FB23

THE 23rd INTERNATIONAL CONFERENCE ON FEW-BODY PROBLEMS IN PHYSICS (FB23)

Sept. 22 -27, 2024 • Beijing, China

Host Institute of High Energy Physics, Chinese Academy of Sciences   Tsinghua University   University of Chinese Academy of Science
China Center of Advanced Science and Technology   Institute of Theoretical Physics, Chinese Academy of Sciences   South China Normal University
Co-host Chinese Physical Society (CPS)   High Energy Physics Branch of CPS

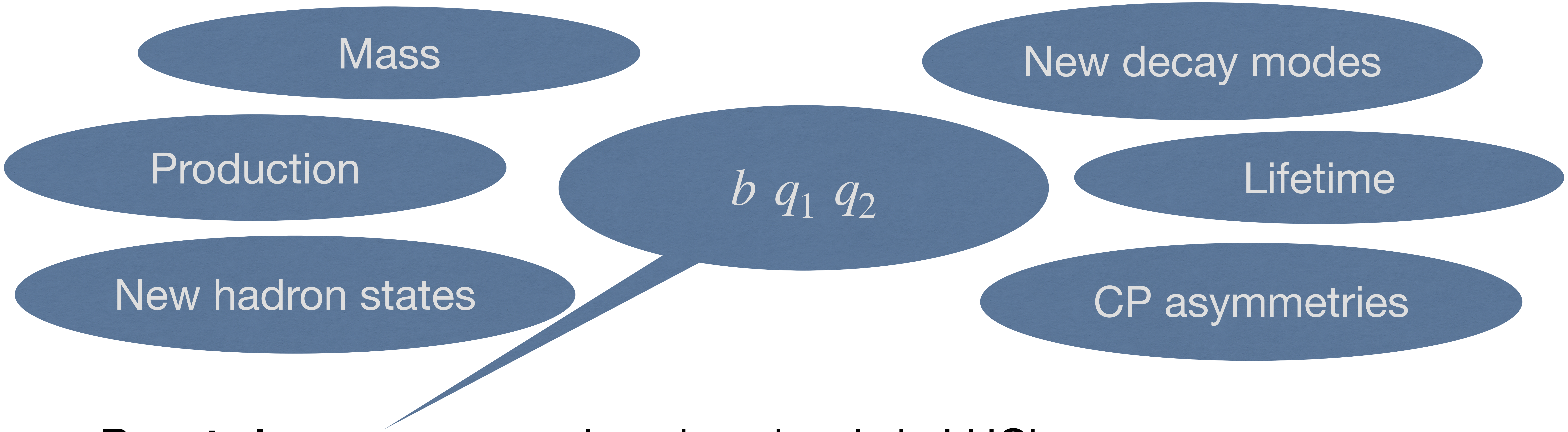
Beauty baryon decays at LHCb

Shuqi Sheng (盛书琪)

Institute of High Energy Physics, Chinese Academy of Sciences (IHEP, CAS)

On behalf of LHCb collaboration

Introduction

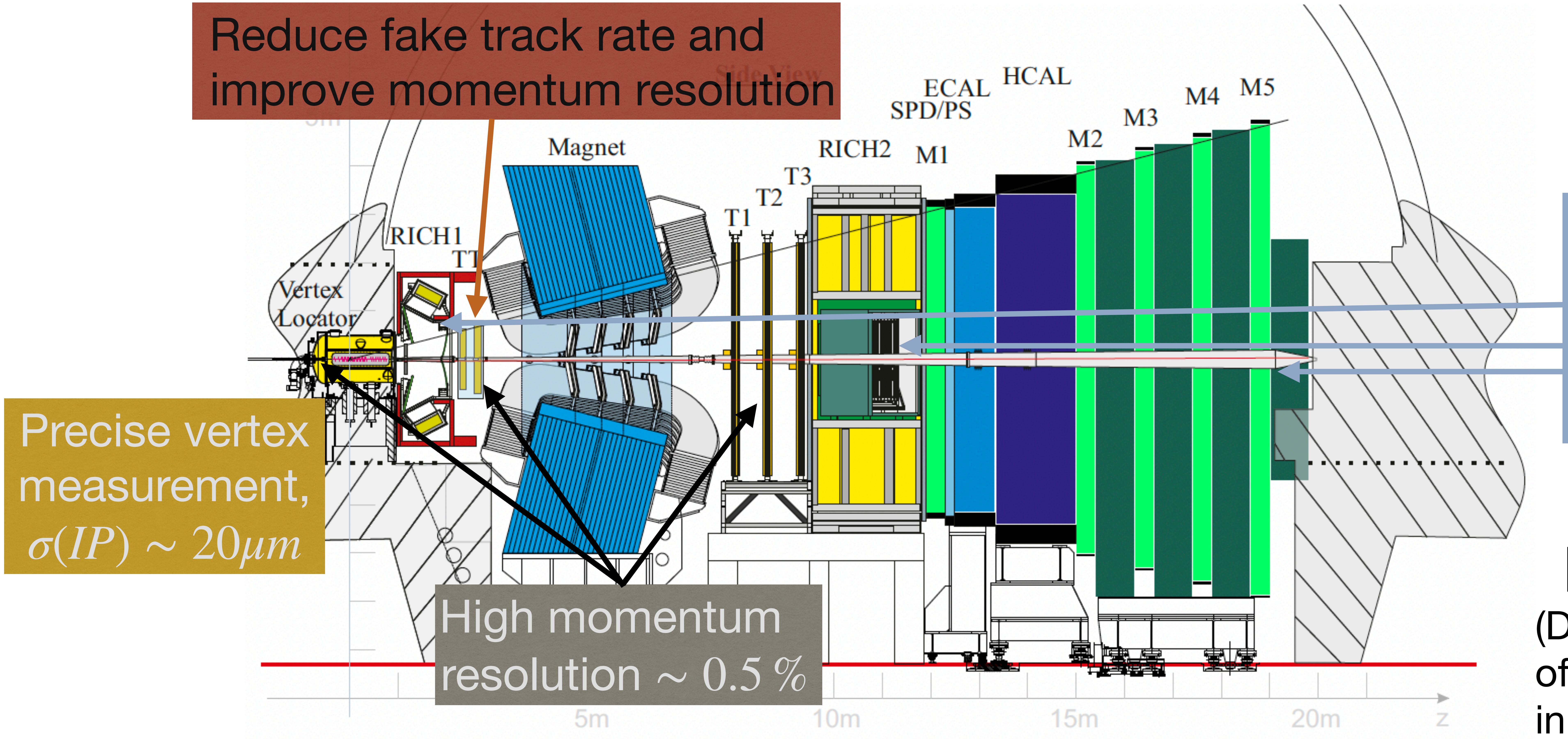


- **Beauty baryons** are produced copiously in LHCb
- Opening up new avenues for studying decays and improving precision of their properties
  - Many of the predicted heavy hadron states have not been found
    - Petaquark states or other exotic states
  - The parameters of some of the known hadrons measured with lower precision

LHCb detector

General purpose detector specialized in beauty and charm hadrons

- Daughters of b and c hadrons decays: $p_T \sim \mathcal{O}(1)\ GeV/c$, flight distance of mother particle $L \sim \mathcal{O}(1)\ mm$
- Excellent performance to reconstruct exclusive b-hadrons decays



