Semi-leptonic Λ_c^+ decays at BESIII

Xudong Yu
Peking University
(On behalf of BESIII collaboration)

2024.5 郑州·BESIII粲强子物理研讨会

Outline

- ➔ Introduction
- ➔ BESIII experiment
- ➔ Published physics results
  - ❖ $\Lambda_c^+ \to \Lambda e^+ \nu_e, \Lambda \mu^+ \nu_\mu$ Phys. Rev. Lett. 129, 231803 (2022). Phys. Rev. D 108, L031105 (2023).
  - ❖ $\Lambda_c^+ \to X e^+ \nu_e$ Phys. Rev. D 107, 052005 (2023).
  - ❖ $\Lambda_c^+ \to p K^- e^+ \nu_e$ Phys. Rev. D 106, 112010 (2022).
  - ❖ $\Lambda_c^+ \to \Lambda \pi^+ \pi^- e^+ \nu_e, p K_S^0 \pi^- e^+ \nu_e$ Phys. Lett. B 843, 137993 (2023).
- ➔ Other ongoing analysis
- ➔ Summary & outlook

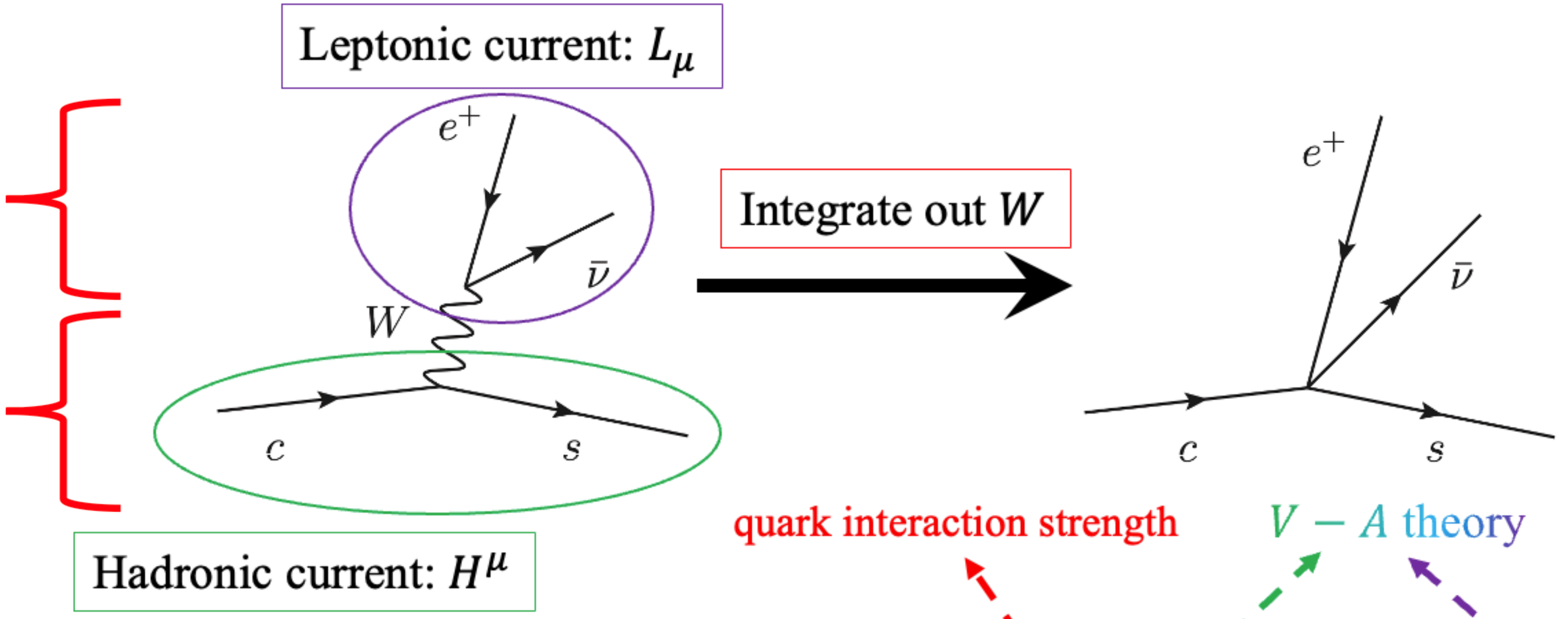
Introduction

Why semi-leptonic decay?

- ➔ Semi-leptonic (SL) decay: good platform to study weak/strong interaction and probe new physics beyond the Standard Model.
- ➔ Take $c(\Lambda_c^+) \to s(\Lambda)$ as an example
  - ❖ Differential decay width: $d\Gamma = \frac{1}{2m_{\Lambda_c^+}}(2\pi)^n d\Phi_n |\bar{\mathscr{M}}|^2$
  - ❖ Helicity amplitude: $\mathscr{M} = \mathscr{H}^\mu \mathscr{L}_\mu$

Leptonic part can be precisely calculated

Hadronic part is hard to calculate from the first principle, since non-perturbative QCD effect is involved.



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

Λ_c^+ SL decays in theory

➔ With the help of effective field theory, hadronic amplitude can be parameterized by **Form Factors (FFs)** 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 $q = p_1 - p_2$

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

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

➔ Total helicity amplitude: $H_{\lambda_\Lambda\lambda_W} = H_\mu(\lambda_\Lambda)\epsilon^\mu(\lambda_W) = [H_V(\lambda_\Lambda) - H_A(\lambda_\Lambda)]_\mu\epsilon^\mu(\lambda_W) = H_V(\lambda_\Lambda\lambda_W) - H_A(\lambda_\Lambda\lambda_W)$

- 6 helicity amplitudes: $H_V\left(\frac{1}{2},0\right), H_V\left(\frac{1}{2},1\right), H_V\left(\frac{1}{2},t\right), H_A\left(\frac{1}{2},0\right), H_A\left(\frac{1}{2},1\right), H_A\left(\frac{1}{2},t\right)$
- In the limit of negligible lepton mass, only four of them remained

➔ Physical observables:

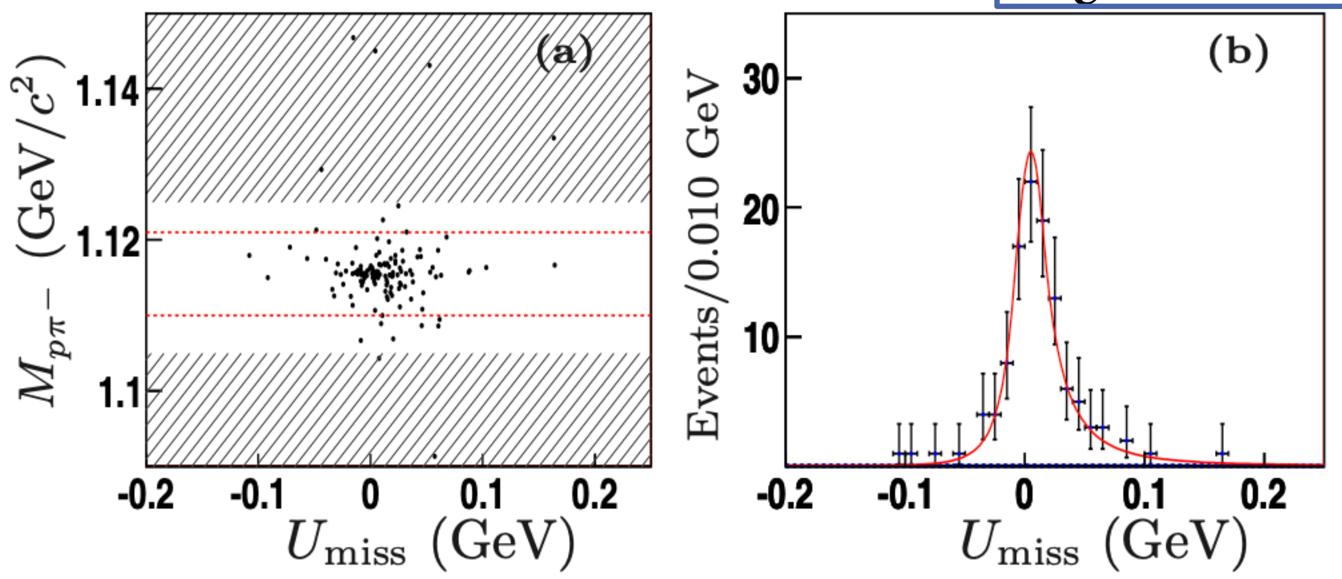
- Branching Fraction (BF), Lepton Flavor Universality (LFU)
- q^2- and angular dependent differential decay width, FF, Forward-backward asymmetry (A_{FB}), decay asymmetry, polarization…
- New physics observables

➔ Various theoretical prediction: LQCD, HQET, Quark models, Bag model, Sum rules, $SU(3)_F$, …

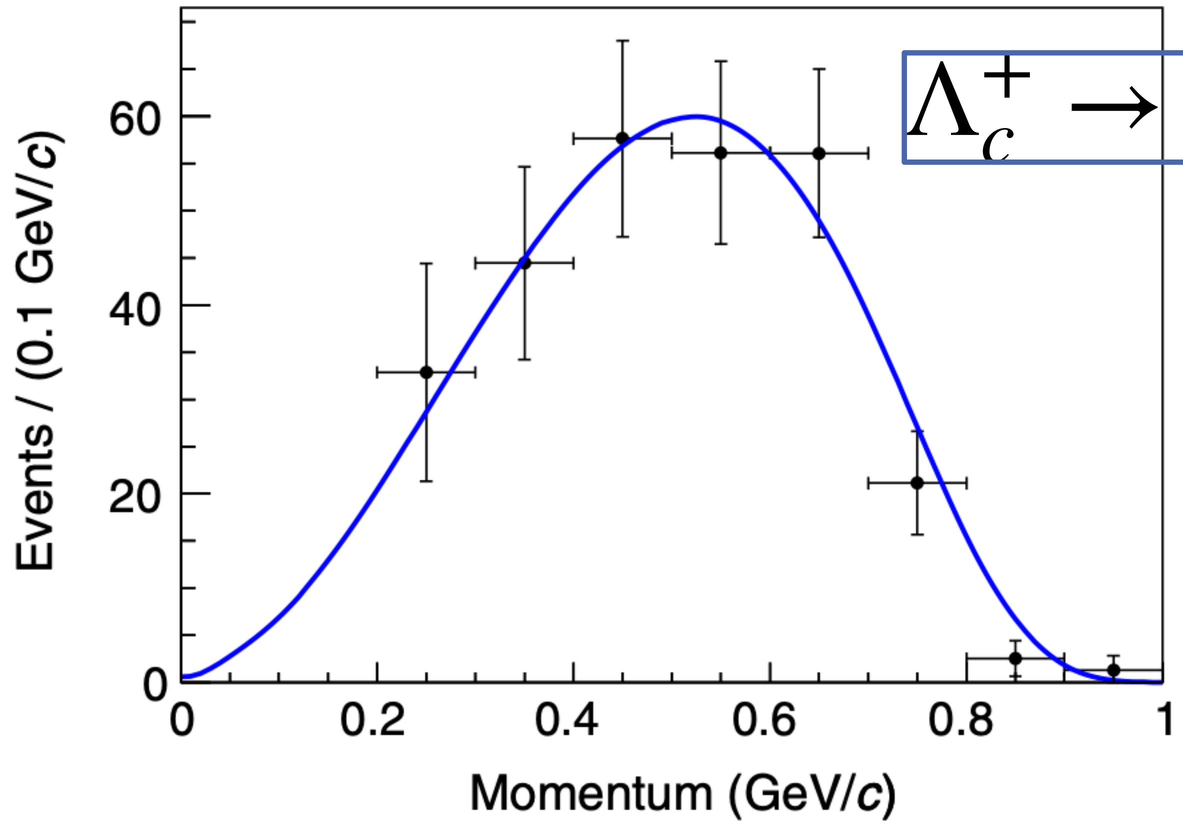
Λ_c^+ SL decays in experiment

- Before 2019, few Λ_c^+ SL decay channels were measured
  - Before 2005, $\Lambda_c^+ \to \Lambda e^+ \nu_e$ studied by ARGUS & CLEO
    - $\Lambda_c^+ \to \Lambda e^+ \nu_e$ observed by ARGUS[1], decay asymmetry & FFs measured by CLEO[2,3,4]
  - Using 587 fb^{-1} data, BESIII reported several absolute BF measurement results
    - $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.63 \pm 0.38_{\mathrm{stat.}} \pm 0.20_{\mathrm{syst.}})\ \%$[5]
    - $\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu) = (3.49 \pm 0.46_{\mathrm{stat.}} \pm 0.27_{\mathrm{syst.}})\ \%$[6]
    - $\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e) = (3.95 \pm 0.34_{\mathrm{stat.}} \pm 0.09_{\mathrm{syst.}})\ \%$[7]
    - $\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu)/\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (96 \pm 16_{\mathrm{stat.}} \pm 4_{\mathrm{syst.}})\ \%$[6]
    - $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)/\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e) = (91.9 \pm 12.5_{\mathrm{stat.}} \pm 5.4_{\mathrm{syst.}})\ \%$[5]

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



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

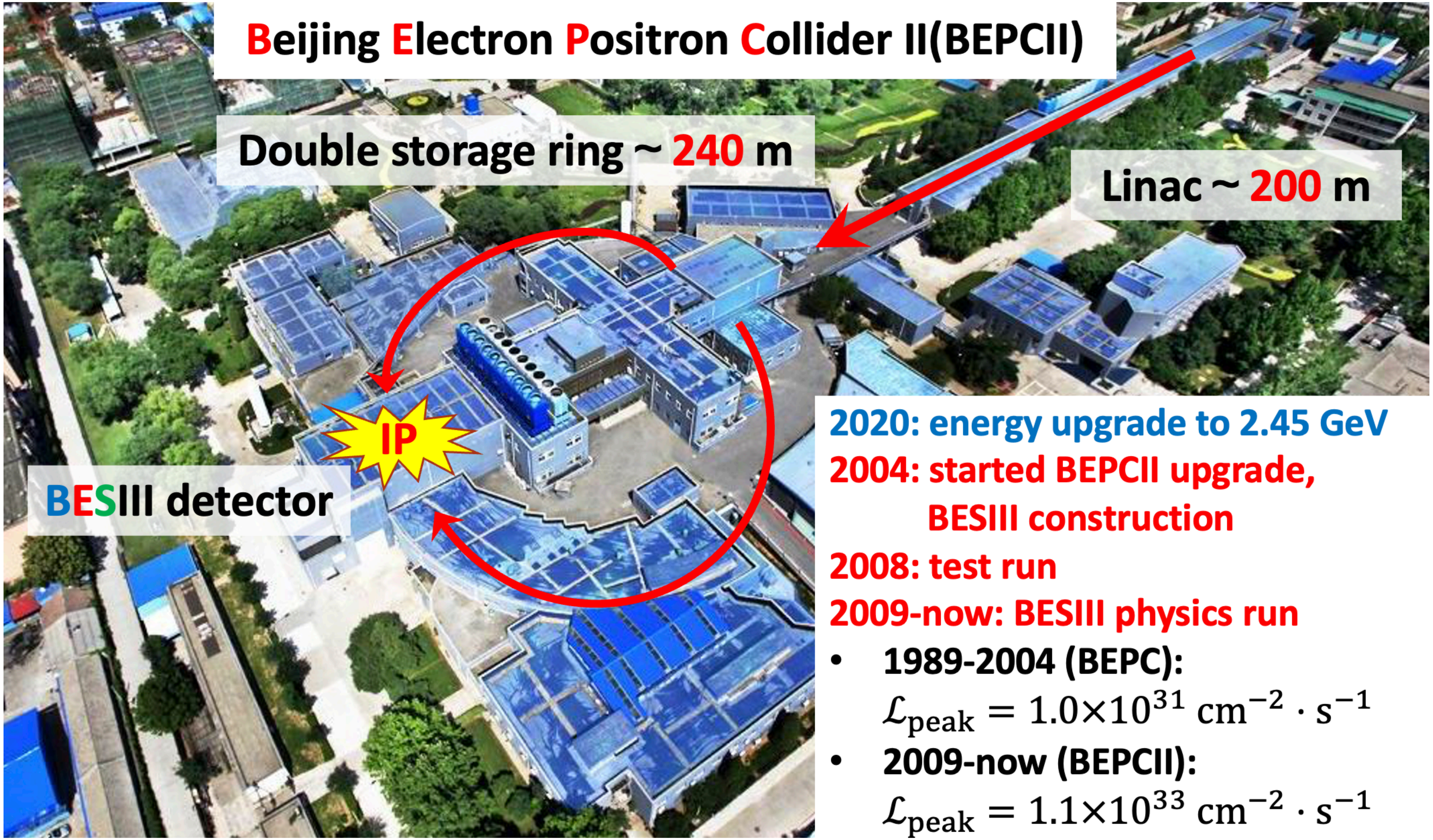


- After 2019, BESIII took new $\Lambda_c^+\bar{\Lambda}_c^-$ data. What we do?
  - Precise measurement of golden channel $\Lambda_c^+ \to \Lambda e^+ \nu_e, \Lambda \mu^+ \nu_\mu$
    - Improve precision (BF, LFU), dynamics study (FF)
  - Search for other Λ_c^+ SL decays
    - Any rooms? 80% or 100%? Much less than D case $\Rightarrow$ improve precision of BF of inclusive decay
    - Excited state: $\Lambda_c^+ \to \Lambda^*$? Cabibbo-suppressed: $\Lambda_c^+ \to n$?

[1] Phys. Lett. B 269, 234 (1991)
[2] Phys. Lett. B 323, 219 (1994)
[3] Phys. Rev. Lett. 75, 624 (1995)
[4] Phys. Rev. Lett. 94, 191801 (2005)
[5] Phys. Rev. Lett. 115, 221805 (2015)
[6] Phys. Lett. B 767,42 (2017)
[7] Phys. Rev. D 121, 251801 (2018)

BESIII experiment

BEPCII



2020: energy upgrade to 2.45 GeV

2004: started BEPCII upgrade, BESIII construction

2008: test run

2009-now: BESIII physics run

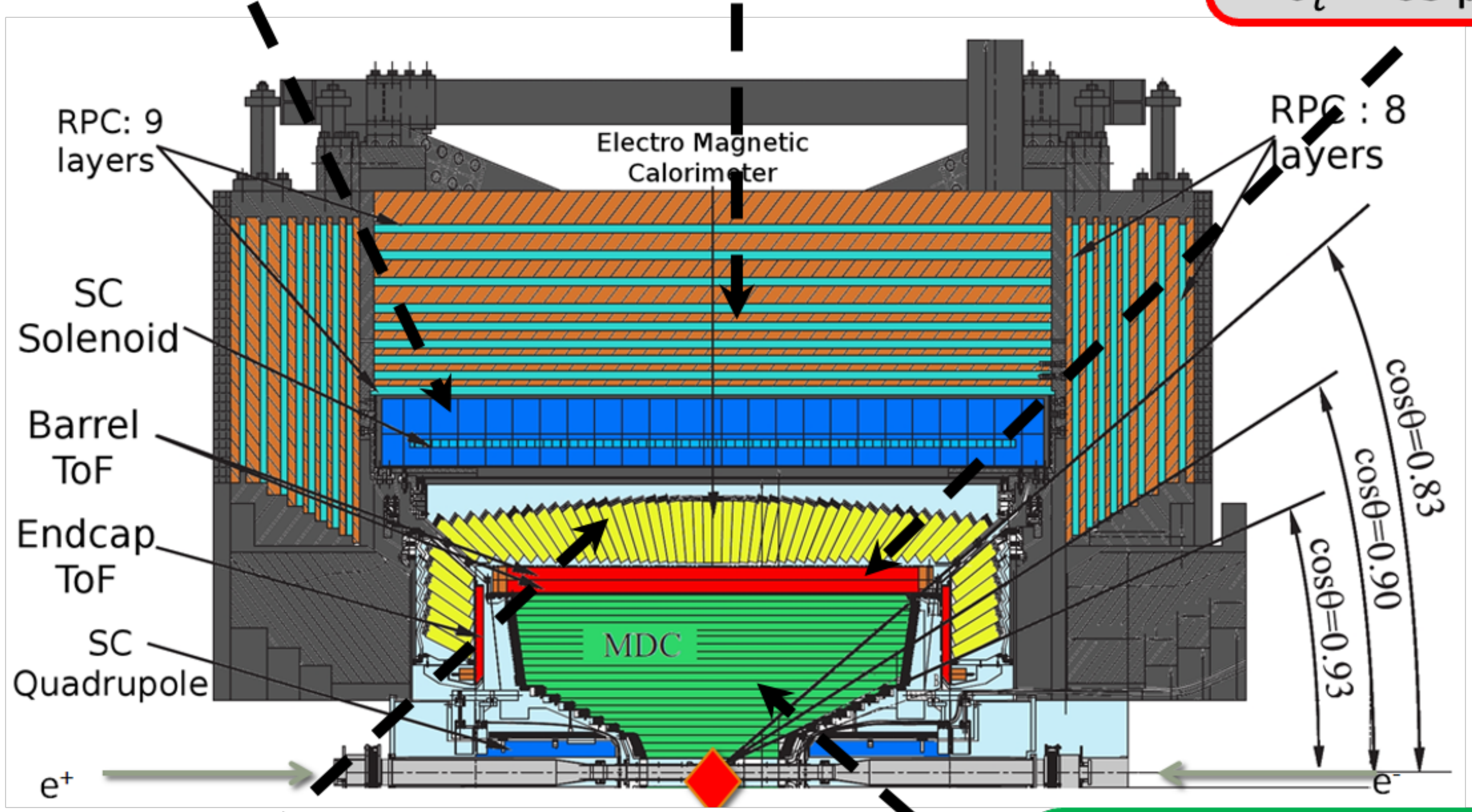
- **1989-2004 (BEPC):** $\mathcal{L}_{\text{peak}} = 1.0\times10^{31}\ \text{cm}^{-2}\cdot\text{s}^{-1}$
- **2009-now (BEPCII):** $\mathcal{L}_{\text{peak}} = 1.1\times10^{33}\ \text{cm}^{-2}\cdot\text{s}^{-1}$

