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Charm physics studies at CMS(*)

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Summary. — The extraction of the charm cross section provides a test of Quantum Chromodynamics. At the CMS experiment, measurements are performed by studying the decay chain of the D^* meson. Some common aspects of the studies performed are discussed, together with recent results concerning fragmentation non-universality.

1. – Introduction

The charm quark mass is larger compared to Λ_{QCD}, and measurement of its cross section provides a test of perturbative Quantum Chromodynamics (QCD), giving constraints on the charm mass or parton density functions (PDFs). Currently, theoretical predictions for the charm production cross section $\sigma_{c\bar{c}}$ are available up to Next-to-Next-to-Leading Order (NNLO) for the total cross section, and Next-to-Leading Order (NLO) with Next-to-Leading Log (NLL) contibutions for transverse momentum and rapidity differential cross sections [1] [2]. Hadron production in a *pp* collision is described assuming the factorization theorem, separating the perturbative and non-perturbative contribution to the cross section. At leading-order, the cross section reads:

$$\frac{d\sigma}{dz} \sim \int dx_1 dx_2 f(x_1, \mu_F) f(x_2, \mu_F) \hat{\sigma}_{q\bar{q}\to c\bar{c}} [D_q^h(z) + D_{\bar{q}}^h(z)] \tag{1}$$

where $\sigma_{q\bar{q}\to c\bar{c}}$ is the point-like cross section, which is a perturbative quantity. The functions $f(x_1, \mu_F)$ and $f(x_2, \mu_F)$ are the PDFs and $D^h(z)$ are the fragmentation functions (FFs), describing the probability for a hadron h to emerge from a parton q, with a fraction z of its momentum. PDFs and FFs are non-perturbatively calculable and depend logarithmically on the energy scale through the DGLAP equations [3] [4] [5] [6]. In the context of CMS experiment, results on charm cross section has been obtained with LHC Run 2 data, at a center of mass energy of $\sqrt{s} = 13\ TeV$ [7]. Other studies, which share the same decay chain and similar analysis strategy, are either in preparation or have

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been published in Phd theses [8] [9] [10] for the different energies reached at the LHC ($\sqrt{s} = 0.9\ TeV, 5.02\ TeV, 7\ TeV, 13\ TeV$). The final goal of this set of measurements will be the extraction of the center of mass energy dependence of the total charm cross section $\sigma(\sqrt{s})$.

2. – Signal extraction

The open charm (mesons containing only a single charm quark) production cross section can be extracted using the production and decay chain of the $D^{*\pm}$ meson (in the following the two charge conjugation states are assumed). The decay chain under study, with a total branching ratio of $\sim 2.67\%$ is $D^{*+} \rightarrow D^0\pi_s \rightarrow K^-\pi^+\pi_s^+$, that shows the best signal-to-background ratio thanks to some characteristics that facilitate the signal reconstruction. In the initial decay, $D^* \rightarrow D^0\pi_s$, the pion labeled π_s denotes the "slow pion" as it exhibits a low transverse momentum ($p_T^{\pi_s} \sim 0.3\,\mathrm{GeV}$). This slow momentum arises from the small mass difference between the two charmed hadrons D^* and D^0, which constrains the available phase space. A dedicated particle identification in the CMS apparatus is not available for K and π, and the assignment is done based on the charge of the final state particles. Signal and background can be distinguished by the charge combination of the reconstructed particles in the final state, in fact, neglecting doubly Cabibbo suppressed processes, the background corresponds to the "wrong charge" final-state combination in which the K has the same charge sign of the slow pion π_s, *i.e*, while the signal corresponds to the "right combination" where, K and π have an opposite charge. This decay chain has the greatest branching ratio compared to other possible decays, which do not have all charged particles in the final state ($D^{*\pm} \rightarrow D^{\pm}\gamma$, $D^*\pm \rightarrow D^{\pm}\pi^0$). Having access to tracks with the lowest possible transverse momentum can improve the data available for the analysis because of the presence of slow pion. Therefore, for $7\,TeV$ and $0.9\,TeV$ analysis, data from the 2010 Run1 of CMS are included, as this period featured special low-p_T tracking that enhanced the reconstruction of K and π [11].

The cross section is extracted with the formula:

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

where N_{sub} is the number of signal events, ϵ the signal reconstruction efficiency, $BR(D^* \rightarrow K\pi\pi_s)$ the branching ratio of the decay under study and Δp_T,$\Delta|y|$ the bin width of transverse momentum and rapidity respectively. For a better resolution, the signal is extracted in the $\Delta M = M_{K\pi\pi_s} - M_{K\pi}$ variable. Figure 1 shows an example of signal extraction in the $\Delta M = M_{K\pi\pi_s} - M_{K\pi}$ variable, for two different bins with data collected during Run 3 at $0.9\,TeV$, with an integrated luminosity of $3.3\ nb^{-1}$. The event yields are extracted with a subtraction method: the combinatorial background due to the wrong charge combination is first computed in the side bands and then subtracted in the signal region.

