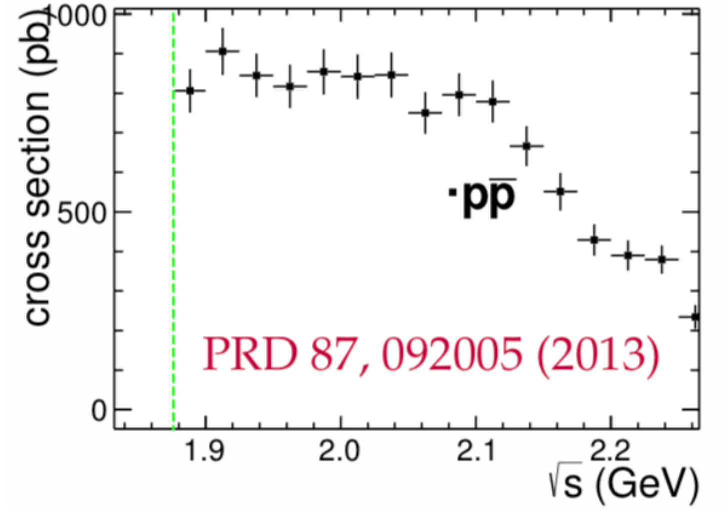
- **We have chance to improve the precisions of Λ_c decay rates to the level of charmed mesons!**
- **Very critical to improve our knowledges on the charmed baryon sector**

The cross-section of baryon pair

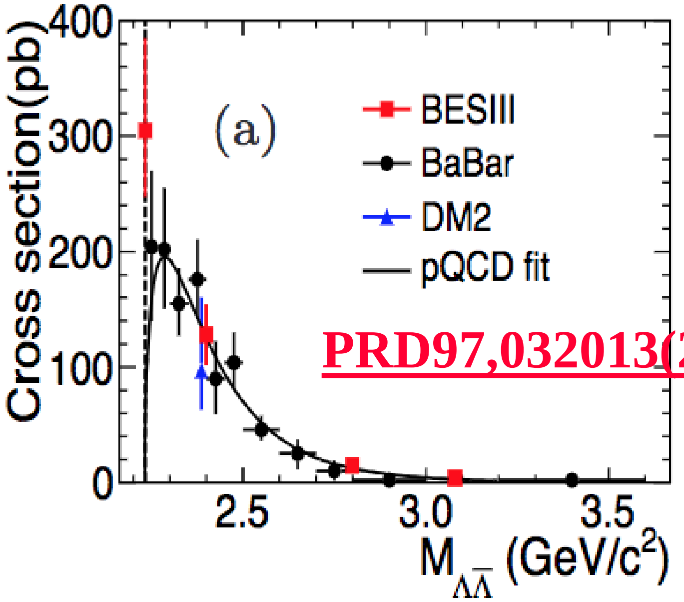
The Born cross section of the reaction $e^+e^- \to \gamma^* \to B\bar{B}$ can be parameterized in terms of electromagnetic form factors:

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

- 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



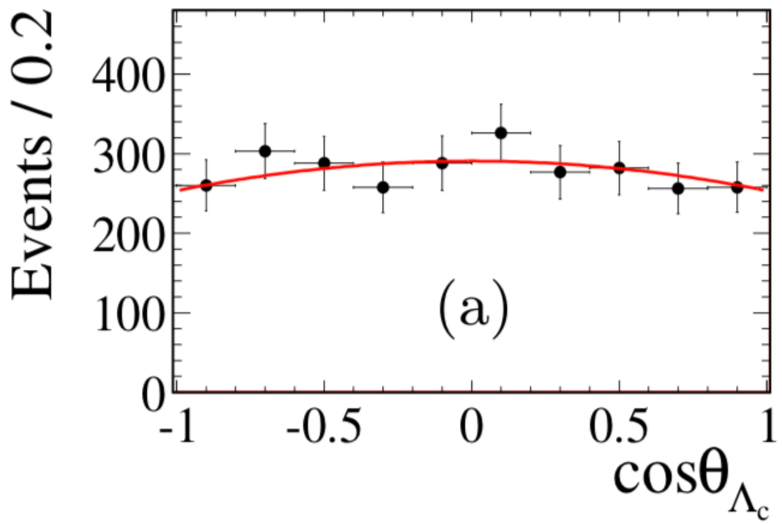
- $e^+e^- \to p\bar{p}$: an enhancement and wide-range plateau in the line-shape
- $e^+e^- \to \Lambda\bar{\Lambda}$: non-zero cross section near threshold
- It can be anticipate that Λ_c^+ has a similar behaviour with proton
- Belle collaboration has measured the cross section of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ using ISR technique PRL 101, 172001 (2008)

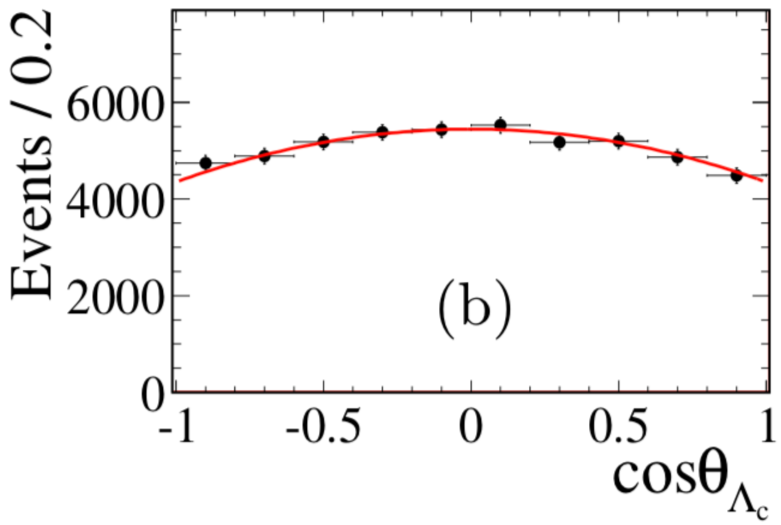


PRD97,032013(2018)

