Colloquia: LaThuile15

Measurements of CP violation and mixing in charm decays

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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.

PACS `13.20.Fc` – Decays of charmed mesons.
PACS `13.25.Ft` – Decays of charmed mesons.
PACS `11.30.Er` – Charge conjugation, parity, time reversal, and other discrete symmetries.
PACS `14.40.Lb` – Charmed mesons ($|C| > 0$, $B = 0$).

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. Indeed, 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]. Therefore, the observation of sizeable CPV could 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 $D^0(\bar{D}^0) \to hh$ decays and on the search for direct CPV in $D^0 \to \pi^+\pi^-\pi^0$ decays are presented.

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

(a) Prompt tag: the D flavour is tagged by the sign of the pion (π_s) from the D^{*+} decay.

(b) Semileptonic tag: the D flavour is tagged by the sign of the muon from a semileptonic B decay
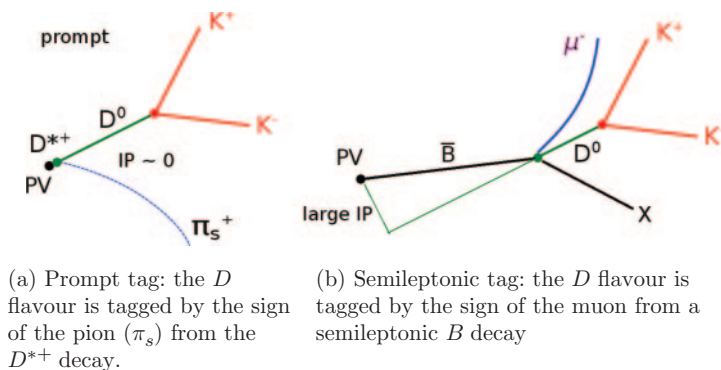
Fig. 1. – Methods to tag the neutral D meson flavour at production. PV is the primary proton-proton interaction vertex and IP is the impact parameter of the D meson, defined as the distance between the PV and the backward extrapolation of the D flight path.

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 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.

The connection between mixing and CPV is manifest in 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 determined in two ways at LHCb, as shown in fig. 1. 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 $1\,\text{fb}^{-1}$ 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

$$A_\Gamma(KK) = (-0.035 \pm 0.062 \pm 0.012)\%,$$
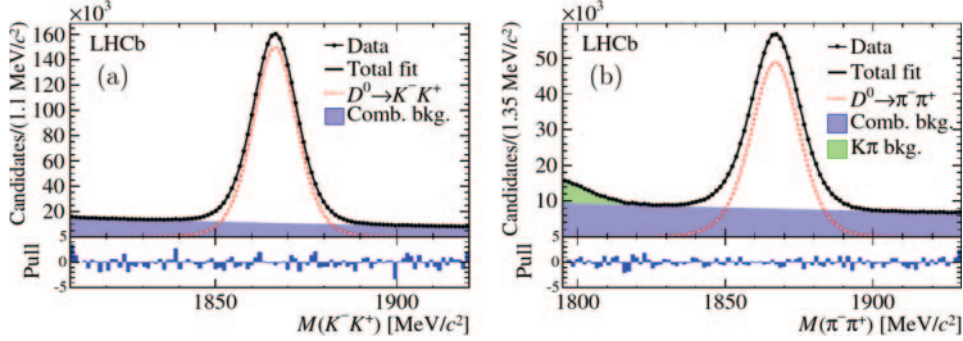
$$A_\Gamma(\pi\pi) = (0.033 \pm 0.106 \pm 0.014)\%,$$

Fig. 2. – Fits to the mass distributions of $D \to KK$ and $D \to \pi\pi$ candidates. The signal yields are 2.36×10^6 and 0.79×10^6 events.

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 $3\,\mathrm{fb}^{-1}$ of integrated luminosity. The analysis is performed using a sample of D mesons tagged using semileptonic B decays. The corresponding mass histograms of the D candidates, with superimposed a fit to signal and background contributions, are shown in fig. 2.

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. 3, 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 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 $A_\Gamma = (-0.125 \pm 0.073)\%$.
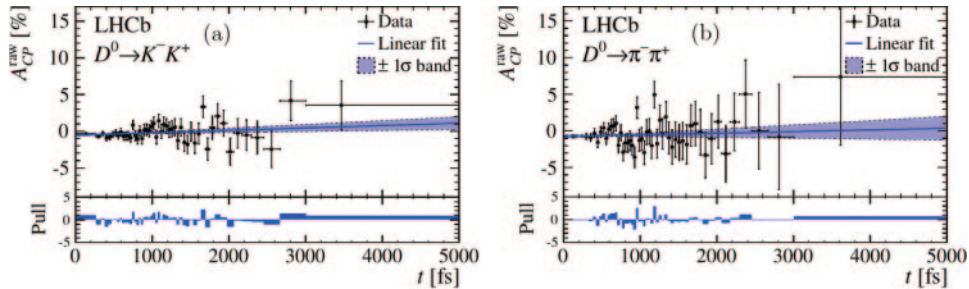

Fig. 3. – Yield asymmetry for $D^0(\bar{D}^0 \to K^+ K^-)$ and $D^0(\bar{D}^0 \to \pi^+ \pi^-)$.
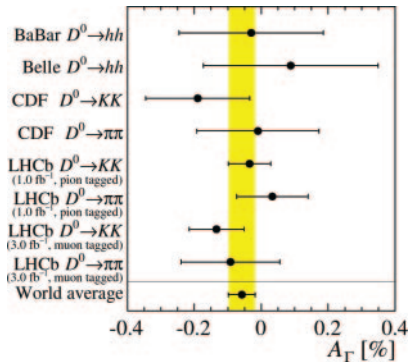
Fig. 4. – Summary of the results on A_Γ from various collaborations.

