PEKING UNIVERSITY

Charm baryon decays at BESIII

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(On behalf of BESIII collaboration)

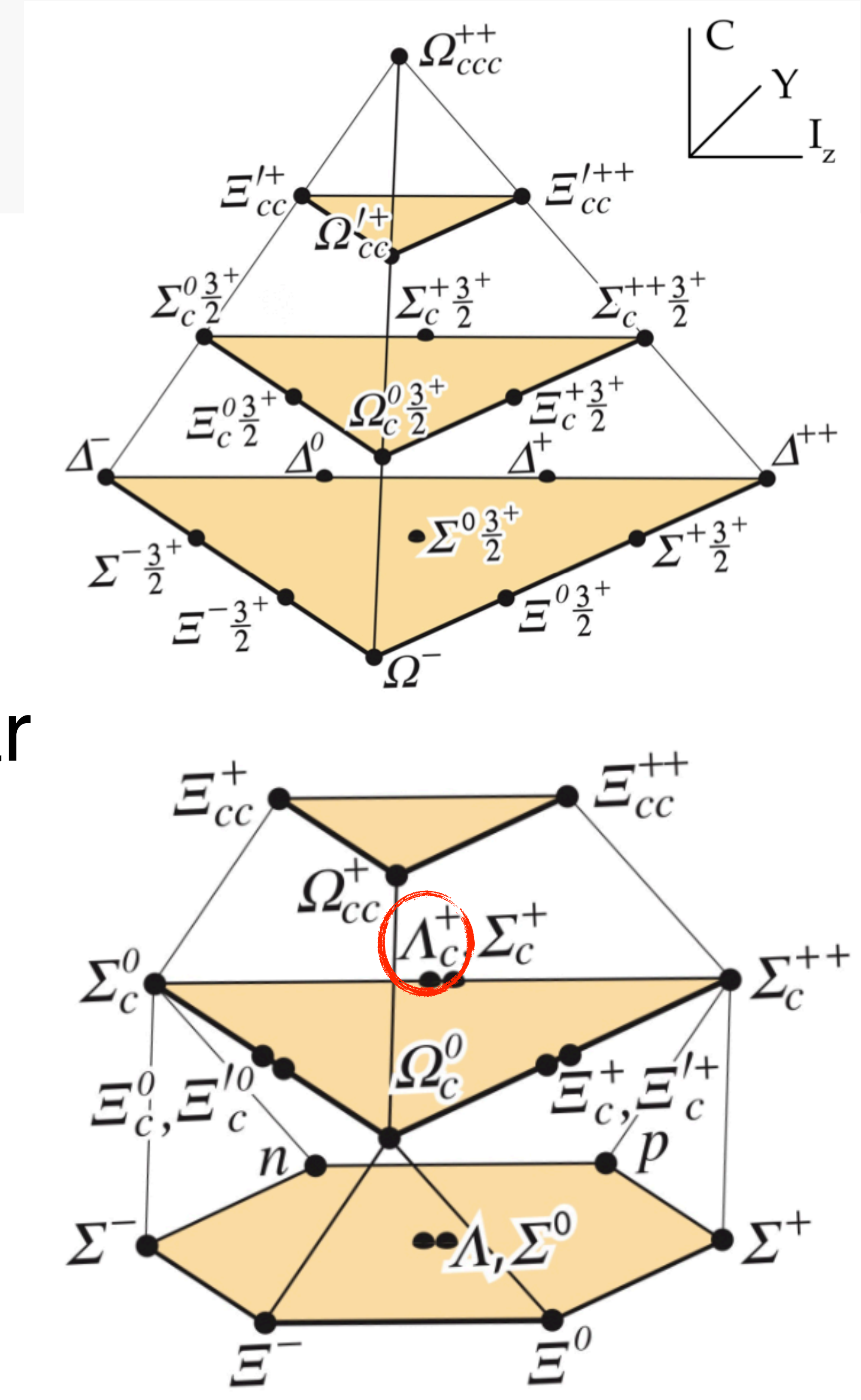
Outline

- ➔ Introduction
- ➔ BESIII experiment
- ➔ Recent physics results
- ➔ Other ongoing analysis
- ➔ Summary & outlook

Introduction

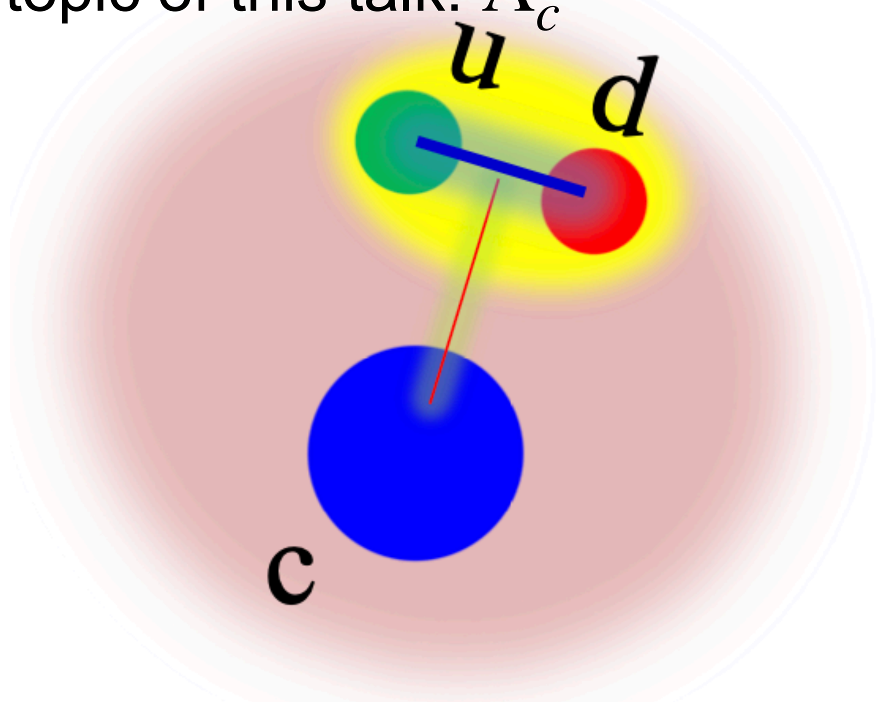
Charm baryon family

- ➔ Singly charmed baryons
  - ❖ Established groud states: $\Lambda_c^+, \Sigma_c, \Xi_c, \Omega_c$
  - ❖ Excited states are being explored
- ➔ Doubly charmed baryons Ξ_{cc}^{++} observed in recent year
- ➔ No observations of triply charmed baryons

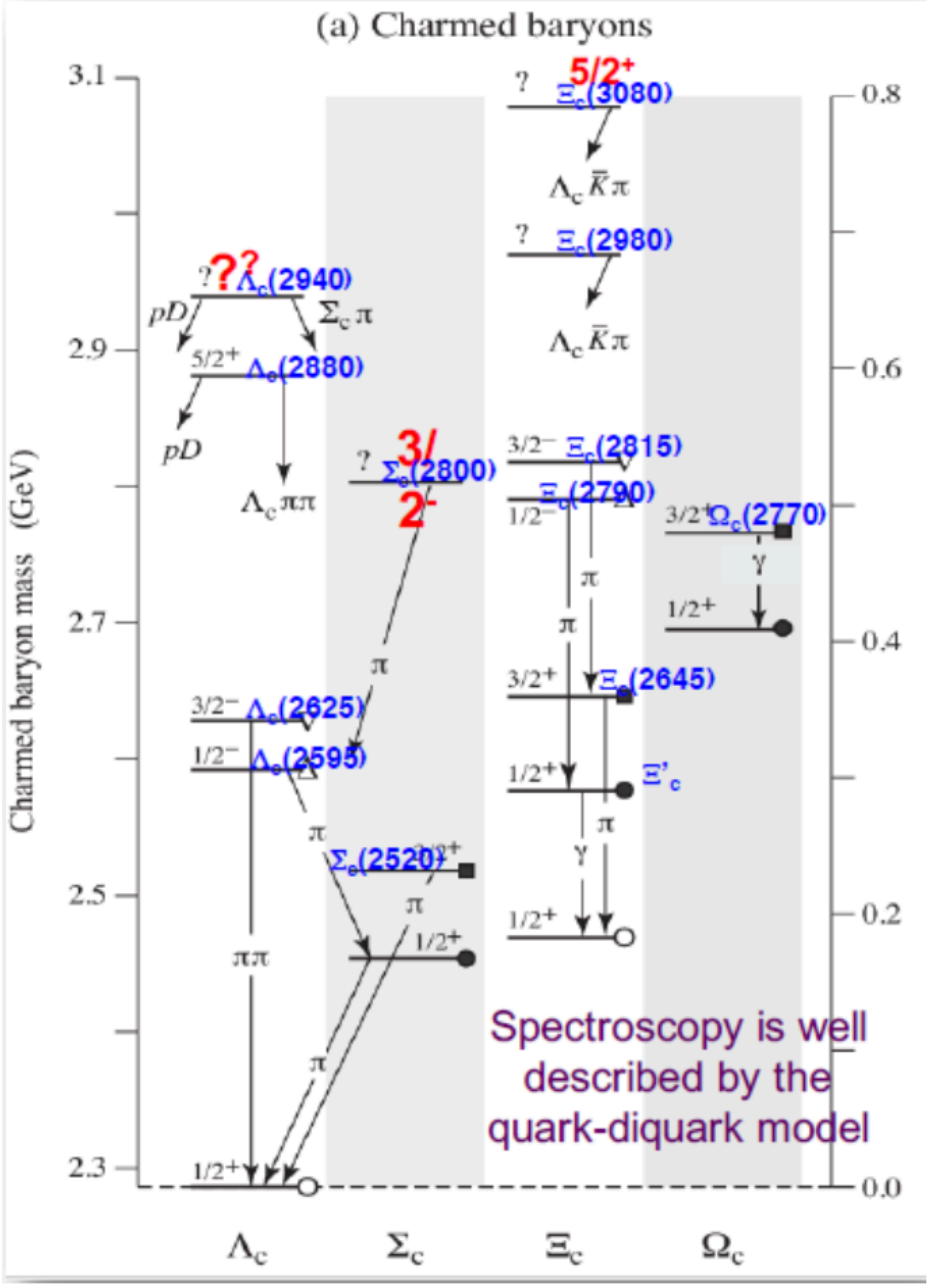


- ➔ Λ_c^+: the lightest charmed baryon
  - ❖ Important tagging for charmed baryons and Bottom baryons
- ➔ Naive quark model: a heavy quark (c) and an unexcited spin-zero diquark (u-d)
  - ❖ HQET: diquark correlation is enhanced by weak Color Magnetic Interaction with a heavy quark
  - ❖ Λ_c^+ reveal more information of strong- and weak- interactions in charm region, complementary to $D_{(s)}$

Main topic of this talk: Λ_c^+



$m_u, m_d \gg m_c \Rightarrow$ diquark(qq) + quark(Q)



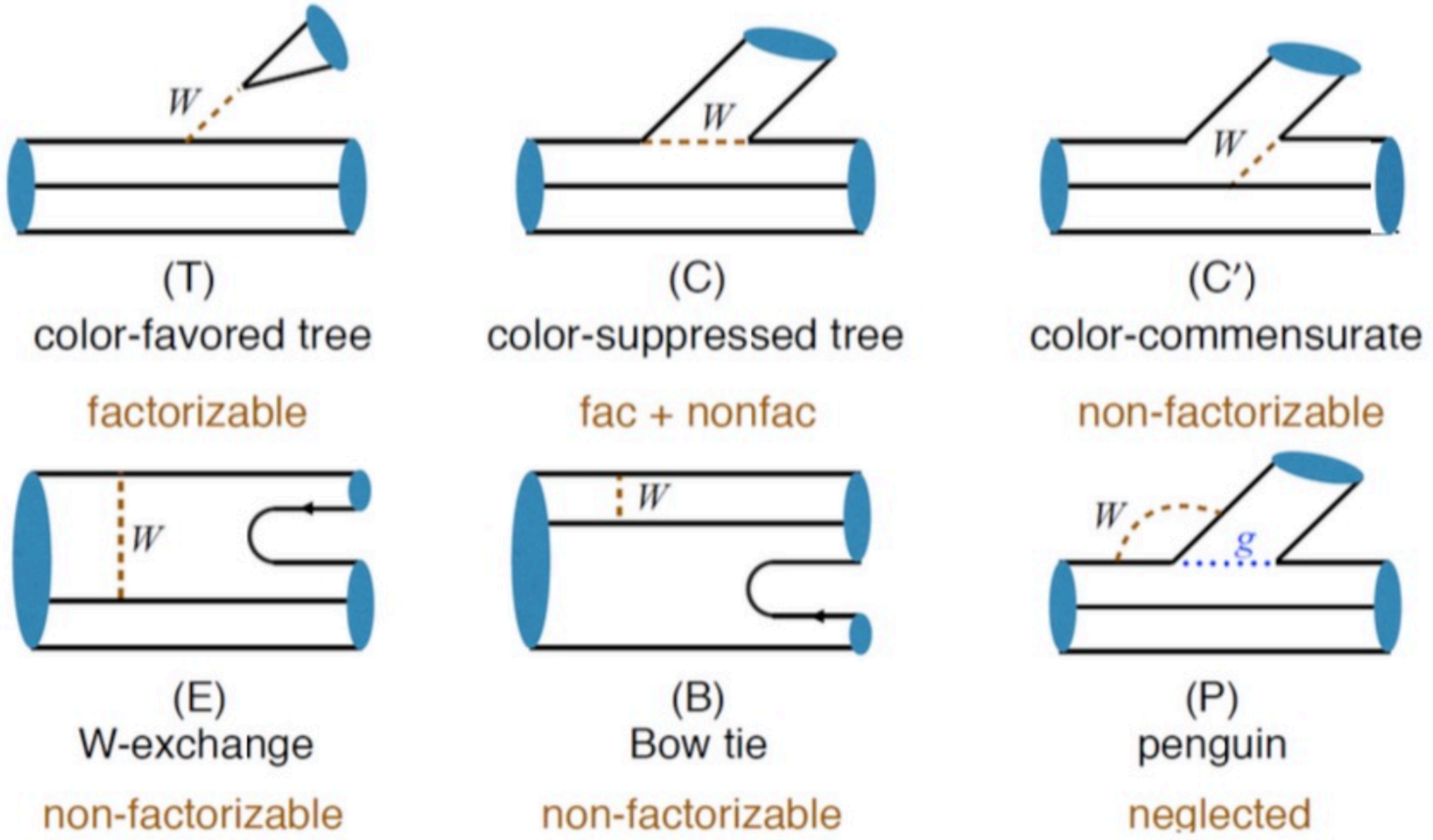
Λ_c^+ weak decay picture in theory

➔ Dilemma in theory

- Λ_c^+ energy scale: **perturbative ⇔ non-perturbative**
- Well known factorization method failed, non-factorizable diagram plays an important role in Λ_c^+ decay

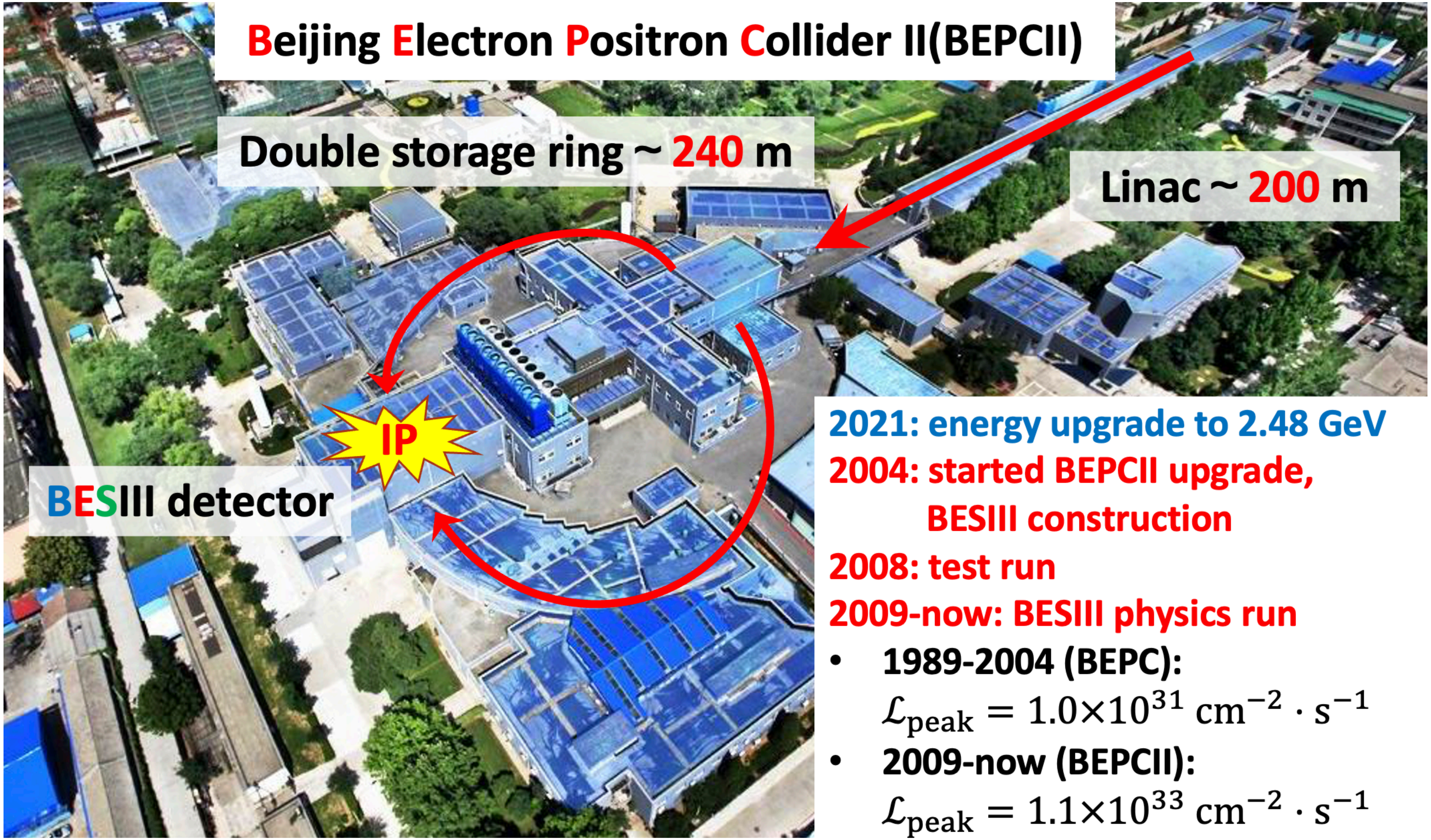
➔ Many phenomenology methods are developed to explain data and predict observables

- HQET, factorization
- Various quark models, pole model+current algebra, …
- $SU(3)$ flavor symmetry, topological diagram, irreducible diagram, … (parametrize & fit to data)
- LQCD (from first principle)



BESIII experiment

BEPCII



2021: energy upgrade to 2.48 GeV

2004: started BEPCII upgrade,
BESIII construction

2008: test run

2009-now: BESIII physics run

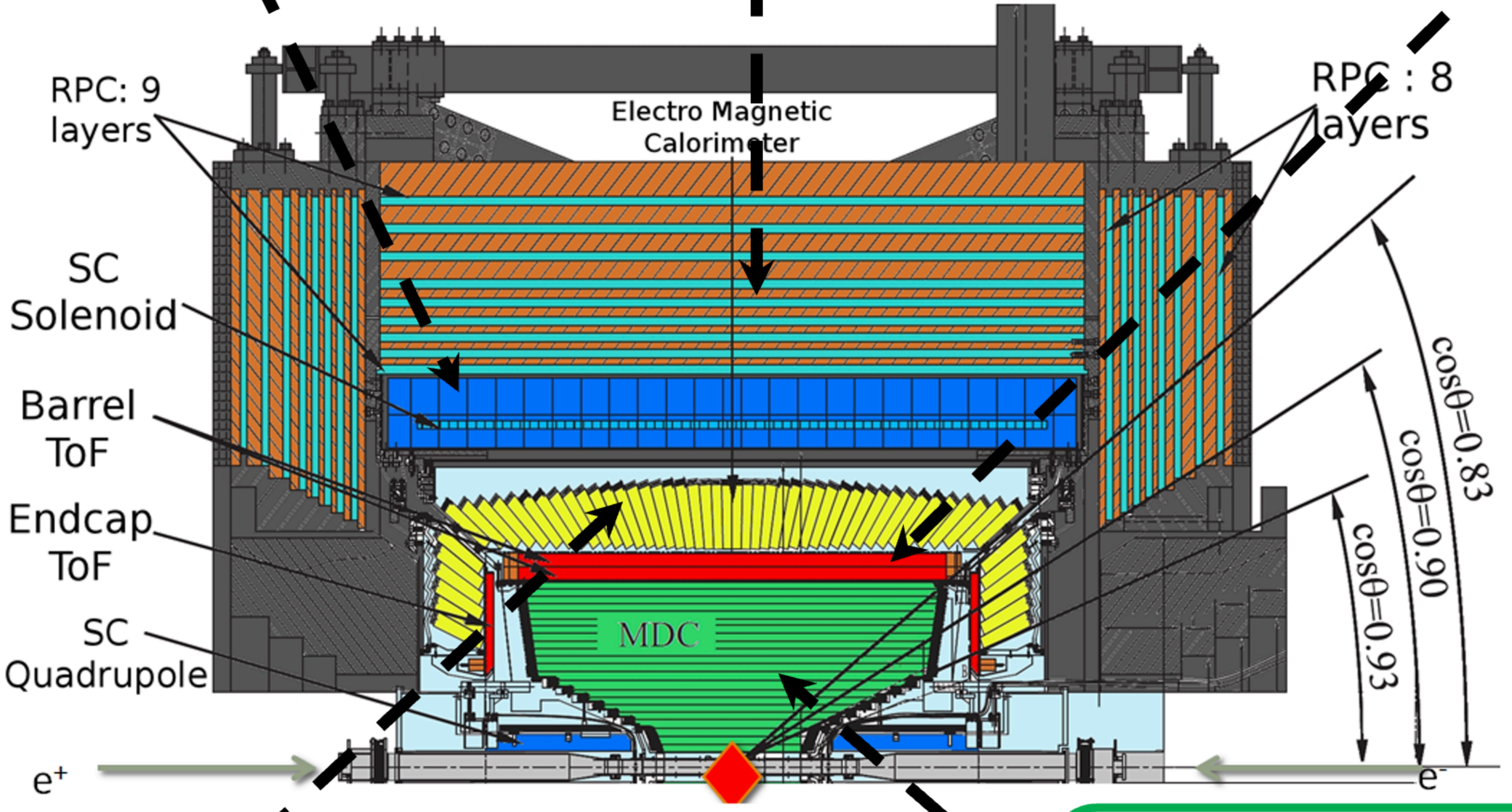
- 1989-2004 (BEPC):
  $\mathcal{L}_{\text{peak}} = 1.0\times10^{31}\ \text{cm}^{-2}\cdot\text{s}^{-1}$
- 2009-now (BEPCII):
  $\mathcal{L}_{\text{peak}} = 1.1\times10^{33}\ \text{cm}^{-2}\cdot\text{s}^{-1}$

BESIII detector

Superconducting solenoid
- 1.0 T

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

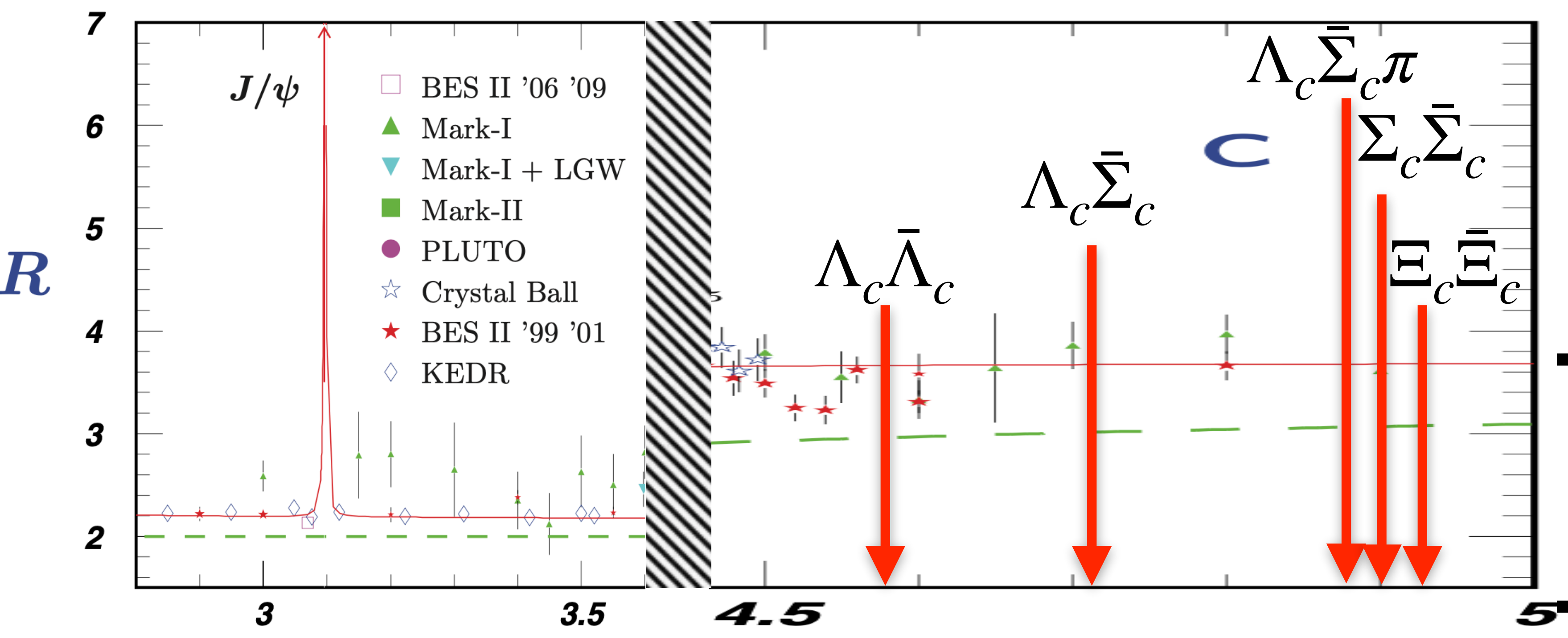
Time Of Flight (TOF)
- $\sigma_t = 90$ ps (barrel)
- $\sigma_t = 65$ ps (end cap)



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

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

New data samples in 2020 and 2021



Chin. Phys. C 46, 113003 (2022)

Sample	$E_{\rm cms}$/MeV	$\mathscr{L}_{\rm Bhabha}$/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

➔ In 2014, BESIII took 35 days data at 4.6 GeV with luminosity 0.587 fb^{-1} ~ 0.1M $\Lambda_c^+\bar{\Lambda}_c^-$

➔ During 2020-2021, BESIII took new data samples at charm baryon pair threshold

➔ Two major changes in BEPCII machine:

- ❖ Max beam energy: 2.30 → 2.35 (2020) → 2.48 GeV (2021)
- ❖ Top-up injection: data taking efficiency increased by 20~30%

➔ New data samples taken during 2021-2022

- ❖ 3.9 fb^{-1} scan at 4.61, 4.63, 4.64, 4.66, 4.68, 4.7 GeV (186 days in 2020) ~ 0.66M $\Lambda_c^+\bar{\Lambda}_c^-$
- ❖ 1.93 fb^{-1} scan at 4.74, 4.75, 4.78, 4.84, 4.92, 4.95 GeV (99 days in 2021) ~ 0.21M $\Lambda_c^+\bar{\Lambda}_c^-$
  - Accessible to $\Sigma_c/\Xi_c/\Lambda_c^*$ production and decays

Pair production near threshold & tag method

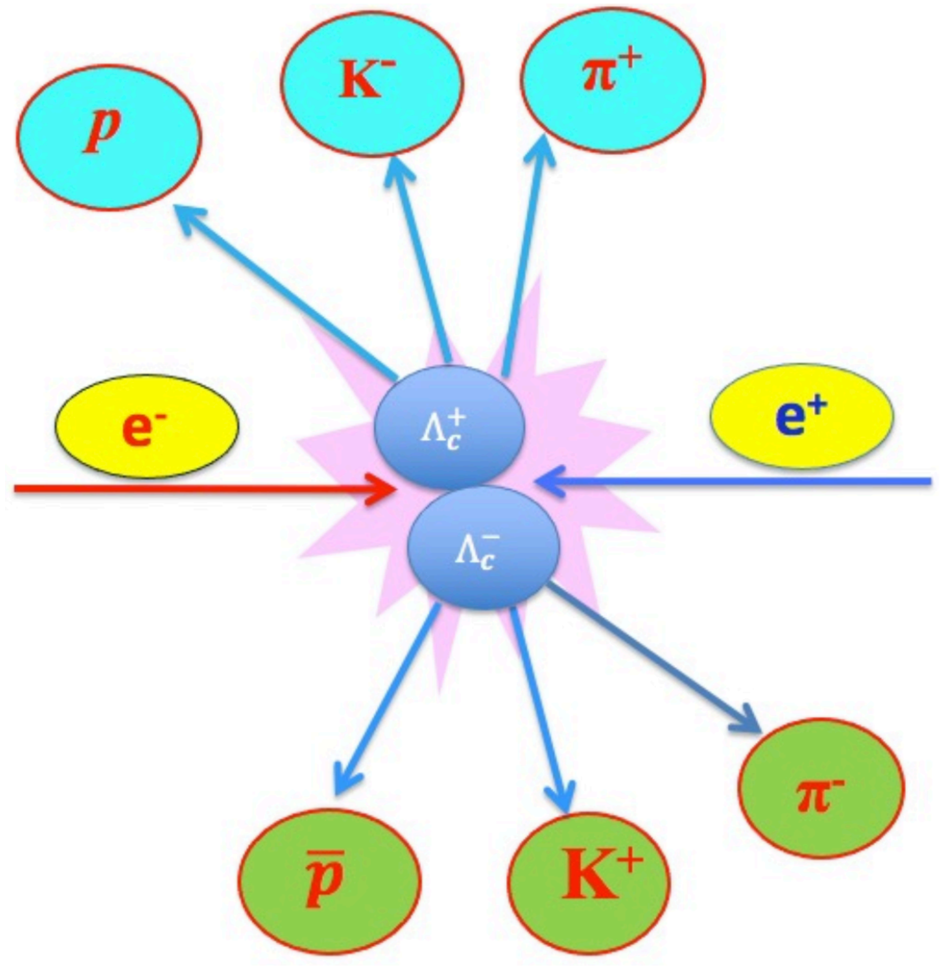
- $e^+e^- \to \gamma^* \to \Lambda_c^+\bar{\Lambda}_c^-$: production without accompanying hadrons at 4.6~4.7 GeV
- Clean backgrounds and well constrained kinematics
  - $\Delta E = E_{\Lambda_c} - E_{\text{beam}}$
  - $M_{\text{BC}} = \sqrt{E_{\text{beam}}^2/c^4 - p^2c^2}$
- **Single Tag (ST) method**: detect one of the $\Lambda_c^+\bar{\Lambda}_c^-$
  - Relative higher background with higher efficiencies
  - Full reconstruction only
- **Double Tag (DT) Method**: detect both of the $\Lambda_c^+\bar{\Lambda}_c^-$
  - Lower background with lower efficiency
  - Full or partial reconstruction (technique for missing particle: ν, n, K_L^0)
    - Reconstruct $\bar{\Lambda}_c^-$ by dominant and clean decay modes, e.g., $\bar{\Lambda}_c^- \to \bar{p}K_S^0, \bar{p}K^+\pi^-, \ldots$ with $\mathscr{B}^{\text{ST}} \cdot \varepsilon^{\text{ST}} \approx 8\,\%$
    - Search for Λ_c^+ signal decay in the recoiling side
  - Systematic in tag side are mostly cancelled

DT BF formula

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

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

$$N_{\text{DT}}^{i,j} = 2N_{\Lambda_c^+\bar{\Lambda}_c^-}^{j}\mathcal{B}_{\text{tag}}^{i}\mathcal{B}_{\text{sig}}\epsilon_{\text{DT}}^{i,j}, \qquad N_{\text{ST}} = \sum_{i,j} N_{\text{ST}}^{i,j}$$



Recent physics results

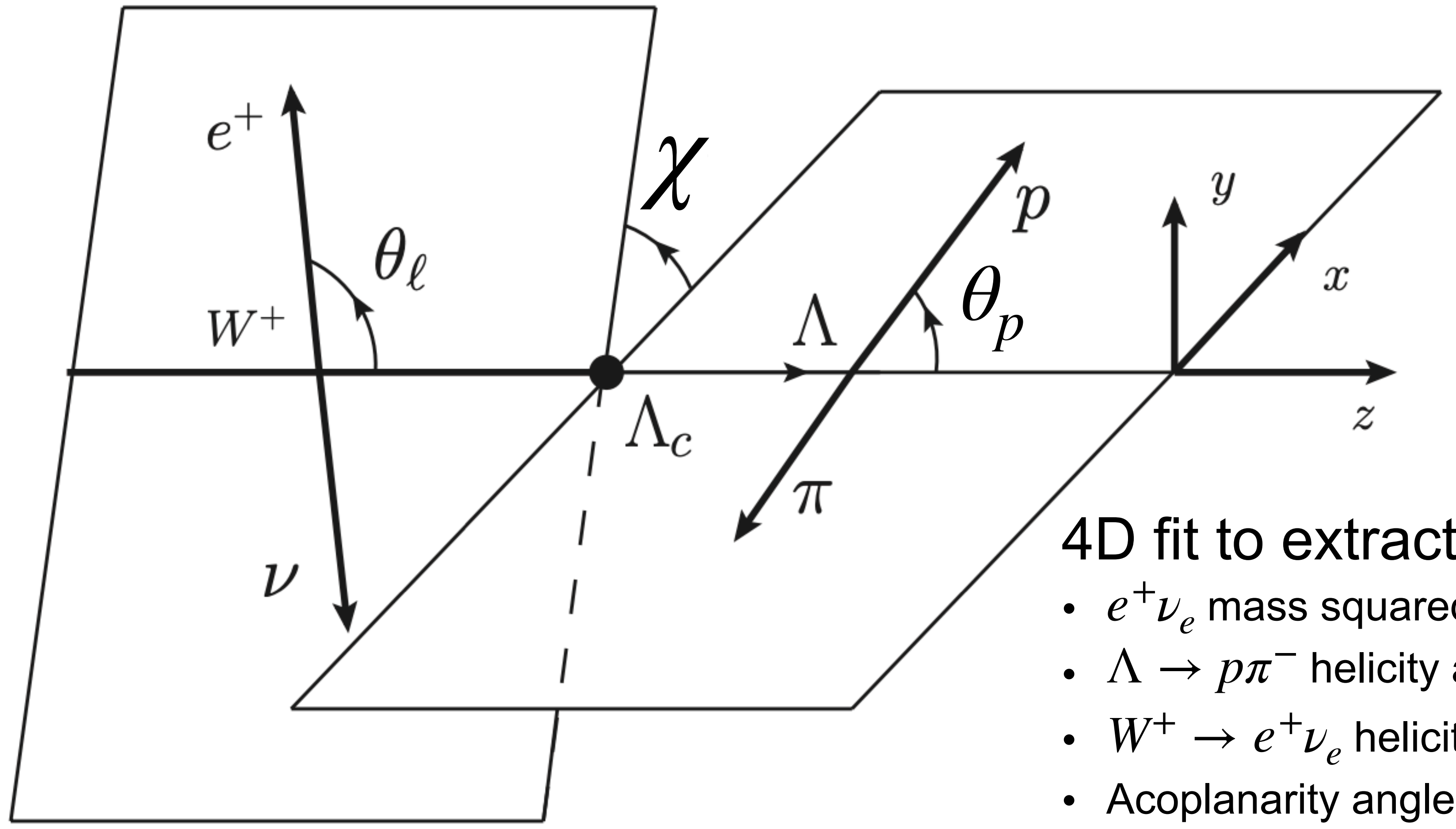
Recent studies on the Λ_c^+ measurments at BESIII

- Λ_c^+ **semi-leptonic decays**
  - $\Lambda_c^+ \to \Lambda e^+\nu_e, \Lambda\mu^+\nu_\mu$ — Phys. Rev. Lett. 129, 231803 (2022). Phys. Rev. D 108, L031105 (2023).
  - $\Lambda_c^+ \to Xe^+\nu_e$ — Phys. Rev. D 107, 052005 (2023).
  - $\Lambda_c^+ \to pK^-e^+\nu_e$ — Phys. Rev. D 106, 112010 (2022).
  - $\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e, pK_S^0\pi^-e^+\nu_e$ — Phys. Lett. B 843, 137993 (2023).
- Λ_c^+ **hadronic decays (two-body)**
  - $\Lambda_c^+ \to n\pi^+$ — Phys. Rev. Lett. 128, 142001 (2022).
  - $\Lambda_c^+ \to p\eta'$ — Phys. Rev. D 106, 072002 (2023).
  - $\Lambda_c^+ \to p\eta, p\omega$ — JHEP 11, 137 (2023).
  - $\Lambda_c^+ \to p\pi^0, p\eta$ — Phys. Rev. D 109, L091101 (2024).
  - $\Lambda_c^+ \to \Lambda K^+$ — Phys. Rev. D 106, L111101 (2022).
  - $\Lambda_c^+ \to \Sigma^0K^+, \Sigma^+K_S^0$ — Phys. Rev. D 106, 052003 (2022).
  - $\Lambda_c^+ \to \Xi^0K^+$ — Phys. Rev. Lett. 132, 031801 (2024).
- Λ_c^+ **hadronic decays (multi-body)**
  - $\Lambda_c^+ \to n\pi^+\pi^0, n\pi^+\pi^-\pi^-, nK^-\pi^+\pi^+$ — Chin. Phys. C 47, 023001 (2023).
  - $\Lambda_c^+ \to nK_S^0\pi^+, nK_S^0K^+$ — Phys. Rev. D 109, 072010 (2024).
  - $\bar{\Lambda}_c^- \to \bar{n}X$ — Phys. Rev. D 108, L031101 (2023).
  - $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ — JHEP 12, 013 (2022).
  - $\Lambda_c^+ \to \Lambda K^+\pi^0, \Lambda K^+\pi^+\pi^-$ — Phys. Rev. D 109, 032003 (2024).
  - $\Lambda_c^+ \to \Sigma^-K^+\pi^+$ — Phys. Rev. D 109, L071103 (2024).
  - $\Lambda_c^+ \to \Xi^0K^+\pi^0, nK^+\pi^0, \Sigma^0K^+\pi^0, \Lambda K^+\pi^0$ — Phys. Rev. D 109, 052001 (2024).