Angular dependence analysis of $e^+e^- \to \Lambda_c^+ \Lambda_c^-$ near threshold

PRL 120, 132001 (2018)





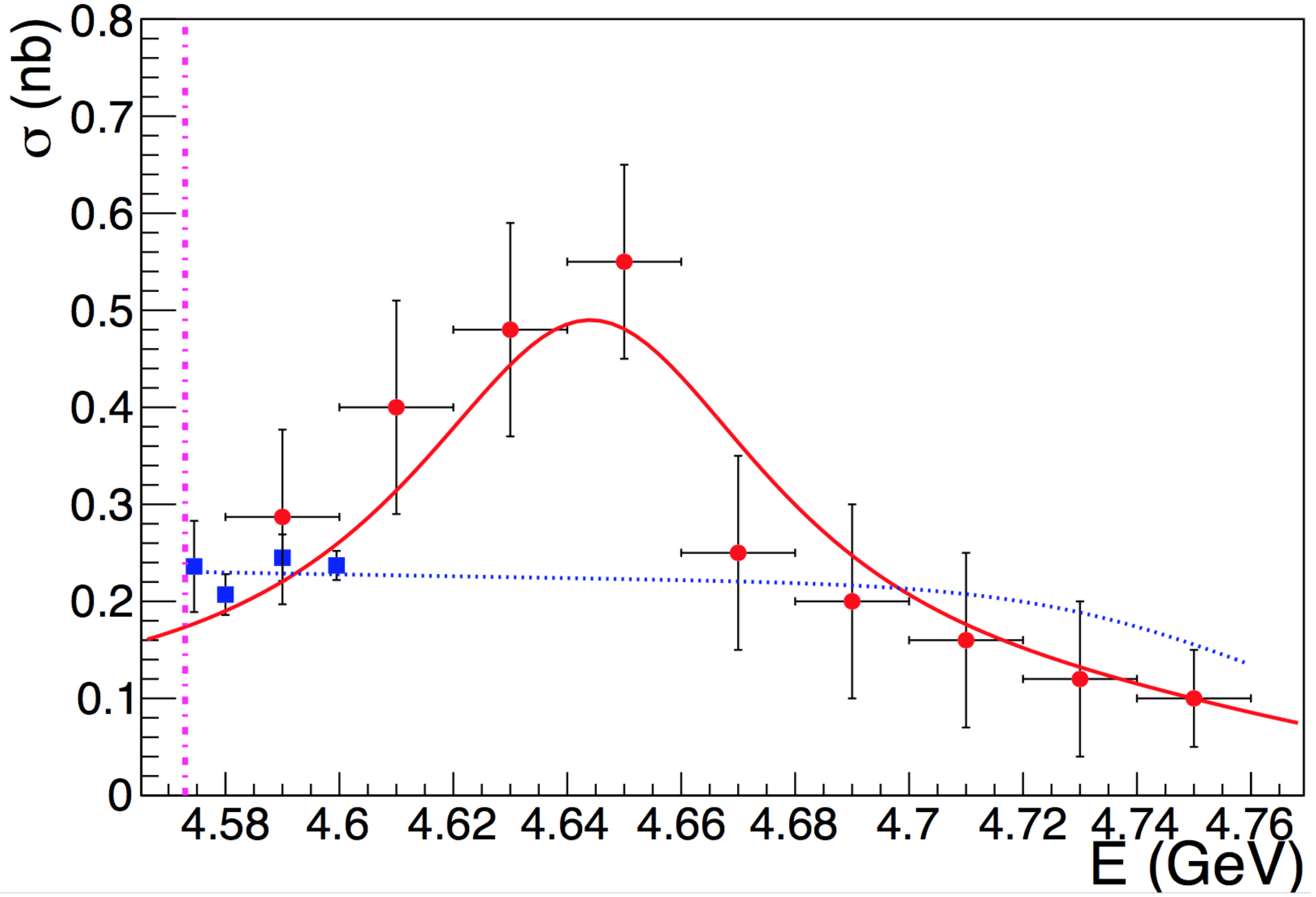
$$f(\theta) \propto (1 + \alpha_{\Lambda_c} \cos^2\theta)$$

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

$\sqrt{s}$ (MeV)	α_{Λ_c}	$\lvert G_E/G_M \rvert$
4574.5	$-0.13 \pm 0.12 \pm 0.08$	$1.14 \pm 0.14 \pm 0.07$
4599.5	$-0.20 \pm 0.04 \pm 0.02$	$1.23 \pm 0.05 \pm 0.03$