A combination with the previous LHCb results exploiting the prompt-tagged sample has been performed, the results are

$$A_\Gamma(KK) = (-0.072 \pm 0.050)\%,$$

$$A_\Gamma(\pi\pi) = (-0.010 \pm 0.087)\%,$$

that 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, as summarised in fig. 4.

3. – Search for direct CP violation in $D^0 \to \pi^+\pi^-\pi^0$ 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 $D^0(\bar{D}^0) \to \pi^+\pi^-\pi^0$ performed recently at LHCb [11]. This is the first search for CPV perfomed at 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 (and consequently the D candidates) at LHCb can be reconstructed in two ways, hereafter referred to as "resolved" and "merged". Resolved π^0s are reconstructed using two distinct cluster in the electromagnetic calorimeter produced by the two photons in the decay $\pi^0 \to \gamma\gamma$. Merged π^0s are reconstructed from a single cluster. Resolved D candidates have a relatively good mass resolution and lower transverse momentum. On the other hand, candidates formed with merged π^0 have a worse mass resolution but a higher purity can be achieved exploiting the larger average transverse momentum.

The analysis uses the 2012 LHCb dataset $(2\,\text{fb}^{-1})$ and the distribution of events in the D meson Dalitz plane is shown in fig. 5 from which differences in acceptance for the
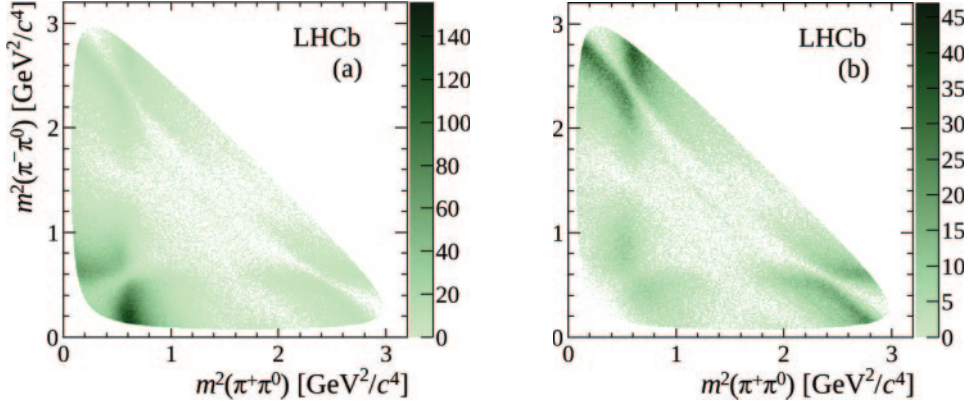
(a) Resolved π^0, 416×10^3 events, purity 82% (b) Merged π^0, 247×10^3 events, purity 91%

Fig. 5. – Distribution of events in the D meson Dalitz plane.

merged and the resolved sample across the Dalitz plane are evident. These differences are irrelevant as long as the acceptance is the same for D^0 and $\bar{D}^0$ in each π^0 category.

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

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

The distance between two point in phase space is given by $\overrightarrow{\Delta x_{ij}} = \overrightarrow{\Delta x_{ij}} = (m_{12}^{2,j} - m_{12}^{2,i}, m_{23}^{2,j} - m_{23}^{2,i}, m_{13}^{2,j} - m_{13}^{2,i})$, where the 1,2,3 subscripts indicate the final state particles. The distance is weighted using a Gaussian metric $\psi(\overrightarrow{\Delta x_{ij}}) = \exp\left(\overrightarrow{\Delta x_{ij}^2}/2\sigma^2\right)$. 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 so that any possible CP asymmetry is completely diluted. 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
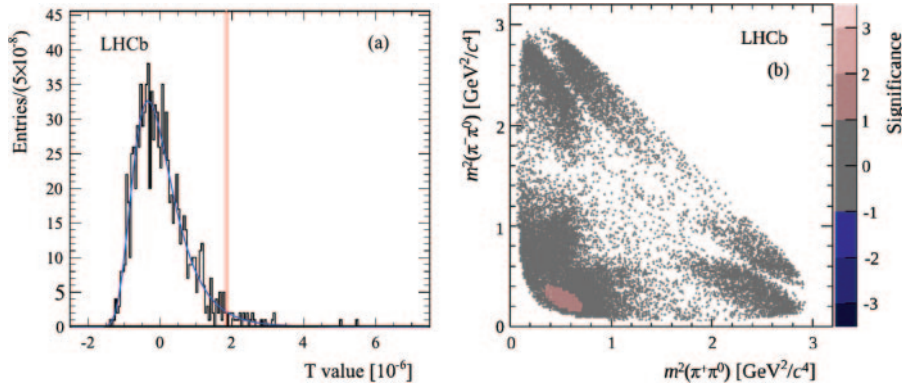
Fig. 6. – (a) T values from permutations with superimposed fit to GEV function. The measured T value is in represented by the red line. (b) Significance for the T_i coefficients across the Dalitz plane.

of the function above the nominal T value. This approach is used for the sensitivity studies.

The final result, summarised in fig. 6(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. 6(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.

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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