Semi-leptonic Λ_c^+ decays at BESIII

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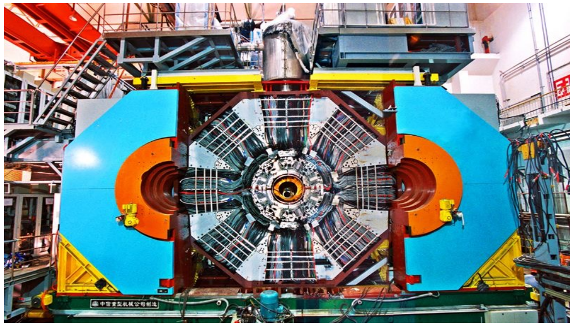
(on behalf of the BESIII collaboration)



Outline

- Introduction
- BESIII experiment
- $\Lambda_c^+ \to \Lambda e^+ \nu_e$ — Based on arXiv:2207.14149
- $\Lambda_c^+ \to p K^- e^+ \nu_e$ — Based on arXiv:2207.11483
- $\Lambda_c^+ \to \Lambda \pi^+ \pi^- e^+ \nu_e$ and $\Lambda_c^+ \to p K_S^0 \pi^- e^+ \nu_e$ — BESIII preliminary
- Other ongoing analysis
- Summary

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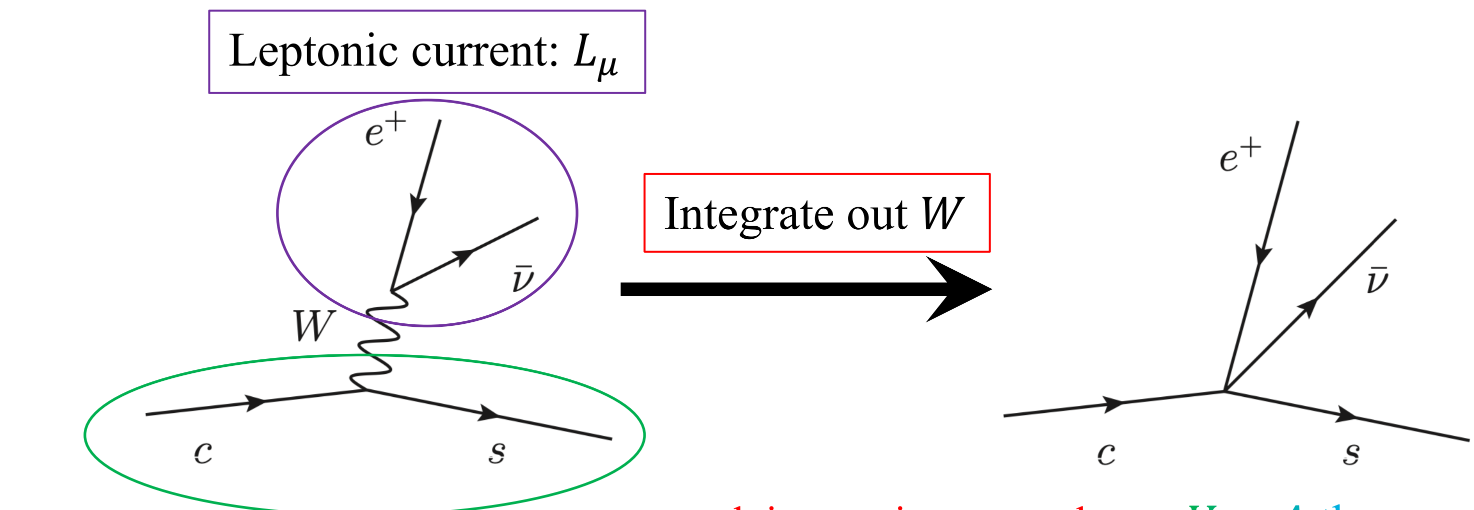
Introduction-Theory(I)

- Weak decay of heavy baryons: $\Lambda_c^+ \to \Lambda(p\pi^-)e^+\nu_e$
- Differential decay width: $d\Gamma = \frac{1}{2m_{\Lambda_c}}(2\pi)^4 d\Phi_4 \overline{|\mathcal{M}|^2}$ → Four-body phase space
- Helicity amplitude formalism: $\mathcal{M} = H^\mu L_\mu$

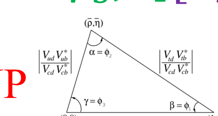


Hadronic current: H^μ

quark interaction strength $V-A$ theory

Weak decay effective Hamiltonian: $\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} V_{cs}^* [\bar{s}\gamma^\mu(1-\gamma_5)c][\bar{\nu}\gamma_\mu(1-\gamma_5)l]$

Test SM and probe NP



Introduction-Theory(II)

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- Leptonic part can be precisely calculated.
- Hadronic part is hard to calculate from first principle, since strong interaction is involved.
- With the help of effective field theory, hadronic amplitude can be parameterized by form factors which are hybrids of on-shell states and off-shell operators.
  - $\langle\Lambda(p_2,s_2)|H_{\rm eff}|\Lambda_c(p_1,s_1)\rangle = \langle\Lambda(p_2,s_2)|(V-A)|\Lambda_c(p_1,s_1)\rangle$ Form factor is a function of transfer momentum $q = p_1 - p_2$
  - $H_V(\lambda)_\mu = \langle\Lambda(p_2,s_2)|V_\mu|\Lambda_c(p_1,s_1)\rangle = \bar{u}(p_2,s_2)\left[\gamma_\mu f_1(q^2) + i\sigma_{\mu\nu}\frac{q^\nu}{m_1}f_2(q^2) + \frac{q^\mu}{m_1}f_3(q^2)\right]u(p_1,s_1)$
  - $H_A(\lambda)_\mu = \langle\Lambda(p_2,s_2)|A_\mu|\Lambda_c(p_1,s_1)\rangle = \bar{u}(p_2,s_2)\left[\gamma_\mu g_1(q^2) + i\sigma_{\mu\nu}\frac{q^\nu}{m_1}g_2(q^2) + \frac{q^\mu}{m_1}g_3(q^2)\right]u(p_1,s_1)$
- $H_{\lambda_\Lambda\lambda_W} = H_\mu(\lambda_\Lambda)\epsilon^\mu(\lambda_W) = [H_V(\lambda_\Lambda) - H_A(\lambda_\Lambda)]_\mu\epsilon^\mu(\lambda_W) = H_V(\lambda_\Lambda\lambda_W) - H_A(\lambda_\Lambda\lambda_W)$
- Six helicity amplitude: $H_V\left(\frac{1}{2},0\right)$, $H_V\left(\frac{1}{2},1\right)$, $H_V\left(\frac{1}{2},t\right)$, $H_A\left(\frac{1}{2},0\right)$, $H_A\left(\frac{1}{2},1\right)$, $H_A\left(\frac{1}{2},t\right)$
- In the limit of negligible lepton mass, only four of them remained: ~~$H_V\left(\frac{1}{2},t\right)$~~, ~~$H_A\left(\frac{1}{2},t\right)$~~
- Decay asymmetry: $\alpha_{\Lambda_c} = \frac{|H_{1/2\;1}|^2 - |H_{-1/2\;-1}|^2 + |H_{1/2\;0}|^2 - |H_{-1/2\;0}|^2}{|H_{1/2\;1}|^2 + |H_{-1/2\;-1}|^2 + |H_{1/2\;0}|^2 + |H_{-1/2\;0}|^2}$
- How to obtain FF in theory?
  - **Model prediction: NRQM, MIT bag model, RQM, LFQM, QCD sum rules, SU(3) flavor symmetry**
  - **LQCD**

- In 2015, BESIII reported the first measurement of absolute branching fraction(BF)
  - $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.63 \pm 0.38_{\text{stat.}} \pm 0.20_{\text{syst.}})\%$
  - $\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu) = (3.49 \pm 0.46_{\text{stat.}} \pm 0.27_{\text{syst.}})\%$ } **Exclusive**
  - $\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e) = (3.95 \pm 0.34_{\text{stat.}} \pm 0.09_{\text{syst.}})\%$ } **Inclusive**

- What about other decays: $\Lambda_c \to \Lambda(1520), \Lambda(1405), \Lambda(1600)$?
  - $\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)}{\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e)} = (91.9 \pm 12.5_{\text{stat.}} \pm 5.4_{\text{syst.}})\%$ **~1**
  - $\frac{\mathcal{B}(D^0 \to K^- e^+ \nu_e)}{\mathcal{B}(D^0 \to X e^+ \nu_e)} = (54.7 \pm 1.0)\%$ **~0.5**

Table 1: BFs of the SL decay $\Lambda_c^+ \to \Lambda^* e^+ \nu_e$ compared with different theoretical estimations. To distinguish different papers using constituent quark model, HR denotes Hussain and Roberts, PRCI denotes Pervin, Roberts and Capstick. All the values are given in unit ot %.

