D-meson production in proton-proton collisions with ALICE at the LHC

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Abstract

In this paper, an overview of recent $D^0$, $D^+$ and $D^{++}$ measurements, performed by ALICE in proton–proton collisions at $\sqrt{s} = 2.76, 5, 7, 8$ and 13 TeV, is reported. The minimum-bias production cross sections, as well as their energy and species dependences, are compared to perturbative QCD calculations. The evolution of the D-meson yields with the event multiplicity is compared to phenomenological models.

Keywords: Quantum Chromo-Dynamics, heavy flavours, charm, D mesons, ALICE, LHC

1. Motivations

Heavy quarks (charm and beauty) are powerful probes to investigate the properties of the Quark-Gluon Plasma, the hot and dense state of matter produced in ultra-relativistic heavy-ion collisions. Because of their large masses, heavy quarks are produced in parton hard-scatterings, occurring at the very beginning of hadronic collisions. Thus, they participate in the whole evolution of the heavy-ion collision.

In addition to providing the essential baseline for nucleus-nucleus collision studies, the study of production of heavy-flavour hadrons in proton-proton (pp) collisions allow for studying also the perturbative sector of Quantum Chromo-Dynamics (pQCD). Indeed, the large heavy quark masses ($m_{c,b} \gg \Lambda_{QCD}$) act as hard scales allowing the use of perturbation series in various kinematic regions. In this context, Fixed-Order-Next-to-Leading-Log (FONLL) \cite{1} and General Mass Variable Flavour Number Scheme (GM-VFNS) \cite{2} represent the state-of-the-art of pQCD calculations of heavy-flavour hadron productions. Both models implement, in two different ways, the standard collinear factorisation theorem at next-to-leading order (NLO). Alternatively, calculations based on $k_T$-factorisation \cite{3} are performed at leading order in $\alpha_s$, including a part of real higher order corrections.

The measurements of heavy-flavour hadron productions at the Large Hadron Collider (LHC) energies allow for testing those pQCD calculations down to zero transverse momentum ($p_T$). Besides, differential measurements can help in studying more in detail ingredients on which the pQCD calculations are based, namely the parton distribution functions (PDF), the partonic hard scatterings and the fragmentation functions (FF). As an example, the study of the species dependence of the production of heavy-flavour hadrons allows the fragmentation functions to be investigated. By comparing the heavy-flavour hadron productions in different rapidity regions and/or different energies, pQCD models become sensitive to gluon PDF. Partons with proton momentum fraction $x_B \sim 10^{-5}$ might be accessed with LHC experiments \cite{4}. Finally, several hard partonic interactions occurring in a single pp collision are expected to play a role in the production of heavy quarks at LHC energies. Such a phenomenon is usually referred as multi-parton interactions. Multiplicity-dependent measurements of heavy-flavour hadron productions can shed light on the relation between the production of charm hadrons and the event particle multiplicities.

2. Topological reconstruction of D mesons in ALICE

The ALICE experiment \cite{5,6} has measured the production of charm and beauty mesons since the first data taking period of the LHC (Run 1). Open-charm
mesons $D^0$, $D^+$, $D^{*+}$ and $D_s^+$ have been studied over a wide $p_t$ range, typically from 1 to 24 GeV/c, depending on the D-meson species and the colliding system. The exclusive reconstruction of these four D mesons is performed at mid-rapidity ($|y| < 0.5$) via their hadronic decay channels: $D^0 \rightarrow K^- \pi^+$ (with branching ratio, BR, of $3.93 \pm 0.04\%$), $D^+ \rightarrow K^- \pi^+ \pi^+$ (BR of $9.46 \pm 0.24\%$), $D^{*+} \rightarrow D^0 \pi^+$ (BR of $67.7 \pm 0.5\%$) and $D_s^+ \rightarrow \phi \pi^+ \rightarrow K^+ K^- \pi^+$ (BR of $2.27 \pm 0.08\%$) [7]. A detailed description of D-meson reconstruction in ALICE can be found in [8].

The analysis of D mesons is based on the displacement of the reconstructed decay vertices with respect to the interaction vertex, taking advantage of the D-meson decay length of few hundreds of $\mu$m. Open-charm meson candidates are built up as pairs or triplets of tracks, with the proper charge combination and taking into account particle identification (from energy loss or time of flight information). Kinematic and geometrical selections, such as the minimum distance between the decay and interaction vertices, are then optimised to maximise the statistical significance of the signal per $p_t$ interval. The raw yields of the reconstructed D mesons is extracted with the help of a fit of invariant mass distributions.

