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Centrality dependence of high-p_T D meson suppression in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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Abstract: The nuclear modification factor, R_{AA}, of the prompt charmed mesons D^0, D^+ and D^{*+}, and their antiparticles, was measured with the ALICE detector in Pb-Pb collisions at a centre-of-mass energy $\sqrt{s_{NN}} = 2.76$ TeV in two transverse momentum intervals, $5 < p_T < 8\,\mathrm{GeV}/c$ and $8 < p_T < 16\,\mathrm{GeV}/c$, and in six collision centrality classes. The R_{AA} shows a maximum suppression of a factor of 5–6 in the 10% most central collisions. The suppression and its centrality dependence are compatible within uncertainties with those of charged pions. A comparison with the R_{AA} of non-prompt J/ψ from B meson decays, measured by the CMS Collaboration, hints at a larger suppression of D mesons in the most central collisions.

Keywords: Charm physics, Heavy Ions, Heavy-ion collision

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1 Introduction

When heavy nuclei collide at high energy, a state of strongly-interacting matter with high energy density is expected to form. According to Quantum Chromodynamics (QCD) calculations on the lattice, this state of matter, the so-called Quark-Gluon Plasma (QGP) is characterised by the deconfinement of the colour charge (see e.g. [1–4]). High-momentum partons, produced at the early stage of the nuclear collision, lose energy as they interact with the QGP constituents. This energy loss is expected to proceed via both inelastic (gluon radiation) [5, 6] and elastic (collisional) processes [7–9].

The nuclear modification factor R_{AA} is used to characterise parton energy loss by comparing particle production yields in nucleus-nucleus collisions to a scaled proton-proton (pp) reference, that corresponds to a superposition of independent nucleon-nucleon collisions. R_{AA} is defined as

$$R_{\mathrm{AA}} = \frac{1}{\langle T_{\mathrm{AA}} \rangle} \cdot \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}\,, \tag{1.1}$$

where $\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}$ and $\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}$ are the transverse momentum (p_{T}) differential cross section and yield in proton-proton and nucleus-nucleus (AA) collisions, respectively. $\langle T_{\mathrm{AA}} \rangle$ is the average nuclear overlap function, estimated within the Glauber model of the nucleus-nucleus collision geometry, and proportional to the average number of nucleon-nucleon (binary) collisions [10, 11]. Energy loss shifts the momentum of quarks and gluons, and thus hadrons, towards lower values, leading to a suppression of hadron yields with respect to binary scaling at p_{T} larger than few GeV/c ($R_{\mathrm{AA}} < 1$).

Energy loss is expected to be smaller for quarks than for gluons because the colour charge factor of quarks is smaller than that of gluons [5, 6]. In the energy regime of the Large Hadron Collider (LHC), light-flavour hadrons with p_{T} ranging from 5 to 20 GeV/c originate predominantly from gluon fragmentation (see e.g. [12]). At variance, charmed mesons provide an experimental tag for a quark parent. Because of their large mass $m_{\mathrm{c,b}}$

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($m_c \approx 1.3$ GeV/c^2, $m_b \approx 4.5$ GeV/c^2 [13]), heavy quarks are produced at the initial stage of heavy-ion collisions in hard scattering processes that are characterised by a timescale $\Delta t < 1/(2\, m_{c,b}) \sim 0.1\,(0.01)$ fm/c for c (b) quarks. This time is shorter than the formation time of the QGP medium (a recent estimate for the LHC energy is about 0.3 fm/c [14]). As discussed in ref. [15], this should be the case also for charm and beauty quarks produced in gluon splitting processes, if their transverse momentum is lower than about 50 GeV/c. Therefore, the comparison of the heavy-flavour hadron R_{AA} with that of pions allows the colour-charge dependence of parton energy loss to be tested. The softer fragmentation of gluons than that of charm quarks, and the observed increase of the charged hadron R_{AA} towards high p_T [16], tend to counterbalance the effect of the larger energy loss of gluons on the R_{AA}. The model predictions range from a rather moderate effect $R^{\pi}_{AA} < R^{D}_{AA}$ [17–20] to an overall compensation $R^{\pi}_{AA} \approx R^{D}_{AA}$ (as recently shown in [12]) in the p_T interval from 5 to about 15 GeV/c.

Several mass-dependent effects are expected to influence the energy loss for quarks (see [15] for a recent review). The dead-cone effect should reduce small-angle gluon radiation for quarks that have moderate energy-over-mass values, i.e. for c and b quarks with momenta up to about 10 and 30 GeV/c, respectively [18, 21–24]. Likewise, collisional energy loss is expected to be reduced for heavier quarks, because the spatial diffusion coefficient that regulates the momentum exchange with the medium is expected to scale as the inverse of the quark mass [25]. In the p_T interval up to about 20 GeV/c, where the masses of heavy quarks are not negligible with respect to their momenta, essentially all models predict $R^{D}_{AA} < R^{B}_{AA}$ [17–20, 26–35], which stems directly from the mass dependence of the quark-medium interaction and is only moderately affected by the different production and fragmentation kinematics of c and b quarks (see e.g. [36]).

A first comparison of light-flavour, charm and beauty hadron nuclear modification factors based on measurements by the ALICE and CMS Collaborations [16, 37, 38] from the 2010 LHC Pb-Pb data at a centre-of-mass energy $\sqrt{s_{NN}} = 2.76$ TeV was presented in [37]. In this paper we present the centrality dependence of the D meson R_{AA} in Pb-Pb collisions at the same energy, measured with the ALICE detector [39] using data from both 2010 and 2011 periods (integrated luminosities of about 2.2 and 21 μb^{-1}, respectively). The focus here is on the study of the parton energy loss; therefore, the data are presented for the high-p_T interval 5–16 GeV/c, where the largest suppression relative to binary scaling was observed [37]. The results are compared with charged pions, measured by the ALICE Collaboration [40], with non-prompt J/ψ mesons, measured by the CMS Collaboration [38], and with model predictions.

2 Experimental apparatus and data sample

The Pb-Pb collisions were recorded using a minimum-bias interaction trigger, based on the information of the signal coincidence of the V0 scintillator detectors that cover the full azimuth in the pseudo-rapidity intervals $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$ [41]. The measurement of the summed signal amplitudes from the V0 detectors was used to sort the events in classes of collision centrality, defined in terms of percentiles of the Pb-Pb

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hadronic cross section [42]. The trigger efficiency is 100% for the events considered in this analysis, which correspond to the most central 80% of the Pb-Pb hadronic cross section. An online selection based on the information of the V0 detectors was applied to increase the statistics of central collisions for the 2011 data sample. An offline selection using the V0 and the neutron Zero-Degree Calorimeters (ZDC) was applied to remove background from interactions of the beams with residual atoms in the vacuum tube. Events with a reconstructed primary vertex outside the interval ± 10 cm from the interaction point along the beam direction (z coordinate) were removed. The event sample used in the analysis corresponds to an integrated luminosity $L_{\rm int} = (21.3 \pm 0.7)\ \mu{\rm b}^{-1}$ in the 0–10% centrality class (16.4×10^6 events) and $(5.8 \pm 0.2)\ \mu{\rm b}^{-1}$ in each of the 10–20%, 20–30%, 30–40%, 40–50% classes (4.5×10^6 events per class). In the 50–80% class, where 2010 data were used, the analyzed event sample corresponds to $(2.2 \pm 0.1)\ \mu{\rm b}^{-1}$ (5.1×10^6 events).