State	HR [28]	PRCI [17]	Chiral unitary approach [29]	Light-front quark model [31]	Lattice QCD [32]
$\Lambda(1405)\frac{1}{2}^-$	0.24	0.38	$(2-5)\times 10^{-3}$	0.31 ± 0.08	—
$\Lambda(1520)\frac{3}{2}^-$	5.94×10^{-2}	10.00×10^{-2}	—	—	$(5.12\pm 0.82)\times 10^{-2}$
$\Lambda(1600)\frac{1}{2}^+$	1.26×10^{-2}	4.00×10^{-2}	—	$(7\pm 2)\times 10^{-3}$	—
$\Lambda(1890)\frac{3}{2}^+$	3.16×10^{-4}	—	—	—	—
$\Lambda(1820)\frac{5}{2}^+$	1.32×10^{-4}	—	—	—	—

- Goals:
  - Improve the precision of BF
  - Measurement of form factors $\Lambda_c \to \Lambda$
  - Search for more Λ_c semi-leptonic(SL) decay channels

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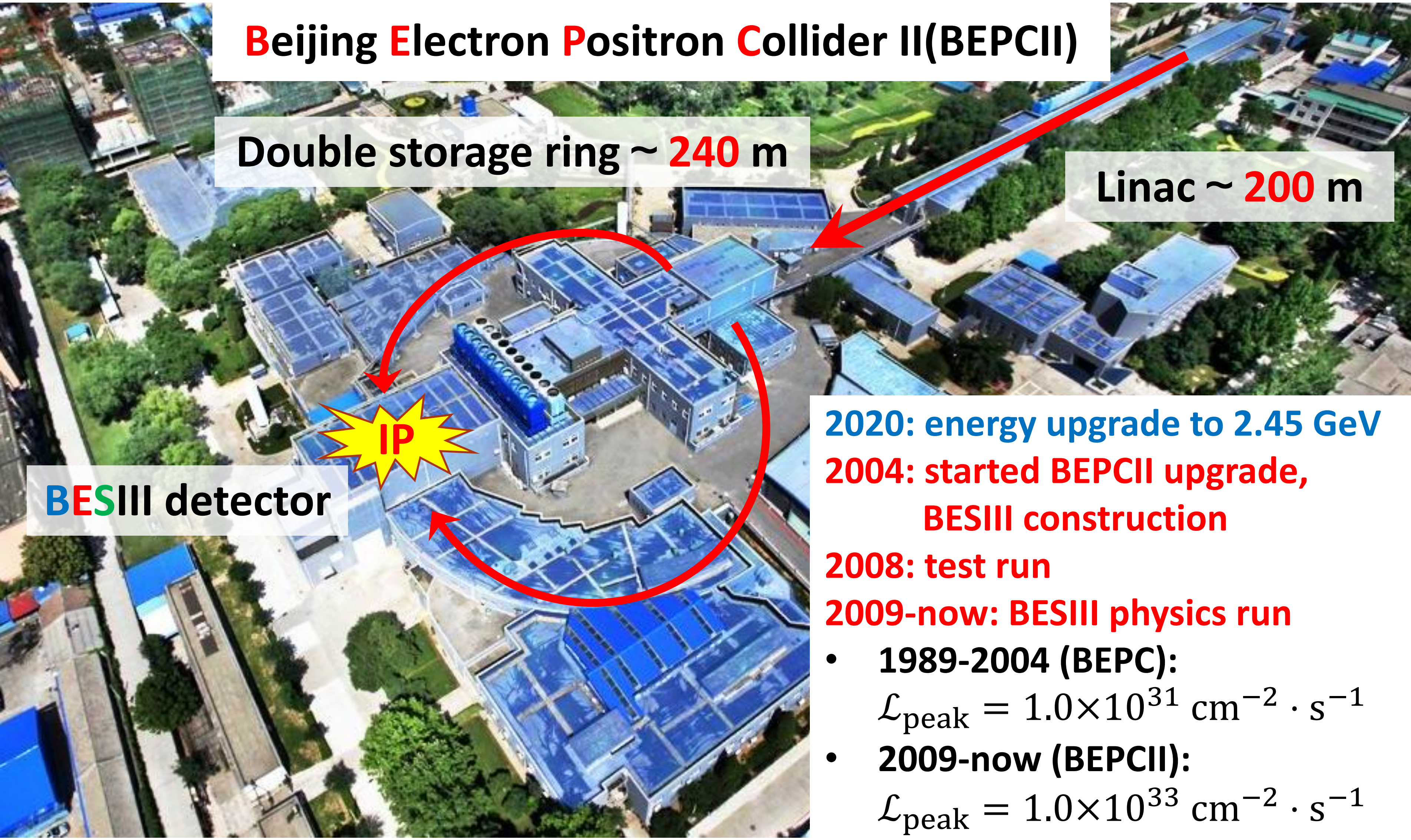


2020: energy upgrade to 2.45 GeV

2004: started BEPCII upgrade,
BESIII construction

2008: test run

2009-now: BESIII physics run

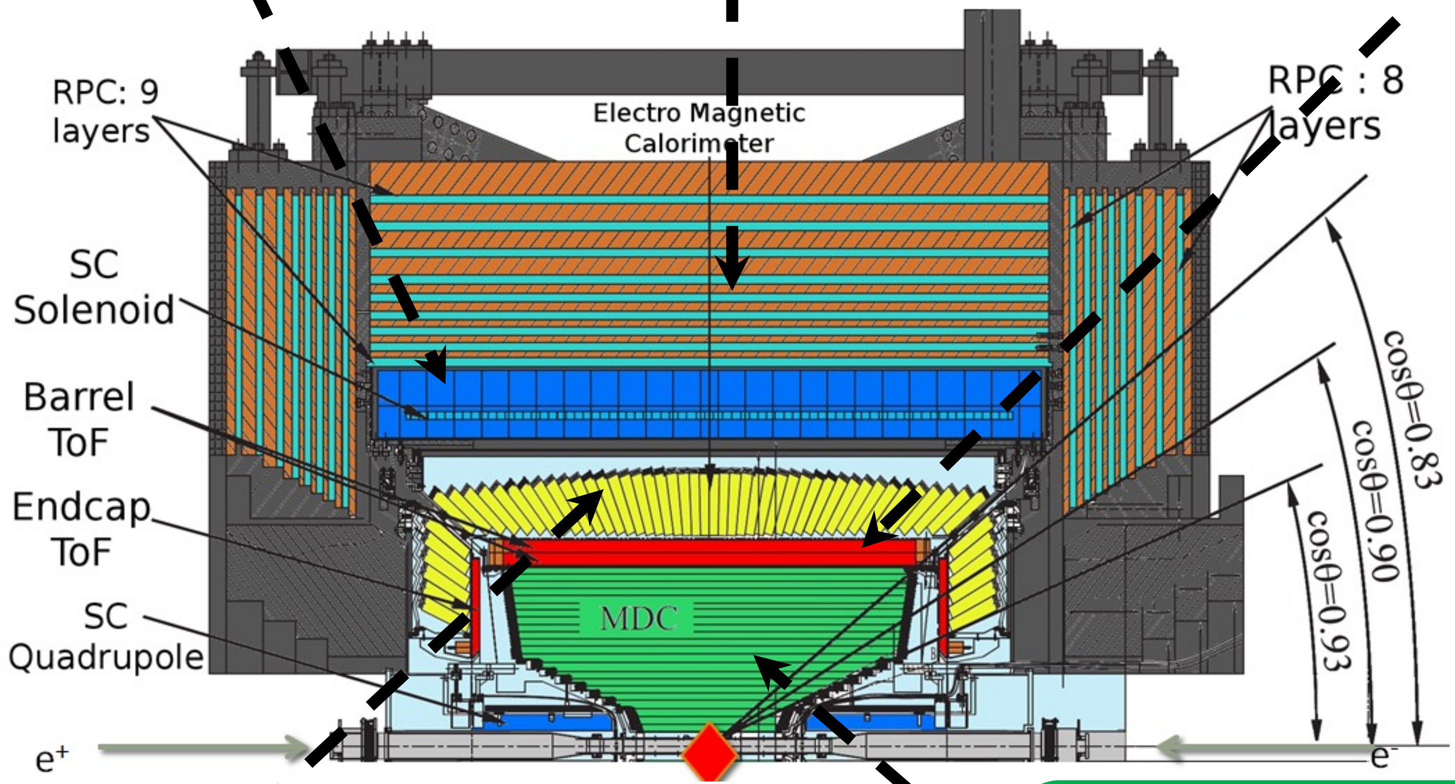
- **1989-2004 (BEPC):**
  $\mathcal{L}_{\rm peak} = 1.0\times10^{31}\ \mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$
- **2009-now (BEPCII):**
  $\mathcal{L}_{\rm peak} = 1.0\times10^{33}\ \mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$

BESIII detector

Superconducting solenoid
- 0.9~1.0 T

Muon Counter (MUC)
- 9 layers (barrel) + 8 layer (end-cap)

Time Of Flight (TOF)
- $\sigma_t = 90$ ps (barrel)
- $\sigma_t = 65$ ps (end cap)

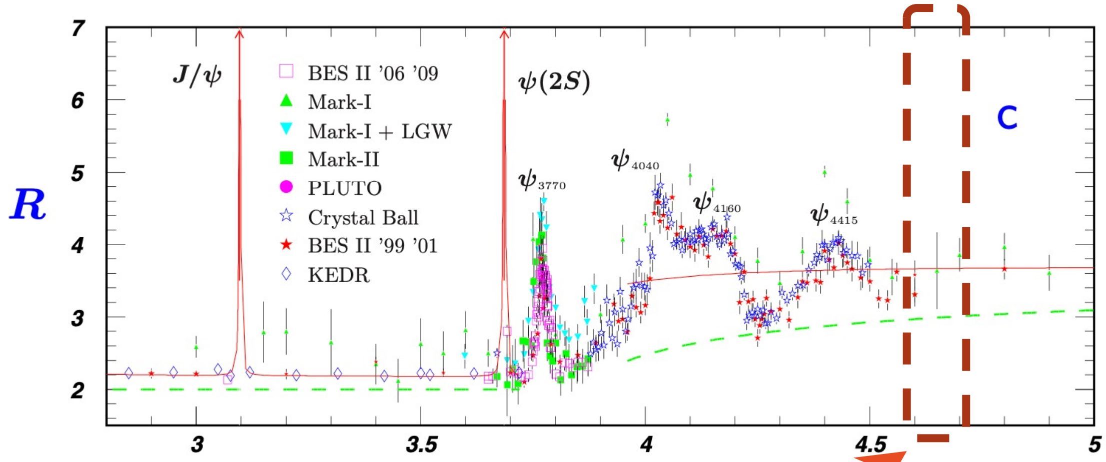


Electromagnetic Calorimeter(EMC)
- $\Delta E/E = 2.5\%$ @ 1.0 GeV
- $\sigma_{\phi z} = 0.6$ cm @ 1.0 GeV

