Search for CP violation in $\Lambda_b \rightarrow p\pi^-\pi^+\pi^-$ decays

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Outline

1 Motivation

2 Novel Approach: Energy Test

3 Selection

4 Simulation

5 Sensitivity studies: Energy Test method

6 Cross-checks

7 Conclusions
Theoretical Motivation

- Transitions governed by $b \to ud\bar{u}$ tree and $b \to du\bar{u}$ penguin amplitudes of similar magnitude. Large relative weak phase in SM from the CKM elements, $\alpha = \text{arg}\left[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*\right]$
- CPV is well established in B-meson decays
CPV has never been observed in baryons.

First evidence of CPV in baryons has been found in this channel with significance of $3.3\sigma$ using Run 1 data.

*Probing matter-antimatter asymmetries in beauty baryon decays (Nature Physics 13, 391-396 (2017))*
Novel Approach: Energy Test

- System $\rightarrow$ Phase Space
- $\Lambda_b / \bar{\Lambda}_b \rightarrow$ opposite flavour decays
- $\psi(d_{ij}) = e^{-d_{ij}^2/2\delta^2}$: Weighting function
- $n, \bar{n}$: number of $\Lambda_b, \bar{\Lambda}_b$ candidates
- $d_{ij}$: distance in phase space
- $\delta$: distance parameter to be optimized

$$T = \sum_{i,j>i}^n \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i}^{\bar{n}} \frac{\psi_{ij}}{\bar{n}(\bar{n}-1)} - \sum_{i,j}^n \frac{\psi_{ij}}{n\bar{n}},$$

Observing CP violation in many-body decays (*Phys. Rev. D* 84, 054015)
Novel Approach: Energy Test

- Model independent
- Going from sample (I to III) or (II to IV) constitutes a CP transformation
- Can look for CPV in two combinations: P-even (I + II) vs (III + IV) and P-odd (I + IV) vs (II + III) CPV
- Not sensitive to global production and detection asymmetries

\[ C_T \equiv \vec{p}_p \cdot (\vec{p}_{h^-} \times \vec{p}_{h^+}) \]

P
C
I Particle, C_T > 0
II Particle, C_T < 0
IV Anti-Particle, -C_T < 0
III Anti-Particle, -C_T > 0
Novel Approach: Energy Test

1. Randomly assign a flavour to get a sample consistent with no CPV
2. T-value is compared against permutations
3. T consistent with 0 means CP conservation
4. T significantly greater than 0 implies differences between samples
5. Plot shows T-value distribution from permutations and discovery limits
6. Fraction of permuted samples with $T > T_{data}$ sets the p-value of the test
7. P-even and P-odd versions of Energy Test will be run
Previous applications of the Energy Test

- **Search for CP violation in** \( D^0 \to \pi^- \pi^+ \pi^0 \) **decays with the energy test** (https://arxiv.org/abs/1410.4170)
- **Search for CP violation in the phase space of** \( D^0 \to \pi^+ \pi^- \pi^+ \pi^- \) **decays** (https://arxiv.org/abs/1612.03207)
- **Calculating p-values and their significances with the Energy Test for large datasets** (https://arxiv.org/abs/1801.05222)
- **Biased bootstrap sampling for efficient two-sample testing** (https://arxiv.org/abs/1810.00335)
Selection: Signal channel fit results

- Previous analysis signal yield: 6636
- Run 2 yield approx. 6 times bigger
Selection: Pion ordering

\[ \Lambda_b \rightarrow p\pi^- \pi^+ \pi^- \]

- For unique definition, pions must be ordered
- Without same charge pion ordering CPV asymmetries vanish
- Different ordering schemes investigated
- Decision to use previous pion ordering made
- Order negative pions by the magnitude of their momenta in \( \Lambda_b \) rest frame

\[ \Lambda_b \rightarrow p\pi_{\text{fast}}^- \pi^+ \pi_{\text{slow}}^- \]
Simulation

- This decay has a rich resonance sub-structure
- There is no amplitude model for this channel
- The default MC cocktail is not optimized for the resonances we explore
- Custom MC cocktail was created using mass distributions as reference for resonance contributions
- *TensorFlow* package was used for creating MC
- Example of amplitude model for specific decay topology provided by theorist (G. Durieux (*arXiv:1608.03288*))
Simulation: attempts for a full model