The decays ${\rm D}^0 \to {\rm K}^-\pi^+$, ${\rm D}^+ \to {\rm K}^-\pi^+\pi^+$ and ${\rm D}^{*+} \to {\rm D}^0\pi^+$, and their charge conjugates, were reconstructed as described in [37] using the central barrel detectors, which are located in a solenoid that generates a 0.5 T magnetic field parallel to the beam direction. Charged particle tracks were reconstructed with the Time Projection Chamber (TPC) [43] and the Inner Tracking System (ITS), which consists of six cylindrical layers of silicon detectors [44]. Both detectors provide full azimuthal coverage in the interval $|\eta| < 0.9$. ${\rm D}^0$ and ${\rm D}^+$ candidates were formed from pairs and triplets of tracks with $|\eta| < 0.8$, $p_{\rm T} > 0.4$ GeV/c, at least 70 associated space points in the TPC, and at least two hits in the ITS, out of which one had to be in either of the two innermost layers. ${\rm D}^{*+}$ candidates were formed by combining ${\rm D}^0$ candidates with tracks with $|\eta| < 0.8$, $p_{\rm T} > 0.1$ GeV/c, and at least three associated hits in the ITS for the 10% most central collisions (two in the other centrality classes). The decay tracks of the candidate D mesons were identified on the basis of their specific ionization energy deposition ${\rm d}E/{\rm d}x$ in the TPC and of their flight times to the Time Of Flight (TOF) detector, which has the same η acceptance as the TPC. Particles were identified as pions (kaons) by requiring the measured signal to be within three times the resolution ($\pm 3\,\sigma$) around the expected mean values of ${\rm d}E/{\rm d}x$ and time-of-flight for pions (kaons). Only D meson candidates with rapidity $|y| < 0.8$ were considered, because the acceptance decreases rapidly outside this interval.

3 Data analysis

The selection of the D meson decay topology is mainly based on the displacement of the decay tracks from the primary vertex, and on the pointing of the reconstructed D meson momentum to the primary vertex [37]. The raw yields were determined in each centrality and $p_{\rm T}$ interval using fits to the distributions of invariant mass $M({\rm K}^-\pi^+)$ and $M({\rm K}^-\pi^+\pi^+)$, in the case of ${\rm D}^0$ and ${\rm D}^+$ mesons, and of the difference $M({\rm K}^-\pi^+\pi^+) - M({\rm K}^-\pi^+)$ for ${\rm D}^{*+}$ mesons. The fit function is the sum of a Gaussian, for the signal, and either an exponential function (${\rm D}^0$ and ${\rm D}^+$) or a power-law multiplied with an exponential function (${\rm D}^{*+}$) to describe the background distribution [37].

For ${\rm D}^0$ mesons, an additional term was included in the fit function to account for the so-called 'reflections', i.e. signal candidates that are present in the invariant mass distribution

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	$5 < p_{\mathrm{T}} < 8$ GeV/c			$8 < p_{\mathrm{T}} < 16$ GeV/c		
	D^0	D^+	D^{*+}	D^0	D^+	D^{*+}
Pb-Pb yields:						
Yield Extraction	6	8	6	7	8	7
Tracking efficiency	10	15	15	10	15	15
PID identification	5	5	5	5	5	5
Cut efficiency	5	10	5	5	10	5
D p_{T} distribution in sim.	2	2	2	2	2	2
Feed-down subtraction	$^{+12}_{-13}$	$^{+10}_{-10}$	$^{+6}_{-8}$	$^{+12}_{-12}$	$^{+10}_{-10}$	$^{+7}_{-10}$
$\langle T_{\mathrm{AA}} \rangle$ [42]		4			4	
pp reference	16	20	17	16	19	17
Reference scaling in $\sqrt{s}$		$^{+6}_{-12}$			$^{+5}_{-6}$	
Centrality limits			< 0.1			

Table 1. Systematic uncertainties (%) on R_{AA} of prompt D mesons with $5 < p_{\mathrm{T}} < 8$ GeV/c and $8 < p_{\mathrm{T}} < 16$ GeV/c in the 0–10% centrality class.

also when the (K, π) mass hypothesis for the decay tracks is swapped. A large fraction (about 70%) of these reflections is rejected by the particle identification selection. The residual contribution was studied with Monte Carlo simulations (described later in this section). It was found that the reflections have a broad invariant mass distribution, which is well described by a sum of two Gaussians, and its integral amounts to about 30% of the yield of the signal in the p_{T} interval used in the analysis presented in this article. In order to account for the contribution of reflections in the data, a template consisting of two Gaussians was included in the fit. The centroids and widths, as well as the ratios of the integrals of these Gaussians to the signal integral, were fixed to the values obtained in the simulation (see [45] for more details).

In the most central centrality class (0–10%), the statistical significance of the invariant mass signal peaks varies from 8 to 18 depending on the D meson species and p_{T}, while the signal-over-background ratio ranges from 0.1 to 0.4. In the most peripheral centrality class (50–80%), the statistical significance varies from 4 to 11, while the signal-over-background ranges from 0.4 to 1.5. In figure 1 the invariant mass distributions of the three meson species are shown in the 0–10% centrality class and in the transverse momentum intervals $5 < p_{\mathrm{T}} < 8$ GeV/c and $8 < p_{\mathrm{T}} < 16$ GeV/c.

The correction for acceptance and efficiency was determined using Monte Carlo simulations. Pb-Pb events were simulated using the HIJING generator [46] and D meson signals were added with the PYTHIA 6 generator [47]. The p_{T} distribution of the D mesons was weighted in order to match the shape measured for D^0 mesons in central Pb-Pb collisions [37]. A detailed description of the detector response, based on the GEANT3 transport package [48], was included. The contribution of feed-down from $\mathrm{B} \to \mathrm{D} + X$ to the inclusive D meson raw yield depends on p_{T} and on the geometrical selection criteria, because the secondary vertices of D mesons from B-hadron decays are typically more displaced from