Main Drift Chamber (MDC)
- $\sigma_{xy} = 130\ \mu\text{m}$
- $\Delta P/P = 0.5\%$ @ 1.0 GeV
- $\sigma_{dE/dx} = 6-7\%$

Dataset

- **Threshold effect:** pair production of charmed baryons without accompanying hadrons!
  - $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$



PDG2022

- Center-of-mass energy: $E_{\text{cms}} = 4.6\sim4.7$ GeV
- Integrated luminosity: $4.50\ \text{fb}^{-1}$

E_{cms} (MeV)	$\mathcal{L}$ (pb^{-1})
$4599.53 \pm 0.07 \pm 0.74$	$586.9 \pm 0.1 \pm 3.9$
$4611.86 \pm 0.12 \pm 0.32$	$103.83 \pm 0.05 \pm 0.55$
$4628.00 \pm 0.06 \pm 0.32$	$521.52 \pm 0.11 \pm 2.76$
$4640.91 \pm 0.06 \pm 0.38$	$552.41 \pm 0.12 \pm 2.93$
$4661.24 \pm 0.06 \pm 0.29$	$529.63 \pm 0.12 \pm 2.81$
$4681.92 \pm 0.08 \pm 0.29$	$1669.31 \pm 0.21 \pm 8.85$
$4698.82 \pm 0.10 \pm 0.39$	$536.45 \pm 0.12 \pm 2.84$

Double Tag Method can be used. Kinematic relation to constrain missing particle.

Chin.Phys.C 39 (2015) 9, 093001

arXiv:2205.04809

Analysis method

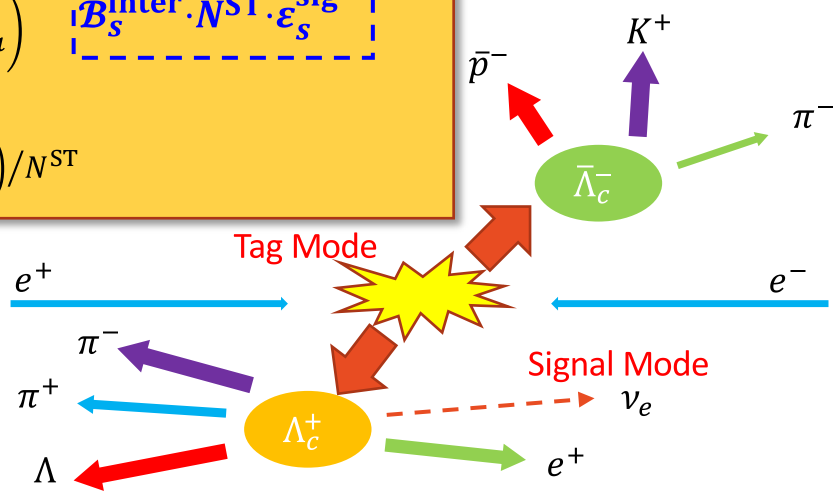
• Double Tag(DT) Method

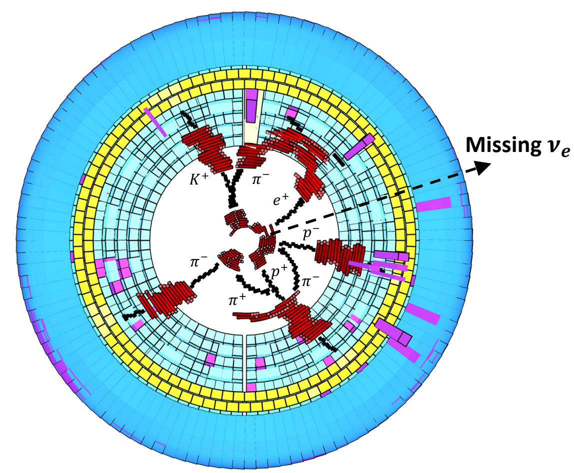
- $N_{i,a}^{\rm ST} = 2N_{\Lambda_c^+\bar{\Lambda}_c^-} \cdot \mathcal{B}_i \cdot \mathcal{B}_i^{\rm inter} \cdot \varepsilon_{i,a}^{\rm ST}$
  - i for Tag mode, a for energy point
- $N_{is,a}^{\rm DT} = 2N_{\Lambda_c^+\bar{\Lambda}_c^-} \cdot \mathcal{B}_i \cdot \mathcal{B}_i^{\rm inter} \cdot \mathcal{B}_s \cdot \mathcal{B}_s^{\rm inter} \cdot \varepsilon_{is,a}^{\rm DT}$
  - s for signal mode
- $N_s^{\rm DT} = \sum_{i,a} N_{is,a}^{\rm DT} = \mathcal{B}_s \cdot \mathcal{B}_s^{\rm inter} \cdot \sum_{i,a}\left(\frac{N_{i,a}^{\rm ST}}{\varepsilon_{i,a}^{\rm ST}} \cdot \varepsilon_{is,a}^{\rm DT}\right)$
- $\mathcal{B}_s = \frac{N_s^{\rm DT}}{\mathcal{B}_s^{\rm inter} \cdot \sum_{i,a}\left(\frac{N_{i,a}^{\rm ST}}{\varepsilon_{i,a}^{\rm ST}} \cdot \varepsilon_{is,a}^{\rm DT}\right)} = \boldsymbol{\frac{N_s^{\rm DT}}{\mathcal{B}_s^{\rm inter} \cdot N^{\rm ST} \cdot \varepsilon_s^{\rm sig}}}$
  - $N^{\rm ST} = \sum_{i,a} N_{i,a}^{\rm ST}$
  - $\varepsilon_s^{\rm sig} = \sum_{i,a}\left(\frac{N_{i,a}^{\rm ST}}{\varepsilon_{i,a}^{\rm ST}} \cdot \varepsilon_{is,a}^{\rm DT}\right)/N^{\rm ST}$

• $U_{\rm miss}$ definition

- $E_{\rm miss} = E_{\rm beam} - \sum_{f\in\text{Signal Mode}} E_f$;
- $\vec{p}_{\rm miss} = \vec{p}_{\Lambda_c^+} - \sum_{i\in\text{Signal Mode}} \vec{p}_f$
- $\boldsymbol{U_{\rm miss} = E_{\rm miss} - c|\vec{p}_{\rm miss}|}$
- Characteristic variable of the signal
  signal events peak at 0 in $U_{\rm miss}$ distribution

Example of
$\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e$
vs.
$\bar{\Lambda}_c^- \to \bar{p}^-K^+\pi^-$





Drawn with Besvis
Developed by Z.Y. You, S.H.Huang @SYSU,
P.X. Long, Y. Zhang, etc @IHEP

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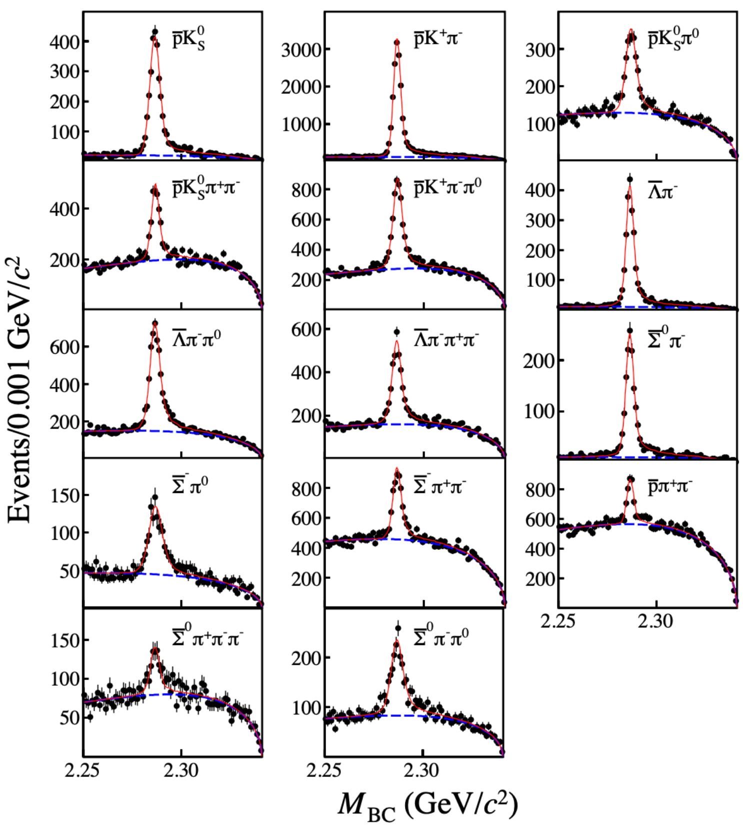
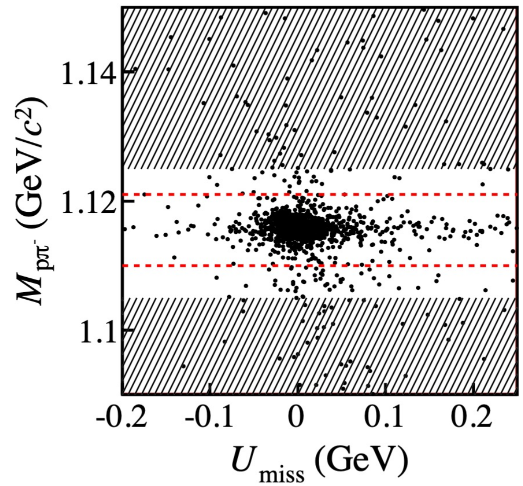
BF measurement

