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# *CP* violation and related measurements with baryons at LHCb

**Alex Pearce***, **on behalf of the LHCb collaboration**
*CERN, Switzerland*
*E-mail:* alex.pearce@cern.ch

The rich dynamics available within the decay of heavy flavour baryons provides a laboratory to study the interplay between strong and weak dynamics, as well as allowing many amplitudes in which physics beyond the Standard Model can enter. This contribution will highlight several recent results from the LHCb experiment on *CP* and baryon number violation.

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## 1. Introduction

The non-zero net baryon-antibaryon number observed in our universe is one of the fundamental unexplained problems in particle physics. The Sakharov conditions outline the conditions necessary for *baryogenesis* to occur [1], the process through which a baryon-antibaryon imbalance can manifest, and these include processes which violate baryon number conservation and processes which are not of equal rate under the *CP* transformation. The Standard Model (SM) does not allow for a large enough contribution from either of these phenomena to explain the existence of our universe, however the small rates it does predict can be used as sensitive probes to contributions arising from physics beyond the SM, which may in turn help explain the puzzle. The LHCb experiment at the Large Hadron Collider (LHC) [2, 3] is principally designed to the study of heavy flavour hadrons, containing charm and beauty quarks, and the decays of these objects admit a broad set of observables through which *CP* violation (CPV) and baryon number violation (BNV) can be probed. These proceedings summarise relevant results from the LHCb experiment that have become available since the last LHCP conference.

Measurements of heavy flavour baryons at the LHC benefit from the large charm and beauty cross-sections [4, 5] in proton-proton collisions at high centre-of-mass energies, rising from $\sqrt{s} = 7\,\text{TeV}$ in 2011, to $8\,\text{TeV}$ in 2012, to $13\,\text{TeV}$ since the beginning of Run 2 in 2015. The LHCb experiment has already collected the world's largest samples of charm and beauty baryons. The latter is of particular interest as CPV has been observed in the three lightest beauty meson ground states, but is yet to be observed in beauty baryons (nor, indeed, in the decays of any baryon), and a similarly large dataset is not foreseen to be collected by the Belle 2 experiment, which will otherwise be competitive in many heavy flavour measurements. Recent evidence of CPV in the decays of the lightest beauty baryon, $\Lambda_b^0$, has been reported by LHCb [6], warranting a thorough exploration in this and similar areas.

In general, the study of baryon decays offers a rich laboratory to study strong and weak dynamics. The inclusion of transitions which are suppressed in analogous meson decays, such as those involving $W$-exchange, allows for additional amplitudes through which new physics may enter, altering the value of CPV and BNV observables. In addition, the presence of a proton (antiproton) in the final state of a given multi-body baryon (antibaryon) decay typically increases the number of degrees of freedom required to fully describe that decay, in comparison with a similar heavy flavour meson decays. Both CPV and new physics (NP) effects may vary as a function of the multi-dimensional phase space, across which experimental efficiencies are typically not constant, and so an analyst must take particular care to correct for experimental effects to be maximally sensitive.

Experimental study of CPV is further complicated by particle-antiparticle matter interaction asymmetries, which mimic matter-antimatter asymmetries in decay. Accounting for these effects directly requires a measurement of the detection asymmetry, and while this exists for pions, kaons, and muons at LHCb, it does not yet exist for protons, as finding a clean, abundant control sample is challenging. Observables which are insensitive to these effects, such as asymmetry differences between similar decay modes, are an effective way of dealing with this lack of experimental input, but can be harder to interpret theoretically. The measurements presented in this contribution use a combination of robust observable definitions and studies using simulation to deal with such 'background' asymmetries, and in all cases are able to probe down to the percent level, at which both SM and NP effects could feasibly enter.

