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CP Violation and Mixing in Charm at LHCb

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LHCb has completed its first year of data taking at the LHC. The prolific production of open charm at $\sqrt{s} = 7$ TeV already allows precision measurements to be made. The prospects for time-dependent mixing and CP violation measurements, in particular y_{CP} and A_Γ are discussed and results from preparatory studies are presented. First results on time-integrated CP violation measurements in two-body charm decays at LHCb are presented. The measurement of the CP violation difference in the channels $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ yields $A_{CP}(KK) - A_{CP}(\pi\pi) = (-0.28 \pm 0.70_{stat} \pm 0.25_{syst})\%$.

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1. Introduction

LHCb has completed its first year of data taking at the LHC in 2010 accumulating an integrated luminosity of 37 pb^{-1}. The charm production cross-section in proton proton collisions at $\sqrt{s} = 7$ TeV has been measured to be $\sigma(c\bar{c}X) = 6.10 \pm 0.93$ mb [1]. This means that roughly one in ten visible events contain a charm hadron, which underlines the potential for high precision charm measurements at LHCb.

This potential is supported by a detector dedicated to precision heavy flavour physics [2]. The forward orientation of the LHCb experiment exploits the boost with which heavy flavour particles are predominantly produced. A high precision vertex locator (VELO) enables efficient detection of displaced vertices. Together with a spectrometer consisting of a dipole magnet and silicon and straw trackers this leads to an excellent proper time resolution which is more than adequate for measurements of D mixing related phenomena.

Two ring imaging Cherenkov detectors provide highly efficient particle identification for decays into charged hadrons. The LHCb detector is completed by calorimeter and muon systems which, for the analyses concerned here, play an important role in the trigger. The trigger is designed to select decays with high transverse momentum and displaced vertices. This intrinsically favours decays of charm particles which originate from B meson decays. The distinction of promptly produced D mesons and those from B decays is an important point in many analyses and is discussed in more detail below.

2. Time-Dependent Measurements

The LHCb experiment is especially well suited for time-dependent measurements. This allows measurements of mixing and indirect CP violation parameters. Mixing of neutral charm mesons has only been established recently [3]. Despite an ever increasing precision no single measurement has established mixing at a level above 5 σ. However, averaging the various constraints the no-mixing hypothesis is excluded with more than 10 σ [5].

Two-body hadronic charm decays offer great prospects for mixing and CP violation measurements at LHCb. One such measurement is that of the parameter y_{CP} which is based on the measurement of a ratio of lifetimes. It exploits the difference in lifetime in the singly Cabibbo-suppressed CP eigenstate decay mode $D^0 \to K^+K^-$ and the Cabibbo-favoured mode $D^0 \to K^-\pi^+$[1]. The parameter y_{CP} is defined as

$$y_{CP} = \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to K^+K^-)} - 1 = y\cos\phi - \left(\frac{1}{2}A_M + A_{prod}\right) x\sin\phi, \tag{2.1}$$

where $x = \frac{\Delta m}{\Gamma}$ and $y = \frac{\Delta\Gamma}{2\Gamma}$ are the usual mixing parameters, A_M and ϕ parametrise CP violation as $|\lambda_{KK}|^{\pm 1} \approx 1 \pm \frac{A_M}{2}$ and $\arg(\lambda_{KK}) = \phi$, and A_{prod} is the D meson production asymmetry. In the absence of CP violation y_{CP} is a pure mixing measurement as it directly measures y. Information on CP violation can be extracted from a comparison of y_{CP} and a direct measurement of y. For a quantitative interpretation the production asymmetry has to be known, however, it alone cannot

[1] As long as not explicitly stated otherwise any decay mode implicitly includes its charge conjugate

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fake a signal for CP violation as this also requires a non-zero phase ϕ. The production asymmetry at LHCb has been measured to be at the level of 1% [6].

A second, related measurement is that of the CP violation parameter A_Γ. This is given by the lifetime asymmetry of flavour-tagged CP eigenstates:

$$\begin{aligned} A_\Gamma &= \frac{\tau(\overline{D}^0 \to K^+K^-) - \tau(D^0 \to K^+K^-)}{\tau(\overline{D}^0 \to K^+K^-) + \tau(D^0 \to K^+K^-)} \\ &= \frac{1}{2}A_M y \cos\phi - x \sin\phi. \end{aligned} \tag{2.2}$$

A measurement of A_Γ which significantly deviates from zero is an unambiguous sign for CP violation as it requires a non-zero value for A_M or ϕ (assuming non-zero values for x and y).