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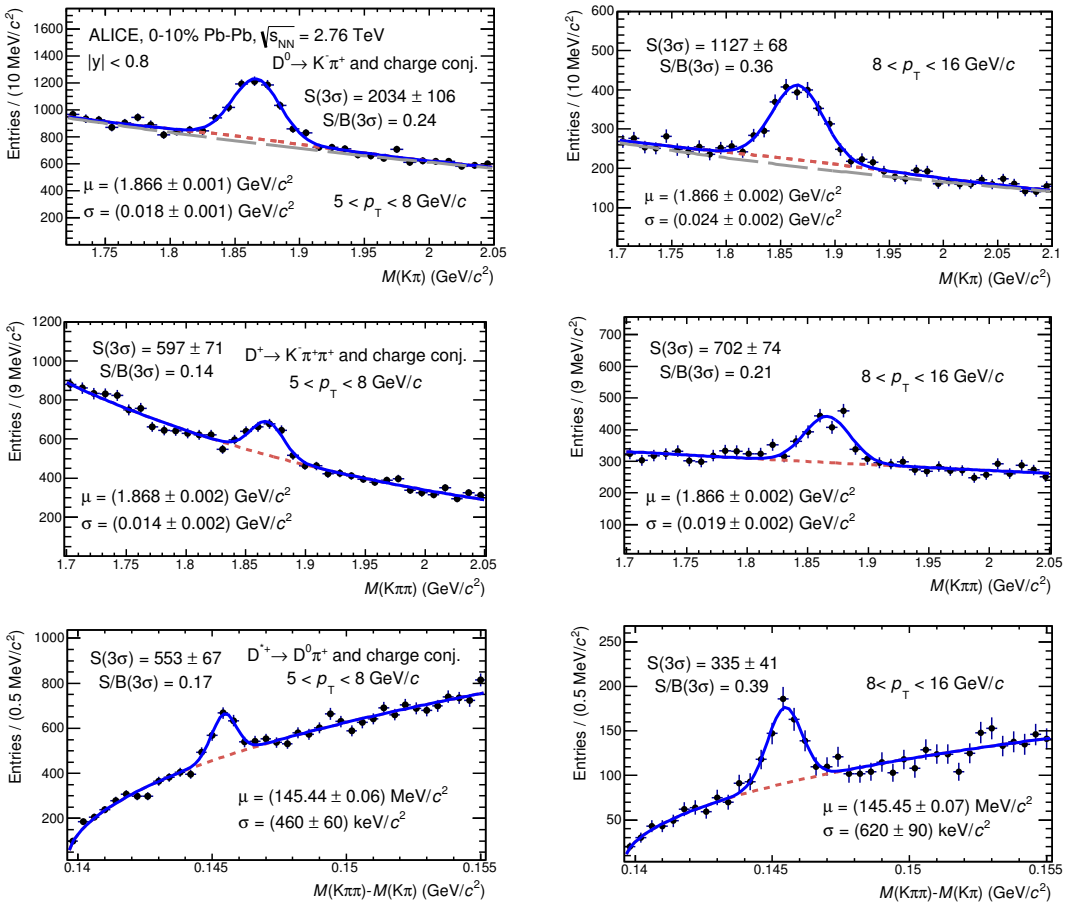

Figure 1. Distributions of the Kπ invariant mass for D^0 candidates (upper panels) and K$\pi\pi$ invariant mass for D^+ candidates (central panels) and of the invariant mass difference $M(\mathrm{K}\pi\pi) - M(\mathrm{K}\pi)$ for D^{*+} candidates (lower panels) and the corresponding charge conjugates in two p_T intervals (left and right panels) for 16.4×10^6 Pb-Pb collisions in the 0–10% centrality class. The curves show the fit functions described in the text. The red short-dashed line represents the background fit function. For the D^0 meson, the gray dashed line represents the background without the inclusion of the template for the contribution of reflections, i.e. signal candidates with swapped (K, π) mass hypothesis. The template is defined as the sum of two Gaussians with parameters fixed to the values obtained in simulation.

the primary vertex than those of prompt D mesons. This contribution was subtracted using the beauty-hadron production cross section in pp collisions from FONLL calculations [49], convoluted with the decay kinematics as implemented in the EvtGen decay package [50] and multiplied by the efficiency for feed-down D mesons from the simulation, the average nuclear overlap function $\langle T_\mathrm{AA} \rangle$ in each centrality class, and an assumed value for R_AA of feed-down D-mesons [37]. On the basis of the comparison shown in this paper, this assumption was taken as $R_\mathrm{AA}^{\text{feed-down D}} = 2\, R_\mathrm{AA}^{\text{prompt D}}$ and a systematic uncertainty was estimated by varying it in the interval $1 < R_\mathrm{AA}^{\text{feed-down D}} / R_\mathrm{AA}^{\text{prompt D}} < 3$. The feed-down contribution is about 20–25%, depending on the D meson species and on the p_T interval.

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The p_{T}-differential cross section of prompt D mesons with $|y| < 0.5$ in pp collisions at $\sqrt{s} = 2.76$ TeV, used as reference for R_{AA}, was obtained by scaling the measurement at $\sqrt{s} = 7$ TeV [51]. The p_{T}-dependent scaling factor and its uncertainty were determined with FONLL calculations [52]. The result of the scaling was validated by comparison with the measurement obtained from a smaller sample of pp collisions at $\sqrt{s} = 2.76$ TeV [53]. This measurement covers a reduced p_{T} interval 1–12 GeV/c with a statistical uncertainty of 20–25 % and was, therefore, not used as a pp reference in the present analysis. The yields in Pb–Pb collisions were normalized to the same rapidity interval as the reference ($|y| < 0.5$) by dividing them by $\Delta y = 1.6$.

The systematic uncertainties were estimated as a function of p_{T} and centrality using the procedure described in [37, 45] and briefly outlined in the following. The sources of systematic uncertainty on the nuclear modification factor are listed in table 1, along with their values for the two p_{T} intervals in the most central collisions (0–10%). The uncertainties are approximately independent of centrality.

The systematic uncertainty on the yield extraction was estimated by varying the fit conditions (fit interval and functional form used to describe the background) or by considering, as an alternative method, the bin counting of the invariant mass distribution obtained after subtracting the background estimated from a fit in the side-bands of the signal peak. The uncertainty amounts to about 6–8%. This includes in the case of the D^0 a contribution of about 5% obtained by varying the ratio of the integral of the reflections to the integral of the signal by $\pm$ 50%.

The systematic uncertainty on the tracking efficiency correction was evaluated by varying the track selection criteria and amounts to 5% per track, thus 10% for the D^0 (two-track final state) and 15% for the D^+ and D^{*+} mesons (three-track final states). The correction for the particle identification (PID) efficiency introduces a systematic uncertainty of 5%, which was estimated by repeating the analysis without this selection and comparing the corrected yields. A systematic uncertainty of 5–10% associated with the selection efficiency correction was estimated by varying the D meson selection cuts. The D meson p_{T} distribution used in the simulation to calculate the acceptance and efficiency was varied between the measured distribution and the prediction of a theoretical calculation including parton energy loss [32, 54, 55]. The resulting variation of 2% of the efficiencies was assigned as a systematic uncertainty.

The systematic uncertainty on the correction for feed-down from B-hadron decays was estimated, as described in [45], by varying the parameters of the FONLL calculation and the hypothesis on the R_{AA} of the feed-down D mesons in the range $1 < R_{\mathrm{AA}}^{\text{feed-down D}}/R_{\mathrm{AA}}^{\text{prompt D}} < 3$. This variation yields the main contribution to the uncertainty, which amounts to 6–13%, depending on the D meson species and p_{T} interval.