## 2. *CP* violation in multi-body beauty baryon decays

The first evidence of CPV in the decay of a baryon was reported by LHCb using samples of $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays [6]. Triple products of the momenta of the final state objects are defined as

$$C_{\widehat{T}} = \mathbf{p}_p \cdot (\mathbf{p}_{h_1^-} \times \mathbf{p}_{h_2^+}), \quad \overline{C}_{\widehat{T}} = \mathbf{p}_{\overline{p}} \cdot (\mathbf{p}_{h_1^+} \times \mathbf{p}_{h_2^-}),$$

and then $P$-odd and $\widehat{T}$-odd observables are formed

$$A_{\widehat{T}}(C_{\widehat{T}}) = \frac{N(C_{\widehat{T}} > 0) - N(C_{\widehat{T}} < 0)}{N(C_{\widehat{T}} > 0) + N(C_{\widehat{T}} < 0)}, \quad \text{and}$$
$$\overline{A}_{\widehat{T}}(\overline{C}_{\widehat{T}}) = \frac{\overline{N}(-\overline{C}_{\widehat{T}} > 0) - \overline{N}(-\overline{C}_{\widehat{T}} < 0)}{\overline{N}(-\overline{C}_{\widehat{T}} > 0) + \overline{N}(-\overline{C}_{\widehat{T}} < 0)},$$

respectively, where $N$ and $\overline{N}$ represent the number of signal $\Lambda_b^0$ and $\overline{\Lambda}_b^0$ decays in the sample. Finally, parity- and *CP*-violating observables are defined as

$$a_P^{\widehat{T}\text{-odd}} = \frac{1}{2}(A_{\widehat{T}} + \overline{A}_{\widehat{T}}), \quad \text{and}$$
$$a_{CP}^{\widehat{T}\text{-odd}} = \frac{1}{2}(A_{\widehat{T}} - \overline{A}_{\widehat{T}})$$

respectively. These are measured both integrated across the phase space and in binning schemes defined within it, and the *CP*-violating quantity is found to deviate from zero with a significance of $3.3\,\sigma$ with the latter technique. As well as not requiring precise knowledge on the resonant character of the decay (which can proceed via multiple paths through intermediate, strongly-decaying resonances), this method is also largely insensitive to asymmetries arising from detector and production effects.

The same triple product technique is used in a recent analysis reported here using samples of $\Lambda_b^0 \to pK^-\pi^+\pi^-$, $\Lambda_b^0 \to pK^-K^+K^-$, and $\Xi_b^0 \to pK^-K^+\pi^-$ decays [7]. As in the previous analysis, $3.0\,\text{fb}^{-1}$ of integrated luminosity collected at $\sqrt{s} = 7$ and $8\,\text{TeV}$ is used to reconstruct the $\Lambda_b^0$ and $\Xi_b^0$ samples, which are purified through the use of a boosted decision tree (BDT) and particle identification requirements. Each sample is then split by proton charge into baryon and antibaryon samples, and each of these is further split by the sign of $C_{\widehat{T}}$ or $\overline{C}_{\widehat{T}}$. Spectra of the $\Lambda_b^0$ and $\Xi_b^0$ invariant masses are shown for these various samples in Figure 1, where it can be seen that no significant net parity- or *CP*-violating effects are present. For the two $\Lambda_b^0$ decay modes, where the sample sizes are sufficiently large, two binning schemes are defined to maximise sensitivity to asymmetries for each mode: scheme A defines regions around dominant intermediate resonances, and scheme B defines equally-spaced regions in the decay angle $\Phi$, given by the relative position of two-body $ph^-$ and $h^+h^-$ decay planes. Example asymmetry distributions in these schemes are shown in Figure 2. In all cases, the distributions are compatible with the no-CPV hypothesis.



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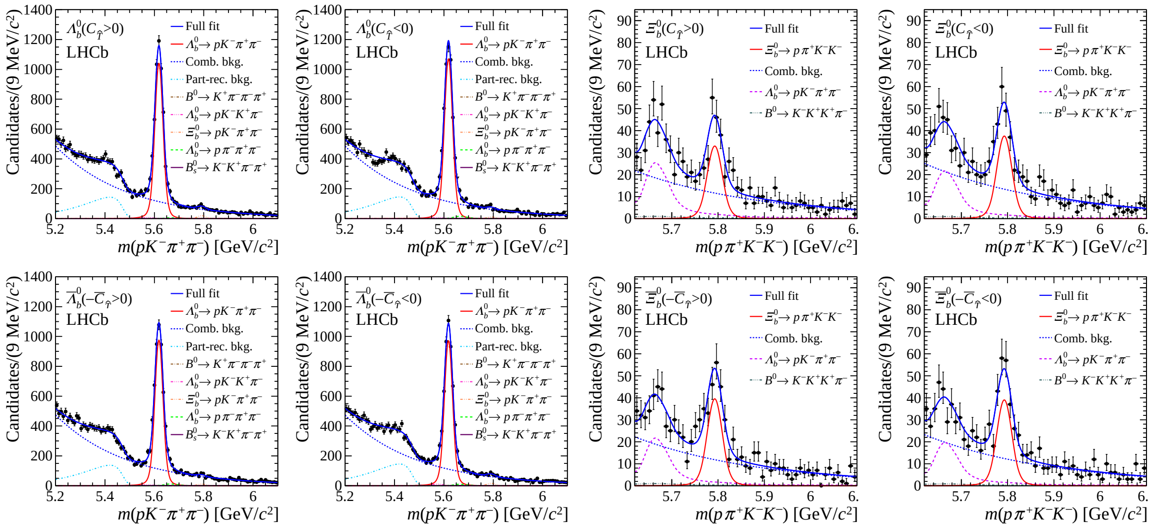


