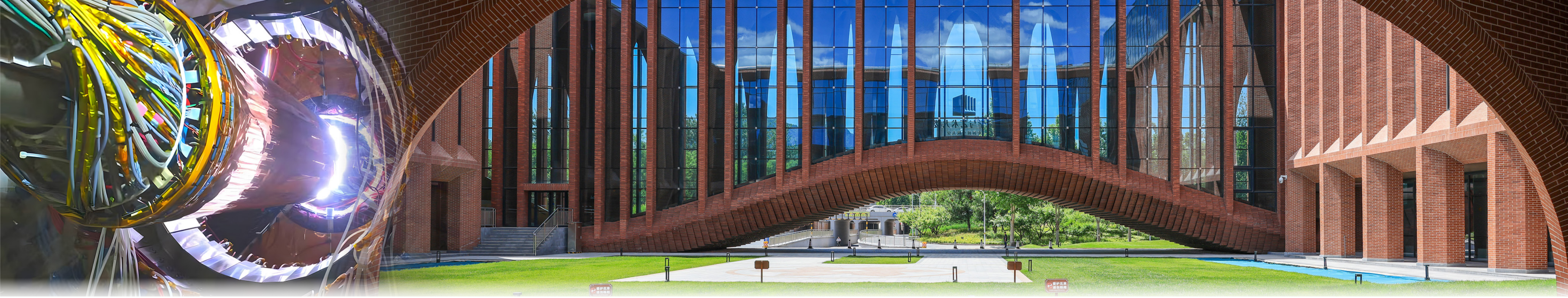


Semi-leptonic decays of Λ_c^+ at BESIII

Yangu Li

University of Chinese Academy of Sciences

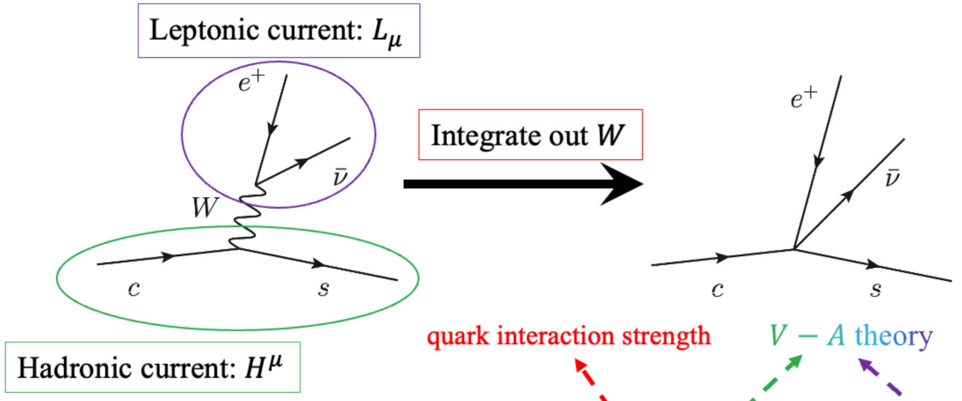
Workshop on charm hadron physics at BESIII

August 6, 2025

Introduction

- Λ_c^+ **semi-leptonic decays provide ideal probes to study weak & strong interactions**
  - Weak interaction determines quark flavor change
  - Strong interaction isolated in initial-final hadron transition

- **Formalism in a nutshell**
  - Helicity amplitude as a product of leptonic current L_μ and hadronic current H^μ
    - L_μ is well understood, H^μ is hard to calculate due to non-perturbative QCD effect
  - H^μ can be parameterized by form factors (FFs)
    - Six FFs $f_0, g_0, f_+, g_+, f_\perp, g_\perp$
    - At $m_l \to 0$ limit, reduced to four FFs $f_+, g_+, f_\perp, g_\perp$
    - Functions of momentum transfer q^2



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

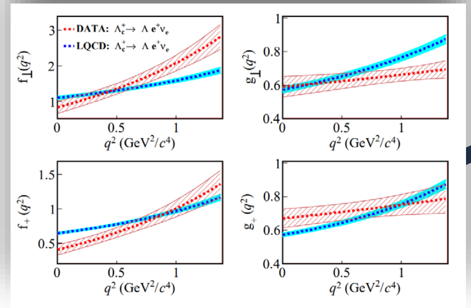
$$\langle \Lambda(p_2,s_2)|H_{\rm eff}|\Lambda_c(p_1,s_1)\rangle = \langle \Lambda(p_2,s_2)|(V-A)|\Lambda_c(p_1,s_1)\rangle$$

$$H_V(\lambda)_\mu = \langle \Lambda(p_2,s_2)|V_\mu|\Lambda_c(p_1,s_1)\rangle = \bar{u}(p_2,s_2)\left[\gamma_\mu f_1(q^2) + i\sigma_{\mu\nu}\frac{q^\nu}{m_1} f_2(q^2) + \frac{q^\mu}{m_1} f_3(q^2)\right] u(p_1,s_1)$$

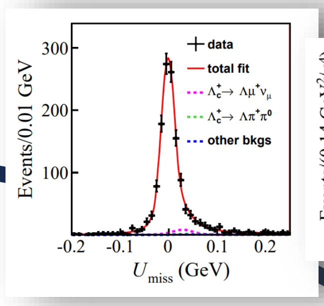
$$H_A(\lambda)_\mu = \langle \Lambda(p_2,s_2)|A_\mu|\Lambda_c(p_1,s_1)\rangle = \bar{u}(p_2,s_2)\left[\gamma_\mu g_1(q^2) + i\sigma_{\mu\nu}\frac{q^\nu}{m_1} g_2(q^2) + \frac{q^\mu}{m_1} g_3(q^2)\right] u(p_1,s_1)$$

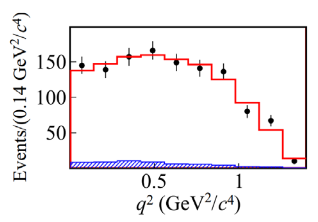
Introduction

- **Test of SM from various aspects**



Physics observables
BF, differential decay width, etc.





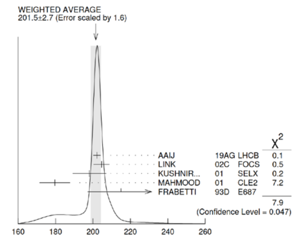
Form factors
Calculated by LQCD, HQET, quark models, sum rules, SU(3)...

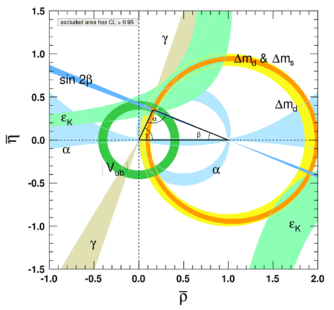
Formalism

$$\int \frac{d\Gamma}{dq^2} dq^2 = \frac{\mathcal{B}(\Lambda_c^+ \to h e^+ \nu_e)}{\tau_{\Lambda_c^+}},$$

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{cq}|^2}{192\pi^3 M_{\Lambda_c}^2} \times Pq^2 \times \left[\left|H_{\frac{1}{2}1}\right|^2 + \left|H_{-\frac{1}{2}-1}\right|^2 + \left|H_{\frac{1}{2}0}\right|^2 + \left|H_{-\frac{1}{2}0}\right|^2 \right]$$

Λ_c^+ lifetime
Input from other experiments





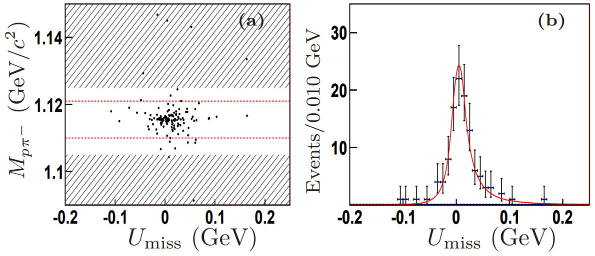
CKM unitarity
Access to $|V_{cs}|, |V_{cd}|$ & test LFU

*Thanks to Xudong Yu (PKU)

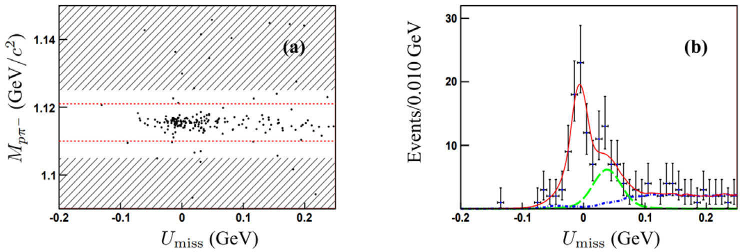
Experimental status

- **Before 2015, knowledge for Λ_c^+ semi-leptonic decays was very limited**
  - Only relative BF and FFs for $\Lambda_c^+ \to \Lambda e^+ \nu_e$ reported by ARGUS & CLEO
- **First-round BESIII data made significant progress in 2015-2019**
  - $587\ \mathrm{fb}^{-1}$ dataset collected at $\sqrt{s} = 4.600$ GeV
  - First absolute BF measurements for $\Lambda_c^+ \to \Lambda e^+ \nu_e$ & $\Lambda \mu^+ \nu_\mu$
  - First inclusive BF measurement for $\Lambda_c^+ \to X e^+ \nu_e$
- **Second-round BESIII data aimed for a larger scope**
  - Precise studies on golden channel $\Lambda_c^+ \to \Lambda l^+ \nu_l$
    - BF, LFU, FFs
  - Search for other Λ_c^+ semi-leptonic decays
    - $\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)}{\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e)} = 80\% \sim 100\%$, much greater than D meson cases
    - Excited state $\Lambda_c^+ \to \Lambda^*$?
    - Cabibbo-suppressed $\Lambda_c^+ \to n$?