The flavour tagging information is obtained from the decay chain $D^{*+} \to D^0\pi^+$ where the tagging pion is very soft due to the small mass difference of mother and daughter particles. LHCb concentrates on the analysis of charm decays from promptly produced particles for the time-dependent measurements in order to exploit their significantly higher yield. In return, this requires the precise determination and modelling of the contribution from charm decays originating in decays of B hadrons (secondary charm).

The distinction of prompt and secondary charm decays uses the information of the impact parameter of the D meson with respect to the primary interaction vertex, i.e. the shortest distance between the particle trajectory and the vertex. For prompt decays this impact parameter is zero apart from resolution effects. For secondary decays it gets additional contributions depending on the distance of flight of the heavier particle and the angle with which the D is produced. The resolution changes with the flight distance, i.e. it depends on the D proper time. Using the χ^2 of the impact parameter this time-dependence is removed as information on the uncertainty of the impact parameter is taken into account. However, secondary decays still have a time-dependence due to the correlation of the B flight distance with the measured D proper time. This time-dependence is modelled using Monte Carlo simulation.

Another challenge for time-dependent analyses is the correction of proper time acceptance effects (lifetime acceptance). These lifetime acceptance effects originate in selection criteria which bias the measured proper time distribution. Lifetime biasing selections are unavoidable and have to be applied already at trigger level to suppress background from the large number of particles produced promptly in the proton proton collisions. One example for such a cut is a minimum threshold on the impact parameter of the D decay products. This parameter depends on the distance of flight of the D meson and on the decay angle of the daughters and thus produces a non-trivial, proper time-dependent acceptance.

The approach currently used to account for this acceptance determines this bias on an event by event basis. This is achieved by scanning the selection decision as function of the measured proper time. Therefore, the position of the primary interaction vertex is changed in steps and the decision of the selection (trigger or offline) is re-evaluated. Points at which the selection decision changes are stored. They define the range of acceptance for each event. Trigger and offline decisions are merged, thus providing a binary acceptance function which simply translates into a set of accepted intervals when integrating the proper time probability density functions. Hence, this method removes both the need for a complex parametrisation of the lifetime acceptance and the

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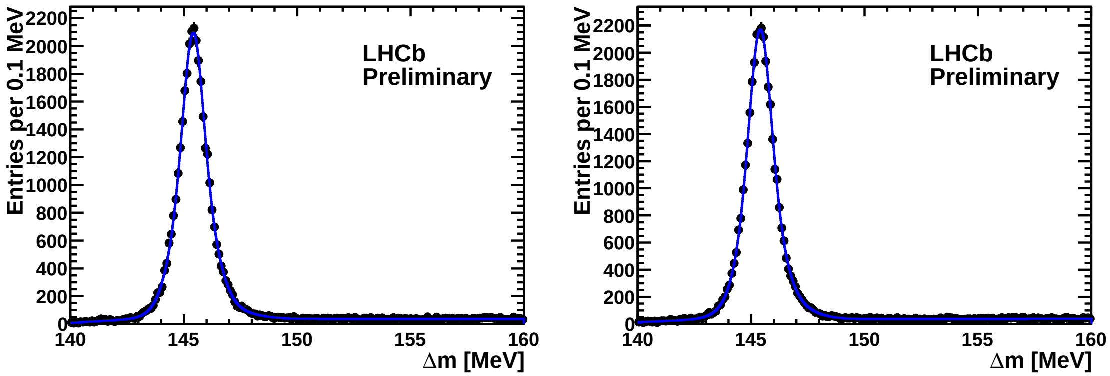

Figure 1: Invariant mass difference of the D^* daughters to the D^0 daughters, Δm, for D^0 decays (left) and $\overline{D}^0$ decays (right).

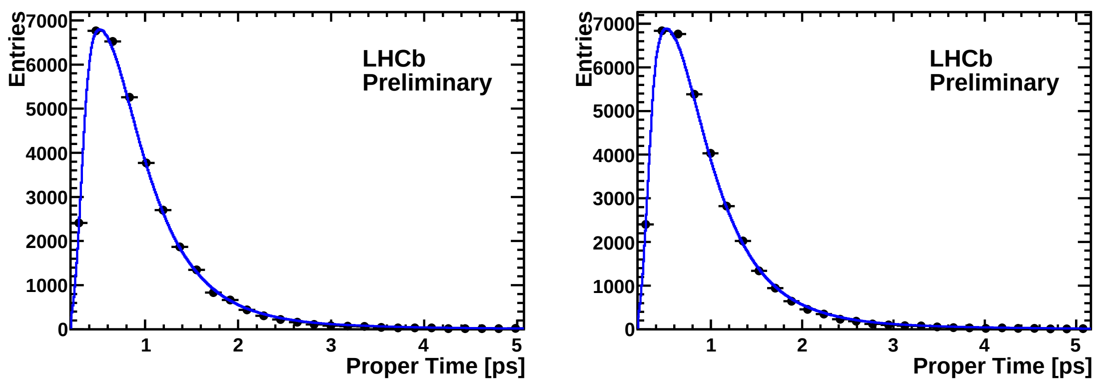

Figure 2: Lifetime fit projection for D^0 decays (left) and $\overline{D}^0$ decays (right).

need for relying on the precision of the Monte Carlo simulation. This approach was pioneered by CDF [7] and is now being applied at LHCb [8, 9].

