BESIII实验上粲重子衰变研究

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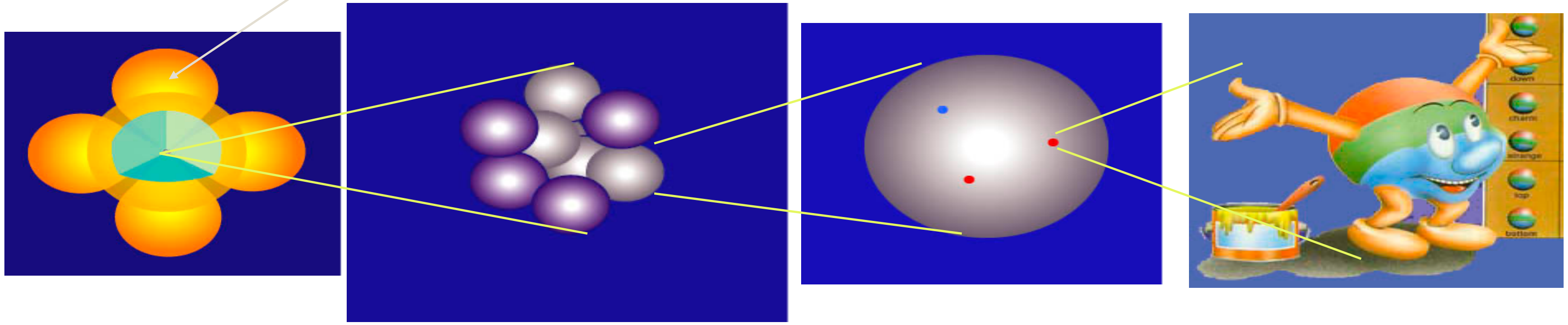
Outline

- **Introduction of the charm baryon**
- **BESIII data taking at Λ_c^+ pair threshold**
- **BESIII results of Λ_c^+ decay**
- **summary**

物质的组成单元

Electron （10^{-18} m）

电子



Atom
原子
10^{-10} m

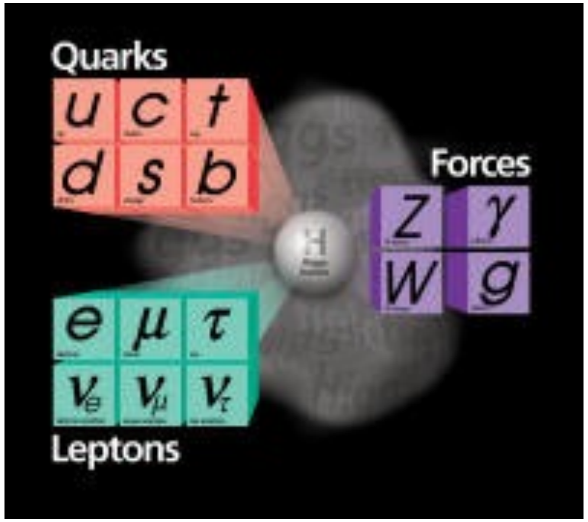
nucleus
核子(质子,中子)
10^{-14} m

nucleon
核子
10^{-15} m

quark
夸克
10^{-18} m

标准模型

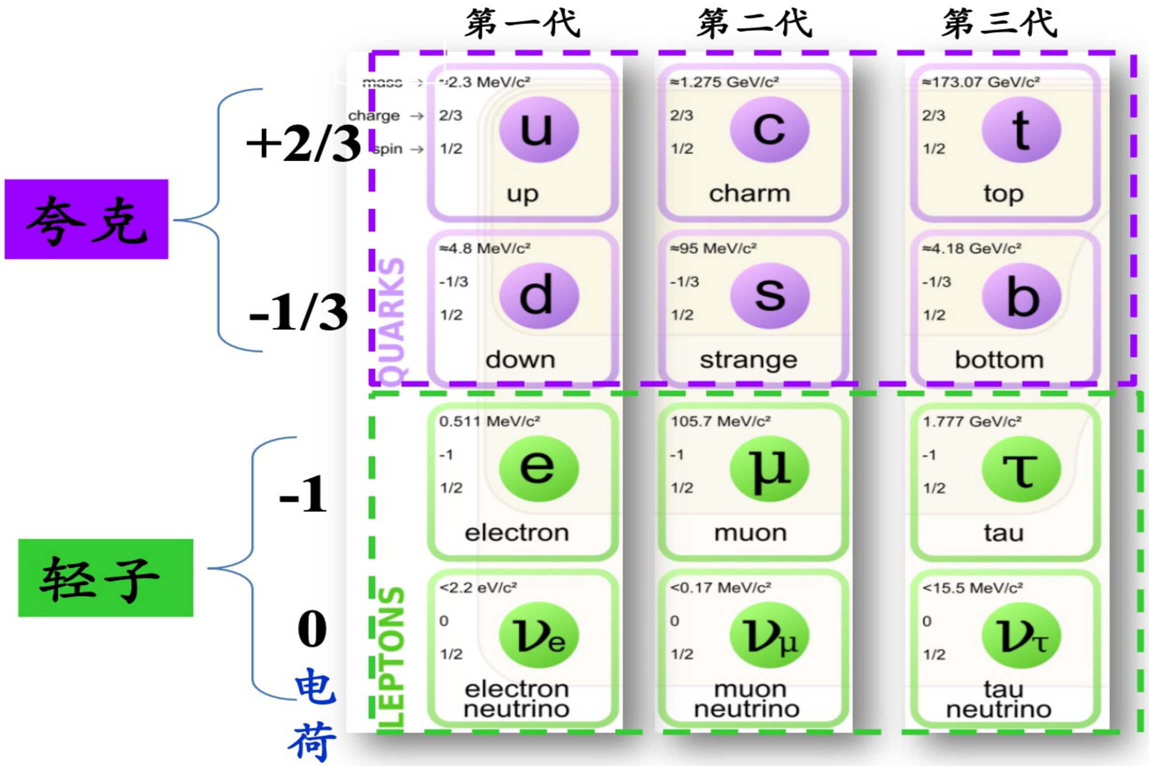
- 发展于上世纪60－70年代
- 描述了物质的基本组成单元及之间的相互作用
- 在非常高的精度内，包容了目前几乎所有观测到的实验现象
- 许多预言已经被实验所验证
- 是一个非常成功的理论



标准模型

所有物质由6种夸克，6种轻子构成

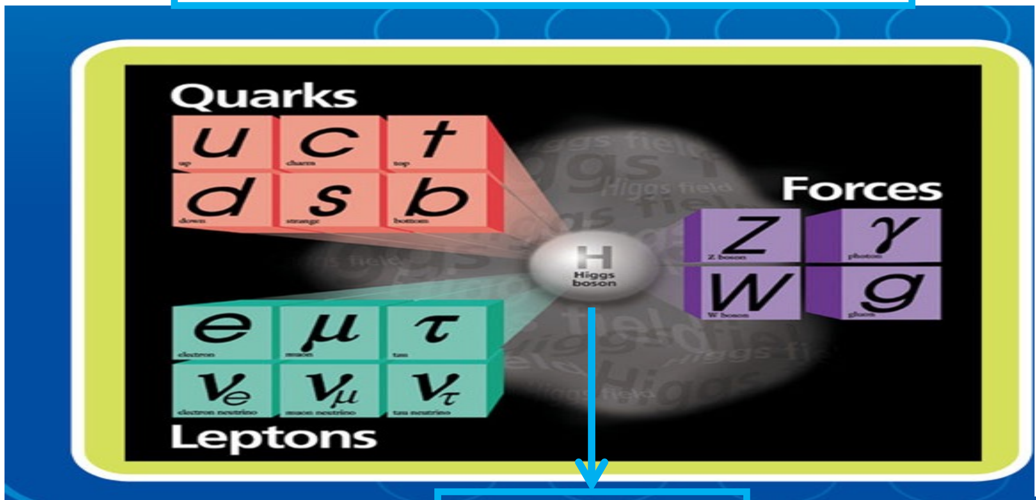
我们周围存在的稳定物质都是由第一代基本粒子组成的



物质的组成的“标准”答案

电磁相互作用：量子电动力学
强相互作用:量子色动力学
弱相互作用：量子味动力学
引力：量子引力?

粒子物理标准模型
电磁、强、弱相互作用



基本粒子
的质量来源

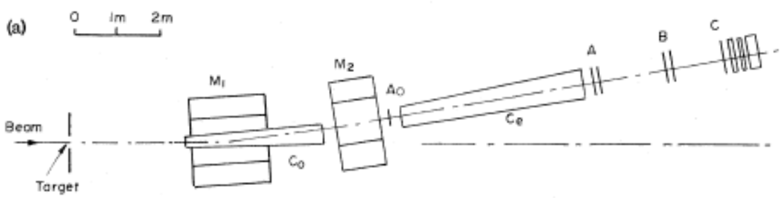
	强相互作用	电磁相互作用	弱相互作用	引力相互作用
源	色荷	电荷	弱超荷	质量
作用常数	$\alpha_s=\frac{g_s^2}{4\pi\hbar c}$ $\cong 1\sim 10$	$\alpha=\frac{e^2}{4\pi\varepsilon_0\hbar c}$ $\cong 1/137$	$\frac{G_F(M_pc^2)^2}{(\hbar c)^3}$ $\cong 1\times10^{-5}$	$\frac{G_N M^2}{4\pi\hbar c}$ $\cong 5\times10^{-40}$
力的传递者	胶子（g）	光子（γ）	中间玻色子（$W^\pm$，Z^0）	——
典型作用时间	10^{-23}秒	10^{-16}秒	10^{-10}秒	——
力程	1fm	∞	1/400 fm	∞

物质组成


q
q̄
q
q
q
q
q̄
q
q̄
q
q̄
q
q̄
q
q
q
q
q̄
介子
重子
分子态
四夸克态
五夸克态
常规的
有，极少
实验上没有确凿证据
理论上都是允许的

Introduction: Charm in 1974:

Charm discovery in 1974



$$p + \mathrm{Be} \rightarrow \mathrm{e}^{+} + e^{-} + x$$

measuring $m_{e^{+}e^{-}}$

J/ψ: M=3.1GeV, Γ≤1.3MeV

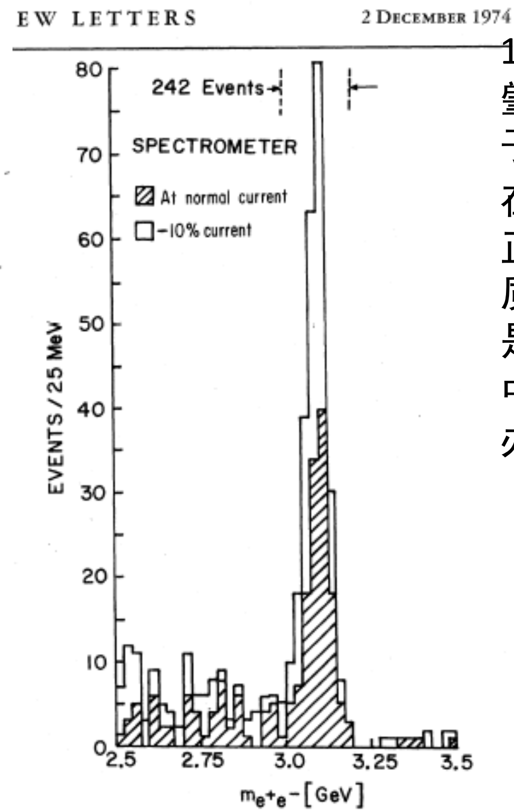
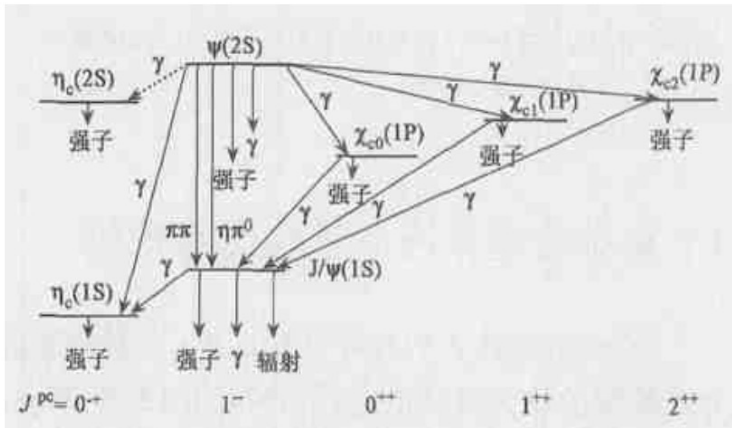


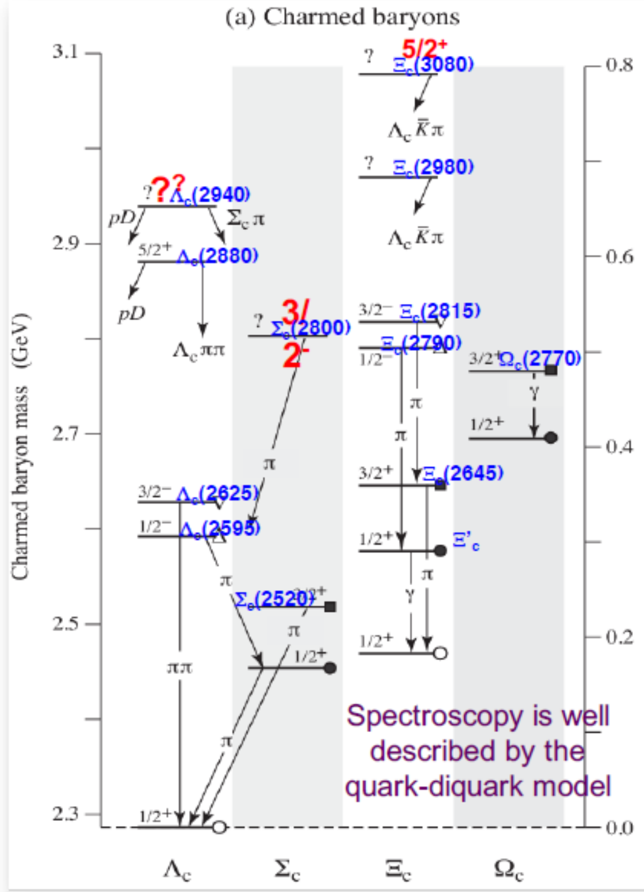
FIG. 2. Mass spectrum showing the existence of J. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

1974年12月PRL同时发表了三篇文章:其一是丁肇中先生在美国布鲁克海文国家实验室利用质子打击铍靶产生正负电子对；其二是 Richter B 在美国斯坦福电子正电子对撞机通过改变电子正电子对撞束流能量的办法进行扫描，在不变质量为3.1GeV 处找到一个新的共振态 。其三是意大利的 Frascati 加速器中心在知道了丁肇中发现 J 粒子的消息后，改变对撞束流能量的办法进行扫描实验。



Renaissance on the charmed heavy baryon

- Before 2014, the charmed baryons 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).
- Large uncertainties in experiment=>Retarder development in theory.
- Afterwards, more extensive measurements on charmed baryons are performed at 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 doubly charmed baryon Ξ_{cc}^{++} at LHCb.
- These experimental progresses have evoked the activities in the theoretical efforts



The charmed baryon family

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

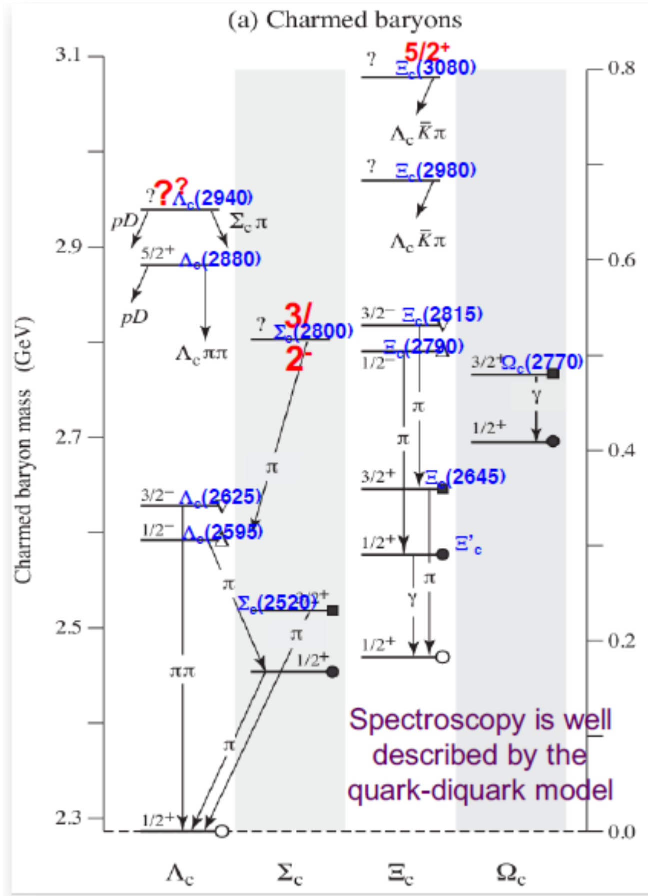
$$\Lambda_c^+ = udc\ ,\ \Sigma_c^{++} = uuc\ ,\ \Sigma_c^+ = udc\ ,\ \Sigma_c^0 = ddc\ ,$$
$$\Xi_c^+ = usc\ ,\ \Xi_c^0 = dsc\ ,\ \Omega_c^0 = ssc$$

✓ $\boldsymbol{\Lambda_c^+}$ decay only weakly, many recent experimental progress since 2014.

