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Mixing and indirect CP violation using two-body decays at LHCb

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The LHCb experiment at the Large Hadron Collider is currently the main player in the charm sector. Huge and very clean samples of D meson decays are reconstructed at LHCb, several orders of magnitude larger in size than in the past, allowing for the first time to approach the range of Standard Model expectations, that for CP-violation are below the 10^{-3} level. In this write-up the most recent LHCb results on mixing and time-dependent CP-violation parameters in $D^0 \to h^+h'^-$ decays (where h and h' stands for a kaon or a pion) are reported.

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1. Introduction

Since November 1974, when the discovery of the J/ψ was announced, the Charm physics has played a major role in the understanding of the Standard Model (SM) dynamics. In recent years, the interest for charm physics has been renewed in particular due to the discovery of oscillations of D^0–$\overline{D}^0$ meson system [1, 2] and the opportunity to collect huge samples of charm decays at the current facilities. Although precise SM calculations in the Charm sector are challenging due to the large theoretical uncertainties of long distance contributions [5, 6, 7, 8], the Charm sector provides a unique environment to probe SM physics being fully complementary to the K and B systems, offering a privileged door to look for unexpected processes.

The LHCb detector [9] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector is composed of a silicon-strip vertex detector surrounding the pp interaction region that allows c- and b-hadrons to be identified from their typically long flight distance, and a tracking system that provides a measurement of momentum of charged particles. In addition, two ring-imaging Cherenkov detectors are present to discriminate between different species of charged hadrons. An electromagnetic and a hadron calorimeters, located upstream the muon stations, complete the detector. In the Run I (2010-2012) of the LHC, the LHCb experiment collected $3\,\text{fb}^{-1}$ of integrated luminosity at an instantaneous luminosity of about $4\times10^{32}\,\text{cm}^{-2}\text{s}^{-1}$. The data have been collected at two different energies of $7\,\text{TeV}$ $(1\,\text{fb}^{-1})$ and $8\,\text{TeV}$ $(2\,\text{fb}^{-1})$. All the measurements reported in thefollowing are based on this data sample.

2. Double-tagged mixing

The D^0–$\overline{D}^0$ mixing has been observed for the first time by a single experiment at LHCb in the decay time dependent ratio $D^0 \to K^+\pi^-$ to $D^0 \to K^-\pi^+$ decay rates[1] [1, 2], where the flavour of the D^0 mesons is inferred through the charge of soft pions in the strong $D^{*+} \to D^0\pi^+$ and $D^{*-} \to \overline{D}^0\pi^-$ decays. The measurement of the mixing parameters has been recently extended to a disjoint data sample of $D^0 \to K\pi$ decays, where the D^0 mesons are produced in $\overline{B} \to D^{*+}\mu^-X$ with $D^{*+} \to D^0\pi^+$ and $D^0 \to K^{\mp}\pi^{\pm}$ [10]. This chain allows a double tag of the flavour of D^0 mesons: in the semileptonic decay the charge of the muon carries the information of the D^0 flavour thanks to the transitions processes $b \to cW^-$ and $\overline{b} \to \overline{c}W^+$, while the charge of the pion in strong $D^{*\pm}$ decays provides a second tag of the D^0 flavour. This sample collected requiring the double tag is very pure and the decay time distribution of reconstructed D^0 meson is not sculpted towards higher decay-time by trigger and selection requirements since $\overline{B} \to D^{*+}\mu^-X$ are selected without cutting on variables related to the D^0 decay time. Therefore, mixing at low decay time can be explored with respect to the measurements in Refs. [1, 2]. The time dependent ratio of doubly Cabibbo-suppressed (DCS) $D^0 \to K^+\pi^-$, to the Cabibbo-favoured (CF) $D^0 \to K^-\pi^+$ can be written (in the limit of a slow mixing rate $|x| \ll 1, |y| \ll 1$) as [10]

$$R(t)^{\pm} = R_D^{\pm} + \sqrt{R_D^{\pm}}y'^{\pm} + \frac{(x'^{\pm})^2 + (y'^{\pm})^2}{4}\left(\frac{t}{\tau}\right)^2, \tag{2.1}$$

[1] Charge-conjugate processes are implied if not explicitly stated.