BESIII detector

Superconducting solenoid
- **0.9~1.0 T**

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

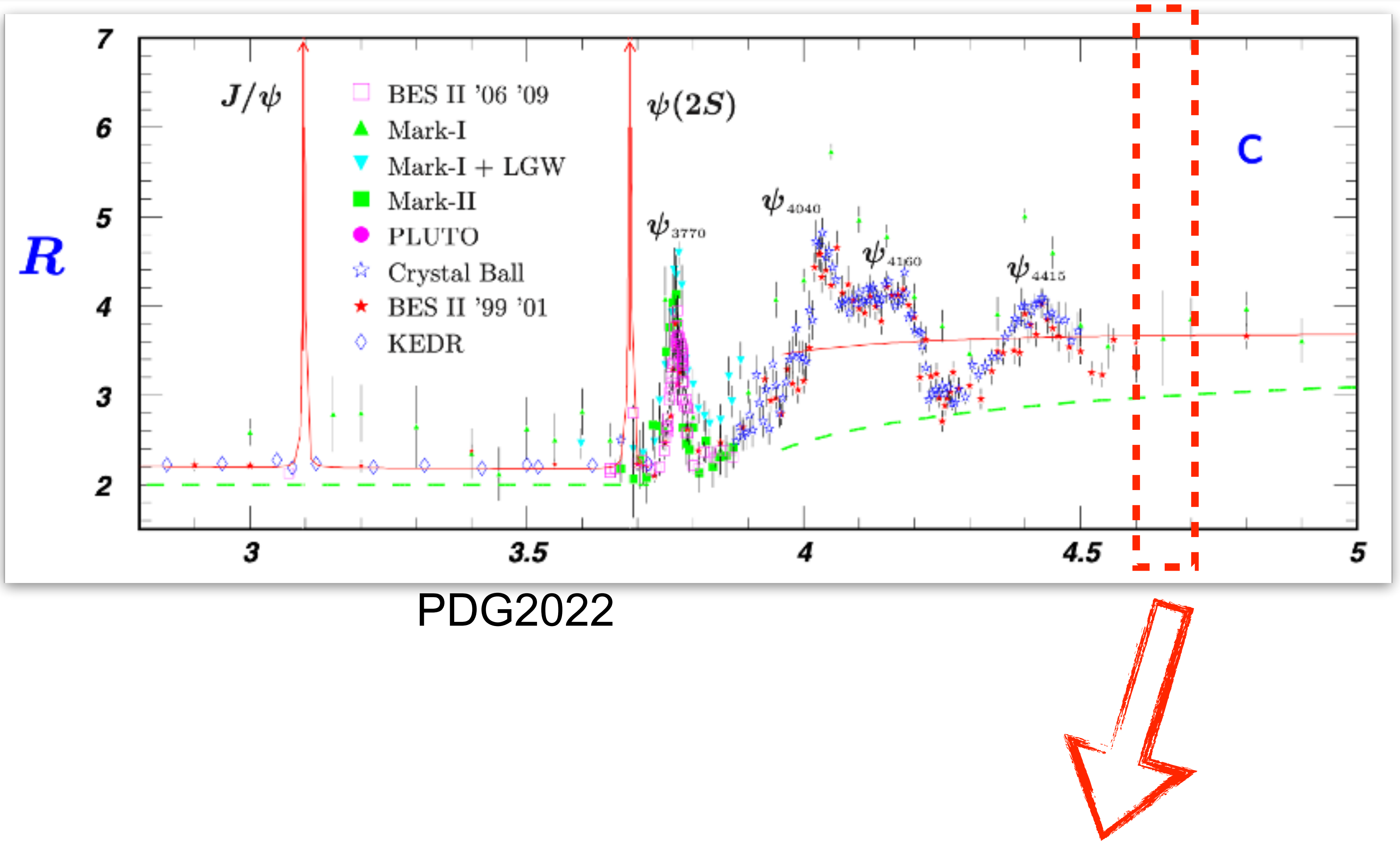
Time Of Flight (TOF)
- $\sigma_t = 90$ ps (barrel)
- $\sigma_t = 65$ ps (end cap)



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

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

Pair production at threshold



PDG2022

Sample	$\sqrt{s}$ (MeV)	$\mathcal{L}^i_{\rm int}$ (pb^{-1})
4600	$4599.53 \pm 0.07 \pm 0.74$	$586.9 \pm 0.1 \pm 3.9$
4612	$4611.86 \pm 0.12 \pm 0.30$	$103.65 \pm 0.05 \pm 0.55$
4626	$4628.00 \pm 0.06 \pm 0.32$	$521.53 \pm 0.11 \pm 2.76$
4640	$4640.91 \pm 0.06 \pm 0.38$	$551.65 \pm 0.12 \pm 2.92$
4660	$4661.24 \pm 0.06 \pm 0.29$	$529.43 \pm 0.12 \pm 2.81$
4680	$4681.92 \pm 0.08 \pm 0.29$	$1667.39 \pm 0.21 \pm 8.84$
4700	$4698.82 \pm 0.10 \pm 0.36$	$535.54 \pm 0.12 \pm 2.84$

- **Threshold effect**: pair production of charmed baryons without accompanying hadrons
  - $e^+e^- \to \gamma^* \to \Lambda_c^+\bar{\Lambda}_c^-$
- Center-of-mass energy: $E_{\rm cms} = 4.6 \sim 4.7$ GeV
  - $2M_{\Lambda_c} < E_{\rm cms} < (2M_{\Lambda_c} + M_\pi)$
- Clean backgrounds and well constrained kinematics
  - $\Delta E = E_{\Lambda_c} - E_{\rm beam}$
  - $M_{\rm BC} = \sqrt{E^2_{\rm beam}/c^4 - p^2c^2}$
- Integrated luminosity: 4.5 fb^{-1} (~7.5x 4600 data)
  - 1.9 fb^{-1} data @ 4740 ~ 4950 GeV (not used in published SL analysis)

Double tag method & Partial reconstruction

→ Double Tag (DT) Method

- Reconstruct $\bar{\Lambda}_c^-$ by dominant and clean decay modes, e.g., $\bar{\Lambda}_c^- \to \bar{p}K_S^0, \bar{p}K^+\pi^-, \ldots$
- Search for Λ_c^+ signal decay in the recoiling side
- BF formula:

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

$$N_{\rm ST} = \sum_{i,j} N_{\rm ST}^{i,j}$$

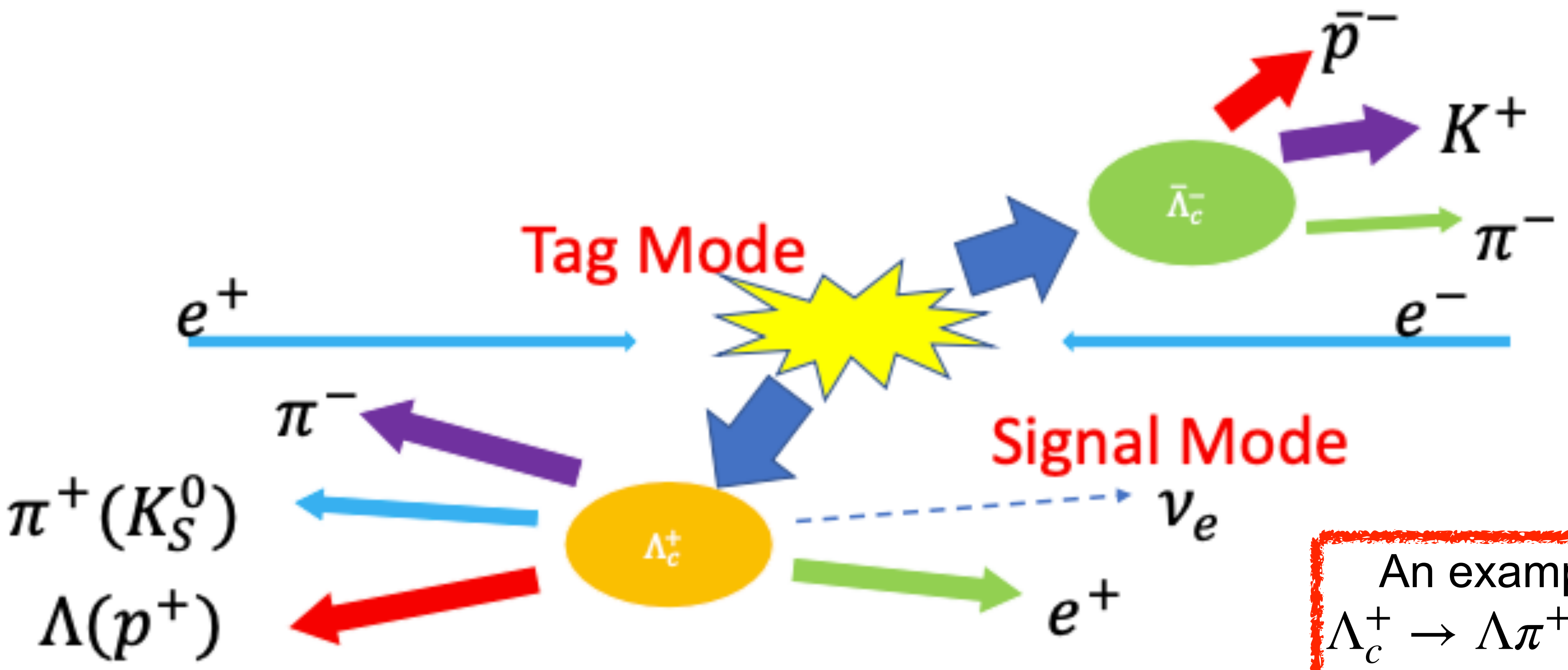
$$N_{\rm ST}^{i,j} = 2N^j_{\Lambda_c^+\bar{\Lambda}_c^-}\mathcal{B}^i_{\rm tag}\epsilon^{i,j}_{\rm ST},$$

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

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

→ Partial reconstruction technique

- Neutrino can not be detected at BESIII
- Determinant variable $U_{\rm miss} = E_{\rm miss} - c\,|\vec{p}_{\rm miss}|$
- Signal events peak at 0 in $U_{\rm miss}$



An example of
$\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e$
Vs.
$\bar{\Lambda}_c^- \to \bar{p}^-K^+\pi^-$

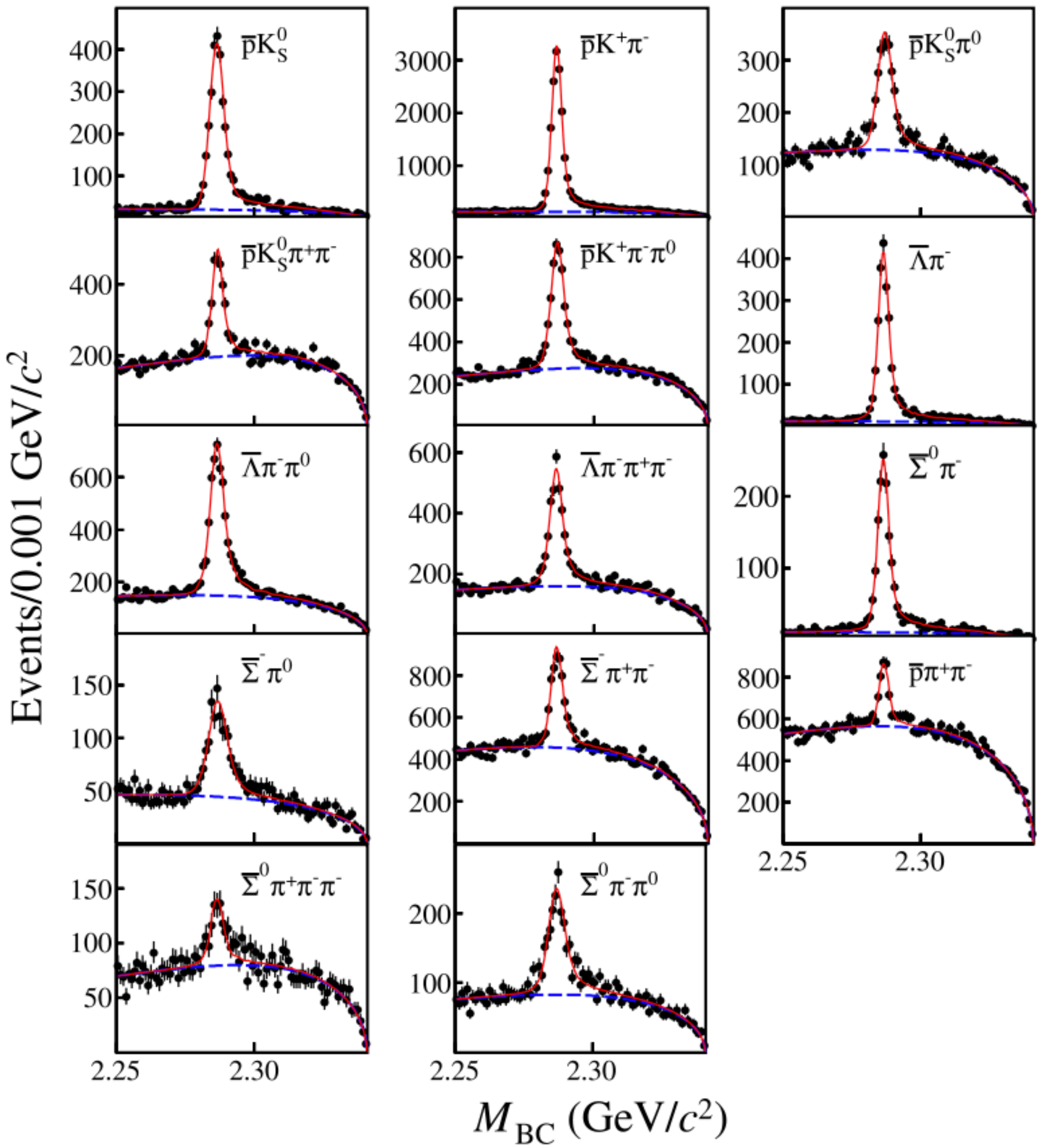
Published physics results

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

Highlight

- ➔ ST data set reconstructed by 14 hadronic Λ_c^+ decay mode

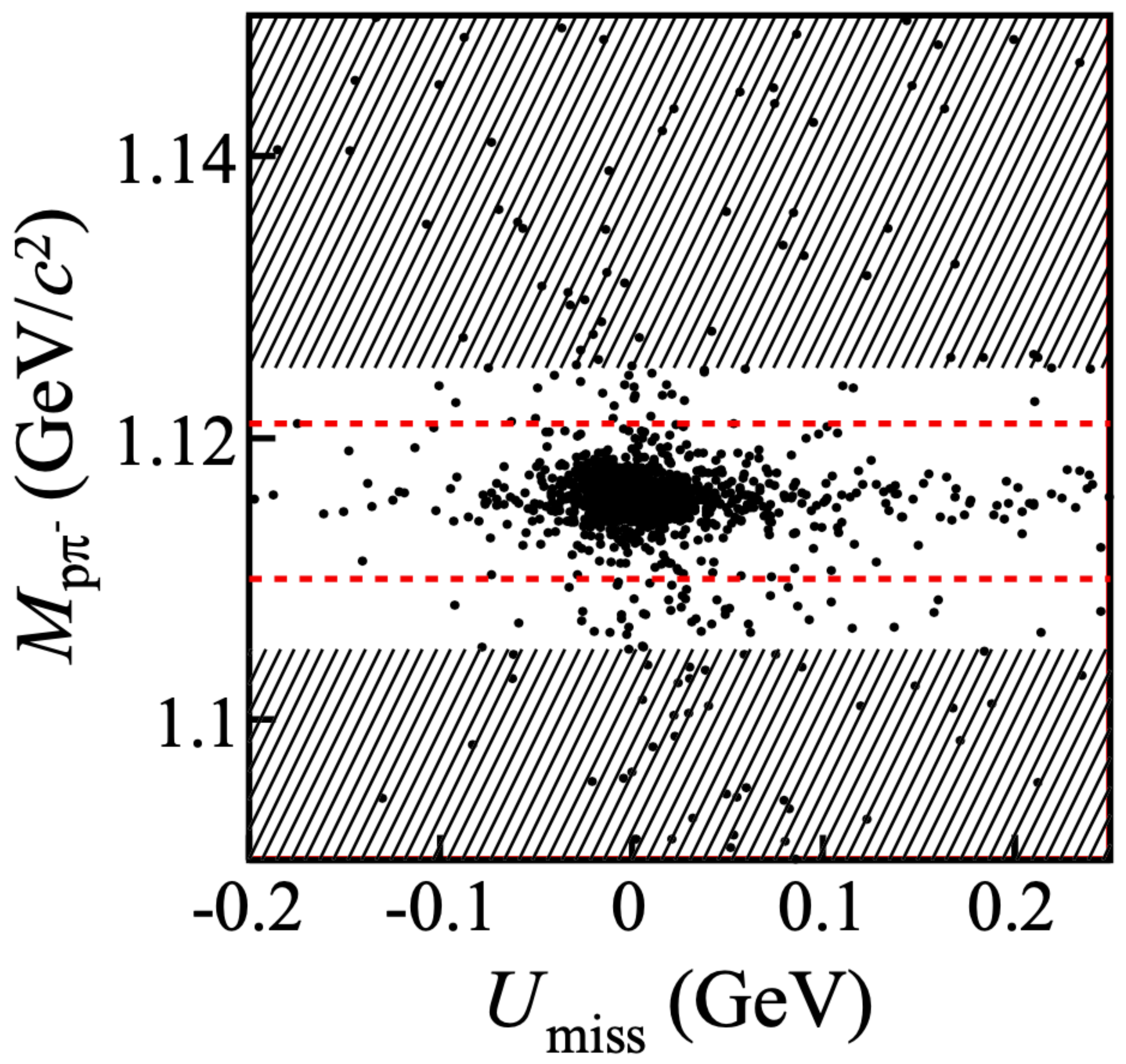
$N_{\rm ST} = 122268 \pm 474$

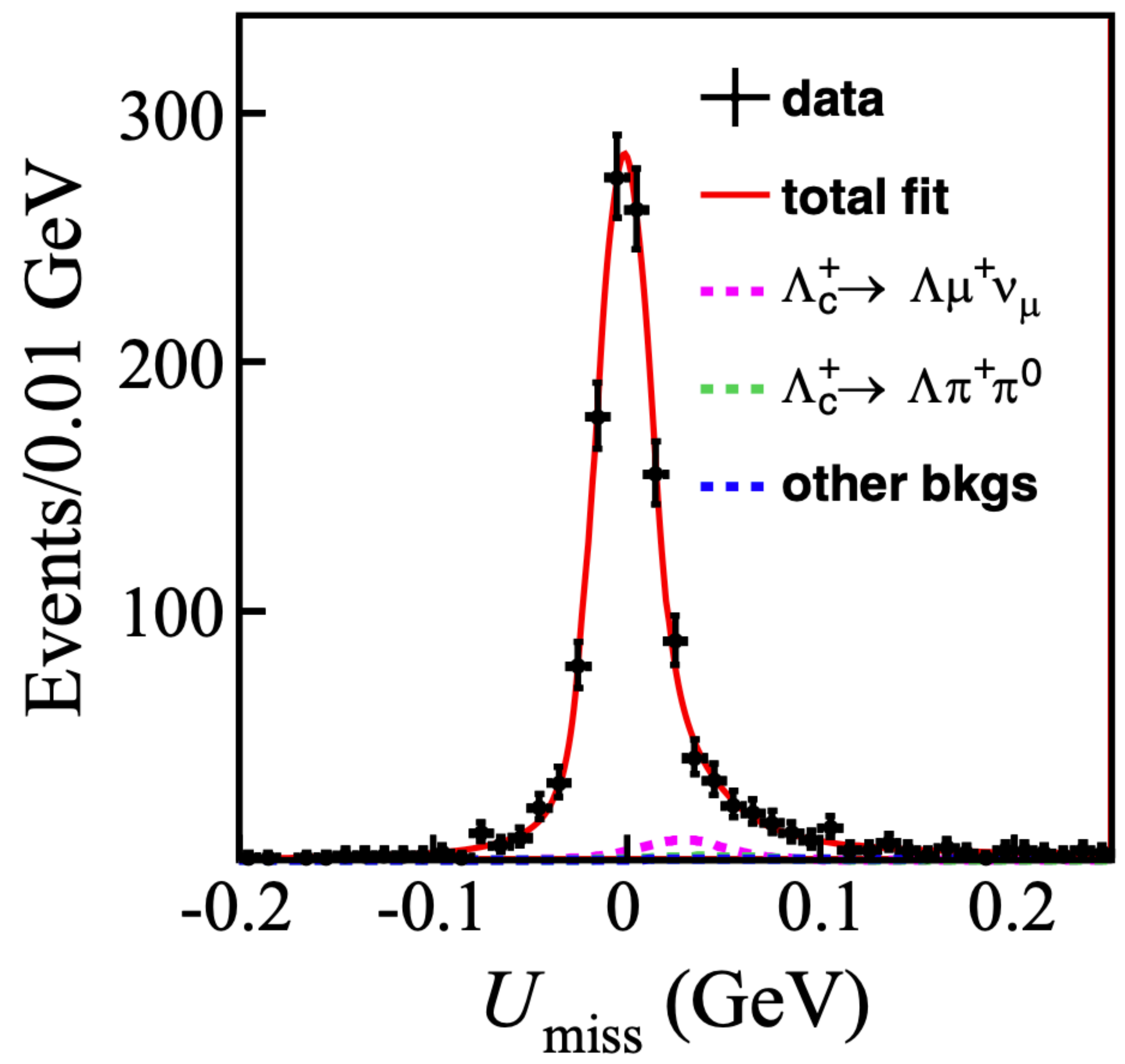


Fits to $M_{\rm BC}$ distributions for different ST modes at $\sqrt{s} = 4.682$ GeV

