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Charm Physics at LHCb

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LHCb is a heavy flavour precision experiment at the LHC. In addition to the core beauty physics program, LHCb will have a large charm data sample which will be used to measure the $D^0 - \overline{D}^0$ mixing parameters and search for CP-Violation and rare decays in various charm meson decay modes. In this review, an overview of the charm physics program of LHCb is given through a series of illustrative examples.

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1. Introduction

LHCb is a dedicated b-physics experiment at LHC. It consists of a single arm forward detector [1] with an angular coverage between $10-250$ mrad in the vertical and $10-300$ mrad in the horizontal direction, designed to operate at a center of mass energy $\sqrt{s}=14$ TeV, with a luminosity of $2-5\times10^{32}$ cm^{-2} s^{-1}. One nominal year of LHCb operation corresponds thus to an integrated luminosity of 2 fb^{-1}. Operational conditions for the first year of data taking in 2010 however correspond to a center of mass energy of $\sqrt{s}=7-10$ TeV and an integrated luminosity of around 100 pb^{-1} of data.

In addition to the core beauty physics program, LHCb expects to have a large charm data sample, which will be used for measurements of $D^0-\overline{D}^{\,0}$ mixing parameters, and searches for CP-Violation and rare decay in several charm meson decay modes. Charm at LHCb will come from two different sources: secondary charm coming from B-meson decays and, prompt charm, which is produced at the interaction vertex. Most part of the secondary charm will be produced through the decays chains $B\to D^{*\pm}X$ (BR $\sim$ 0.23), $B\to D^0X$ (BR $\sim$ 0.63) and $B\to D^{\pm}X$ (BR $\sim$ 0.24). The prompt charm sample is expected to be of the order of seven times greater in size than the secondary charm data sample, according to predictions of MC generation programs, but will require a simultaneous optimization of the trigger for beauty and charm physics. In addition, the former sample is expected to have potentially less background than the latter category. At the design energy, the $c\bar{c}$ total cross section predicted by PYTHIA [2] is 8.31 mb, while at 7 TeV, the cross section is expected to be lower by a factor of about 2.

There currently exist several performance studies on charm physics using both, prompt and secondary charm samples. These studies have been performed including a full simulation of the detector response. These studies will be described in this review.

2. The LHCb trigger and expected charm samples

The LHCb trigger is organized in a two-fold structure. The earliest stage, L0, is a hardware trigger which will select high p_T particles. The second stage, the High Level Trigger (HLT), is a software trigger which is also divided in two parts. The first, HLT1, is aimed to reconfirm the L0 decision while the second one, HLT2, is dedicated to inclusive selections [3], based on information from all subdetectors.

The low luminosity run expected for 2010 will allow for lower p_T thresholds than in nominal conditions, which will translate in a better performance of the detector for charm physics. Monte Carlo (MC) studies indicate a combined L0 and HLT1 trigger efficiency reaching 70 % in the $D^0\to hh$ and 92 % in the $D^0\to\mu\mu$ channels. Regarding the HLT2, several different scenarious are still under consideration. MC studies have shown that, for a likely trigger scenario in 2010, the estimated efficiencies with respect to the combined L0 and HLT1 output can reach up to 86 % in the $D^*\to D^0(hh)\pi$, and 65 % in the $D^+\to KK\pi$ decay modes. The estimated prompt charm yields for the low luminosity run in 2010, for 100 pb^{-1} of data, are about 24×10^6 events in the $D^0\to K^-\pi^+$ channel and 2.4×10^6 $D^0\to K^+K^-$ events, which will allow high precision $D^0-\overline{D}^{\,0}$ mixing studies and CP Violation searches.

