

Studies of charm mixing and CP violation at LHCb

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The LHCb detector at CERN is an LHC experiment focused on the study of beauty and charm physics. This document presents an LHCb result devoted to the measurement of the mixing parameter γ_{CP} , related to the mixing parameter γ , and three searches for charm CP violation. Sensitivity to both mixing and CP violation in LHCb has become very promising.

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1. Introduction to mixing of neutral D mesons

For a system of a pair of neutral D mesons, different neutral states are relevant to the discussion of different processes:

- The two flavor eigenstates, $|D^0\rangle$ and $|\bar{D}^0\rangle$, have a definite quark flavor content and are those relevant to particle production and decay processes. They are mixed with each other as they propagate through space and time.
- The two Hamiltonian eigenstates, $|D_1\rangle$ and $|D_2\rangle$, have definite mass and lifetime, and they propagate through space and time in a definite way. The Hamiltonian eigenstates are written in the flavor basis as

$$|D_{1,2}\rangle = p |D^0\rangle \pm q |\bar{D}^0\rangle. \quad (1.1)$$

- If CP were preserved, the Hamiltonian eigenstates would also be CP eigenstates, namely $|D_+\rangle$ and $|D_-\rangle$.

For the system of the two neutral kaons, it is relevant to observe that their mass eigenstates have different average lifetimes, although similar masses, so it is convenient to define their states as K_L^0 and K_S^0 for the long-lived and short-lived states, respectively. However, for neutral D mesons, the mixing rate is slower than the decay rate, so the flavor eigenstates are the most convenient basis for them.

An arbitrary linear combination of the neutral D flavor eigenstates, $a|D^0\rangle + b|\bar{D}^0\rangle$, evolves in time according to the time-dependent Schrödinger equation

$$i \frac{d}{dt} \begin{pmatrix} a \\ b \end{pmatrix} = \mathcal{H} \begin{pmatrix} a \\ b \end{pmatrix} \equiv \left(M - \frac{i}{2} \Gamma \right) \begin{pmatrix} a \\ b \end{pmatrix}, \quad (1.2)$$

where M and Γ are 2×2 Hermitian matrices, but the effective Hamiltonian \mathcal{H} is not. $|D_1\rangle$ and $|D_2\rangle$ are the eigenstates of \mathcal{H} , with eigenvalues $(m_1 + \frac{i}{2}\Gamma_1)$ and $(m_2 + \frac{i}{2}\Gamma_2)$, respectively.

The mixing parameters x and y are defined as

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}, \quad x = \frac{m_1 - m_2}{\Gamma}, \quad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}, \quad (1.3)$$

and the time evolution of the elements of any D meson basis can be consistently expressed with respect to them.

2. Introduction to CP violation in D meson decays

The possible manifestations of CP violation can be classified in a model-independent way:

- CP violation in the decay occurs in decays of both charged and neutral mesons. It occurs when the amplitude of a decay is different from that of the decay of its CP conjugate.
- CP violation in the mixing occurs in neutral meson decays, when the Hamiltonian eigenstates cannot be chosen to be CP eigenstates as well.
- CP violation in the interference between decays with and without mixing occurs in decays into final states that are common to $|D^0\rangle$ and $|\bar{D}^0\rangle$.

3. Standard model predictions of D meson mixing and CPV

Mixing in the standard model originates from short and long distance contributions. Short distance contributions come from box diagrams with quarks and W^\pm bosons. The standard model predicts small mixing effects because b quarks are CKM suppressed and s and d quarks are GIM suppressed [1]. The main short distance contribution is to the x mixing parameter. Long distance contributions come from loop diagrams with hadronic intermediate states. These contributions are expected to be dominant, but still small. Since they are not perturbative, they are difficult to estimate, but predictions exist [2, 3] that bound x and y in the range $[0.001, 0.01]$, with $|x| < |y|$.

New physics could arise through new particles in loops. For example, if $|x|$ was found to be much larger than $|y|$, this could be a hint of new physics.

The standard model predicts CPV in the D sector to be $\sim 10^{-3}$. If CPV was to be found with the current sensitivity ($\sim 10^{-2}$), this would also be a hint of new physics [3].

4. Mixing and CP violation searches

Mixing has been studied using a variety of suppressed hadronic decays: in the time dependence of the wrong sign events in $D^0 \rightarrow K^+\pi^-$ [4, 5, 6], in the ratio of lifetimes of $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ events with respect to $D^0 \rightarrow K^-\pi^+$ events [7, 8, 9], and in a D^0 time-dependent amplitude analysis of $D^0 \rightarrow K^+\pi^-\pi^0$ events [10]. Mixing has also been studied in semileptonic events [11, 12, 13] by the BaBar and Belle collaborations, and in a time-dependent amplitude analysis of $K_s\pi^+\pi^-$ events [14, 15].

