Observation of Charge-Parity Symmetry Breaking in Baryon Decays (LHCb collaboration, 2025)

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Overview

1. CP Violation in SM Flavour Physics
2. Direct and Indirect Detection Methodology
3. Milestones in CP Violation Detection

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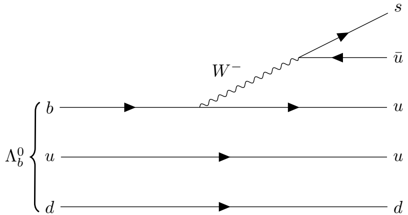
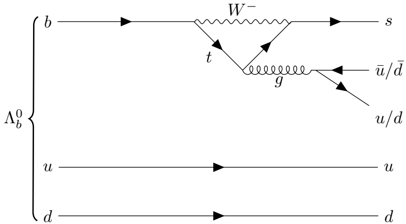
4. Theoretical Framework for Baryon Decay
5. Experimental Approach and Results
6. Discussion

A review of https://arxiv.org/abs/2503.16954 (LHCb collaboration, 2025).

Process

- Compare $\Lambda_b^0 \to pK^-\pi^-\pi^+$ and its conjugate $\bar{\Lambda}_b^0 \to \bar{p}K^+\pi^+\pi^-$





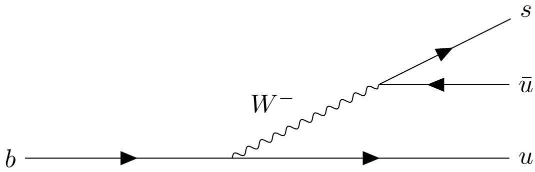
- Amount of CP violation is quantified by relative difference between decay rates:

$$\mathcal{A}_{CP} \equiv \frac{\Gamma(\Lambda_b^0 \to pK^-\pi^-\pi^+) - \Gamma(\bar{\Lambda}_b^0 \to \bar{p}K^+\pi^+\pi^-)}{\Gamma(\Lambda_b^0 \to pK^-\pi^-\pi^+) + \Gamma(\bar{\Lambda}_b^0 \to \bar{p}K^+\pi^+\pi^-)}$$

4. Theoretical Framework for Baryon Decay

Tree-level Process

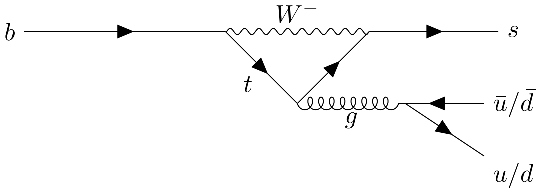
- $b \to uW^-$: vertex $\propto V_{ub} \approx A\lambda^3(\rho - i\eta)$
- $W^- \to \bar{u}s$: vertex $\propto V_{us}^* \approx \lambda^*$
- Total CKM factor: $\propto V_{ub}V_{us}^*$, weak phase $\phi_T = \arg(V_{ub}V_{us}^*) \approx -65.4^\circ$



4. Theoretical Framework for Baryon Decay

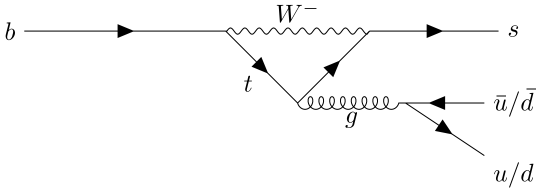
Loop-level Process

- Flavour-changing neutral current (FCNC) process
- Suppressed at tree-level in the SM, since Z boson and gluon do not change flavour
- $b \to s$ transition via a loop with a W^- boson and internal quark t
- Emission of a gluon from the loop, which produces the $u\bar{u}$ pair



Loop-level Process (cont.)

- $b \to tW^-$: vertex $\propto V_{tb} \approx -A\lambda^2$
- $tW^- \to s$: vertex $\propto V_{ts}^* \approx 1$
- Total CKM factor: $\propto V_{tb}V_{us}^*$, weak phase $\phi_L = \arg(V_{tb}V_{us}^*) \approx 0$



Interference between Tree and Loop Amplitudes

- Amplitude of decays:

$$A(\Lambda_b^0) = |A_T|e^{+i\phi_T}e^{i\delta_T} + |A_L|e^{+i\phi_L e^{i\delta_L}}$$
$$A(\bar{\Lambda}_b^0) = |A_T|e^{-i\phi_T}e^{i\delta_T} + |A_L|e^{-i\phi_L e^{i\delta_L}}$$

- Weak phases $\phi_{T/L}$: defined by CKM elements $V_{ub}V_{us}^*$ and $V_{tb}V_{ts}^*$
- Strong phases $\delta_{T/L}$: process-dependent, difficult to calculate due to non-perturbative QCD effects at low energies

(M. Beneke+, 1999)

Interference between Tree and Loop Amplitudes (cont.)