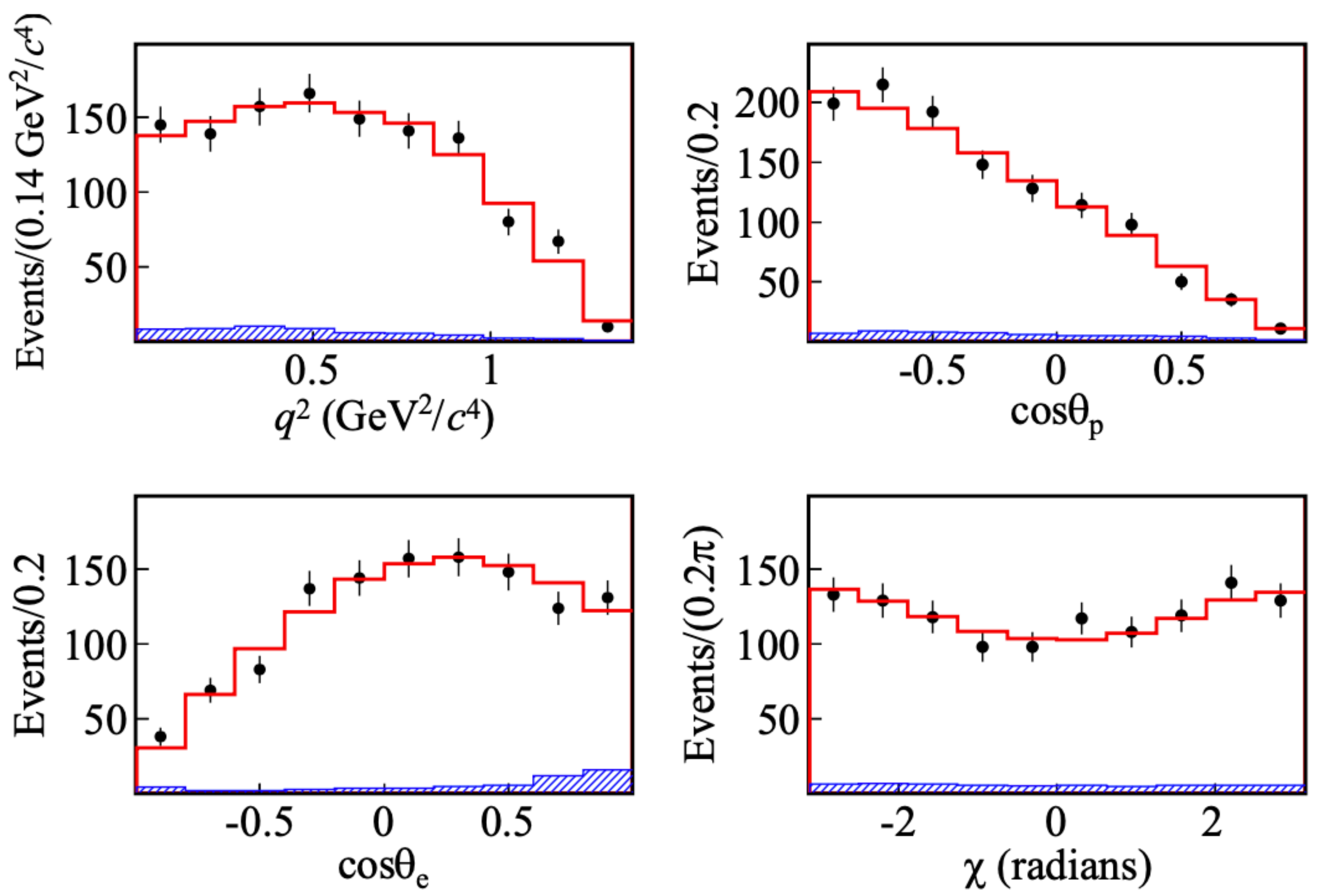
Decay dynamics of $\Lambda_c^+ \to \Lambda e^+ \nu_e$

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

Definition of the polar and the azimuthal angles



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



Differential decay width

Helicity amplitudes:

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

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

Neglect lepton mass term

Parameterized by "***Weinberg form factor***"

$$H^V_{\frac{1}{2}1} = \sqrt{2Q_-}[F^V_1(q^2) + \frac{(M_{\Lambda_c^+}+M_\Lambda)}{M_{\Lambda_c^+}}F^V_2(q^2)],$$
$$H^A_{\frac{1}{2}1} = \sqrt{2Q_+}[F^A_1(q^2) - \frac{(M_{\Lambda_c^+}-M_\Lambda)}{M_{\Lambda_c^+}}F^A_2(q^2)],$$
$$H^V_{\frac{1}{2}0} = \sqrt{\frac{Q_-}{q^2}}[(M_{\Lambda_c^+}+M_\Lambda)F^V_1(q^2) + \frac{q^2}{M_{\Lambda_c^+}}F^V_2(q^2)],$$
$$H^A_{\frac{1}{2}0} = \sqrt{\frac{Q_+}{q^2}}[(M_{\Lambda_c^+}-M_\Lambda)F^A_1(q^2) - \frac{q^2}{M_{\Lambda_c^+}}F^A_2(q^2)].$$

$$F^V_1(q^2) = \frac{1}{(M_{\Lambda_c^+}+M_\Lambda)^2 - q^2}[f_+(q^2)(M_{\Lambda_c^+}+M_\Lambda)^2 - f_\perp(q^2)\cdot q^2],$$
$$F^V_2(q^2) = \frac{M_{\Lambda_c^+}\cdot(M_{\Lambda_c^+}+M_\Lambda)}{(M_{\Lambda_c^+}+M_\Lambda)^2 - q^2}[f_\perp(q^2) - f_+(q^2)],$$
$$F^A_1(q^2) = \frac{1}{(M_{\Lambda_c^+}-M_\Lambda)^2 - q^2}[g_+(q^2)(M_{\Lambda_c^+}-M_\Lambda)^2 - g_\perp(q^2)\cdot q^2],$$
$$F^A_2(q^2) = \frac{M_{\Lambda_c^+}\cdot(M_{\Lambda_c^+}-M_\Lambda)}{(M_{\Lambda_c^+}-M_\Lambda)^2 - q^2}[g_+(q^2) - g_\perp(q^2)].$$

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

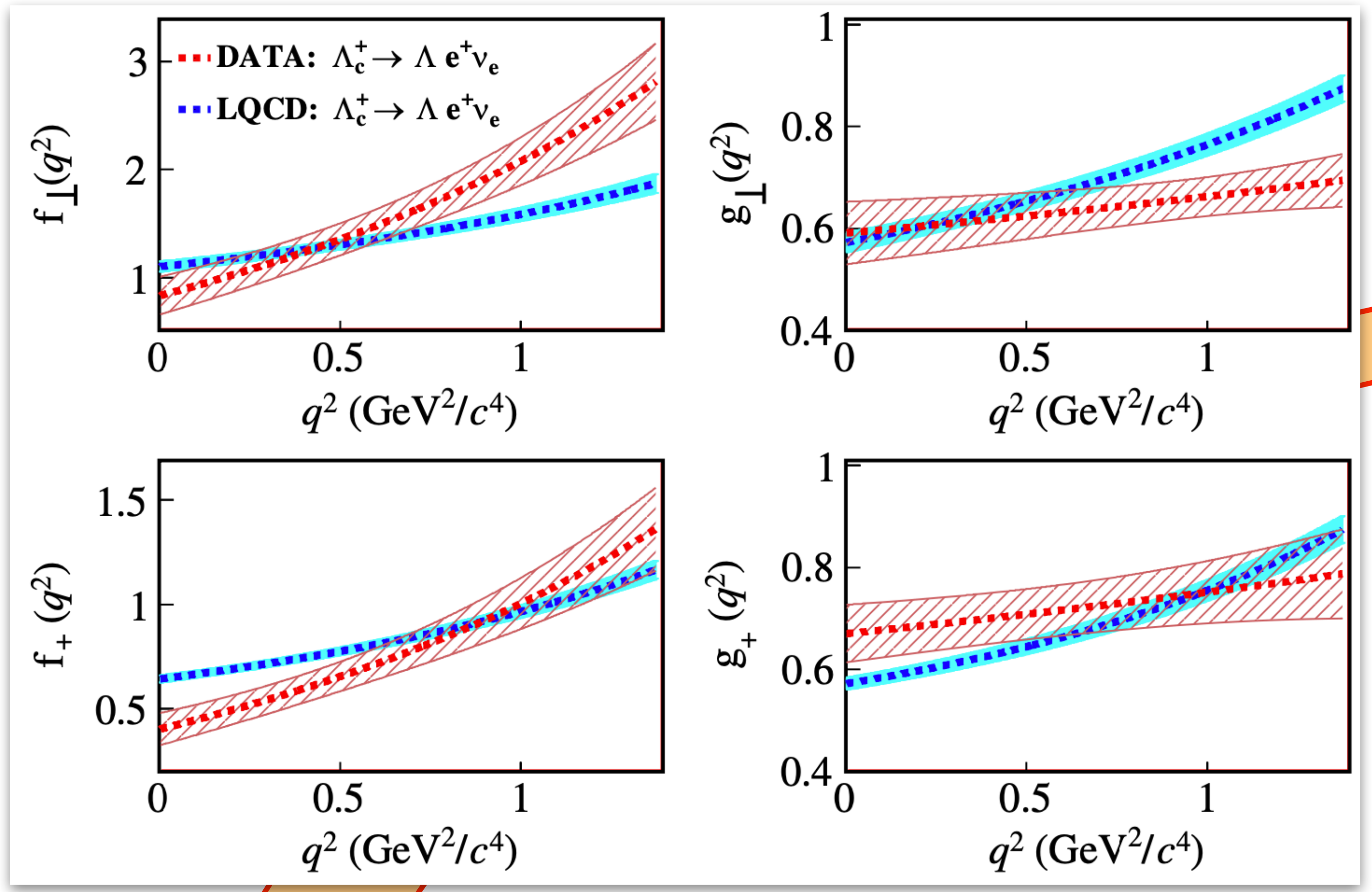
Parameterized by "***Helicity form factor***"

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

Following LQCD

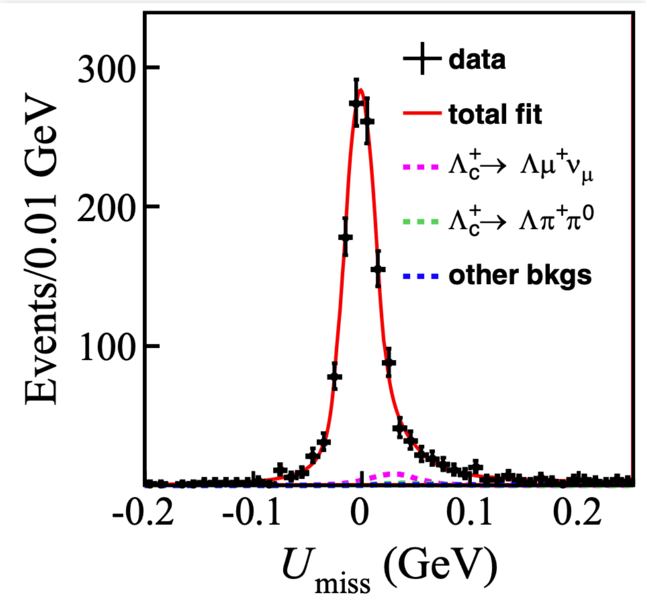
Indirect test of SM in $\Lambda_c^+ \to \Lambda e^+ \nu_e$

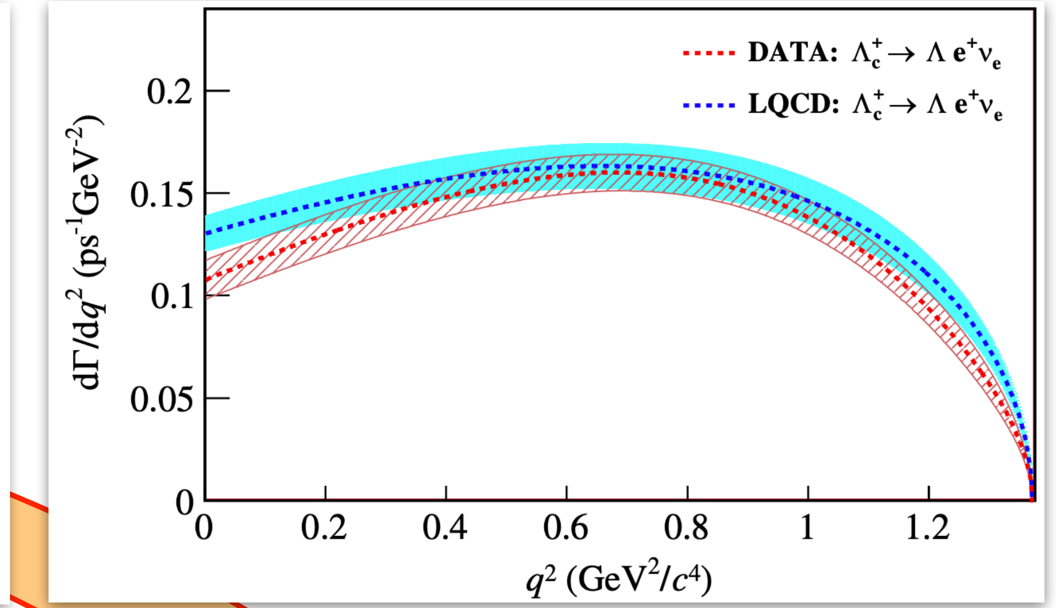
Steeper slope Gentler slope



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

First direct comparison to LQCD





Branching Fraction

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

Precision improved

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

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

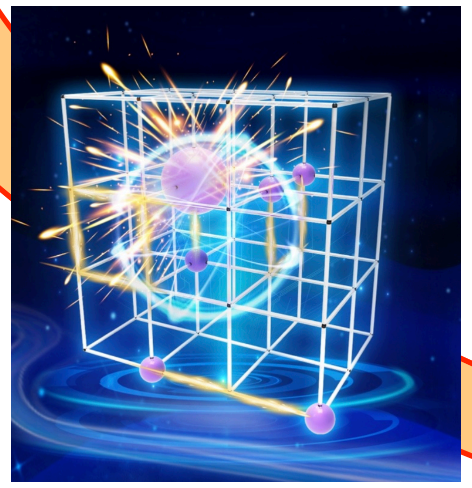
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{cs}|^2}{192\pi^3 M_{\Lambda_c}^2} \times P q^2 \times \left[|H_{\frac{1}{2}1}|^2 + |H_{-\frac{1}{2}-1}|^2 + |H_{\frac{1}{2}0}|^2 + |H_{-\frac{1}{2}0}|^2\right].$$

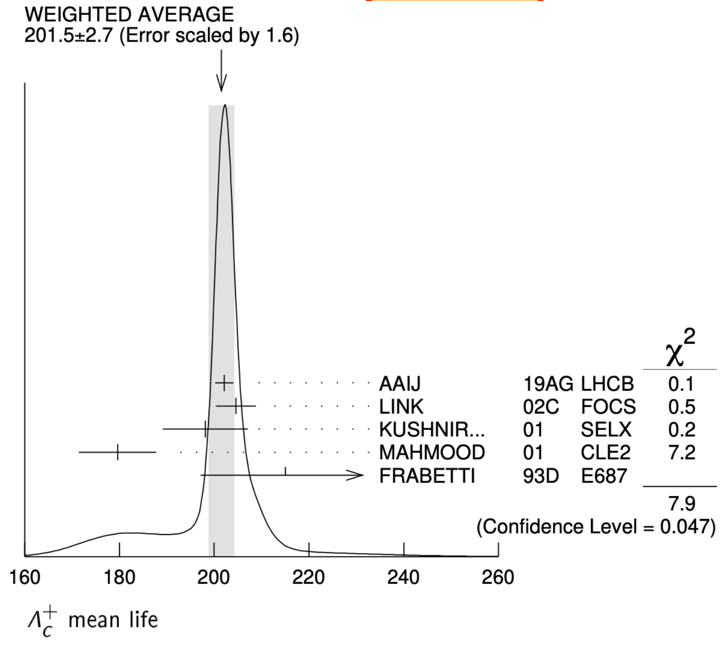
Form Factor

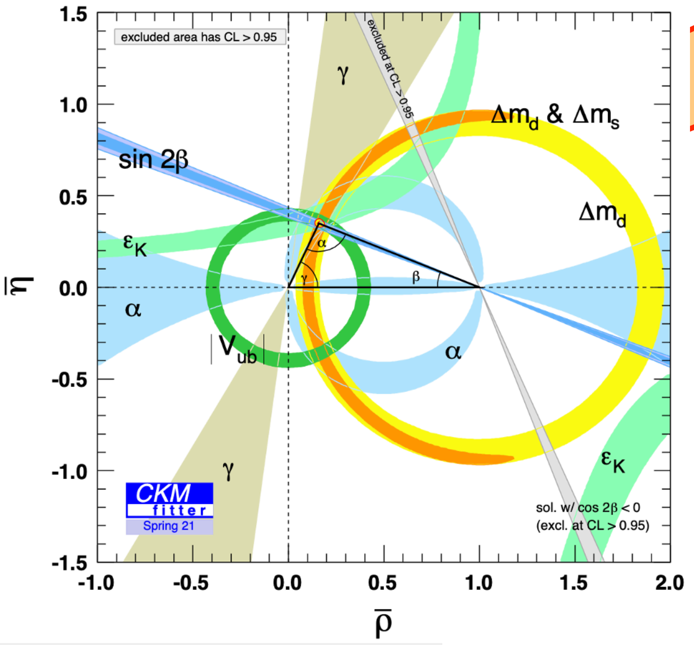
Calculated from LQCD and models

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

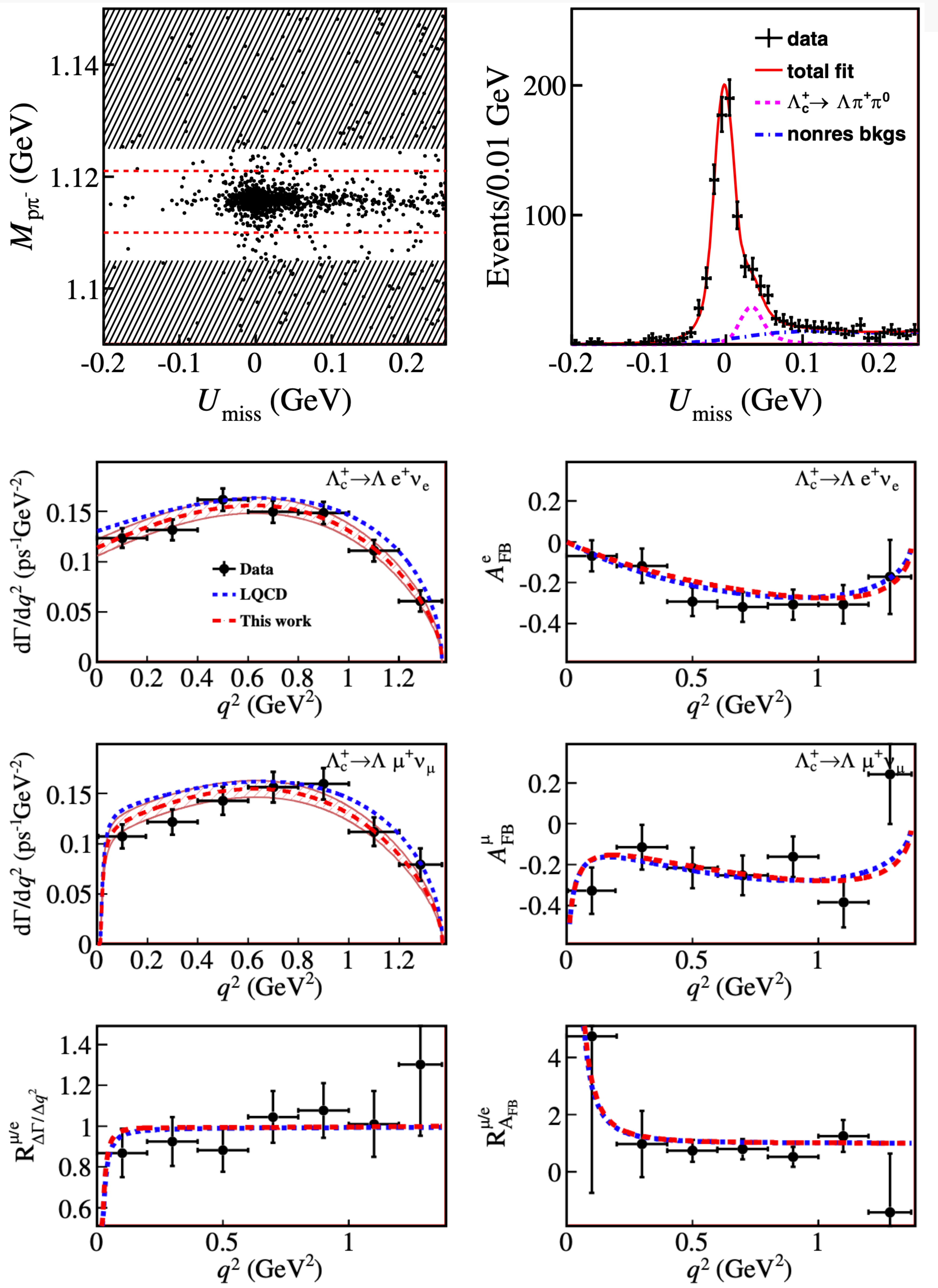
$|V_{cs}| = 0.936 \pm 0.017_{\mathcal{B}} \pm 0.024_{\rm LQCD} \pm 0.007_{\tau_{\Lambda_c}}$

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

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

Phys. Rev. D 108, L031105 (2023).

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



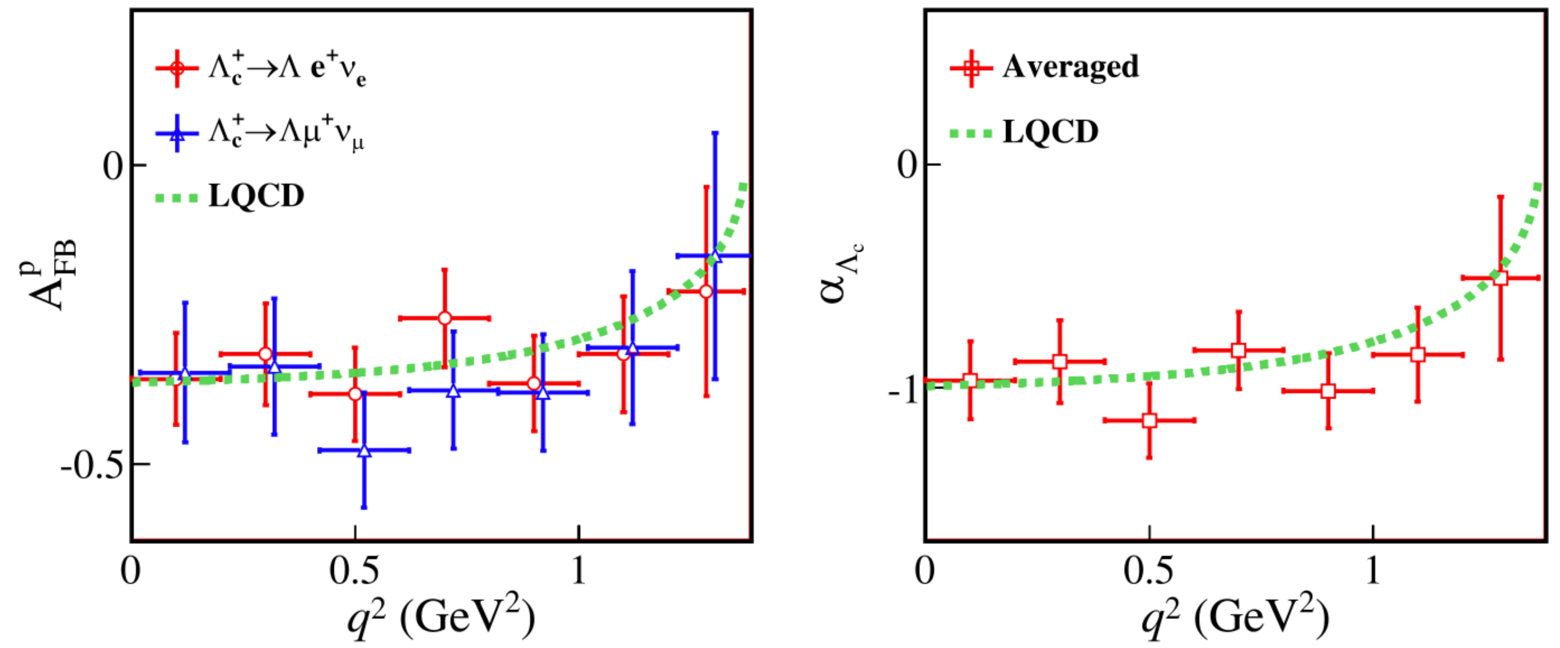
Decay asymmetry and FF measurement for $\Lambda_c^+ \to \Lambda l^+ \nu_l$

- Decay asymmetry α_{Λ_c} vs Forward-backward asymmetry $A_{\rm FB}^p$ $\quad \alpha_{\Lambda_c}(q^2) = \frac{2}{\alpha_\Lambda}[A_{\rm FB}^p(q^2)]$
  - 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

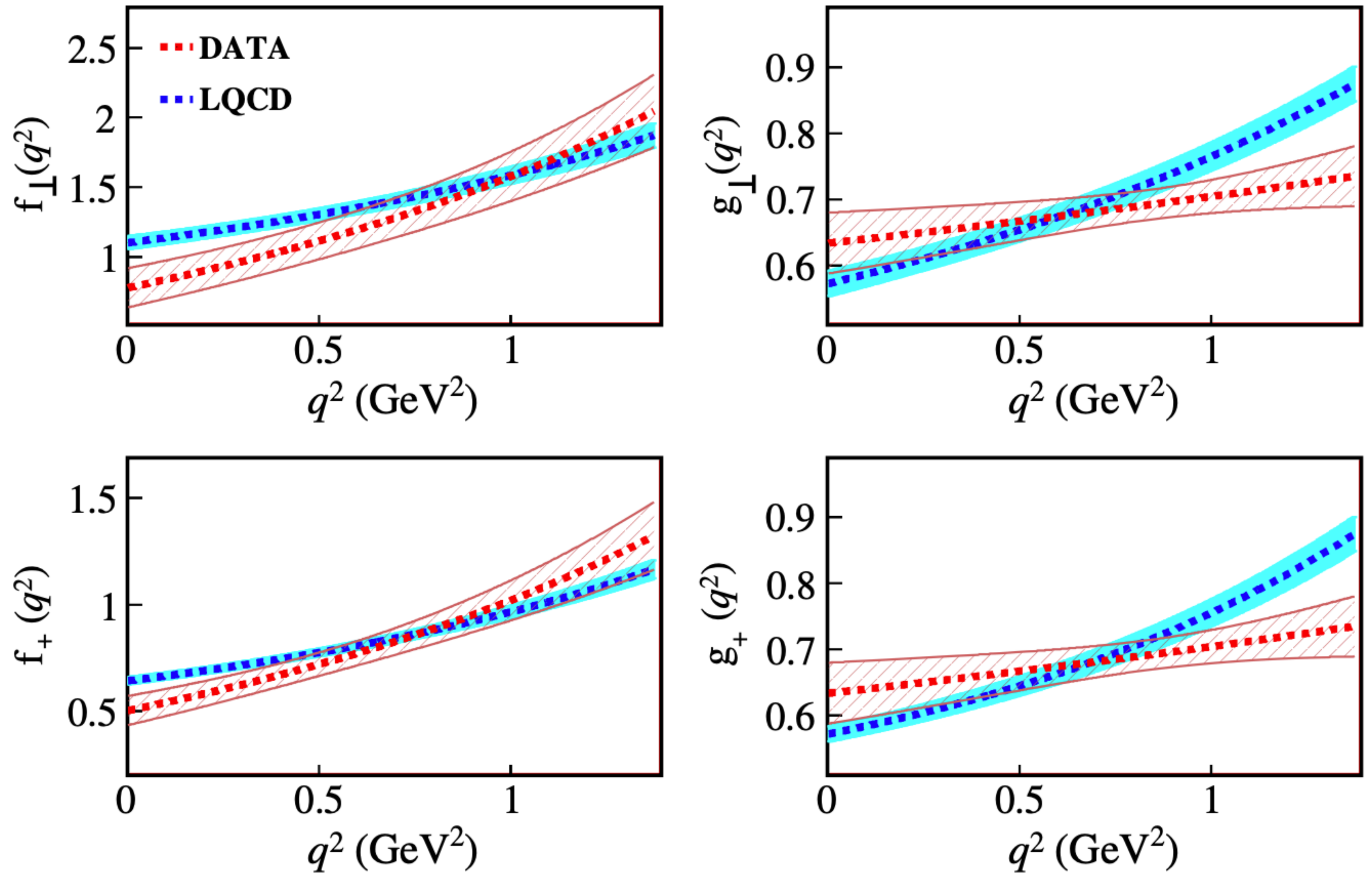
$\langle A_{\rm FB}^p \rangle = -0.33 \pm 0.03_{\rm stat.} \pm 0.01_{\rm syst.}$ Only for $\Lambda_c^+ \to \Lambda e^+ \nu_e$

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

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



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

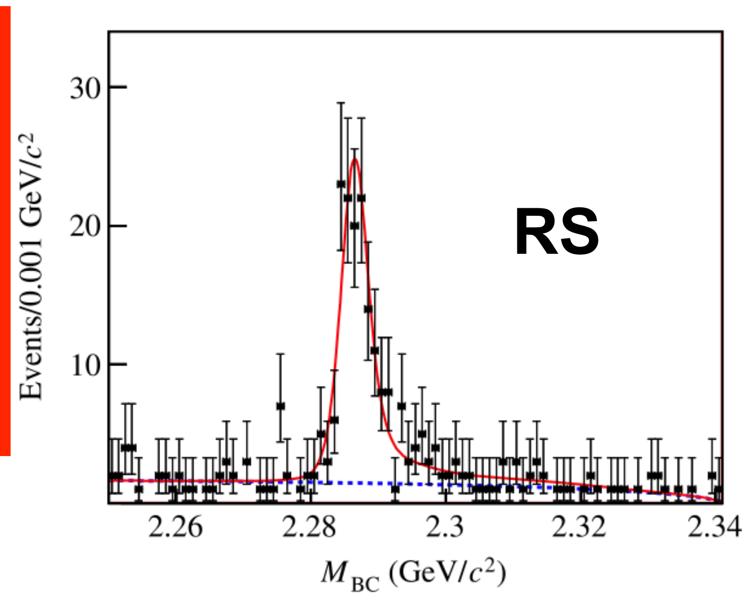


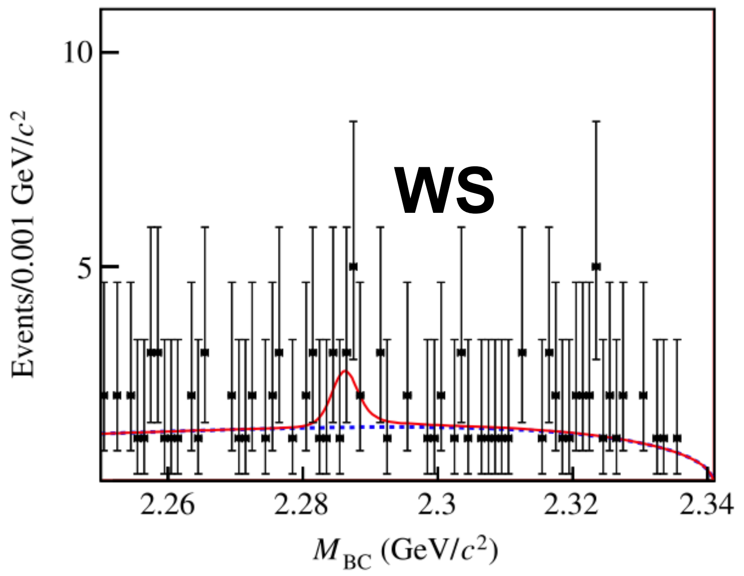
Measurement of $\Lambda_c^+ \to Xe^+\nu_e$

Phys. Rev. D 107, 052005 (2023).

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

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

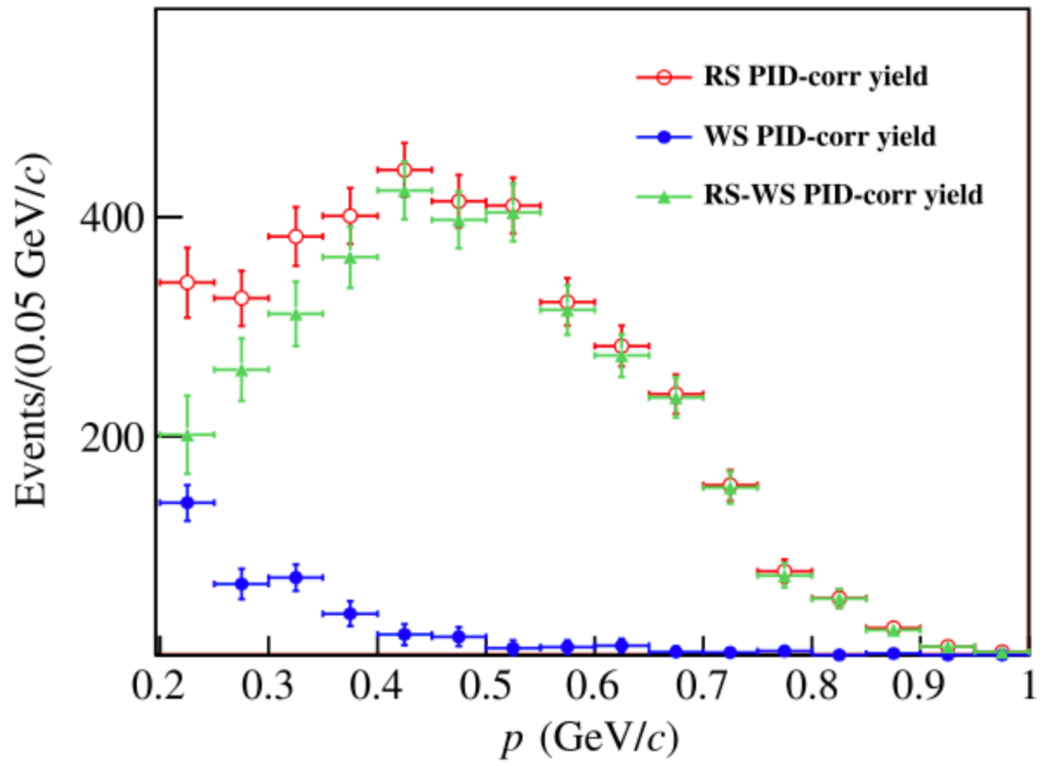




$$\begin{bmatrix} N_e^{\rm obs} \\ N_\pi^{\rm obs} \\ N_K^{\rm obs} \\ N_p^{\rm obs} \end{bmatrix} = \begin{bmatrix} P_{e\to e} & P_{\pi\to e} & P_{K\to e} & P_{p\to e} \\ P_{e\to\pi} & P_{\pi\to\pi} & P_{K\to\pi} & P_{p\to\pi} \\ P_{e\to K} & P_{\pi\to K} & P_{K\to K} & P_{p\to K} \\ P_{e\to p} & P_{\pi\to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

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

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

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

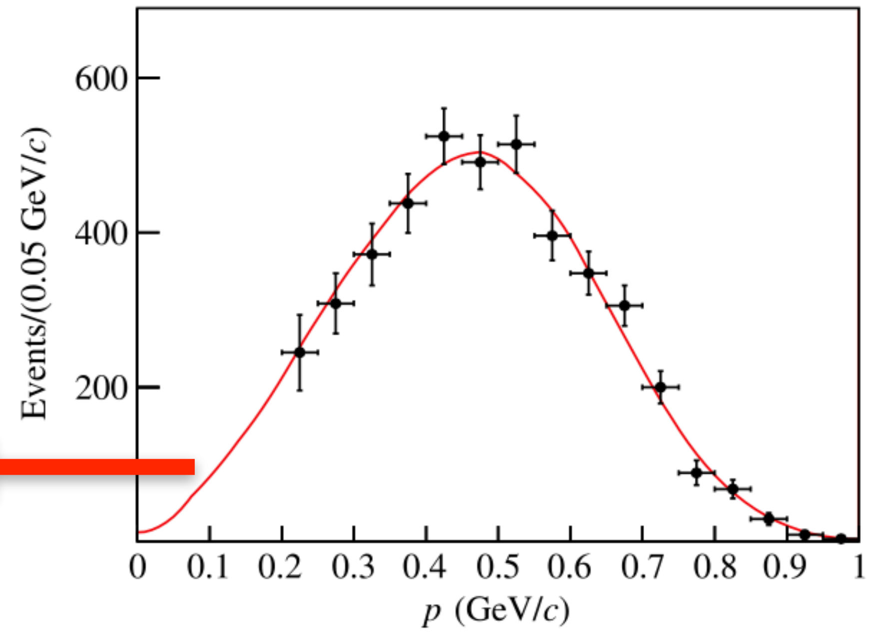
Compared with HQE(1.2), EQM(1.67)

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

- 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



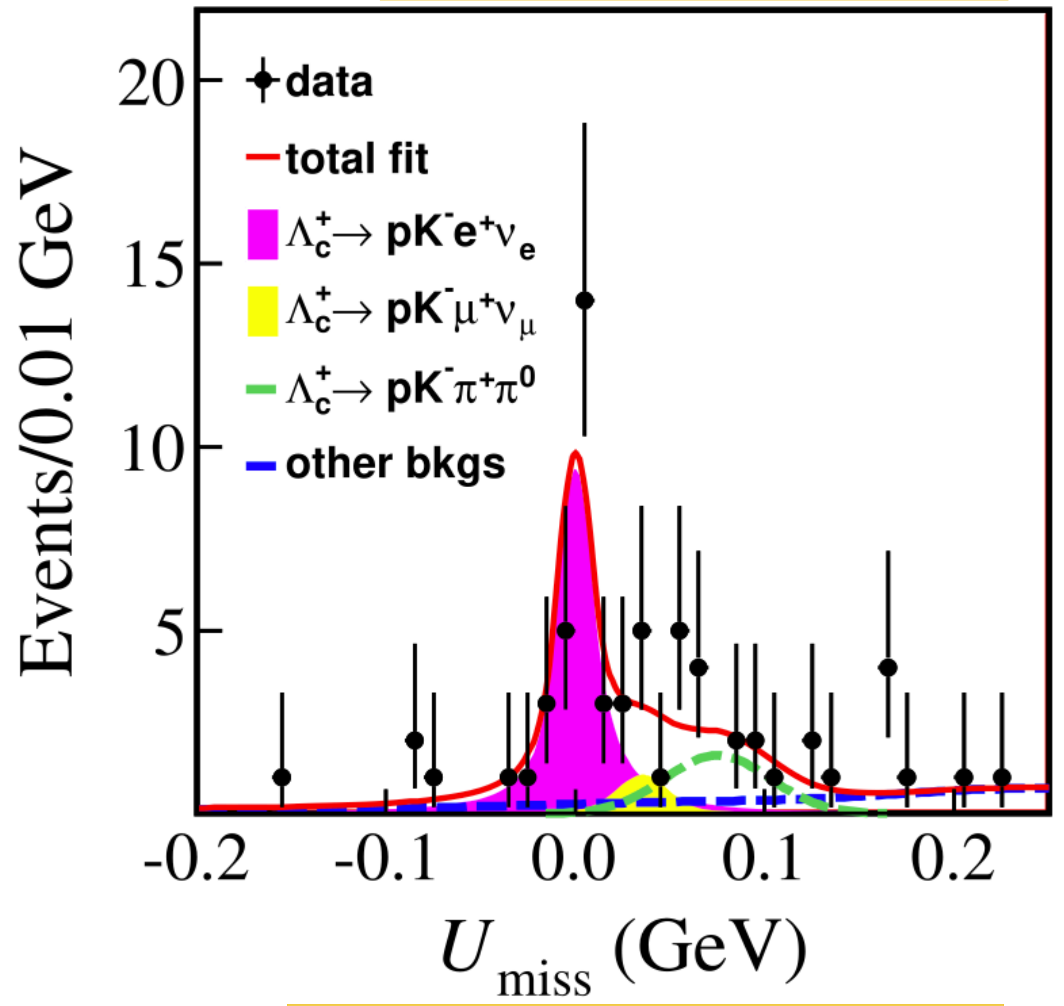
Study of $\Lambda_c^+ \to pK^-e^+\nu_e$ & search for $\Lambda(1405)/\Lambda(1520)$

Phys. Rev. D 106, 112010 (2022).