The contribution to the systematic uncertainty due to the 1.1% relative uncertainty on the fraction of hadronic cross section used in the Glauber fit to determine the centrality classes was obtained as in [37] and estimated to be $< 0.1\%$ in the central centrality class (0–10%) and 3% in the most peripheral centrality class (50–80%).

The systematic uncertainties on the denominator of the nuclear modification factor include the uncertainty on $\langle T_{\mathrm{AA}} \rangle$, which ranges from 4% in the 0–10% centrality class to

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7.5% in the 50–80% centrality class [42], and the uncertainty on the pp reference. The latter has a contribution of about 16–20% from the pp measurement at $\sqrt{s} = 7$ TeV and a contribution of $^{+12}_{-6}$% from the energy scaling down to $\sqrt{s} = 2.76$ TeV.

4 Results and discussion

Figure 2 shows the R_{AA} as a function of centrality for D^0, D^+ and D^{*+} in the intervals $5 < p_{\mathrm{T}} < 8$ GeV/c (left) and $8 < p_{\mathrm{T}} < 16$ GeV/c (right). Centrality is quantified in terms of the average number of nucleons participating in the collision in each multiplicity class, $\langle N_{\mathrm{part}} \rangle$, evaluated with a Monte Carlo Glauber calculation [42]. The bars represent the statistical uncertainties. The filled and empty boxes represent the quadratic sum of the systematic uncertainties that are, respectively, correlated between centrality intervals (pp reference, B-hadron cross section used for feed-down correction, particle identification, track reconstruction efficiency, $\langle T_{\mathrm{AA}} \rangle$) and uncorrelated (yield extraction, selection efficiency corrections, value of feed-down D meson R_{AA}). The latter category also includes the systematic uncertainties that are partially correlated between adjacent centrality classes. The measurements for the three D meson species share part of the systematic uncertainties and are consistent within statistical uncertainties. The suppression increases with centrality and reaches a factor of 5–6 in the most central collisions for both p_{T} intervals.

A weighted average of the R_{AA} of the three D meson species was computed using the inverse of the relative statistical uncertainties as weights. The systematic uncertainties of the weighted average were calculated considering the contributions from the tracking efficiency, the feed-down correction, and the reference energy scaling factor from 7 to 2.76 TeV as fully correlated among the three D meson species.

Figure 3 shows the average of the D^0, D^+ and D^{*+} nuclear modification factors as a function of centrality, for the intervals $5 < p_{\mathrm{T}} < 8$ GeV/c (left) and $8 < p_{\mathrm{T}} < 16$ GeV/c (right), compared with the R_{AA} of charged pions with $|y| < 0.8$ for the same p_{T} intervals[1], and of non-prompt J/ψ mesons measured by the CMS Collaboration for $6.5 < p_{\mathrm{T}} < 30$ GeV/c in $|y| < 2.4$ [38]. Care has to be taken when comparing with the non-central CMS data point as it is plotted at the N_{part} mean value of the broad 20–100% centrality interval.

The p_{T} interval 8–16 GeV/c for D mesons was chosen in order to obtain a significant overlap with the p_{T} distribution of B mesons decaying to J/ψ particles with $6.5 < p_{\mathrm{T}} < 30$ GeV/c. Using a simulation based on the FONLL calculation [49] and the EvtGen particle decay package [50], it was estimated that about 70% of these parent B mesons have $8 < p_{\mathrm{T}} < 16$ GeV/c, with a median of the p_{T} distribution of about 11.3 GeV/c. A median value of (9.5 ± 0.5) GeV/c was estimated for D mesons with $8 < p_{\mathrm{T}} < 16$ GeV/c in the 0–10% centrality class. The estimate was based on the p_{T} distribution of D^0 mesons in p_{T} intervals with a width of 1 GeV/c. The effect of the different width of the rapidity interval for D and non-prompt J/ψ mesons ($|y| < 0.5$ and $|y| < 2.4$, respectively) is expected to be mild because the intervals are partially overlapping and a preliminary measurement by the CMS Collaboration does not indicate a significant y dependence of the R_{AA} of non-prompt J/ψ mesons in $|y| < 2.4$ [56].

[1]The charged pion results were obtained with the analysis method described in [40].

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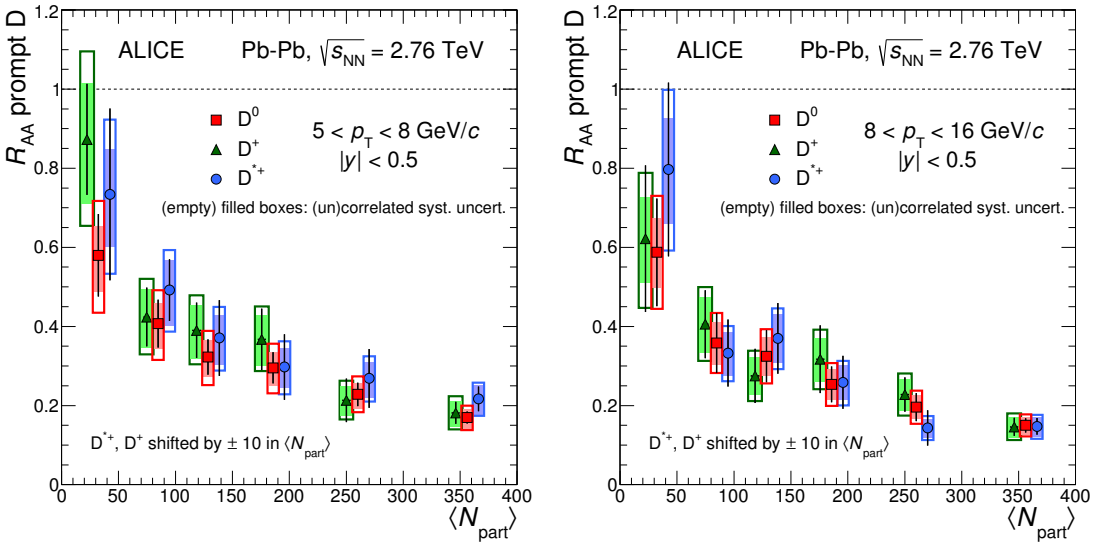

Figure 2. R_{AA} as a function of centrality ($\langle N_{part}\rangle$, see text) of D^0, D^+ and D^{*+} in $5 < p_T < 8$ GeV/c (left) and $8 < p_T < 16$ GeV/c (right). The bars represent the statistical uncertainty while the filled (empty) boxes represent the systematic uncertainties that are correlated (uncorrelated) among centrality intervals. The symbols for D^{*+} and D^+ are shifted by $\langle N_{part}\rangle = 10$ for better visibility.