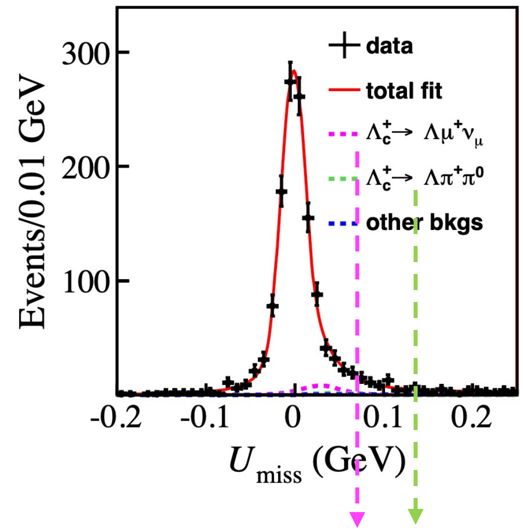
- ST data set reconstructed by 14 hadronic Λ_c decay mode
  - $N_{\mathrm{ST}} = 122268 \pm 474$

Fits to the M_{BC} distributions for different ST modes at $\sqrt{s} = 4.682$ GeV.



- Select signal Λ and e^+ in the recoiling side of $\overline{\Lambda}_c^-$





MC-simulated background shapes

Signal
- Core: Gaussian
- Tail: power law ⇐ ISR & FSR

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

- ➢ $N^{\mathrm{DT}}_{\Lambda e^+\nu_e} = 1253 \pm 39$
- ➢ $\varepsilon^{\mathrm{sig}}_{\Lambda e^+\nu_e} = 0.2876$

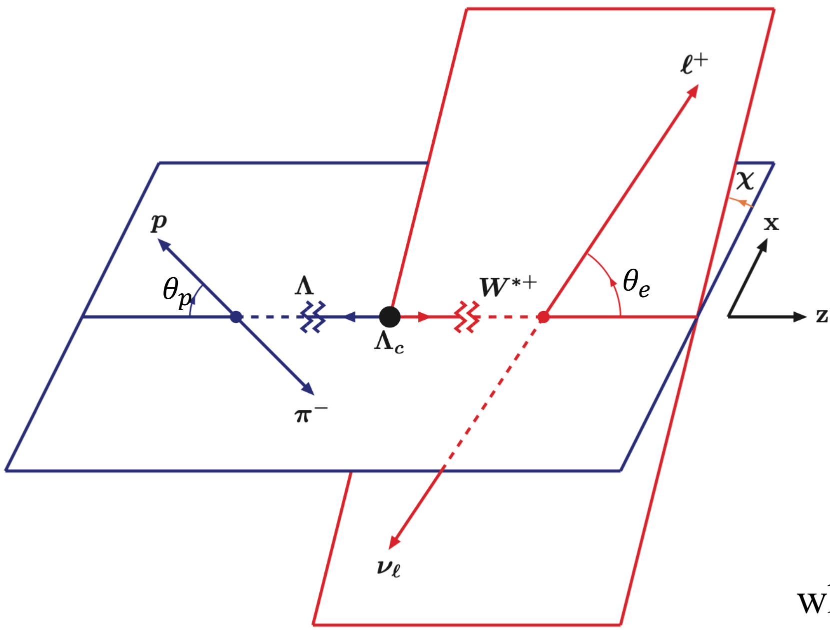
systematic

e tracking	0.4%	ST yields	1.0%
e PID	0.5%	U_{miss} fit model	1.0%
Λ reconstruction	0.2%	Quoted BF	0.8%
SL signal model	0.6%	MC statistic	0.8%

Total: 2.0%

Decay amplitude of $\Lambda_c^+ \to \Lambda e^+ \nu_e$

Definition of the polar and the azimuthal angles



Differential decay width

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

where: $H_{\lambda_\Lambda\lambda_W} = H^V_{\lambda_\Lambda\lambda_W} - H^A_{\lambda_\Lambda\lambda_W}$ and $H^{V(A)}_{-\lambda_\Lambda-\lambda_W} = +(-)H^{V(A)}_{\lambda_\Lambda\lambda_W}$

$Q_\pm = (M_{\Lambda_c} \pm M_\Lambda)^2 - q^2$

parameterized by "**Weinberg form factors**"

$$H^V_{\frac{1}{2}1} = \sqrt{2Q_-}[F_1^V(q^2) + \frac{(M_{\Lambda_c^+}+M_\Lambda)}{M_{\Lambda_c^+}}F_2^V(q^2)],$$
$$H^A_{\frac{1}{2}1} = \sqrt{2Q_+}[F_1^A(q^2) - \frac{(M_{\Lambda_c^+}-M_\Lambda)}{M_{\Lambda_c^+}}F_2^A(q^2)],$$
$$H^V_{\frac{1}{2}0} = \sqrt{\frac{Q_-}{q^2}}[(M_{\Lambda_c^+}+M_\Lambda)F_1^V(q^2) + \frac{q^2}{M_{\Lambda_c^+}}F_2^V(q^2)],$$
$$H^A_{\frac{1}{2}0} = \sqrt{\frac{Q_+}{q^2}}[(M_{\Lambda_c^+}-M_\Lambda)F_1^A(q^2) - \frac{q^2}{M_{\Lambda_c^+}}F_2^A(q^2)].$$

$$F_1^V(q^2) = \frac{1}{(M_{\Lambda_c^+}+M_\Lambda)^2-q^2}[f_+(q^2)(M_{\Lambda_c^+}+M_\Lambda)^2 - f_\perp(q^2)\cdot q^2],$$
$$F_2^V(q^2) = \frac{M_{\Lambda_c^+}\cdot(M_{\Lambda_c^+}+M_\Lambda)}{(M_{\Lambda_c^+}+M_\Lambda)^2-q^2}[f_\perp(q^2) - f_+(q^2)],$$
$$F_1^A(q^2) = \frac{1}{(M_{\Lambda_c^+}-M_\Lambda)^2-q^2}[g_+(q^2)(M_{\Lambda_c^+}-M_\Lambda)^2 - g_\perp(q^2)\cdot q^2],$$
$$F_2^A(q^2) = \frac{M_{\Lambda_c^+}\cdot(M_{\Lambda_c^+}-M_\Lambda)}{(M_{\Lambda_c^+}-M_\Lambda)^2-q^2}[g_+(q^2) - g_\perp(q^2)].$$

The bridge of "**Weinberg form factors**" and "**Helicity form factors**"

parameterized by "**Helicity form factors**"

Following LQCD

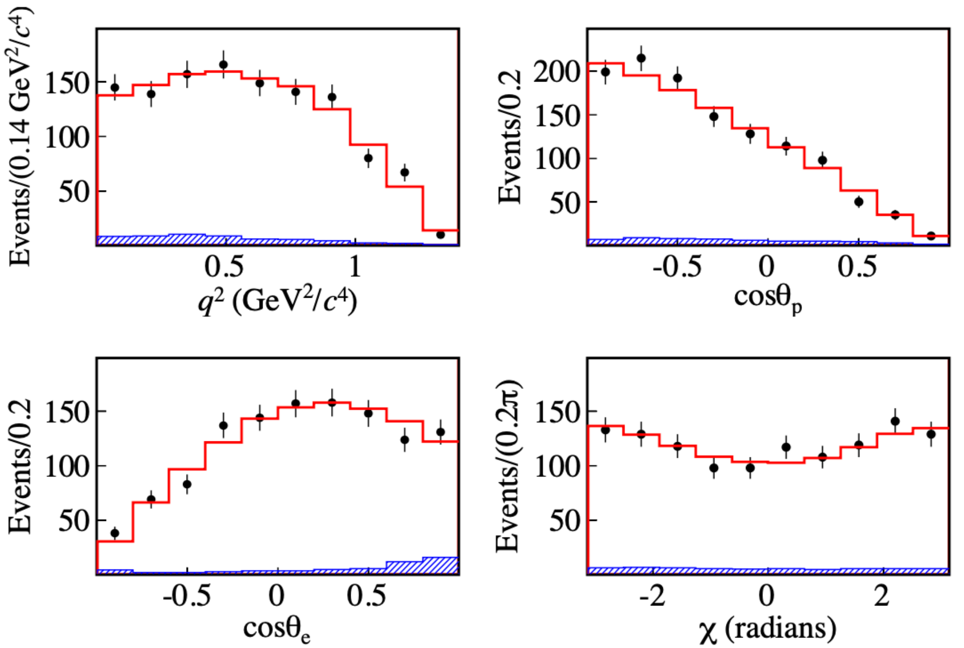
$$H^V_{\frac{1}{2}1} = \sqrt{2Q_-}f_\perp(q^2),$$
$$H^A_{\frac{1}{2}1} = \sqrt{2Q_+}g_\perp(q^2),$$
$$H^V_{\frac{1}{2}0} = \sqrt{Q_-/q^2}f_+(q^2)(M_{\Lambda_c}+M_\Lambda),$$
$$H^A_{\frac{1}{2}0} = \sqrt{Q_+/q^2}g_+(q^2)(M_{\Lambda_c}-M_\Lambda).$$

