ALICE perspectives for the study of charm and beauty energy loss at the LHC

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Received: March 30, 2022

Abstract. At LHC energy, heavy quarks will be abundantly produced and the design of the ALICE detector will allow us to study their production using several channels. The expected heavy-quark in-medium energy loss in nucleus-nucleus collisions at the LHC is calculated within a model, that is compared to the available heavy-quark quenching measurements at RHIC. The nuclear modification factors and heavy-to-light ratios of charm and beauty mesons are considered. The capability of the ALICE experiment for addressing this phenomenology is discussed.

PACS. 25.75.-q, 14.65.Dw, 13.25.Ft

1 Introduction

The ALICE experiment [1,2] will study Pb–Pb collisions at the LHC, with a centre-of-mass energy $\sqrt{s_{_{\text{NN}}}} = 5.5$ TeV, in order to investigate the properties of QCD matter at energy densities of up to several hundred times the density of atomic nuclei. Under these conditions a deconfined state of quarks and gluons is expected to be formed.

The measurement of open charm and open beauty production allows to investigate the mechanisms of heavy-quark production and propagation in the hot and dense medium formed in the collision. In particular, medium-induced partonic energy loss of heavy quarks has recently become one of the most exciting and disputed issues within high-energy heavy-ion physics, after the observation at RHIC of a large suppression in the production of high-transverse-momentum electrons from heavy-flavour decays.[3] In Section 2 we describe these experimental results and we compare them to a model implementation of a particular energy loss calculation. Within this model we then obtain predictions for relevant charm and beauty energy loss observables at LHC energy. After providing, in Section 3, a general overview of the heavy-flavour capabilities of the ALICE detector, we present the expected sensitivity in the measurement of energy loss effects, in Section 4.

2 Heavy-quark energy loss from RHIC to LHC

Believed to be the main origin of the jet quenching effects observed[3] in nucleus–nucleus collisions at RHIC energy $\sqrt{s_{_{\text{NN}}}} = 62–200$ GeV, parton energy loss via gluon-radiation is expected to depend on the properties of the medium and on the properties (colour charge and mass) of the ‘probe’ parton. Glauber-model based description of the local $\hat{q}$ profile in the transverse plane [12].

Quenching effects for heavy quarks can be estimated by supplementing perturbative QCD calculations of the baseline $p_t$ distributions with in-medium energy loss. Here, we consider the particular radiative energy loss calculation that is implemented in the BDMPS formalism [9]. The energy loss probability distributions (quenching weights) were computed for light quarks and gluons in [10] and for heavy quarks in [11]. They depend on the medium transport coefficient $\hat{q}$, the average transverse momentum squared transferred from probe parton to the scattering centres in the medium per unit mean free path, and on the in-medium path length $L$ of the probe parton. The collision geometry is included by evaluating $\hat{q}$ and $L$ on a parton-by-parton level, using a Glauber-model based description of the local $\hat{q}$ profile in the transverse plane [12].

The parton-averaged $\langle q \rangle$ value (hereafter called $\hat{q}$ for brevity) is chosen in order to reproduce the factor 4–5 suppression measured for the nuclear modification factor

$$R_{_{\text{AA}}}(p_t) = \frac{1}{\langle N_{_{\text{coll}}} \rangle} \times \frac{d^2N_{_{\text{AA}}}/dp_t\,d\eta}{d^2N_{_{\text{pp}}}/dp_t\,d\eta} \quad (1)$$

of light-flavour particles in central Au–Au collisions at $\sqrt{s_{_{\text{NN}}}} = 200$ GeV. The range favoured by the data is $\hat{q} = 4–14$ GeV$^2$/fm [13,14].

Heavy-quark energy loss is presently studied at RHIC using measurements of the nuclear modification factor $R_{_{\text{AA}}}$ of ‘non-photonic’ ($\gamma$-conversion- and $\pi^0$-Dalitz-subtracted)
single electrons. Since this is an inclusive measurement, with charm decays dominating at low $p_t$ and beauty decays dominating at high $p_t$, the comparison with mass-dependent energy loss predictions should rely on a solid and data-validated pp baseline. Such baseline is still lacking at the moment. The state-of-the-art perturbative predictions (FONLL), usually employed as a baseline, indicate that, in pp collisions, charm decays dominate the electron $p_t$ spectrum up to about 5 GeV [15]. However, there is a large perturbative uncertainty on the position in $p_t$ of the c-decay/b-decay crossing point: depending on the choice of the factorization and renormalization scales this position can vary from 3 to 9 GeV [15], as illustrated in Fig. 1 (upper panel). In addition, as shown in the insert, the calculation underpredicts the non-photonic electron spectrum measured in pp collisions [17].