**Figure 1:** Invariant mass distributions of the four-body final states in the (left) $\Lambda_b^0 \to pK^-\pi^+\pi^-$ and (right) $\Xi_b^0 \to pK^-K^+\pi^-$ phase-space-integrated samples, split by proton charge into (top) baryon and (bottom) antibaryon samples [7].

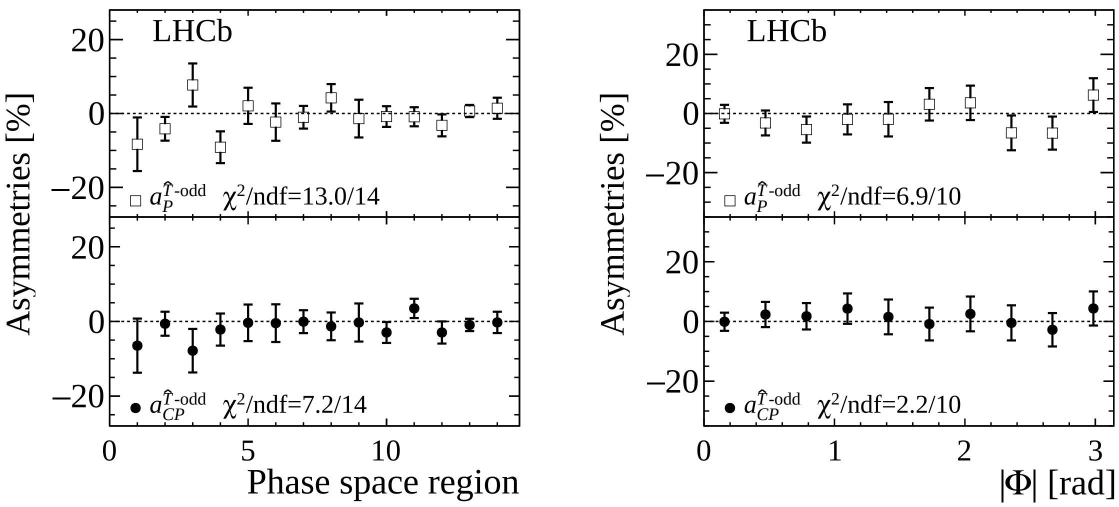


**Figure 2:** Measured (top) parity- and (bottom) *CP*-violating asymmetries in bins defined by (left) intermediate resonances in the $\Lambda_b^0 \to pK^-\pi^+\pi^-$ sample and (right) the decay angle $\Phi$ in the $\Lambda_b^0 \to pK^-K^+K^-$ sample [7].

## 3. *CP* violation in two-body beauty baryon decays

Baryon-antibaryon asymmetries in the two-body $\Lambda_b^0$ decay modes $p\pi^-$ and $pK^-$ have been predicted to have magnitudes from $\mathcal{O}(1\,\%)$ [8, 9] to $\mathcal{O}(10\,\%)$ [10]. Such large asymmetries are in principle simpler to measure experimentally, but even a non-observation can help to disambiguate between models.

Measurements of CPV are commonly made using decay rate differences, for example

$$A_{CP}(\Lambda_b^0 \to ph) = \frac{\Gamma(\Lambda_b^0 \to ph^-) - \Gamma(\overline{\Lambda}_b^0 \to \overline{p}h^+)}{\Gamma(\Lambda_b^0 \to ph^-) + \Gamma(\overline{\Lambda}_b^0 \to \overline{p}h^+)}, \quad (3.1)$$

where $h$ represents either a charged pion or kaon. Until recently, the most precise measurements of these quantities were from the CDF collaboraton, and were consistent with no CPV with a precision of 8–9 % [11]. A recent LHCb measurement of both $A_{CP}(p\pi^-)$ and $A_{CP}(pK^-)$ is reported here that uses the same 3 $\text{fb}^{-1}$ of integrated luminosity described in the previous Section [12].