✓ $\boldsymbol{\Sigma_c}$: B($\boldsymbol{\Sigma_c} \to \boldsymbol{\Lambda_c^+}\pi$)~100%, B($\boldsymbol{\Sigma_c} \to \boldsymbol{\Lambda_c^+}\boldsymbol{\gamma}$)?

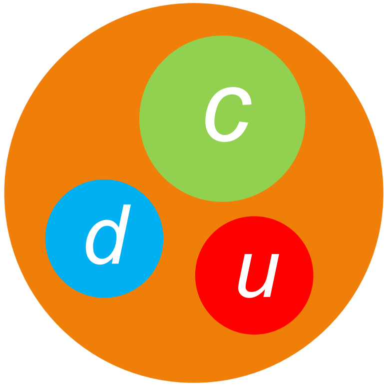
✓ Ξ_c : decay only weakly;

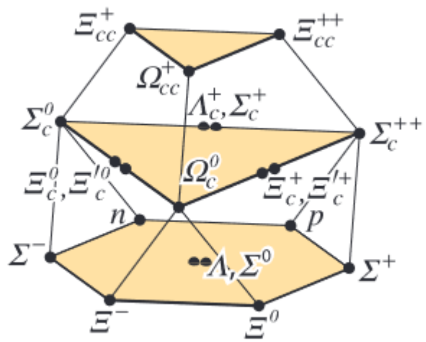
✓ $\boldsymbol{\Omega_c}$:decay only weakly;

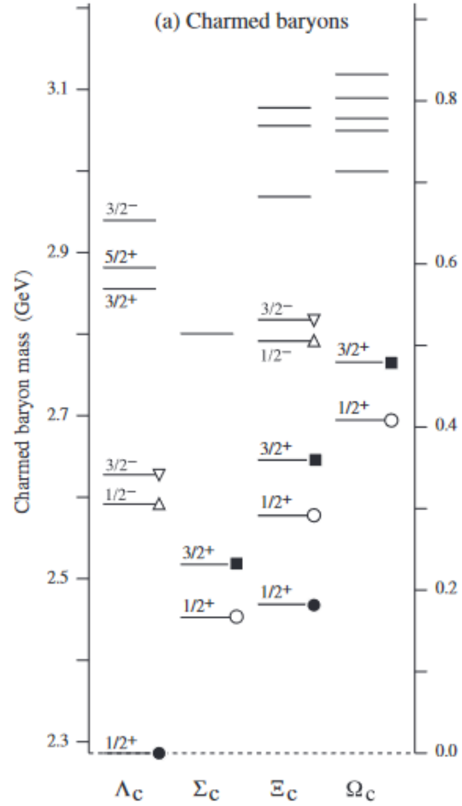


粲重子简介

- Λ_c^+
  - 1979年，美国 Mark II 实验首次发现 。
  - 最轻的基态粲重子。
  - 衰变模式由弱衰变主导。
- **研究Λ_c^+的衰变模式：**
  - ➢ 检验理论预言：
    - ✓ 弱相互作用理论模型
    - ✓ 非微扰强相互作用(NRQCD)
    - ✓ 重夸克有效理论(HQET)
    - ✓ 夸克——双夸克模型(quark-diquark model)
  - ➢ 重要的实验输入：
    - ➢ $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$
    - ➢ $\Lambda_c^+ \to \Lambda l^+ \nu_l$ 形状因子





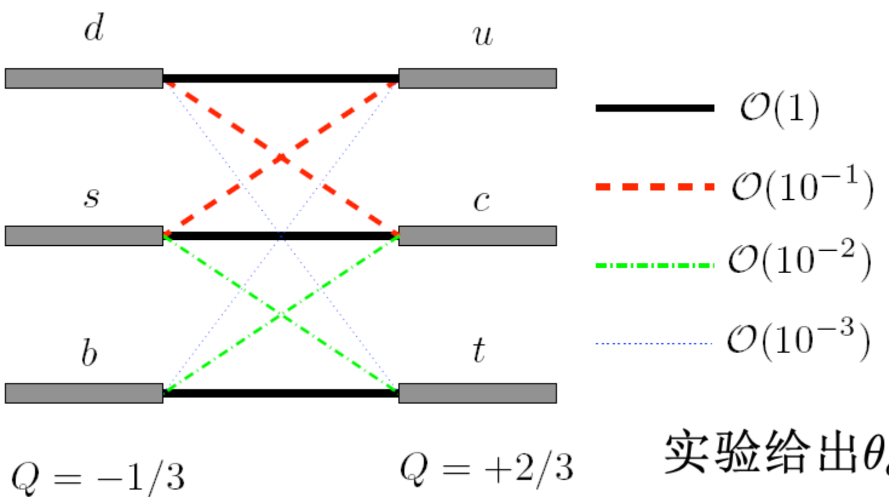


Weak interaction and CKM in Standard Model

$$\Gamma_{\Delta S=0}\left(n \to p + e^- + \bar{\nu}\right) \gg \Gamma_{\Delta S=1}\left(\Lambda \to p + e^- + \bar{\nu}\right)$$

卡比玻引入卡比玻角和强子弱流
d和s夸克要先混合再参加弱相互作用

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix} = V_{CKM} \begin{bmatrix} d \\ s \\ b \end{bmatrix}.$$

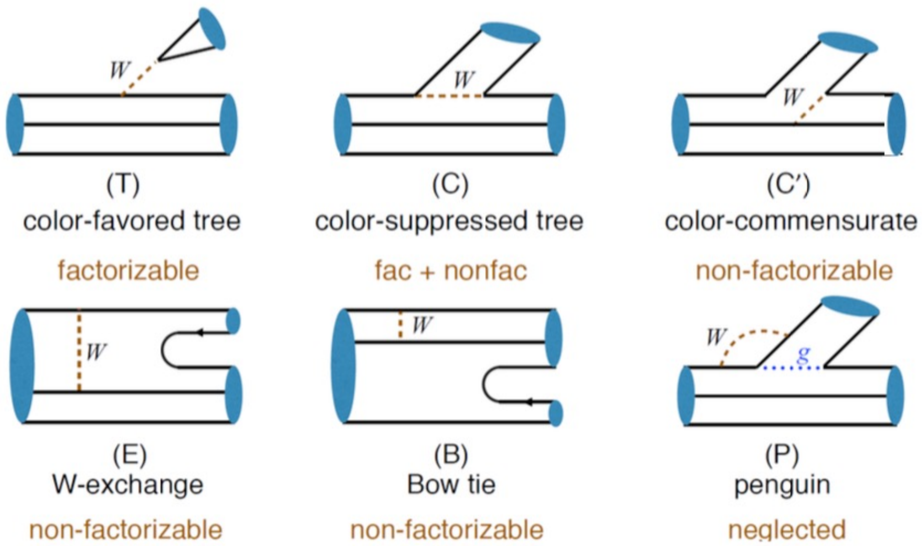


由此引入三种衰变分类:Cabibbo 压低(CS)、Cabibbo 双压低(DCS)和 Cabibbo 允许(CF)过程。
其中 CF 衰变过程中夸克味道在同代内改变，其衰变率正比于 $\cos^2\theta_c$ ；
CS 过程包含一个跨代的夸克味道改变过程，衰变率正比于 $\sin^2\theta_c$ ；
DCS 过程包含两个跨代的夸克味道改变过程，其衰变率正比于 $\sin^4\theta_c$ 。

实验给出$\theta_c \sim 12^\circ$ $\cos^2\theta_c \sim 0.95$ $\sin^2\theta_c \sim 0.05$，所以是大约20倍

Λ_c^+ weak decays

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



- Phenomenology aim at explain data and predict important observables.
- Calculate what they can (HQET, factorization)+parametrize what they cannot + some non-perturbations extracted from data=> explain and predict.

强相互作用

- 粒子物理标准模型中描述强相互作用的量子色动力学(QCD)理论在高能区非常成功，其在高能量下的渐近自由性质和实验结果一致，并获得了 2004 年的诺贝尔物理学奖。
- 在低能区，非微扰不再适用。

- 夸克和胶子的有效耦合常数

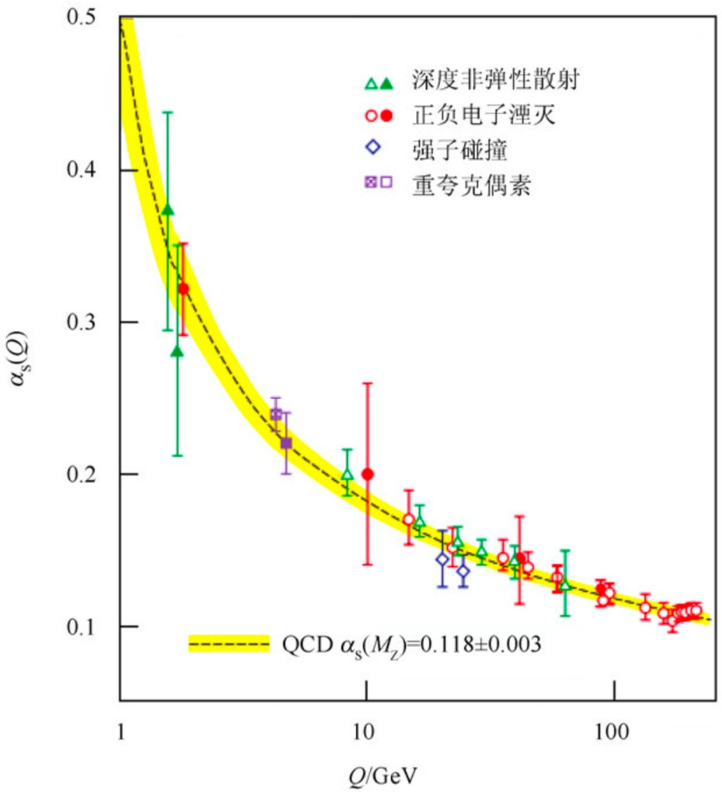
$$\alpha_s(Q^2)=\frac{g_s^2}{4\pi}=\frac{4\pi}{\beta_0\log\frac{Q^2}{\Lambda^2}},$$

$\beta^0=-\left(\frac{2}{3}\mathrm{N_f}-11\right)$单圈近似下的$\beta$函数值

$\mathrm{N_f}$:夸克的味数

Λ:QCD标度参量 $\Lambda=213^{+38}_{-35}$ MeV

Q^2 :能量



Λ_c^+: The lightest charmed baryon spectroscopy

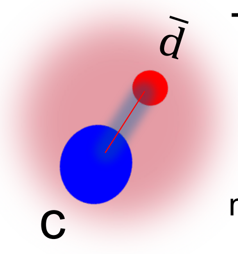
- Most of the charmed baryons will eventually decay to $\mathbf{\Lambda_c^+}$.
- The $\mathbf{\Lambda_c^+}$ is one of important tagging hadrons in c-quark counting in the productions at high energy experiment.

2016 年 LHCb 实验通过$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$首次发现了$\Xi_{cc}^{++}$

- Also important input to $\boldsymbol{\Lambda_b}$ (including Ξ_{cc}^{++}) physics as $\boldsymbol{\Lambda_b}$ decay preferentially to $\boldsymbol{\Lambda_c}$.

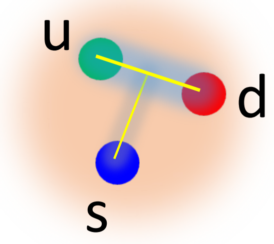
  ==>Important input to B physics and V_{ub} calculations.

- $\mathbf{\Lambda_c^+}$ may provide more powerful test on internal dynamics than D/Ds does !
- Naive 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).



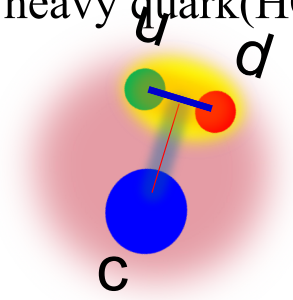
→ Charmed meson ($D^+[c\bar{d}]$)

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



→ Strange baryons (Λ[uds])

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



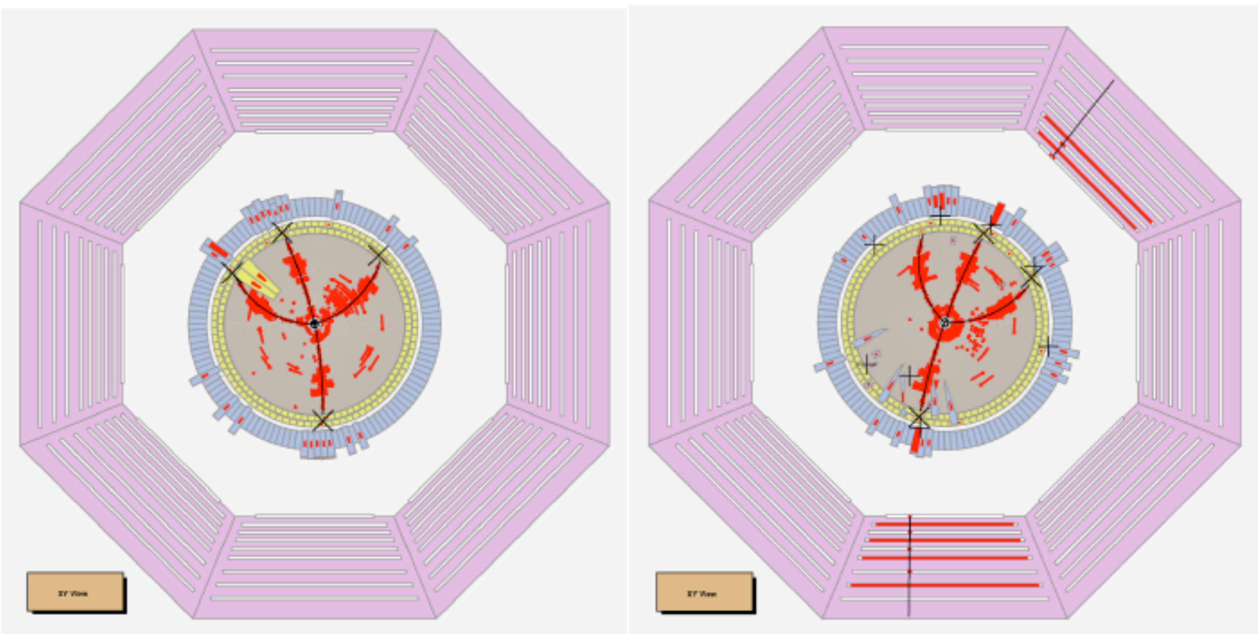
→ Charmed baryon (Λ_c[udc])

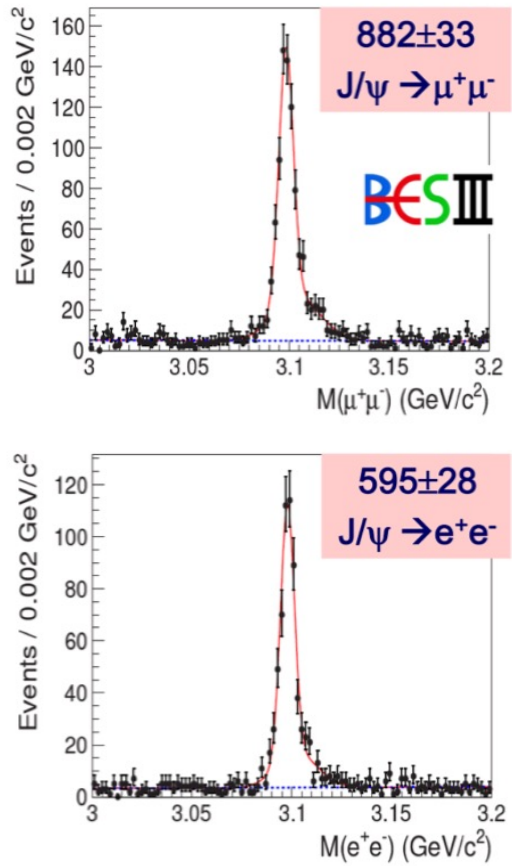
$m_u, m_d << m_c$ → **diquark + quark**
(qq) (Q)

