

Studies of CP violation and mixing in charm decays at LHCb

A. CONTU

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Summary. — LHCb has collected the world’s largest sample of charmed hadrons. This sample is used to search for direct and indirect CP violation in charm, and to measure D^0 mixing parameters. New and updated measurements are presented, with complementary time-dependent and time-integrated analyses of D^0 meson decays.

1. – Introduction

The search for CP violation (CPV) in decays of charmed hadrons is a unique probe of New Physics (NP) beyond the Standard Model, complementary to searches in the down-type quark sector where these effects are relatively large. The CPV in charm is expected to be small within the Standard Model (SM) [1,2], although recent calculations show that CPV at the level of few 10^{-3} may be possible [3-5]. The observation of sizeable CPV would provide strong indication for NP. The large charm yields at the LHC and the excellent capabilities of the LHCb detector allow for high precision measurements of mixing and CPV observables in the charm sector, which are a crucial part of the LHCb physics programme, particularly in the upgrade.

In this paper, the recent LHCb results on the measurement of A_Γ in $D^0(\bar{D}^0) \rightarrow hh$ decays and on the search for direct CPV in $D^0 \rightarrow \pi^+\pi^-\pi^0$ decays are presented.

2. – Measurement of A_Γ in $D^0 \rightarrow hh$ decays

The neutral D meson system is a powerful tool to search both for direct and indirect CPV . This meson is produced as one of the two flavour eigenstates, D^0 and \bar{D}^0 , which then propagate as mass eigenstates D_1 and D_2 . The two sets do not coincide and are related by the transformations $|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle$ and $|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle$. Mixing can occur if there is a mass difference, $\Delta M = M_1 - M_2$, or a width difference, $\Delta\Gamma = \Gamma_1 - \Gamma_2$, between the D_1 and D_2 states and is normally quantified in terms of “mixing parameters” defined as $x = \Delta M/\Gamma$ and $y = \Delta\Gamma/\Gamma$. Indirect CPV can occur in *mixing* if $|q/p| \neq 1$, *i.e.* if the rate at which a D^0 oscillates to a \bar{D}^0 is different from

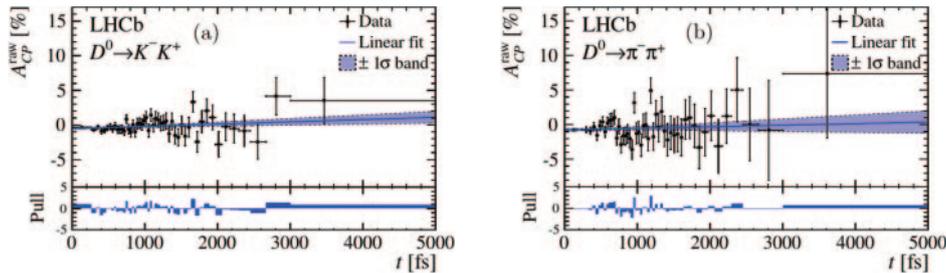


Fig. 1. – Yield asymmetry for $D^0(\bar{D}^0 \rightarrow K^+ K^-)$ and $D^0(\bar{D}^0 \rightarrow \pi^+ \pi^-)$.

the rate of the opposite process, or in *interference between mixing and decay* if the phase $\phi = \arg\left(\frac{q\bar{A}_f}{pA_f}\right)$ is different from zero, where \bar{A}_f and A_f are the amplitude describing the decay to a common final state f for the \bar{D}^0 and the D^0 respectively. It is noted that indirect CPV requires non-zero mixing and although this is well established, a precision measurement of x and y will be crucial in the future to improve the sensitivity on CPV observables.

A_Γ , defined as the asymmetry in the effective lifetime of the flavour eigenstates decaying into a CP eigenstate such as $K^+ K^-$ or $\pi^+ \pi^-$, which appears as an almost clean measurement of indirect CPV

$$A_\Gamma = \frac{\tau_{\bar{D}^0}^{eff} - \tau_{D^0}^{eff}}{\tau_{\bar{D}^0}^{eff} + \tau_{D^0}^{eff}} \approx \left(\left| \frac{q}{p} \right| - \left| \frac{p}{q} \right| \right) y \cos \phi - \left(\left| \frac{q}{p} \right| + \left| \frac{p}{q} \right| \right) x \sin \phi.$$

The flavour of the neutral D meson at production can be tagged in two ways at LHCb: using the sign of the muon from semileptonic B decays or the sign of the pion in $D^{*\pm} \rightarrow D^0 \pi^\pm$ decays. The two tagging methods provide statistically independent samples to perform similar analyses. Indeed, LHCb already produced the world's best determination of A_Γ using 1 fb^{-1} of data collected in 2011 and a prompt-tagged sample of D mesons [6].

