Search for baryon $CP$ violation at the LHCb

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On behalf of the LHCb collaboration

CKM 2021

Melbourne, 22-26 November 2021
CP violation established in $K$, $B$ and $D$ meson decays and well consistent with SM prediction

CP violation not yet observed in baryon decays

In this talk:
- Search for CP violation in $\Xi_b^- \rightarrow pK^-K^-$
- Measurement of CP asymmetry for the decay $\Lambda_b^0 \rightarrow DpK^-$
- Search for CP violation in $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$
Experiment at the LHC mainly dedicated to heavy flavour physics
It ran (until 2018) at \( \mathcal{L} = 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \)
Covers only 4\% of solid angle, but detects \( \approx 25\% \) of \( b\bar{b} \) pairs produced in the collisions
Very efficient at identifying \( p, K \) and \( \pi \) in the final state thanks to PID information provided by the two RICH detectors
Integrated luminosity of 5 fb$^{-1}$ collected with the LHCb detector at $\sqrt{s}= 7, 8$ and 13 TeV

First amplitude analysis of any baryon decay mode allowing for CP-violation effects

Signal purity of $(63 \pm 3)\%$ and $(70 \pm 2)\%$ for Run 1 and Run 2 in the region $\pm 40$ MeV around the $\Xi_b^-$ mass
Phase space asymmetries extracted using an amplitude analysis:

- $\Xi^-_b$ baryons assumed to be produced with negligible polarization in $pp$ collisions, as observed for the $\Lambda^0_b$ baryons
- **2 kinematic variables are sufficient to characterise the phase space instead of 5**
- Use variables $m^{2}_{low}(pK^-)$ and $m^{2}_{high}(pK^-)$ to remove Bose symmetry given by the presence of two identical kaons in the final state
Decay assumed to proceed through one intermediate resonance R:

$$\Xi^{-}_b \rightarrow (R \rightarrow pK^-)K^-$$

Analysis done using the **helicity formalism**

- $\frac{d\Gamma^Q}{d\Omega}$ is written as:

$$\frac{d\Gamma^Q}{d\Omega} = \frac{1}{(8\pi m_{\Xi^-_b})^3} \sum_{M_{\Xi^-_b},\lambda_p} |A_{R,M_{\Xi^-_b},\lambda_p}^Q(\Omega)|^2$$

- $A_{R,M_{\Xi^-_b},\lambda_p}^Q(\Omega)$ is the symmetrized decay amplitude for a given intermediate state R
- Resonances are parameterized with relativistic Breit–Wigner functions
$\Xi_b^- \to pK^- K^-$ may decay through various $\Lambda^*$ and $\Sigma^*$ resonances:

- Only sufficiently well established resonances are considered in this study
- Baseline model obtained by adding resonances iteratively to maximise the change in $-2\ln L$

<table>
<thead>
<tr>
<th>State</th>
<th>Mass (MeV/$c^2$)</th>
<th>Width (MeV/$c^2$)</th>
<th>$J^P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda(1405)$</td>
<td>1405.1 ± 1.3</td>
<td>50.5 ± 2.0</td>
<td>$\frac{1}{2}^-$</td>
</tr>
<tr>
<td>$\Lambda(1520)$</td>
<td>1518 to 1520</td>
<td>15 to 17</td>
<td>$\frac{3}{2}^-$</td>
</tr>
<tr>
<td>$\Lambda(1670)$</td>
<td>1660 to 1680</td>
<td>25 to 50</td>
<td>$\frac{1}{2}^-$</td>
</tr>
<tr>
<td>$\Sigma(1385)$</td>
<td>1383.7 ± 1</td>
<td>36 ± 5</td>
<td>$\frac{3}{2}^+$</td>
</tr>
<tr>
<td>$\Sigma(1775)$</td>
<td>1770 to 1780</td>
<td>105 to 135</td>
<td>$\frac{5}{2}^-$</td>
</tr>
<tr>
<td>$\Sigma(1915)$</td>
<td>1900 to 1935</td>
<td>80 to 160</td>
<td>$\frac{5}{2}^+$</td>
</tr>
</tbody>
</table>