如何寻找共振态

“Typical” ψ(2S) Events

$\Psi(2S) \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow e^+e^-$ $\Psi(2S) \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow \mu^+\mu^-$





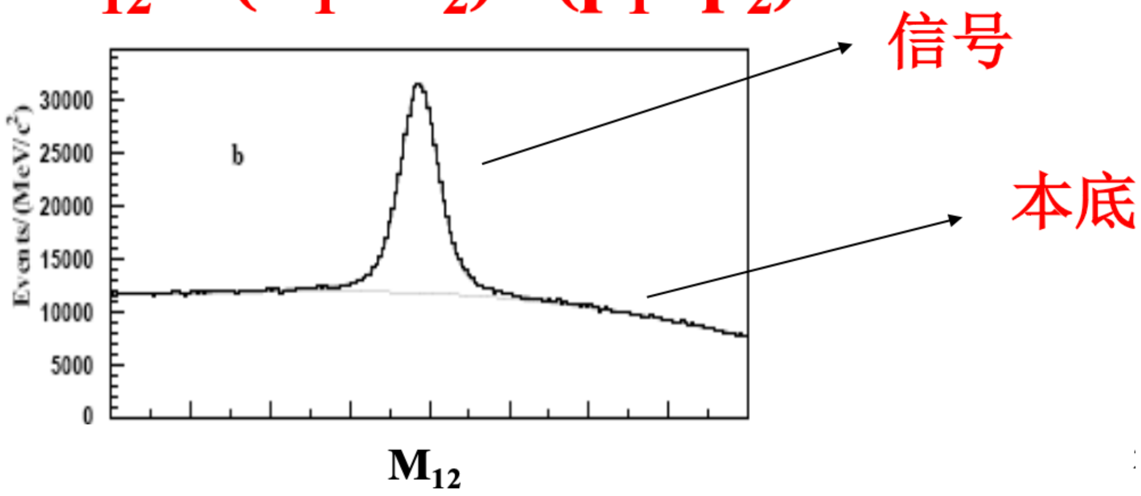
信号与本底

$J/\psi \rightarrow \rho^0\pi^0 \rightarrow \pi^+\pi^-\gamma\gamma$

不变质量(invariant mass)

$$E_1^2=p_1^2+m_1^2;\ E_2^2=p_2^2+m_2^2$$

$$M_{12}^2=(E_1+E_2)^2-(p_1+p_2)^2$$



事例筛选

- 去除本底，保留信号。
- 压低本底的同时，尽量提高信号的选择效率。
- 好的事例选择条件是得到高质量物理结果的最关键的基础！

Event selections for tagging Λ_c^-

- **charged track**
  - $|V_r|<1.0$cm, $|V_z|<10.0$cm; $|\cos\theta|<0.93$
- **PID**
  - K : prob(K)>0 && prob(K)>prob(π)
  - π : prob(π)>0 && prob(π)>prob(K)
  - p : prob(p)>0 && prob(p)>prob(K) && prob(p)>prob(π)
- **K_S (Λ)**
  - π^+ and π^- (p and π^-) with $|V_z|<20.0$ cm , $|\cos\theta|<0.93$, and no PID
  - Primary vertex fit, $\chi^2<100$
  - Second vertex fit, $L/\sigma>2$
  - $0.487 < M(\pi^+\pi^-) < 0.511$ GeV/c^2 ($1.111 < M(p\pi^-) < 1.121$ GeV/c^2)
- **π^0**
  - $E_{barrel}>0.025$ GeV, ($|\cos\theta|<0.8$) $E_{endcap}>0.05$ GeV ($0.86<\cos\theta<0.92$)
  - $0\leq$ TDC≤ 14
  - $0.115 < M(\gamma\gamma) < 0.150$ GeV/c^2
  - 1C kinematic fit, $\chi^2<200$
- **Σ^0**
  - $E_{barrel}>0.025$ GeV, ($|\cos\theta|<0.8$) $E_{endcap}>0.05$ GeV ($0.86<\cos\theta<0.92$)
  - $0\leq$ TDC≤ 14
  - $1.179 < M(\Lambda\gamma) < 1.203$GeV/$c^2$
- **Σ^+**
  - $1.176 < M(p\pi^0) < 1.200$ GeV/c^2

BESIII data taking at Λ_c^+ pair threshold

2286.46 ± 0.14 MeV

- Measurement using the threshold pair-productions via e+e- annihilations is unique: the most simple and straightforward.
- In 2014, BESIII took data above Λ_c^+ pair threshold and run machine at 4.6GeV with excellent performance! $\sim 106\times 10^3$ $\Lambda_c^+\Lambda_c^-$ pairs make sensitivity to 10^{-3}.
- First time to systematically study Λ_c^+ at threshold.
- From December 2019 to June 2021, the BESIII experiment collected approximately 5.85 fb^{-1} of data at center-of-mass energies between 4.61 and 4.95 GeV.
- will allow to improve the precision of Λ_c^+ decay rates to a level comparable to the charmed mesons,
- Provide an opportunity to study many unexplored physics observables related to Λ_c^+ decays
- Boost our understanding of the non-perturbative effects in the charmed baryon sector.

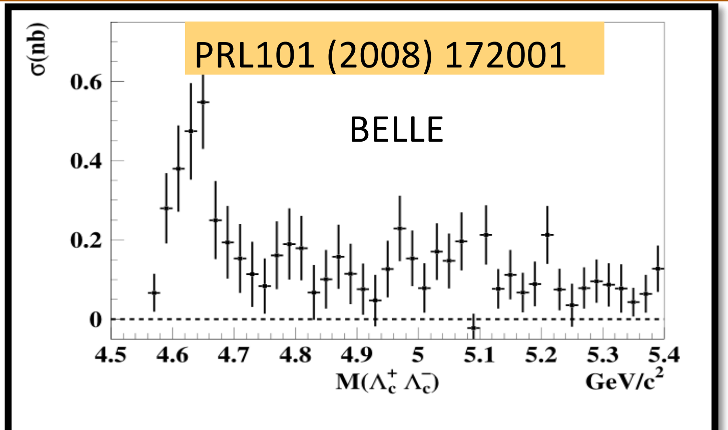
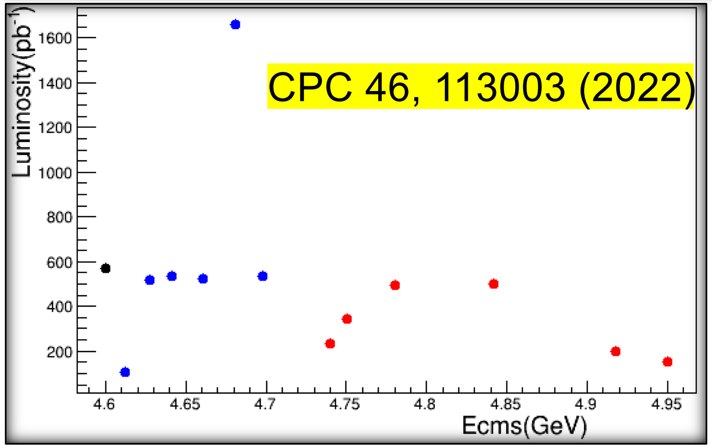


FIG. 4: The cross section for the exclusive process $e^+e^- \to \Lambda_c^+\Lambda_c^-$.



BESIII result of Λ_c^+ hadronic decay

Data 4.600 GeV

✓ **hadronic decay**

1. BF($\Lambda_c^+ \to pK^-\pi^+$) +11hadronic modes PRL 116, 052001 (2016)(update)
2. BF($\Lambda_c^+ \to pK^+K^-, p\pi^+\pi^-$) SCS PRL 117, 232002 (2016)(update)
3. BF($\Lambda_c^+ \to$ n$K_S\pi^+$):PRL 118, 12001 (2017) (update)
4. BF($\Lambda_c^+ \to p\eta, p\pi^0$) :PRD 95, 111102(R) (2017) (update)
5. BF($\Lambda_c^+ \to \Sigma^-\pi^+\pi^+(\pi^0)$) PLB 772, 388 (2017) (update)
6. BF($\Lambda_c^+ \to \Xi^{(*)0}K^+$) W-exchange only PLB 783,200 (2018) (update)
7. BF($\Lambda_c^+ \to \Sigma^+\eta, \Sigma^+\eta'$) W-emission and W-exchange CPC 43, 083002, (2019) （update）
8. BF($\Lambda_c^+ \to \Lambda\,\eta\,\pi^+$) BF($\Lambda_c^+ \to \Sigma^{*+}\eta$) PRD 99, 032010,(2019)(update)
9. BF($\Lambda_c^+ \to pK_S^0\eta$) PLB 817, 136327 (2021) (update)

BESIII result of Λ_c^+ decay

Data 4.600 GeV

✓ **semi-leptonic decay**

1. BF($\Lambda_c^+ \to \Lambda e^+\nu_e$) PRL 115, 221805(2015)
2. BF($\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$) PLB 767, 42 (2017)

✓ inclusive decay

1. BF($\Lambda_c^+ \to \Lambda X$) PRL 121, 062003(2018)(update)
2. BF($\Lambda_c^+ \to eX$)PRL 121, 251801(2018)
3. BF($\Lambda_c^+ \to K_S X$) EPJC 80, 935 (2020)

✓ Cross section of $\Lambda_c^+\Lambda_c^-$ pair PRL 120,132001(2018) (update)

✓ Decay parameters measurement Λ_c^+ PRD 100, 072004 (2019) （update)

BESIII result of Λ_c^+ decay

Data 4.600~ GeV

1. Partial wave analysis of $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ JHEP 12, 033 (2022)
2. BF($\Lambda_c^+ \to \Lambda\mathrm{K}^+$) PRD 106, L111101 (2022)
3. BF($\Lambda_c^+ \to \Lambda\mathrm{K}^+\pi^0, \Lambda\mathrm{K}^+\pi^+\pi^-$) PRD 109, 3, 032003 (2024)
4. BF($\Lambda_c^+ \to \mathrm{p}\eta'$) PRD 106, 072002 (2022)
5. BF($\Lambda_c^+ \to \mathrm{p}\eta, p\omega$) JHEP11,137(2023)
6. BF($\Lambda_c^+ \to \Sigma^- K^+\pi^+$) PRD 109, 7, L071103 (2024)
7. BF($\Lambda_c^+ \to \Sigma^+ K_S^0, \Sigma^0 K^+$) PRD 106, 052003 (2022)
8. BF($\Lambda_c^+ \to p\eta, p\pi^0$) SCS PRD 109 (2024) 9, L091101
9. BF($\Lambda_c^+ \to \Xi^0 K^+$) W-exchange only PRL132 (2024) 3, 031801
10. BF($\Lambda_c^+ \to \Xi^0 K^+\pi^0$) PRD 109, 5, 052001 (2024)
11. BF($\Lambda_c^+ \to \Lambda\mathrm{e}^+\nu_e, \Lambda\mu^+\nu_\mu$) PRL 129, 231803 (2022)
12. BF($\Lambda_c^+ \to pK^-\mathrm{e}^+\nu_e$) PRD 106, 112010 (2023)
13. BF($\Lambda_c^+ \to \Lambda\pi^+\pi^-\mathrm{e}^+\nu_e$, $\Lambda_c^+ \to \mathrm{p}K_S\pi^-\mathrm{e}^+\nu_e$) PLB 843, 137993 (2023)

BESIII result of Λ_c^+ decay

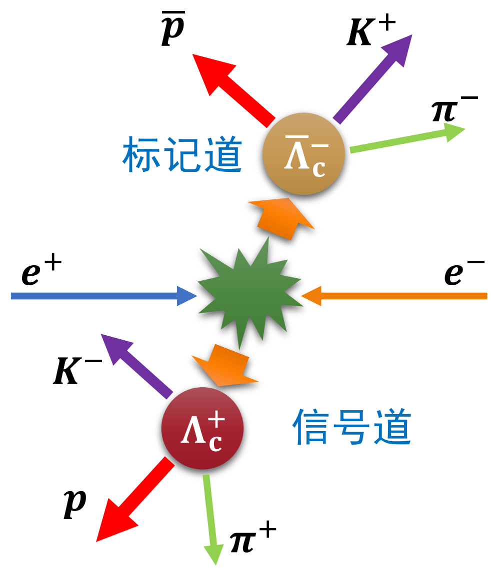
Data 4.600~ GeV

1. $\mathrm{BF}(\Lambda_c^+ \to n\pi^+)$ PRL 128,142001 (2022)
2. $\mathrm{BF}(\Lambda_c^+ \to n\pi^+\pi^0, n\pi^+\pi^-\pi^+, nK^-\pi^+\pi^+)$ CPC 47,023001 (2023)
3. $\mathrm{BF}(\Lambda_c^+ \to nK_S^0\pi^+, nK_S^0K^+)$ PRD 109, 7, 072010 (2024)
4. $\mathrm{BF}(\overline{\Lambda}_c^- \to \bar{n}X)$ PRD 108, L031101(2023)
5. $\mathrm{BF}(\Lambda_\mathrm{c}^+ \to X\mathrm{e}^+\nu_\mathrm{e})$ PRD 107, 052005 (2023)
6. Cross section of $\Lambda_\mathrm{c}^+\Lambda_\mathrm{c}^-$ PRL131, 19, 191901 (2023)

$\Lambda_c^+ \to pK\pi$ + 11 CF Modes 绝对分支比测量

➢ BESIII上利用 567pb^{-1} @ 4.6 GeV 数据，阈值产生，测量 Λ_c^+ 绝对分支比。

- **绝对分支比如何测量(以 $\Lambda_c^+ \to pK^-\pi^+$ 为例)？单标记方法**
  - ➢ $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = \frac{N(\Lambda_c^+ \to pK^-\pi^+ + c.c.)}{2N(\Lambda_c^+\bar{\Lambda}_c^-)}$
  - ➢ $N(\Lambda_c^+ \to pK^-\pi^+ + c.c.) = \frac{N_{sig}}{\varepsilon}$, N_{sig} →重建， ε →MC 模拟。
  - ➢ **$2N(\Lambda_c^+\bar{\Lambda}_c^-)$?**

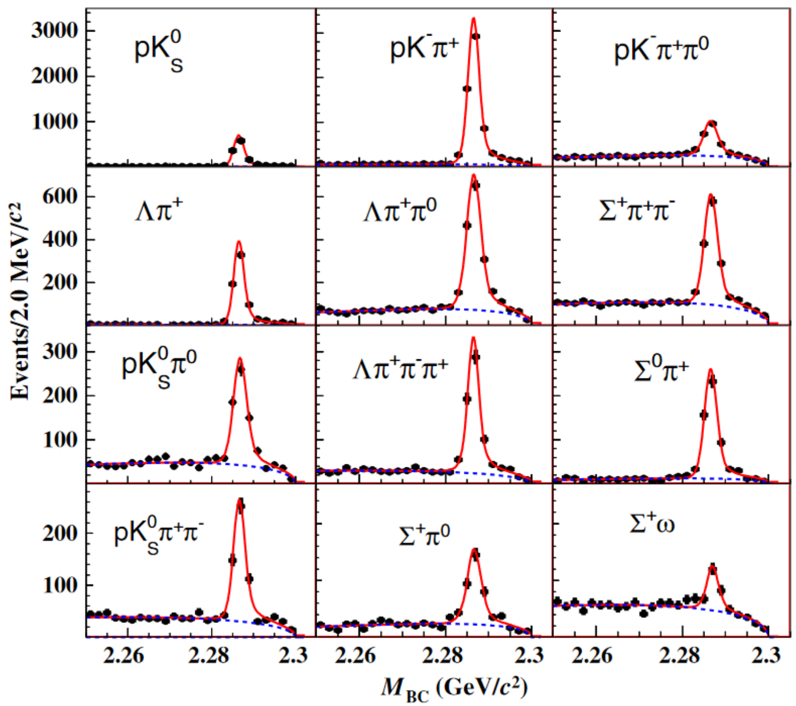


- **近阈产生----双标记方法：**
  - ➢ 数据中重建出一个$\bar{\Lambda}_c^-$时，一定伴随一个Λ_c^+产生。
  - ➢ $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = \frac{N'(\Lambda_c^+ \to pK^-\pi^+)}{N_{tag}} \times \frac{\varepsilon_{tag}}{\varepsilon_{sig}}$
  - ➢ $N'(\Lambda_c^+ \to pK^-\pi^+)$为重建出$\bar{\Lambda}_c^-$的同时也重建出$\Lambda_c^+ \to pK^-\pi^+$的事例数。
  - ➢ N_{tag} 为标记道重建得到的$\bar{\Lambda}_c^-$总数。