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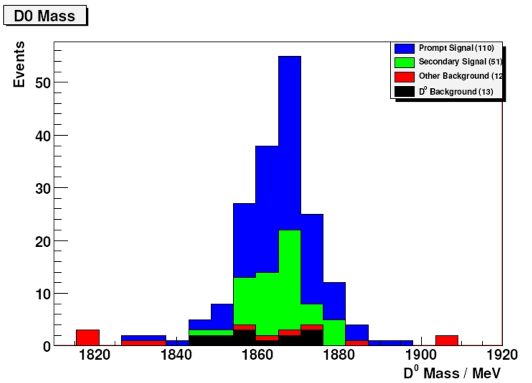

Figure 1: $D^0 \to K^-\pi^+$ prompt (blue) and secondary (green) passing the LO and HLT trigger.

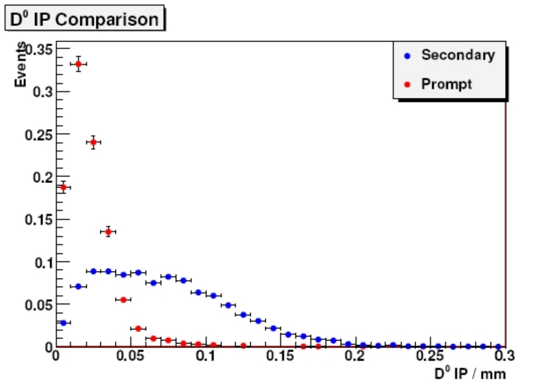

Figure 2: IP with respect to the primary vertex for prompt (red dots) and secondary (blue dots) charm. Both distributions are normalized to unit area.

For secondary charm it is expected of the order of 10^8 tagged D^0 per nominal year of LHCb operation at full luminosity, equivalent to 2 fb^{-1} of data, coming from the decay chain $B \to D^*(D^0\pi) + X$. The yields for some specific $D^0 \to hh$ decay channels have been estimated using MC samples including the full simulation of the detector. They are 50×10^6 $D^0 \to K^-\pi^+$, 0.2×10^6 $D^0 \to K^+\pi^-$, 5×10^6 $D^0 \to K^+K^-$ and 2×10^6 $D^0 \to \pi^-\pi^+$ events. Altough no detailed studies exist yet, the expected charm data sample shows an interesting potential in other D decay modes, such as three and four body decays, semileptonic decays, etc.

An example of the expected $D^0 \to K^-\pi^+$ prompt and secondary samples selected with the trigger scenario for 2010 is shown in Figure 1. Studies have been also performed in order to determine how to separate the prompt from the secondary charm samples. One of the most promising cuts is on the Impact Parameter (IP) of the reconstructed meson with respect to the primary vertex. As shown in Fig. 2, this variable has a very different distribution for prompt and secondary mesons and can be fitted to determine the relative population of each category in the sample.

3. y_{CP} mixing measurement

Several measurements are planned of the $D^0 - \overline{D}^0$ mixing parameters x and y,

$$x = \frac{m_1 - m_2}{\Gamma}; \quad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} , \tag{3.1}$$

where the indices $1,2$ refer to the mass eigenstates. As well as being interesting in their own right, these studies are important as they can also be used to look for evidence of CP-Violation in mixing related phenomena, which would be a clear indication of New Physics (NP).

The lifetime ratio of the decays to CP eigenstates $D^0 \to K^+\pi^+$ and $D^0 \to K^+K^-$ can be written as

$$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 = y\cos\phi - \frac{1}{2}A_M x \sin\phi , \tag{3.2}$$

where $|q/p| = 1 \pm A_M$ parameterizes CP-Violation in mixing, and ϕ is a weak phase [4]. If CP is conserved, $A_M = \phi = 0$ and $y_{CP} = y$. To date, the best measurement is $y_{CP} = (1.31 \pm 0.32 \pm 0.25)\%$, by the Belle Collaboration [5].

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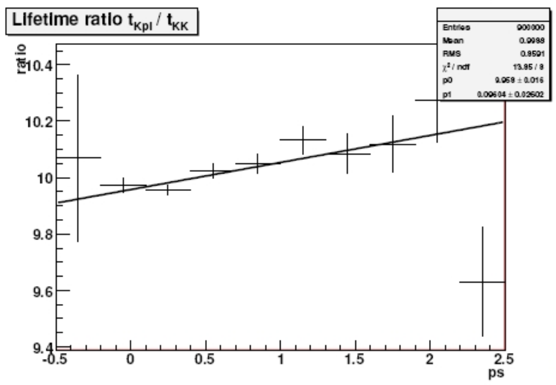

Figure 3: Binned fit to the ratio $R_i(t)$. The straigt line is the resul of the fit of the MC data to eq. 3.3.

