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Measurement of Direct *CP* Violation in $\Lambda_b^0 \to ph^-$ Decays at LHCb

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In these proceedings the latest measurement of direct *CP* asymmetry in the $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ decays measured using data collected during the Large Hadron Collider Run 1 and 2 by the LHCb experiment is presented. The datasets were collected in proton-proton collisions with centre-of-mass energy of 7, 8 and 13 TeV, corresponding to a total integrated luminosity of 9 fb^{-1}. The Run 1 measurement supersedes the previous LHCb results, while the combination of the two Runs provides the most accurate values of the quantities to date, namely:

$$A_{CP}^{pK^-} = (-1.1 \pm 0.7 \pm 0.4)\%,$$
$$A_{CP}^{p\pi^-} = (\ \ 0.2 \pm 0.8 \pm 0.4)\%,$$

compatible, within 1.5 σ at a precision of the order of 1%, with the hypothesis of *CP* conservation in these decays.

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1. Introduction

The Standard Model of particle physics (SM) predicts the non-invariance of the weak interaction under the *CP* transformation, given by the combination of charge conjugation (C) and spatial parity reversal (P), due to the complex phase of the CKM matrix given by 3 generations of quark families [1, 2]. After years of searches, no significant departures from SM predictions have been found and it is worth noticing that the magnitude of the *CP*-violating effects observed so far is not sufficient to explain the observed matter-antimatter asymmetry of the Universe. Furthermore, searches in the baryon sector have been extensively performed, but no hints of *CP* Violation (*CP*V) have been found until 2024, when a first evidence (3.1σ) was found in $\Lambda_b^0 \to \Lambda K^+K^-$ decays [3].

Charmless decays of beauty hadrons are an excellent laboratory for *CP*V searches since penguin contributions become dominant and New Physics effects can appear enhancing *CP*V effects. The analysed decays are particularly promising since they are described by the same diagrams mediating the $B^0 \to K^+\pi^-$ decays, where *CP*V is already well established [4]. In these proceedings, the latest search for direct *CP*V in $\Lambda_b^0 \to ph^-$ with $h \in [\pi, K]$ decays performed by the LHCb Collaboration is presented [5], using the full sample collected during Run 1 and Run 2 by the detector [6], with centre-of-mass energies of 7, 8 and 13 TeV, corresponding to an integrated luminosity of 9 fb^{-1}. The Run 1 sample had already been analysed in the past [7], but thanks to the improvements presented in these proceedings previous results were updated.

The *CP* asymmetry is defined as

$$A_{CP}^{f} = \frac{\Gamma(\Lambda_b^0 \to f) - \Gamma(\overline{\Lambda}_b^0 \to \overline{f})}{\Gamma(\Lambda_b^0 \to f) + \Gamma(\overline{\Lambda}_b^0 \to \overline{f})}, \tag{1}$$

where f is the final state ($f \in \{pK^-, p\pi^-\}$, $\overline{f} \in \{\overline{p}K^+, \overline{p}\pi^+\}$) and Γ is the partial width of the considered decay.

2. Analysis Strategy

The observed asymmetry is given as a difference of the countings in the detector

$$A_{\text{raw}}^{f} = \frac{N(\Lambda_b^0 \to f) - N(\overline{\Lambda}_b^0 \to \overline{f})}{N(\Lambda_b^0 \to f) + N(\overline{\Lambda}_b^0 \to \overline{f})}. \tag{2}$$

A_{raw} is related to the physical asymmetry A_{CP}^{f} by accounting for all the possible experimental asymmetries, which in the case of $\Lambda_b^0 \to ph^-$ decays leads to

$$A_{CP}^{ph^-} = A_{\text{raw}}^{ph^-} - A_{\text{D}}^{p} - A_{\text{D}}^{h} - A_{\text{PID}}^{ph^-} - A_{\text{T}}^{ph^-} - A_{\text{P}}^{\Lambda_b^0}, \tag{3}$$

where A_{D} denotes the detection asymmetry of the final-state particle/track, A_{PID} the asymmetry of the Particle IDentification (PID) efficiencies, A_{T} the asymmetry induced by the trigger selection and A_{P} the production asymmetry of the Λ_b^0 baryons. Since the production asymmetry has been measured only for Run 1 [8], two different strategies are implemented depending on the Run. For Run 1, (3) holds and therefore A_{CP}^{f} can be directly computed from it. On the other hand, no

