Open heavy-flavour measurements in Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV with ALICE

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Abstract. In ultra-relativistic heavy-ion collisions, heavy quarks, i.e charm and beauty, are produced in the early stage of the reaction. Therefore, they are uniquely suited to probe the Quark-Gluon-Plasma (QGP), which is formed in such reactions, and to study the parton-medium interactions. In 2010 and 2011, Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV have been recorded by ALICE at the LHC. We present results of open heavy-flavour production using hadronic $D$ meson decays, as well as semi-electronic and semi-muonic decays of $D$ and $B$ mesons. The corresponding nuclear modification factors are measured as a function of the transverse momentum and the collision centrality in the ALICE central-barrel at mid-rapidity and in the forward muon detector. First elliptic flow measurements are also shown.

1. Introduction
Ultra-relativistic nuclear collisions allow to study nuclear matter under extreme conditions. In such collisions a deconfined state of quarks and gluons, the Quark-Gluon Plasma (QGP), is expected to be formed. Among the possible probes of the QGP, heavy quarks are of particular interest since they are produced at the beginning of the collision and interact strongly with the surrounding medium. Therefore the measurement of open heavy-flavour production allows to test models of in-medium parton energy-loss and provides essential information on the properties of the strongly-interacting system formed in the early stages of heavy-ion collisions. In addition, the elliptic flow measurements of $D$ mesons probe the level of thermalization of heavy quarks in the medium at low momentum, and the path length dependence of the parton energy loss at higher momentum.

In November 2010 and 2011, ALICE (A Large Ion Collider Experiment) collected data during the first Pb-Pb collisions at a center-of-mass energy per nucleon pair $\sqrt{s_{NN}}=2.76$ TeV delivered by the LHC (Large Hadron Collider) at CERN. A detailed description of the experiment can be found in [1]. 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) and two innermost layers of Silicon Pixel Detectors (SPD). In total 17 million minimum-bias and 16 million semi-central (15-50 %) Pb-Pb collisions, recorded in 2011 and 2011 respectively, were used for the analysis. The summed amplitudes in the VZERO scintillator tiles were used to determine the centrality of the Pb-Pb collision, together with a model of particle production based on a Glauber description of the nuclear collision geometry.
2. *D* meson production at mid-rapidity (|y|<0.5)

The *D*\(^0\), *D*\(^+\) and *D*\(^{++}\) mesons and their charge conjugates are reconstructed from their decays into charged hadrons, *D*\(^0\)→*K*\(^-\)π\(^+\) (with branching ratio, BR of 3.87±0.05 %), *D*\(^+\)→*K*\(^-\)π\(^+\)π\(^+\) (BR of 9.13±0.19 %), and *D*\(^{++}\)→*D*\(^0\)π\(^+\) (BR of 67.7±0.5 %), in the central barrel of ALICE. Due to their large lifetime (\(\tau=123\ \mu\text{m}\), \(312\ \mu\text{m}\) for *D*\(^0\) and *D*\(^\pm\) respectively), the *D* mesons decay further away from the primary vertex. The tracking capabilities of the Inner Tracking System (ITS) and Time Projection Chamber (TPC) are used to reconstruct the displaced secondary vertices. The TPC and Time Of Flight (TOF) detector provide moreover the possibility to identify \(\pi^\pm\) and \(K^\pm\).

Figure 1 shows the invariant mass distributions for *D*\(^0\) candidates and their charge conjugates for different *D*\(^0\) \(p_t\) intervals in 0-20 % central Pb-Pb collisions. In the case of the *D*\(^{++}\) decay, the *D*\(^0\) candidate is first reconstructed via its decay topology and then combined with low momentum \(\pi^\pm\). The *D*\(^0\), *D*\(^+\) and *D*\(^{++}\) yields are extracted by fitting the invariant mass distributions. The \(p_t\)-differential production yields in the \(p_t\) range \(2<p_t<16\ \text{GeV/c}\) at mid-rapidity (|y|<0.5) are determined after efficiency and feed-down correction for *B* decays in 0-20 % and 40-80 % central Pb-Pb collisions [2]. The fraction of prompt *D* mesons, \(f_{\text{prompt}}\), depends on the *D* meson species, \(p_t\), the analysis selection criteria, the parameters used in the FONLL B prediction [4], and the hypothesis on the B suppression in Pb-Pb collisions. The values of \(f_{\text{prompt}}\) range from about 0.95 in the \(p_t\) range \(2<p_t<3\ \text{GeV/c}\) to about 0.85 at high \(p_t\).

