Measurement of Λ_b^0, Λ_c^+ and Λ decay parameters

[arXiv: 2409.02759]

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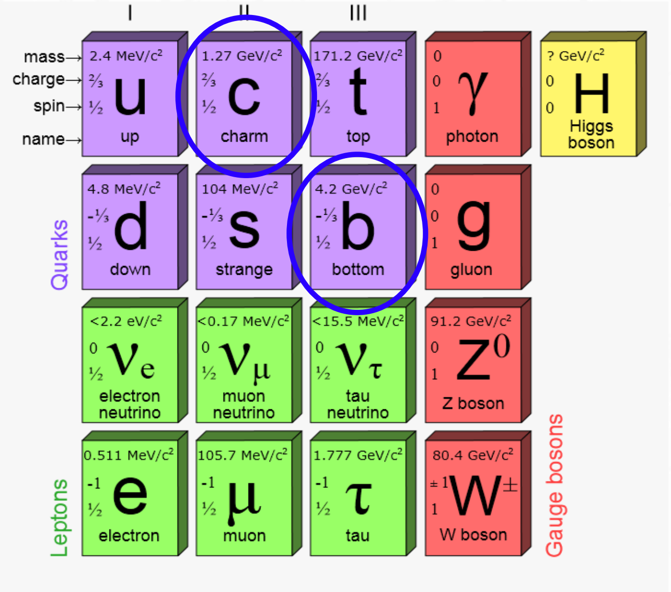
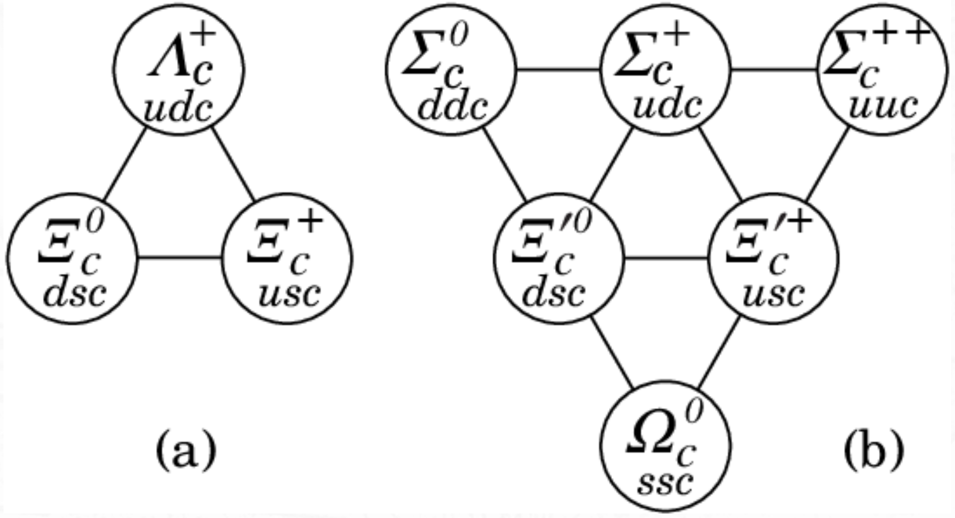
Introduction

- Heavy flavor physics
  - ➢ Test standard model (QCD, electroweak)
  - ➢ Indirectly probe new physics

- Rich study on beauty and charm baryons
  - ➢ Spectroscopy
  - ➢ Lifetime
  - ➢ CP violation
  - ➢ Radiative decay
  - ➢ …





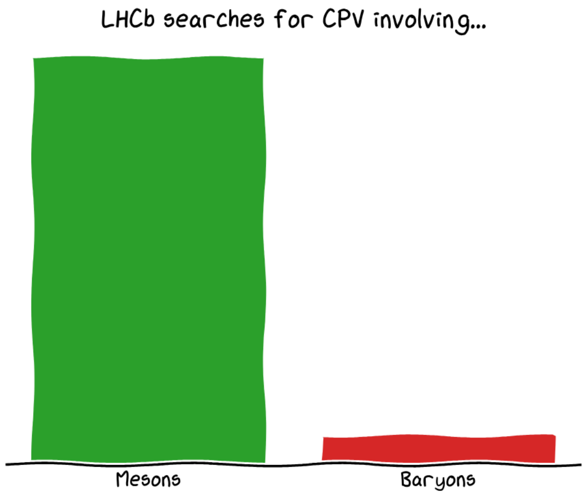
CPV in baryon system

- An excellent platform for understanding of the **baryon decay dynamics** and **the matter–antimatter asymmetry**

- Only a few CP violation searches performed using baryons

- Many results from different experiments recently
  - ➢ LHCb, Belle, BES, BaBar, … [Chin.J.Phys. 78 (2022) 324-362]

- E.g. for charm baryons
  - ➢ Only access to mixing and CPV involving up-type quark
  - ➢ Searches are performed all in Λ_c^+ decays
  - ➢ Precisions in range $O(1\sim10\ \%)$, not enough to reach $O(0.1\%)$ SM expectations
  - ➢ Typically probe decay asymmetry parameters α and $\overline{\alpha}$



Λ_c^+ $I(J^P) = 0(1/2^+)$

The parity of the Λ_c^+ is defined to be positive (as are the parities of the proton, neutron, and Λ). The quark content is udc. Results of an analysis of $pK^-\pi^+$ decays (JEZABEK 1992) are consistent with $J = 1/2$. ABLIKIM 2021N determines the Λ_c^+ spin to be $J = 1/2$, from an angular analysis of various 2-body Λ_c^+ decays in $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-$. We have omitted some results that have been superseded by later experiments. The omitted results may be found in earlier editions.

▸ Expand all sections

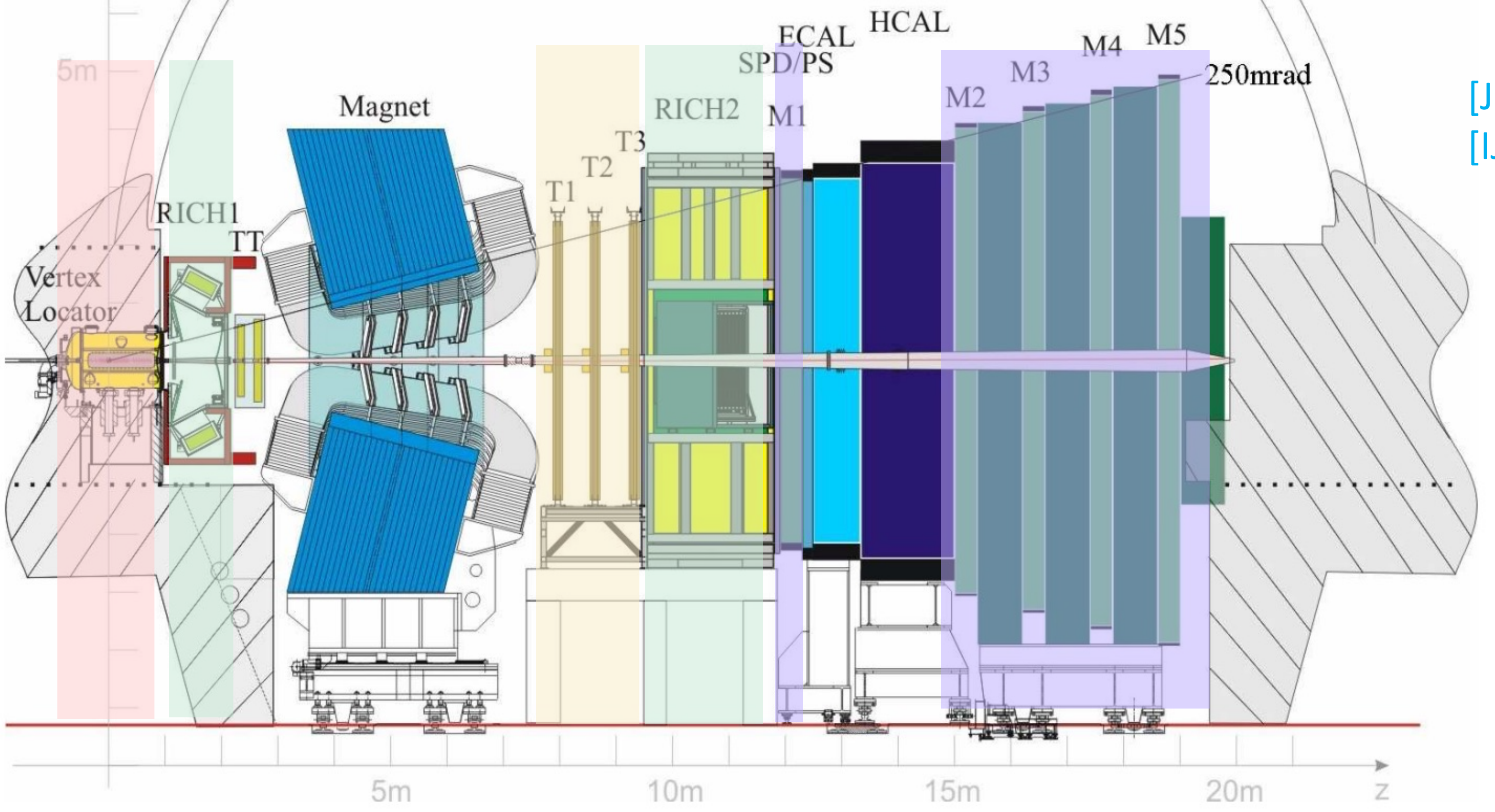
Λ_c^+ MASS	2286.46 ± 0.14 MeV
Λ_c^+ MEAN LIFE	$(2.026 \pm 0.010) \times 10^{-13}$ s
▸ **Λ_c^+ DECAY PARAMETERS**	
α FOR $\Lambda_c^+ \to \overline{K}_0^*(1430)^0 p$	0.34 ± 0.14
▾ **Λ_c^+, $\overline{\Lambda}_c^-$ CP-VIOLATING DECAY ASYMMETRIES**	
$(\alpha + \bar{\alpha})/(\alpha - \bar{\alpha})$ in $\Lambda_c^+ \to \Lambda\pi^+$, $\overline{\Lambda}_c^- \to \overline{\Lambda}\pi^-$	0.020 ± 0.016
$(\alpha + \bar{\alpha})/(\alpha - \bar{\alpha})$ in $\Lambda_c^+ \to \Sigma^0\pi^+$, $\overline{\Lambda}_c^- \to \overline{\Sigma}^0\pi^-$	-0.02 ± 0.05
$(\alpha + \bar{\alpha})/(\alpha - \bar{\alpha})$ in $\Lambda_c^+ \to \Lambda e^+\nu_e$, $\overline{\Lambda}_c^- \to \overline{\Lambda} e^-\overline{\nu}_e$	0.00 ± 0.04
$(\alpha + \bar{\alpha})/(\alpha - \bar{\alpha})$ in $\Lambda_c^+ \to \Lambda K^+$, $\overline{\Lambda}_c^- \to \overline{\Lambda}K^-$	-0.02 ± 0.11
$(\alpha + \bar{\alpha})/(\alpha - \bar{\alpha})$ in $\Lambda_c^+ \to \Sigma^0 K^+$, $\overline{\Lambda}_c^- \to \overline{\Sigma}^0 K^-$	0.1 ± 0.4
$A_{CP}(\Lambda X)$ in $\Lambda_c \to \Lambda X$, $\overline{\Lambda}_c \to \overline{\Lambda}X$	0.02 ± 0.07
$A_{CP}(\Lambda K^+)$ in $\Lambda_c \to \Lambda K^+$, $\overline{\Lambda}_c \to \overline{\Lambda}K^-$	0.021 ± 0.026
$A_{CP}(\Sigma^0 K^+)$ in $\Lambda_c \to \Sigma^0 K^+$, $\overline{\Lambda}_c \to \overline{\Sigma}^0 K^-$	0.03 ± 0.05
$\Delta A_{CP} = A_{CP}(\Lambda_c^+ \to pK^+K^-) - A_{CP}(\Lambda_c^+ \to p\pi^+\pi^-)$	0.003 ± 0.011