- ➔ Select signal Λ and e^+ in the recoiling side of $\bar{\Lambda}_c^-$
- ➔ Fit to $U_{\rm miss}$ distribution

$N^{\rm DT}_{\Lambda e^+\nu_e} = 1253 \pm 39$



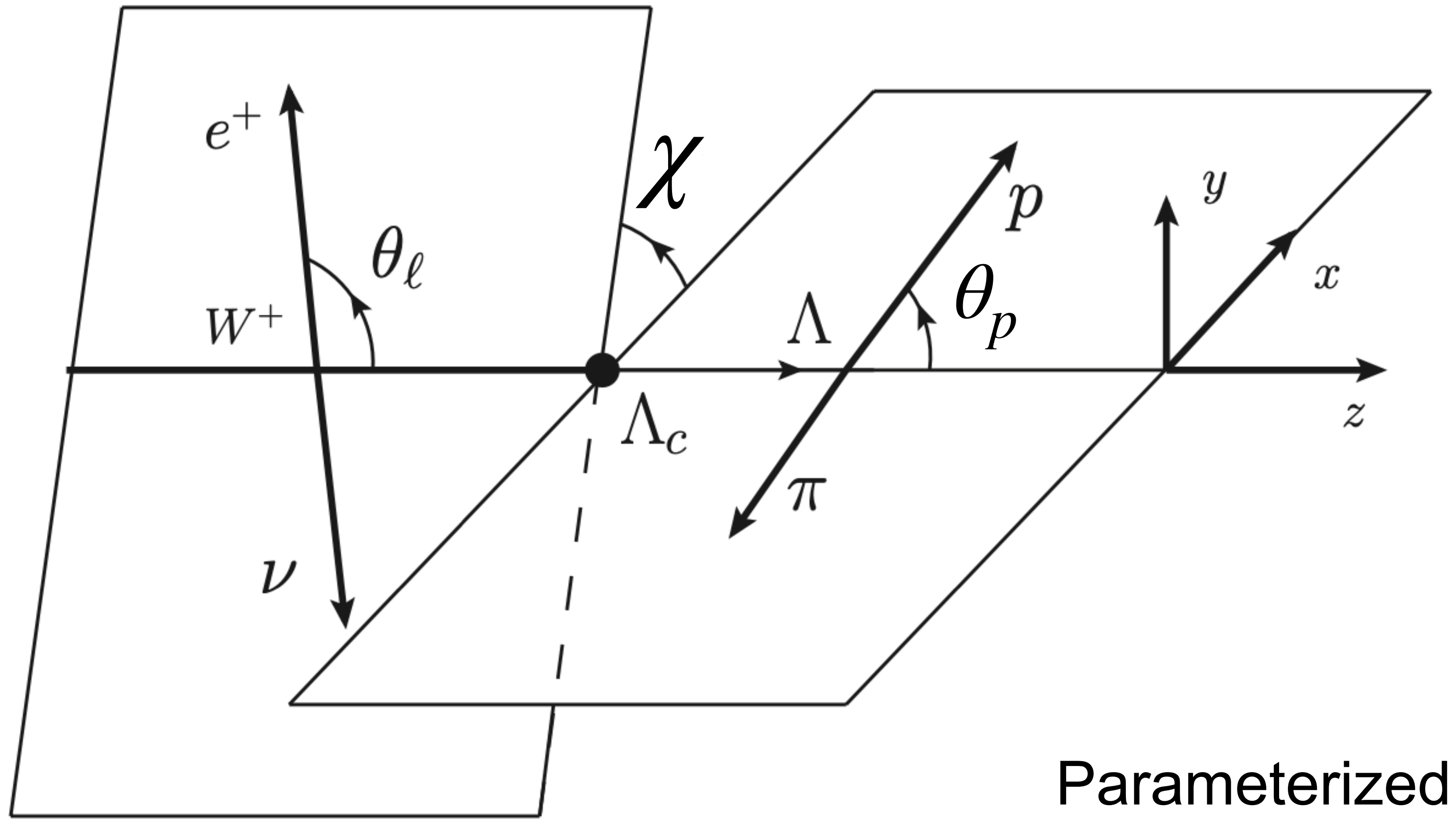


$\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.56 \pm 0.11_{\rm stat.} \pm 0.07_{\rm syst.})\,\%$

Precision improved

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

Definition of the polar and the azimuthal angles



Differential decay width

Helicity amplitudes:

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

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

Neglect lepton mass term

4D fit to extract FFs

- $e^+\nu_e$ mass squared: q^2
- $\Lambda \to p\pi^-$ helicity angle: θ_p
- $W^+ \to e^+\nu_e$ helicity angle: θ_e
- Acoplanarity angle between Λ and W^+: χ

Parameterized by "*Weinberg form factor*"

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

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

The relation between "*Weinberg form factor*" & "*Helicity form factor*"

Parameterized by "*Helicity form factor*"

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

Following LQCD

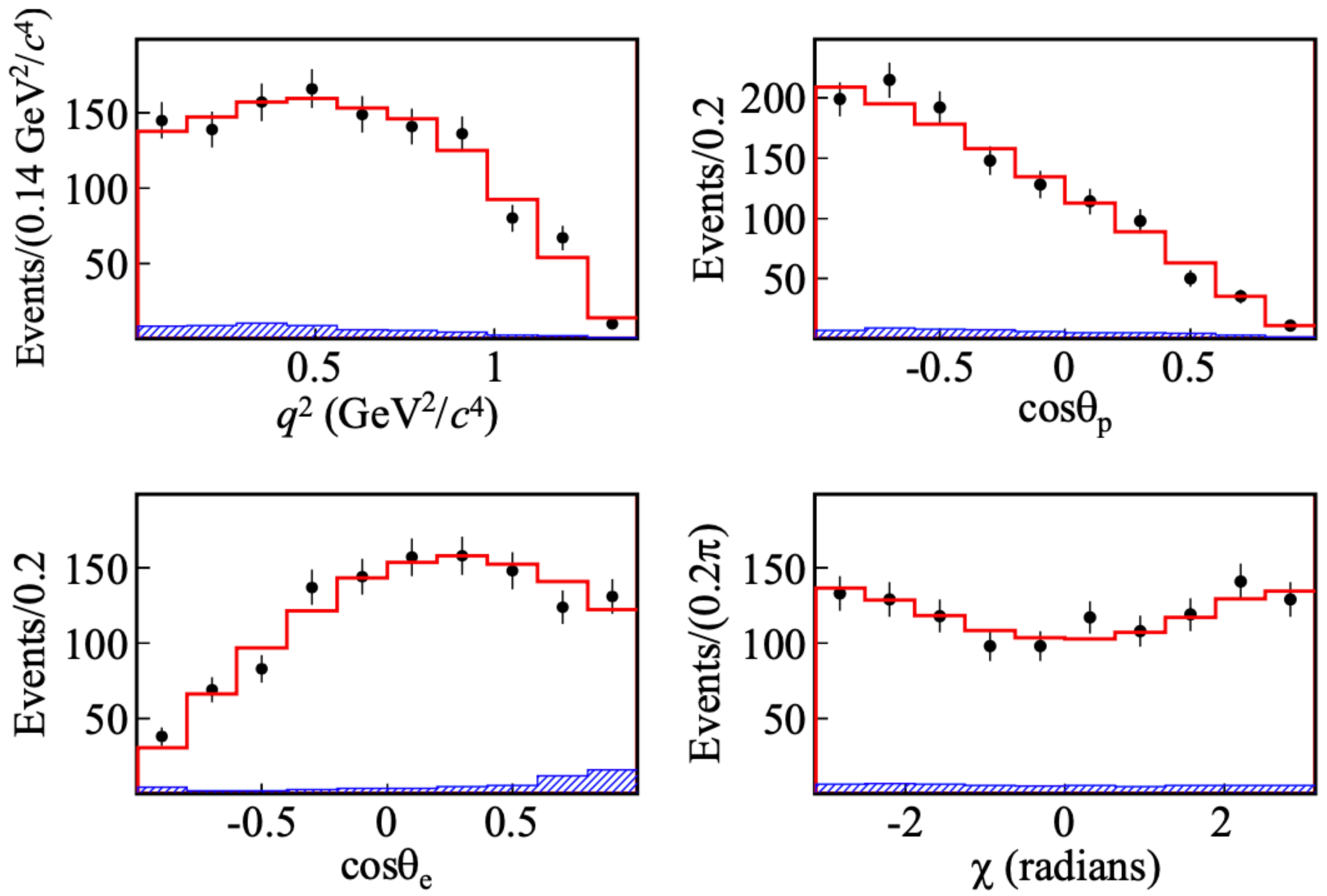
Four-dimensional fit

- ➔ z-expansion: FF is q^2 dependent, refer to LQCD parameterization
  - Free parameters: a_0^f and α_1^f

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

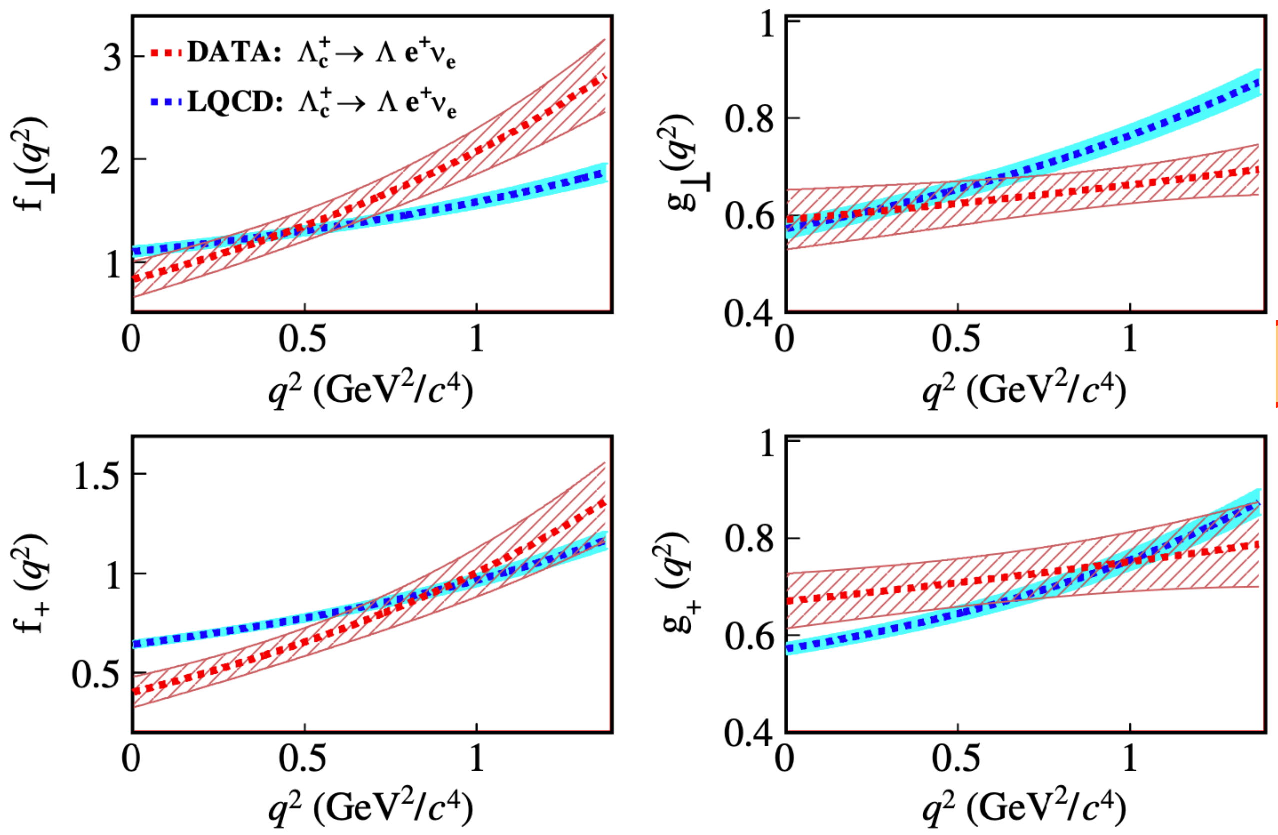
- ➔ Five independent free parameters in the fit: $a_1^{g_\perp}, a_1^{f_\perp}, r_{f_+} = a_0^{f_+}/a_0^{g_\perp}, r_{f_\perp} = a_0^{f_\perp}/a_0^{g_\perp}, r_{g_+} = a_0^{g_+}/a_0^{g_\perp}$
  - Choose $a_0^{g_\perp}$ as the reference
  - Set $a_1^{g_\perp} = a_1^{g_+}$ and $a_1^{f_\perp} = a_1^{f_+}$

- ➔ Four-dimensional fit to events within $-0.06 < U_{\rm miss} < 0.06$
  - Normalization using BF: $a_0^{g_\perp} = 0.54 \pm 0.04_{\rm stat.} \pm 0.01_{\rm syst.}$



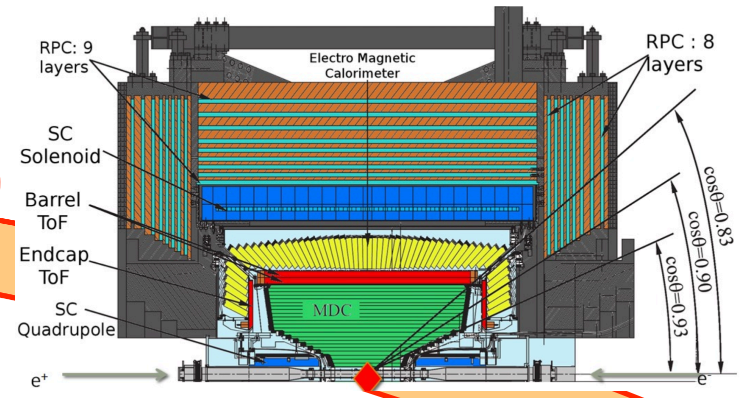
Parameters	$\alpha_1^{g_\perp}$	$\alpha_1^{f_\perp}$	r_{f_+}	$r_{f_\perp}$	r_{g_+}
Values	$1.43 \pm 2.09 \pm 0.16$	$-8.15 \pm 1.58 \pm 0.05$	$1.75 \pm 0.32 \pm 0.01$	$3.62 \pm 0.65 \pm 0.02$	$1.13 \pm 0.13 \pm 0.01$
Coefficients	$\alpha_1^{g_\perp}$	$\alpha_1^{f_\perp}$	r_{f_+}	$r_{f_\perp}$	r_{g_+}
$a_0^{g_\perp}$	−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

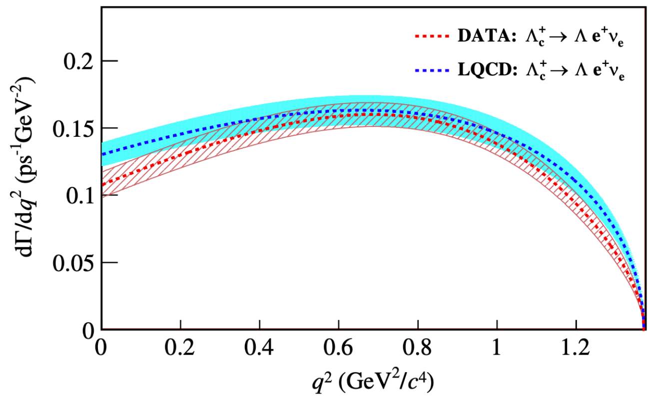
Indirect Test of SM



Branching Fraction

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



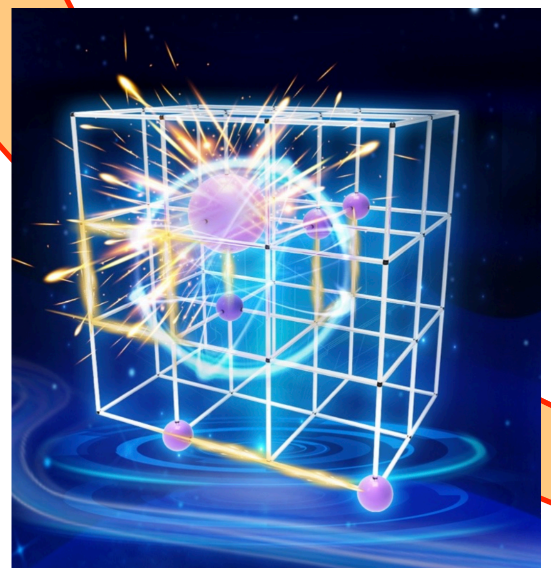


$$\int_0^{q^2_{\max}} \frac{d\Gamma}{dq^2} dq^2 = \frac{\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)}{\tau_{\Lambda_c}},$$

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

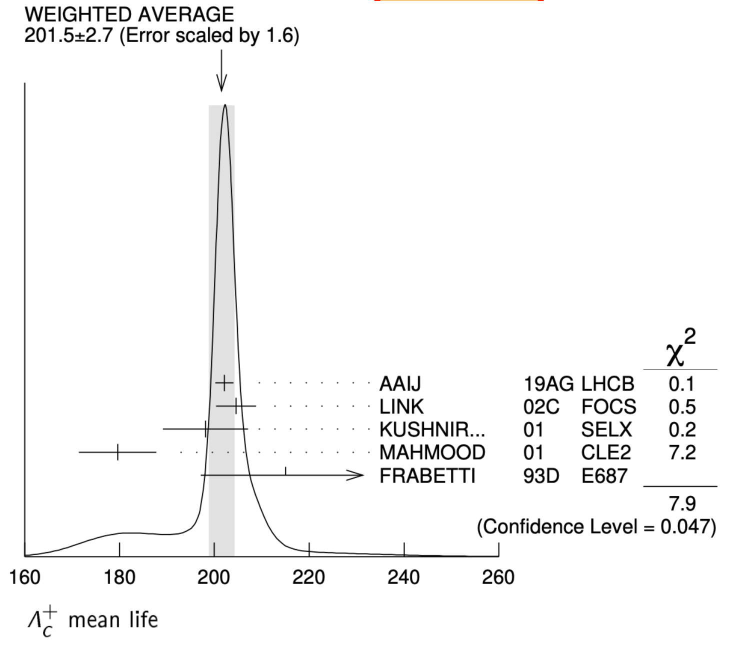
Form Factor

Calculated from LQCD and models



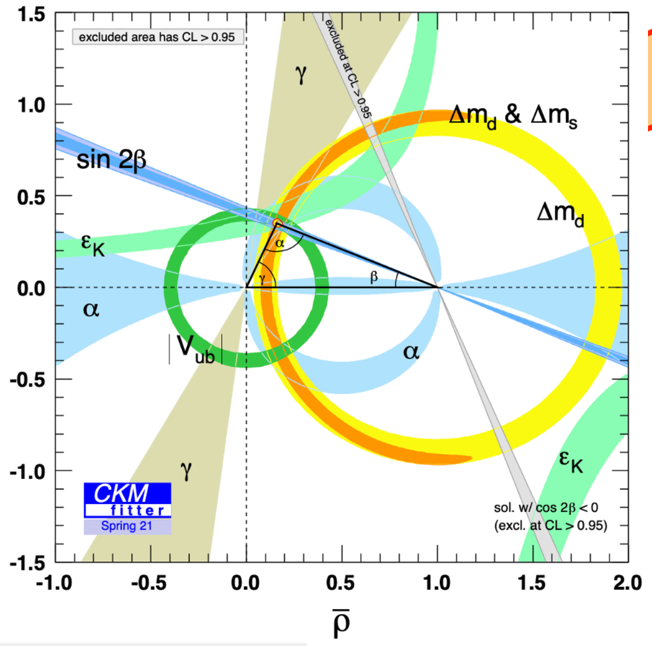
Lifetime

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



CKM unitarity

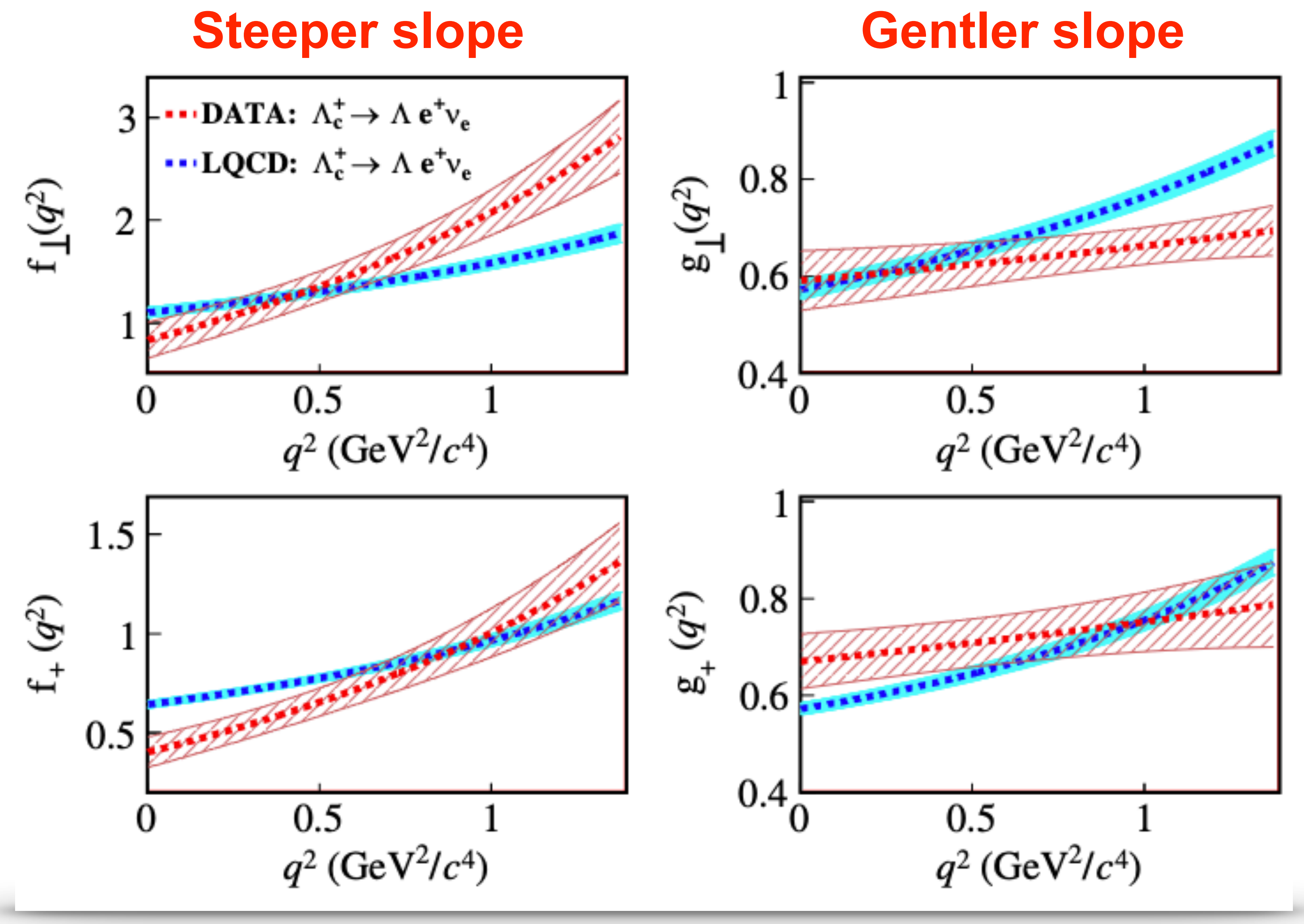
$|V_{cs}| = 0.97320 \pm 0.00011$ from CKM unitarity fit

