Charm Physics at LHCb

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Abstract. LHCb is set to significantly increase the world charm sample in the next data taking period, leading charm physics to a new level of precision. In these proceedings we present recent LHCb results and prospects for the 2011/2012 data taking period.

1. Introduction

LHCb [1], the dedicated flavour physics experiment at the LHC [2], will exploit the huge $b\bar{b}$ and $c\bar{c}$ cross section of $> 7$ TeV proton proton collisions to explore the precision frontier at the LHC. The same characteristics that optimise LHCb for B physics, also optimise it for charm physics. The charm cross section is about 20 times larger than the $b$ cross section. LHCb is expected to select huge charm samples, leading to new opportunities of high-precision measurements in charm, with unique sensitivity to physics beyond the Standard Model. In these proceedings we review the current status of the LHCb charm physics programme and prospects for the future, especially for the 2011/2012 run, which is also discussed in [3].

Figure 1. Schematic of the LHCb detector inside the cavern. The interaction point is on the left hand side of the diagram, inside the VELO detector.

Figure 2. Pseudo rapidity ($\eta$) and transverse momentum ($p_T$) coverage of different LHC experiments. (Also shown: approximate $b\bar{b}$ cross section integrated over the corresponding $\eta, p_T$ region.)
2. Charm Cross Sections

Heavy flavour hadro-production is an experiment-led field which has continued to defy theoretical predictions ever since the heavy flavour production cross sections was found to be much larger than predicted by Next-to-Leading-Order (NLO) QCD calculations (see for example [4] and [5]). The discrepancy between data and theory was particularly dramatic in the quarkonium production, where the “Colour Singlet Model” leading-order QCD calculation underestimates the measured cross section by more than an order of magnitude (e.g.[6]).

Since these measurements were made about a decade ago, there has been a number of theoretical advances. Fixed-Order Next to Leading Logarithm (FONLL) calculations [7] describe the open charm and \( b \) production cross sections well. Competing models have been put forward that describe the observed quarkonium production rates and \( p_T \) spectra well. None of these predicted however the \( J/\psi \) polarisation as a function of \( p_T \) measured by CDF [8]. More recent models devised since this measurement provide a better, but still not perfect description of the observed \( J/\psi \) polarisation [9, 10, 11, 12, 13].

It is clear that LHCb, the dedicated flavour physics experiment at the LHC, covering a unique kinematic range, will play a crucial role in further investigating the hadro-production mechanisms of heavy flavour.

2.1. Hidden Charm Cross Section Results

The differential \( J/\psi \) cross section as a function of transverse momentum for both prompt and secondary \( J/\psi \) is shown in Fig. 3. Prompt production is distinguished from \( J/\psi \) resulting from \( b \) decays using the characteristically long lifetime of \( b \) hadrons, which leads to displaced vertices. Figure 3(a) shows the measured prompt cross section, Fig. 3(b) the cross section for \( J/\psi \) from \( b \) decays.

This measurement is in good agreement with, and considerably extends the kinematic range of the recent measurement by CMS [15]. The authors of the LHCb paper [14] compare the result to various theoretical models and find acceptable agreement. The integrated prompt \( J/\psi \) production cross section over the fiducial region \( p_T < 14 \text{ GeV} \) and \( 2.0 < y < 4.5 \) is found to be [14]

\[
\sigma_{J/\psi \text{prompt}} (p_T < 14 \text{ GeV}, 2.0 < y < 4.5) = (10.52 \pm 0.04 \pm 1.40^{+1.64}_{-2.20}) \mu b
\]
where the first uncertainty is statistical, the second systematic, and the third due to the unknown polarisation of the $J/\psi$. For $J/\psi$ from $b$ decays, this is [14]

$$\sigma_{J/\psi \text{ from } b} = (1.14 \pm 0.01 \pm 0.16) \mu b$$

where the first uncertainty is statistical, the second systematic (for secondary $J/\psi$ the polarisation is not an additional source of uncertainty). This measurement can be used to calculate the $b\bar{b}$ cross section, and the result, $\sigma (pp \rightarrow b\bar{b}X) = (288 \pm 48) \mu b$, is in excellent agreement with a previous measurement by LHCb, based on semileptonic $b$ decays to charm, of $\sigma (pp \rightarrow b\bar{b}X) = (288 \pm 20 \pm 49) \mu b$ [16].

### 2.2. Double $J/\psi$ Production

In 2011, LHCb performed the first observation of double $J/\psi$ production in proton proton collisions. For this measurement, the invariant mass of two muon pairs, $(\mu^+\mu^-)_1$ and $(\mu^+\mu^-)_2$ is reconstructed. Figure 5 shows the number of $J/\psi$ found in $(\mu^+\mu^-)_1$ as a function of the reconstructed mass in $(\mu^+\mu^-)_2$.