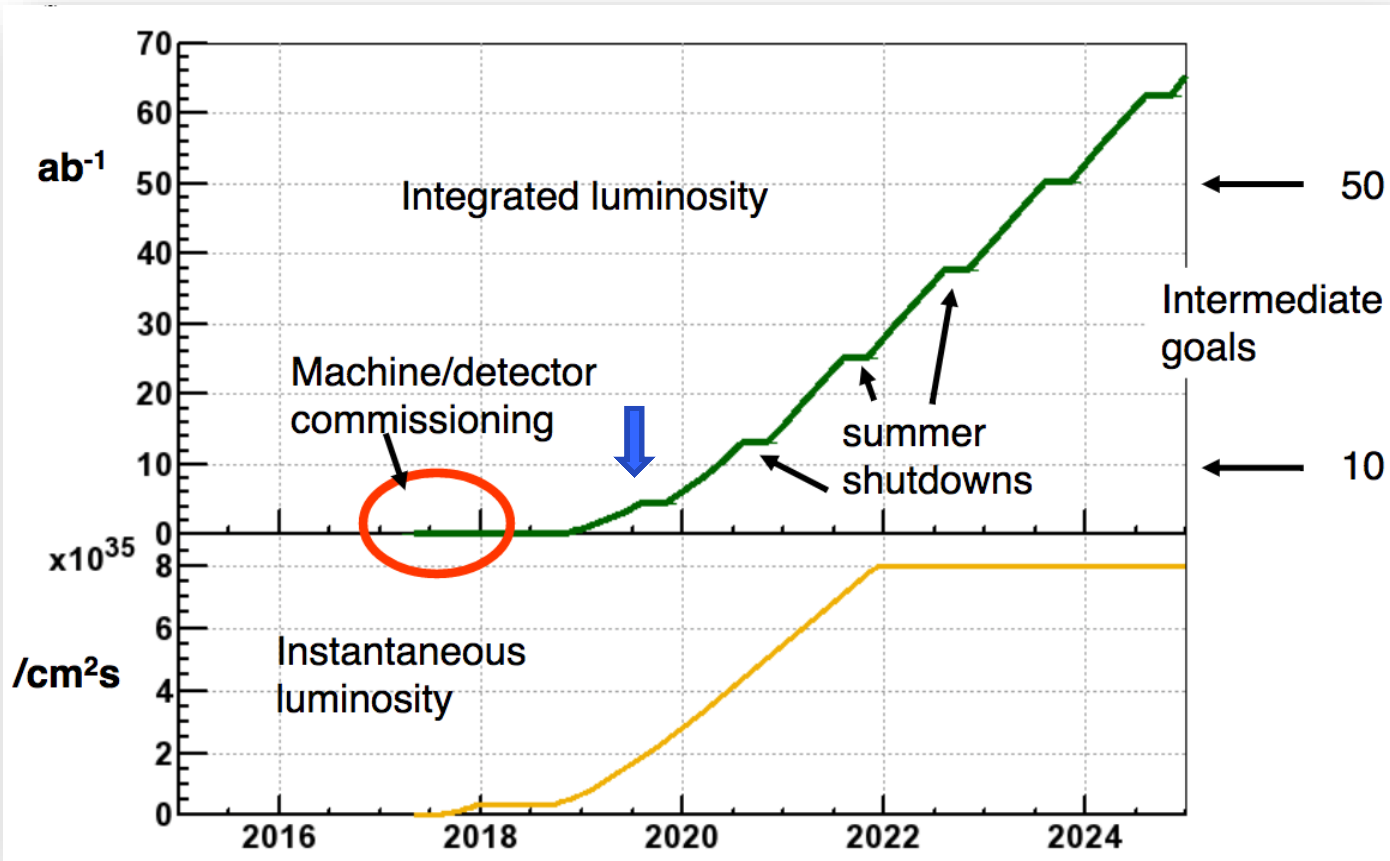
- One of the most basic observables that intimately related to the internal structure of the nucleon.
- One of the most challenging questions in contemporary physics is why and how quarks are confined into hadrons.
- The electromagnetic form factors (EMFFs) have been a powerful tool in understanding the structure of nucleons.
- First measurements of the EMFFs of the Λ_c^+

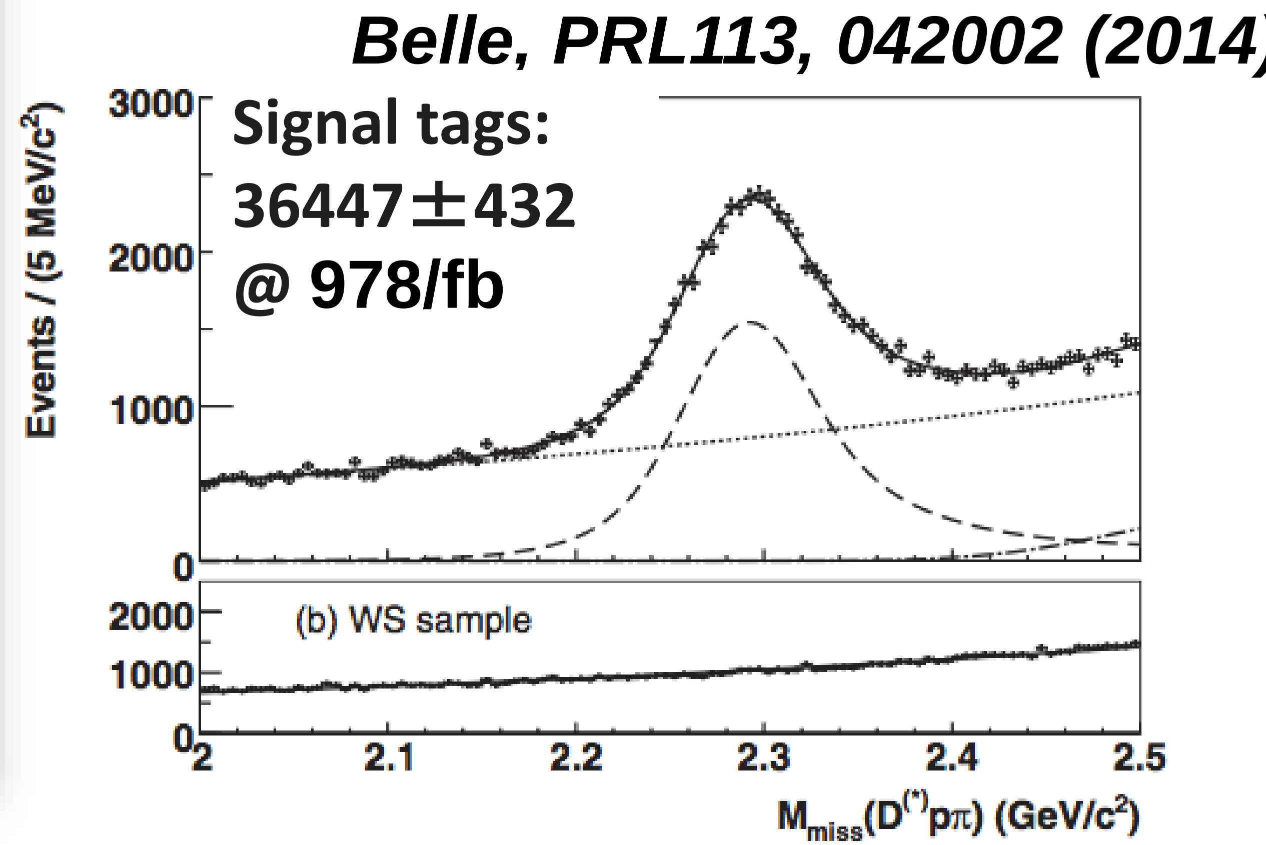
Lineshape of the Λ_c pairs and it's form factor



