Open heavy-flavor measurements with ALICE at the LHC

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Abstract. ALICE is well equipped to reconstruct heavy-flavor particles down to low transverse momentum $p_T$ at mid and forward rapidity. An overview of the ALICE results obtained with the Run 1 data in pp ($\sqrt{s}=2.76$ TeV and $\sqrt{s}=7$ TeV), Pb-Pb ($\sqrt{s_{NN}}=2.76$ TeV) and p-Pb ($\sqrt{s_{NN}}=5.02$ TeV) collisions is presented. In pp collisions the measured cross sections are well described by pQCD calculations. The charged-particle multiplicity dependence of heavy-flavor yields indicates that Multi-Parton Interactions contribute to the high-multiplicity pp collisions and affect charm and beauty production in a similar way. In p-Pb and Pb-Pb collisions the measured nuclear modification factors indicate a final-state energy loss of heavy-quarks in central Pb-Pb collisions. Furthermore, the observed positive heavy-flavor elliptic flow in semi-central Pb-Pb collisions gives a hint that charm quarks participate in the collective expansion of the medium at low $p_T$. In high-multiplicity p-Pb collisions, a double-ridge structure is observed in the heavy-flavor decay electron-hadron azimuthal correlations at low $p_T$ similar to what is measured in the light-flavor sector. Such long-range correlations in $\eta$ could originate from a collective expansion of the system, as well as from gluon saturation in the initial state (color-glass condensate) or other mechanisms.

1. Introduction

Ultra-relativistic nuclear collisions allow the study of strongly-interacting matter under extreme conditions. A deconfined state of quarks and gluons, the Quark-Gluon Plasma (QGP), is expected to be formed in such collisions. The study of heavy-quark production is of particular interest, since charm and beauty quarks are produced via hard partonic scattering processes at the beginning of the collision and interact strongly with the surrounding medium. Therefore, the measurements of open heavy-flavor yields and elliptic flow allow one to test models of in-medium parton energy loss and probe the level of thermalization of heavy quarks in the medium at low transverse momentum $p_T$. For this purpose, open heavy-flavor production in pp and p-Pb collisions has to be measured as well to provide the necessary baselines for heavy-ion studies. In pp collisions, the measurements of cross sections allow the testing of perturbative QCD calculations, whereas more differential measurements give deeper insight into the charm-production mechanisms. In p-Pb collisions, cold nuclear matter effects can be studied such that these can be better disentangled from hot and dense matter effects in Pb-Pb collisions. Possible cold nuclear matter effects are modification of Parton Distribution Functions (PDFs) in nuclei (shadowing [1]/gluon saturation [2] at small Bjorken-x), $k_T$-broadening from multiple soft scatterings [3] and possible energy loss.
ALICE (A Large Ion Collider Experiment) collected data during the pp, Pb-Pb and p-Pb running periods at center-of-mass energies \( \sqrt{s} = 7 \) and 2.76 TeV, \( \sqrt{s_{\text{NN}}} = 5.02 \) TeV, and \( \sqrt{s_{\text{NN}}} = 2.76 \) TeV, respectively, at the LHC (Large Hadron Collider) at CERN. A detailed description of the experimental setup can be found in [4]. At mid rapidity \(|\eta|<0.9\), open heavy-flavor production is measured in the central barrel via the hadronic decay of D mesons (D\(^0\), D\(^+\), D\(^{**}+\) and D\(^s\)), the semileptonic decays to electrons of charm and beauty hadrons and the non-prompt J/\(\psi\) from beauty-hadron decays. At forward rapidity \(-4<\eta<-2.5\), muons from heavy-flavor hadron decays are reconstructed in the muon spectrometer. The data readout was triggered by a minimum-bias interaction trigger based on the trigger signals from two forward scintillator hodoscopes (VZERO-A and VZERO-C). The summed amplitudes in the VZERO scintillator tiles were used to determine the centrality of Pb-Pb collisions, employing a model of particle production based on a Glauber description of the nuclear collision geometry. In addition to the minimum-bias trigger, the muon spectrometer provided a single muon trigger at forward rapidity for the heavy-flavor decay muon analysis. At mid rapidity, the ElectroMagnetic Calorimeter (EMCal) allowed us to trigger on single electrons for the heavy-flavor decay electron analysis.

