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

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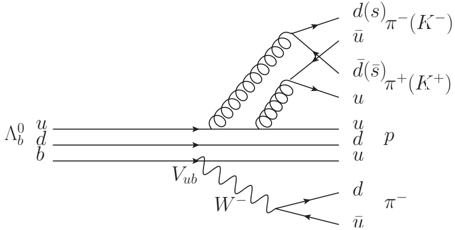
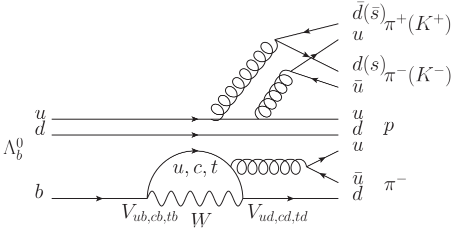
Outline

Theoretical Motivation

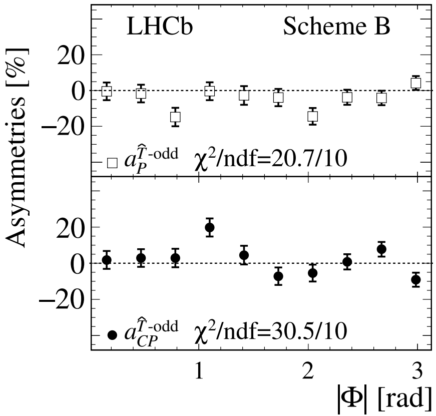
- Transitions governed by $b \to ud\bar{u}$ tree and $b \to du\bar{u}$ penguin amplitudes of similar magnitude. Large relative weak phase in SM from the CKM elements, $\alpha = arg[-V_{td}V^*_{tb}/V_{ud}V^*_{ub}]$
- CPV is well established in B-meson decays





Motivation: First Evidence of CPV in Baryons

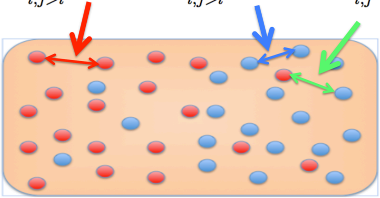
- CPV has never been observed in baryons.
- First evidence of CPV in baryons has been found in this channel with significance of 3.3σ using Run 1 data
- *Probing matter-antimatter asymmetries in beauty baryon decays (Nature Physics 13, 391-396 (2017))*



Novel Approach: Energy Test

- System $\rightarrow$ Phase Space
- Λ_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
- δ: distance parameter to be optimized

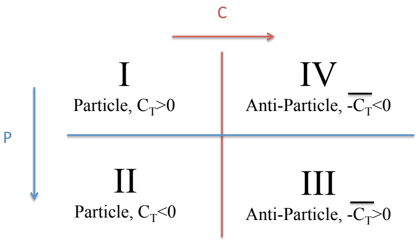
$$T = \sum_{i,j>i}^{n} \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i}^{\bar{n}} \frac{\psi_{ij}}{\bar{n}(\bar{n}-1)} - \sum_{i,j}^{n,\bar{n}} \frac{\psi_{ij}}{n\bar{n}},$$



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

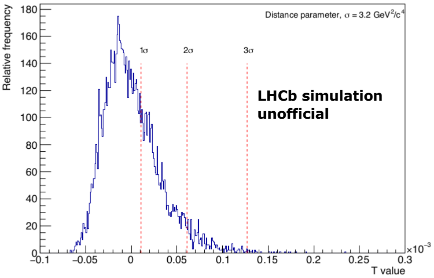


Triple Product:

$$C_{\hat{T}} \equiv \vec{p}_p \cdot (\vec{p}_{h^-} \times \vec{p}_{h^+})$$

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

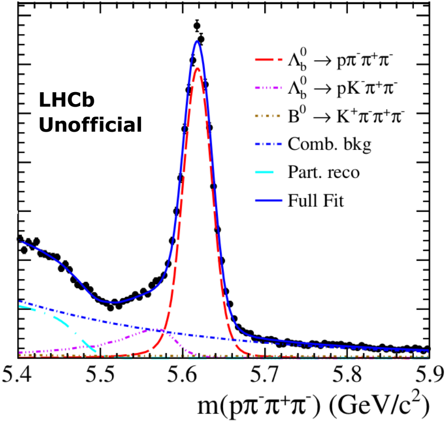


Previous applications of the Energy Test

- *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)*
- *On model-independent searches for direct CP violation in multi-body decays* *(https://arxiv.org/abs/1612.04705)*
- *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
- Integrated Luminosity (2011,2012,2015,2016,2017): $7fb^{-1}$