$\Lambda_c^+ \to pK\pi + 11$ CF Modes 绝对分支比测量

- $\Lambda_c^+\overline{\Lambda}_c^-$ 成对产生，利用束流能量分辨高的特点：
  - 定义变量ΔE ：
    $$\Delta E = E - E_{\text{beam}}$$
  - 通过选取合适的$|\Delta E|$信号窗压低本底。
  - 定义束流约束质量M_{BC} ：
    $$M_{\text{BC}} = \sqrt{E_{\text{beam}}^2 - |\vec{p}|_{\Lambda_c}^2}$$
  - 通过拟合M_{BC}分布得到第j个标记道的信号数N_j^{ST}。
  - 用MC估计标记道重建效率ε_j^{ST}。

=>Relative higher backgrounds
=>Higher efficiencies
=>Full reconstruction



标记道产额

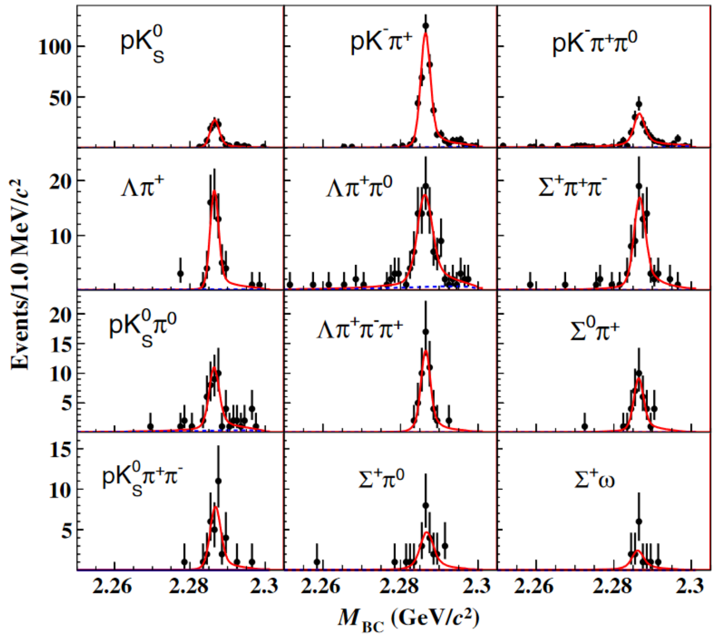
$\Lambda_c^+ \to pK\pi + 11$ CF Modes 绝对分支比测量

- **选取标记侧M_{BC}信号窗内的事例，在剩余tracks中重建信号过程：**
  - 拟合信号侧M_{BC}分布得到信号道总产额$N_{i-}^{DT} = \sum_j N_{ij}^{DT}$，其中$N_{ij}^{DT}$为信号道$i$在标记道$j$下的双标记产额。
  - MC模拟得到同时重建出标记道j和信号道i的效率ε_{ij}^{DT}。
  - 则信号道i绝对分支比$\mathcal{B}_i$可由

$$N_{i-}^{\mathrm{DT}} = \mathcal{B}_i \cdot \Sigma_j \left(\frac{N_j^{ST}}{\varepsilon_j^{ST}} \cdot \varepsilon_{ij}^{DT}\right)$$

得到。

=>Smaller backgrounds.
=>Missing technique.
=>Lower efficiencies.
=>Systematic in tag side are mostly cancelled.



双标记产额

$\Lambda_c^+ \to pK\pi$ + 11 CF Modes 绝对分支比测量

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	

PRL 116, 052001 (2016)

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

$\Lambda_c^+ \to pK\pi$ + 11 CF Modes 绝对分支比测量

Experimental precision reaches of the charmed hadrons

Table 5.5. Measured or projected precision of charmed hadrons, with the relative precision in parenthesis. For the future Λ_c^+ precision, it is estimated for 5 fb^{-1} of data at $\sqrt{s}$ = 4.64 GeV.

CPC 44,040001 (2020)

	Leading hadronic decay	Typical two-body decay	Leading SL decay
Λ_c^+	$\mathcal{B}(K^-p\pi^+)$ = 2014: (5.0±1.3)% (26%) 2017(w/ BESIII): (6.35±0.33)% (5.2%) 5 fb^{-1}: $\frac{\delta\mathcal{B}}{\mathcal{B}}$ <2%	$\mathcal{B}(K_S^0 p)$ = 2014: (1.2±0.3)% (26%) BESIII: (1.52±0.08)% (5.6%) 5 fb^{-1}: $\frac{\delta\mathcal{B}}{\mathcal{B}}$ <2%	$\mathcal{B}(\Lambda e^+\nu_e)$ = 2014: (2.1±0.6)% (29%) BESIII: (3.63±0.43)% (12%) 5 fb^{-1}: $\frac{\delta\mathcal{B}}{\mathcal{B}}$ ~3.3%
D^0	$\mathcal{B}(K^-\pi^+)$ =(3.89±0.04)% (1.0%)	$\mathcal{B}(K_S^0\pi^0)$ =(1.19±0.04)% (3.4%)	$\mathcal{B}(K^-e^+\nu_e)$ =(3.53±0.03)% (0.8%)
D^+	$\mathcal{B}(K^-\pi^+\pi^+)$ =(8.98±0.28)% (3.1%)	$\mathcal{B}(K_S^0\pi^+)$ =(1.47±0.08)% (5.4%)	$\mathcal{B}(K_S^0 e^+\nu_e)$ =(4.41±0.07)% (1.5%)
D_s^+	$\mathcal{B}(K^-K^+\pi^+)$ =(5.45±0.17)% (3.8%)	$\mathcal{B}(K_S^0 K^+)$ =(1.40±0.05)% (3.6%)	$\mathcal{B}(\phi e^+\nu_e)$ =(2.39±0.23)% (9.6%)

$\mathcal{B}[\Lambda_c^+ \to \Lambda e^+\nu_e]$ = (3.56 ± 0.11 ± 0.07)%

- The precisions of Λ_c^+ decay rates is reaching to the level of charmed mesons!
- More data input will further constrain the HFLAV fit.
- However, search for more unknown modes are important

$\Lambda_c^+ \to pK\pi$ + 11 CF Modes 绝对分支比测量

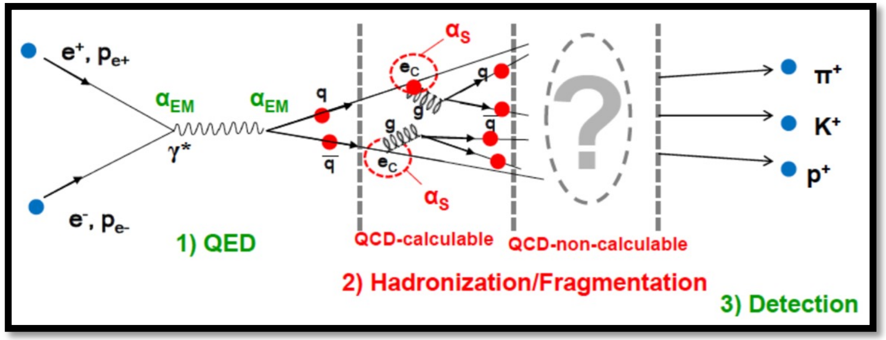
- stringent Fragmentation Function of b/c quark to baryon
  - [Eur. Phys. J. C12, 225 (2000); Eur. Phys. J. C 16, 597 (2000); Phys. Rev. D 85, 032008 (2012), Phys. Rev.D 66, 091101 (2002).]
  - Fragmentation Function (FF) is an important probe in experiment to test and calibrate QCD theory.

PhysRevD.85.032008

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

Source	Error (%)
Bin-dependent errors	2.2
$\mathcal{B}(\Lambda_b^0 \to D^0 pX\mu^-\bar{\nu})$	2.0
Monte Carlo modelling	1.0
Backgrounds	3.0
Tracking efficiency	2.0
Γ_{sl}	2.0
Lifetime ratio	2.6
PID efficiency	2.5
Subtotal	6.3
$\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$	26.0
Total	26.8

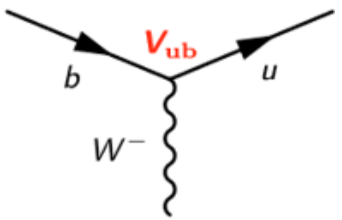
3.7



- Now B($pK^-\pi^+$) are still dominated

$\Lambda_c^+ \to pK\pi$ + 11 CF Modes 绝对分支比测量

CKM matrix element V_{ub}



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

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

Nature Physics 11 (2015) 743

Source	Relative uncertainty (%)
$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$	$^{+4.7}_{-5.3}$
Trigger	[illegible]
Tracking	3.0
Λ_c^+ selection efficiency	3.0
$\Lambda_b^0 \to N^*\mu^-\overline{\nu}_\mu$ shapes	2.3
Λ_b^0 lifetime	1.5
Isolation	1.4
Form factor	1.0
Λ_b^0 kinematics	0.5
q^2 migration	0.4
PID	0.2
Total	$^{+7.8}_{-8.2}$

$\to$ 3.7

$\mathrm{B}(pK^-\pi^+)$ are dominated systematic uncertainty

Decay asymmetry parameter in $\Lambda_c^+ \to \Xi^0 K^+$

Theory or experiment	$\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)$ ($\times 10^{-3}$)	$\alpha_{\Xi^0 K^+}$	$\lvert A \rvert$ ($\times 10^{-2} G_F$ GeV^2)	$\lvert B \rvert$ ($\times 10^{-2} G_F$ GeV^2)	$\delta_p - \delta_s$ (rad)
Körner (1992), CCQM [7]	2.6	0	-	-	-
Xu (1992), Pole [8]	1.0	0	0	7.94	-
Źencaykowski (1994), Pole [9]	3.6	0	-	-	-
Ivanov (1998), CCQM [10]	3.1	0	-	-	-
Sharma (1999), CA [11]	1.3	0	-	-	-
Geng (2019), SU(3) [12]	5.7 ± 0.9	$0.94^{+0.06}_{-0.11}$	2.7 ± 0.6	16.1 ± 2.6	-
Zou (2020), CA [5]	7.1	0.90	4.48	12.10	-
Zhong (2022), SU(3)[a] [13]	$3.8^{+0.4}_{-0.5}$	$0.91^{+0.03}_{-0.04}$	3.2 ± 0.2	$8.7^{+0.6}_{-0.8}$	-
Zhong (2022), SU(3)[b] [13]	$5.0^{+0.6}_{-0.9}$	0.99 ± 0.01	$3.3^{+0.5}_{-0.7}$	$12.3^{+1.2}_{-1.8}$	-
BESIII (2018) [14]	$5.90 \pm 0.86 \pm 0.39$	-	-	-	-
PDG Fit (2022) [3]	5.5 ± 0.7	-	-	-	-

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- $\Lambda_c^+ \to \Xi^0 K^+$ is pure W-exchange process which have significant contributions in charmed baryon decay.
- Nonfactorizable W-exchange diagram cannot be calculated using theoretical approaches.
-
- Long-standing puzzle on how large the S-wave amplitude.
- Experimental measurement of decay asymmetry is crucial and urgent.

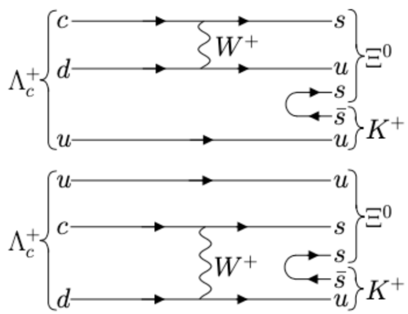
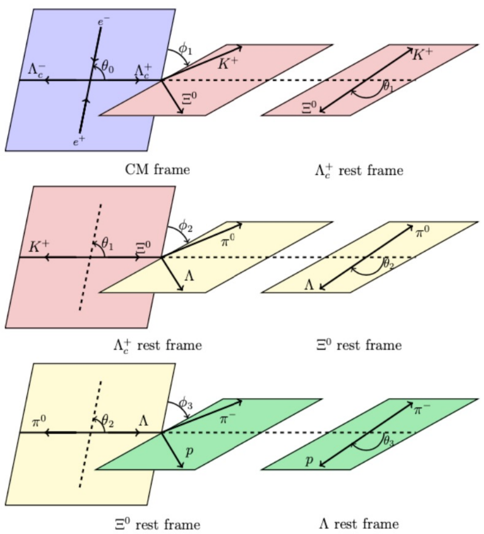


FIG. 1. Feynman diagrams for $\Lambda_c^+ \to \Xi^0 K^+$

Decay asymmetry parameter in $\Lambda_c^+ \to \Xi^0 K^+$

$$\alpha_{BP} = \frac{2\mathrm{Re}(s^* p)}{|s|^2 + |p|^2}, \quad \beta_{BP} = \frac{2\mathrm{Im}(s^* p)}{|s|^2 + |p|^2}, \quad \gamma_{BP} = \frac{|s|^2 - |p|^2}{|s|^2 + |p|^2},$$

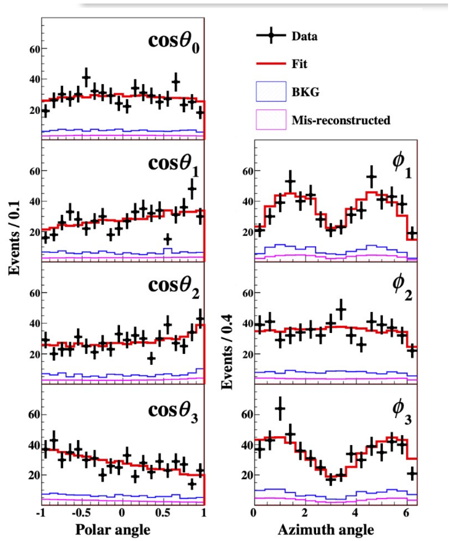
Level	Decay	Helicity angle	Helicity amplitude
0	$e^+e^- \to \Lambda_c^+(\lambda_1)\bar{\Lambda}_c^-(\lambda_2)$	(θ_0)	A_{λ_1,λ_2}
1	$\Lambda_c^+ \to \Xi^0(\lambda_3)K^+$	(θ_1,ϕ_1)	B_{λ_3}
2	$\Xi^0 \to \Lambda(\lambda_4)\pi^0$	(θ_2,ϕ_2)	C_{λ_4}
3	$\Lambda \to p(\lambda_5)\pi^-$	(θ_3,ϕ_3)	D_{λ_5}



