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Charmless b-hadron decays at LHCb

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Violation of charge-parity (*CP*) symmetry in the Standard Model is driven by a single global phase. However, manifestations of *CP* violating quantities are often non-trivial due to the role of the strong interaction in contributing to observable *CP* violating effects. Here we explore how the role of the strong phase in $B^+ \to \pi^+\pi^+\pi^-$ decays, described by the intermediate resonance structure and final-state rescattering effects, governs the manifestation of large *CP* violation. Significant *CP* violation is observed in the scalar and tensor contributions, along with the first observation of *CP* violation in the interference between two competing decay amplitudes. Additionally, *P* and *CP* violation are tested for in the phase-space of $\Lambda_b^0 \to p^+\pi^-\pi^+\pi^-$ decays using model-independent triple-product asymmetry and energy-test methods, with a first observation of *P* violation in b-baryon decays.

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1. Introduction

For the observation of charge-parity (*CP*) symmetry violation in decay, a difference in both the weak phase (which changes sign under *CP*) and strong phase (which is invariant under *CP*) is required. In the Standard Model, weak phase differences are governed by the global phase of the Cabibbo-Cobayashi-Maskawa (CKM) matrix, which is well constrained by experimental measurements, but nevertheless is too small to generate the empirical baryon asymmetry of the universe [1].

Charmless *b*-hadron decays, such as $B^+ \to \pi^+\pi^+\pi^-$ and $\Lambda_b^0 \to p^+\pi^-\pi^+\pi^-$, are of particular interest as tree-level and loop-level diagrams can contribute to the total amplitude with similar magnitudes, such that large observable *CP*-violating effects are possible. Furthermore, strong phase differences can be obtained in multi-body decays via the dynamics of intermediate resonances. Analyses of these decays using data collected by the LHCb experiment are described in the following.

The analysis of the $B^+ \to \pi^+\pi^+\pi^-$ decay [2, 3] proceeds by constructing an explicit model of the decay amplitude, incorporating intermediate resonances and multi-body rescattering effects, with three complementary descriptions of the large S-wave contribution in order to explore the effects of the variation of the strong phase on the observed *CP* violation in the Dalitz plot. Manifestations of *CP* and *P* violation are explored in the $\Lambda_b^0 \to p^+\pi^-\pi^+\pi^-$ decay [4] by utilising two complementary model-independent methods, which incorporate local kernel approximations to the data, along with binned triple-product asymmetries.

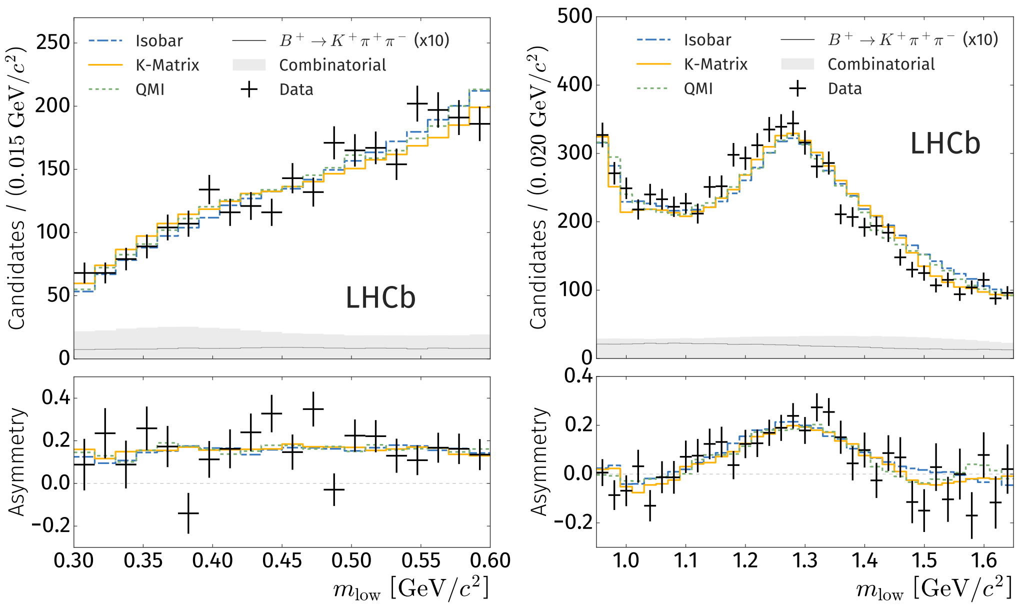

Figure 1: Projections of data and fit results (top) on the low $\pi^+\pi^-$ mass combination in (left) the low $m(\pi^+\pi^-)$ region and (right) the $f_2(1270)$ region, with (bottom) the corresponding *CP* asymmetries in these ranges.