LHCb detector

- A single-arm forward spectrometer covering the pseudorapidity range 2 < η < 5

By design: study CP-violating processes and rare *b*- and *c*-hadrons decays

Vertex Locator	Tracking stations	RICHs	Muon system
$\sigma_{\mathrm{IP}} \sim 20$ μm	$\epsilon_{\mathrm{tracking}} \sim 96\%$	$\epsilon(K \to K) \sim 95\%$	$\epsilon(\mu \to \mu) \sim 97\%$
$\sigma_{\tau} \sim 45$ fs	$\sigma_p/p \sim 0.5\% - 1\%$ (5 − 200 GeV)	mis-ID $\epsilon(\pi \to K) \sim 5\%$	mis-ID $\epsilon(\pi \to \mu) \sim 1 - 3\%$



[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]

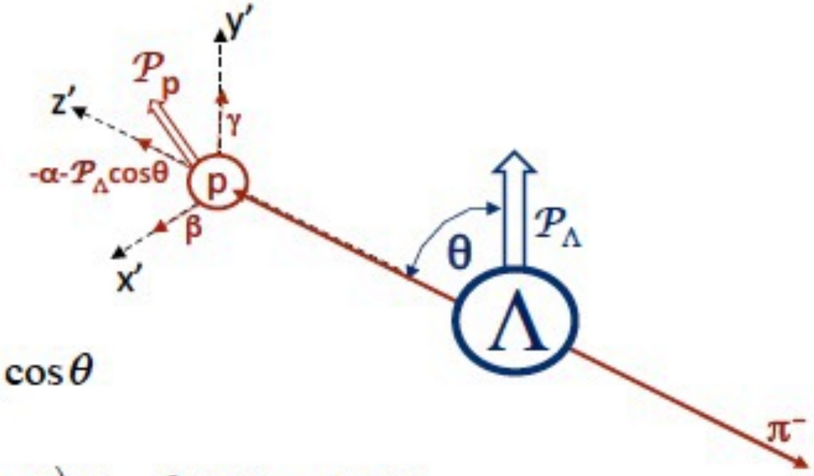
Motivation

- Decay parameters can be defined for $\frac{1}{2}^+ \to \frac{1}{2}^+ 0^-$ decays, by s and p waves

$$M \sim \psi_2^+ (s + p\,\vec{\sigma}\cdot\vec{n})\psi_1$$

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

- Proposed by Lee and Yang to search for parity violation in hyperon decays



$$\frac{d\Gamma}{d\cos\theta} \propto 1+\alpha P_\Lambda \cos\theta$$

$$P_p = \frac{(\alpha + P_\Lambda\cos\theta)\bar{z}' + \beta P_\Lambda \bar{x}' + \gamma P_\Lambda \bar{y}'}{1+\alpha P_\Lambda \cos\theta}$$

[Int.J.Mod.Phys.A 37 (2022) 27, 2250169]

Chen Ning Yang

Tsung-Dao Lee

[Phys. Rev. 108 (1957) 1645]

CP violation

- Probe parity (P) and charge conjugation parity (CP) violation

$\alpha \neq 0$ ⟹ P violation

$\alpha \neq -\bar{\alpha}$
$\beta \neq -\bar{\beta}$ ⟹ CP violation

- CP violation quantified by

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

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

$$R'_\beta \equiv \frac{\beta - \bar{\beta}}{\alpha - \bar{\alpha}} = \tan\Delta\delta$$

$$s = |s|e^{i\delta_s}e^{i\phi_s}, \quad \bar{s} = -|s|e^{i\delta_s}e^{-i\phi_s}$$

$$p = |p|e^{i\delta_p}e^{i\phi_p}, \quad \bar{p} = |p|e^{i\delta_p}e^{-i\phi_p}$$

$$\Delta\delta = \delta_s - \delta_p$$
$$\Delta\phi = \phi_s - \phi_p$$

- At leading order, related to strong phase difference $\Delta\delta$ and weak phase difference $\Delta\phi$ between s and p waves

[PRD 34 (1986) 833]

Status of decay parameter measurements

- No result for bottom-baryon decay

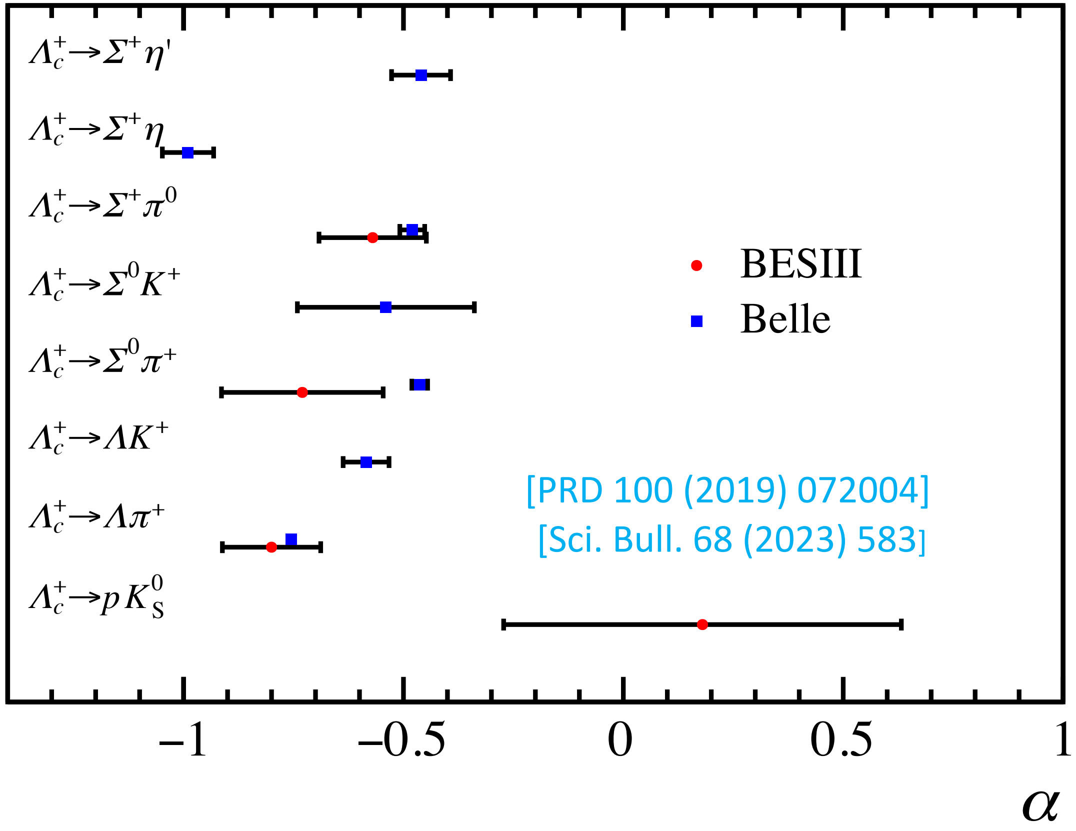
- For charm-baryon decays,
  - Precisely measured α parameters
  - Limited precision of β, γ

$$\beta(\Lambda_c^+ \to \Lambda\pi^+) = -0.06^{+0.58+0.05}_{-0.47-0.06}$$
$$\gamma(\Lambda_c^+ \to \Lambda\pi^+) = -0.60^{+0.96+0.17}_{-0.05-0.03}$$

