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CP violation in B decays

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The recent LHCb results related to the charmless B decays are reported, including an update of searches for CP violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays and observation of several sources of CP violation in $B^+ \to \pi^+\pi^+\pi^-$ decays.

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1. Introduction

CP violation (CPV) has been observed in the K, B and D meson decays, and experimental measurements are well consistent with Standard Model prediction. However, it is still too small to explain the absence of antimatter in the universe. More searches for CPV are needed in different systems.

In the three-body or multibody decays, strong phase variation across the phase space, due to rich hadronic structures, allows to search for enhancement of CPV. $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ and $B^+ \to \pi^+\pi^+\pi^-$ decays, governed mainly by tree and loop diagrams, are expected to be of similar magnitude, such that large CP-violating effects are possible.

2. Search for CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays

An evidence for CPV with a significance of 3.3σ in the $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays, with a method using triple product asymmetries (TPA), has been found on 3fb^{-1} of LHCb data [1]. An update, with re-optimised TPA method and unbinned energy test method, is performed with 6.6fb^{-1} data [2].

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 $\overline{\Lambda}{}_b^0$, respectively. The following asymmetries may then be defined as

$$A_{\hat{T}} = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}, \quad \overline{A}_{\hat{T}} = \frac{\overline{N}(-\overline{C}_{\hat{T}} > 0) - \overline{N}(-\overline{C}_{\hat{T}} < 0)}{\overline{N}(-\overline{C}_{\hat{T}} > 0) + \overline{N}(-\overline{C}_{\hat{T}} < 0)}, \tag{1}$$

where N and $\overline{N}$ are the yields of Λ_b^0 and $\overline{\Lambda}{}_b^0$ decays, respectively. These asymmetries, changed sign under P or $\hat{T}$ transformations, are P-odd and $\hat{T}$-odd. The CP-and P-violating observables are defined as

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

The observables, $A_{\hat{T}}$, $\overline{A}_{\hat{T}}$, $a_{CP}^{\hat{T}\text{-odd}}$ and $a_P^{\hat{T}\text{-odd}}$ are ,by construction, largely insensitive to particle-antiparticle production asymmetries and detector-induced charge asymmetries [3, 4].

The measured asymmetries integrated over phase space are $a_{CP}^{\hat{T}\text{-odd}} = (-0.7 \pm 0.7 \pm 0.2)\%$ and $a_P^{\hat{T}\text{-odd}} = (-4.0 \pm 0.7 \pm 0.2)\%$. There is no deviation from CP-conserving hypothesis, while a significance of 5.5σ deviation from P-conserving hypothesis. With an approximate amplitude analysis on $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays, the improved binning scheme consists in dividing the data sample to explore $a_1(1260)^-$ and N^{*+} resonances and the distribution of the polar and azimuthal angles of the proton (Δ^{++}) in the Δ^{++} (N^{*+}) rest frame. The measured asymmetries in bins of phase space are shown in Figure 1. There are significant deviations from P-conserving hypothesis in Scheme A_1 and B_1, which corresponding to the $\Lambda_b^0 \to pa_1(1260)^-$ decays. The evidence of CP violation previously observed [1] is not confirmed.

The energy test, sensitive to local differences bwteen two samples which might arise from CPV, has superior discriminating power than tranditional χ^2 tests. The energy test is performed by calculating a test statistic

$$T \equiv \frac{1}{2n(n-1)} \sum_{i \neq j}^{n} \psi_{ij} + \frac{1}{2\overline{n}(\overline{n}-1)} \sum_{i \neq j}^{\overline{n}} \psi_{ij} - \frac{1}{n\overline{n}} \sum_{i=1}^{n} \sum_{j=1}^{\overline{n}} \psi_{ij} \tag{3}$$

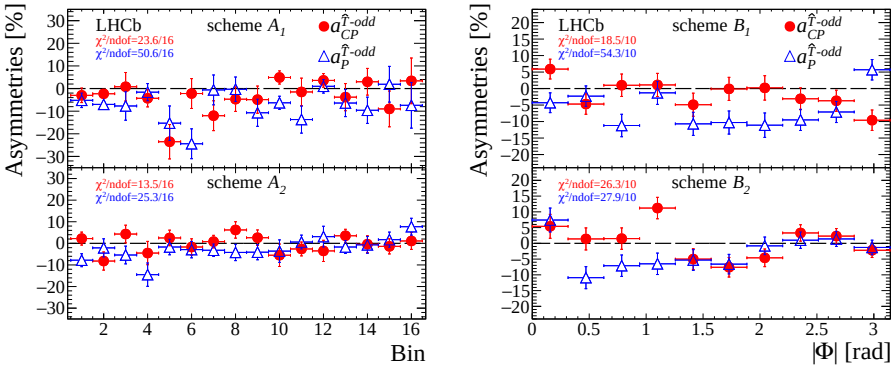

Figure 1: Measured asymmetries in the four different optimised binning schemes. The error bars represent the sum in quadrature of the statistical and systematic uncertainties. The χ^2 per ndof is calculated with respect to the null hypothesis and includes statistical and systematic uncertainties.

in two samples, n and $\overline{n}$, with a weight function $\psi_{ij} = e^{-d_{ij}^2/2\delta^2}$ where d_{ij} is Euclidean distance in phase space and the tunable parameter δ determines the distance scale.

