Searches for CP violation in charmless b-baryon decays at LHCb

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On behalf of the LHCb collaboration

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- CPV established in K, B and D meson decays and well consistent with SM prediction
- CPV not yet observed in b-baryon decays, despite some interesting indications of non vanishing CP asymmetries **[Nature Physics 13 (2017) 391]**.
- Λ_b^0 and Ξ_b^0 production is abundant in proton-proton collisions at the LHC. This gives the LHCb experiment the opportunity to study multi-body decays of b-flavoured baryons
- Multi-body final states can have a rich resonant structure: interference can enhance CPV

In this talk:
Search for CP violation in $X_b^0 \to phh'h''$ charmless decays, where X_b^0 stands for Λ_b^0 or Ξ_b^0 and h,h',h'' either for a pion or a kaon

- **direct CPV** is measured as the asymmetry between the decay rate of a baryon and its charge-conjugate state

$$A^{CP} = \frac{\Gamma(X_b^0 \to f) - \Gamma(\bar{X}_b^0 \to \bar{f})}{\Gamma(X_b^0 \to f) + \Gamma(\bar{X}_b^0 \to \bar{f})}$$

- **Triple product asymmetries (TPA)**
  Build a $\hat{T} - odd$ observable combining the momentum $\vec{p}_i$ of three final state particles in the mother C.M frame: $C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_h \times \vec{p}_{h'})$, $\overline{C}_{\hat{T}} = \vec{p}_{\bar{p}} \cdot (\vec{p}_{\bar{h}} \times \vec{p}_{\bar{h}'})$:

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

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

  where N and $\overline{N}$ are the total number of X_b^0 and $\overline{X}_b^0$ decays
  True CP and P violating observables are defined as:

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

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

TPA and direct CPV are complementary:

A. Datta and D.London
Int.J.Mod.Phys. A19 (2004) 2505

$$a_{CP} \propto \sin\Delta\delta \sin\Delta\phi$$

$$a_{CP}^{\hat{T}-odd} \propto \cos\Delta\delta \sin\Delta\phi$$

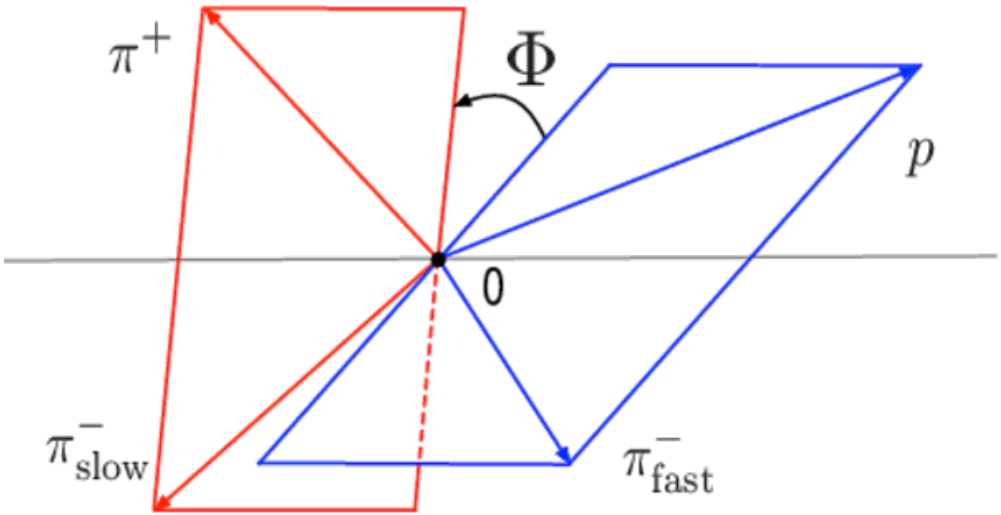
- a_{CP} more sensitive to CPV effects when difference in strong phase between interfering amplitudes is large
- $a_{CP}^{\hat{T}-odd}$ more sensitive to CPV effects when difference in strong phase between interfering is small

Different sensitivity to systematic effects:
$a_{CP}^{\hat{T}-odd}$ not affected by reconstruction efficiency and $b-$hadron production asymmetries $\rightarrow$ $A_{\hat{T}}$ and $\overline{A}_{\hat{T}}$ are calculated separately on the same final state