Parameterization of helicity form factors

- **z-expansion**: $f(q^2) = \frac{a_0^f}{1-q^2/\left(m_{\rm pole}^f\right)^2}[1+\alpha_1^f \times z(q^2)]$
  - $m_{\rm pole}^f$: pole mass, $m_{\rm pole}^{f_+,f_\perp} = 2.112\ {\rm GeV}/c^2$ and $m_{\rm pole}^{g_+,g_\perp} = 2.460\ {\rm GeV}/c^2$
  - a_0^f and α_1^f: free parameters
  - $z(q^2) = \frac{(\sqrt{t_+-q^2}-\sqrt{t_+-t_0})}{(\sqrt{t_+-q^2}+\sqrt{t_+-t_0})}$ with $t_0 = q^2_{\rm max} = \left(m_{\Lambda_c} - m_\Lambda\right)^2$, $t_+ = (m_D - m_K)^2$
  - $m_D = 1.870\ \ {\rm GeV}/c^2$ and $m_K = 0.494\ \ {\rm GeV}/c^2$

- Five independent free parameters: $a_1^{g_\perp}$, $a_1^{f_\perp}$ and $r_{f_+} = a_0^{f_+}/a_0^{g_\perp}$, $r_{f_\perp} = a_0^{f_\perp}/a_0^{g_\perp}$ and $r_{g_+} = a_0^{g_+}/a_0^{g_\perp}$
  - Choose $a_0^{g_\perp}$ as the reference and set $a_1^{g_\perp} = a_1^{g_+}$ and $a_1^{f_\perp} = a_1^{f_+}$

- **Four-dimensional ML fit** performed
  - Only ratios of amplitudes can be determined in ML fit.
  - Absolute values needs BF input normalization.
  - Form factor $\Lambda_c \to \Lambda$ firstly measured!



Indirect Test of SM

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$$\frac{d\Gamma}{dq^2} = \frac{G_F^2|V_{cs}|^2}{192\pi^3 M_{\Lambda_c}^2} \times P q^2 \times [|H_{\frac{1}{2}1}|^2 + |H_{-\frac{1}{2}-1}|^2 + |H_{\frac{1}{2}0}|^2 + |H_{-\frac{1}{2}0}|^2]$$

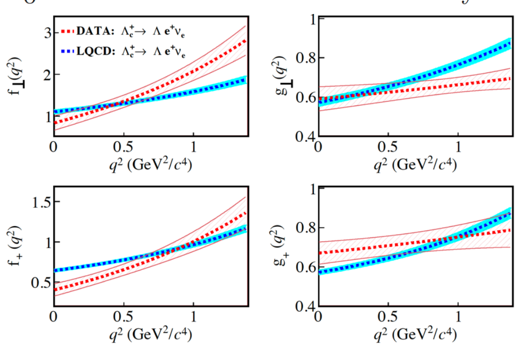
$$\int_0^{q^2_{\rm max}} \frac{d\Gamma}{dq^2} dq^2 = \frac{\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)}{\tau_{\Lambda_c}}$$

Four-dimensional ML fit to data

Parameters	$\alpha_1^{g_\perp}$	$\alpha_1^{f_\perp}$	r_{f_+}	$r_{f_\perp}$	r_{g_+}
Values	$1.43 \pm 2.09 \pm 0.16$	$-8.15 \pm 1.58 \pm 0.05$	$1.75 \pm 0.32 \pm 0.01$	$3.62 \pm 0.65 \pm 0.02$	$1.13 \pm 0.13 \pm 0.01$

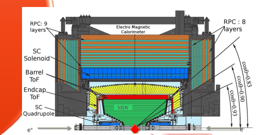
Coefficients	$\alpha_1^{g_\perp}$	$\alpha_1^{f_\perp}$	r_{f_+}	$r_{f_\perp}$	r_{g_+}
$a_0^{g_\perp}$	-0.64	0.60	-0.66	-0.83	-0.40
$\alpha_1^{g_\perp}$		-0.63	0.62	0.53	-0.33
$\alpha_1^{f_\perp}$			-0.79	-0.67	-0.07
r_{f_+}				0.57	-0.09
$r_{f_\perp}$					0.39

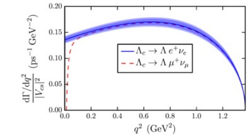
$$a_0^{g_\perp} = 0.54 \pm 0.04_{\rm stat.} \pm 0.01_{\rm syst.}$$



LQCD: $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = \left(3.80 \pm 0.19_{\rm LQCD} \pm 0.11_{\tau_{\Lambda_c}}\right)\%$

BF





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

Measured from BESIII data

FF

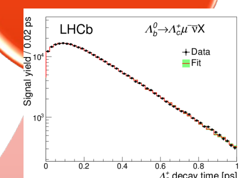
LQCD

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

PDG2020

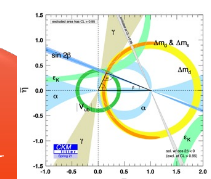
$\tau_{\Lambda_c} = (202.4 \pm 3.1) \times 10^{-3}$ ps

Lifetime



$|V_{cs}| = 0.97320 \pm 0.00011$

CKM unitarity fit



CKM

Consistent with $|V_{cs}|$ measured in $D \to K l \nu_l$

$|V_{cs}| = 0.936 \pm 0.017_{\mathcal{B}} \pm 0.024_{\rm LQCD} \pm 0.007_{\tau_{\Lambda_c}}$

Comparison with theoretical predictions

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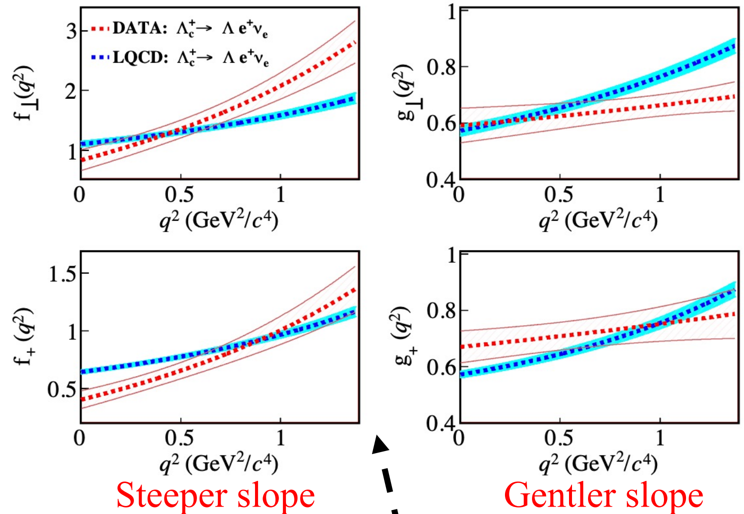

FIG. 3. Comparison of form factors with LQCD calculations. The bands show the total uncertainties.

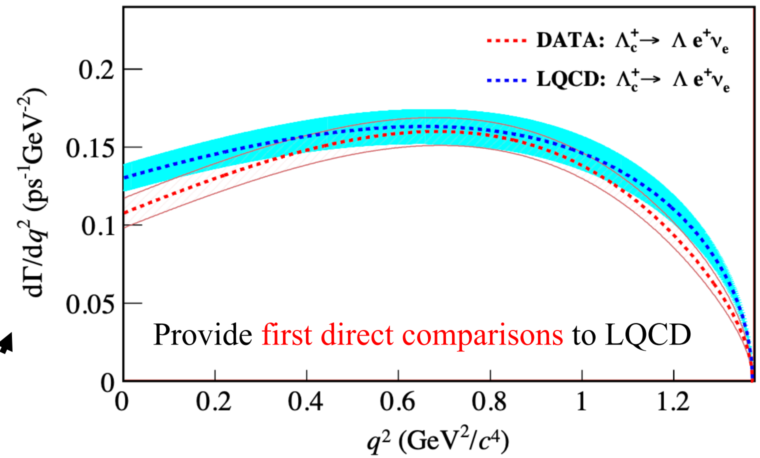

FIG. 4. Comparison of the differential decay rates with LQCD predictions. The band show the total uncertainties.

- Dependences of measured FFs show different kinematic behavior compared to those predicted from LQCD calculations.
- No clear difference is observed within uncertainties for the resulting differential decay rate of LQCD.
- The comparison between other theoretical models.

