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Overview of the ALICE potentials for heavy flavour physics

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Summary. — The ALICE experiment, currently in the commissioning phase, will study nucleus-nucleus and proton-proton collisions at the CERN Large Hadron Collider (LHC). I review the ALICE heavy-flavour physics program and present a selection of results on the expected performance.

PACS 25.75.-q – Relativistic heavy-ion collisions.
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The main physics goal of the ALICE experiment [1, 2] at the CERN LHC is to study nucleus-nucleus collisions in order to investigate the properties of nuclear matter at high energy density and high temperature. The centre-of-mass energy per nucleon-nucleon collision will be $\sqrt{s_{\rm NN}} = 5.5\,\text{TeV}$ for the Pb-Pb system, which will allow to reach energy densities larger than $10\,\text{GeV/fm}^3$ and temperature higher than $0.2\,\text{GeV}$. Under these conditions a deconfined state of quarks and gluons is expected to be formed. In addition the experiment will also study collisions of lower-mass ions, and protons.

Heavy-flavour particles are regarded as effective probes of the system conditions. In particular: i) open charm and beauty hadrons would be sensitive to the energy density, through the mechanism of in-medium energy loss of heavy quarks; ii) quarkonium states would be sensitive to the initial temperature of the system through their dissociation due to colour screening [3].

The ALICE apparatus [1,2] has excellent capabilities for heavy-flavour measurements, for both open heavy-flavoured hadrons and quarkonia [3]. For reasons of space, we shall limit the discussion to the detection of open charm and beauty in the central barrel and of quarkonium states at forward rapidity.

Due to the large mass of c and b quarks, the production of $c\bar{c}$ and $b\bar{b}$ pairs occurs in primary hard scatterings with large virtualities. Hence, the open heavy-flavour production cross-section in nucleon-nucleon collisions can be calculated, within the assumption of factorization, starting from the DGLAP evolved Parton Distribution Functions (PDF) and Fragmentation Functions and from the heavy-quark production cross-section at the partonic level. The latter can be calculated with perturbative QCD beyond the LO [4]. In nucleus-nucleus collision, the initial heavy-quark production is not expected to be affected by the presence of the medium due to the shortness of the time-scale for the relevant hard processes. It can therefore be evaluated, starting from the nucleon-nucleon pQCD calculations, assuming scaling with the number of inelastic nucleon-nucleon collisions (binary scaling) and correcting for initial state effects, such as modifications of the PDF inside the nuclei, parton saturation at small x, and $k_{\rm T}$ broadening. Final-state effects, due to the presence of the medium created in the heavy-ion collisions, can break binary scaling at high heavy-quark transverse momentum. In fact, a coloured parton is predicted to lose energy while traversing a coloured medium by both radiative and collisional mechanisms [5]. The experimental observable that is used to study these effects is the nuclear modification factor R_{AA} defined as $R_{AA}(p_{\rm T}) = \frac{{\rm d}^2 N_{AA}/{\rm d}p_{\rm T}{\rm d}y}{\langle N_{\rm coll}\rangle {\rm d}^2 N_{pp}/{\rm d}p_{\rm T}{\rm d}y}$ which describes the deviation with respect to binary scaling. Due to different color charges, the radiative energy loss is expected to be larger for gluons than for quarks, thus leading to the expectation of larger quenching at high $p_{\rm T}$ for heavy flavoured hadrons (mostly coming from a quark jet) than for light hadrons (mostly coming from a gluon jet). Furthermore, due to their large mass, the energy loss for heavier quarks is expected to be reduced with respect to lighter quarks by the dead cone effect [6]. Of particular interest in this context are the double ratios [7]:

$$R_{Dh}(p_{\rm T}) = \frac{R_{AA}^{\rm D\ mesons}(p_{\rm T})}{R_{AA}^{\rm light\ hadrons}(p_{\rm T})}\,, \qquad R_{BD}(p_{\rm T}) = \frac{R_{AA}^{\rm B\ mesons}(p_{\rm T})}{R_{AA}^{\rm D\ mesons}(p_{\rm T})}\,. \tag{1}$$