- Some tension between BELLE and BESIII data
- BESIII data above 4.6 GeV will follow a sharp rise of the Y(4660) or a flat cross section near threshold
- Accessible to the form factor and polarization of the Λ_c at higher Q^2

Competition from Belle & BelleII



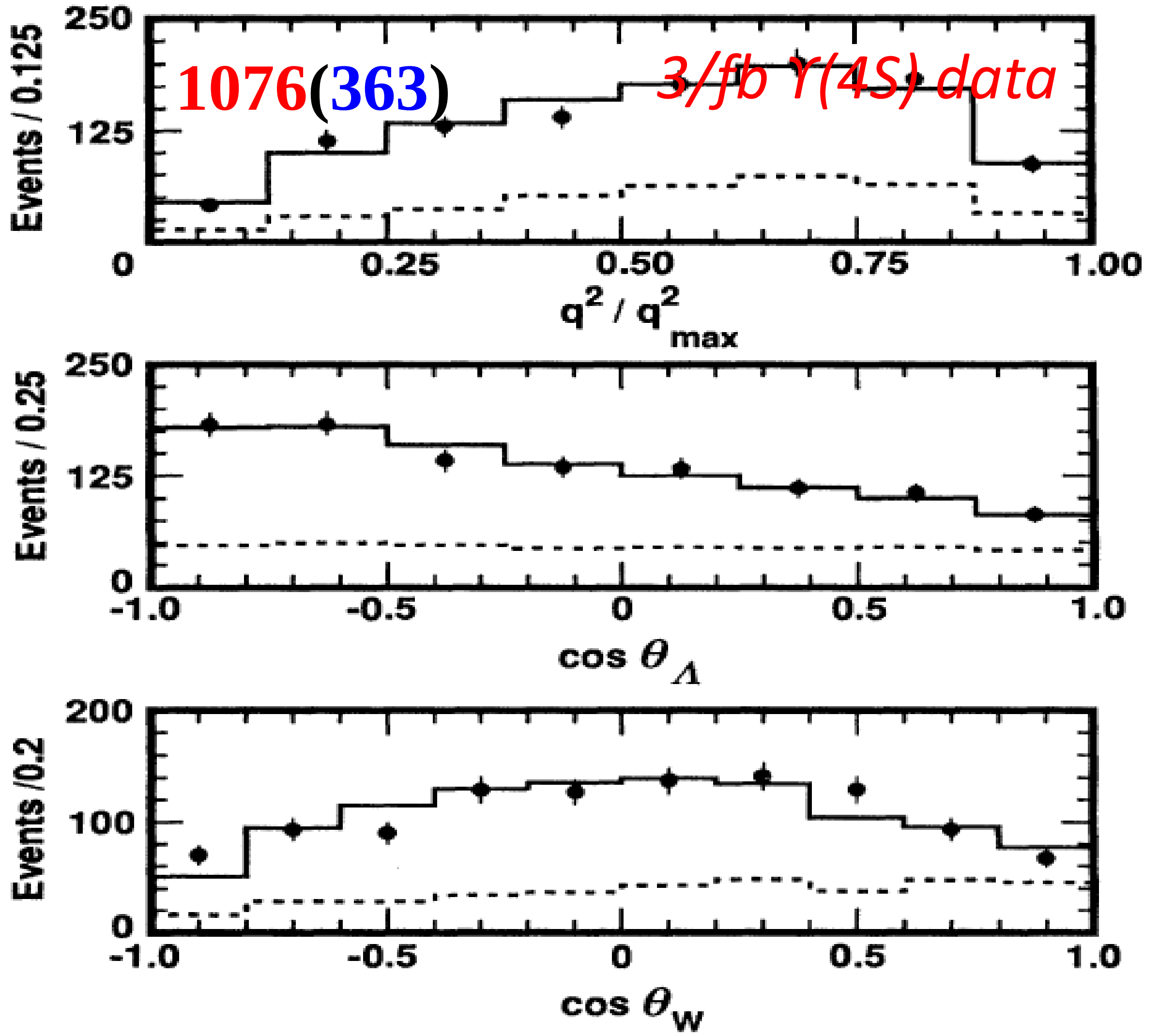


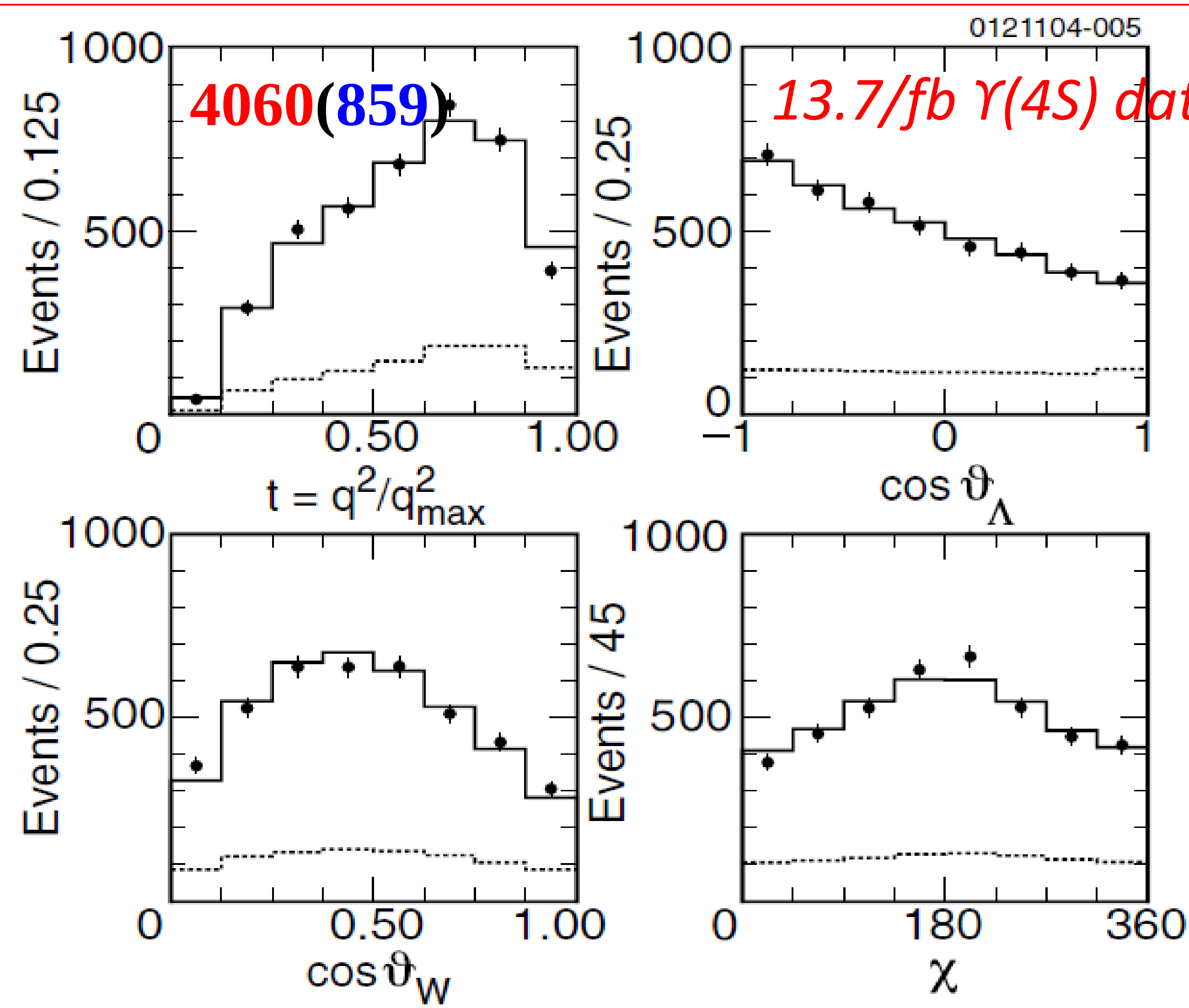
- Belle tags ~36K Λ_c^+, while BESIII now tags 15K Λ_c^+ (567/pb@4.6GeV)
- By middle of 2019, BELLEII will have 5/ab data, 5x of BELLE data;
  ➔ 180K tagged Λ_c^+;
- We will have 150K tagged Λ_c^+, however, BESIII is very clean
- Many precise measurements at BESIII will reach to the level of systematic dominated
