

Suppression of high- p_T heavy-flavour particles in Pb–Pb collisions at the LHC, measured with the ALICE detector

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The ALICE experiment studies nucleus–nucleus collisions at the LHC in order to investigate the properties of QCD matter at extreme energy densities. The measurement of open charm and open beauty production allows one to probe the mechanisms of heavy-quark propagation, energy loss and hadronization in the hot and dense medium formed in high-energy nucleus-nucleus collisions. In particular, in-medium energy loss is predicted to be different for massless partons (light quarks and gluons) and heavy quarks at moderate momentum. The ALICE apparatus allows us to measure open heavy-flavour particles in several decay channels and with a wide phase-space coverage.

We present the results on the nuclear modification factors for heavy-flavour particle production in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Using proton–proton and lead–lead collision samples at $\sqrt{s} = 2.76$ and 7 TeV and at $\sqrt{s_{NN}} = 2.76$ TeV, respectively, nuclear modification factors $R_{AA}(p_T)$ were measured for D mesons at central rapidity (via displaced decay vertex reconstruction), and for electrons and muons from heavy-flavour decays, at central and forward rapidity, respectively. A large suppression is observed, by a factor 2.5–4 in central Pb–Pb collisions with respect to the pp reference, in the high p_T region, indicating a strong in-medium energy loss of heavy quarks.

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1. Introduction

The ALICE experiment [1] studies proton–proton, proton–nucleus and nucleus–nucleus collisions at the Large Hadron Collider (LHC), with the main goal of investigating the properties of the high-density, colour-deconfined, state of strongly-interacting matter that is expected to be formed in Pb–Pb collisions. Pb–Pb data were collected in November 2010 and in November 2011 at a centre-of-mass energy $\sqrt{s_{NN}} = 2.76$ TeV per nucleon–nucleon collision.

Heavy-flavour particles, abundantly produced at LHC energies, are regarded as effective probes of the conditions of the system (medium) formed in nucleus–nucleus collisions. In particular, they should be sensitive to the energy density, through the mechanism of in-medium energy loss of heavy quarks. The nuclear modification factor R_{AA} of particle p_T distributions is well-established as a sensitive observable for the study of the interaction of hard partons with the medium. This factor is defined as the ratio of the p_T spectrum measured in nucleus–nucleus (AA) to that expected on the basis of the proton–proton spectrum scaled by the number N_{coll} of binary nucleon–nucleon collisions in the nucleus–nucleus collision: $R_{AA}(p_T) = (1/\langle T_{AA} \rangle) \cdot (dN_{AA}/dp_T)/(d\sigma_{pp}/dp_T)$, where the AA spectrum corresponds to a given collision-centrality class and $\langle T_{AA} \rangle$, proportional to $\langle N_{coll} \rangle$, is the average nuclear overlap function resulting for that centrality class from the Glauber model of the collisions geometry [2]. Due to the QCD nature of parton energy loss, quarks are predicted to lose less energy than gluons (that have a higher colour charge) and, in addition, the ‘dead-cone effect’ and other mechanisms are expected to introduce a mass-dependence in the coupling of hard partons with the medium constituents [3, 4, 5, 6]. Therefore, one should observe a pattern of gradually decreasing R_{AA} suppression when going from the mostly gluon-originated light-flavour hadrons (e.g. pions) to D and to B mesons [5, 7]: $R_{AA}^\pi < R_{AA}^D < R_{AA}^B$. The measurement and comparison of these different medium probes provide a unique test of the colour-charge and mass dependence of parton energy loss.

The ALICE experiment was designed to detect heavy-flavour hadrons over a wide phase-space coverage and in various decay channels, as we will discuss in section 2. The production of heavy-flavour probes was measured in proton–proton collisions at $\sqrt{s} = 2.76$ and 7 TeV and compared to perturbative QCD (pQCD) predictions. These results, summarized in section 3, provide a well-defined, calibrated, reference for R_{AA} measurements. The Pb–Pb analysis results and the nuclear modification factors of D mesons, and of electrons and muons from heavy-flavour decays are presented in section 4, along with a comparison with other measurements and with model calculations.