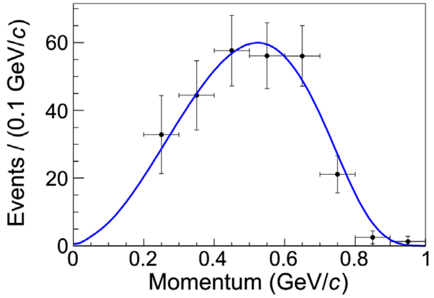
$\Lambda_c^+ \to \Lambda e^+ \nu_e$, PRL **115**, 221805 (2015)



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

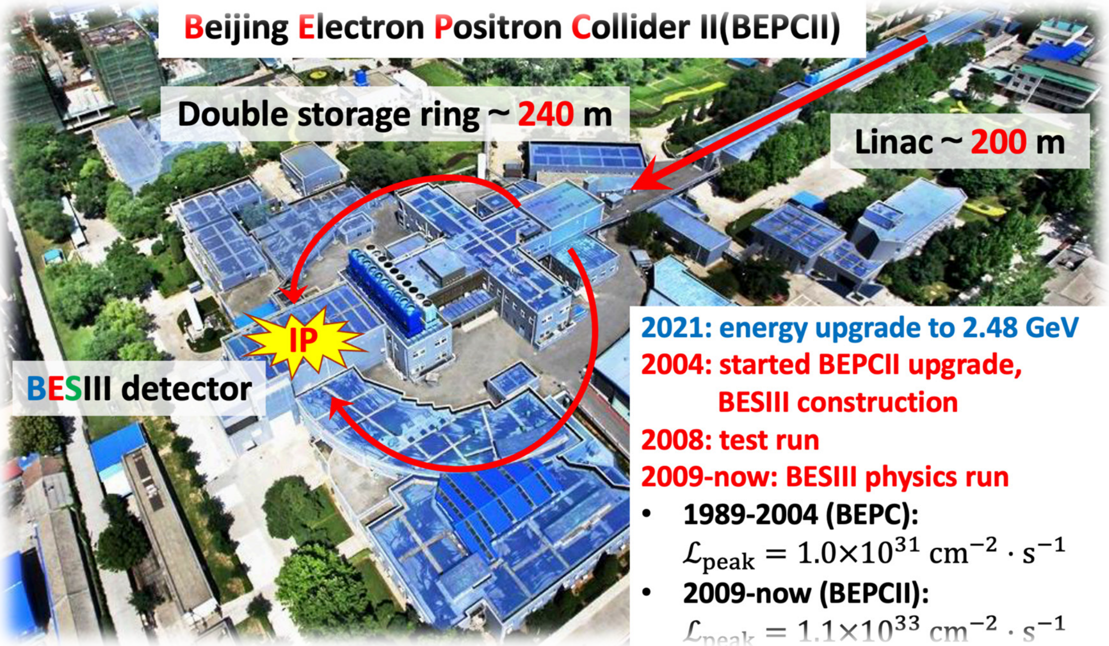


$\Lambda_c^+ \to X e^+ \nu_e$, PRD **121**, 251801 (2018)



BESIII experiment

- **Beijing Electron-Positron Collider II (BEPCII)**



2021: energy upgrade to 2.48 GeV
2004: started BEPCII upgrade, BESIII construction
2008: test run
2009-now: BESIII physics run

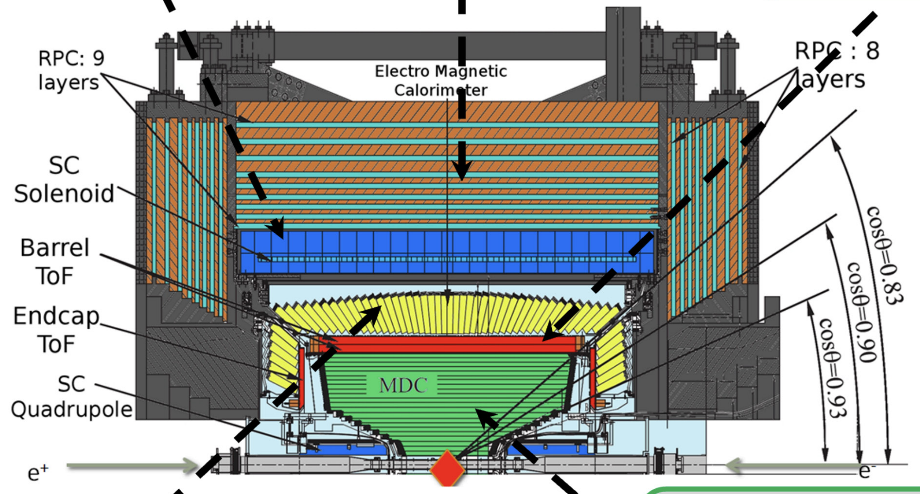
- **1989-2004 (BEPC):** $\mathcal{L}_{\text{peak}} = 1.0\times10^{31}\ \text{cm}^{-2}\cdot\text{s}^{-1}$
- **2009-now (BEPCII):** $\mathcal{L}_{\text{peak}} = 1.1\times10^{33}\ \text{cm}^{-2}\cdot\text{s}^{-1}$

- **Beijing Spectrometer III (BESIII)**

Superconducting solenoid
- 1.0 T

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

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



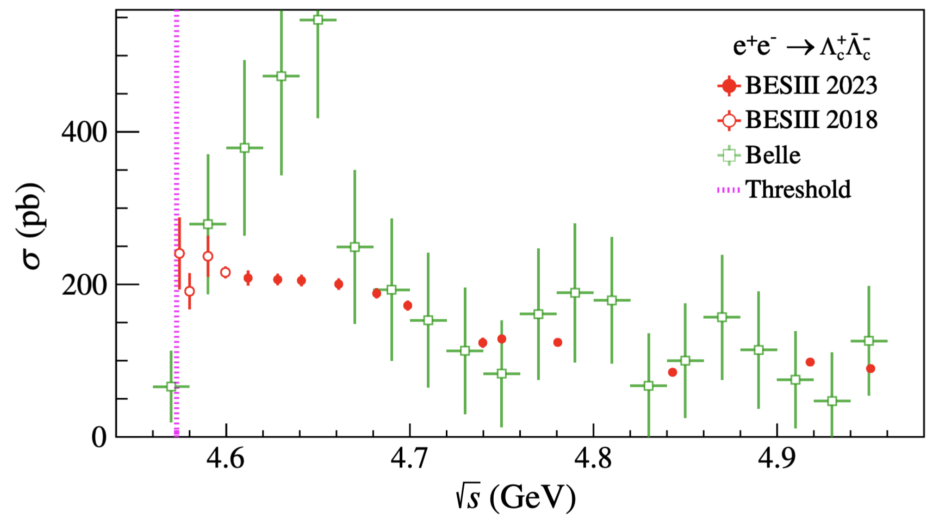
Electromagnetic Calorimeter(EMC)
- $\Delta E/E = 2.5\%$ @ 1.0 GeV
- $\sigma_{\phi z} = 0.6$ cm @ 1.0 GeV

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

Data samples

- **Overall:** about 50 fb^{-1} @ $\sqrt{s} = 1.8\sim4.95$ GeV after 15 years of data taking
- **Dedicated to charmed baryon studies**
  - 2014: 587 pb^{-1} @ $\sqrt{s} = 4.60$ GeV
  - 2020-2021: 3.9 fb^{-1} @ $\sqrt{s} = 4.61\sim4.70$ GeV
  - 2021-2022: 1.9 fb^{-1} @ $\sqrt{s} = 4.74\sim4.95$ GeV
  - Totally 6.5 fb^{-1} data from 13 energy points, about 1 million $\Lambda_c^+\bar{\Lambda}_c^-$ events

PRL **131**, 191901 (2023)



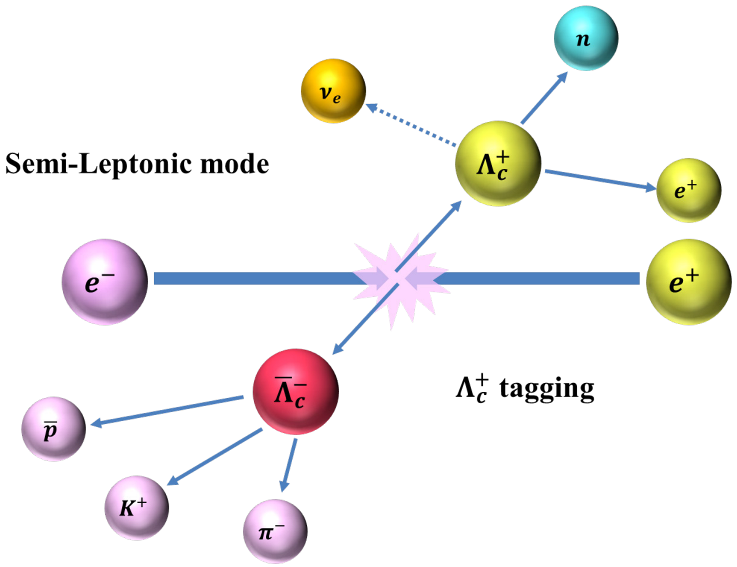
CPC **46**, 113003 (2022)

Sample	E_{cms}/MeV	$\mathscr{L}_{\text{Bhabha}}$/pb^{-1}
4610	4611.86±0.12±0.30	103.65±0.05±0.55
4620	4628.00±0.06±0.32	521.53±0.11±2.76
4640	4640.91±0.06±0.38	551.65±0.12±2.92
4660	4661.24±0.06±0.29	529.43±0.12±2.81
4680	4681.92±0.08±0.29	1667.39±0.21±8.84
4700	4698.82±0.10±0.36	535.54±0.12±2.84
4740	4739.70±0.20±0.30	163.87±0.07±0.87
4750	4750.05±0.12±0.29	366.55±0.10±1.94
4780	4780.54±0.12±0.30	511.47±0.12±2.71
4840	4843.07±0.20±0.31	525.16±0.12±2.78
4920	4918.02±0.34±0.34	207.82±0.08±1.10
4950	4950.93±0.36±0.38	159.28±0.07±0.84