The nuclear modification factors of charged pions and D mesons are compatible within uncertainties in all centrality classes and in the two p_T intervals. The value of the D meson R_{AA} in the centrality classes 0–10% and 10–20% for $8 < p_T < 16$ GeV/c is lower than that of non-prompt J/ψ mesons in the centrality class 0–20%. However, the difference between the R_{AA} values is not larger than $3\,\sigma$, considering the statistical and systematic uncertainties. A preliminary higher-statistics measurement by the CMS Collaboration of non-prompt J/ψ production in the same p_T interval (6.5–30 GeV/c) and in a narrower rapidity interval ($|y| < 1.2$) is also available [56]. Considering this measurement, the average difference of the R_{AA} values of D mesons and non-prompt J/ψ in the 0–10% and 10–20% centrality classes is larger than zero with a significance of 3.5 σ, obtained including the systematic uncertainties, and taking into account their correlation between the two centrality classes.

The nuclear modification factors of D mesons (average of D^0, D^+ and D^{*+}) and charged pions in the interval $8 < p_T < 16$ GeV/c and that of non-prompt J/ψ mesons in $6.5 < p_T < 30$ GeV/c were compared with theoretical calculations. Figure 4 shows the comparison with the calculation by Djordjevic et al. [57]. This model implements energy loss for gluons, light and heavy quarks, including both radiative (DGLV formalism [23]) and collisional processes and considers dynamical scattering centres in the medium. The heavy-quark production p_T-differential cross sections are obtained from FONLL calculations [49] and hadronization assumes fragmentation outside the medium. In the left-hand panel, the calculation closely describes the similarity of the D meson and charged pion R_{AA} over the entire centrality range. As mentioned in the introduction, in this calculation the colour-charge dependence of energy loss introduces a sizeable difference in the suppression of the

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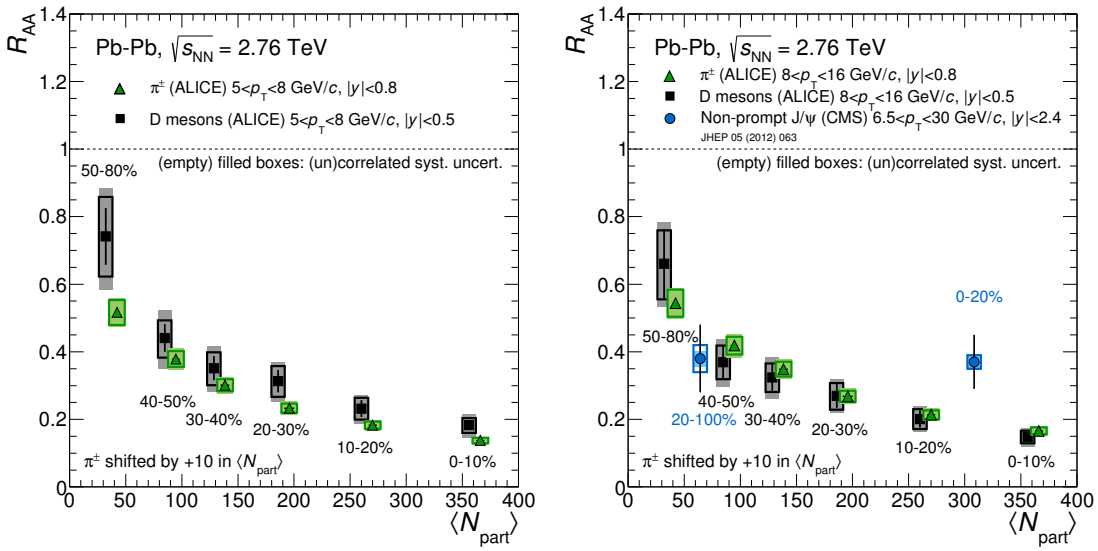

Figure 3. Comparison of the D meson R_{AA} (average of D^0, D^+ and D^{*+}) and of the charged pion R_{AA} [40] in $5 < p_T < 8$ GeV/c (left) and in $8 < p_T < 16$ GeV/c (right). The right panel also includes the R_{AA} of non-prompt J/ψ mesons in $6.5 < p_T < 30$ GeV/c measured by the CMS Collaboration [38]. The vertical bars represent the statistical uncertainties. The D meson systematic uncertainties are displayed as in the previous figures. The total systematic uncertainties of charged pions are shown by boxes. The centrality-dependent systematic uncertainties are shown by boxes on the individual data points.

gluon and c quark production. However, the softer fragmentation and p_T spectrum of gluons with respect to those of c quarks, together with the increase of the parton-level R_{AA} with increasing p_T, lead to a compensation effect that results in a very similar R_{AA} for D mesons and pions [12]. As shown in the right-hand panel of the figure, this calculation results in a larger suppression of D mesons with respect to non-prompt J/ψ, in qualitative agreement with the data for the most central collisions. In order to study the origin of this large difference in the calculation, the result for a test case with the energy loss of b quarks calculated using the c quark mass was considered [15]. In this case, the R_{AA} of non-prompt J/ψ was found to be quite close to that of D mesons. This indicates that, in the calculation, the large difference in the R_{AA} of D mesons and non-prompt J/ψ derives predominantly from the quark mass dependence of the parton energy loss.

In figure 5 the D meson and non-prompt J/ψ data are compared with two theoretical models that implement heavy-quark interactions in an expanding hydrodynamical medium. The MC@sHQ+EPOS2 model [58], shown in the left-hand panel, includes radiative and collisional energy loss. The hydrodynamical evolution of the medium is simulated using the EPOS2 model [59, 60]. Heavy-quark transport in the medium is based on the Boltzmann equation, with collisional processes and radiative corrections. The TAMU elastic model [29], shown in the right-hand panel, includes collisional (elastic) processes only. In this model, the heavy-quark transport coefficient is calculated within a non-perturbative T-matrix approach, where the interactions proceed via resonance formation that transfers

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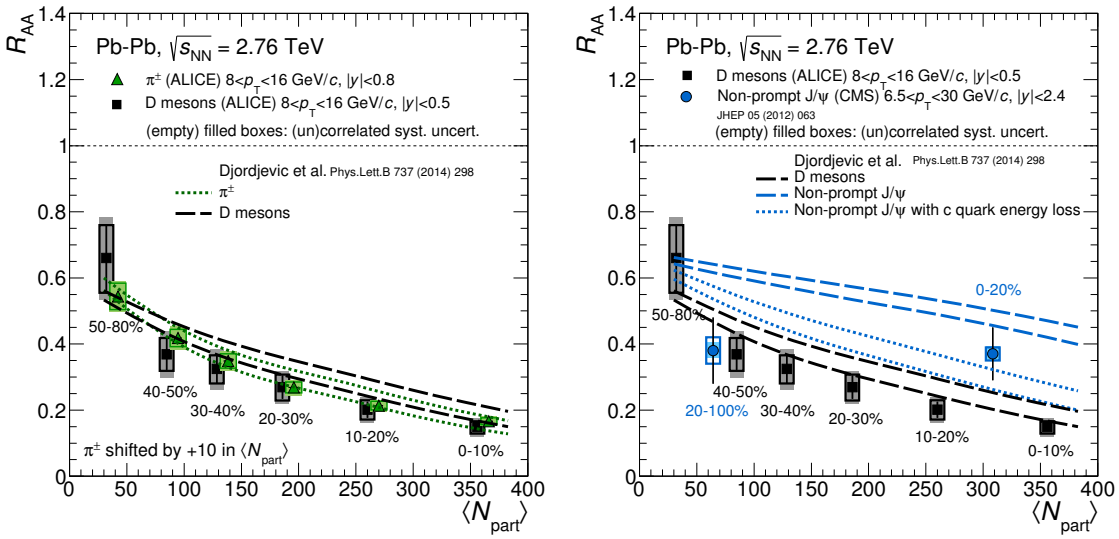