2. Amplitude analysis of $B^+ \to \pi^+\pi^+\pi^-$

A previous model-independent test for *CP* violation in $B^+ \to \pi^+\pi^+\pi^-$ decays indicated that significant *CP* violation was present in very specific regions of the phase space [5], some of which were not easily associated to a single resonant contribution. It was speculated that these effects could be due to $\rho(770)^0 - \omega(782)$ mixing, interference of the $\rho(770)^0$ resonance and the broad S-wave, or final-state rescattering.

In order to investigate these effects further, an explicit model of the $B^+ \to \pi^+\pi^+\pi^-$ decay amplitude is constructed, where the dominant S-wave is modelled using three separate but complementary approaches. The 'isobar' approach describes the S-wave as a coherent sum of separate contributions; the 'K-matrix' approach employs a monolithic unitarity preserving model, incorporating five poles and five open channels, empirically determined from legacy scattering data; and the 'quasi-model-independent' approach separates the phase space into approximately equally populated bins and fits for an independent magnitude and phase for each.

In addition to the S-wave, contributions with spin > 0 were selected via an iterative likelihood-ratio test procedure, starting with the BaBar amplitude model [6] and including well established resonances until no significant improvements in the likelihood could be achieved. Additionally, tests were performed using alternative models for well established states, investigation of more speculative states, along with non-resonant and virtual excited B^* contributions, and scans for latent resonant contributions. The final model is comprised of contributions from the $\rho(770)^0$ modelled using the Gounaris–Sakurai function, and the $\omega(782)$ modelled using a relativistic Breit–Wigner function (where these contributions are combined to fit directly for the electromagnetic mixing effect), along with the $f_2(1270)$, $\rho(1450)^0$, and $\rho_3(1690)$ resonances, which are all modelled using relativistic Breit–Wigner functions.

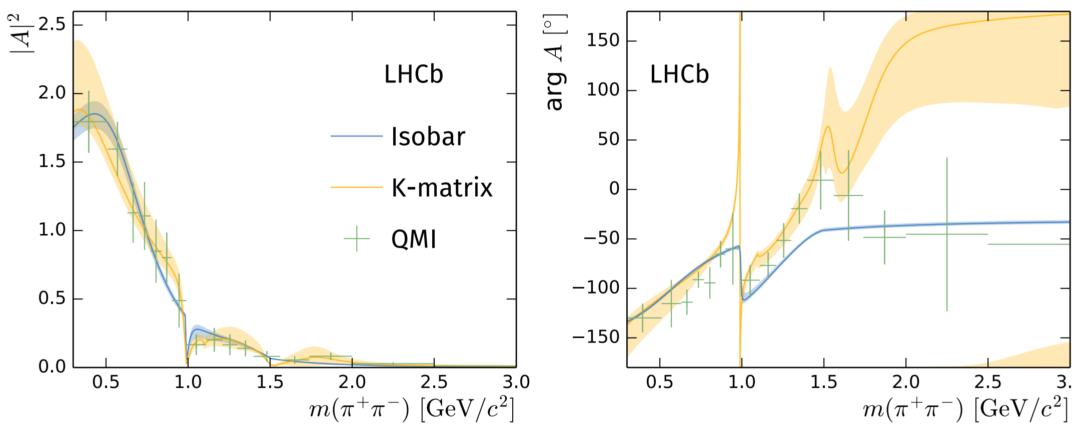

Figure 2: Comparison of the *CP* averaged (left) absolute-magnitude squared and (right) phase of the three S-wave models.

The projection of the three S-wave models in terms of the absolute magnitude squared and phase of the amplitudes is shown in Figure 2, and it can be seen that they agree reasonably well, particularly at low $\pi^+\pi^-$ mass. All capture the opening of the $K\bar{K}$ channel, and the K-matrix and QMI approaches both agree fairly well up to the $f_0(1500)$ resonance, where they diverge somewhat.