Results for different configurations of the energy test are summarized in Table1. All tests are consistent with CP conservation within 3σ, while larger than 5σ deviation from P-conserving hypothesis is confirmed.

Table 1: The p-values from the energy test for different distance scales and 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}

3. Search for CPV in $B^+ \to \pi^+\pi^-\pi^+$ decays

Previouse LHCb model-independent analysis of $B^+ \to \pi^+\pi^-\pi^+$ decays observed large asymmetries localised in regions of Dalitz plot, which may arise from $\rho^0 - \omega(782)$ mixing, the interference between the $\rho(770)^0$ resonance and the broad S-wave contribution, or $KK \leftrightarrow \pi\pi$ rescattering [5]. An amplitude analysis of $B^+ \to \pi^+\pi^-\pi^+$ decays on 3fb^{-1} of LHCb data is perfomed, which could find the sources of these large asymmetries [6, 7].

Given the fact that many broad overlapping resonances and decay-channel thresholds are particularly challenging to model, the dominant S-wave amplitude is described using three complementary approaches. The isobar approach comprises the coherent sum of σ pole together with a $KK \leftrightarrow \pi\pi$ rescattering term. The K-matrix approach takes parameters obtained from scattering data. The "quasi-model-independent" (QMI) approach divides dipion mass spectrum into bins with independent magnitudes and phases that are free in the fit.

From amplitude fit, the dominant contributions are from $\rho(770)^0$ and S-wave components. There are large CPV integrated over phase space from S-wave components and $f_2(1270)$ component,

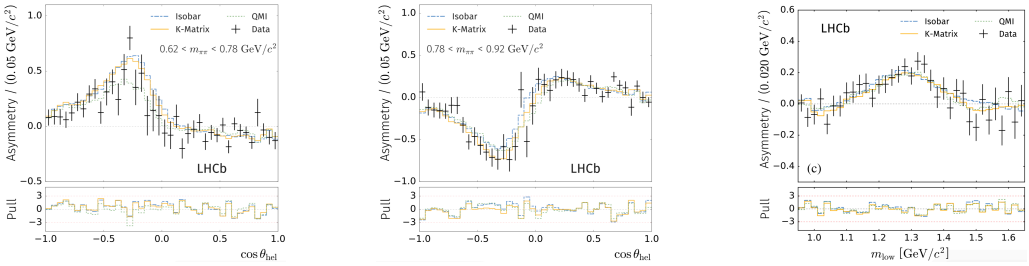

Figure 2: Asymmetry projections in the region (left) below or (middle) above $\rho(770)^0$ resonance and in (right) $f_2(1270)$ resonance. The pull distribution is shown below each fit projection.

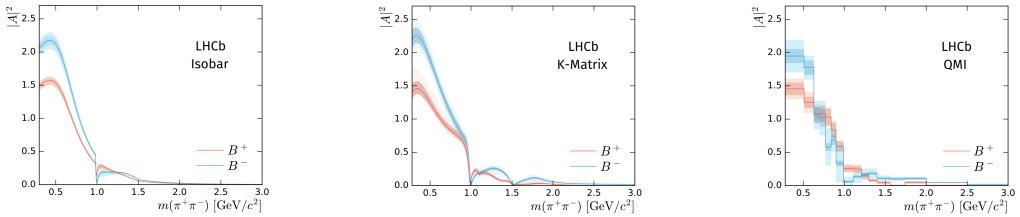

Figure 3: The (left) isobar, (middle) K-matrix and (right) QMI S-wave results show the magnitude squared. Red curves indicate B^+ while blue curves represent B^- decays, with the statistical and total uncertainties bounded by the dark and light bands.

but no asymmetries for $\rho(770)^0$ component. Results with three approaches are in good agreement. An additional source of CPV, associated principally with the interference between S and P waves, is observed in the $\cos\theta_{\rm hel}$ distributions above and below the $\rho(770)^0$ peak, as shown in Figure 2. A very large quasi-two-body CPV of around 40% in $f_2(1270)$ is observed as shown in Figure 2, which is the first observation of CPV in tensor process. The region below $\rho(770)^0$ is dominated by the S-wave component, where large CP asymmetries are also observed in three approaches, as shown in Figure 3. At low dipion mass region, S-wave description by three approaches agree, and all models have the similar behavior around 1 GeV/c^2.

4. Summary

In summary, multibody charmless B decays are of particular interest to search for CPV, as rich phase space structures associated with different strong phases could improve the sensitivity to CP-violating effects. With an updated analysis of $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays, there is no evidence for CPV confirmed while a significance of 5.5σ deviation from P-conserving hypothesis. With amplitude analysis of $B^+ \to \pi^+\pi^+\pi^-$ decays, a new CPV pattern in $\rho(770)^0$ process is established, a large CPV is observed in tensor $f_2(1270)$ process for the first time, and significant CPV is found in $\pi^+\pi^-$ S wave at low invariant mass.

5. Acknowledgement

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