ALICE potential for heavy-flavour physics

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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 and present a selection of results on the expected performance.

1 Introduction

The Large Hadron Collider (LHC) will deliver ion beams at ultra-relativistic energies and produce proton-proton, proton-nucleus and nucleus-nucleus collisions with a center-of-mass energy per nucleon-nucleon collision up to $\sqrt{s_{\text{NN}}} = 14$ TeV and $\sqrt{s_{\text{NN}}} = 5.5$ TeV for pp and Pb–Pb systems, respectively. ALICE [2, 3, 4] is the dedicated heavy-ion experiment at the LHC. Its main physics goal is to study the properties of the strongly-interacting matter in the conditions of high energy density ($> 10$ GeV/fm$^3$) and high temperature ($> 0.6$ GeV) expected to be reached in central Pb–Pb collisions. Under these conditions, according to lattice QCD calculations, the quarks should be no longer confined into hadrons and a deconfined Quark-Gluon Plasma (QGP) should be formed.

Due to the large mass of $c$ and $\bar{b}$ 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 [5]. In nucleus-nucleus collision, the initial heavy quark production is not expected to be affected by the presence of the medium created in the heavy ion collision, 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 $k_T$ broadening.

Final state effects, due to the presence of the medium, 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 [6]. The experimental observable that is used to study these effects is the nuclear modification factor $R_{AA}$ defined as $R_{AA}(p_T) = \frac{d^2N_{AA}/dp_Tdy}{(N_{\text{coll}})d^2N_{pp}/dp_Tdy}$ 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 smaller quenching at high $p_T$ 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 [7]. Of particular interest in this context are the double ratios [8]:

\[ R_{Dh}(p_T) = \frac{R_{DAA}^{D\text{ mesons}}(p_T)}{R_{DAA}^{\text{light hadrons}}(p_T)} \quad R_{BD}(p_T) = \frac{R_{DAA}^{B\text{ mesons}}(p_T)}{R_{DAA}^{D\text{ mesons}}(p_T)} \]  

(1)

Moreover, the quenching due to energy loss may also influence 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 [9], 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. Finally, the total open charm (open beauty) cross-sections will also provide a natural normalization for the charmonia (bottomonia) production.

Quarkonium production is one of the main observables in ultrarelativistic heavy-ion physics since the early prediction [10] that the production of quarkonium would be suppressed in the Quark Gluon Plasma (QGP), because the binding of the heavy $Q\bar{Q}$ pair would be hindered in the deconfined medium by the strong interaction equivalent of the Debye screening. Anomalous suppression of the production of $J/\psi$ was indeed observed in central Pb–Pb collisions at the CERN Super Proton Synchrotron (SPS), beyond 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 $J/\psi$ by interaction with comoving hadrons. In both cases, it was expected that the effect would be stronger at RHIC [12, 13, 14]. Experimentally, however, the amount of $J/\psi$ suppression observed at RHIC turned out to be very similar to that at the SPS [15]. Better agreement with the data is obtained if some mechanism of $J/\psi$ regeneration, e.g. by recombination, is introduced [12, 13]. In this picture, 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 dominate. The suppression would then be reduced and may even turn into an enhancement [16].

2 Heavy flavour detection in ALICE

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. The ALICE central barrel covers the pseudo-rapidity region $-0.9 < \eta < 0.9$ and is equipped with tracking detectors and particle identification systems embedded in a magnetic field $B = 0.5$ T along the z axis. The combined information from the central barrel detectors allows to track charged particles down to low transverse momenta (low $p_T$ cut-off $\approx 100$ MeV/c) and provides hadron and electron identification as well as an accurate measurement of the positions of the primary (interaction) vertex and of the secondary (decay) vertices. The main tracking detector is the Time Projection Chamber (TPC), which provides track reconstruction and particle identification via $dE/dx$. The Inner Tracking System (ITS) is the innermost central barrel detector and is composed of six cylindrical layers of silicon detectors. The two layers closest to the beam pipe (radii $\approx 4$ and 7 cm) are equipped with pixel detectors, the two intermediate layers (radii $\approx 15$ and 24 cm) are made of drift detectors, while strip detectors are used for the two outermost layers (radii $\approx 39$ and 44 cm). The ITS is a key detector for open heavy-flavour studies because it allows to measure the track impact parameter (i.e. the distance of
closest approach of the track to the primary vertex) with a resolution better than 50 µm for \( p_T > 1.3 \) GeV/c, thus providing the capability to detect the secondary vertices originating from heavy-flavour decays. Two other systems play an important role in the heavy-flavour analyses, due to their particle identification capabilities. They are the Transition Radiation Detector (TRD) for high-momentum electron identification and the Time-Of-Flight (TOF) for pion, kaon and proton separation. All four detectors have full azimuthal coverage.