Unique abilities in Λ_c^+ study

- **Near-threshold pair production**
  - $e^+e^- \to \gamma^* \to \Lambda_c^+\bar{\Lambda}_c^-$ without accompanying hadrons
  - Clean backgrounds and well constrained kinematics

- **Double-tag method**
  - Reconstruct $\Lambda_c^+ \to$ signal & $\bar{\Lambda}_c^- \to$ hadronic tag modes sequentially
  - Allow to:
    - Measure absolute BF
    - Suppress hadronic background
    - Recoil missing neutrino
    - Cancel systematics
  - Relatively low efficiency ~ 15%
    - Only 12 out of $\mathcal{O}(100)$ Λ_c^+ decays are used as tag modes
    - Deep learning methods are being explored to improve efficiency



$$\mathcal{B}_{\rm sig} = \frac{\sum_{i,j} N_{\rm DT}^{i,j}}{\sum_{i,j}\left(\frac{N_{\rm ST}^{i,j}}{\epsilon_{\rm ST}^{i,j}} \cdot \epsilon_{\rm DT}^{i,j}\right)} = \frac{N_{\rm DT}}{\sum_{i,j}\left(\frac{N_{\rm ST}^{i,j}}{\epsilon_{\rm ST}^{i,j}} \cdot \epsilon_{\rm DT}^{i,j}\right)} = \frac{N_{\rm DT}}{N_{\rm ST} \cdot \epsilon^{\rm sig}},$$

$$N_{\rm ST}^{i,j} = 2N^j_{\Lambda_c^+\bar{\Lambda}_c^-}\mathcal{B}^i_{\rm tag}\epsilon^{i,j}_{\rm ST}, \qquad \epsilon^{\rm sig} = \sum_{i,j}\left(\frac{N_{\rm ST}^{i,j}}{\epsilon_{\rm ST}^{i,j}} \cdot \epsilon_{\rm DT}^{i,j}\right) / \sum_{i,j} N_{\rm ST}^{i,j},$$

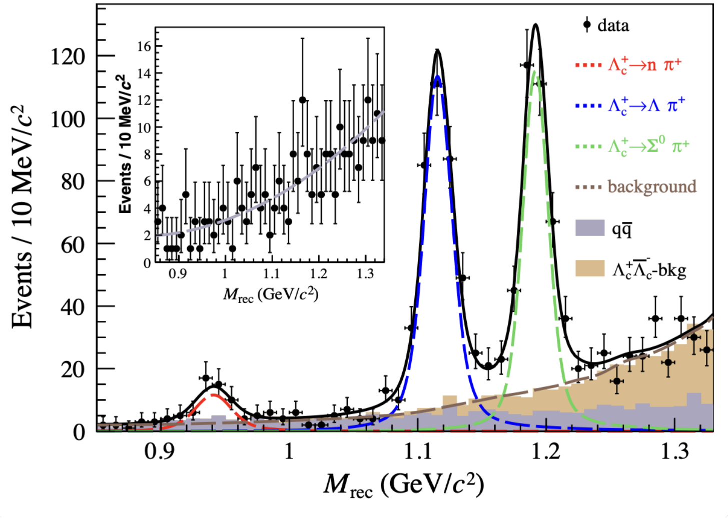
$$N_{\rm DT}^{i,j} = 2N^j_{\Lambda_c^+\bar{\Lambda}_c^-}\mathcal{B}^i_{\rm tag}\mathcal{B}_{\rm sig}\epsilon^{i,j}_{\rm DT}, \qquad N_{\rm ST} = \sum_{i,j} N_{\rm ST}^{i,j}$$

Unique abilities in Λ_c^+ study

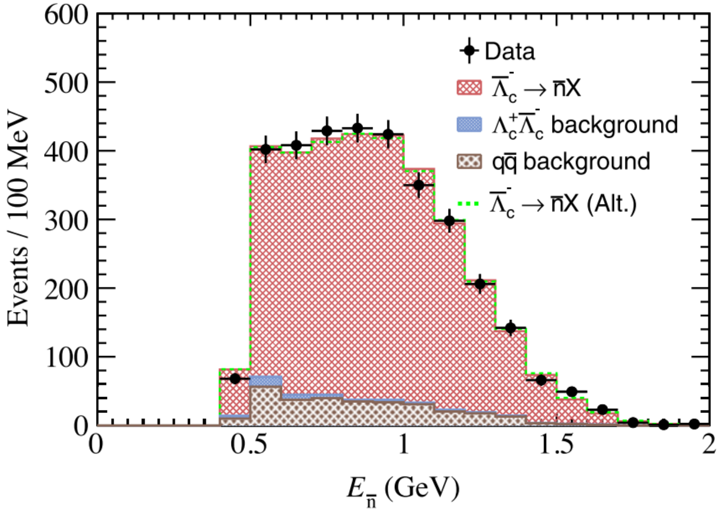
Neutral particle detection

- BESIII has high acceptance & performance EMC
- Reconstruction for γ & π^0 is effective and precise
- Reconstruction for n & K_L^0 is challenging yet possible
  - Deep learning methods are being explored

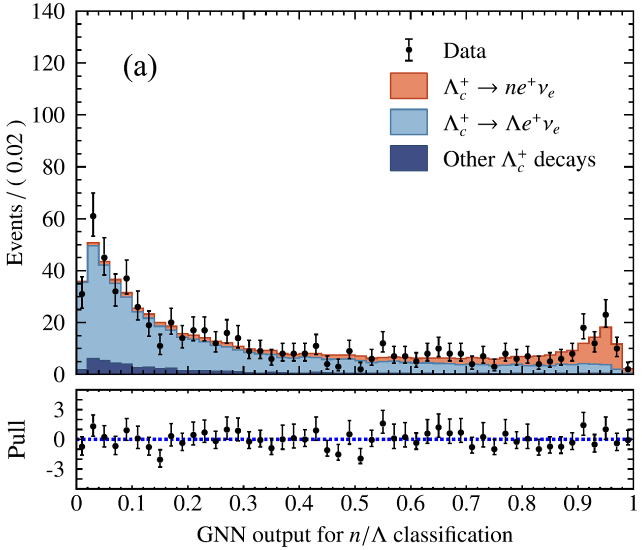
$\Lambda_c^+ \to n\pi^+$, PRL **128**, 142001 (2022)



$\bar{\Lambda}_c^- \to \bar{n} + X$, PRD **108**, L031101 (2023)



$\Lambda_c^+ \to ne^+\nu_e$, NatComm **16**, 681 (2025)



Published results from second-round BESIII data

- $\Lambda_c^+ \to \Lambda e^+ \nu_e$ — PRL **129**, 231803 (2022)
- $\Lambda_c^+ \to \Lambda \mu^+ \nu_e$ — PRD **108**, L031105 (2023)
- $\Lambda_c^+ \to p K^- e^+ \nu_e$ — PRD **106**, 112010 (2022)
- $\Lambda_c^+ \to \Lambda \pi^+ \pi^- e^+ \nu_e$ & $p K_S^0 \pi^- e^+ \nu_e$ — PLB **843**, 137933 (2023)
- $\Lambda_c^+ \to n e^+ \nu_e$ — NatComm **16**, 681 (2025)
- $\Lambda_c^+ \to X e^+ \nu_e$ — PRD **107**, 052005 (2023)

$\Lambda_c^+ \to \Lambda l^+ \nu_l \ (l = e, \mu)$

PRL **129**, 231803 (2022)
PRD **108**, L031105 (2023)

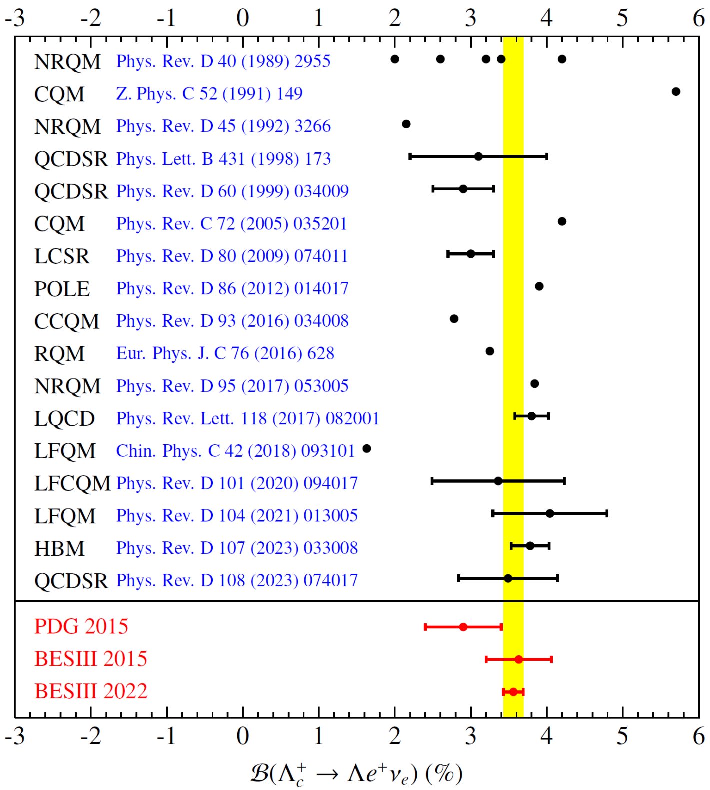
Event selection

- ST dataset reconstructed from 14 $\bar{\Lambda}_c^-$ tag modes
- Select DT $\Lambda \to p\pi^-$ and e^+ in the recoiling side
- Fit to U_{miss} distribution