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production asymmetry measurement has been performed for Run 2, but its contribution can be removed by means of a control sample of $\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\pi^-$ decays. The production asymmetry term appearing in this Cabibbo-favoured decay, where *CP*V effects are expected to be small compared to those in the studied channels, can be used to remove the dependence of the production term in (3), leading to

$$A_{CP}^{ph^-} = \Delta A_{\text{raw}} - \Delta A_{\text{D}}^{p} - \Delta A_{\text{D}}^{h^-} - \Delta A_{\text{PID}} - \Delta A_{\text{T}} - A_{\text{D}}^{h'^-} - A_{\text{D}}^{\pi^+} + A_{CP}^{\Lambda_c^+\pi^-}, \tag{4}$$

where the ΔA terms indicate the asymmetry difference between signal and control samples, A_{D} are the control-sample asymmetries not already accounted for and h' denotes the other π/K final state with respect to the ph^- signal. To guarantee the cancellation of the production asymmetry term, which is kinematic dependent [8], the control sample is reweighted to match the $\Lambda_b^0 \to ph^-$ kinematics in (p_T, η).

3. Data Selection and Invariant-Mass Fit

The event selection is performed in two steps: an online trigger selection followed by an offline optimisation.

First, pairs of oppositely charged tracks with $p_T > 1\,\text{GeV}/c$, inconsistent with being produced in a primary vertex (PV) are matched. The invariant mass of the pair, where both final states are assumed to be pions, is required to lie within a certain range ($m_{\pi\pi} \in [4.6, 6.4]\,\text{GeV}/c^2$ for Run 1, $[4.7, 6.2]$ for Run 2). The b-hadron candidate is required to have been produced in a PV. In order to reduce systematic uncertainties, a fiducial requirement to the final-state tracks is applied in the (p, η) plane, ensuring kinematic coverage of the PID-calibration samples.

The offline optimisation procedure is the same used during the Run 1 analysis [7]. PID variables are used to divide the dataset in mutually exclusive subsamples, each one corresponding to one of the eight $h^+h'^-$ final state hypotheses ($pK^-, \overline{p}K^+, p\pi^-, \overline{p}\pi^+, K^+K^-, K^+\pi^-, \pi^+K^-, \pi^+\pi^-$). Furthermore, a BDT selection distinguishing signal and combinatorial background is applied. By means of pseudoexperiments, the optimal combinations of BDT and PID requirements, one for $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$, are found for Run 2. The same requirements in [7] are used instead for Run 1 data.

The dataset is split in 12 subsamples, representing each possible combination of LHCb magnet polarity and data taking year. Two extended binned maximum-likelihood fits, one for each optimal combination of BDT and PID requirements, are performed on each year/magnet-polarity subsample simultaneously to the invariant mass of all the $h^+h'^-$ final states ($m_{h^+h^-}$), yielding to an A_{raw} for each fit. The PID efficiencies $\varepsilon_{\text{PID}}^{f}$ of reconstructing each final state f, given a set of PID requirements, are obtained with high-statistics and high-purity calibration samples ($D^{*+} \to (D^0 \to K^-\pi^+)\pi^+$ for π/K and $\Lambda \to p\pi^-$ and $\Lambda_c^+ \to pK^-\pi^+$ for p) [9]. Figure 1 shows the invariant-mass fit for the 2018-magnet down $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ selections.

4. Experimental Asymmetries

Once the A_{raw} of the subsamples are obtained, it is necessary to correct for all the experimental asymmetries appearing in (3) and (4).

