CHARM PHYSICS RESULTS AND PROSPECTS WITH LHCb

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Precision measurements in charm physics offer a window into a unique sector of potential New Physics interactions. LHCb is poised to become a world leading experiment for charm physics, recording enormous samples with a detector tailored for flavor physics. This article presents recent charm production, CPV, and mixing studies from LHCb, including LHCb’s first charm CP asymmetry measurement with 37 pb$^{-1}$ of data collected in 2010. Significant updates to the material presented at the 2011 Rencontres de Moriond QCD and High Energy Interactions are included.

1 Charm production at the LHCb experiment

LHCb, the dedicated flavor experiment at CERN’s Large Hadron Collider (LHC), is the only LHC experiment with a broad charm physics program including measurements of charm CP violation (CPV) and $D^0$-$\bar{D}^0$ mixing. The cross-section to produce charm hadrons into the LHCb acceptance in the LHC’s $\sqrt{s} = 7$ TeV proton-proton collisions is 1.23 ± 0.19 mb, creating a huge potential data set. The LHCb trigger system has a flexible design that includes charm triggers so that this prolific production can be exploited.

LHCb recorded a total integrated luminosity of 37.7 pb$^{-1}$ in 2010. The charm samples collected in 2010 are already large enough for LHCb to be competitive in several measurements. With an expectation of more than 1 fb$^{-1}$, the 2011-12 run will yield even larger samples.

Because the LHC collides protons, there may be asymmetries in the production of charm and anti-charm hadrons. LHCb has measured the production asymmetry of $D^0$/$\bar{D}^0$ using 37 pb$^{-1}$ of 2010 data. The analysis uses both untagged samples of reconstructed $D^0$ decays and tagged samples that are reconstructed as the product of a $D^*+ \rightarrow D^0 \pi^{+}\text{slow}$ decay. In the tagged sample, the initial flavor of the $D$ is identified (tagged) as $D^0$ or $\bar{D}^0$ by the charge of the tagging slow pion, $\pi^{\pm}_{\text{slow}}$. In both samples, $D^0$ is reconstructed in the final states $K^-\pi^+$, $K^-K^+$, and $\pi^-\pi^+$. For a final state $f$, the raw observed untagged asymmetry, $A_{\text{Raw}}(f)$, and the raw observed $D^*$-tagged asymmetry, $A^*_{\text{Raw}}(f)$, can be factored into components:

$$A_{\text{Raw}}(f) \equiv \frac{N(D^0 \rightarrow f) - N(\bar{D}^0 \rightarrow \bar{f})}{N(D^0 \rightarrow f) + N(\bar{D}^0 \rightarrow \bar{f})} = A_{CP}(f) + A_D(f) + A_P(D^0),$$

$$A^*_{\text{Raw}}(f) \equiv \frac{N(D^*+ \rightarrow D^0(f)\pi^{+}_{\text{slow}}) - N(D^{*-} \rightarrow D^0(f)\pi^{-}_{\text{slow}})}{N(D^*+ \rightarrow D^0(f)\pi^{+}_{\text{slow}}) + N(D^{*-} \rightarrow D^0(f)\pi^{-}_{\text{slow}})} = A_{CP}(f) + A_D(f) + A_D(\pi_{\text{slow}}) + A_P(D^*+),$$

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*aOn behalf of the LHCb Collaboration*
where the $N(\text{decay})$ are the numbers of reconstructed decays, $A_{\text{CP}}(f)$ is the $CP$ asymmetry of the $D^0$ decay (further studied in Section 2), $A_D(f)$ and $A_D(\pi_{\text{slow}})$ are the detection asymmetries of $f$ and $\pi^{+}_{\text{slow}}$, and $A_P(D^0)$ and $A_P(D^{*+})$ are the production asymmetries. For the self-conjugate final states $K^- K^+$ and $\pi^- \pi^+$, $A_D(K^- K^+) = A_D(\pi^- \pi^+) = 0$. Therefore, the remaining detection asymmetries can be canceled by considering combinations of raw asymmetries,

$$A_{\text{Raw}}(K^- \pi^+) - A_{\text{Raw}}(K^- \pi^+) + A_{\text{Raw}}(K^- \pi^+) = A_P(D^0) + A_{\text{CP}}(K^- K^+),$$

$$A_{\text{Raw}}(K^- \pi^+) - A_{\text{Raw}}(K^- \pi^+) + A_{\text{Raw}}(\pi^- \pi^+) = A_P(D^0) + A_{\text{CP}}(\pi^- \pi^+).$$

Using the HFAG world averages of $A_{\text{CP}}(K^- K^+)$ and $A_{\text{CP}}(\pi^- \pi^+)$ and a Bayesian minimizer to optimally solve this over-constrained system for $A_P(D^0)$, we measure a mean value of $A_P(D^0) = [-1.08 \pm 0.32 (\text{stat}) \pm 0.12 (\text{syst})] \%$ in LHCb’s acceptance.