- $\Lambda_c^+ \to pK^-e^+\nu_e$ is firstly observed with significance of 8.2σ!
  - $\mathscr{B}(\Lambda_c^+ \to pK^-e^+\nu_e) = (0.82 \pm 0.15 \pm 0.06) \times 10^{-3}$
- The only observed SL channel beyond $\Lambda_c^+ \to \Lambda l^+\nu_l$
  - $\frac{\mathscr{B}(\Lambda_c^+ \to pK^-e^+\nu_e)}{\mathscr{B}(\Lambda_c^+ \to Xe^+\nu_e)} = (2.1 \pm 0.4_{\rm stat.} \pm 0.1_{\rm syst.}) \times 10^{-3}$

Λ_c^+ SL is not saturated by $\Lambda l^+\nu_l$!

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



- Evidence of $\Lambda_c^+ \to \Lambda(1520)e^+\nu_e$ (3.3σ) & $\Lambda_c^+ \to \Lambda(1405)e^+\nu_e$ (3.2σ)
  - $\mathscr{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e) = (1.02 \pm 0.52_{\rm stat.} \pm 0.11_{\rm syst.}) \times 10^{-3}$
  - $\mathscr{B}(\Lambda_c^+ \to \Lambda(1405)[\to pK^-]e^+\nu_e) = (0.42 \pm 0.19_{\rm stat.} \pm 0.04_{\rm syst.}) \times 10^{-3}$
- Comparisons of $\mathscr{B}(\Lambda_c^+ \to \Lambda(1520)/\Lambda(1405)e^+\nu_e)$ with predicted values from theoretical models and LQCD
  - Consistent within two standard deviations

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

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

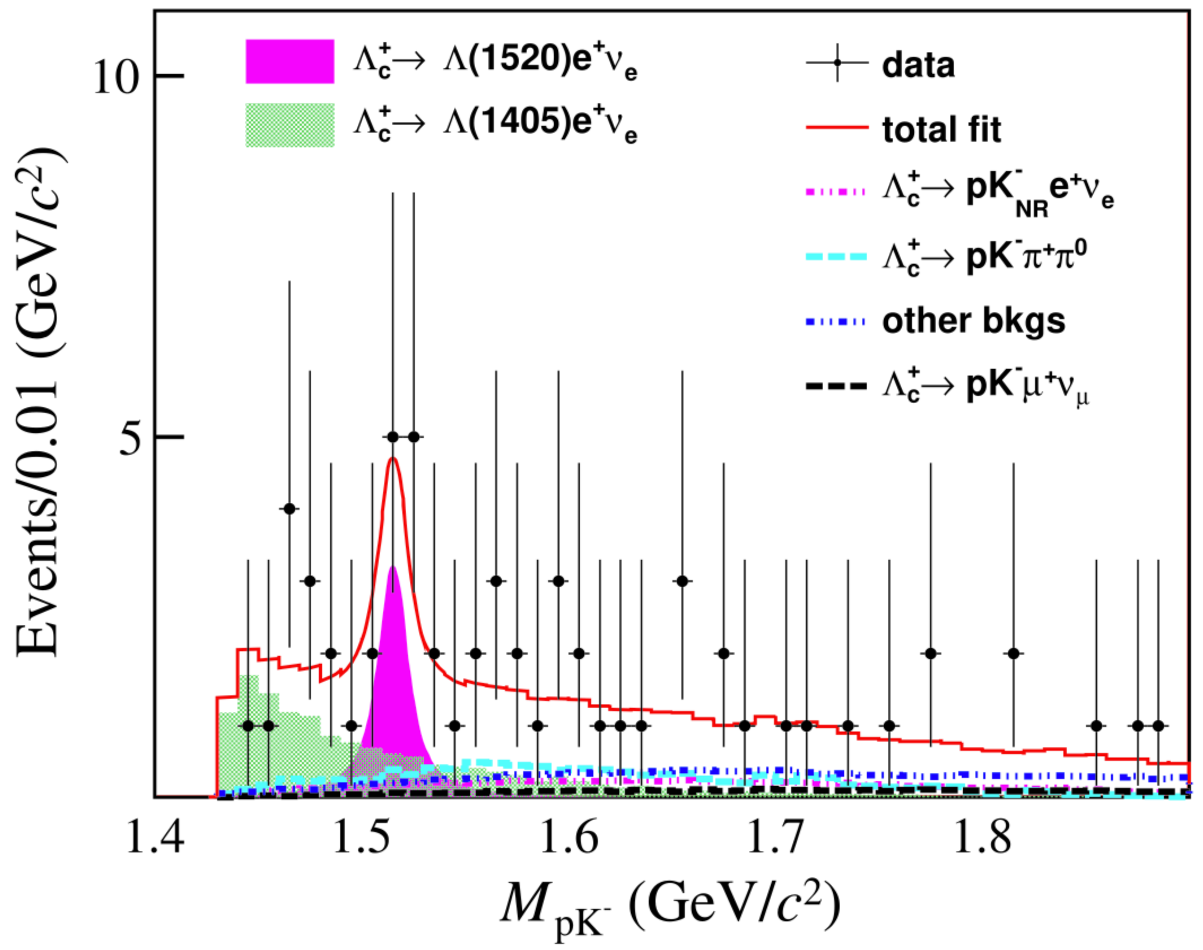


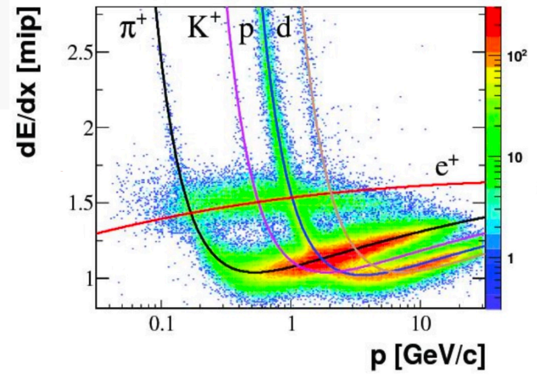
TABLE I. Comparison of $\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)/\Lambda(1405)e^+\nu_e)$ [in $\times 10^{-3}$] between theoretical calculations and this measurement. The BF of $\Lambda(1405) \to pK^-$ is unknown [2].

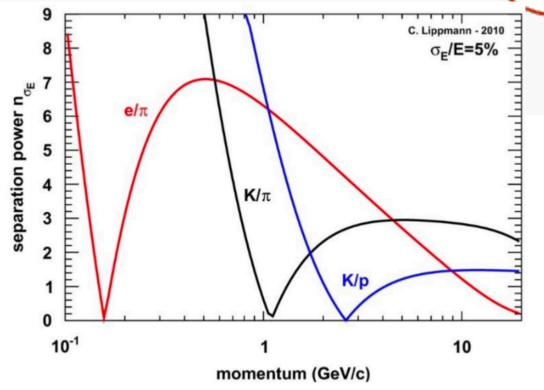
	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e)$	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1405)e^+\nu_e)$
Constituent quark model [8]	1.01	3.04
Molecular state [9]	...	0.02
Nonrelativistic quark model [10]	0.60	2.43
Lattice QCD [12,13]	0.512 ± 0.082	...
Measurement	$1.02 \pm 0.52 \pm 0.11$	$\frac{0.42 \pm 0.19 \pm 0.04}{\mathcal{B}(\Lambda(1405) \to pK^-)}$

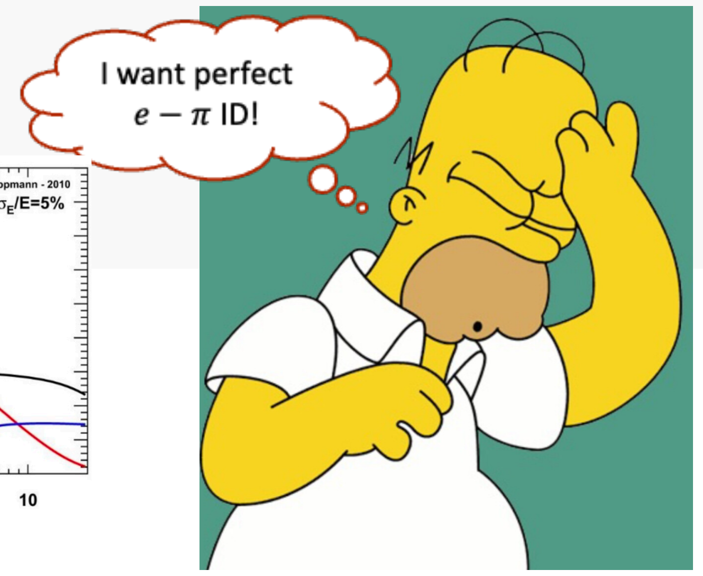
Prospect:
1. Amplitude analysis of pK^- mass spectrum to study Λ^*
2. Extraction of $\Lambda_c^+ \to \Lambda(1520)$ FF

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

Phys. Lett. B 843, 137993 (2023).



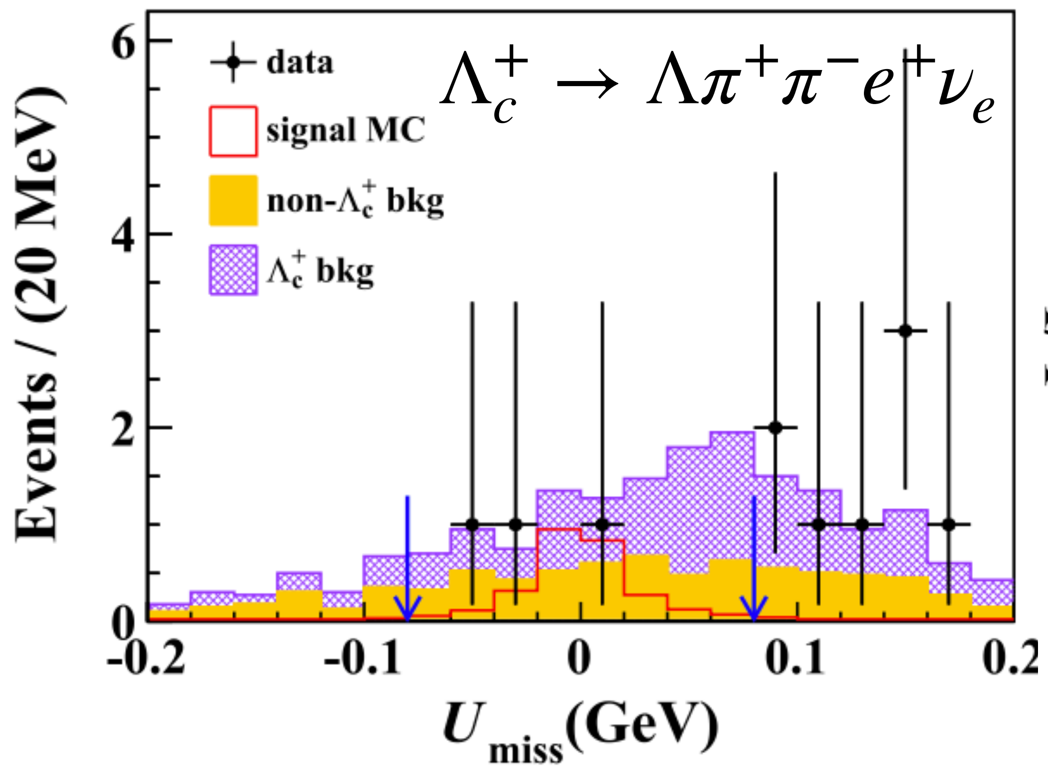


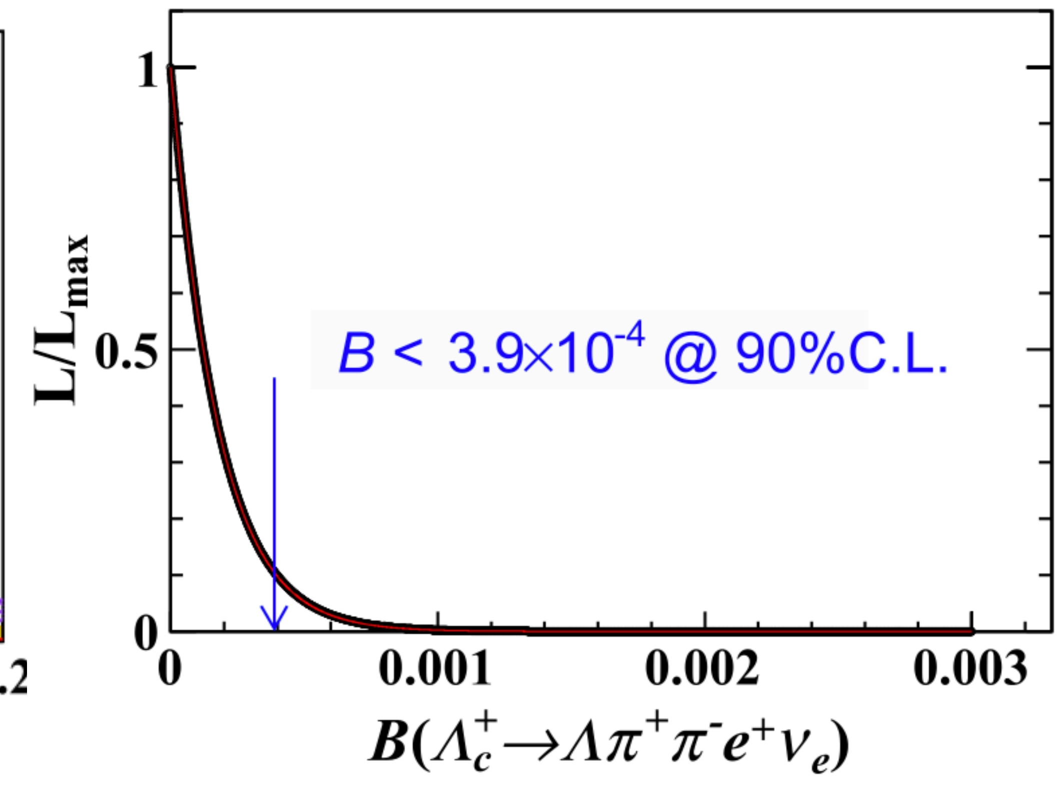


- ➔ Search for $\Lambda_c^+ \to \Lambda^* e^+\nu_e$: $\Lambda\pi^+\pi^-$ and $pK_S^0\pi^-$ are used to tag Λ^*
  - ❖ $\mathscr{B}(\Lambda(1520) \to \Lambda\pi^+\pi^-) = (10 \pm 1)\,\%$
  - ❖ Higher excited Λ^* states may decay to $pK^*(892)^-$, $K^*(892)^- \to K_S^0\pi^-$

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

- ➔ No significant signal is observed, and hence the ULs are set
  - ❖ $\mathscr{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^- e^+\nu_e) < 3.9 \times 10^{-3}\,@\,90\,\%\,\mathrm{CL}$
  - ❖ $\mathscr{B}(\Lambda_c^+ \to pK_S^0\pi^- e^+\nu_e) < 3.3 \times 10^{-3}\,@\,90\,\%\,\mathrm{CL}$

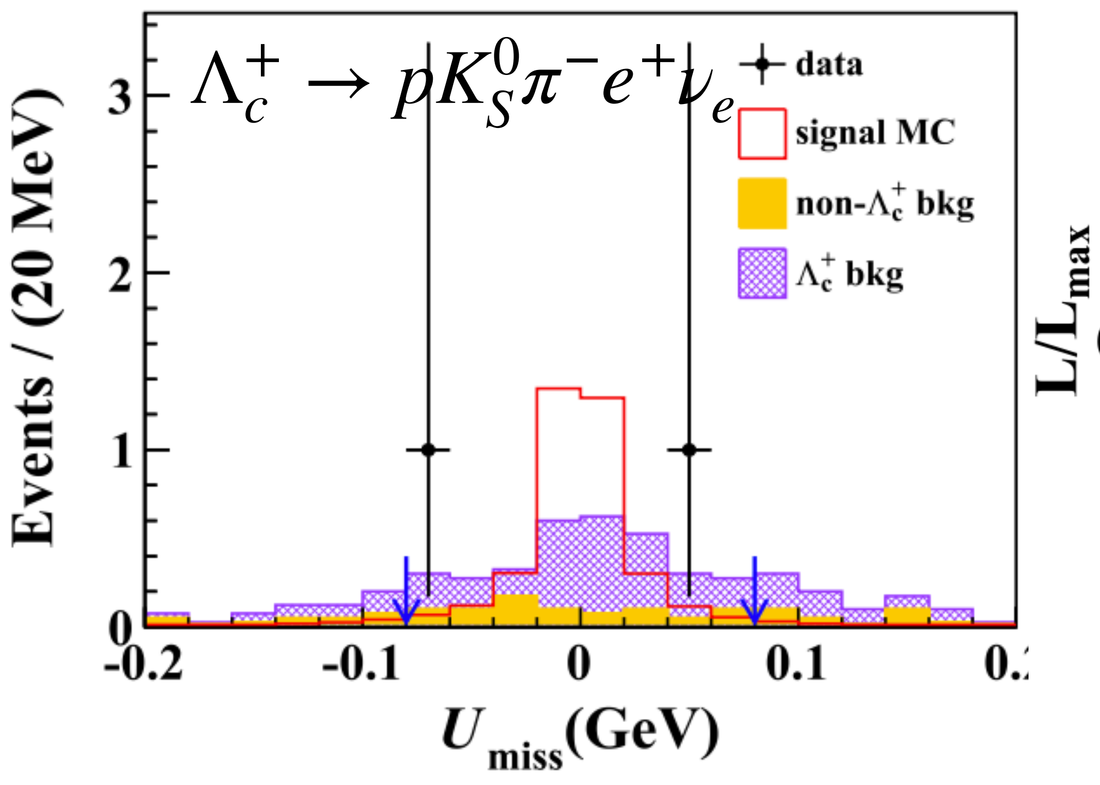


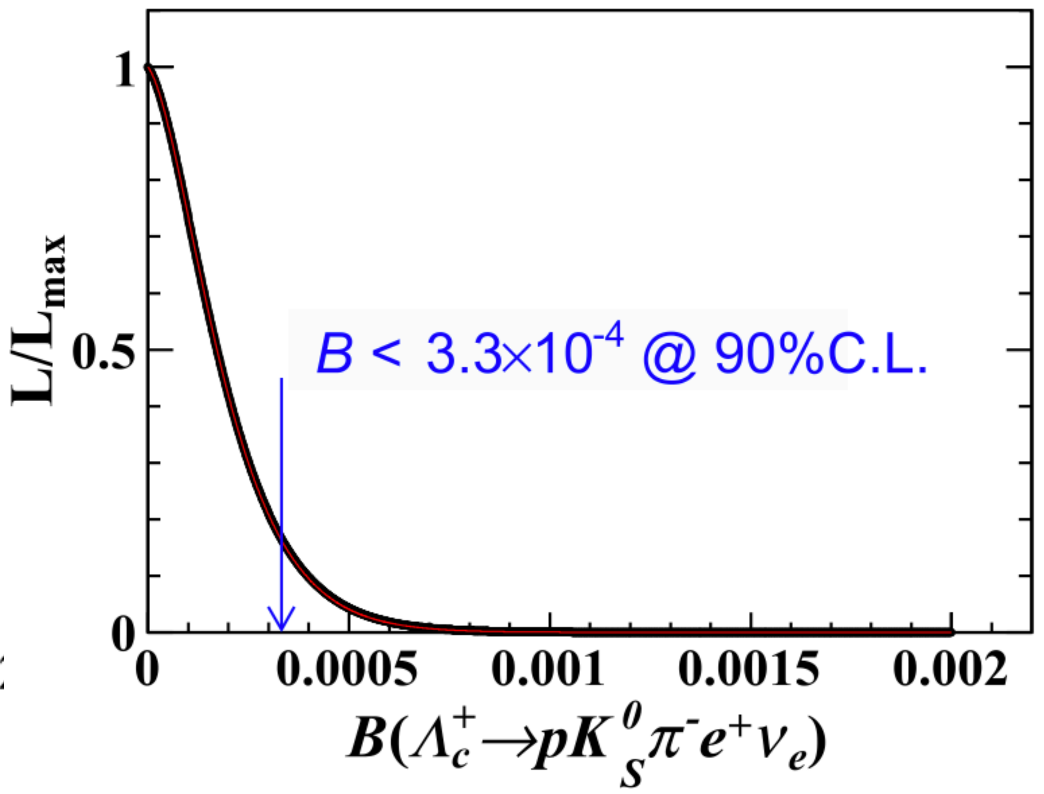


- ➔ Assuming that all the $\Lambda\pi^+\pi^-$ combinations come from Λ^*,
  $\mathscr{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e) < 4.3 \times 10^{-3}\,@\,90\,\%\,\mathrm{CL}$
  $\mathscr{B}(\Lambda_c^+ \to \Lambda(1600)e^+\nu_e) < 9.0 \times 10^{-3}\,@\,90\,\%\,\mathrm{CL}$

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}	--	--



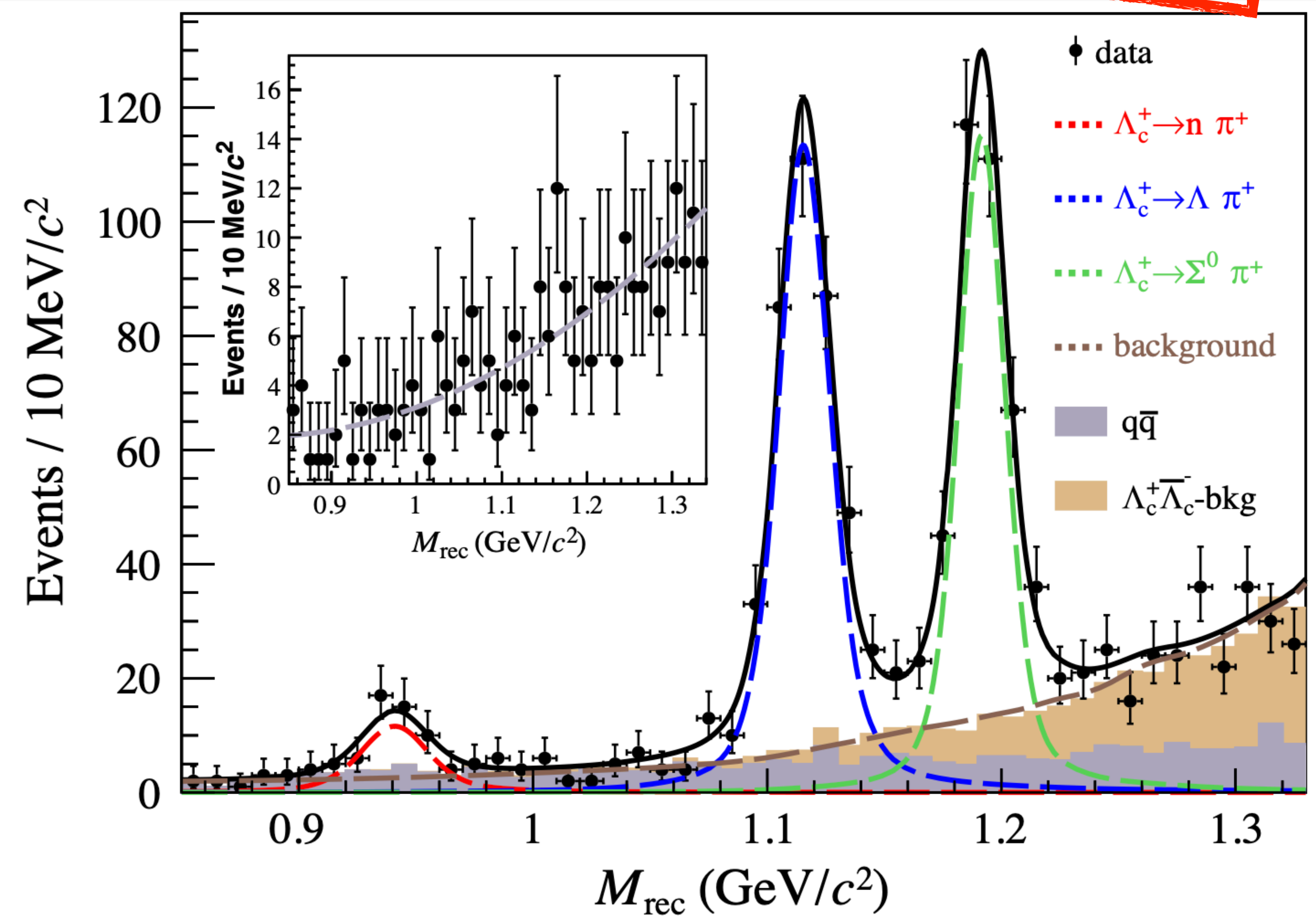


Limited sensitivity to identify different theoretical calculations

First observation of $\Lambda_c^+ \to n\pi^+$

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

Highlight



- ➔ First observation of SCS decay $\Lambda_c^+ \to n\pi^+$ (7.3σ)
- ➔ BF is measured to be $\mathscr{B}(\Lambda_c^+ \to n\pi^+) = (6.6 \pm 1.2_{\text{stat.}} \pm 0.4_{\text{syst.}}) \times 10^{-4}$
  - ❖ Consistent with SU(3) flavor symmetry prediction[1]
  - ❖ Twice larger than the dynamical calculation based on pole model and CA[2]

[1] PLB 790, 225 (2019)
[2] PRD 97, 074028 (2018)

- ➔ Byproduct:
  - ❖ $\mathscr{B}(\Lambda_c^+ \to \Lambda\pi^+) = (1.31 \pm 0.08_{\text{stat.}} \pm 0.05_{\text{syst.}}) \times 10^{-2}$
  - ❖ $\mathscr{B}(\Lambda_c^+ \to \Sigma^0\pi^+) = (1.22 \pm 0.08_{\text{stat.}} \pm 0.07_{\text{syst.}}) \times 10^{-2}$

  } Consistent with previous BESIII results

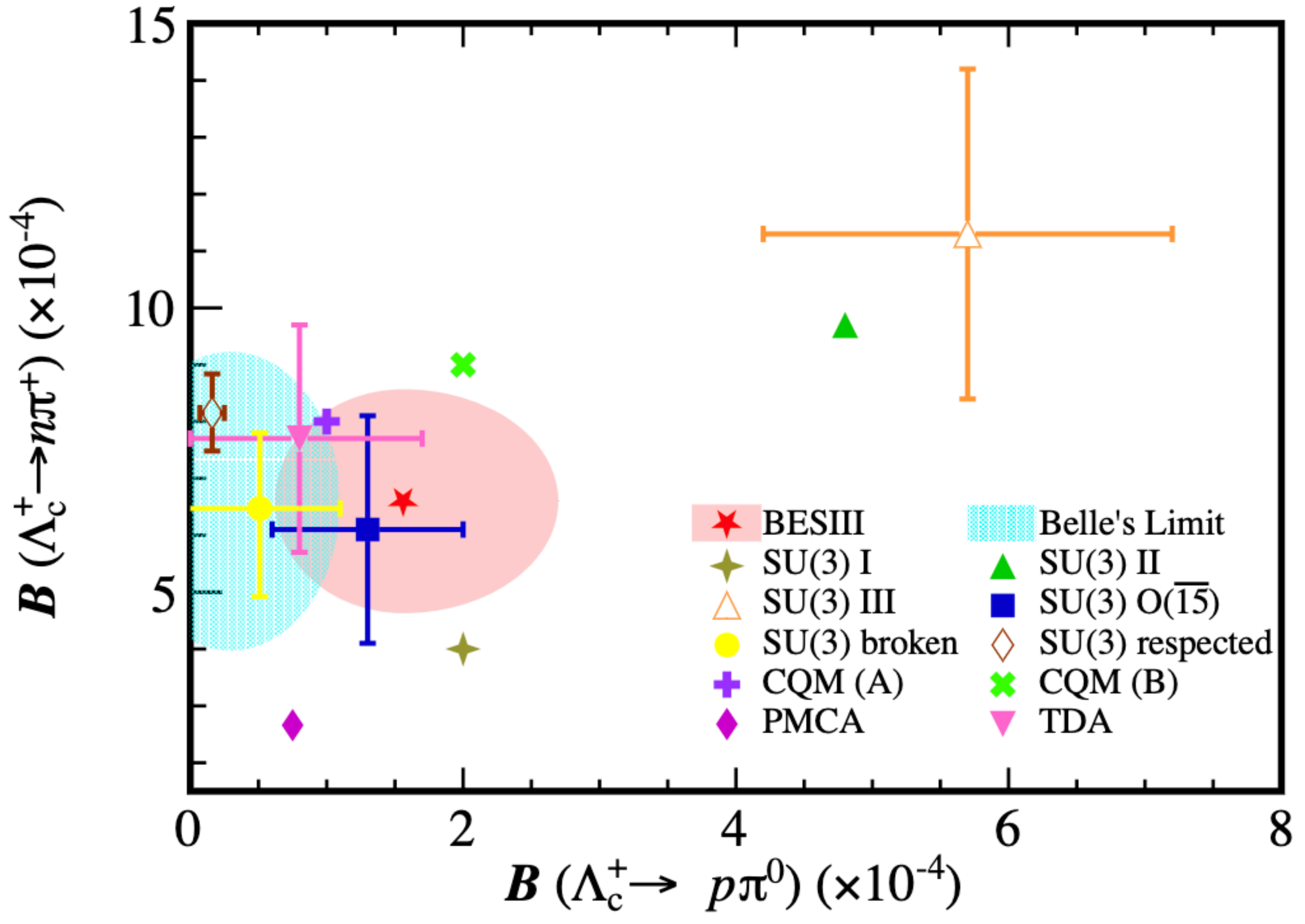
- ➔ $R = \dfrac{\mathscr{B}(\Lambda_c^+ \to n\pi^+)}{\mathscr{B}(\Lambda_c^+ \to p\pi^0)} > 7.2\,@\,90\,\%\,\text{CL}$ with input from Belle $\mathscr{B}(\Lambda_c^+ \to p\pi^0) < 8.0 \times 10^{-5}\,@\,90\,\%\,\text{CL}$
  - ❖ Disagree with $SU(3)$ flavor symmetry and dynamical calculation[3-12] while in consistent with topological-diagram approach[13-14]

Need more measurements of $\Lambda_c^+ \to p\pi^0$!

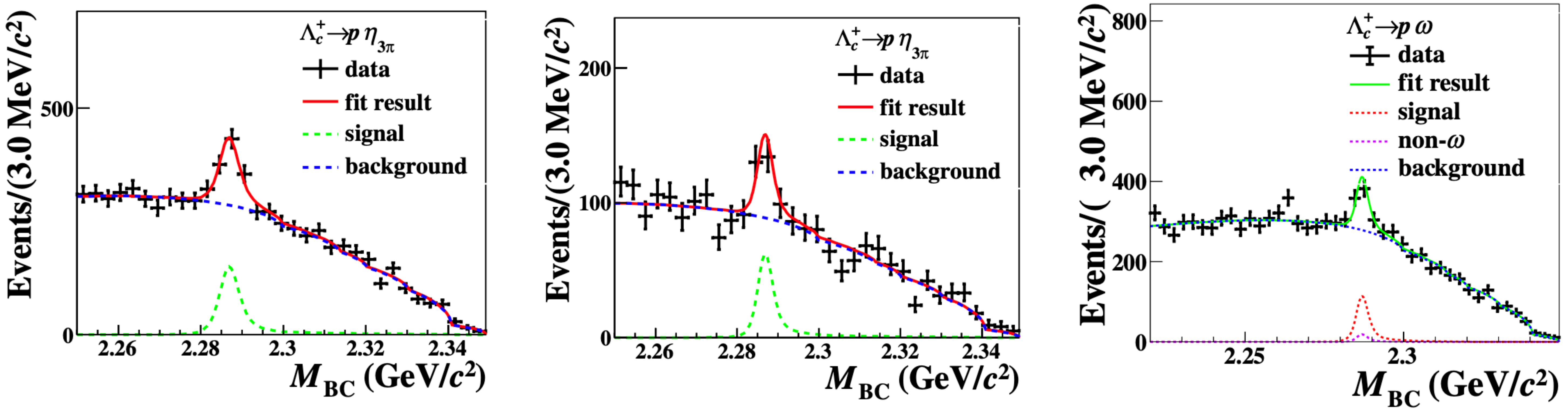
[3] Phys. Rev. D 49, 3417 (1994).
[4] Commun. Theor. Phys. 40, 563 (2003).
[5] Phys. Rev. D 97, 074028 (2018).
[6] Phys. Rev. D 101, 014011 (2020).
[7] Phys. Rev. D 55, 7067 (1997).
[8] Phys. Rev. D 93, 056008 (2016).
[9] Phys. Rev. D 97, 073006 (2018).
[10] Phys. Lett. B 790, 225 (2019).
[11] Phys. Lett. B 794, 19 (2019).
[12] Phys. Rev. D 108, 053004 (2023).
[13] JHEP 02 (2020) 165.
[14] JHEP 09 (2022) 035.

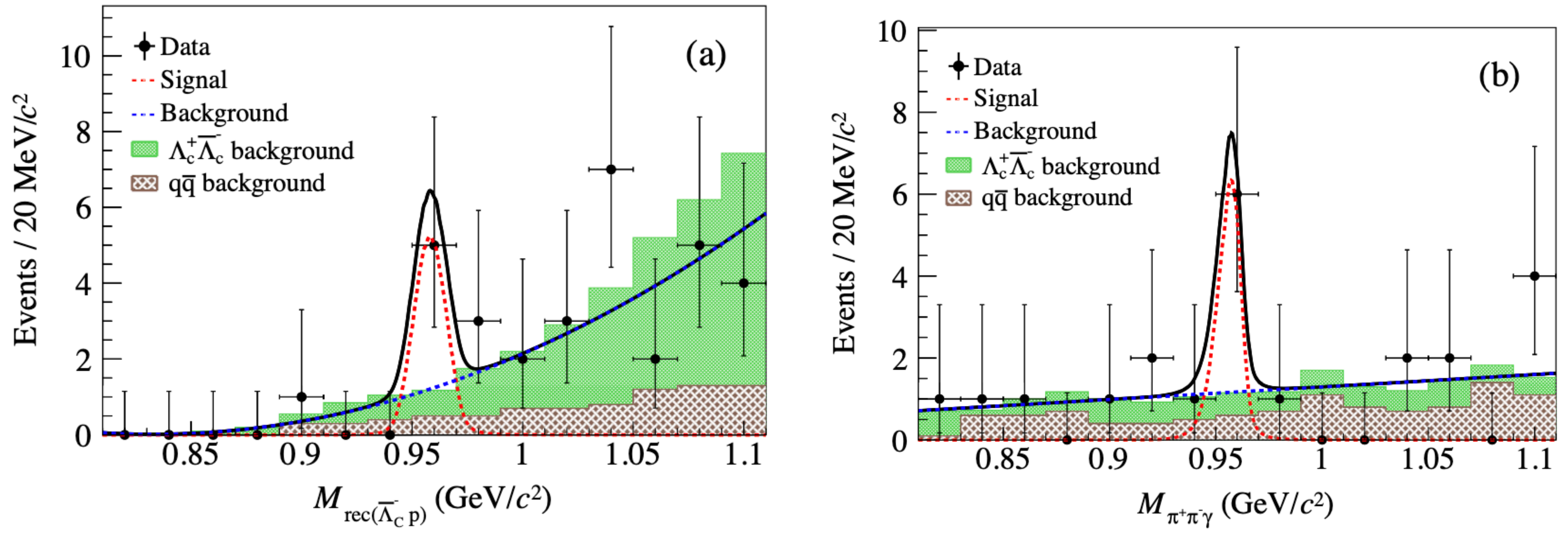
Measurements of $\Lambda_c^+ \to p\pi^0, p\eta, p\eta', p\omega$

Phys. Rev. D 109, L091101 (2024)
JHEP 11, 137 (2023).
Phys. Rev. D 106, 072002 (2023).