2. Heavy-flavour production measurements in ALICE

The heavy-flavour detection capability of the ALICE detector, described in detail in [1], is mainly provided by:

- Tracking system; the silicon Inner Tracking System (ITS) and the Time Projection Chamber (TPC), embedded in a magnetic field of 0.5 T, provide track reconstruction in the pseudo-rapidity range $|\eta| < 0.9$ with a momentum resolution better than 4% for $p_T < 20$ GeV/ c and a transverse impact parameter¹ resolution better than 65 μm for $p_T > 1$ GeV/ c with a

¹The transverse impact parameter, d_0 , is defined as the distance of closest approach of the track to the interaction vertex, in the plane transverse to the beam direction.

high- p_T value of $20 \mu\text{m}$ [8].

- Particle identification system; charged hadrons are separated via their specific energy deposit dE/dx in the TPC and via time-of-flight measurement in the Time Of Flight (TOF) detector; electrons are identified at low p_T ($< 6 \text{ GeV}/c$) via TPC dE/dx and time-of-flight, and at intermediate and high p_T ($> 2 \text{ GeV}/c$) in the dedicated Transition Radiation Detector (TRD) and in the Electromagnetic Calorimeter (EMCal); muons are identified in the muon spectrometer covering the pseudo-rapidity range $-4 < \eta < -2.5$.

The main detection modes are listed below.

- Charm hadronic decays in $|y| < 0.5$ using displaced vertex identification: $D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$, $D^{*+} \rightarrow D^0 \pi^+$, and $D_s^+ \rightarrow K^- K^+ \pi^+$.
- Leptons from heavy-flavour decays: inclusive $D/B \rightarrow e + X$ in $|y_e| < 0.8$ and $D/B \rightarrow \mu + X$ in $2.5 < y_\mu < 4$; $B \rightarrow e + X$ using displaced electron identification and $B \rightarrow J/\psi (\rightarrow e^+ e^-) + X$ (only in pp for the moment).

The detection strategy for D mesons at central rapidity is based, for both pp and Pb–Pb collisions, on the selection of displaced-vertex topologies, i.e. separation of tracks from the secondary vertex from those from the primary vertex, large decay length (normalized to its estimated uncertainty), and good alignment between the reconstructed D meson momentum and flight-line. The identification of the charged kaon in the TPC and TOF detectors helps to further reduce the background at low p_T . An invariant-mass analysis is then used to extract the raw signal yield, to be then corrected for detector acceptance and for PID, selection and reconstruction efficiency, evaluated from a detailed detector simulation. The contamination of D mesons from B meson decays is estimated to be of about 15%, using the beauty production cross section predicted by the FONLL (fixed-order next-to-leading log) calculation [9] and the detector simulation, and it is subtracted from the measured raw p_T spectrum, before applying the efficiency corrections. The systematic uncertainty related to the FONLL theoretical uncertainty is correlated in the pp and Pb–Pb spectra, thus it partly cancels in the R_{AA} ratio. An additional source of systematic uncertainty arises from the unknown nuclear modification of B meson production. To estimate this uncertainty, the prompt D meson R_{AA} was evaluated for the range of hypotheses $0.3 < R_{AA}^B/R_{AA}^D < 3$ [8].

At central rapidity, heavy-flavour production is measured also using semi-electronic decays. The basis of this measurement is a robust electron identification. This uses the signals of four different detectors: TPC, TOF, EMCal and TRD (only in pp collisions for the moment). The residual pion contamination in the electron sample is measured with fits to the TPC dE/dx and EMCal E/p distributions in momentum slices, and subtracted. The p_T -differential cross section of electrons from charm and beauty particle decays is obtained by subtracting from the efficiency-corrected inclusive spectrum the components of background electrons. The main components are electrons from Dalitz decays of light-flavour hadrons (mainly π^0 and η , in addition to ρ , ω , and ϕ), γ conversions in the beam pipe and innermost pixel layer, and electrons from J/ψ decays. The latter is estimated with simulations using the measured J/ψ production in pp collisions and its nuclear modification factor in Pb–Pb collisions. The first two components are estimated using two different methods: for the pp analysis, a simulation “cocktail” with measured hadron cross sections as input [10]; for the Pb–Pb analysis, the direct reconstruction of the two-track vertices of internal and in-material photon conversions.