2 Time-integrated $CPV$ in D mesons

LHCb is searching for evidence of new sources of $CP$ asymmetry in the time-integrated decay rates of D mesons. The time-integrated $CP$ asymmetry, $A_{\text{CP}}(f)$, is conventionally defined as

$$A_{\text{CP}}(f) = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

for a given final state $f$. For $D^0$ decays, $A_{\text{CP}}$ may have contributions from both indirect and direct $CPV$. In the Standard Model, $CPV$ in the charm system is highly suppressed. Indirect $CPV$ is negligibly small and should be common for all decay modes. Direct $CPV$ is expected to be $\mathcal{O}(10^{-3})$ or less and to vary among decay modes. In $CPV$ searches in singly Cabibbo suppressed decays, such as $D^0 \to K^- K^+$, participation of well-motivated new physics (NP) particles in the interfering penguin amplitude could enhance direct $CPV$ up to $\mathcal{O}(10^{-2})$.

LHCb recently presented its first time-integrated $CPV$ measurement with decays $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$. The analysis uses the tagged samples of $D^{*+} \to D^0 \pi^+_{\text{slow}}$ decays also used in the measurement of $A_P(D^0)$ (Section 1). Using Equation 2, the difference in $A_{\text{CP}}(f)$ for $f = K^- K^+$ and $\pi^- \pi^+$ can be measured precisely with the production and detection asymmetries canceling exactly:

$$\Delta A_{\text{CP}} = A_{\text{CP}}(K^- K^+) - A_{\text{CP}}(\pi^- \pi^+),$$

$$= A_{\text{Raw}}(K^- K^+) - A_{\text{Raw}}(\pi^- \pi^+).$$

In 37 pb$^{-1}$ of LHCb 2010 data, we measure $\Delta A_{\text{CP}} = [-0.28 \pm 0.70 (\text{stat}) \pm 0.25 (\text{syst})] \%$, consistent with zero. This result is approaching the sensitivity of $CPV$ measurements performed by the B-factories in these decay modes but not yet at the level of CDF’s recent measurement. Due to differential proper-time acceptance between the $K^- K^+$ and $\pi^- \pi^+$ samples, the measured value of $\Delta A_{\text{CP}}$ includes a residual 10% of the mode-independent indirect $CP$ asymmetry. No limiting systematic bias has been identified in the method, so future iterations of the measurement with the much larger data set anticipated for 2011-2012 will be significantly more precise.

3 Time-dependent $CPV$ and mixing measurements in D$^0$

The conventional parameterization of charm mixing is fully explained elsewhere. Briefly, the mass eigenstates of the neutral D system $D_1$ and $D_2$ are expressed as normalized superpositions of the flavor eigenstates $D^0$ and $\bar{D}^0$, $D_{1,2} = p D^0 \pm q \bar{D}^0$, where $p$ and $q$ are complex scalars, $|p|^2 + |q|^2 = 1$. The relative argument of $q$ and $p$ is conventionally chosen equal to the phase that parameterizes $CPV$ in the interference between mixing and direct decays, $\arg \frac{q}{p} = \phi$. $CP$ is
violated in the mixing if $|\frac{y}{p}| \neq 1$ and in the interference between mixing and decay if $\phi \neq 0$. Letting $m_{1,2}$ and $\Gamma_{1,2}$ represent respectively the masses and widths of $D_{1,2}$, mixing is parameterized by the mass difference $x \equiv \frac{m_1 - m_2}{\Gamma_2}$ and the width difference $y \equiv \frac{\Gamma_1 - \Gamma_2}{\frac{1}{2}\Gamma_1 + \Gamma_2}$.