Candidate $\Lambda_b^0$ baryons are reconstructed as two-track $h^+h^-$ vertices, and then each possible two-body mass hypothesis is computed (for $h \in \{\pi, K, p\}$). The eight resulting invariant-mass spectra are fit simultaneously to control the large contributions to the dataset from two-body beauty meson decays and to maximise sensitivity. Spectra split by proton charge are shown in Figure 3.

Rather than measure $A_{CP}$ directly from decay rates as in Equation (3.1), the *raw* asymmetry is defined using the reconstructed and selected yields $N$

$$A_{\text{Raw}}(\Lambda_b^0 \to ph) = \frac{N(\Lambda_b^0 \to ph^-) - N(\overline{\Lambda}_b^0 \to \overline{p}h^+)}{N(\Lambda_b^0 \to ph^-) + N(\overline{\Lambda}_b^0 \to \overline{p}h^+)}. \quad (3.2)$$

This is approximately equal to the linear sum of $A_{CP}$, the $\Lambda_b^0/\overline{\Lambda}_b^0$ production asymmetry [13], and the pion, kaon, and proton detection asymmetries. As discussed earlier, measurements of the kaon and pion detection asymmetries have been made at LHCb and so the contribution from these sources can be subtracted directed from $A_{\text{Raw}}$. The proton detection asymmetry contribution is taken from simulation, and carries a relatively large systematic uncertainty due to the uncertainty on the LHCb material budget, the poor knowledge of proton/antiproton cross-sections with the chemical elements that comprise the detector, and the uncertainty on the measured $\Lambda_b^0/\overline{\Lambda}_b^0$ production asymmetry [13] which is taken as input. Additional sources of systematic uncertainty include the finite size of the sample used for measuring particle identification efficiencies, and the choice of models used in the yield extraction procedure. The mode-dependent asymmetries are measured to be

$$A_{CP}(\Lambda_b^0 \to pK^-) = (-1.9 \pm 1.3\,(\text{stat.}) \pm 1.7\,(\text{syst.}))\,\%, \quad \text{and}$$
$$A_{CP}(\Lambda_b^0 \to p\pi^-) = (-3.5 \pm 1.7\,(\text{stat.}) \pm 1.8\,(\text{syst.}))\,\%.$$

In the limit that the experimental asymmetries are independent of the $\Lambda_b^0$ decay mode, the difference $\Delta A_{CP}(ph^-) = A_{\text{Raw}}(pK^-) - A_{\text{Raw}}(p\pi^-)$ is equal to the difference in *CP* asymmetries $\Delta A_{CP} = A_{CP}(pK^-) - A_{CP}(p\pi^-)$. The various background asymmetries are dependent only on the kinematic properties of the object involved, for example the $\Lambda_b^0$ rapidity in the case of $\Lambda_b^0$ production asymmetry. These distributions are seen to be sufficiently similar such that the contribution from background asymmetries cancel in the difference, giving

$$\Delta A_{CP} = A_{CP}(\Lambda_b^0 \to pK^-) - A_{CP}(\Lambda_b^0 \to p\pi^-)$$
$$= (1.5 \pm 2.1\,(\text{stat.}) \pm 1.1\,(\text{syst.}))\,\%.$$

These measurements are consistent with the no-CPV hypothesis, and represent a significant improvement in precision with respect to previous results.