Powerful particle-ID:
$\epsilon(\mathrm{K} \to \mathrm{K}) \sim 95\,\%$
misID $\epsilon(\pi \to \mathrm{K}) \sim 5\,\%$
$\epsilon(\mu \to \mu) \sim 97\,\%$
misID $\epsilon(\pi \to \mu) \sim 1-3\,\%$

[IJMPA 30 (2015) 1530022]

(Diagram and performance of Run 2 detector, more details in Liupan's talk)

Outline

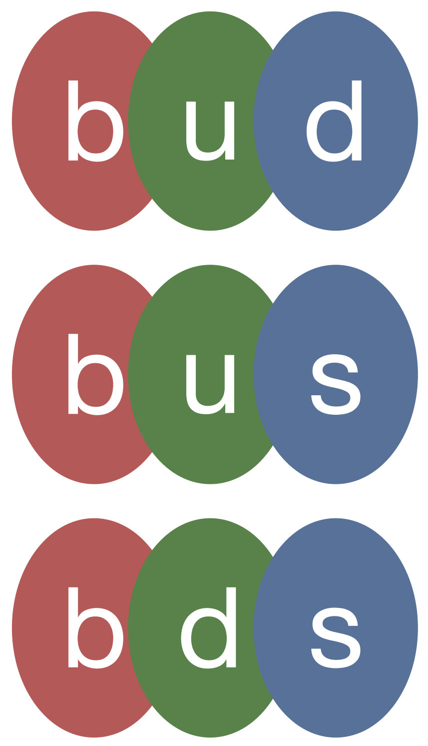
- Production and mass
  - Observation of the $\Xi_b^0 \to \Xi_c^+ D_s^-$ and $\Xi_b^- \to \Xi_c^0 D_s^-$ decays [Eur. Phys. J. C 84, 237 (2024)]
- New decay mode:
  - First observation of the $\Lambda_b^0 \to D^+ D^- \Lambda$ [JHEP07(2024)140]
- Lifetime:
  - Precision measurement of the Ξ_b^- baryon lifetime [arXiv: 2406.12111]
- CPV:
  - Measurement of the Λ_b^0, Λ_c^+ and Λ decay parameters using $\Lambda_b^0 \to \Lambda_c^+ h^-$ decays [arXiv: 2409.02759]

Observation of the $\Xi_b^0 \to \Xi_c^+ D_s^-$ and $\Xi_b^- \to \Xi_c^0 D_s^-$ decays

[Eur. Phys. J. C 84, 237 (2024)]

Motivation

- According to the quark model, Λ_b^0, Ξ_b^0 and Ξ_b^- form an SU(3) flavour multiplet



$$\left.\begin{array}{l} \Lambda_b^0 \to \Lambda_c^+ D_s^- \\ \Xi_b^0 \to \Xi_c^+ D_s^- \\ \Xi_b^- \to \Xi_c^0 D_s^- \end{array}\right\}$$

According to the heavy quark effective theory, they should have approximately the same decay width

- $Br(\Lambda_b^0 \to \Lambda_c^+ D_s^-) = (1.10 \pm 0.10) \times 10^{-2}$ [Phys. Rev. Lett. 112 (2014) 202001]
- Ξ_b mass and branching measurement

- Test isospin symmetry
- Can further investigate for other $\Xi_b \to \Xi_c D$ measurement

Analysis strategy

- Measured quantities:

$$\mathcal{R}\left(\frac{\Xi_b^0}{\Lambda_b^0}\right) = \frac{\sigma(\Xi_b^0)}{\sigma(\Lambda_b^0)} \times \frac{\mathcal{B}(\Xi_b^0 \to \Xi_c^+ D_s^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} \quad (1)$$

$$\mathcal{R}\left(\frac{\Xi_b^-}{\Lambda_b^0}\right) = \frac{\sigma(\Xi_b^-)}{\sigma(\Lambda_b^0)} \times \frac{\mathcal{B}(\Xi_b^- \to \Xi_c^0 D_s^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} \quad (2)$$

$$\mathcal{R}\left(\frac{\Xi_b^0}{\Xi_b^-}\right) = \frac{\sigma(\Xi_b^0)}{\sigma(\Xi_b^-)} \times \frac{\mathcal{B}(\Xi_b^0 \to \Xi_c^+ D_s^-)}{\mathcal{B}(\Xi_b^- \to \Xi_c^0 D_s^-)} \quad (3)$$

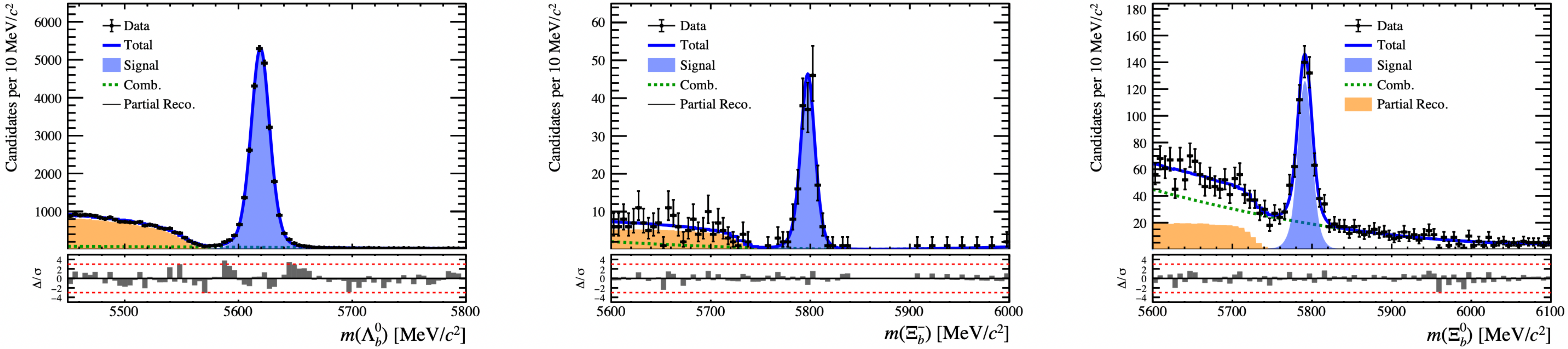
- The isospin symmetry assures that $\frac{\sigma(\Xi_b^0)}{\sigma(\Xi_b^-)} \approx 1$

Results

Observation of the $\Xi_b^0 \to \Xi_c^+ D_s^-$ and $\Xi_b^- \to \Xi_c^0 D_s^-$ decays

[Eur. Phys. J. C 84, 237 (2024)]

- Fit to the mass of $\Lambda_b^0, \Xi_b^-, \Xi_b^0$



$$\mathscr{R}\left(\frac{\Xi_b^0}{\Lambda_b^0}\right) = (15.8 \pm 1.1(stat) \pm 0.5(syst) \pm 7.7(ext))\,\%$$

$$\mathscr{R}\left(\frac{\Xi_b^-}{\Lambda_b^0}\right) = (18.0 \pm 1.5(stat) \pm 0.8(syst) \pm 4.6(ext))\,\%$$

$$\mathscr{R}\left(\frac{\Xi_b^0}{\Xi_b^-}\right) = (87.4 \pm 9.2(stat) \pm 5.2(syst) \pm 47.6(ext))\,\%$$