Heavy-flavour production at forward rapidity is measured using the single-muon p_T distribution. The extraction of the heavy-flavour contribution from the single muon spectra requires the subtraction of three main sources of background: muons from the decay-in-flight of light hadrons (decay muons); muons from the decay of hadrons produced in the interaction with the front absorber (secondary muons); hadrons that punch through the front absorber. The last contribution, about 20% for $p_T > 2$ GeV/ c , can be efficiently rejected by requiring the matching of the reconstructed tracks with the tracks in the trigger system. Due to the lower mass of the parent particles, the light-hadron decay muons have a softer transverse momentum than the heavy-flavour muons, and dominate the low- p_T region. In the pp analysis this background is subtracted using simulations, as detailed in [11]. In the Pb–Pb analysis, instead, it is extrapolated from the π and K spectra measured at central rapidity [12].

The results that we present are obtained from data recorded with minimum-bias, single muon and EMCal trigger selections during the Pb–Pb runs of 2010 (D mesons [8] and muons [12]) and 2011 (electron preliminary data). Pb–Pb collision-centrality classes are defined in terms of percentiles of the distribution of the sum of amplitudes in the VZERO scintillator detectors, located in the forward and backward pseudo-rapidity regions of the experiment.

3. Reference measurements in pp collisions at $\sqrt{s} = 2.76$ and 7 TeV

The D^0 , D^+ , and D^{*+} p_T -differential production cross sections in $|y| < 0.5$ were measured in pp collisions at $\sqrt{s} = 2.76$ [13] and 7 TeV [14], using data samples with integrated luminosities of 1.1 and 5.0 nb $^{-1}$ and covering the p_T intervals 1–24 and 1–12 GeV/ c , respectively.

The heavy-flavour decay electron cross section in $|y| < 0.5$ was measured in pp collisions at $\sqrt{s} = 7$ TeV [10] in the range 0.5–8 GeV/ c with an integrated luminosity of 2.6 nb $^{-1}$. At forward rapidity $2.5 < y < 4$, the heavy-flavour decay muon cross section was measured in pp collisions at $\sqrt{s} = 2.76$ [12] and 7 TeV [11], using data samples with integrated luminosities of 19.0 and 16.5 nb $^{-1}$ and covering the p_T intervals 2–10 and 2–12 GeV/ c , respectively.

All these measurements are described within uncertainties by theoretical predictions based on pQCD calculations. For the electron and muon spectra, the FONLL calculation indicates that beauty decays are the dominant contribution for p_T larger than about 5–7 GeV/ c .

The reference pp cross sections used for the determination of the nuclear modification factors R_{AA} in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV were defined as follows:

- for D mesons, the cross section measured at $\sqrt{s} = 7$ TeV, scaled to 2.76 TeV;
- for heavy-flavour decay electrons, the cross section measured at $\sqrt{s} = 7$ TeV, scaled to 2.76 TeV ($p_T < 8$ GeV/ c), and the FONLL cross section with its theoretical uncertainty ($p_T > 8$ GeV/ c);
- for heavy-flavour decay muons, the cross section measured at $\sqrt{s} = 2.76$ TeV (which has the same precision as at 7 TeV).

The scaling factors for D mesons and electrons were defined as the ratios of the cross sections from the FONLL pQCD calculation at 2.76 and 7 TeV [15]. The scaled D meson cross sections were found to be consistent with those measured, though with limited precision of 20–25% in pp collisions at $\sqrt{s} = 2.76$ TeV [13].