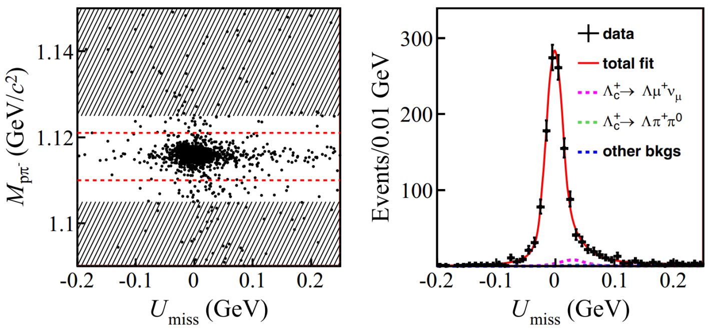
$$U_{\rm miss} = E_{\rm miss} - c|\vec{p}_{\rm miss}|$$
$$E_{\rm miss} = E_{\rm beam} - E_{\Lambda} - E_{e^+},$$
$$\vec{p}_{\rm miss} = \vec{p}_{\Lambda_c^+} - \vec{p}_{\Lambda} - \vec{p}_{e^+},$$

Precise measurement on BFs

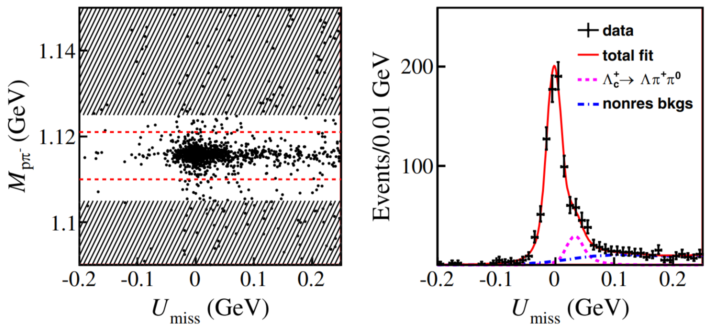
- $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.56 \pm 0.11_{\rm stat.} \pm 0.07_{\rm syst.})\%$
- $\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu) = (3.48 \pm 0.14_{\rm stat.} \pm 0.10_{\rm syst.})\%$



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



$\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu$



$\Lambda_c^+ \to \Lambda l^+ \nu_l \ (l = e, \mu)$

PRL **129**, 231803 (2022)
PRD **108**, L031105 (2023)

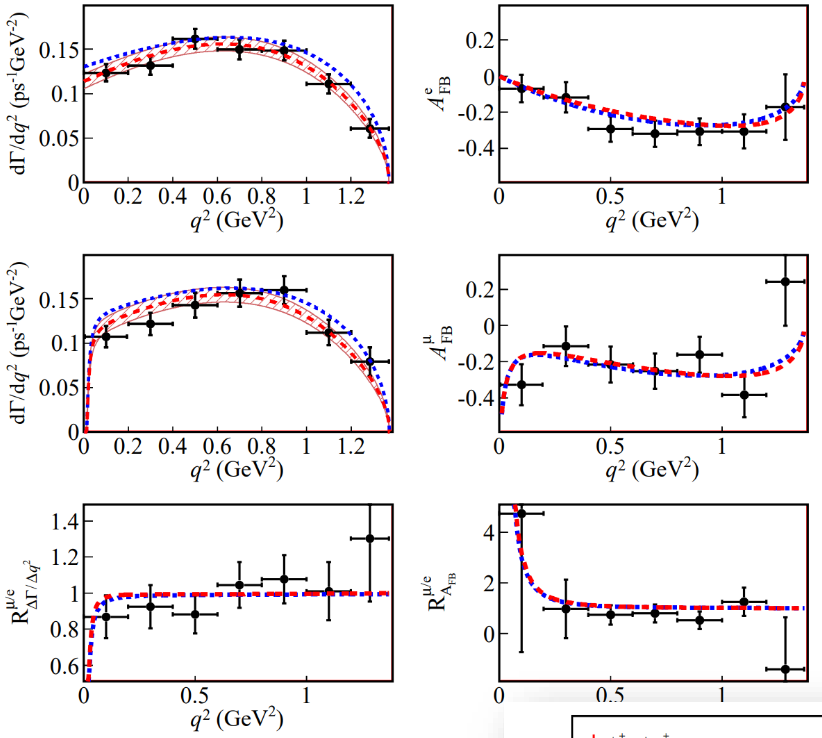
- **Test of lepton flavor universality**
  - Ratio of integrated BFs
    - $\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)}{\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu)} = 0.98 \pm 0.05_{\text{stat.}} \pm 0.03_{\text{syst.}}$
    - Consistent with LQCD prediction 0.97
  - Differential decay rates in q^2 binning

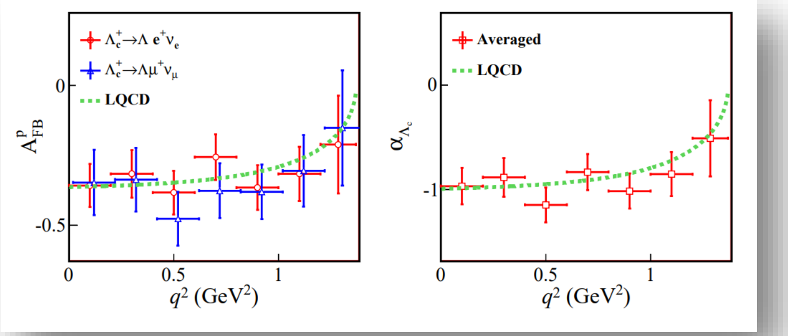
$$\Delta\Gamma_i = \int_i \frac{d\Gamma}{dq^2} dq^2 = \sum_{j=1}^{N_{\text{bins}}} (\epsilon^{-1})_{ij} N^j_{\text{DT}} / (\tau_{\Lambda_c} \times N^{\text{ST}})$$

    - $\mathcal{R}^{\mu/e}$ consistent with LQCD prediction
  - Forward-backward asymmetries
    - For both lepton system & $p\pi^-$ system

$$A_{\text{FB}}^{\ell,p}(q^2) = \frac{\int_0^1 \frac{d^2\Gamma}{dq^2 d\cos\theta_{\ell,p}} d\cos\theta_{\ell,p} - \int_{-1}^0 \frac{d^2\Gamma}{dq^2 d\cos\theta_{\ell,p}} d\cos\theta_{\ell,p}}{\int_0^1 \frac{d^2\Gamma}{dq^2 d\cos\theta_{\ell,p}} d\cos\theta_{\ell,p} + \int_{-1}^0 \frac{d^2\Gamma}{dq^2 d\cos\theta_{\ell,p}} d\cos\theta_{\ell,p}}$$

    - Also consistent with LQCD prediction





$\Lambda_c^+ \to \Lambda l^+ \nu_l \ (l = e, \mu)$

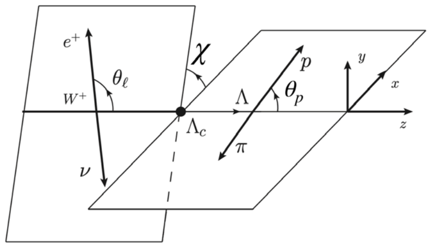
PRL **129**, 231803 (2022)
PRD **108**, L031105 (2023)

- **Extraction of form factors**
  - 4-dimensional fits to differential decay width
    - $e^+\nu_e$ mass square q^2
    - $\Lambda \to p\pi^-$ helicity angle θ_p
    - $W^+ \to e^+\nu_e$ helicity angle θ_e
    - Acoplanarity angle between Λ & W^+ decay planes χ
  - FFs parameterized with z-expansion

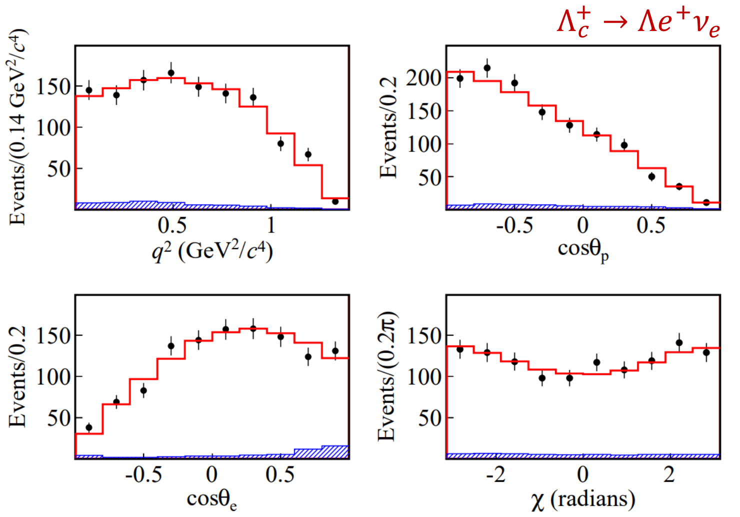
$$f(q^2) = \frac{a_0^f}{1 - q^2/\left(m_{\rm pole}^f\right)^2}\left[1 + \alpha_1^f \times z(q^2)\right]$$