TABLE III. Comparison of $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)$ from theoretical calculations and our measurement. Disfavor at C.L. more than 95%

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

Outline

北京大學 PEKING UNIVERSITY

- Introduction
- BESIII experiment
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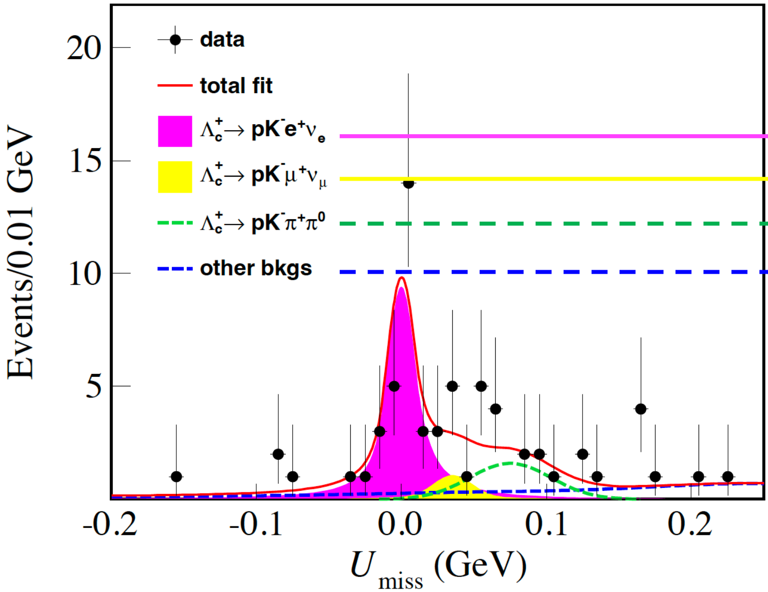
- ST data set is same with last analysis.
- Select signal pK^-e^+ in the recoiling side of $\overline{\Lambda}_c^-$
  $\Rightarrow$ Contamination from $\Lambda_c^+ \to pK^-\pi^+$ and $\Lambda_c^+ \to pK^-\pi^+\pi^0$

$M_{pK^-e^+} < 2.15\ \mathrm{GeV}/c^2$

Additional π^0 searched and veto M_{BC} signal region

- Fit to the U_{miss} distribution



Signal { Core: Gaussian; Tail: power law $\Leftarrow$ ISR & FSR

MC-simulated background shapes

8.9σ!

$$\boldsymbol{\mathcal{B}(\Lambda_c^+ \to pK^-e^+\nu_e) = (0.82 \pm 0.15 \pm 0.06)\times 10^{-3}}$$

- $N^{\mathrm{DT}}_{pK^-e^+\nu_e} = 33.5 \pm 6.3$
- $\varepsilon^{\mathrm{sig}}_{pK^-e^+\nu_e} = 0.3337$

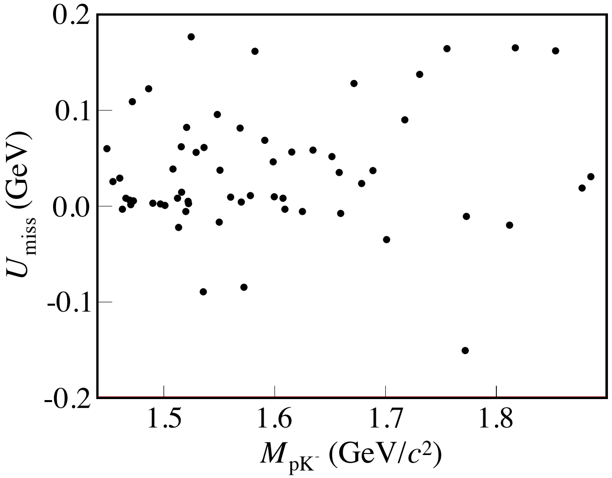
systematic

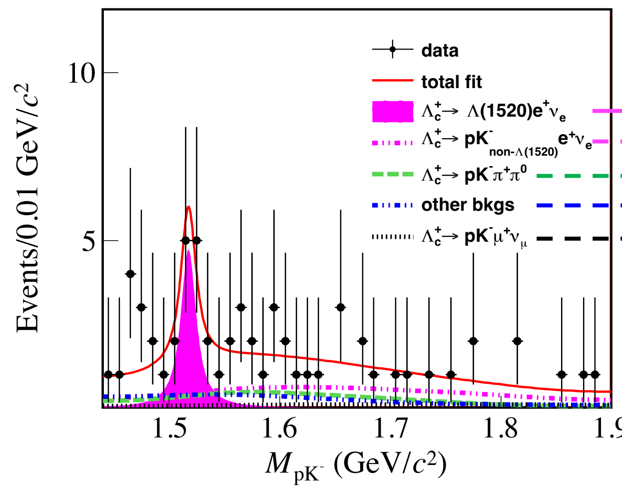
p tracking(PID)	1% (1%)	ST yields	1.0%
K tracking(PID)	1% (1%)	U_{miss} fit model	3.8%
e tracking(PID)	0.4% (0.5%)	$\mathcal{R}_{\mathcal{B}}$	3.6%
SL signal model	2.7%	MC statistic	1.0%
M_{BC} requirement	2.1%	$M_{pK^-e^+}$	3.1%

Total: 7.5%

Search for $\Lambda_c^+ \to \Lambda(1520)e^+\nu_e$

- To extract the yield of $\Lambda_c^+ \to \Lambda(1520)e^+\nu_e$, a two-dimensional (2D) likelihood fit is performed to the M_{pK^-} and $U_{\rm miss}$ distributions.





fixed to PDG | fixed to MC simulation

$RBW(m_0, \Gamma_0) * \mathcal{G}(\mu = 0, \sigma)$

MC-simulated background shapes

$\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e) = (1.36 \pm 0.56 \pm 0.11)\times 10^{-3}$

- $N^{\rm DT}_{\Lambda(1520)e^+\nu_e} = 11.5 \pm 4.7$
- $\varepsilon^{\rm sig}_{\Lambda(1520)e^+\nu_e} = 0.0691$

Evidence with 3.8σ!

systematic

$\mathcal{B}(\Lambda_c^+ \to pK^-_{\rm non-\Lambda(1520)}e^+\nu_e) = (0.53 \pm 0.15 \pm 0.06)\times 10^{-3}$

- $N^{\rm DT}_{pK^-_{\rm non-\Lambda(1520)}e^+\nu_e} = 21.0 \pm 6.0$
- $\varepsilon^{\rm sig}_{pK^-_{\rm non-\Lambda(1520)}e^+\nu_e} = 0.3222$

1. **Non-resonant(NR) decay**
2. **Broad excited Λ^* states:**
   - $\Lambda(1405), \Lambda(1600)$ ...

Sources	$\Lambda(1520)e^+\nu_e$	$pK^-_{\rm non-\Lambda(1520)}e^+\nu_e$
p tracking(PID)	1% (1%)	1% (1%)
K tracking(PID)	1% (1%)	1% (1%)
e tracking(PID)	0.4% (0.5%)	0.4% (0.5%)
SL signal model	2.1%	8.5%
$M_{\rm BC}$ requirement	2.1%	2.1%
ST yields	1.0%	1.0%
Fit model	4.5%	4.8%
$\mathcal{R}_\mathcal{B}$	1.7%	1.4%
MC statistic	1.0%	1.0%
$M_{pK^-e^+}$	3.1%	3.1%
Quoted BF	4.2%	---
Interference	6.1%	---
Total	10.2%	11.0%

- Considering systematic uncertainty,
  - $\Lambda_c^+ \to pK^-e^+\nu_e$ is observed with **8.2σ** significance.
  - An Evidence for $\Lambda_c^+ \to \Lambda(1520)e^+\nu_e$ with a significance of **3.3σ**.
- Comparing with BESIII measurement for the inclusive SL BF,
  - $[\mathcal{B}(\Lambda_c^+ \to pK^-e^+\nu_e)/\mathcal{B}(\Lambda_c^+ \to Xe^+\nu_e)] = (2.1 \pm 0.4_{\text{stat.}} \pm 0.1_{\text{syst.}})\%$
  - $[\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e)/\mathcal{B}(\Lambda_c^+ \to Xe^+\nu_e)] = (3.4 \pm 1.4_{\text{stat.}} \pm 0.4_{\text{syst.}})\%$
- Comparing with theoretical calculations, the measured BF for $\Lambda_c^+ \to \Lambda(1520)e^+\nu_e$ is consistent with all these predictions within 2σ.

	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e)$ $[\times 10^{-3}]$
Constituent quark model [4]	1.01
Nonrelativistic quark model [5]	0.60
Lattice QCD [17, 18]	$0.512 \pm 0.082 \pm 0.008$
Measurement	$1.36 \pm 0.56 \pm 0.14$

- Extending the understanding of Λ_c^+ SL decays beyond the mode $\Lambda_c^+ \to \Lambda l^+\nu_l$.
- Prospects: amplitude analysis of pK^- mass spectrum, form factors