![Invariant Mass Distributions](image)

**Figure 1.** Invariant mass distributions for *D*\(^0\) candidates and their charge conjugates in selected \(p_t\) intervals for \(3.2\times10^6\) 0-20 % central Pb-Pb collisions at \(\sqrt{s_{NN}}=2.76\ \text{TeV}\). The uncertainties on the signal yields reported in the figures are statistical only [2].

The *D* meson production in Pb-Pb collisions can be compared to pp collisions at the same \(\sqrt{s_{NN}}\) energy with the nuclear modification factor \(R_{AA}\):

\[
R_{AA}(p_t) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_t}{d\sigma_{pp}/dp_t}
\]

where \(\langle T_{AA} \rangle\) is the average nuclear overlap function for the given centrality class proportional to the number of nucleon-nucleon collisions, \(dN_{AA}/dp_t\) is the measured yield for this centrality class in Pb-Pb collisions, and \(d\sigma_{pp}/dp_t\) is the corresponding cross section in pp collisions. A suppression of *D* meson production in central Pb-Pb collisions compared to pp collisions implies a nuclear modification factor smaller than 1.0.

The *D*\(^0\), *D*\(^+\) and *D*\(^{++}\), and their charge conjugates are measured in pp collisions at \(\sqrt{s}=2.76\ \text{TeV}\) in the transverse momentum range \(1<p_t<12\ \text{GeV/c}\) [3]. The analysis was performed on an event sample collected in 2011 with a minimum-bias trigger, corresponding
to an integrated luminosity of 1.35 nb$^{-1}$. Since the statistics is limited and does not allow a comparison with the Pb-Pb measurements for every $p_t$ interval, the reference used for the calculation of the $D$ meson $R_{AA}$ is obtained from a pQCD-based (FONLL [4]) energy scaling of the 7 TeV $p_t$ differential cross sections to 2.76 TeV. Figure 2 shows the 2.76 TeV measured $p_t$ differential cross section, together with the 7 TeV results scaled down to 2.76 TeV. The agreement is very good.

Figure 3. $R_{AA}$ for prompt $D^0$, $D^+$ and $D^{++}$ in 0-20 % (left) and 40-80 % (right) central Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV. Statistical (bars), systematic (empty boxes), and normalization (full box) uncertainties are shown [2].

The nuclear modification factor of prompt $D^0$, $D^+$ and $D^{++}$ is shown for central (0-20 %) and semi-peripheral (40-80 %) Pb-Pb collisions in Fig. 3. The central values of $R_{AA}$ are
calculated under the assumption that the nuclear modification factors for feed-down from $B$ mesons and prompt $D$ mesons are equal ($R_{AA}^{feed-down}=R_{AA}^{prompt}$). The systematic uncertainties are estimated by varying the hypothesis in the range $1/3<R_{AA}^{feed-down}/R_{AA}^{prompt}<3$. The $D$ mesons are suppressed by a factor 3-4 above 5 GeV/c in 0-20% Pb-Pb collisions. The suppression is reduced when going to more peripheral collisions.

Figure 4. Average $R_{AA}$ of $D$ mesons in 0-20% central Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV compared to: left, the nuclear modification factors of charged hadrons [5] and non-prompt $J/\psi$ from $B$ decays [6]; right, the expectation from NLO pQCD [8] with nuclear shadowing [7].

On the left panel of Fig. 4, the nuclear modification of prompt $D$ mesons, charged hadrons [5] and non-prompt $J/\psi$ from $B$ decays [6] are compared in 0-20% Pb-Pb collisions. There is an indication for $R_{AA}^{D}>R_{AA}^{charged}$, whereas the suppression of non-prompt $J/\psi$, although the $y$ range is wider, is clearly weaker than that of charged hadrons.

On the right panel of Fig. 4, the nuclear modification of prompt $D$ mesons in 0-20% Pb-Pb collisions is compared to the expectation from NLO pQCD [8] with nuclear shadowing [7]. The effect of shadowing on the $R_{AA}$ is of the order of $\pm 15\%$ for $p_t>6$ GeV/c. This suggests that the strong suppression observed in the data is dominated by final-state effects. The upcoming pPb collisions at 4 ZTeV, which will be delivered by the LHC in 2012, will allow to measure directly the initial state effects.

