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Charm mixing and CP violation at LHCb

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Recent LHCb results on charm mixing and *CP* violation are presented. The results include the first observation of *CP* violation in charm decays and the most precise measurement of the mass difference between the mass eigenstates of neutral *D* mesons. A search for indirect *CP* violation is also presented. The results are compared to the Standard Model predictions.

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1. Introduction

Flavour oscillations and *CP* violation in decays of charmed mesons are very small effects due to a severe suppression from the GIM mechanism. To a good approximation, the unitarity relation $\lambda_d + \lambda_s + \lambda_b = 0$ ($\lambda_q \equiv V_{cq}V^*_{uq}$) is fullfilled considering only the first two generations (λ_b is $O(10^{-4})$). The real parts of λ_d and λ_s are very similar and have opposite signs, leading to a large GIM cancellation, whereas the very small imaginary parts leave little room for *CP* violation.

Mixing changes the flavour quantum numbers by two units, a transition that cannot occur at tree level. The magnitude of the amplitudes involving loops depends on the ratios $(m_q/M_W)^2$, where m_q denotes the masses of the internal quarks. The dominant contribution comes from the top quark, in the b sector, and from the b quark, in the case of charm, implying a three orders of magnitude difference between the size of the loop amplitudes in two systems [1].

2. First observation of *CP* violation in charm

Direct *CP* violation can occur in Cabibbo-suppressed decays of D mesons. For neutral mesons, the observable *CP* asymmetry, A_{CP}, is time dependent due to mixing. The time-integrated *CP* asymmetry, to first order in $D^0-\overline{D}^0$ mixing, can be written as [2]

$$A_{CP}(f) \approx a^{\rm dir}_{CP}(f) - \frac{\langle t(f)\rangle}{\tau(D^0)}A_\Gamma(f), \tag{1}$$

where f stands for the *CP* conjugate modes K^-K^+ and $\pi^+\pi^-$, $\langle t(f)\rangle$ is the mean reconstructed decay time of $D^0 \to f$, $\tau(D^0)$ is the known D^0 lifetime and A_Γ is the asymmetry between the effective decay widths of $D^0 \to f$ and $\overline{D}^0 \to f$, which combines the two forms of mixing-induced *CP* violation.

In the limit of U-spin symmetry, the direct *CP* asymmetry is equal in magnitude and opposite in sign for $D^0 \to K^-K^+$ and $D^0 \to \pi^+\pi^-$. In this case, the observable $\Delta A_{CP} \equiv A_{CP}(KK) - A_{CP}(\pi\pi)$ has larger sensitivity to a *CP* violation signal. In addition, important systematic effects and nuisance asymmetries are cancelled in the difference of *CP* asymmetries.

The analysis reported on [2] is based on the full Run2 data set (5.9 fb^{-1} of pp collisions at 13 TeV). Two disjoint samples are used: D^0 mesons (*CP* conjugation is always implied, unless otherwise stated) originated from the strong decay $D^*(2010)^+ \to D^0\pi^+$, in which the $D^*(2010)^+$ is produced at the pp collision point, hereafter referred to as "prompt" sample; D^0 mesons from partially-reconstructed b-hadron decays, $\overline{B} \to D^0\mu^-\overline{\nu}_\mu X$, referred to as "semileptonic" sample. In total, there are approximately 53×10^6 $D^0 \to K^+K^-$ and 17×10^6 $D^0 \to \pi^+\pi^-$ signal candidates. In the prompt and semileptonic samples, the flavour of the neutral D meson at production is determined by the charges of accompanying pion and muon, respectively.

The raw charge asymmetry is obtained from the measured yields of the D^0 and $\overline{D}^0$ to a given final state and can be approximated as

$$A_{\rm raw} \approx A_{CP} + A_{\rm D}(\pi,\mu) + A_{\rm P}(D^*, B), \tag{2}$$

where $A_{\rm D}(\pi,\mu)$ is the asymmetry caused by the difference in detection efficiency of the tagging particle, and $A_{\rm P}(D^*, B)$ is the asymmetry in the production of the $D^*(2010)^+$ or the b-hadron.

