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Charm physics studies at CMS

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Summary. — Measuring the charm cross-section at CMS experiment at the LHC provides a test of Quantum Chromodynamics. The differential cross-section is extracted by studying the decay of D^* mesons, in a final state with $K\pi\pi$. Some common aspects of the studies performed so far, such as signal extraction and separation of charm and beauty contributions, are described.

1. – Introduction

The charm cross-section measurement provides a test of Quantum Chromodynamics (QCD), the Standard Model (SM) theory of strong interaction. Since the charm quark mass is larger compared to Λ_{QCD}, this cross-section measurement provides a test of perturbative QCD (pQCD). A hadron production event in pp collision at the LHC must be described by both perturbative and non-perturbative QCD contributions. The factorization theorem allows the separation of contributions related to non-perturative QCD from those of perturbative QCD. A general cross-section formula for hadron production is expressed as a convolution of these terms,

$$\sigma_{pp\to hX} \approx PDF_1 \otimes PDF_2 \otimes \hat{\sigma}_{pQCD} \otimes FF. \tag{1}$$

Here, $\hat{\sigma}_{pQCD}$ is the point-like cross-section at the quark level, PDF_i are the Parton Distribution Functions relative to the partons in the colliding protons and FF refers to the Fragmentation Function. These last two components constitute the non perturbative contribution, energy-dependent through the DGLAP equations. In the case of $c\bar{c}$ production, the perturbative component arises from gluon-gluon fusion or quark-antiquark annhilation. Calculation of charm cross-section are currently available up to Next-to-Next Leading Order (NNLO) for total cross-section ($\sim \alpha_s^4$) [1] and Next-to-Leading Order (NLO) ($\sim \alpha_s^3$) with Next-to-Leading Log (NLL) ($\sim \log^2 \alpha_s$) contributions for differential cross-section in p_T and rapidity [2]. Within the context of the CMS experiment, results on charm cross-section have been obtained using the LHC Run II data at a centre-of-mass energy of 13 TeV [3], along with findings published in PhD theses based on data collected at $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 7$ TeV [4,5]. During the initial phase of the LHC Run III, data at a centre of mass energy $\sqrt{s} = 0.9$ TeV have been collected before moving to an energy of 13.6 TeV. The analysis at 0.9 TeV is still in preparation. Measurements at different energies can be used to extract, as a final goal, the cross-section as a function of the centre-of-mass energy.

The next two sections describe some common key aspects of charm cross-section extraction at CMS.

2. – Signal extraction

The extraction of open charm production cross-section involves the decay chain of the D^* charmed meson $D^{*+} \to D^0\pi^+ \to K^-\pi^+\pi^+$, and its charge conjugate. This decay process exhibits some characteristics used to separate it from other possible contributions. Due to the little mass difference between the D^* and D^0 charmed mesons, the D^0 and π_s are produced almost at rest in the D^* rest frame. The pion coming from the primary vertex is referred as "slow pion" (π_s) since it has a slow momentum compared to K and π from D^0, resulting in a little phase space available. The decay of the D^0, neglecting doubly Cabibbo suppressed contributions, can only proceeds with a K having an opposite charge with respect to the π_s. This charge combination allows to separate signal from background. Additionally, compared to the other possible decays ($D^{*+} \to D^+\pi^0$ and $D^{*+} \to D^+\gamma$), this final state have only charged particles and an higher branching ratio. The cross-section is then experimentally computed, in the case of doubly differential cross-section, by using the following formula:

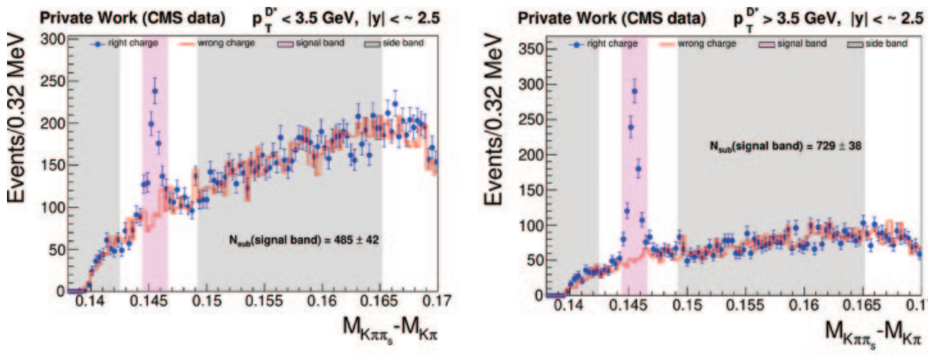
$$\frac{\Delta\sigma}{\Delta p_T \Delta|y|} = \frac{N_{sub}}{\Delta p_T \Delta|y| \epsilon \cdot BR(D^* \to K\pi\pi_s) \cdot \mathcal{L}}, \tag{2}$$

where N_{sub} is the number of signal events, ϵ the signal reconstruction efficiency computed from the simulated samples, $BR(D^* \to K\pi\pi_s)$ the branching ratio of the decay under study (2.7%), Δp_T and $\Delta|y|$ the bin width of transverse momentum and rapidity, respectively, and $\mathcal{L}$ the integrated luminosity.