The nuclear modification factor of prompt $D$ mesons in 0-20% central Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV are compared to several theoretical models in Fig. 5, along with the comparison to the charged-hadron $R_{AA}$, see Ref. [2] for more details and references to the models. The model based on radiative energy loss with in-medium $D$ meson dissociation (I) and the ones based on the radiative plus collisional energy loss (II,VII) describe reasonably well at the same time the charm and charged-hadron suppression. A model based on AdS/CFT drag coefficients underestimates significantly the charm $R_{AA}$ and has large errors for the light-flavour $R_{AA}$.

3. Measurements of open heavy-flavour production via semi-leptonic decays of $D$ and $B$ mesons
Open heavy-flavour hadrons can be measured indirectly via their semi-electronic decays at mid-rapidity ($|y|<0.8$) in the central barrel of ALICE and via their semi-muonic decays at forward rapidity ($2.5<y<4.0$) in the ALICE muon spectrometer.

Electrons are tracked with the ITS and TPC, and identified using the energy loss in the TPC gas and the measured time of flight in TOF. In Fig. 6, the $p_t$ differential electron spectrum at mid-rapidity, fully corrected for acceptance and detector efficiency, is compared to a cocktail of known
background electrons for central Pb-Pb collisions (0-10%). At low $p_t$, the main contributions from the estimated background come from electrons from Dalitz decays of $\pi^0$ and from gamma conversion in the detector material. At high $p_t$, the signal to background ratio increases. The $\pi^{\pm}$ spectra measured in ALICE, are used as input for the cocktail in the different centrality classes, together with the decay kinematics from PYTHIA, and the knowledge of the material budget within 6% uncertainty. The contribution from direct photons is estimated based on Next-to-Leading order calculations [10] assuming a scaling with the number of nucleon-nucleon collisions.

**Figure 5.** Average $R_{AA}$ of $D$ mesons (left) and charged hadrons (right) in 0-20% central Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV compared to model calculations [2].

**Figure 6.** Inclusive electron spectrum in 0-10% central Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV at mid-rapidity, compared to a cocktail of known background electrons.

At low $p_t$ ($p_t<3.5$ GeV/c), an excess is observed in central Pb-Pb collisions, which could point
Figure 7. Left: The $p_t$-differential cross section at mid-rapidity of electrons from charm and beauty hadron decays in pp collisions at 7 TeV, compared to FONLL calculations [9]. Right: Nuclear modification factors of cocktail-subtracted electrons in central (0-10%) and peripheral (60-80%) Pb-Pb collisions at 2.76 TeV.

Electrons from heavy-flavour hadron decays are measured at mid-rapidity in pp collisions at 7 TeV. The analysis was performed with data collected in 2010, using two different approaches for the electron identification: the TPC, TOF and Transition Radiation Detector (TRD) in the $p_t$ range $0.5<p_t<8$ GeV/c, and the TPC and ElectroMagnetic Calorimeter in the $p_t$ range $3<p_t<6$ GeV/c. The left panel of Fig. 7 shows the comparison of the $p_t$-differential cross section of electrons from heavy-flavour hadron decays with FONLL calculations [9]. The theory reproduces well the data. The 7 TeV data were scaled in the same way as the $D$ meson measurements to 2.76 TeV to obtain the reference for the computation of the nuclear modification factor of heavy-flavour electrons.

On the right panel of Fig. 7, $R_{AA}$ of the cocktail-subtracted electrons is shown for central (0-10%) and peripheral (60-80%) Pb-Pb collisions. Above 3.5 GeV/c, heavy-flavour electrons are expected to dominate. The suppression factor is of the order of 1.5 to 4 for central Pb-Pb collisions, whereas it is consistent with 1.0 for peripheral collisions.

