Measurements of mixing and indirect CP violation

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LHCb has collected the world's largest sample of charmed hadrons. This sample is used to measure the mixing parameters in the D^0-$\overline{D}^0$ system and to search for indirect CP violation. This contribution focuses on measurements of A_Γ with D^* and semileptonic B decays and on mixing measurements and a search for CP violation in $D \to K\pi$ decays.

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1 Introduction

In the Standard Model, D^0-$\overline{D}^0$ mixing is suppressed due to a cancellation via the GIM mechanism [1] and CKM suppression [2, 3] and therefore measurements of the mixing parameters x and y are experimentally challenging. Although traditionally the Standard Model predicts CP asymmetries in D^0-$\overline{D}^0$ to be $\leq 10^{-5}$ [4], more recent theoretical calculations [5] find sizable effects on this limit due to the corrections from the leading Heavy Quark Expansion [6] contributions. Evidence for New Physics could be found if discrepancies between experimental observations and the predicted level of indirect CP violation in the Standard Model occur.

In this proceedings, LHCb's latest measurements of A_Γ and of the time-dependent ratio of $D^0 \rightarrow K^-\pi^+$ (right-sign) to $D^0 \rightarrow K^+\pi^-$ (wrong-sign) decays will be reported. Charge conjugation is implied throughout this report.

2 Theory

In the charm sector, mixing occurs if the mass and width difference between the two mass eigenstates $|D_1\rangle$ and $|D_2\rangle$ with masses $m_{1,2}$ and widths $\Gamma_{1,2}$ is non zero. The mixing parameters x and y are defined as

$$x = \frac{2(m_1 - m_2)}{\Gamma_1 + \Gamma_2}, \tag{1}$$

$$y = \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}. \tag{2}$$

The mass eigenstates are a superposition of the flavour eigenstates $|D^0\rangle$ and $|\overline{D^0}\rangle$

$$|D_{1,2}\rangle = p\,|D^0\rangle \pm q\,|\overline{D^0}\rangle \tag{3}$$

with complex coefficients q, p satisfying the normalisation condition $|q|^2 + |p|^2 = 1$. One distinguishes between direct and indirect CP violation. Direct CP violation or CP violation in decay is present if the asymmetry

$$A_d \equiv \frac{|A_f|^2 - |\overline{A}_{\overline{f}}|^2}{|A_f|^2 + |\overline{A}_{\overline{f}}|^2}, \tag{4}$$

is different from zero.

The amplitude of a D^0 into a final state f is denoted by A_f and the decay of a $\overline{D}^0$ into the charge-conjugated decay is $\overline{A}_{\overline{f}}$. Indirect CP violation refers to CP violation and CP violation in interference. The former is defined through the asymmetry

$$A_m \equiv \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}, \tag{5}$$

and the interference between mixing and decay is present if the phase

$$\phi \equiv arg(\frac{q\overline{A}_{\overline{f}}}{pA_f}) \tag{6}$$

is non-zero.

