D meson production in Pb-Pb collisions with the ALICE detector

Riccardo Russo

Università degli studi di Torino
Istituto Nazionale di Fisica Nucleare, Sezione di Torino
(ALICE Collaboration)
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Open heavy-flavour hadrons are a powerful tool to investigate the properties of the high-density medium created in heavy-ion collisions at high energies as they come from the hadronization of heavy quarks. The latter are created in the early stage of the interaction and experience the whole collision history. Heavy quarks in-medium energy loss can be investigated by comparing the heavy flavour production cross sections in p-p and nucleus-nucleus collisions. In addition, initial spatial anisotropy of the fireball can be reconstructed in the central rapidity region using the tracking and PID detectors. We report on the measurements of $D^+$, $D^0$, $D^{++}$ and $D_s^+$ production as a function of transverse momentum in pp collisions at $\sqrt{s} = 7$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV which allow one to calculate the nuclear modification factor expected to be sensitive to the in-medium energy loss of charm quarks, and on the elliptic flow in central and semi peripheral collisions.

I. OPEN HEAVY FLAVOURS AS A PROBE OF QGP FORMATION

Different QCD-based models, such as lattice QCD \cite{1}, predict that at extremely high density or temperature the nuclear matter undergoes a phase transition to a state called Quark Gluon Plasma (QGP) in which quarks and gluons are no more bound inside hadrons, but behave as free particles over large volumes. The QGP is characterized by a larger number of degrees of freedom than ordinary nuclear matter, therefore larger energy and entropy densities are expected. Such conditions can be experimentally created in heavy-ion collisions, where the large number of participant nucleons results in the creation of a fireball characterized by large volume (several fm/c) and number of constituents. The fireball expands reaching the phase boundary between QGP and hadron gas. The properties of the QGP can be investigated through the study of many different observables, which can be reconstructed in the experimental apparatus, in our case ALICE. In particular, D mesons can give information about the evolution of charm quarks in the medium. Charm quarks are produced in high-$Q^2$ scattering processes. Given their short production timescale ($\sim 1/Q^2$), they are expected to experience the full evolution of the created medium before hadronizing. In particular, it is expected that partons, while traversing the medium, lose part of their energy via elastic collisions with the other constituents and gluon radiation \cite{2}. This in-medium energy loss can be studied by comparing transverse momentum ($p_T$) spectra of D mesons in AA and pp collisions, where no medium is produced, by means of the nuclear modification factor $R_{AA}$

$$R_{AA}(p_T) = \frac{1}{N_{\text{coll}}} \frac{dN_{\text{AA}}}{dp_T}/\frac{dN_{\text{pp}}}{dp_T}$$

where $N_{\text{coll}}$ is the average number of binary collisions that occur in a single nucleus-nucleus collision, $N_{\text{AA}}$ and $N_{\text{pp}}$ are the measured D meson yields in AA and pp collisions respectively. $R_{AA}=1$ is expected if heavy quarks production is not affected by the hot medium. Energy loss causes $R_{AA} < 1$ at intermediate and high $p_T$. Gluon radiation is a QCD effect and is expected to depend on the parton color charge: gluons are expected to lose more energy than quarks, so D mesons should show a lower suppression than light charged hadrons, mainly coming from gluon fragmentation. A suppression of gluon radiation at small angles relative to the parton momentum is also expected. The angle of this “dead cone” is expected to increase with the parton mass \cite{3}. As a consequence, hadrons originating from b quarks are expected to be less suppressed than those coming from c quarks which in turn are less suppressed than light hadrons. In addition, the relative yield of $D_s^+$ with respect to that of non-strange D mesons is expected to be enhanced in Pb-Pb collisions at low-intermediate $p_T$ if charm quarks hadronize via recombination in the medium, due to strangeness enhancement in AA collisions \cite{4} \cite{5}. The interpretation of the $R_{AA}$ measurements has also to take into account the presence of initial state effects in AA collisions, such as nuclear modification of the Parton Distribution Functions (shadowing, anti-shadowing, EMC effect) and gluon saturation which would affect the production of c-quarks in heavy-ion collisions. These effects can be also observed in pA collisions, where no medium is created. The analysis on the 2013 p-Pb data sample at the LHC is currently ongoing.

Another observable that will be discussed in these proceedings is the elliptic flow of D mesons. In non-central collisions, the spatial anisotropy of the overlap region of the colliding nuclei is converted into momentum anisotropy of final state particles due to interactions.

\* rrusso@to.infn.it
among the medium constituents \[7\]. The anisotropy is quantified by the coefficients of the Fourier expansion of the distribution of the final state particles azimuthal angles relative to the reaction plane, which is defined by the impact parameter of the collision and the beam direction

\[
\frac{dN}{d\phi - \Psi_{RP}} \propto 1 + 2v_1 \cos(\phi - \Psi_{RP}) + 2v_2 \cos(2(\phi - \Psi_{RP})) + \ldots
\]

In particular, \(v_2\) is called elliptic flow and it reflects the initial almond-shaped geometry in non-central collisions. The study of D meson \(v_2\) is a tool to understand how c quarks interact with the other constituents and participate to the collective expansion of the fireball. In addition, a positive \(v_2\) is expected at high \(p_T\) due to the path-length dependence of energy loss, as c quarks emitted perpendicular to the reaction plane traversed a longer distance in the medium.