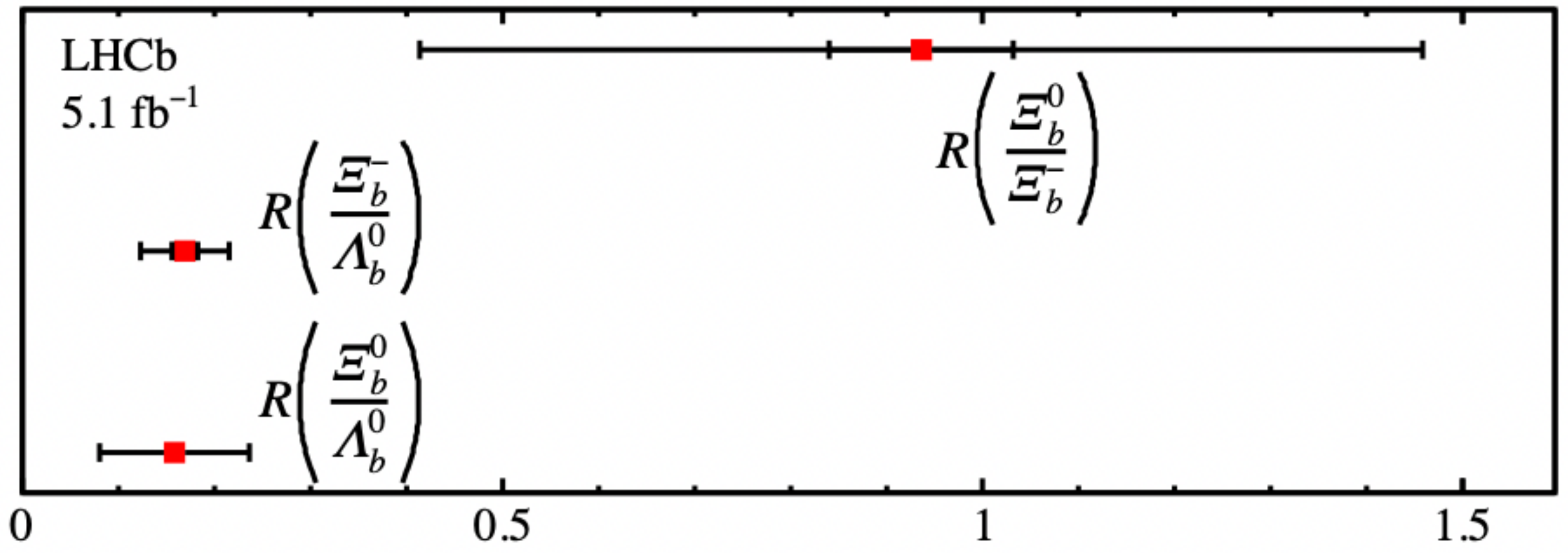
Theory prediction

$(6.42 - 10.09)\,\%$

$(6.82 - 11.64)\,\%$

$(94.15 - 94.27)\,\%$

[Phys. Rev. D 56, 2799][Chinese Phys. C 42 093101]
[Phys. Rev. D 100, 034025]



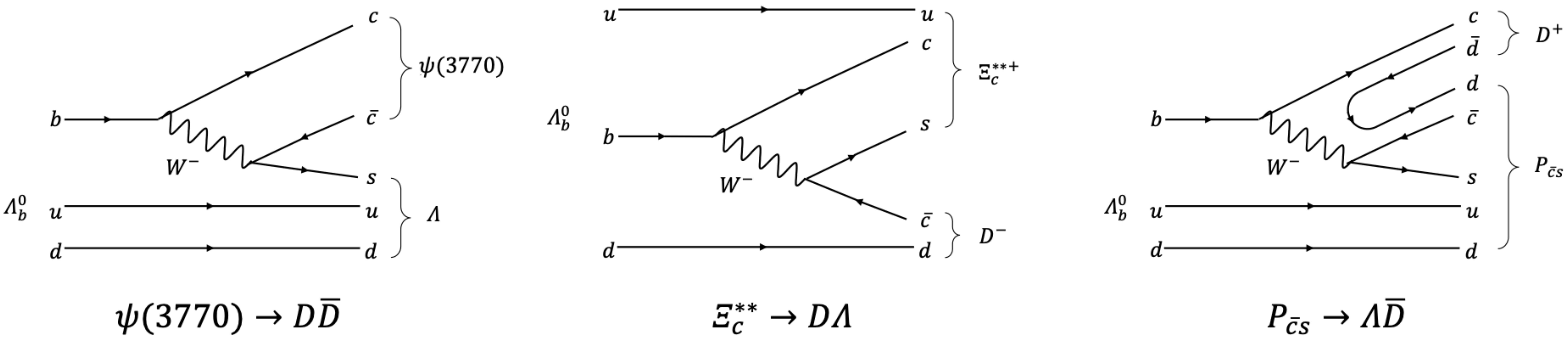
- Consistent with SU(3) flavor symmetry and several predictions for relative production rates

First observation of the $\Lambda_b^0 \to D^+ D^- \Lambda$

[JHEP07(2024)140]

Motivation

- $\Lambda_b^0 \to D^+D^-\Lambda$ proceed at quark level through $b \to c\bar{c}s$, not observed yet
- Predicted via two types of two-body intermediate states: [Phys. Rev. D 103, 114013 (2021)]
    - Existence of a $D\bar{D}$ bound states X(3700)
    - Environment for conventional resonances: excited Ξ_c states $\Xi_c^{**} \to D\Lambda$
    - Pentaquark $\to \Lambda\bar{D}$ may also be present