[PRD 100 (2019) 072004]

$$\beta(\Xi_c^+ \to \Xi^0 K^+) = -0.64 \pm 0.69$$
$$\gamma(\Xi_c^+ \to \Xi^0 K^+) = -0.77 \pm 0.58$$

[PRL 132 (2024) 031801]



- $\alpha(\Lambda \to p\pi^+)$ has a great change after the recent BESIII and CLAS results

$$0.642 \pm 0.013 \ \to 0.747 \pm 0.009$$

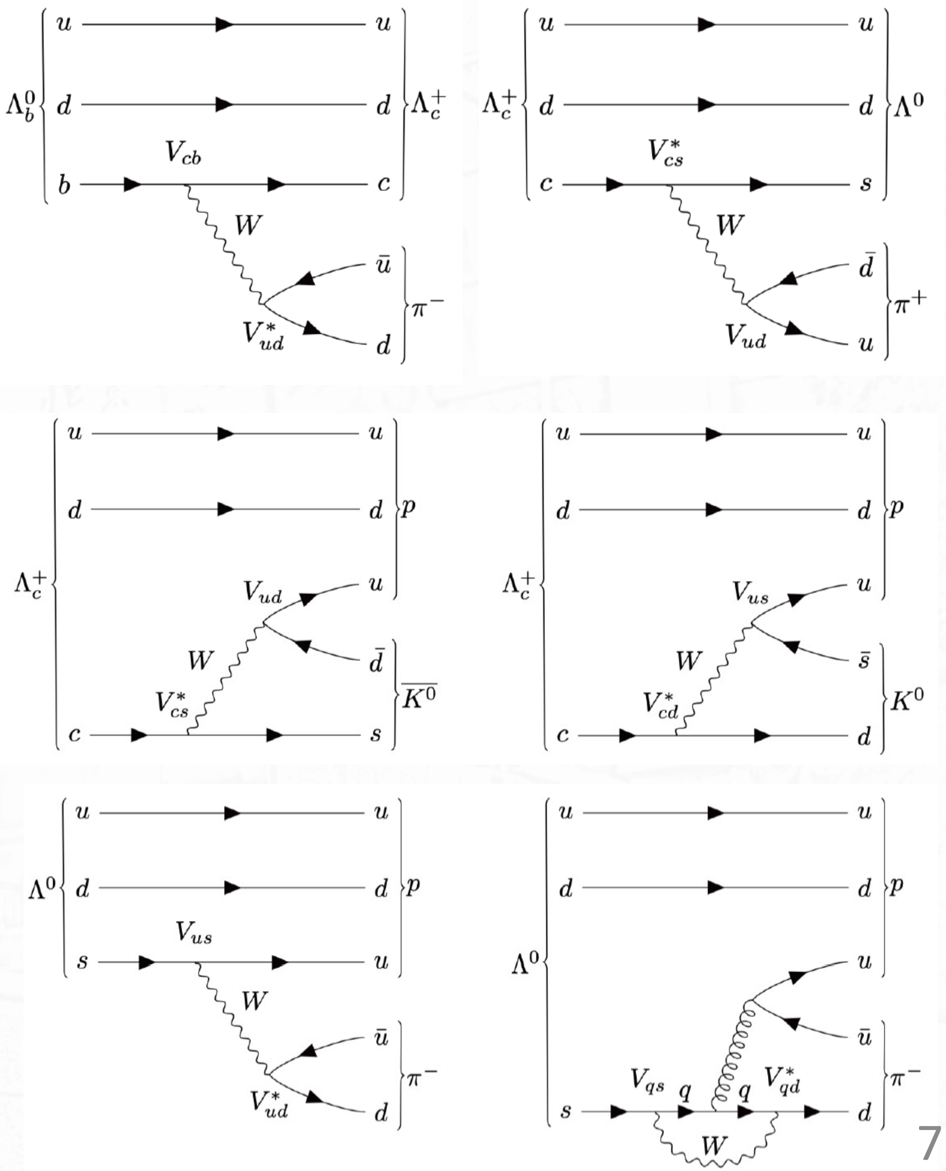
[Nature Phys. 15 (2019) 631]
[PRL 129 (2022) 131801]
[PRL 123 (2019) 182301]

Analysis overview

- 9 fb^{-1} pp collision samples collected by the LHCb experiment
- Decay channels
  - ➢ $\Lambda_b^0 \to \Lambda_c^+ h^- \ (h = \pi, K)$
  - ➢ Followed by

    $\Lambda_c^+ \to \Lambda\, h^+ \ (h = \pi, K)$ with $\Lambda \to p\,\pi^-$,

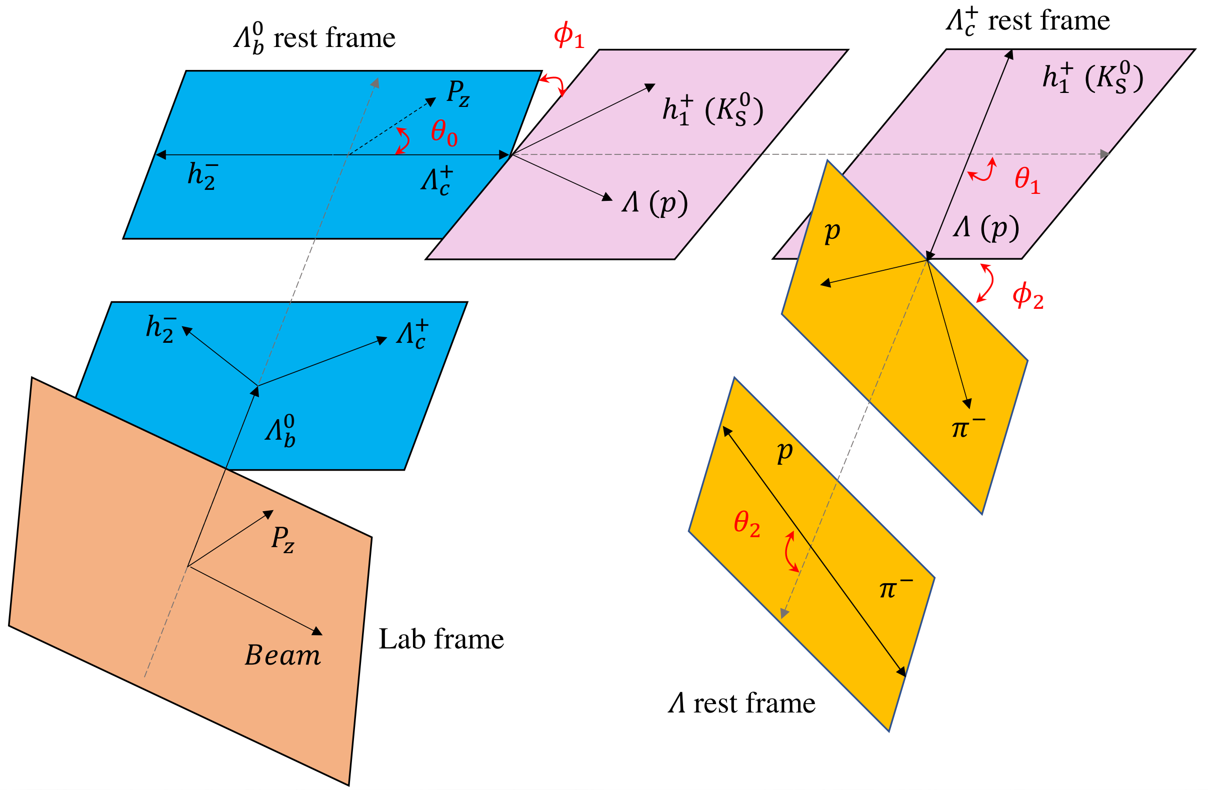
    and $\Lambda_c^+ \to p K_s^0$ with $K_s^0 \to \pi^+\pi^-$
- Decay parameters extracted from angular distributions
- Inclusion of charge-conjugate processes, unless stated