- Decay rate $\Gamma \propto |A|^2$, so

$$\mathcal{A}_{CP} = \frac{|A(\Lambda_b^0)|^2 - |A(\bar{\Lambda}_b^0)|^2}{|A(\Lambda_b^0)|^2 + |A(\bar{\Lambda}_b^0)|^2} = \frac{2\sin\Delta\delta\sin\Delta\phi}{|A_T/A_L| + |A_L/A_T| + 2\cos\Delta\delta\cos\Delta\phi},$$

  where $\Delta\phi = \phi_T - \phi_L \approx -65.7^\circ$, $\Delta\delta = \delta_T - \delta_L$

- Sizable $\mathcal{A}_{CP}$ requires $A_T \sim A_L$, big $\Delta\phi$ and $\Delta\delta$

Data and Bias

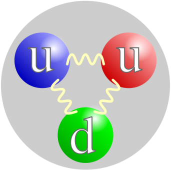
- Λ_b^0 and $\bar{\Lambda}_b^0$ produced in proton-proton (pp) collisions
- Data collected by the Large Hadron Collider (LHC) from 2011 to 2018, total integrated luminosity $\sim 9\mathrm{fb}^{-1}$
- Yield asymmetry: difference of numbers (N) of observed decays, defined as

$$\mathcal{A}_N \equiv \frac{N(\Lambda_b^0 \to pK^-\pi^-\pi^+) - N(\bar{\Lambda}_b^0 \to \bar{p}K^+\pi^+\pi^-)}{N(\Lambda_b^0 \to pK^-\pi^-\pi^+) + N(\bar{\Lambda}_b^0 \to \bar{p}K^+\pi^+\pi^-)}$$

$\mathcal{A}_N \neq \mathcal{A}_{CP}$.

Data and Bias (cont.)

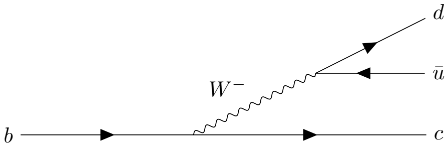
- Production asymmetry: $\sigma(\Lambda_b^0) > \sigma(\bar{\Lambda}_b^0)$ in pp collisions. Protons contain more valence quarks (u, d) than antiquarks $(\bar{u},\ \bar{d})$ $\implies$ b combines with the proton's valence u and d more readily to form a Λ_b^0



- Detection asymmetry: particles and antiparticles interact with the detector material differently

Control Channel

- $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ with $\Lambda_c^+ \to pK^-\pi^+$, dominated by the tree-level $b \to cud$ transition
- Its asymmetry reflects only nuisance effects
- Subtracted from the signal channel's yield asymmetry to obtain $\mathcal{A}_{CP}$

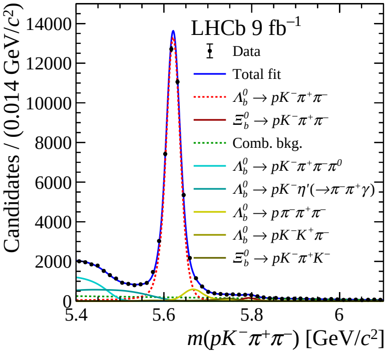


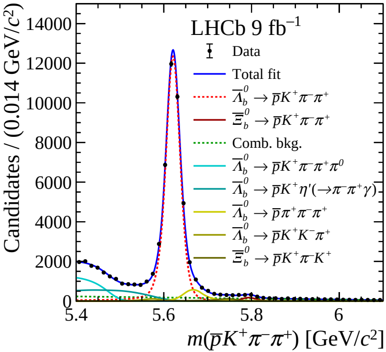
5. Experimental Approach and Results

Event Selection

- Reduce background from random combinations of final-state particles
- Decay vertex is displaced from the pp collision point, since Λ_b^0 has a long lifetime
- High p_T for final-state particles due to large Λ_b^0 mass
- Particle identification (PID) reduces misidentification (e.g. π^- reconstructed as K^- in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$)
- Mass distributions are fit to extract signal yields, with a peak at $m_{\Lambda_b^0} \approx 5619\mathrm{MeV}/c^2$

5. Experimental Approach and Results





$$\mathcal{A}_{CP} = (2.45 \pm 0.46 \pm 0.10)\% \quad (5.2\sigma)$$

Phase-Space Analysis

- The $\Lambda_b^0 \to pK^-\pi^+\pi^-$ decay involves multiple intermediate resonances, identified by two/three-body invariant masses
- $\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$: $\mathcal{A}_{CP} = (5.4 \pm 0.9 \pm 0.1)\% \quad (6.0\sigma)$
- $\Lambda_b^0 \to R(pK^-)R(\pi^+\pi^-)$: $\mathcal{A}_{CP} = (5.3 \pm 1.3 \pm 0.2)\%$
- Other decay topologies show smaller asymmetries
  - $\Lambda_b^0 \to R(p\pi^-)R(K^-\pi^+)$: $\mathcal{A}_{CP} = (2.7 \pm 0.8 \pm 0.1)\%$
  - $\Lambda_b^0 \to R(K^-\pi^+\pi^-)$: $\mathcal{A}_{CP} = (2.0 \pm 1.2 \pm 0.3)\%$

These variations arise because different resonances have distinct tree and loop amplitude contributions, with unique strong phases.

