Search for *CPV* in 4-body charmless decays within LHCb Run I data.

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GDR Intensity Frontier
Current trends in flavour physics.

Outline.

- Analyses motivations.
- Establishment of the signals.
  → Selection.
  → Method : simultaneous fit.
  → Branching Fraction measurements.
- Search for *CPV*.
  → ΔA_{CP} measurements.
  → TPA analysis : first evidence of *CP* violation in baryon decays.
- Outlook.

→ Disclaimer: some material shown here is not public yet but in the very last phase of the editorial evaluation of the experiment (Will be tagged as **LHCb Unofficial**).

Analyses motivations.

- Search for the fully charged 4-body charmless decays of weakly decaying neutral b-baryons, namely $\Lambda_b^0/\Xi_b^0 \to phhh$ where h stands either for π or K.

- Aim at measuring CP asymmetries in 7 charmless decay modes (using Run I data), defining 5 experimental spectra. These multibody decays are expected to present rich interference pattern of quasi-2body amplitudes.

  $\to$ decays can proceed simultaneously through CP-violating $b \to u$ transition or Flavour Changing Neutral Current penguin transition $b \to s$.
  $\to$ sometimes with amplitudes proportional to the same power of λ.
  $\to$ CP asymmetries might receive enhancement from additional strong phases.

$$\Lambda_b^0 \to p\pi^-\pi^+\pi^- \ , \Lambda_b^0 \to pK^-\pi^+\pi^- \ , \Lambda_b^0 \to pK^-K^+\pi^- \ , \Lambda_b^0 \to pK^-K^+K^- \ .$$
$$\Xi_b^0 \to pK^-\pi^+\pi^- \ , \Xi_b^0 \to pK^-\pi^+K^- \ , \Xi_b^0 \to pK^-K^+K^- \ .$$

Analyses motivations.

Measuring *CPV* at LHCb.

- *b*-baryons are produced abundantly[1] in the LHC proton-proton collisions. LHCb spectrometer is a unique tool to study multibody fully charged charmless decays.
- Non-vanishing *CP* asymmetries have been observed in mesons systems, and are yet unobserved in b-baryon decays.
- A first evidence has been recently reported by the LHCb collaboration in one of the modes discussed here.

[1] arXiv:1111.2357

Establishment of the signals.

Selection - Particle IDentification (PID), Multi Variable Analysis (MVA).

⋆ Simultaneous fit:

- The signals are cross-feeding from one spectrum to another.
  → the simultaneous fit allows to control from the data themselves these possibly dominant background contributions.
  → the five experimental invariant mass spectra are described by similar parameterisations sharing common features (and parameters).

⋆ PID (K/π) selection:

- Driven by two objectives:
  → optimally reject signal cross-feeds.
  → mutually exclusive definition of each signal spectrum

⋆ PID (p) selection:

- Necessary to reject $B \to 4$ or 5-body background contributions.

⋆ MVA selection:

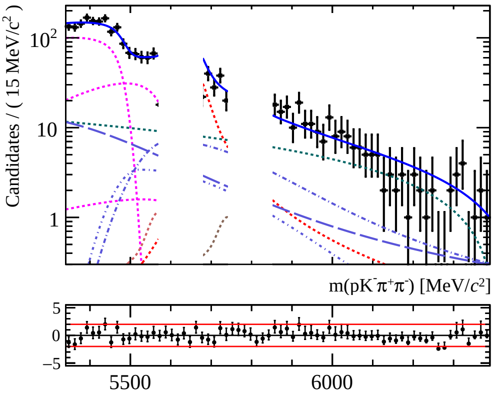
- A discriminant based on topological and isolation variables is built aiming at combinatorics rejection.

Establishment of the signals.

Method - fit model, simultaneous fit.

⋆ The measurement consists at first in the simultaneous fit of the five selected signal spectra and control channels, split in p and $\bar{p}$, 2011 and 2012, all built in a mutually exclusive way. Charmless signal regions and p and $\bar{p}$ yields are blinded. The fit model has been developed in these conditions.

