

Searches for CP violation in multibody D decays

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Multibody charm decays are a good place to search for *CP* violation. The results of the LHCb collaboration in the decays of $D^+ \rightarrow \pi^- \pi^+ \pi^+$, $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ and $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ are presented.

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1. Introduction

CP violation (CPV) is an interference effect, in which at least two amplitudes with different strong and weak phases are required. In the standard model, CPV in charm decays is very suppressed [1, 2]. Multibody charm decays are a good place to search for CPV , due to their rich resonant structures with interfering amplitudes. In this way, CPV can also be probed in different phase space regions.

In the analyses performed by the LHCb collaboration, model-independent methods are used to search for CPV in 3- and 4-body decays. The measurements in the self-tagged decays of $D^+ \rightarrow \pi^- \pi^+ \pi^+$ [3] and D^* -tagged promptly-produced decays of $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ and $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ [4] use the Miranda method. The measurements in decays of $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ [5] selected from semileptonic B decays use the T -odd correlations method. Charge conjugated states are implicit, unless otherwise stated.

2. Miranda method

The Miranda method [6] is based on a direct comparison between the D and \bar{D} phase space. The multi-body phase space is divided into bins. For each bin, a significance is defined from the difference in bin occupation between CP conjugate decays:

$$S_{CP}^i \equiv \frac{N_i(D) - \alpha N_i(\bar{D})}{\sqrt{\alpha(\sigma_i^2(D) + \sigma_i^2(\bar{D}))}}, \quad \alpha \equiv \frac{\sum_i N_i(D)}{\sum_i N_i(\bar{D})}. \quad (2.1)$$

The number of signal events in each bin is given by N_i with an uncertainty σ_i . The parameter α removes global production and detection asymmetries.

In absence of CPV , S_{CP} is expected to be a Gaussian distribution with a mean of zero and a width of one. A χ^2 statistic with $N_{bins} - 1$ degree of freedom is constructed by the sum of squared S_{CP}^i ,

$$\chi^2 = \sum_i (S_{CP}^i)^2, \quad (2.2)$$

from which a p -value is calculated. The p -value gives the probability of getting a χ^2 as extreme as the one measured, assuming the no CPV hypothesis is true.

Using 1 fb^{-1} data sample recorded at $\sqrt{s} = 7$ TeV in 2011, about 3.1 million $D^+ \rightarrow \pi^- \pi^+ \pi^+$ candidate decays with a purity of 82% are reconstructed. Adaptive and uniform binning schemes in the phase space are used for different binning sizes. The χ^2 test is performed for the adaptive binning scheme, using 20, 30, 40, 49 and 100 bins. All p -values are above 50%, consistent with no CPV hypothesis. The χ^2 test is also performed for the uniform binning scheme, using 20, 32, 52 and 98 bins. All p -values are above 90%, consistent with no CPV hypothesis. The results of the adaptive binning schemes with 49 and 100 bins are shown in Fig. 1.

Using the same 1 fb^{-1} data sample, about 5.7×10^4 $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ and 3.3×10^5 $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ decays are reconstructed from $D^{*+} \rightarrow D^0 \pi^+$ decays. Signal yields are extracted from a two-dimensional maximum likelihood fit in $m(hhhh)$ and $\Delta m = m(\pi, hhhh) - m(hhhh)$, where h represents a pion or a kaon candidate. Projection plots from fit are shown in Fig. 2. The phase space is more complicated than the one in 3-body decays, and can be described with five invariant