3   The LHCb experiment

The analysed data are recorded by the LHCb experiment at the Large Hadron Collider (LHC) [7, 8, 9] at CERN. Pure proton beams are produced by stripping off the electron of hydrogen atoms and the protons are then initially accelerated by the linear collider. Successively, the protons are accelerated further in the Booster, the Proton Synchrotron and the Super Proton Synchrotron before being injected into the LHC and reaching their final collision energy.
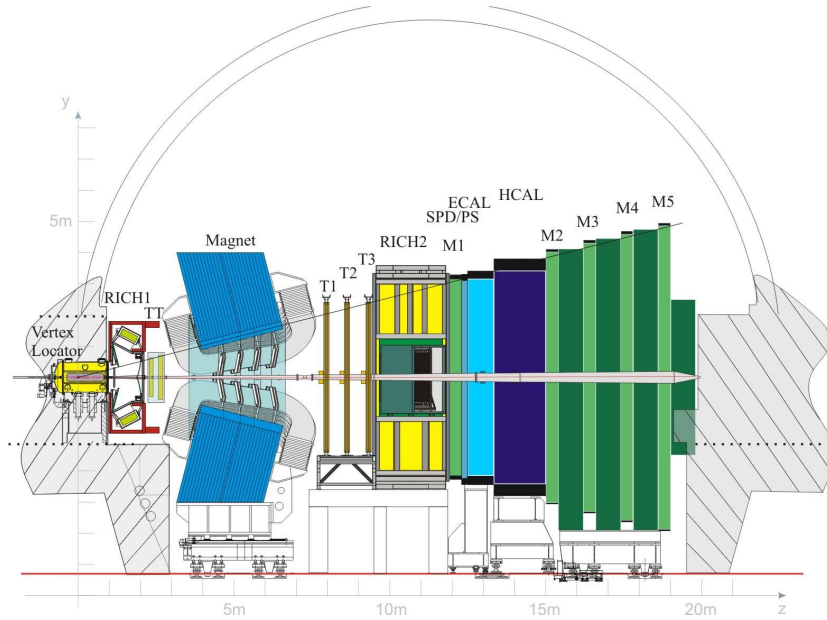

Figure 1: The LHCb detector. The figure is taken from Ref. [10].

The description of the LHCb detector is based on Ref. [10]. The LHCb detector is a single-arm spectrometer illustrated in Fig. 1 where the collision point is chosen as the origin of a right-handed coordinate system depicted in Fig. 1. With a cross section of 10% of all visible events inside the LHCb detector acceptance for producing charm quarks [12], the LHCb detector is very well suited for studies in the charm system. The beam pipe is enclosed by the Vertex Locator (VELO) aligned such that the collision point of the protons is located in the centre of the x-y plane of the VELO. Built of silicon strip sensors, the VELO provides measurements of track and vertex coordinates with high precision. Apart from the VELO, the tracking system consists of the Tracker Turicensis (TT), and three tracking stations (T1-T3) subdivided into the Inner and Outer Trackers, (IT) and (OT). The TT as well as the IT are composed of silicon microstrip sensors whereas the OT employs straw tubes. Embedded in a 4 Tm dipole magnet, this system provides both track coordinate and momentum measurements. Approximately a third of all K_S^0 mesons decay inside the VELO acceptance - so-called long tracks (L) - and exhibit a better momentum resolution than so-called downstream tracks (D) of K_S^0 mesons decaying outside the VELO acceptance. A system of Ring Imaging Cherenkov Detectors (RICH) is used to obtain excellent separation between kaons and pions. The C_4F_{10} and aerogel radiators of RICH1 ensure particle identification for low-momentum charged particles whereas the CF_4 radiators of RICH2 show a better performance for the high-momentum range. The shashlik calorimeter system composed of scintillating tiles and lead absorbers in the Electromagnetic Calorimeter (ECAL) and iron absorbers in the Hadronic Calorimeters (HCAL), respectively, provide identification and energy measurements of electrons, photons and hadrons. To identify electrons in the trigger, a Scintillator Pad Detector (SPD) and a Preshower Detector (PS) are installed in front of the ECAL. The muon system (M1-M5) uses mostly multi wire proportional chambers filled with a gas mixture of $Ar : C0_2 : CF_4$ to measure the spatial coordinates of muon tracks. In the the inner region of M1, triple-GEM detectors are installed instead of multi wire proportional chambers. Iron blocks between stations M2 to M5 serve as absorbers.

$D^0 \to h^+ h^-$ with $h = (\pi, K)$ decays are classified as either prompt or semileptonic decays. The term prompt refers to a D^0 candidates originating from a $D^{*+} \to D^0 \pi^+$ decay where the D^{*+} was directly produced in the pp collision. If the D^0 candidates originates from a semileptonic B decay where the B meson was produced in the pp collision, the D^0 is a semileptonic candidate. A measure to distinguish between prompt and semileptonic decays is the impact parameter (IP). The IP is defined as the distance of closest approach of the reconstructed trajectory to the pp collision vertex. For semileptonic decays, the impact parameter is large whereas for prompt decays, it is close to zero.