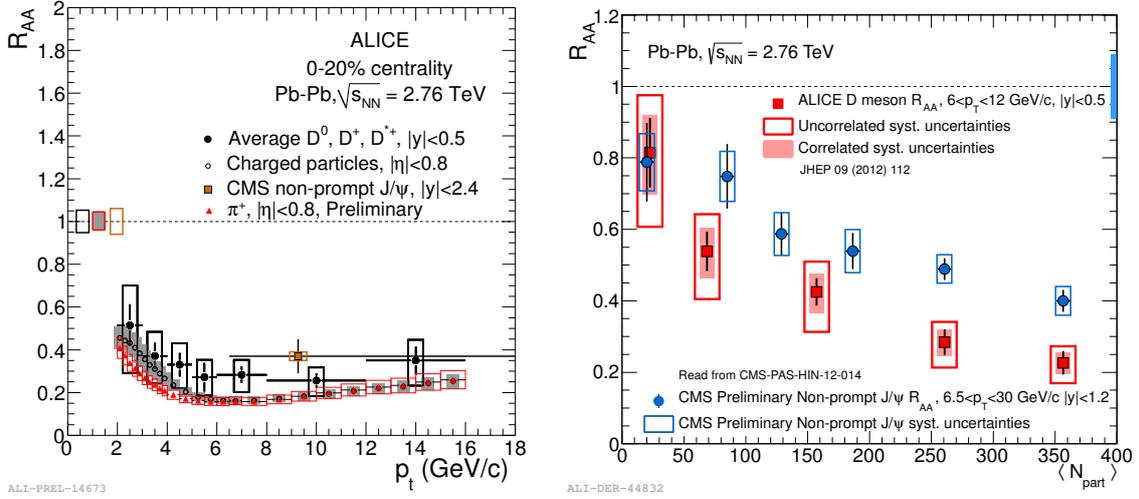


Figure 1: Left: Average R_{AA} of D mesons in the 0–20% centrality class [8], compared to that of charged particles [16], π^+ , and non-prompt J/ψ from B decays [17] in the same centrality class. Right: Average R_{AA} of D mesons as a function of centrality [8] (average number of nucleons participating in the collision, from the Glauber model [2], in each centrality class), compared to that of non-prompt J/ψ from B decays [18].

4. Heavy-flavour nuclear modification factors in Pb–Pb at $\sqrt{s_{NN}} = 2.76$ TeV

The nuclear modification factor of prompt D mesons (average of D^0 , D^+ and D^{*+}) in Pb–Pb collisions is shown in figure 1: as a function of p_T in central collisions (left) and as a function of centrality for $6 < p_T < 12$ GeV/c (right) [8]. A strong suppression is observed in central collisions, reaching a factor about 4 for $p_T > 5$ GeV/c. R_{AA} is compatible with that of charged pions and charged particles [16], although there seems to be a tendency for $R_{AA}^D > R_{AA}^\pi$ at low p_T . In the figure, the nuclear modification of non-prompt J/ψ from B decays, measured by the CMS Collaboration [17, 18], is also shown. The comparison with D mesons indicates a different suppression for charm and beauty hadrons in central collisions, consistent with the expectation $R_{AA}^D < R_{AA}^B$. However, the different p_T and rapidity ranges still prevent from a clear conclusion on this point.

A large suppression is also observed for heavy-flavour decay muons [12] and electrons, at forward and central rapidity, respectively, as shown for the centrality class 0–10% in figure 2. Both lepton species exhibit a suppression of factor of about 3 up to 10 GeV/c, and about 2 for electrons up to $p_T = 18$ GeV/c in a momentum range where beauty decays should be dominant.

Several theoretical models based on parton energy loss compute the heavy-flavour nuclear modification factor: (I) [19, 20], (II) [21], (III) [22], (IV) [23], (V) [24], (VI) [25], (VII) [26], (VIII) [7]. Figure 3 displays the comparison of these models to the average D meson R_{AA} , for central Pb–Pb collisions (0–20%), along with the comparison to the charged-particle R_{AA} [16], for those models that also compute this observable. Radiative energy loss supplemented with in-medium D meson dissociation (I) [19] and radiative plus collisional energy loss in the WHDG (II) [21] and CUJET1.0 (VII) [26] implementations describe reasonably well at the same time the charm and light-flavour suppression. A model based on AdS/CFT drag coefficients (III) [22]