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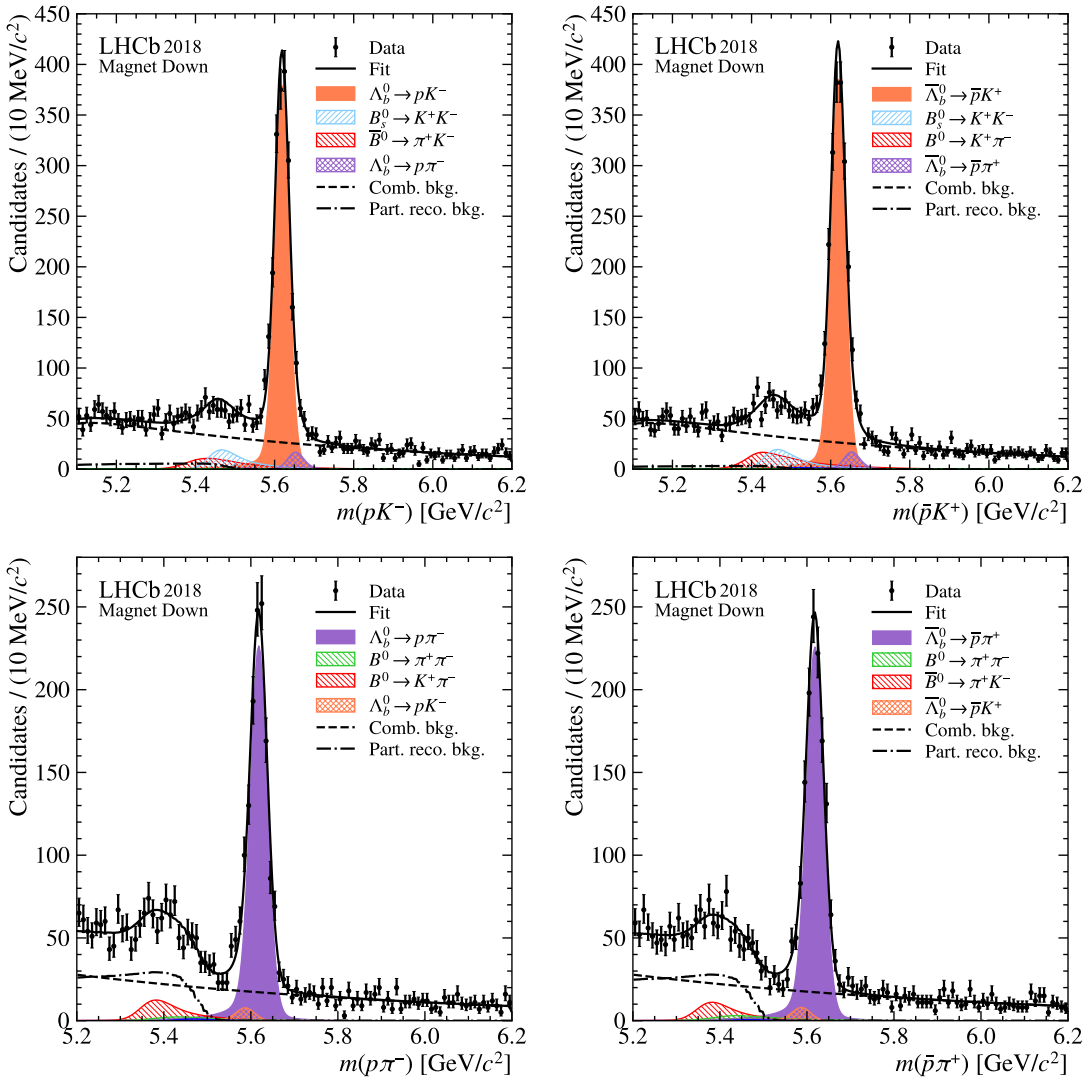

Figure 1: Invariant-mass fits for the 2018-magnet down $\Lambda_b^0 \to pK^-$ (top) and $\Lambda_b^0 \to p\pi^-$ (bottom) selections.