Figure 4. Comparison of the R_{AA} measurements with the calculations by Djordjevic et al. [57] including radiative and collisional energy loss. Lines of the same style enclose a band representing the theoretical uncertainty. Left: D mesons and charged pions in $8 < p_T < 16$ GeV/c. Right: D mesons in $8 < p_T < 16$ GeV/c and non-prompt J/ψ mesons in $6.5 < p_T < 30$ GeV/c [38]. For the latter, the model results for the case in which the b quark interactions are calculated using the c quark mass are shown as well [15].

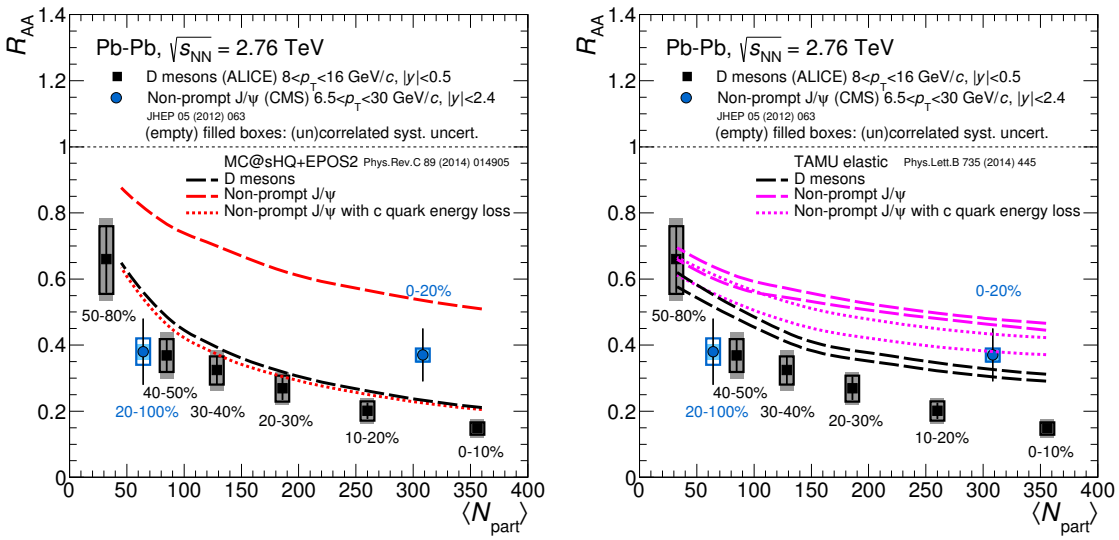

Figure 5. Comparison of the R_{AA} measurements for D mesons ($8 < p_T < 16$ GeV/c) and non-prompt J/ψ mesons ($6.5 < p_T < 30$ GeV/c) [38] with the MC@sHQ+EPOS2 model [58] including radiative and collisional interactions (left) and with the TAMU elastic model [29] including collisional interactions via in-medium resonance formation. For both models, results for the case in which the b quark interactions are calculated using the c quark mass are shown as well [15]. In the right-hand panel, the band between lines with the same style represents the theoretical uncertainty.

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momentum from the heavy quarks to the medium constituents. The model includes hydrodynamic medium evolution, constrained by light-flavour hadron production data. Elastic diffusion of heavy-flavour hadrons in the hadronic phase is included as well. In both models, similarly to that of Djordjevic et al., the heavy-quark production cross sections are obtained from the FONLL calculation [49]. Both models implement a contribution of quark recombination in the hadronization of heavy quarks, in addition to fragmentation outside the medium. The dotted lines correspond to the test case in which the b quark mass is decreased to the c quark mass value in the calculation of the in-medium interactions [15].

The MC@sHQ+EPOS2 model qualitatively describes the two measurements in these p_{T} intervals. In this model a large difference in the suppression of D mesons and non-prompt J/ψ is caused by the mass dependence of energy loss as in Djordjevic et al. model. The TAMU elastic model tends to overestimate R_{AA} for both the non-prompt J/ψ and the D mesons, in particular in central collisions. At variance with the other two models, in this case the quark mass effect accounts for only about half of the difference in the suppression of D and non-prompt J/ψ mesons. This model does not include radiative energy loss, which is expected to have a strong mass dependence.

The nuclear modification factors of D mesons and non-prompt J/ψ are also described by a model calculation by the Duke group [61], that includes radiative and collisional energy loss within an hydro- dynamical medium and performs the hadronization of heavy quarks using recombination and fragmentation.

5 Summary

The centrality dependence of the nuclear modification factor of prompt D mesons in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV was presented in the intervals $5 < p_{\mathrm{T}} < 8$ GeV/c and $8 < p_{\mathrm{T}} < 16$ GeV/c. A suppression is observed already in the centrality class 50–80% and it increases towards more central collisions, reaching a maximum of a factor about 5–6 in the most central collisions.

The centrality dependence and the magnitude of the suppression are similar to those of charged pions in the same p_{T} intervals. The comparison of the D meson R_{AA} with the non-prompt J/ψ meson R_{AA} hints at a difference in the suppression of particles originating from c and b quarks in the most central collisions.

These results are described by theoretical calculations in which in-medium parton energy loss increases with increasing colour charge factor and decreases with increasing quark mass. Calculations that include radiative energy loss, in addition to collisional energy loss, provide a better quantitative description of the data.

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References

[1] F. Karsch, *Lattice simulations of the thermodynamics of strongly interacting elementary particles and the exploration of new phases of matter in relativistic heavy ion collisions*, *J. Phys. Conf. Ser.* **46** (2006) 122 [hep-lat/0608003] [INSPIRE].

[2] Wuppertal-Budapest collaboration, S. Borsányi et al., *Is there still any T_c mystery in lattice QCD? Results with physical masses in the continuum limit III*, *JHEP* **09** (2010) 073 [arXiv:1005.3508] [INSPIRE].

[3] S. Borsányi, Z. Fodor, C. Hölbling, S.D. Katz, S. Krieg and K.K. Szabo, *Full result for the QCD equation of state with 2+1 flavors*, *Phys. Lett.* **B 730** (2014) 99 [arXiv:1309.5258] [INSPIRE].

[4] A. Bazavov et al., *The chiral and deconfinement aspects of the QCD transition*, *Phys. Rev.* **D 85** (2012) 054503 [arXiv:1111.1710] [INSPIRE].

