CP violation in charm and other recent charm results from LHCb

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The LHCb experiment has accumulated an unprecedented sample of charm data. In these proceedings we present measurements of CP violation and rare in charm in LHCb data accumulated in 2010 and 2011. Many of these measurements are the most precise today.

1 Introduction

The LHCb experiment [1] is designed to exploit the huge $b\bar{b}$ cross section at pp collisions at LHC energies [2] for precision flavour physics. The same characteristics that optimise LHCb for b physics, also make it an excellent charm physics experiment, benefiting from a charm cross section of (6.10 ± 0.93) mb in 7 TeV proton-proton collisions [3], approximately $20\times$ larger than the $b\bar{b}$ cross section. In these proceedings we present recent LHCb results for CP violation in charm and, new for this conference, results on the rare decay $\mathrm{D}^0 \to \mu^+\mu^-$.

2 Data sample and flavour tagging

The results reported here use a variety of LHCb data samples, from $29\,\mathrm{pb}^{-1}$ up to $0.92\,\mathrm{fb}^{-1}$ of 2010/2011 data, approximately half the recorded data sample at the time of publication of these proceedings (July 2012).

A common feature amongst the analyses described below is the identification the flavour of the D meson be reconstructing the decays $\mathrm{D}^{*+} \to \mathrm{D}^0\pi_\mathrm{s}^+$ and $\mathrm{D}^{*-} \to \overline{\mathrm{D}}^0\pi_\mathrm{s}^-$. The charge of the "slow pion", $\pi_\mathrm{s}^\pm$ (which derives this name from the fact that it is nearly at rest in the $\mathrm{D}^{*\pm}$ frame), tags the flavour of the D meson. The characteristic kinematics of the $\mathrm{D}^{*+} \to \mathrm{D}^0\pi_\mathrm{s}^+$ also provide excellent background rejection, the "D*-trick" is therefore also used in untagged analyses to provide very clean data samples.

3 Time-dependent CP violation

3.1 D Mixing and CP violation parameters

Like other neutral mesons, the D^0 and $\overline{\mathrm{D}}^0$ mesons mix to form mass eigenstates

$$|\mathrm{D}_1^0\rangle = p|\mathrm{D}^0\rangle + q|\overline{\mathrm{D}}^0\rangle\,, \qquad |\mathrm{D}_2^0\rangle = p|\mathrm{D}^0\rangle - q|\overline{\mathrm{D}}^0\rangle. \tag{1}$$

The interference between mixing and decay to a CP eigenstate f_{CP} is sensitive to the parameter

$$\lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f} = -\eta_{CP}\left|\frac{q}{p}\frac{\overline{A}_f}{A_f}\right| e^{i\phi} \tag{2}$$

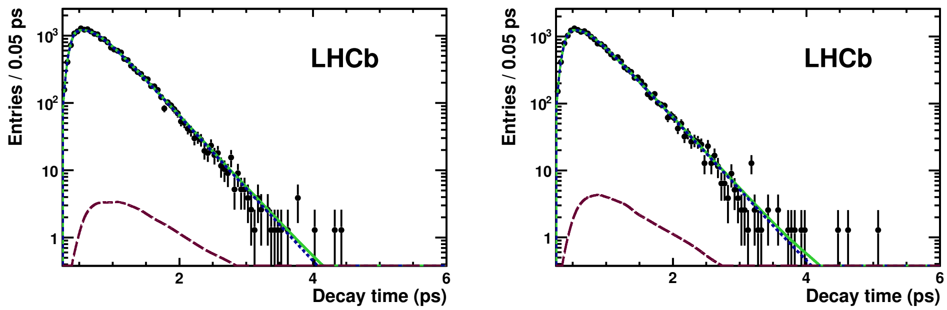

Figure 1: Proper-time fit projections of (left) $D^0 \to K^+K^-$ and (right) $\overline{D}^0 \to K^+K^-$ candidates. Shown are data (points), the total fit (green, solid), the prompt signal (blue, short-dashed), and the secondary signal (purple, long-dashed).

where A_f and $\overline{A}_f$ are the decay amplitudes of D^0 and $\overline{D}^0$ to f_{CP}, respectively, and η_{CP} is the CP eigenvalue of the final state. The CP violating phase ϕ is usually assumed to be independent of f_{CP} to a good approximation [4,5], and taken as the phase of q/p. Further, we define [6]:

$$A_m \equiv \frac{1}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) \approx \left|\frac{q}{p}\right| - 1, \qquad A_d \equiv \frac{1}{2}\left(\left|\frac{\overline{A}_f}{A_f}\right| - \left|\frac{A_f}{\overline{A}_f}\right|\right) \approx \left|\frac{\overline{A}_f}{A_f}\right| - 1 \tag{3}$$

which parametrise CP violation in the mixing and direct CP violation, respectively.