The most recent data by PHENIX [18] and STAR [19] on the nuclear modification factor $R_{AA}$ of non-photonic electrons in central Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV are shown in Fig. 1 (lower panel). The theoretical expectation is superimposed to the data, with the uncertainty on the medium density (curves for $\hat{q} = 4, 10, 14$ GeV$^2$/fm) and the perturbative uncertainty, obtained by varying the values of the scales and of the c and b quark masses (shaded band associated to the $\hat{q} = 14$ GeV$^2$/fm curve) [15]. The calculation tends to overpredict the measured $R_{AA}$. It has recently been argued [20] that parton energy loss would have a significant collisional contribution, comparable to the radiative one. Although the quantitative relevance of the collisional contribution is still debated [21], the effect has been included in heavy-quark energy loss calculations [20]. Yet, the large suppression measured for $R_{AA}$ can not be well reproduced [20].

It is important to note that, in general, the perturbative uncertainty in calculating the partonic baseline spectrum is comparable to the model-intrinsic uncertainty in determining $\hat{q}$. Thus, the strongest limitation to the sensitivity in the theory-data comparison comes from the inability of the RHIC experiments, in their present detector setup, to disentangle the charm and beauty contributions to single electrons.

Heavy quarks will be produced with large cross sections at LHC energy and the experiments will be equipped with detectors optimized for the separation of charm and beauty decay vertices. Thus, it will possible to carry out a direct comparison of the attenuation of light-flavour hadrons, D mesons, and B mesons.

The expected nuclear modification factors $R_{AA}$ were calculated in [11] exploring a large range in the medium density for central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV: $25 < \hat{q} < 100$ GeV$^2$/fm. Figure 2 (thick lines) shows the results for the heavy-to-light ratios of D and B mesons [11], defined as the ratios of the nuclear modification factors of D(B) mesons to that of light-flavour hadrons ($h$): $R_{D(B)/h} = R_{D(B)AA}/R_{AA}$. The effect of the mass is illustrated by artificially neglecting the mass dependence of parton energy loss (thin curves). The enhancement above unity that persists in the $m_c(b) = 0$ cases is mainly due to the colour-charge dependence of energy loss, since at LHC energy most of the light-flavour hadrons will originate from a gluon parent. The calculation results indicate that, for D mesons, the mass effect is small and limited to the region $p_t \lesssim 10$ GeV, while for B mesons a large enhancement can be expected up to 20 GeV. Therefore, the comparison of the $p_t$ suppression for D mesons and for light-flavour hadrons would test the colour-charge dependence (quark parent vs. gluon parent) of parton energy loss, while the comparison for B mesons and for light-flavour hadrons would test its mass dependence [11].
3 Heavy-flavour detection in ALICE

The ALICE experimental setup [11] was designed so as to allow the detection of D and B mesons in the high-multiplicity environment of central Pb–Pb collisions at LHC energy, where up to several thousand charged particles might be produced per unit of rapidity. The heavy-flavour capability of the ALICE detector is provided by:

- Tracking system; the Inner Tracking System (ITS), the Time Projection Chamber (TPC) and the Transition Radiation Detector (TRD), embedded in a magnetic field of 0.5 T, allow track reconstruction in the pseudorapidity range $-0.9 < \eta < 0.9$ with a momentum resolution better than 2% for $p_t < 20$ GeV and a transverse impact parameter resolution better than 60 $\mu$m for $p_t > 1$ GeV (the two innermost layers of the ITS are equipped with silicon pixel detectors)\(^1\).

\(^1\) The 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.

\(^2\) Note that, for pp collisions, the impact parameter resolution may be slightly worse, due to the larger transverse size of the beam at the ALICE interaction point. This is taken into account in the studies presented here.

- Particle identification system; charged hadrons are identified via $dE/dx$ in the TPC and in the ITS and via time-of-flight measurement in the Time Of Flight (TOF) detector; electrons are separated from charged pions in the dedicated TRD, and in the TPC; muons are identified in the forward muon spectrometer covering in acceptance the range $-4 < \eta < -2.5$.

Detailed studies [2], based on full simulation of the detector and of the background sources, have shown that ALICE has a good potential to carry out a rich heavy-flavour physics programme. Several analyses aimed at investigating quenching effects for c and b quarks are being prepared. Here, we focus on the two most advanced studies in the central barrel: exclusive reconstruction of charm particles, in the $D^0 \rightarrow K^- \pi^+$ decay channel, and inclusive measurement of beauty particles, in the semi-electronic decay channels $B \rightarrow e^+ X$. Excellent performance is also expected for the measurement of beauty production at forward rapidity in the semi-muonic decay channels [22].