  - 5 independent variables in the fit
    - Normalized using BF result

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



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

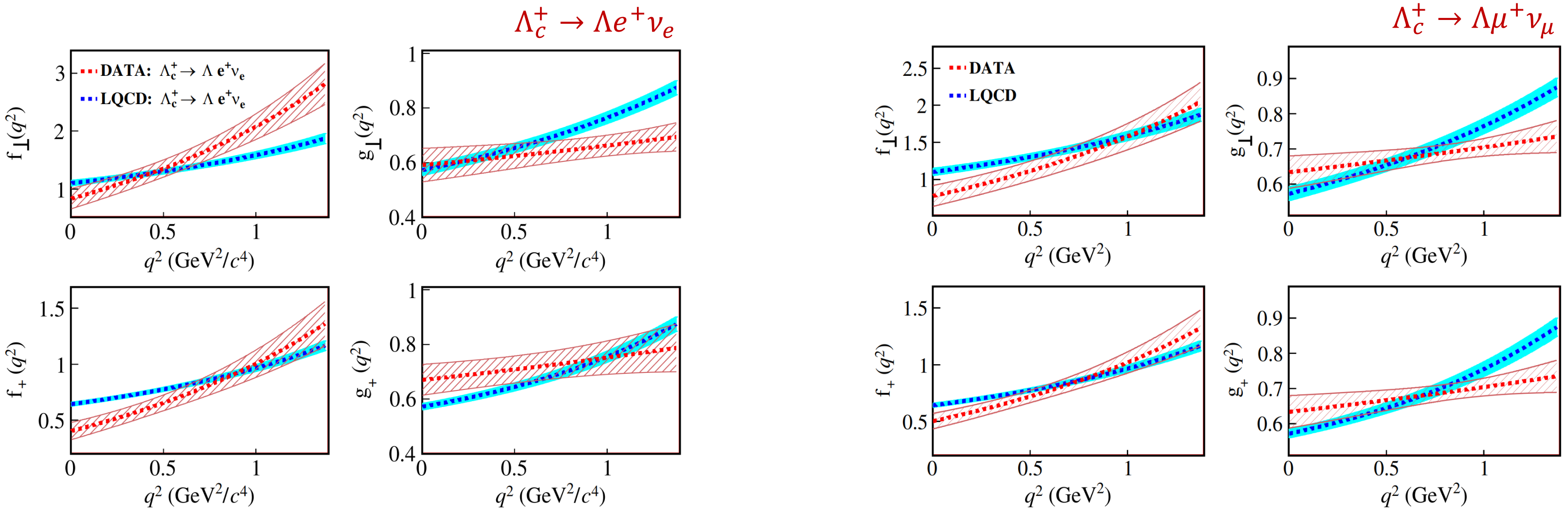


$\Lambda_c^+ \to \Lambda l^+ \nu_l \ (l = e, \mu)$

PRL **129**, 231803 (2022)
PRD **108**, L031105 (2023)

Extraction of form factors

- Show different kinematic behaviors compared to LQCD predictions

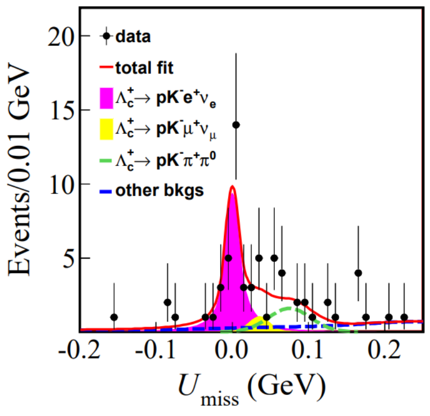


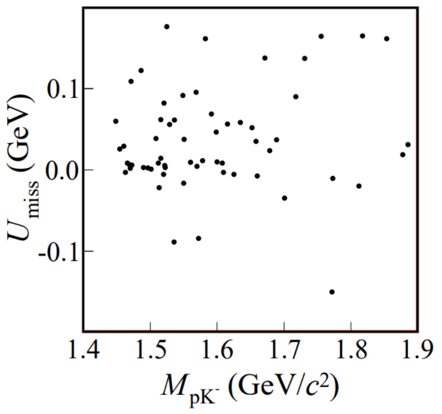
Extraction of CKM matrix element $|V_{cs}|$

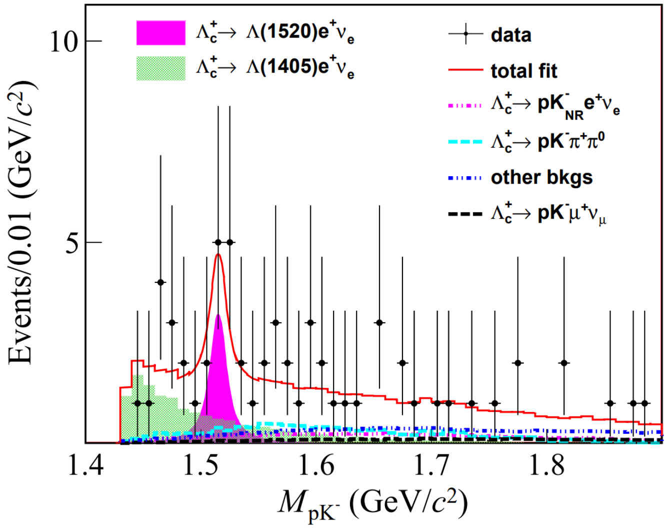
- Combine measured BFs of $\Lambda_c^+ \to \Lambda e^+ \nu_e$ & $\Lambda \mu^+ \nu_\mu$
- Take FFs from LQCD and τ_{Λ_c} from PDG as input
- Yield $|V_{cs}| = 0.937 \pm 0.014_{\mathcal{B}} \pm 0.024_{\mathrm{LQCD}} \pm 0.007_{\tau_{\Lambda_c}}$
  - Consistent with $D \to K l^+ \nu_l$ measurement within 1.2σ

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

PRD **106**, 112010 (2022)







The second observed Λ_c^+ semi-leptonic decay

- $\mathcal{B}(\Lambda_c^+ \to pK^- e^+ \nu_e) = (0.88 \pm 0.17 \pm 0.07) \times 10^{-3}$ with 8.2σ

Evidences found for $\Lambda_c^+ \to \Lambda^* e^+ \nu_e$

- $\mathcal{B}(\Lambda_c^+ \to \Lambda(1520) e^+ \nu_e) = (1.02 \pm 0.52 \pm 0.11) \times 10^{-3}$ with 3.3σ
- $\mathcal{B}(\Lambda_c^+ \to \Lambda(1405)[\to pK^-] e^+ \nu_e) = (0.42 \pm 0.19 \pm 0.04) \times 10^{-3}$ with 3.2σ

Elusive nature,
Potential molecular state or pentaquark candidate

- Comparison with quark models and LQCD

	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1520) e^+ \nu_e)$	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1405) e^+ \nu_e)$
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	$1.02 \pm 0.52 \pm 0.11$	$\frac{0.42 \pm 0.19 \pm 0.04}{\mathcal{B}(\Lambda(1405) \to pK^-)}$

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

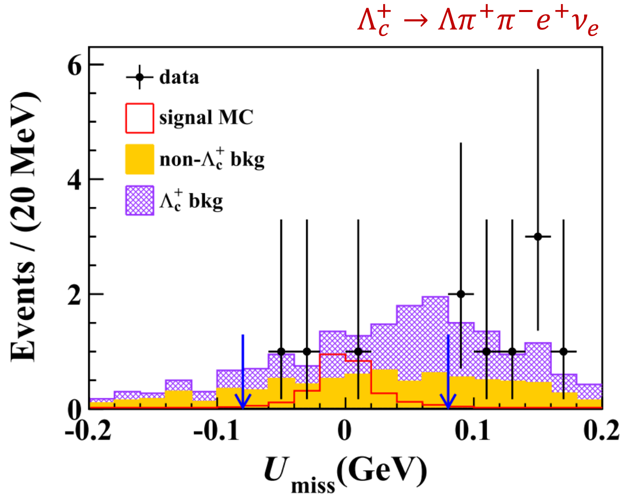
PLB **843**, 137933 (2023)

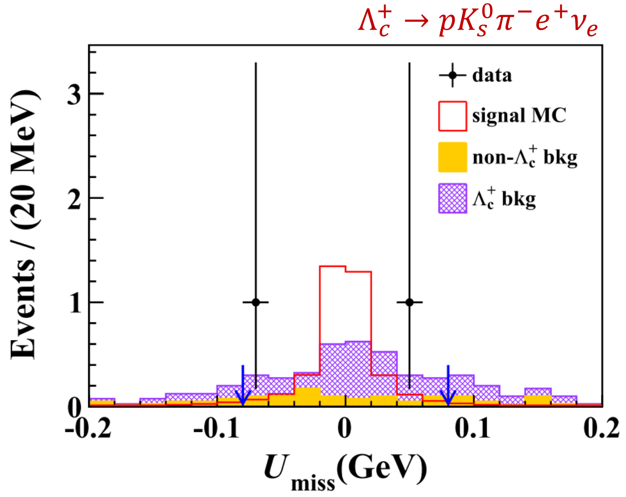
- **Search for $\Lambda_c^+ \to \Lambda^* e^+\nu_e$ via $\Lambda^* \to \Lambda\pi^+\pi^-$ & $pK_S^0\pi^-$**
  - $\mathcal{B}(\Lambda(1520) \to \Lambda\pi^+\pi^-) = (10 \pm 1)\%$
  - Higher Λ^* excited states may decay to $pK^*(892)^-[\to K_S^0\pi^-]$

- **Upper limits set @ 90% C.L.**
  - $\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^- e^+\nu_e) < 3.9 \times 10^{-4}$
  - $\mathcal{B}(\Lambda_c^+ \to pK_S^0\pi^- e^+\nu_e) < 3.3 \times 10^{-4}$
  - $\mathcal{B}(\Lambda_c^+ \to \Lambda(1520) e^+\nu_e) < 4.3 \times 10^{-3}$
  - $\mathcal{B}(\Lambda_c^+ \to \Lambda(1600) e^+\nu_e) < 9.0 \times 10^{-3}$
  - Limited sensitivity to examine theoretical calculations

The BFs for $\Lambda_c^+ \to \Lambda^* e^+\nu_e$ predicted by different theoretical models, in units of 10^{-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}	--	--