- Partially reconstructed background contributions are parameterised with an Argus function convoluted with a Gaussian.
- Signal reflections (CF) are determined from the yields measured in the original spectrum and the data-driven PID misid. probabilities.
- B $\rightarrow$ 4 or 5-body background contributions can exhibit significant CP asymmetries (and a significant background for BF measurements as well) and thus need to be properly handled. We use the RHSB as a leverage to identify and control those contributions (see back-up slide).

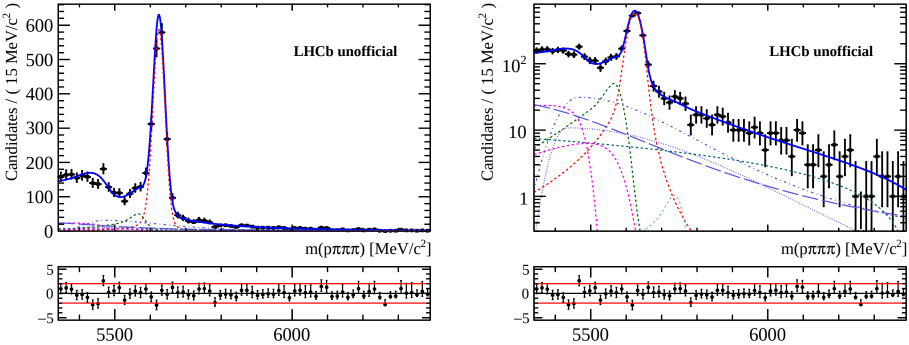


Branching Fraction measurements - Addition of p and $\bar{p}$ spectra.

- The fit model has been blessed during the review of this analysis (not yet completed though, hence you'll see LHCb unofficial everywhere) and we added up the proton and antiproton spectra for branching fraction measurements while keeping blind the individual spectra for CP asymmetries measurements.
- We aimed at having the very same model for both measurements (ΔA_{CP} and BF).
- For BF measurements, the key point is to design a selection which "minimally" biased the phase space of the decay,
  - $\rightarrow$ cut on events Triggered Independently on Signal at the first level of trigger.
  - $\rightarrow$ no kinematical cuts on daughter particles (serves also the ΔA_{CP} measurement)

Branching Fraction measurements - Addition of p and $\bar{p}$ spectra.

- The combined plots are made by summing the proton and antiproton individual probability density functions (p.d.f.s) for each component without unblinding the charge-dependant spectra.



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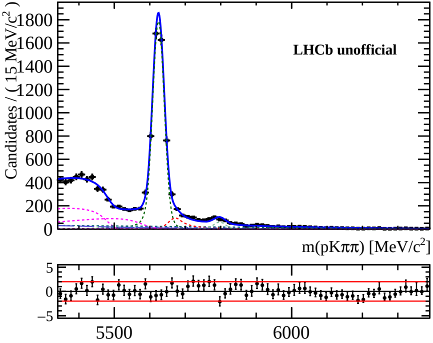