$$\begin{aligned}
&\frac{d\Gamma}{d\cos\theta_0\ d\cos\theta_1\ d\cos\theta_2\ d\cos\theta_3\ d\phi_1\ d\phi_2\ d\phi_3} \\
&\propto 1 + \alpha_0\cos^2\theta_0 \\
&+ (1+\alpha_0\cos^2\theta_0)\ \alpha_{\Xi^0 K^+}\alpha_{\Lambda\pi^0}\cos\theta_2 \\
&+ (1+\alpha_0\cos^2\theta_0)\ \alpha_{\Xi^0 K^+}\alpha_{p\pi^-}\cos\theta_2\cos\theta_3 \\
&+ (1+\alpha_0\cos^2\theta_0)\ \alpha_{\Lambda\pi^0}\alpha_{p\pi^-}\cos\theta_3 \\
&- (1+\alpha_0\cos^2\theta_0)\ \alpha_{\Xi^0 K^+}\sqrt{1-\alpha^2_{\Lambda\pi^0}}\ \alpha_{p\pi^-}\sin\theta_2\sin\theta_3\cos(\Delta_{\Lambda\pi^0}+\phi_3) \\
&+ \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\alpha_{\Xi^0 K^+}\sin\theta_1\sin\phi_1 \\
&+ \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\alpha_{\Lambda\pi^0}\sin\theta_1\sin\phi_1\cos\theta_2 \\
&+ \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\alpha_{\Xi^0 K^+}\alpha_{\Lambda\pi^0}\alpha_{p\pi^-}\sin\theta_1\sin\phi_1\cos\theta_3 \\
&+ \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\alpha_{p\pi^-}\sin\theta_1\sin\phi_1\cos\theta_2\cos\theta_3 \\
&- \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Lambda\pi^0}}\ \alpha_{p\pi^-}\sin\theta_1\sin\phi_1\sin\theta_2\sin\theta_3\cos(\Delta_{\Lambda\pi^0}+\phi_3) \\
&+ \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0 K^+}}\ \alpha_{\Lambda\pi^0}\cos\phi_1\sin\theta_2\sin(\Delta_{\Xi^0 K^+}+\phi_2) \\
&+ \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0 K^+}}\ \alpha_{\Lambda\pi^0}\cos\theta_1\sin\phi_1\sin\theta_2\cos(\Delta_{\Xi^0 K^+}+\phi_2) \\
&+ \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0 K^+}}\ \alpha_{p\pi^-}\cos\theta_1\sin\phi_1\sin\theta_2\cos(\Delta_{\Xi^0 K^+}+\phi_2)\cos\theta_3 \\
&+ \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0 K^+}}\ \alpha_{p\pi^-}\cos\phi_1\sin\theta_2\sin(\Delta_{\Xi^0 K^+}+\phi_2)\cos\theta_3 \\
&- \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0 K^+}}\sqrt{1-\alpha^2_{\Lambda\pi^0}}\ \alpha_{p\pi^-}\cos\theta_1\sin\phi_1\sin(\Delta_{\Xi^0 K^+}+\phi_2)\sin\theta_3\sin(\Delta_{\Lambda\pi^0}+\phi_3) \\
&+ \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0 K^+}}\ \sqrt{1-\alpha^2_{\Lambda\pi^0}}\ \alpha_{p\pi^-}\cos\theta_1\sin\phi_1\cos\theta_2\cos(\Delta_{\Xi^0 K^+}+\phi_2)\sin\theta_3\cos(\Delta_{\Lambda\pi^0}+\phi_3) \\
&+ \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0 K^+}}\sqrt{1-\alpha^2_{\Lambda\pi^0}}\ \alpha_{p\pi^-}\cos\phi_1\cos(\Delta_{\Xi^0 K^+}+\phi_2)\sin\theta_3\sin(\Delta_{\Lambda\pi^0}+\phi_3) \\
&+ \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0 K^+}}\sqrt{1-\alpha^2_{\Lambda\pi^0}}\ \alpha_{p\pi^-}\cos\phi_1\cos\theta_2\sin(\Delta_{\Xi^0 K^+}+\phi_2)\sin\theta_3\cos(\Delta_{\Lambda\pi^0}+\phi_3)
\end{aligned}$$

The joint angular distribution for $\Lambda_c^+ \to \Xi^0 K^+$ is derived based on helicity amplitude

Decay asymmetry parameter in $\Lambda_c^+ \to \Xi^0 K^+$

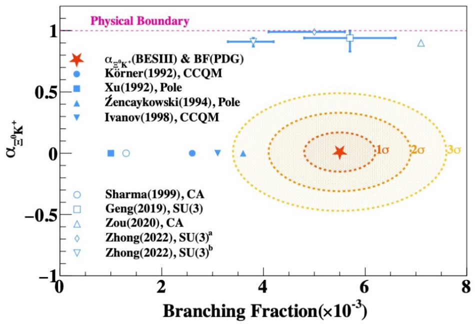


- From the fit, we obtain $\alpha_{\Xi^0 K^+} = 0.01 \pm 0.16_{stat} \pm 0.03_{syst}$ and $\beta_{\Xi^0 K^+} = -0.64 \pm 0.69_{stat} \pm 0.13_{syst}$ and $\gamma_{\Xi^0 K^+} = -0.77 \pm 0.58_{stat} \pm 0.11_{syst}$
- $\alpha_{\Xi^0 K^+}$ is in good agreement with zero=>strong identification for theoretical predictions.

$$\Gamma = \frac{\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)}{\tau_{\Lambda_c^+}} = \frac{|\vec{p}_c|}{8\pi}\left[\frac{(m_{\Lambda_c^+} + m_{\Xi^0})^2 - m_{K^+}^2}{m_{\Lambda_c^+}^2}|A|^2 + \frac{(m_{\Lambda_c^+} - m_{\Xi^0})^2 - m_{K^+}^2}{m_{\Lambda_c^+}^2}|B|^2\right]$$

$$\alpha_{\Xi^0 K^+} = \frac{2\kappa|A||B|\cos(\delta_p - \delta_s)}{|A|^2 + \kappa^2|B|^2},$$

$$\Delta_{\Xi^0 K^+} = \arctan\frac{2\kappa|A||B|\sin(\delta_p - \delta_s)}{|A|^2 - \kappa^2|B|^2},$$



- Especially, $\cos(\delta_p - \delta_s)$ is measured to close to zero.=>not considered in previous literature.
- Fills the long-standing puzzle on how to model $\alpha_{\Xi^0 K^+}$ and $\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)$ simultaneously.

Decay asymmetry parameter in $\Lambda_c^+ \to \Xi^0 K^+$

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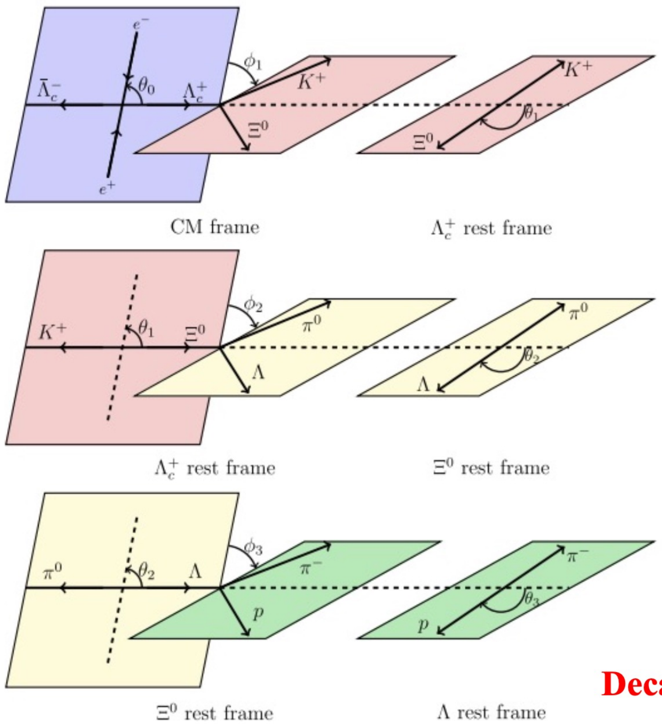
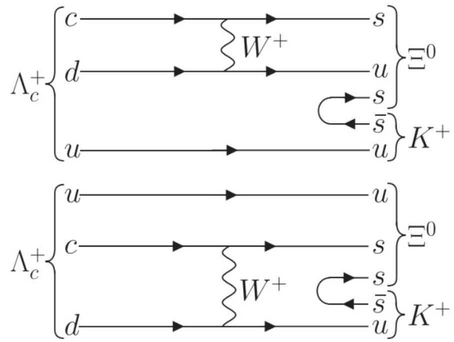
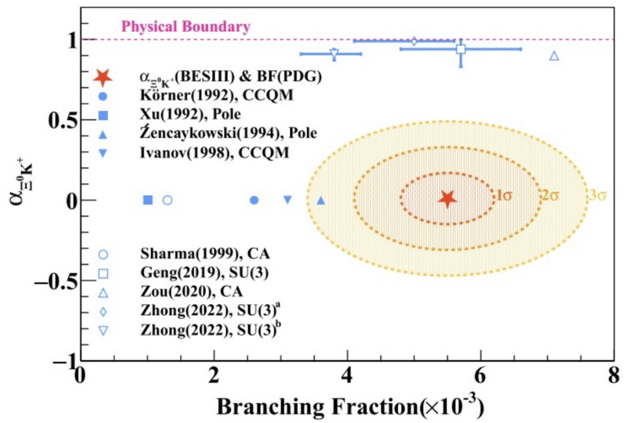
- Helicity frame:



W-boson-exchange decay:



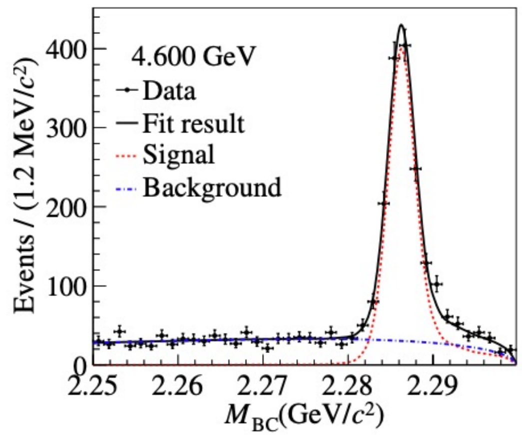


Decay asymmetry parameter: $\alpha = 0.01 \pm 0.16 \pm 0.03$

Phase between S and P wave: $\delta_P - \delta_S = -1.55 \pm 0.25 \pm 0.05, or\ 1.59 \pm 0.25 \pm 0.05$

Partial wave analysis of $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

- BF of decay $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ has been measured by BESIII with high precision [Phys. Rev. Lett. 116, 052001 (2016)], but no previous study on intermediate structure.
- Perform Partial Wave Analysis to obtain the information of intermediate resonances $\rho^+, \Sigma(1385)^+, \Sigma(1385)^0$ and the decay asymmetry.



Signal purity > 80%

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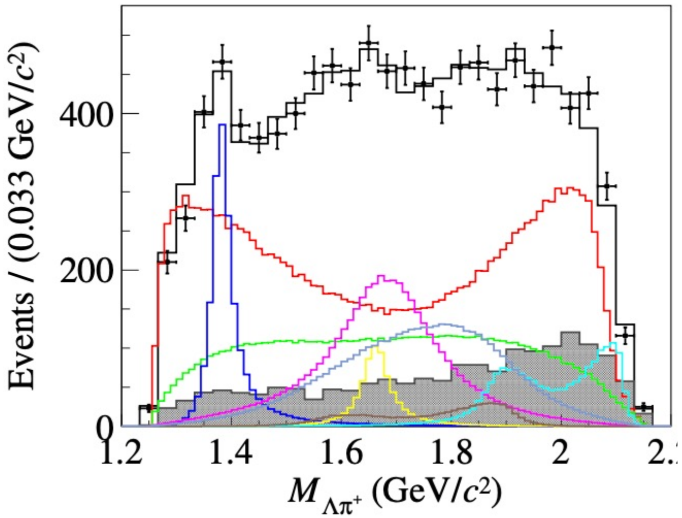
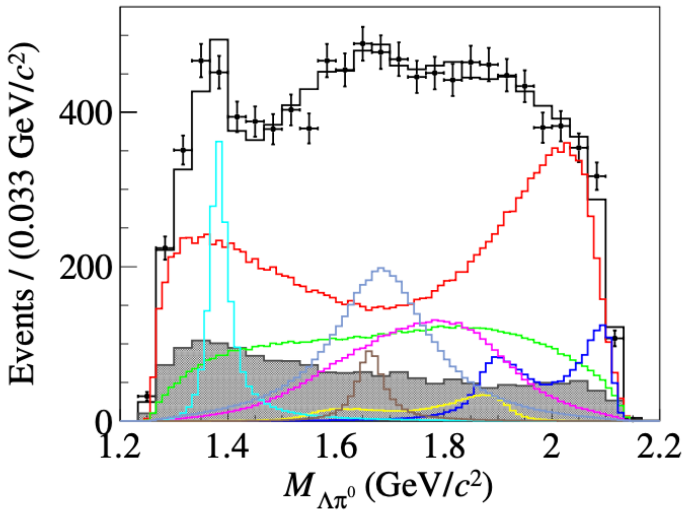
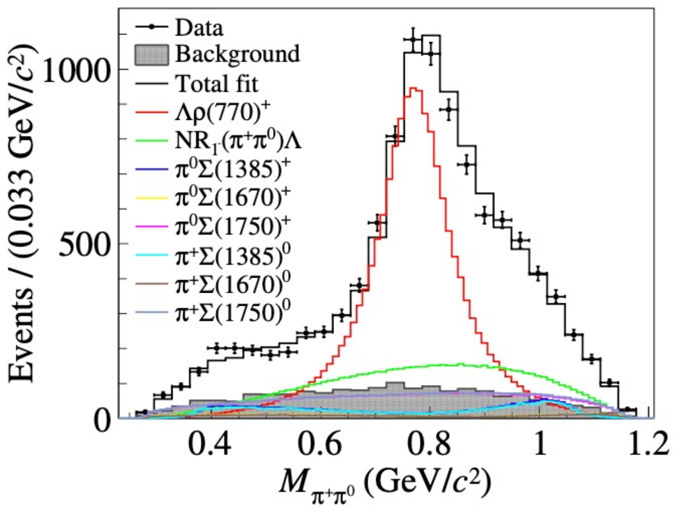






Partial wave analysis of $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

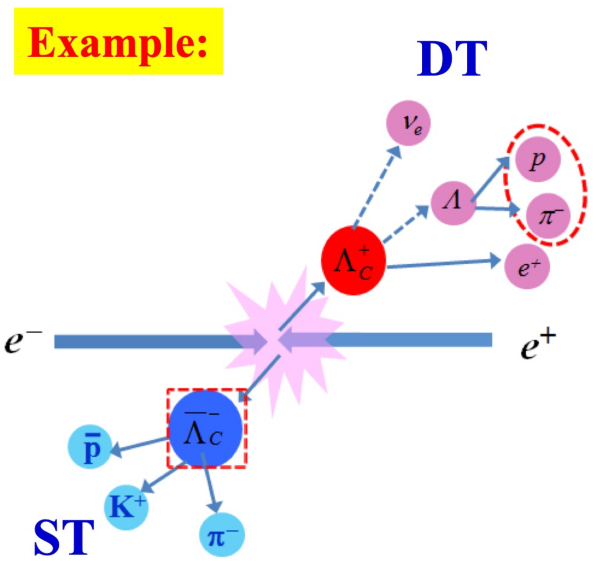
1. The first PWA of the charmed baryon hadronic decay at BESIII.
2. The decay asymmetry parameters for the resonant components are determined for the first time.
3. Consistent with some theoretical predictions. None of them is able to explain both the BFs and the decay asymmetries.

JHEP 12 (2022), 033	Theoretical calculation		This work	PDG
$10^2 \times \mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+)$	4.81 ± 0.58 [13]	4.0 [14, 15]	4.06 ± 0.52	< 6
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0)$	2.8 ± 0.4 [16]	2.2 ± 0.4 [17]	5.86 ± 0.80	—
$10^3 \times \mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^0\pi^+)$	2.8 ± 0.4 [16]	2.2 ± 0.4 [17]	6.47 ± 0.96	—
$\alpha_{\Lambda\rho(770)^+}$	-0.27 ± 0.04 [13]	-0.32 [14, 15]	-0.763 ± 0.070	—
$\alpha_{\Sigma(1385)^+\pi^0}$	$-0.91^{+0.45}_{-0.10}$ [17]		-0.917 ± 0.089	—
$\alpha_{\Sigma(1385)^0\pi^+}$	$-0.91^{+0.45}_{-0.10}$ [17]		-0.79 ± 0.11	—

[13] C. Q. Geng, C. W. Liu and T. H. Tsai, Phys. Rev. D 101 (2020) 053002.
[14] H. Y. Cheng and B. Tseng, Phys. Rev. D 46(1992) 1042.
[15] H. Y. Cheng and B. Tseng, Phys. Rev. D 55 (1997) 1697.
[16] Y. K. Hsiao, Q. Yi, S. T. Cai and H. J. Zhao, Eur. Phys. J. C 80 (2020) 1067.
[17] C. Q. Geng, C. W. Liu, T. H. Tsai and Y. Yu, Phys. Rev. D 99 (2019) 114022.

Production near threshold and tag technique

- $\Lambda_c^+\bar{\Lambda}_c^-$ produced in pairs with no additional accompany hadrons (4.6~4.7 GeV).
- Clean backgrounds and well constrained kinematics.