Finally, the quenching due to energy loss may influence also the hadronization mechanisms at low/intermediate momenta. In this domain, the hadronization of the slowed-down heavy quarks is expected to occur mainly through quark coalescence in the medium, thus modifying the relative abundances of particle species with respect to the case of hadronization via parton fragmentation in the vacuum. In particular, this would lead to an increased baryon/meson ratio as well as to an enhanced relative abundance of hadrons containing strange quarks.

Among the most promising channels for open charm detection are the $\rm D^0 \to K^-\pi^+$ ($c\tau \approx 120\,\mu$m, branching ratio $\approx 3.8\%$) and $\rm D^+ \to K^-\pi^+\pi^+$ ($c\tau \approx 300\,\mu$m, branching ratio $\approx 9.2\%$) decays. The detection strategy to cope with the large combinatorial background from the underlying event in Pb-Pb is based on the selection of displaced-vertex topologies [3, 8] performed in the Inner Tracking System (ITS). 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 expected accessible $p_{\rm T}$ range for the $\rm D^0$ is 1–20 GeV/c in Pb-Pb for 10^7 central events (corresponding to one month of data taking) and 0.5–20 GeV/c in proton-proton for 10^9 minimum-bias events (corresponding to eight months of data-taking), with statistical errors better than 15–20% at high $p_{\rm T}$. A similar performance is expected for the $\rm D^+$. The systematic errors (acceptance and efficiency corrections, centrality selection for Pb-Pb) are estimated to be smaller than 15%.

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 and pions misidentified as electrons. Given that electrons from beauty have average impact parameter $d_0 \simeq 500\,\mu$m and a harder $p_{\rm T}$ spectrum, it is possible to obtain a high-purity sample with a strategy that relies on: electron identi-

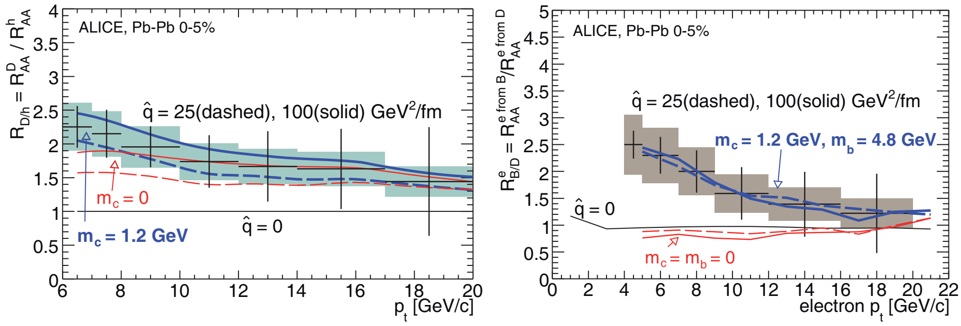

Fig. 1. – (Colour on-line) Ratio of the nuclear modification factors for D^0 mesons and for charged hadrons (left) and ratio of the nuclear modification factors for B-decay and for D-decay electrons (right). The case of massless quarks ($m_c = m_b = 0$, in red) is also shown for comparison. Errors corresponding to the centre of the prediction bands for massive quarks are shown: bars = statistical, shaded area = systematic.

fication with a combined $\mathrm{d}E/\mathrm{d}x$ (in the Time Projection Chamber, TPC) and transition radiation (in the Transiton Radiation Detector, TRD) selection; impact parameter cuts (with the ITS) to reduce the charm-decay component and reject misidentified $\pi^{\pm}$ and $e^{\pm}$ from Dalitz decays and γ conversions. As an example, with $200 < d_0 < 600\,\mu$m and $p_T > 2\,\mathrm{GeV}/c$ the expected signal purity of electrons from B decays is 80% and the statistics is 8×10^4 for 10^7 central Pb-Pb events, allowing the measurement of electron-level p_T-differential cross-section in the range $2 < p_T < 20\,\mathrm{GeV}/c$ with statistical errors smaller than 15% at high p_T. Similar performances are expected for pp collisions [3].