4 A_Γ measurements

The asymmetry of the inverse effective lifetimes of D^0 and $\overline{D}^0$, $\hat{\Gamma}_{D^0}$ and $\hat{\Gamma}_{\overline{D}^0}$, into CP-even final states, A_Γ is defined as

$$A_\Gamma = \frac{\hat{\Gamma}_{D^0} - \hat{\Gamma}_{\overline{D}^0}}{\hat{\Gamma}_{D^0} + \hat{\Gamma}_{\overline{D}^0}} \approx \left(\frac{A_d + A_m}{2} \right) y \cos(\varphi) - x \sin(\varphi), \quad \varphi = arg(q, p). \tag{7}$$

A measurement of A_Γ is an almost pure measurement of indirect CP violation since measurements have shown that A_d is small compared to the precision of A_Γ [13]. In the Standard Model, the CP-violating phase is independent of the final state thus $A_\Gamma(\pi^+\pi^-) = A_\Gamma(K^+K^-) = A_\Gamma$ is expected to hold.

4.1 A_Γ from prompt decays

The measurement of $A_\Gamma(\pi^+\pi^-)$ and $A_\Gamma(K^+K^-)$ [14] is based on the dataset recorded in 2011 with the LHCb detector. The data was taken at a centre-of-mass energy of $\sqrt{s} = 7\,\text{TeV}$ and corresponds to an integrated luminosity of 1fb^{-1}.

The D^0 flavour is determined from the charge of the π^+ from the D^{*+} decay. The measurement relies on 3.1M prompt $D^0 \to K^+K^-$ signal candidates with a purity of 93% and on 1.0M $D^0 \to \pi^+\pi^-$ signal candidates with a purity of 91%. The determination of the effective lifetimes $\hat{\Gamma}_{D^0}$ and $\hat{\Gamma}_{\overline{D}^0}$ is carried out in two steps: a multivariate unbinned maximum likelihood fit to $m(h^+h^-)$ with $h = K, \pi$ and $\Delta m \equiv m(D^*) - m(D^0)$ is performed to extract the signal yields. In a second step, the effective lifetime is extracted from a multivariate unbinned maximum

Figure 2: Fit projection on decay time to $\overline{D}^0 \to K^-K^+$ and corresponding pull plot for candidates for a subset of the data [14].

likelihood fit to D^0 decay time and to $\ln(\chi^2_{\text{IP}})$. The observable χ^2_{IP} is defined as the difference in χ^2 of a given pp collision vertex reconstructed with and without the considered track. Fitting in decay time and $\ln(\chi^2_{\text{IP}})$ allows the separation of prompt and semileptonic components. Figure 2 illustrates the fit projection on decay time for $\overline{D}^0 \to K^-K^+$ decays.
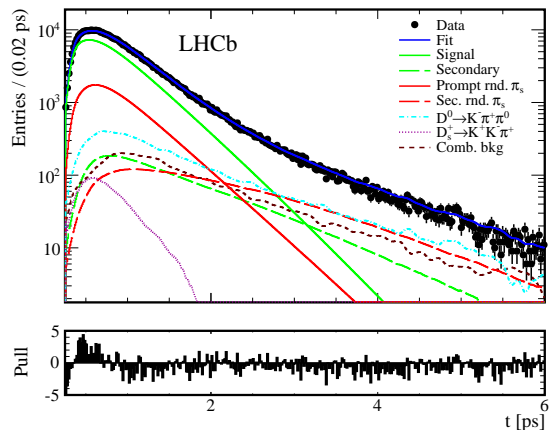
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The systematic uncertainties arise from partially reconstructed and other backgrounds, charm decays from semileptonic decays and mainly from a per-event data-driven acceptance function. The results are $A_\Gamma(K^+K^-) = (-0.035 \pm 0.062 \pm 0.012)\%$ and $A_\Gamma(\pi^+\pi^-) = (0.033 \pm 0.016 \pm 0.014)\%$ with statistical and systematic uncertainties. The measurements are in agreement with the no indirect CP violation hypothesis.