  ➔ BESIII has advantages on backgrounds and systematics

Interest topics—FFs in $\Lambda_c^+ \rightarrow \Lambda l^+ \nu_l$

- *Previous Measurements from CLEO.*

$$\Gamma_S = \frac{d\Gamma}{dq^2 d\cos\Theta_W d\cos\Theta_\Lambda} = B(\Lambda \to p\pi)\,\frac{1}{2}\,\frac{G_F^2}{(2\pi)^4}|V_{cs}|^2\frac{q^2 P}{24 M_{\Lambda_c}^2}$$
$$\times \{\tfrac{3}{8}(1 - \cos\Theta_W)^2|H_{(1/2)1}|^2(1 + \alpha_\Lambda\cos\Theta_\Lambda) + \tfrac{3}{8}(1 + \cos\Theta_W)^2|H_{(-1/2)-1}|^2(1 - \alpha_\Lambda\cos\Theta_\Lambda)$$
$$+ \tfrac{3}{4}\sin^2\Theta_W[|H_{(1/2)0}|^2(1 + \alpha_\Lambda\cos\Theta_\Lambda) + |H_{(-1/2)0}|^2(1 - \alpha_\Lambda\cos\Theta_\Lambda)]\},$$





f_2/f_1=-0.25±0.14±0.08 (64%)