In this context, the study of the single-inclusive muon distribution in the range $20 \lesssim p_t \lesssim 50$ GeV is a new promising tool to address energy loss effects for b quarks. At LHC energy, single muons are dominated by decays of b quarks, expected to strongly interact with the medium, for $3 \lesssim p_t \lesssim 30$ GeV and by decays of weakly-interacting, thus ‘medium-blind’, $W^\pm$ bosons for $p_t \gtrsim 30$ GeV [23]. Therefore, the position in $p_t$ of the crossing point between b-decay and W-decay muons should be sensitive to the medium energy loss of b quarks.

For all studies a multiplicity of $dN_{ch}/dy = 6000$ was assumed for central Pb–Pb collisions\(^3\). We report the results corresponding to the expected statistics collected by ALICE per LHC year: $10^7$ central (0–5% $\sigma^{inel}$) Pb–Pb events at $\sqrt{s_{NN}} = 5.5$ TeV and in pp collisions at $\sqrt{s} = 14$ TeV are $5.3 \times 10^{-4}$ and $7.5 \times 10^{-4}$ per event, respectively [2].

Figure 2 shows a sketch of the decay: the main feature of this topology is the presence of two tracks with impact parameters $d_0 \sim 100$ $\mu$m. The detection strategy [24] to cope with the large combinatorial background from the underlying event is based on:

1. selection of displaced-vertex topologies, i.e. two tracks with large impact parameters and small pointing angle

3 This value of the multiplicity can be taken as a conservative assumption, since extrapolations based on RHIC data predict $dN_{ch}/dy = 2000–3000$.\n
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\[ R_{ch} \] is the ratio of the number of charged particles in the central (0–5% $\sigma^{inel}$) Pb–Pb events at $\sqrt{s_{NN}} = 5.5$ TeV to the number of charged particles in pp events at $\sqrt{s} = 14$ TeV.

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\[ p_t \] is the transverse momentum.

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\[ m_c \] and \[ m_b \] are the masses of the charm and bottom quarks, respectively.

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\[ BR \] is the branching ratio.

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\[ \sigma^{inel} \] is the inelastic cross-section.

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\[ N_{ch} \] is the number of charged particles.

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\[ \sqrt{s} \] is the center-of-mass energy.

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\[ t \] is the transverse impact parameter.

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\[ \eta \] is the pseudorapidity.

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\[ \Delta \eta \] is the rapidity gap.

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\[ \Delta \phi \] is the azimuthal angle.

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\[ \Delta R \] is the pseudorapidity gap.

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\[ \Delta \phi \] is the azimuthal angle difference.

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\[ \Delta \eta \] is the rapidity difference.

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\[ \theta_{\text{pointing}} \] between the \( D^0 \) momentum and flight-line (see sketch in Fig. 3):

1. electron identification with a combined \( dE/dx \) (TPC) and transition radiation selection, which is expected to reduce the pion contamination by a factor \( 10^4 \);
2. impact parameter cut to reject misidentified \( \pi^\pm \) and \( e^\pm \) from Dalitz decays and \( \gamma \) conversions (the latter have small impact parameter for \( p_t > 1 \text{ GeV} \));
3. \( p_t \) cut to reject electrons from charm decays.

As an example, with \( d_0 > 200 \text{ m} \) and \( p_t > 2 \text{ GeV} \), the expected statistics of electrons from b decays is \( 8 \times 10^4 \) for \( 10^7 \) central Pb–Pb events, allowing the measurement of electron-level \( p_t \)-differential cross section in the range \( 2 < p_t < 20 \text{ GeV} \). The residual contamination of about 10% of electrons from prompt charm decays, from misidentified charged pions and \( \gamma \)-conversion electrons can be evaluated and subtracted using a Monte Carlo simulation tuned to reproduce the measured cross sections for pions and \( D^0 \) mesons. In Fig. 5 we show the expected relative statistical errors on the measurement of the cross section of electrons from beauty decays. A Monte-Carlo-based procedure can then be used to compute, from the electron-level cross section, the B-level cross section \( d\sigma^B(p_t > p_t^{\text{min}})/dp_t \). The covered range is \( 2 < p_t^{\text{min}} < 30 \text{ GeV} \).