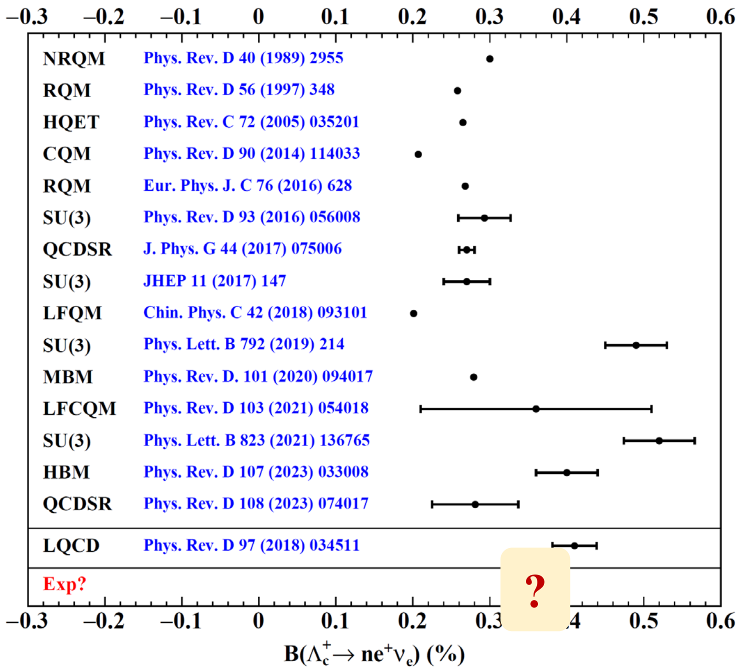


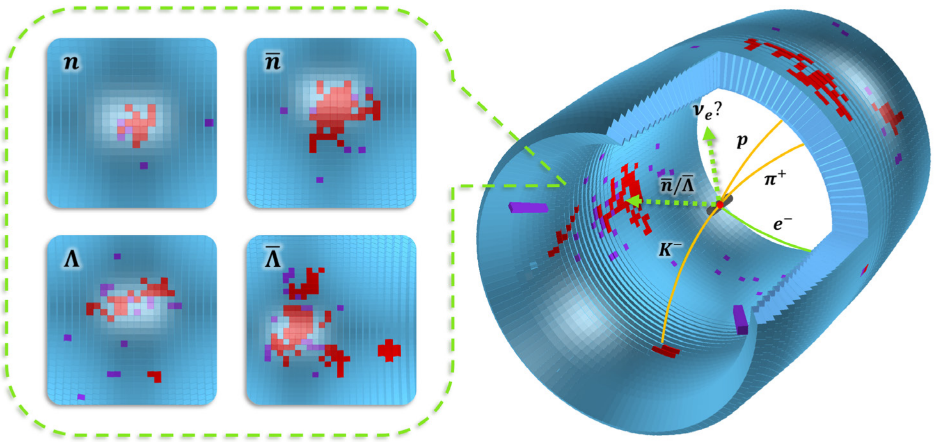
$\Lambda_c^+ \to n e^+ \nu_e$

NatComm **16**, 681 (2025)

- **Cabibbo-suppressed $c \to d$ transition must exist**
  - $\frac{|V_{cd}|}{|V_{cs}|} \sim 0.2 \to \frac{\mathcal{B}(\Lambda_c^+ \to n e^+ \nu_e)}{\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)} \sim \mathcal{O}(10^{-1})$
  - Dozens of theoretical predications with zero experimental result

- **Experimental study is very challenging**
  - Co-existence of “missing particles” n & ν_e
  - Dominant background from $\Lambda_c^+ \to \Lambda(n\pi^0)e^+\nu_e$
  - Need very powerful tool to identify n from $\pi^0 \to \gamma\gamma$ on EMC



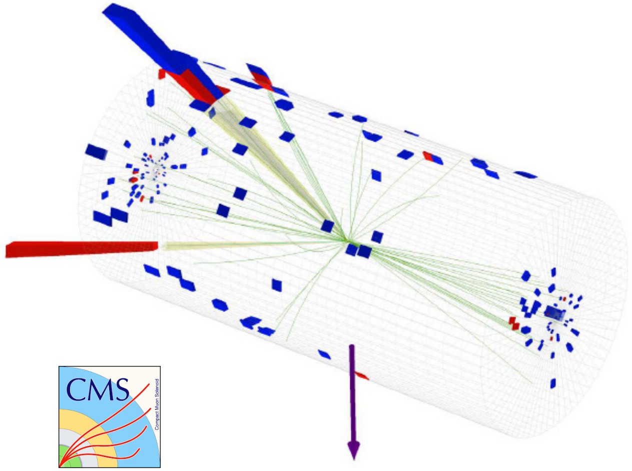


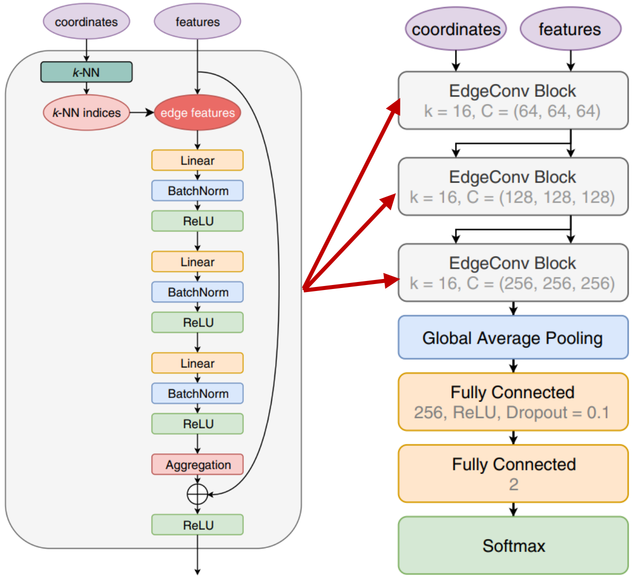
Distinction in n/Λ EMC patterns can be noticed from eyes.

Deep learning may recognize such distinctions in a smart & flexible way.

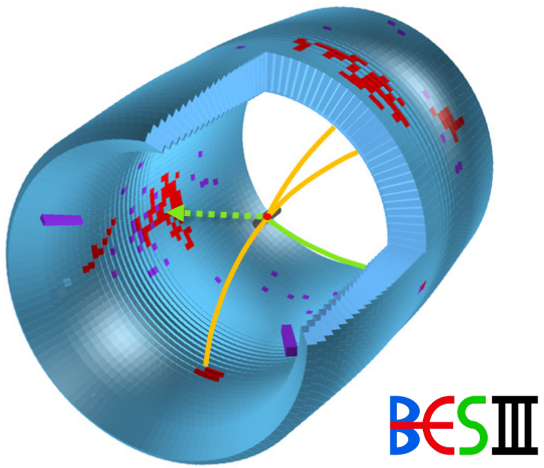
NatComm **16**, 681 (2025)

- **Use Graph Neural Network (GNN) to identify between n/Λ EMC shower maps**
  - A task parallels jet tagging in LHC experiments but at a new energy scale
  - Inspired from the successful graph-based architecture ParticleNet





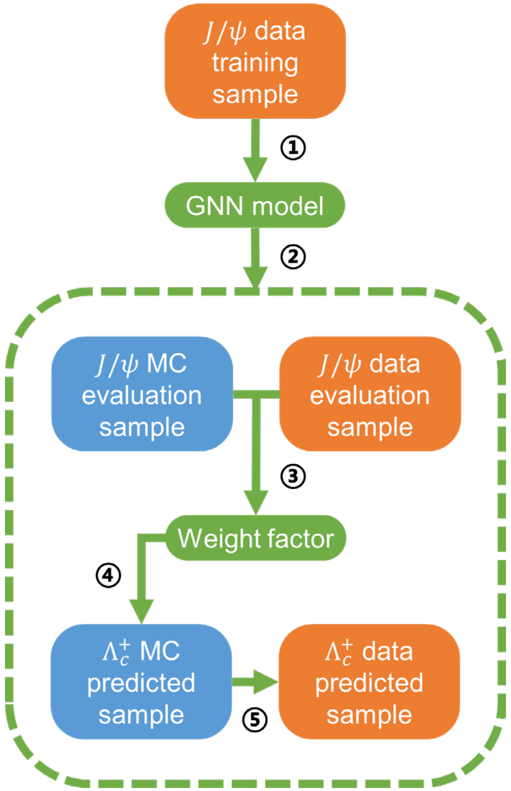
PRD **101**, 056019 (2020)