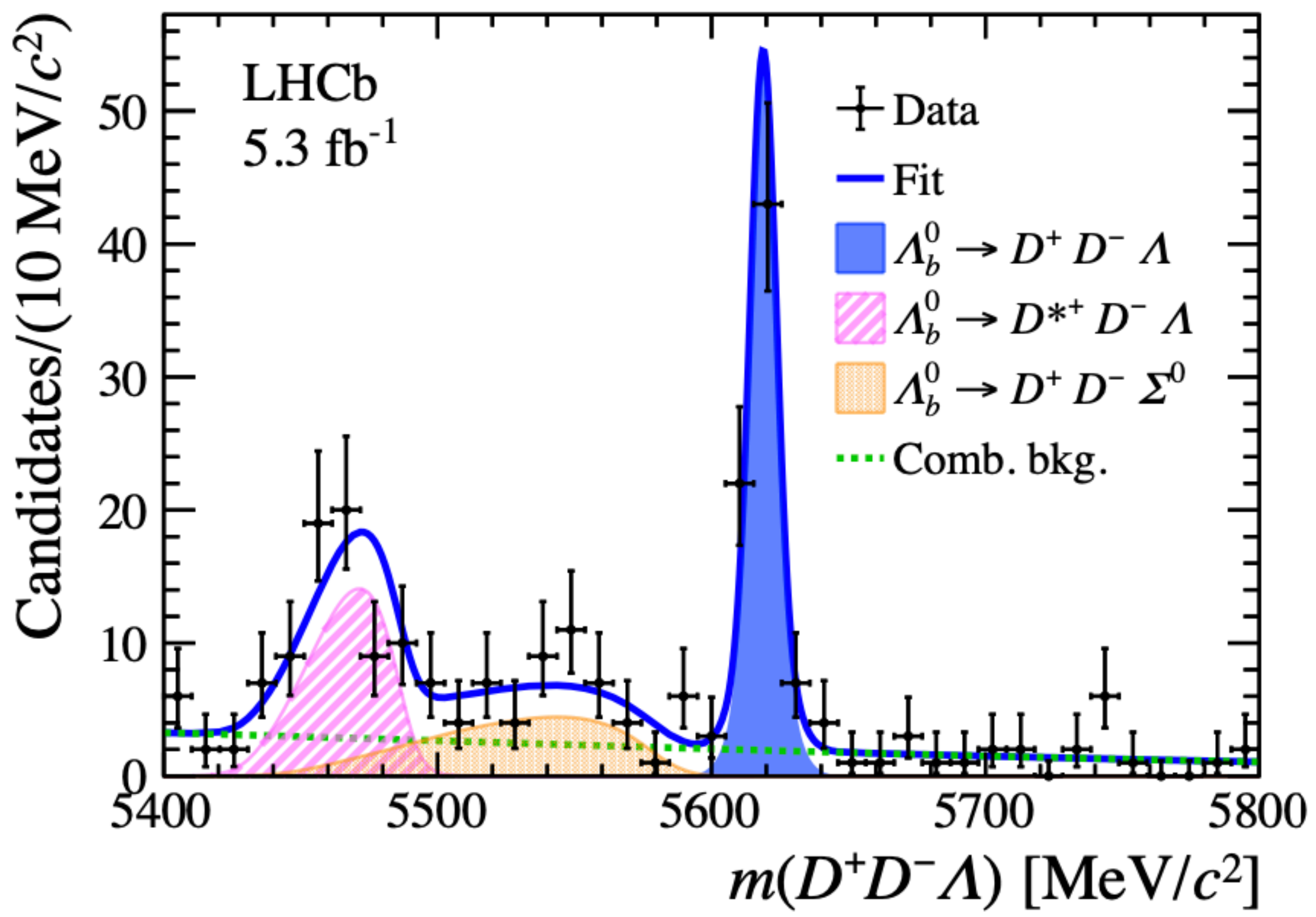


Results

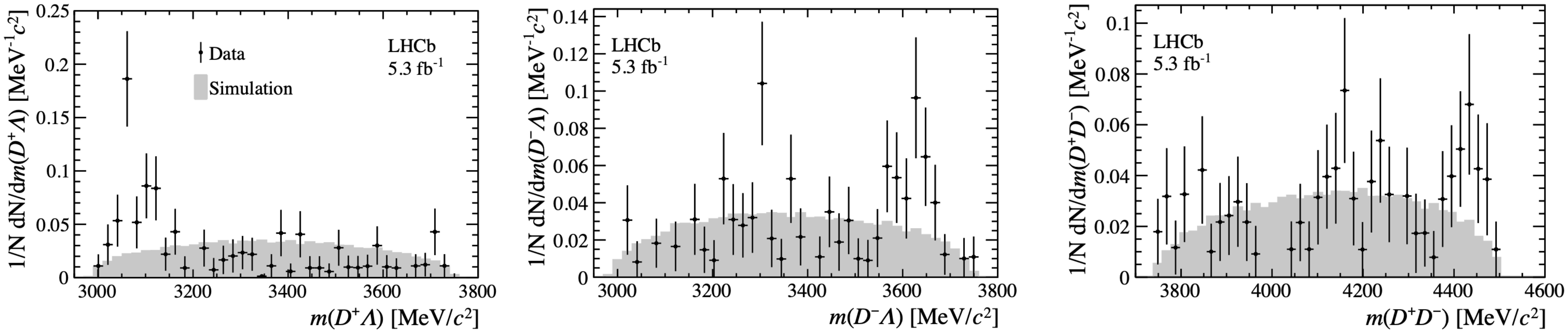
- First observation of $\Lambda_b^0 \to D^+D^-\Lambda$ decay

- Branching fraction measured

  - $\mathcal{R}(\Lambda_b^0 \to D^+D^-\Lambda) =$
    $(1.24 \pm 0.15(stat) \pm 0.10(syst) \pm 0.28(ext_{br}) \pm 0.11(ext_{f_{\Lambda_b^0}/f_{B^0}}) \times 10^{-4}$



- Two body invariant masses:



Precision measurement of the Ξ_b^- baryon lifetime

[arXiv: 2406.12111]
Submitted to PRD

Introduction

- The heavy quark expansion (HQE) framework predicts the beauty hadrons
  - Predictions of lifetime is a stringent test of the HQE framework
  - At the leading order, the decay width of all b hadrons is equal to that of the b quark
  - Lifetime measurements provide a direct quantitative test of the HQE high-order corrections

Lifetimes	Theoretical uncertainties	Experimental uncertainties
$\tau_{\Xi_b^-}/\tau_{\Lambda_b^0}$	1.9%	2.5%
$\tau_{\Omega_b^-}/\tau_{\Lambda_b^0}$	4.2%	11%

- Higher exotic b baryons start with Ξ_b^- lifetime measurement relative to that of Λ_b^0 ($\tau = 1.464 \pm 0.010$ ps)
- Update Run 1 [Phys. Rev. Lett. 113 (2014) 242002] using larger Run2 samples