4.2 A_Γ from semileptonic decays

A measurement of $A_\Gamma(\pi^+\pi^-)$ and $A_\Gamma(K^+K^-)$ [15] is performed on the 2011 and 2012 dataset. In 2011, 1fb^{-1} was recorded at $\sqrt{s} = 7\,\text{TeV}$ whereas the centre-of-mass energy in 2012 was increased to $\sqrt{s} = 8\,\text{TeV}$ and 2fb^{-1} of data were taken.

In this analysis, D^0 decays are required to originate from semileptonic $B^- (\overline{B}^0) \to D^0 \mu^- \overline{\nu}_\mu X$ decays and the D^0 flavour is determined from the muon charge. The dataset contains 2.3M $D^0 \to K^+K^-$ and 0.8M $D^0 \to \pi^+\pi^-$ signal candidates. A_Γ is determined from a χ^2 fit to the time-dependent raw CP asymmetry $A_{CP}^{\text{raw}}(t)$

$$A_{CP}^{\text{raw}}(t) \approx A_d - A_\Gamma \frac{t}{\tau}. \qquad (8)$$

The raw CP asymmetry is determined from simultaneous fits to $m(h^+h^-)$ with $h = K, \pi$ in 50 bins of D^0 decay time to D^0 and $\overline{D}^0$ samples. The time-dependent $A_{CP}^{\text{raw}}(t)$ is shown in Figs. 3 and 4. The systematic uncertainties arise from the D^0 mass fit model and the decay time resolution, $B^0 - \overline{B}^0$ mixing, detection and production asymmetries, and the time-dependent efficiency. The main contributions to the systematic uncertainty result from the mistag probability and the mistag asymmetry. The mistag probability is defined as the probability of the muon to have the wrong charge with respect to the true D^0 flavour.
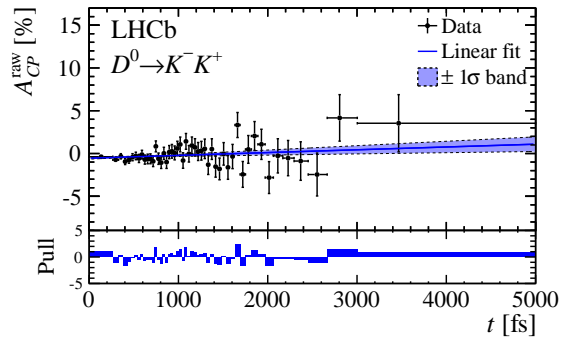

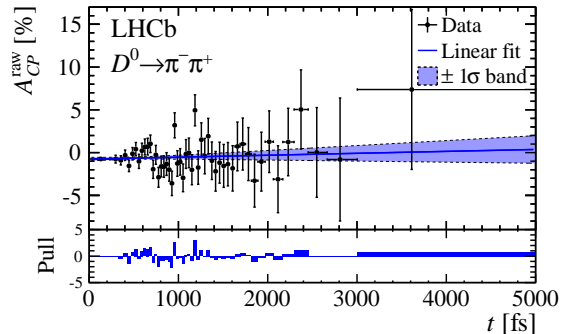Figure 3: Raw CP asymmetry as a function of D^0 decay time for $D^0 \to K^+K^-$ candidates [15].

Figure 4: Raw CP asymmetry as a function of D^0 decay time for $D^0 \to \pi^+\pi^-$ candidates [15].