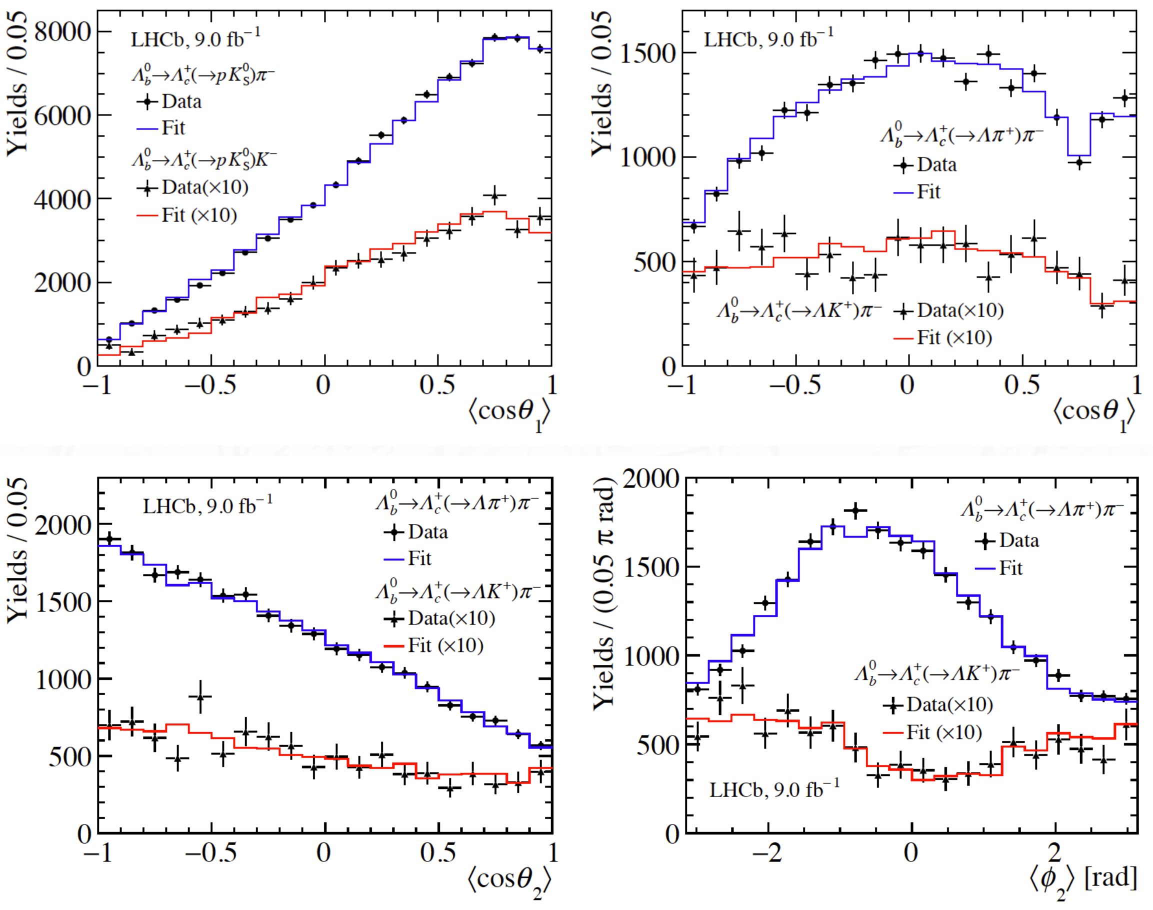


Angular fit

- Joint unbinned maximum-likelihood fit of five channels
- Eight independent fit parameters, without external input
- sFit method for background subtraction

[Nucl. Instrum. Meth. A555 (2005) 356]





Λ_b^0 polarization assumed to be 0 based on previous measurements at the LHC

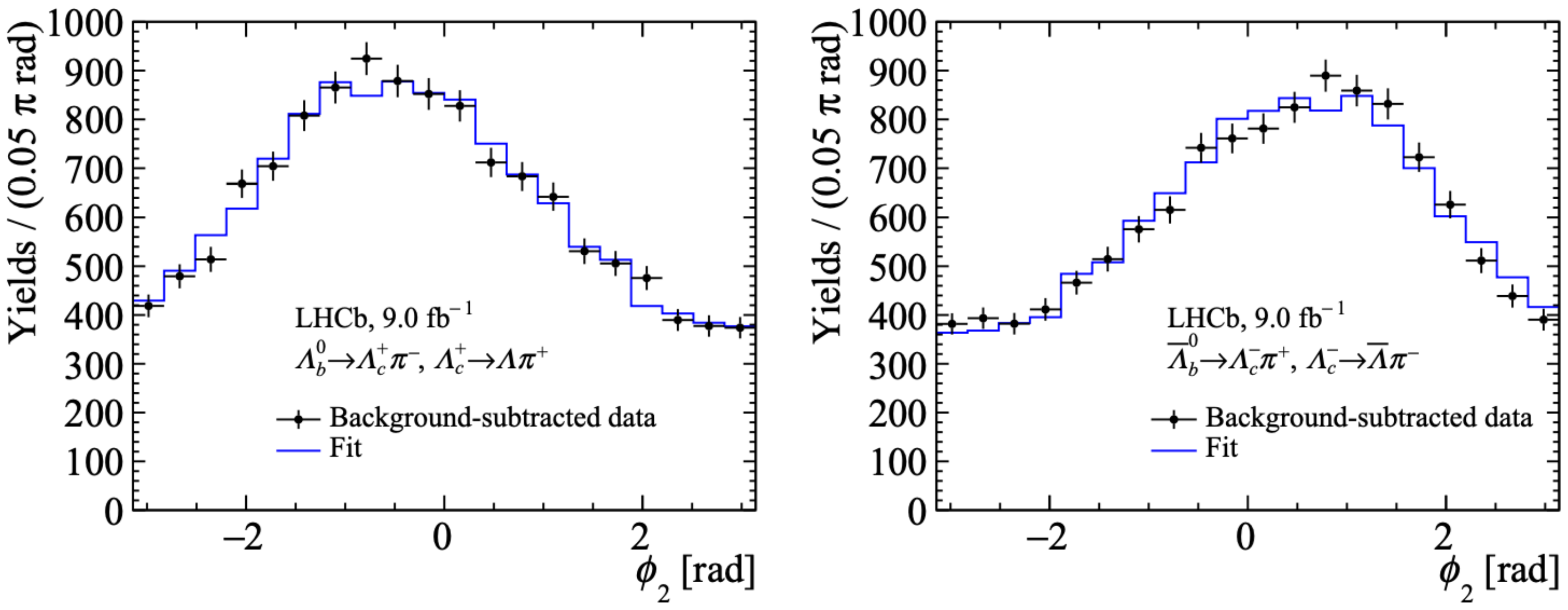
[Phys. Lett. B724 (2013) 27]
[Phys. Rev. D89 (2014) 092009]
[Phys. Rev. D97 (2018) 072010]

CP measurement

- Fit to Λ_b^0 and $\overline{\Lambda}_b^0$ samples simultaneously
- Using CP-related parameters as fit parameters

$$\langle\alpha\rangle = \frac{1}{2}(\alpha - \bar{\alpha}),\ A_\alpha \equiv \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}},\ R_\beta \equiv \frac{\beta + \bar{\beta}}{\alpha - \bar{\alpha}},\ R'_\beta \equiv \frac{\beta - \bar{\beta}}{\alpha - \bar{\alpha}}$$

- No significant CP violation found



Results of Λ_b^0 decays

- First measurement
- $\alpha \approx -1$ ⇨ V – A nature of the weak current and maximal parity violation

Decay	$\Lambda_b^0 \to \Lambda_c^+ \pi^-$	$\Lambda_b^0 \to \Lambda_c^+ K^-$
α	$-1.010 \pm 0.011 \pm 0.003$	$-0.933 \pm 0.042 \pm 0.014$
$\bar{\alpha}$	$0.996 \pm 0.011 \pm 0.003$	$0.995 \pm 0.036 \pm 0.013$
$\langle\alpha\rangle$	$-1.003 \pm 0.008 \pm 0.005$	$-0.964 \pm 0.028 \pm 0.015$
A_α	$0.007 \pm 0.008 \pm 0.005$	$-0.032 \pm 0.029 \pm 0.006$

- Various model calculations predict $\alpha \approx -1$ [Phys. Rev. D105 (2022) 073005]

Mode	This work	[88]	[13][a]	[86,87][a]	[89]	[16]	[78]	[80][a]	[79]	[82]
$\alpha(\Lambda_b \to \Lambda_c \pi)$	−99.2	−100	−99	−99	⋯	−99.9	−99.8	−99.9	$-99.99^{+4.70}_{-0.00}$	-100.0 ± 0.0
$\alpha(\Lambda_b \to \Lambda_c K)$	−98.2	⋯	⋯	⋯	⋯	−100	−100	−99.9	$-99.97^{+5.02}_{-0.01}$	-100.0 ± 0.0

Results of Λ_c^+ decays

- The most precise measurement
- Benefit from the large Λ_c^+ polarization from Λ_b^0 decay

BESIII: [Phys. Rev. D100 (2019) 072004]
Belle : [Sci. Bull. 68 (2023) 583]