- ➔ $\mathscr{B}(\Lambda_c^+ \to p\pi^0) = (1.56^{+0.72}_{-0.58} \pm 0.20) \times 10^{-4}$ (3.7σ) ⇒ first evidence
  - ❖ Result distinctly exceeds the upper limit measured by Belle ($< 8.0 \times 10^{-5}$)
- ➔ $\mathscr{B}(\Lambda_c^+ \to n\pi^+)/\mathscr{B}(\Lambda_c^+ \to p\pi^0) = 3.2^{+2.2}_{-1.2}$
  - ❖ Consistent with majority of phenomenological predictions
  - ❖ 2D plot shows the importance of considering $\mathcal{O}(\overline{15})$ which indicates the non-factorizable contribution





- ➔ $\mathscr{B}(\Lambda_c^+ \to p\eta) = (1.57 \pm 0.11_{stat.} \pm 0.04_{syst.}) \times 10^{-3}$ (>10σ)
  - ❖ Most precise to date
- ➔ $\mathscr{B}(\Lambda_c^+ \to p\omega) = (1.11 \pm 0.20_{stat.} \pm 0.07_{syst.}) \times 10^{-3}$ (5.7σ)

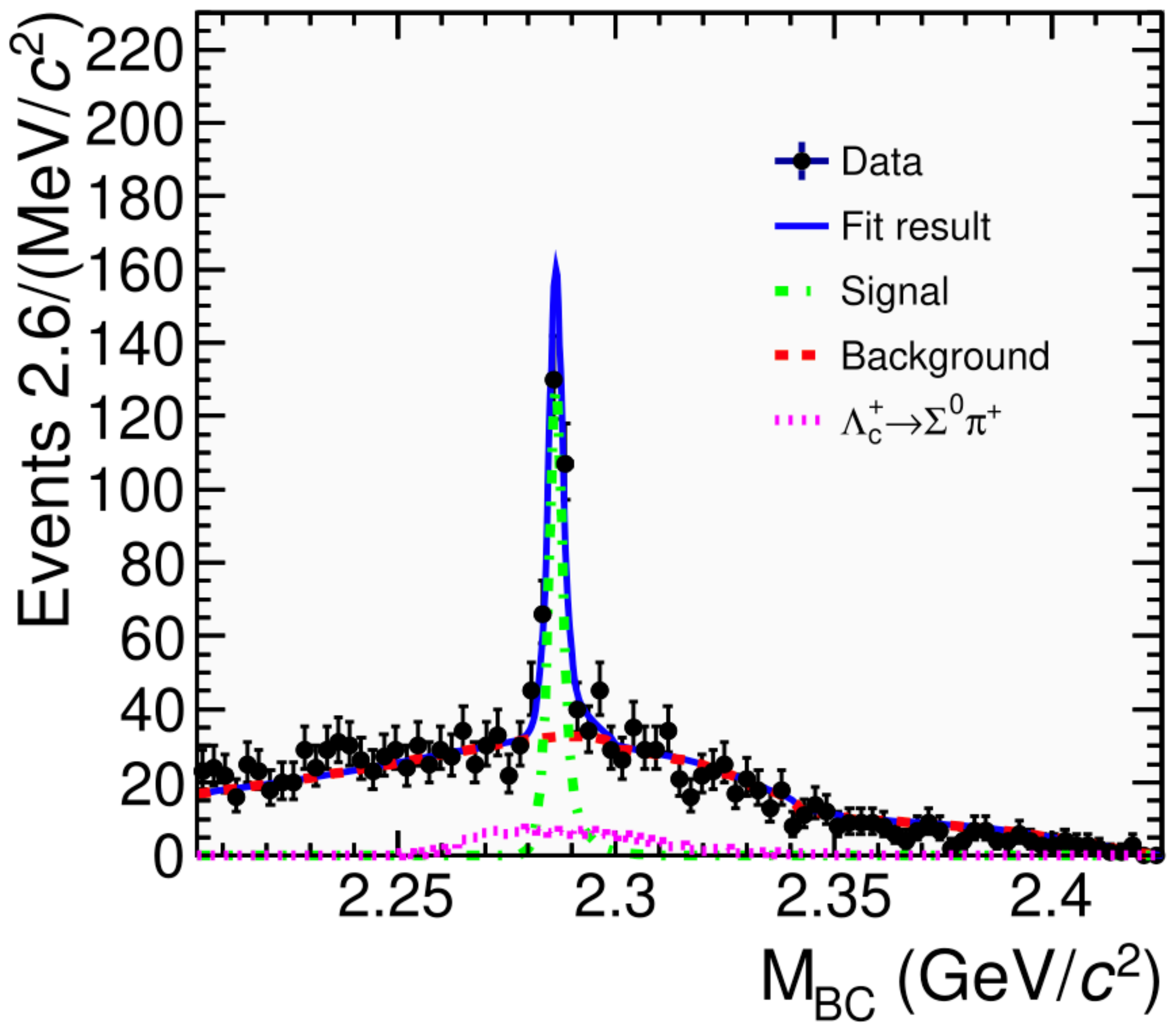
- ➔ $\mathscr{B}(\Lambda_c^+ \to p\eta') = (5.62^{+2.46}_{-2.04}) \times 10^{-4}$ (3.6σ)
  - ❖ Consistent with Belle's relative measurement
  - ❖ Obviously higher than Constituent quark model prediction.

Measurement of $\Lambda_c^+ \to \Lambda K^+$

Phys. Rev. D 106, L111101 (2022).

- SCS decay, measurement relative to CF channel

- $\mathscr{R} = \frac{\mathscr{B}(\Lambda_c^+ \to \Lambda K^+)}{\mathscr{B}(\Lambda_c^+ \to \Lambda \pi^+)} = (4.78 \pm 0.34_{\rm stat.} \pm 0.20_{\rm syst.})\,\%$
  - Consistent with Belle $(7.4 \pm 1.0_{\rm stat.} \pm 1.2_{\rm syst.})\,\%$ and BaBar $(4.4 \pm 0.4_{\rm stat.} \pm 0.3_{\rm syst.})\,\%$
  - Naive estimation of factorizable contribution $\sim (\tan\theta_c f_K/f_\pi)^2 = 7.6\,\%$
    More careful calculation: $\mathscr{R}_{\rm fac} = (7.43 \pm 0.14)\,\%$
  - Different from Λ_b decay: $\mathscr{B}(\Lambda_b \to \Lambda_c^+ K^-)/\mathscr{B}(\Lambda_b \to \Lambda_c^+ \pi^-) = (7.31 \pm 0.16 \pm 0.16)\,\%$
  - Nonfactorizable contributions in Λ_c^+ decay are important and significantly underestimated?



- $\mathscr{B}(\Lambda_c^+ \to \Lambda K^+) = (6.21 \pm 0.44_{\rm stat.} \pm 0.26_{\rm syst.} \pm 0.34_{\rm ref.}) \times 10^{-4}$
  - Significantly lower (~40%) than the predictions based on the $SU(3)$ flavor symmetry, constituent quark model, or current algebra

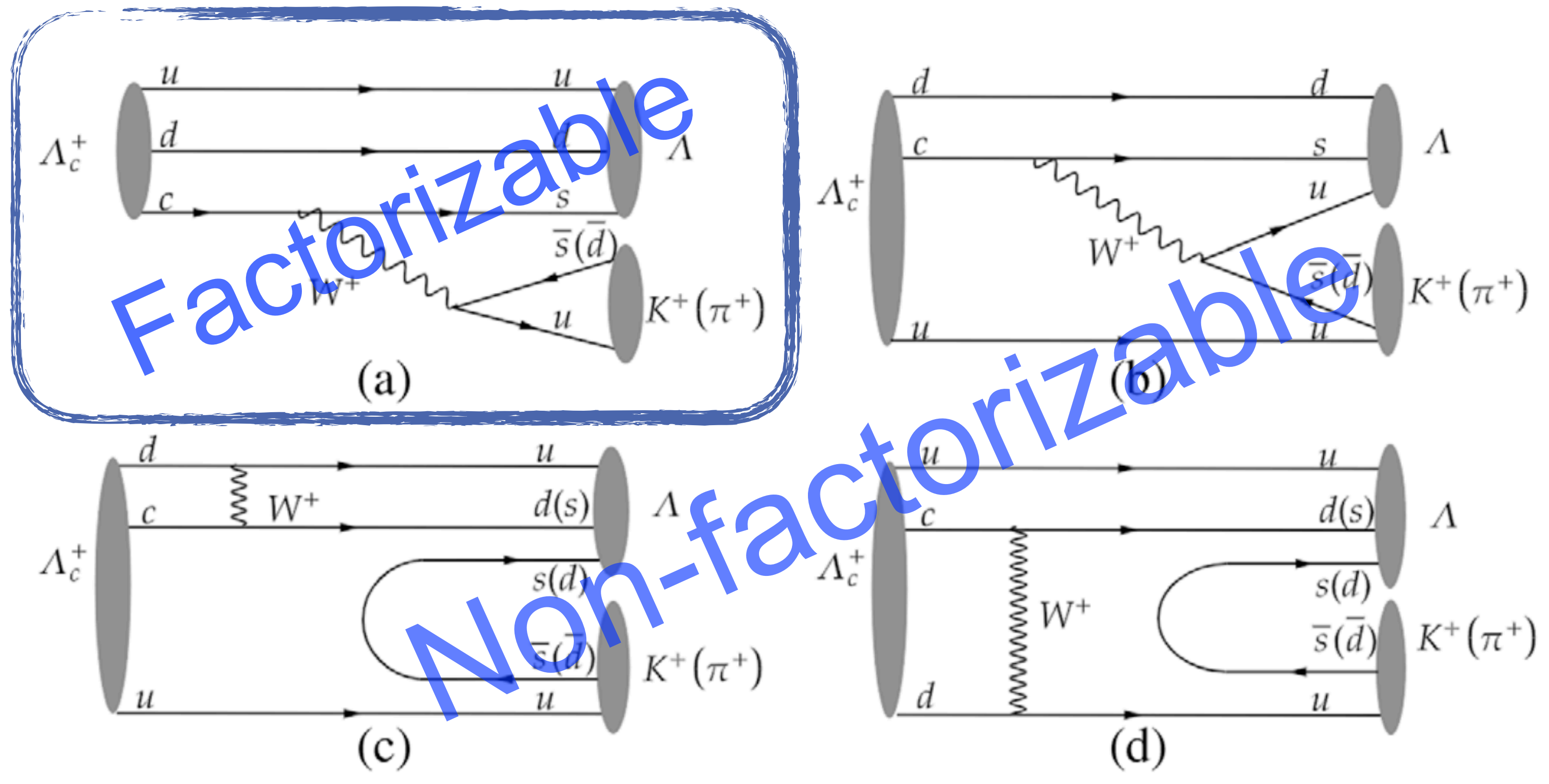


TABLE I. Theoretical predictions on the branching fraction of $\Lambda_c^+ \to \Lambda K^+$.

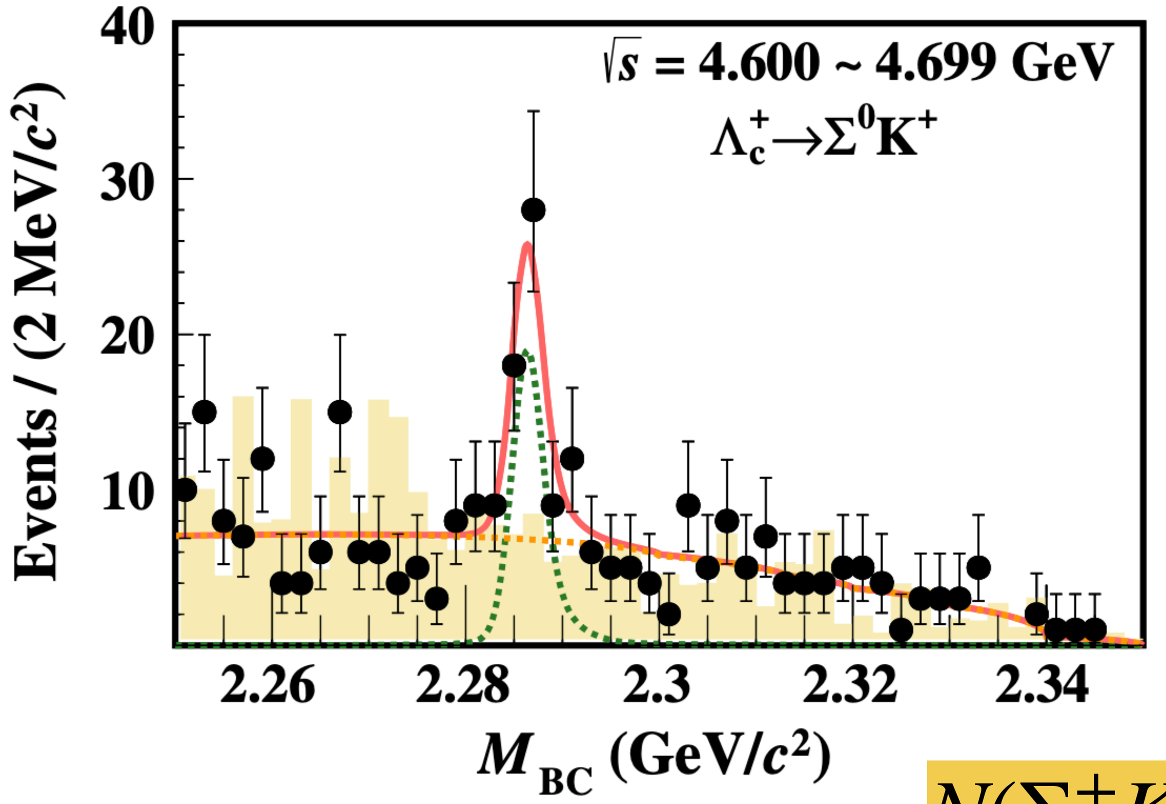
Theoretical predictions	$\mathcal{B}(\Lambda_c^+ \to \Lambda K^+)$ $(\times 10^{-3})$
$SU(3)$ flavor symmetry [8]	1.4
Constituent quark model [14]	1.2
Current algebra [15]	1.06
Diquark picture [16]	0.18–0.39
$SU(3)$ flavor symmetry [17]	0.46 ± 0.09

Measurement of $\Lambda_c^+ \to \Sigma^0 K^+, \Sigma^+ K_S^0$

Phys. Rev. D 106, 052003 (2022).

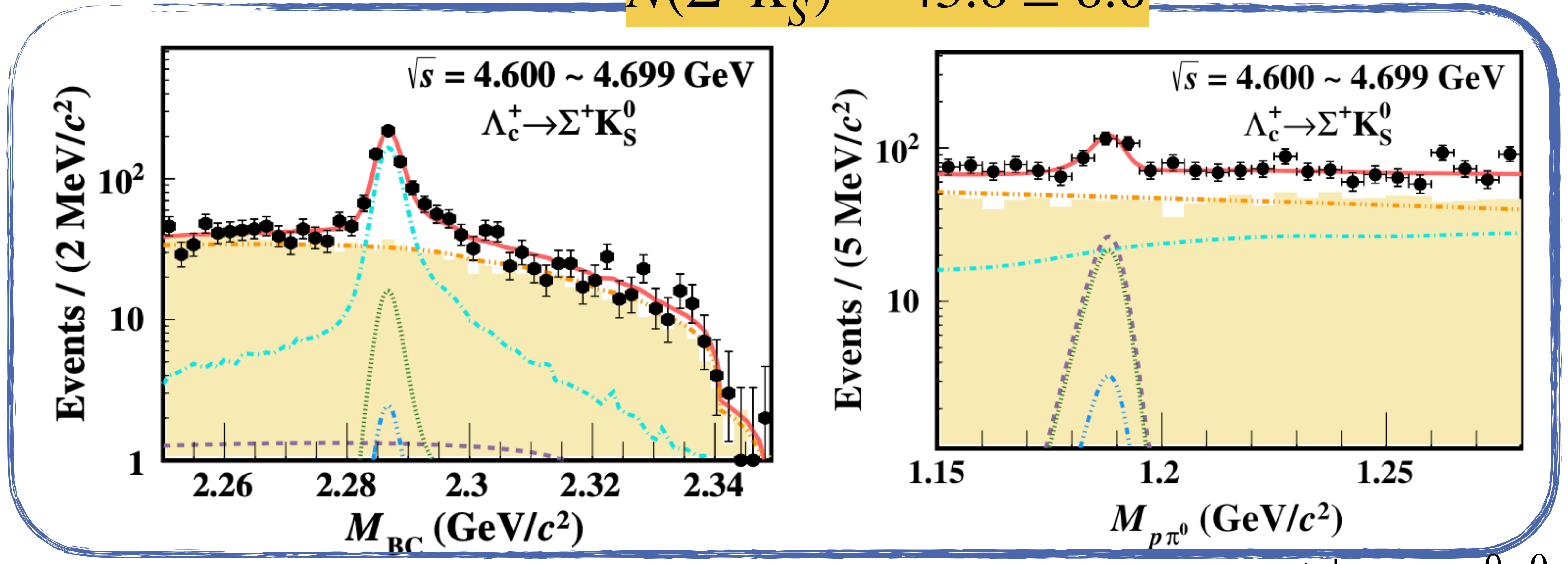
- ➔ Two SCS decays which only receive non-factorizable contribution
- ➔ $R = \frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)}{\mathcal{B}(\Lambda_c^+ \to \Sigma^0 \pi^+)} = 0.0361 \pm 0.0073_{\text{stat.}} \pm 0.0005_{\text{syst.}}$
- ➔ $R = \frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K_S^0)}{\mathcal{B}(\Lambda_c^+ \to \Sigma^+ \pi^+ \pi^-)} = 0.0106 \pm 0.0031_{\text{stat.}} \pm 0.0004_{\text{syst.}}$
- ➔ $\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+) = (4.7 \pm 0.9_{\text{stat.}} \pm 0.1_{\text{syst.}} \pm 0.3_{\text{ref.}}) \times 10^{-4}$
- ➔ $\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K_S^0) = (4.8 \pm 1.4_{\text{stat.}} \pm 0.2_{\text{syst.}} \pm 0.3_{\text{ref.}}) \times 10^{-4}$
  - ❖ First measurement for $\Sigma^+ K_S^0$
  - ❖ $\Lambda_c^+ \to \Sigma^0 K^+$ is consistent and comparable with Belle and BaBar
  - ❖ Consistent with $SU(3)$ flavor symmetry
- ➔ $\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)}{\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K_S^0)} = 0.98 \pm 0.35(\text{stat.}) \pm 0.04(\text{syst.}) \pm 0.08(\text{ref.})$
  - ❖ Körner-Pati-Woo theorem is confirmed!

$N(\Sigma^0 K^+) = 43.3 \pm 4.2$

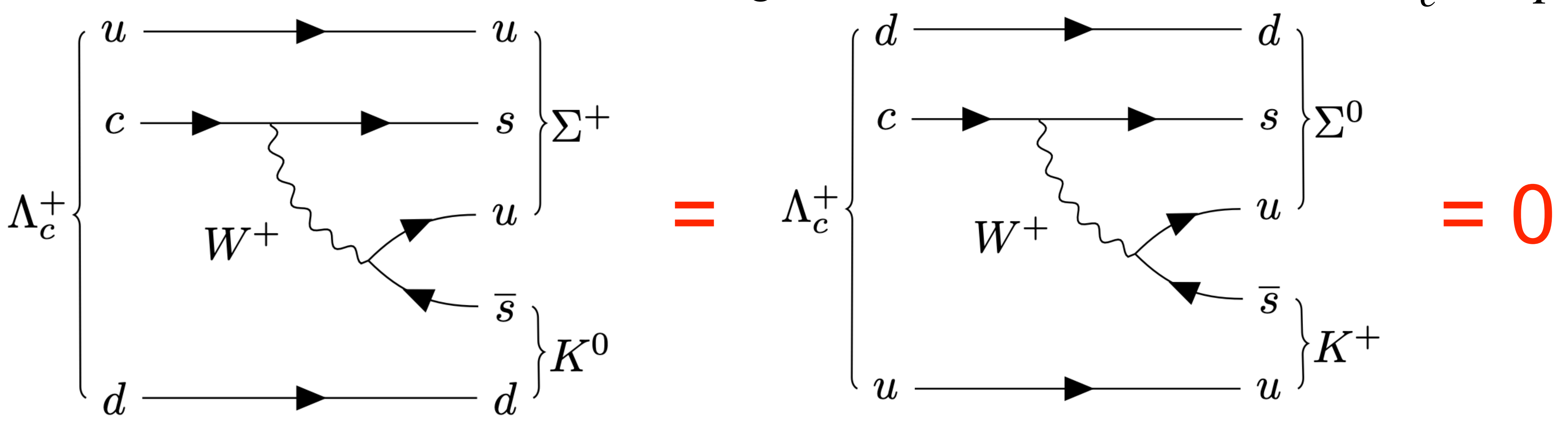


	$\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)$	$\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K_S^0)$
QCD corrections [2]	2(8)	2(4)
MIT bag model [3]	7.2 ± 1.8	7.2 ± 1.8
Diagrammatic analysis [4]	5.5 ± 1.6	9.6 ± 2.4
$SU(3)_F$ flavor symmetry [5]	5.4 ± 0.7	5.4 ± 0.7
IRA method [6]	5.0 ± 0.6	1.0 ± 0.4
PDG 2020 [28]	5.2 ± 0.8	...

$N(\Sigma^+ K_S^0) = 43.6 \pm 6.0$



2D fitting since the contamination of $\Lambda_c^+ \to p K_S^0 \pi^0$



Decay asymmetry for $\Lambda_c^+ \to \Xi^0 K^+$

Phys. Rev. Lett. 132, 031801 (2024).

Highlight

Theory or experiment	$\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)$ $(\times 10^{-3})$	$\alpha_{\Xi^0 K^+}$	$\lvert A\rvert$ $(\times 10^{-2} G_F\ \mathrm{GeV}^2)$	$\lvert B\rvert$ $(\times 10^{-2} G_F\ \mathrm{GeV}^2)$	$\delta_p - \delta_s$ (rad)
Körner (1992), CCQM [7]	2.6	0	...	...	...
Xu (1992), Pole [8]	1.0	0	0	7.94	...
Źencaykowski (1994), Pole [9]	3.6	0	...	...	...
Ivanov (1998), CCQM [10]	3.1	0	...	...	...
Sharma (1999), CA [11]	1.3	0	...	...	...
Geng (2019), SU(3) [12]	5.7 ± 0.9	$0.94^{+0.06}_{-0.11}$	2.7 ± 0.6	16.1 ± 2.6	...
Zou (2020), CA [6]	7.1	0.90	4.48	12.10	...
Zhong (2022), SU(3)^a [13]	$3.8^{+0.4}_{-0.5}$	$0.91^{+0.03}_{-0.04}$	3.2 ± 0.2	$8.7^{+0.6}_{-0.8}$	...
Zhong (2022), SU(3)^b [13]	$5.0^{+0.6}_{-0.9}$	0.99 ± 0.01	$3.3^{+0.5}_{-0.7}$	$12.3^{+1.2}_{-1.8}$	...
BESIII (2018) [14]	$5.90 \pm 0.86 \pm 0.39$	...	...	...	...
PDG fit (2022) [2]	5.5 ± 0.7	...	...	...	...

Early calculations:
Small BF due to strong cancellation in S- and P-wave amplitudes
Zero decay asymmetry owing to the vanising S-wave amplitude

Recent calculations (after BESIII 2018 result):
Theorists made modification to match with experimental measurement
Much closer BF but introducing a large positive decay asymmetry

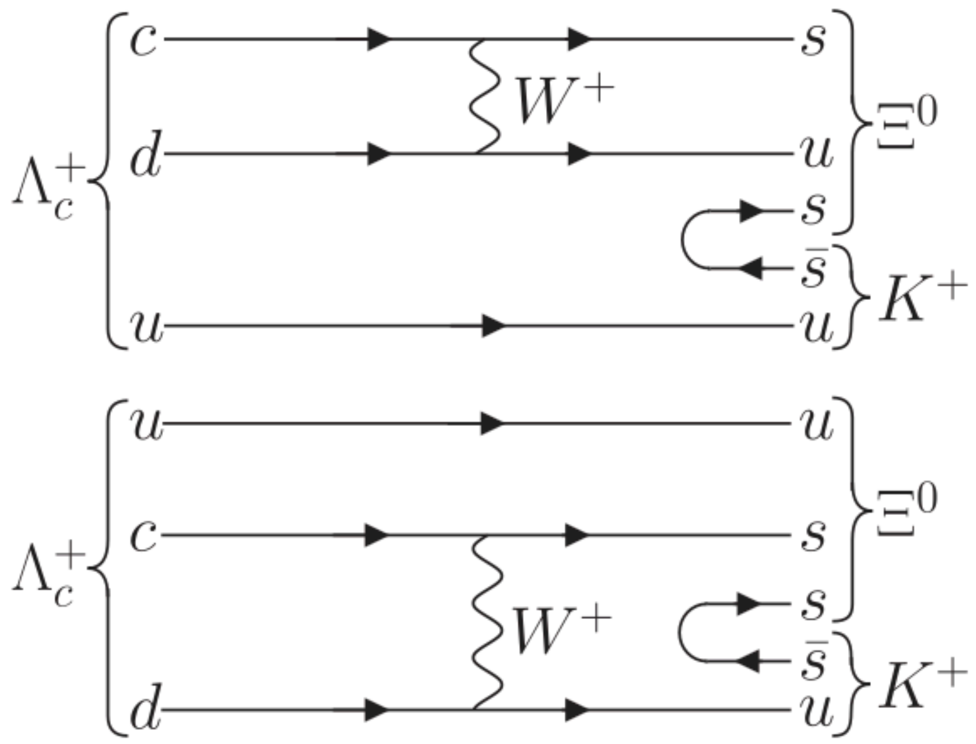
Need experimetal measurement of decay asymmetry!

➔ $\Lambda_c^+ \to \Xi^0 K^+$ is pure W-exchange process which has significant contributions in charm baryon decay.

➔ Non-factorizable W-exchange diagram cannot be calculated using theoretical approaches.

➔ Long-standing puzzle on how large the S-wave amplitude.

➔ Experimental measurement of decay asymmetry is crucial and urgent.



Decay asymmetry for $\Lambda_c^+ \to \Xi^0 K^+$

- ➔ Partial decay width for $\Lambda_c^+ \to \Xi^0 K^+, \Xi^0 \to \Lambda\pi^+, \Lambda \to p\pi^-$ based on helicity amplitude.
- ➔ Fit to angular distribution

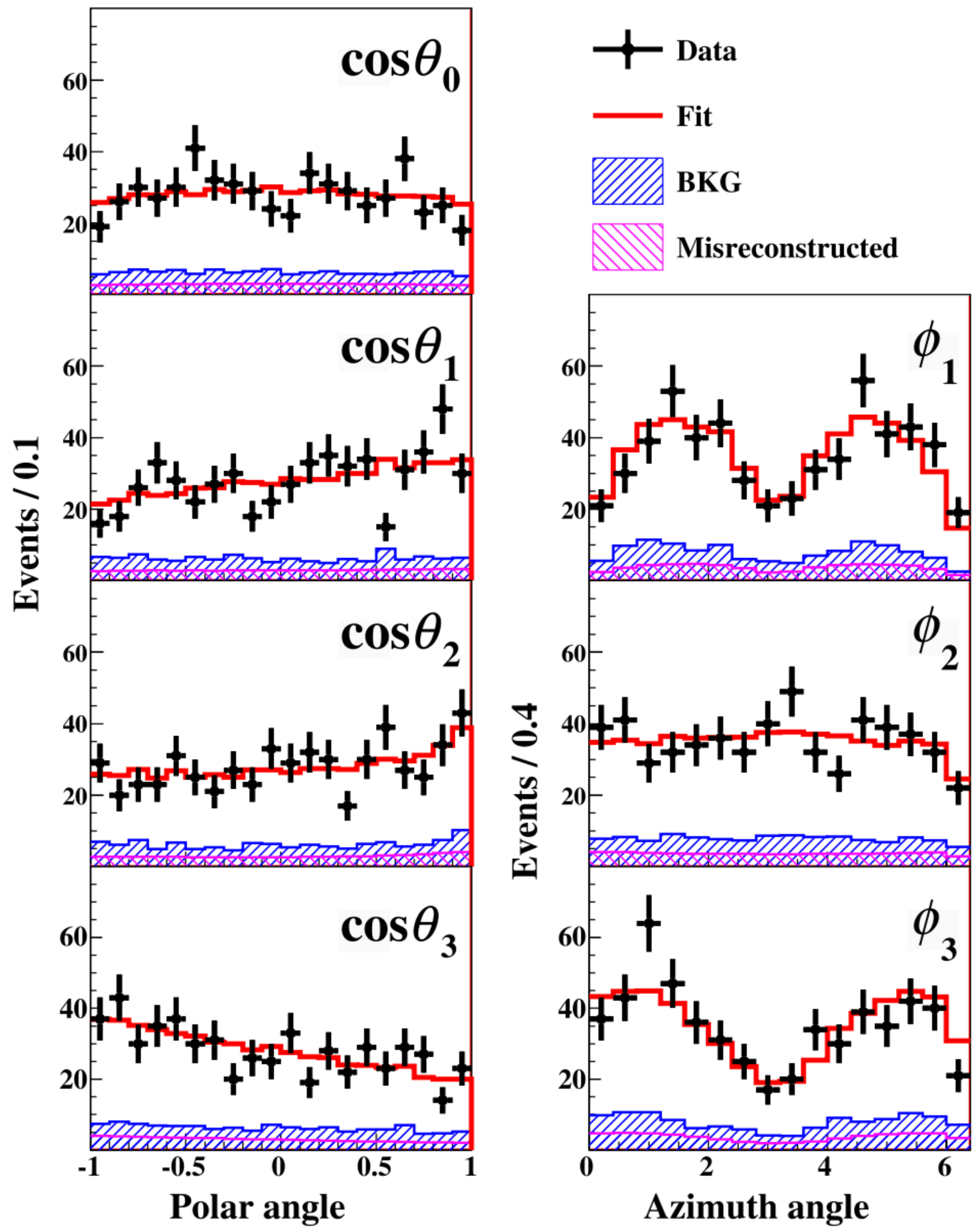
Lee-Yang parameters

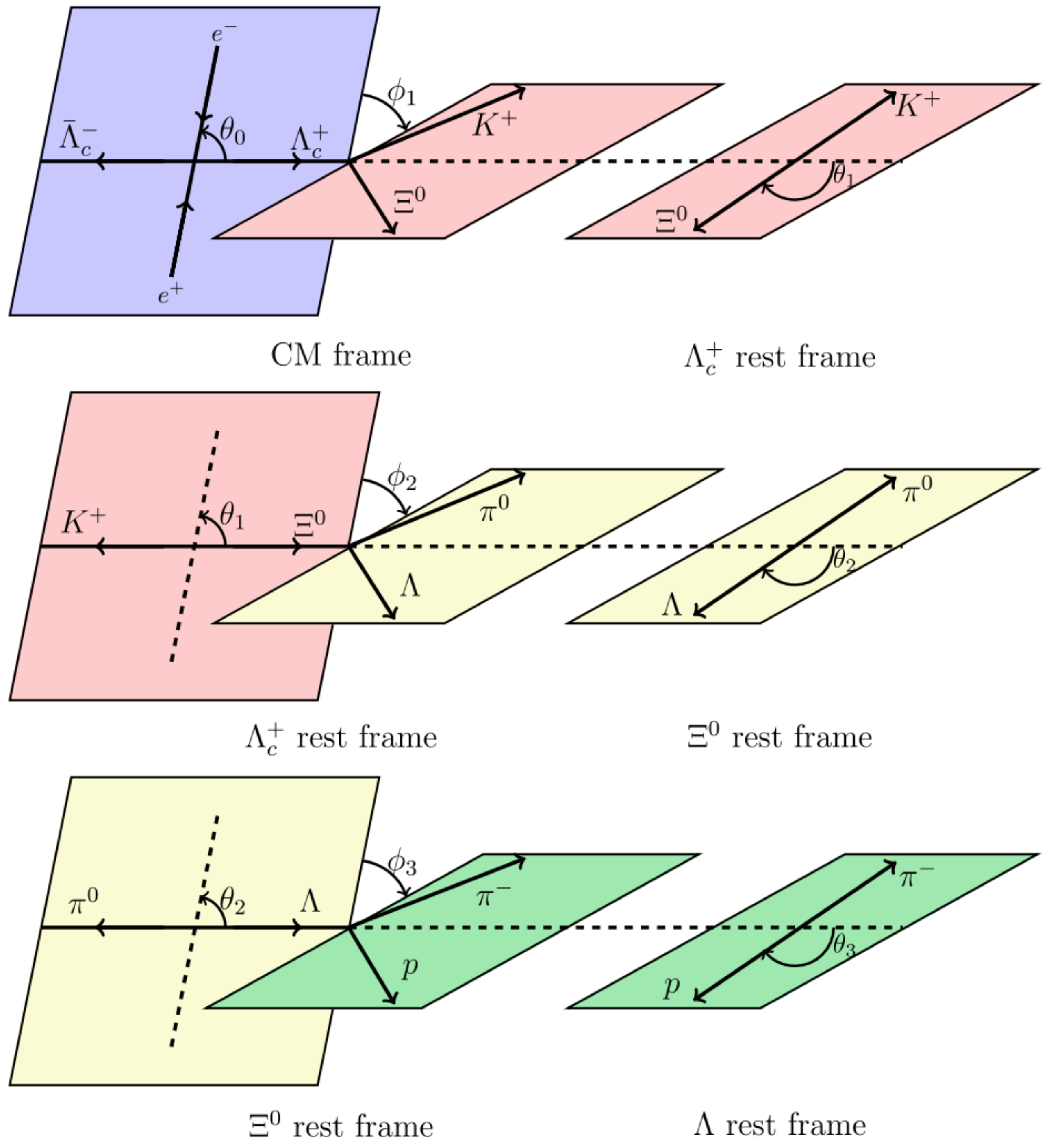
$$\alpha_{BP} = \frac{2\mathrm{Re}(s^*p)}{|s|^2+|p|^2}, \quad \beta_{BP} = \frac{2\mathrm{Im}(s^*p)}{|s|^2+|p|^2}, \quad \gamma_{BP} = \frac{|s|^2-|p|^2}{|s|^2+|p|^2},$$

$$\alpha_{BP} = |\mathcal{H}_{\frac{1}{2}}|^2 - |\mathcal{H}_{-\frac{1}{2}}|^2,$$
$$\beta_{BP} = \sqrt{1-\alpha_{BP}^2}\sin\Delta_{BP},$$
$$\gamma_{BP} = \sqrt{1-\alpha_{BP}^2}\cos\Delta_{BP},$$

Joint angular distribution formula

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

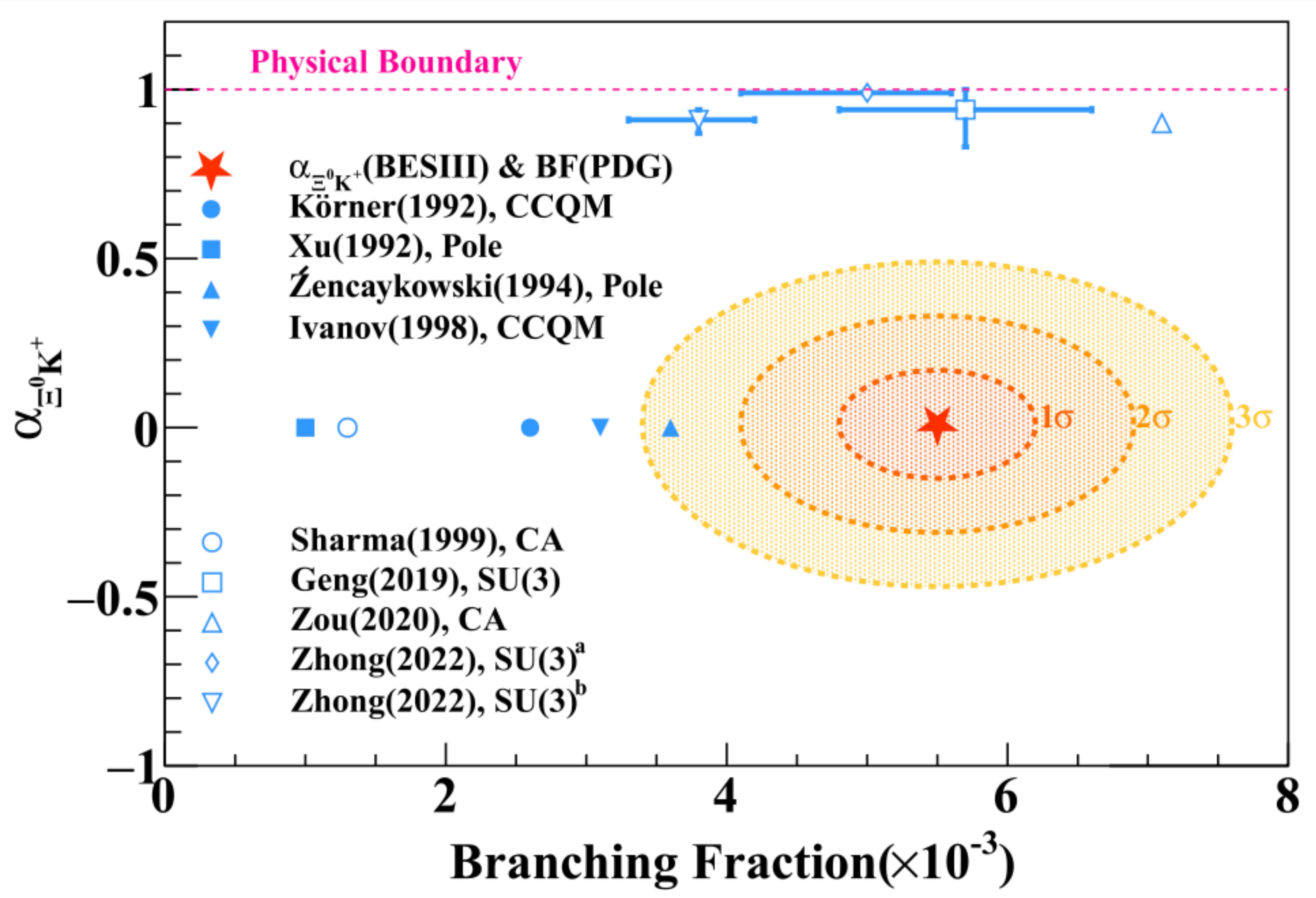




Level	Decay	Helicity angle	Helicity amplitude
0	$e^+e^- \to \Lambda_c^+(\lambda_1)\,\bar{\Lambda}_c^-(\lambda_2)$	(θ_0)	$\mathcal{A}_{\lambda_1,\lambda_2}$
1	$\Lambda_c^+ \to \Xi^0(\lambda_3)\,K^+$	(θ_1,ϕ_1)	$\mathcal{B}_{\lambda_3}$
2	$\Xi^0 \to \Lambda(\lambda_4)\,\pi^0$	(θ_2,ϕ_2)	$\mathcal{C}_{\lambda_4}$
3	$\Lambda \to p(\lambda_5)\,\pi^-$	(θ_3,ϕ_3)	$\mathcal{D}_{\lambda_5}$

Decay asymmetry for $\Lambda_c^+ \to \Xi^0 K^+$

- Decay asymmetry results:
  - $\alpha_{\Xi^0 K^+} = 0.01 \pm 0.16_{\text{stat.}} \pm 0.03_{\text{syst.}}$
  - $\Delta_{\Xi^0 K^+} = 3.84 \pm 0.90_{\text{stat.}} \pm 0.17_{\text{syst.}}$ rad
  - $\beta_{\Xi^0 K^+} = -0.64 \pm 0.69_{\text{stat.}} \pm 0.13_{\text{syst.}}$
  - $\gamma_{\Xi^0 K^+} = -0.77 \pm 0.58_{\text{stat.}} \pm 0.11_{\text{syst.}}$
- $\alpha_{\Xi^0 K^+}$ is in good agreement with zero
  $\Rightarrow$ strong identification for theoretical predictions



- Especially, $\cos(\delta_p - \delta_s)$ is measured to close to zero $\Rightarrow$ not considered in previous literature
  - Two solutions: $\delta_p - \delta_s = -1.55 \pm 0.25_{\text{stat.}} \pm 0.05_{\text{syst.}}$ or $1.59 \pm 0.25_{\text{stat.}} \pm 0.05_{\text{syst.}}$

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

S-wave P-wave

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

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

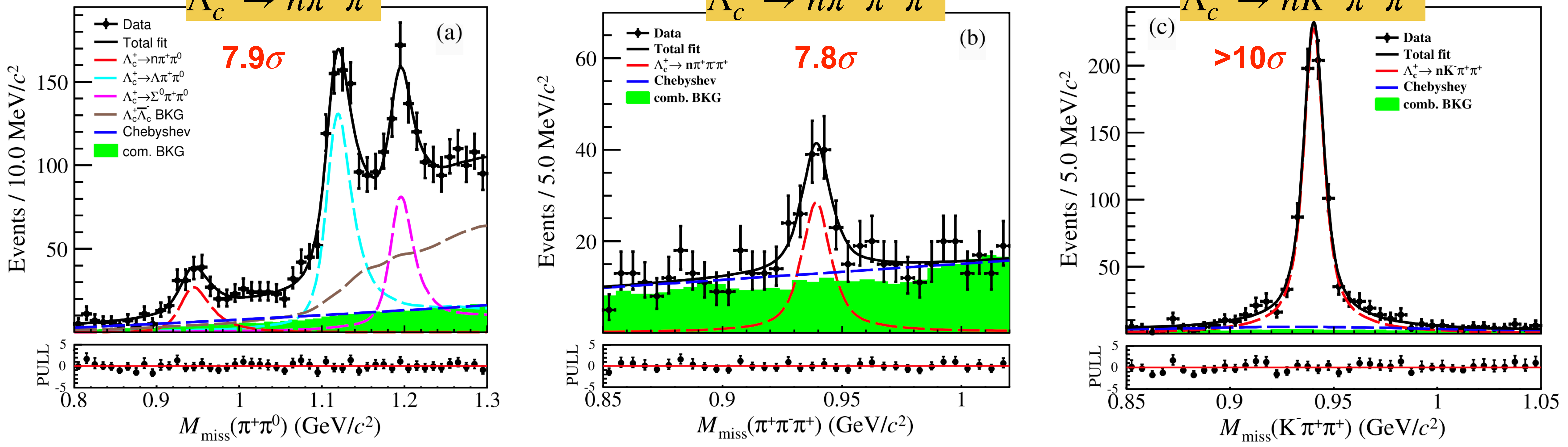
Phase difference between S- and P-wave

- Fill the long-standing puzzle on how to model $\alpha_{\Xi^0 K^+}$ and $\mathscr{B}(\Lambda_c^+ \to \Xi^0 K^+)$ simultaneously

First observation of $\Lambda_c^+ \to n\pi^+\pi^0, n\pi^+\pi^-\pi^+, nK^-\pi^+\pi^+$

Chin. Phys. C 47, 023001 (2023).