Triple product are calculated in the Λ_b^0 rest frame:

G.Durieux, JHEP 10 (2016) 005
G.Durieux, PRD 92 (2015) 07601

$$C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{\pi_{fast}} \times \vec{p}_{\pi^+}) \propto \sin\Phi$$
$$\overline{C}_{\hat{T}} = \vec{p}_{\bar{p}} \cdot (\vec{p}_{\pi_{fast}} \times \vec{p}_{\pi^-}) \propto \sin\Phi$$



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

$\Lambda_b^0 \to N^{*+}\pi^-$, $N^{*+} \to \Delta^{++}(1234)\pi^-$, $\Delta^{++} \to p\pi^+$

$\Lambda_b^0 \to p a_1^-(1260)$, $a_1^-(1260) \to \rho^0(770)\pi^-$, $\rho^0(770) \to \pi^+\pi^-$

Search for CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ using TPA

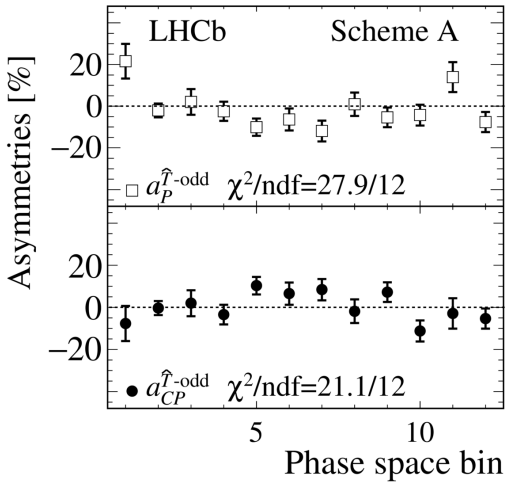
▸ Nature Physics volume 13, 391–396(2017)

Integrated luminosity of 3 fb^{-1} collected in 2011 and 2012 at $\sqrt{s}$ of 7 TeV and 8 TeV

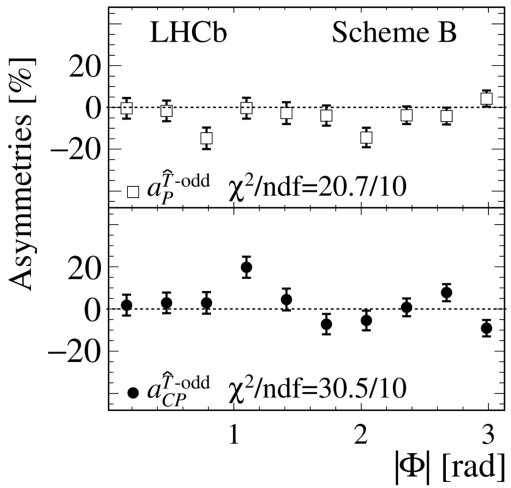
- Phase space integrated asymmetry

$$a_{CP}^{\hat{T}-odd} = (1.15 \pm 1.45 \pm 0.32)\% \quad \textbf{Consistent with CP symmetry}$$
$$a_{P}^{\hat{T}-odd} = (-3.71 \pm 1.45 \pm 0.32)\% \quad \textbf{Consistent with P symmetry}$$

- Asymmetries in regions of the phase space



Binning on resonances:
$\Delta^{++}, \rho(770), N^*$



Binning angle between planes:
$p\ \pi_{fast}$ and $\pi^+\ \pi_{slow}$

First evidence for local CPV at the 3.3σ level in the baryonic sector

Search for CPV in Λ_b^0 decaying to $pK^-\pi^+\pi^-$, $pK^-K^+K^-$ and in $\Xi_b^0 \to pK^-\pi^+\pi^-$ using TPA

▸ JHEP 08 (2018) 039

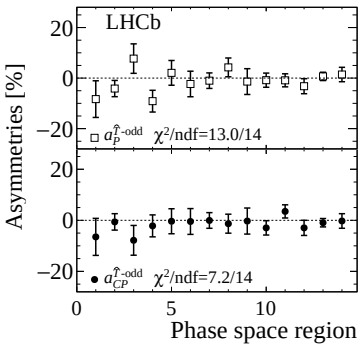
Integrated luminosity of 3 fb^{-1} collected in 2011 and 2012 at $\sqrt{s}$ of 7 TeV and 8 TeV