- Combinatorial background modeling from $5890$ MeV/$c^2 < m(pK^-K^-) < 6470$ MeV/$c^2$ sideband
Asymmetries extracted with an unbinned maximum-likelihood fit

- Fit performed simultaneously to the Run 1 and Run 2 data
The asymmetry for each contributing component shows no significant $CP$ violation effect

<table>
<thead>
<tr>
<th>Component</th>
<th>$A_{CP}(10^{-2})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda(1405)$</td>
<td>$-27 \pm 34$ (stat) $\pm 73$ (syst)</td>
</tr>
<tr>
<td>$\Lambda(1520)$</td>
<td>$-1 \pm 24$ (stat) $\pm 32$ (syst)</td>
</tr>
<tr>
<td>$\Lambda(1670)$</td>
<td>$-5 \pm 9$ (stat) $\pm 8$ (syst)</td>
</tr>
<tr>
<td>$\Sigma(1385)$</td>
<td>$3 \pm 14$ (stat) $\pm 10$ (syst)</td>
</tr>
<tr>
<td>$\Sigma(1775)$</td>
<td>$-47 \pm 26$ (stat) $\pm 14$ (syst)</td>
</tr>
<tr>
<td>$\Sigma(1915)$</td>
<td>$11 \pm 26$ (stat) $\pm 22$ (syst)</td>
</tr>
</tbody>
</table>

**Main source of systematics:**
- $\Xi_b$ Polarization
- Production asymmetries
- Relativistic Breit-Wigner parameters
- Alternative fit model
- Efficiency
- Background shape
Two $\Lambda_b^0 \rightarrow DpK^-$ decays:

- $\Lambda_b^0 \rightarrow [K^- \pi^+]_DpK^-$ with same sign kaon is favoured
- $\Lambda_b^0 \rightarrow [K^+ \pi^-]_DpK^-$ with opposite sign kaon is suppressed

- suppressed by a factor $R \sim \left| \frac{V_{cb}V_{us}^*}{V_{ub}V_{cs}^*} \right|^2 = 7.4$
- receives contributions from $b \rightarrow c$ and $b \rightarrow u$ amplitudes
- interference between these two amplitudes depends upon the CKM angle $\gamma$

Beauty-baryon decays to final states involving a single charm meson are promising for measurements of $CP$ violation:

$$A = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow [K^+ \pi^-]_DpK^-) - \mathcal{B}(\bar{\Lambda}_b^0 \rightarrow [K^- \pi^+]_D\bar{p}K^+)}{\mathcal{B}(\Lambda_b^0 \rightarrow [K^+ \pi^-]_DpK^-) + \mathcal{B}(\bar{\Lambda}_b^0 \rightarrow [K^- \pi^+]_D\bar{p}K^+)}$$
Data sample corresponding to an integrated luminosity of 9 fb$^{-1}$ collected with the LHCb detector at $\sqrt{s} = 7$, 8, and 13 TeV

Suppressed decay $\Lambda_{b}^{0} \rightarrow [K^{+}\pi^{-}]_{D}pK^{-}$ seen for the first time

The measured yield in the full phase space is:

- $1437 \pm 92$ for the favoured mode
- $241 \pm 22$ for the suppressed mode
CP asymmetry measurement

CP asymmetry extracted after applying efficiency correction factors

- The efficiency corrections are determined as a function of the $\Lambda^0_b$ phase-space variables $M^2(Dp)$ and $M^2(pK^-)$ using simulation

$$A_{CP} = \frac{\sum_i w_{SUP,\Lambda_b^0}^i / \epsilon^i - \sum_i w_{SUP,\Lambda_b^0}^i / \epsilon^i}{\sum_i w_{SUP,\Lambda_b^0}^i / \epsilon^i + \sum_i w_{SUP,\Lambda_b^0}^i / \epsilon^i}$$