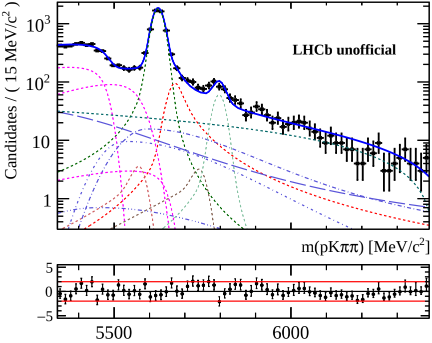

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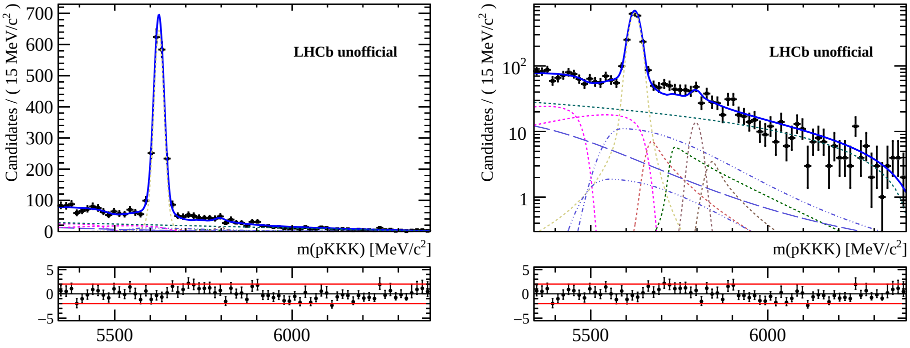
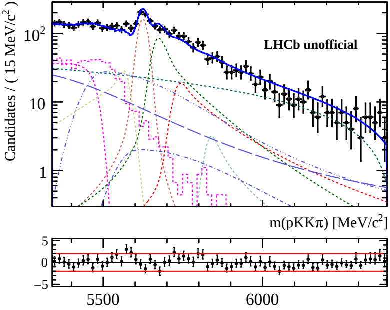
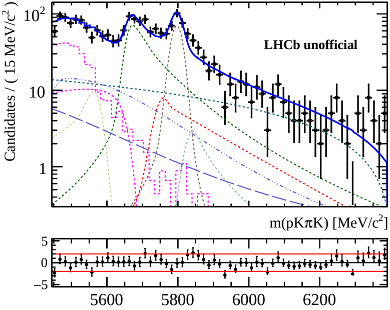
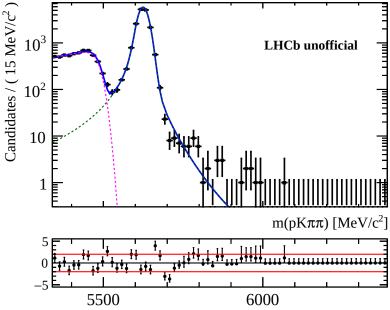








- ⋆ Analysis is completed and in the very final stage of the internal review process of the collaboration.
- ⋆ All relevant signals searched for have been established and in some cases a large statistics is obtained, paving the way to precise *CP* asymmetry measurements.

⋆ Linear y-axis plots are displayed in back-up.

CPV measurement.

- Experimental aspects can mimic the small effect we want to measure :
  $\rightarrow$ Collisions inital state is two protons $\rightarrow$ production asymmetry
  $\rightarrow$ Detector made of matter $\rightarrow$ detection asymmetry

- These effects (as large as 1%) have either to be measured or cancelled.
  - ΔA_{CP} technique: raw asymmetries of the charmless decays are compared to $b \rightarrow c$ transitions in order to cancel out production and detection asymmetries.
  - Triple product asymmetries: by construction insensitive to production and detection asymmetries.

ΔA_{CP} measurements.

- Our measurement is performed with ΔA_{CP} technique: Charmed decays leading to the very same final state than the decay modes of interest are used as control channels.

$$\Lambda_b^0 \to \Lambda_c^+(\to p\pi^-\pi^+)\pi^- \ , \Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^- \ , \Xi_b^0 \to \Xi_c^+(\to pK^-\pi^+)\pi^- .$$

- The observable is defined as

$$\Delta A_{CP} = A_{CP}(\Lambda_b \to pK\pi\pi) - A_{CP}(\Lambda_b \to \Lambda_c(\to pK\pi)\pi)$$
$$\text{with } A_{CP}(\Lambda_b \to pK\pi\pi) = \frac{\mathcal{N} - \bar{\mathcal{N}}}{\mathcal{N} + \bar{\mathcal{N}}} + A_{Prod.}(\Lambda_b) + A_{reco.}(trks.)$$

$\to$ this difference cancels out at first order detection and production asymmetries.