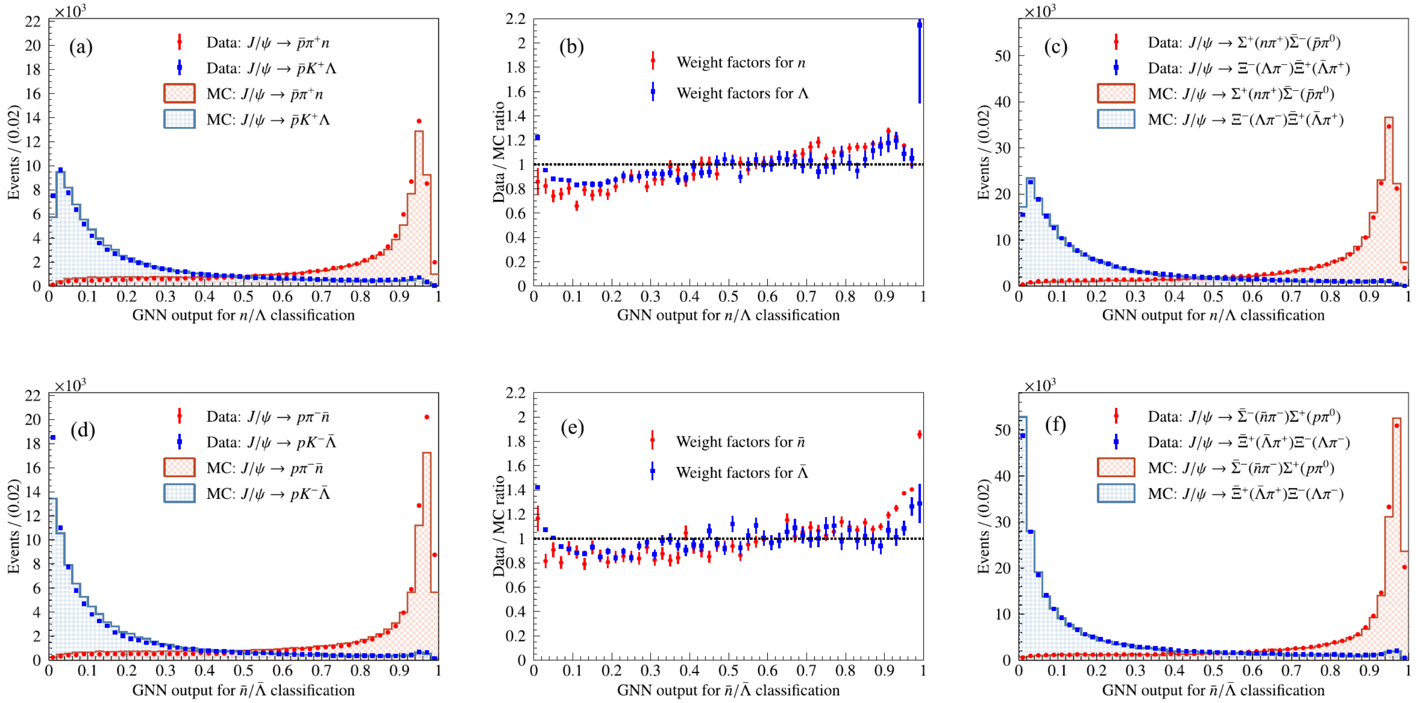


$\Lambda_c^+ \to n e^+ \nu_e$

NatComm **16**, 681 (2025)

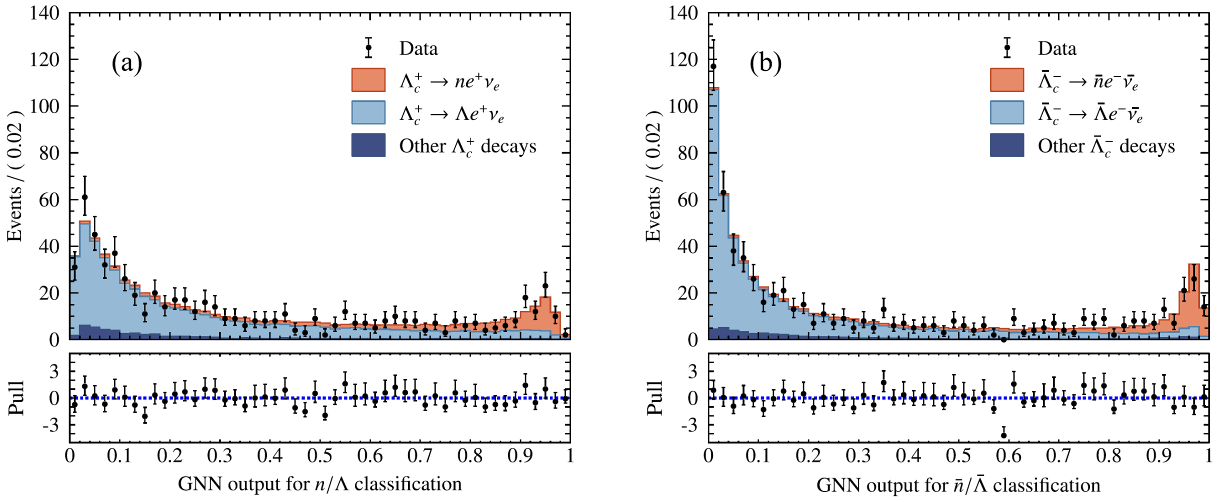
- **The interpretability & robustness of neural networks is concerning in HEP experiments**
  - Establish a data-driven pipeline for GNN training, calibration, validation and uncertainty quantification
  - Extensively utilize control samples from 10 billion J/ψ events at BESIII

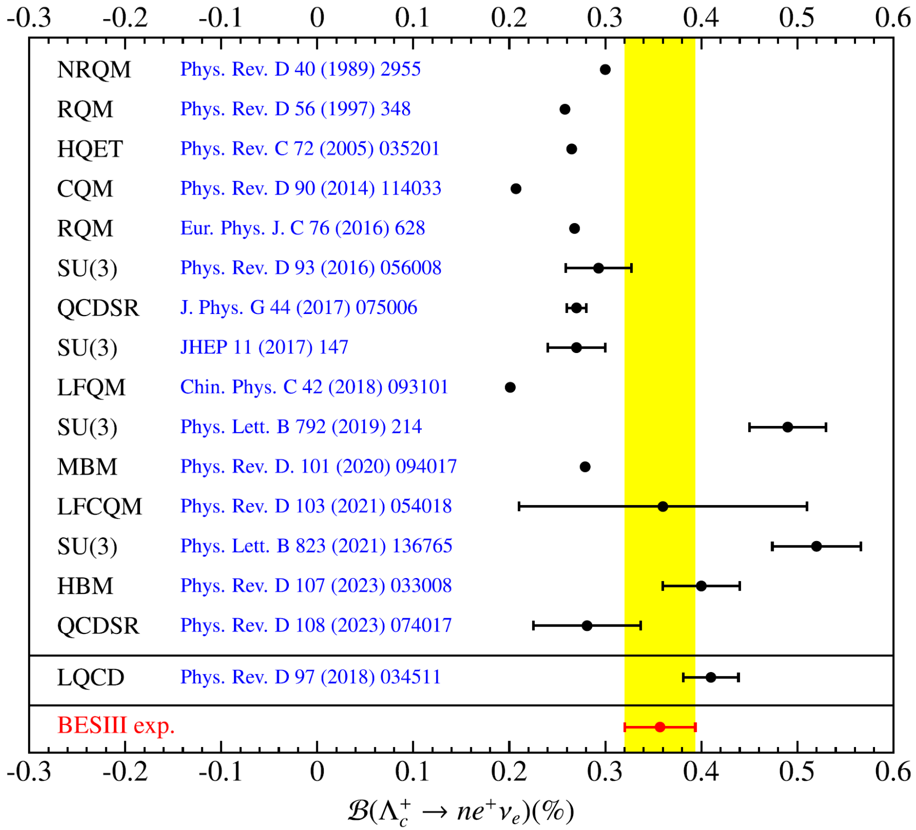




$\Lambda_c^+ \to n e^+ \nu_e$

NatComm **16**, 681 (2025)



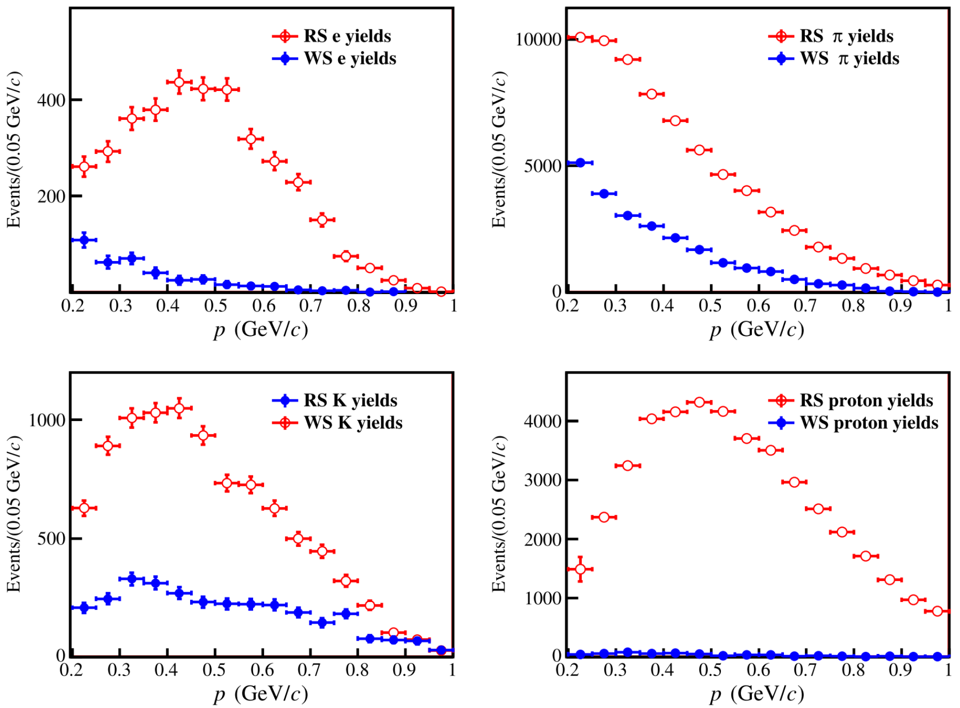


- **First observation of $\Lambda_c^+ \to n e^+ \nu_e$ with over 10σ significance**
  - $\mathcal{B} = (0.357 \pm 0.334_{\text{stat.}} \pm 0.014_{\text{syst.}})\%$
- **First determination of $|V_{cd}|$ from charmed baryon decays**
  - Take FFs from LQCD as input
  - $|V_{cd}| = 0.208 \pm 0.011_{\text{exp.}} \pm 0.007_{\text{LQCD}} \pm 0.011_{\tau_{\Lambda_c^+}}$

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

- **Improved measurement of inclusive Λ_c^+ semi-leptonic decays**
  - $\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e) = \left(4.06 \pm 0.10_{\text{stat.}} \pm 0.09_{\text{syst.}}\right)\%$
- **Ratio between charmed meson/baryon decay widths**
  - $\frac{\Gamma(\Lambda_c^+ \to X e^+ \nu_e)}{\bar{\Gamma}(D \to X e^+ \nu_e)} = 1.28 \pm 0.05$
- **Use unfolding method to calibrate particle misidentification**

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



- **Constraint on unobserved Λ_c^+ semi-leptonic decays**
  - Combine inclusive & exclusive measurements, assume all uncertainties are uncorrelated:
    $\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e)_{X \neq \Lambda, n, pK^-} = \left(0.55 \pm 1.53_{\text{stat.}} \pm 1.15_{\text{syst.}}\right) \times 10^{-3}$
  - The majority of experimental gap has been filled.