LHCb is working towards its first measurements of CPV and mixing in $D^0$-$\bar{D}^0$ with lifetime ratios of $D^0 \rightarrow K^-\pi^+$ and $D^0 \rightarrow K^-\pi^+$ decays. The lifetime of decays to the CP-even eigenstate $K^-K^+$, $\tau(K^-K^+)$, is related to the lifetime of the flavor-specific final state $K^-\pi^+$, $\tau(K^-\pi^+)$, by the mixing parameters:

$$y_{CP} \equiv \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 = y \cos \phi - \frac{1}{2} \left( \frac{|q|}{p} - \frac{|p|}{q} \right) x \sin \phi. \quad (8)$$

If CP is conserved, $y_{CP} = y$. The asymmetry in the lifetimes of $D^0$ and $\bar{D}^0$ decays to the CP eigenstate $K^-K^+$ is related to the CPV and mixing parameters by

$$A_\Gamma \equiv \frac{\tau(\bar{D}^0 \rightarrow K^-K^+) - \tau(D^0 \rightarrow K^-K^+)}{\tau(\bar{D}^0 \rightarrow K^-K^+) + \tau(D^0 \rightarrow K^-K^+)} = \frac{1}{2} \left( \frac{|q|}{p} - \frac{|p|}{q} \right) y \cos \phi - x \sin \phi. \quad (9)$$

$D^*$-tagged candidates are used in the measurement of $A_\Gamma$, while $y_{CP}$ can be measured with the larger untagged sample.

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**Figure 1:** Distributions of the mass difference, $\Delta m$, between $D^0$ ($\bar{D}^0$) candidates and their parent $D^{*+}$ ($D^{*-}$) candidates for decays $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^-\pi^+$ (c.c.).

In the 2010 run, we collected a sample of untagged $D^0 \rightarrow K^-K^+$ decays comparable in size to those of recent Belle and BaBar measurements. In 2011-2012, LHCb expects to have the world’s largest charm sample in this mode. The measurements of $y_{CP}$ and $A_\Gamma$ are currently blinded. As a test, the $A_\Gamma$ analysis was applied to a subset of the 2010 data in the right-sign (RS) control channel $D^0 \rightarrow K^-\pi^+$. Figure 1 shows the distributions of the differences $\Delta m$ between the masses of the reconstructed $D^0$ candidates and their parent $D^{*+}$ candidates for the RS validation sample. The purity of the sample is better than 90%.

Since the most powerful signal/background discriminants in hadronic collisions exploit the relatively long lifetime of D mesons, the trigger and selection criteria introduce a proper-time acceptance for the reconstructed $D^0$ decays. Unbiased time-dependent measurements require careful treatment of the acceptance effects of these discriminants. LHCb can precisely evaluate the proper-time acceptance on an event-by-event basis with the swimming method. Statistical separation of $D^0$ mesons produced at the primary interaction vertex from those produced in the decays of $b$-hadrons is accomplished using the impact parameter (IP) $\chi^2$ of the $D^0$. The
event-by-event acceptance and the IP $\chi^2$ are incorporated into an unbinned multi-dimensional likelihood fit to measure the lifetimes. Figure 2 shows the proper-time distributions for the tagged RS validation sample. The lines on the plots are the fitted distributions from the unbinned multi-dimensional likelihood fit.

Figure 2: Distributions of the reconstructed proper time of $D^0$ ($\bar{D}^0$) candidates for decays $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^-\pi^+$ (c.c.). The line on each plot is the result of a likelihood fit incorporating per-event acceptance distributions computed with the swimming method.

4 Summary

LHCb had a successful year of data taking in 2010, collecting 37.7 pb$^{-1}$ of pp collisions at $\sqrt{s} = 7$ TeV. We observe an asymmetry in $D^0$ production of $A_P(D^0) = [-1.08 \pm 0.32 \text{(stat)} \pm 0.12 \text{(syst)}]\%$, which is the first evidence for an asymmetry in heavy flavor production at the LHC. In our first precision charm $CPV$ measurement with this data, the difference between the time-integrated $CP$ asymmetries of $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ decays is measured to be $\Delta A_{CP} = [-0.28 \pm 0.70 \text{(stat)} \pm 0.25 \text{(syst)}]\%$. A broad program of charm physics is underway and further results in more channels are soon to follow. With the large data set expected in 2011-2012, LHCb is poised to become a leader in charm physics.

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