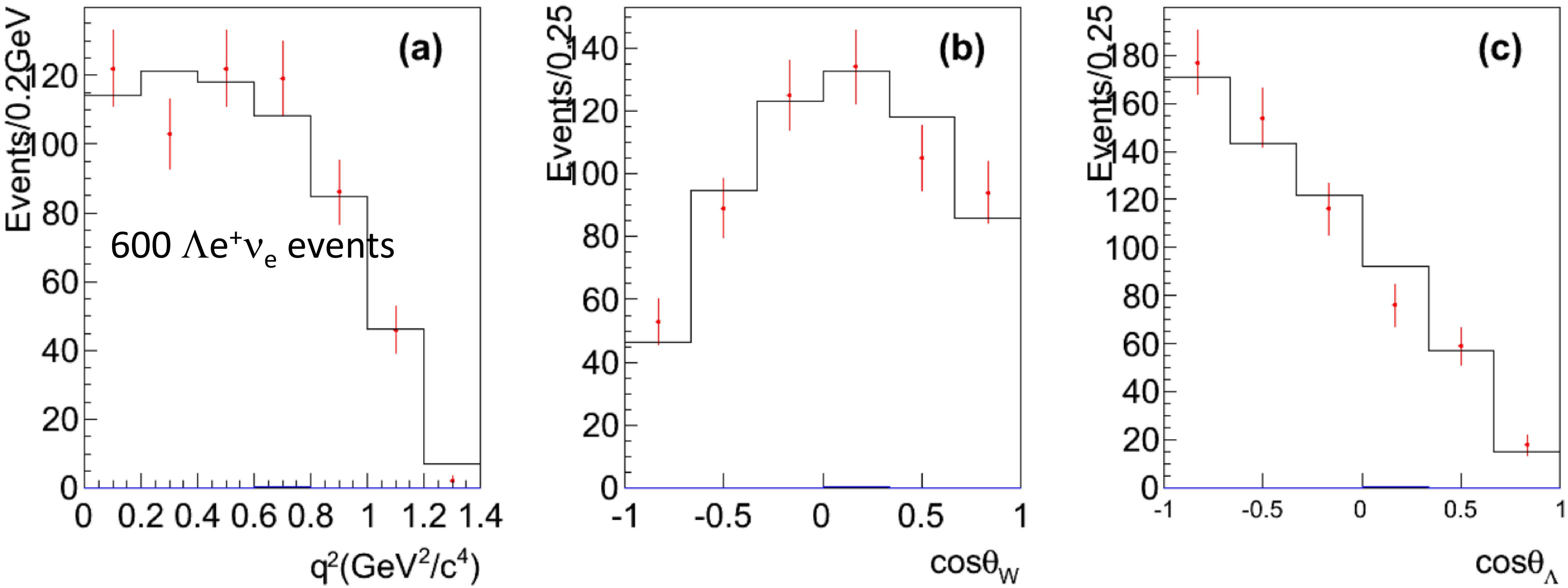
CLEO Collaboration, PRL75, 624(1995);

f_2/f_1=-0.31±0.05±0.04 (21%)

CLEO Collaboration, PRL94, 191801(2005);

Interest topics—FFs in $\Lambda_c^+ \rightarrow \Lambda l^+ \nu_l$

- *MC simulation (~6 times of current data sample)-[3-D fit].*



✓ Based on MC simulation, we obtain f_2/f_1=-0.31±0.08(25%), input: -0.31;

✓ with 20 times data, the precision for f_2/f_1 will be ~15%;

✓ If we combine the data from electron and muon channels, the precision for measuring f_2/f_1 will expected to reach ~12%.

Λ_c^+ Hadronic decay

- Systematically study channels via W-exchanges.

Comparisons of the lift time of Λ_c, D^0 and D^+ [PDG2017]:

$\tau_{\Lambda C}$ =(200$\pm$6)$\times 10^{-15}$ s τ_{D0} =(410.1$\pm$1.5)$\times 10^{-15}$ s τ_{D+} =(1040$\pm$7)$\times 10^{-15}$ s

Theoretically, two explanations for D^0 and D^+ lifetime difference[ZPC33,297]:
[1] light quark interference(D^+: c->sud-bar and d-bar);
[2] W-exchange (D^0: cu-bar -> sd-bar, W-exchange but suppressed by helicity conservation)

✓It is expected that the W-exchange (no helicity suppression) mechanism plays an important role in Λ_c^+ decays.

✓ The channels proceeds only through W-exchange in Λ_c^+ decays!!

	BFs in PDG 2017	
$\Lambda_c^+ \to \Xi^0 K^+$	$(5.0\pm1.2)\times10^{-3}$	BESIII can systematically study and precisely measure the branching fractions for these channels.
$\Lambda_c^+ \to \Delta^{++} K^-$	$(1.09\pm0.25)\times10^{-2}$	
$\Lambda_c^+ \to \Sigma^+ K^+ K^-$	$(3.6\pm0.4)\times10^{-3}$	
$\Lambda_c^+ \to \Sigma^+ \phi$	$(4.0\pm0.6)\times10^{-3}$	