Analysis strategy

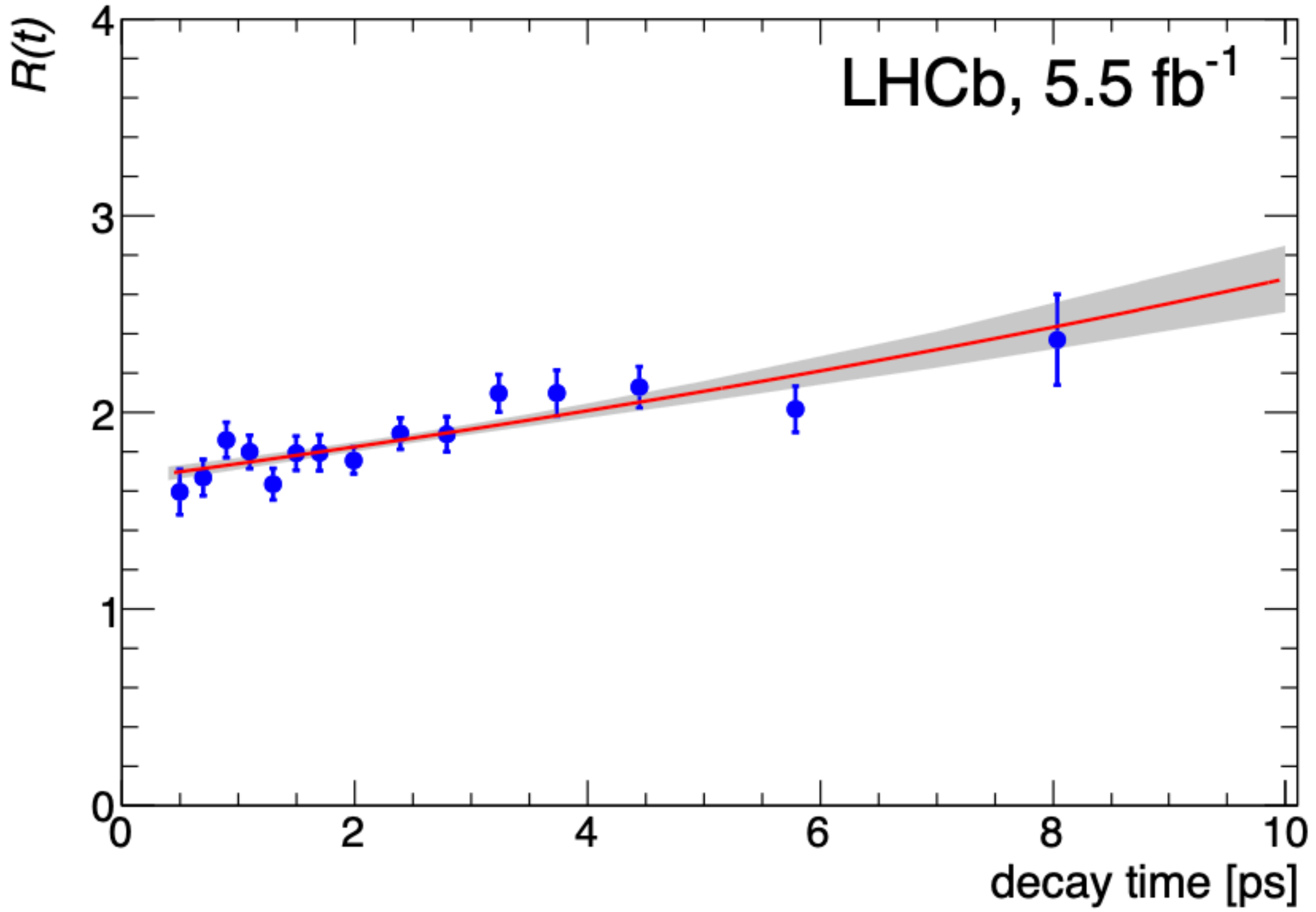
- Measure lifetime ratio $\tau_{\Xi_b^-}/\tau_{\Lambda_b^0}$
  - World average: $(\tau_{\Xi_b^-}/\tau_{\Lambda_b^0})_{WA} = 1.089 \pm 0.028$ (precision dominated by LHCb $\Xi_b^- \to \Xi_c^0\pi^-$)
  - Latest HQE prediction: $(\tau_{\Xi_b^-}/\tau_{\Lambda_b^0})_{HQE} = 1.078 \pm 0.021$ [J. High Energ. Phys. 2023, 34 (2023)]
- Measure the ratio of efficiency-corrected signal yields as a function of decay time

$$R(t) \equiv \frac{N[\Xi_b^- \to \Xi_c^0\pi^-](t)}{N[\Lambda_b^- \to \Lambda_c^0\pi^-](t)} \cdot \frac{\epsilon[\Lambda_b^- \to \Lambda_c^0\pi^-](t)}{\epsilon[\Xi_b^- \to \Xi_c^0\pi^-](t)} = R_0 exp(\lambda t)$$

$$\lambda \equiv \frac{1}{\tau_{\Lambda_b^0}} - \frac{1}{\tau_{\Xi_b^-}}$$

$$\frac{\tau_{\Xi_b^-}}{\tau_{\Lambda_c^0}} = \frac{1}{1 - \lambda\tau_{\Lambda_b^0}}$$

Results



[Phys. Rev. Lett. 113 (2014) 242002]

- Most precise measurement of the Ξ_b^- lifetime
- Improvement on the world-average value by about a factor of two
- Consistent with HQE expectation

	Run1	Run2 (this work)	Run1+2
$\tau_{\Xi_b^-}/\tau_{\Lambda_b^0}$	$1.089 \pm 0.026 \pm 0.011$	$1.076 \pm 0.013 \pm 0.006$	$1.078 \pm 0.012 \pm 0.007$
$\tau_{\Xi_b^-}(ps)$	$1.599 \pm 0.041 \pm 0.022$	$1.575 \pm 0.019 \pm 0.009 \pm 0.011$	$1.578 \pm 0.018 \pm 0.010 \pm 0.011$

Measurement of the Λ_b^0, Λ_c^+ and Λ decay parameters using $\Lambda_b^0 \to \Lambda_c^+ h^-$ decays

[arXiv: 2409.02759]

Submitted to PRL

Introduction

- Decay parameters were first proposed by Lee and Yang to study parity violation in hyperon decays [Phys. Rev. 108 (1957) 1645]

$$\alpha \equiv \frac{2\mathrm{Re}(S^*P)}{|S|^2+|P|^2}, \qquad \beta \equiv \frac{2\mathrm{Im}(S^*P)}{|S|^2+|P|^2}, \qquad \gamma \equiv \frac{|S|^2-|P|^2}{|S|^2+|P|^2}, \qquad \text{with } \alpha^2+\beta^2+\gamma^2=1$$

  - S: Parity violating S-wave amplitude, P: Parity conserving P-wave amplitude

- Probe parity ($\alpha \neq 0$) and charge conjugation parity (CP) violation ($\alpha \neq -\bar{\alpha}, \beta \neq -\bar{\beta}$)

- Can be defined for $\Lambda_b^0 \to \Lambda_c^+ h^-$: $(\frac{1}{2})^+ \to (\frac{1}{2})^+ 0^-$ decays:

$$A_\alpha = \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}} = -\tan\Delta\delta\tan\Delta\phi$$

$$R_{\beta_1} = \frac{\beta+\bar{\beta}}{\alpha-\bar{\alpha}} = \tan\Delta\phi$$

$$R_{\beta_2} = \frac{\beta-\bar{\beta}}{\alpha-\bar{\alpha}} = \tan\Delta\delta.$$