- Phase space integrated asymmetry

	$\Lambda_b^0 \to pK^-\pi^+\pi^-$	$\Lambda_b^0 \to pK^-K^+K^-$	$\Xi_b^0 \to pK^-K^-\pi^+$
$a_P^{\hat{T}\text{-odd}}$ (%)	$-0.60 \pm 0.84 \pm 0.31$	$-1.56 \pm 1.51 \pm 0.32$	$-3.04 \pm 5.19 \pm 0.36$
$a_{CP}^{\hat{T}\text{-odd}}$ (%)	$-0.81 \pm 0.84 \pm 0.31$	$1.12 \pm 1.51 \pm 0.32$	$-3.58 \pm 5.19 \pm 0.36$

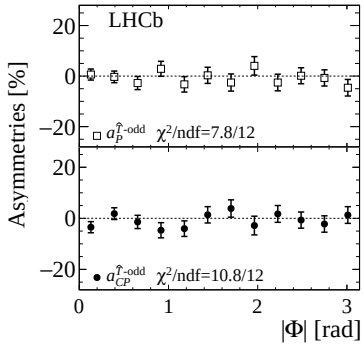
- Asymmetries in regions of the phase space

$\Lambda_b^0 \to pK^-\pi^+\pi^-$



Binning on resonances:
$\Delta(1232)^{++}$,$f_0(980)$, $\overline{K}^*(892)$,ϕ

$\Lambda_b^0 \to pK^-\pi^+\pi^-$

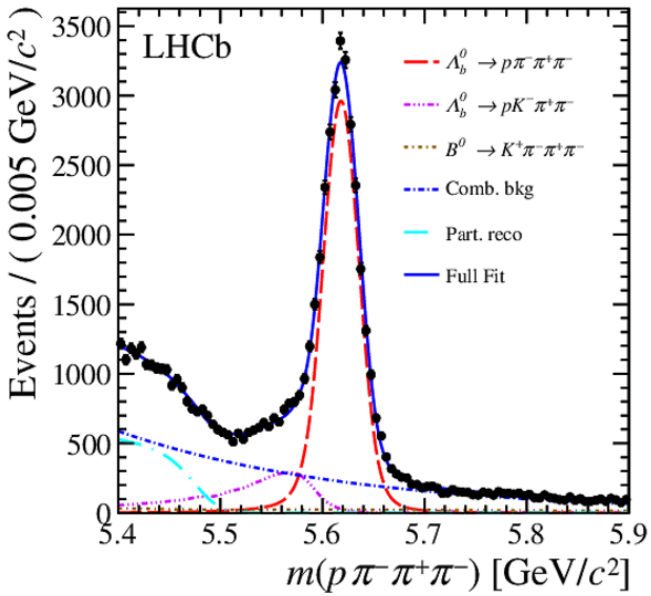


Binning angle between planes:
ph and $h^{'}h^{''}$

No evidence for CPV in these channels

arXiv:1912.10741, submitted to Phys. Rev. Lett.

- Integrated luminosity of 6.6 fb^{-1} collected from 2011 to 2017 at $\sqrt{s}$ of 7, 8 and 13 TeV
- Optimised selection
- Yields 4 time larger than the previous (Run1) analysis [Nature Physics volume 13, 391–396(2017)]
- 2 independent methods:
  - TPA with optimized binning scheme (approximate amplitude analysis) to maximize local sensitivity to CPV effects
    - **16 bins** on polar and azimuthal angles of proton in the Δ^{++} frame
    - **10 bins** on Φ angle between decay planes $\pi^+\pi^-_{slow}$ and $p\pi^-_{fast}$
  - Unbinned energy test