$\Lambda_c^+ \to n\pi^+\pi^0$ $\Lambda_c^+ \to n\pi^+\pi^-\pi^+$ $\Lambda_c^+ \to nK^-\pi^+\pi^+$



➔ Two SCS $\Lambda_c^+ \to n\pi^+\pi^0, n\pi^+\pi^-\pi^+$ decays and one CF $\Lambda_c^+ \to nK^-\pi^+\pi^+$ decay was firstly observed.

➔ Absolute BFs are measured to be

- $\mathscr{B}(\Lambda_c^+ \to n\pi^+\pi^0) = (0.64 \pm 0.09_{\text{stat.}} \pm 0.02_{\text{syst.}})\ \%$

$$\frac{\mathscr{B}(\Lambda_c^+ \to p\pi^-\pi^+)}{\mathscr{B}(\Lambda_c^+ \to n\pi^0\pi^+)} = 0.72 \pm 0.11 \Rightarrow$$ useful input to test of isospin symmetry

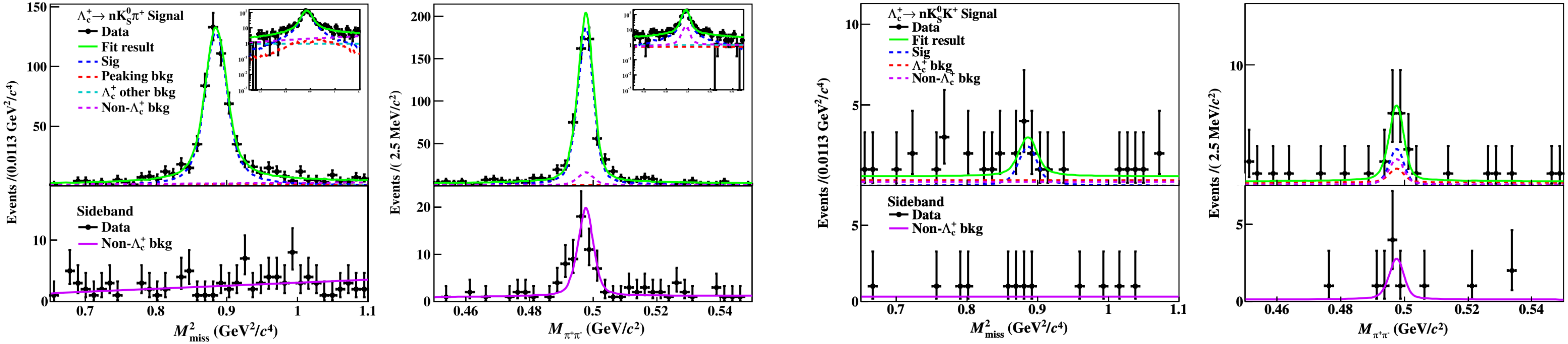
$$\frac{\mathscr{B}(\Lambda_c^+ \to n\pi^+\pi^0)}{\mathscr{B}(\Lambda_c^+ \to n\pi^+)} = 9.7 \pm 2.4 \Rightarrow$$ intermediate resonances contributions need to decouple

- $\mathscr{B}(\Lambda_c^+ \to n\pi^+\pi^-\pi^+) = (0.45 \pm 0.07_{\text{stat.}} \pm 0.03_{\text{syst.}})\ \%$
- $\mathscr{B}(\Lambda_c^+ \to nK^+\pi^+\pi^+) = (1.90 \pm 0.08_{\text{stat.}} \pm 0.09_{\text{syst.}})\ \%$

$$\frac{\mathscr{B}(\Lambda_c^+ \to n\pi^+\pi^-\pi^+)}{\mathscr{B}(\Lambda_c^+ \to n\pi^+K^-\pi^+)} = 0.24 \pm 0.04 \Rightarrow$$ consistent with $|V_{cd}|/|V_{cs}| = (0.224 \pm 0.005)$

Measurement of $\Lambda_c^+ \to nK_S^0\pi^+, nK_S^0K^+$

Phys. Rev. D 109, 072010 (2024).



- Improved measurement of $\mathcal{B}(\Lambda_c^+ \to nK_S^0\pi^+)$
- First evidence of SCS decay $\Lambda_c^+ \to nK_S^0K^+$ (3.7σ)
- $$\frac{|I^{(1)}|}{|I^{(0)}|} = \sqrt{\frac{\mathcal{B}(pK^-\pi^+) + \mathcal{B}(n\bar{K}^0\pi^+) - \mathcal{B}(p\bar{K}^0\pi^0)}{2\mathcal{B}(p\bar{K}^0\pi^0)}} = 0.88 \pm 0.05$$
  - Isospin triplet $I^{(1)}$ is important ⇒ violation of factorization scheme
- $$\cos\delta = \frac{\mathcal{B}(n\bar{K}^0\pi^+) - \mathcal{B}(pK^-\pi^+)}{2\sqrt{\mathcal{B}(p\bar{K}^0\pi^0)(\mathcal{B}(pK^-\pi^+) + \mathcal{B}(n\bar{K}^0\pi^+) - \mathcal{B}(p\bar{K}^0\pi^0))}} = -0.26 \pm 0.03$$
  - Useful experimental input for daynamical method
- Tension with $SU(3)$ flavor symmetry prediction
  - $\Lambda_c^+ \to nK_S^0\pi^+$: $SU(3)$ predictions are 3-4 times smaller than BESIII ⇒ resonance states? High-wave contributions?
  - $\Lambda_c^+ \to nK_S^0K^+$: measured BF is lower than prediction 2-4σ

TABLE VI. Comparisons of the BFs of $\Lambda_c^+ \to nK_S^0\pi^+$ and $\Lambda_c^+ \to nK_S^0K^+$ between experimental measurements and theoretical predictions.

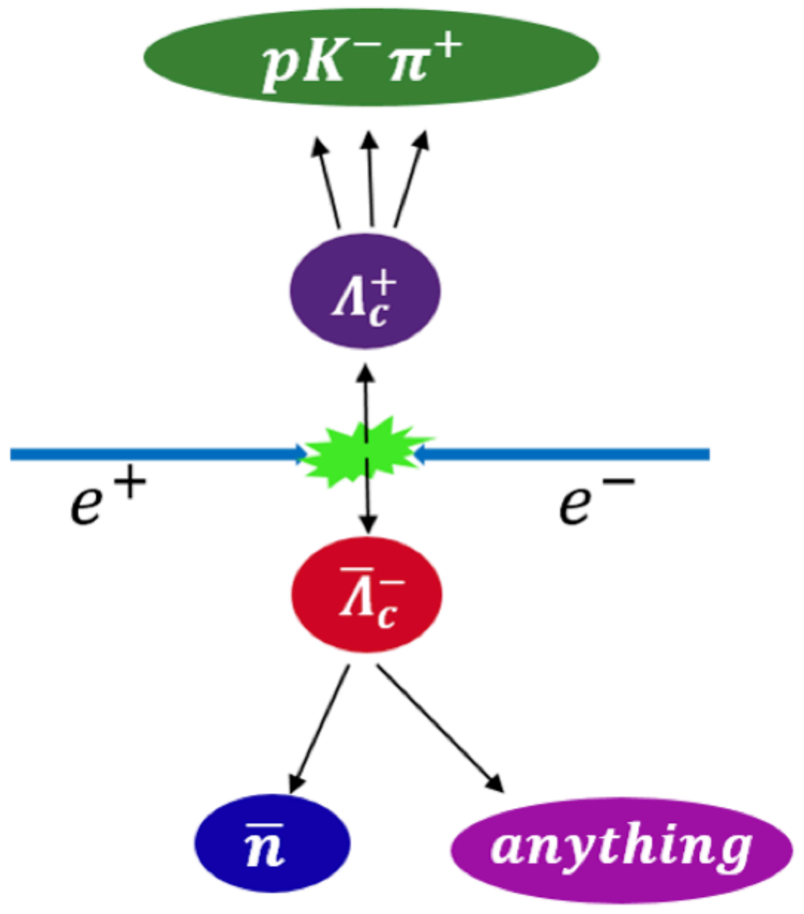
	$n\bar{K}^0\pi^+$ ($\times 10^{-2}$)	$n\bar{K}^0K^+$ ($\times 10^{-4}$)
Geng [33]	0.9 ± 0.8	59 ± 13
Cen [34]	1.1 ± 0.1	31 ± 9
Previous result [7]	3.64 ± 0.50	...
This work	$3.72 \pm 0.16 \pm 0.08$	$7.8^{+3.5}_{-2.8} \pm 0.6$

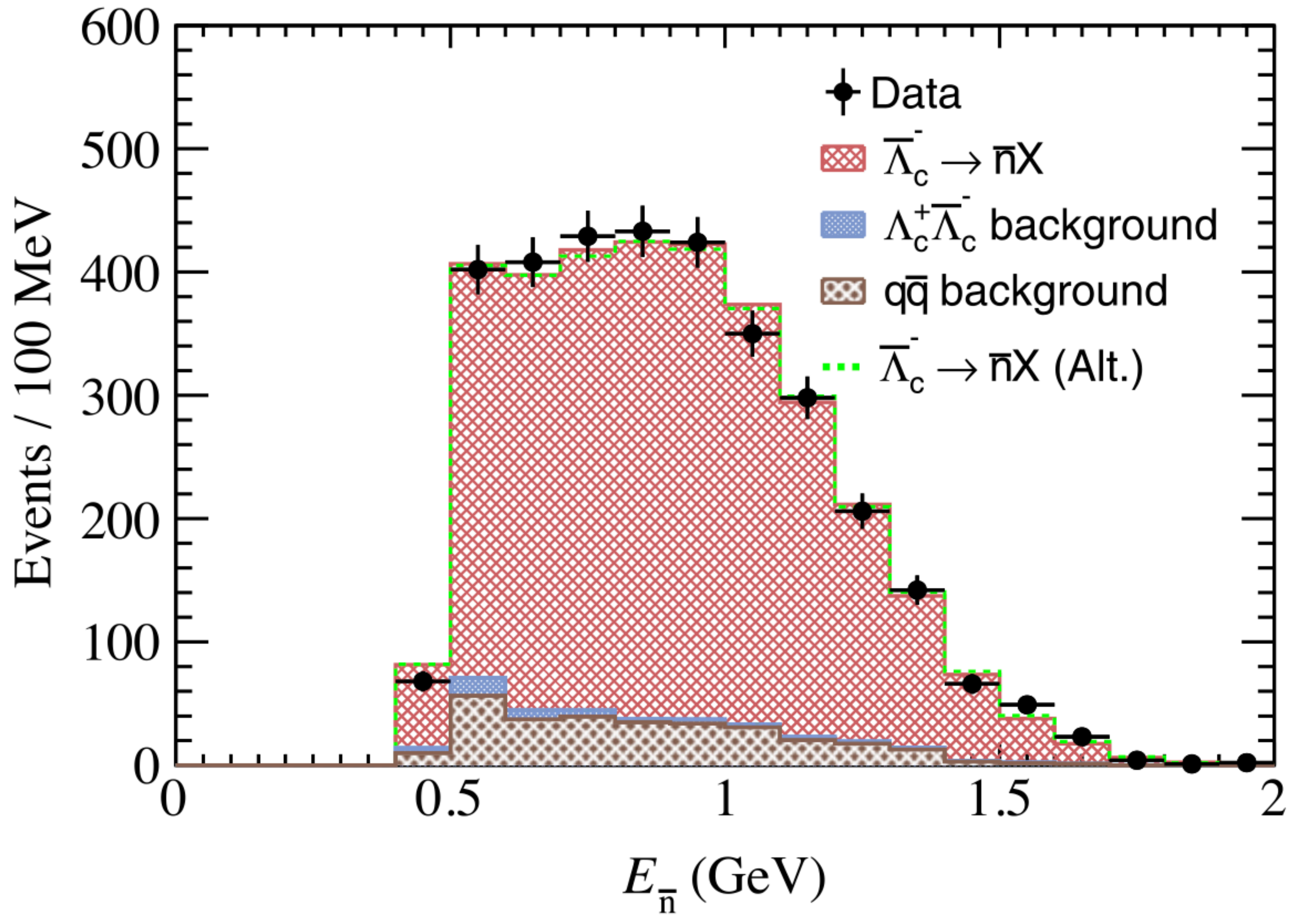
Improved by a factor of 2.8

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

Phys. Rev. D 108, L031101 (2023).

- Physics motivation and experimental challenge:
  - Previous estimation from CLEO with large uncertainty: $\mathscr{B}(\Lambda_c^+ \to nX) \approx \mathscr{B}(\Lambda_c^+ \to pX) = (50 \pm 16)\,\%$
  - Direction of searches for unkown channels
  - Investigation of isospin symmetry between inclusive proton and inclusive neutron
  - Annihilation betwee $\bar{n}$ and material in EMC results in a larger energy deposition
  - Extropolate to $\Lambda_c^+ \to nX$ assuming negligible CPV
- The deposited energy in EMC is used to identify $\bar{n}$
- Data-driven method technique to model $\bar{n}$ behaviour in the detector
- Absolute BF is determined to be $\mathscr{B}(\bar{\Lambda}_c^- \to \bar{n}X) = (32.4 \pm 0.7_{\mathrm{stat.}} \pm 1.5_{\mathrm{syst.}})\,\%$ precision up to 5%
  - All known exclusive decays with neutron in final state is about 25% $\Rightarrow$ more space to explored
- Asymmetry between $\mathscr{B}(\Lambda_c^+ \to nX)$ and $\mathscr{B}(\Lambda_c^+ \to pX)$ is observed.





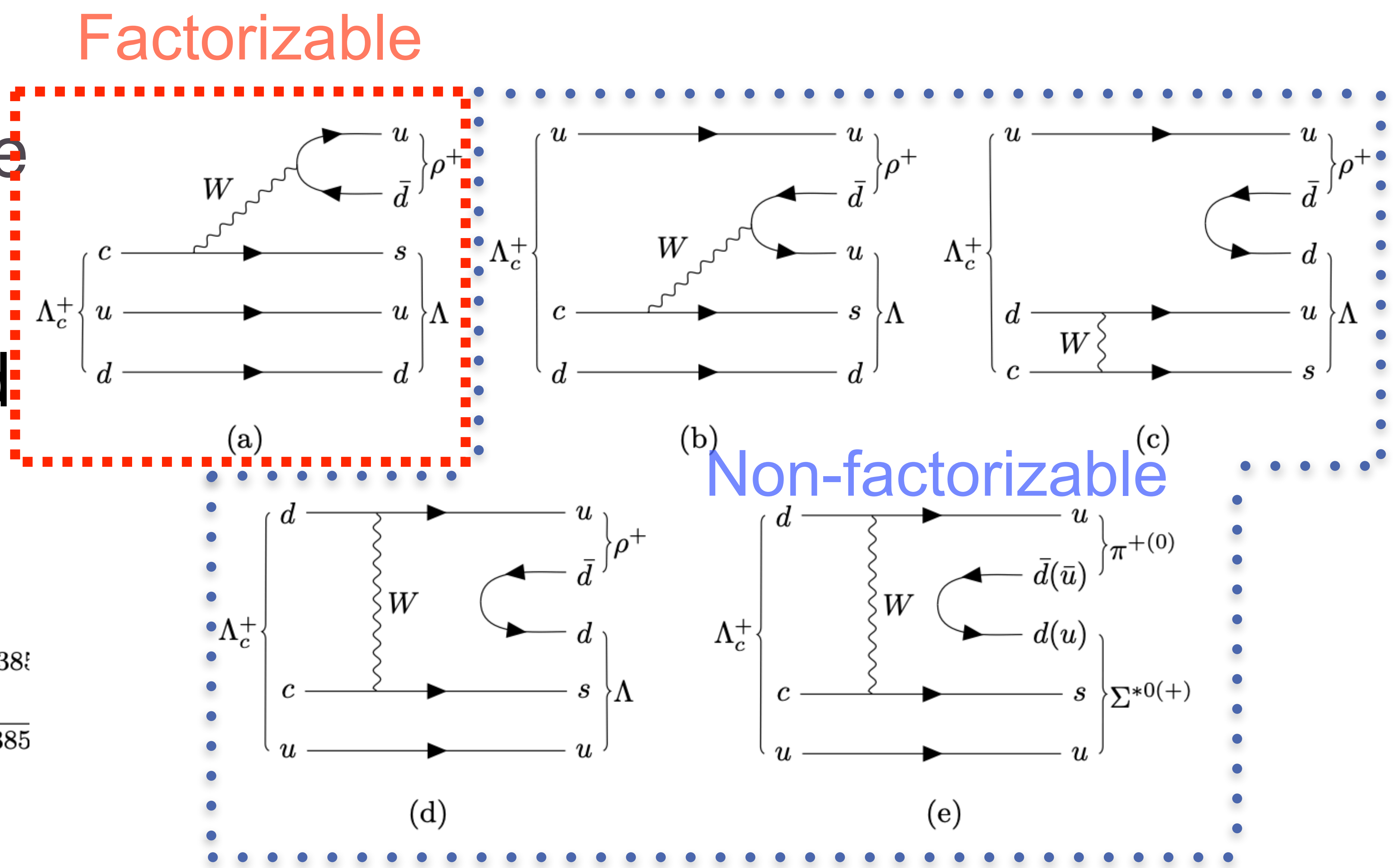
$\bar{n}$ deposited energy distribution is consistent between data and MC after using data-driven method

PWA for $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

JHEP 12, 033 (2022).

Highlight

- ➔ First PWA analysis for charm baryon at BESIII
  - ❖ Using advanced PWA technique TF-PWA, based on helicity amplitude
- ➔ About 10K events survived which purity is larger than 80%
- ➔ FFs and decay asymmetries of $\Lambda_c^+ \to \Lambda\rho, \Sigma(1385)\pi$ are extracted

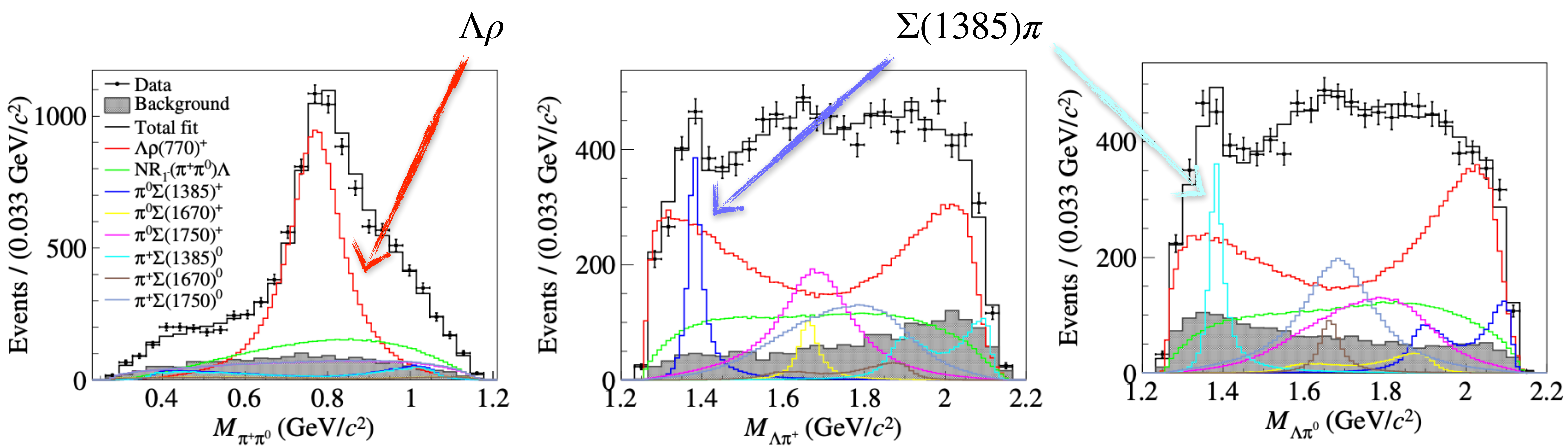


The definition of decay asymmetry

$$\alpha_{\Lambda\rho(770)^+} = \frac{|H^{\rho}_{\frac{1}{2},1}|^2 - |H^{\rho}_{-\frac{1}{2},-1}|^2 + |H^{\rho}_{\frac{1}{2},0}|^2 - |H^{\rho}_{-\frac{1}{2},0}|^2}{|H^{\rho}_{\frac{1}{2},1}|^2 + |H^{\rho}_{-\frac{1}{2},-1}|^2 + |H^{\rho}_{\frac{1}{2},0}|^2 + |H^{\rho}_{-\frac{1}{2},0}|^2}$$

$$= \frac{\sqrt{\frac{1}{9}} \cdot 2 \cdot \Re\left(g^{\rho}_{0,\frac{1}{2}} \cdot \bar{g}^{\rho}_{1,\frac{1}{2}} - g^{\rho}_{1,\frac{3}{2}} \cdot \bar{g}^{\rho}_{2,\frac{3}{2}}\right) - \sqrt{\frac{8}{9}} \cdot 2 \cdot \Re\left(g^{\rho}_{0,\frac{1}{2}} \cdot \bar{g}^{\rho}_{1,\frac{3}{2}} + g^{\rho}_{1,\frac{1}{2}} \cdot \bar{g}^{\rho}_{2,\frac{3}{2}}\right)}{|g^{\rho}_{0,\frac{1}{2}}|^2 + |g^{\rho}_{1,\frac{1}{2}}|^2 + |g^{\rho}_{1,\frac{3}{2}}|^2 + |g^{\rho}_{2,\frac{3}{2}}|^2}.$$

$$\alpha_{\Sigma(1385)\pi} = \frac{|H^{\Sigma(1385)}_{0,\frac{1}{2}}|^2 - |H^{\Sigma(1385)}_{0,-\frac{1}{2}}|^2}{|H^{\Sigma(1385)}_{0,\frac{1}{2}}|^2 + |H^{\Sigma(1385)}_{0,-\frac{1}{2}}|^2} = \frac{2\Re\left(g^{\Sigma(1385)}_{1,\frac{3}{2}} \cdot \bar{g}^{\Sigma(1385)}_{2,\frac{3}{2}}\right)}{|g^{\Sigma(1385)}_{1,\frac{3}{2}}|^2 + |g^{\Sigma(1385)}_{2,\frac{3}{2}}|^2}$$



Process	Magnitude	Phase ϕ (rad)	FF (%)	Significance
$\Lambda\rho(770)^+$	1.0 (fixed)	0.0 (fixed)	57.2 ± 4.2	$36.9\,\sigma$
$\Sigma(1385)^+\pi^0$	0.43 ± 0.06	-0.23 ± 0.18	7.18 ± 0.60	$14.8\,\sigma$
$\Sigma(1385)^0\pi^+$	0.37 ± 0.07	2.84 ± 0.23	7.92 ± 0.72	$16.0\,\sigma$
$\Sigma(1670)^+\pi^0$	0.31 ± 0.08	-0.77 ± 0.23	2.90 ± 0.63	$5.1\,\sigma$
$\Sigma(1670)^0\pi^+$	0.41 ± 0.07	2.77 ± 0.20	2.65 ± 0.58	$5.2\,\sigma$
$\Sigma(1750)^+\pi^0$	1.75 ± 0.21	-1.73 ± 0.11	16.6 ± 2.2	$10.1\,\sigma$
$\Sigma(1750)^0\pi^+$	1.83 ± 0.21	1.34 ± 0.11	17.5 ± 2.3	$10.2\,\sigma$
$\Lambda + NR_{1^-}$	4.05 ± 0.47	2.16 ± 0.13	29.7 ± 4.5	$10.5\,\sigma$

PWA for $\Lambda_c^+ \to \Lambda\pi^+\pi^0$

	Result
$\frac{\mathcal{B}(\Lambda_c^+\to\Lambda\rho(770)^+)}{\mathcal{B}(\Lambda_c^+\to\Lambda\pi^+\pi^0)}$	$(57.2 \pm 4.2 \pm 4.9)\%$
$\frac{\mathcal{B}(\Lambda_c^+\to\Sigma(1385)^+\pi^0)\cdot\mathcal{B}(\Sigma(1385)^+\to\Lambda\pi^+)}{\mathcal{B}(\Lambda_c^+\to\Lambda\pi^+\pi^0)}$	$(7.18 \pm 0.60 \pm 0.64)\%$
$\frac{\mathcal{B}(\Lambda_c^+\to\Sigma(1385)^0\pi^+)\cdot\mathcal{B}(\Sigma(1385)^0\to\Lambda\pi^0)}{\mathcal{B}(\Lambda_c^+\to\Lambda\pi^+\pi^0)}$	$(7.92 \pm 0.72 \pm 0.80)\%$
$\mathcal{B}(\Lambda_c^+ \to \Lambda\rho(770)^+)$	$(4.06 \pm 0.30 \pm 0.35 \pm 0.23) \times 10^{-2}$
$\mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^+\pi^0)$	$(5.86 \pm 0.49 \pm 0.52 \pm 0.35) \times 10^{-3}$
$\mathcal{B}(\Lambda_c^+ \to \Sigma(1385)^0\pi^+)$	$(6.47 \pm 0.59 \pm 0.66 \pm 0.38) \times 10^{-3}$
$\alpha_{\Lambda\rho(770)^+}$	$-0.763 \pm 0.053 \pm 0.045$
$\alpha_{\Sigma(1385)^+\pi^0}$	$-0.917 \pm 0.069 \pm 0.056$
$\alpha_{\Sigma(1385)^0\pi^+}$	$-0.789 \pm 0.098 \pm 0.056$

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

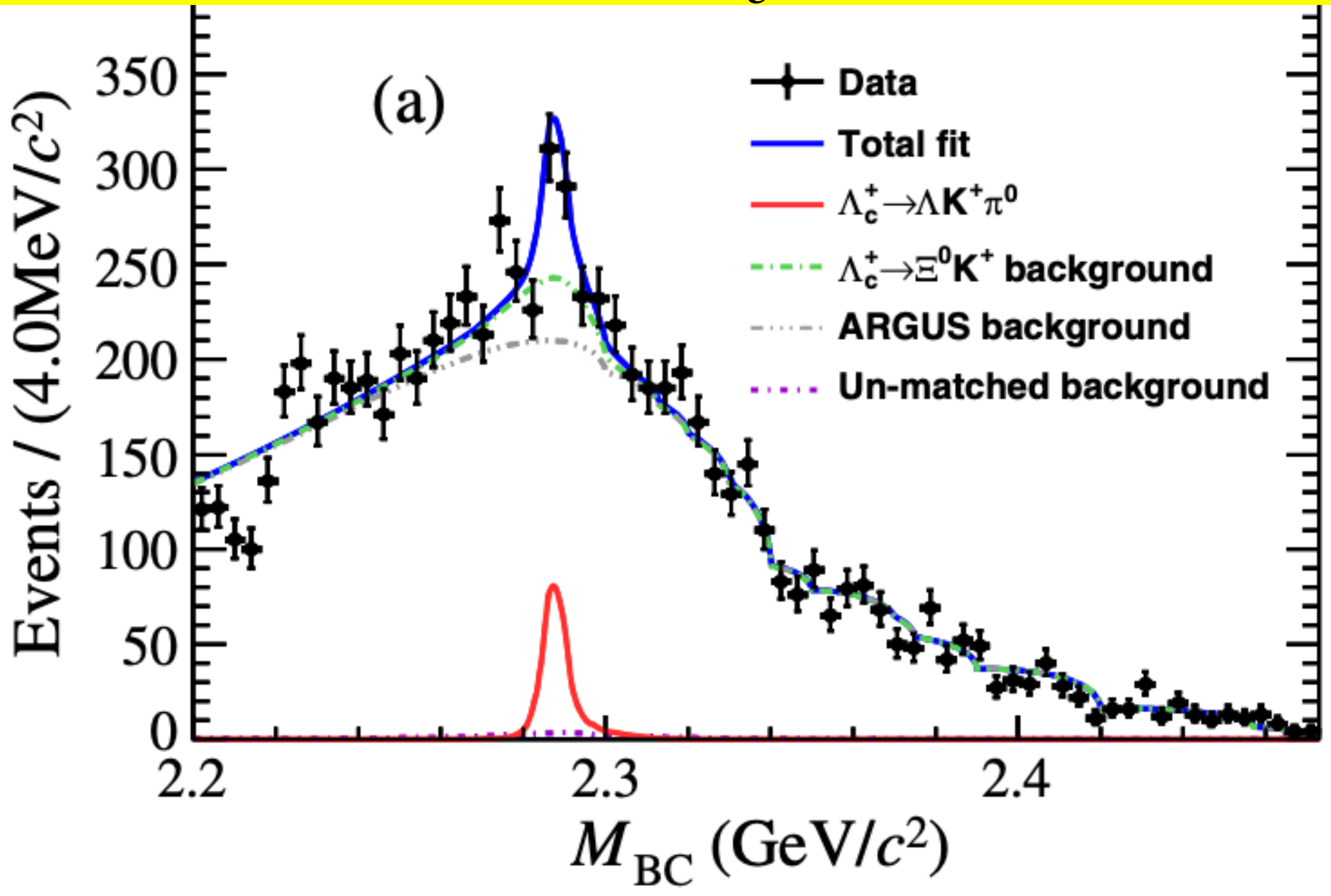
➔ NO theoretical models is able to explain both BFs and decay asymmetries simultaneously.

➔ Fruitful results are extracted which provide crucial input to extend the understanding of dynamics of charmed baryon hadronic decays.

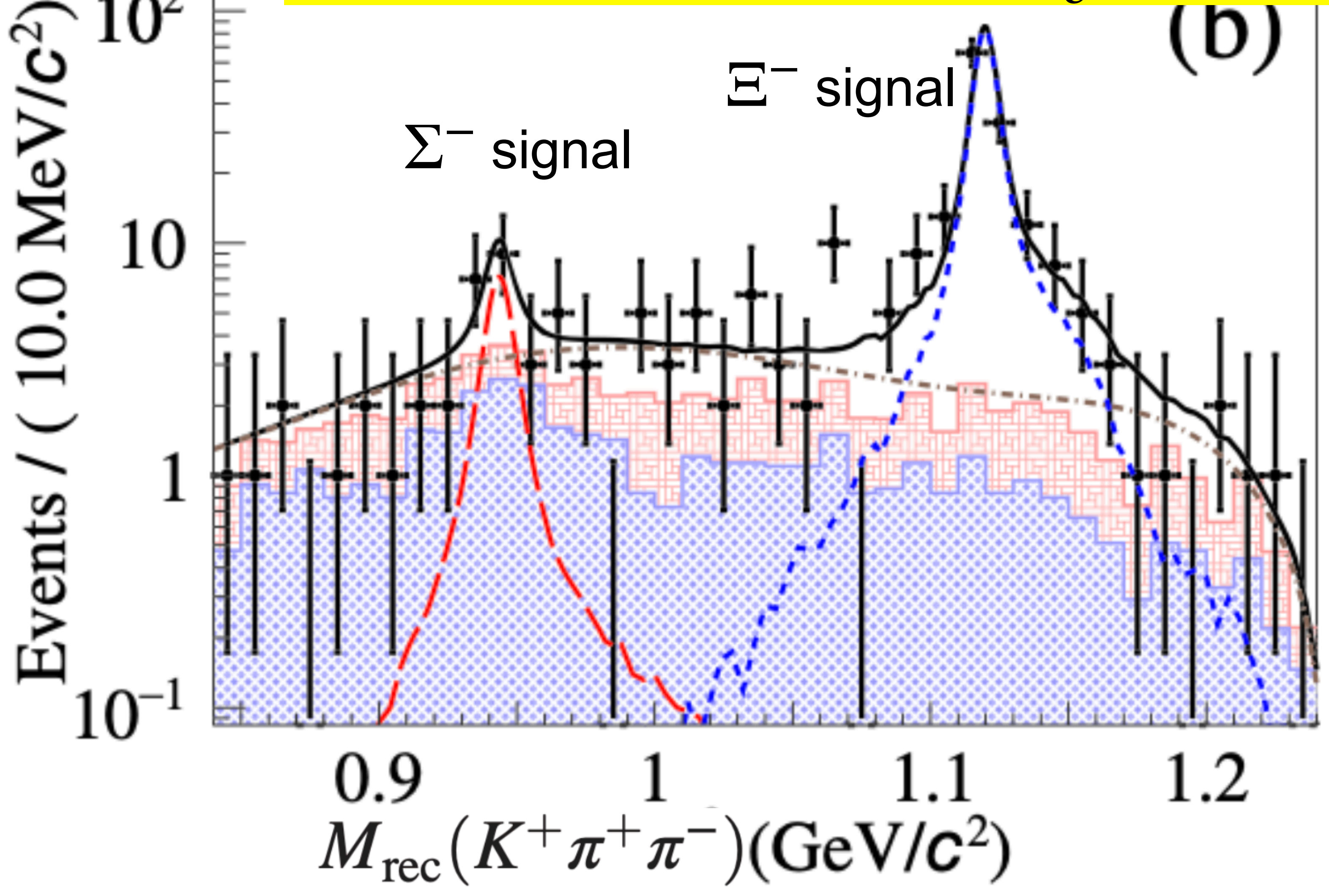
Measurements of $\Lambda_c^+ \to$ hyperon + kaon + pions

Phys. Rev. D 109, 032003 (2024).
Phys. Rev. D 109, L071103 (2024).
Phys. Rev. D 109, 052001 (2024).