- Single Tag (ST)

$$\Delta E = E_{\Lambda_c^+} - E_{beam}$$

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

- Double Tags (DT)

$$U_{miss} = E_{miss} - |\vec{p}_{miss}|$$

$$M_{miss} = \sqrt{E_{miss}^2 - |\vec{p}_{miss}|^2}$$

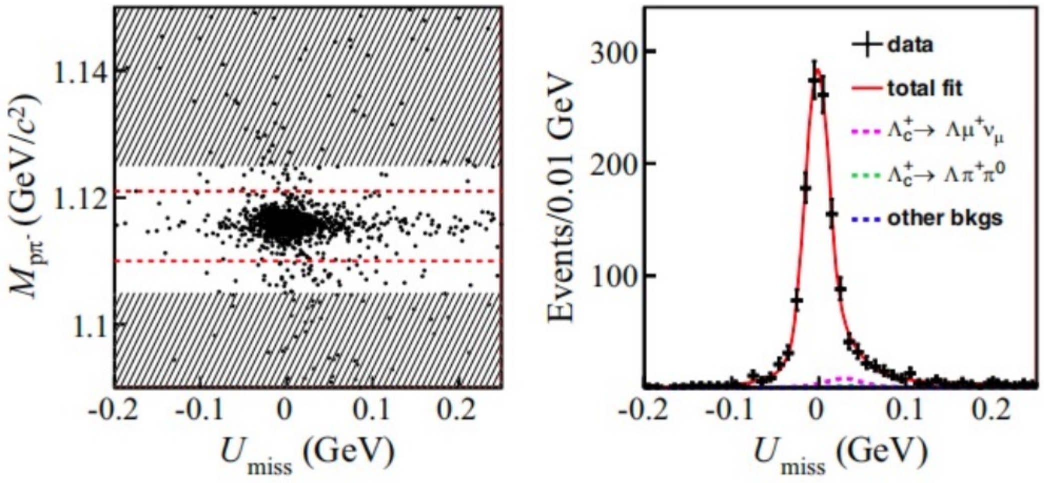
- Branching Fraction ($\mathcal{B}$)

$$\mathcal{B}_{SL} = \frac{N_{SL}}{N^{tag} \times \epsilon}$$

Study of $\Lambda_c^+ \to \Lambda e^+ \nu_e$ decays

- The measurement is done with 4.4 fb^{-1} data from $\sqrt{s}$ = 4.6 − 4.7 GeV.
- The precision of the BF is improved by threefold [Phys. Rev. Lett. 115, 221805 (2015)], providing necessary inputs for testing various theoretical models.
- The first determination of form factors in $\boldsymbol{\Lambda_c^+ \to \Lambda e^+ \nu_e}$ decays.

Phys. Rev. Lett. 129, 231803 (2022)



$\mathcal{B}[\boldsymbol{\Lambda_c^+ \to \Lambda e^+ \nu_e}]$ = (3.56 ± 0.11 ± 0.07)%

	$\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)$ [%]
Constituent quark model (HONR) [8]	4.25
Light-front approach [9]	1.63
Covariant quark model [10]	2.78
Relativistic quark model [11]	3.25
Non-relativistic quark model [12]	3.84
Light-cone sum rule [13]	3.0 ± 0.3
Lattice QCD [14]	3.80 ± 0.22
$SU(3)$ [15]	3.6 ± 0.4
Light-front constituent quark model [16]	3.36 ± 0.87
MIT bag model [16]	3.48
Light-front quark model [17]	4.04 ± 0.75
This work	$3.56 \pm 0.11 \pm 0.07$

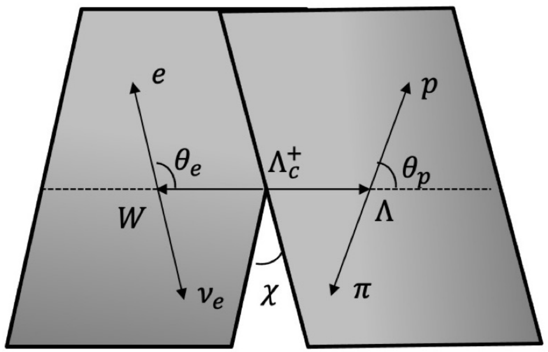
Comparisons between measurement and theoretical predictions.

Study of the kinematics in $\Lambda_c^+ \to \Lambda e^+ \nu_e$ decay

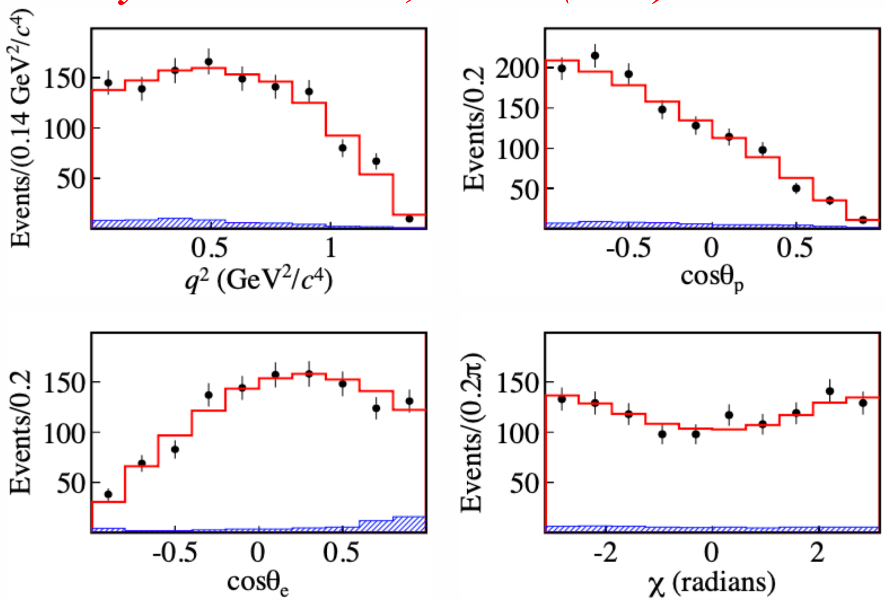
- Helicity amplitude and form factors

$$
\begin{aligned}
\frac{d^4\Gamma}{dq^2 d\cos\theta_e d\cos\theta_p d\chi} = {} & \frac{G_F^2 |V_{cs}|^2}{2(2\pi)^4} \cdot \frac{P q^2}{24 M_{\Lambda_c}^2} \times \\
& \left\{ \frac{3}{8}(1-\cos\theta_e)^2 |H_{\frac{1}{2}1}|^2 (1+\alpha_\Lambda \cos\theta_p) \right. \\
& + \frac{3}{8}(1+\cos\theta_e)^2 |H_{-\frac{1}{2}-1}|^2 (1-\alpha_\Lambda \cos\theta_p) \\
& + \frac{3}{4}\sin^2\theta_e [|H_{\frac{1}{2}0}|^2 (1+\alpha_\Lambda \cos\theta_p) + |H_{-\frac{1}{2}0}|^2 (1-\alpha_\Lambda \cos\theta_p)] \\
& + \frac{3}{2\sqrt{2}} \alpha_\Lambda \cos\chi \sin\theta_e \sin\theta_p \times \\
& \left. [(1-\cos\theta_e) H_{-\frac{1}{2}0} H_{\frac{1}{2}1} + (1+\cos\theta_e) H_{\frac{1}{2}0} H_{-\frac{1}{2}-1}] \right\} \quad (2)
\end{aligned}
$$

$$
\begin{aligned}
H^V_{\frac{1}{2}1} &= \sqrt{2Q_-}\, f_\perp(q^2), \quad H^A_{\frac{1}{2}1} = \sqrt{2Q_+}\, g_\perp(q^2), \\
H^V_{\frac{1}{2}0} &= \sqrt{Q_-/q^2}\, f_+(q^2)\,(M_{\Lambda_c} + M_\Lambda), \\
H^A_{\frac{1}{2}0} &= \sqrt{Q_+/q^2}\, g_+(q^2)\,(M_{\Lambda_c} - M_\Lambda),
\end{aligned}
$$

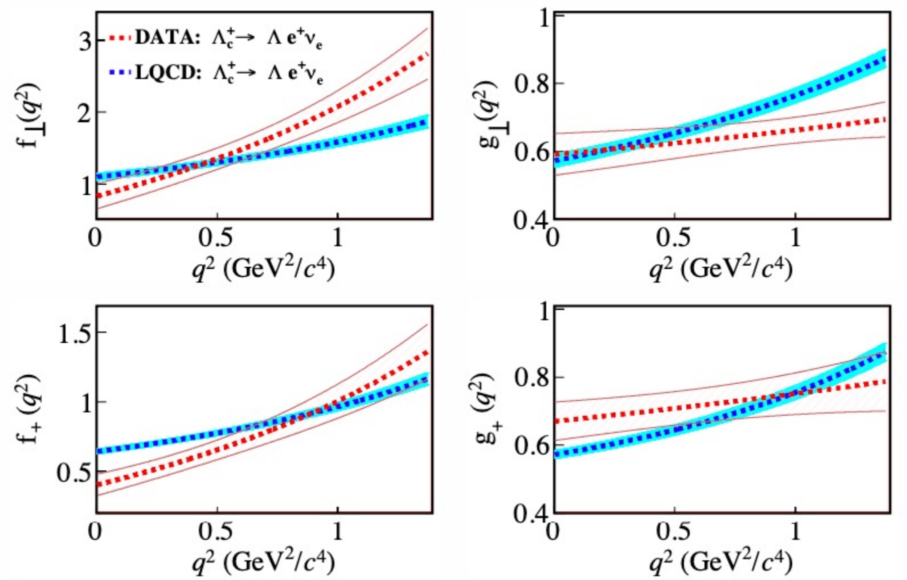


Phys. Rev. Lett. 129, 231803 (2022)

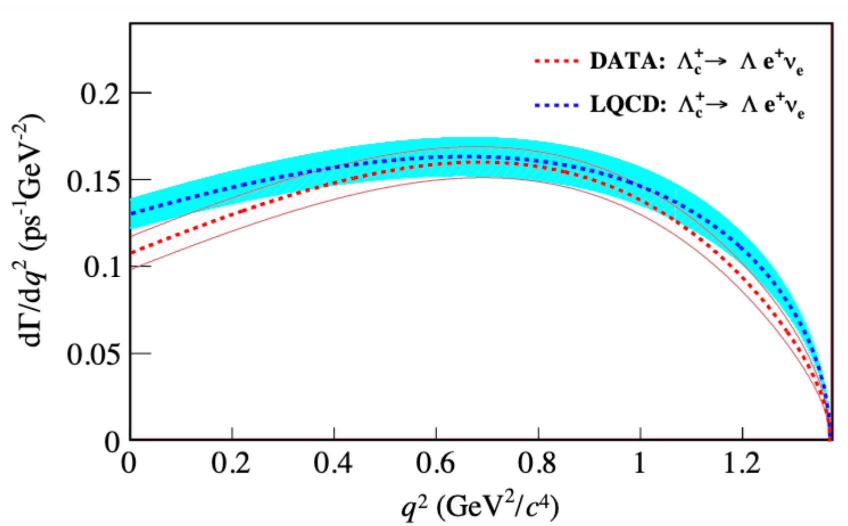


Comparisons between data and LQCD prediction

1.This analysis provides the first direct comparisons on the differential decay rates and form factors with LQCD calculations.
2.Discrepancies can be seen at high q^2 and low q^2 regions. The measurement result tends to have steeper slope than those from LQCD calculations.
2. The results provide important inputs in understanding the SL decays of charmed baryons and help to calibrate the theoretical calculation.



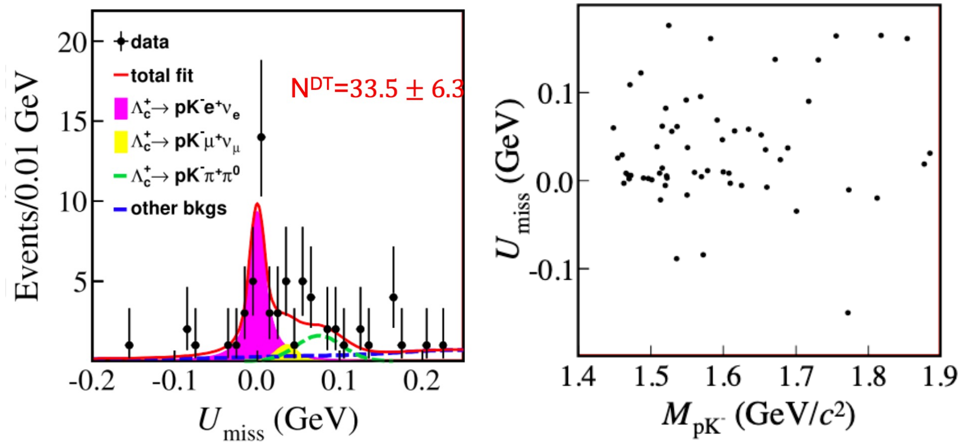
Phys. Rev. Lett. 129, 231803 (2022)



Observation of $\Lambda_c^+ \to pK^-e^+\nu_e$

Phys. Rev. D 106, 112010 (2023)

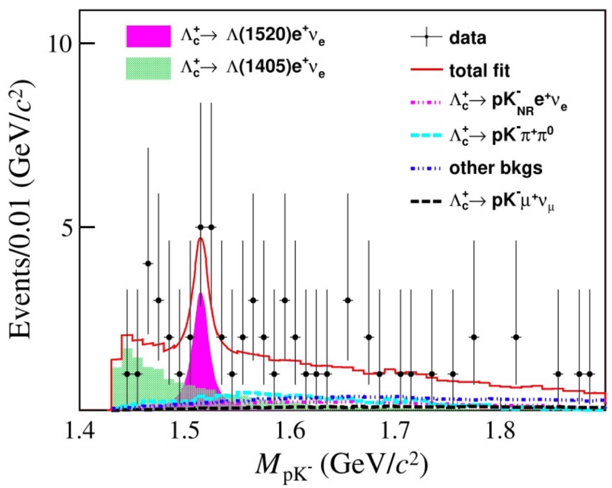
- The data we used is about 4.4 fb^{-1} data from $\sqrt{s}$ = 4.6 – 4.7 GeV.
- The new observed SL decay mode
- $\mathcal{B}(\boldsymbol{\Lambda_c^+ \to pK^-e^+\nu_e}) = (\mathbf{0.88 \pm 0.15 \pm 0.07}) \times \mathbf{10^{-3}}$
- Significance : 8.2σ
- This work provides a clear confirmation that the SL $\boldsymbol{\Lambda_c^+}$ decays are not saturated by the $\boldsymbol{\Lambda\ell^+\nu_\ell}$ final state.
- Study of pK^- mass spectrum can be used to understand the nature of excited Λ^* states.



	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e)$	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1405)e^+\nu_e)$
Constituent quark model [8]	1.01	3.04
Molecular state [9]	−−	0.02
Nonrelativistic quark model [10]	0.60	2.43
Lattice QCD [12, 13]	0.512 ± 0.082	−−
Measurement	$1.02 \pm 0.52 \pm 0.11$	$\frac{0.42\pm0.19\pm0.04}{\mathcal{B}(\Lambda(1405)\to pK^-)}$

Evidence of $\Lambda_c^+ \to \Lambda^*(\to pK^-)e^+\nu$

Phys. Rev. D 106, 112010 (2023)



	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e)$	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1405)e^+\nu_e)$
Constituent quark model [8]	1.01	3.04
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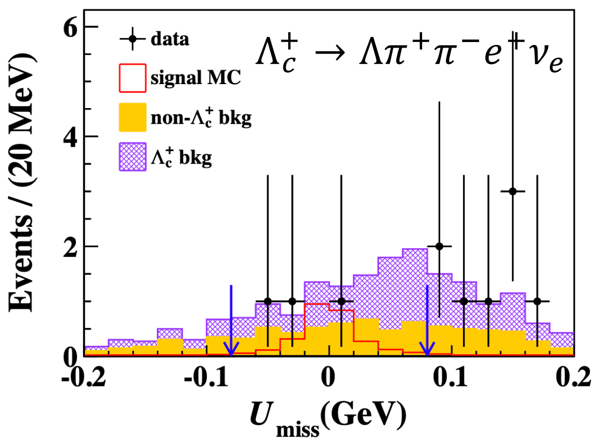
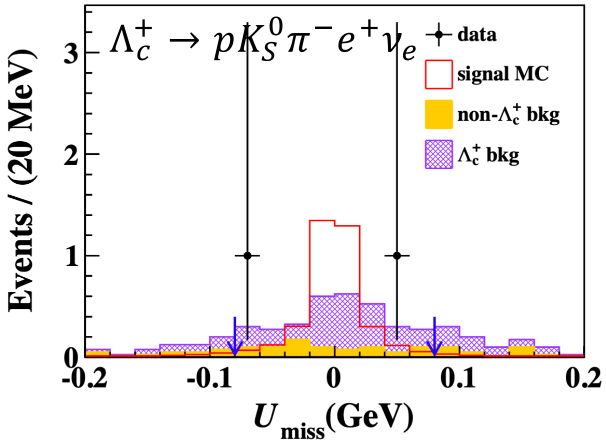
Lattice QCD [12, 13]	0.512 ± 0.082	−−
Measurement	$1.02 \pm 0.52 \pm 0.11$	$\frac{0.42\pm0.19\pm0.04}{\mathcal{B}(\Lambda(1405)\to pK^-)}$

$\mathcal{B}(\Lambda_c^+ \to \Lambda\,(1520)[\to pK^-]e^+\nu_e) = (0.23 \pm 0.12 \pm 0.02)\times10^{-3}$ significance : 3.3σ
$\mathcal{B}(\Lambda_c^+ \to \Lambda\,(1405)[\to pK^-]e^+\nu_e) = (0.42 \pm 0.19 \pm 0.04)\times10^{-3}$ significance : 3.2σ

- The measured $\mathcal{B}(\Lambda_c^+ \to \Lambda\,(1520)[\to pK^-]e^+\nu_e)$ is consistent with these theoretical calculations within two standard deviations.