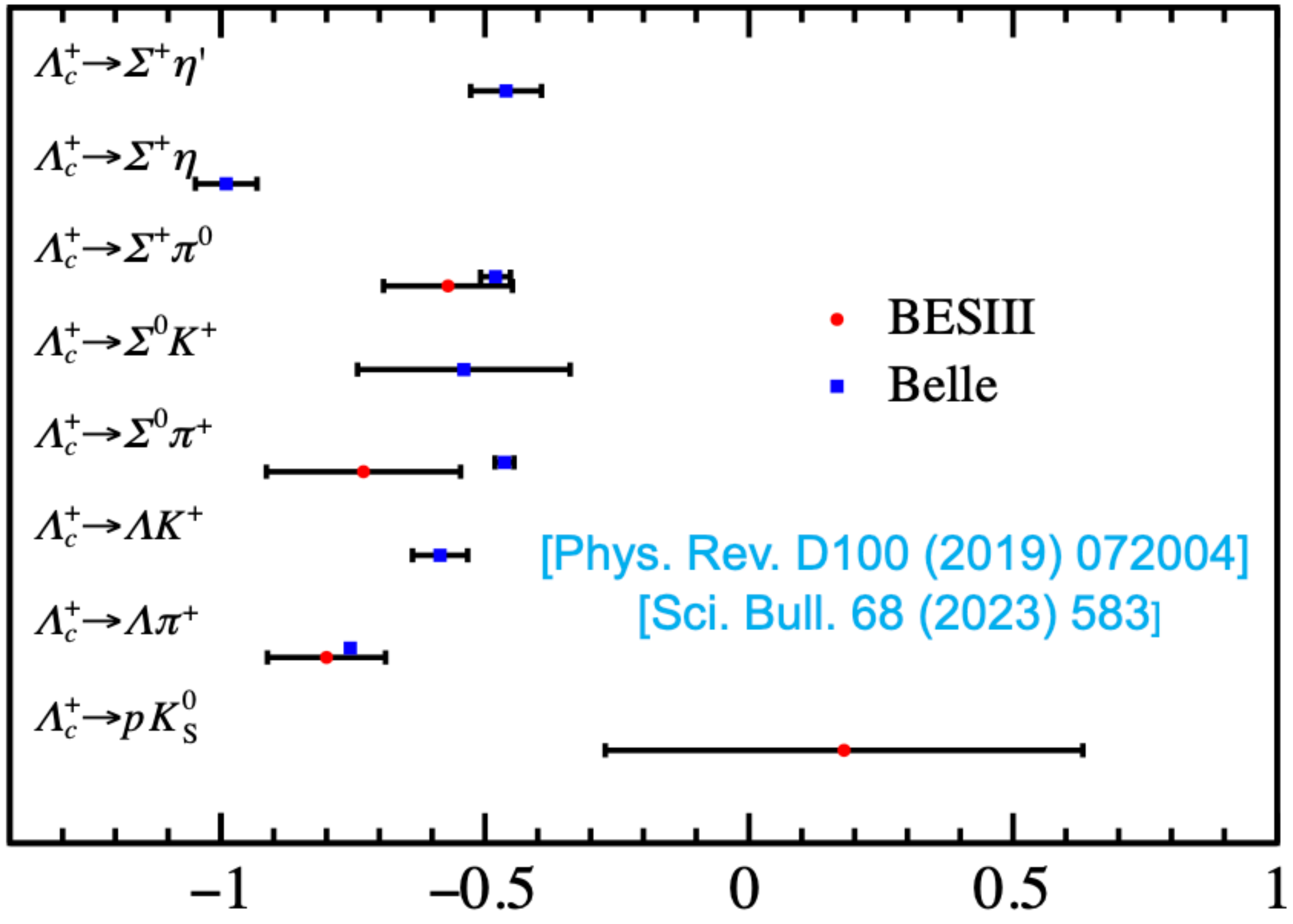
  - $\Delta\delta$: strong phase difference
  - $\Delta\phi$: weak phase difference between the S and P wave amplitudes

Analysis overview

- For charm-baryon decays
  - Precisely measured α parameters
  - Limited precision of β, γ

$$\beta(\Lambda_c^+ \to \Lambda\pi^+) = -0.06^{+0.58+0.05}_{-0.47-0.06}$$
$$\gamma(\Lambda_c^+ \to \Lambda\pi^+) = -0.60^{+0.96+0.17}_{-0.05-0.03}$$
$$\beta(\Xi_c^+ \to \Xi^0\pi^+) = -0.64 \pm 0.69$$
$$\gamma(\Xi_c^+ \to \Xi^0\pi^+) = -0.77 \pm 0.58$$

[Phys. Rev. D100 (2019) 072004]
[Phys. Rev. Lett. 132 (2024) 031801]



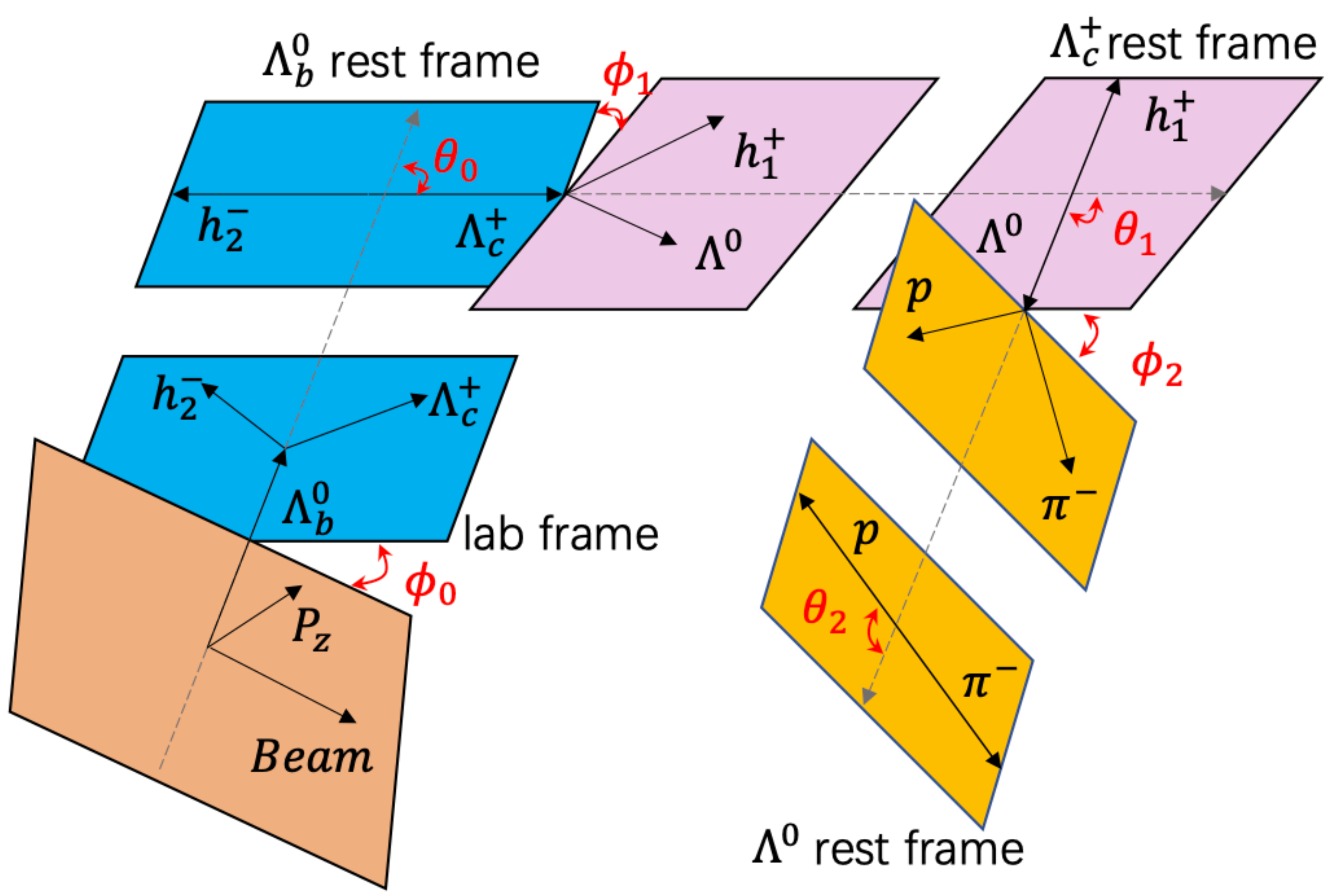
- $\alpha(\Lambda \to p\pi^+)$ has a great precision measured by BESIII [Phys. Rev. Lett. 129, 131801 (2022)]
- No previous result for bottom-baryon decay