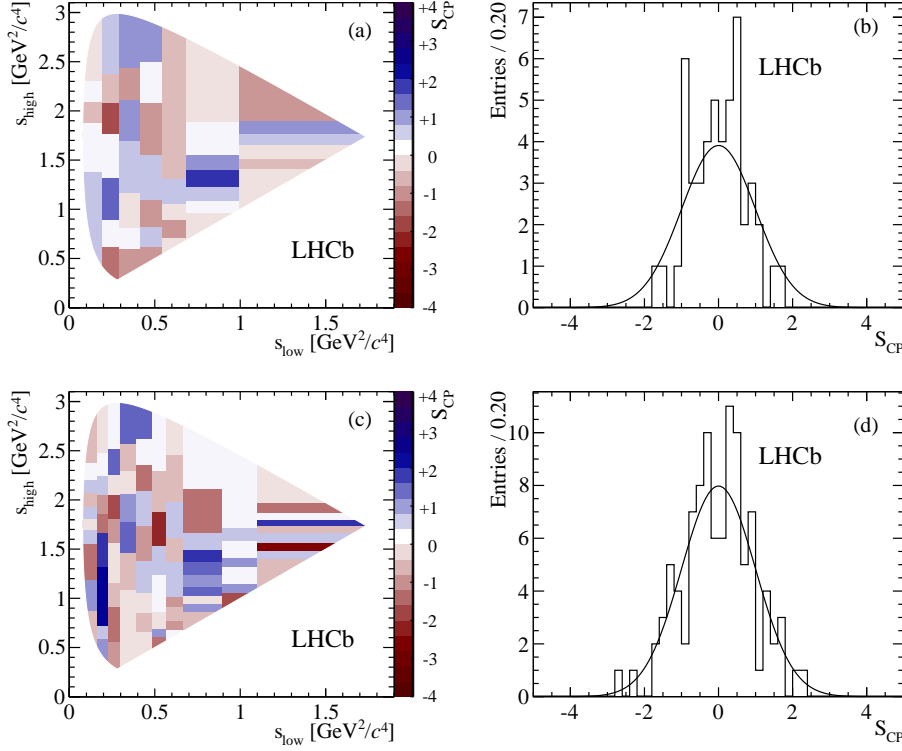


Figure 1: Distributions of S_{CP}^i across the D^+ Dalitz plane, with the adaptive binning scheme of uniform population for the total $D^+ \rightarrow \pi^- \pi^+ \pi^+$ data sample with (a) 49 and (c) 100 bins. The corresponding one-dimensional S_{CP}^i distributions (b) and (d) are shown with a standard normal Gaussian function superimposed (solid line).

mass-squared combinations of final particles. An adaptive binning algorithm is devised to partition the phase space into 5-dimensional hypercubes. The χ^2 test is performed using 16, 32, 64 and 256 bins. All results are consistent with no CPV hypothesis. The results of 32 and 128 bins are shown in Fig. 3.

3. T -odd correlations method

T -odd correlations are defined as the triple products of final states particle momenta in the D^0 center-of-mass frame, $C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$ for D^0 and $\bar{C}_T \equiv \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})$ for \bar{D}^0 decays. Then we can build two T -odd observables:

$$A_T \equiv \frac{\Gamma_{D^0}(C_T > 0) - \Gamma_{D^0}(C_T < 0)}{\Gamma_{D^0}(C_T > 0) + \Gamma_{D^0}(C_T < 0)}, \quad \bar{A}_T \equiv \frac{\Gamma_{\bar{D}^0}(-\bar{C}_T > 0) - \Gamma_{\bar{D}^0}(-\bar{C}_T < 0)}{\Gamma_{\bar{D}^0}(-\bar{C}_T > 0) + \Gamma_{\bar{D}^0}(-\bar{C}_T < 0)}, \quad (3.1)$$

where Γ_{D^0} ($\Gamma_{\bar{D}^0}$) is the partial decay width of D^0 (\bar{D}^0) decays to $K^+ K^- \pi^+ \pi^-$ in the indicated C_T (\bar{C}_T) range. However, final state interaction (FSI) could introduce asymmetries [7, 8]. A true CP -violating observable is defined as:

$$a_{CP}^{T\text{-odd}} \equiv \frac{1}{2}(A_T - \bar{A}_T), \quad (3.2)$$

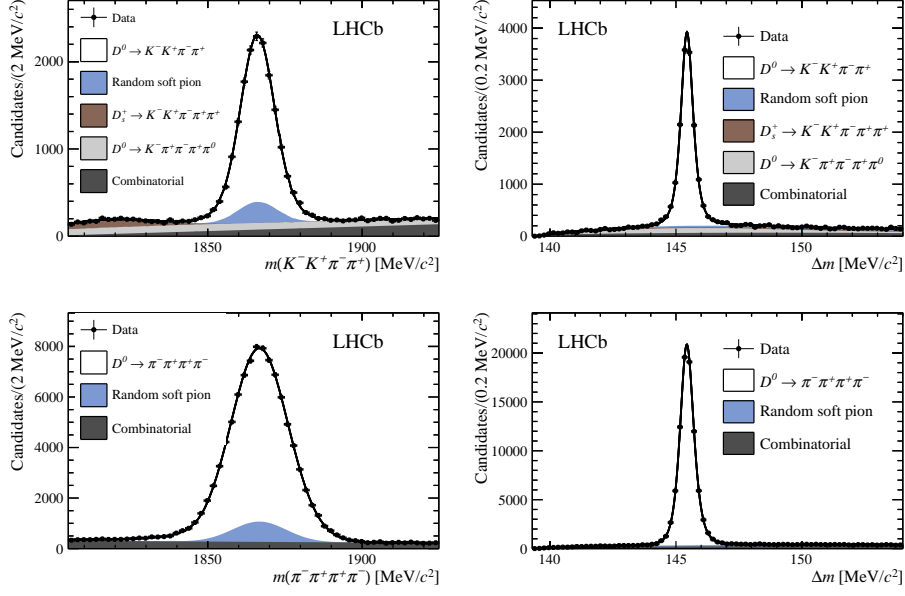


Figure 2: Distributions of (a), (c) $m(hhhh)$ and (b), (d) $\Delta(m)$ for (a), (b) $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$, and (c), (d) $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ candidates. Different backgrounds are described in [4].

where FSI effects cancel out in the difference. The physics observables A_T , \bar{A}_T and $a_{CP}^{T\text{-odd}}$ are by construction insensitive to the production asymmetry of D^0 and \bar{D}^0 , detector- and reconstruction-induced charge asymmetries. In contrast to the asymmetry between the phase-space integrated rates in a $D^0 \rightarrow V_1 V_2$ decay (where V_i indicates a vector meson), $a_{CP}^{T\text{-odd}}$ is sensitive to CP violation in interference between even- and odd- partial waves of the $V_1 V_2$ system [10]. Previous measurements of $a_{CP}^{T\text{-odd}}$ are compatible with no CPV : FOCUS measured $a_{CP}^{T\text{-odd}} = (1.0 \pm 5.7 \pm 3.7)\%$ [11], and BaBar measured $a_{CP}^{T\text{-odd}} = (0.10 \pm 0.51 \pm 0.44)\%$ [12].

Using 1 fb^{-1} data sample recorded at $\sqrt{s} = 7 \text{ TeV}$ in 2011, and 2 fb^{-1} data sample recorded at $\sqrt{s} = 8 \text{ TeV}$ in 2012, about 1.7×10^5 $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ decays are reconstructed from $B \rightarrow D^0 \mu^- X$ decays (where X indicates any system composed of charged and neutral particles). The selected data sample is split into four subsamples according to the flavor of the D^0 , which is determined by the charge of the muon candidate, and the sign of C_T (\bar{C}_T). A simultaneous maximum likelihood fit to the $m(K^+ K^- \pi^+ \pi^-)$ distribution of the four subsamples is used to determine the signal number and the asymmetries A_T and \bar{A}_T . The fit model consists of two Gaussian functions with common mean for the signal and an exponential function for the background. The two asymmetries A_T and \bar{A}_T are included in the fit model as

$$\begin{aligned}
 N_{D^0, C_T > 0} &= \frac{1}{2} N_{D^0} (1 + A_T), \\
 N_{D^0, C_T < 0} &= \frac{1}{2} N_{D^0} (1 - A_T), \\
 N_{\bar{D}^0, -\bar{C}_T > 0} &= \frac{1}{2} N_{\bar{D}^0} (1 + \bar{A}_T), \\
 N_{\bar{D}^0, -\bar{C}_T < 0} &= \frac{1}{2} N_{\bar{D}^0} (1 - \bar{A}_T).
 \end{aligned} \tag{3.3}$$