Decay	$\Lambda_c^+ \to \Lambda\pi^+$	$\Lambda_c^+ \to \Lambda K^+$	$\Lambda_c^+ \to pK_S^0$
α	$-0.782 \pm 0.009 \pm 0.004$	$-0.569 \pm 0.059 \pm 0.028$	$-0.744 \pm 0.012 \pm 0.009$
$\bar{\alpha}$	$0.787 \pm 0.009 \pm 0.003$	$0.464 \pm 0.058 \pm 0.017$	$0.765 \pm 0.012 \pm 0.007$
$\langle\alpha\rangle$	$-0.785 \pm 0.006 \pm 0.003$	$-0.516 \pm 0.041 \pm 0.021$	$-0.754 \pm 0.008 \pm 0.006$
A_α	$-0.003 \pm 0.008 \pm 0.002$	$0.102 \pm 0.080 \pm 0.023$	$-0.014 \pm 0.011 \pm 0.008$
α	$-0.784 \pm 0.008 \pm 0.006$ (Belle)	$-0.556 \pm 0.071 \pm 0.028$ (Belle)	$-0.18 \pm 0.43 \pm 0.14$ (BESIII)

[Chin.J.Phys. 78 (2022) 324-362]

- Theoretical predictions complicated due to nonfactorizable contributions

Decay	Körner	Xu	Cheng		Ivanov	Żenczykowski	Sharma	Zou	Geng	Experiment (PDG)
$\Lambda_c^+ \to \Lambda\pi^+$	-0.70	-0.67	-0.99	-0.95	-0.95	-0.99	-0.99	-0.93	-0.87 ± 0.10	-0.84 ± 0.09
$\Lambda_c^+ \to p\bar{K}^0$	-1.0	0.51	-0.90	-0.49	-0.97	-0.66	-0.99	-0.75	$-0.89^{+0.26}_{-0.11}$	0.2 ± 0.5

Results of Λ_c^+ decays (cont.)

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- β, γ parameters

Decay	$\Lambda_c^+ \to \Lambda\pi^+$	$\Lambda_c^+ \to \Lambda K^+$
β	$0.368 \pm 0.019 \pm 0.008$	$0.35 \pm 0.12 \pm 0.04$
$\bar{\beta}$	$-0.387 \pm 0.018 \pm 0.010$	$-0.32 \pm 0.11 \pm 0.03$
γ	$0.502 \pm 0.016 \pm 0.006$	$-0.743 \pm 0.067 \pm 0.024$
$\bar{\gamma}$	$0.480 \pm 0.016 \pm 0.007$	$-0.828 \pm 0.049 \pm 0.013$
Δ	$0.633 \pm 0.036 \pm 0.013$	$2.70 \pm 0.17 \pm 0.04$
$\bar{\Delta}$	$-0.678 \pm 0.035 \pm 0.013$	$-2.78 \pm 0.13 \pm 0.03$
R_β	$0.012 \pm 0.017 \pm 0.005$	$-0.04 \pm 0.15 \pm 0.02$
R'_β	$-0.481 \pm 0.019 \pm 0.009$	$-0.65 \pm 0.17 \pm 0.07$

- Strong and weak phase differences between s and p waves

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

$$R'_\beta \equiv \frac{\beta - \bar{\beta}}{\alpha - \bar{\alpha}} = \tan \Delta\delta$$

Decay	$\Lambda_c^+ \to \Lambda\pi^+$	$\Lambda_c^+ \to \Lambda K^+$
$\Delta\phi$	0.01 ± 0.02	-0.03 ± 0.015
$\Delta\delta$	2.693 ± 0.017	2.57 ± 0.19

- Serve as essential inputs for some theoretical models
  - ➢ Topological diagrams

[PRD 109 (2024) 114027]

Analysis of hadronic weak decays of charmed baryons in the topological diagrammatic approach

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We perform a global fit to the experimental data of two-body charmed baryon decays based on the topological diagrammatic approach (TDA) and take into account the phase shifts between *S*- and *P*-wave amplitudes as inspired by the recent BESIII measurement of the decay asymmetry in the decay $\Lambda_c^+ \to \Xi^0 K^+$. The TDA has the advantage that it is more intuitive, graphic, and easier to implement

Results of Λ decay

- Independent measurement, consistent with BESIII results

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

Dominated by BESIII results

- Comparison between baryon decays with different flavors

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

Summary

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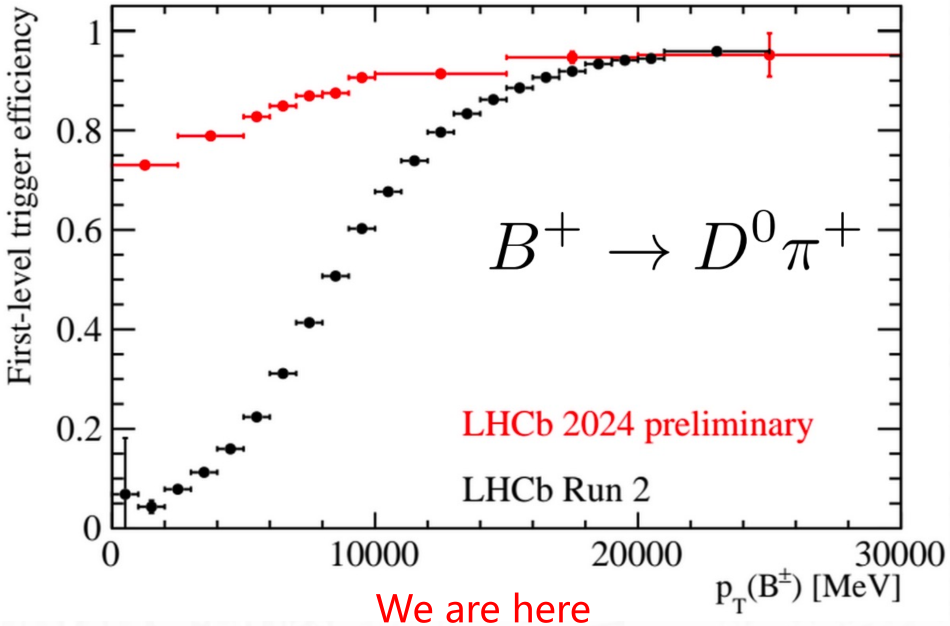
- The decay parameters and their CP asymmetries of Λ_b^0, Λ_c^+ and Λ decays are measured
  - First measurement of decay parameters of $\Lambda_b^0 \to \Lambda_c^+ h^-$
  - Precise measurements of α, β, γ of $\Lambda_c^+ \to \Lambda h^+$, and the weak and strong phase differences
  - Precision of $\alpha(\Lambda_c^+ \to p K_s^0)$ significantly improves
  - Independent measurement of $\Lambda \to p\pi^-$, consistent with BESIII results
  - Negligible CP violation in these processes
- Valuable insights into the weak decay dynamics of baryons
- Demonstrating LHCb's great potential to study CP violation in baryon decays via angular analysis

Outlook

- LHCb is highly active in beauty and charm sector and leading many studies of heavy baryons
  - ➢ One of the largest recorded b/c samples with high purity and excellent PID information
  - ➢ Many still ongoing analyses using Run 1 and Run 2 data
- In RunIII, the LHCb experiment will keep making important contributions to charm sector with
  - ➢ Higher luminosity ($L_{Run3} > L_{Run1} + L_{Run2}$)
  - ➢ Upgraded detector (e.g. UT)
  - ➢ Improved techniques (e.g. fully reconstruction in software trigger)
  - ➢ …



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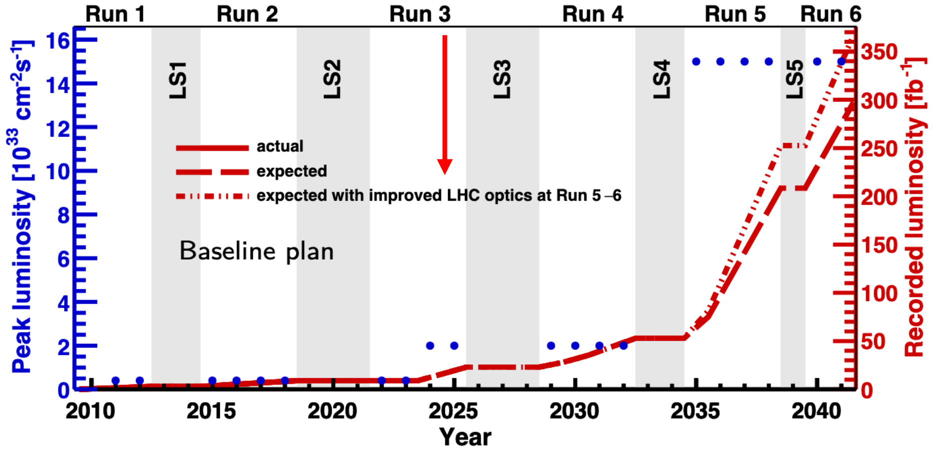
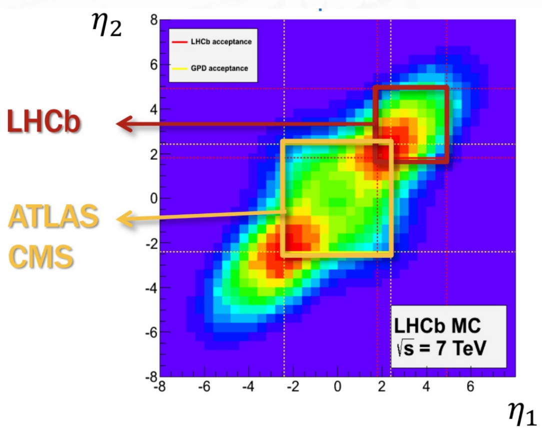


Many Thanks!