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Particularly at low $\pi^+\pi^-$ mass, a small but measurable *CP* asymmetry in the S-wave can be seen, with a significance of 10σ. More striking is the considerable size of the *CP* violation observed in the phase differences between the $\rho(770)^0$ and S-wave contributions, in B^+ and B^+ decays, around the $\rho(770)^0$ mass (Figure 3, right). This manifests itself as an almost total cancellation when integrating over $m(\pi^+\pi^-)$ or the cosine of the helicity angle (Figure 3, left), indicating that the *CP* violation in this region is characteristic of being exclusively present in the interference terms of the *S*- and *P*-wave amplitudes, and generated by the strong phase evolution of the $\rho(770)^0$ resonance. This is the first time such an effect has been observed, with a significance in excess of 25σ. No evidence is seen for *CP* violation in $\rho-\omega$ mixing, or in the quasi-two-body $B^+ \to \rho(770)^0\pi^+$ decay.

Significant *CP* violation is observed in the $B^+ \to f_2(1270)\pi^+$ decay (Figure 1), with a quasi-two-body *CP* asymmetry of around 40%, and significance in excess of 10σ, both of which are consistent between the S-wave approaches. In this region, there is some mismodelling around the $f_2(1270)$ peak, which noticeably causes the peak of the $f_2(1270)$ distribution to shift compared to the world-average mass value. This effect is consistent with either an additional broad spin-2 resonance, where the effect would be due due to interference, or with a real discrepancy between the world-average and the apparent mass in this decay. Both of these considerations result in a systematic uncertainty assigned to the subsequent numerical results, neither of which affect the significance of the observed *CP* violation, which is well modelled.

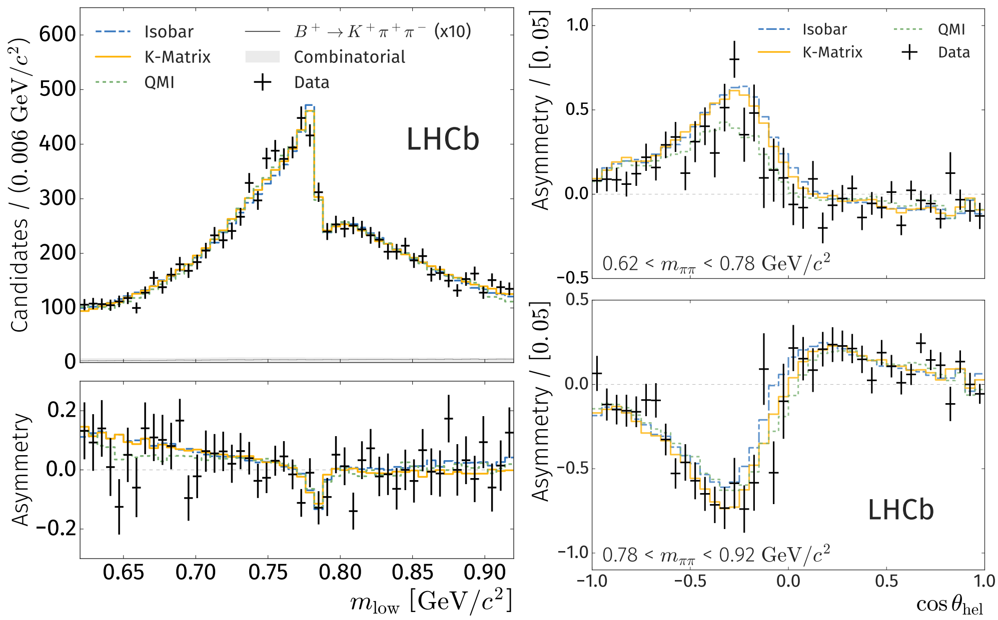

Figure 3: Projections of data and fit results (top left) on the low $\pi^+\pi^-$ mass combination in the low $\rho(770)^0$ region, with (bottom left) the corresponding *CP* asymmetry. Cosine of the helicity angle below (top right) and above (bottom right) the $\rho(770)^0$ pole mass.

These measurements confirm several long-held assumptions as to how the interplay between strong and weak phases in multibody non-leptonic decays gives rise to in observable *CP* violation [7]. Furthermore, these form valuable input into models of QCD in the low-energy regime [8], and will inform future measurements of the CKM angles using related multibody decays.