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 Λ_b rest frame

$$\Lambda_b \rightarrow p\pi^-_{fast}\pi^+\pi^-_{slow}$$

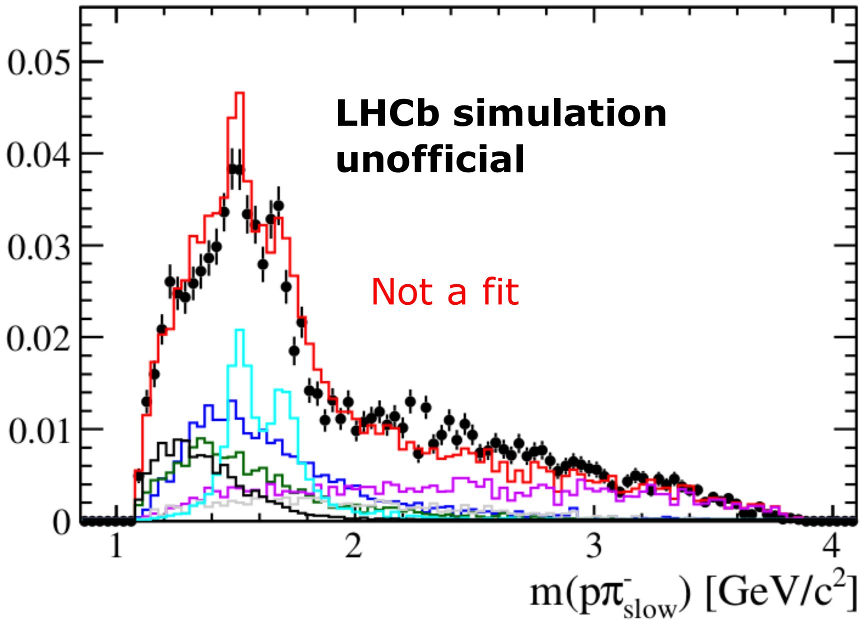
Simulation

- 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)*)

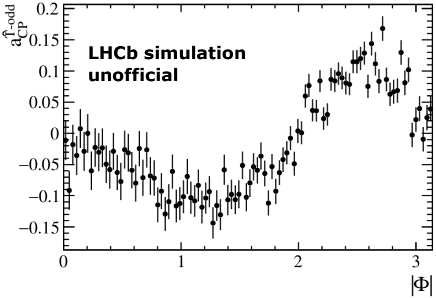
Simulation: attempts for a full model

- $\Lambda_b \to (N^{+*} \to (\Delta^{++} \to p\pi^+)\pi^-)\pi^-$
  $N^{+*}(1520), N^{+*}(1535), N^{+*}(1650), N^{+*}(1675), N^{+*}(1680)$
  $N^{+*}(1700), N^{+*}(1710), N^{+*}(1720), N^{+*}(1875), N^{+*}(1900), N^{+*}(2190)$
- $\Lambda_b \to (N^{+*} \to p(\rho \to \pi^+\pi^-))\pi^-$
  $N^{+*}(1720), N^{+*}(1875), N^{+*}(1900)$
- $\Lambda_b \to (N^{+*} \to p(\sigma \to \pi^+\pi^-))\pi^-$
  $N^{+*}(1535), N^{+*}(1650), N^{+*}(1675), N^{+*}(1680), N^{+*}(1700), N^{+*}(1875)$
  $N^{+*}(1900)$
- $\Lambda_b \to (a_1^- \to (\rho \to \pi^-\pi^+)\pi^-)p$
- Non resonant $\Lambda_b \to p\pi^-\pi^+\pi^-$

Simulation: mass distributions of MC model vs Data



Simulation: P-odd CPV introduces to relevant variables



- Φ 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

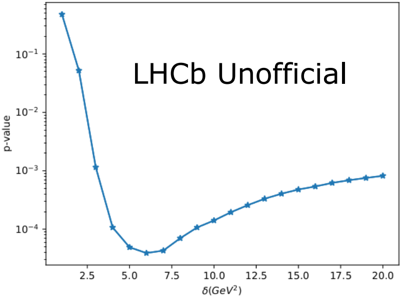
- Choice of ET distance variables:
  $m^2(p\pi^+), m^2(\pi^+\pi_s^-), m^2(p\pi_s^-), m^2(p\pi^+\pi_s^-), m^2(\pi^+\pi_s^-\pi_f^-)$
- Other variables (e.g. helicity angles) investigated, sensitivity to CPV was not majorly affected
- Existing pion ordering and mass variable choice enhances Δ^+ contribution