II. DATA SAMPLE AND ANALYSIS

All the details on the ALICE detector can be found in Ref. \[6\]. The results presented here are obtained from the 2011 Pb-Pb data sample at \(\sqrt{s_{NN}} = 2.76\) TeV. Data have been collected with a minimum bias trigger, based on the VZERO detector (array of scintillators covering the full azimuth at \(-3.7 < \eta < -1.7\) and \(2.8 < \eta < 5.1\)); to enhance the number of events in the desired centrality classes, an online selection based on the VZERO signal amplitude has been used. Only events with a vertex found within 10 cm from the centre of the detector along the beam axis were used.

The analysed sample consists of \(16 \times 10^6\) events in the centrality class 0-7.5\% corresponding to an integrated luminosity of \(28 \mu\text{b}^{-1}\). For the more peripheral samples, \(9.5 \times 10^6\) events in 30-50\%, and \(7.1 \times 10^6\) in 15-30\%, corresponding to an integrated luminosity of \(6 \mu\text{b}^{-1}\), were analyzed.

A. Nuclear modification factor

The analysis is based on the reconstruction of D mesons in the following hadronic decay channels \(D^0 \rightarrow K^-\pi^+, D^+ \rightarrow K^-\pi^+\pi^+, D^{+*} \rightarrow D^0\pi^+\) and \(D_s^+ \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+\) in the ALICE central barrel (\(|\eta| < 0.9\)). The Inner Tracking System (ITS) and Time Projection Chamber (TPC) provide excellent tracking performance, with impact parameter resolution of few tens of \(\mu\text{m}\) for \(p_T > 1\) GeV/c and transverse momentum resolution of better than 2\% up to 10 GeV/c for Pb-Pb collisions. D meson candidates are formed by combining pairs and triplets of tracks within each event.

Topological cuts are applied to reduce the large combinatorial background, requiring in particular a significant separation between the primary and secondary vertices (\(c\tau \sim 100-300\) depending on the D meson species) and small pointing angle (angle between the reconstructed momentum and the D meson flight line).

A further background rejection is obtained applying a PID selection on the decay tracks by combining information from the TPC and the Time of Flight detectors. After these selections, the signal yield is obtained from a fit to the invariant mass distributions in the different \(p_T\) bins. The 2011 Pb-Pb data sample allowed us to reconstruct the spectra in 10 \(p_T\) bins in the \(p_T\) range \([1,24]\) GeV/c for \(D^0\), \([3,36]\) GeV/c for \(D^+\) and \(D^{+*}\), and 3 \(p_T\) bins in \([4,12]\) GeV/c for \(D_s^+\).

The raw yield is corrected for the reconstruction and selection efficiencies, extracted from Monte Carlo simulations based on \(c\bar{c}\) (\(b\bar{b}\)) pairs generated with PYTHIA with Perugia-0 tuning and embedded into HIJING Pb-Pb events.

A fraction of the total D meson raw yields comes from the decay of B mesons. The contribution of D mesons coming from B decay was estimated starting from FONLL \[8\] predictions for B cross-sections, which describe well beauty production at Tevatron \[9\] and LHC \[10,11\]. The \(p_T\)-differential cross section of feed-down D mesons \(\left(\frac{d\sigma}{dp_T}\right)_{B\rightarrow D^+X}\) was then obtained using the EvtGen \[15\] package for the \(B \rightarrow D^+X\) decay kinematics. The non-prompt contribution to the raw yield was finally computed as:

\[
\frac{dN}{dp_T} = \Delta_{p_T} T_{AA} R_{AA} \left(\frac{d\sigma}{dp_T}\right)_{B\rightarrow D^+X}
\]

where \(T_{AA}\) is the nuclear overlap function (from Glauber Model) and the \(R_{AA}\) of D mesons from B decays was varied in the range \(1/3 < R_{AA} < 3\) since the energy loss of b quarks is not measured.

The pp reference (denominator in the \(R_{AA}\) formula) was extracted from the 2010 data sample (300 M events) at \(\sqrt{s} = 7\) TeV \[12\], rescaled at 2.76 TeV using the ratio of the FONLL predictions for the D meson cross sections at the two energies. The measured \(p_T\) differential cross section covers the \(p_T\) range \([1,24]\) GeV/c. The results have been validated with the 2011 pp data sample at \(\sqrt{s} = 2.76\) TeV \[13\], which covers a narrower \(p_T\) range \([2,12]\) GeV/c due to low statistics (70 M events).

To obtain the p-p reference up to 36 GeV/c an extrapolation based on FONLL/data ratio has been used.