Backup

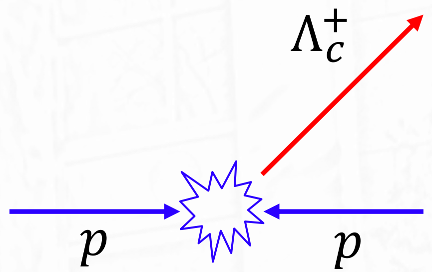
Charm baryons at LHCb



- Collected **the largest sample** of heavy baryons
  - $\sigma(pp \rightarrow b\bar{b}X) = 154.3 \pm 1.5 \pm 14.3$ μb at 13 TeV in the forward region
    $\Rightarrow \sim 60\text{k}\ b\bar{b}/s$ inside LHCb acceptance
  - $\sigma(pp \rightarrow c\bar{c}X) = 2369 \pm 3 \pm 198$ μb at 13 TeV in the forward region
    $\Rightarrow \sim 1\ M\ c\bar{c}/s$ inside LHCb acceptance

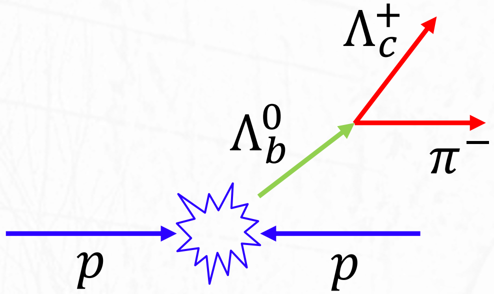
- **Prompt sample**: directly produced from pp colisions
  - Spectroscopy
  - Precise measurement (mass, lifetime, BF, ...)
  - Search for rare decay

Large statistics

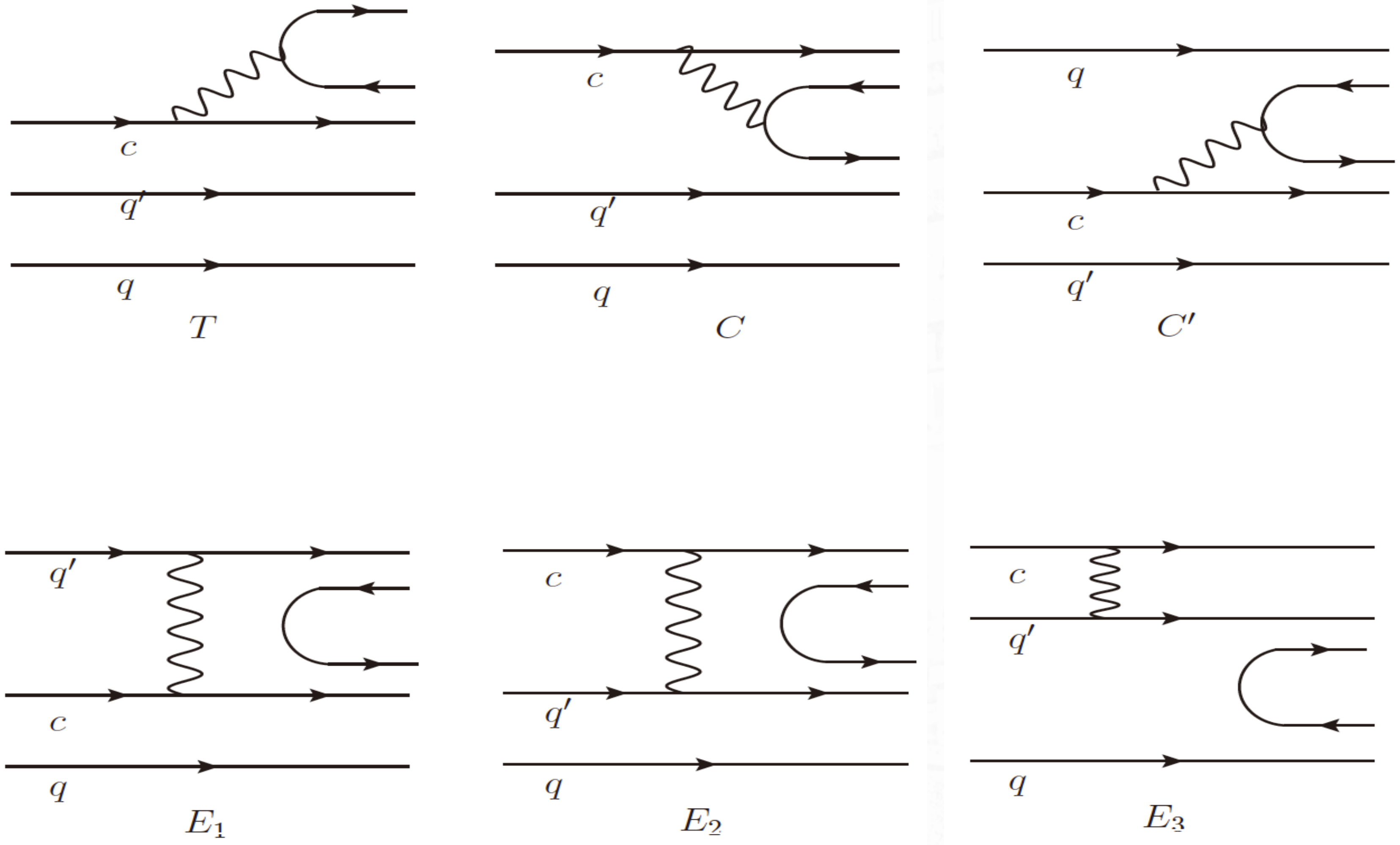


- **From b sample**: from beauty hadron decays
  - All above, but less statistics
  - J^P determination
  - Decay dynamics (β, γ, ...)