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 should provide a measurement of the beauty p_T-differential cross-section down to $p_T \approx 0$. The pseudo-proper decay time, $x = L_{xy} \cdot M(J/\psi)/p_T$, where L_{xy} is the signed projection of the J/ψ flight distance on its transverse direction, $L_{xy} = \vec{L} \cdot \vec{p}_T(J/\psi)/|p_T|$, can be used to separate J/ψ from the B decay products from that of prompt decays. In this expression, the $M(J/\psi)$ is taken as the known J/ψ mass [9].

The expected performance in the measurement of the double ratios in the range $5 < p_T < 20\,\mathrm{GeV}/c$ is presented in fig. 1. The expected experimental errors for those observables are compared to theoretical predictions from a model with parton energy loss [7]. Predictions with and without the effect of the heavy-quark mass, for a medium transport coefficient in the range 25–100 $\mathrm{GeV}^2/\mathrm{fm}$, are shown. For $5 < p_T < 10\,\mathrm{GeV}/c$, the measurement of the expected enhancement of heavy-to-light ratios with respect to unity appears to be feasible.

Quarkonia production is one of the main observables in ultrarelativistic heavy-ion physics since the early prediction [10] that the production of quarkonia would be suppressed in the Quark Gluon Plasma (QGP), because the binding of the heavy $Q\overline{Q}$ pair would be hindered in the deconfined medium by the strong interaction equivalent of the Debye screening. Anomalous suppression of the production of J/ψ was indeed observed in central Pb-Pb collisions at the CERN Super Proton Synchrotron (SPS), on top of the expected nuclear suppression systematics observed with lighter systems [11]. As an alternative to the QGP explanation, it was also proposed that the anomalous suppression could be due to an effect of dissociation of the produced J/ψ by interaction with comoving hadrons. In both cases, it was expected that the effect would be stronger at RHIC [12-14]. Experimentally, however, the amount of J/ψ suppression observed at RHIC turned out to be very similar to the SPS one [15]. Better agreement with the data is obtained if some mechanism of J/ψ regeneration, *e.g.*, by recombination, is introduced [12, 13]. In this view, the similarity of the suppression at SPS and RHIC would be the result of a cancellation of the extra suppression at RHIC by an increase in the $c\bar{c}$ abundance. At the LHC, however, due to the much higher $c\bar{c}$ cross-section, regeneration should then have the upper hand. The suppression would then be reduced and may even turn into an enhancement [16]. In ALICE, $\mu^-\mu^+$ pairs from the decay of quarkonium particles should generate a very clean signal in the muon arm (see also [3]). At the LHC energy one expects a significant ($\approx 30\%$) contribution to the J/ψ yield from B decays. This contribution will be controlled in the experiment by measuring open B production both in the central detector, as discussed above, and directly in the muon arm [3]. We expect a mass resolution around 70 MeV (100 MeV) for charmonia (bottomonia) in central Pb-Pb collisions. The detector acceptance extends down to almost zero p_{T} for both charmonia and bottomonia. The simulated performance on the dimuon mass spectrum for 10^6 s Pb-Pb running at a luminosity of $5 \times 10^{26}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ shows that we should be able to measure out to a p_{T} around 20 GeV for J/ψ and around 10 GeV for $\Upsilon(1S)$ and $\Upsilon(2S)$.

Heavy quarks, abundantly produced at LHC energies, will allow to address several prime issues of 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. We presented the expected performance of ALICE for the study of open heavy flavour and quarkonium states in nucleus-nucleus collisions at the LHC. The excellent tracking, vertexing and particle identification performance of ALICE will allow to fully explore this rich phenomenology.

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