[5] M. Gyulassy and M. Plumer, *Jet Quenching in Dense Matter*, *Phys. Lett.* **B 243** (1990) 432 [INSPIRE].

[6] R. Baier, Y.L. Dokshitzer, A.H. Mueller, S. Peigne and D. Schiff, *Radiative energy loss and p_T broadening of high-energy partons in nuclei*, *Nucl. Phys.* **B 484** (1997) 265 [hep-ph/9608322] [INSPIRE].

[7] M.H. Thoma and M. Gyulassy, *Quark Damping and Energy Loss in the High Temperature QCD*, *Nucl. Phys.* **B 351** (1991) 491 [INSPIRE].

[8] E. Braaten and M.H. Thoma, *Energy loss of a heavy quark in the quark-gluon plasma*, *Phys. Rev.* **D 44** (1991) 2625 [INSPIRE].

[9] E. Braaten and M.H. Thoma, *Energy loss of a heavy fermion in a hot plasma*, *Phys. Rev.* **D 44** (1991) 1298 [INSPIRE].

[10] W.E. Brittin et al. (ed.), *R.J. Glauber in Lectures in Theoretical Physics*, Interscience Publishers, NY, Vol. 1 (1959).

[11] M.L. Miller, K. Reygers, S.J. Sanders and P. Steinberg, *Glauber modeling in high energy nuclear collisions*, *Ann. Rev. Nucl. Part. Sci.* **57** (2007) 205 [nucl-ex/0701025] [INSPIRE].

[12] M. Djordjevic, *Heavy flavor puzzle at LHC: a serendipitous interplay of jet suppression and fragmentation*, *Phys. Rev. Lett.* **112** (2014) 042302 [arXiv:1307.4702] [INSPIRE].

[13] Particle Data Group collaboration, J. Beringer et al., *Review of Particle Physics (RPP)*, *Phys. Rev.* **D 86** (2012) 010001 [INSPIRE].

[14] F.-M. Liu and S.-X. Liu, *quark-gluon plasma formation time and direct photons from heavy ion collisions*, *Phys. Rev.* **C 89** (2014) 034906 [arXiv:1212.6587] [INSPIRE].

[15] A. Andronic et al., *Heavy-flavour and quarkonium production in the LHC era: from proton-proton to heavy-ion collisions*, arXiv:1506.03981 [INSPIRE].

[16] ALICE collaboration, *Centrality Dependence of Charged Particle Production at Large Transverse Momentum in Pb–Pb Collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV*, *Phys. Lett.* **B 720** (2013) 52 [arXiv:1208.2711] [INSPIRE].

JHEP11(2015)205

[17] N. Armesto, A. Dainese, C.A. Salgado and U.A. Wiedemann, *Testing the color charge and mass dependence of parton energy loss with heavy-to-light ratios at RHIC and CERN LHC*, *Phys. Rev.* **D 71** (2005) 054027 [hep-ph/0501225] [INSPIRE].

[18] S. Wicks, W. Horowitz, M. Djordjevic and M. Gyulassy, *Elastic, inelastic and path length fluctuations in jet tomography*, *Nucl. Phys.* **A 784** (2007) 426 [nucl-th/0512076] [INSPIRE].

[19] W.A. Horowitz and M. Gyulassy, *The Surprising Transparency of the sQGP at LHC*, *Nucl. Phys.* **A 872** (2011) 265 [arXiv:1104.4958] [INSPIRE].

[20] W.A. Horowitz, *Testing pQCD and AdS/CFT Energy Loss at RHIC and LHC*, *AIP Conf. Proc.* **1441** (2012) 889 [arXiv:1108.5876] [INSPIRE].

[21] Y.L. Dokshitzer and D.E. Kharzeev, *Heavy quark colorimetry of QCD matter*, *Phys. Lett.* **B 519** (2001) 199 [hep-ph/0106202] [INSPIRE].

[22] N. Armesto, C.A. Salgado and U.A. Wiedemann, *Medium induced gluon radiation off massive quarks fills the dead cone*, *Phys. Rev.* **D 69** (2004) 114003 [hep-ph/0312106] [INSPIRE].

[23] M. Djordjevic and M. Gyulassy, *Heavy quark radiative energy loss in QCD matter*, *Nucl. Phys.* **A 733** (2004) 265 [nucl-th/0310076] [INSPIRE].

[24] B.-W. Zhang, E. Wang and X.-N. Wang, *Heavy quark energy loss in nuclear medium*, *Phys. Rev. Lett.* **93** (2004) 072301 [nucl-th/0309040] [INSPIRE].

[25] H. van Hees, V. Greco and R. Rapp, *Heavy-quark probes of the quark-gluon plasma at RHIC*, *Phys. Rev.* **C 73** (2006) 034913 [nucl-th/0508055] [INSPIRE].

[26] A. Adil and I. Vitev, *Collisional dissociation of heavy mesons in dense QCD matter*, *Phys. Lett.* **B 649** (2007) 139 [hep-ph/0611109] [INSPIRE].

[27] R. Sharma, I. Vitev and B.-W. Zhang, *Light-cone wave function approach to open heavy flavor dynamics in QCD matter*, *Phys. Rev.* **C 80** (2009) 054902 [arXiv:0904.0032] [INSPIRE].

[28] A. Buzzatti and M. Gyulassy, *A running coupling explanation of the surprising transparency of the QGP at LHC*, *Nucl. Phys.* **A904-905** (2013) 779c–782c [arXiv:1210.6417] [INSPIRE].

[29] M. He, R.J. Fries and R. Rapp, *Non-perturbative Heavy-Flavor Transport at RHIC and LHC*, *Nucl. Phys.* **A910-911** (2013) 409 [arXiv:1208.0256] [INSPIRE].

[30] M. He, R.J. Fries and R. Rapp, *Heavy Flavor at the Large Hadron Collider in a Strong Coupling Approach*, *Phys. Lett.* **B 735** (2014) 445 [arXiv:1401.3817] [INSPIRE].

[31] P.B. Gossiaux, M. Nahrgang, M. Bluhm, T. Gousset and J. Aichelin, *Heavy quark quenching from RHIC to LHC and the consequences of gluon damping*, *Nucl. Phys.* **A904-905** (2013) 992c [arXiv:1211.2281] [INSPIRE].

[32] J. Uphoff, O. Fochler, Z. Xu and C. Greiner, *Open Heavy Flavor in Pb+Pb Collisions at* $\sqrt{s} = 2.76$ *TeV within a Transport Model*, *Phys. Lett.* **B 717** (2012) 430 [arXiv:1205.4945] [INSPIRE].

[33] W.M. Alberico et al., *Heavy flavors in AA collisions: production, transport and final spectra*, *Eur. Phys. J.* **C 73** (2013) 2481 [arXiv:1305.7421] [INSPIRE].

[34] S. Cao, G.-Y. Qin and S.A. Bass, *Heavy-quark dynamics and hadronization in ultrarelativistic heavy-ion collisions: Collisional versus radiative energy loss*, *Phys. Rev.* **C 88** (2013) 044907 [arXiv:1308.0617] [INSPIRE].