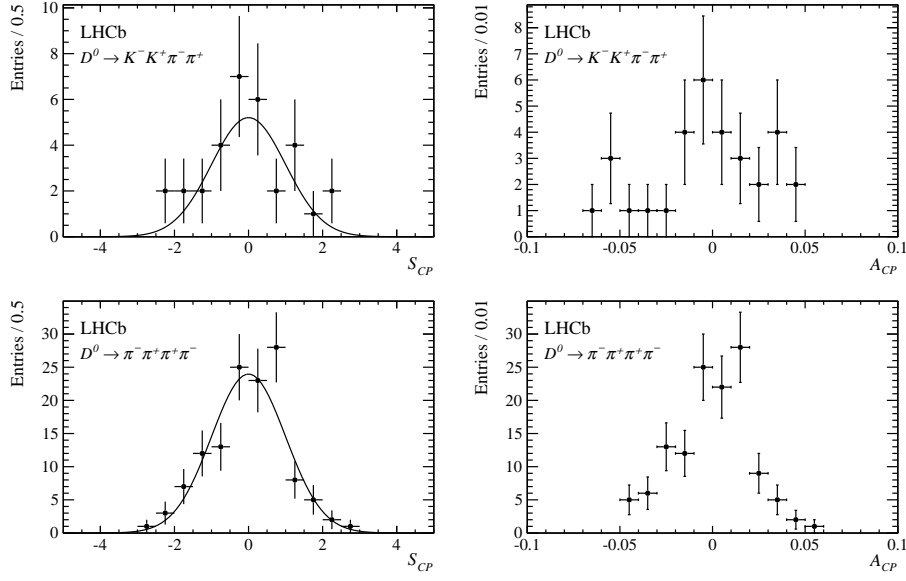


Figure 3: Distributions of (a), (c) S_{CP} and (b), (d) local CP asymmetry per bin for (a), (b) $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ decays with 32 bins, for (c), (d) $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ decays with 128 bins.

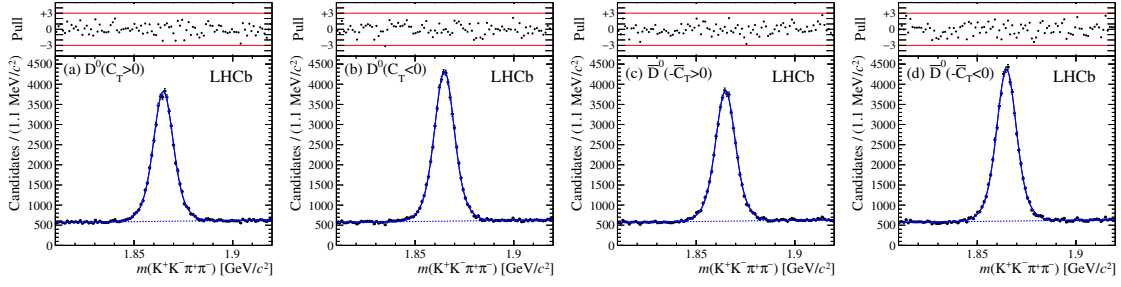


Figure 4: Distributions of the $K^+ K^- \pi^+ \pi^-$ invariant mass in the four samples defined by D^0 (\bar{D}^0) flavour and the sign of C_T (\bar{C}_T). The results of the fit are overlaid as a solid line, and a dashed line is used for representing the background. The normalised residuals (pulls) of the difference between the fit results and the data points, divided by their uncertainties, are shown on top of each distribution.

The CP -violating asymmetry $a_{CP}^{T\text{-odd}}$ is then calculated from A_T and \bar{A}_T . The results of the fit are shown in Fig. 4.

Three different approaches have been followed to search for CPV : the phase space integrated measurement, measurements in different regions of phase space, and measurements as a function of the D^0 decay time. By fitting the full data sample, the results of the first approach are:

$$\begin{aligned} A_T &= (-7.18 \pm 0.41(\text{stat}) \pm 0.13(\text{syst})\%, \\ \bar{A}_T &= (-7.55 \pm 0.41(\text{stat}) \pm 0.12(\text{syst})\%, \\ a_{CP}^{T\text{-odd}} &= (0.18 \pm 0.29(\text{stat}) \pm 0.04(\text{syst})\%, \end{aligned}$$

The relatively large asymmetries observed in A_T and \bar{A}_T are due to FSI effects [7, 8], which are difficult to predict [9]. $a_{CP}^{T\text{-odd}}$ is consistent with no CPV hypothesis.

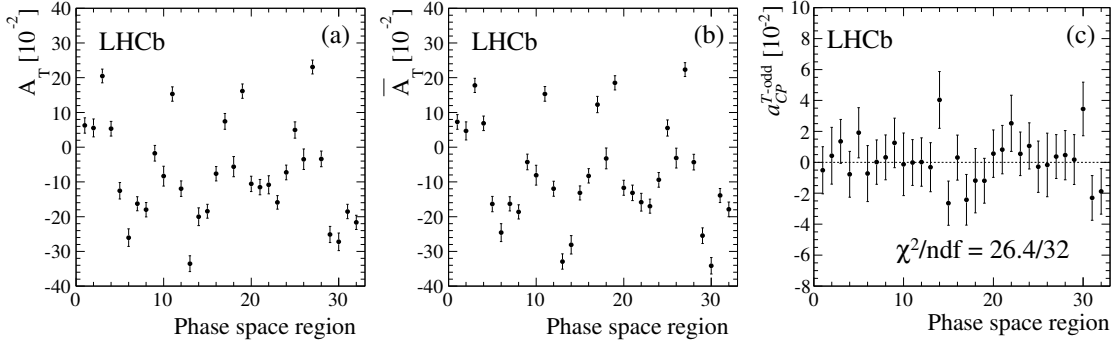


Figure 5: Distributions of the asymmetry parameters (a) A_T , (b) \bar{A}_T and (c) $a_{CP}^{T\text{-odd}}$ in 32 regions of the phase space.