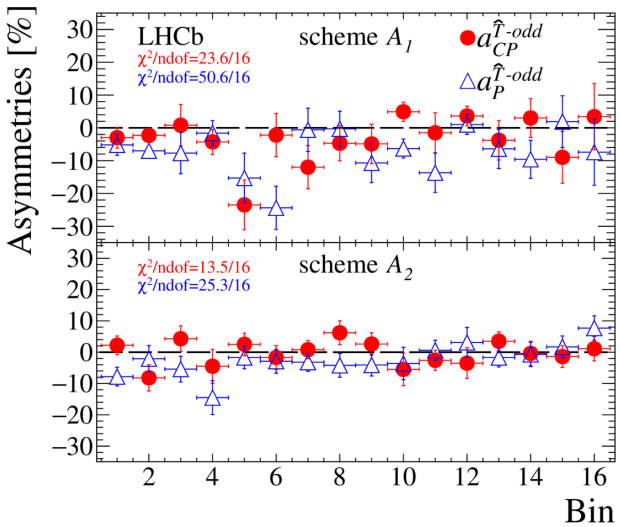


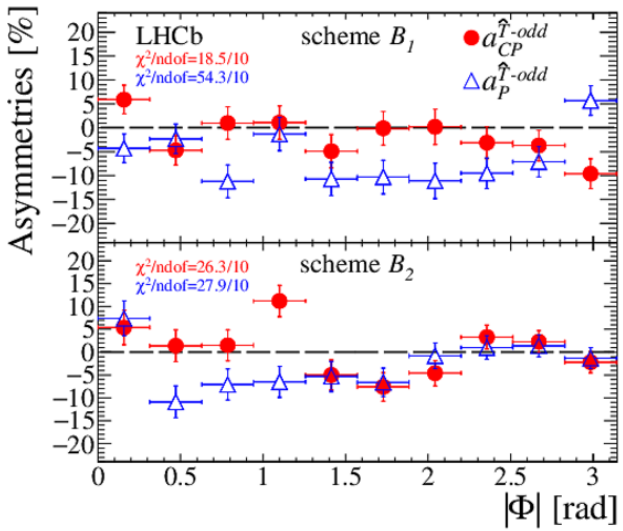
arXiv:1912.10741, submitted to Phys. Rev. Lett.

- Integrated measurement:

$$a_{CP}^{\hat{T}-odd} = (-0.7 \pm 0.7 \pm 0.2)\% \quad \textbf{consistent with CP symmetry}$$
$$a_{P}^{\hat{T}-odd} = (-4.0 \pm 0.7 \pm 0.2)\% \quad \textbf{5.5}\sigma \textbf{ deviation from P symmetry}$$

- Cut on $m(p\pi^+\pi^-_{slow})$ invariant mass:
  - > 2.8 GeV/c^2 to enhance the $\Lambda_b^0 \to p a_1^-(\to \rho\pi^-)$ (A_1 and B_1 schemes)
  - < 2.8 GeV/c^2 to enhance the $\Lambda_b^0 \to N^*(\Delta^{++}\pi^-)\pi^-$ (A_2 and B_2 schemes)





No evidence for CPV, highest significance 2.9σ in B2

Energy test method

arXiv:1912.10741, submitted to Phys. Rev. Lett.

- Model-independent unbinned test
- Method sensitive to local differences between two samples

$$T \equiv \frac{1}{2n(n-1)} \sum_{i \neq j}^{n} \psi_{ij} + \frac{1}{2\overline{n}(\overline{n}-1)} \sum_{i \neq j}^{\overline{n}} \psi_{ij} - \frac{1}{n\overline{n}} \sum_{i=1}^{n} \sum_{j=1}^{\overline{n}} \psi_{ij}$$

$\psi_{ij} = e^{-d_{ij}^2/2\delta^2}$, d_{ij} Euclidean distance between two candidates in the phase space

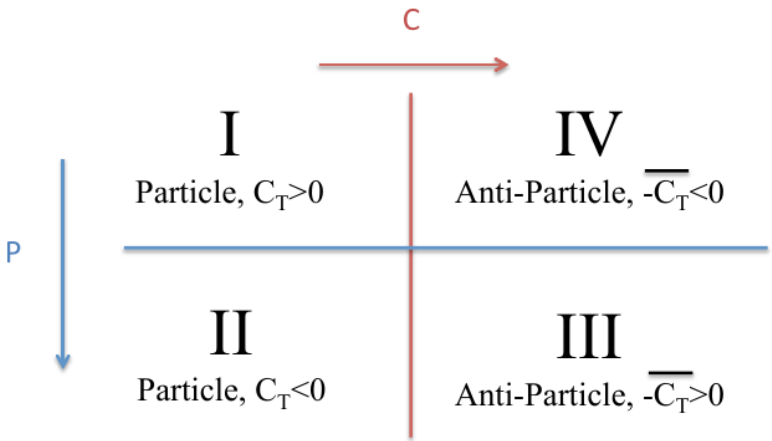
PHS: $m^2(p\pi^+)$, $m^2(\pi^+\pi^-_{slow})$, $m^2(p\pi^+\pi^-_{slow})$, $m^2(\pi^+\pi^-_{slow}\pi^-_{fast})$, $m^2(p\pi^-_{slow})$

δ 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

Energy test method

arXiv:1912.10741, submitted to Phys. Rev. Lett.