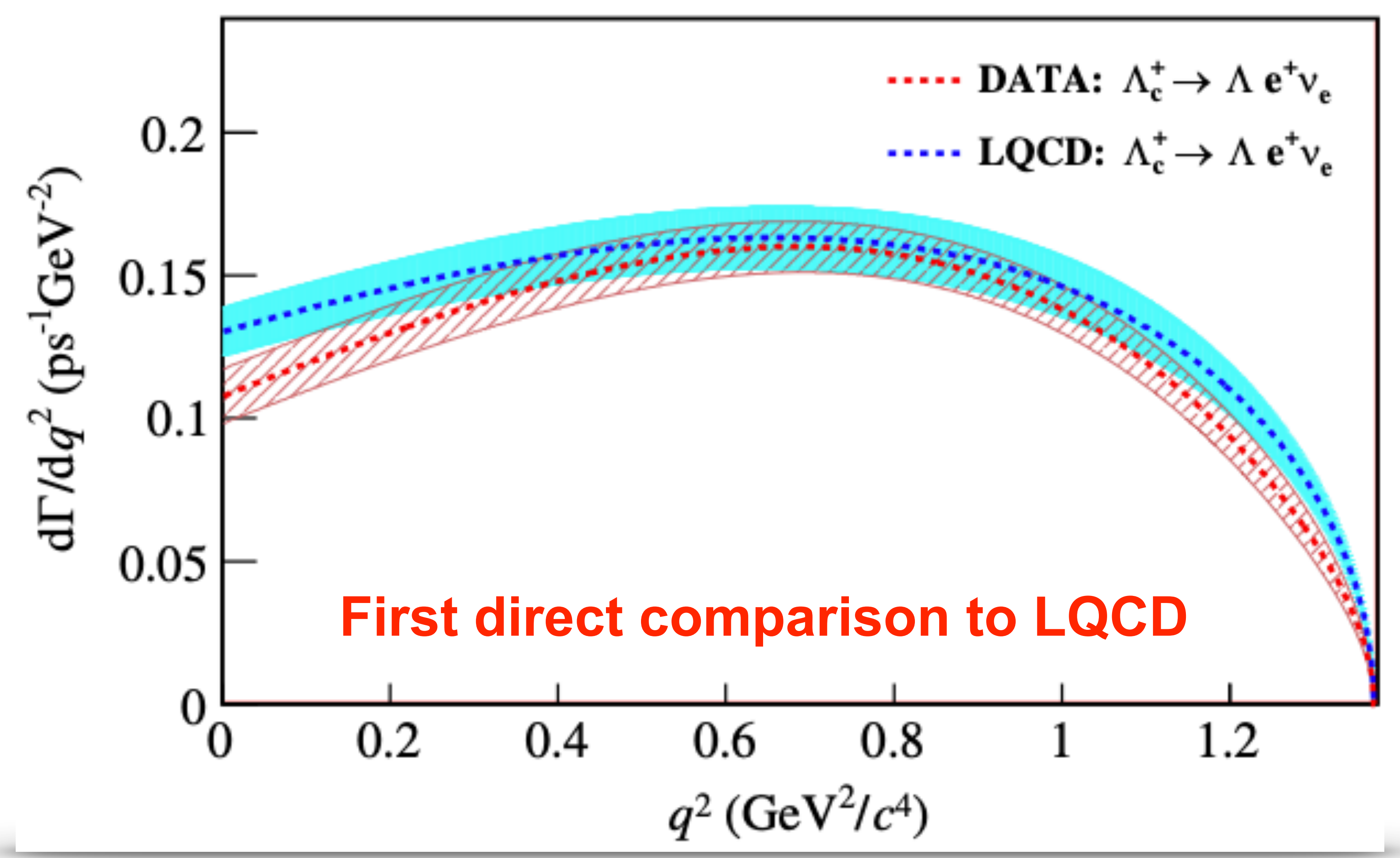


$|V_{cs}| = 0.936 \pm 0.017_{\mathscr{B}} \pm 0.024_{\rm LQCD} \pm 0.007_{\tau_{\Lambda_c}}$

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

Comparison with theoretical predictions





No clear difference is observed within uncertainties for the resulting differential decay rate of LQCD

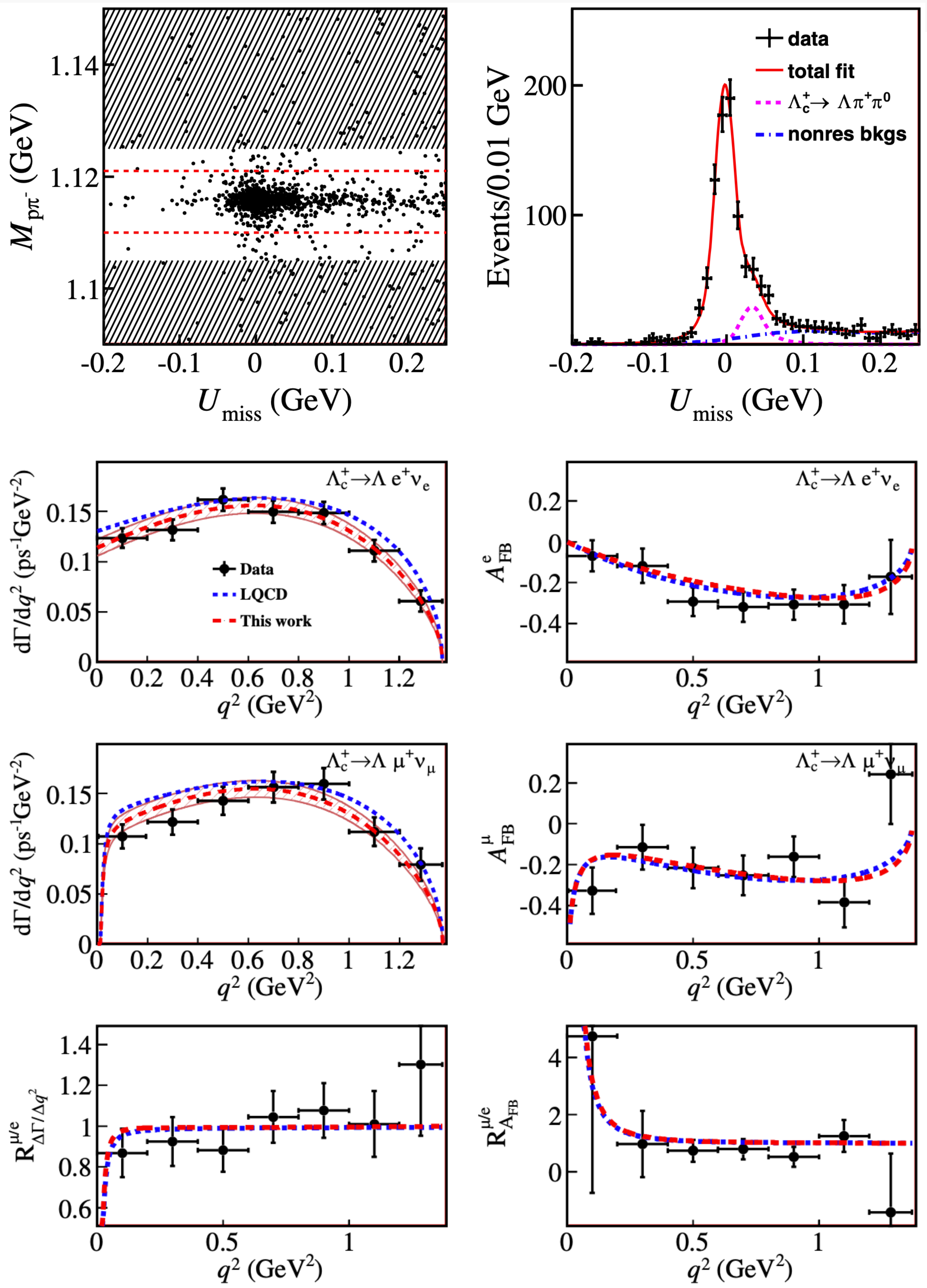
TABLE III. Comparison of $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)$ from theoretical calculations and our measurement.

Differ by > 2σ

	$\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)$ (%)
Constituent quark model (HONR) [9]	4.25
Light-front approach [10]	1.63
Covariant quark model [11]	2.78
Relativistic quark model [12]	3.25
Non-relativistic quark model [13]	3.84
Light-cone sum rule [14]	3.0 ± 0.3
Lattice QCD [15]	3.80 ± 0.22
$SU(3)$ [16]	3.6 ± 0.4
Light-front constituent quark model [17]	3.36 ± 0.87
MIT bag model [17]	3.48
Light-front quark model [18]	4.04 ± 0.75
This Letter	$3.56 \pm 0.11 \pm 0.07$

LFU test in $\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$

- ➔ Improved measurement of $\mathscr{B}(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu) = (3.48 \pm 0.14_{\rm stat.} \pm 0.10_{\rm syst.})\,\%$
  - ❖ 3 times more precise than prior results
  - ❖ $\mathscr{B}(\Lambda_c^+ \to \Lambda e^+\nu_e)/\mathscr{B}(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu) = 0.98 \pm 0.05_{\rm stat.} \pm 0.03_{\rm syst.}$ consistent with LQCD (0.97)
- ➔ **Differential decay rates** in separate four-momentum transfer regions
  - ❖ $$\Delta\Gamma_i = \int_i \frac{d\Gamma}{dq^2}dq^2 = \sum_{j=1}^{N_{\rm bins}}(\epsilon^{-1})_{ij}N^j_{\rm DT}/(\tau_{\Lambda_c} \times N^{\rm ST})$$
  - ❖ ϵ_{ij}: efficiency matrix for reconstruction efficiency and migration effects across q^2 bins
- ➔ **Model-independent forward-backward asymmetries** for lepton system and $p\pi^-$ system
  - ❖ $$A_{\rm FB}^{\ell,p}(q^2) = \frac{\int_0^1 \frac{d^2\Gamma}{dq^2 d\cos\theta_{\ell,p}}d\cos\theta_{\ell,p} - \int_{-1}^0 \frac{d^2\Gamma}{dq^2 d\cos\theta_{\ell,p}}d\cos\theta_{\ell,p}}{\int_0^1 \frac{d^2\Gamma}{dq^2 d\cos\theta_{\ell,p}}d\cos\theta_{\ell,p} + \int_{-1}^0 \frac{d^2\Gamma}{dq^2 d\cos\theta_{\ell,p}}d\cos\theta_{\ell,p}}$$
  - ❖ Average lepton FB asymmetry: $\langle A^e_{\rm FB}\rangle = -0.24 \pm 0.03_{\rm stat} \pm 0.01_{\rm syst}$
    $\langle A^\mu_{\rm FB}\rangle = -0.22 \pm 0.04_{\rm stat} \pm 0.01_{\rm syst}$
- ➔ **No evidence for a violation of LFU**



Decay asymmetry and New physics search in $\Lambda_c^+ \to \Lambda l^+ \nu_l$

- Decay asymmetry α_{Λ_c} vs Forward-backward asymmetry A_{FB}^p

$$\alpha_{\Lambda_c}(q^2) = \frac{2}{\alpha_\Lambda}[A_{FB}^p(q^2)]$$

  - Model-dependent determination:

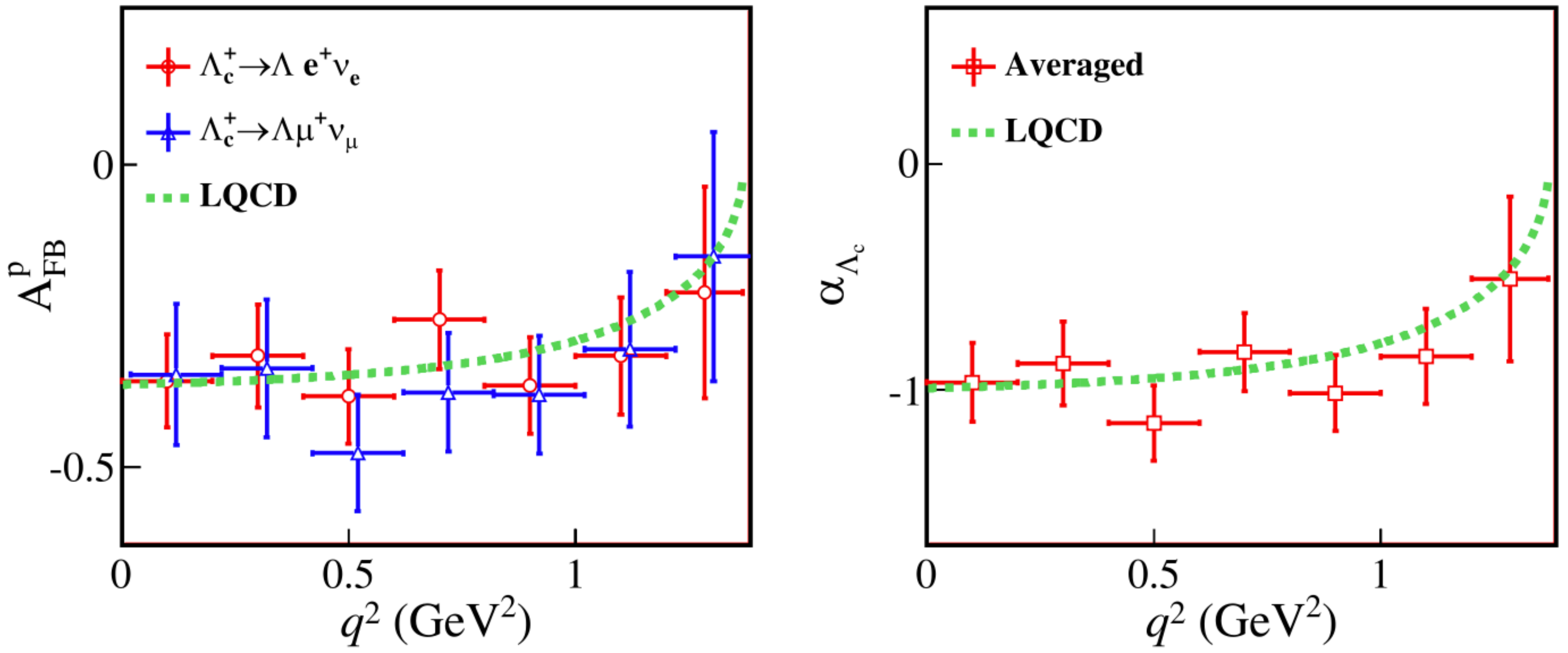
$$\alpha_{\Lambda_c} = \frac{|H_{1/2\,1}|^2 - |H_{-1/2\,-1}|^2 + |H_{1/2\,0}|^2 - |H_{-1/2\,0}|^2}{|H_{1/2\,1}|^2 + |H_{-1/2\,-1}|^2 + |H_{1/2\,0}|^2 + |H_{-1/2\,0}|^2}$$

  - First model-independent determination of $\alpha_{\Lambda_c}(q^2)$
  - q^2 averaged asymmetry

$\langle A_{FB}^p \rangle = -0.33 \pm 0.03_{stat.} \pm 0.01_{syst.}$ Only for $\Lambda_c^+ \to \Lambda e^+ \nu_e$

$\langle A_{FB}^p \rangle = -0.37 \pm 0.04_{stat.} \pm 0.01_{syst.}$ Only for $\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu$

$\langle \alpha_{\Lambda_c} \rangle = -0.94 \pm 0.07_{stat} \pm 0.03_{syst}$ Combine e and μ channels



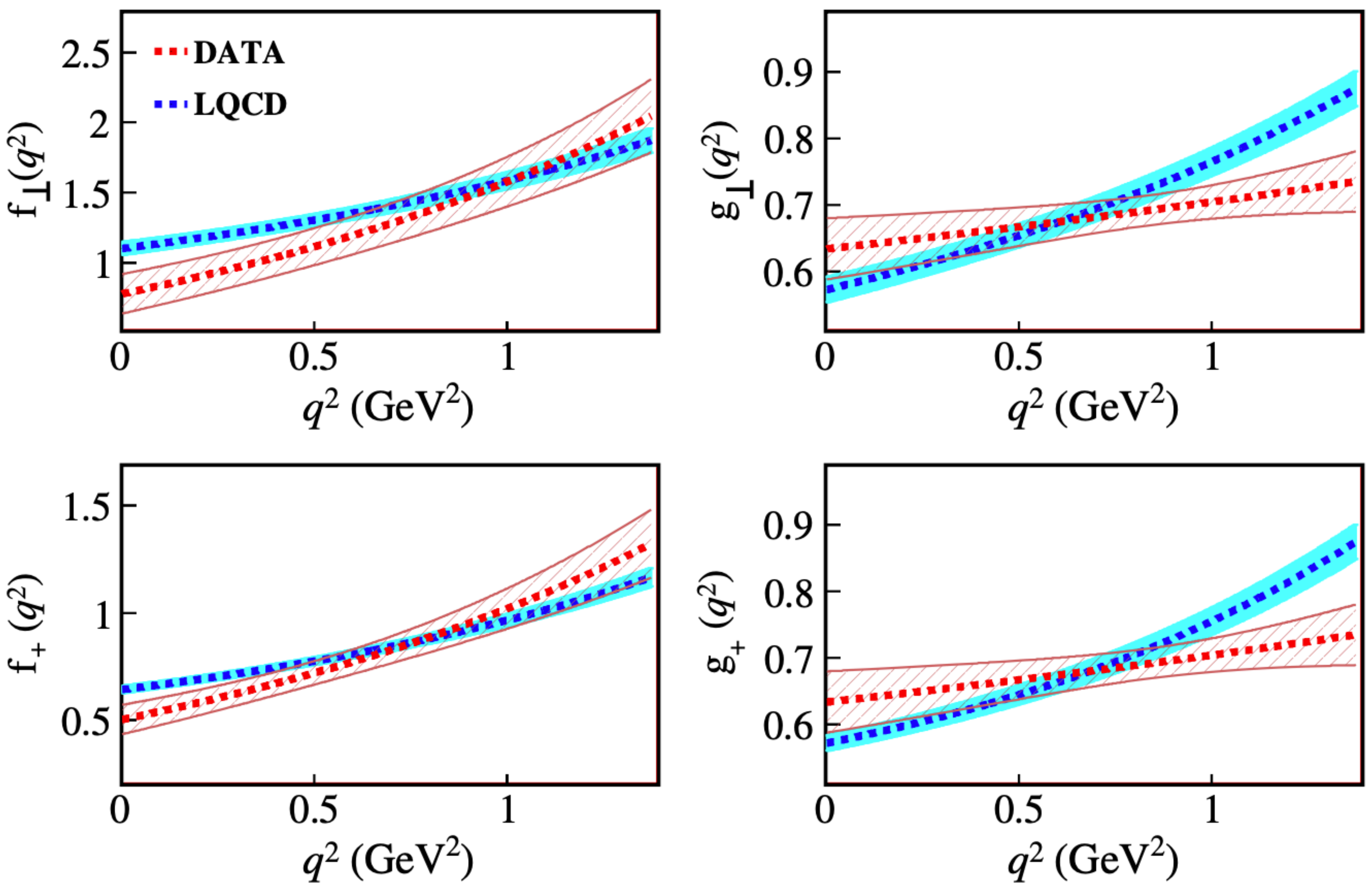
- New physics search: T asymmetry parameter $\mathcal{T}_p$

$$\mathcal{T}_p = \frac{[(\int_{-\pi}^{0} - \int_0^{\pi})d\chi][(\int_0^1 - \int_{-1}^{0})d\cos\theta_p]\Gamma^{\ell}_{\chi,\cos\theta_p}}{\alpha_\Lambda \Gamma^{\ell}}$$