LHCb has conducted two different performance studies using a MC sample including the full simulation of the detector, the first one consisting in a fit to the lifetime distribution of the $D^0 \to K^-K^+, K^-\pi^+$, and the second one performing a binned fit to the ratio

$$R_i(t) = \frac{N_i^{K\pi}(t)}{R_i^{KK}(t)} \, , \tag{3.3}$$

where $N_i^{KK,K\pi}$ is the number of $D^0 \to KK, K\pi$ events respectively, in the i-th bin of proper time t. The ratio of Eq. 3.3 can be writen as

$$R(t) \simeq \frac{N^{K\pi}}{N^{KK}} \frac{\tau_{KK}}{\tau_{K\pi}} \left(1 - \frac{y_{CP}}{\tau_{K\pi}} t\right) \, , \tag{3.4}$$

from where y_{CP} can be estimated (See Fig. 3). In both cases, using the 2010 trigger scenario and assuming 100 pb^{-1}, the estimated statistical error is $\sigma_{stat}(y_{CP}) \sim 1.1 \times 10^{-3}$, which is significantly more precise than the existing world best measurement.

4. Wrong sign $D^0 \to K\pi$ mixing measurement

$D^0 - \overline{D}^{\,0}$ mixing searches can be performed by looking at the Wrong Sign (WS) time dependent decay rate in the $D^0 \to K^+\pi^-$ channel,

$$r_{WS}(t) = e^{-\Gamma t} \left(R_D + \sqrt{R_D} y' \, \Gamma t + \frac{1}{2} R_M (\Gamma t)^2 \right) \, , \tag{4.1}$$

where R_D is the ratio of the Doubly Cabibbo Suppressed (DCS) to Cabibbo Favoured (CF) decay rates, $R_M = (x^2 + y^2)/2 = (x'^2 + y'^2)/2$ is the mixing rate and $x' = x\cos\delta + y\sin\delta$, $y' = y\cos\delta - x\sin\delta$, where δ is the strong phase difference between these two decay paths.

LHCb has performed an extensive study by using a selected sample of $D^0 \to K^-\pi^+$. $D^0/\overline{D}^{\,0}$ candidates are tagged at the creation and their origin and decay vertices have to be precisely estimated. So far only secondary charm events have been considered in the analysis [6]. Tagging is acomplished by requiring that the $D^0/\overline{D}^{\,0}$ candidate originate in a $D^+ \to \pi^+ D^0$ decay, or its charge conjugate. The sign of the 'slow pion', $\pi^\pm$, tags the original flavor of the candidate as D^0

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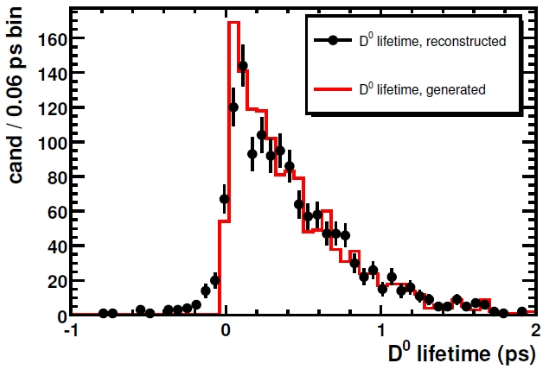

Figure 4: Lifetime of the D^0 candidates for the generated (red line) and reconstructed (black dots) $D^0 \to K^-\pi^+$ samples.