Search for $\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e$ and $\Lambda_c^+ \to pK_S^0\pi^-e^+\nu_e$





$\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e) < 3.9\times10^{-4}$ $\mathcal{B}\left(\Lambda_c^+ \to pK_S^0\pi^-e^+\nu_e\right) < 3.3\times10^{-4}$

Λ^* state	CQM [8]	NRQM [9]	LFQM [10]	LQCD [11]
$\Lambda(1520)$	10.00	5.94	—	5.12 ± 0.82
$\Lambda(1600)$	4.00	1.26	(0.7 ± 0.2)	—
$\Lambda(1890)$	—	3.16×10^{-2}	—	—
$\Lambda(1820)$	—	1.32×10^{-2}	—	—

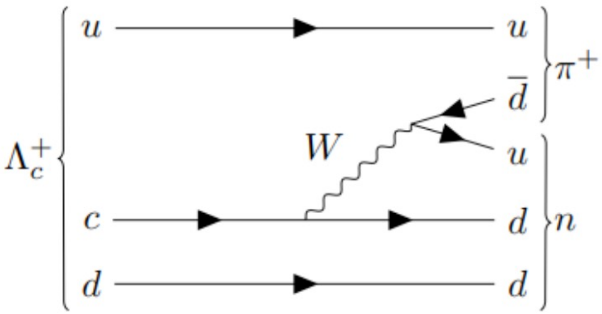
The predicted Branching fractions of $\Lambda_c^+ \to \Lambda^* e^+\nu_e$ in units of 10^{-4}.

PLB 843,137993(2023)

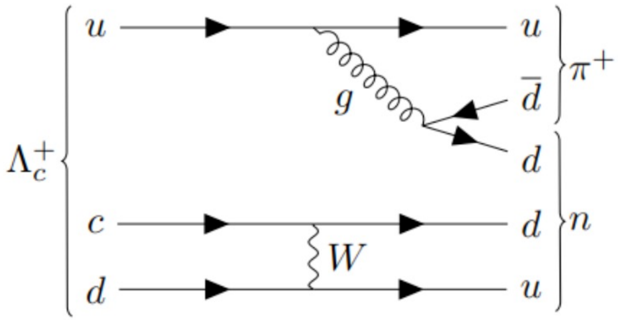
- Many theoretical calculations concerning $\Lambda_c^+ \to \Lambda^*$ form factors and Branching fractions.
- No significant signals are observed, and the upper limits on the decay branching fractions are obtained.
- Assuming all the $\Lambda\pi\pi$ combinations come from Λ^* :
  - $\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e) < 4.3\times10^{-3}$
  - $\mathcal{B}(\Lambda_c^+ \to \Lambda(1600)e^+\nu_e) < 9.0\times10^{-3}$
  - Due to the limitation of statistics, the results are consistent with all theoretical calculations.
  - $\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e)$ is consistent with the one measured via $\mathbf{\Lambda_c^+} \to \mathbf{\Lambda}\,(\mathbf{1520})[\to \mathbf{pK^-}]\mathbf{e^+}\boldsymbol{\nu_e}$ [Phys. Rev. D 106, 112010 (2023)].

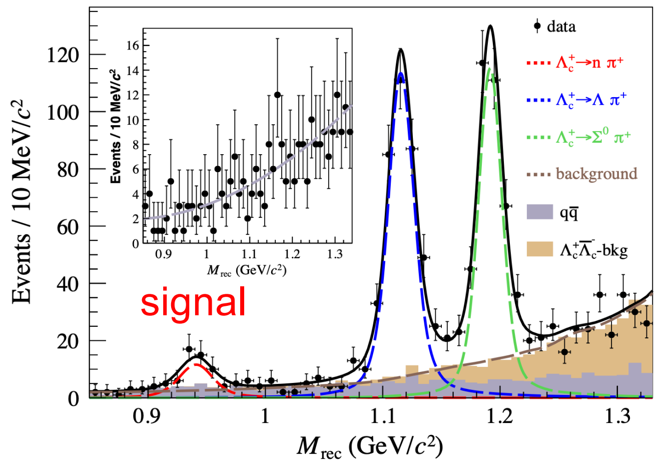
Measurement of $\Lambda_c^+ \to n\pi^+$

Internal W emission



W exchange





Experimental input

Phys. Rev. Lett. 128, 142001 (2022)

- Studies of nonfactorizable components are critical to understanding the underlining dynamics of charmed baryon decays.

$$M_{rec}^2 = (E_{beam} - E_{\pi^+})^2/c^4 - |\rho \cdot \vec{p}_0 - \vec{p}_{\pi^+}|^2/c^2$$

- $\rho = \sqrt{E_{beam}^2/c^2 - m_{\Lambda_c^+}^2 c^2}$
- $\vec{p}_0 = -\vec{p}_{\bar{\Lambda}_c^-}/|\vec{p}_{\bar{\Lambda}_c^-}|$ is the unit direction opposite to the ST $\bar{\Lambda}_c^-$

Measurement of $\Lambda_c^+ \to n\pi^+$

- The branching fraction and R value disagrees with the most predictions of phenomenological models, implying that the non-factorization contributions are overestimated.
- The results from this analysis provide an essential input for the phenomenological studies on the underlying dynamics of charmed baryon decays.

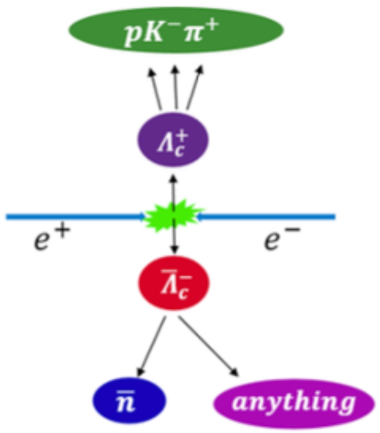
Phys. Rev. Lett. 128, 142001 (2022)

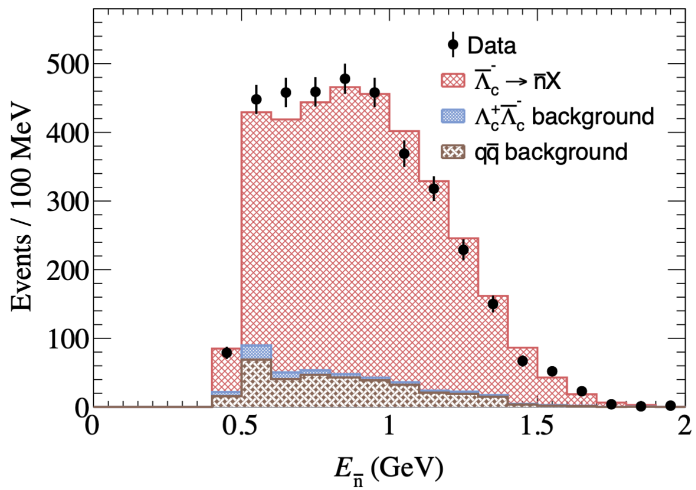
- $\mathcal{B}(\Lambda_c^+ \to n\pi^+) = (6.6 \pm 1.2 \pm 0.4)\times 10^{-4}$
- $\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+) = (1.31 \pm 0.08 \pm 0.05)\times 10^{-2}$
- $\mathcal{B}(\Lambda_c^+ \to \Sigma^0\pi^+) = (1.22 \pm 0.08 \pm 0.07)\times 10^{-2}$
- $R = \frac{\mathcal{B}(\Lambda_c^+ \to n\pi^+)}{\mathcal{B}(\Lambda_c^+ \to p\pi^0)} > 7.2\ at\ 90\%\ \mathrm{C.L.}$同位旋对称
- Use $\mathcal{B}(\Lambda_c^+ \to p\pi^0) < 8.0\times 10^{-5}\ at\ 90\%\ \mathrm{C.L.}$ of Belle from PRD 103, 072004 (2021)

$\mathcal{B}(\Lambda_c^+ \to n\pi^+) \times 10^{-4}$	R	Reference
4	2	PRD 55, 7067 (1997)
9	2	PRD 93, 056008 (2016)
11.3 ± 2.9	2	PRD 97, 073006 (2018)
8 or 9	4.5 or 8.0	PRD 49, 3417 (1994)
2.66	3.5	PRD 97, 074028 (2018)
6.1 ± 2.0	4.7	PLB 790, 225 (2019)
7.7 ± 2.0	9.6	JHEP 02 (2020) 165

Measurement of $\overline{\Lambda}_c^- \to \bar{n}X$

PRD 108, L031101(2023)

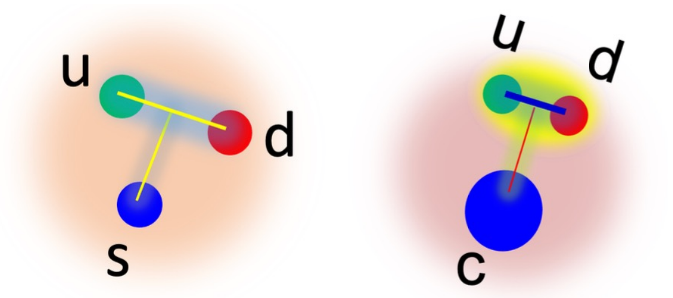




- Data-driven technique to model $\bar{n}$ behavior in the detector.
- The deposited energy in EMC ($E_{\bar{n}}$) is used to identify $\bar{n}$.
- $\mathcal{B}(\overline{\Lambda}_c^- \to \bar{n}X) = (32.5 \pm 0.7 \pm 1.5)\%$
- The branching fraction of the inclusive decay is greater than the sum of the known exclusive decays, that is about 25%, which means that about one-fourth of the Λ_c^+ decays with a neutron in the final state remain to be explored in experiments.
- The result indicates the existence of an asymmetry in $\mathcal{B}(\Lambda_c^+ \to nX)$ and $\mathcal{B}(\Lambda_c^+ \to pX)$.

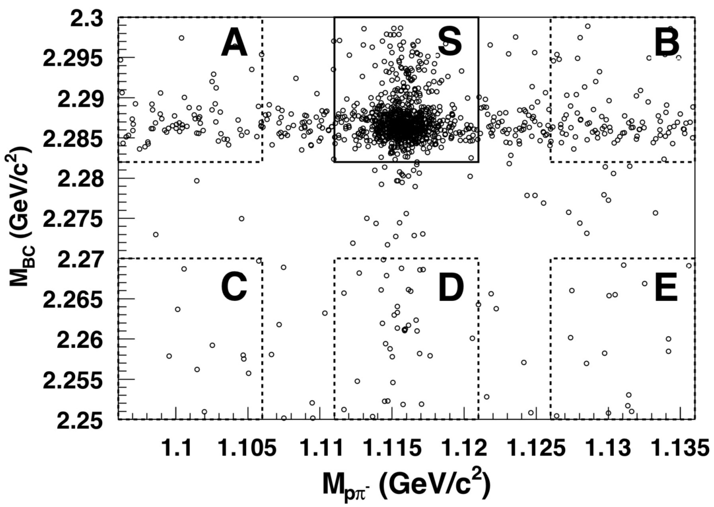
The inclusive channel $\Lambda_c^+ \to \Lambda + X$

- 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.



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

PRL 121, 062003(2018)



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

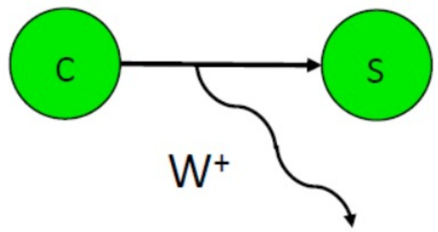
- In the ST modes of $\Lambda_c^+ \to pK^-\pi^+$ and pK_S^0, to measure the probability of find a Λ in the final states.
- Extract yields from 2D distributions in bins of p−$|cos\theta|$
- Data-driven 2D efficiency correction using several Λ control samples.
- $\mathcal{B}(\Lambda_C^+ \to \Lambda + X) = (38.2^{+2.8}_{-2.2} \pm 0.8)\%$
  (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.)

First measurement $\Lambda_c^+ \to K_S^0 X$

$K^+ = u\,\bar{s},\ K^0 = d\,\bar{s},\ \overline{K}^0 = \bar{d}\,s,\ K^- = \bar{u}\,s,$

EPJC 80, 935 (2020)

- The Λ_c^+ Cabibbo-favored (CF) decay dominantly includes $\Lambda_c^+ \to \Lambda X$ and $\Lambda_c^+ \to KX$ ($K^\pm, K^0, \bar{K}^0$).
- Measuring the BF of $\Lambda_c^+ \to K_S^0 X$ can provide an important information for understanding the missing CF decay modes.
- Comparing the BF of $\Lambda_c^+ \to K_S^0 X$ with that of the charmed mesons provides some information about the nature of these charmed particles.



Cabibbo-favored decay

PDG result

$\boldsymbol{\mathcal{B}(D^0 \to K_S^0 + X) = (20.75 \pm 0.23)\%}$

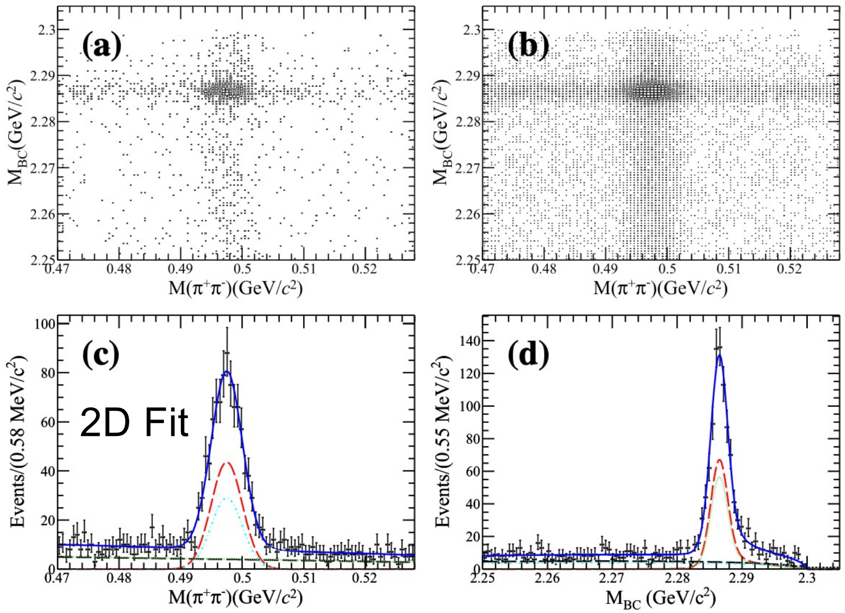
$\boldsymbol{\mathcal{B}(D^+ \to K_S^0 + X) = (33.1 \pm 0.4)\%}$

$\boldsymbol{\mathcal{B}(D_S^+ \to K_S^0 + X) = (19.0 \pm 1.1)\%}$

Inclusive modes

Γ_{100}	e^+ anything	$(4.06 \pm 0.13)\%$
Γ_{101}	p anything	$(50 \pm 16)\%$
Γ_{102}	n anything	$(32.6 \pm 1.6)\%$
Γ_{103}	Λ anything	$(38.2^{+2.9}_{-2.4})\%$
Γ_{104}	K_S^0 anything	$(9.9 \pm 0.7)\%$
Γ_{105}	3prongs	$(24 \pm 8)\%$

First measurement $\Lambda_c^+ \to K_S X$ EPJC 80, 935 (2020)



$$\mathcal{B}(\Lambda_c^+ \to K_S^0 + X) = (9.9 \pm 0.6 \pm 0.4)\%$$

$$\mathcal{B}(\Lambda_c^+ \to \bar{K}^0/K^0 + X) = (19.8 \pm 1.2 \pm 0.8 \pm 1.0)\%$$

- The relative deviation between the branching fractions for the inclusive decay and the observed exclusive decays is $(18.7 \pm 8.3)\%$.
- There may be some unobserved decay modes with a neutron or excited baryons in the final state.