  - Consistent with zero as predicted from the SM
  - No indication of new physics in $\Lambda_c^+ \to \Lambda l^+ \nu_l$ decays

$$\mathcal{T}_p(\Lambda_c^+ \to \Lambda e^+ \nu_e) = -0.021 \pm 0.041_{stat} \pm 0.001_{syst}$$
$$\mathcal{T}_p(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu) = 0.068 \pm 0.055_{stat} \pm 0.002_{syst}$$

Improvement of $\Lambda_c^+ \to \Lambda$ FF parameters



$$\frac{d^4\Gamma}{dq^2 d\cos\theta'_\ell d\cos\theta_p d\chi} = \frac{G_F^2|V_{cs}|^2}{2(2\pi)^4}\cdot\frac{Pq^2(1-m_\ell^2/q^2)^2}{24M_{\Lambda_c}^2}\Big\{\frac{3}{8}(1-\cos\theta'_\ell)^2|H_{\frac{1}{2}1}|^2(1+\alpha_\Lambda\cos\theta_p)$$
$$+\frac{3}{8}(1+\cos\theta'_\ell)^2|H_{-\frac{1}{2}-1}|^2(1-\alpha_\Lambda\cos\theta_p)$$
$$+\frac{3}{4}\sin^2\theta'_\ell[|H_{\frac{1}{2}0}|^2(1+\alpha_\Lambda\cos\theta_p)+|H_{-\frac{1}{2}0}|^2(1-\alpha_\Lambda\cos\theta_p)]+\frac{3}{2\sqrt{2}}\alpha_\Lambda\cos\chi\sin\theta'_\ell\sin\theta_p$$
$$\times[(1-\cos\theta'_\ell)H_{-\frac{1}{2}0}H_{\frac{1}{2}1}+(1+\cos\theta'_\ell)H_{\frac{1}{2}0}H_{-\frac{1}{2}-1}]+\mathcal{H}_{m_\ell^2}\Big\},$$

$$H^{V/A}_{\frac{1}{2}1} = \sqrt{2Q_\mp}f_\perp/g_\perp(q^2),$$
$$H^{V/A}_{\frac{1}{2}0} = \sqrt{Q_\mp/q^2}f_+/g_+(q^2)(M_{\Lambda_c}\pm M_\Lambda),$$
$$H^{V/A}_{\frac{1}{2}t} = \sqrt{Q_\pm/q^2}f_0/g_0(q^2)(M_{\Lambda_c}\mp M_\Lambda),$$

➔ Improve measurement of the FF parameters in the $\Lambda_c^+ \to \Lambda$ transition

➔ Differential decay width formula needs to consider lepton mass term

➔ Test and calibrate LQCD

Comparison with theoretical calculations

TABLE I. Comparisons of $\mathcal{B}(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu)$ (in %), $\langle\alpha_{\Lambda_c}\rangle$, $\langle A_{\rm FB}^e\rangle$, and $\langle A_{\rm FB}^\mu\rangle$ from theories and measurement.

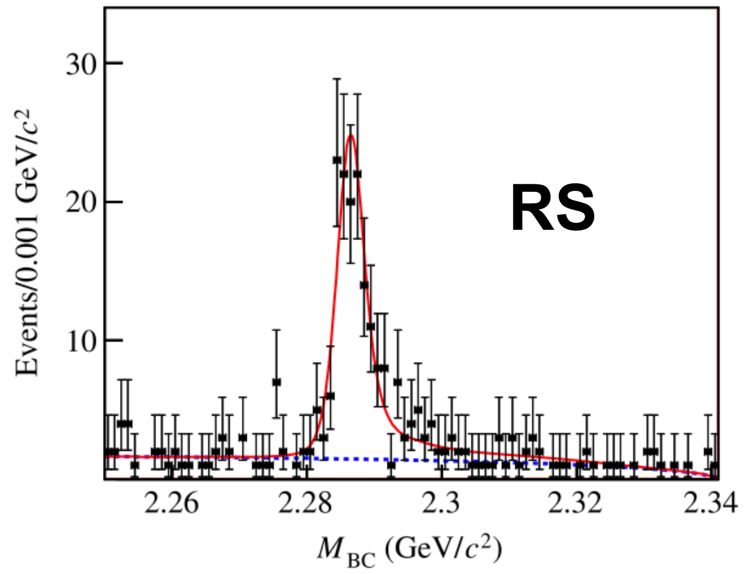
	$\mathcal{B}(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu)$	$\langle\alpha_{\Lambda_c}\rangle$	$\langle A_{\rm FB}^e\rangle$	$\langle A_{\rm FB}^\mu\rangle$
CQM [20]	2.69	−0.87	−0.2	−0.21
RQM [21]	3.14	−0.86	−0.209	−0.242
CQM(HONR) [49]	4.25			
NRQM [50]	3.72			
HBM [24]	3.67 ± 0.23	−0.826	−0.176(5)	−0.143(6)
LQCD [28]	3.69 ± 0.22	−0.874(10)	−0.201(6)	−0.169(7)
LCSR [51]	3.0 ± 0.3			
$SU(3)$ [25]	3.6 ± 0.4	−0.86(4)		
LFCQM [27]	3.21 ± 0.85	−0.97(3)		
MBM [27]	3.38	−0.83		
LFQM [22]	3.90 ± 0.73	−0.87(9)	0.20(5)	0.16(4)
LFCQM [26]	3.40 ± 1.02	−0.97(3)		
$SU(3)$ [52]	3.45 ± 0.30			
This work	3.48 ± 0.17	−0.94(8)	−0.24(3)	−0.22(4)

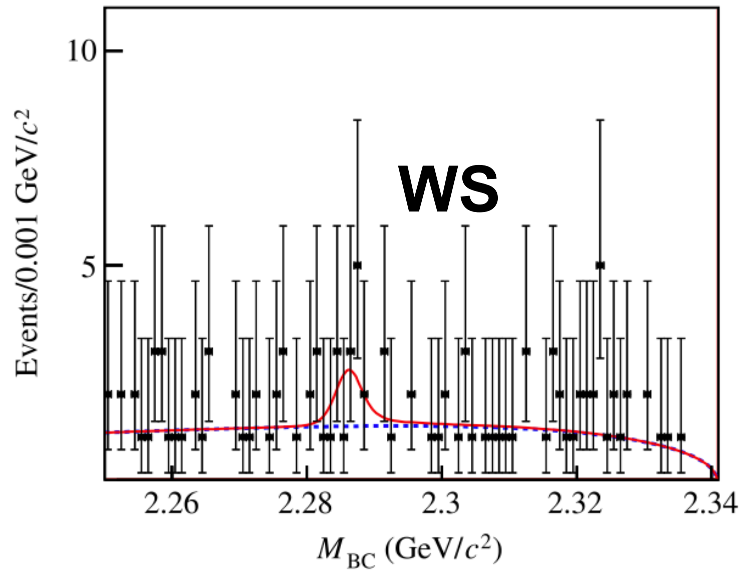
- ➔ $\mathscr{B}(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu)$: Disfavor Refs. [20,49] based on CQM at a confidence level of more than 95%
- ➔ Decay asymmetry: consistent with all theoretical prediction and model-dependent measurement by CLEO
- ➔ Lepton forward-backward asymmetry: clearly differ from Ref. [22] based on LFQM

$\Lambda_c^+ \to Xe^+\nu_e$

WS technique is used to subtract charge symmetric backgrounds in each momentum bin, e.g., $\pi^0 \to \gamma e^+ e^-$

Momentum range: 500-550 MeV/c
Data collected at 4682 MeV

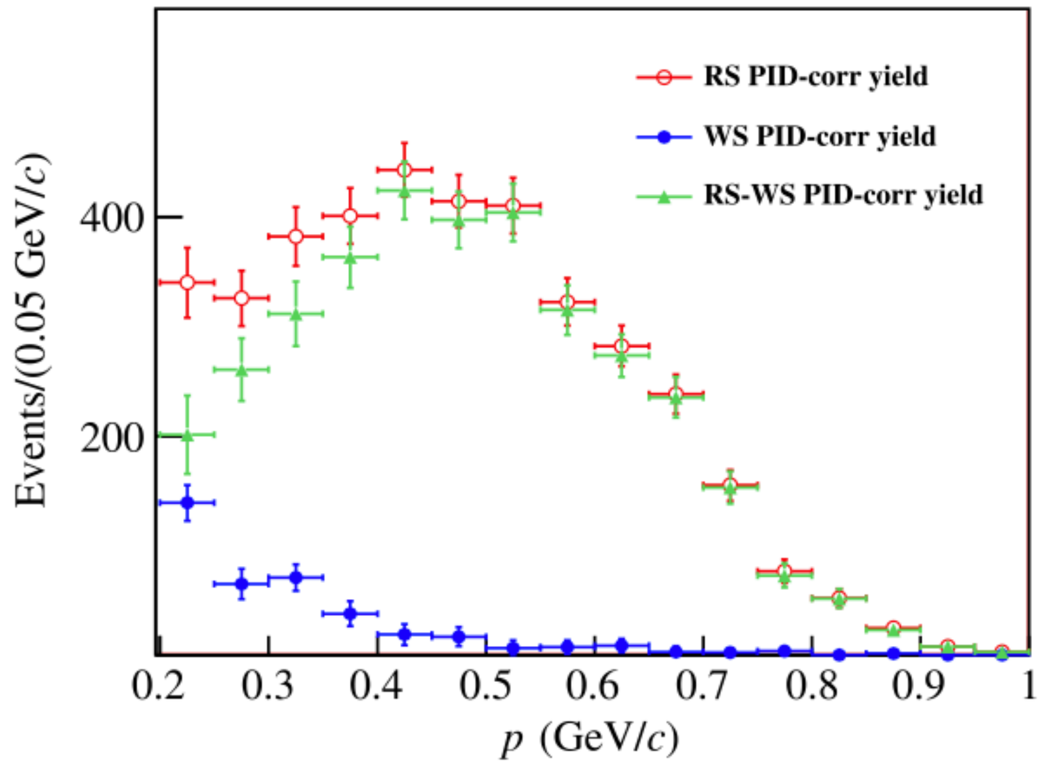




$$\begin{bmatrix} N_e^{\rm obs} \\ N_\pi^{\rm obs} \\ N_K^{\rm obs} \\ N_p^{\rm obs} \end{bmatrix} = \begin{bmatrix} P_{e\to e} & P_{\pi\to e} & P_{K\to e} & P_{p\to e} \\ P_{e\to \pi} & P_{\pi\to \pi} & P_{K\to \pi} & P_{p\to \pi} \\ P_{e\to K} & P_{\pi\to K} & P_{K\to K} & P_{p\to K} \\ P_{e\to p}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

PID migration matrix

Contamination of other particle types (p, π^+, K^+)



Reconstruct RS and WR sample
In different momentum bin

PID unfolding

WS subtraction

Tracking efficiency unfolding

PHSP Extrapolation

BF determination

$$\mathcal{B}(\Lambda_c^+ \to Xe^+\nu_e) = (4.06 \pm 0.10_{\rm stat} \pm 0.09_{\rm syst})\%.$$

$$\frac{\Gamma(\Lambda_c^+ \to Xe^+\nu_e)}{\bar{\Gamma}(D \to Xe^+\nu_e)} = 1.28 \pm 0.05$$

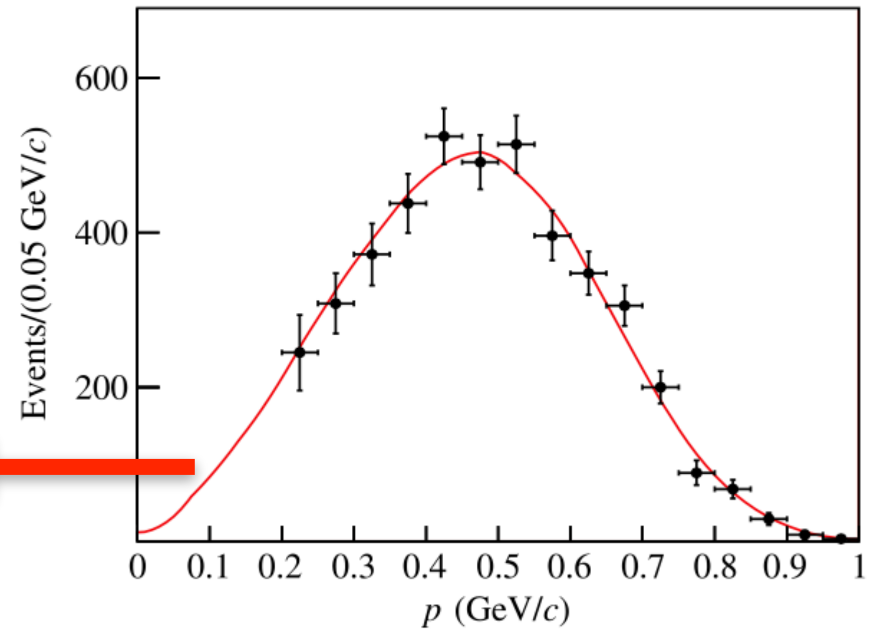
Compared with HQE(1.2), EQM(1.67)

$$N_{\rm e}^{\rm true}(i) = \sum_j A_{\rm TRK}(e|i,j) N_{\rm e}^{\rm prod}(j)$$

- Geometrical acceptance
- Track reconstruction efficiency
- Resolution smearing

Decay	$\mathcal{B}$ [%]	Model
$\Lambda_c^+ \to \Lambda e^+\nu_e$	$3.56 \pm 0.11 \pm 0.07$	References [6]
$\Lambda_c^+ \to pK^-(n\bar{K}^0)e^+\nu_e$	$0.088 \pm 0.017 \pm 0.007$	PHSP [7]
$\Lambda_c^+ \to \Lambda(1405)e^+\nu_e$	0.24	HQET [27,28]
$\Lambda_c^+ \to \Lambda(1520)e^+\nu_e$	0.06	HQET [27,28]
$\Lambda_c^+ \to ne^+\nu_e$	0.20	Quark model [29]

Based on our knowledge of MC model

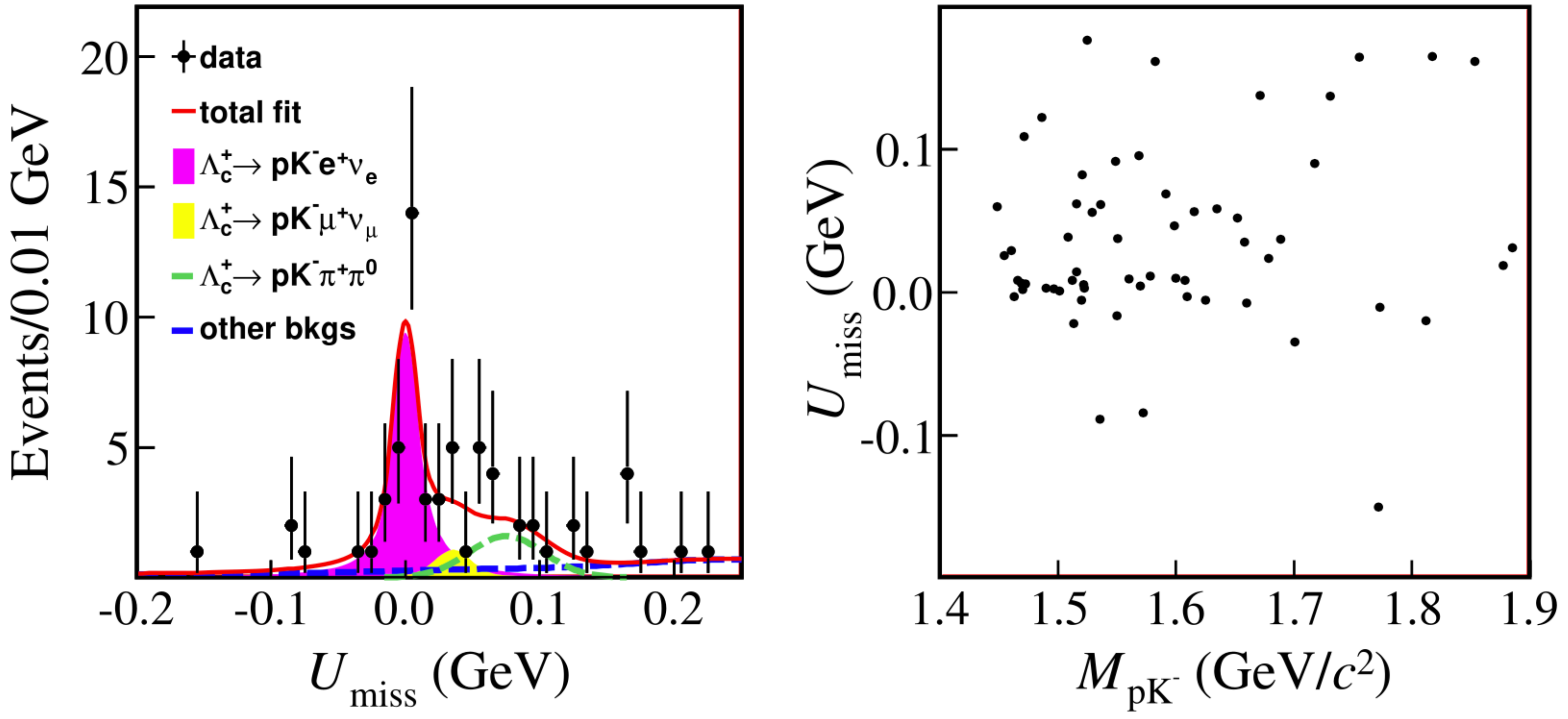


$\Lambda_c^+ \to pK^-e^+\nu_e$

- ST data set is same with last analysis

- Select signal pK^-e^+ in the recoiling side of $\bar{\Lambda}_c^-$
- Background veto
  - Suppress $\Lambda_c^+ \to pK^-\pi^+$: $M_{pK^-e^+} < 2.15\,\mathrm{GeV}/c^2$
  - Suppress $\Lambda_c^+ \to pK^-\pi^+\pi^0$: Additional π^0 search and veto M_{BC} signal region

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



- $\Lambda_c^+ \to pK^-e^+\nu_e$ is firstly observed with significance of 8.2σ!
  - $\mathcal{B}(\Lambda_c^+ \to pK^-e^+\nu_e) = (0.82 \pm 0.15 \pm 0.06) \times 10^{-3}$

- The only observed SL channel beyond $\Lambda_c^+ \to \Lambda l^+\nu_l$
  - $\dfrac{\mathcal{B}(\Lambda_c^+ \to pK^-e^+\nu_e)}{\mathcal{B}(\Lambda_c^+ \to Xe^+\nu_e)} = (2.1 \pm 0.4_{\mathrm{stat.}} \pm 0.1_{\mathrm{syst.}}) \times 10^{-3}$

- Signal: Gaussian core + power law tail (ISR & FSR)
- BKG: $\Lambda_c^+ \to pK^-\pi^+\pi^0$ and $\Lambda_c^+ \to pK^-\mu^+\nu_\mu$

  Yield of $\Lambda_c^+ \to pK^-\mu^+\nu_\mu$ is fixed

  $N^{pK^-\mu^+\nu_\mu}_{\mathrm{DT}} = N^{pK^-e^+\nu_e}_{\mathrm{DT}} \times R_\epsilon \times R_{\mathcal{B}}$

  $R_{\mathcal{B}} = \dfrac{\mathcal{B}(\Lambda_c^+ \to pK^-\mu^+\nu_\mu)}{\Lambda_c^+ \to pK^-e^+\nu_e} = 0.88 \pm 0.03$

  Relative detection efficiency $R_\epsilon = 0.15$

Search for $\Lambda(1405)$ and $\Lambda(1520)$ in pK^- spectrum

- 2D fit is performed to the M_{pK^-} and $U_{\rm miss}$ distributions
- Evidence of $\Lambda_c^+ \to \Lambda(1520)e^+\nu_e$ (3.3σ) & $\Lambda_c^+ \to \Lambda(1405)e^+\nu_e$ (3.2σ)
  - $\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e) = (1.02 \pm 0.52_{\rm stat.} \pm 0.11_{\rm syst.}) \times 10^{-3}$
  - $\mathcal{B}(\Lambda_c^+ \to \Lambda(1405)[\to pK^-]e^+\nu_e) = (0.42 \pm 0.19_{\rm stat.} \pm 0.04_{\rm syst.}) \times 10^{-3}$
- Comparisons of $\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)/\Lambda(1405)e^+\nu_e)$ with predicted values from theoretical models and LQCD
  - Consistent within two standard deviations
- Prospects
  - Amplitude analysis of pK^- mass spectrum to study Λ^*
  - Extraction of $\Lambda_c^+ \to \Lambda(1520)$ FF