The measured values of A_Γ for the KK and $\pi\pi$ cases were

$$\begin{aligned} A_\Gamma(KK) &= (-0.035 \pm 0.062 \pm 0.012)\%, \\ A_\Gamma(\pi\pi) &= (0.033 \pm 0.106 \pm 0.014)\%, \end{aligned}$$

where the first uncertainty is statistical and the second one is systematic. These results are compatible with CP symmetry conservation.

The most recent LHCb measurement of A_Γ [7] exploits the entire Run1 dataset which amounts to 3 fb^{-1} of integrated luminosity. The analysis is performed using a sample of D mesons tagged using semileptonic B decays.

The value of A_Γ is determined by fitting the function $A_{CP}^{raw}(t) = A_0 - A_\Gamma \frac{t}{\tau}$ to the raw yield asymmetry shown in fig. 1, where A_0 is a constant term which includes possible direct CP but also production and detector induced asymmetries. The main source of systematic uncertainty is the mis-tag rate of the D flavour which increases as a function of its lifetime and is controlled using a similar data sample where the D meson decays

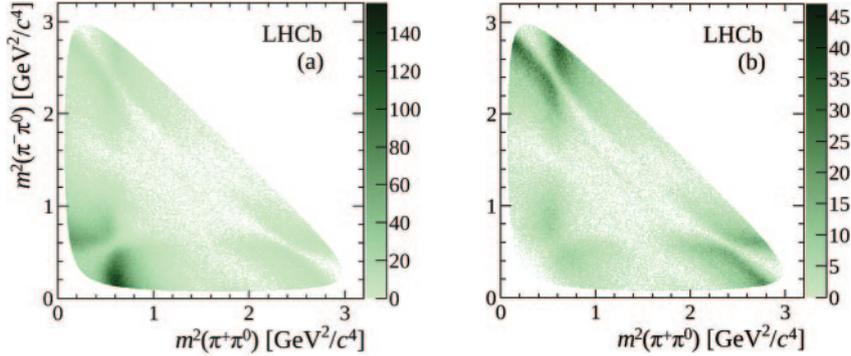


Fig. 2. – Distribution of events in the D meson Dalitz plane. (a) Resolved π^0 , 416×10^3 events, purity 82%. (b) Merged π^0 , 247×10^3 events, purity 91%.

to $K^\mp \pi^\pm$ final state. The results obtained are the following

$$A_\Gamma(KK) = (-0.134 \pm 0.077^{+0.026}_{-0.034})\%,$$

$$A_\Gamma(\pi\pi) = (-0.092 \pm 0.145^{+0.025}_{-0.033})\%,$$

where the first uncertainty is statistical and the second is systematic. Assuming that the indirect CP violation is universal, *i.e.* it does not depend on the specific final state, the two results for KK and $\pi\pi$ can be combined, yielding $A_\Gamma = (-0.125 \pm 0.073)\%$.

The combination with the previous LHCb measurements exploiting the prompt-tagged sample yields the result $A_\Gamma(KK) = (-0.072 \pm 0.050)\%$, $A_\Gamma(\pi\pi) = (-0.010 \pm 0.087)\%$. If universal indirect CP violation is assumed, can be combined into $A_\Gamma = (-0.056 \pm 0.044)\%$. Finally, a combination with A_Γ measurements from Belle [8], BaBar [9] and CDF [10] collaborations results into

$$A_\Gamma = (-0.058 \pm 0.040)\%.$$

All results so far are compatible with CP conservation.

3. – Search for direct CP violation in $D^0 \rightarrow \pi^+ \pi^- \pi^0$ decays

The neutral D meson system is also an important probe for *direct CPV* as in the search for time-integrated CP asymmetry in decays of $D^0(\bar{D}^0) \rightarrow \pi^+ \pi^- \pi^0$ performed recently at LHCb [11]. This is the first search for CPV in LHCb with a neutral pion in the final state and as such, it is an important milestone for experiments at hadronic machines, where usually the reconstruction of π^0 mesons is challenging.

Neutral pions at LHCb can be reconstructed in two ways, hereafter referred to as “resolved” and “merged”. Resolved π^0 s are reconstructed using two distinct cluster in the electromagnetic calorimeter produced by the two photons in the decay $\pi^0 \rightarrow \gamma\gamma$. Merged π^0 s are reconstructed from a single cluster.

The analysis uses the 2012 LHCb dataset ($\sim 2 \text{ fb}^{-1}$). The distribution of events in the D meson Dalitz plane is shown in fig. 2.