Decay channels

- Decay parameters extracted from angular distribution

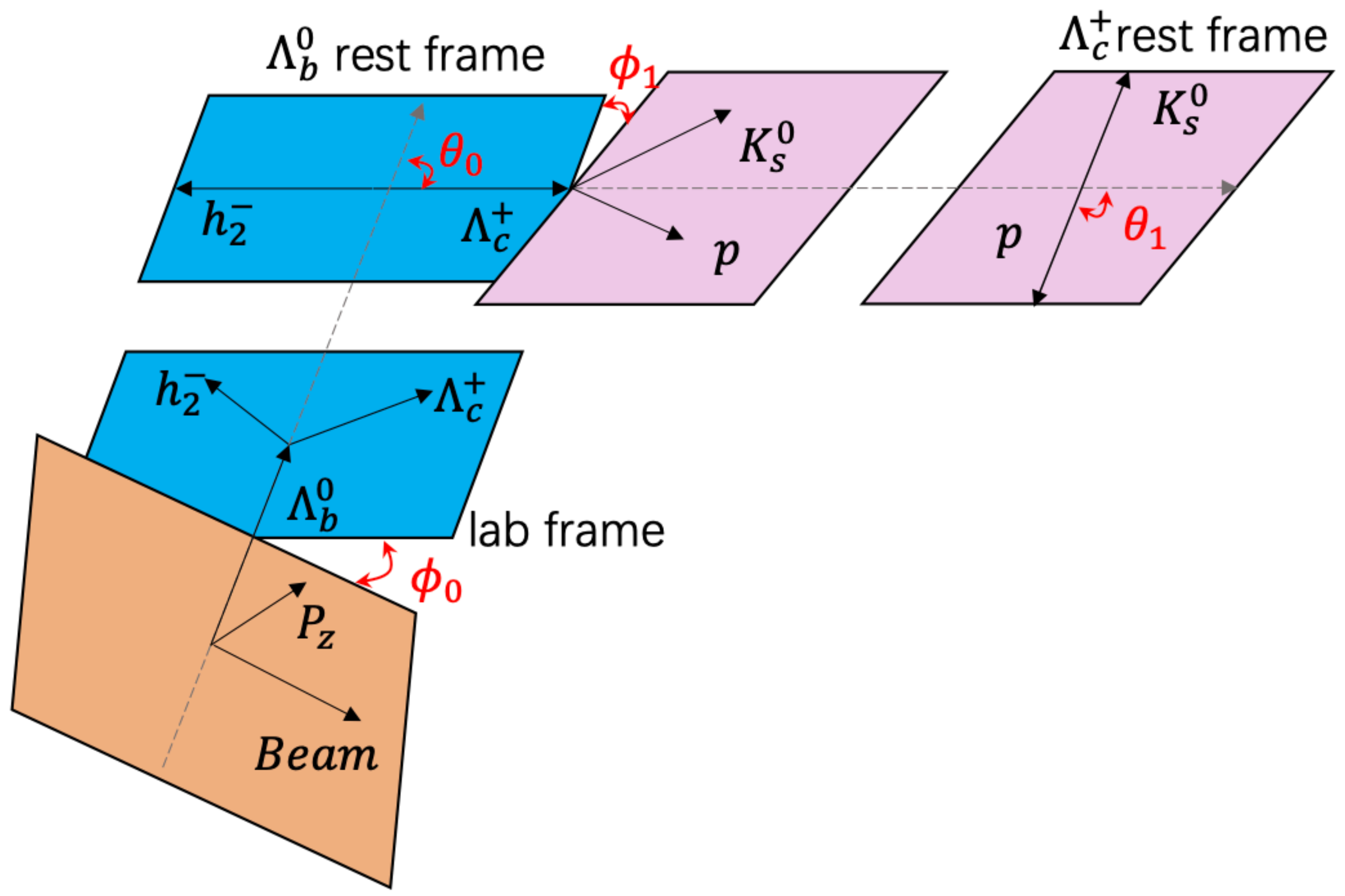
$$\Lambda_b^0 \to \Lambda_c^+ h_1^- \begin{cases} \Lambda_c^+ \to \Lambda h_2^+,\ \Lambda \to p\pi^-\ (h_{1,2} = \pi, K) \\ \Lambda_c^+ \to pK_S^0 \end{cases}$$

$$\Lambda_b^0 \to \Lambda_c^+(\to \Lambda h_1^+)h_2^-$$



$$\frac{d\Phi}{d\Omega} \propto 1 + \alpha_b\alpha_c \cos\theta_1 + \alpha_c\alpha_s \cos\theta_2 + \alpha_b\alpha_s \cos\theta_1 \cos\theta_2 - \alpha_b\alpha_s\sqrt{1-\alpha_c^2}\cos(\phi_2+\delta_c)\sin\theta_1\sin\theta_2$$

$$\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)h_2^-$$



$$\frac{d\Phi}{d\Omega} = 1 + \alpha_b\alpha_c \cos\theta$$

Results

- No CPV observed in these decay modes
  - A_α, R_β are compatible with 0
  - $\alpha \approx -1$ in Λ_b^0 decays shows V – A nature of the weak current and maximal parity violation. Various model predict $\alpha \approx -1$ [Phys. Rev. D105 (2022) 073005]
- β, γ of $\Lambda_c^+ \to \Lambda\pi^+/K^+$ are measured most precisely, serve as essential inputs for some theoretical model. Strong and weak phase differences between S and P waves

Decay	Parameter	Result
$\Lambda_c^+ \to \Lambda\pi^+$	β	$0.368 \pm 0.019 \pm 0.008$
	$\bar{\beta}$	$-0.387 \pm 0.018 \pm 0.010$
	γ	$0.502 \pm 0.016 \pm 0.006$
	$\bar{\gamma}$	$0.480 \pm 0.016 \pm 0.007$
$\Lambda_c^+ \to \Lambda K^+$	β	$0.353 \pm 0.124 \pm 0.046$
	$\bar{\beta}$	$-0.316 \pm 0.104 \pm 0.028$
	γ	$-0.743 \pm 0.067 \pm 0.023$
	$\bar{\gamma}$	$-0.828 \pm 0.049 \pm 0.020$

Decay	$\Lambda_c^+ \to \Lambda\pi^+$	$\Lambda_c^+ \to \Lambda K^+$
$\Delta\phi$	0.01 ± 0.02	-0.448 ± 0.017
$\Delta\delta$	-0.03 ± 0.015	-0.57 ± 0.19

Results

- Independent measurement of Λ, consistent with BESIII

Decay	Our result	PDG 2024
α	$0.717 \pm 0.017 \pm 0.009$	0.747 ± 0.009
$\bar{\alpha}$	$-0.748 \pm 0.016 \pm 0.007$	-0.757 ± 0.004
$\langle\alpha\rangle$	$0.733 \pm 0.012 \pm 0.006$	-
A_α	$-0.022 \pm 0.016 \pm 0.007$	-0.001 ± 0.004