$N^{\rm DT}_{\Lambda(1520)e^+\nu_e} = 8.4 \pm 4.3$

$N^{\rm DT}_{\Lambda(1405)e^+\nu_e} = 14.8 \pm 6.7$

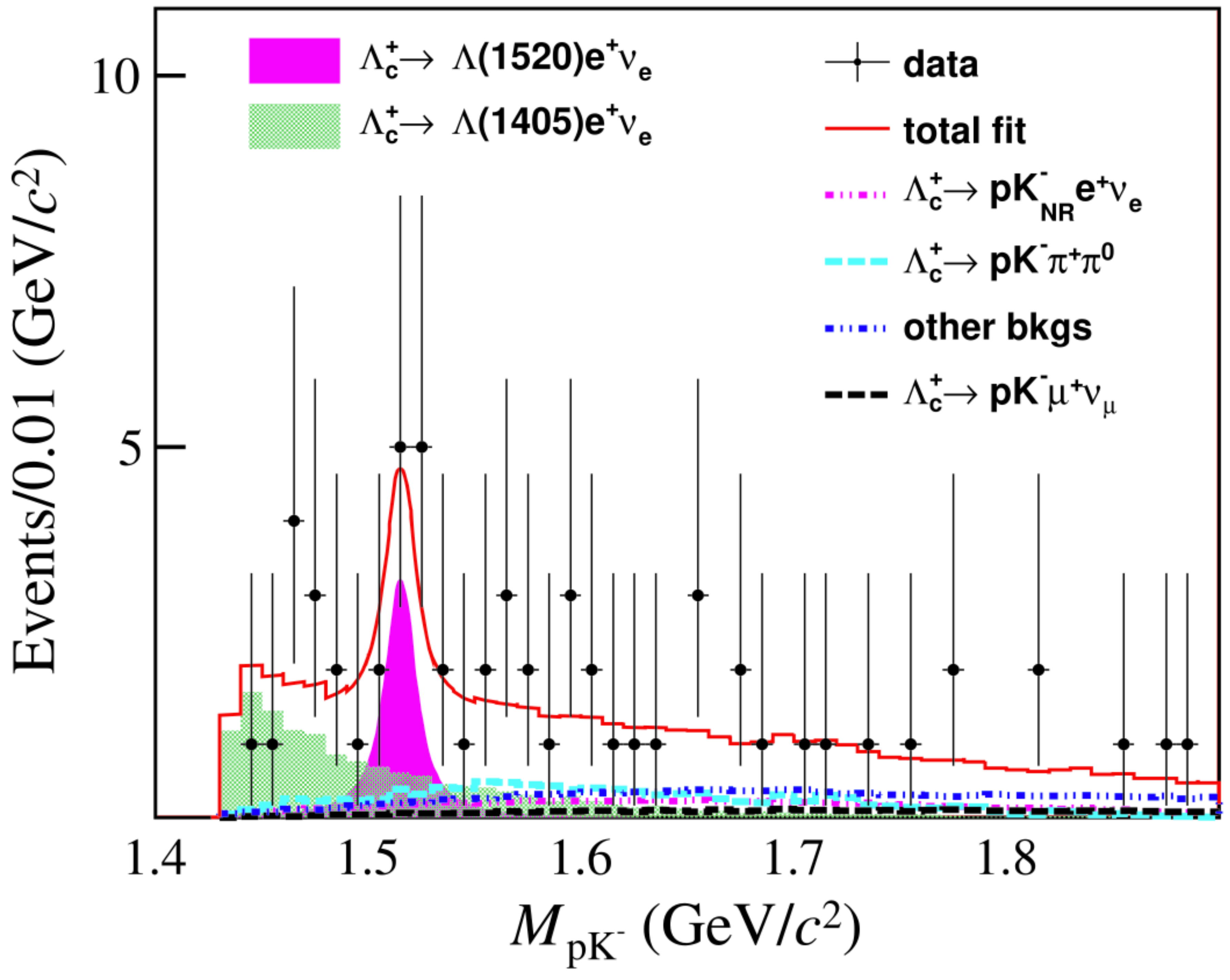


TABLE I. Comparison of $\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)/\Lambda(1405)e^+\nu_e)$ [in $\times 10^{-3}$] between theoretical calculations and this measurement. The BF of $\Lambda(1405) \to pK^-$ is unknown [2].

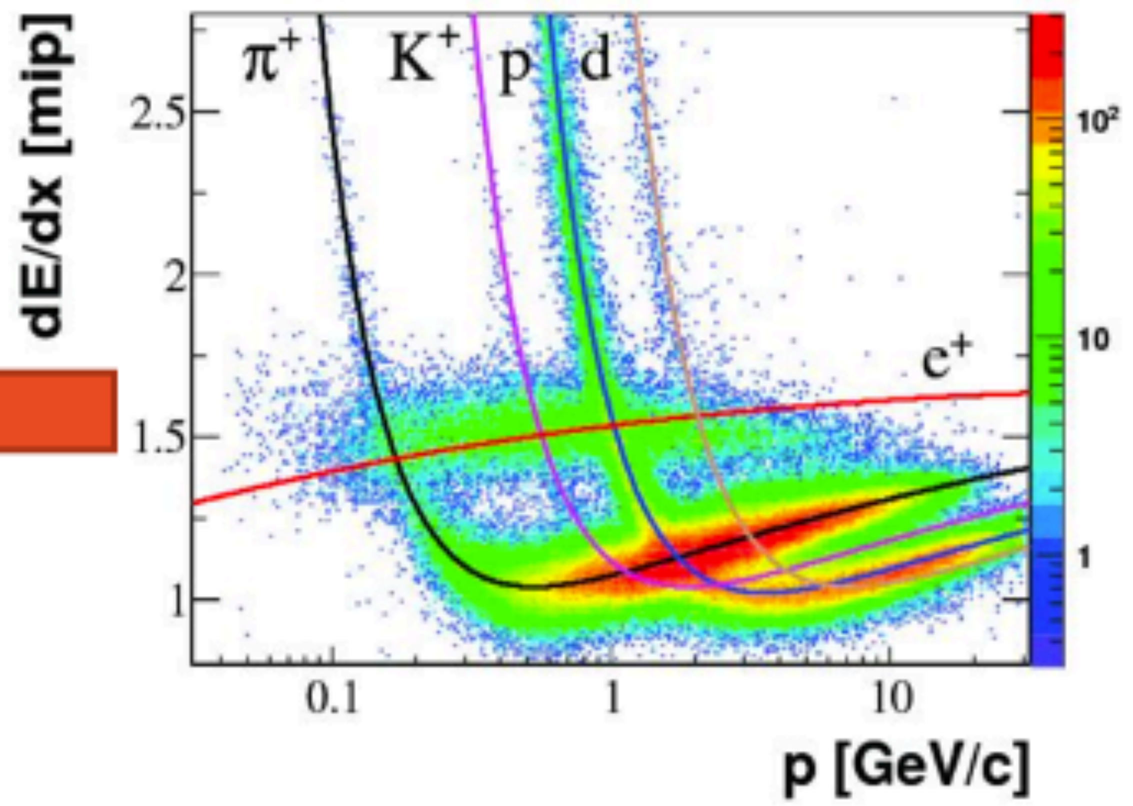
	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e)$	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1405)e^+\nu_e)$
Constituent quark model [8]	1.01	3.04
Molecular state [9]	...	0.02
Nonrelativistic quark model [10]	0.60	2.43
Lattice QCD [12,13]	0.512 ± 0.082	...
Measurement	$1.02 \pm 0.52 \pm 0.11$	$\frac{0.42\pm0.19\pm0.04}{\mathcal{B}(\Lambda(1405)\to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

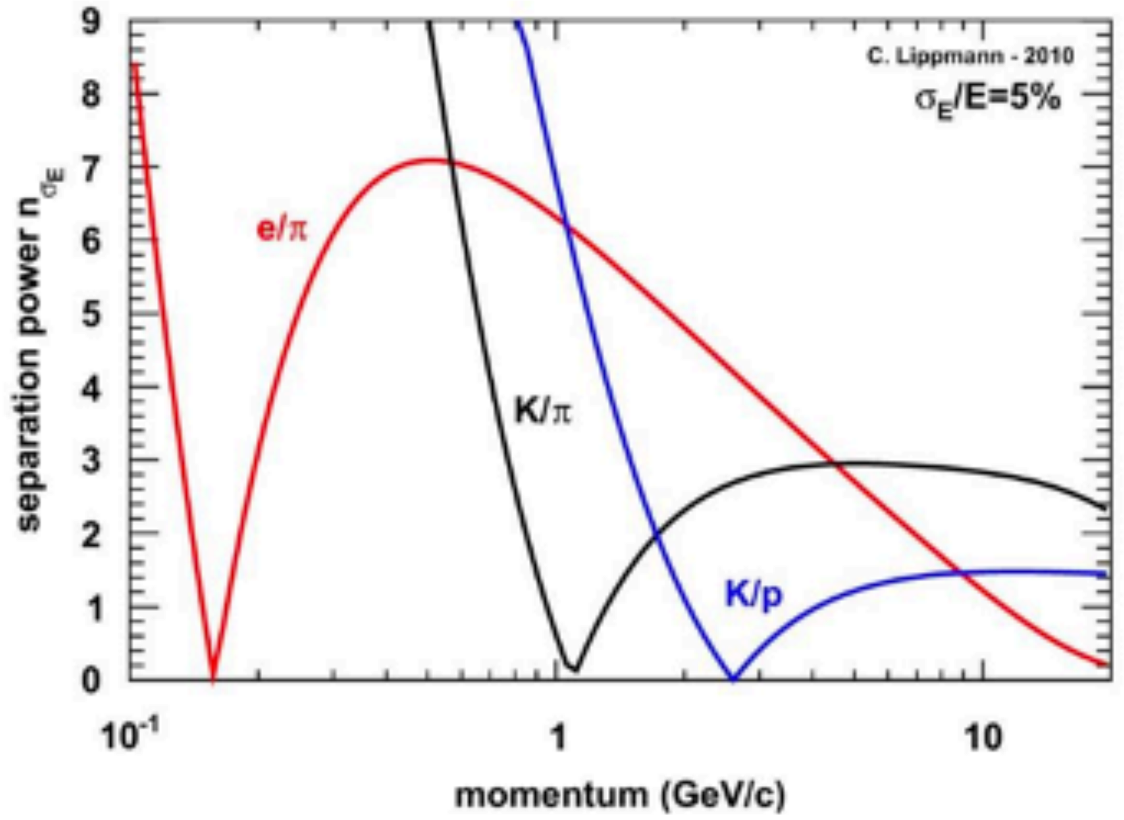
$\Lambda_c^+ \to \Lambda\pi^+\pi^- e^+\nu_e, pK_S^0\pi^- e^+\nu_e$

- Search for $\Lambda_c^+ \to \Lambda^* e^+\nu_e$: $\Lambda\pi^+\pi^-$ and $pK_S^0\pi^-$ are used to tag Λ^*
  - $\mathscr{B}(\Lambda(1520) \to \Lambda\pi^+\pi^-) = (10 \pm 1)\,\%$
  - Higher excited Λ^* states may decay to $pK^*(892)^-$, $K^*(892)^- \to K_S^0\pi^-$

- ST data set reconstructed by 12 hadronic $\bar{\Lambda}_c^-$ decay mode
- Reconstruct $\Lambda[\to p\pi^-]\pi^+\pi^- e^+$ and $pK_S^0[\to \pi^+\pi^-]\pi^- e^+$ in the recoiling side of $\bar{\Lambda}_c^-$
- Challenge from misID between e and π

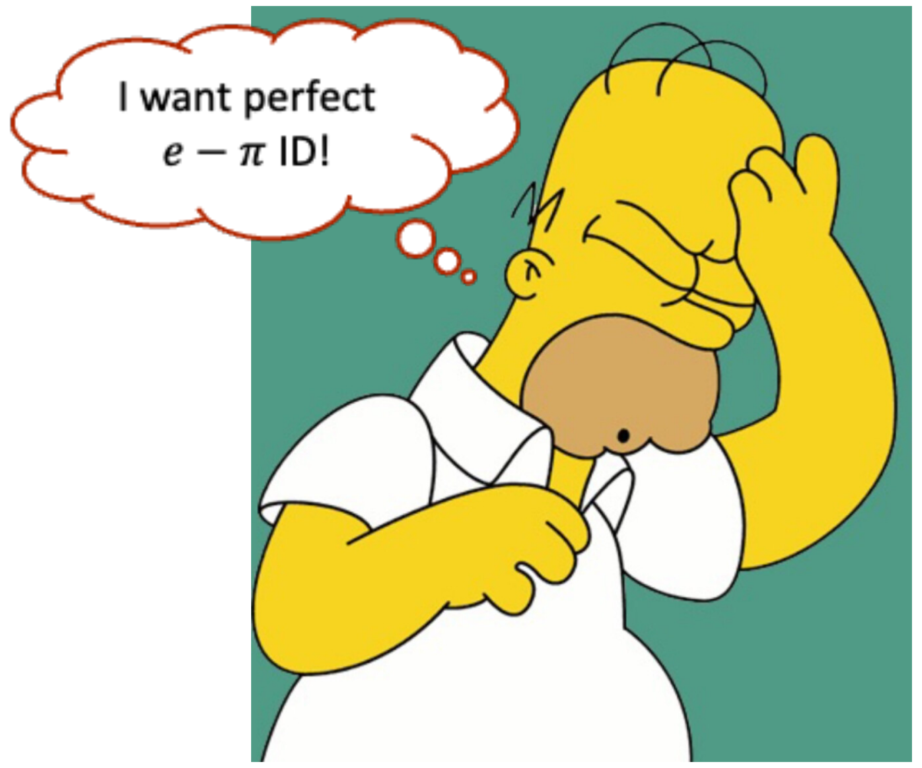
✓ The phase space of 5-body decay is very small
✓ Low momentum of e/π causes serious misidentification





Background Study

- ➔ Tight PID requirement to generally improve PID ability
  - ❖ Valid e EMC hit information
  - ❖ Tight Prob(e)/[Prob(e)+Prob(π)+Prob(K)] requirement

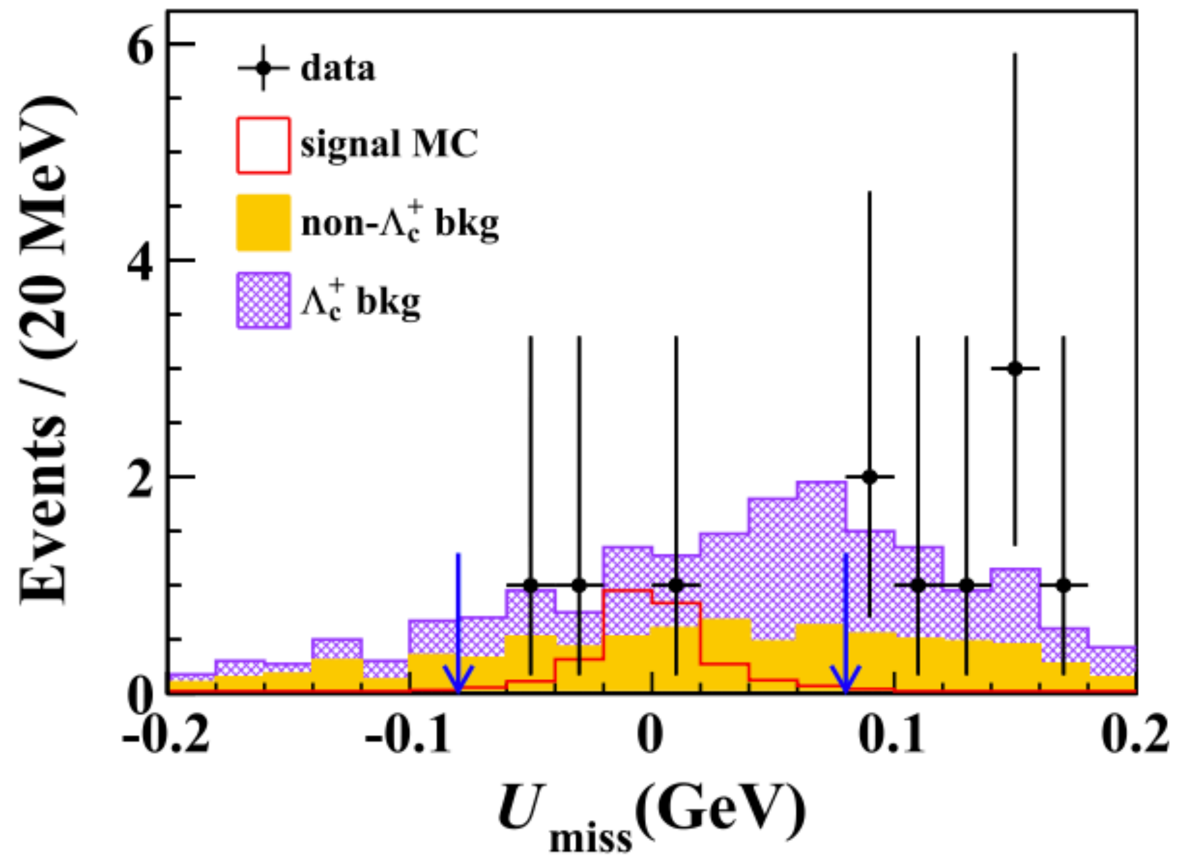


- ➔ γ-conversion background
  - ❖ $\Lambda_c^+ \to \Lambda\pi^+\pi^0, \Sigma^0\pi^+\pi^0(pK_S^0\pi^0, pK_S^0\eta), \pi^0/\eta \to \gamma\gamma$
  - ❖ Under the action of the nucleus, γ converts into electron-positron pair
  - ❖ Require a large angle between e and π

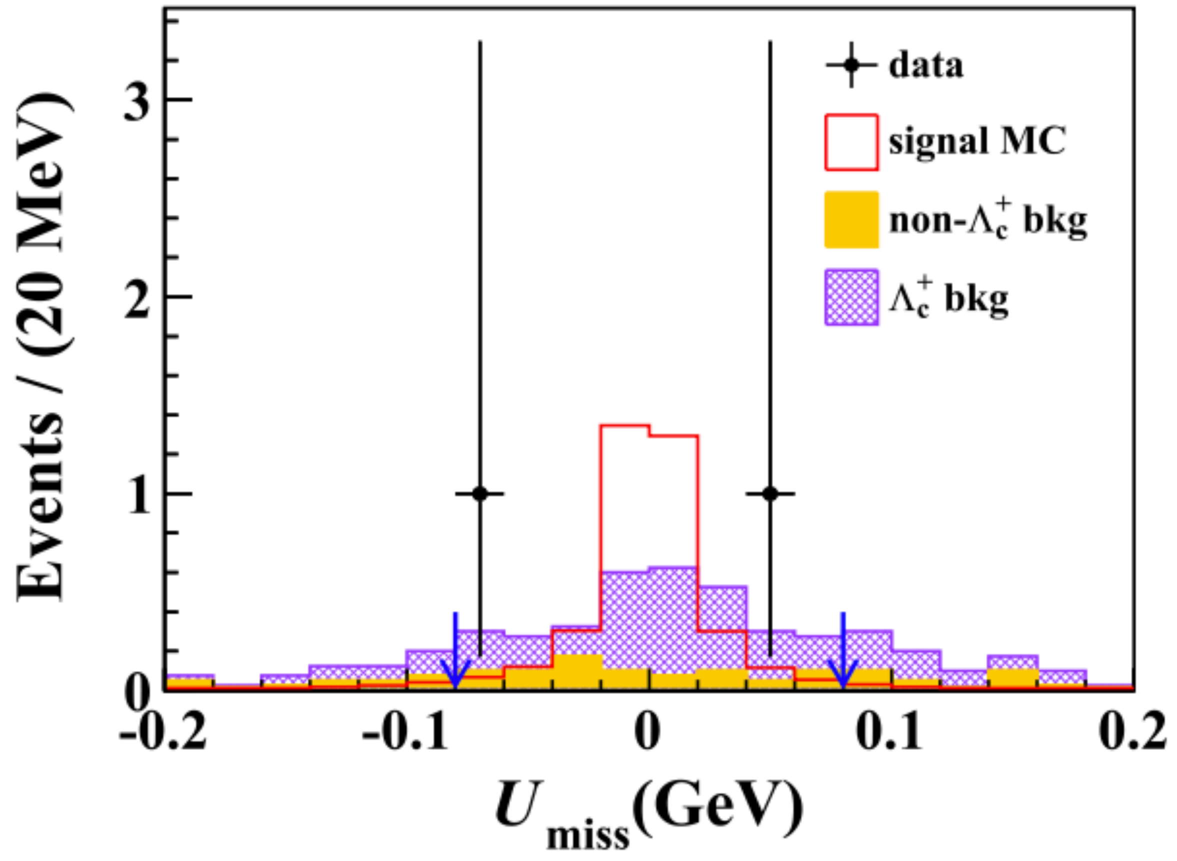
- ➔ $\Lambda\pi^+\pi^-\pi^+(pK_S^0\pi^-\pi^+)$ background
  - ❖ Veto $M_{\Lambda\pi^+\pi^-e(\pi)^+}(M_{pK_S^0\pi^-e(\pi)^+})$, where $e(\pi)^+$ means that M_{e^+} is replaced by M_{π^+}

- ➔ Miss-$\pi^0(\gamma)$ background
  - ❖ $\Lambda_c^+ \to \Lambda\pi^+\omega/\eta, \omega/\eta \to \pi^+\pi^-\pi^0$ or $\Sigma^0\pi^+\pi^-\pi^+, \Sigma^0 \to \gamma\Lambda$,
    $\Lambda_c^+ \to pK_S^0\eta, \eta \to \pi^+\pi^-\pi^0$ or $\eta \to \gamma e^+e^-$
  - ❖ Require a large angle between P_{miss} and the most energetic shower