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A weighting procedure equalizes the kinematics of both final states, ensuring the cancellation of $A_{\rm D}$ and $A_{\rm P}$ in the difference between the raw asymmetries

$$\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi) = A_{\rm raw}(K^+K^-) - A_{\rm raw}(\pi^+\pi^-). \tag{3}$$

In the prompt sample, the dominant source of systematic uncertainties is due to the signal and background models used in the determination of the D^0 and $\overline{D}^0$ yields. In the case of the semileptonic sample, the main systematic uncertainty arises from combinations of a D^0 and an unrelated muon, resulting in a wrong flavour tag.

The measured values of ΔA_{CP} are

$$\Delta A_{CP}^{\pi\ \rm tag} = [-18.2 \pm 3.2({\rm stat}) \pm 0.9({\rm syst})] \times 10^{-4}, \quad \Delta A_{\rm CP}^{\mu\ \rm tag} = [-9 \pm 8({\rm stat}) \pm 5({\rm syst})] \times 10^{-4}. \tag{4}$$

The above results, still limited by the statistical uncertainties, when combined with previous LHCb measurements [3, 4] render the first observation of *CP* violation in charm, with a significance of 5.3 standard deviations:

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}, \tag{5}$$

with the statistical and systematic uncertainties added in quadrature.

Using the LHCb average value $A_\Gamma = (-2.8 \pm 2.8) \times 10^{-4}$ [5] and the measured values of $\Delta\langle t\rangle$ from both the prompt and semileptonic samples, the small contribution from indirect *CP* violation in eq. (1) is subtracted. The direct component of ΔA_{CP} is

$$\Delta a_{CP}^{\rm dir} = (-15.7 \pm 2.9) \times 10^{-4}. \tag{6}$$

The value is in agreement with the Standard Model (SM) predictions, typically in the range $10^{-3} - 10^{-4}$. The measurement, however, is at the upper end of the SM expectations, indicating that further measurements, combined with theoretical improvements, are required for a correct interpretation of this result.

3. Measurement of the mass difference between neutral D mesons

Mixing in flavoured neutral-meson systems occurs due to the existence of both virtual and real transitions common to particle and antiparticle. As a consequence, the mass eigenstates are linear combinations of states with definite flavour, $|D_{1,2}\rangle = p|D^0\rangle + q|\overline{D}^0\rangle$, where p and q are complex parameters.

Mixing is governed by four parameters,

$$x \equiv \frac{\Delta m}{\Gamma}, \quad y \equiv \frac{\Delta\Gamma}{2\Gamma}, \quad \left|\frac{q}{p}\right|, \quad \phi_f \equiv \arg\left(\frac{q\overline{A}_f}{pA_f}\right), \tag{7}$$

where $\Delta m = m_1 - m_2$ and $\Delta\Gamma = \Gamma_1 - \Gamma_2$ are the difference between the masses and natural widths of the mass eigenstates, respectively, Γ is the average decay width, and A_f ($\overline{A}_f$) is the amplitude $A[D^0(\overline{D}^0) \to f]$. The parameters $|p/q|$ and ϕ are related to *CP* violation in mixing ($|p/q| \neq 1$) and in the interference between the amplitudes for decays with and without mixing ($\phi_f \neq 0$).

The current average value of the parameter x does not differ significantly from zero. Improving the knowledge of x is critical for two reasons: the sensitivity to the angle ϕ_f depends on observables proportional to $x \sin\phi_f$; new heavy particles may appear in the dispersive part of the mixing amplitude, increasing the magnitude of x with respect to the SM expectations.