CP asymmetry measured in two regions of the phase space:

- Phase space integrated asymmetry
- Asymmetry in the region involving excited $\Lambda^*$ states $\Lambda^0_b \rightarrow D\Lambda^*$
Asymmetries show no significant \( CP \)-violation effect

- Phase space integrated asymmetry
  \[
  A_{CP} = 0.12 \pm 0.09(\text{stat})^{+0.02}_{-0.03}(\text{syst.})
  \]

- \( M(pK^-)^2 < 5 \text{ GeV}^2/c^4 \) region
  \[
  A_{CP} = 0.01 \pm 0.16(\text{stat})^{+0.03}_{-0.02}(\text{syst.})
  \]

- **Main source of systematics:**
  - Fit model
  - Efficiency corrections
  - Hardware trigger efficiency
  - PID efficiency
  - \( \Lambda_b^0 \) production asymmetry
  - \( p \) detection asymmetry
  - \( \pi \) detection asymmetry
Integrated luminosity of 6.6 $fb^{-1}$ collected from 2011 to 2017 at $\sqrt{s} = 7, 8$ and $13$ TeV

$CP$ asymmetry measured using two different approaches:
- Triple product correlations
- Energy test method

$N_{\Lambda_b^0 + \bar{\Lambda}_b^0} = 27600 \pm 200$
Triple product correlations

- $\hat{T} - \text{odd}$ observables are built using the momenta $\vec{p}_i$ of three final state particles in the mother C.M. frame: $C_\hat{T} = \vec{p}_p \cdot (\vec{p}_h \times \vec{p}_h')$, $\bar{C}_\hat{T} = \vec{p}_\bar{p} \cdot (\vec{p}_\bar{h} \times \vec{p}_\bar{h}')$:

$$A_{\hat{T}} = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}$$

$$\bar{A}_{\hat{T}} = \frac{\bar{N}(-\bar{C}_{\hat{T}} > 0) - \bar{N}(-\bar{C}_{\hat{T}} < 0)}{\bar{N}(-\bar{C}_{\hat{T}} > 0) + \bar{N}(-\bar{C}_{\hat{T}} < 0)}$$

- True $CP$ and $P$ violating observables are defined as:

$$a_{\hat{T} - \text{odd}}^{\hat{T} - \text{odd}} = \frac{1}{2} (A_{\hat{T}} - \bar{A}_{\hat{T}})$$

$$a_{\hat{T} - \text{odd}}^{\hat{T} - \text{odd}} = \frac{1}{2} (A_{\hat{T}} + \bar{A}_{\hat{T}})$$

Different sensitivity to systematic effects:

$a_{\hat{T} - \text{odd}}^{\hat{T} - \text{odd}}$ marginally affected by reconstruction efficiency and $b$–hadron production asymmetries
Triple product correlations

Triple products are calculated in the $\Lambda^0_b$ rest frame:

$C_T = \vec{p}_p \cdot (\vec{p}_{\pi^\text{fast}} \times \vec{p}_{\pi^+}) \propto \sin \Phi$

$\overline{C}_T = \vec{p}_{\bar{p}} \cdot (\vec{p}_{\pi^\text{fast}} \times \vec{p}_{\pi^-}) \propto \sin \Phi$

Asymmetries are measured both integrating over the full phase space and in bins of the phase space to enhance local sensitivity to CP violation
Search for $CP$ asymmetries in regions of the phase space

Very rich resonant structure in the decay, dominant contributions proceed through:

- $\Lambda^0_b \to N^{*+}\pi^-, N^{*+} \to \Delta^{++}(1234)\pi^-, \Delta^{++} \to p\pi^+$
- $\Lambda^0_b \to pa_1^-(1260), a_1^-(1260) \to \rho^0(770)\pi^-, \rho^0(770) \to \pi^+\pi^-$

Phase space binning according to two schemes

- Scheme A: 
  16 bins on polar and azimuthal angles of proton in the $\Delta^{++}$ frame