D mesons are tagged at production by means of $D^{*\pm} \rightarrow D^0\pi_s^\pm$ and its conjugate, where the charge of the low momentum pion π_s^\pm tags the flavor of the produced D meson.

CP violation has been studied in single Cabibbo-suppressed decays with CP even final states $D^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow K^+K^-$ [16, 17] and $D^0 \rightarrow \pi^+\pi^-\pi^0$ [18, 19] and $D^0 \rightarrow K^+K^-\pi^0$ [18]. The standard model predicts CP violation in these modes to be $\sim 10^{-4} - 10^{-5}$, so evidence of CP violation in them would be a sign of physics beyond the standard model [3]. CP violation has also been studied in $D^0 \rightarrow K^+\pi^-\pi^0$ events [10, 20] and in $D^0 \rightarrow K^+K^-\pi^+\pi^-$ decays.

5. LHCb results

The analyses presented in this document are devoted to measure the mixing parameters and CP violation effects by means of different techniques. In all analyses that require D meson flavor tagging at production, the $D^{*\pm} \rightarrow \tilde{D}^0\pi^\pm$ decay is used, where \tilde{D}^0 represents either a D^0 or a \bar{D}^0 , and the charge of the soft pion determines its flavor.

5.1 Measurement of y_{CP} and A_Γ

The y_{CP} mixing parameter is the equivalent of the y mixing parameter under the assumption that CP symmetry is conserved. It can be obtained from lifetime measurements in D meson two-body decays,

$$y_{CP} = \frac{\tau(D^0 \rightarrow K^-\pi^+)}{\tau(D^0 \rightarrow K^-K^+)} - 1. \quad (5.1)$$

The A_Γ CP violation parameter is the relative difference between the D^0 and \bar{D}^0 decay rates, which is evaluated as

$$A_\Gamma = \frac{\tau(\bar{D}^0 \rightarrow K^- K^+) - \tau(D^0 \rightarrow K^- K^+)}{\tau(\bar{D}^0 \rightarrow K^- K^+) + \tau(D^0 \rightarrow K^- K^+)}. \quad (5.2)$$

These two measurements require a good reconstruction of the D meson lifetime and, in particular, the lifetime biases introduced by the trigger are accounted for with the so called **swimming** technique [21, 22], which evaluates the lifetime acceptance from data by means of faking a different position of the primary vertex and running the trigger algorithms on it.

The LHCb result with 29 pb^{-1} of data measured in 2010 at a center of mass energy of 7 TeV is [23]

$$y_{CP} = [5.5 \pm 6.3(\text{stat}) \pm 4.1(\text{syst})] \cdot 10^{-3}, \quad (5.3)$$

$$A_\Gamma = [-5.9 \pm 5.9(\text{stat}) \pm 2.1(\text{syst})] \cdot 10^{-3}. \quad (5.4)$$

5.2 Measurement of CPV in $D \rightarrow h^+ h^-$ decays

The CP asymmetry of a D meson decay to a CP eigenstate f is given by

$$A_{CP}(f, t) = \frac{\Gamma(D^0(t) \rightarrow f) - \Gamma(\bar{D}^0(t) \rightarrow f)}{\Gamma(D^0(t) \rightarrow f) + \Gamma(\bar{D}^0(t) \rightarrow f)}, \quad (5.5)$$

which in general depends on the CP eigenstate f and the D meson lifetime t . The time integrated ΔA_{CP} parameter is defined as the time integrated difference of CP asymmetries between D meson decays to the CP eigenstates KK and $\pi\pi$,

$$\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi). \quad (5.6)$$

$D^{*\pm}$ production asymmetry and soft pion and D meson detection asymmetries cancel at first order. Therefore, to a good approximation,

$$\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi) = A_{\text{raw}}(KK) - A_{\text{raw}}(\pi\pi), \quad (5.7)$$

with

$$A_{\text{raw}} = \frac{N(D^{*+} \rightarrow D^0(f)\pi_s^+) - N(D^{*-} \rightarrow \bar{D}^0(f)\pi_s^-)}{N(D^{*+} \rightarrow D^0(f)\pi_s^+) + N(D^{*-} \rightarrow \bar{D}^0(f)\pi_s^-)}. \quad (5.8)$$

Data are split in 216 bins of kinematics (transverse momentum p_t and pseudorapidity η), LHCb magnet polarity and running periods. The yields N are obtained from fits to $\delta m = m_{D^*} - m_D - m_\pi$ in these bins, and the measured asymmetries are consistent in all of them.