3. Search for *P* and *CP* violation in $\Lambda_b^0 \to p^+\pi^-\pi^+\pi^-$ decays

A previous analysis on 3fb^{-1} of Run 1 LHCb data found evidence for *CP* violation in the $\Lambda_b^0 \to p^+\pi^-\pi^+\pi^-$ decay with a significance of 3.3σ, with a method using binned triple-product asymmetries [9]. An update of this measurement is performed with 6.6fb^{-1} of 2011–2017 data with a re-optimised triple-product binning scheme to account for potential intermediate resonances, and with a second test using a complementary local kernel 'energy test' method.

The scalar triple products are defined as $C_{\hat{T}} \equiv \vec{p}_{p^+} \cdot (\vec{p}_{\pi^-_{\text{fast}}} \times \vec{p}_{\pi^+})$ and $\overline{C}_{\hat{T}} \equiv \vec{p}_{\overline{p}^-} \cdot (\vec{p}_{\pi^+_{\text{fast}}} \times \vec{p}_{\pi^-})$, for Λ_b^0 and $\overline{\Lambda}_b^0$ decays, respectively. Asymmetries of these triple products can be constructed as

$$A_{\hat{T}} = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)} \tag{3.1}$$

and

$$\overline{A}_{\hat{T}} = \frac{\overline{N}(-\overline{C}_{\hat{T}} > 0) - \overline{N}(-\overline{C}_{\hat{T}} < 0)}{\overline{N}(-\overline{C}_{\hat{T}} > 0) + \overline{N}(-\overline{C}_{\hat{T}} < 0)}, \tag{3.2}$$

where N and $\overline{N}$ are yields of Λ_b^0 and $\overline{\Lambda}_b^0$ decays, respectively. Quantities can then be constructed that are *P* or *CP* conjugate, depending on the sign of $C_{\hat{T}}$ and $\overline{C}_{\hat{T}}$, and comparisons between these can be made to test for *P* and *CP* violation. The *P* and *CP* violating T-odd asymmetries are then defined as

$$a_{CP}^{\hat{T}-\text{odd}} = \frac{1}{2}(A_{\hat{T}} - \overline{A}_{\hat{T}}) \tag{3.3}$$

and

$$a_{P}^{\hat{T}-\text{odd}} = \frac{1}{2}(A_{\hat{T}} + \overline{A}_{\hat{T}}). \tag{3.4}$$

In addition to being calculated over the full phase-space, these quantities are also evaluated in phase-space bins, optimised using amplitude models that contain intermediate a_1, Δ^{++}, and N^* resonances.

The energy test involves calculating a test statistic

$$T \equiv \frac{1}{2n(n-1)}\sum_{i\neq j}^{n}\psi_{ij} + \frac{1}{2\bar{n}(\bar{n}-1)}\sum_{i\neq j}^{\bar{n}}\psi_{ij} - \frac{1}{n\bar{n}}\sum_{i=1}^{n}\sum_{j=1}^{\bar{n}}\psi_{ij}, \tag{3.5}$$

over two samples, n and $\bar{n}$, with a Gaussian kernel $\psi_{ij} = e^{-d_{ij}^2/2\delta^2}$ incorporating the distance between points i and j, with a tunable distance scale δ. Three tests are performed using this statistic, with distance scales $\delta = 1.6$, 2.7, and 13 GeV^2. Similarly to the triple-product asymmetry, these are evaluated in different regions of the phase-space, depending on the sign of $C_{\hat{T}}$ and $\overline{C}_{\hat{T}}$, probing *P* and *CP* violation.

In the Λ_b^0 candidate selection, a sample of $\Lambda_b^0 \to \Lambda_c^+(p^+K^+\pi^-)\pi^-$ is selected to act as a control sample, and $a_{CP}^{\hat{T}-\text{odd}}$ calculated in this region is consistent with zero, as expected. Furthermore, systematic uncertainties associated with detector and reconstruction effects are also calculated using this control sample. The energy test method is insensitive to global production or detection asymmetries, such as from a production asymmetry between Λ_b^0 and $\overline{\Lambda}_b^0$ decays, but is sensitive to local asymmetries. No such asymmetries are identified using the control sample. Additionally, no indications of *CP* violation are present in any background samples.