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 δ:

Distance scale δ	1.6 GeV$^2/c^4$	2.7 GeV$^2/c^4$	13 GeV$^2/c^4$
p-value (CP conservation, P even)	3.1×10^{-2}	2.7×10^{-3}	1.3×10^{-2}
p-value (CP conservation, P odd)	1.5×10^{-1}	6.9×10^{-2}	6.5×10^{-2}
p-value (P conservation)	1.3×10^{-7}	4.0×10^{-7}	1.6×10^{-1}

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

- Integrated luminosity of 3 fb^{-1} pp collisions collected in 2011 and 2012 at $\sqrt{s}$ of 7 TeV and 8 TeV
- Six decays studied:
  1. $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$
  2. $\Lambda_b^0 \to pK^-\pi^+\pi^-$
  3. $\Lambda_b^0 \to pK^-K^+\pi^-$
  4. $\Lambda_b^0 \to pK^-K^+K^-$
  5. $\Xi_b^0 \to pK^-\pi^+\pi^-$
  6. $\Xi_b^0 \to pK^-\pi^+K^-$
- CP-asymmetries measured for 18 decay channels (full phase space or in specific regions of the decay phase space)

- Clear experimental signature:
  - 4 charged tracks with high IP wrt PV
  - Ξ_b^0 candidates are required to form a vertex with good fit quality
  - Ξ_b^0 vertex significantly separated from any PV
  - PID assigned using informations from the RICH

▸ Eur. Phys. J. C79 (2019) 745

CP asymmetry defined as:

$$A^{CP} = \frac{\Gamma(X_b^0 \to f) - \Gamma(\bar{X}_b^0 \to \bar{f})}{\Gamma(X_b^0 \to f) + \Gamma(\bar{X}_b^0 \to \bar{f})}$$

- Experimental charge-asymmetric effects such as track detection efficiency and b-baryon production asymmetries
- Use charmed-control channels with similar kinematics and no CP violation

Charmless mode	Control channel
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	$\Lambda_b^0 \to (\Lambda_c^+ \to p\pi^-\pi^+)\pi^-$
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	$\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\pi^-$
$\Lambda_b^0 \to pK^-K^+\pi^-$	$\Lambda_b^0 \to (\Lambda_c^+ \to p\pi^-\pi^+)\pi^-$
$\Lambda_b^0 \to pK^-K^+K^-$	$\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\pi^-$
$\Xi_b^0 \to pK^-\pi^+\pi^-$	$\Xi_b^0 \to (\Xi_c^+ \to pK^-\pi^+)\pi^-$
$\Xi_b^0 \to pK^-\pi^+K^-$	$\Xi_b^0 \to (\Xi_c^+ \to pK^-\pi^+)\pi^-$