The time integrated asymmetry ΔA_{CP} contains contributions from both direct (a_{CP}^{dir}) and indirect (a_{CP}^{ind}) CP violation, which can be expressed as a function of the average reconstructed D lifetime difference $\Delta\langle t \rangle$ in the KK and $\pi\pi$ samples [24, 25],

$$\Delta A_{CP} = [a_{CP}^{\text{dir}}(KK) - a_{CP}^{\text{dir}}(\pi\pi)] + \frac{\Delta\langle t \rangle}{\tau_D} a_{CP}^{\text{ind}}. \quad (5.9)$$

The LHCb measurement with 0.62 fb^{-1} of data taken in 2011 shows the first evidence of CP violation in the charm sector [26],

$$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})] \cdot 10^{-2}, \quad (5.10)$$

also confirmed by CDF with 9.7 fb^{-1} of collisions taken from 2002 to 2011 [27, 28],

$$\Delta A_{CP} = [-0.62 \pm 0.21(\text{stat}) \pm 0.10(\text{syst})] \cdot 10^{-2}. \quad (5.11)$$

5.3 Search for CP violation in $D^+ \rightarrow K^- K^+ \pi^+$ decays

This CP violation measurement is a model independent search based on the distribution of the **asymmetry significance** in bins k of the phase space, defined as

$$S_{CP}^k = \frac{N_k(D^+) - \alpha N_k(D^-)}{\sqrt{N_k(D^+) + \alpha^2 N_k(D^-)}}, \quad (5.12)$$

where the factor α , defined as

$$\alpha = \frac{N_{\text{total}}(D^+)}{N_{\text{total}}(D^-)}, \quad (5.13)$$

removes any global asymmetries.

If CP is conserved, the distribution of all the S_{CP}^k is expected to be normal (Gaussian centered at $\mu = 0$ and with width $\sigma = 1$). Monte Carlo studies show that this method would be sensitive to a CP violating phase difference of 5° in the $\phi \pi^+$ resonance at 90% confidence level, or a magnitude difference of 11% in the $\kappa(800)K^+$ resonance with a significance of 3σ . However, none of these discrepancies have been found on a data sample of 35 pb^{-1} at LHCb [29], consisting of approximately 403000 selected candidates.

5.4 Search for CP violation in $D \rightarrow \pi^- \pi^+ \pi^+ \pi^-$ decays

This CP violation search is a model independent search, similar to the previously described 3-body analysis. The Cabibbo favored $D \rightarrow K \pi \pi \pi$ mode, with a branching fraction about 10 times larger, is used as control channel to study detector and production asymmetries.

The **asymmetry significance**, obtained from expression (5.12), is evaluated in different bins across the phase space. An adaptive binning technique is used such that all bins contain at least 100 entries. For different number of bins, p-values are computed using

$$\chi^2 = \sum_k \left(S_{CP}^k \right)^2. \quad (5.14)$$

To minimize detector and production asymmetries, equal amounts of LHCb magnet up and down data are used. Also, fiducial cuts are applied to areas with large asymmetry, and the D^0 meson sample is reweighted to force the same amount of D^0 and \bar{D}^0 in each bin of η and p_t .

Rectangular cuts are applied to reconstruct candidates, and a neural network is used to select signal candidates. The same neural network is also used to select candidates in the control channel.

The sensitivity to CP violating effects is obtained from a toy study with events generated from a FOCUS model described in [30], by forcing a relative phase or magnitude difference between the D^0 and the \bar{D}^0 . This study shows that the method would be sensitive to a CP violating phase difference of 10° in the $\rho \pi$ resonance and a magnitude difference of 10% in the $\kappa(800)K^+$ resonance. However, no CP violation has been observed at LHCb, with a data sample of 180000 $D \rightarrow \pi^- \pi^+ \pi^+ \pi^-$ reconstructed candidates.

6. Conclusion

This document has presented searches for y_{CP} and A_{Γ} in two-body charm decays, and CP violation searches in $D^0 \rightarrow h^+h^-$, $D^+ \rightarrow K^-K^+\pi^+$ and $D^0 \rightarrow \pi^-\pi^+\pi^+\pi^-$ decays. In particular, the latter is the first model-independent search for local CP violation in a charm four-body decay. Sensitivity to charm CP violation and charm mixing in LHCb has become very promising.

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