HEAVY FLAVOURS IN HEAVY-ION COLLISIONS AT THE LHC:
ALICE PERFORMANCE

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We present the latest results on the ALICE performance for heavy-quark production and quenching measurements, focusing in particular on charm particles.

1 Introduction: heavy quarks as probes of QCD matter

The ALICE experiment will study nucleus–nucleus (AA) collisions at the LHC, with a centre-of-mass energy $\sqrt{s_{NN}} = 5.5$ TeV per nucleon–nucleon (NN) pair for the Pb–Pb system, in order to investigate the properties of QCD matter at energy densities of up to several hundred times the density of atomic nuclei. In these conditions a deconfined state of quarks and gluons is expected to be formed. As we shall detail in the following paragraphs, heavy quarks are sensitive probes of such a medium.

Heavy-quark pairs ($Q\bar{Q}$) are produced in the early stage of the collision in primary partonic scatterings with large virtuality $Q$ and, thus, on temporal and spatial scales, $\Delta t \sim \Delta r \sim 1/Q$, which are sufficiently small for the production to be unaffected by the properties of the medium. In fact, the minimum virtuality $Q_{\text{min}} = 2m_Q$ in the production of a $Q\bar{Q}$ pair implies a space-time scale of $\sim 1/(2m_Q) \simeq 1/2.4$ GeV$^{-1} \simeq 0.1$ fm (for charm), to be compared to the expected life-time of the deconfined state at the LHC, $\gtrsim 10$ fm. Thus, the initially-produced heavy quarks experience the full collision history.

Hard partons are regarded as probes of the medium as they are expected to lose energy by gluon radiation while propagating through high-density QCD matter. The attenuation (quenching) of leading hadrons observed in Au–Au collisions at RHIC is thought to be due to such a mechanism. Due to the large values of their masses, the charm and beauty quarks are

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Figure 1: Schematic representation of the $D^0 \rightarrow K^- \pi^+$ decay (left). $K\pi$ invariant-mass distribution corresponding to $10^7$ central Pb–Pb events (right); the background-subtracted distribution is shown in the inset.

qualitatively different probes with respect to light partons, since the ‘dead-cone effect’ is expected to reduce the in-medium energy loss of massive partons. Therefore, a comparative study of the attenuation of massless and massive probes at the LHC will allow to test the consistency of the interpretation of quenching effects as due to energy loss in a deconfined medium and to further investigate the properties (density) of such a medium.

2 Heavy-flavour detection in ALICE

The ALICE experimental setup was designed in order 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 $|\eta| < 0.9$ with a momentum resolution better than 2% for $p_t < 10$ GeV/$c$ and an impact parameter resolution better than 60 µm for $p_t > 1$ GeV/$c$, mainly provided by the two layers of pixel detectors of the ITS.
- Particle identification system; charged hadrons are separated 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 pions in the Transition Radiation Detector (TRD); muons are identified in the forward muon arm covering the range $2.5 < \eta < 4$.

Detailed simulation analyses, based on a realistic description of the experimental effects and of the background sources, have shown that ALICE has a good potential to carry out the comparative quenching studies mentioned in Section 1. In Section 3 we describe the expected performance for the exclusive reconstruction of $D^0 \rightarrow K^- \pi^+$ decays and the estimated sensitivity for the study of charm energy loss. In Section 4 we present the first results on the possibility to detect $B$ mesons in the inclusive $B \rightarrow e^{\pm} + X$ channels. In both studies a multiplicity of $dN_{ch}/dy = 6000$ was assumed for central Pb–Pb collisions. We report the results corresponding to the expected number of events collected by ALICE per LHC year: $10^7$ for central Pb–Pb and $10^9$ for pp collisions. The strategies for the measurement of $D$ and $B$ mesons in the muon arm are currently being optimized; we will not discuss these topics here.

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bThe 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.
3 Measurement of charm production and in-medium quenching

One of the most promising channels for open charm detection is the $D^0 \rightarrow K^-\pi^+$ decay (and its charge conjugate) which has a branching ratio of about 3.8%. The expected production yields (dN/dy at y = 0), estimated on the basis of next-to-leading order pQCD calculations, for $D^0$ and $\bar{D}^0$ mesons decaying in a $K^\pm\pi^\mp$ pair in central Pb–Pb (5% $\sigma_{\text{tot}}$) at $\sqrt{s_{\text{NN}}} = 5.5$ TeV and in pp collisions at $\sqrt{s} = 14$ TeV are $5.3 \times 10^{-1}$ and $7.5 \times 10^{-4}$ per event, respectively.