JHEP11(2015)205

[35] T. Lang, H. van Hees, J. Steinheimer and M. Bleicher, *Heavy quark transport in heavy ion collisions at RHIC and LHC within the UrQMD transport model*, arXiv:1211.6912 [INSPIRE].

[36] N. Armesto et al., *Heavy Ion Collisions at the LHC - Last Call for Predictions*, *J. Phys.* **G 35** (2008) 054001 [arXiv:0711.0974] [INSPIRE].

[37] ALICE collaboration, *Suppression of high transverse momentum D mesons in central Pb-Pb collisions at* $\sqrt{s_{NN}} = 2.76$ *TeV*, *JHEP* **09** (2012) 112 [arXiv:1203.2160] [INSPIRE].

[38] CMS collaboration, *Suppression of non-prompt* J/ψ*, prompt* J/ψ *and Y(1S) in PbPb collisions at* $\sqrt{s_{NN}} = 2.76$ *TeV*, *JHEP* **05** (2012) 063 [arXiv:1201.5069] [INSPIRE].

[39] ALICE collaboration, *The ALICE experiment at the CERN LHC*, 2008 *JINST* **3** S08002 [INSPIRE].

[40] ALICE collaboration, *Production of charged pions, kaons and protons at large transverse momenta in pp and Pb-Pb collisions at* $\sqrt{s_{\rm NN}}$ *=2.76 TeV*, *Phys. Lett.* **B 736** (2014) 196 [arXiv:1401.1250] [INSPIRE].

[41] ALICE collaboration, *Performance of the ALICE VZERO system*, 2013 *JINST* **8** P10016 [arXiv:1306.3130] [INSPIRE].

[42] ALICE collaboration, *Centrality determination of Pb-Pb collisions at* $\sqrt{s_{NN}}$ *= 2.76 TeV with ALICE*, *Phys. Rev.* **C 88** (2013) 044909 [arXiv:1301.4361] [INSPIRE].

[43] J. Alme et al., *The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events*, *Nucl. Instrum. Meth.* **A 622** (2010) 316 [arXiv:1001.1950] [INSPIRE].

[44] ALICE collaboration, *Alignment of the ALICE Inner Tracking System with cosmic-ray tracks*, 2010 *JINST* **5** P03003 [arXiv:1001.0502] [INSPIRE].

[45] ALICE collaboration, *Azimuthal anisotropy of D meson production in Pb-Pb collisions at* $\sqrt{s_{\rm NN}} = 2.76$ *TeV*, *Phys. Rev.* **C 90** (2014) 034904 [arXiv:1405.2001] [INSPIRE].

[46] X.-N. Wang and M. Gyulassy, *HIJING: A Monte Carlo model for multiple jet production in p-p, p-A and A-A collisions*, *Phys. Rev.* **D 44** (1991) 3501 [INSPIRE].

[47] T. Sjöstrand, S. Mrenna and P.Z. Skands, *PYTHIA 6.4 Physics and Manual*, *JHEP* **05** (2006) 026 [hep-ph/0603175] [INSPIRE].

[48] R. Brun, F. Carminati and S. Giani, *GEANT Detector Description and Simulation Tool*, CERN-W5013, CERN-W-5013 (1994).

[49] M. Cacciari, S. Frixione, N. Houdeau, M.L. Mangano, P. Nason and G. Ridolfi, *Theoretical predictions for charm and bottom production at the LHC*, *JHEP* **10** (2012) 137 [arXiv:1205.6344] [INSPIRE].

[50] D.J. Lange, *The EvtGen particle decay simulation package*, *Nucl. Instrum. Meth.* **A 462** (2001) 152 [INSPIRE].

[51] ALICE collaboration, *Measurement of charm production at central rapidity in proton-proton collisions at* $\sqrt{s} = 7$ *TeV*, *JHEP* **01** (2012) 128 [arXiv:1111.1553] [INSPIRE].

[52] R. Averbeck, N. Bastid, Z.C. del Valle, P. Crochet, A. Dainese and X. Zhang, *Reference Heavy Flavour Cross sections in pp Collisions at* $\sqrt{s} = 2.76$ *TeV, using a pQCD-Driven* $\sqrt{s}$ *– Scaling of ALICE Measurements at* $\sqrt{s} = 7$ *TeV*, arXiv:1107.3243 [INSPIRE].

JHEP11(2015)205

[53] ALICE collaboration, *Measurement of charm production at central rapidity in proton-proton collisions at* $\sqrt{s} = 2.76$ *TeV*, *JHEP* **07** (2012) 191 [arXiv:1205.4007] [INSPIRE].

[54] J. Uphoff, O. Fochler, Z. Xu and C. Greiner, *Elliptic Flow and Energy Loss of Heavy Quarks in Ultra-Relativistic heavy Ion Collisions*, *Phys. Rev.* **C 84** (2011) 024908 [arXiv:1104.2295] [INSPIRE].

[55] O. Fochler, J. Uphoff, Z. Xu and C. Greiner, *Jet quenching and elliptic flow at RHIC and LHC within a pQCD-based partonic transport model*, *J. Phys.* **G 38** (2011) 124152 [arXiv:1107.0130] [INSPIRE].

[56] CMS Collaboration, *J/psi results from CMS in PbPb collisions, with 150* μb^{-1} *data*, CMS-PAS-HIN-12-014.

[57] M. Djordjevic, M. Djordjevic and B. Blagojevic, *RHIC and LHC jet suppression in non-central collisions*, *Phys. Lett.* **B 737** (2014) 298 [arXiv:1405.4250] [INSPIRE].

[58] M. Nahrgang, J. Aichelin, P.B. Gossiaux and K. Werner, *Influence of hadronic bound states above* T_c *on heavy-quark observables in Pb + Pb collisions at at the CERN Large Hadron Collider*, *Phys. Rev.* **C 89** (2014) 014905 [arXiv:1305.6544] [INSPIRE].

[59] K. Werner, I. Karpenko, T. Pierog, M. Bleicher and K. Mikhailov, *Event-by-Event Simulation of the Three-Dimensional Hydrodynamic Evolution from Flux Tube Initial Conditions in Ultrarelativistic Heavy Ion Collisions*, *Phys. Rev.* **C 82** (2010) 044904 [arXiv:1004.0805] [INSPIRE].

[60] K. Werner, I. Karpenko, M. Bleicher, T. Pierog and S. Porteboeuf-Houssais, *Jets, Bulk Matter and their Interaction in Heavy Ion Collisions at Several TeV*, *Phys. Rev.* **C 85** (2012) 064907 [arXiv:1203.5704] [INSPIRE].

[61] S. Cao, G.-Y. Qin and S.A. Bass, *Energy loss, hadronization and hadronic interactions of heavy flavors in relativistic heavy-ion collisions*, *Phys. Rev.* **C 92** (2015) 024907 [arXiv:1505.01413] [INSPIRE].

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