The production cross section is evaluated from the raw yield correcting for the detector acceptance (Acc) and efficiency ($\epsilon$), by means of realistic Monte Carlo simulations, which include the detector configuration and the LHC beam condition, according to

$$\frac{d^2\sigma^D}{dp_tdy}|_{|y|<0.5} = \frac{1}{f_{\text{prompt}} \cdot N_{D,\text{raw}}^D \cdot \Delta p_t \cdot \Delta y} \frac{1}{L_{\text{int}} \cdot BR} \frac{d^2\sigma^D}{dp_tdy} |_{|y|<0.5}$$

where $\Delta y$ and $\Delta p_t$ are the rapidity and transverse momentum intervals, $L_{\text{int}}$ is the integrated luminosity, $f_{\text{prompt}}$ is the fraction of prompt D mesons present in the raw yield, evaluated with theory-driven methods [9]. The factor $\frac{1}{f_{\text{prompt}}}$ account for the fact that the raw yield contains particles and antiparticles.

3. Production cross section of D mesons in minimum-bias pp collisions

The $p_t$-differential production cross sections of prompt $D^0$, $D^+$, $D^{*+}$ and $D_s^+$ have been measured at central rapidity by ALICE in minimum-bias pp collisions collected during LHC Run 1, for various centre-of-mass energies: $\sqrt{s} = 2.76$ [10], 7 [8, 9, 11] and 8 TeV [12].

More recently, the measurement of the production cross sections of prompt $D^0$, $D^+$ and $D^{*+}$ have been performed at $\sqrt{s} = 5$ TeV and at the highest available LHC energy, $\sqrt{s} = 13$ TeV. The preliminary results for $D^{*+}$ in pp collisions at 5 TeV and for $D^0$ at 13 TeV are presented Fig. [1] and [2] respectively. Perturbative QCD calculations at NLO, carried out within the FONLL and GM-VFNS frameworks, describe the measured D-meson cross-sections, within uncertainties, over a large energy range. Interestingly, such theoretical models manage to describe at the same time the whole $p_t$ range of the measurement, though theoretical uncertainties are quite large at low $p_t$. In particular, FONLL is compatible with the $p_t$-differential production cross section of prompt $D^0$ from $p_t = 0$ to 36 GeV/c [9, 11].

![Figure 1: Preliminary $p_t$-differential production cross section of prompt $D^{*+}$, measured by ALICE in pp collisions at $\sqrt{s} = 5$ TeV, compared to FONLL prediction.](image)

Furthermore, ALICE has evaluated the total charm cross-section in minimum-bias pp collisions at $\sqrt{s} = 7$ TeV, by extrapolating the measured $D^0$ production cross section to the full phase space and compensating fragmentation contribution of charm quarks into $D^0$ mesons [9, 11]. The resulting excitation function of the $c\bar{c}$ cross section, taking into account measurements from other experiments, is in agreement with pQCD calculations at NLO (MNR [13]), though data are at the upper edge of the theory uncertainty band. It is worth mentioning that the MNR calculation is consistent with data over more than three orders of magnitude in $\sqrt{s}$. All in all, pQCD calculations of production cross sections of hadrons containing a heavy quark usually have large systematic uncertainties, compared to measurements,
mainly driven by scale uncertainties.

The species dependence of the production cross sections of heavy-flavour hadrons has been studied in minimum-bias pp collisions at $\sqrt{s} = 7$ TeV by ALICE [9]. Such a dependence is studied in terms of cross-section ratios amongst D-meson species. Preliminary results are also available at LHC Run 2 energy, as shown in Figs. 3 and 4, where the production cross sections, in minimum-bias pp collisions at $\sqrt{s}$ = 13 TeV, of D*+, D^0 and of D^*+ and D^0 are respectively compared. Similarly, ratios of D-meson production cross sections at two different LHC energies have been tackled to investigate the energy dependence of the heavy-flavour hadron productions. The preliminary measurements of the ratio of the D^0 production cross sections at mid-rapidity in pp collisions at 5 and 13 TeV are presented in Fig. 5. An overall agreement of measurements with FONLL calculations is observed. It can be noted that the FONLL systematic uncertainties are significantly reduced due to the independence of the renormalisation and factorisation scales with respect to beam energies and meson species [4].