6. Discussion

Comparison with Mesons

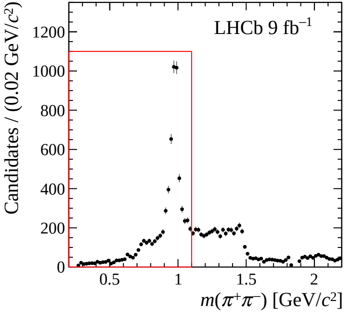
- $B_s^0 \to K^- \pi^+$ shows 23.6% CP asymmetry, while $\Lambda_b^0 \to p h^-$ ($h = \pi, K$) shows no asymmetry at 0.7% precision
- Meson decays often involve simpler final states (e.g., two particles)
- Baryon decays like $\Lambda_b^0 \to p K^- \pi^+ \pi^-$ involve multi-body final states with multiple resonances, leading to more complex interference patterns

(LHCb, 2013 & 2021 & 2024)

6. Discussion

Complex Dynamics in the Decay

- Resonant (e.g., $f_0(500)/\rho(770)/f_0(980) \to \pi^+\pi^-$) and non-resonant contributions (e.g., direct $\pi^+\pi^-$ pairs production) interfere
- Hadronic effects: relative magnitudes and strong phases of tree and loop amplitudes vary across phase space

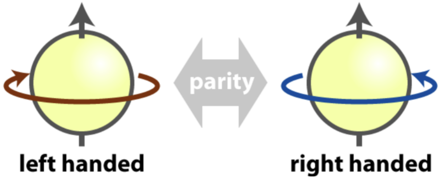


Significance and Implications Beyond the SM

- Complex phase of the CKM matrix provides CP violation, but is orders of magnitude too small to explain the observed baryon-to-photon ratio $\eta_B \approx 6 \times 10^{-10}$
- First observation of CP violation in baryons, offers opportunities to probe for deviations from SM predictions that might reveal new physics
- Encourages further experiments to study other baryon decays like $\Lambda_b^0/\Xi_b^0 \to ph^-h^+h^-$, where h denotes π, K, dominant diagrams with amplitudes of similar magnitude and significant phase differences

What is CP Violation?

- Laws of physics are not invariant under the combined operation of charge conjugation (C) and parity (P) transformations
- Particles and antiparticles have different behaviours
- Required to create matter (Sakharov conditions)



(A. D. Sakharov, 1967)

3. Milestones in CP Violation Detection (Back-up)

Meson Decays Observed

- $K_L^0 \to \pi^+\pi^-$ (1964)
- $B^0 \to J/\Psi K_S^0$ (2001)
- $D^0 \to K^+K^-, \pi^+\pi^-$ (2019)

Despite expectations of similar CP violation in baryons, it had not been observed until this study: $\Lambda_b^0(bud) \to pK^-\pi^-\pi^+$.

$$\mathcal{A}_{CP} = (2.45 \pm 0.46 \pm 0.10)\% \quad (5.2\sigma)$$

(J. H. Christenson+, 1964; BaBar, 2001; Belle, 2001; LHCb, 2019)

Cabibbo–Kobayashi–Maskawa (CKM) Matrix

- Only known source of CP symmetry breaking in the Standard Model (SM)

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}, \quad \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\mathrm{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Charged-current interaction Lagrangian:

$$\mathcal{L}_{\mathrm{C}} = -\frac{g}{\sqrt{2}} \sum_{i,j} \bar{u}_i \gamma^{\mu} P_L V_{ij} d_j W_{\mu}^{+} + \mathrm{h.c.},$$

where g is the $SU(2)_L$ weak coupling constant, $P_L = (1 - \gamma^5)/2$ is the left-handed projector

Cabibbo–Kobayashi–Maskawa (CKM) Matrix (cont.)

- Wolfenstein Parametrization:

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4),$$

  with $\lambda \approx 0.225$, $A \approx 0.826$, $\rho \approx 0.159$, $\eta \approx 0.348$

- Highlights hierarchical structure of quark mixing and allows for a convenient approximation accurate up to 0.3%

Loop-level Process (cont.)

- Effective Hamiltonian:

$$H_{eff} = \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i \mathcal{O}_i + \text{h.c.},$$

  where C_i are Wilson coefficients that encode loop effects and $\mathcal{O}_i$ are four-fermion operators, e.g., $(\bar{s}\gamma^\mu b)(\bar{u}\gamma_\mu u)$
- $b \to tW^-$: vertex $\propto V_{tb} \approx -A\lambda^2$
- $tW^- \to s$: vertex $\propto V_{ts}^* \approx 1$
- Total CKM factor: $\propto V_{tb}V_{us}^*$, weak phase $\phi_L = \arg(V_{tb}V_{us}^*) \approx 0$