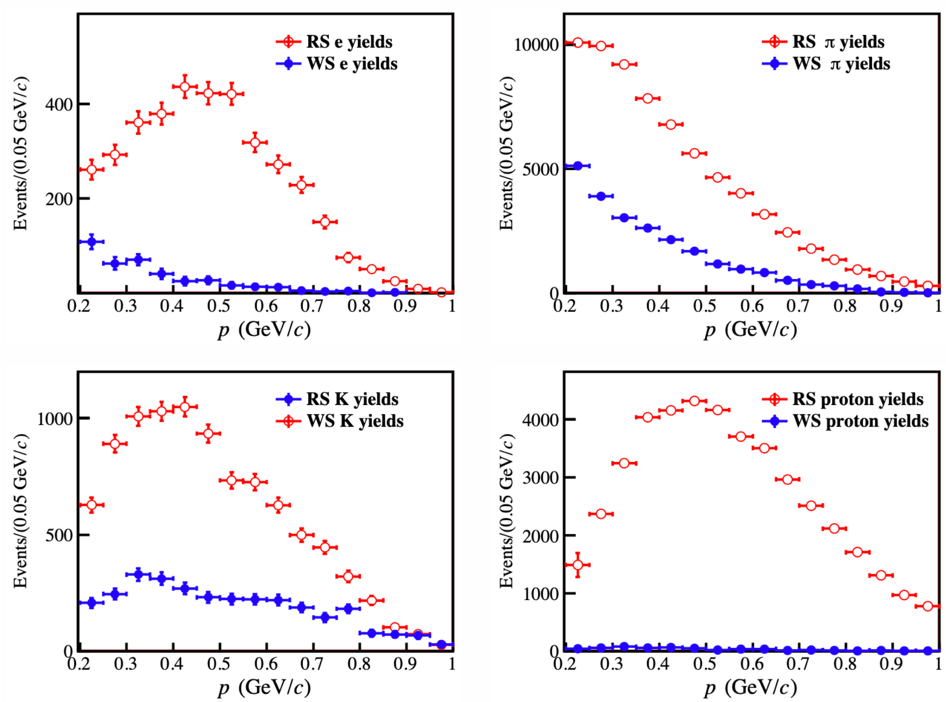
Mode	Value (%)	Mode	Value (%)
Observed BF		Extrapolated BF	
$p\bar{K}^0$	3.18±0.16	$n\bar{K}^0\pi^+\pi^0$	3.07±0.16
$p\bar{K}^0\pi^0$	3.94±0.26	$p\bar{K}^0\pi^0\pi^0$	1.36±0.07
$p\bar{K}^0\pi^+\pi^-$	3.20±0.24	$n\bar{K}^0\pi^+\pi^+\pi^-$	0.14±0.09
$n\bar{K}^0\pi^+$	3.64±0.50	$p\bar{K}^0\pi^+\pi^-\pi^0$	0.22±0.14
$p\bar{K}^0\eta$	1.60±0.40	$n\bar{K}^0\pi^+\pi^0\pi^0$	0.10±0.06
$\Lambda K^+\bar{K}^0$	0.57±0.11	$p\bar{K}^0\pi^0\pi^0\pi^0$	0.03±0.02
		$(\Sigma K)^+\bar{K}^0$	0.68±0.34
		$\Xi^0 K^0\pi^+$	0.62±0.06
Total	16.1 ± 0.8	Total	6.3 ± 0.4
Total		22.4±0.9	

Inclusive SL decay $\Lambda_c^+ \to X e^+ \nu_e$

Phys. Rev. D 107, 052005 (2023)

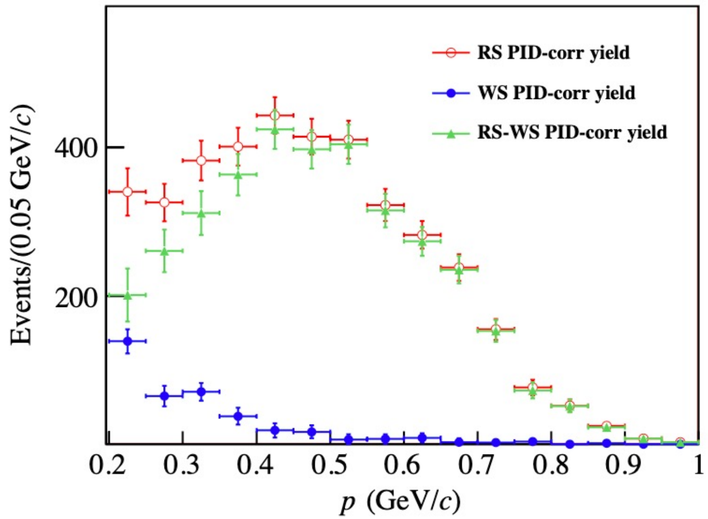
- Further $\mathbf{\Lambda_c^+}$ SL decays may exist.
- Comparing with the charge-averaged non-strange D SL decay width is helpful for testing current theoretical predictions.
- Unfolding method to obtain true signal yields. The matrix can be obtained using selected control samples.

$$\begin{bmatrix} N_e^{\rm obs} \\ N_\pi^{\rm obs} \\ N_K^{\rm obs} \\ N_p^{\rm obs} \end{bmatrix} = \begin{bmatrix} P_{e\to e} & P_{\pi\to e} & P_{K\to e} & P_{p\to e} \\ P_{e\to\pi} & P_{\pi\to\pi} & P_{K\to\pi} & P_{p\to\pi} \\ P_{e\to K} & P_{\pi\to K} & P_{K\to K} & P_{p\to K} \\ P_{e\to p} & P_{\pi\to p} & P_{K\to p} & P_{p\to p} \end{bmatrix} \begin{bmatrix} N_e^{\rm true} \\ N_\pi^{\rm true} \\ N_K^{\rm true} \\ N_p^{\rm true} \end{bmatrix}$$

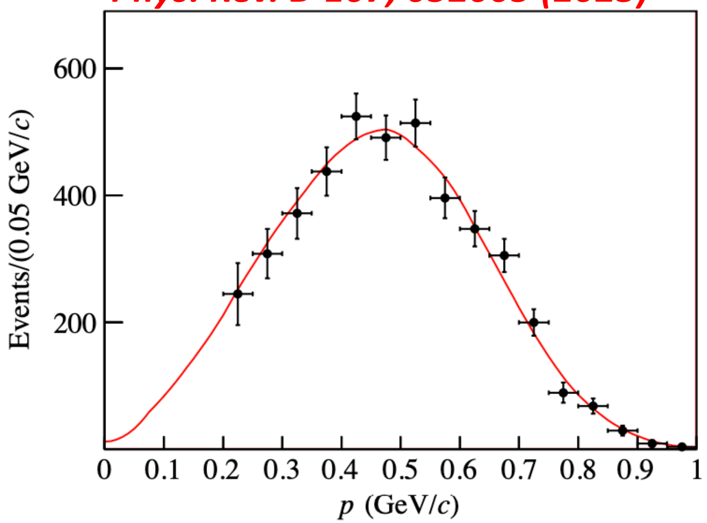


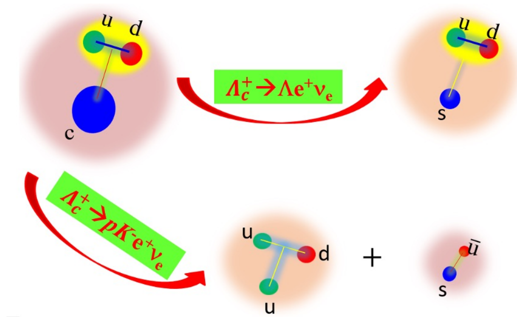
RS (WS) :the charge of the track is required to be opposite (equal) to the ST $\mathbf{\Lambda_c^-}$ candidate.

Inclusive SL decay $\Lambda_c^+ \to X e^+ \nu_e$



Phys. Rev. D 107, 052005 (2023)





Correction (see text)	RS yields	WS yields
Observed yields	3706 ± 71	394 ± 31
PID unfolding yields	3865 ± 80	376 ± 33
WS subtraction	3489 ± 87	
Tracking unfolding yields	4333 ± 107	
Extrapolation	4692 ± 117	

- $\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e) = (4.06 \pm 0.10 \pm 0.09)\%$

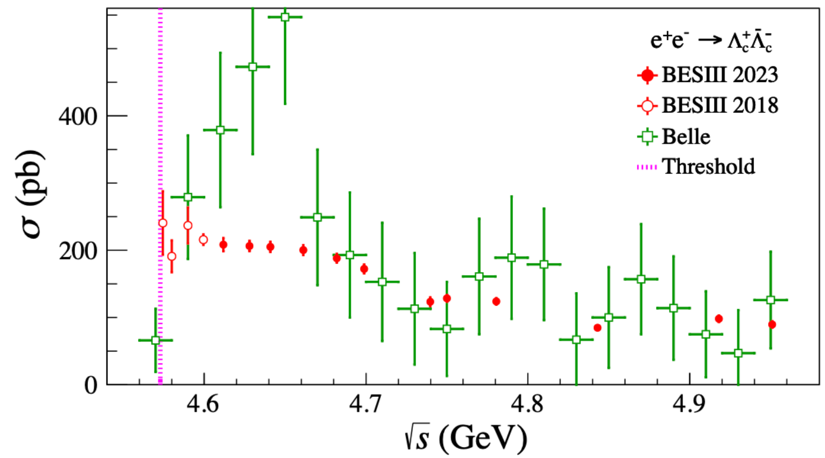
The precision is improved by threefold [Phys. Rev. Lett. 121, 251801 (2018)].

- $$\frac{\Gamma(\Lambda_c^+ \to X e^+ \nu_e)}{\bar{\Gamma}(D \to X e^+ \nu_e)} = 1.28 \pm 0.05,$$

$\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e) = (4.06 \pm 0.10 \pm 0.09)\%$
$\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.56 \pm 0.11 \pm 0.07)\%$
$\mathcal{B}(\Lambda_c^+ \to p K^- e^+ \nu_e) = (0.88 \pm 0.15 \pm 0.07)\times 10^{-3}$

Unknow decay: 0.5%

Energy-Dependent Electromagnetic Form Factors of Λ_c^+



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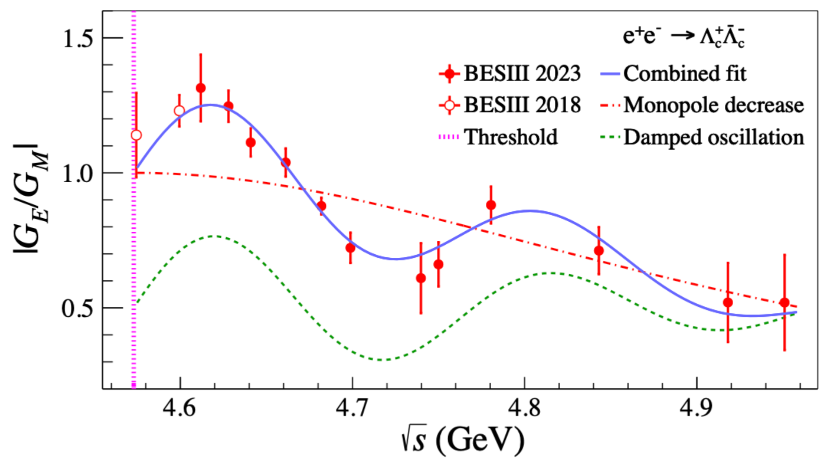


- The Born cross sections and effective form factors ($|G_{\rm eff}|$) are determined.

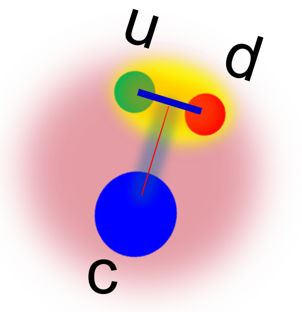
$$\sigma_\pm = \frac{N^\pm_{\rm ST}}{\varepsilon^\pm_{\rm ST} f_{\rm ISR} f_{\rm VP} \mathcal{L}_{\rm int} \mathcal{B}_\pm}, \quad |G_{\rm eff}| = \sqrt{\frac{\sigma}{\frac{\sigma_0}{3}\left(1+\frac{\kappa}{2}\right)}},$$

- No indication of the resonant structure Y (4630), as reported by Belle [Phys. Rev. Lett. 101, 172001 (2008)].
- No oscillatory behavior is discerned in the $|G_{\rm eff}|$ energy-dependence of Λ_c^+, in contrast to what is seen for the proton and neutron cases.
- Form factor ratio $|G_E/G_M|$ is observed, which can be well described by an oscillatory function.

$$|G_E/G_M|(s) = \frac{1}{1+\omega^2/r_0}\left[1 + r_1 e^{-r_2\omega}\sin(r_3\omega)\right],$$

Summary

- Studying the Λ_c^+ decays allows a deeper understanding charmed baryon.
- Threshold data at BESIII opens a new door to direct measurements of the decays : precise study of Λ_c^+ decays
- The knowledge of Λ_c^+ decays is still very limited in comparison with charmed mesons.



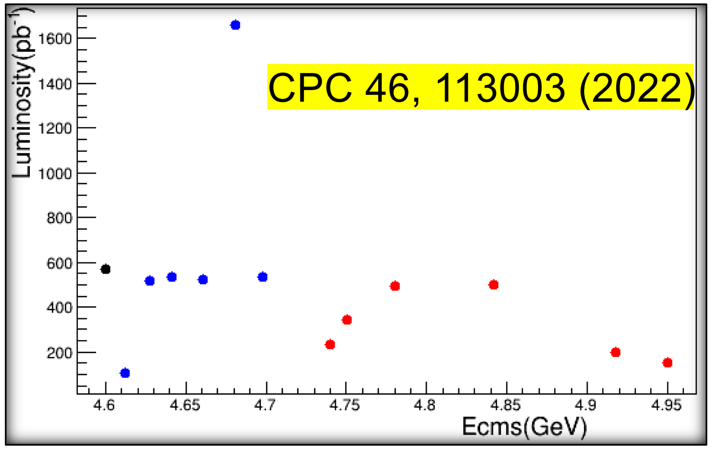
	Leading hadronic decay	Typical two-body decay
Λ_c^+	$\mathcal{B}(K^- p\pi^+)=$ 2014: (5.0±1.3)% (26%) 2017(w/ BESIII): (6.35±0.33)% (5.2%) 5 fb^{-1}: $\frac{\delta\mathcal{B}}{\mathcal{B}}$ <2%	$\mathcal{B}(K_S^0 p)=$ 2014: (1.2±0.3)% (26%) BESIII: (1.52±0.08)% (5.6%) 5 fb^{-1}: $\frac{\delta\mathcal{B}}{\mathcal{B}}$ <2%
D^0	$\mathcal{B}(K^-\pi^+)$ =(3.89±0.04)% (1.0%)	$\mathcal{B}(K_S^0\pi^0)$ =(1.19±0.04)% (3.4%)
D^+	$\mathcal{B}(K^-\pi^+\pi^+)$ =(8.98±0.28)% (3.1%)	$\mathcal{B}(K_S^0\pi^+)$ =(1.47±0.08)% (5.4%)
D_s^+	$\mathcal{B}(K^-K^+\pi^+)$ =(5.45±0.17)% (3.8%)	$\mathcal{B}(K_S^0K^+)$ =(1.40±0.05)% (3.6%)

CPC 44,040001 (2020)

Prospects in Λ_c^+ physics

CPC 44,040001 (2020)

- Amplitude analyses
  - The multi-body final states. such as $\Lambda_c^+ \to pK^-\pi^+, pK_S^0\pi^0$. From these analyses, additional two-body decay patterns can be extracted.
  - Provide a good opportunity to study the light hadron spectroscopy, such as the study of $\Lambda^*$and scalar meson.
- The EM form factor of charmed baryons
- Asymmetry parameter
- CP violation



CPC 46, 113003 (2022)