- Comparison between baryon decays with different flavour

Decay	α	Comments
$\Lambda_b^0 \to \Lambda_c^+ \pi^-$	$-1.010 \pm 0.011 \pm 0.003$	Fully left-handed
$\Lambda_c^+ \to \Lambda \pi^-$	$-0.782 \pm 0.009 \pm 0.004$	Nearly left-handed
$\Lambda \to p \pi^-$	$0.717 \pm 0.017 \pm 0.009$	Not left-handed

[Phys. Rev. D 99, 014023]

Summary

- Production, decays, b-baryon properties and CPV are presented
- Demonstrate great potential at LHCb to study baryon decays, especially in CP violation via angular analysis
- Valuable insights into weak decay dynamic of baryons
- Other precise measurements are ongoing
  - Ξ_b^0, Ω_B^0 lifetime measurement
  - …

Back up

Helicity formalism

$\Lambda_b^0 \to \Lambda_c^+(\to \Lambda h_1^+)h_2^-$

$$\begin{aligned}
\frac{\mathrm{d}^5\Gamma}{\mathrm{d}\cos\theta_0 \mathrm{d}\cos\theta_1 \mathrm{d}\phi_1 \mathrm{d}\cos\theta_2 \mathrm{d}\phi_2} \propto \quad & (1 + \alpha_b\alpha_c\cos\theta_1 + \alpha_c\alpha_s\cos\theta_2 + \alpha_b\alpha_s\cos\theta_1\cos\theta_2 \\
& - \alpha_b\gamma_c\alpha_s\sin\theta_1\sin\theta_2\cos\phi_2 + \alpha_b\beta_c\alpha_s\sin\theta_1\sin\theta_2\sin\phi_2) \\
+P_z \cdot & (\alpha_b\cos\theta_0 + \alpha_c\cos\theta_0\cos\theta_1 + \alpha_b\alpha_c\alpha_s\cos\theta_0\cos\theta_2 \\
& + \alpha_s\cos\theta_0\cos\theta_1\cos\theta_2 \\
& - \gamma_b\alpha_c\sin\theta_0\sin\theta_1\cos\phi_1 \\
& + \beta_b\alpha_c\sin\theta_0\sin\theta_1\sin\phi_1 \\
& - \gamma_c\alpha_s\cos\theta_0\sin\theta_1\sin\theta_2\cos\phi_2 \\
& + \beta_c\alpha_s\cos\theta_0\sin\theta_1\sin\theta_2\sin\phi_2 \\
& - \gamma_b\alpha_s\sin\theta_0\sin\theta_1\cos\theta_2\cos\phi_1 \\
& + \beta_b\alpha_s\sin\theta_0\sin\theta_1\cos\theta_2\sin\phi_1 \\
& + \beta_b\beta_c\alpha_s\sin\theta_0\sin\theta_2\cos\phi_1\cos\phi_2 \\
& + \beta_b\gamma_c\alpha_s\sin\theta_0\sin\theta_2\cos\phi_1\sin\phi_2 \\
& + \gamma_b\beta_c\alpha_s\sin\theta_0\sin\theta_2\sin\phi_1\cos\phi_2 \\
& + \gamma_b\gamma_c\alpha_s\sin\theta_0\sin\theta_2\sin\phi_1\sin\phi_2 \\
& - \gamma_b\gamma_c\alpha_s\sin\theta_0\cos\theta_1\sin\theta_2\cos\phi_1\cos\phi_2 \\
& + \gamma_b\beta_c\alpha_s\sin\theta_0\cos\theta_1\sin\theta_2\cos\phi_1\sin\phi_2 \\
& + \beta_b\gamma_c\alpha_s\sin\theta_0\cos\theta_1\sin\theta_2\sin\phi_1\cos\phi_2 \\
& - \beta_b\beta_c\alpha_s\sin\theta_0\cos\theta_1\sin\theta_2\sin\phi_1\sin\phi_2)
\end{aligned} \tag{33}$$

where $\alpha_b, \beta_b, \gamma_b$ are decay parameters in Λ_b^0 decay, $\alpha_c, \beta_c, \gamma_c$ are decay parameters in Λ_c^+ decay, α_s is decay parameter in Λ^0 decay.

Helicity formalism

$\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)h_2^-$

$$\begin{aligned}\frac{\mathrm{d}^3\Gamma}{\mathrm{d}\cos\theta_0 \mathrm{d}\cos\theta_1 \mathrm{d}\phi_1} \propto \quad & 1+\alpha_b\alpha_c\cos\theta_1 \\ & +P_z\cdot(\alpha_b\cos\theta_0 \\ & \quad +\alpha_c\cos\theta_0\cos\theta_1 \\ & \quad -\gamma_b\alpha_c\sin\theta_0\sin\theta_1\cos\phi_1 \\ & \quad +\beta_b\alpha_c\sin\theta_0\sin\theta_1\sin\phi_1)\end{aligned} \tag{26}$$

where $\alpha_b, \beta_b, \gamma_b$ are decay parameters in Λ_b^0 decay, α_c is decay parameter in Λ_c^+ decay.

Fit to Λ_b^0 and $\bar{\Lambda}_b^0$ simultaneously

Eight independent fit parameters, without external input

$$\alpha_b^{\pi},\ \alpha_b^{K},\ \alpha_c^{\Lambda\pi}, \delta_c^{\Lambda\pi},\ \alpha_c^{\Lambda K}, \delta_c^{\Lambda K},\ \alpha_c^{pK_S^0},\ \alpha_s$$

$$\alpha_b^{\pi},\ \alpha_b^{K},\ \beta_c^{\Lambda\pi}, \gamma_c^{\Lambda\pi},\ \beta_c^{\Lambda K}, \gamma_c^{\Lambda K},\ \alpha_c^{pK_S^0},\ \alpha_s$$

Table 36: Decays involved and the corresponding measurable decay parameters. Note, $\delta = \arctan \beta/\gamma$.

Decay	Parameter
$\Lambda_b^0 \to \Lambda_c^+\pi^-$ $\Lambda_c^+ \to pK_S^0$	$\alpha_b^{\pi} \cdot \alpha_c^{pK_S^0}$
$\Lambda_b^0 \to \Lambda_c^+K^-$ $\Lambda_c^+ \to pK_S^0$	$\alpha_b^{K} \cdot \alpha_c^{pK_S^0}$
$\Lambda_b^0 \to \Lambda_c^+\pi^-$ $\Lambda_c^+ \to \Lambda\pi^+$ $\Lambda \to p\pi^-$	α_b^{π} $\alpha_c^{\Lambda\pi},\ \beta_c^{\Lambda\pi},\ \gamma_c^{\Lambda\pi},\ \delta_c^{\Lambda\pi}$ α_s
$\Lambda_b^0 \to \Lambda_c^+K^-$ $\Lambda_c^+ \to \Lambda\pi^+$ $\Lambda \to p\pi^-$	α_b^{K} $\alpha_c^{\Lambda\pi},\ \beta_c^{\Lambda\pi},\ \gamma_c^{\Lambda\pi},\ \delta_c^{\Lambda\pi}$ α_s
$\Lambda_b^0 \to \Lambda_c^+\pi^-$ $\Lambda_c^+ \to \Lambda K^+$ $\Lambda \to p\pi^-$	α_b^{π} $\alpha_c^{\Lambda K},\ \beta_c^{\Lambda K},\ \gamma_c^{\Lambda K},\ \delta_c^{\Lambda K}$ α_s