U_{miss} distribution after all cuts

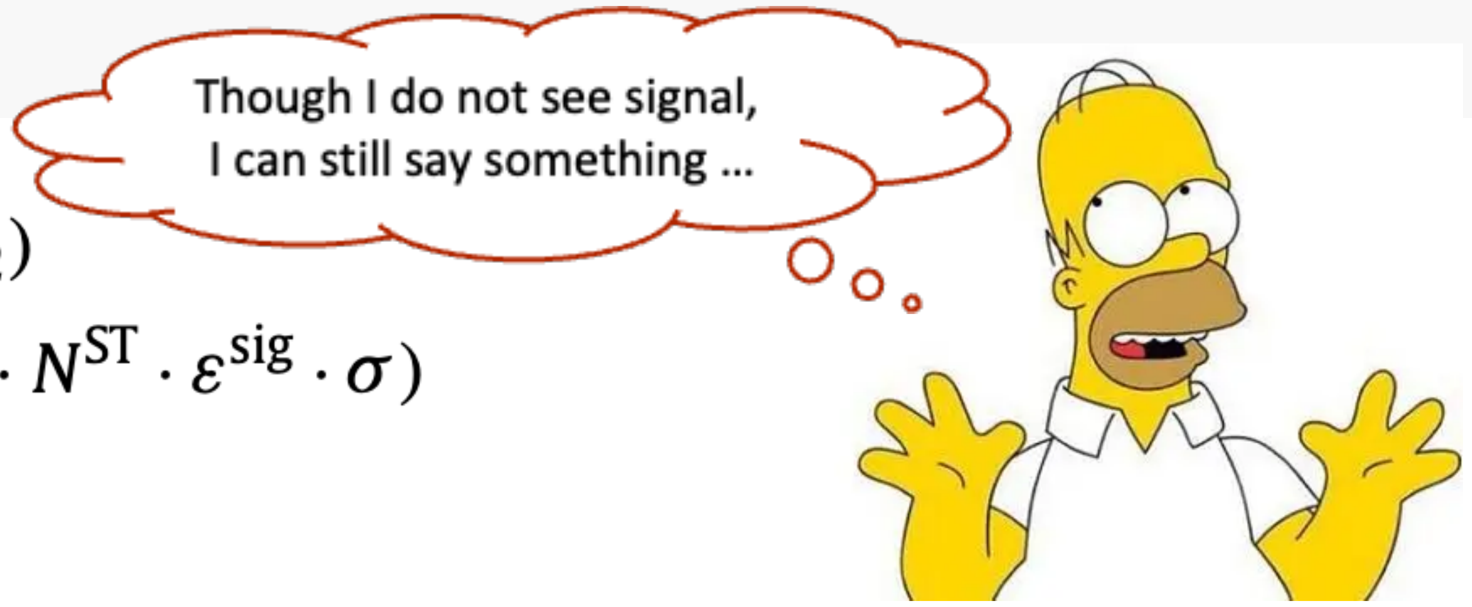


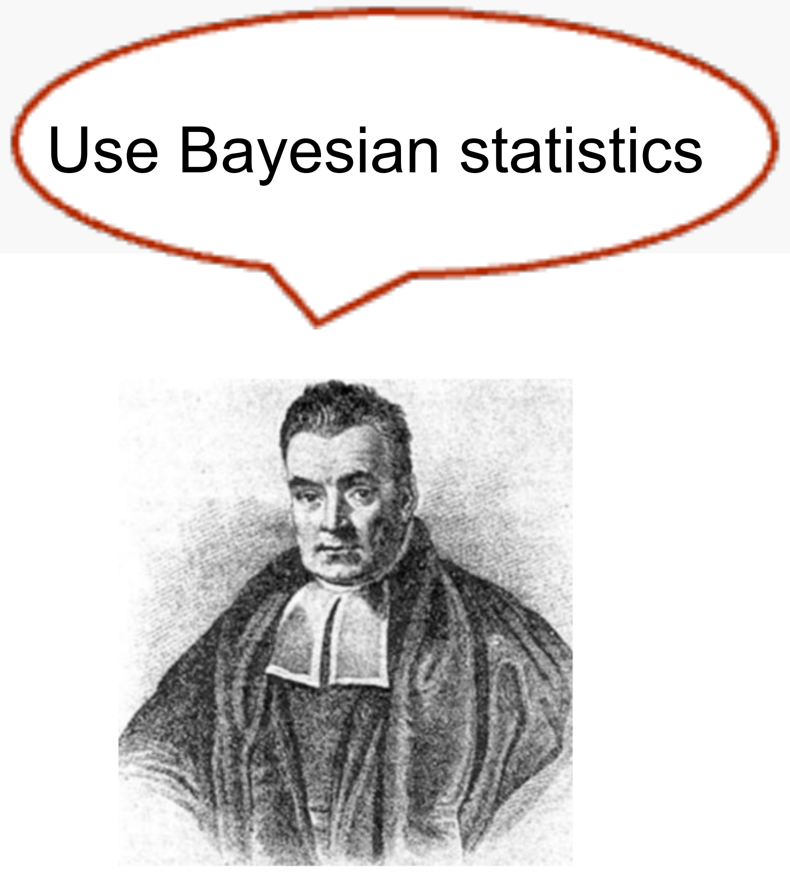
$\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e$



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

Upper limits

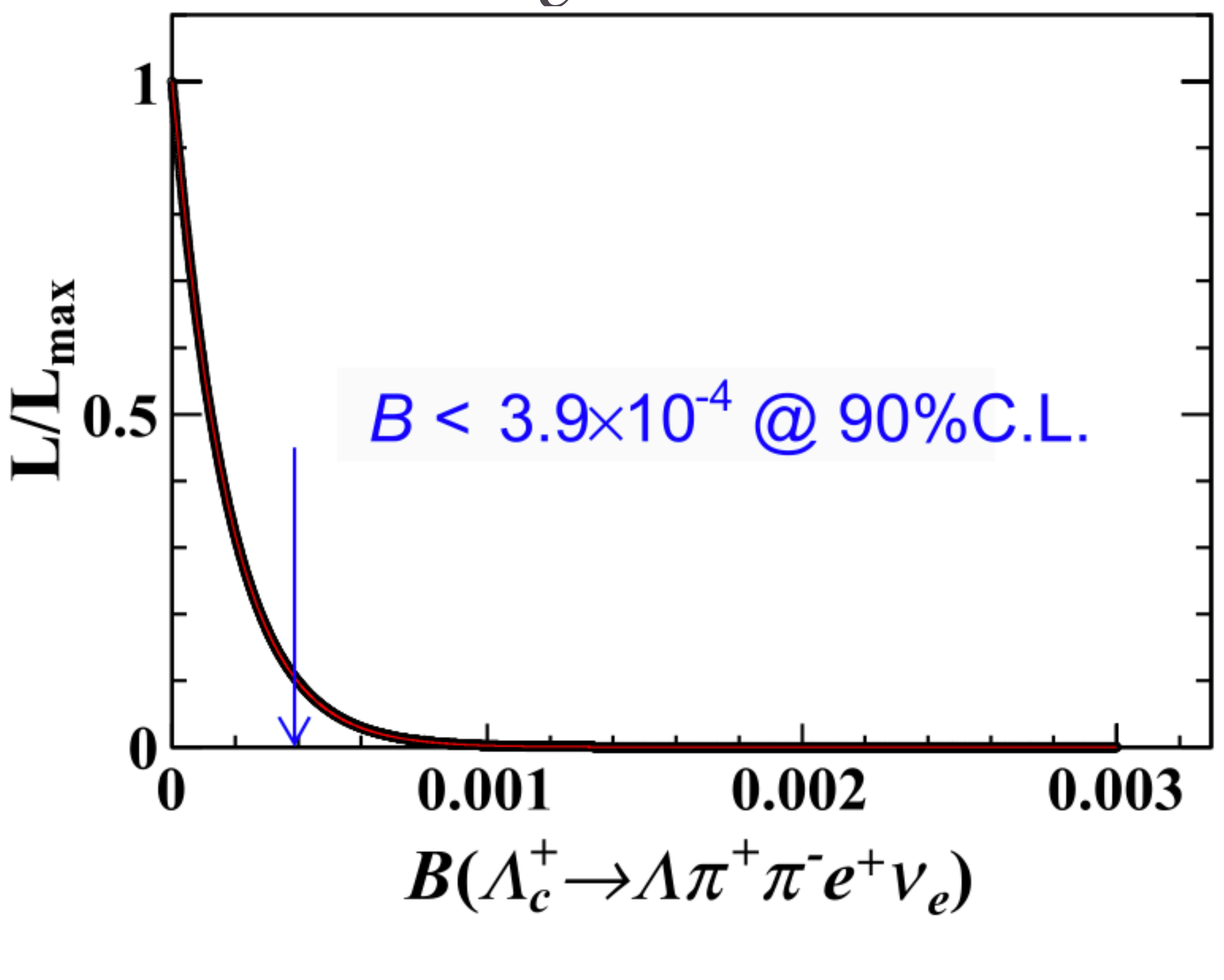


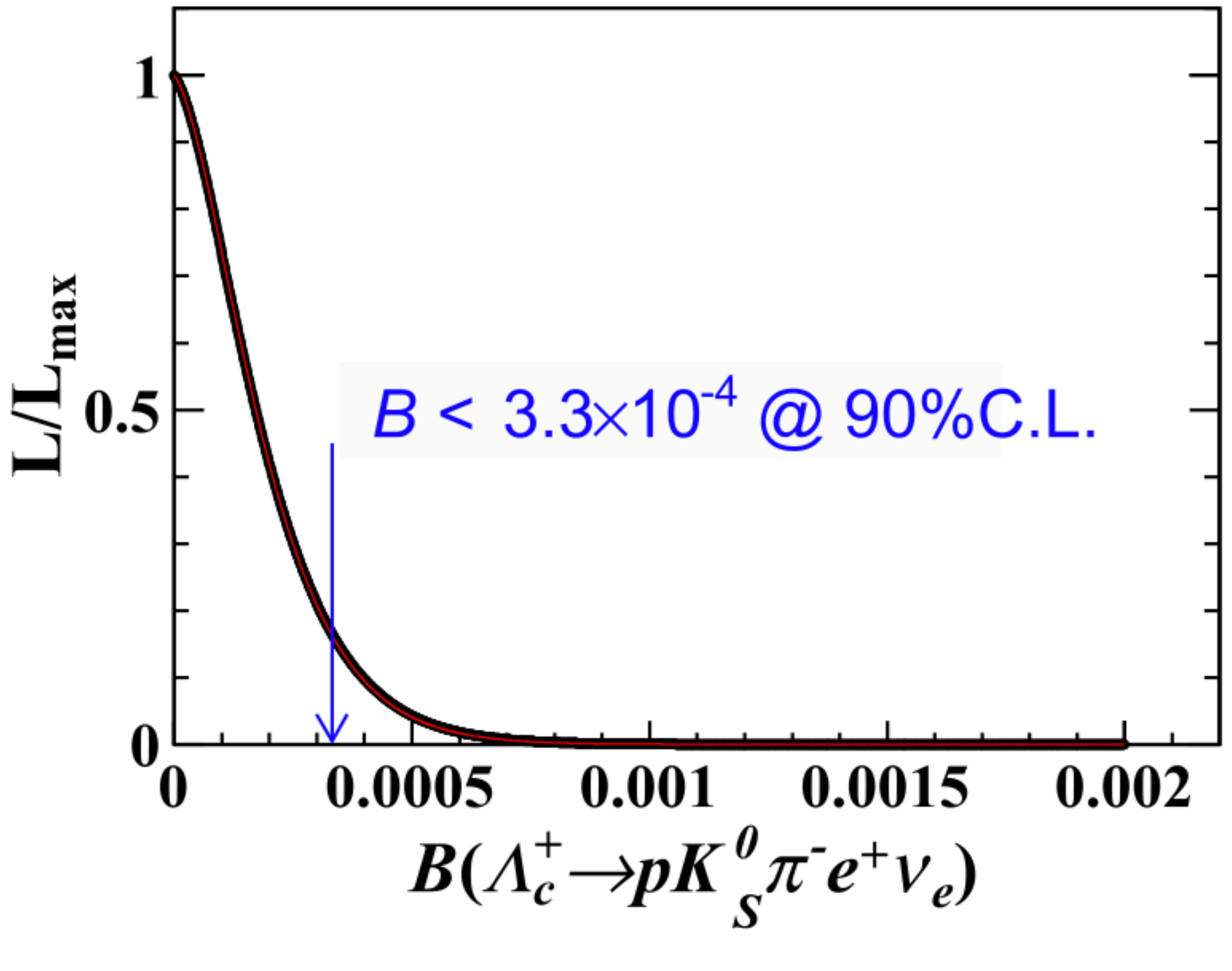


- ➔ Profile likelihood method
- ➔ Joint likelihood

$$\mathcal{L} = \mathcal{P}(N^{\rm obs}|N^{\rm eff}\cdot\mathcal{B}+N_{\rm bkg1}+N_{\rm bkg2}) \cdot \mathcal{G}(N^{\rm eff}|\mathcal{B}^{\rm inter}\cdot N^{\rm ST}\cdot\varepsilon^{\rm sig}, \mathcal{B}^{\rm inter}\cdot N^{\rm ST}\cdot\varepsilon^{\rm sig}\cdot\sigma) \cdot \mathcal{P}(N^{\rm SB}_{\rm bkg1}|N_{\rm bkg1}/r) \cdot \mathcal{G}(N_{\rm bkg2}|N^{\rm MC}_{\rm bkg2}, \sigma^{\rm MC}_{\rm bkg2}).$$

- ➔ Based on the Bayesian statistics, the likelihood distribution as a function of BF is obtained
- ➔ The ULs at the 90% confidence level (CL) are determined
  - ❖ Assuming that all the $\Lambda\pi^+\pi^-$ combinations come from $\Lambda(1520)/\Lambda(1600)$,
    $\mathscr{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e) < 4.3\times10^{-3}$ @ 90 % CL
    $\mathscr{B}(\Lambda_c^+ \to \Lambda(1600)e^+\nu_e) < 9.0\times10^{-3}$ @ 90 % CL





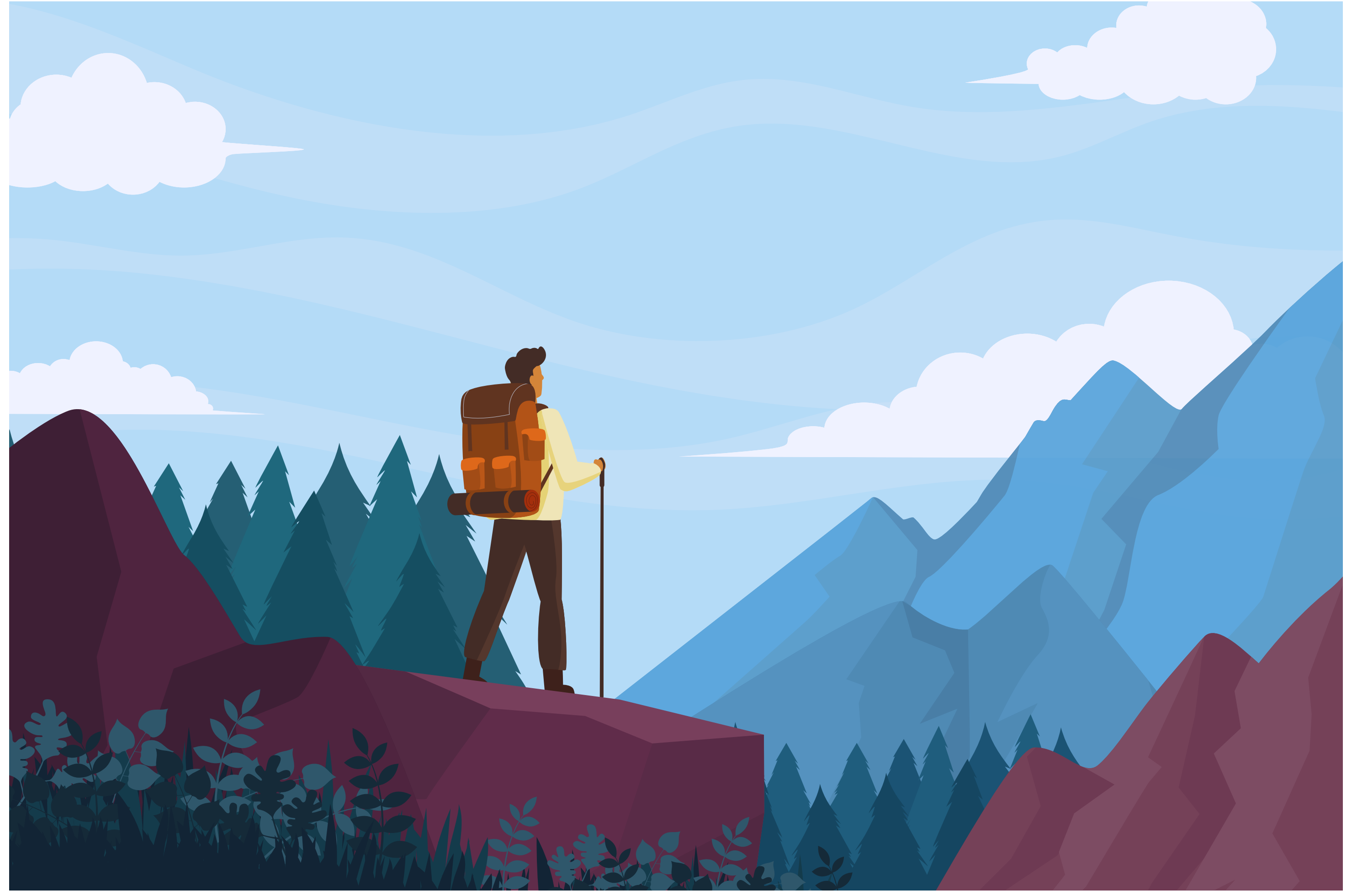
The BFs for $\Lambda_c^+ \to \Lambda^* e^+\nu_e$ predicted by different theoretical models, in units of 10^{-4}.

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}	— —	— —

Limited sensitivity to identify different theoretical calculations

Other ongoing analysis

Roadmap of Λ_c^+ SL



- ➔ $\mathcal{B}(\Lambda_c^+ \to Xe^+\nu_e) = (4.06 \pm 0.10_{\text{stat.}} \pm 0.09_{\text{syst.}})\,\%$
- ➔ $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+\nu_e) = (3.56 \pm 0.11_{\text{stat.}} \pm 0.07_{\text{syst.}})\,\%$
- ➔ $\mathcal{B}(\Lambda_c^+ \to pK^-e^+\nu_e) = (0.82 \pm 0.15 \pm 0.06) \times 10^{-3}$
  - ❖ $\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e) = (1.02 \pm 0.52_{\text{stat.}} \pm 0.11_{\text{syst.}}) \times 10^{-3}$

- ➔ $\dfrac{\mathcal{B}(\Lambda_c^+ \to \Lambda e^+\nu_e) + \mathcal{B}(\Lambda_c^+ \to pK^-e^+\nu_e)}{\mathcal{B}(\Lambda_c^+ \to Xe^+\nu_e)} = (89.7 \pm 4.3)\,\% \Rightarrow (85.4 \sim 94.0)\,\%$
- ➔ $\mathcal{B}(\Lambda_c^+ \to \text{non}[\Lambda, pK^-]e^+\nu_e) = (4.18 \pm 1.75) \times 10^{-3} \Rightarrow (2.43 \sim 5.93) \times 10^{-3}$

- ➔ $\Lambda^* e^+\nu_e$: $\Sigma\pi e^+\nu_e$, $n\bar{K}^0 e^+\nu_e$
- ➔ $N^{(*)}e^+\nu_e$: $ne^+\nu_e$, $N(1535)e^+\nu_e$

Next stage

sub-10^{-3} level rooms

Stay tuned

- ➔ $\Lambda_c^+ \to n e^+ \nu_e$
  - ❖ Singly Cabibbo-suppressed transition $c \to d$
  - ❖ Various theoretical-model calculations
  - ❖ Challenge in experimental study
    - ▸ Two missing particles: n and ν_e
    - ▸ Huge background from $\Lambda_c^+ \to \Lambda e^+ \nu_e$
- ➔ $\Lambda_c^+ \to \Sigma\pi e^+ \nu_e$
  - ❖ $\mathscr{B}(\Lambda(1405) \to \Sigma\pi) \approx 100\,\%$ and $\mathscr{B}(\Lambda(1520) \to \Sigma\pi) \approx (42 \pm 1)\,\%$
  - ❖ Search for Λ^* in $\Sigma\pi$ invariant mass spectrum
  - ❖ Nature of $\Lambda(1405)$?
    - ▸ uds bound state, dynamically generated molecular state, multi-quark state
- ➔ $\Lambda_c^+ \to p\pi^-(\mathrm{non}-\Lambda)e^+\nu_e$
  - ❖ Singly Cabibbo-suppressed transition to nucleon excited states $c(\Lambda_c^+) \to d(N^*)$
  - ❖ $\mathscr{B}(\Lambda_c^+ \to N^*(1535)e^+\nu_e)$: $4.03 \times 10^{-5}(8.06 \times 10^{-5})$[1], $6.4 \times 10^{-3}(7.7 \times 10^{-4})$[2]
- ➔ $\Lambda_c^+ \to n K_S^0 e^+ \nu_e$
  - ❖ Isospin-symmetric channel to pK^-
  - ❖ Similar challenge with $ne^+\nu_e$: two missing particles