The detection of heavy quarkonia in the di-muonic decay channel is performed by the ALICE Muon Spectrometer in the forward pseudo-rapidity region 2.5 < \( \eta < 4 \). The system includes a front absorber of composite material, predominantly made of carbon and concrete, which is placed at 90 cm from the interaction vertex to reduce the free decay length of pions and kaons. The detector is composed of five tracking stations with two planes of Multi-Wire Proportional Chambers each, having a spatial resolution of about 100 µm, a dipole magnet with an integral field of 3 T·m and two trigger stations of Resistive Plate Chambers placed behind an iron-wall muon filter with a thickness of about 7 interaction lengths. It includes a beam shield made of tungsten, lead and stainless steel to protect the chambers from particles and secondaries produced at large rapidities. The spectrometer can detect quarkonia down to \( p_T = 0 \) and is designed to achieve an invariant-mass resolution of 100 (70) MeV/c² at \( m_{inv} = 10 (3) \) GeV/c², needed to resolve the bottomonium resonances.

Among the most promising channels for open charm detection are the \( D^0 \rightarrow K^-\pi^+ \) (\( c\tau \approx 120 \) µm, branching ratio \( \approx 3.8\% \)) and \( D^+ \rightarrow K^-\pi^+\pi^+ \) (\( c\tau \approx 300 \) µm, 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, 17] performed in the ITS. An invariant-mass analysis is used to extract the raw signal yield, which is then corrected for selection and reconstruction efficiency and for detector acceptance. The expected accessible \( p_T \) range for the \( D^0 \) is 1–20 GeV/c in Pb–Pb for 10⁷ central events (corresponding to one month of data-taking) and 0.5–20 GeV/c in proton–proton for 10⁹ minimum-bias events (corresponding to eight months of data-taking), with statistical errors better than 15–20% at high \( p_T \). A similar performance is expected for the \( D^+ \). 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 \( \approx 10\% \). The main sources of background electrons are: decays of D mesons; \( \pi^0 \) Dalitz decays and decays of light vector mesons (e.g., \( \rho \) and \( \omega \)); 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 \( d_0 \approx 500 \) µm and a harder \( p_T \) 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 and impact parameter cuts (with the ITS) to reduce the charm-decay component and reject misidentified \( \pi^\pm \) and \( e^\pm \) from Dalitz decays and \( \gamma \) conversions. As an example, with 200 < \( d_0 < 600 \) µm and \( p_T > 2 \) GeV/c the expected signal purity of electrons from B decays is 80% and the statistics are 8 x 10⁴ for 10⁷ central Pb–Pb events, allowing the measurement of electron-level \( p_T \)-differential cross section in the range 2 < \( p_T < 20 \) GeV/c with statistical errors smaller than 15% at high \( p_T \). Similar performance is expected for pp collisions [3].

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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

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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 $J/\psi$ flight distance on its transverse direction, $L_{xy} = \hat{L} \cdot \hat{p}_t(J/\psi)/|p_T|$, can be used to separate $J/\psi$ from the B decay products from that of prompt decays.

The expected performance in the measurement of the double ratios in the range $5 < p_T < 20$ GeV/c is presented in figure 1. The expected experimental errors for those observables are compared to theoretical predictions from a model with parton energy loss [8].

Figure 1: 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.

with and without the effect of the heavy-quark mass, for a medium transport coefficient in the range 25–100 GeV$^2$/fm, are shown. For $5 < p_T < 10$ GeV/c, the measurement of the expected enhancement of heavy-to-light ratios with respect to unity appears to be feasible.

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 $J/\psi$ 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]. The simulated performance of the dimuon mass spectrum after subtraction of the combinatorial background for $10^8$ s Pb–Pb running at a luminosity of $5 \times 10^{26}$ cm$^{-2}$ s$^{-1}$ is shown in figure 2 for central collisions ($b < 3$ fm). We expect a mass resolution around 70 MeV (100 MeV) for charmonium (bottomonium) in central Pb–Pb collisions. The detector acceptance extends down to essentially zero $p_T$ for both charmonium and bottomonium. The statistics collected in a $10^8$ s Pb–Pb run should allow us to measure out to a $p_T$ around 20 GeV for $J/\psi$ and around 10 GeV for $\Upsilon(1S)$ and $\Upsilon(2S)$.

3 Conclusions

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.

References

[1] Slides: http://indico.cern.ch/contributionDisplay.py?contribId=141&sessionId=5&confId=53294