A control sample of $D^0 \to K^-\pi^+$ decays is used to measure the mistag probability depicted in Fig. 5. Since the mistag probability can differ for positive and negative muons, the slope of this mistag asymmetry is calculated on the control sample. The slope of the mistag asymmetry is found to be non time-dependent. The statistical uncertainty on the slope is included in the systematic uncertainty and is the dominant contribution.
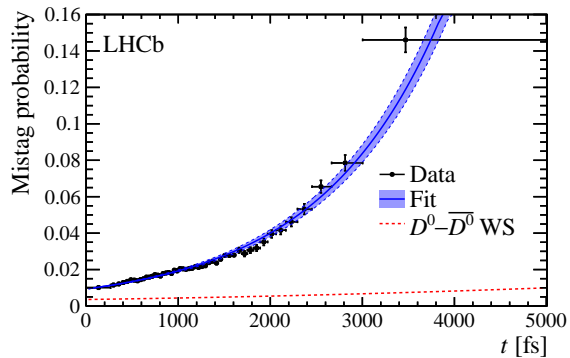

Figure 5: Mistag probability overlaid with an exponential fit [15].

A_Γ is measured to be $A_\Gamma(K^+K^-) = (-0.134 \pm 0.077\,^{+0.026}_{-0.034})\%$ and $A_\Gamma(\pi^+\pi^-) = (-0.092 \pm 0.145\,^{+0.025}_{-0.033})\%$ where the uncertainties are statistical and systematic, respectively. This measurement is in agreement with the conservation of CP symmetry.

5 Mixing measurement and search for CP violation in $\mathbf{D \to K\pi}$ decays

Mixing can be measured from the time-dependent ratio of $D^0 \to K^-\pi^+$ (right-sign) to $D^0 \to K^+\pi^-$ (wrong-sign) decays. The right-sign decay $D^0 \to K^-\pi^+$ is a Cabibbo-favoured decay whereas the decay $D^0 \to \overline{D}^0 \to K^-\pi^+$ is doubly-Cabibbo suppressed. For the wrong-sign decays, $D^0 \to K^+\pi^-$ is doubly-Cabibbo suppressed and $D^0 \to \overline{D}^0 \to K^+\pi^-$ is a Cabibbo-favoured mode. In the limit of small mixing and for negligible CP violation, the time-dependent ratio of right-sign to wrong-sign decays $R(t)$ [16] is given by

$$R(t) \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2. \tag{9}$$

The mixing parameters are rotated by the strong phase-difference δ between the doubly-Cabibbo suppressed and Cabibbo-favoured amplitudes $\mathcal{A}(D^0 \to K^+\pi^-)/\mathcal{A}(\overline{D}^0 \to K^+\pi^-) = -\sqrt{R_D}\,e^{-i\delta}$ and are given by

$$x' \equiv x\cos\delta + y\sin\delta, \tag{10}$$
$$y' \equiv y\cos\delta - x\sin\delta. \tag{11}$$

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The analyses presented in the following allow to measure x'^2, y'. The flavour of the prompt $D \to K\pi$ decay is determined by the charge of the pion from the D^{*+} decay.

5.1 Mixing in D → Kπ on 2011 data

On the 2011 dataset corresponding to an integrated luminosity of 1fb^{-1}, 8M right-sign and 36k wrong-sign decays are found [16]. The signal yields are extracted in 13 bins of D^0 decay time. From a binned χ^2 fit to the time-dependent ratio of right-sign to wrong-sign decays illustrated in Fig. 7, x'^2 and y' are extracted.

In the ratio, most systematic uncertainties are cancelling. Non-cancelling contributions arise from misidentified or partially recon-structed D^0 mesons and from charm decays originating from semileptonic decays.

The results are $R_D = (3.52 \pm 0.15) \times 10^{-3}$, $x'^2 = (-0.9 \pm 1.3) \times 10^{-4}$ and $y' = (7.2 \pm 2.4) \times 10^{-3}$ where the uncertainties include both statistical and systematic uncertain-ties. This measurement excludes the no-mixing hypothesis at 9.1σ.
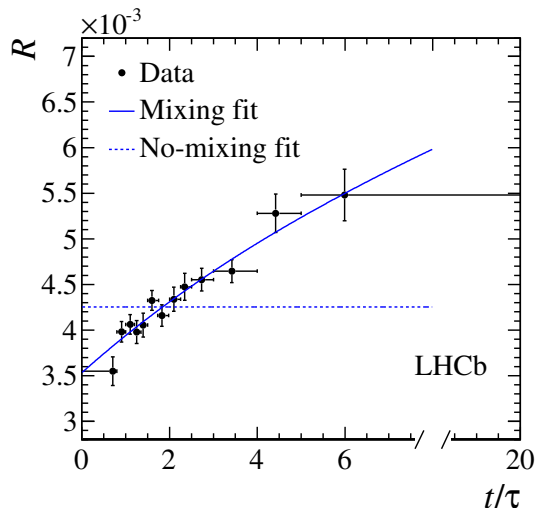

Figure 6: Ratio R as a function of D^0 decay time [16].