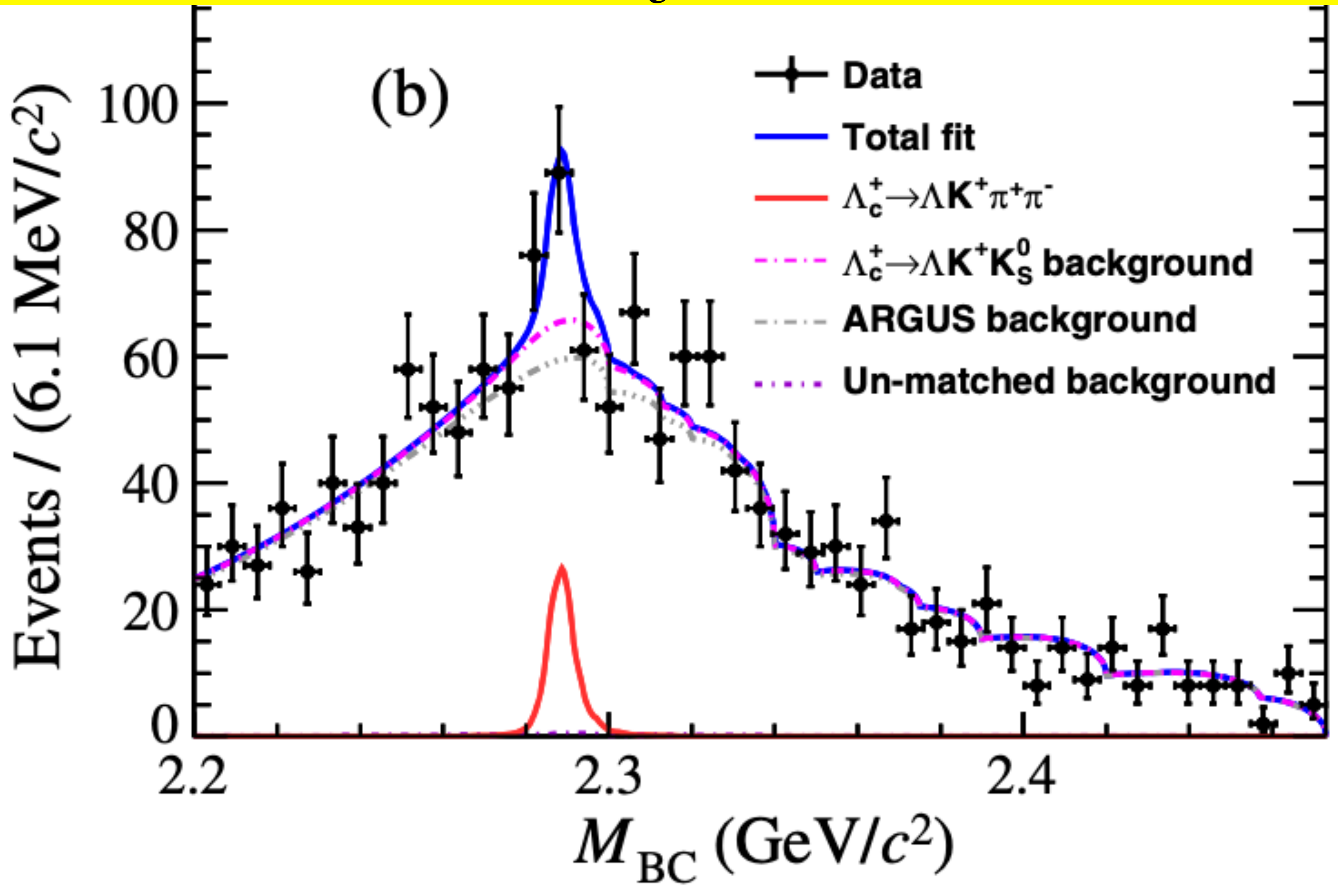
First observation of $\Lambda_c^+ \to \Lambda K^+ \pi^0$ 5.7σ



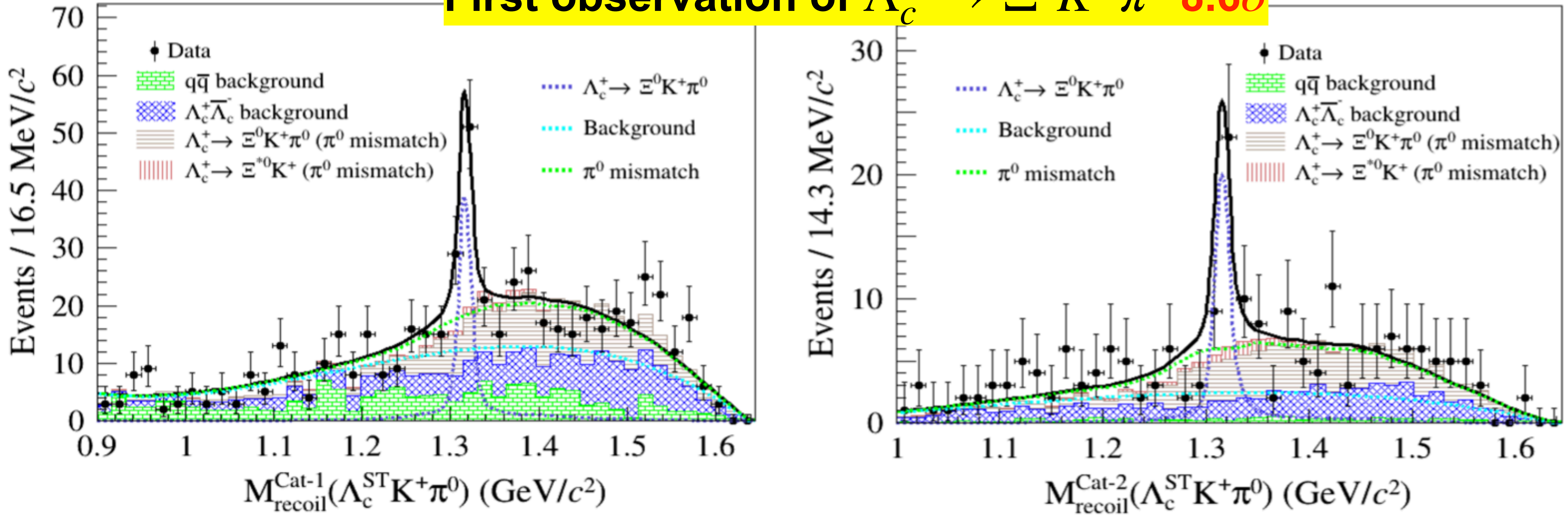
First observation of $\Lambda_c^+ \to \Sigma^- K^+ \pi^+$ 5.4σ



First evidence of $\Lambda_c^+ \to \Lambda K^+ \pi^+ \pi^-$ 3.1σ

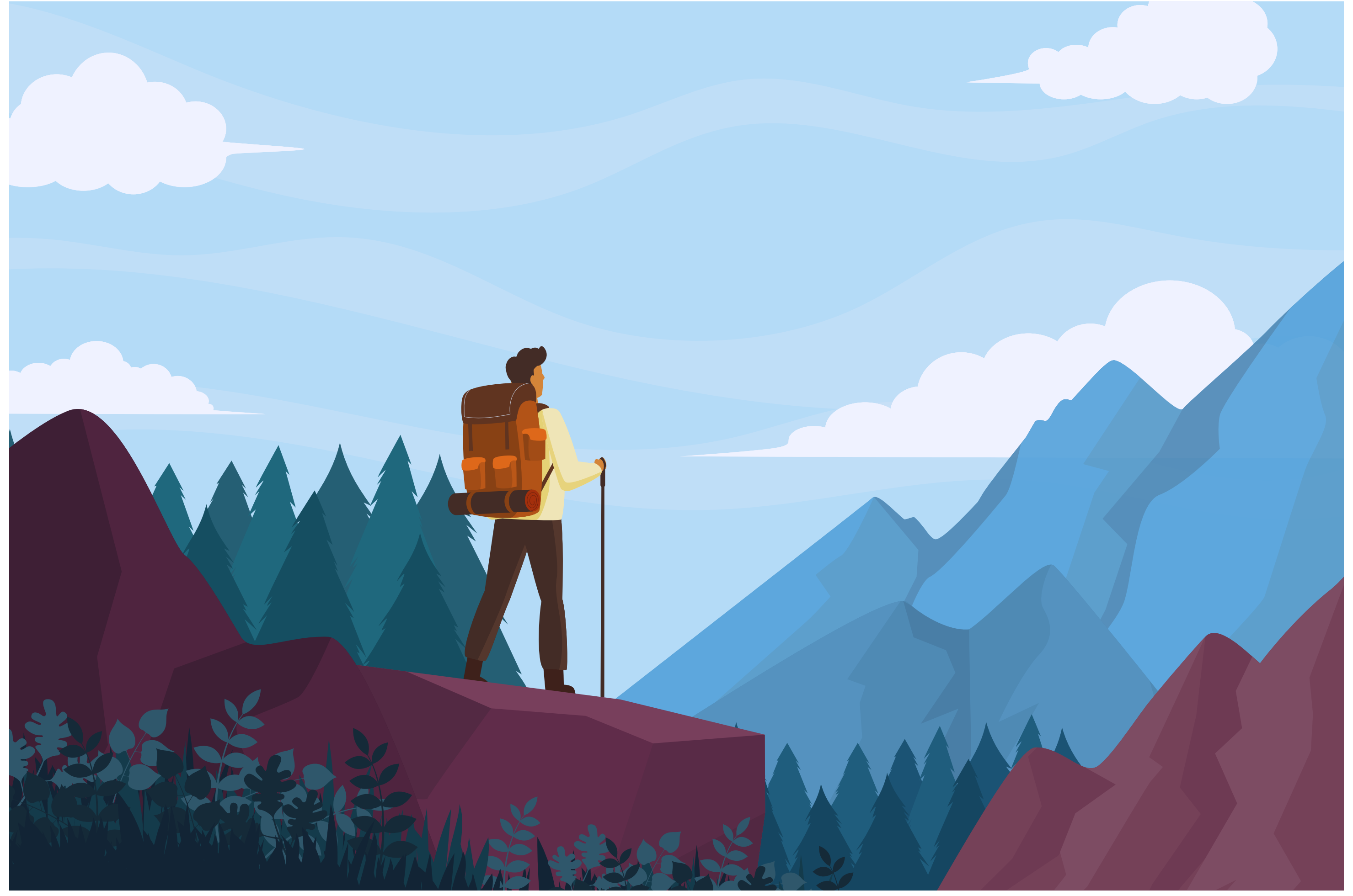


First observation of $\Lambda_c^+ \to \Xi^0 K^+ \pi^0$ 8.6σ



Other ongoing analysis

Roadmap of charm baryon physics at BESIII

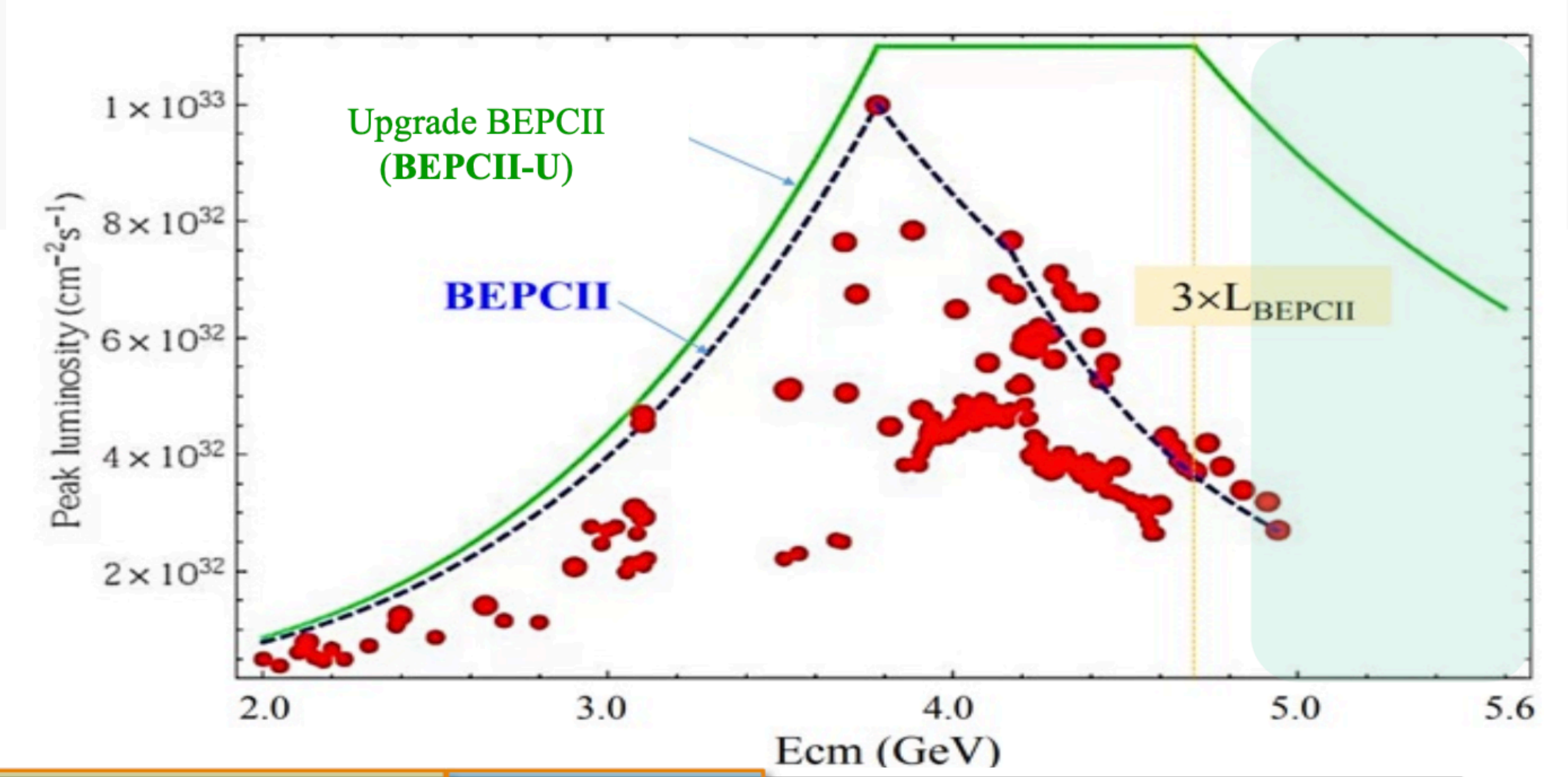


- ➔ SL: search for more CF $\Lambda^{(*)}e^+\nu_e$ and CS $N^{(*)}e^+\nu_e$ decays
  - ❖ $\Lambda_c^+ \to \Sigma^+\pi^-e^+\nu_e, \Sigma^-\pi^+e^+\nu_e, nK_S^0e^+\nu_e$
  - ❖ $\Lambda_c^+ \to ne^+\nu_e, p\pi^-e^+\nu_e$
- ➔ Final-state involving K_L^0: $K_S^0 - K_L^0$ asymmetry
  - ❖ $\Lambda_c^+ \to pK_L^0, pK_L^0\pi^0, pK_L^0\pi^+\pi^-$
- ➔ Decay asymmetry and polarization:
  - ❖ $\Lambda_c^+ \to pK_S^0, \Lambda\pi^+, \Sigma^0\pi^+, \Sigma^+\pi^0$
- ➔ PWA: extraction of intermediate state in three-body decays
  - ❖ $\Lambda_c^+ \to pK^+\pi^-, pK_S^0\pi^0, nK_S^0\pi^+, pK^+K^-(\phi)$
  - ❖ $\Lambda_c^+ \to \Lambda\pi^+\eta, \Sigma^0\pi^+\pi^0, \Sigma^+\pi^+\pi^-, \Sigma^-\pi^+\pi^+$
- ➔ Two-body BF: increasing dataset & improved technique
  - ❖ $\Lambda_c^+ \to \Sigma^+\eta, \Sigma^+\eta', p\pi^0, p\eta'$
- ➔ Multi-body BF:
  - ❖ $\Lambda_c^+ \to \Lambda K_S^0K^+, \Lambda K_S^0\pi^+(\Lambda K^{*+}), \Sigma^0K_S^0K^+, \Xi^0K_S^0K^+, \Xi^-K^+\pi^+$
- ➔ Inclusive:
  - ❖ $\Lambda_c^+ \to pX, nX, K_S^0X, \Lambda X$

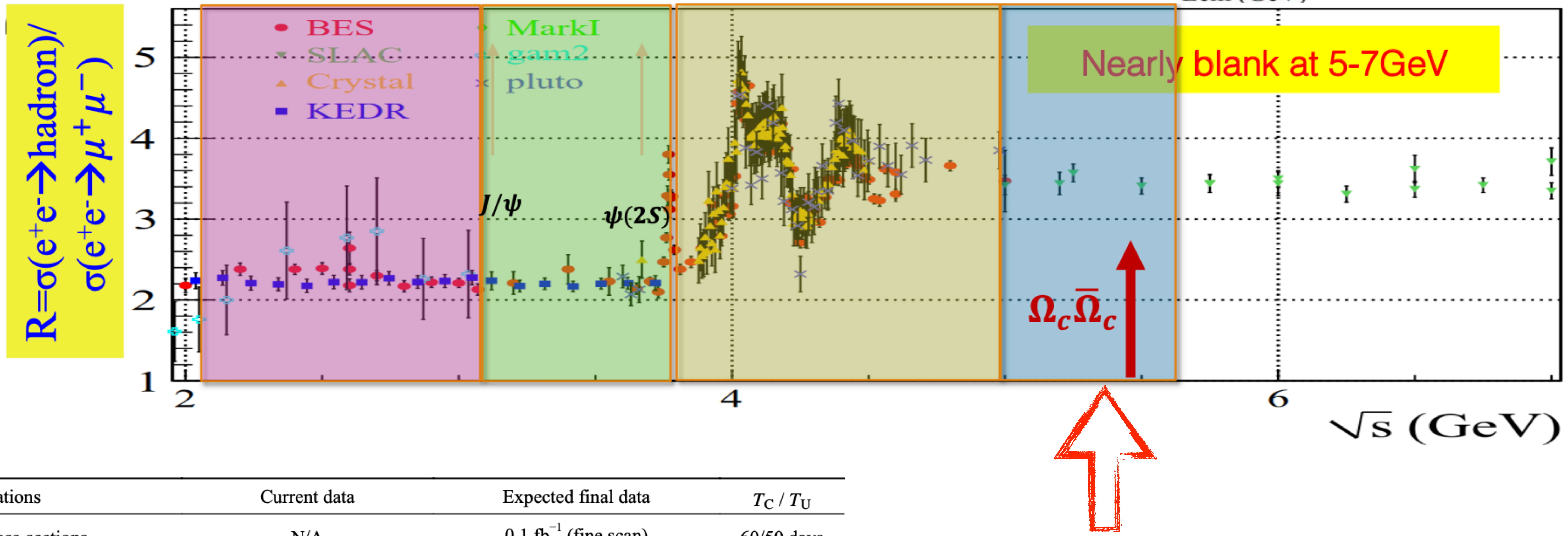
Comming soon
&
Stay tuned

Summary & outlook

Proposal of BEPCII upgrade



- ➔ BEPCII-U plans to be completed before 2025
- ➔ Improved luminosity by 3 times higher than current BEPCII at 4.7 GeV
- ➔ Extended the maximum energy to 5.6 GeV
  - ❖ Energy thresholds:
  - ❖ $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c^-$ 4.74 GeV
  - ❖ $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c\pi$ 4.88 GeV
  - ❖ $e^+e^- \to \Sigma_c\bar{\Sigma}_c$ 4.91 GeV
  - ❖ $e^+e^- \to \Xi_c\bar{\Xi}_c$ 4.94 GeV
  - ❖ $e^+e^- \to \Omega_c^0\bar{\Omega}_c^0$ 5.40 GeV



4.95~5.6 GeV: new energy coverage of BEPCII-U

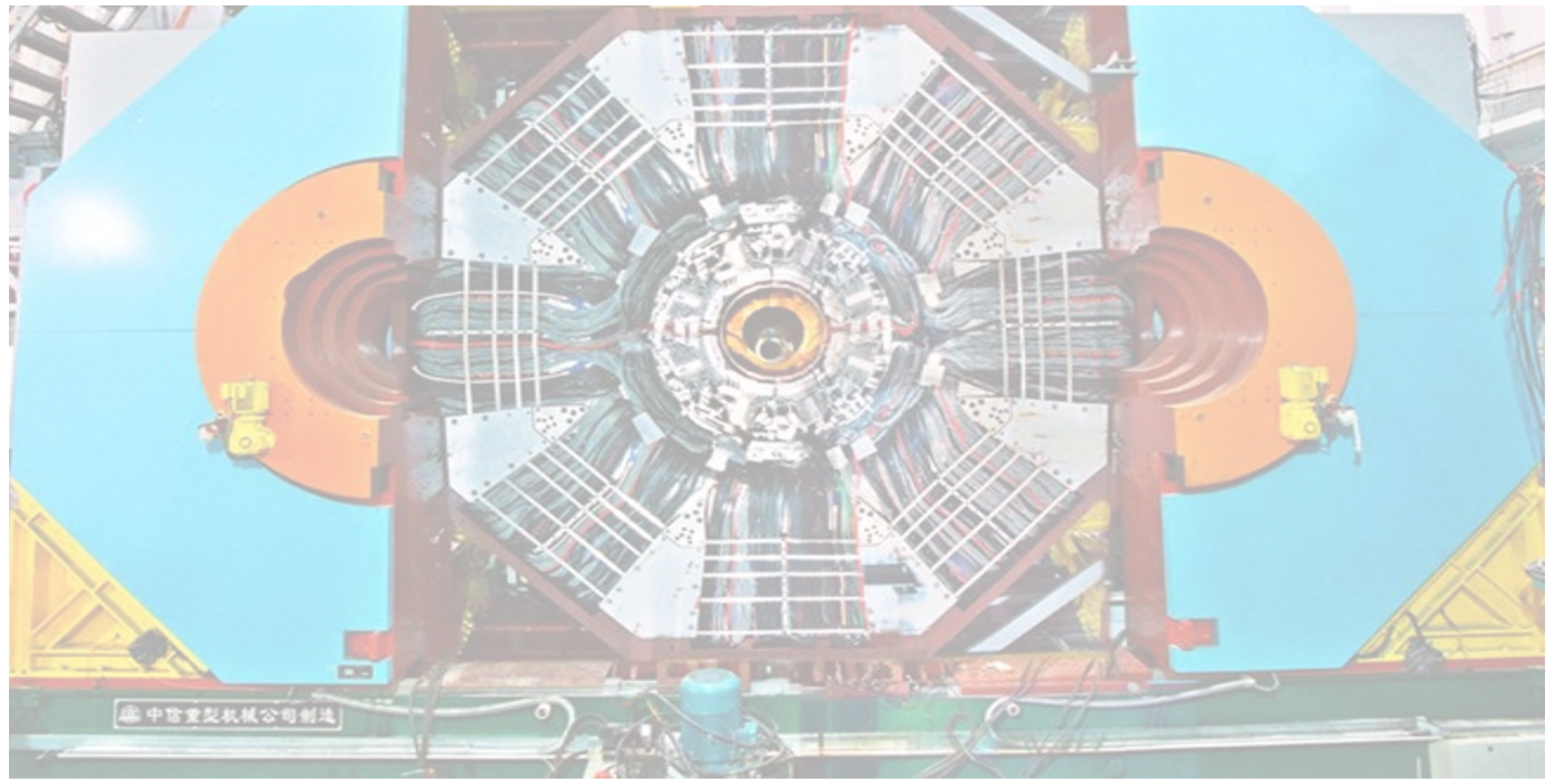
- ➔ BESIII white paper:

Energy	Physics motivations	Current data	Expected final data	T_C / T_U
1.8 - 2.0 GeV	R values Nucleon cross-sections	N/A	0.1 fb^{-1} (fine scan)	60/50 days
2.0 - 3.1 GeV	R values Cross-sections	Fine scan (20 energy points)	Complete scan (additional points)	250/180 days
J/ψ peak	Light hadron & Glueball J/ψ decays	3.2 fb^{-1} (10 billion)	3.2 fb^{-1} (10 billion)	N/A
$\psi(3686)$ peak	Light hadron & Glueball Charmonium decays	0.67 fb^{-1} (0.45 billion)	4.5 fb^{-1} (3.0 billion)	150/90 days
$\psi(3770)$ peak	$D^0/D^\pm$ decays	2.9 fb^{-1}	20.0 fb^{-1}	610/360 days
3.8 - 4.6 GeV	R values XYZ/Open charm	Fine scan (105 energy points)	No requirement	N/A
4.180 GeV	D_s decay XYZ/Open charm	3.2 fb^{-1}	6 fb^{-1}	140/50 days
4.0 - 4.6 GeV	XYZ/Open charm Higher charmonia cross-sections	16.0 fb^{-1} at different $\sqrt{s}$	30 fb^{-1} at different $\sqrt{s}$	770/310 days
4.6 - 4.9 GeV	Charmed baryon/XYZ cross-sections	0.56 fb^{-1} at 4.6 GeV	15 fb^{-1} at different $\sqrt{s}$	1490/600 days
4.74 GeV	$\Sigma_c^+\bar{\Lambda}_c^-$ cross-section	N/A	1.0 fb^{-1}	100/40 days
4.91 GeV	$\Sigma_c\bar{\Sigma}_c$ cross-section	N/A	1.0 fb^{-1}	120/50 days
4.95 GeV	Ξ_c decays	N/A	1.0 fb^{-1}	130/50 days

Summary & outlook

- ➔ BEPCII energy upgrade during 2020-2021 has improved the BESIII capability in Λ_c^+ physics by accumulating more statistics at different energy points and pose opportunity to study Λ_c^+ production and decays.
- ➔ BESIII has been playing significant role in studying Λ_c^+ decay.
- ➔ Fruitful Λ_c^+ physics results have been published during 2022-2024.
- ➔ More physics results coming soon
- ➔ Larger data samples will be collected at BESIII after BEPCII-U (3x luminosity and energy up to 5.6 GeV)
  $\Rightarrow$ more physics opportunities in charm baryon phyiscs

Thanks for your attention!

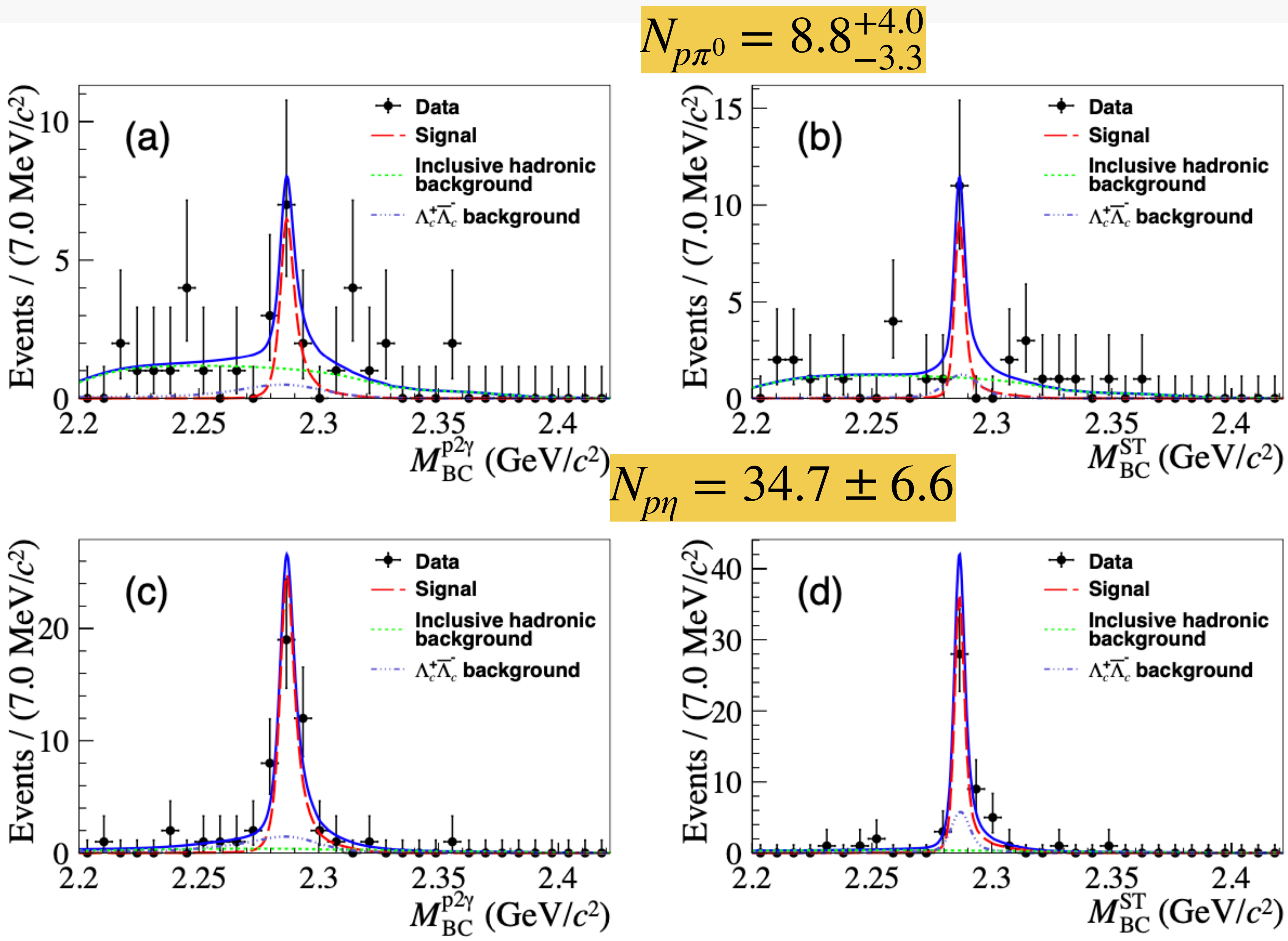


Backup

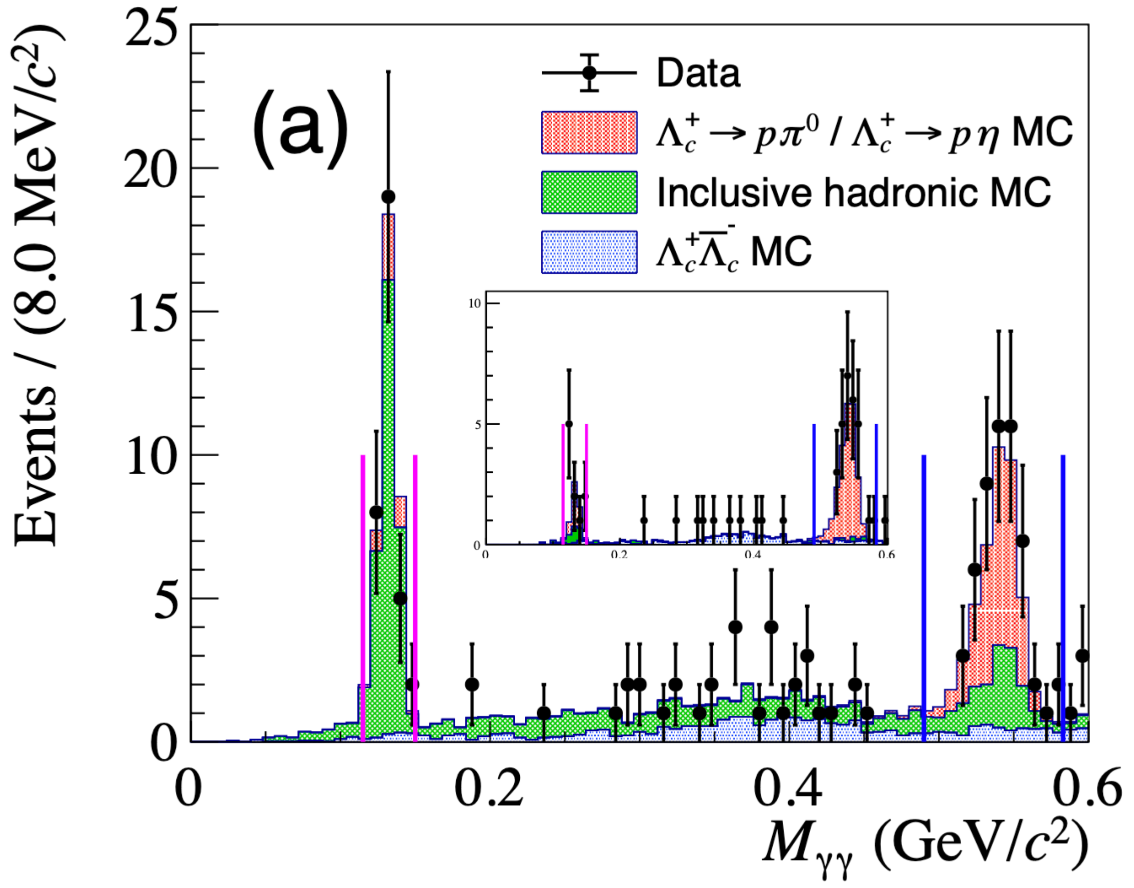
Measurement of $\Lambda_c^+ \to p\pi^0, p\eta$

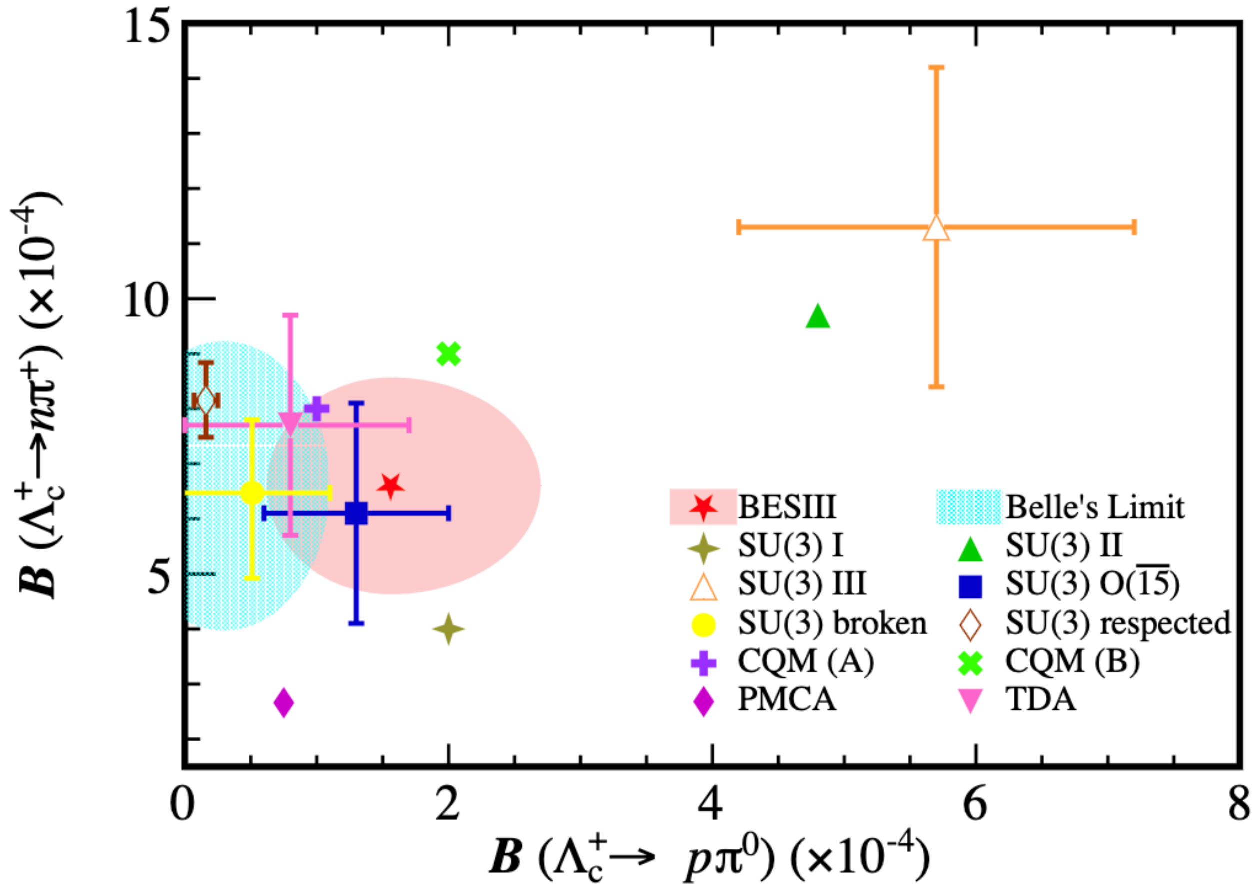
Phys. Rev. D 109, L091101 (2024)

- DT method, reconstructed by $\gamma\gamma$ channel, simultaneous fit to $M_{\rm BC}^{\rm ST}$ and $M_{\rm BC}^{p2\gamma}$



- $\mathcal{B}(\Lambda_c^+ \to p\pi^0) = (1.56^{+0.72}_{-0.58} \pm 0.20) \times 10^{-4}$ (3.7σ) $\Rightarrow$ first evidence
  - Result distinctly exceeds the upper limit measured by Belle ($< 8.0 \times 10^{-5}$)
- $\mathcal{B}(\Lambda_c^+ \to n\pi^+)/\mathcal{B}(\Lambda_c^+ \to p\pi^0) = 3.2^{+2.2}_{-1.2}$
  - Consistent with majority of phenomenological predictions
  - 2D plot shows the importance of considering $\mathcal{O}(\overline{15})$ which indicates the non-factorizable contribution
- $\mathcal{B}(\Lambda_c^+ \to p\eta) = (1.63 \pm 0.31_{\rm stat.} \pm 0.11_{\rm syst.}) \times 10^{-3}$ $\Rightarrow$ consistent with previous results