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

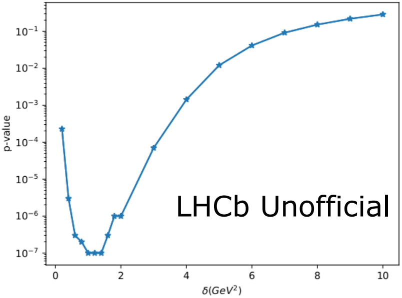
$$T = \sum_{i,j>i}^{n} \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i}^{\overline{n}} \frac{\psi_{ij}}{\overline{n}(\overline{n}-1)} - \sum_{i,j}^{n,\overline{n}} \frac{\psi_{ij}}{n\overline{n}},$$

Sensitivity studies: Energy Test method choice of δ

- The choice of optimal δ 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 δ



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



P-odd CPV included in $\sin(\phi)$ amplitude of the Δ^+ 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 $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^-$ control sample with no expected CPV.
- Energy Test was applied on unblinded high mass side band Λ_b signal sample with $m(\Lambda_b) = [5.75 - 6.1 GeV/c^2]$
- Additionally Energy Test was applied to $\Lambda_b^0 \to pK^-\pi^+\pi^-$ peaking background with no CPV observed
- Effect due to $\sim 3\%$ proton detection asymmetry was investigated

Conclusions

- Search for CPV in $\Lambda_b \to p\pi^-\pi^+\pi^-$ 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

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/pdf/0802.4035.pdf
- https://arxiv.org/pdf/1212.1856.pdf
- https://arxiv.org/abs/1308.3189
- https://arxiv.org/pdf/1110.3970.pdf
- https://arxiv.org/abs/1310.7953

Backup: $\Lambda_b \to (\Delta^+ \to (\Delta^{++} \to p\pi^+)\pi^-)\pi^-$ Cascade topology amplitudes by Durieux

$\sqrt{2}$	$Re((A_+^* B_+ + A_-^* B_-)(b_{1+}^* b_{3+} + b_{1-}^* b_{3-}^*))$	$(1+3\cos^2\theta_p)$	$\cos\theta_{\Delta^{++}}$	
$1/2$	$(\|B_+\|^2 + \|B_-\|^2)(\|b_{3+}\|^2 + \|b_{3-}\|^2)$	$(1+3\cos^2\theta_p)$		
$9/4$	$(\|A_+\|^2 + \|A_-\|^2)(\|b_{2+}\|^2 + \|b_{2-}\|^2)$	$\sin^2\theta_p$	$\sin^2\theta_{\Delta^{++}}$	
$1/4$	$(\|A_+\|^2 + \|A_-\|^2)(\|b_{1+}\|^2 + \|b_{1-}\|^2)$	$(1+3\cos^2\theta_p)$	$(1+3\cos^2\theta_{\Delta^{++}})$	
$-3\sqrt{2}/2$	$Re((A_+^* B_+ + A_-^* B_-)(b_{2+}^* b_{3+} + b_{2-}^* b_{3-}))$	$\sin 2\theta_p$	$\sin\theta_{\Delta^{++}}$	$\cos\phi_p$
$-3/2$	$(\|A_+\|^2 + \|A_-\|^2)Re(b_{1+}^* b_{2+} + b_{1-}^* b_{2-})$	$\sin 2\theta_p$	$\sin 2\theta_{\Delta^{++}}$	$\cos\phi_p$
$3/2$	$(\|A_+\|^2 + \|A_-\|^2)Re(b_{1+}^* b_{2-} + b_{1-}^* b_{2+})$	$\sin^2\theta_p$	$\sin^2\theta_{\Delta^{++}}$	$\cos 2\phi_p$
$-3\sqrt{2}/4$	$Im((A_+^* B_+ - A_-^* B_-)(b_{2+}^* b_{3+} + b_{2-}^* b_{3-}))$	$\sin 2\theta_p$	$\sin 2\theta_{\Delta^{++}}$	$\sin\phi_p$
$-3/2$	$(\|A_+\|^2 - \|A_-\|^2)Im(b_{1+}^* b_{2+} + b_{1-}^* b_{2-})$	$\sin 2\theta_p$	$(1-3\cos^2\theta_{\Delta^{++}})\sin\theta_{\Delta^{++}}$	$\sin\phi_p$
$3\sqrt{2}/2$	$Im((A_+^* B_- - A_-^* B_-)(b_{2+}^* b_{3-} + b_{2-}^* b_{3+}))$	$\sin^2\theta_p$	$\sin^2\theta_{\Delta^{++}}$	$\sin 2\phi_p$
$-9/4$	$(\|A_+\|^2 - \|A_-\|^2)Im(b_{1+}^* b_{2-} + b_{1-}^* b_{2+})$	$\sin^2\theta_p$	$\sin\theta_{\Delta^{++}}\sin 2\theta_{\Delta^{++}}$	$\sin 2\phi_p$

Backup: Scaling Method for Energy Test

- 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 5σ 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

Backup: Scaling Method for Energy Test