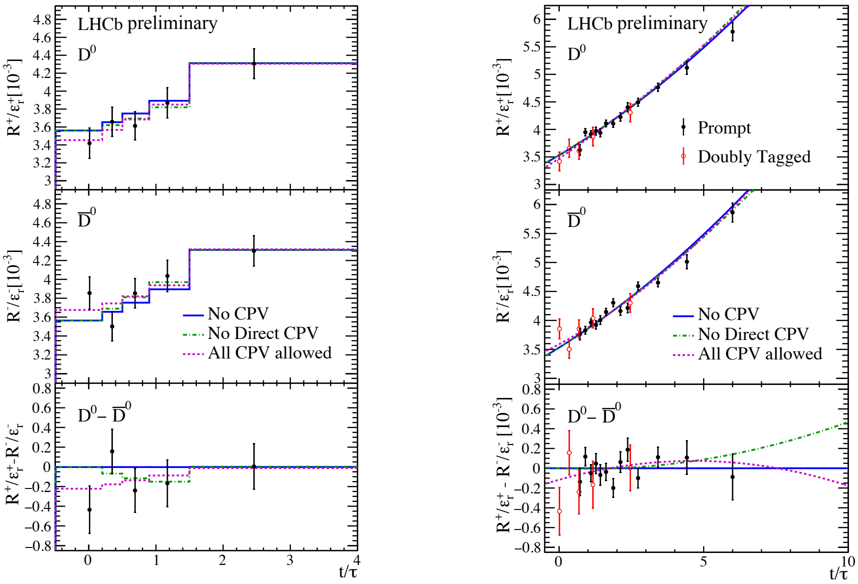

Figure 1: Data and fit projections (left) for doubly-tagged data [10] and (right) doubly-tagged (red open circles) plus prompt data (black filled circles) sample [1, 2].

where the $\pm$ sign denotes the flavour at production of D^0 $(+)$ and $\overline{D}^0$ $(-)$. R_D is the ratio of DCS to CF decay rates, $x' = x\cos\delta + y\sin\delta$, $y' = y\cos\delta - x\sin\delta$, where δ is the strong phase difference between DCS and CF amplitudes. $x = 2(m_2 - m_1)/(\Gamma_1 + \Gamma_2)$ and $y = (\Gamma_1 - \Gamma_2)/(\Gamma_1 + \Gamma_2)$ are the D^0 mixing parameters, corresponding to the mass eigenstates $|D_{1,2}\rangle = p\,|D^0\rangle \pm q\,|\overline{D}^0\rangle$, where p and q are two complex numbers satisfying the condition $|p|^2 + |q|^2 = 1$. t/τ is the D^0 decay time expressed in units of the average D^0 lifetime τ. The sample is split in bins of decay time with approximatively the same number of $D^0 \to K^-\pi^+$ decays. D^{*+} signal yields are extracted through a binned maximum likelihood fit to the $D^0\pi_s^+$ mass. The total yields, integrated on the decay time, are 1.73×10^6 and 6.68×10^3 for the CF and the DCS decays, respectively. The yields extracted in each decay time for CF and DCS decays are used to calculate the ratio reported in Eq. (2.1) in three different configurations:

- assuming CP symmetry, this requires that $R_D^+ = R_D^-$, $(x'^+)^2 = (x'^-)^2$ and $y'^+ = y'^-$;
- allowing CP violation in the mixing but requiring CP symmetry in the CF and DCS amplitudes ($R_D^+ = R_D^-$);
- allowing all the parameters to be different between D^0 $(+)$ and $\overline{D}^0$ $(-)$.

Results are reported in Fig. 1. A simultaneous fit of the doubly-tagged data sample and the prompt data sample [1, 2], improves the precision of the measured parameters of about 10%-20% [10] with respect to the prompt data sample alone.

3. Indirect *CP* violation

Clean experimental channels allowing the study of CP violation in the charm system are singly-Cabibbo-suppressed decays into CP-eigenstates, such as $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

decays. A useful observable commonly used to study time-dependent CP asymmetry is

$$A_{CP}(t) = \frac{\Gamma(t; D^0 \to f) - \Gamma(t; \overline{D}^0 \to f)}{\Gamma(t; D^0 \to f) + \Gamma(t; \overline{D}^0 \to f)}, \tag{3.1}$$

where $\Gamma(t; D^0 \to f)$ is the time-dependent decay rate of $D^0 \to f$ decays. Due to the slow D^0 mixing, $A_{CP}(t)$ can be approximated at the first order in $x \cdot (t/\tau)$ and $y \cdot (t/\tau)$ as [11, 12]