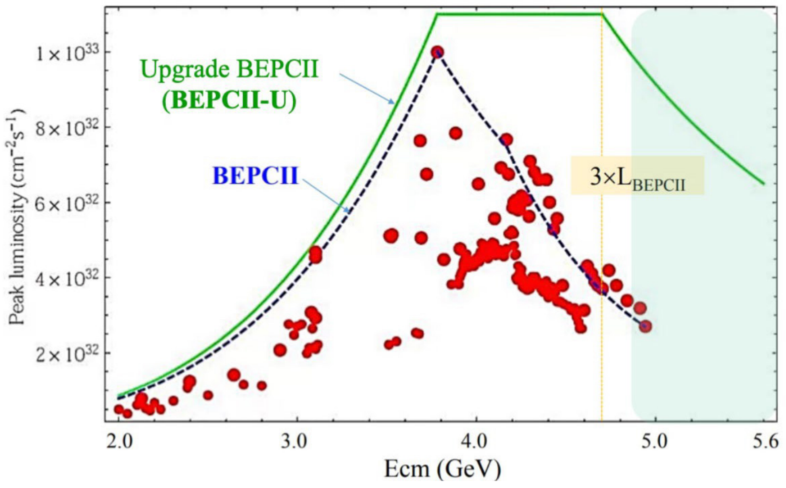
Ongoing physics analyses at BESIII

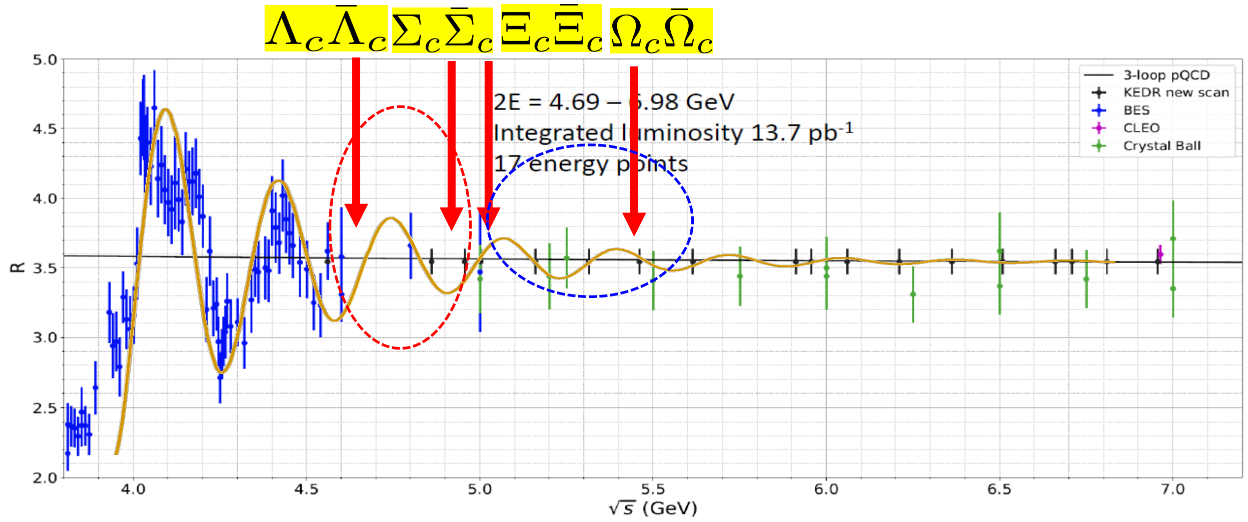
- **$\Lambda_c^+ \to \Lambda^*$ transition**
  - $\Lambda_c^+ \to \Sigma^{\pm}\pi^{\mp}e^+\nu_e$
    - $\Lambda(1405)$ behaves differently in $\Sigma\pi$ and NK channels
  - $\Lambda_c^+ \to nK_S^0 e^+\nu_e$
    - Isospin-symmetric channel to pK^-
    - Similar challenge with $ne^+\nu_e$
  - $\Lambda_c^+ \to \Lambda(1405/1520)[\to pK^-]e^+\nu_e$
    - Aim for a decisive observation

- **$\Lambda_c^+ \to N^*$ transition**
  - $\Lambda_c^+ \to p\pi^- e^+\nu_e$ (non-Λ component)
    - $\mathcal{B}(\Lambda_c^+ \to N^*(1535)e^+\nu_e)$ predictions vary in $4.03 \times 10^{-5} \sim 6.4 \times 10^{-3}$

Prospect

- **BEPCII(-U) & BESIII just finished a major machine upgrade.**
  - Triple the luminosity @ 4.7 GeV → more Λ_c^+ data
  - Extend c.m. energy up to 5.6 GeV → near-threshold pair production for $\Sigma_c, \Xi_c, \Omega_c$
  - Replace inner MDC with CGEM detector



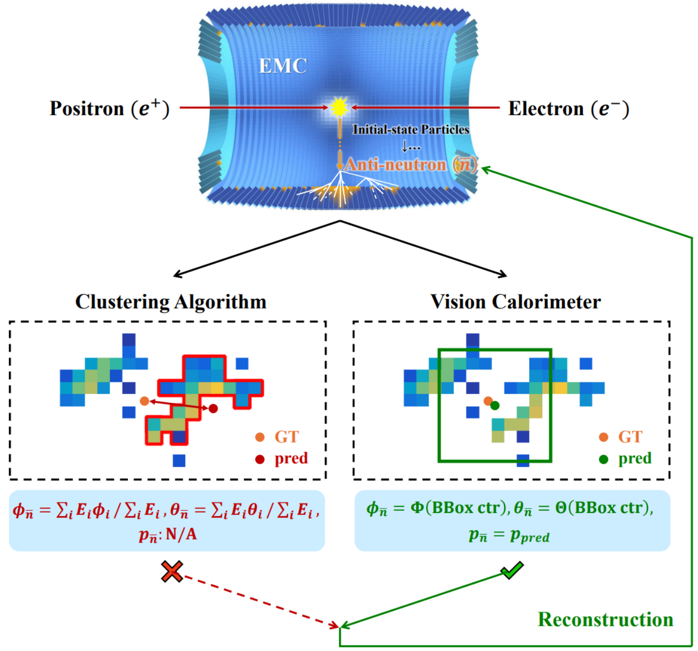


- **According to latest time schedule:**
  - New Λ_c^+ data taking will start in 2026
  - Above-5-GeV data taking will start in 2028

Wishlist

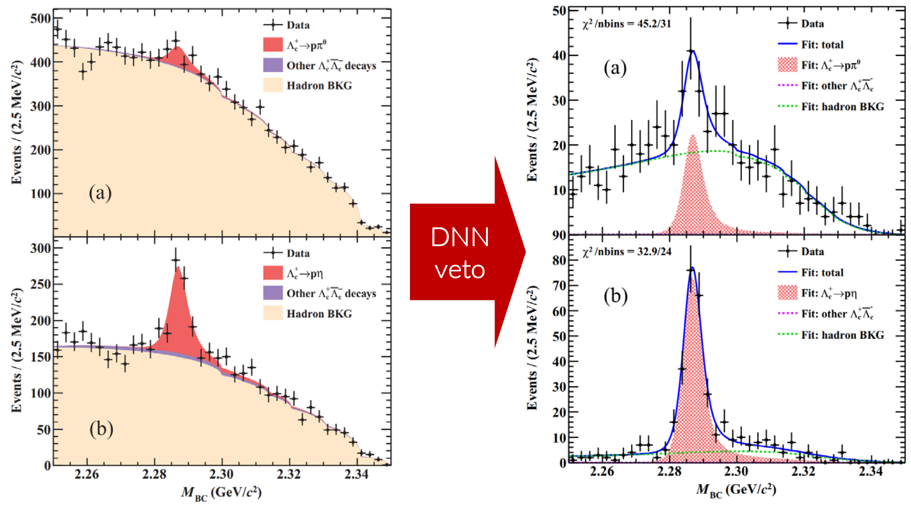
- **Extraction of FFs for $\Lambda_c^+ \to n e^+ \nu_e$**
  - Require 4-momentum of neutron to calculate q^2
  - New deep learning methods are being explored
  - Estimated signal yield under 15 fb^{-1} dataset: $\sim$750

arXiv: 2408.10599
"Vision calorimeter"
Analyze EMC hits with computer vision models



- **Decisive observation for $\Lambda_c^+ \to \Lambda(1405/1520) e^+ \nu_e$**
  - With higher statistics and lower BKG, a partial wave analysis can address both Λ^* interference and FFs
  - New deep learning methods are being explored
  - Estimated signal yields under 15 fb^{-1} dataset: $\sim$500 for $\Lambda(1405/1520)$ each

PRD **111**, L051101 (2025)
Observation of $\Lambda_c^+ \to p\pi^0$
High-sensitivity Λ_c^+ tagging with Transformer model



Summary

- Λ_c^+ **semi-leptonic decays** provide good opportunities to study charmed baryon dynamics and test SM.

- **BESIII made significant experimental contributions in recent years,** including
  - Most precise measurements of $\Lambda_c^+ \to \Lambda l^+ \nu_l$
  - First observation of Cabibbo-suppressed $\Lambda_c^+ \to n e^+ \nu_e$
  - Active searches for $\Lambda_c^+ \to \Lambda^* e^+ \nu_e$ via $pK^-, \Lambda\pi^+\pi^-, pK_S^0\pi^-$
  - Closed gaps between inclusive & exclusive BFs

- **Deep learning methods** can bring impressive and reliable physics results in these investigations.

- **BEPCII(-U) & BESIII machine upgrade** will provide more opportunities for charm baryon physics.

Thanks for your attention!