- Scheme B: 
  10 bins on $\Phi$ angle between decay planes $\pi^+\pi^-_{\text{slow}}$ and $p\pi^-_{\text{fast}}$
Phase space integrated asymmetries

\[ a_{CP}^{T-\text{odd}} = (-0.7 \pm 0.7 \pm 0.2)\% \quad \text{consistent with } CP \text{ symmetry} \]

\[ a_{P}^{T-\text{odd}} = (-4.0 \pm 0.7 \pm 0.2)\% \quad \text{5.5 } \sigma \text{ deviation from } P \text{ symmetry} \]

Systematics assigned using high statistics control sample containing charm \( \Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \)

Main source of systematics:
  - Reconstruction
  - Detector acceptance
Asymmetries measured in bins of the phase space

Cut on $m(p\pi^+\pi^-_{slow})$ invariant mass:

- $m > 2.8$ GeV/$c^2$ to enhance the $\Lambda_b^0 \rightarrow p a_1^- (\rightarrow \rho\pi^-)$ (A$_1$ and B$_1$ schemes)
- $m < 2.8$ GeV/$c^2$ to enhance the $\Lambda_b^0 \rightarrow N^* (\Delta^{++}\pi^-)\pi^-$ (A$_2$ and B$_2$ schemes)

$CP$ violation hypothesis checked with a $\chi^2$ test

No evidence for $CP$ violation, highest significance 2.9 $\sigma$ in B$_2$
Model-independent unbinned test  

\[ M. \text{ Williams}, \text{ Phys. Rev. D 84, 054015} \]

Method sensitive to local differences between two samples

\[ \psi_{ij} = e^{-d_{ij}^2/2\delta^2} \]

\[ d_{ij} \text{ Euclidean distance between two candidates in the phase space} \]

**PHS:** \( m^2(p\pi^+), m^2(\pi^+\pi_{\text{slow}}^-), m^2(p\pi^+\pi_{\text{slow}}^-), m^2(\pi^+\pi_{\text{slow}}^-\pi_{\text{fast}}^-), m^2(p\pi_{\text{slow}}^-) \)

\( \delta \) is the distance scale (free parameter)

\( T \) large when significant localized differences between samples exist and has an expectation of 0 when there is no difference
3 Tests:
- CP test
  - $P$-odd: I+IV vs II+III
  - $P$-even: I+II vs III+IV
- P test: I+III vs II+IV

$p$-values calculated for 3 different values of $\delta$:

<table>
<thead>
<tr>
<th>Distance scale $\delta$</th>
<th>1.6 GeV$^2$/c$^4$</th>
<th>2.7 GeV$^2$/c$^4$</th>
<th>13 GeV$^2$/c$^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$-value (CP conservation, $P$ even)</td>
<td>$3.1 \times 10^{-2}$</td>
<td>$2.7 \times 10^{-3}$</td>
<td>$1.3 \times 10^{-2}$</td>
</tr>
<tr>
<td>$p$-value (CP conservation, $P$ odd)</td>
<td>$1.5 \times 10^{-1}$</td>
<td>$6.9 \times 10^{-2}$</td>
<td>$6.5 \times 10^{-2}$</td>
</tr>
<tr>
<td>$p$-value ($P$ conservation)</td>
<td>$1.3 \times 10^{-7}$</td>
<td>$4.0 \times 10^{-7}$</td>
<td>$1.6 \times 10^{-1}$</td>
</tr>
</tbody>
</table>

- Combined significance $< 3.0 \sigma$ in CP test
- $5.3 \sigma$ significance in $P$ test
Conclusions

Summary of this talk:

- Multibody decays are interesting place to search for $CP$ violation due to their rich phase space structure
- No evidence for $CP$ violation in $\Lambda_b^0$ and $\Xi_b^-$ decays for the moment
- Expected significant improvement in sensitivity in Run3:
  - Higher instantaneous luminosity
  - Channels with final state hadrons will be selected with higher efficiencies after the removal of the L0 hardware trigger