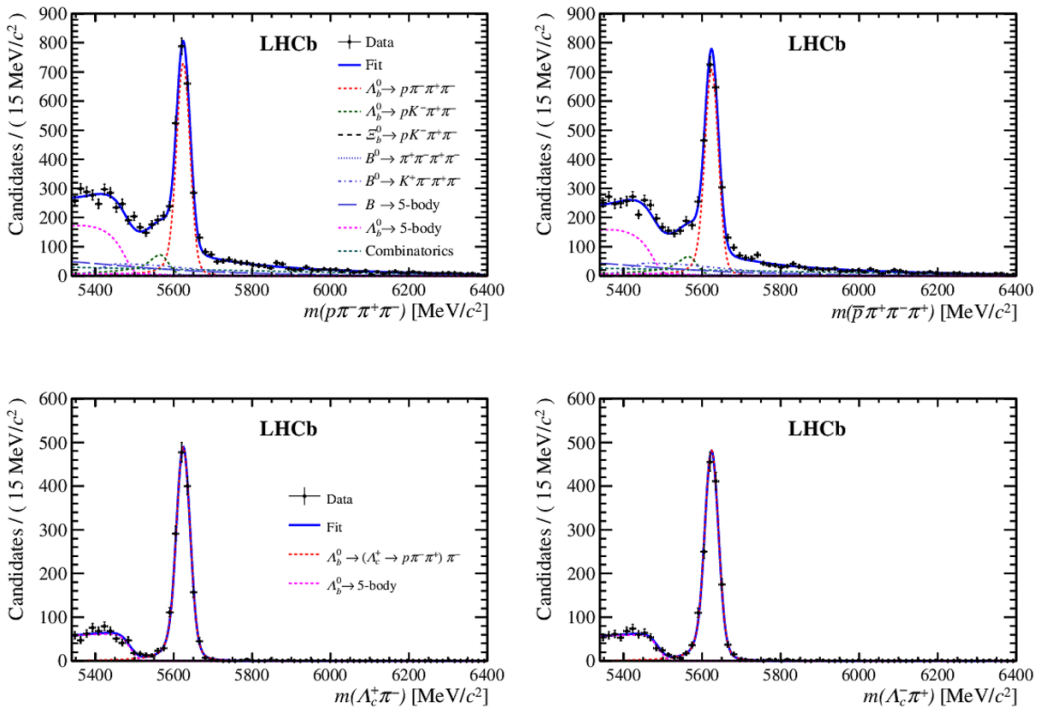
The following CP-violating observable is measured:

$$\Delta A^{CP} = A^{CP}_{no-c} - A^{CP}_{c}$$

Phase space integrated asymmetry

▸ Eur. Phys. J. C79 (2019) 745

- Simultaneous UML fit $\rightarrow$ data are split according to the charge of the proton to extract the raw asymmetries A^{CP}_{no-c}
- Main components:
  1. Signal
  2. Combinatorial background
  3. Partially reconstructed five-body X^0_b decays
  4. Signal and background cross-feeds
  5. Four and five body decays of B mesons



- Eur. Phys. J. C79 (2019) 745

The integrated ΔA^{CP} asymmetry differences are measured to be:

$$\begin{aligned}
\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) &= (+1.1 \pm 2.5 \pm 0.6)\,\%, \\
\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) &= (+3.2 \pm 1.1 \pm 0.6)\,\%, \\
\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-K^+\pi^-) &= (-6.9 \pm 4.9 \pm 0.8)\,\%, \\
\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-K^+K^-) &= (+0.2 \pm 1.8 \pm 0.6)\,\%, \\
\Delta\mathcal{A}^{CP}(\Xi_b^0 \to pK^-\pi^+\pi^-) &= (-17 \pm 11 \pm 1)\,\%, \\
\Delta\mathcal{A}^{CP}(\Xi_b^0 \to pK^-\pi^+K^-) &= (-6.8 \pm 8.0 \pm 0.8)\,\%.
\end{aligned}$$

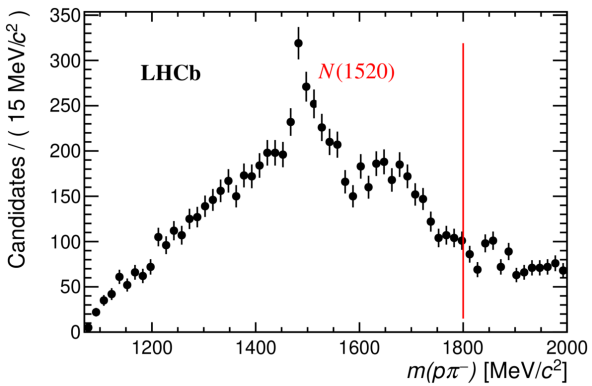
No evidence for CP violation in the phase-space integrated asymmetries