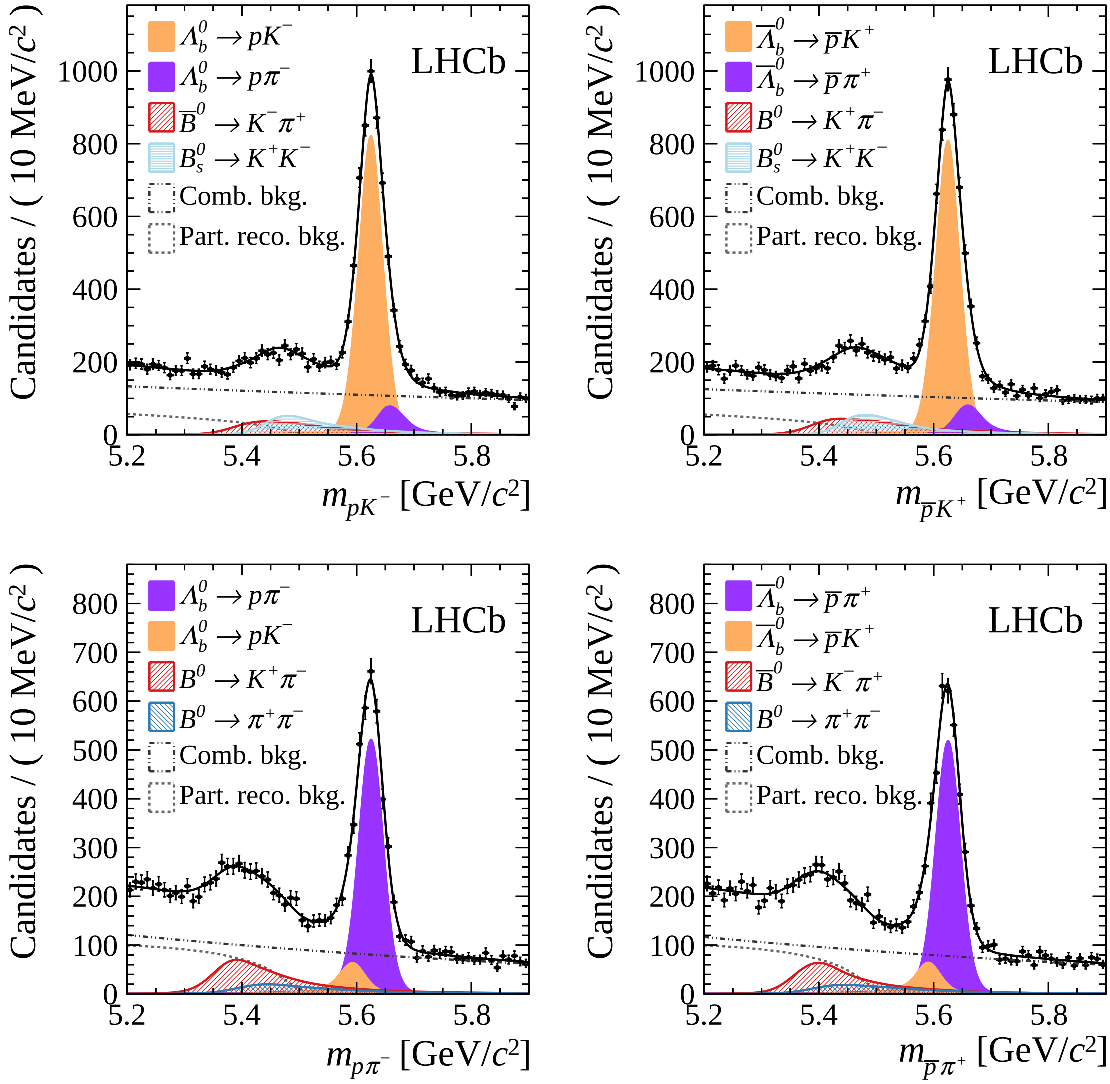


**Figure 3:** Mass spectra for reconstructed (left) $\Lambda_b^0$ and (right) $\overline{\Lambda}_b^0$ decays in the (top) $pK^-/\overline{p}K^+$ and (bottom) $p\pi^-/\overline{p}\pi^+$ final states.

## 4. Baryon-antibaryon oscillations

As mentioned previously, one requirement of baryogenesis is the existence of a process that violates baryon number conservation. Many NP models have been ruled out by stringent lower bounds on the half-life of the proton, but some still remain. In particular, certain models that introduce couplings between quarks and leptons (via leptoquarks), as well as $R$-parity violating models, include six-fermion operators that require the simultaneous interaction of fermions from all three generations [14, 15]. These are strongly suppressed in proton decay due to the need for two flavour-changing neutral currents, and so are not ruled out by existing measurements.

A promising experimental avenue to probe these operators is searching for baryon-antibaryon oscillations with the $\Xi_b^0$ ($usb$) baryon. As this comprises one quark from each generation, the oscillation $\Xi_b^0$–$\bar{\Xi}_b{}^0$ could proceed via a six-fermion vertex ($usb\overline{usb}$), as illustrated in Figure 4.