	Data Set	N_{WS}	x'^2 $(\times 10^{-3})$	y' $(\times 10^{-3})$
BaBar	384 fb^{-1}	4030	$-0.22 \pm 0.30 \pm 0.212$	$9.7 \pm 4.4 \pm 3.1$
Belle	400 fb^{-1}	4024	$0.18^{+0.21}_{-0.23}$	$0.6^{+4.0}_{-3.9}$
CDF	1.5 fb^{-1}	12700	-0.12 ± 0.35	8.5 ± 7.6
LHCb	10 fb^{-1}	232500	$x'^2 \pm 0.064$ $(stat)$	$y' \pm 0.87$ $(stat)$

Table 1: Sensitivity of LHCb in comparison to results by BaBar [9], Belle [5] and CDF [10] for the $D^0 - \overline{D}^0$ mixing measurement using the WS $D^0 \to K^+\pi^-$ decay.

or $\overline{D}^0$. The WS final state can be produced either as a direct DCS decay, $D^0 \to K^+\pi^-$, either as an oscillation followed by a CF decay. In order to achieve the required precision in the determination of the birth vertex of the $D^0/\overline{D}^0$ decay candidates, a partial reconstruction of the mother B-meson has to be done. By means of this procedure, the resolution in the determination of both, the birth and decay vertices of the $D^0/\overline{D}^0$ candidates becomes equivalent and within the scale of precision set by the mean lifetime of the D^0 [7], $\tau_{D^0} \sim (410.1 \pm 1.5) \times 10^{-15}$ s. The obtained resolution in the proper time is then of about 0.045 ps. A comparison of the lifetime of the generated and reconstructed samples is shown in Fig. 4.

The sensitivity of LHCb for the $D^0 - \overline{D}^0$ mixing measurement using this technique has been estimated for 10 fb^{-1}, corresponding to 5 years of nominal data taking of the experiment. Results, in comparison to recent measurements by the BaBar [8], Belle [5] and CDF [9] Collaborations are displayed in Table 1.

Studies are underway to investigate performing this measurement with prompt charm, where the higher production cross-section may allow for even higher precision to be attained.

5. Other CP-Violation measurements

Performance studies on CP-Violation searches in the $D^+ \to K^+K^-\pi^+$ channel are also being done. CP-Violation in Singly Cabibbo suppressed decays in the Standard Model (SM) is predicted to be of $\mathcal{O}(10^{-3})$, meaning that an enhancement beyond this order could be a clear signal of NP. The important role of gluonic Penguins in these decays make them particularly sensitive to the

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intervention of NP effects [10]. Studies are being conducted using the Dalitz Plot technique, which will provide a better sensitivity than a rate analysis[11]. Dalitz Plot analyses are also relatively insensitive to effects coming from the production asymmetries. A D^+ sample of about 10^6 events is expected in the $KK\pi$ decay mode within the trigger scenario for 2010.

6. Rare decays

A search for the rare decay $D^0 \to \mu^+\mu^-$ will be performed with high priority during the first physics run of LHCb. The SM prediction for this decay is a branching fraction $BR < 10^{-12}$, however in presence of R-Parity violating SUSY, the branching fraction can grow up to 10^{-6} [12]. The best limit up to date is from the Belle Collaboration which has found $BR < 1.4 \times 10^{-7}$ at a 90 % CL [13] with 360 pb^{-1} of data. LHCb expects a significant improvement on the previous measurements thanks to the high charm statistics expected for the 2010 run. A multivariate analysis using tagged D^0s is being currently considered to conduct this search.

7. Conclusions

LHCb expects to accumulate a large charm sample which will allow for several precise charm physics studies. Efforts are underway to exploit both the prompt charm, which will be produced at the interaction vertex, as well as the secondary charm, coming from the decay of B mesons. Performance studies are promising in the areas of $D^0 - \overline{D}^{\,0}$ mixing measurements, the search of CP-violation and rare decays, etc. There are also on-going performance analysis on doubly charm baryons, X, Y, Z spectroscopy, J/Ψ, $D_{s,1,2,J}$ production, etc. In summary, LHCb has many exiting possibilities even for the first physics run in 2010, which is expected to correspond to around 100 pb^{-1} of data.

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