- $\Lambda_b \rightarrow (N^{*+} \rightarrow (\Delta^{++} \rightarrow p\pi^+))\pi^-$
  - $N^{*+}(1520), N^{*+}(1535), N^{*+}(1650), N^{*+}(1675), N^{*+}(1680)$
  - $N^{*+}(1700), N^{*+}(1710), N^{*+}(1720), N^{*+}(1875), N^{*+}(1900), N^{*+}(2190)$

- $\Lambda_b \rightarrow (N^{*+} \rightarrow p(\rho \rightarrow \pi^+\pi^-))\pi^-$
  - $N^{*+}(1720), N^{*+}(1875), N^{*+}(1900)$

- $\Lambda_b \rightarrow (N^{*+} \rightarrow p(\sigma \rightarrow \pi^+\pi^-))\pi^-$
  - $N^{*+}(1535), N^{*+}(1650), N^{*+}(1675), N^{*+}(1680), N^{*+}(1700), N^{*+}(1875)$
  - $N^{*+}(1900)$

- $\Lambda_b \rightarrow (a_1^- \rightarrow (\rho \rightarrow \pi^-\pi^+)\pi^-)p$

- Non resonant $\Lambda_b \rightarrow p\pi^-\pi^+\pi^-$
Simulation: mass distributions of MC model vs Data

LHCb simulation unofficial

Not a fit
Simulation: P-odd CPV introduces to relevant variables

- $\Phi$ is the angle between the decay planes used in previous analysis.
- This is new compared to previous analysis and allows to perform sensitivity studies.
- This model includes interference between resonances and was implemented in the helicity formalism.
Sensitivity studies: Energy Test method

- Choice of ET distance variables:
  \[ m^2(p\pi^+), m^2(\pi^+\pi_s^-), m^2(p\pi^-), m^2(p\pi^+\pi_s^-), m^2(\pi^+\pi_s^-\pi_f^-) \]

- Other variables (e.g. helicity angles) investigated, sensitivity to CPV was not majorly affected

- Existing pion ordering and mass variable choice enhances \( \Delta^+ \) contribution

\[
\psi(d_{ij}) = e^{-d_{ij}^2/2\delta^2}
\]

\[
T = \sum_{i,j>i}^{n} \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i}^{\bar{n}} \frac{\psi_{ij}}{\bar{n}(\bar{n}-1)} - \sum_{i,j}^{n,\bar{n}} \frac{\psi_{ij}}{n\bar{n}},
\]
Sensitivity studies: Energy Test method choice of $\delta$

- The choice of optimal $\delta$ is different depending on how CPV is introduced.
- It can depend on overall size of phase space, width of contributing resonances, yield and other factors.
- Toy studies show the dependence of sensitivity on the choice of $\delta$.

P-even CPV scenario with 11% asymmetry in the $a_1$.

P-odd CPV included in $\sin(\phi)$ amplitude of the $\Delta^+$ cascade topology.
Energy Test: Cross-checks

- Energy Test is largely insensitive to global detection/production asymmetries by construction.
- Cross-checks on control and high mass side band samples have been performed (sample sizes set to yields expected in data).
- Energy Test was applied on $\Lambda^0_b \rightarrow \Lambda^+_c (\rightarrow pK^-\pi^+)\pi^-$ control sample with no expected CPV.
- Energy Test was applied on unblinded high mass side band $\Lambda_b$ signal sample with $m(\Lambda_b) = [5.75 - 6.1\text{GeV}/c^2]$.
- Additionally, Energy Test was applied to $\Lambda^0_b \rightarrow pK^-\pi^+\pi^-$ peaking background with no CPV observed.
- Effect due to $\sim 3\%$ proton detection asymmetry was investigated.
Conclusions

- Search for CPV in $\Lambda_b \rightarrow p\pi^-\pi^+\pi^-$ decays analysis has been presented
- All major cross-checks have been completed
- Analysis is mature and will be unblinded soon
- Potentially, this analysis could lead to the first observation of CPV in baryons
Backup: Note on systematic effect of Energy Test