Outline

北京大學 PEKING UNIVERSITY

- Introduction
- BESIII experiment
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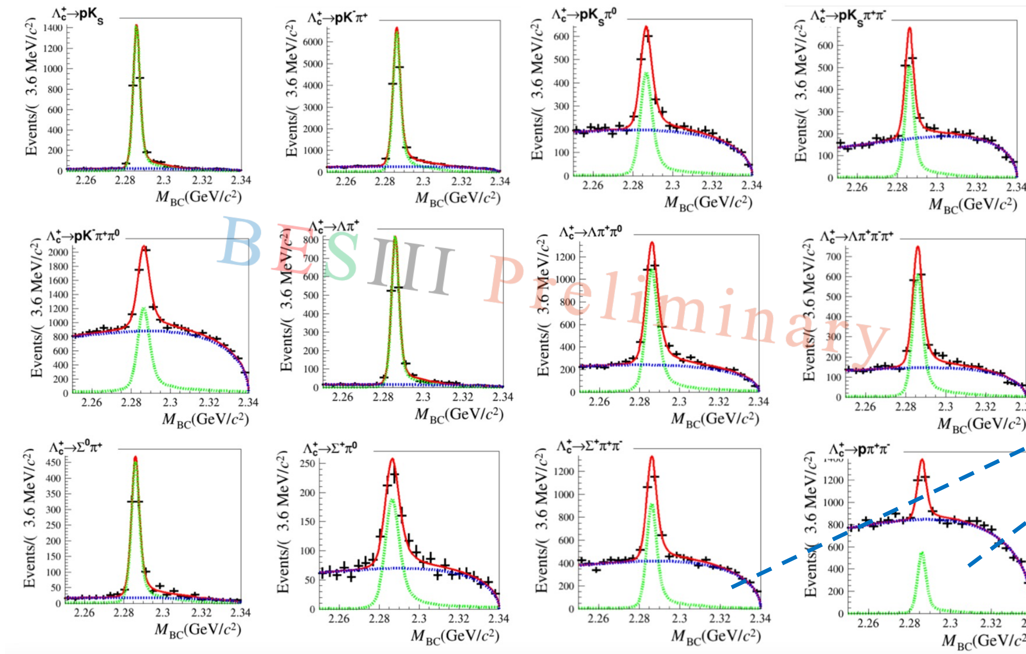
Signal selection

- ST data set reconstructed by 12 hadronic Λ_c decay mode
  - $N_{\mathrm{ST}} \sim 120\mathrm{K}$

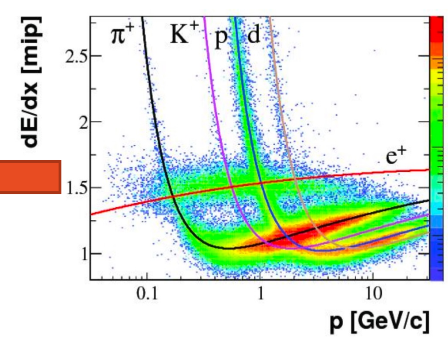
Fits to the M_{BC} distributions for different ST modes at $\sqrt{s} = 4.682$ GeV.

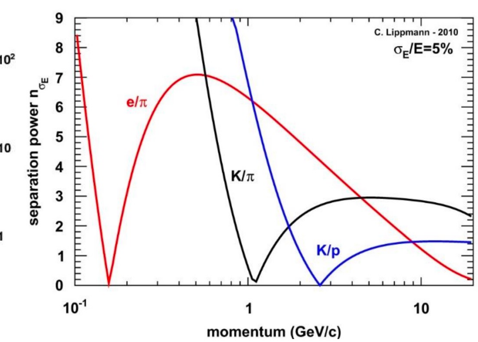


Relative high background level

- Select signal $\Lambda\pi^+\pi^-e^+(pK_S^0\pi^-e^+)$ in the recoiling side of $\overline{\Lambda}_c^-$
  $\Rightarrow$ Challenge from misidentification between e and π

✓ The phase space of 5-body decay is very small
✓ Low momentum of e/π causes serious misidentification





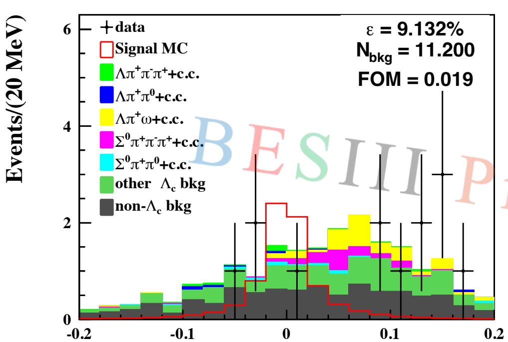
Background rejection

- $\Lambda\pi^+\pi^-e^+\nu_e(pK_S^0\pi^-e^+\nu_e)$ mode

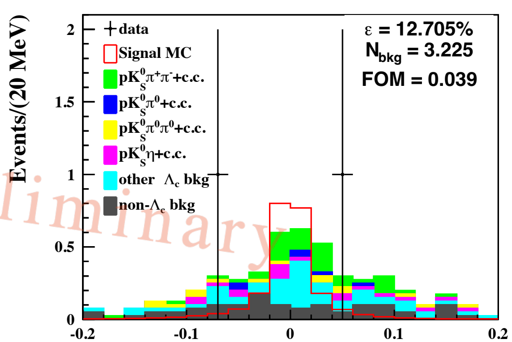
1. **Tight PID requirement**
   - Tag mode $\Lambda_c^+ \to p\pi^+\pi^-$ and $\Lambda_c^+ \to \Sigma^+\pi^+\pi^-$ electron EMC Info valid
   - $\mathrm{Prob}(e)/[\mathrm{Prob}(e)+\mathrm{Prob}(\pi)+\mathrm{Prob}(K)] > 0.99(0.98)$
2. **γ-conversion background**
   - $\cos\theta(e,\pi) < 0.88(0.92)$
3. **$\Lambda\pi^+\pi^-\pi^+(pK_S^0\pi^-\pi^+)$ background**
   - $M(\Lambda\pi^+\pi^-e(\pi)^+) < 2.27\ \mathrm{GeV}/c^2$ $(M(pK_S^0\pi^-e(\pi)^+) < 2.28\ \mathrm{GeV}/c^2)$
4. **Miss-$\pi^0(\gamma)$ background**
   - $\cos\theta(\mathrm{miss},\gamma) < 0.81(0.90)$

Cuts optimized with FOM scanning by using Punzi-FOM[1] $= \frac{\varepsilon}{3/2+\sqrt{B}}$

[1] G. Punzi, eConf C030908, MODT002 (2003)



$\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e$



$\Lambda_c^+ \to pK_S^0\pi^-e^+\nu_e$

Signal MC is arbitrarily normalized

Signal yields estimation

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- No signals observed on data, setting ULs on BF.
- Maximum likelihood estimator extended from the **profile likelihood method**[1].

[1] NIMA 551, 493 (2005).

- The backgrounds separated into two categories:
  - non-Λ_c background, denoted as bkg1 → **Estimated by data sideband**
  - Λ_c background, denoted as bkg2 → **Estimated by MC simulation**
- The observed events consist of three parts: signal, bkg1 and bkg2
  - $N^{\rm obs} = N_{\rm sig} + N_{\rm bkg1} + N_{\rm bkg2}$ → **Background estimation**
  - $N^{\rm obs}$ follows a Poisson distribution($\mathcal{P}$), $N^{\rm obs} \sim \mathcal{P}\left(N_{\rm obs},\ N_{\rm sig} + N_{\rm bkg1} + N_{\rm bkg2}\right)$
- $N_{\rm sig} = \mathcal{B}_{\rm sig} \cdot \mathcal{B}^{\rm inter} \cdot N^{\rm ST} \cdot \varepsilon^{\rm sig} = \mathcal{B}_{\rm sig} \cdot N^{\rm eff}$
  - $N^{\rm eff}$ expected to follow a Gaussian distribution ($\mathcal{G}$) with mean $\mathcal{B}^{\rm inter} \cdot N^{\rm ST} \cdot \varepsilon^{\rm sig}_{\rm MC}$ and width $\mathcal{B}^{\rm inter} \cdot N^{\rm ST} \cdot \varepsilon^{\rm sig}_{\rm MC} \cdot \sigma$, $N^{\rm eff} \sim \mathcal{G}\left(N^{\rm eff},\ \mathcal{B}^{\rm inter} \cdot N^{\rm ST} \cdot \varepsilon^{\rm sig}_{\rm MC},\ \mathcal{B}^{\rm inter} \cdot N^{\rm ST} \cdot \varepsilon^{\rm sig}_{\rm MC} \cdot \sigma\right)$
  - $\frac{\delta N^{\rm eff}}{N^{\rm eff}} = \frac{\delta \mathcal{B}_{\rm sig}}{\mathcal{B}_{\rm sig}} = \sigma$ → **Systematic uncertainties estimation**

Profile likelihood method & Upper Limit

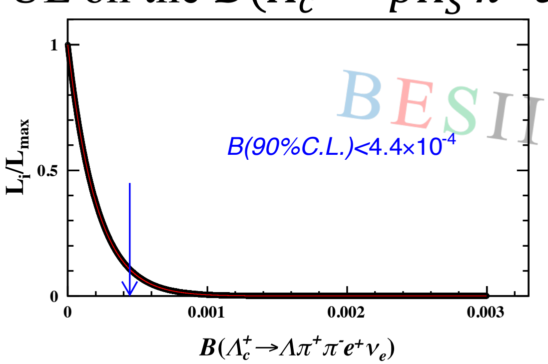
- Joint likelihood function:
  - $\mathcal{L} = \mathcal{P}\left(N_{\text{obs}} \mid N^{\text{eff}} \cdot \boldsymbol{\mathcal{B}} + \boldsymbol{N_{\text{bkg1}}} + \boldsymbol{N_{\text{bkg2}}}\right) \cdot \mathcal{G}\left(N^{\text{eff}} \mid \mathcal{B}^{\text{inter}} \cdot N^{\text{ST}} \cdot \varepsilon_{\text{MC}}^{\text{sig}}, \mathcal{B}^{\text{inter}} \cdot N^{\text{ST}} \cdot \varepsilon_{\text{MC}}^{\text{sig}} \cdot \sigma\right) \cdot \mathcal{P}\left(N_{\text{data}}^{\text{SB}} \mid N_{\text{bkg1}}/r\right) \cdot \mathcal{G}\left(N_{\text{bkg2}} \mid N_{\text{bkg2}}^{\text{MC}}, \sigma_{\text{bkg2}}^{\text{MC}}\right)$
- Based on the Bayesian method, likelihood is a function of signal BF $\mathcal{B}$, with variation of N^{eff}, N_{bkg1} and N_{bkg2}.