$$A_{CP}(t) \approx a_{CP}^{\mathrm{dir}} + a_{CP}^{\mathrm{ind}} \frac{t}{\tau}, \tag{3.2}$$

where a_{CP}^{dir} is related to the CP violation in the decay rates (direct), while a_{CP}^{ind} to CP violation in mixing or interference of decays with and without mixing (indirect). The indirect CP violation is well approximated by $-A_\Gamma$ in the limit of small direct CP violation [11, 12], where A_Γ is the asymmetry between D^0 and $\overline{D}^0$ effective decay widths[2], $\hat{\Gamma}$ and $\hat{\bar{\Gamma}}$ respectively, $A_\Gamma \equiv (\hat{\Gamma} - \hat{\bar{\Gamma}})/(\hat{\Gamma} + \hat{\bar{\Gamma}})$. The value of A_Γ is related to the mixing parameters as [11, 12]

$$A_\Gamma = \frac{1}{2}\left[\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y \cos\phi_D - \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x \sin\phi_D\right], \tag{3.3}$$

where $\phi_D = \arg(q/p)$ is the D^0 mixing phase. A measurement of A_Γ has been performed in the LHCb experiment with the 2011 data sample corresponding to $1\,\mathrm{fb}^{-1}$ of integrated luminosity [15]. The same analysis methodology is used to extend the measurement of A_Γ to the full Run I data sample of $3\,\mathrm{fb}^{-1}$ by directly measuring the D^0 and $\overline{D}^0$ effective lifetime, defined as $\hat{\tau} = 1/\hat{\Gamma}$ and $\hat{\bar{\tau}} = 1/\hat{\bar{\Gamma}}$ respectively, obtained using a single exponential model for the lifetime. Flavour tagging is provide by strong $D^{*+} \to D^0\pi^+$ and $D^{*-} \to \overline{D}^0\pi^-$ decays. The analysis described in detail in Ref. [13] uses a two-stage unbinned maximum likelihood fit to extract the D^0 and $\overline{D}^0$ lifetime. In the first stage, a two-dimensional fit to D^0 candidate mass $m(hh)$ and to the $\Delta m = m(hh\pi_s) - m(hh)$ variable (where h stands for K or π) is performed to calculated signal yields, while, in the second stage, a two-dimensional fit to the D^0 decay time distribution and to the $\ln[\chi^2_{\mathrm{IP}}(D^0)]$ is performed to extract the effective lifetimes, see Fig. 2. The $\chi^2_{\mathrm{IP}}(D^0)$ is a variable used to disentangle prompt D^0 mesons, coming from the primary vertex, and secondary D^0 decays which are not originating from the primary vertex.[3] A data-driven technique in which the per-event acceptance function is calculated moving the D^0 along its momentum-direction and rerunning the trigger and the reconstruction algorithms [16] is used to account for trigger and selection requirements. The analysis is validated on the CF $D^0 \to K^-\pi^+$ decays where pseudo-A_Γ ($A_\Gamma^{K\pi}$) is expected to be undetectable with the current sensitivity [11], obtaining $A_\Gamma^{K\pi} = (-0.07 \pm 0.15) \times 10^{-3}$. The results are $A_\Gamma(D^0 \to K^+K^-) = (-0.03 \pm 0.46 \pm 0.10) \times 10^{-3}$ and $A_\Gamma(D^0 \to \pi^+\pi^-) = (0.03 \pm 0.79 \pm 0.16) \times 10^{-3}$. These results are combined with those from the previous analysis on $1\,\mathrm{fb}^{-1}$ obtaining [13]

$$\begin{aligned} A_\Gamma(D^0 \to K^+K^-; 1\,\mathrm{fb}^{-1} + 2\,\mathrm{fb}^{-1}) &= (-0.14 \pm 0.37(\mathrm{stat.}) \pm 0.10(\mathrm{syst.})) \times 10^{-3}, \\ A_\Gamma(D^0 \to \pi^+\pi^-; 1\,\mathrm{fb}^{-1} + 2\,\mathrm{fb}^{-1}) &= (\;\;0.14 \pm 0.63(\mathrm{stat.}) \pm 0.15(\mathrm{syst.})) \times 10^{-3}, \end{aligned} \tag{3.4}$$

[2]The effective decay width is defined as $\hat{\tau} = 1/\hat{\Gamma} \equiv \int t\Gamma(t)dt / \int \Gamma(t)dt$, where $\hat{\tau}$ is the effective lifetime.