- Different control samples used to check for systematic effects
- If such test are passed, no additional systematic uncertainties are assigned
- The p-value calculated relates to statistical effects alone
- This was done in previous LHCb applications of the Energy Test and other two-sample test analyses from LHCb and BaBar.

https://arxiv.org/abs/1308.3189
Backup: $Λ_b \rightarrow (Δ^+ \rightarrow (Δ^{++} \rightarrow p\pi^+)\pi^{-})\pi^-$ Cascade topology amplitudes by Durieux

| $\sqrt{2}$ | $\text{Re}((A^*_+ B_+ + A^*_B_-)(b^*_1 b^*_3 + b^*_1 b^*_3))$ | $(1 + 3 \cos^2 \theta_p)$ | $\cos \theta_{Δ^{++}}$ |
| $1/2$ | $(|B_+|^2 + |B_-|^2)(|b^*_3|^2 + |b^*_3|^2)$ | $(1 + 3 \cos^2 \theta_p)$ | $\cos \theta_{Δ^{++}}$ |
| $9/4$ | $(|A^*_+|^2 + |A^*_B|^2)(|b^*_2|^2 + |b^*_2|^2)$ | $\sin^2 \theta_p$ | $\sin^2 \theta_{Δ^{++}}$ |
| $1/4$ | $(|A^*_+|^2 + |A^*_B|^2)(|b^*_1|^2 + |b^*_1|^2)$ | $(1 + 3 \cos^2 \theta_p)$ | $(1 + 3 \cos^2 \theta_{Δ^{++}})$ |
| $-3\sqrt{2}/2$ | $\text{Re}((A^*_+ B_+ + A^*_B_-)(b^*_2 b^*_3 + b^*_2 b^*_3))$ | $\sin 2\theta_p$ | $\sin \theta_{Δ^{++}}$ | $\cos \phi_p$ |
| $-3/2$ | $(|A^*_+|^2 + |A^*_B|^2)\text{Re}(b^*_1 b^*_2 + b^*_1 b^*_2)$ | $\sin 2\theta_p$ | $\sin 2\theta_{Δ^{++}}$ | $\cos \phi_p$ |
| $3/2$ | $(|A^*_+|^2 + |A^*_B|^2)\text{Re}(b^*_1 b^*_2 + b^*_1 b^*_2)$ | $\sin^2 \theta_p$ | $\sin^2 \theta_{Δ^{++}}$ | $\cos 2\phi_p$ |
| $-3\sqrt{2}/4$ | $\text{Im}((A^*_+ B_+ - A^*_B_-)(b^*_2 b^*_3 + b^*_2 b^*_3))$ | $\sin 2\theta_p$ | $\sin 2\theta_{Δ^{++}}$ | $\sin \phi_p$ |
| $-3/2$ | $(|A^*_+|^2 - |A^*_B|^2)\text{Im}(b^*_1 b^*_2 + b^*_1 b^*_2)$ | $\sin 2\theta_p$ | $(1 - 3 \cos^2 \theta_{Δ^{++}})\sin \theta_{Δ^{++}}$ | $\sin \phi_p$ |
| $3\sqrt{2}/2$ | $\text{Im}((A^*_+ B_+ - A^*_B_-)(b^*_2 b^*_3 - b^*_2 b^*_3))$ | $\sin^2 \theta_p$ | $\sin^2 \theta_{Δ^{++}}$ | $\sin 2\phi_p$ |
| $-9/4$ | $(|A^*_+|^2 - |A^*_B|^2)\text{Im}(b^*_1 b^*_2 - b^*_1 b^*_2)$ | $\sin^2 \theta_p$ | $\sin \theta_{Δ^{++}} \sin 2\theta_{Δ^{++}}$ | $\sin 2\phi_p$ |
The generation of permutations for Energy Test can be greatly sped up using Scaling Method.

The T value of the sample is calculated using all the events.

The CP symmetric T values of the permutation can be calculated using a small fraction of full sample.

This means it is permissible to run enough permutations to check results of $5\sigma$ and above.

The distribution of $n*T$ is independent of $n$, for moderate and large $n$, under the null hypothesis.

https://arxiv.org/abs/1801.05222
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