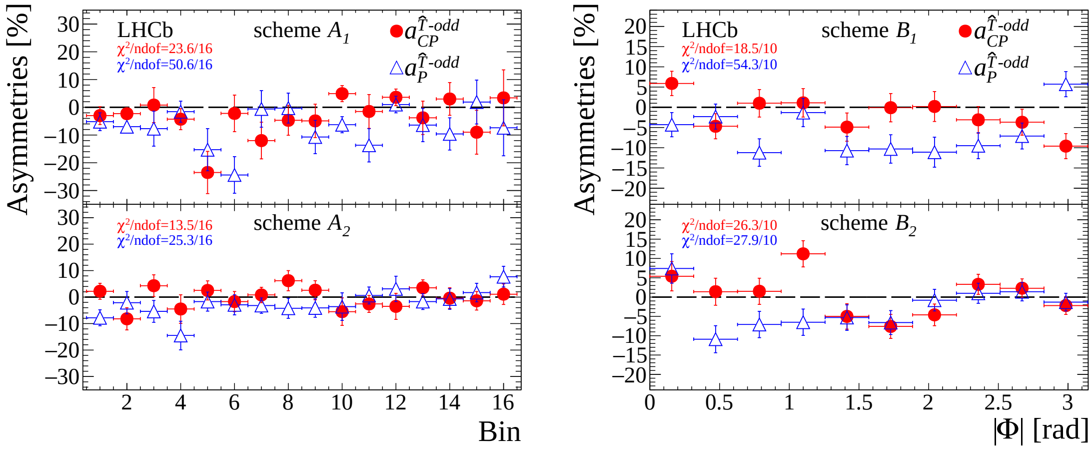

Figure 4: Triple-product P and CP-violating asymmetries in the four different optimised phase-space binning schemes, where the error bars represent the sum in quadrature of the statistical and systematic uncertainties. These uncertainties are also both taken into account for the χ^2 calculation with respect to the null hypothesis of no symmetry violation.

The value of the P-violating triple-product asymmetry evaluated across the full phase-space, $a_P^{\hat{T}-\text{odd}} = (-4.0 \pm 0.7 \pm 0.2)\%$, is measured with a significance of 5.5 Gaussian standard deviations from zero, evaluated using a profile likelihood-ratio test. This indicates P violation in the $\Lambda_b^0 \to p^+\pi^-\pi^+\pi^-$ decay. Inspecting the values of the asymmetry in bins of phase space, indicated in Figure 4, significant deviations from the P-symmetry hypothesis can be seen particularly in the region associated with the $\Lambda_b^0 \to p^+a_1(1260)^-$ decay. All values for $a_{CP}^{\hat{T}-\text{odd}}$ are consistent with zero.

Results for the energy test are given in Table 1, where it can be seen that all tests are consistent with CP conservation within 3σ. For the P-even test, a new test statistic is constructed from the product of the three distance-scale p-values, and the resulting p-value is 4.6×10^{-3}. The two smallest distance-scale measurements for P conservation are inconsistent with the P-conservation hypothesis.

Table 1: Energy-test p-values for the different test configurations.

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}

4. Summary

Multibody charmless b-hadron decays are an ideal place to study CP violating phenomena, as intermediate resonance structures can generate the strong phases required for observable CP violation in decay. Here we report the observation of CP violation in the quasi-two-body $B^+ \to f_2(1270)\pi^+$ decay with a significance in excess of 10σ, in the $B^+ \to \pi^+\pi^+\pi^-$ S-wave with a significance again in excess of 10σ, and in the interference between the $\rho(770)^0$ and S-wave in excess of 25σ - the first observation of *CP* violation in the interference between two resonant structures. Additionally, whilst no evidence for *CP* violation is observed in the $\Lambda_b^0 \to p^+\pi^-\pi^+\pi^-$ decay, the first observation of *P* violation in the decay of a *b*-baryon is obtained, with significance in excess of 5σ.

These measurements give insight into how the fundamental *CP*-violating phase in the Standard Model gives rise to observable *CP* violation in practice, and indicate that an understanding of low-energy QCD is essential for further investigations. Furthermore, they motivate further study into the underlying processes that govern *CP* violation at low $\pi^+\pi^-$ invariant mass.

References

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