![Figure 4. Reconstructed mass of $D^\pm, D_s \rightarrow \pi\pi\pi$ candidates for the $D_s$ cross section measurement in 1.8 nb$^{-1}$ of LHCb data. (The $D^+$ cross section has been measured in $D^\pm \rightarrow \pi\pi\pi$).](image)

![Figure 5. The invariant mass of two muon pairs, $(\mu^+\mu^-)_1$ and $(\mu^+\mu^-)_2$ is reconstructed. The plot shows the number of $J/\psi$ found in $(\mu^+\mu^-)_1$ as a function of the reconstructed mass in $(\mu^+\mu^-)_2$.](image)

where the first error is statistical and the second systematic.

### 2.3. Open Charm Cross Section Results

LHCb have measured the open charm production cross section in various channels. Figure 6 shows the differential cross sections as function of $p_T$ in different $y$ bins for $D^0$, $D^*$, $D^\pm$, and $D_s$ production, which are in good agreement with calculations by M. Cacciari, S. Frixione, M. Mangano, P. Nason, G. Ridolfi [20]; and B.A. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger [18]; both groups have updated earlier calculations [21, 22, 19] to account for LHC running conditions and LHCb’s unique kinematic range. We use the measured differential cross sections to extrapolate to a total $c\bar{c}$ cross section for $pp$ collisions at $\sqrt{s} = 7$ TeV of:

$$\sigma(pp \rightarrow c\bar{c}) = (6.10 \pm 0.93) \text{ mb}$$

approximately 20× the $b\bar{b}$ cross section.
between up-type quarks, which can be affected by new physics in a very different way than those in down-type quarks, which can be investigated in the $B^0_{s,d}$ and $K^0$ systems. Particularly interesting is CP violation in the D system, which is essentially zero in the Standard Model, but could

3. Charm mixing and CP violation

3.1. The neutral $D^0$ system

The neutral D system is the only neutral meson system that mixes and consists of up-type quarks. It therefore provides a unique window on Flavour Changing Neutral Currents (FCNC’s) between up-type quarks, which can be affected by new physics in a very different way than those in down-type quarks, such as investigated in the $B^0_{s,d}$ and $K^0$ systems. Particularly interesting is CP violation in the D system, which is essentially zero in the Standard Model, but could

Figure 6. Open charm production cross sections as a function of transverse momentum $p_T$ for different rapidity ($y$) ranges using 1.8 nb$^{-1}$ of LHCb data. Also shown: The cross section from Pythia (LHCb tune, in red) and calculations by B.A. Kniehl, G. Kramer, I. Schienbein, and H. Spiesberger (broken line) [18, 19]; and M. Cacciari, S. Frixione, M. Mangano, P. Nason, G. Ridolfi (solid line), [20, 21, 22]. All experimental results are preliminary.
be significant in many New Physics scenarios. The discovery of CP violation in charm decays would be a clear signal for physics beyond the Standard Model.

**Mixing Parameters** The physical mass eigenstates $D_1$, $D_2$ of the neutral D meson are superpositions of the flavour-specific states $D^0$ and $\bar{D}^0$:

$$D_1 = pD^0 + q\bar{D}^0, \quad D_2 = pD^0 - q\bar{D}^0$$

where $p$ and $q$ are complex numbers satisfying $|p|^2 + |q|^2 = 1$. The mass and the width difference between $D_1$ and $D_2$ are $\Delta m$ and $\Delta \Gamma$. Mixing in the neutral D system is conventionally parametrised by the parameters $x$ and $y$ given by

$$x = \frac{\Delta m}{\bar{\Gamma}}, \quad y = \frac{\Delta \Gamma}{2\bar{\Gamma}},$$

where $\bar{\Gamma}$ is the average width of the D system. Evidence for mixing has been found by BaBar, BELLE and CDF [24, 25, 26, 27, 28, 29, 30, 31]. While no single experiment has found 5$\sigma$ evidence for mixing, combining these measurements provides evidence for mixing beyond 5$\sigma$ [32]. With $x = 0.65^{+0.18}_{-0.19}$ and $y = 0.74 \pm 0.12$, values that are consistent with the (rather broad) Standard Model expectation [33, 34, 35, 36, 37, 38].

**CP Violation in Charm** CP violation in charm can manifest itself as CP violation in mixing, CP violation in the interference between mixing and decay and as direct CP violation. In the Standard Model, CP violation in charm decays is expected to be small, at a level $\lesssim 10^{-3}$ [39, 40, 41]. Observing it would be a clear sign of physics beyond the Standard Model.
CP violation in the mixing occurs if \(|q/p| \neq 1\). CP violation in the interference between mixing and decay is parametrised by the phase \(\phi\). The phase \(\phi\) is the exact equivalent in the neutral \(D^0\) system of the parameter \(-2\beta\) in the neutral \(B^0_d\) system or \(\phi_s = -2\beta_1\) in the \(B_s\) system. The phase of the ratio \(q/p\) is convention dependent; usually, a phase convention is chosen where \(q/p = |q/p| e^{i\phi}\), so that both of the aforementioned types of CP violation are encoded in the same complex ratio \(q/p\). Current world-averages for \(|q/p|\) and \(\phi\) are consistent with the no CP violation hypothesis [32]. Finally, CP violation in charm decays can also manifest itself as direct CP violation in time-integrated decay rate asymmetries:

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

Of particular interest are singly Cabibbo suppressed (SCS) decays which are sensitive to new contributions from QCD penguin operators. This could yield direct CP violating effects of \(\mathcal{O}(10^{-2})\) [42, 43]. Current limits are already approaching this level of precision. Particularly encouraging are the recent CDF results [44, 45] \(A_{CP}(D \to \pi\pi) = (0.22 \pm 0.24(\text{stat}) \pm 0.11(\text{sys}))\) \% and \(A_{CP}(D \to KK) = (-0.24 \pm 0.22(\text{stat}) \pm 0.10(\text{sys}))\) \% which constitute the single most precise measurements in the respective channels, with approximately the same precision as the previous world-averages [32]. This demonstrates that such difficult measurements are possible at hadron colliders. Of course, LHCb will have to deal with the additional complication of the non CP symmetric proton-proton initial state, in contrast to CDF’s \(pp\), but on the other hand will have far greater statistical power. At least initially, rather than measuring \(A_{CP}(D \to \pi\pi)\) and \(A_{CP}(D \to KK)\) individually, LHCb will measure the difference \(A_{CP}(D \to KK) - A_{CP}(D \to \pi\pi)\) in order to control systematic uncertainties.

3.2. Mixing and CP violation through lifetime ratios

The parameter \(y_{CP}\) is the ratio of \(D^0\) lifetimes measured in decays to a (nearly) flavour specific and a CP-specific states:

\[
y_{CP} \equiv \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to KK)} - 1 = y \cos \phi - \frac{1}{2} \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) x \sin \phi
\]

In the absence of CP violation, \(y_{CP} = y\). Even in the presence of CP violation, the deviation of \(y_{CP}\) from \(y\) will be only be of second order in terms of the CP violating parameters. In contrast, the lifetime asymmetry between CP-conjugate decays to CP eigenstates, is linearly sensitive to CP violation [46]:

\[
A_f \equiv \frac{\tau(\bar{D}^0 \to K^+K^-) - \tau(D^0 \to K^+K^-)}{\tau(\bar{D}^0 \to K^-K^+) + \tau(D^0 \to K^-K^+)} = \frac{1}{2} \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y \cos \phi - x \sin \phi
\]

As well as \(D \to KK\), any other CP-specific final state such as \(\pi\pi\) is suitable. Both measurements, \(y_{CP}\) and \(A_f\), have the appealing feature that many detector effects cancel in the lifetime ratio, which will help control systematics - crucial given the excellent statistical precision we expect at LHCb. The current world average for \(y_{CP}\) is \((1.107 \pm 0.217)\) \% [32], dominated by BaBar’s measurement [47], based on 2.7 M \(K\pi\) and 260 k KK events in 0.38 ab\(^{-1}\). The world average of \(A_f\) is \((0.123 \pm 0.248)\) \% [32] which is based on measurements by BaBar [48] and BELLE [49], with a combined event sample of approximately 2 M \(K\pi\) pairs, 180 k KK and 80 k \(\pi\pi\) events. At LHCb, this measurement will be performed using \(D^{*+} \to D^0\pi^+\) and \(D^{*-} \to \bar{D}^0\pi^-\) decays. The
(a) $\sim 862,000$ tagged $D \rightarrow K\pi$ events. (b) $\sim 97,000$ tagged $D \rightarrow KK$ events. (c) $\sim 34,000$ tagged $D \rightarrow \pi\pi$ events.

Figure 8. The plots show the mass difference $\Delta m = m_{D\pi} - m_D$ between reconstructed mass of $D^* \rightarrow D\pi$ and $D$ candidates, for different decay modes of the $D$, in $34\text{ pb}^{-1}$ of LHCb data. Note the logarithmic scale - the background levels are small.

4. Dalitz Analyses
Dalitz plot [50] analyses and their 4-body generalisations are of huge significance for the extraction of $\gamma$ from $B^\pm \rightarrow DK^\pm$ decays [51, 52, 53, 54, 55, 56], and for charm mixing and CP violation measurements [24, 27, 57, 58], and form a central element of LHCb’s charm programme. To illustrate LHCb’s progress in this area, one of the first Dalitz plots at LHCb is shown in Fig. 9.

5. Summary
With a charm cross section that is $20 \times$ the $b\bar{b}$ cross section, the LHC is set to produce vast quantities of charm, and LHCb, optimised for flavour physics, is the experiment in the best position to exploit this bonanza. With these data, LHCb will soon be able to turn charm mixing from a discovery into a precision measurement, and probe for CP violation in charm in a variety of ways, providing a unique window on possible new physics contributions. Charm physics at LHCb is an extremely rich and varied field, and in these proceedings we had to leave out many important topics such as rare decays, charm spectroscopy, amplitude analyses, charm’s impact on $\gamma$ and many more [3]. The step-change in precision offers the potential for new and surprising result, and will truly over-constrain the description of charm in the Standard Model, and in fact any other model that might be a candidate to take its place.