A novel model-independent method, called “the energy test”, has been used to maximise the sensitivity to local asymmetries in the Dalitz plane of multi-body decays [12]. The method is based on a test statistic T , defined as

$$T = \underbrace{\frac{1}{n(n-1)} \sum_{i,j>i}^n \psi(\vec{\Delta x}_{ij})}_{i,j \text{ are } D^0 \text{ tagged events}} + \underbrace{\frac{1}{\bar{n}(\bar{n}-1)} \sum_{i,j>i}^{\bar{n}} \psi(\vec{\Delta x}_{ij})}_{i,j \text{ are } \bar{D}^0 \text{ tagged events}} - \underbrace{\frac{1}{n\bar{n}} \sum_{i,j}^{n,\bar{n}} \psi(\vec{\Delta x}_{ij})}_{i(j) \text{ is a } D^0(\bar{D}^0) \text{ tagged event}} .$$

The distance between two point in phase space is given by $\vec{\Delta x}_{ij} = \vec{\Delta x}_{ij} = (m_{12}^{2,j} - m_{12}^{2,i}, m_{23}^{2,j} - m_{23}^{2,i}, m_{13}^{2,j} - m_{13}^{2,i})$, where the 1,2,3 subscripts indicate the final state particles. The distance is weighted using a Gaussian metric $\psi(\vec{\Delta x}_{ij}) = \exp\left(-\vec{\Delta x}_{ij}^2/2\sigma^2\right)$. By definition, T is not sensitive to global asymmetries. In the no- CPV scenario the T expectation value is zero while in case of non-zero CPV it is positive.

The value of T extracted from data has to be compared with the distribution of T in the hypothesis of no CPV . Such distribution is constructed using a data-driven approach by performing 1000 permutations of the events in the dataset by randomly assigning the D meson flavour. The distribution of T obtained from the permutations can be fitted with a generalised extreme value (GEV) function

$$f(T; \mu, \delta, \xi) = N \left[1 + \xi \left(\frac{T - \mu}{\delta} \right) \right]^{(-1/\xi)-1} \exp - \left[1 + \xi \left(\frac{T - \mu}{\delta} \right) \right]^{-1/\xi}$$

with normalisation N , location parameter μ , scale parameter δ , and shape parameter ξ . The p -value from the fitted T distribution can be calculated as the fraction of the integral of the function above the nominal T value. This approach is used for the sensitivity studies.

The final result, summarised in fig. 3(a) is given in terms of a p -value

$$p\text{-value} = (2.6 \pm 0.5) \times 10^{-2},$$

obtained by counting the fraction of permutations with values of T larger than the one obtained in data. The result is consistent with CP conservation. In addition, local asymmetries in the Dalitz plane have been investigated by considering the quantity

$$T_i = \frac{1}{2n(n-1)} \sum_{j \neq i}^n \psi_{ij} - \frac{1}{n\bar{n}} \sum_{j \neq i}^{\bar{n}} \psi_{ij}.$$

The significance of the obtained T_i across the Dalitz plane is shown in fig. 3(b) with the significance exceeding 1σ in the region dominated by the ρ^+ resonance.

The results have been cross-checked by changing the parameters in the metric and by splitting the sample according to various criteria such as magnet polarity and trigger configuration. Furthermore, additional checks have been performed to ensure that asymmetries in the background or induced by the detector have a negligible impact on the result.

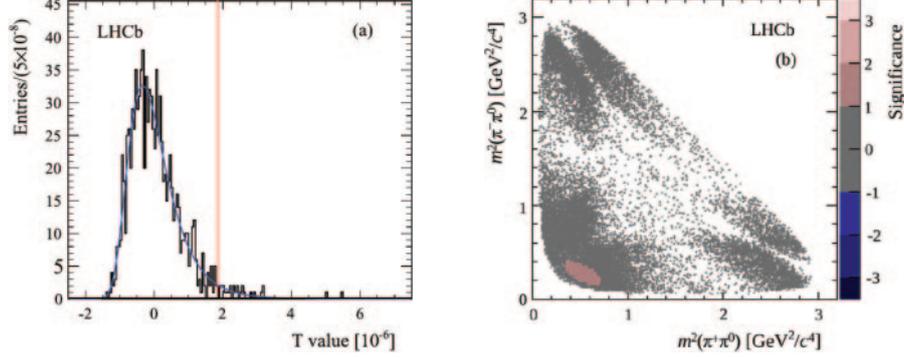


Fig. 3. – (a) T values from permutations with superimposed fit to GEV function. The measured T value is represented by the red line. (b) Significance for the T_i coefficients across the Dalitz plane.

4. – Conclusions

LHCb has performed world leading precision measurements in the charm sector. Along with measurements of CPV sensitive observables such as A_Γ , new methods are being considered to fully exploit its statistical power and extend its scope to final states with neutral pions. Current results, still statistically limited, are in agreement with the SM predictions and will significantly improve in the upgrade era.

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