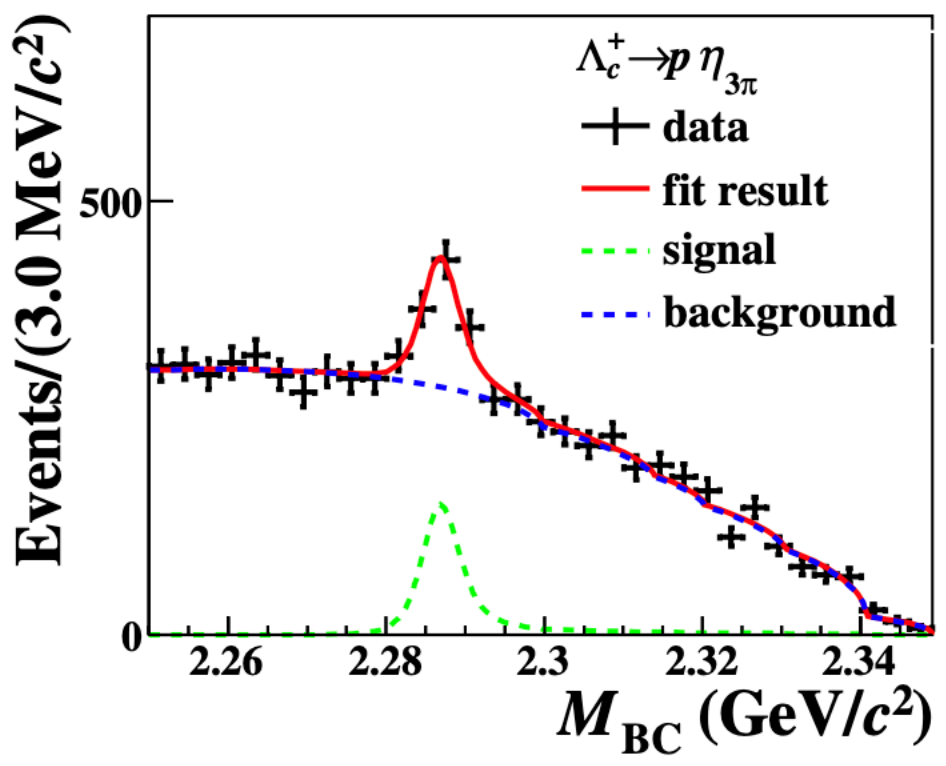


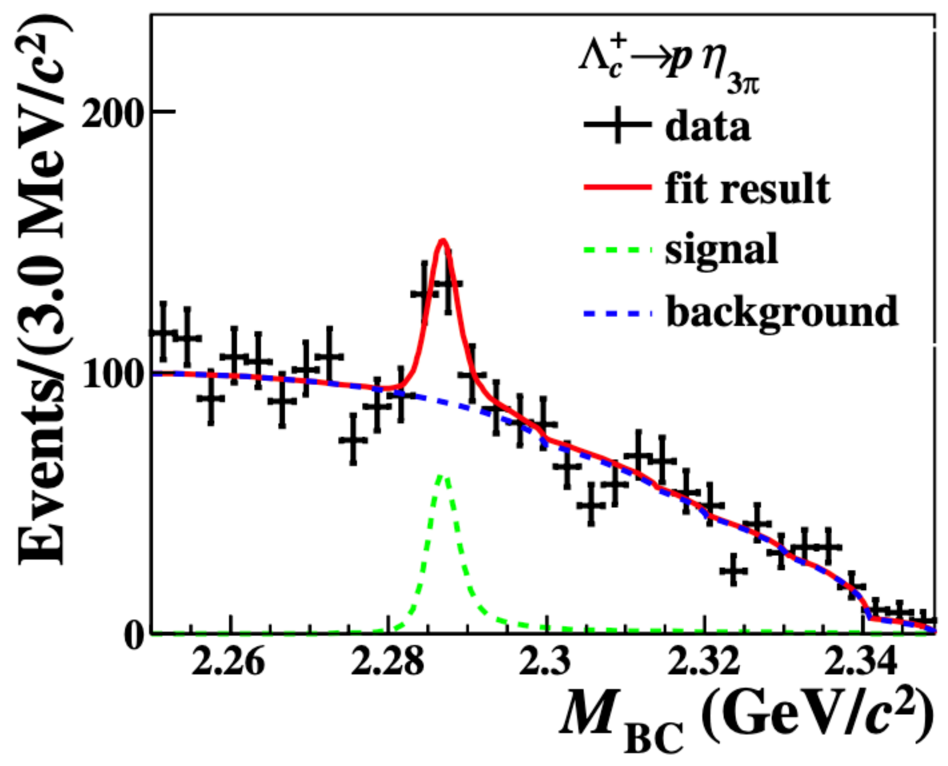
Measurement of $\Lambda_c^+ \to p\eta, p\omega$

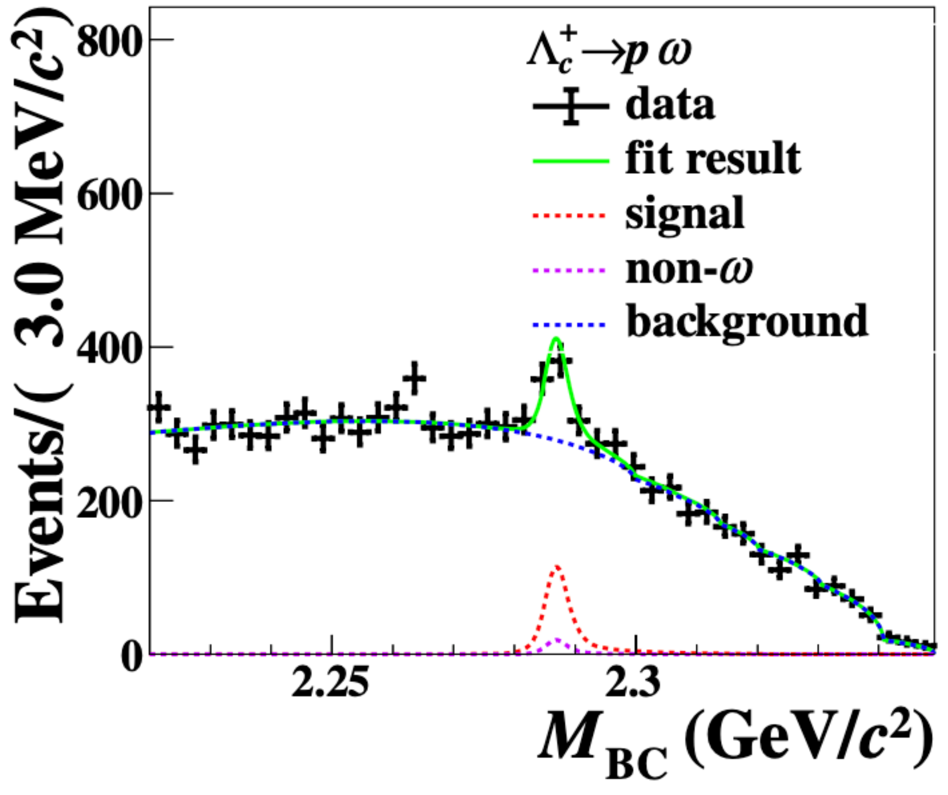
JHEP 11, 137 (2023).

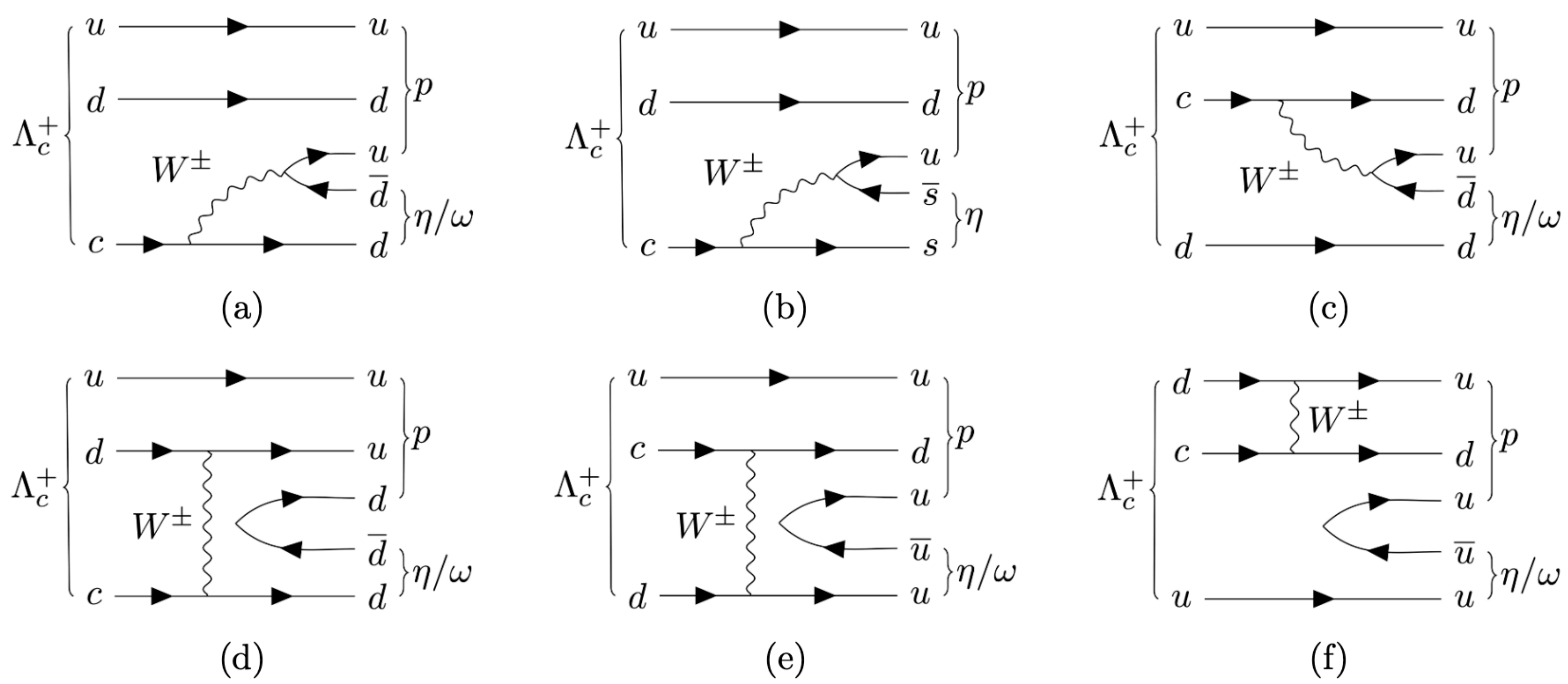
- ➔ ST method, $\eta \to \gamma\gamma$, $\eta \to \pi^+\pi^-\pi^0$ and $\omega \to \pi^+\pi^-\pi^0$
- ➔ $\mathcal{B}(\Lambda_c^+ \to p\eta) = (1.57 \pm 0.11_{\text{stat.}} \pm 0.04_{\text{syst.}}) \times 10^{-3}$ (>10σ)
  - ❖ Most precise to date
- ➔ $\mathcal{B}(\Lambda_c^+ \to p\omega) = (1.11 \pm 0.20_{\text{stat.}} \pm 0.07_{\text{syst.}}) \times 10^{-3}$ (5.7σ)
- ➔ Provide more stringent test for different theoretical models

		$\mathcal{B}(\Lambda_c^+ \to p\eta)$	$\mathcal{B}(\Lambda_c^+ \to p\omega)$
BESIII		$1.24 \pm 0.28 \pm 0.10$ [22]	—
LHCb		—	$0.94 \pm 0.32 \pm 0.22$ [23]
Belle		$1.42 \pm 0.05 \pm 0.11$ [24]	$0.827 \pm 0.075 \pm 0.075$ [25]
This paper		$1.57 \pm 0.11 \pm 0.04$	$1.11 \pm 0.20 \pm 0.07$
Current algebra	Uppal [13]	0.3	—
	Cheng [26]	1.28	—
SU(3) flavor symmetry	Sharma [14]	$0.2^a(1.7^b)$	—
	Geng [27]	$1.25^{+0.38}_{-0.36}$	—
	Geng [28]	1.30 ± 0.10	—
	Hsiao [29]	1.24 ± 0.21	—
	Geng [30]	—	0.63 ± 0.34
	Hsiao [31]	—	1.14 ± 0.54
	Zhong [32]	$1.36^a(1.27^b)$	—
Topological diagram method	Hsiao [33]	1.42 ± 0.23^c (1.47 ± 0.28^d)	—
Heavy quark effective theory	Singer [34]	—	0.36 ± 0.02









Measurement of $\Lambda_c^+ \to p\eta'$

Phys. Rev. D 106, 072002 (2023).

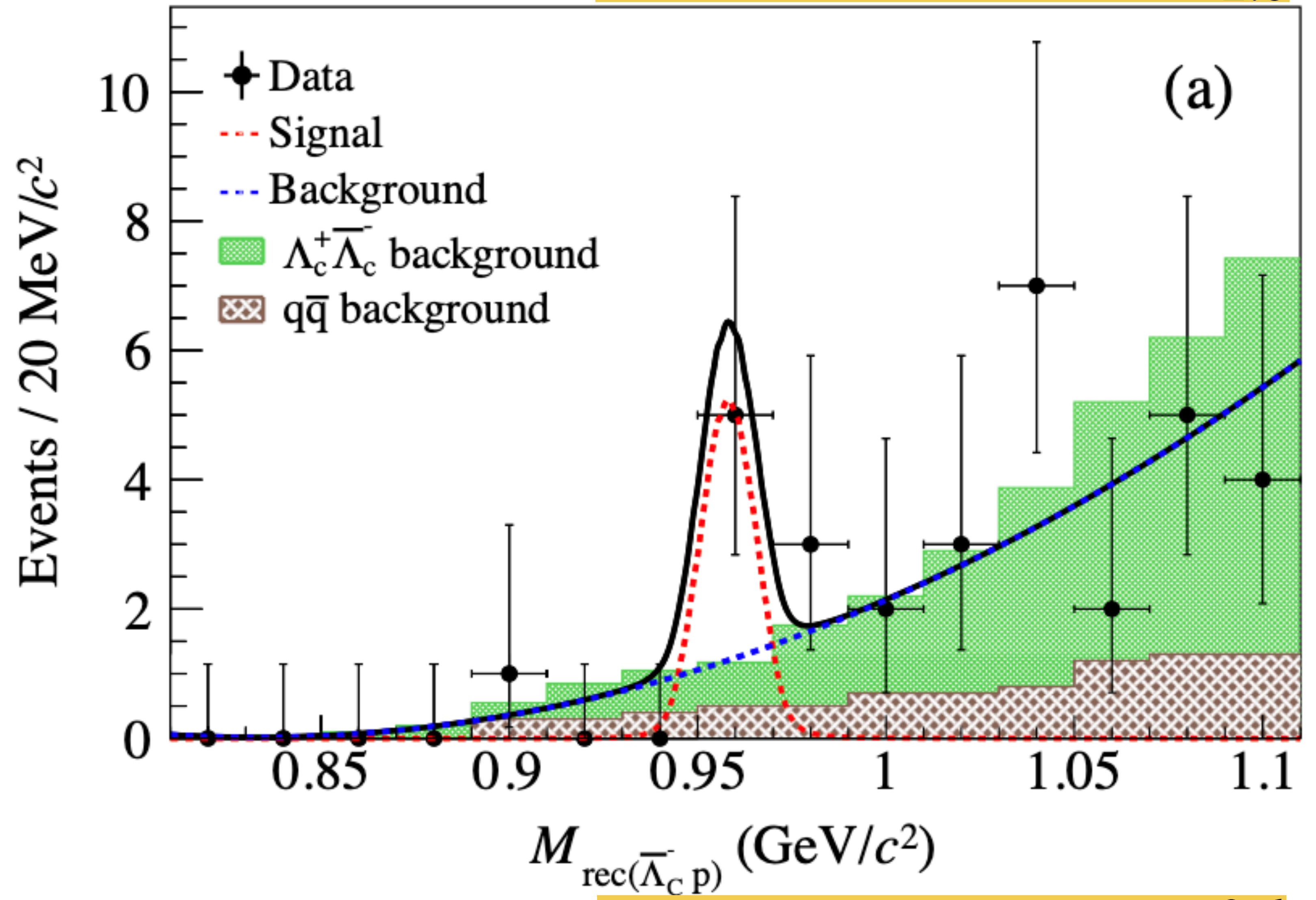
- ➔ DT method, reconstructed by $\eta' \to \pi^+\pi^-\eta$ and $\pi^+\pi^-\gamma$
  - ❖ For $\pi^+\pi^-\eta$ channel, using recoiling η method
  - ❖ For $\pi^+\pi^-\gamma$ channel, using full reconstruction method

- ➔ Absolute branching fraction is measured to be $\mathscr{B}(\Lambda_c^+ \to p\eta') = (5.62^{+2.46}_{-2.04}) \times 10^{-4}$ with 3.6σ
  - ❖ Consistent with Belle's relative measurement
  - ❖ Obviously higher than Constituent quark model prediction.

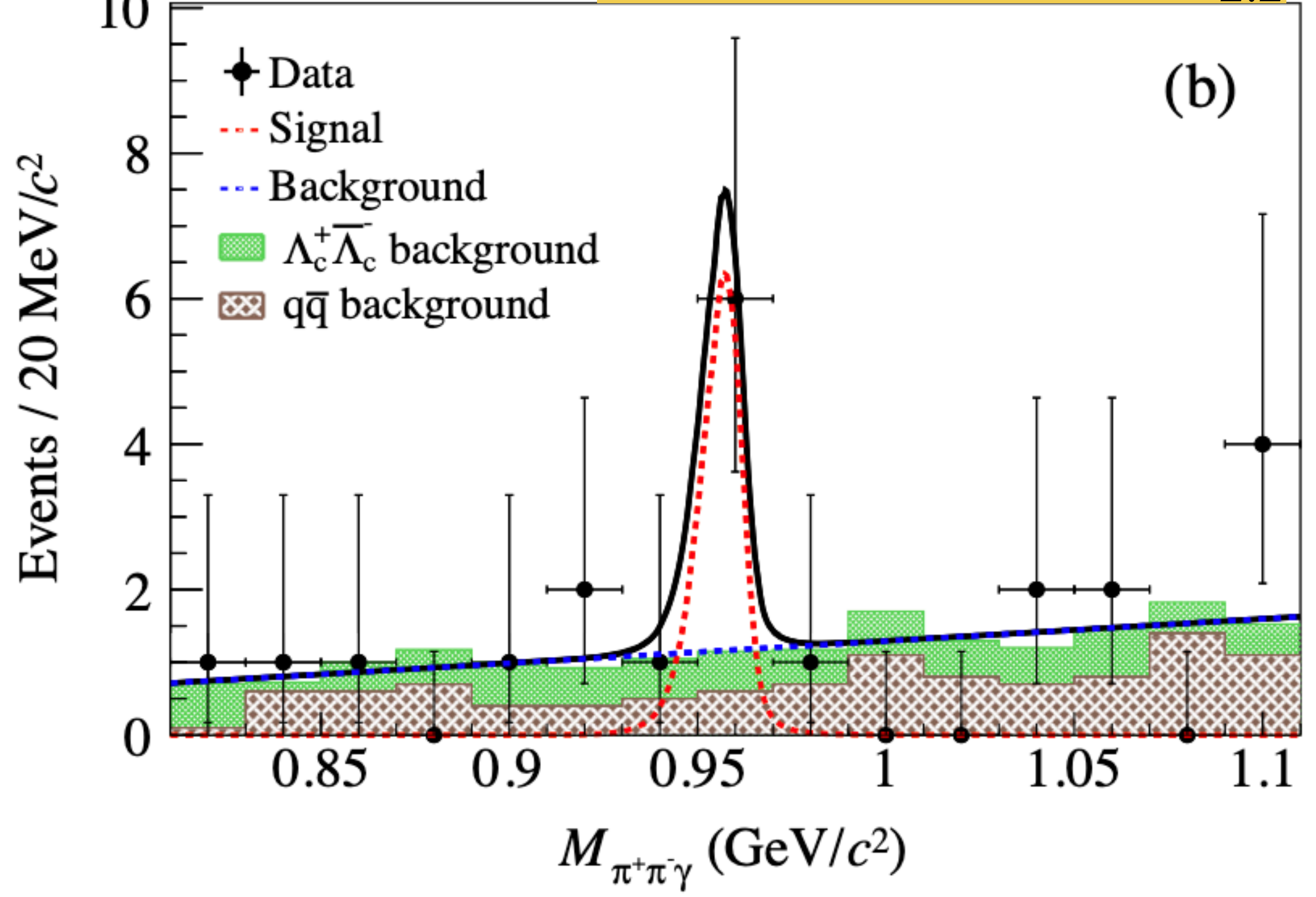
TABLE VI. Comparison of the measured branching fraction (in 10^{-4}) of $\Lambda_c^+ \to p\eta'$ to theoretical predictions and the Belle result.

	$\Lambda_c^+ \to p\eta'$
BESIII	$5.62^{+2.46}_{-2.04} \pm 0.26$
Belle [19]	4.73 ± 0.97
Sharma *et al.* [41]	4–6
Uppal *et al.* [42]	0.4–2
Geng *et al.* [17]	$12.2^{+14.3}_{-8.7}$

$N(p\eta', \pi^+\pi^-\eta) = 4.9^{+3.2}_{-2.6}$



$N(p\eta', \pi^+\pi^-\gamma) = 4.3^{+2.6}_{-2.2}$



The statistics of data is quite limited

Data-driven method for anti-neutron reconstruction

- Data-driven $\bar{n}$ reconstruction efficiency

Algorithm 1 Simulation of detection efficiency of the anti-neutron. Event accepted means that the corresponding event is detected for a given set of selection criteria, otherwise that event is lost.

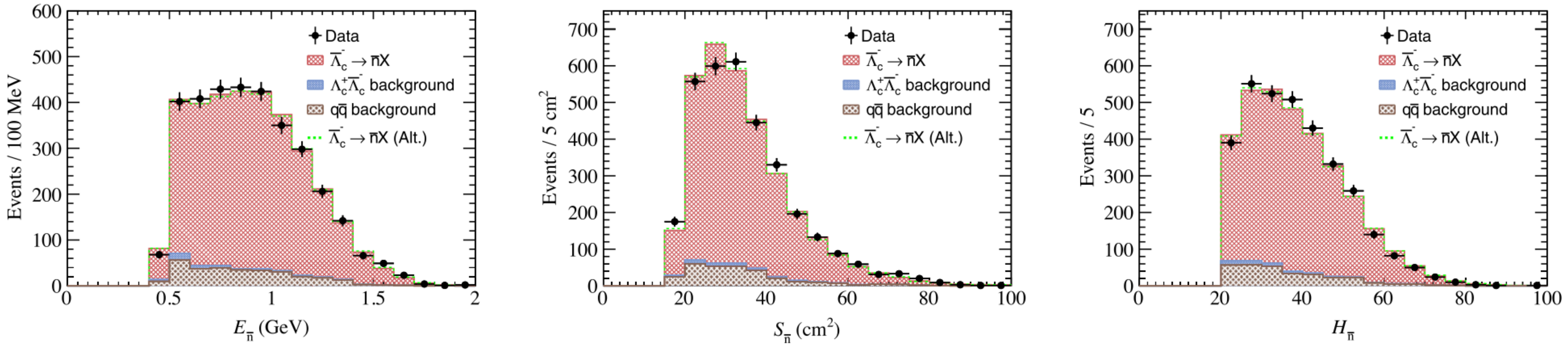
for all events (after preliminary selection criteria) **do**
  Extract the momentum $p_{\bar{n}}$ and polar angle $\cos\theta_{\bar{n}}$ of anti-neutron from generator;
  Determine detection efficiency of anti-neutron ε_i according to Eq. 4;
  Generate $u_i \sim \mathcal{U}(0, 1)$ (the uniform distribution over the unit interval).
  if $u_i \leq \varepsilon_i$ **then**
    Anti-neutron has information in EMC, event accepted.
  else
    No information of anti-neutron is left in EMC, event rejected.
  end if
end for

- Data-driven $\bar{n}$ detector response

Algorithm 2 Simulation of observables for anti-neutron in EMC, taking $E_{\bar{n}}$ as an example.

for all anti-neutrons with information in EMC from Algorithm 1 **do**
  Generate $u \sim \mathcal{U}(0, 1)$ (the uniform distribution over the unit interval).
  Find the inverse of the desired CDF, *e.g.* $E^{-1}(x)$.
  Calculate $E_{\bar{n}}$ by $E_{\bar{n}} = E^{-1}(u)$.
end for

- Control sample: $J/\psi \to p\bar{n}\pi^-$

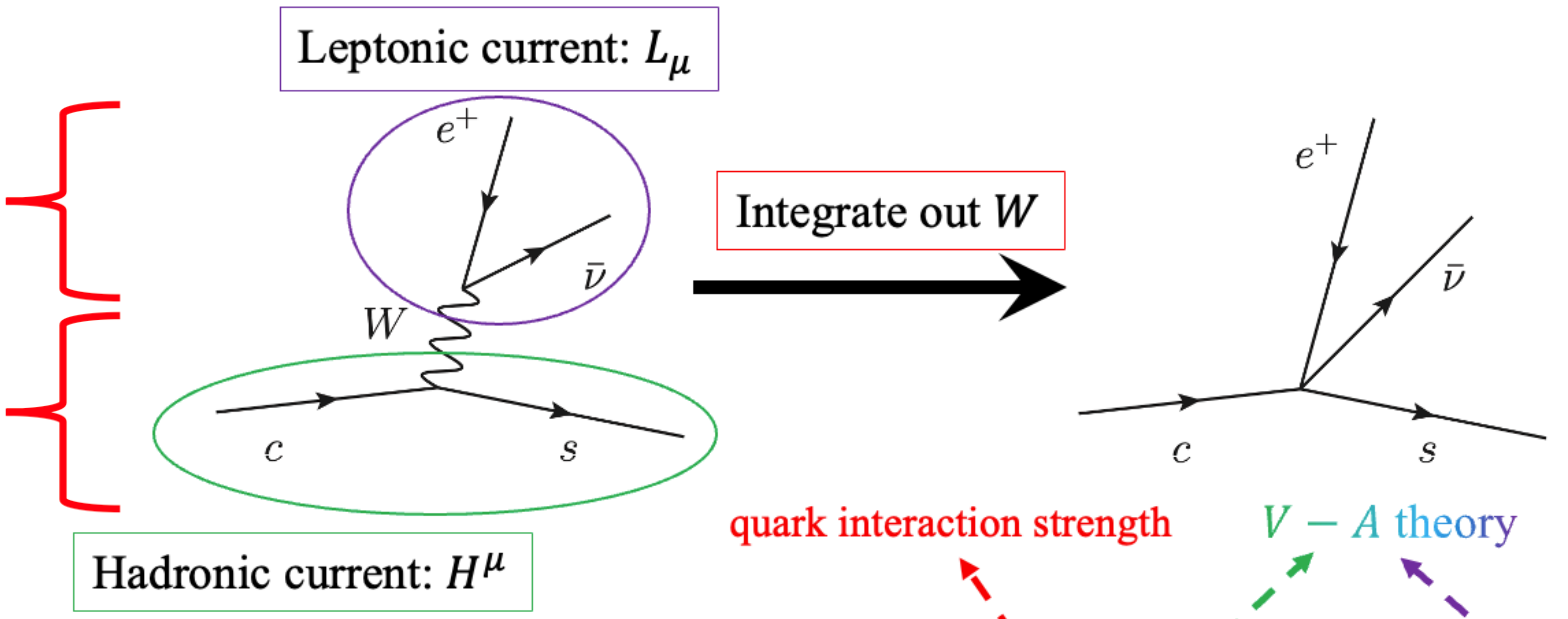


Why semi-leptonic decay?

- Semi-leptonic (SL) decay: good platform to study weak/strong interaction and probe new physics beyond the Standard Model.
- Take $c(\Lambda_c^+) \rightarrow s(\Lambda)$ 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.

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

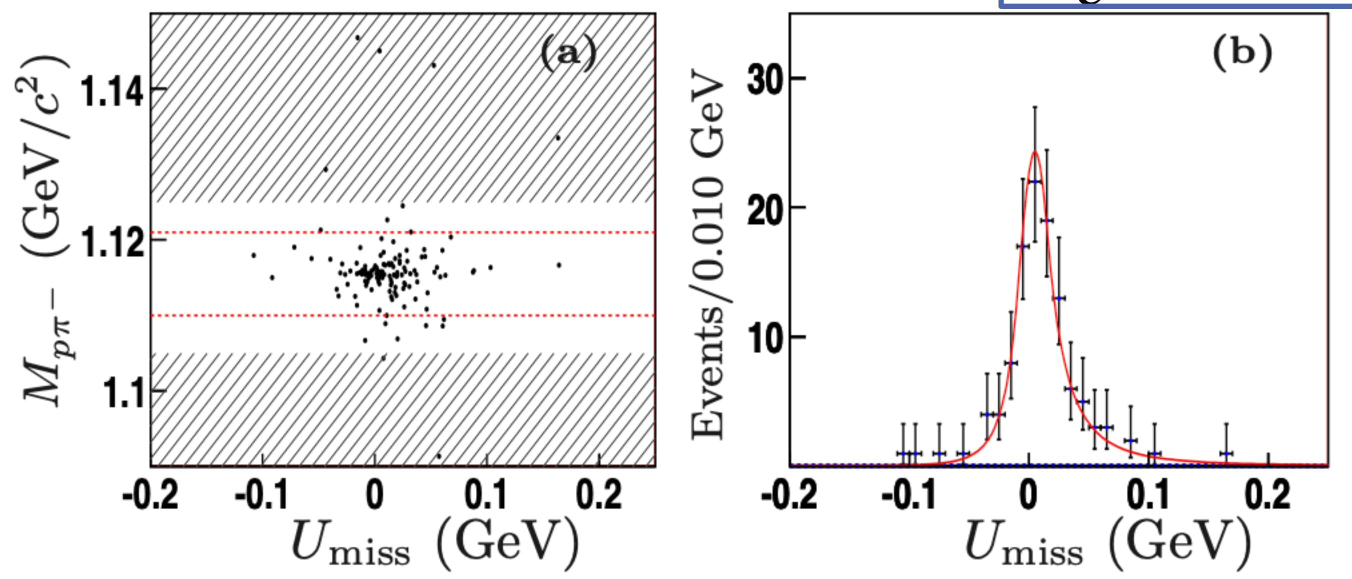
- ❖ Branching Fraction (BF), Lepton Flavor Universality (LFU)
- ❖ q^2- and angular dependent differential decay width, FF, Forward-backward asymmetry (A_{FB}), decay asymmetry, polarization…
- ❖ New physics observables

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

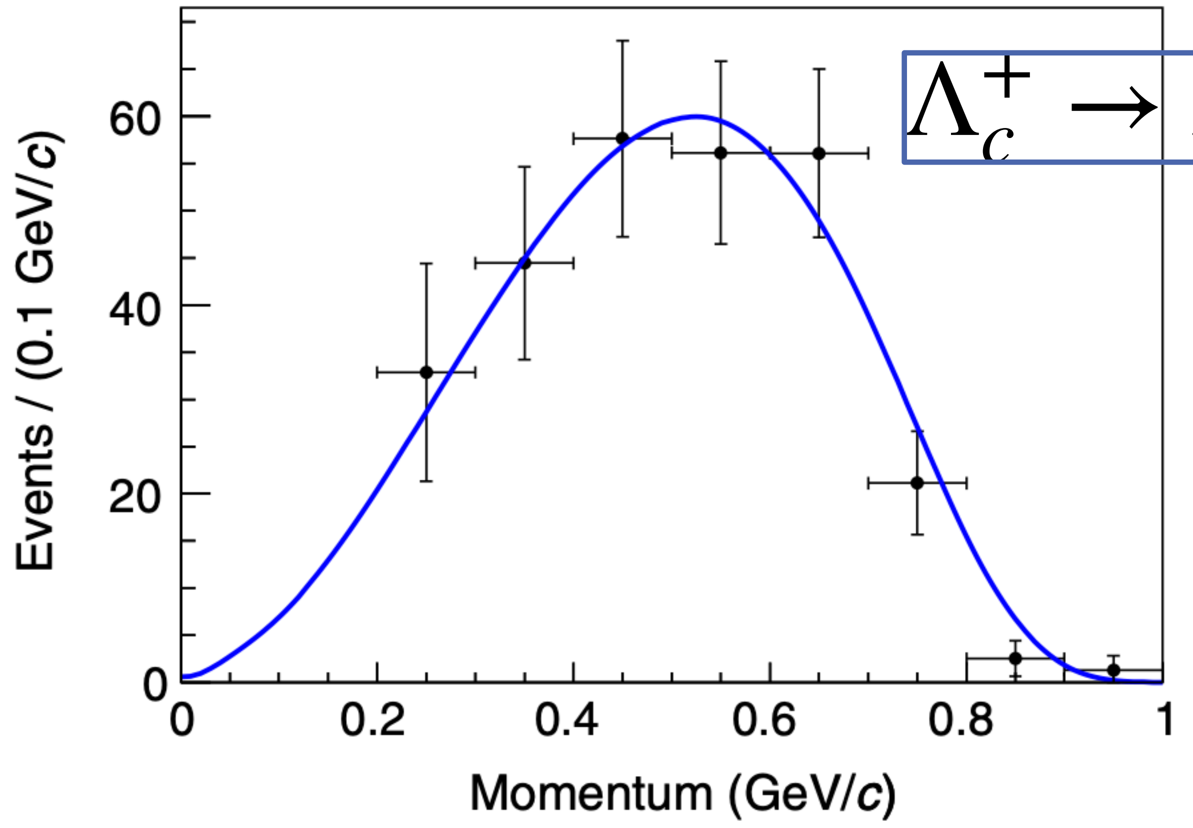
Λ_c^+ SL decays in experiment

- 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
    - $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.63 \pm 0.38_{\text{stat.}} \pm 0.20_{\text{syst.}})\ \%$[5]
    - $\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu) = (3.49 \pm 0.46_{\text{stat.}} \pm 0.27_{\text{syst.}})\ \%$[6]
    - $\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e) = (3.95 \pm 0.34_{\text{stat.}} \pm 0.09_{\text{syst.}})\ \%$[7]
    - $\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu)/\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (96 \pm 16_{\text{stat.}} \pm 4_{\text{syst.}})\ \%$[6]
    - $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)/\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e) = (91.9 \pm 12.5_{\text{stat.}} \pm 5.4_{\text{syst.}})\ \%$[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 ⇒ 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)

BF measurements of $\Lambda_c^+ \to \Lambda e^+ \nu_e$

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

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

Differ by > 2σ

Four-dimensional fit for $\Lambda_c^+ \to \Lambda e^+ \nu_e$

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

- z-expansion: FF is q^2 dependent, refer to LQCD parameterization
  - Free parameters: a_0^f and α_1^f
  - m_{pole}^f: pole mass, $m_{\text{pole}}^{f_+,f_\perp} = 2.112\,\text{GeV}/c^2$ and $m_{\text{pole}}^{g_+,g_\perp} = 2.460\,\text{GeV}/c^2$
  - a_0^f and α_1^f: free parameters
  - $z(q^2) = [(\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0})/(\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0})]$ with $t_0 = q^2_{\text{max}} = (m_{\Lambda_c} - m_\Lambda)^2, t_+ = (m_D - m_K)^2$
  - $m_D = 1.870\,\text{GeV}/c^2$ and $m_K = 0.494\,\text{GeV}/c^2$
- 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 $-0.06 < U_{\text{miss}} < 0.06$
  - Normalization using BF: $a_0^{g_\perp} = 0.54 \pm 0.04_{\text{stat.}} \pm 0.01_{\text{syst.}}$

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

Comparison with theoretical calculations for $\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$

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

	$\mathcal{B}(\Lambda_c^+ \to \Lambda\mu^+\nu_\mu)$	$\langle\alpha_{\Lambda_c}\rangle$	$\langle A_{FB}^e\rangle$	$\langle A_{FB}^\mu\rangle$
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

FF measurement and New physics search in $\Lambda_c^+ \to \Lambda l^+ \nu_l$

- ➔ Partial decay width for $\Lambda_c^+ \to \Lambda l^+ \nu_l$
  - ❖ Considering lepton mass term

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

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

- ➔ New physics search: T asymmetry parameter $\mathcal{T}_p$
  - ❖ Consistent with zero as predicted from the SM
  - ❖ No indication of new physics in $\Lambda_c^+ \to \Lambda l^+ \nu_l$ decays

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

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

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

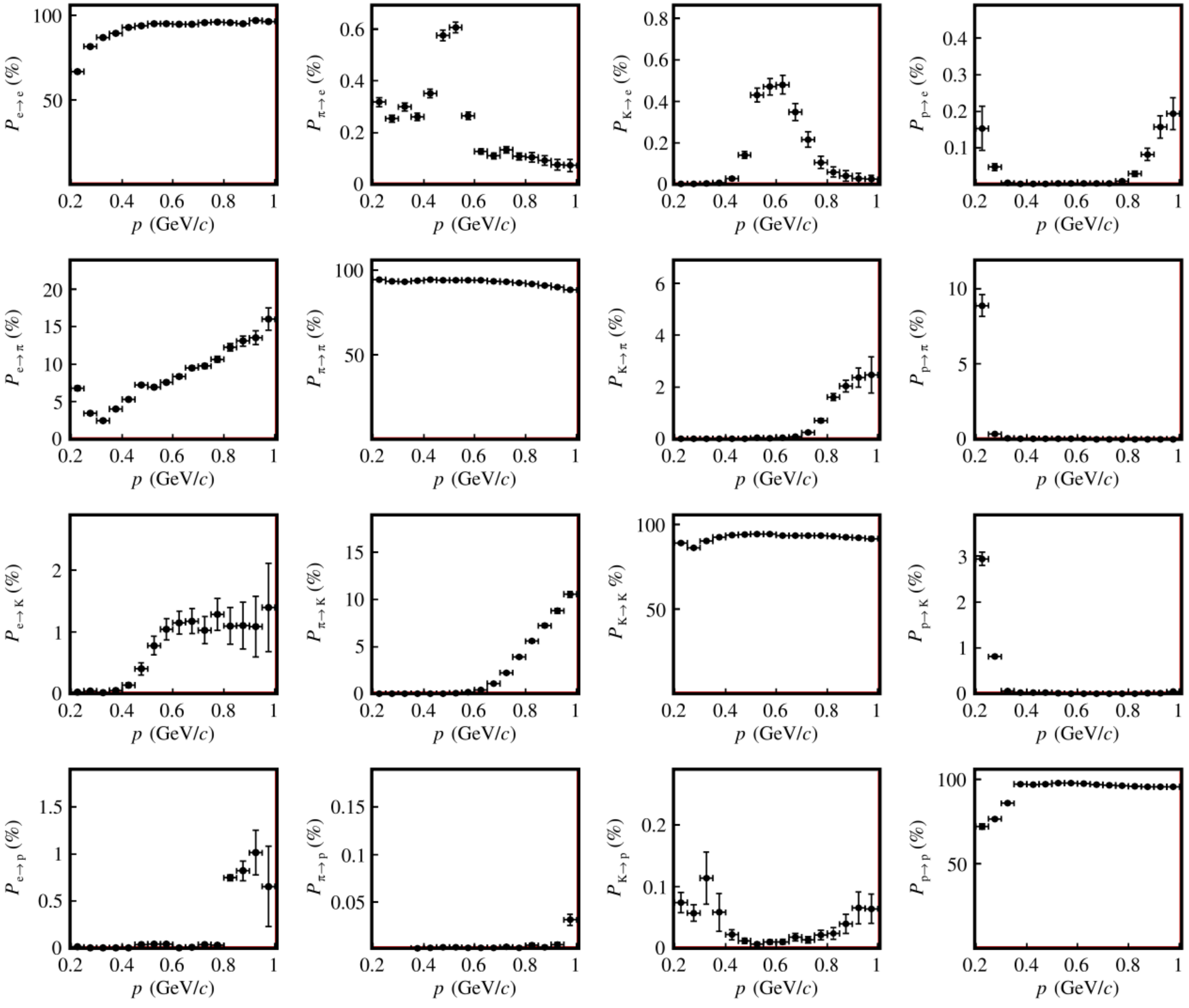


FIG. 4. PID efficiencies as a function of momentum used to populate the $A_{\rm PID}$ matrices.