4 Sensitivity to energy loss

We investigated the possibility of using the described charm and beauty measurements to study the dependences of parton energy loss. This study could be carried out by measuring:

The main sources of background electrons are: (a) decays of \( D \) mesons; (b) neutral pion Dalitz decays \( \pi^0 \rightarrow \gamma e^+e^- \) and decays of light mesons (e.g. \( \rho \) and \( \omega \)); (c) conversions of photons in the beam pipe or in the inner detector layer and (d) pions misidentified as electrons. Given that electrons from beauty have average impact parameter \( d_0 \approx 500 \mu \text{m} \) and a hard momentum spectrum, it is possible to obtain a high-purity sample with a strategy that relies on:

1. electron identification with a combined \( dE/dx \) (TPC) and transition radiation selection, which is expected to reduce the pion contamination by a factor \( 10^4 \);
2. impact parameter cut to reject misidentified \( \pi^\pm \) and \( e^\pm \) from Dalitz decays and \( \gamma \) conversions (the latter have small impact parameter for \( p_t > 1 \text{ GeV} \));
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the nuclear modification factor of D mesons as a function of transverse momentum, \( R_{AA}^{D}(p_t) \);
- the nuclear modification factor of b-decay electrons as a function of transverse momentum, \( R_{AA}^{D_{\text{b}}}(p_t) \);
- the heavy-to-light ratio, \( R_{D/h}(p_t) \), defined as the ratio of the nuclear modification factors of D mesons and of charged light-flavoured hadrons.

We compare the expected experimental errors on these observables to recent theoretical predictions parton energy loss [11].

The expected performance for the measurement of the nuclear modification factor for \( D^0 \) mesons is reported in Fig. 6. Only nuclear shadowing and parton intrinsic transverse-momentum broadening are included (no energy loss). The reported statistical (bars) and systematic (shaded areas) errors are obtained combining the errors for Pb–Pb and pp collisions and assuming that the contributions due to cross section normalization, feed-down from beauty decays and, partially, acceptance/efficiency corrections will cancel out in the ratio. An expected uncertainty of about 12% [2] introduced in the extrapolation of the pp results from 14 TeV to 5.5 TeV by pQCD is also included.

The effect of shadowing, included via the EKS98 parametrisation [20], is visible as a suppression of \( R_{AA} \) at low transverse momenta, corresponding to small Bjorken \( x \). The effect is negligible for \( p_t > 6-7 \) GeV. Since there is significant uncertainty on the magnitude of shadowing in the low-\( x \) region, we studied the effect of such uncertainty on \( R_{AA} \) by varying the nuclear modification of parton distribution functions. Also in the case of shadowing 50% stronger than in EKS98 (curve labelled ‘c’), we find \( R_{AA} > 0.95 \) for \( p_t > 8 \) GeV. Under these assumptions, for \( p_t > 8 \) GeV only parton energy loss is expected to affect the nuclear modification factor of D mesons.

Figure 7 presents the predicted [11] nuclear modification factor without \((\hat{q} = 0)\) and with energy loss (the bands correspond to the range \( 25 < \hat{q} < 100 \text{ GeV}^2/\text{fm} \)).

Ordinary light quarks are massless and, partially, acceptance/efficiency corrections will cancel out in the ratio. An expected uncertainty of about 12% [2] introduced in the extrapolation of the pp results from 14 TeV to 5.5 TeV by pQCD is also included.

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Figure 8 presents the predicted [11] nuclear modification factor without \((\hat{q} = 0)\) and with energy loss (the bands correspond to the range \( 25 < \hat{q} < 100 \text{ GeV}^2/\text{fm} \)).

Owing to the predicted suppression of about a factor 5 for \( p_t > 5 \) GeV, the relative statistical errors in Pb–Pb are larger by more than a factor 2, with respect to the case of no suppression, and they become the dominant contribution to the statistical error on \( R_{AA}^{D} \).

The expected performance for the measurement of the nuclear modification factor of electrons from B-meson decays is shown in Fig. 8 along with the predicted suppres-
two bands coincide and predict \( R \) range 25–100 GeV

respond to including or not including the effect of the \( R \) in Fig. 9. Like for the case of ratio energy loss. The ALICE sensitivity to the heavy-to-light originated hadrons may be the tool best suited to sin-

Fig. 9. Ratio of the nuclear modification factors for \( D^0 \) mesons and for charged hadrons. Errors corresponding to the centre of the prediction band for \( m_t = 1.2 \) GeV are shown: bars = statistical, shaded area = systematic.

5 Conclusions

Heavy-quark quenching studies have become one of the most intriguing topics in heavy-ion physics, with the ob-

ervation at RHIC of a large suppression for heavy-flavour decay electrons, which is at present not clearly understood within parton energy loss models.

At LHC energy, charm and beauty production cross sections are expected to be larger by factors of approximately 10 and 100, respectively, with respect to RHIC energy. The ALICE experiment will be equipped with high-resolution silicon vertex detectors, allowing direct and pre-

cise measurements of the main observables that are sug-

gested to be sensitive to the colour-charge and mass de-

pendences of parton energy loss.

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