Detection asymmetries for pions and kaons are obtained as a function of momentum and pseudorapidity as done in [10–12]. For pions, the Run 1 measurement makes use of the detection efficiencies obtained from $D^{*+} \to (D^0 \to K^-\pi^+\pi^-\pi^+)\pi^+$ decays comparing fully reconstructed decays against decays where a single pion is lost. The Run 2 term was found analysing $K_s^0 \to \pi^+\pi^-$ decays (from $D^0 \to (K_s^0 \to \pi^+\pi^-)\pi^+\pi^-$ decays), comparing the number of tracks reconstructed only in the VErtex LOcator (VELO) to the number of VELO tracks matched to long tracks. Kaon asymmetries are found by removing the pion asymmetry from the detection asymmetry of $K^-\pi^+$ pairs using $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to K_s^0\pi^+$ decays. For protons, only Run 1 detection asymmetry is available [7]. Since no major changes to the LHCb detector [6] were performed between Runs 1 and 2, the Run 1 asymmetry is applied to Run 2 data too. This procedure is validated by comparing the measured pion and kaons detection asymmetries between Runs.

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PID asymmetries can be retrieved using the efficiencies introduced in Section 3 as

$$A_{\text{PID}}(f) = \frac{\varepsilon^f_{\text{PID}} - \varepsilon^{\bar{f}}_{\text{PID}}}{\varepsilon^f_{\text{PID}} + \varepsilon^{\bar{f}}_{\text{PID}}}. \tag{5}$$

Trigger induced asymmetries can be defined in a way similar to (5). During the analysed campaigns, the LHCb detector employed both hardware and software triggers, both introducing asymmetry terms. For what concerns the hardware trigger, two contributions are expected, depending on whether the triggering was caused by the investigated b-hadron (Trigger On Signal (TOS) events) or by the other b-hadron produced in the collision (Trigger Independent of Signal (TIS)). TIS-induced asymmetries were estimated with $B^+ \to J/\psi K^+$ decays, while TOS ones by studying semileptonic $\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\mu\nu X$ for protons and $B^0 \to (D^0 \to K^+\pi^-)\mu\nu X$ decays for pions/kaons. The combination of TIS and TOS hardware contribution provides the total asymmetry term for the hardware trigger. The software trigger also introduces TOS asymmetries, which were studied with the same semileptonic decays used for the hardware trigger study.

5. Results and Systematic Uncertainties

Once all the terms in (3) and (4) are measured for each one of the year/magnet subsamples, $A_{CP}^{ph^-}$ can be determined.

Systematic uncertainties receive several contributions. Those related to the fit model are estimated by generating 1000 pseudoexperiments from the nominal values obtained by the analysis and refitting with the original and alternative models, where the systematic is given by the difference of the two. Similarly, to estimate the contributions from calibration samples, maps containing the efficiencies used in the analysis are gaussianly resampled around their nominal values, with their uncertainties as standard deviations. These maps are then reused to recompute $A_{CP}^{ph^-}$, finding the correlations among all subsamples. Finally, the single $A_{CP}^{ph^-}$ values can be combined, leading to the final measured values for both Runs and their combination. For Run 1 this leads to

$$A_{CP}^{pK^-} = (-0.3 \pm 1.5 \pm 0.6)\%,$$
$$A_{CP}^{p\pi^-} = (-0.6 \pm 1.9 \pm 0.5)\%,$$

where the first uncertainties are statistical and the second ones are systematic. This measurement supersedes the previously published LHCb Run 1 measurements. The Run 2 measured asymmetries are

$$A_{CP}^{pK^-} = (-1.4 \pm 0.7 \pm 0.4)\%,$$
$$A_{CP}^{p\pi^-} = (\ \ 0.4 \pm 0.9 \pm 0.4)\%.$$

Finally, the combination of both Runs yields

$$A_{CP}^{pK^-} = (-1.1 \pm 0.7 \pm 0.4)\%,$$
$$A_{CP}^{p\pi^-} = (\ \ 0.2 \pm 0.8 \pm 0.4)\%,$$

which is the most precise measurement of the quantities to date, compatible with the hypothesis of *CP* conservation in the decays.

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6. Conclusion

These proceedings presented the latest measurements of the *CP* asymmetries for $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ decays with both Run 1 and Run 2 datasets, superseding the previous Run 1 measurement and producing the most precise measurement of the quantities to date. No hints of *CP*V are observed, as both quantities are compatible with the *CP* symmetry hypothesis within $1.5\,\sigma$.

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