With the discovery of the excited $\Xi_b^0$ states $\Xi_b^{\prime -}$ and $\Xi_b^{*-}$ by the LHCb collaboration in 2014 [16], an oscillation measurement can be made by tagging the flavour the $\Xi_b^0$ at production using the charge of the pion in the $\Xi_b^{\prime,*-} \to \Xi_b^0\pi^-$ decay, and then the flavour at decay is given by the proton charge. Such a measurement is presented here [17], where the $\Xi_b^0 \to \Xi_c^+\pi^-$, $\Xi_c^+ \to pK^-\pi^+$ decay chain is reconstructed in the same $3\,\text{fb}^{-1}$ of integrated luminosity used for the discovery. A near-identical selection is employed, with the addition of a cut to suppress events where the soft pion from the $\Xi_b^{\prime,*-}$ is assigned the wrong charge. The $\Xi_b\pi^-$ spectrum is given in Figure 4, where the two excited states are clearly visible.

The analysis determines the 'opposite-sign' yields, where the state at production and decay have the same flavour, and 'same-sign' yields simultaneously. The opposite-sign and same-sign signal models are equivalent, and so their parameters are determined from the opposite-sign sample. The same-sign background model is determined from the $\Xi_b\pi^-$ mass regions outside the signal peaks. The expected same-sign signal yields are then defined completely by the $\Xi_b^0$–$\bar{\Xi}_b{}^0$ mixing frequency $\omega$, and so the likelihood is minimised with respect to this parameter. A best fit value of $\hat{\omega} = 0\,\text{ps}^{-1}$ is found, corresponding to no oscillations, and an upper limit on the mixing frequency of $\omega < 0.08\,\text{ps}^{-1}$ at a confidence level of 95 % is set through pseudo-experiments.

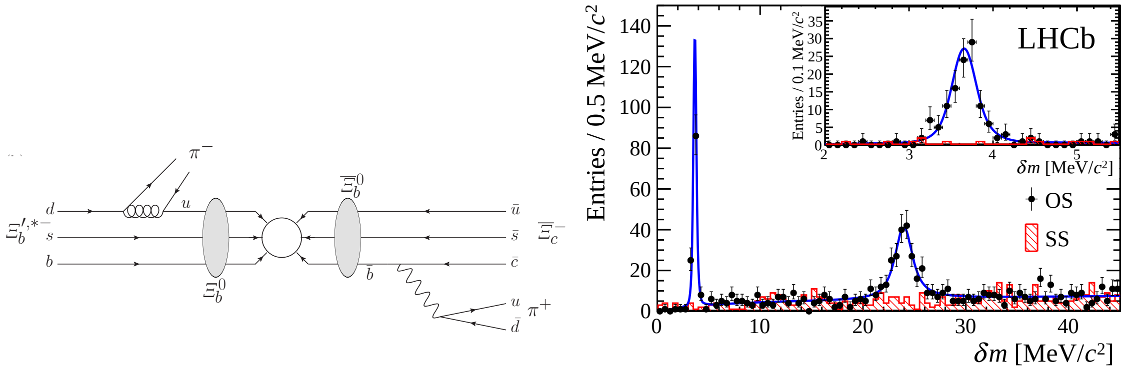


**Figure 4:** (Left) Baryon-antibaryon oscillation diagram in the $\Xi_b^0$ system, illustrating the six-fermion vertex proposed by some NP models [14, 15], and (right) the spectrum of reconstructed and selected $\Xi_b\pi^-$ candidates [17].

## 5. *CP* violation in charm baryon decays

Charm hadrons offer a complementary avenue in which to search for effects beyond the Standard Model due to particularly small predictions for CPV in their decays, typically being no larger than $\mathcal{O}(10^{-3})$. The LHCb experiment has already made significant contributions to this area, and has a large potential to make a similar impact in the future with charm baryon decays, where little experimental focus has been placed so far.