The upper panel of Fig.1 shows the \(R_{AA}\) of the 4 mesons species as a function of \(p_T\). For \(D^0\), \(D^+\) and \(D^{+*}\) a suppression of up to a factor 5 for \(p_T > 5\) GeV/c is observed.

The \(R_{AA}\) values of \(D^0\), \(D^+\) and \(D^{+*}\) have been averaged. This average D meson \(R_{AA}\) shows a similar suppression as that of charged hadrons, as it can be seen in the lower panel of Fig.1. For \(D_s^+\), the large statistical and systematic uncertainties with the present data sample do not allow to conclude about low and intermediate \(p_T\) region, while for \(8 < p_T < 12\) GeV/c the measured suppression is similar to the one of non-strange D mesons.
Fig. 1. Upper panel: $D^0$, $D^+$, $D^{*+}$ and $D_\pi^+$ $R_{AA}$ as a function of $p_T$. Lower panel: average $D$ meson $R_{AA}$ as a function of $p_T$ compared to charged hadrons $R_{AA}$.

Fig. 2 shows $D$ meson $R_{AA}$ (data coming from the 2010 data sample [14]) as a function of centrality compared to non-prompt $J/\psi$ (CMS preliminary data) and indicates that c quarks are more affected by the medium than b quarks. It should be noted that $D$ meson and $J/\psi$ are measured in a different $p_T$ and rapidity range. The comparison of the measured $D$ meson $R_{AA}$ to models, shown in the bottom panel of Fig. 2, indicates that shadowing alone, NLO(MNR) model, cannot explain such a strong suppression; models including in-medium parton energy loss can give a reasonable description of the data.

**B. Elliptic Flow**

The $v_2$ analysis was performed in three centrality classes: 0-7.5%, 15-30% and 30-50%. $D$ meson candidates are divided into two sub-samples, depending on the reconstructed $D$ meson azimuthal angle $\phi$ relative to the event plane $\psi_{EP}$, which is an estimator of the reaction plane. $\psi_{EP}$ is computed for each event from the azimuthal distribution of reconstructed TPC tracks. The two azimuthal regions are: in plane for $|\Delta \phi| < \pi/4$ and out of plane for $\pi/4 < |\Delta \phi| < 3\pi/4$. The invariant mass spectra in the two regions are fitted to get the in-plane and out-of-plane yields, $N_{IN}$ and $N_{OUT}$, and the elliptic flow coefficient $v_2$ is calculated as

$$v_2 = \frac{N_{IN} - N_{OUT}}{2R_2 N_{IN} + N_{OUT}}$$

where $R_2$ is the event plane resolution, estimated by reconstructing the event plane angle using two sub-samples of tracks for each event.

Results in the centrality range 30-50%, shown in the upper panel of Fig. 3, indicate non-zero $D^0 v_2$ (3$\sigma$ for $2 < p_T < 6$ GeV/$c$), in agreement with that of $D^+$ and $D^{*+}$ within uncertainties. In addition, $v_2$ is comparable to that of charged hadrons in the same centrality. An increase of $v_2$ is observed going from central (0-7.5%) to peripheral (30-50%) events (central panel of Fig. 3), as expected from the smaller initial geometrical anisotropy in central collisions. The lower panel of Fig. 3 shows the comparison between the measured $D$ meson $v_2$ as a function of $p_T$ in 30-50% centrality class, together with some model predictions. The measured $v_2$ tends to favour the models that predict larger anisotropy at low $p_T$, suggesting that c quarks...
participation to the collective motion gives an important contribution to the onset of D meson elliptic flow.

III. SUMMARY

From the analysis of the 2011 Pb-Pb data sample collected with the ALICE detector, the reconstruction of D mesons through their hadronic decay channels has allowed the measurement of D⁰, D⁺, D*⁺ and, for the first time, D*⁺ yield in heavy-ion collisions.

In order to study the effect of the medium on the D meson momentum distributions, these results were compared to a pp reference to compute the nuclear modification factor. The R_AA of D⁰, D⁺ and D*⁺ was measured over a wide p_T range and shows a suppression up to a factor 5 for p_T > 5 GeV/c. Conclusions about a possible enhancement of D*⁺ at low-intermediate p_T still need more statistics, which is expected to be achieved after the LHC and ALICE upgrade plans.

D mesons show significantly (3σ) non-zero v₂ up to 6 GeV/c for D⁰, D⁺ and D*⁺ in semi-peripheral (30-50%) collisions with a hint of v₂ decrease going to more central collisions.

Different theoretical models can describe the nuclear modification factor and the elliptic flow separately, while a simultaneous description of both observables is still challenging.

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FIG. 3. Upper panel: $D^0$, $D^+$ and $D^*$ $v_2$ as a function of $p_T$ in 30-50% centrality compared to that of charged hadrons. Middle panel: $D^0$ $v_2$ as a function of centrality. Lower panel: $D^0$, $D^+$ and $D^*$ $v_2$ as a function of $p_T$ in 30-50% centrality compared to models.