Figure 1 (left) shows a sketch of the decay: the main feature of this topology is the presence of two tracks with impact parameters $d_0 \sim 100$ µm. The detection strategy 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 $\Theta_p$ between the $D^0$ momentum and flight-line (see sketch in Fig. 1);
2. identification of the $K$ track in the TOF detector;
3. invariant-mass analysis (see $p_t$-integrated distribution in Pb–Pb after selections in Fig. 1).

This strategy was optimized separately for pp and Pb–Pb collisions, as a function of the $D^0$ transverse momentum. The accessible $p_t$ range is 1–14 GeV/c for Pb–Pb and 0.5–14 GeV/c for pp, with a statistical error better than 15–20% and a systematic error (acceptance and efficiency corrections, centrality selection for Pb–Pb) better than 20%. More details are given in Ref. 11.

We studied the sensitivity for a comparison of the energy loss of charm quarks and of massless partons by considering:

- the nuclear modification factor of $D$ mesons as a function of $p_t$

$$R_{AA}^{D}(p_t) \equiv \frac{dN_{AA}^D}{dp_t}/\text{binary NN collisions} \frac{dN_{pp}^D}{dp_t},$$

which would be equal to 1 if the AA collision was a mere superposition of independent NN collisions, without nuclear or medium effects;

- the ratio of the nuclear modification factors of $D$ mesons and of charged hadrons:

$$R_{D/h}(p_t) \equiv R_{AA}^{D}(p_t)/R_{AA}^{h}(p_t).$$

Medium-induced parton energy loss was simulated using the ‘quenching weights’, an approximation of the dead-cone effect for charm quarks and a Glauber-model based description of the collision geometry to calculate in-medium parton path lengths. The density of the medium was estimated in order to have $R_{AA}^{h} \approx 0.2–0.3$, similarly to that measured at RHIC.
The results for $R_{AA}^D$ and $R_{D/h}$ are presented in Fig. 2. The reported uncertainties are discussed in detail in Refs. 9, 11. The effect of nuclear shadowing, introduced via the EKS98 parameterization, is clearly visible in the $R_{AA}^D$ without energy loss for $p_t \lesssim 7$ GeV/c. Above this region, only parton energy loss is expected to affect the nuclear modification factor of $D$ mesons. The relative importance of the energy-loss and dead-cone effects can be disentangled using the $R_{D/h}$ ratio, which can be measured with good sensitivity as it is a double ratio $(AA/pp) / (AA/pp)$ (many systematic uncertainties cancel out). We find that this ratio is enhanced, with respect to 1, only by the dead cone and, consequently, it appears as a very clean tool to investigate and quantify this prediction of QCD.

4 Perspectives for the detection of beauty in the semi-electronic decay channels

The production of open beauty can be studied by detecting the semi-electronic decays of $B$ mesons. Such decays have a branching ratio of $\sim 10\%$. The expected yield ($dN/dy$ at $y = 0$) for $B \rightarrow e^\pm + X$ in central (5% $\sigma_{\text{tot}}$) Pb–Pb collisions at $s_{\text{NN}} = 5.5$ TeV is $9 \times 10^{-2}$ per event.

The main sources of background electrons are: (a) decays of $D$ mesons; (b) decays of light mesons (e.g. $\rho$ and $\omega$); (c) conversions of photons in the beam pipe or in the inner layers of the ITS and (d) pions identified as electrons. Given that electrons from beauty have impact parameter $d_0 \sim 500 \mu m$ and a hard momentum spectrum, we expect to obtain a high-purity sample with a strategy that relies on:

1. electron identification with a combined $dE/dx$ (TPC) and transition radiation (TRD) selection, which allows to reduce the pion contamination by a factor $10^4$;
2. impact parameter cut to reject misidentified pions and electrons from sources (b) and (c);
3. transverse momentum cut to reject electrons from charm decays.

As an example, with $d_0 > 180 \mu m$ and $p_t > 2$ GeV/c, the expected statistics of electrons from $B$ decays is $5 \times 10^4$ for $10^7$ central Pb–Pb events, with a contamination of about 10%, mainly given by the decays $D \rightarrow e^\pm + X$ and $B \rightarrow D + X \rightarrow e^\pm + X + X'$. The sensitivity on the extraction of the $b\bar{b}$ production cross section and of the $B$-meson $p_t$ distribution is currently being investigated.

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