Muons with $p_t>0.5$ GeV/c are reconstructed and identified in the muon spectrometer ($2.5<y<4.0$). From the inclusive muon spectrum, the muon background component, mainly muons from primary $\pi^{\pm}$ and $K^{\pm}$ decays, must be subtracted. The $p_t$-distributions of $\pi^{\pm}$ and $K^{\pm}$ measured at mid-rapidity in ALICE are used as input to estimate the muon background at forward rapidity. The pp reference used for the determination of the $R_{AA}$ of heavy-favour decay muons is obtained from the analysis of muon-triggered events collected during the pp run at $\sqrt{s}=2.76$ TeV in 2011 [12]. The corresponding integrated luminosity is 19 nb$^{-1}$. Figure 8 shows on the left panel the measured $p_t$ differential cross section of muons from heavy-flavour decays in the $p_t$ range $2<p_t<10$ GeV/c in pp collisions at $\sqrt{s}=2.76$ TeV, together with FONLL calculations. The ratio between data and FONLL calculations is shown in the bottom panel. The measurements are well reproduced by the model, although at the upper limit of the calculations.
Figure 8. Left: $p_t$-differential inclusive cross section of muons from heavy-flavour decays in the rapidity range $2.5 < y < 4$, in pp collisions at $\sqrt{s}=2.76$ TeV, compared to FONLL calculations. Error bars (open boxes) are statistical (systematics) uncertainties. The lower panel shows the ratio between data and FONLL calculations. Right: $R_{AA}$ of muons from heavy-flavour decays as a function of the mean number of participating nucleons, in $2.5<y<4$ and $6<p_t<10$ GeV/c. The horizontal bars indicate the uncertainty on $\langle N_{part} \rangle$ [12].

The nuclear modification of heavy-flavour muons with $6<p_t<10$ GeV/c is presented on the right panel of Fig. 8 as function of the mean number of participants $\langle N_{part} \rangle$ in Pb-Pb collisions [12], determined with the Glauber model. In this $p_t$ range, the contribution of muons from $B$ decays becomes dominant in pp collisions according to the central value of the FONLL calculations. The heavy-flavour muons exhibit a strong suppression increasing with $\langle N_{part} \rangle$, reaching a factor of about 3-4 in the 10 % most central collisions. The suppression of $D$ mesons at mid-rapidity is similar to that of muons from heavy flavour decays at forward rapidity.

4. Elliptic flow of $D$ mesons at mid-rapidity ($|y|<0.5$)

In heavy-ion collisions the spatial anisotropy in non-central collisions is converted into a momentum anisotropy, if the medium mean free path allows for sufficient rescattering. The azimuthal distribution of the final particles reflects then the initial anisotropy and the medium characteristics, and can be quantified via the coefficients of a Fourier expansion, in particular the second coefficient, called the elliptic flow $v_2$.

The elliptic flow of $D^0$ and $D^+$ mesons, measured with the event plane method, is shown in Fig. 9 in 30-50 % central Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV. For comparison the $v_2$ of charged particles is also plotted. There is an indication for a non-zero elliptic flow of $D^0$ and $D^+$ mesons qualitatively near the charged hadron result.

5. Summary

We presented the nuclear modification factor $R_{AA}$ of $D$ mesons in central (0-20 %) and semi-peripheral (40-80 %) Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV at mid-rapidity in the transverse momentum range $2<p_t<16$ GeV/c. The $D$ mesons are suppressed by a factor 3-4 above 5 GeV/c in 0-20 % Pb-Pb collisions, increasing with centrality. Compared to charged hadrons,
there is a hint for $R_{AA}^{D^0}>R_{AA}^{charged}$. Effects due to shadowing can not explain such a large suppression. Theoretical models with radiative energy loss describe reasonably well at the same time the charm and the charged-hadron suppression. We showed the nuclear modification factor of electrons from heavy-flavour hadron decays at mid-rapidity for central (0-10 %) and peripheral (60-80 %) Pb-Pb collisions up to 6 GeV/c. The suppression factor is of the order of 1.5 to 4 for central Pb-Pb collisions. The nuclear modification factor of muons from heavy-flavour hadron decays was measured at forward rapidity ($2.5<y<4$) in the transverse momentum range $6<p_t<10$ GeV/c as a function of the centrality of the Pb-Pb collisions. The suppression increases with centrality and reaches a factor of about 3-4 in the 10 % most central collisions, similar to the $D$ mesons. Finally the measured elliptic flow of $D^0$ and $D^+$ mesons in 30-50 % Pb-Pb collisions shows an indication for a non-zero elliptic flow.

6. References
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