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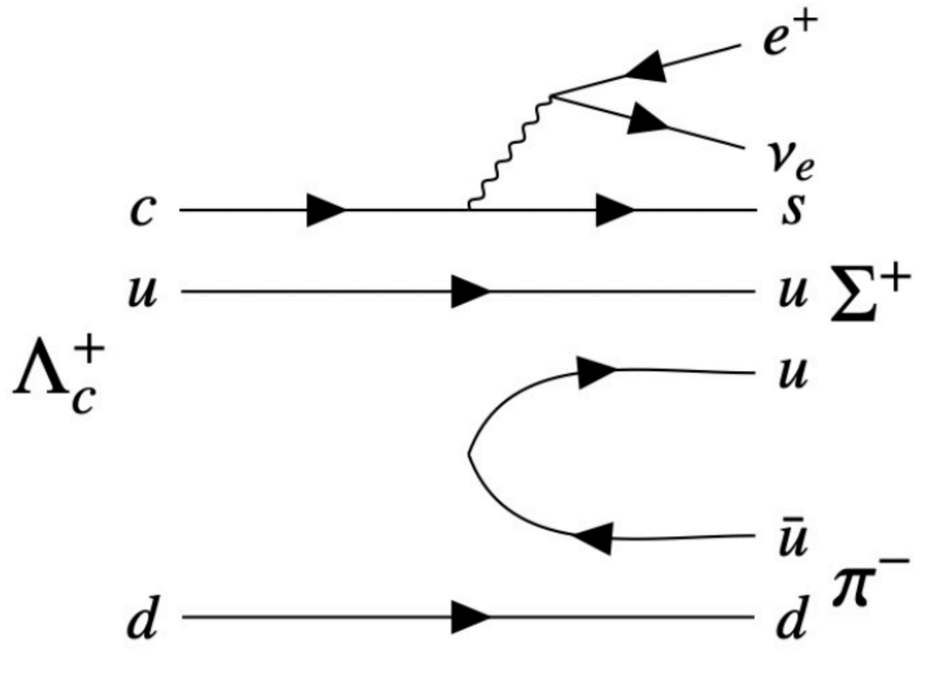
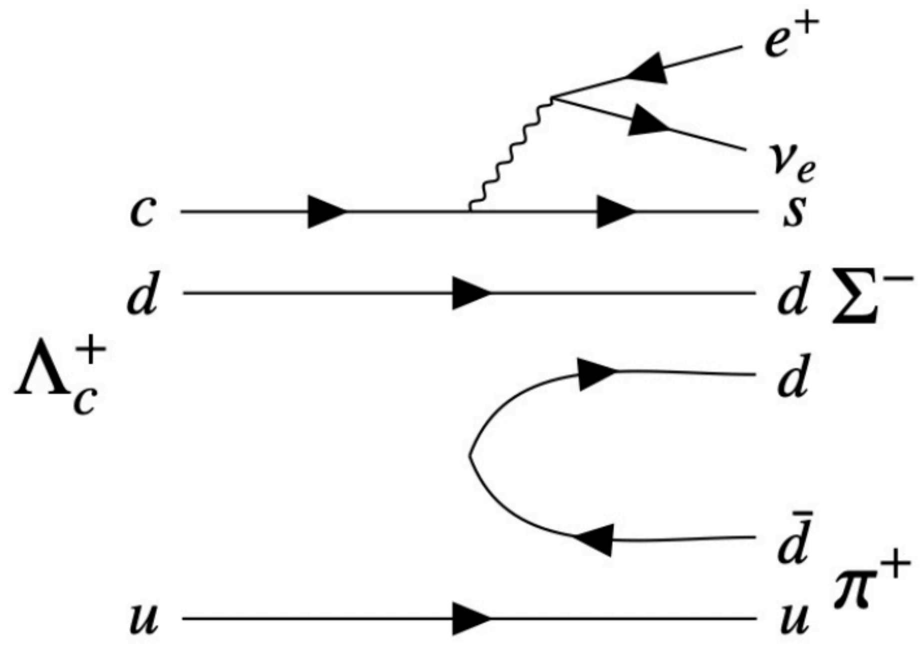
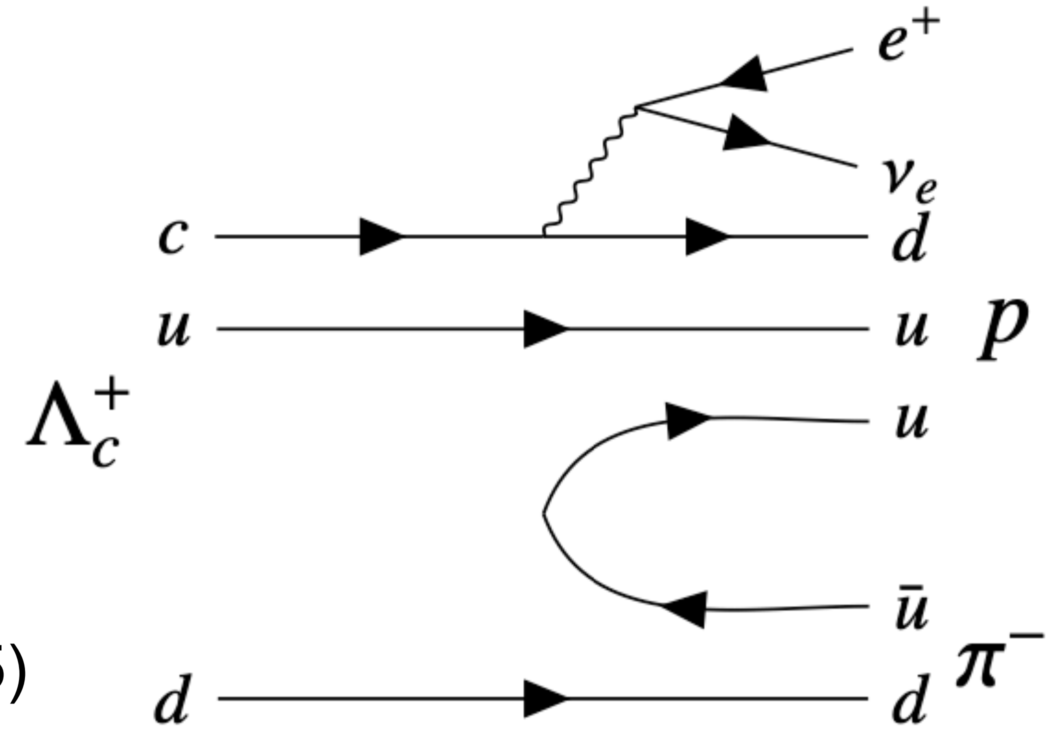
Process	NRQM [232]	RQM [236]	RQM [237]	QSR [243]	QSR [244]	CQM [238]	LQCD [248, 249]	LFQM [227]	SU(3) [251]	Expt [31]
$\Lambda_c^+ \to \Lambda^0 e^+ \nu_e$	3.0 (2.2)	1.4	3.25	2.6 ± 0.4	3.0 ± 0.3	2.78	3.8 ± 0.2	4.04	3.6 ± 0.4	3.6 ± 0.4
		-0.812		-1	-0.88 ± 0.03				-0.86 ± 0.03	-0.86 ± 0.04
$\Lambda_c^+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



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



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



[1] Phys.Rev.C 72, 035201 (2005)
[2] J.Phys.G 43, 115003 (2016)

Summary

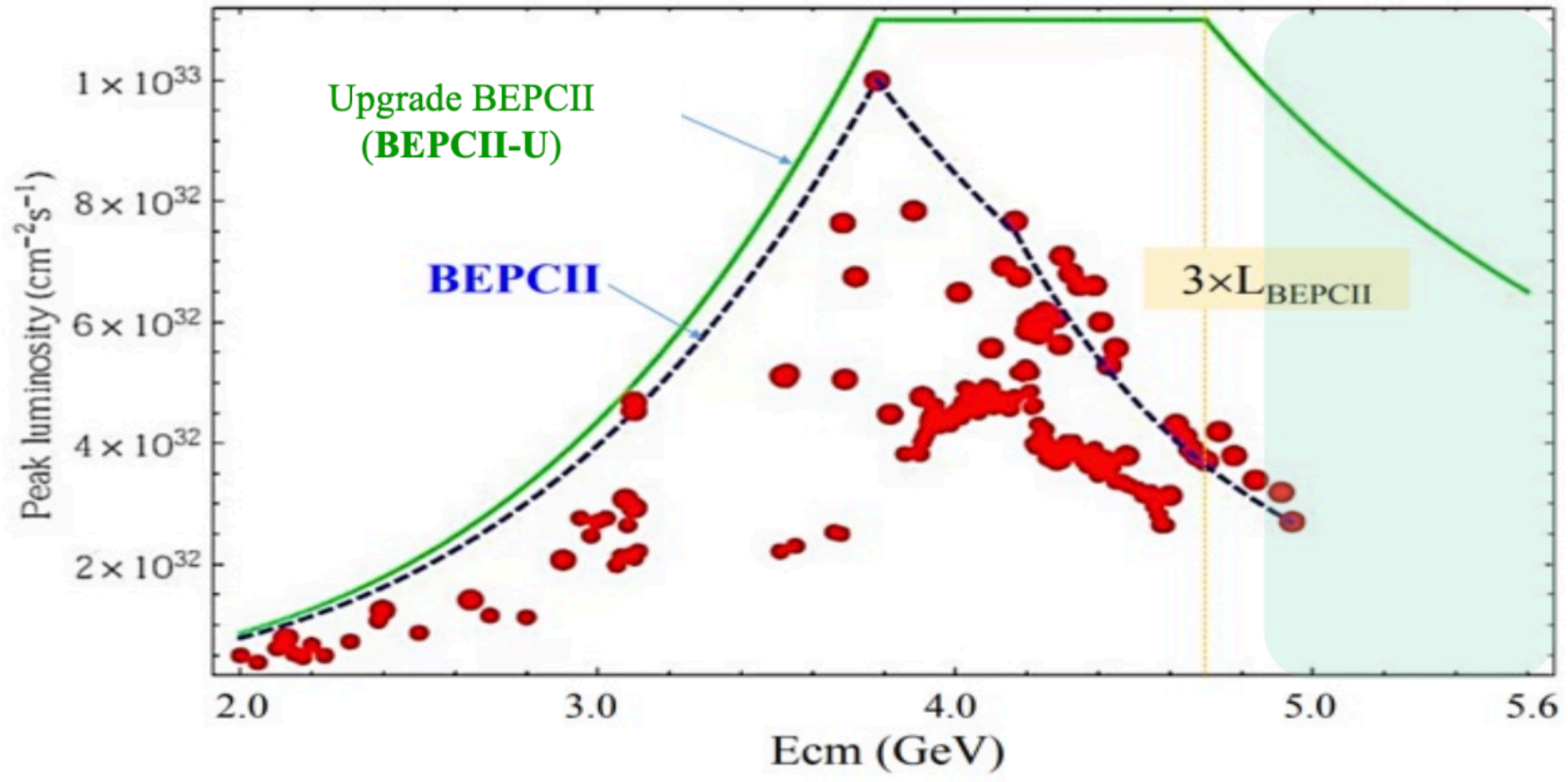
Summary & outlook

- ➔ Semi-leptonic Λ_c^+ decays provide good opportunities to study the dynamics of charm baryons, test Standard Model and probe new physics

- ➔ Improved measurement of $\Lambda_c^+ \to \Lambda l^+ \nu_l$ and $\Lambda_c^+ \to X e^+ \nu_e$
- ➔ First search for $\Lambda_c^+ \to \Lambda^* e^+ \nu_e$ in $pK^-, \Lambda\pi^+\pi^-, pK_S^0\pi^-$ channels

- ➔ More physics results coming soon

- ➔ Larger data samples will be collected at BESIII after BEPCII-U



Thanks for your attention!

Backup

z-expansion

➔ z-expansion: FF is q^2 dependent, refer to LQCD parameterization

- $m^f_{\rm pole}$: pole mass, $m^{f_+,f_\perp}_{\rm pole} = 2.112\,\mathrm{GeV}/c^2$ and $m^{g_+,g_\perp}_{\rm pole} = 2.460\,\mathrm{GeV}/c^2$
- a^f_0 and α^f_1: free parameters
- $z(q^2) = [(\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0})/(\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0})]$ with $t_0 = q^2_{\rm max} = (m_{\Lambda_c} - m_\Lambda)^2$, $t_+ = (m_D - m_K)^2$
- $m_D = 1.870\,\mathrm{GeV}/c^2$ and $m_K = 0.494\,\mathrm{GeV}/c^2$

$$f(q^2) = \frac{a^f_0}{1 - q^2/(m^f_{\rm pole})^2}\left[1 + \alpha^f_1 \times z(q^2)\right]$$

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

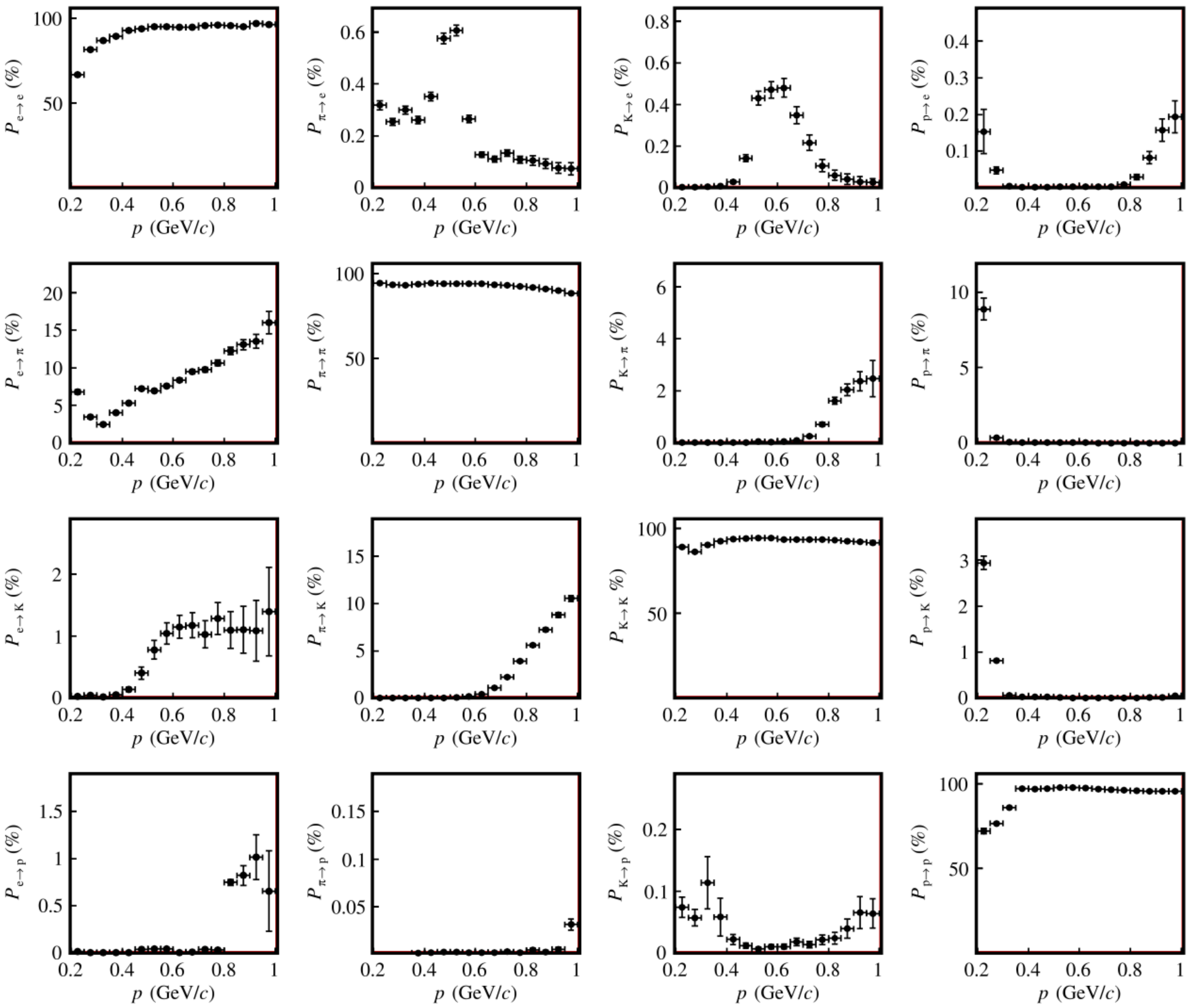


FIG. 4. PID efficiencies as a function of momentum used to populate the A_{PID} matrices.

TABLE I. Positron yield in data after each procedure. The listed uncertainties are statistical.

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	

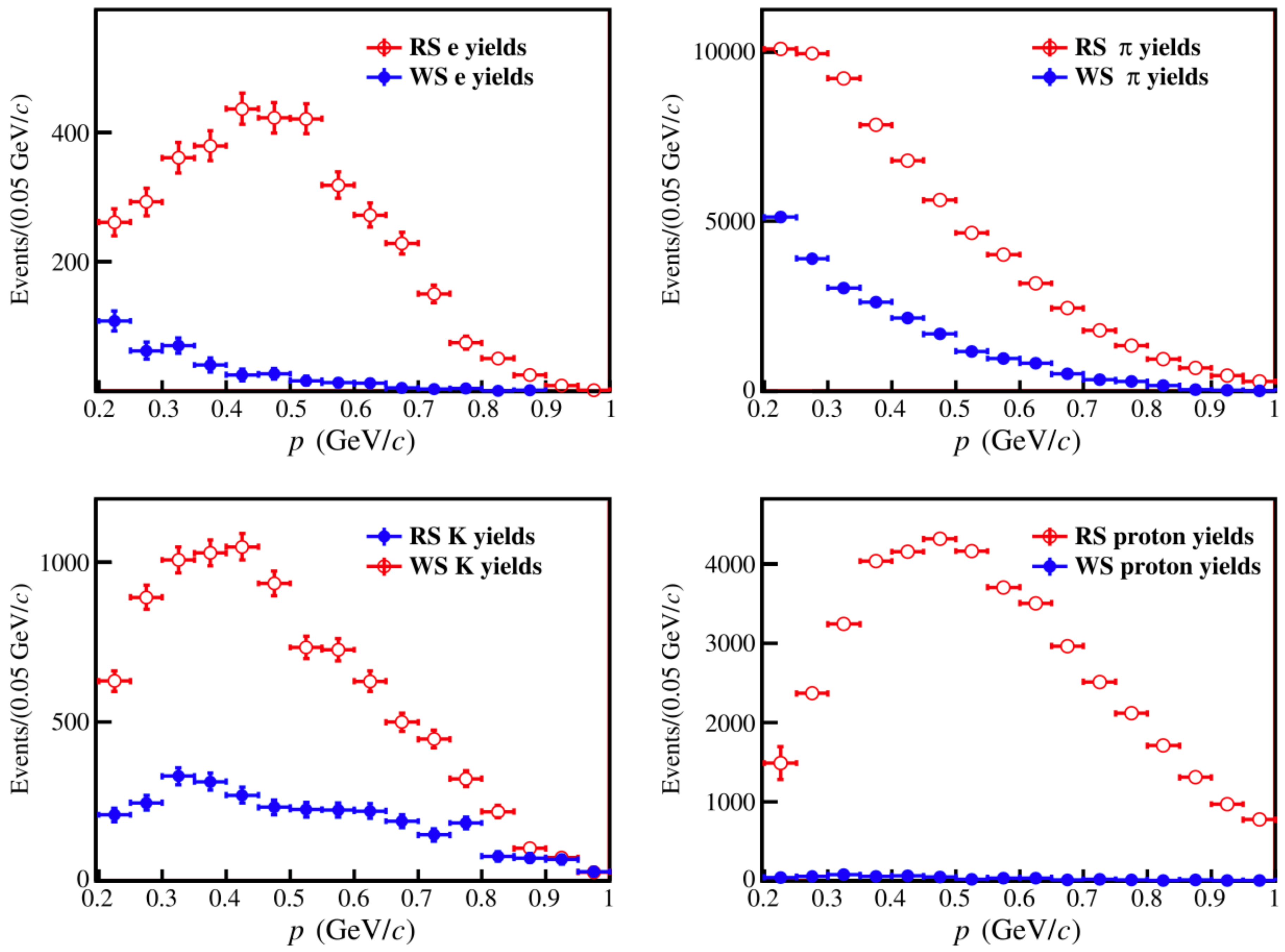


FIG. 3. Measured RS (blue) and WS (red) yields for each particle category as a function of momentum.

$\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e, pK_S^0\pi^-e^+\nu_e$ Signal yields & BKG number estimation

➔ No signals observed on data, plan to setting upper limits (ULs) on BFs 😟

➔ The backgrounds separated into two categories:

- Non-Λ_c^+ background, denoted as bkg1 ⇒ Estimated by data sideband region
- Λ_c^+ background, denoted as bkg2 ⇒ Estimated by MC simulation

➔ The observed events N^{obs} follows a Poisson distribution($\mathscr{P}$)

- $N^{\mathrm{obs}} \sim \mathscr{P}(N^{\mathrm{obs}} \,|\, N_{\mathrm{sig}} + N_{\mathrm{bkg1}} + N_{\mathrm{bkg2}})$

➔ The signal event number $N_{\mathrm{sig}} = \mathscr{B}_{\mathrm{sig}} \cdot \mathscr{B}^{\mathrm{inter}} \cdot N^{\mathrm{ST}} \cdot \varepsilon^{\mathrm{sig}} = \mathscr{B}_{\mathrm{sig}} \cdot N^{\mathrm{eff}}$

- $N^{\mathrm{eff}} \sim \mathscr{G}(N^{\mathrm{eff}} \,|\, \mathscr{B}^{\mathrm{inter}} \cdot N^{\mathrm{ST}} \cdot \varepsilon^{\mathrm{sig}}, \mathscr{B}^{\mathrm{inter}} \cdot N^{\mathrm{ST}} \cdot \varepsilon^{\mathrm{sig}} \cdot \sigma)$ ⇒ Rely on systematic uncertainty study