3.2 Time dependent mixing and CP violation measurements at LHCb

We report recent LHCb measurements [7] of mixing and CP-violation parameters in time-dependent analyses of the decays $D^0 \to KK$, $D^0 \to K\pi$ and $D^0 \to \pi\pi$ (CP-conjugate decay modes are implied throughout). We define the following observables in terms of the D lifetimes τ [6,8]:

$$y_{CP} \equiv \frac{\tau\left(D^0 \to K^-\pi^+\right)}{\tau\left(D^0 \to KK\right)} - 1 \approx y\left(1 - \frac{1}{8}A_m^2\right)\cos\phi - \frac{1}{2}A_m x \sin\phi \tag{4}$$

and

$$A_\Gamma \equiv \frac{\tau\left(\overline{D}^0 \to K^+K^-\right) - \tau\left(D^0 \to K^+K^-\right)}{\tau\left(\overline{D}^0 \to K^+K^-\right) + \tau\left(D^0 \to K^+K^-\right)} \approx \frac{1}{2}\left(A_m + A_d\right) y \cos\phi - x \sin\phi \tag{5}$$

where K^+K^- can be substituted for any CP-even state, including $\pi^+\pi^-$. The parameters x and y are the usual charm mixing parameters related to the mass and lifetime difference between the mass eigenstates respectively. In the absence of CP violation, $y_{CP} = y$ and $A_\Gamma = 0$. Both observables have the attractive feature that many experimental uncertainties cancel in the measured ratio.

The LHCb hadronic trigger exploits the relatively long lifetimes of B and D hadrons, and triggers on signatures indicating detached decay vertices. This results in one of the main experimental challenges for lifetime measurements at LHCb, as it biases in the measured lifetime distribution. In the analysis shown here [7], this bias is removed in a data driven, simulation-independent way [9,10,11,12,13]. The good match of the fitted distribution and the data in Fig. 1, especially at low lifetimes where the shape is dominated by the trigger efficiency, demonstrates the success of this method. Using $29\,\mathrm{pb}^{-1}$ of 2010 data, LHCb obtain the following results for the charm mixing and CP-violation parameters defined in Eqs. 4 and 5:

$$y_{CP} = (5.5 \pm 6.3_{\mathrm{stat}} \pm 4.1_{\mathrm{syst}}) \cdot 10^{-3}$$

and

$$A_\Gamma = (-5.9 \pm 5.9_{\rm stat} \pm 2.1_{\rm syst}) \cdot 10^{-3}$$

This compares to a previous world average[14] of $y_{CP} = (11.1 \pm 2.2) \cdot 10^{-3}$ and $A_\Gamma = (1.2 \pm 2.5) \cdot 10^{-3}$. We expect significant improvements with the full dataset not only in the statistical but also in the systematic uncertainty.

4 Direct CP violation

Especially singly Cabibbo suppressed decays, which can proceed both via tree and via penguin amplitudes, are sensitive to CP violating phases. CP violating phases exist in the SM penguin contributions, but their contribution is expected to be small. BSM physics could significantly enhance CP violation in these processes.

4.1 Direct CP violation $\mathrm{D}^0 \to \mathrm{KK}$ *and* $\mathrm{D}^0 \to \pi\pi$, ΔA_{CP}

We define the CP-violating rate asymmetry $A_{CP}(f)$ between CP-conjugate decays, $\mathrm{D}^0 \to f$ versus $\overline{\mathrm{D}}^0 \to \overline{f}$ (where f and $\overline{f}$ are CP-conjugate final states):

$$A_{CP}(f) \equiv \frac{\Gamma(\mathrm{D}^0 \to f) - \Gamma(\overline{\mathrm{D}}^0 \to \overline{f})}{\Gamma(\mathrm{D}^0 \to f) + \Gamma(\overline{\mathrm{D}}^0 \to \overline{f})} \tag{6}$$

Choosing as final states $\mathrm{K}^+\mathrm{K}^-$ and $\pi^+\pi^-$ ensures that there are no detection asymmetries related to the final state of the D^0. Production asymmetries and detection asymmetries related to the "slow pion" π_s are independent of the D^0 decay mode and cancel to first order in the difference

$$\Delta A_{CP} \equiv A_{CP}(KK) - A_{CP}(\pi\pi). \tag{7}$$

Because the asymmetries involved are small, higher order effects are negligible at the current experimental precision. Isospin considerations suggest that for direct CP violation $A^{dir}_{CP}(KK) \approx -A^{dir}_{CP}(\pi\pi)$ [15], so that we expect the direct CP-violation signal to be enhanced in this difference compared to individual measurements. Signals induced by time-dependent CP violation would largely cancel in the difference [4,5,16].