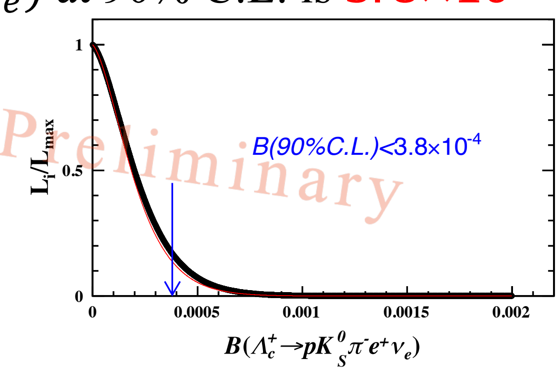
The fixed parameters for joint likelihood fit.

Decay mode	N^{obs}	N^{ST}	$\mathcal{B}^{\text{inter}}$	$\varepsilon_{\text{MC}}^{\text{sig}}$	σ	$N_{\text{data}}^{\text{SB}}$	r	$N_{\text{bkg2}}^{\text{MC}}$	$\sigma_{\text{bkg2}}^{\text{MC}}$
$\Lambda_c^+ \to \Lambda\pi^+\pi^- e^+\nu_e$	4	123147	63.9%	9.13%	5.2%	9	1.533	5.3	0.4
$\Lambda_c^+ \to pK_S^0\pi^- e^+\nu_e$	2	123147	69.2%	12.70%	7.5%	0	1.533	2.2	0.2

- The UL on the $\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^- e^+\nu_e)$ at 90% C.L. is **4.4×10^{-4}**.
  - If assuming all the final states from $\Lambda(1520)$, the UL on $\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e)$ at 90% C.L. is 4.9×10^{-3}.
  - If assuming all the final states from $\Lambda(1600)$, the UL on $\mathcal{B}(\Lambda_c^+ \to \Lambda(1600)e^+\nu_e)$ at 90% C.L. is 1.0×10^{-2}.
- The UL on the $\mathcal{B}(\Lambda_c^+ \to pK_S^0\pi^- e^+\nu_e)$ at 90% C.L. is **3.8×10^{-4}**.

$\mathcal{B}(\Lambda(1520) \to \Lambda\pi^+\pi^-) = (10 \pm 1)\%$
$\mathcal{B}(\Lambda(1600) \to \Sigma(1385)\pi) = (9 \pm 4)\%$
$\mathcal{B}(\Sigma(1385) \to \Lambda\pi) = (87.5 \pm 1.5)\%$





Outline

北京大學 PEKING UNIVERSITY

- Introduction
- BESIII experiment
- $\Lambda_c^+ \to \Lambda e^+ \nu_e$
- $\Lambda_c^+ \to p K^- e^+ \nu_e$
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Other ongoing analysis

➢$\Lambda_c^+ \to ne^+\nu_e$

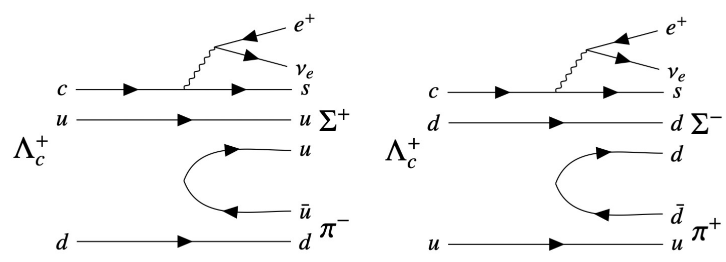
- Singly Cabibbo-suppressed transition $c \to d$
- Many theoretical-model calculations
- Challenge in experiment:
  1. Two missing particles: n and ν_e
  2. Huge background from $\Lambda_c^+ \to \Lambda e^+\nu_e$

Quoted form Table XXI in arXiv:2109.01216

Process	NRQM [232]	RQM [236]	RQM [237]	QSR [243]	QSR [244]	CQM [238]	LQCD [248, 249]	LFQM [227]	SU(3) [251]	Expt [31]
$\Lambda_c^+ \to \Lambda^0 e^+\nu_e$	3.0 (2.2)	1.4	3.25	2.6 ± 0.4	3.0 ± 0.3	2.78	3.8 ± 0.2	4.04	3.6 ± 0.4	3.6 ± 0.4
		-0.812		-1	-0.88 ± 0.03				-0.86 ± 0.03	-0.86 ± 0.04
$\Lambda_c^+ \to \Lambda^0 \mu^+\nu_\mu$			3.14				3.7 ± 0.2	3.90	3.6 ± 0.4	3.5 ± 0.5
									-0.86 ± 0.04	
$\Lambda_c^+ \to ne^+\nu_e$	0.22 (0.34)	0.26	0.268			0.20	0.41		0.49 ± 0.05	
									-0.89 ± 0.04	

➢$\Lambda_c^+ \to \Sigma\pi e^+\nu_e$

- $\mathcal{B}(\Lambda(1405) \to \Sigma\pi) = 100\%$ and $\mathcal{B}(\Lambda(1520) \to \Sigma\pi) = (42 \pm 1)\%$
- Search for Λ^* in $\Sigma\pi$ invariant mass spectrum
- Nature of $\Lambda(1405)$? uds bound state, dynamically generate molecular state, multi-quark state



(a) $\Lambda_c^+ \to \Sigma^+\pi^-e^+\nu_e$ (b) $\Lambda_c^+ \to \Sigma^-\pi^+e^+\nu_e$

Outline

北京大學 PEKING UNIVERSITY

- Introduction
- BESIII experiment
- $\Lambda_c^+ \to \Lambda e^+ \nu_e$
- $\Lambda_c^+ \to p K^- e^+ \nu_e$
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Summary

- Semi-leptonic Λ_c decays provide good opportunities to study the dynamics of charm baryons, test standard model and probe new physics.
- $\Lambda_c^+ \to \Lambda e^+ \nu_e$
  - Improved measurement of BF
  - Form factors, comparing with LQCD
- $\Lambda_c^+ \to p K^- e^+ \nu_e$
  - First observed with 8.2σ significance
  - Evidence of $\Lambda(1520)$ in pK^- invariant mass spectrum
- $\Lambda_c^+ \to \Lambda \pi^+ \pi^- e^+ \nu_e$ and $\Lambda_c^+ \to p K_S^0 \pi^- e^+ \nu_e$
  - Search for $\Lambda_c^+ \to \Lambda^* e^+ \nu_e$ and ULs are given
- Other ongoing analysis desperately run to you.

Thanks for you attention!

Backup

Systematic uncertainty

- Form factors $\Lambda_c^+ \to \Lambda$

TABLE II. Systematic uncertainties (in %) of the fitted parameters.

Parameter	Tracking&PID&Λ	Normalization	α_Λ	Total
$a_1^{f_\perp}$	0.6	0.5	0.1	0.8
$a_1^{g_\perp}$	6.0	7.2	2.8	9.8
r_{f_+}	0.1	0.5	0.7	0.9
$r_{g_\perp}$	0.3	0.1	0.6	0.7
r_{g_+}	0.3	1.5	0.1	1.5

Systematic uncertainty

Sources	$\mathcal{B}_{\Lambda_c^+\to\Lambda\pi^+\pi^-e^+\nu_e}(\%)$	$\mathcal{B}_{\Lambda_c^+\to pK_S^0\pi^-e^+\nu_e}(\%)$
MC statistics	0.3	0.2
Number of ST Λ_c	0.4	0.4
BFs of the intermediate states	0.8	0.1
p tracking	—	0.3
p PID	—	0.2
π tracking	2.5	0.3
π PID	0.7	0.3
e tracking	0.5	0.1
e PID	2.8	3.5
Λ reconstruction	2.2	—
K_S^0 reconstruction	—	3.1
$\cos\theta(e,\pi)$	1.4	1.4
$\cos\theta(\text{miss},\gamma)$	0.1	0.1
FSR recovery	0.2	0.2
$M(\Lambda\pi^+\pi^-e(\pi)^+)$ / $M(pK_S^0\pi^-e(\pi)^+)$	—	—
Signal model	2.2	5.6
Total	5.2	7.5

BESIII Preliminary

- For $\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e$ mode, $N^{\text{eff}} \sim \mathcal{G}\left(N^{\text{eff}}, \mathcal{B}^{\text{inter}} \cdot N^{\text{ST}} \cdot \varepsilon_{\text{MC}}^{\text{sig}}, \mathcal{B}^{\text{inter}} \cdot N^{\text{ST}} \cdot \varepsilon_{\text{MC}}^{\text{sig}} \cdot \sigma\right)|_{\sigma=5.2\%}$
- For $\Lambda_c^+ \to pK_S^0\pi^-e^+\nu_e$ mode, $N^{\text{eff}} \sim \mathcal{G}\left(N^{\text{eff}}, \mathcal{B}^{\text{inter}} \cdot N^{\text{ST}} \cdot \varepsilon_{\text{MC}}^{\text{sig}}, \mathcal{B}^{\text{inter}} \cdot N^{\text{ST}} \cdot \varepsilon_{\text{MC}}^{\text{sig}} \cdot \sigma\right)|_{\sigma=7.5\%}$