On the path to measuring y_{CP} and A_Γ, LHCb has performed a control measurement using the Cabibbo favoured $D^0 \to K^-\pi^+$ decay. Using the full analysis chain, including flavour-tagging, a measurement equivalent to that of A_Γ has been performed. Figure 2 shows the distribution in the invariant mass difference of the D^* daughters and the D^0 daughters for $D^0 \to K^-\pi^+$ and $\overline{D}^0 \to K^+\pi^-$ decays, respectively. This distribution shows a narrow peak due to the small amount of free energy in the D^* decay. For events in the peak of the distribution the charge of the D^* determines the D^0 flavour tag as described above.

The lifetimes of the two decays $D^0 \to K^-\pi^+$ and $\overline{D}^0 \to K^+\pi^-$ were measured and combined in the observable

$$A_\Gamma^{K\pi} = \frac{\tau(\overline{D}^0 \to K^+\pi^-) - \tau(D^0 \to K^-\pi^+)}{\tau(\overline{D}^0 \to K^+\pi^-) + \tau(D^0 \to K^-\pi^+)}, \tag{2.3}$$

which is expected to be zero.

The fit was performed on a data sample which corresponds to about 20% of the sample that is available for measuring A_Γ. About 40 thousand candidates were selected for each flavour tag. The level of background was determined to be below 2% and was ignored in the analysis. Prompt and secondary decays were distinguished using the distribution in $\log\chi^2(IP_D)$ as described above. The lifetimes were measured to be $\tau(D^0 \to K^-\pi^+) = 407.6 \pm 2.4$ fs and $\tau(\overline{D}^0 \to K^+\pi^-) = 409.2 \pm 2.4$ fs where only statistical uncertainties are given. The fit projections are shown in Figure 2. The asymmetry is therefore computed to be

$$A_\Gamma^{K\pi} = (2 \pm 4) \times 10^{-3}, \tag{2.4}$$

in agreement with zero. Both lifetimes individually are in agreement with the PDG average of 410.1 ± 1.5 fs [10]. This underlines that both acceptance correction and separation of prompt and secondary decays work to sub per-cent precision. The statistical uncertainty anticipated with the available $D^0 \to K^-K^+$ sample is around 0.5%, which is already similar to those of the measurements performed at B-factories.

However, data acquired in 2011 should allow a significant improvement of the world average. The sample for the measurement of y_{CP} based on flavour untagged decays is significantly larger such that a measurement with an interesting precision using these decays should already be possible based on 2010 data alone.

3. Time-Integrated Measurements

The search for direct CP violation in two-body D^0 decays provides a complement to the measurement of A_Γ (see Sec. 2). Searches for direct CP violation are affected by production and detection asymmetries. At the proton-proton collider LHC a non-zero production asymmetry is expected. Detection asymmetries cancel for D^0 decays with self-conjugate final states, e.g. $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$.

The flavour-tagging is performed as for the time-dependent measurements using the decay chain $D^{*+} \to D^0\pi^+$. The observable, raw asymmetry is defined as

$$\begin{aligned} A_{RAW}(f) &\equiv \frac{N(D^{*+} \to D^0(f)\pi^+) - N(D^{*-} \to \overline{D}^0(f)\pi^-)}{N(D^{*+} \to D^0(f)\pi^+) + N(D^{*-} \to \overline{D}^0(f)\pi^-)} \\ &= A_{CP}(f) + A_D(f) + A_D(\pi_s) + A_P(D^{*+}), \end{aligned} \tag{3.1}$$

where $N(X)$ is the background subtracted number of reconstructed events of decay X. As described above, the detection asymmetry of the D^0 decay products, $A_D(f)$, is zero. The detection asymmetry of the tagging pion, $A_D(\pi_s)$, and the D^{*+} production asymmetry, $A_P(D^{*+})$, do not cancel a priori.