Correlations between the production kinematics and detection efficiencies can destroy the exact cancellation of the production and detection asymmetries in ΔA_{CP}. To remove such correlations, the data are analysed in 3-dimensional bins of transverse momentum p_T and pseudorapidity η of the $\mathrm{D}^0/\overline{\mathrm{D}}^0$, and the momentum p_{π_s} of the slow pion.

Using $0.62\,\mathrm{fb}^{-1}$ of 2011 data, LHCb obtain the following result [16]:

$$\Delta A_{CP} = [-0.82 \pm 0.21(\mathrm{stat}) \pm 0.11(\mathrm{sys})]\,\%$$

which is 3.5σ different from zero. The result is found to be stable (amongst others) across different kinematic bins, data taking periods, magnet orientations and detector regions.

This result is compatible with the previous world average [14] as well as the more recent result by CDF [17] - leading to a new world average of $\Delta A_{CP} = [-0.62 \pm 0.17]\,\%$ [14]. The LHCb results constitutes the first evidence of CP violation in the charm sector, at a level that is somewhat larger than expected [4,18,19], but that might still be compatible with the SM [20,21,22,23,24], although many explanations beyond the SM have been proposed [25,26,27,28,29]. At the same time, it excludes BSM models that predict ΔA_{CP} significantly larger than $\mathcal{O}(1\%)$.

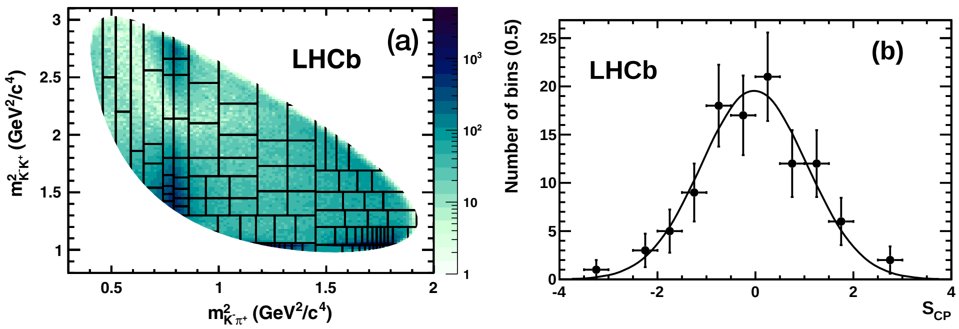

Figure 2: $D^{\pm} \to K^{+}K^{-}\pi^{+}$ Dalitz plot with a binning scheme super-imposed (a), and the pulls of the bins, i.e. the difference in event numbers (after correcting for global event yields) divided by its uncertainty (b). The $p-$value between the D^{+} and D^{-} Dalitz plot for this binning scheme is 11%.

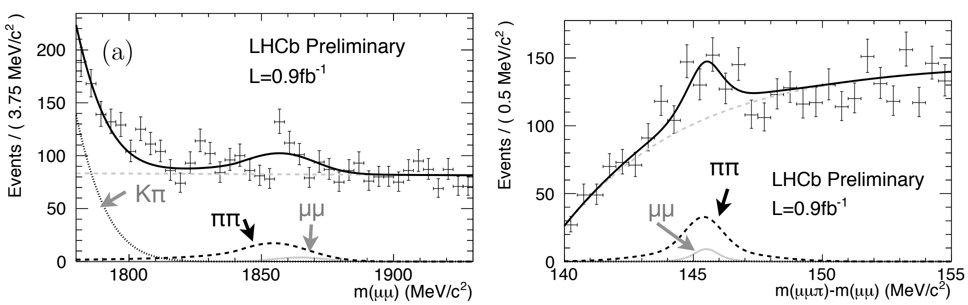

Figure 3: The mass distribution of the reconstructed $D^{0} \to \mu^{+}\mu^{-}$ events (left) and the difference between the reconstructed D^{*} and D^{0} mass for those events with the di-muon mass in the signal region $[1820, 1880]$ MeV (right). The broken grey line represents the combinatorial background, the black solid line the combined fit. Other contributions are identified in the plot. The $D^{0} \to \mu^{+}\mu^{-}$ is compatible with zero events.

