Heavy flavour in ALICE

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The ALICE experiment, currently in the commissioning phase, will study nucleus–nucleus and proton–proton collisions at the CERN Large Hadron Collider (LHC). We review the ALICE heavy-flavour physics program.

1 Introduction

ALICE [1, 2] is the dedicated heavy-ion experiment at the Large Hadron Collider (LHC). The main physics goal of the experiment is the study of strongly-interacting matter in the conditions of high energy density ($> 10 \text{ GeV/fm}^3$) and high temperature ($\gtrsim 0.2 \text{ GeV}$), expected to be reached in central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5 \text{ TeV}$. Under these conditions, according to lattice QCD calculations, quark confinement into colourless hadrons should be removed and a deconfined Quark–Gluon Plasma should be formed [1].

Heavy-flavour particles are regarded as effective probes of the system conditions. In particular:

- open charm and beauty hadrons would be sensitive to the energy density, through the mechanism of in-medium energy loss of heavy quarks;
- quarkonium states would be sensitive to the initial temperature of the system through their dissociation due to colour screening.

2 Heavy-flavour phenomenology in nucleus–nucleus collisions at the LHC

The expected $c\bar{c}$ and $b\bar{b}$ production yields for pp collisions at $\sqrt{s} = 14 \text{ TeV}$ are 0.16 and 0.0072, respectively [2]. For the 5% most central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5 \text{ TeV}$ the expected yields are 115 and 4.6, respectively. These numbers, assumed as the baseline for ALICE simulation studies, are obtained from pQCD calculations at NLO [3], including the nuclear modification of the parton distribution functions in the Pb nucleus. Note that the predicted yields have large uncertainties, of about a factor 2, estimated by varying the values of the calculation parameters.

Experiments at the Relativistic Heavy Ion Collider (RHIC) have shown that the nuclear modification factor of particles p_t distributions, $R_{AA}(p_t, \eta) = \frac{1}{\langle N_{coll} \rangle} \cdot \frac{d^2 N_{AA}/dp_t d\eta}{d^2 N_{pp}/dp_t d\eta}$, is a sensitive observable for the study of the interaction of the hard partons with the medium produced in nucleus–nucleus collisions. Heavy quark medium-induced quenching is one of the most captivating topics to be addressed in Pb–Pb collisions at the LHC. 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’ is expected to reduce the energy loss of massive quarks with respect to light partons [4]. Therefore, one should observe a pattern of gradually decreasing R_{AA} suppression when going from the mostly gluon-originated

light-flavour hadrons ($h^\pm$ or π^0) to D and to B mesons: $R_{AA}^h \lesssim R_{AA}^D \lesssim R_{AA}^B$. The measurement of D and B meson production cross sections will also serve as a baseline for the study of medium effects on quarkonia. Two of the most interesting items in the quarkonia sector at the LHC will be: (a) understanding the interplay between colour-screening-induced (and medium-temperature-dependent) suppression and statistical regeneration for J/ψ production in a medium containing on the order of 100 $c\bar{c}$ pairs; (b) measuring for the first time medium effects on the bottomonia resonances, expected to be affected by colour-screening only if the temperature of the medium will be larger than about 0.4 GeV.

3 Heavy-flavour detection in ALICE

The ALICE experimental setup, described in detail in [1], allows the detection of open charm and beauty hadrons and of quarkonia in the high-multiplicity environment of central Pb–Pb collisions at LHC energy, where a few 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/ c and a transverse impact parameter^a resolution better than 60 μm for $p_t > 1$ GeV/ c (the two innermost layers of the ITS, $r \approx 4$ and 7 cm, are equipped with silicon pixel detectors).
- Particle identification system; charged hadrons are separated via dE/dx in the TPC and via time-of-flight measurement in the Time Of Flight (TOF) detector; electrons are separated from charged hadrons in the dedicated Transition Radiation Detector (TRD), and in the TPC; muons are identified in the muon spectrometer covering the pseudo-rapidity range $-4 < \eta < -2.5$.

Simulation studies [2] have shown that ALICE has good potential to carry out a rich heavy-flavour physics programme. The main analyses in preparation are:

- Open charm (section 4): fully reconstructed hadronic decays $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, $D_s^+ \rightarrow K^-K^+\pi^+$ (under study), $\Lambda_c^+ \rightarrow pK^-\pi^+$ (under study) in $|\eta| < 0.9$.
- Open beauty (section 4): inclusive single leptons $B \rightarrow e+X$ in $|\eta| < 0.9$ and $B \rightarrow \mu+X$ in $-4 < \eta < -2.5$; inclusive displaced charmonia $B \rightarrow J/\psi(\rightarrow e^+e^-) + X$ (under study).
- Quarkonia (section 5): $c\bar{c}$ (J/ψ , ψ') and $b\bar{b}$ (Υ , Υ' , Υ'') states in the e^+e^- ($|\eta| < 0.9$) and $\mu^+\mu^-$ ($-4 < \eta < -2.5$) channels.

For all simulation studies, a multiplicity $dN_{\text{ch}}/dy = 4000\text{--}6000$ was assumed for central Pb–Pb collisions. In the following, we report the results corresponding to the expected statistics collected by ALICE per LHC year: 10^7 central (0–5% σ^{inel}) Pb–Pb events at $\mathcal{L}_{\text{Pb-Pb}} = 10^{27} \text{ cm}^{-2}\text{s}^{-1}$ and 10^9 pp events at $\mathcal{L}_{\text{pp}}^{\text{ALICE}} = 5 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$, in the barrel detectors; the forward muon arm will collect about 40 times larger samples of muon-trigger events (i.e. 4×10^8 central Pb–Pb events).