The self-conjugate decay $D^0 \to K^0_S\pi^+\pi^-$ allows a direct access to the mixing parameters. The Dalitz plot of this decay is described in terms of the invariants $m^2_\pm = m^2(K^0_S\pi^\pm)$. The Dalitz plot of the CP-conjugate decay $\overline{D}^0 \to K^0_S\pi^+\pi^-$ is symmetric to that of the D^0 with respect to the bisector $m^2_+ = m^2_-$. Due to mixing, some decays originally produced in the lower region of the Dalitz plot migrate to the upper region and viceversa. The mixing parameters are accessed by measuring the relative changes of intensities between symmetric regions as a function of the decay time.

The analysis is model-independent [6], based on the ingenious bin-flip method [7]. The Dalitz plot is divided into bins of nearly constant strong-phase difference between the D^0 and $\overline{D}^0$ decay amplitudes. The bins are symmetric about the bisector $m^2_+ = m^2_-$. The ratios between D^0 and $\overline{D}^0$ yields in symmetric bins (bins b and $-b$) are computed in intervals of decay time,

$$R_b(t_j) = \frac{N_{-b}(t_j)}{N_b(t_j)}, \qquad \overline{R}_b(t_j) = \frac{\overline{N}_{-b}(t_j)}{\overline{N}_b(t_j)}, \tag{8}$$

and fitted to an expression that is a fucntion of the mixing parameters. Detailed formulae can be found in Refs. [6, 7].

The analysis is based on Run1 data (3 fb^{-1} at 7 and 8 TeV), and uses 1.3×10^6 (1.0×10^6) D^0 candidates produced in prompt collisions (b-hadron semileptonic decays). The strong-phase differences are an external input from CLEO [8].

In order to increase the sensitivity to q/p, the ratios $R_b(t)$ and $\overline{R}_b(t)$ are written in terms of the variables z_{CP} and Δz, defined as $z_{CP} \pm \Delta z \equiv -(q/p)^{\pm 1}(y + ix)$. The results are expressed in terms of the CP-averaged parameters $x_{CP} = -\mathrm{Im}(z_{CP})$ and $y_{CP} = -\mathrm{Re}(z_{CP})$, and of the CP-violating parameters $\Delta x = -\mathrm{Im}(\Delta z)$ and $\Delta y = -\mathrm{Re}(\Delta z)$. In the limit of CP symmetry, $x_{CP} = x$, $y_{CP} = y$, and $\Delta x = \Delta y = 0$.

The results are

$$x_{CP} = (0.27 \pm 0.16 \pm 0.04) \times 10^{-2}, \qquad \Delta x = (-0.053 \pm 0.070 \pm 0.022) \times 10^{-2},$$
$$y_{CP} = (0.74 \pm 0.36 \pm 0.11) \times 10^{-2}, \qquad \Delta y = (0.06 \pm 0.16 \pm 0.03) \times 10^{-2}.$$

The results are consistent with CP symmetry and, as for the ΔA_{CP} measurement, are still limited by the statistical uncertainties. With the data set collected by LHCb in Run2, a significant reduction of the statistical uncertainies is expected.

The main sources of systematic uncertainties are associated to the uncertainties on the strong-phase difference, the contamination of D^0 from B decays (prompt sample) and to unrelated combinations of D^0 and muons (semileptonic sample). A likelihood function is formed from the above results to derive the values of x, y, $|q/p|$ and ϕ:

$$x_{CP} = (0.27^{+0.17}_{-0.15}) \times 10^{-2}, \qquad |q/p| = 1.05^{+0.22}_{-0.17}\,,$$
$$y_{CP} = (0.74 \pm 0.37) \times 10^{-2}, \qquad \phi = -0.09^{+0.11}_{-0.16}\ \text{rad}.$$

Although the measured value of x is still consistent with zero, when combined with previous determinations [9] yields $x = (0.39^{+0.11}_{-0.12}) \times 10^{-2}$, contributing to the emerging evidence for a positive mass difference between the neutral charm-meson mass eigenstates.