3. – Non-prompt contribution

The D^* reconstruction selects both prompt and non-prompt contributions, namely events in which a D^* is produced at the primary vertex (PV) or from the decay of a beauty hadron, respectively. Since the goal of the measurements is to extract only

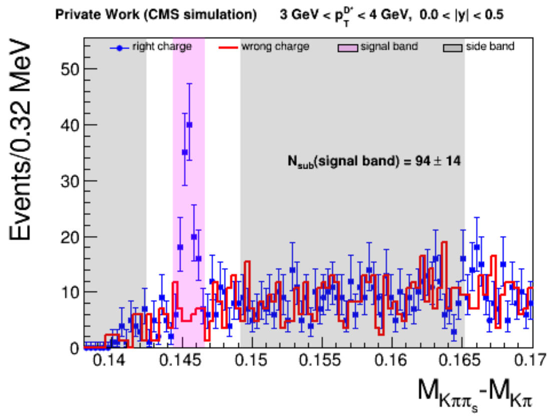


Fig. 1. – Example of signal yield extraction N_{sub} in bin $3\ GeV < p_T < 4\ GeV$. Data collected during Run 3 at $\sqrt{s} = 0.9\ TeV$. The grey bands are the side bands used to compute the combinatorial background that is then subtracted in signal region (pink band).

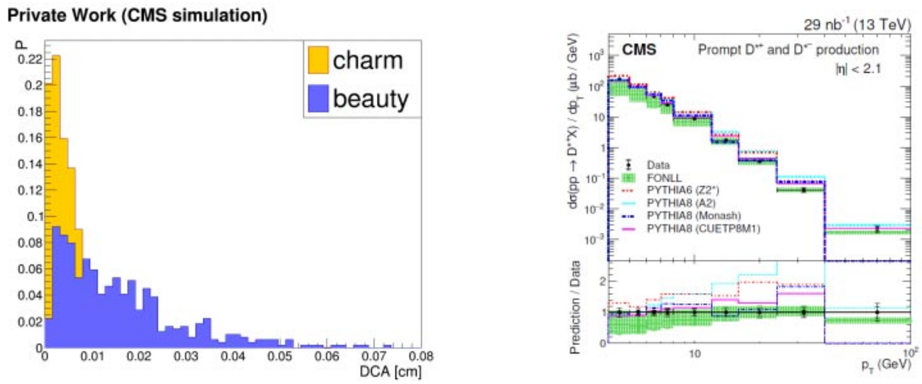
the prompt production cross section, the charmed meson production $B \to D^*X$ must be removed. Contributions from beauty hadrons can be isolated by using a kinematic variable sensitive to the different lifetimes of beauty and charm hadrons. One effective method is to compute the distance of closest approach (DCA). The DCA is a kinematic variable that accounts for the difference in the lifetimes of beauty and charmed hadrons and is defined as:

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

where 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 the secondary vertex (SV). This variable is higher for non-prompt contribution, since the beauty hadrons have a lifetime of the order of $400-500\ \mu m$ against a typical value of around $100-200\mu m$ in the case of charmed hadrons, resulting in a greater value of the angle ϕ since D^* from beauty hadrons are produced displaced form the PV. Figure 2(a) shows the DCA distribution in the 0.9 TeV Run 3 MC sample. The signal yield obtained with the signal extraction strategy described in the previous section is then multiplied by the charm fraction. At this stage, all the necessary components are available to calculate the differential cross-section. As an example, the differential cross section obtained with Run 2 data collected at $\sqrt{s} = 13\ TeV$ is shown in fig. 2(b).

4. – Total cross section and non-universality

The Integral over z of the fragmentation functions for a given hadron h is referred to as fragmentation fraction $f(q \to h)$. This value is often tuned based on data from e^+e^- collisions, assuming the universality of fragmentation from the colliding system. However, recent measurements from various collaborations have questioned this assumption, as well as the assumption of no p_T dependence of the fragmentation fraction for heavy quarks. For instance, the ALICE Collaboration has provided significant results that challenge the universality on the absolute values of fragmentation fractions [12] when compared to