^aThe 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.

Figure 1: Nuclear modification factors for D^0 mesons (left) and for B-decay electrons (right). Errors corresponding to the centre of the prediction bands for massive quarks are shown: bars = statistical, shaded area = systematic.

4 Charm and beauty measurements

Among the most promising channels for open charm detection are the $D^0 \rightarrow K^- \pi^+$ ($c\tau \approx 120 \mu\text{m}$, branching ratio $\approx 3.8\%$) and $D^+ \rightarrow K^- \pi^+ \pi^+$ ($c\tau \approx 300 \mu\text{m}$, branching ratio $\approx 9.2\%$) decays. The detection strategy to cope with the large combinatorial background from the underlying event is based on the selection of displaced-vertex topologies, i.e. separation from the primary vertex of the tracks from the secondary vertex and good alignment between the reconstructed D meson momentum and flight-line [2, 6]. An invariant-mass analysis is used to extract the raw signal yield, to be then corrected for selection and reconstruction efficiency and for detector acceptance. The accessible p_t range for the D^0 is 1–20 GeV/c in Pb–Pb and 0.5–20 GeV/c in pp, with statistical errors better than 15–20% at high p_t . Similar capability is expected for the D^+ . The systematic errors (acceptance and efficiency corrections, centrality selection for Pb–Pb) are expected to be smaller than 20%.

The production of open beauty can be studied by detecting the semi-electronic decays of beauty hadrons, mostly B mesons. Such decays have a branching ratio of $\simeq 10\%$. The main sources of background electrons are: decays of D mesons; π^0 Dalitz decays and decays of light vector mesons (e.g. ρ and ω); conversions of photons in the beam pipe or in the inner detector layer; pions misidentified as electrons. Given that electrons from beauty have average impact parameter $d_0 \simeq 500 \mu\text{m}$ and a hard p_t spectrum, it is possible to obtain a high-purity sample with a strategy that relies on: electron identification with a combined dE/dx (TPC) and transition radiation (TRD) selection; impact parameter cut to reduce the charm-decay component and reject misidentified $\pi^\pm$ and $e^\pm$ from Dalitz decays and γ conversions. As an example, with 10^7 central Pb–Pb events, this strategy is expected to allow the measurement of electron-level p_t -differential cross section in the range $2 < p_t < 20 \text{ GeV}/c$ with statistical errors smaller than 15% at high p_t . Similar performance figures are expected for pp collisions.

B production in pp and Pb–Pb collisions can be measured also in the ALICE muon spectrometer ($-4 < \eta < -2.5$) analyzing the single-muon p_t distribution [2]. The main backgrounds to the ‘beauty muon’ signal are $\pi^\pm$, $K^\pm$ and charm decays. The cut $p_t > 1.5 \text{ GeV}/c$ is applied to all reconstructed muons in order to increase the signal-to-background

ratio. Then, a fit technique allows to extract a p_t distribution of muons from B decays. Since only minimal cuts are applied, the statistical errors are expected to be smaller than 5% up to muon $p_t \approx 30$ GeV/ c .

We investigated the possibility of using the described charm and beauty measurements to study the high- p_t suppression induced by parton energy loss. The sensitivity to R_{AA}^D and $R_{AA}^{e \text{ from B}}$ is presented in Fig. 1. Predictions [5] with and without the effect of the heavy-quark mass, for a medium transport coefficient $\hat{q}$ (a measurement of the medium density) in the range 25–100 GeV²/fm, are also shown.

5 Quarkonia capabilities

ALICE can detect quarkonia in the dielectron channel at central rapidity ($|y| \lesssim 1$) and in the dimuon channel at forward rapidity ($-4 \lesssim y \lesssim -2.5$). In both channels the quarkonia acceptance extends down to zero transverse momentum, since the minimum p_t for e and μ identification is about 1 GeV/ c . The high p_t reach is expected to be 10 (20) GeV/ c for the J/ψ in e^+e^- ($\mu^+\mu^-$), for a Pb–Pb run of one month at nominal luminosity. In the bottomonium sector, the mass resolution of about 90 MeV at $M_{\ell+\ell^-} \sim 10$ GeV, for both dielectrons and dimuons, should allow the separation of the Υ and Υ' states, and thus the measurement of the Υ'/Υ ratio, which is expected to be sensitive to the initial temperature of the medium.

Simulation studies are in progress to prepare a measurement of the fraction of J/ψ that feed-down from B decays. Such measurement can be performed by studying the separation of the dilepton pairs in the J/ψ invariant mass region from the main interaction vertex. The analysis is also expected to provide a measurement of the beauty p_t -differential cross section.

6 Summary

Heavy quarks, abundantly produced at LHC energies, will allow to address several issues at the heart of in heavy-ion physics. They provide tools to probe the density (via parton energy loss and its predicted mass dependence) and the temperature (via the dissociation patterns of quarkonia) of the high-density QCD medium formed in Pb–Pb collisions. The excellent tracking, vertexing and particle identification performance of ALICE will allow to fully explore this rich phenomenology.

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