2. Results in pp collisions at \( \sqrt{s} = 2.76 \) and 7 TeV

The differential cross sections of prompt D mesons (D\(^0\), D\(^+\), D\(^{**}+\) and D\(^s\)), heavy-flavor decay electrons, electrons from beauty-hadron decays and heavy-flavor decay muons were measured in pp collisions at \( \sqrt{s} = 7 \) [5, 6, 7, 8, 9] and 2.76 TeV [10, 11, 12, 13]. They are well described by pQCD calculations [14, 15, 16].

![Figure 1.](image)

**Figure 1.** Prompt D\(^0\), D\(^+\), D\(^{**}+\) meson self-normalized yields (left panel) and average prompt D meson and inclusive J/\(\psi\) self-normalized yields (right panel) as a function of charged-particle multiplicity at mid rapidity. Vertical bars and boxes are statistical and systematic errors, respectively. The feed-down fraction uncertainty for the D mesons is drawn separately in the bottom panel [17].

More differential measurements, e.g. concerning the multiplicity dependence of D-meson yields, were also performed in pp collisions at \( \sqrt{s} = 7 \) TeV [17]. The self-normalized D-meson yields, i.e. the corrected per-event yield normalized to the multiplicity-integrated value, increase faster than linear with the self-normalized charged-particle multiplicity in pp collisions, as shown
in the left panel of Fig. 1. The results for $D^0$, $D^+$, $D^{*+}$ are compatible with each other within uncertainties. A similar trend is observed for inclusive $J/\psi$ at mid rapidity, see right panel of Fig. 1, as well as for non-prompt $J/\psi$ [17]. This suggests that Multi-Parton Interactions (MPI) play a role in high-multiplicity pp collisions and affect charm (open and hidden) and beauty in a similar way. More precise measurements are needed to discriminate among the possible origins of the effect.

3. Results in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

One of the main topics being studied in heavy-ion collisions is the parton energy loss in the medium, where both inelastic (radiative energy loss via medium-induced gluon radiation) and elastic (collisional energy loss) processes play a role. The energy loss for quarks is expected to be smaller than for gluons, because of the smaller color coupling factor of quarks with respect to gluons. In addition, the dead-cone effect should reduce small-angle gluon radiation for quarks that have moderate energy-over-mass values, i.e. for charm and beauty quarks with momenta up to about 10 and 30 GeV/$c$, respectively [18]. Both effects together lead to an expected ordering of the energy loss in the QGP at the parton level ($\Delta E_g > \Delta E_{u,d,s} \geq \Delta E_c > \Delta E_b$). Experimentally, the modification of the measured spectra in Pb-Pb collisions compared to pp collisions at the same energy is quantified by the nuclear modification factor $R_{AA} = 1/\langle T_{AA}\rangle \times (dN_{AA}/dp_T)/(d\sigma_{pp}/dp_T)$, where $\langle T_{AA}\rangle$ is the average nuclear overlap function for a given centrality class, $dN_{AA}/dp_T$ is the measured yield for Pb-Pb collisions in this centrality class and $d\sigma_{pp}/dp_T$ is the corresponding cross section in pp collisions. In the absence of any medium effect, the nuclear modification factor is equal to unity.

Fig. 2 shows $R_{AA}$ as a function of the centrality of Pb-Pb collisions (see text) of $D^0$, $D^+$ and $D^{*+}$. The bars represent the statistical uncertainty, while the filled (empty) boxes represent the systematic uncertainties that are correlated (uncorrelated) among centrality intervals [19].

Fig. 3. Average $D^0$, $D^+$ and $D^{*+}$-meson $R_{AA}$ as a function of $p_T$ compared to $D^+_s R_{AA}$ in the most central Pb-Pb collisions. The bars represent the statistical uncertainty, while the boxes represent the systematic uncertainties.
D-meson species is observed in central Pb-Pb collisions. The $p_T$ dependence of $R_{AA}$ is presented in Fig.3 (see also [20]). Low-$p_T$ measurements in all systems are crucial to study the expected binary scaling of the total charm yield in Pb-Pb collisions. In addition, the comparison of $R_{AA}$ of $D^+_s$ in the 0-7.5% centrality class with the average nuclear modification factor of $D^0$, $D^+$ and $D^{++}$ mesons measured in the same centrality class is presented in Fig.3. An enhancement of the strange $D_s$-meson yield is expected compared to non-strange D mesons because of the in-medium strangeness enhancement observed in the light-flavor sector and hadronization via in-medium coalescence at intermediate and low momentum [21, 22, 23]. The results for the strange and non-strange D mesons are compatible within uncertainties with a hint for an enhancement of $D^+_s$ at low $p_T$. Nevertheless, the uncertainties need to be reduced to make any quantitative statement.