4. Time-dependent *CP* asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

Due to mixing, the time evolution of an initially pure beam of D^0 deviates from a single exponential. Given the small values of the mixing parameters in the D^0 system, the time evolution can be recast into a purely exponential form with effective decay rates. The parameter A_Γ is defined as

$$A_\Gamma(f) \equiv \frac{\hat{\Gamma}(D^0 \to f) - \hat{\Gamma}(\overline{D}^0 \to f)}{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\overline{D}^0 \to f)} \approx x\phi_f + y(|q/p| - 1) - y a_{CP}^{\rm dir}(f). \tag{9}$$

The last term in the above equation is small ($O(10^{-5})$) and can be safely ignored, given the present level of experimental precision.

Recalling eqs. (1) and (2), the time-dependent charge asymmetry is

$$A_{\rm raw}(D^0 \to f;t) \approx A_{CP}(f;t) + A_{\rm D} + A_{\rm P} = a_{CP}^{\rm dir}(f) + A_{\rm D} + A_{\rm P} - A_\Gamma(f)\frac{t}{\tau}. \tag{10}$$

Using the Cabibbo favoured decay $D^0 \to K^-\pi^+$ as a control channel, it is shown that $a_{CP}^{\rm dir}$, $A_{\rm D}$ and $A_{\rm P}$ do not depend on the decay time. Therefore, eq. (10) can be written as

$$A_{\rm raw}(D^0 \to f;t) = {\rm const.} + A_\Gamma(f)\frac{t}{\tau}. \tag{11}$$

If *CP* violation in the decay is neglected, a good approximation considering the current level of accuracy, the phase $\phi_f = \arg(q\overline{A}_f/pA_f) = \arg(q/p) = \phi$ becomes independent of the final state. In this case the measurements of A_Γ for the two final states can be combined into a single result.

The analysis [10] is based on the Run2 data (5.4 fb^{-1} at 13 TeV), and uses D^0 candidates from semileptonic decays of b-hadrons. There are approximately 9×10^6 $D^0 \to K^-K^+$ and 3×10^6 $D^0 \to \pi^-\pi^+$ candidates. The data are divided into 20 bins of decay time with nearly the same population. For each bin, the value of $A_{\rm raw}(\langle t_i \rangle)$ is determined by a simultaneous fit to the invariant mass distribution of the D^0 and $\overline{D}^0$ candidates. The distribution of $A_{\rm raw}(\langle t_i \rangle)$ is then fitted to a linear function to obtain the value of A_Γ.

The dominant sources of systematic uncertainties are the impact of the decay-time acceptance and resolution, and the background due to real D^0 candidates combined with unrelated muons, causing a wrong determination of the flavour at production.

The results are:

$$A_\Gamma(KK) = (-4.3 \pm 3.6 \pm 0.5) \times 10^{-4}, \qquad A_\Gamma(\pi\pi) = (2.2 \pm 7.0 \pm 0.8) \times 10^{-4}. \tag{12}$$

The above results, again still limited by the statistical uncertainties, are combined with previous LHCb measurements [11, 12]. The average of $A_\Gamma(KK)$ and $A_\Gamma(\pi\pi)$ is

$$A_\Gamma = (-2.9 \pm 2.0 \pm 0.6) \times 10^{-4}, \tag{13}$$

showing no indication of indirect *CP* violation.

5. Summary

Fifty-five years after the discovery of *CP* violation, LHCb reported on the first observation of this phenomenon in charm decays. The measured value of $\Delta a_{CP}^{\rm dir}$ is consistent with the SM expectations, but the correct interpretation of this result requires more precise theory predictions and further measurements.

A similar situation occurs with the determination and of the mixing parameter x. Its value is positive at 2.96 standard deviations. More precise measurements of the mass difference as well as improvements in the theory are crucial for the interpretation of the data.

So far, indirect *CP* violation has not been observed in charm decays, but the sensitivity to it is rapidly increasing and soon will reach the range of SM expectations. With Run 3 approaching, charm physics promises exciting years ahead.

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