In a similar manner to the two-body $\Lambda_b^0$ analysis already presented, a recent LHCb result [18] measures the *CP* asymmetry difference between the three-body singly Cabibbo-suppressed $pK^-K^+$ and $p\pi^-\pi^+$ decay modes of the lightest charm baryon $\Lambda_c^+$. As in Equation (3.2), the raw asymmetries in $\Lambda_c^+$ and $\Lambda_c^-$ yields are measured, and then the difference $\Delta A_{CP} = A_{\text{Raw}}(pK^-K^+) -$

$A_{\mathrm{Raw}}(p\pi^-\pi^+)$ is formed, which is equivalent to the difference $A_{CP}(pK^-K^+) - A_{CP}(p\pi^-\pi^+)$ in the limit that the kinematic properties of the objects involved in each contributing background asymmetry are equal.

The analysis reconstructs $\Lambda_c^+ \to ph^+h^-$ decays in association with a high-$p_{\mathrm{T}}$ muon, under the hypothesis that the charm baryon originate from a $\Lambda_b^0 \to \Lambda_c^+\mu^-X$ decay. This technique reduces the background from prompt hadrons and charm mesons decays that would otherwise dominate the sample. It does, however, introduce the $\Lambda_b^0$ production and muon detection asymmetries into the definition of $A_{\mathrm{Raw}}$. A kinematic weighting procedure is employed to equalise the kinematic properties of the larger $p\pi^-\pi^+$ sample to those of the $pK^-K^+$ sample, to ensure that the background asymmetries cancel in the difference $\Delta A_{CP}$. Further to this, a five-dimensional efficiency correction is applied to both samples to ensure any phase-space-dependent CPV behaviour are not distorted by experimental effects. Both the weighting and the efficiency correction are made using an approach based on BDTs.

The selected samples used are shown in Figure 5, and represent by far the largest samples of these decay modes to date. Taking the kinematic weights and five-dimensional efficiency corrections into account, the asymmetry difference is measured to be

$$\Delta A_{CP}^{\mathrm{wgt}} = (0.30 \pm 0.91\,(\mathrm{stat.}) \pm 0.61\,(\mathrm{syst.}))\,\%,$$

where the 'wgt' superscript reflects the alteration of the $p\pi^-\pi^+$ asymmetry due to the kinematic weighting procedure. The weights are provided as supplementary material to the paper [18].

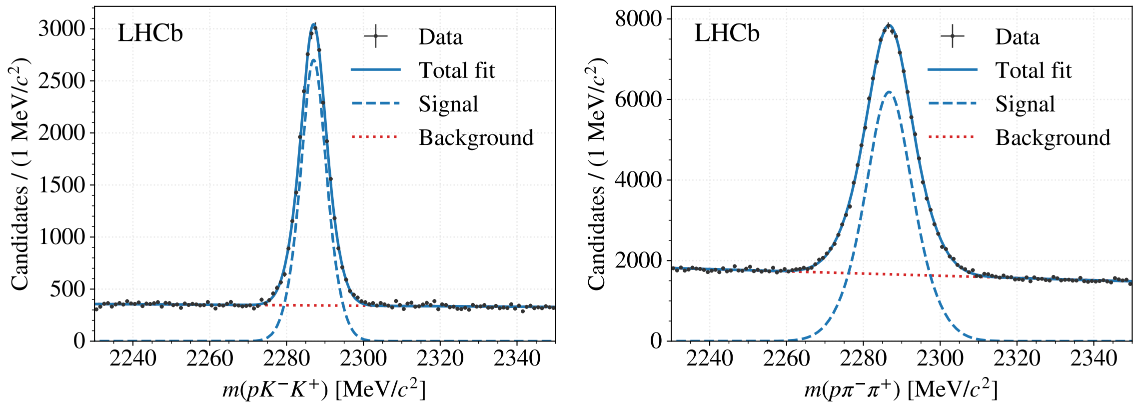


**Figure 5:** Invariant mass distributions of (left) $\Lambda_c^+ \to pK^-K^+$ and (right) $\Lambda_c^+ \to p\pi^-\pi^+$ candidates [18].

## 6. Summary

Measurements of *CP* violation in heavy flavour baryon decays provide a plethora of probes into physics beyond the Standard Model, as well as serving as constraints on notoriously difficult QCD models of hadronic decays. Relative to heavy flavour mesons, baryons have received little theoretical interest and experimental input, but the large cross-sections at the LHC permit both of these points to improve. The LHCb experiment has demonstrated that it is ideally suited to make world-leading, and often world-first, measurements in this field, and a selection of such results have been highlighted in this proceedings contribution.

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