Important to study W-exchanges mechanism, clean and straightforward

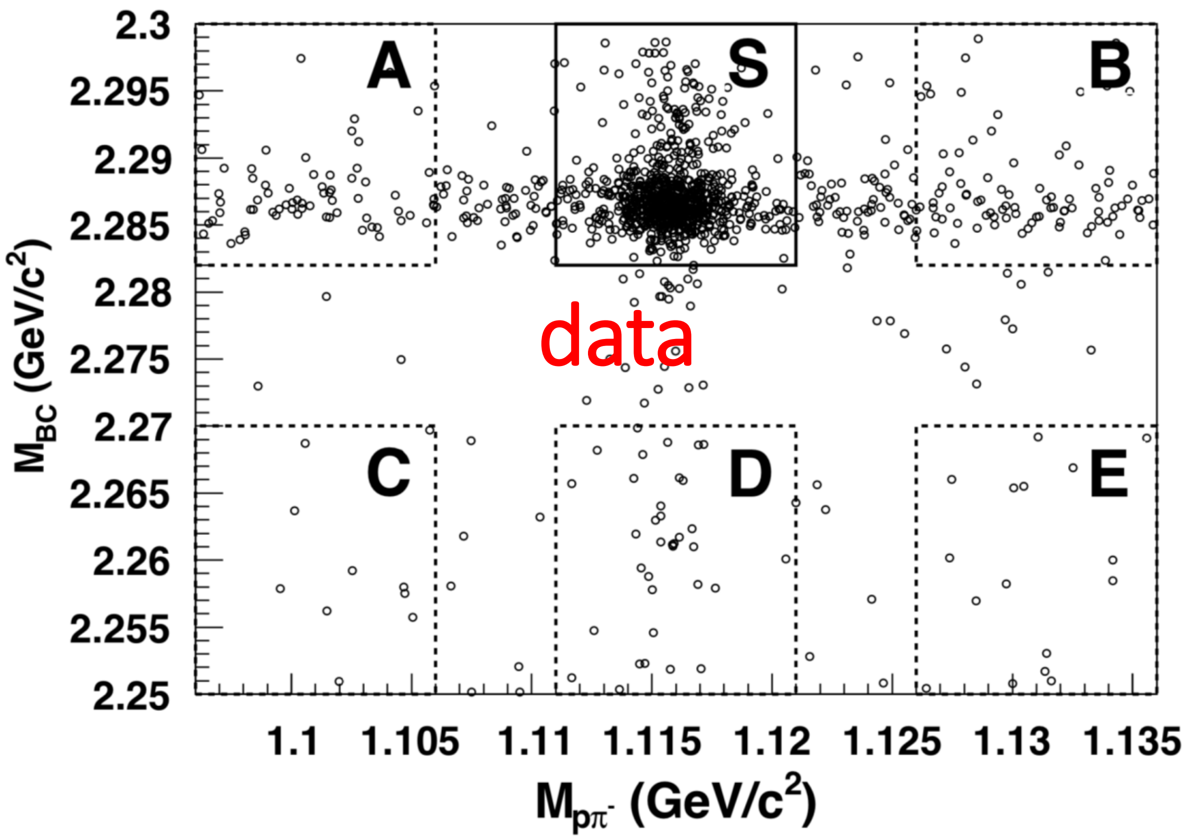
The inclusive channel $\Lambda_c^+ \to \Lambda$+X

- The inclusive process mediated by the *c*-*s* transition.
- Essential input in the calculation of the Λ_c^+ life time.
- Useful in understanding the heavier charmed baryons, esp. the less known double- or triple-charm baryons.
- Current PDG: BF($\Lambda_c^+ \to \Lambda$+X)=(35 ± 11)% with large uncertainty.
- The sum of know exclusive modes only accounts for (24.5 ± 2.1)% => need better understanding of the gap between exclusive and inclusive rates.
- Comparison with K+X will shed light on the Λ_c^+ internal dynamics.
- Search for the CPV by measuring the asymmetry.

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

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

PRL 121, 062003(2018)



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

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

- In the ST modes of $\Lambda_c^+ \to pK^-p^+$ and pK_S^0, to measure the probability of find a Λ in the final states.

- Extract yields from 2D distributions in bins of $p-|cos\theta|$

- Data-driven 2D efficiency correction using several Λ control samples.

- $\mathcal{B}(\Lambda_C^+ \to \Lambda + X) = (38.2^{+2.8}_{-2.2} \pm 0.8)\%$
(excl. rate $(24.5 \pm 2.1)\%$ observed, indicates ~1/3 BFs are unknown)

- $A_{cp} = (2.1^{+7.0}_{-6.6} \pm 1.4)\%$
(No CPV is observed.)

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

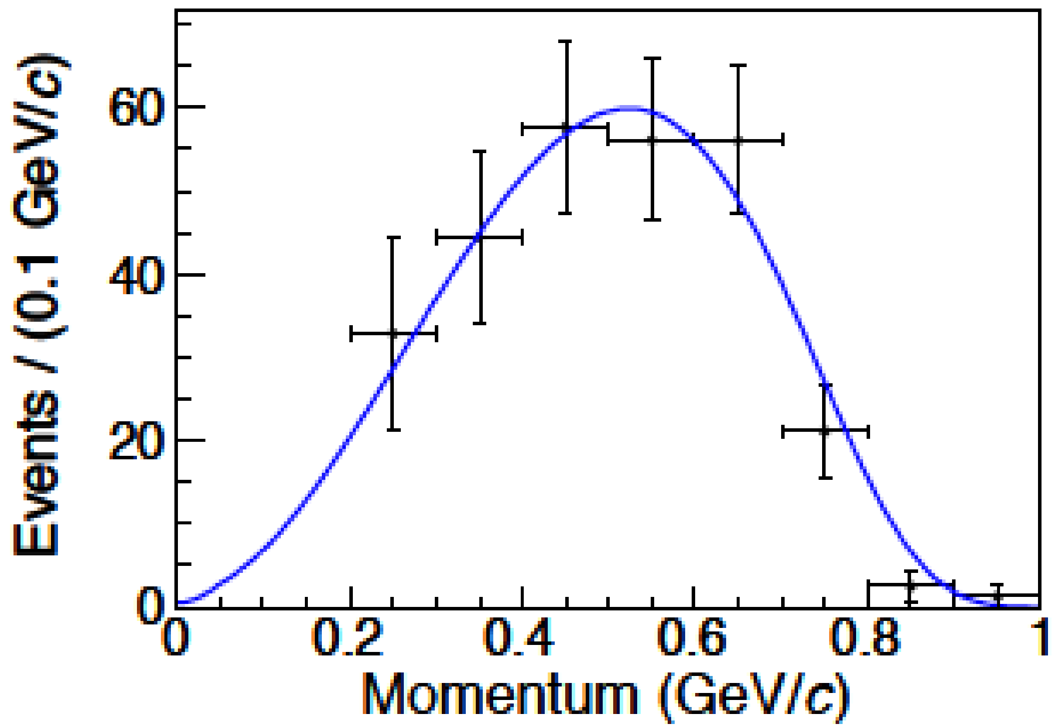
- Current PDG: BF($\Lambda_c^+ \to e$+X)=(4.5±1.7)%.