The color-charge dependence of the parton energy loss can a priori be studied by comparing $R_{AA}$ of D mesons and charged pions, as shown in the left panel of Fig.4, as a function of the centrality of the Pb-Pb collision [19]. A similar suppression is observed for both species. The measurements are reproduced by calculations including a color-charge dependence of the parton energy loss [24]. The latter is compensated by the softer fragmentation and $p_T$ spectrum of gluons with respect to those of charm quarks leading to a very similar $R_{AA}$ for D mesons and charged pions. The mass dependence of parton energy loss was investigated by comparing $R_{AA}$ of prompt D mesons and non-prompt $J/\psi$ from beauty-hadron decays measured by the CMS Collaboration [25, 26] in a similar kinematic region ($p_T^D\approx p_T^{J/\psi}$). A larger suppression is observed for D mesons in central collisions than for non-prompt $J/\psi$, as shown in right panel of Fig.4. In this case, the quark mass used in the model calculation [24] is crucial to reproduce the data, as demonstrated by the non-prompt $J/\psi$ $R_{AA}$ calculated considering the charm-quark mass for the energy loss of beauty quarks. The ALICE collaboration measured at mid rapidity non-prompt $J/\psi$ at lower $p_T$ (1.5<$p_T$<10 GeV/c) compared to the CMS collaboration [27]. The measured $R_{AA}$ seems to be overestimated by some models in the range 4.5<$p_T$<10 GeV/c. More precise data is nevertheless needed to discriminate among models.
Collectivity phenomena can be studied in Pb-Pb collisions via the azimuthal distribution of heavy-flavor hadrons, which reflects the initial spatial anisotropy of the heavy-ion collision in case of sufficient re-scattering of the heavy quarks in the hot and dense matter. The heavy-flavor elliptic flow, the second harmonic in the Fourier expansion of the particle azimuthal distribution, is an observable sensitive to the degree of thermalization of charm and beauty quarks in the medium at low $p_T$, as well as to the path-length dependence of the energy loss of heavy quarks at high $p_T$. The left panel of Fig.5 shows that the $v_2$ of D mesons in Pb-Pb collisions, in the 30-50% centrality class [18, 19], is similar to the charged-particle $v_2$ [28, 29]. A positive $v_2$ of D mesons ($5.7\sigma$ effect in the interval $2<p_T<6$ GeV/c), heavy-flavor decay electrons ($3\sigma$ effect in the interval $2<p_T<5$ GeV/c) and heavy-flavor decay muons [30] ($3\sigma$ effect in the interval $3<p_T<6$ GeV/c) is measured in semi-central Pb-Pb collisions, see Fig.5. This indicates that charm quarks participate in the collective expansion of the medium.

4. Results in p-Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV

Fig.6 shows $R_{p\text{p}Pb}$ of D mesons at mid rapidity in minimum-bias p-Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV [31]. Calculations that include cold nuclear matter effects [32, 3, 2] can describe the measurement. Smaller uncertainties are nevertheless needed to discriminate among models. Cold nuclear matter effects do not lead to a strong suppression in the measured $p_T$ range. $R_{p\text{p}Pb}$ is compatible with unity for $p_T>2$ GeV/c, within uncertainties.

Fig.7 shows $R_{p\text{p}Pb}$ of heavy-flavor decay muons at forward ($2.5<y_{\text{cms}}<3.54$, proton-beam direction) and at backward rapidity ($-4<y_{\text{cms}}<-2.96$, Pb-beam direction), respectively. $R_{p\text{p}Pb}$ at forward rapidity is consistent with unity, as well as $R_{p\text{p}Pb}$ backward rapidity for $p_T>4$ GeV/c. Both observables are well described by calculations [32, 3, 33], within uncertainties. From the results of D mesons, heavy-flavor decay electrons and heavy-flavor decay muons in p-Pb collisions, it can be concluded that the strong suppression of heavy-flavor yields at intermediate and high $p_T$ measured in central Pb-Pb collisions is due to the interaction of heavy quarks with
Figure 6. Average $R_{pPb}$ of prompt $D^0$, $D^+$ and $D^{*+}$ mesons as a function of $p_T$ compared to the D-meson $R_{AA}$ in the 20% most central and in 40-80% central Pb-Pb collisions. Statistical (bars), systematic (empty boxes) and normalization (full boxes) uncertainties are shown [31].