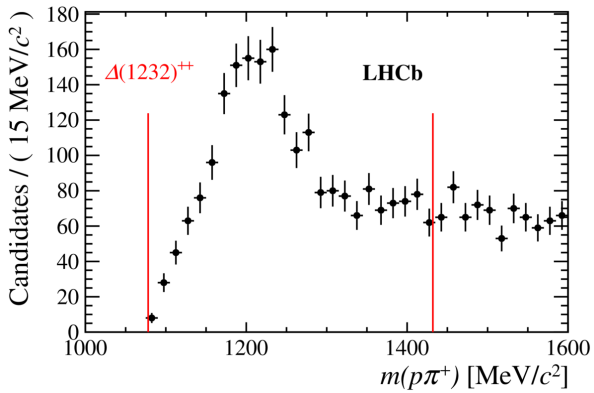
CP asymmetries in phase-space region

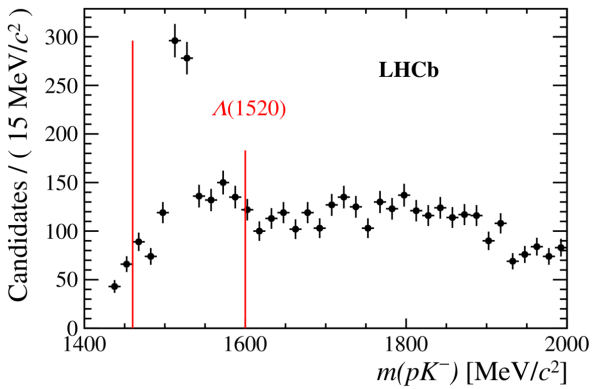
▸ Eur. Phys. J. C79 (2019) 745

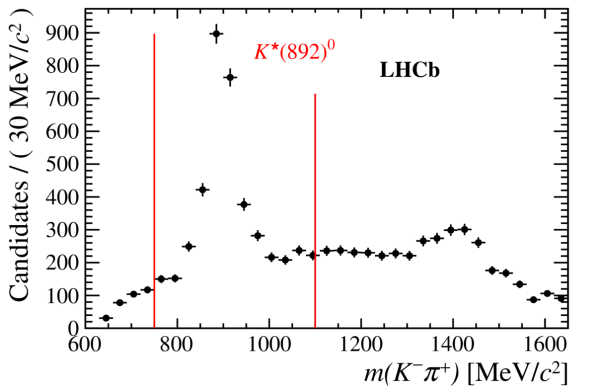
Asymmetries are also measured in regions of the phase-space to search for local effects of CP violation in Λ_b^0

- Region of low invariant mass on the baryonic pair (ph <2 GeV/c^2) and on the pairing of the two other tracks → hereafter referred to as LBM (Low 2×2-Body Mass)
- Regions of the phase space that contain specific quasi-two-body or three-body decays









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- LBM:

$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = (+3.7 \pm 4.1 \pm 0.5)\,\%,$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (+3.5 \pm 1.5 \pm 0.5)\,\%,$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-K^+K^-) = (+2.7 \pm 2.3 \pm 0.6)\,\%.$$

- Quasi two body:

$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pa_1(1260)^-) = (-1.5 \pm 4.2 \pm 0.6)\,\%\,,$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to N(1520)^0\rho(770)^0) = (+2.0 \pm 4.9 \pm 0.4)\,\%,$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to \Delta(1232)^{++}\pi^-\pi^-) = (+0.1 \pm 3.2 \pm 0.6)\,\%,$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK_1(1410)^-) = (+4.7 \pm 3.5 \pm 0.8)\,\%,$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to \Lambda(1520)\rho(770)^0) = (+0.6 \pm 6.0 \pm 0.5)\,\%,$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to N(1520)^0K^*(892)^0) = (+5.5 \pm 2.5 \pm 0.5)\,\%,$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to \Delta(1232)^{++}K^-\pi^-) = (+4.4 \pm 2.6 \pm 0.6)\,\%,$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to \Lambda(1520)\phi(1020)) = (+4.3 \pm 5.6 \pm 0.4)\,\%,$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to (pK^-)_{\text{high-mass}}\phi(1020)) = (-0.7 \pm 3.3 \pm 0.7)\,\%.$$

No evidence for CPV neither in the LBM region nor in the quasi-two body regions

Summary of this talk:

- Multibody decays are interesting place to search for CPV due to their rich phase space structure
- Two complementary approaches with different sensitivities
- No evidence for CPV in Λ_b^0 and Ξ_b^0 decays at LHCb for the moment, but parity violation observed in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ channel at 5.5σ level
- Precision of $\sim$ % already reached in many channels $\to$ expected significant improvement in sensitivity in Run3:
  - LHCb will run at higher instantaneous luminosity
  - Channels with final state hadrons will be selected with higher efficiencies at LHCb after the removal of the L0 hardware trigger