The phase space is divided into 32 regions by choosing the Cabibbo-Maksimowicz [13] variables as basis for the binning scheme. The compatibility with the CP conservation hypothesis is tested by means of a χ^2 test,

$$\chi^2 = R^T V^{-1} R, \quad (3.4)$$

where R is the array of $a_{CP}^{T\text{-odd}}$ measurements, and V^{-1} is the inverse of the covariance matrix V , defined as the sum of the statistical and systematic covariance matrices. The distributions of the asymmetries are shown in Fig. 5. The distribution of $a_{CP}^{T\text{-odd}}$ results is consistent with no CPV hypothesis with a p -value of 74%. The A_T and \bar{A}_T are significantly different among the different regions, which can be explained by the rich resonant structure of the hadronic four-body decay [14] that produces different FSI effects over the phase space. Four alternative binning schemes, one with 8 regions and three with 16 regions, are also tested. All p -value are above 20%, consistent with no CPV hypothesis.

The D^0 decay time is divided into 4 regions. The asymmetry distributions are shown in Fig. 6. The $a_{CP}^{T\text{-odd}}$ results are consistent with no CPV hypothesis with a p -value of 86%. The A_T and \bar{A}_T do not show any significant dependence as a function of the decay time, and are compatible with constant functions with p -values above 30%. Consistent results are obtained when using 3 or 5 regions of D^0 decay time in agreement with no CPV hypothesis with p -values above 80%.

4. Summary

Searches for CPV in 3- and 4-body D decays are performed by the LHCb experiment using data collected from $p-p$ collisions at $\sqrt{s} = 7$ TeV (1 fb^{-1}) and 8 TeV (2 fb^{-1}). From the 1 fb^{-1} dataset, a search for CPV using the Miranda method is performed in $D^+ \rightarrow \pi^- \pi^+ \pi^+$, prompt $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ and $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ decays. A search for CPV using the T -odd method is performed in $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ decays, with the whole 3 fb^{-1} dataset, using semileptonic tagged decays, in which three approaches are exploited: a measurement integrated over the phase space, measurements in different regions of the phase space, and measurements as a function of the D^0 decay time. These results are consistent with no CPV hypothesis.

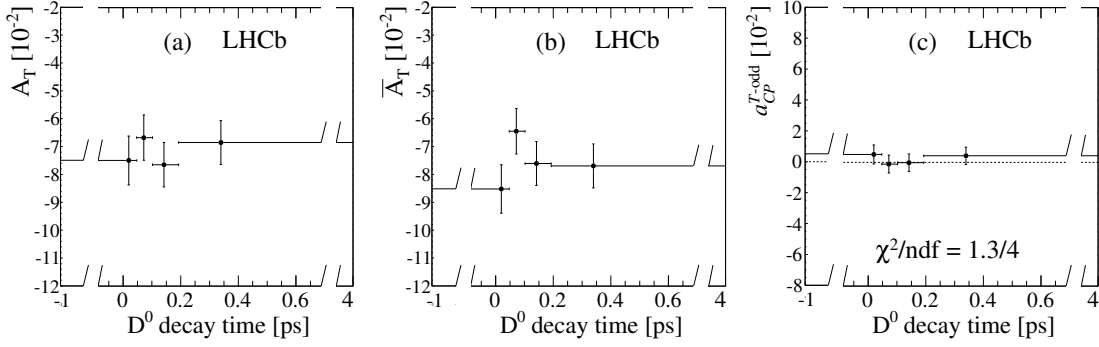


Figure 6: Distributions of the asymmetry parameters (a) A_T , (b) \bar{A}_T and (c) $a_{CP}^{T\text{-odd}}$ as a function of the D^0 decay time. For $a_{CP}^{T\text{-odd}}$, the value of the χ^2/ndf for the CP conservation hypothesis, represented by a dashed line, is also quoted. The scale is broken for the first and last bin.

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