[3]The χ^2_{IP} is defined as the difference between the χ^2 of the primary vertex reconstructed with and without the considered particle.

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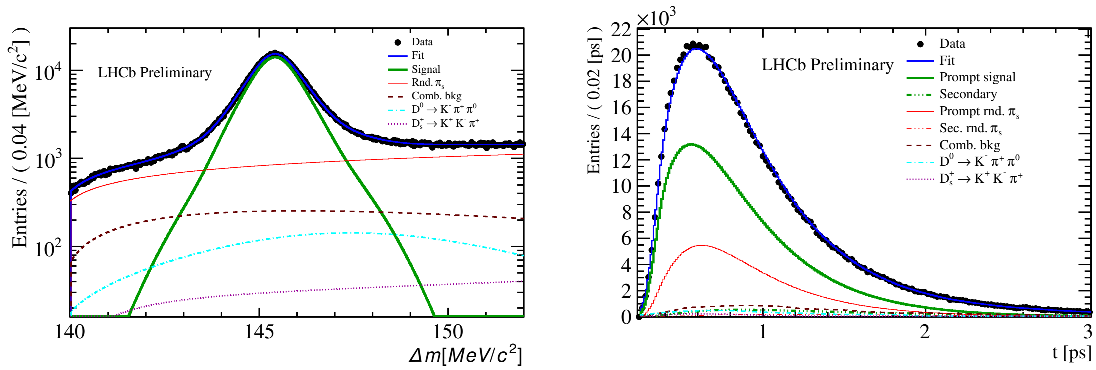

Figure 2: The distributions of (left) Δm and (right) D^0 decay time for $D^0 \to K^+K^-$ decays. The fit results are overlaid. Data showed correspond to one sixth of the full $2\,\text{fb}^{-1}$ data sample.

compatible with no-*CP* violation hypothesis. The methodology used to extract the acceptance function requires to rerun the trigger and the reconstruction algorithms hundreds of times on each event with a non negligile amount of CPU workload [16]. While this technique has been successful in the Run I, it will be demanding to continue to use it in the future data-taking periods where much higher statistics is expected. Therefore, a parallel analysis is performed using a significantly different methodology, exploiting Eq. (3.2) (thanks to the relation $a_{CP}^{\text{ind}} = -A_\Gamma$), where the precise knowledge of the acceptance function it is not required since it cancels out in the asymmetry. The data sample is split in almost equally populated bins of decay time and in each bin the asymmetry is calculated after the subtraction of the combinatorial background. A straight line fit to the time-dependent asymmetry is used to extract the A_Γ value. From an experimental point of view the observed time-dependent raw asymmetry, $A_{\text{raw}}(t;f)$, measured for D^0 decays to a final state f is defined as

$$A_{\text{raw}}(t;f) \equiv \frac{N(t;D^{*+} \to D^0(f)\pi_s^+) - N(t;D^{*-} \to \overline{D}^0(f)\pi_s^-)}{N(t;D^{*+} \to D^0(f)\pi_s^+) + N(t;D^{*-} \to \overline{D}^0(f)\pi_s^-)} \approx A_0(t) - A_\Gamma \frac{t}{\tau}, \tag{3.5}$$

where N is the number of reconstructed signal candidates. A_0 contains time-independent terms as the production asymmetry of $D^{*\pm}$ mesons and the direct *CP* asymmetry, but also a time-dependent term due to the detection asymmetry of soft pions from $D^{*\pm}$ decays [14]. The contribution of the detection asymmetry is corrected with a data-driven technique in which the *CP* symmetry of kinematic distributions of soft pions broken by the detection is restored. This is done by reweighing the three dimensional (k, θ_x, θ_y) distribution of the positive soft pions to the $(k, -\theta_x, \theta_y)$ distribution of negative soft pions, where $k = 1/\sqrt{p_x^2 + p_z^2}$ is proportional to the curvature of the track, and $\theta_x = \arctan(p_x/p_z)$ and $\theta_y = \arctan(p_y/p_z)$ are the emission angles of the soft pions. If there was no asymmetry neither in the sample nor in the detector acceptance, this distribution would be symmetric under the transformation $N^+(k, \theta_x, \theta_y) = N^-(k, -\theta_x, \theta_y)$, where $N^\pm$ is the number of reconstructed $D^{*\pm}$. This reweighing procedure makes the asymmetry of the detector response uniform over the whole parameter space, but does not affect a possibile decay-time dependent physical A_Γ [14]. The method is validated on the high statistic data sample of CF $D^0 \to K^-\pi^+$ decays with a yield of about 87 millions of event in the full $3\,\text{fb}^{-1}$ data sample as reported in Fig. 3. It is worth emphasising that samples with different magnet polarities are corrected in an