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	

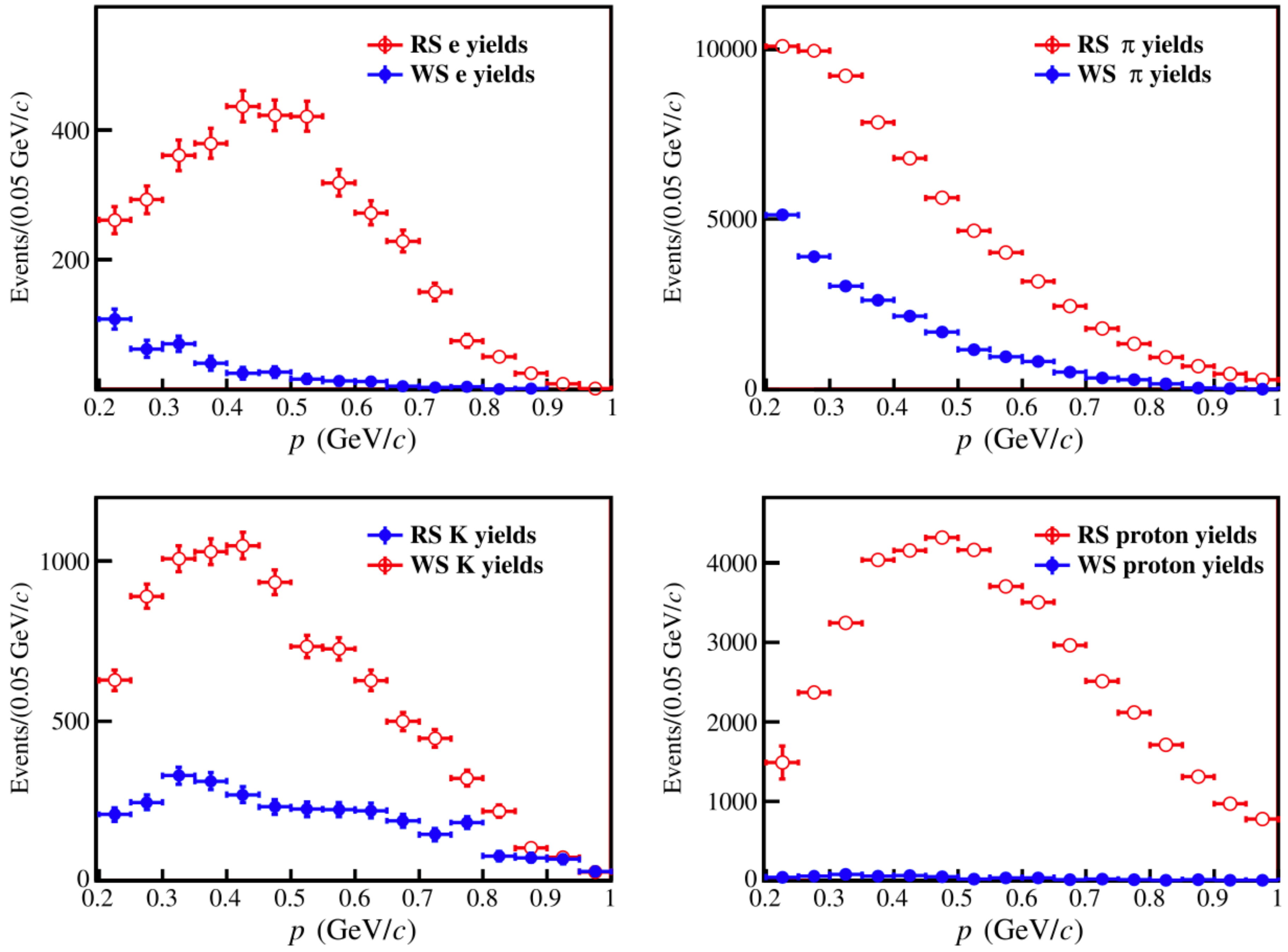


FIG. 3. Measured RS (blue) and WS (red) yields for each particle category as a function of momentum.

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

- ➔ 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 $P_{\rm miss}$ and the most energetic shower

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

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

➔ Profile likelihood method

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

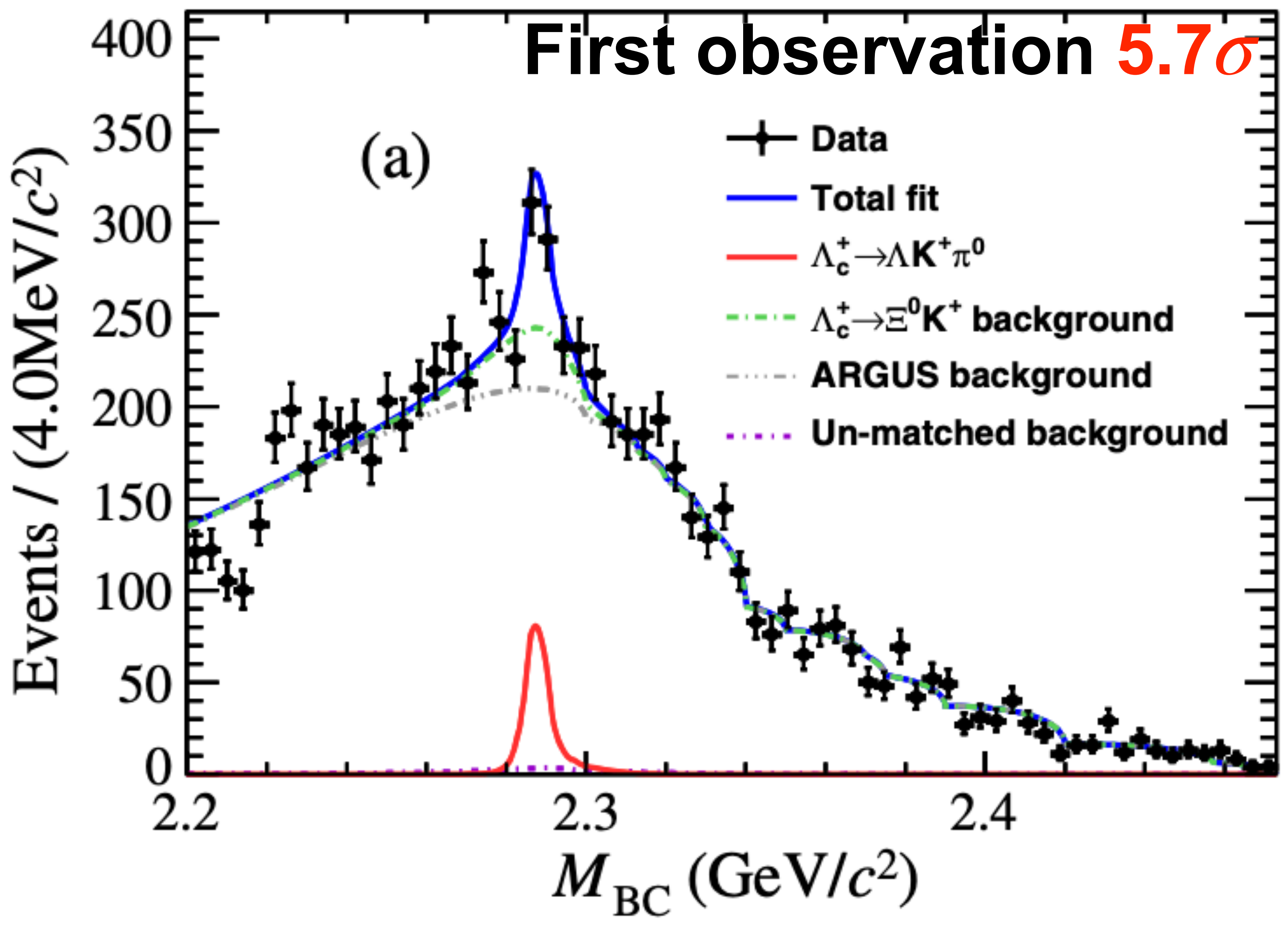
- $N^{\rm obs} \sim \mathscr{P}(N^{\rm obs} \,|\, N_{\rm sig} + N_{\rm bkg1} + N_{\rm bkg2})$

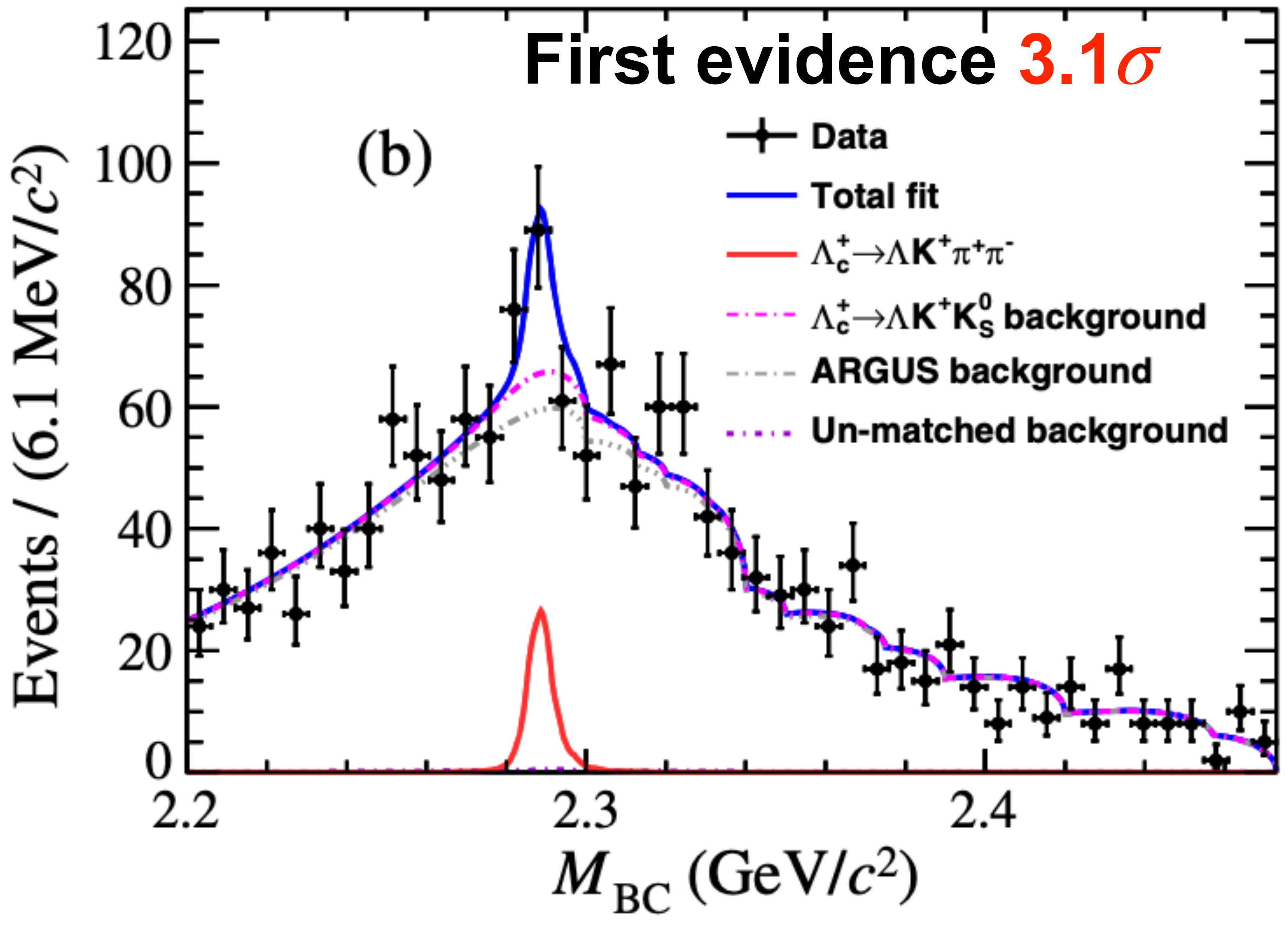
➔ The signal event number $N_{\rm sig} = \mathscr{B}_{\rm sig}\cdot\mathscr{B}^{\rm inter}\cdot N^{\rm ST}\cdot\varepsilon^{\rm sig} = \mathscr{B}_{\rm sig}\cdot N^{\rm eff}$

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

Measurement of $\Lambda_c^+ \to \Lambda K^+\pi^0, \Lambda K^+\pi^+\pi^-$

Phys. Rev. D 109, 032003 (2024).

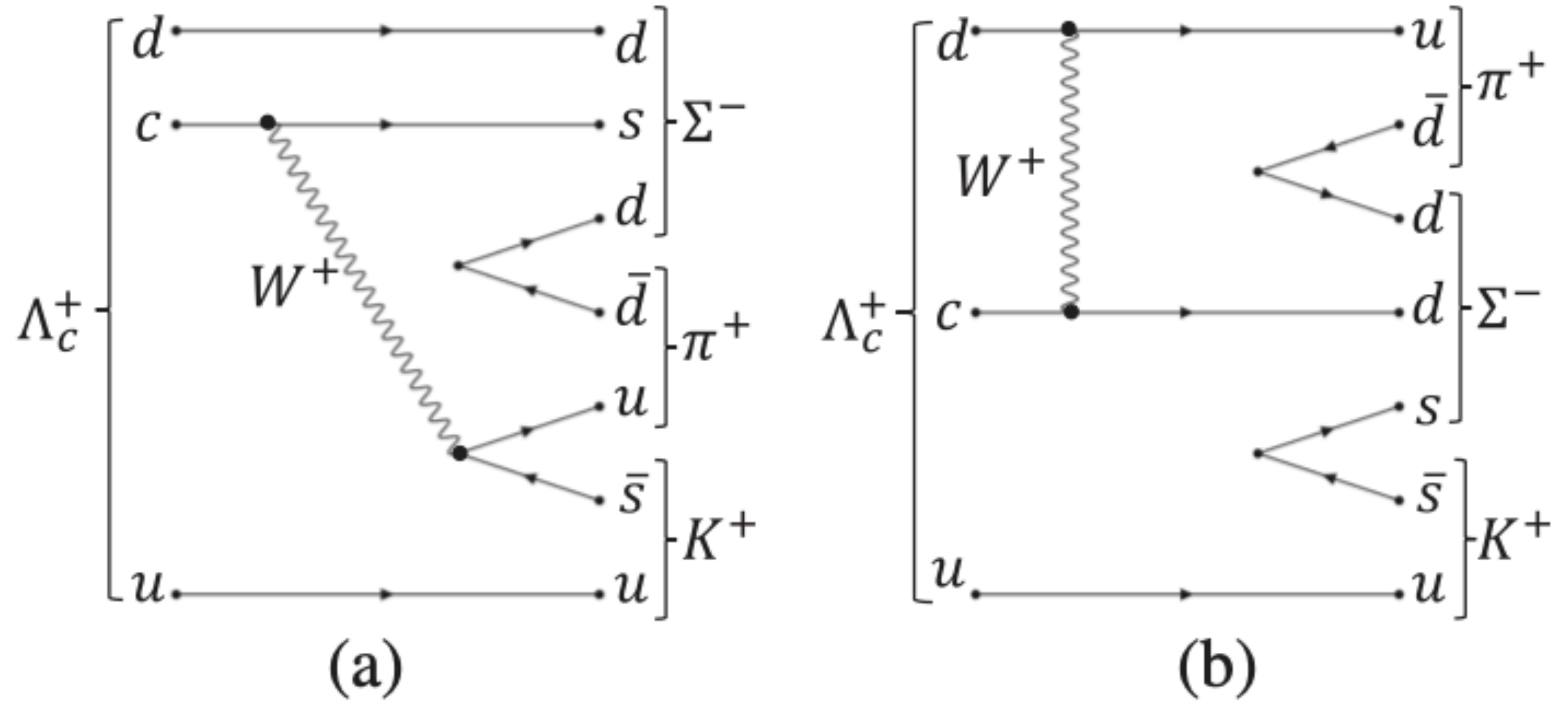


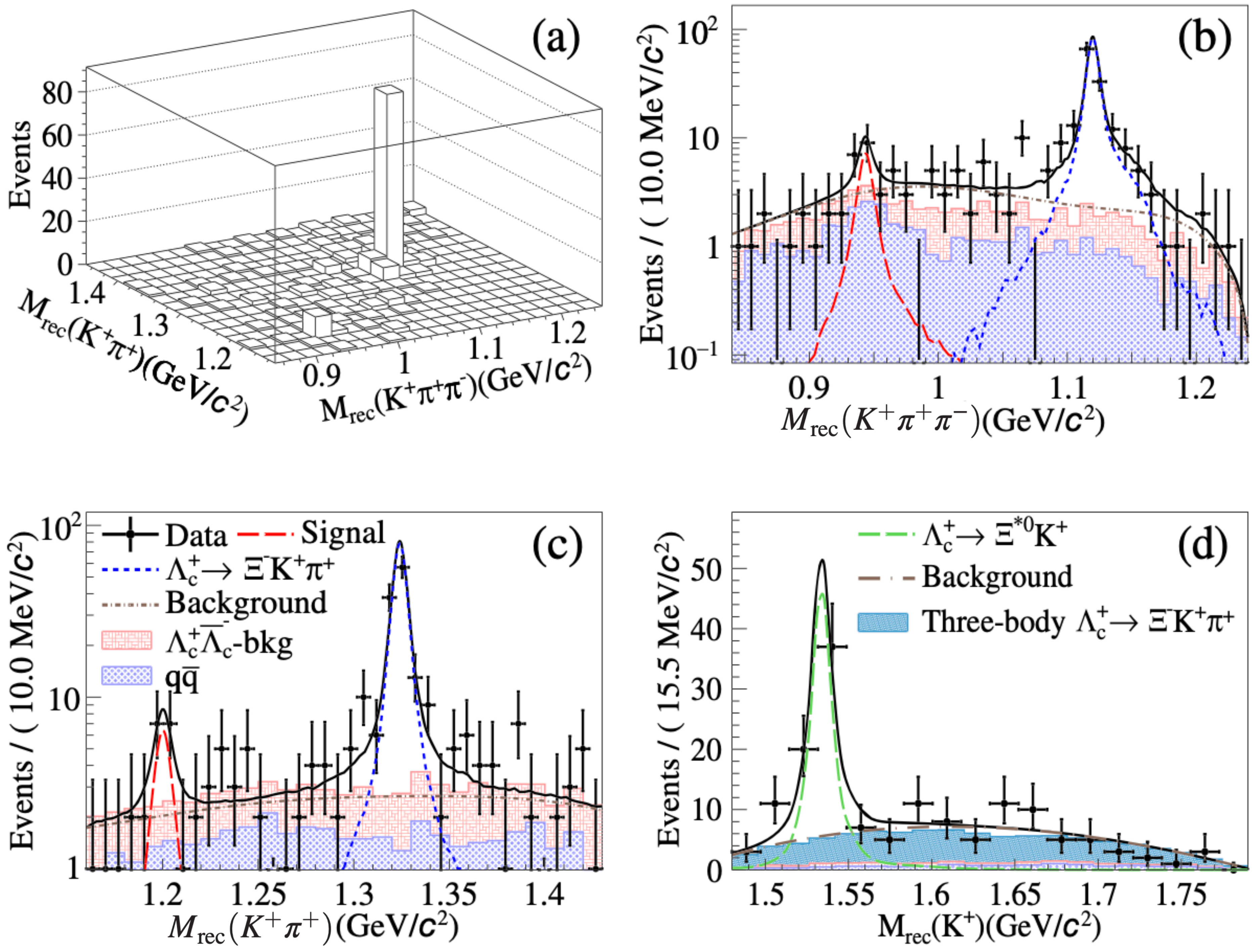


- ➔ Two SCS decays, measurement relative to CF channels
- ➔ $$\frac{\mathscr{B}(\Lambda_c^+ \to \Lambda K^+\pi^0)}{\mathscr{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^0)} = (2.09 \pm 0.39_{\text{stat.}} \pm 0.07_{\text{syst.}}) \times 10^{-2}$$
- ➔ $$\frac{\mathscr{B}(\Lambda_c^+ \to \Lambda K^+\pi^+\pi^-)}{\mathscr{B}(\Lambda_c^+ \to \Lambda\pi^+\pi^-\pi^+)} = (1.13 \pm 0.41_{\text{stat.}} \pm 0.06_{\text{syst.}}) \times 10^{-2}$$
- ➔ Taken BFs of reference channel from PDG
- ➔ $\mathscr{B}(\Lambda_c^+ \to \Lambda K^+\pi^0) = (1.49 \pm 0.27_{\text{stat.}} \pm 0.05_{\text{syst.}} \pm 0.08_{\text{ref.}}) \times 10^{-3}$
  - ❖ Deviate from $SU(3)_F$ predictions by more than 3σ
- ➔ $\mathscr{B}(\Lambda_c^+ \to \Lambda K^+\pi^+\pi^-) = (4.13 \pm 1.48_{\text{stat.}} \pm 0.20_{\text{syst.}} \pm 0.33_{\text{ref.}}) \times 10^{-4}$
  - ❖ Consistent with upper limit measured by *BABAR*

Measurement of $\Lambda_c^+ \to \Sigma^- K^+ \pi^+$

Phys. Rev. D 109, L071103 (2024).

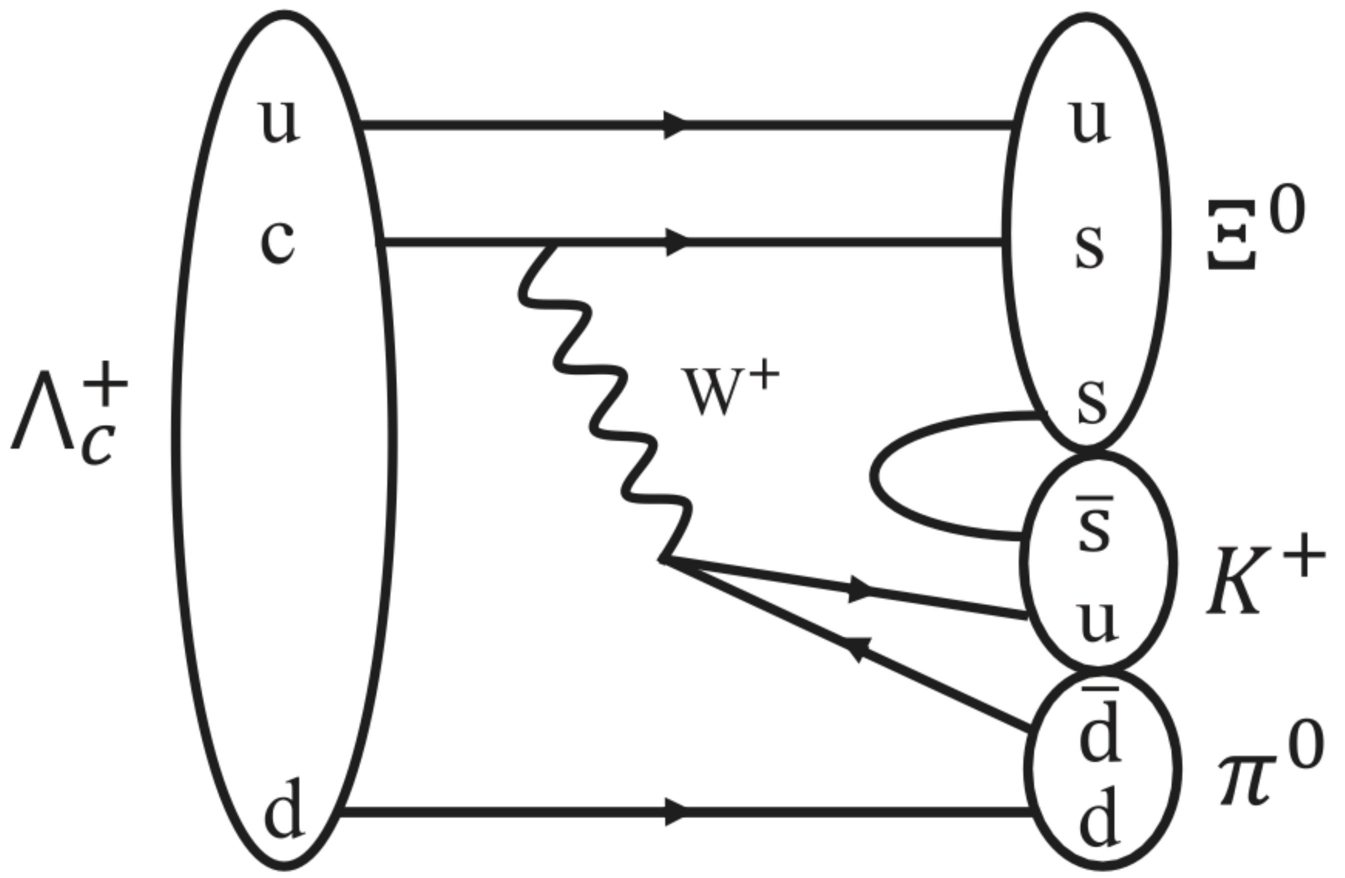


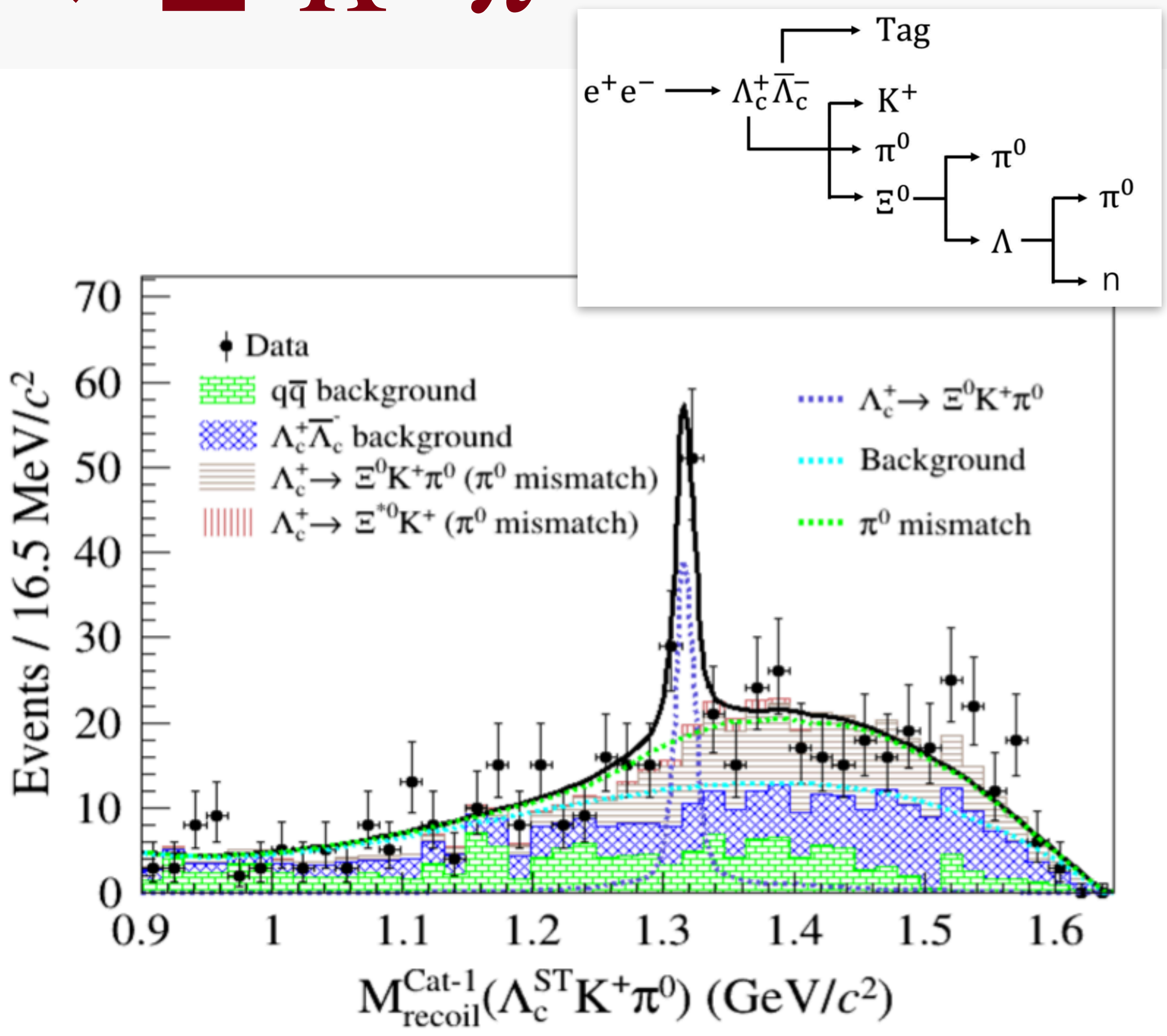


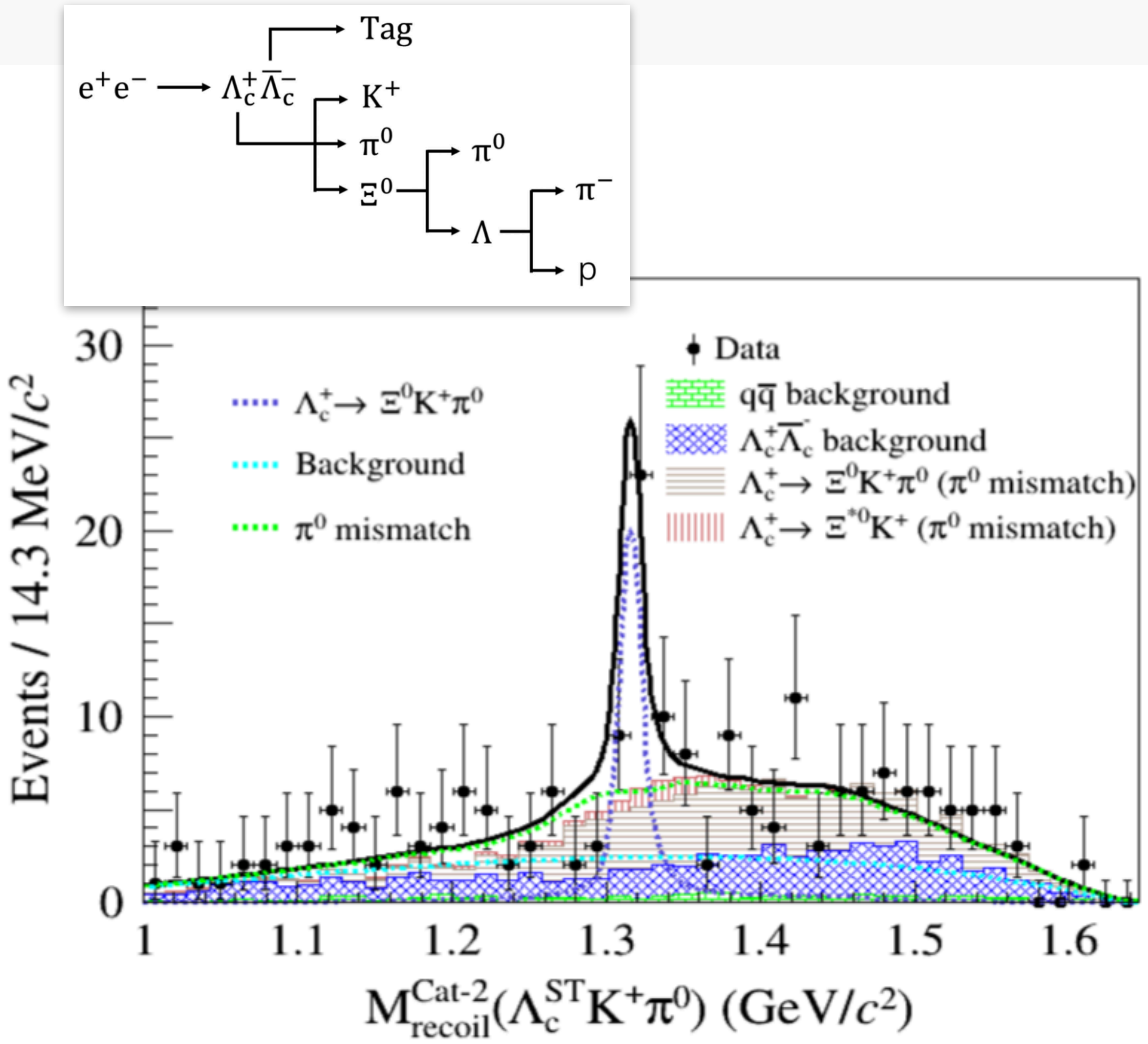
- ➔ First observation (5.4σ) of $\Lambda_c^+ \to \Sigma^- K^+ \pi^+$ which is the simplest SCS decay with Σ^- directly in the final state
- ➔ Absolute BF is measured to be $\mathscr{B}(\Lambda_c^+ \to \Sigma^- K^+ \pi^+) = (3.8 \pm 1.2_{\text{stat.}} \pm 0.2_{\text{syst.}}) \times 10^{-4}$
- ➔ $$\frac{\mathscr{B}(\Lambda_c^+ \to \Sigma^- K^+ \pi^+)}{\mathscr{B}(\Lambda_c^+ \to \Sigma^- \pi^+ \pi^+)} = (2.03 \pm 0.73)\,\% \approx (0.4 \pm 0.1) s_c^2$$
  - ❖ Indicate non-factorization contribution is important or large $SU(3)$ flavor symmetry breaking effect here
- ➔ Byproduct:
  - ❖ $\mathscr{B}(\Lambda_c^+ \to \Xi^- K^+ \pi^+) = (7.74 \pm 0.76_{\text{stat.}} \pm 0.54_{\text{syst.}}) \times 10^{-3}$
  - ❖ $\mathscr{B}(\Lambda_c^+ \to \Xi(1530)^0 K^+) = (5.03 \pm 0.77_{\text{stat.}} \pm 0.20_{\text{syst.}}) \times 10^{-3}$
  - ❖ Consistent with previous measurement

Measurement of $\Lambda_c^+ \to \Xi^0 K^+ \pi^0$

Phys. Rev. D 109, 052001 (2024).







- CF decay $\Lambda_c^+ \to \Xi^0 K^+ \pi^0$ is observed with significance 8.6σ
  $\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+ \pi^0) = (7.79 \pm 1.46_{\text{stat.}} \pm 0.95_{\text{syst.}}) \times 10^{-3}$
  - Smaller than $SU(3)$ flavor symmetry prediction
- Extract $\Xi(1530)^0$ in $\Xi^0\pi^0$
  $\mathcal{B}(\Lambda_c^+ \to \Xi(1530)^0 K^+) = (5.99 \pm 1.04_{\text{stat.}} \pm 0.32_{\text{syst.}}) \times 10^{-3}$
  - Consistent with previous measurement
- Search for SCS $\Lambda_c^+ \to \Lambda K^+ \pi^0, \Sigma^0 K^+ \pi^0$ decays and DCS $\Lambda_c^+ \to n K^+ \pi^0$ decay

TABLE IX. The comparison between the measurement and theoretical predictions ($\times 10^{-3}$). The first and the second uncertainties are statistical and systematic, respectively.

	$\Lambda_c^+ \to \Xi(1530)^0 K^+$	$\Lambda_c^+ \to \Xi^0 K^+ \pi^0$	$\Lambda_c^+ \to \Sigma^0 K^+ \pi^0$	$\Lambda_c^+ \to \Lambda K^+ \pi^0$	$\Lambda_c^+ \to n K^+ \pi^0$
This measurement	$5.99 \pm 1.04 \pm 0.32$	$7.79 \pm 1.46 \pm 0.95$	<1.8	<2.0	<0.71
K. K. Sharma *et al.* [23]	...	45 ± 8	1.2 ± 0.3	4.5 ± 0.8	0.05 ± 0.005
Jian-Yong Cen *et al.* [24]	...	32 ± 6	0.7 ± 0.2	3.5 ± 0.6	0.05 ± 0.006
$\mathcal{B}$(previous results) [48]	$5.02 \pm 0.99 \pm 0.31$	...	...	...	...