- Large rate, but also with large uncertainty

- Tagged with $\Lambda_c^+ \to pK^-\pi^+$ and pK_S^0

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

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

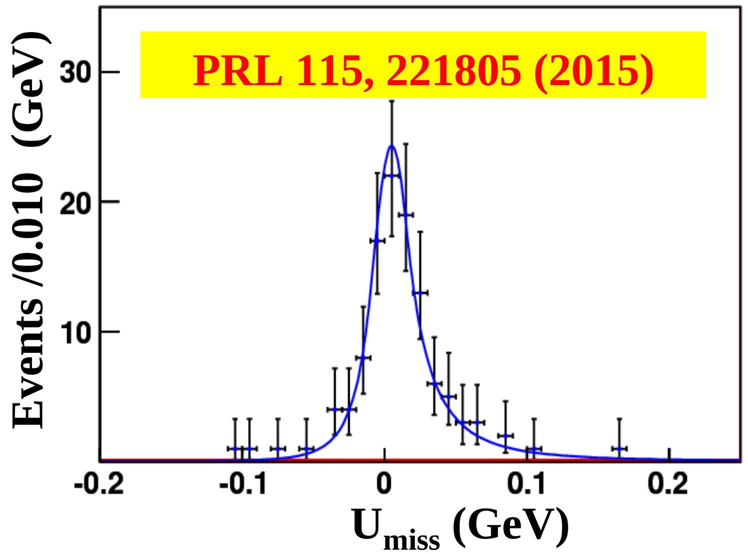


- The $\Lambda l^+ \nu_l$ dominate the l^++X =>$\mathcal{B}$ ($pKl^+\nu_l$)~10^{-3}.

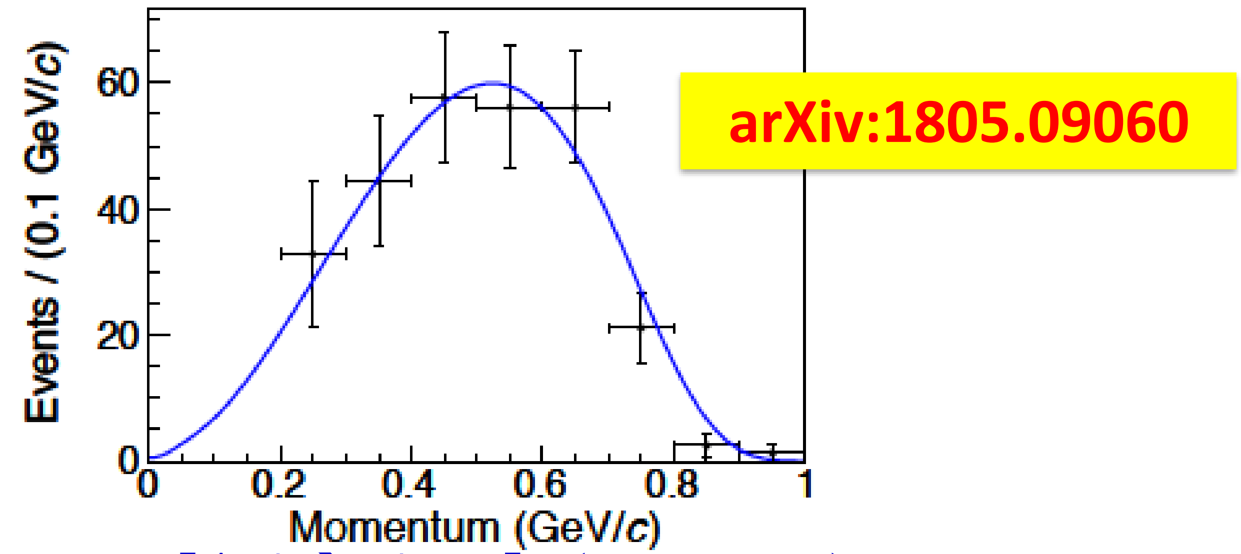
Result	$\Lambda_c^+ \to X e^+ \nu_e$	$\frac{\Gamma(\Lambda_c^+ \to X e^+ \nu_e)}{\bar{\Gamma}(D \to X e^+ \nu_e)}$
BESIII	3.95 ± 0.35	1.26 ± 0.12
MARK II [7]	4.5 ± 1.7	1.44 ± 0.54
Effective-quark Method [9, 10]		1.67
Heavy-quark Expansion [11]		1.2

arXiv:1805.09060

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



$B[\Lambda_c^+ \rightarrow \Lambda e^+ v] = (3.63 \pm 0.38 \pm 0.20)\%$



$B[\Lambda_c^+ \rightarrow e^+ + X] = (4.31 \pm 0.4)\%$

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