4.2 Direct CP violation in multibody decays

The LHCb collaboration recently published the search for CP violation in the singly Cabibbo suppressed decay mode $D^{+} \to K^{+}K^{-}\pi^{+}$ and its charge conjugate [30]. The analysis follows a method proposed in [31]. The Dalitz plot is divided into bins, as illustrated in Fig. 2. The compatibility of the D^{+} with the D^{-} Dalitz plot is evaluated by calculating the χ^2 between the two plots, after accounting for the overall event numbers. Based on $35\,\mathrm{pb}^{-1}$ of data, LHCb reconstruct 0.33M $D^{\pm} \to K^{\mp}K^{\pm}\pi^{\pm}$ signal events and, for the control channels, 3.38M $D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\mp}$ events as well as 0.46M $D_s^{\pm} \to K^{\pm}K^{\mp}\pi^{\pm}$ events, with high signal purity in all modes. Several different binning schemes were used; one example of an adaptive binning scheme is shown in Fig. 2; the corresponding $p-$value is 11%. No evidence for CP violation is found in either the signal mode or the control channels in this or any other binning scheme. The analysis is due to be update with much more data, and further decay modes are being investigated [32].

5 Searching for $D \to \mu^{+}\mu^{-}$

In the SM, the decay $D^{0} \to \mu^{+}\mu^{-}$ the branching fraction is dominated by long-distance contribution with a $\gamma\gamma$ intermediate state. The best upper limit on $D^{0} \to \gamma\gamma$ [33] implies a SM branching fraction of $D^{0} \to \mu^{+}\mu^{-}$ of $< 6 \cdot 10^{-11}$ at 90% C.L. New physics models such as R-parity violating SUSY can enhance this branching fraction by several orders of magnitude [34,35]. Prior to the LHCb results, which are being reported at this conference for the first time, the best limit on this branching fraction had been set by BELLE with $\mathcal{B}(D^{0} \to \mu^{+}\mu^{-}) < 1.4 \cdot 10^{-7}$ at 90% C.L. [36].

Using $0.9\,\mathrm{fb}^{-1}$ of data, LHCb searches for $D^{0} \to \mu^{+}\mu^{-}$ in the decay chain $D^{*} \to D(\mu\mu)\pi$, exploiting the characteristic decay kinematics of the D^* allow for excellent background selection. The kinematically nearly identical mode $D^* \to D(\pi\pi)\pi$ is used for normalisation, and the extremely prolific $D^* \to D(K\pi)\pi$ for a variety of careful cross checks, including the important μ/π particle mis-ID rate.

The invariant mass distribution of the $\mu\mu$ candidates, and the distribution of the reconstructed difference between the D^* candidate mass and the D^0 candidate mass are shown in in Fig. 3. The plots also show the various contributions of the simultaneous fit to these distributions. The size of the $D^* \to D(\mu\mu)\pi$ contribution is compatible with 0, leading to an upper limit of the $D^0 \to \mu^+\mu^-$ branching fraction of[37].

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 1.3 \cdot 10^{-8} \quad \text{at} \quad 95\% \ C.L.$$
$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 1.1 \cdot 10^{-8} \quad \text{at} \quad 90\% \ C.L.$$

which is more than an order of magnitude improvement compared to the previous best result.

6 Conclusion

The LHCb experiment at CERN is collecting vast and remarkably clean charm samples. The precision study of charm with these unprecedented data allows for a new level of sensitivity to physics beyond the Standard Model. We report several world-leading results in the search for CP violation in charm, including the first evidence of CP violation in charm in $D^0 \to KK$ and $D^0 \to \pi\pi$ decays. We also present for the first time LHCb's limit of the branching fraction of the rare decay $D^0 \to \mu^+\mu^-$ which surpasses previous limits by more than an order of magnitude.

At this point, no clear evidence of physics beyond the Standard Model has emerged. As LHCb's data sample is expanding, the phase space for new physics models is contracting rapidly. The absence of any clear BSM signal in flavour physics, despite strong theoretical motivations for new physics at the TeV scale, remains one of the biggest puzzles in particle physics, and one of the strongest constraints on new physics models.

The limits and the sensitivities to BSM physics reported here are set improve further significantly with data sets set to more than double in 2012, and further increases even during the planned LHC shutdown as re-processing with upgraded computing infrastructure will result in a significant increase in charm data available for analysis.

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