Further insight into the charm quark production mechanisms and quark fragmentation in pp collisions, as well as information about additional possible cold-nuclear matter effects in p-Pb collisions and hot and dense matter effects in Pb-Pb collisions can be obtained with measurements of angular correlations between heavy-flavor hadrons (or their decay electrons) and charged particles. Fig. 8 shows the azimuthal-correlation distribution between D mesons and charged particles in the interval $|\Delta \eta|<1$ for $8<p_T^{D}<16$ GeV/c and $p_T^{assoc}>1$ GeV/c. The
azimuthal-correlation distributions measured in pp and p-Pb collisions agree within uncertainties after subtracting the baseline because of the uncorrelated background. Various PYTHIA tunes can describe the data within the relatively large statistical uncertainties. Smaller statistical errors are expected with data from Run 2. The angular-correlation distribution between heavy-flavor decay electrons and charged particles has been measured in p-Pb collisions. After subtracting the correlation distribution of the 60-100% multiplicity class from the one of the 0-20% multiplicity class to remove jet-like contributions, a long-range double-ridge structure is observed as shown in Fig.9. This distribution is qualitatively similar to the one observed in the hadron-hadron correlation analysis [34, 35]. This suggests that the mechanism that generates these long-range correlation structures (by gluon saturation in the initial state as predicted by the Color Glass Condensate (CGC) calculations [36] and/or by a collectively expanding system in the final state as it is assumed in hydrodynamical model calculations [37] or other mechanisms) may also affect heavy quarks.

Figure 8. D meson-charged particle $\Delta\varphi$ correlations in minimum bias pp collisions at $\sqrt{s}=7$ TeV and p-Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV.

Figure 9. Angular correlations in azimuth and pseudorapidity between heavy-flavor decay electrons and charged particles in the 20% highest multiplicity p-Pb collisions after subtracting the correlations in the multiplicity class 60-100%.

5. Conclusion and Outlook
In Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV, a large suppression of the high-$p_T$ heavy-flavor yields is observed in the most-central collisions. The measured nuclear modification factor of prompt D mesons is smaller than the one of non-prompt J/ψ measured by the CMS Collaboration. The quark mass used in model calculations is crucial to reproduce the data. The measured positive heavy-flavor elliptic flow in semi-central Pb-Pb collisions indicates that the interactions of charm quarks with the expanding medium transfer information on the azimuthal anisotropy of the system to the heavy quarks. In pp collisions at $\sqrt{s}=2.76$ and 7 TeV, the measured cross sections are described by perturbative calculations. Measurements of the multiplicity dependence of heavy-flavor yields indicate that Multi-Parton Interactions contribute to the high-multiplicity pp collisions and affect charm and beauty in a similar way. In p-Pb collisions at
$\sqrt{s_{\text{NN}}}=5.02$ TeV, cold nuclear matter effects do not lead to a strong suppression in the measured $p_T$ range. Therefore, the strong suppression observed in Pb-Pb collisions is due to the presence of a hot and dense medium. A double-ridge structure is observed in the heavy-flavor decay electron-hadron azimuthal correlations at low $p_T$ in p-Pb collisions, which indicates that heavy quarks are possibly affected by the processes leading to long-range correlations in $\eta$ of light-flavor hadrons.

The ongoing Run 2 data-taking period at the LHC will allow for the extension of the $p_T$ range of the measurements, for more precise measurements of the azimuthal correlations, beauty and heavy flavor in jets, and for better study of the hadronization of heavy quarks by measuring the heavy baryons and $D_s$ mesons. The major ALICE upgrade between Run 2 and Run 3, including a new Inner Tracking System and a Muon Forward Tracker, opens the possibility to measure beauty production via displaced $D$ mesons or directly via hadronic decays of beauty hadrons, as well as to separate the charm from the beauty contribution at forward rapidity [38].

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