- Currently working on the identification of relevant specific regions of the Phase Space where the ΔA_{CP} analysis can be run (Ongoing), *i.e.*:
  $\to$ pa_1 in $\Lambda_b \to p\pi\pi\pi$,
  $\to$ $\Delta^{++}K^-\pi^-$ in $\Lambda_b \to pK\pi\pi$,
  $\to$ $\Lambda^*\phi$ in $\Lambda_b \to pKKK$.

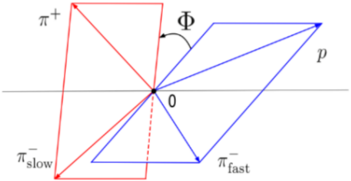
Triple product asymmetries.

Triple products.

- The momenta of the tracks in the final state are used in order to define triple products, which are calculated in the b-baryon decaying rest frame (X_b).

- Are defined:

$$
\begin{aligned}
C_{\hat{T}} &= \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+}) \propto \sin\Phi \text{ for } X_b, \\
\bar{C}_{\hat{T}} &= \vec{p}_{\bar{p}} \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-}) \propto \sin\bar{\Phi} \text{ for } \bar{X}_b.
\end{aligned}
$$



where $\hat{T}$ is the motion reversal operator and h_i stand for two tracks with opposite signs present in the final state.

Triple product asymmetries.

$\hat{T}$-odd observable.

- For each charge of the b-baryon X_b, the data sample is split with respect to the $C_{\hat{T}}$ sign. The CP-violating asymmetry is hence defined as :

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

with

$$A_{\hat{T}} = \frac{\mathcal{N}(C_{\hat{T}} > 0) - \mathcal{N}(C_{\hat{T}} < 0)}{\mathcal{N}(C_{\hat{T}} > 0) + \mathcal{N}(C_{\hat{T}} < 0)} \quad \text{and} \quad \bar{A}_{\hat{T}} = \frac{\bar{\mathcal{N}}(-\bar{C}_{\hat{T}} > 0) - \bar{\mathcal{N}}(-\bar{C}_{\hat{T}} < 0)}{\bar{\mathcal{N}}(-\bar{C}_{\hat{T}} > 0) + \bar{\mathcal{N}}(-\bar{C}_{\hat{T}} < 0)}$$

which are by construction insensitive to the detection and production asymmetries.

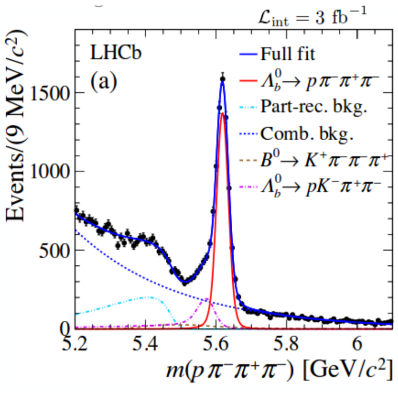
- Complementarity between the ΔA_{CP} and TPA :

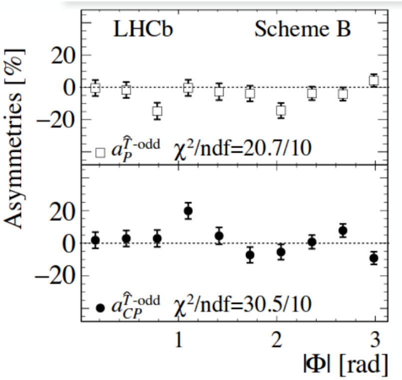
$$\begin{aligned} a_{CP}^{\hat{T}-odd} &\propto \cos(\delta_{even} - \delta_{odd}) \sin(\phi_{even} - \phi_{odd}) \\ A_{CP} &\propto \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2) \end{aligned}$$

- Measurements are performed in different regions of the Phase Space in order to enhance the sensitivity of CPV.

Triple product asymmetries.

Measurements.