The signal extraction is performed using a subtraction method in the $\Delta M = M_{K\pi\pi_s} - M_{K\pi}$ variable for each phase space region independently. Since particle identification for K and π is not possible at CMS, the assignment of mass value is done according to the charge sign of the track (Q_K, Q_π). As a consequence, a non resonant combinatorial background can pass the selection. This background is assessed by categorizing events passing the selection in right ($Q_K \neq Q_\pi$) and wrong ($Q_K = Q_\pi$) charge combinations. Background is first computed in the sidebands in data ($\Delta M < 0.14248, \Delta M > 0.14664$) , then normalized and subtracted from the right charge contribution in the signal region. An illustrative example, based on the Run III 0.9 TeV data from CMS experiment, corresponding to an integrated luminosity of $\mathcal{L} = 3.2\,\mathrm{nb}^{-1}$, is shown in fig. 1, where the phase space is divided in higher ($p_T^{D^*} > 3.5$ GeV) and lower ($p_T^{D^*} < 3.5$ GeV) transverse momentum with a rapidity of $|y| < 2.5$.

3. – Charm and beauty contributions

The goal of these measurements is to quantify the prompt contribution only, namely events where the D^* is produced at the primary vertex (PV), while non-prompt events



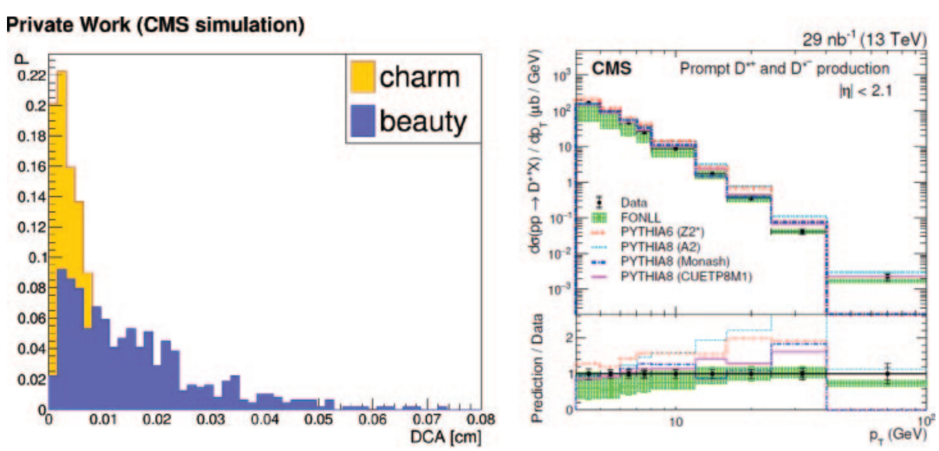
(a) (b)

Fig. 1. – Example of signal extraction: lower (a) and higher (b) transverse momentum regions. The plots also display the sidebands and the signal region where the right-wrong charge subtraction is performed and the number N_{sub} of resulting events.

are those where the D^* comes from the decay of b hadrons ($B \to D^* X$). This component is distinguished from the former by computing the fractions f_c and f_b of matched charm and beauty in the MC samples, following the signal extraction method of the previous section or by using kinematic variables sensitive to B hadron like events, such as the distance of closest approach (DCA). The DCA accounts for the difference in decay length of charmed and beauty mesons and is computed using the following formula:

$$DCA = \Delta_{D^0} \sin(\phi) \tag{3}$$

Here, Δ_{D^0} is the distance between the PV and the point of D^0 decay, while Φ is the angle between the D^0 decay length and the distance between the PV and SV. The DCA value is higher for non-prompt events because, in this case, the point of D^* production



(a) (b)

Fig. 2. – (a) DCA variable for matched charm and beauty, *i.e.*, D^* events that are reconstructed prompt or non-prompt in 0.9 TeV MC sample. (b) p_T differential cross section, sourced from [3], for prompt $D^{*\pm}$ production, $|\eta| < 2.1$, together with some theoretical predictions.

is displaced from the PV. In the non-prompt scenario, in fact, the decay length is of the order of 400–500 μm compared to a typical decay length of 100–200 μm of prompt charmed mesons. The DCA variable in the MC sample for Run III 0.9 TeV is shown in fig. 2(a). The charm fraction is then applied to the number of extracted signal events, replacing N_{sub} to $f_c N_{sub}$ in eq. (2).

At this point, all required elements are avilable to compute the differential cross-section. As an example, fig. 2(b) shows the prompt only D^* production cross-section as a function of the transverse momentum for pseudorapidity $|\eta| < 2.1$, measured at 13 TeV [3]. The analysis of 0.9 TeV data is still in progress.

4. – Summary

The key aspects of the charm cross-section extraction at CMS experiment in the $D^* \rightarrow K\pi\pi_s$ decay have been described. Such studies are seeing a growing interest also due to some recent results from the ALICE Collaboration [6] pointing towards a non-universality of the charm fragmentation fraction, namely a dependence of fragmentation from the quark production process. In the study of [7] charm fragmentation fraction (integral of FF) for D^0 significantly differ from the values expected from simulation based on e^+e^-/ep data. Furthermore, also a p_T dependence of the fragmentation fraction has been observed. These new results can be included in the derivation of the charm cross-section as demonstrated in [8], with the aim of a total cross-section extrapolation as a function of energy.

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