4. Multiplicity dependence of heavy-flavour hadron yields in pp collisions

The event charged-particle multiplicity dependence of the D^0, D^+ and D^{+*} yields, normalised to their respective multiplicity-integrated yields, has been studied by the ALICE experiment in pp collisions at $\sqrt{s}$ = 7 TeV [14]. A steeper-than-linear increase of yields with the particle multiplicities in events, similar for all the measured D mesons, has been observed. Indeed the yields are enhanced by almost a factor of 15, relative to the minimum-bias yield, for events with multiplicity six times higher than average inelastic-collision multiplicities, as can be observed in Fig. 6. Similar enhancements are observed for prompt J/ψ, as well as for J/ψ coming from the decay of beauty hadrons. The comparison of open- and hidden-charm production implies that the observed yield increase is likely related to c\bar{c} and \bb production processes, and not strongly influenced by hadronisation. However it should be noticed that a direct comparison has to be taken with care, since the $\eta$ and $p_T$ regions of D mesons and J/ψ measurements are different.

Figure 2: Preliminary $p_T$-differential production cross section of prompt D^0, measured by ALICE in pp collisions at $\sqrt{s}$ = 13 TeV, compared to FONLL prediction.

Figure 3: Preliminary comparison of the D^+ and D^0 production cross section in minimum-bias pp collisions at $\sqrt{s}$ = 13 TeV, superimpose to the FONLL prediction.

Figure 4: Preliminary comparison of the D^+ and D^{+*} production cross section in minimum-bias pp collisions at $\sqrt{s}$ = 13 TeV, superimpose to the FONLL prediction.
The evolution of the charmed-meson yields with the event activity is foretold by calculations including multi-parton interactions (MPI) at LHC energies. The PYTHIA8 model [15], where several 2→2 hard processes can take place in a given pp collision, predicts an almost linear increase of D-meson yields with event particle multiplicities. The percolation model, assuming exchanges of colour sources with finite spatial extension as driving the hadronic collisions, predicts a steeper-than-linear yield enhancement of D-mesons with event multiplicity [16]. Finally EPOS3, based on the Gribov-Regge formalism, also anticipates a steeper-than-linear increase driven by a hydrodynamic evolution of the pp collision [17]. However, the D-meson yields are underestimated by these three models when the event multiplicity exceeds two times the average inelastic-collision multiplicities, even though calculations reasonably reproduce the data below such event activity. Even if MPI seems to be an important input for hadronic collision event generators at high multiplicity, one should keep in mind that alternative explanations may account for the charmed-meson yields enhancement. For instance, the growth of gluon radiations associated to hard processes could explain the observed yield increase. Nevertheless, no implementation of such effects is currently available in models [14].

![Image](https://via.placeholder.com/150)

Figure 5: Preliminary ratio of the D⁰ production cross sections in minimum-bias proton-proton collisions at √s = 5 and 13 TeV, compared to FONLL prediction.

5. Conclusion

Heavy quarks are key tools to probe the pQCD and its interplay with softer phenomena from the surrounding collectivity. By exploiting LHC Run 1 proton-proton collisions, ALICE has constrained pQCD-inspired models by means of various precise measurements of D mesons. Calculations describe fairly well the production cross sections of open-charm meson over wide pt ranges and at LHC energies ranging from √s = 2.76 to 13 TeV. More differential measurements, as a function of the event multiplicity for instance, allow testing phenomenological models depicting a global view of hadronic collisions. However, the description of softer QCD phenomena remain challenging for hadronic collision event generators.

The increase of the LHC collision energy, for the second data taking period, allows for more precise measurements. Thus, QCD processes occurring at TeV collision energies will further be investigated. Finally, the recent first measurements of open-charm baryons, Λc⁺ and Ξc⁺, by ALICE in pp collisions is an additional input for ab initio and phenomenological models.

![Image](https://via.placeholder.com/150)

Figure 6: Average of D⁰, D⁺, D⁺⁺ relative yield as a function of relative charged-particle multiplicity, at central rapidity [13].

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