High purity, with polarization

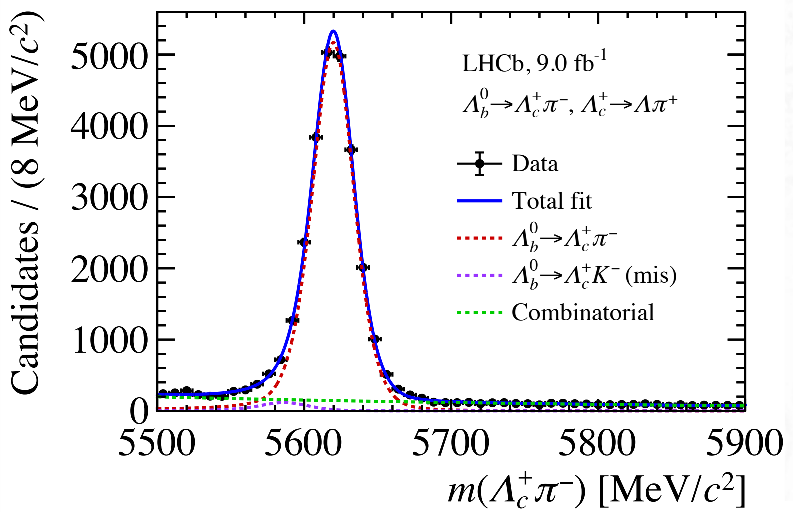


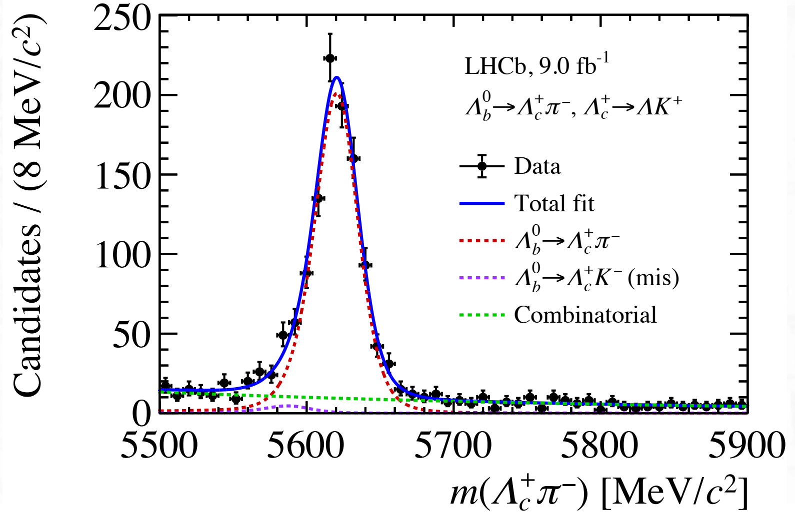
Topological diagrams

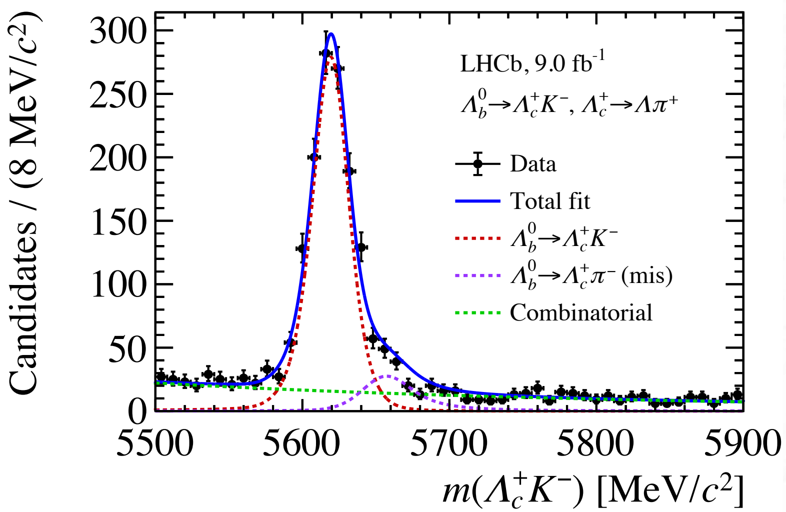


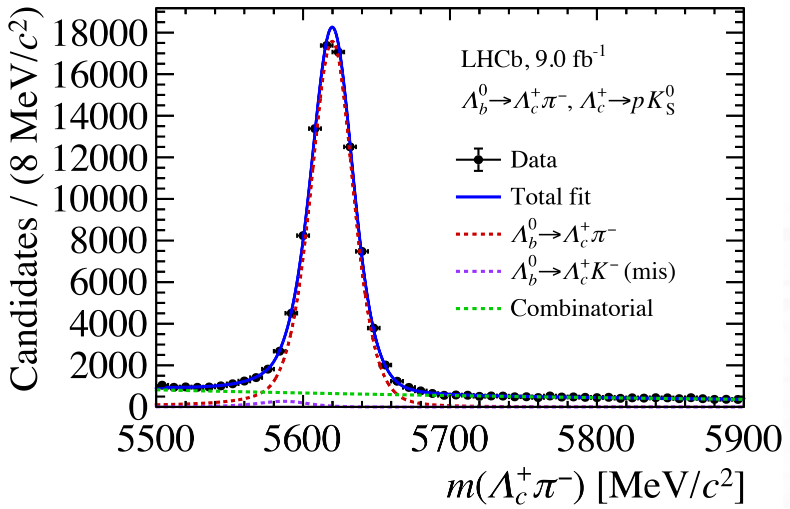
Yields

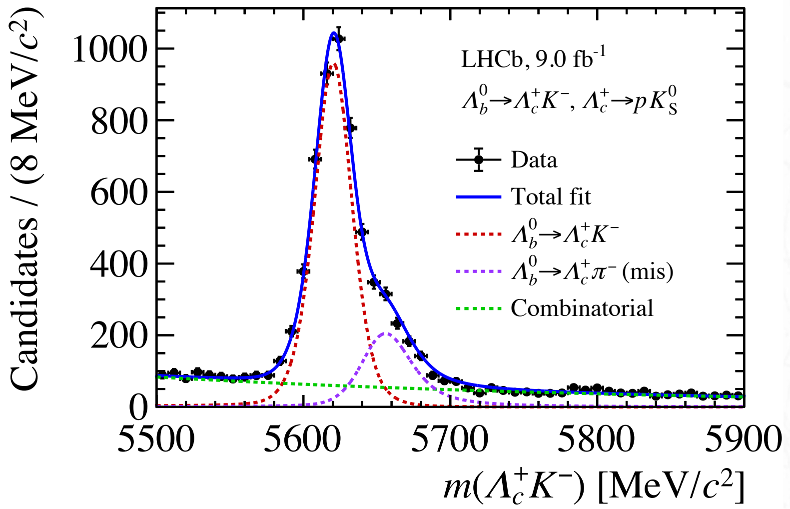
Parameter	$\Lambda_b^0 \to \Lambda_c^+ \pi^-$ $\Lambda_c^+ \to \Lambda \pi^+$	$\Lambda_b^0 \to \Lambda_c^+ K^-$ $\Lambda_c^+ \to \Lambda \pi^+$	$\Lambda_b^0 \to \Lambda_c^+ \pi^-$ $\Lambda_c^+ \to \Lambda K^+$	$\Lambda_b^0 \to \Lambda_c^+ \pi^-$ $\Lambda_c^+ \to p K_S^0$	$\Lambda_b^0 \to \Lambda_c^+ K^-$ $\Lambda_c^+ \to p K_S^0$
N_{sig}	24749 ± 168	1187 ± 37	1010 ± 34	86351 ± 318	4164 ± 72











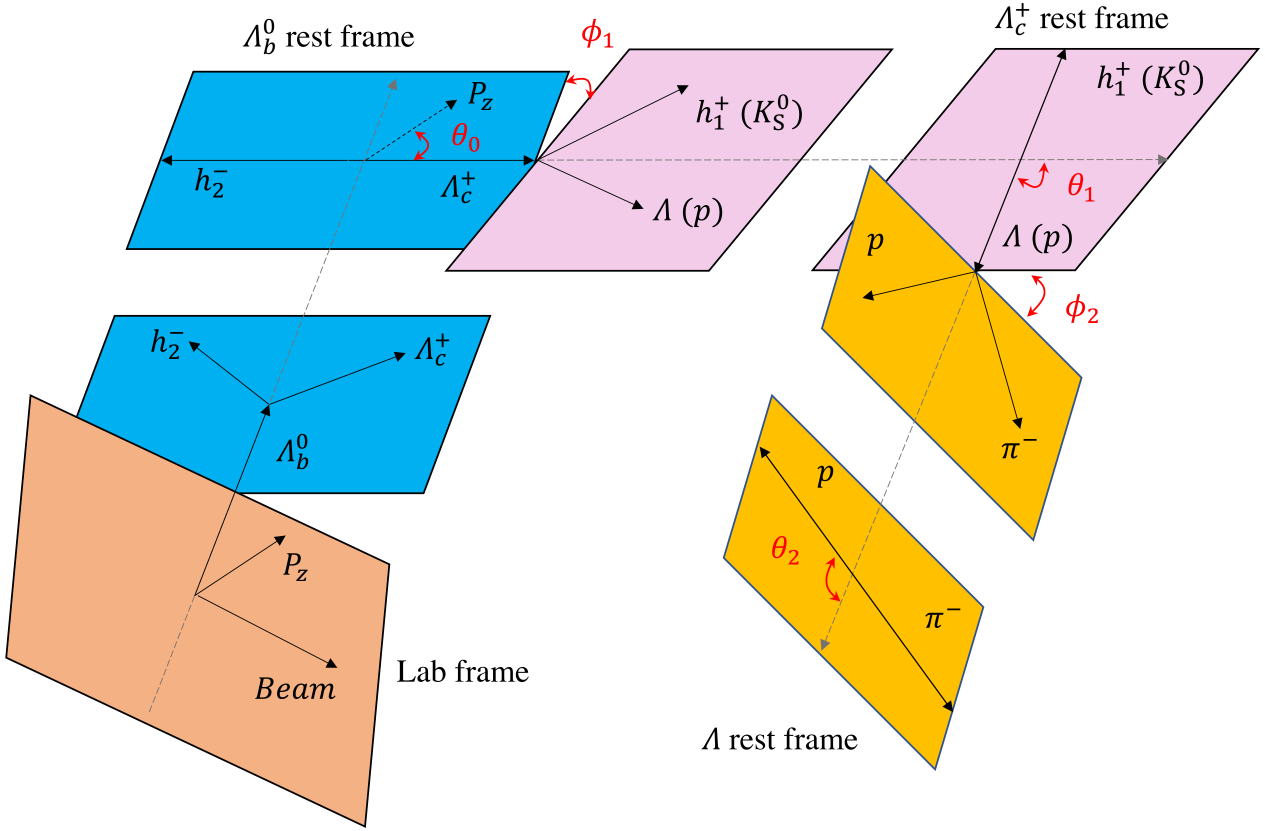
Angular distributions

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

$$\frac{d\Gamma}{d\cos\theta_1} \propto 1 + \alpha_{\Lambda_b^0}\alpha_{\Lambda_c^+}\cos\theta_1,$$

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

$$\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\phi_2} \propto (1 + \alpha_{\Lambda_b^0}\alpha_{\Lambda_c^+}\cos\theta_1 + \alpha_{\Lambda_c^+}\alpha_\Lambda\cos\theta_2 + \alpha_{\Lambda_b^0}\alpha_\Lambda\cos\theta_1\cos\theta_2 - \alpha_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_\Lambda\sin\theta_1\sin\theta_2\cos\phi_2 + \alpha_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_\Lambda\sin\theta_1\sin\theta_2\sin\phi_2),$$



Λ_b^0 polarization assumed to be 0 based on previous measurements at the LHC

[Phys. Lett. B724 (2013) 27]
[Phys. Rev. D89 (2014) 092009]
[Phys. Rev. D97 (2018) 072010]