5.2 Mixing and CP violation in D → Kπ on 2011 and 2012 data

The analysis was performed on the 2011 and 2012 datasets corresponding to an in-tegrated luminosity of 3fb^{-1}. The mixing parameters x'^2 and y' are extracted from 53M right-sign and 230k wrong-sign signal candidates [17]. To search for direct and indirect CP violation, the data is split into D^0 and $\overline{D}^0$ samples. For each sample, the time-dependent ratios $R^{\pm}(t)$ for D^0 and $\overline{D}^0$, respectively, are measured and fitted for parameters $R_D^{\pm}, x'^{2\pm}$ and $y'^{\pm}$. The mixing parameters are defined as

$$x'^{\pm} \equiv |q/p|^{\pm 1} x' \cos\phi \pm y' \sin\phi \tag{12}$$

$$y'^{\pm} \equiv |q/p|^{\pm 1} y' \cos\phi \mp x' \sin\phi. \tag{13}$$

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The fit allows three different scenarios: CP violation allowed, no direct CP violation and no CP violation. The asymmetry $A_D \equiv (R^+ - R^-/(R^+ + R^-))$ is a measure for direct CP violation whereas a difference in (x'^{2+}, y'^+) and (x'^{2-}, y'^-) implies indirect CP violation. Assuming CP conservation, the fit results are $R_D = (3.568 \pm 0.066) \times 10^{-3}$, $x'^2 = (5.5 \pm 4.9) \times 10^{-5}$ and $y' = (4.8 \pm 1.0) \times 10^{-3}$.

Allowing for CP violation, the direct CP asymmetry is $A_D = (-0.7 \pm 1.9)\%$ and at 68.3% C. L., $0.75 < |q/p| < 1.24$ wherefore no evidence for CP violation is found.
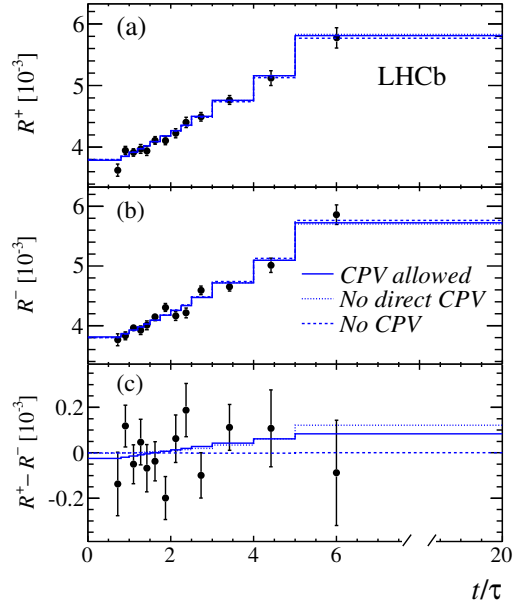

Figure 7: Ratios $R+$ (top), R^- (centre) and their difference (bottom) as a function of D^0 decay time [17].

6   Conclusion

Searches for CP violation in charm provide probes of new physics and LHCb has contributed significantly to the understanding of mixing and CP violation. The world average of A_Γ is dominated by the LHCb measurements with a combined precision of 4×10^{-4}. The measurements of A_Γ and the search for CP violation in $D \to K\pi$ decays are compatible with the conservarion of CP symmetry. The no mixing hypothesis was excluded by the 2011 $D \to K\pi$ analysis by 9.1σ.

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