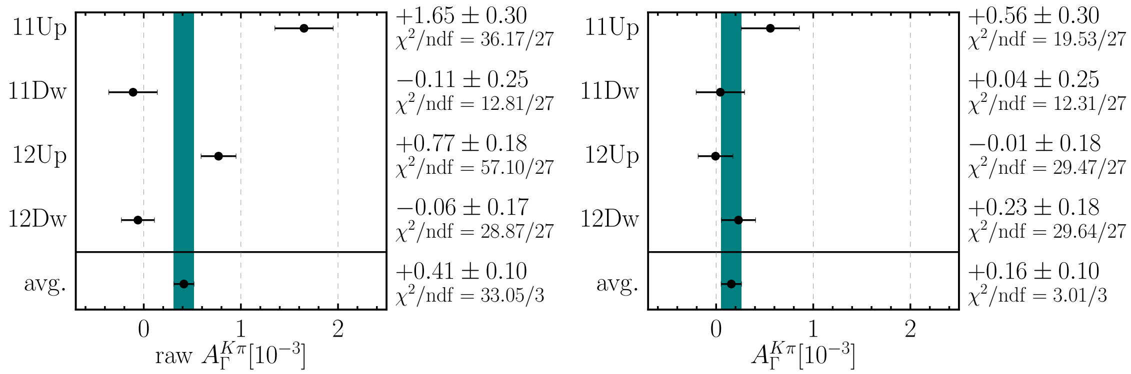

Figure 3: Pseudo-A_Γ results (left) before and (right) after the correction. Data sample is split by year of data taking, 2011 (2012) abbreviated as 11 (12), and by magnet polarity Up or Down (abbreviated Dw). The entry avg. is the weighted average between the four subsamples and is indicated by the teal coloured vertical band.

independent way; the convergence of their slopes to a common value is thus a check of the validity of the method. D^0 not coming from the primary vertex of the interaction is reduced to a few percent level by requiring $(\chi^2_{\rm IP}(D^0) < 9)$ and a systematic uncertainty is assigned to the residual contamination. The final results for A_Γ in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays are [14]

$$\begin{aligned} A_\Gamma(D^0 \to K^+K^-; 3\,\mathrm{fb}^{-1}) &= (-0.30 \pm 0.32(\mathrm{stat.}) \pm 0.14(\mathrm{syst.})) \times 10^{-3}, \\ A_\Gamma(D^0 \to \pi^+\pi^-; 3\,\mathrm{fb}^{-1}) &= (\ \ 0.46 \pm 0.58(\mathrm{stat.}) \pm 0.16(\mathrm{syst.})) \times 10^{-3}. \end{aligned} \tag{3.6}$$

The results for the two modes are consistent and show no evidence of *CP* violation. Neglecting terms of the order $|V^*_{cb}V_{ub}|/|V^*_{cs}V_{us}| \approx 10^{-3}$ [11] , the A_Γ value is independent from the final state and the two values can be averaged to yield a single value $A_\Gamma(KK+\pi\pi; 3\,\mathrm{fb}^{-1}) = (-0.12 \pm 0.28 \pm 0.10) \times 10^{-3}$.These results are the most precise measurements of these quantities and are consistent with those reported in Eq. (3.4) based on the same data, taking into account the correlation between the two measurements.

4. Conclusion

The recent measurements on mixing and indirect *CP* violation of $D^0 \to h^+h'^-$ decays have been reported. Sensitivity on D^0-mixing parameters has been improved by 10%-20% using double-tagged $D^0 \to K^-\pi^+$ decays. The A_Γ observable related to the *CP* violation in the mixing and interference has been measured with the full Run I data sample, leading to world best measurement with a sensitivity of $\mathcal{O}(10^{-4})$. So far, no hint of *CP* violation has been found. Now the Run II is ongoing and more measurements in charm sector are expected soon with unprecedented level of precision.

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