Angular fit

- Joint unbinned maximum-likelihood fit of five channels
- sFit method for background subtraction [Nucl. Instrum. Meth. A555 (2005) 356]
- Eight independent fit parameters, without external input

$$\alpha_{\Lambda_b^0}^{\Lambda_c^+\pi^-},\ \alpha_{\Lambda_b^0}^{\Lambda_c^+K^-},\ \alpha_{\Lambda_c^+}^{\Lambda\pi^+},\ \Delta_{\Lambda_c^+}^{\Lambda\pi^+},\ \alpha_{\Lambda_c^+}^{\Lambda K^+},\ \Delta_{\Lambda_c^+}^{\Lambda\pi^+},\ \alpha_{\Lambda_c^+}^{pK_S^0},\ \alpha_{\Lambda}^{p\pi^-}$$

or

$$\alpha_{\Lambda_b^0}^{\Lambda_c^+\pi^-},\ \alpha_{\Lambda_b^0}^{\Lambda_c^+K^-},\ \beta_{\Lambda_c^+}^{\Lambda\pi^+},\ \gamma_{\Lambda_c^+}^{\Lambda\pi^+},\ \beta_{\Lambda_c^+}^{\Lambda K^+},\ \gamma_{\Lambda_c^+}^{\Lambda K^+},\ \alpha_{\Lambda_c^+}^{pK_S^0},\ \alpha_{\Lambda}^{p\pi^-}$$

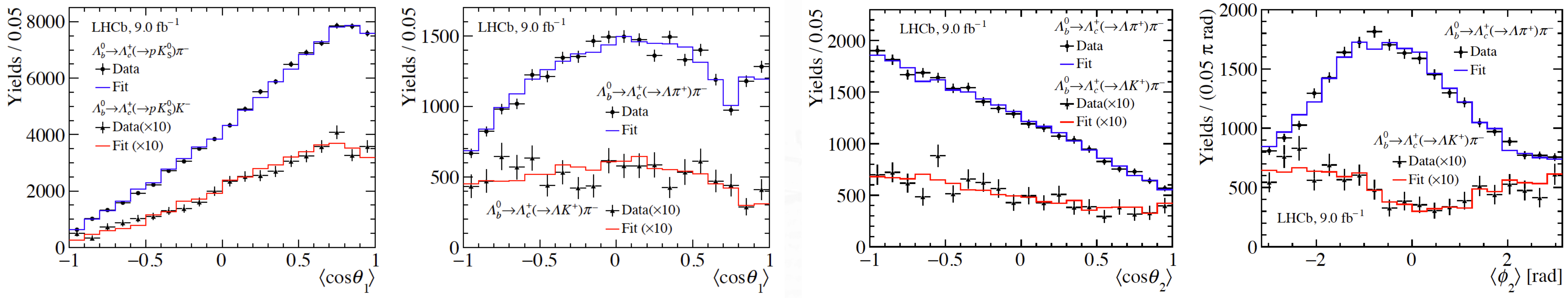
$$\alpha^2 + \beta^2 + \gamma^2 = 1$$

$$\beta = \sqrt{1-\alpha^2}\sin\Delta,$$

$$\gamma = \sqrt{1-\alpha^2}\cos\Delta,$$

$$\Delta = \arg(H_+/H_-)$$

Helicity amplitude



Helicity formalism expansion

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\Omega} \propto |M|^2 = \sum_{\lambda_0,\lambda_0',\lambda_n} \rho_{\lambda_0,\lambda_0'}\ M_{\lambda_0,\lambda_n}\ M^*_{\lambda_0',\lambda_n}, \qquad \rho = \begin{pmatrix} 1+P_z & 0 \\ 0 & 1-P_z \end{pmatrix}.$$

For $\Lambda_b^0 \to \Lambda_c^+(\to pK_\mathrm{S}^0)h^-$ decays, the helicity amplitude is determined as

$$M_{\lambda_b,\lambda_p} = \sum_{\lambda_c} H^b_{\lambda_c}\ d^{\frac{1}{2}}_{\lambda_b,\lambda_c}(\theta_0) \cdot H^c_{\lambda_p}\ e^{i\lambda_c\phi_1}\ d^{\frac{1}{2}}_{\lambda_c,\lambda_p}(\theta_1),$$

$$\begin{aligned}\frac{\mathrm{d}^3\Gamma}{\mathrm{d}\cos\theta_0\mathrm{d}\cos\theta_1\mathrm{d}\phi_1} \propto \quad & 1 + \alpha_{\Lambda_b^0}\alpha_{\Lambda_c^+}\cos\theta_1 \\ & + P_z \cdot (\alpha_{\Lambda_b^0}\cos\theta_0 + \alpha_{\Lambda_c^+}\cos\theta_0\cos\theta_1 \\ & - \gamma_{\Lambda_b^0}\alpha_{\Lambda_c^+}\sin\theta_0\sin\theta_1\cos\phi_1 \\ & + \beta_{\Lambda_b^0}\alpha_{\Lambda_c^+}\sin\theta_0\sin\theta_1\sin\phi_1),\end{aligned}$$

Helicity formalism expansion (cont.)

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For $\Lambda_b^0 \to \Lambda_c^+(\to \Lambda(\to p\pi^-)h_1^+)h_2^-$ decays,

$$M_{\lambda_b,\lambda_p} = \sum_{\lambda_c} H^b_{\lambda_c}\ d^{\frac{1}{2}}_{\lambda_b,\lambda_c}(\theta_0)\cdot H^c_{\lambda_s}\ e^{i\lambda_c\phi_1}\ d^{\frac{1}{2}}_{\lambda_c,\lambda_s}(\theta_1)\cdot H^s_{\lambda_p}\ e^{i\lambda_s\phi_2}\ d^{\frac{1}{2}}_{\lambda_s,\lambda_p}(\theta_2),$$

$$\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_{\Lambda_b^0}\alpha_{\Lambda_c^+}\cos\theta_1+\alpha_{\Lambda_c^+}\alpha_\Lambda\cos\theta_2+\alpha_{\Lambda_b^0}\alpha_\Lambda\cos\theta_1\cos\theta_2\\
&-\alpha_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_\Lambda\sin\theta_1\sin\theta_2\cos\phi_2+\alpha_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_\Lambda\sin\theta_1\sin\theta_2\sin\phi_2)\\
+P_z\cdot\ &(\alpha_{\Lambda_b^0}\cos\theta_0+\alpha_{\Lambda_c^+}\cos\theta_0\cos\theta_1+\alpha_{\Lambda_b^0}\alpha_{\Lambda_c^+}\alpha_\Lambda\cos\theta_0\cos\theta_2\\
&+\alpha_\Lambda\cos\theta_0\cos\theta_1\cos\theta_2-\gamma_{\Lambda_b^0}\alpha_{\Lambda_c^+}\sin\theta_0\sin\theta_1\cos\phi_1+\beta_{\Lambda_b^0}\alpha_{\Lambda_c^+}\sin\theta_0\sin\theta_1\sin\phi_1\\
&-\gamma_{\Lambda_c^+}\alpha_\Lambda\cos\theta_0\sin\theta_1\sin\theta_2\cos\phi_2+\beta_{\Lambda_c^+}\alpha_\Lambda\cos\theta_0\sin\theta_1\sin\theta_2\sin\phi_2\\
&-\gamma_{\Lambda_b^0}\alpha_\Lambda\sin\theta_0\sin\theta_1\cos\theta_2\cos\phi_1+\beta_{\Lambda_b^0}\alpha_\Lambda\sin\theta_0\sin\theta_1\cos\theta_2\sin\phi_1\\
&+\beta_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_\Lambda\sin\theta_0\sin\theta_2\cos\phi_1\cos\phi_2+\beta_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_\Lambda\sin\theta_0\sin\theta_2\cos\phi_1\sin\phi_2\\
&+\gamma_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_\Lambda\sin\theta_0\sin\theta_2\sin\phi_1\cos\phi_2+\gamma_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_\Lambda\sin\theta_0\sin\theta_2\sin\phi_1\sin\phi_2\\
&-\gamma_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_\Lambda\sin\theta_0\cos\theta_1\sin\theta_2\cos\phi_1\cos\phi_2\\
&+\gamma_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_\Lambda\sin\theta_0\cos\theta_1\sin\theta_2\cos\phi_1\sin\phi_2\\
&+\beta_{\Lambda_b^0}\gamma_{\Lambda_c^+}\alpha_\Lambda\sin\theta_0\cos\theta_1\sin\theta_2\sin\phi_1\cos\phi_2\\
&-\beta_{\Lambda_b^0}\beta_{\Lambda_c^+}\alpha_\Lambda\sin\theta_0\cos\theta_1\sin\theta_2\sin\phi_1\sin\phi_2),
\end{aligned}$$

Angular fit method

- sFit method for background subtraction

$$\log \mathcal{L}(\vec{\nu}) = \sum_{k=1}^{5} \left(\mathcal{C}_k \sum_{i=1}^{N_k} w_{k,i} \times \log \left[\mathcal{P}_k(\vec{\Omega}_k^i | \vec{\nu}) \right] \right)$$

- Constant to correct reported statistical uncertainties

$$\mathcal{C}_k \equiv \sum_{i\in\mathrm{data}_k} w_{k,i} / \sum_{i\in\mathrm{data}_k} w_{k,i}^2$$

- Monte Carlo integration method
- Angular acceptance corrected

$$\mathcal{P}_k(\vec{\Omega}_k | \vec{\nu}) = \frac{\epsilon_k(\vec{\Omega}_k) \cdot f_k(\vec{\Omega}_k | \vec{\nu})}{\int \mathrm{d}\vec{\Omega}_k \; \epsilon_k(\vec{\Omega}_k) \cdot f_k(\vec{\Omega}_k | \vec{\nu})},$$