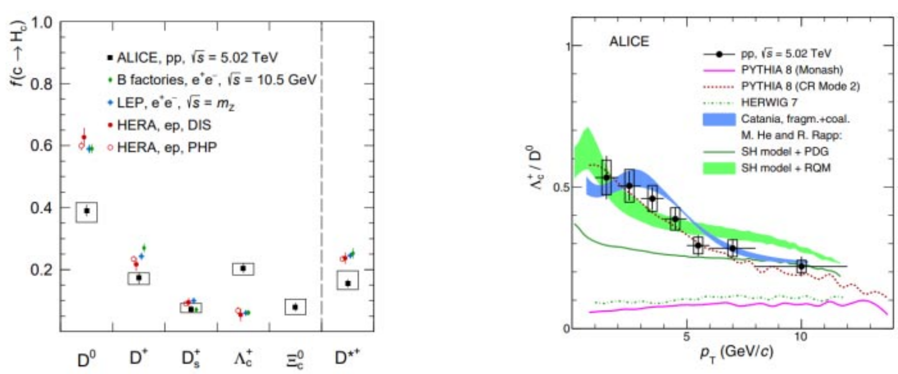


(a) (b)

Fig. 2. – (a) DCA variable distribution 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 [7], for prompt $D^{*\pm}$ production, $|\eta| < 2.1$, together with some theoretical predictions.

e^+e^- or ep measurements (fig. 3(a)). Additionally, they observed p_T dependence [13] in charmed baryons-mesons ratio fragmentation (fig. 3(b)).

As previously mentioned, the final goal of all the charm cross section measurements is to extract the total cross section. Due to the findings on charm fragmentation non-universality, particularly the p_T dependence, new approaches have been studied to properly incorporate this behavior. In [14], an approach based on FONLL (Fixed Order plus Next-to-Leading Logarithms) calculation is proposed to account for the non-constant shape of fragmentation fraction in the extrapolation of the total cross section. This



(a) (b)

Fig. 3. – (a) Values of fragmentation fractions for charmed mesons and baryons measured in pp collision at $\sqrt{s} = 5.02\ TeV$, compared to values extracted from e^+e^- or ep collisions. (b) p_T dependence of Λ_c^+/D^0 ratio. The pink line and the dashed green line show prediction with model based on e^+e^- and ep data. Figures are sourced from [12] and [13], respectively.

approach involves modifying the FONLL prediction by replacing the universal fragmentation fraction $f(c \to h)$ with a p_T-dependent fragmentation fraction $\tilde{f}(p_T)$. The predictions from the FONLL calculation rely on four parameters: μ_F, μ_R, α_k, and m_c, as described in [1]. Here, μ_F and μ_R are the rescaling and factorization scales, α_K the Kartvelishvili parameter for non-perturbative FFs parametrization [15] and m_c the mass of the charm quark. In [14], these parameters are constrained by data, recovering the universality for high p_T, as observed in experimental data.

5. – Conclusions

The common methods for extracting the charm cross section in open charm production have been examined in the decay chain of $D^* \to K\pi\pi_s$. There is increasing interest in these studies due to recent findings on non-universal fragmentation, which must be considered to determine the center-of-mass energy dependence of the total charm cross section. To this end, measurements at energies of 0.9 TeV, 5.02 TeV, 7 TeV, and 13 TeV have been published or are currently under preparation.

REFERENCES

[1] Cacciari M. *et al.*, *J. High Energy Phys.*, **2012** (2012) 137.
[2] Accardi A. *et al.*, *Eur. Phys. J. C*, **76** (2016) 471.
[3] Dokshitzer Y. L., *Sov. Phys. JETP*, **46** (1977) 641.
[4] Gribov V. N., *Sov. J. Nucl. Phys.*, **15** (1972) 438.
[5] Lipatov L. N., *Sov. J. Nucl. Phys.*, **20** (1975) 94.
[6] Altarelli G. and Parisi G., *Nucl. Phys. B*, **126** (1977) 298.
[7] CMS Collaboration, *J. High Energy Phys.*, **2021** (2021) 225.
[8] CMS Collaboration, CMS-PAS-BPH-22-007, `http://cds.cern.ch/record/2905307` (2024).
[9] Metwally J. R., `https://cds.cern.ch/record/2841052`, PhD Thesis (2022).
[10] Johmari Nur Zulaiha, `https://cds.cern.ch/record/2805338`, PhD Thesis (2022).
[11] CMS Collaboration, *Eur. Phys. J. C*, **72** (2012) 1.
[12] ALICE Collaboration, *Phys. Rev. D*, **105** (2022) L011103.
[13] ALICE Collaboration, *Phys. Rev. Lett.*, **127** (2021) 202301.
[14] Geiser A., Yang Y., Moch S. and Zenaiev O., arXiv:2406.03581 (2024).
[15] Kartvelishvili V. G. *et al.*, *Phys. Lett. B*, **78** (1978) 5.