In the difference of $A_{RAW}(K^+K^-)$ and $A_{RAW}(\pi^+\pi^-)$ also $A_D(\pi_s)$ and $A_P(D^{*+})$ cancel, leading to

$$\begin{aligned} \Delta A_{CP} &\equiv A_{RAW}(K^+K^-) - A_{RAW}(\pi^+\pi^-) \\ &= A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-), \end{aligned} \tag{3.2}$$

which allows the measurement of the difference in the CP asymmetries of the K^+K^- and $\pi^+\pi^-$ final states. The individual CP asymmetries can be split in a direct and indirect component, a_{CP}^{dir} and a_{CP}^{ind}, respectively. The indirect component may be assumed to be the same for both final states as it originates in the common box diagram. However, its time dependence has to be taken into account, leading to a non-cancellation if the two final states are reconstructed with a different mean proper time. Thus,

$$\Delta A_{CP} = a_{CP}^{dir}(K^+K^-) - a_{CP}^{dir}(\pi^+\pi^-) + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{ind}, \tag{3.3}$$

where $\Delta\langle t\rangle$ denotes the difference of the mean proper time of the two final states.

The data set used in this analysis corresponds to the full 2010 data set of LHCb with an integrated luminosity of about 37 pb^{-1} [11]. It is split in periods of different polarities of the LHCb dipole magnet and in two periods with different trigger conditions. The event selection requires the candidates to have been selected by dedicated trigger lines. Furthermore, requirements on track and vertex quality, on the D^0 transverse momentum, on the helicity angle of the D^0 decay, and on the non-pointing of the daughter tracks to the primary interaction vertex are placed. Particle identification requirements on the daughter tracks strongly suppress any background involving particle mis-identification. The selection suppresses secondary charm by requiring that the D^0 points back to the primary interaction vertex. The remaining $< 5\%$ of secondary charm are included in the fit as they carry the same CP asymmetry. Finally, a direct cut is placed on the proper time such that the mean proper time of both decay modes is around 0.9 ps and $\frac{\Delta\langle t\rangle}{\tau} = 0.10 \pm 0.01$.

The fit is performed in twelve bins of transverse momentum (p_T) and pseudo rapidity (η) which are chosen to have roughly equal population. The binning is chosen to account for potential variation of production or detection asymmetries in these variables that is different for the two final states, which may be induced in the selection by e.g. particle identification requirements. Furthermore, the aforementioned separation by trigger configuration and dipole polarity leads to 48 independent fits. For each fit the signal yields are extracted by fitting to the mass difference of the reconstructed $D^{*+} - D^0$ mass difference after applying a mass cut on the reconstructed D^0 mass.

The value for ΔA_{CP} is measured in each of the 48 bins and found to be consistent throughout. The weighted average of all bins yields $\Delta A_{CP} = (-0.28 \pm 0.70)\%$. Systematic uncertainties are assigned by choosing different mass line shapes; by changing the D^0 mass window; by randomly selecting only one candidate for multiple candidate events (default is to select all); and by repeating the analysis without binning in (p_T, η). The full change in each case is attributed as a systematic uncertainty and all uncertainties are added in quadrature. It is not excluded that the observed changes are, at least partially, due to statistical fluctuations. The full result is

$$\Delta A_{CP} = (-0.28 \pm 0.70_{stat} \pm 0.25_{syst})\%. \tag{3.4}$$

A significant improvement in the precision of this measurement can be expected using data taken in 2011 as the systematic uncertainty may be expected to decrease with a decreasing statistical uncertainty. Due to the near complete cancellation of the contribution from indirect CP violation, this measurement is an excellent probe for direct CP violation. As such it perfectly complements a measurement of A_Γ.

4. Conclusion

In addition to the measurements presented here many other are under way or planned at LHCb. Most prominent in the range of two-body decays is the measurement of mixing parameters using doubly Cabibbo-suppressed (DCS) $D^0 \to K^+\pi^-$ decays. This measurement gives access to the relative rate of DCS decays R_D and to the mixing parameters x'^2 and y'.

Probably the most powerful measurement is the time-dependent Dalitz analysis of $D^0 \to K_S h^+ h^-$. This gives access to both mixing and CP violation parameters. The complexity of this measurement requires a large data set. However, the data expected to be acquired in 2011 should allow a competitive measurement. In terms of searches for direct CP violation measurements are ongoing looking for CP violation in the Dalitz plane of charged D decays into three charged hadrons (kaons or pions).

In summary, measurements of two-body charm decays at LHCb are well advanced. A first control measurement gives an impression of the precision to be expected from the analysis of data taken in 2010. The measurement of $\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-0.28 \pm 0.70_{stat} \pm 0.25_{syst})\%$ has been presented for the first time. It shows no evidence of CP violation. Significant improvements in precision can be expected from the ongoing data taking period.

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