- For each decay mode, measurements of asymmetries in regions of phase space are perfomed using different binning schemes in order to improve the sensitivity to localised CPV.
- Combining results of 2 binnings schemes : CPV at 3.3σ in $\Lambda_b \to p\pi\pi\pi$ spectrum.
- Published results here.

Outlook.

⋆ Branching fraction measurements:

- Signal of the decays of interest are all established.
- Analysis mostly done and is currently in review.
- Will be published soon, hopefully.

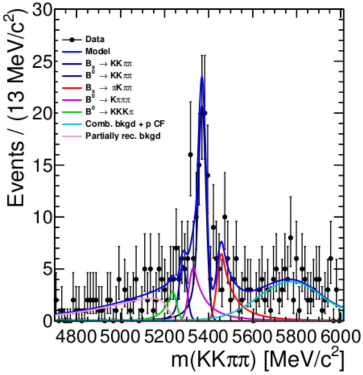
⋆ *CPV* measurements:

- First evidence for *CPV* has recently been published by LHCb in $\Lambda_b \to p\pi\pi\pi$.
  $\to$ this is however not easily interpretable.
  $\to$ Five dimensional amplitude analysis would be required but might happen to be non trivial.
- For ΔA_{CP}: Work on the 2-body decays and Phase Space projections.
- Would see a similar (or more!) deviation, and might highlight *CPV* in other modes.

Backup

Method - $B \rightarrow$ 4 or 5-body background.

- Right-hand side band of invariant mass spectra can provide information on these contributions without any implicit unblinding of the signal events. Only combinatorics, signal CF and B physics events are expected to populate this region.
- For instance, we reconstruct $KK\pi\pi$ invariant mass distribution for $m(pK\pi\pi) > 5840$ MeV/c^2 events.



- Dominant contributions are expected to come from:

$\rightarrow$ 4-body decays where a K is misidentified with a proton,

$\rightarrow$ 4-body decays where a π is misidentified with a proton,

$\rightarrow$ 5-body decays where one track is not reconstructed,

- B physics background contributions are identified in the RHSB and corresponding yields in the whole spectrum are constrained to what is measured in that region.

Branching Fraction measurements - Systematics.

- PhSp variation: we consider the three main sources (acceptance, reco+stripping+trigger+selection and PID) of variation of efficiency in the Phase Space and add the corresponding systematic estimates in quadrature.
  Note: charmed veto cuts efficiency variation is estimated separately.

Table 41: Relative systematic uncertainty estimates related to the dependence of the efficiency over the Phase Space of the decay for 2012. The category RTS2 stands for Reconstruction, Trigger, Stripping and Selection cuts.

Decay mode	RTS2 cuts (%)	PID cuts (%)	All cuts (%)
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	$\pm$ 3.27	$\pm$ 1.78	$\pm$ 4.07
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	$\pm$ 1.27	$\pm$ 2.11	$\pm$ 2.97
$\Lambda_b^0 \to pK^-K^+\pi^-$	$\pm$ 1.10	$\pm$ 2.41	$\pm$ 3.13
$\Lambda_b^0 \to pK^-K^+K^-$	$\pm$ 2.38	$\pm$ 2.41	$\pm$ 3.77
$\Xi_b^0 \to pK^-\pi^+\pi^-$	$\pm$ 0.54	$\pm$ 2.42	$\pm$ 2.98
$\Xi_b^0 \to pK^-\pi^+K^-$	$\pm$ 0.27	$\pm$ 2.34	$\pm$ 2.88
$\Xi_b^0 \to pK^-K^+K^-$	$\pm$ 2.54	$\pm$ 2.26	$\pm$ 3.78

- Fixed parameters: parameters of the shapes have been determined by a simultaneous fit of several simulated events datasets. Pseudo-experiments are generated by varying these fixed parameters of the shapes according to the results of the MC fit and taking into account its covariance matrix. Systematic uncertainty is determined from R.M.S. of the fit results observables.

Appendix - Combined plots.