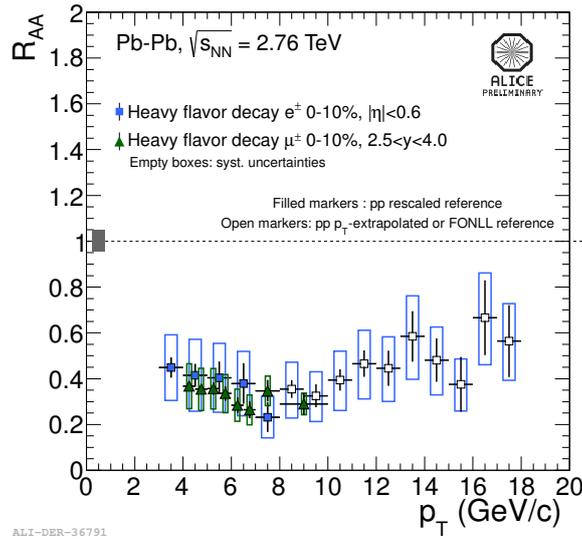


Figure 2: Nuclear modification factors for heavy-flavour decay muons at forward rapidity [12] and electrons at central rapidity in central (0–10%) Pb–Pb collisions, as a function of p_T .

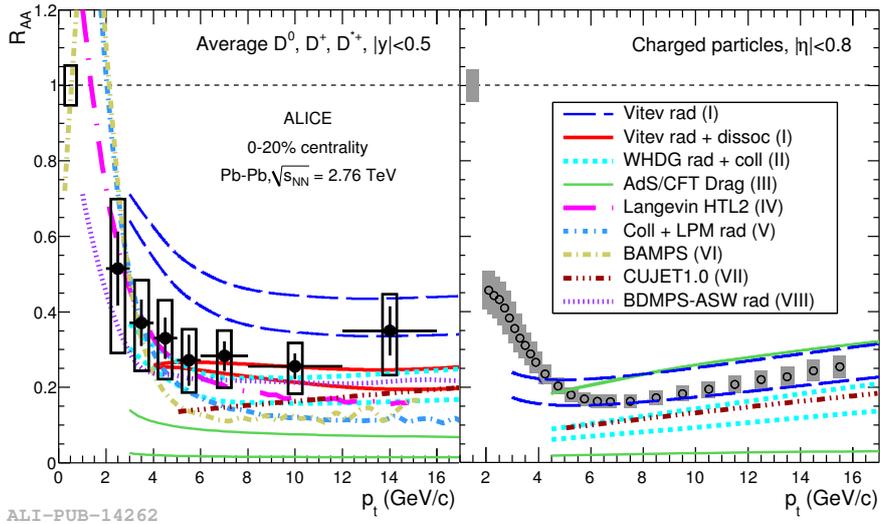


Figure 3: Average R_{AA} of D mesons (left) and R_{AA} of charged particles (right) in the 0–20% centrality class compared to model calculations (details in the text) [8].

underestimates significantly the charm R_{AA} and has very limited predictive power for the light-flavour R_{AA} .

5. Conclusions

The ALICE results on the R_{AA} nuclear modification factors of heavy-flavour hadrons in Pb–Pb collisions at the LHC imply a strong in-medium energy loss for c and b quarks. The D^0 , D^+ and

D^{*+} R_{AA} , measured as a function of p_T and centrality, is as low as 0.2–0.3 for $p_T > 5$ GeV/ c and compatible with the R_{AA} of pions. Below 5 GeV/ c , there is a hint for $R_{AA}^D > R_{AA}^\pi$. The comparison with J/ψ from B decays (CMS Collaboration) reveals a first indication for different suppression of charm and beauty hadrons in central collisions. A large suppression, $R_{AA} \approx 0.3$ –0.5 is observed also for heavy-flavour decay electrons and muons in the p_T range above 5 GeV/ c , where beauty decays are dominant according to pQCD calculations. The completion of the analysis of high-statistics data from the 2011 Pb–Pb run should allow for sharper conclusions on the comparison of the D meson R_{AA} with pions and with beauty measurements. For the latter, the separation of electrons from B decays should also be possible. Finally, data from the p–Pb run scheduled for January 2013 will constrain the relevance of initial-state nuclear effects in the low p_T range.

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