Preparation for heavy-flavour measurements with ALICE at the LHC

Andrea Dainese, for the ALICE Collaboration

INFN - Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy

Abstract

ALICE [1] will study nucleus–nucleus and proton–proton collisions at the LHC. The main goal of the experiment is to investigate the properties of QCD matter at the extreme energy densities that will be reached in Pb–Pb collisions. Heavy quarks (charm and beauty) are regarded as powerful tools for this study. After briefly reviewing the ALICE heavy-flavour program, we will describe the preparation for the first measurements to be performed with pp collisions.

1. Introduction: heavy quarks at the LHC

The measurement of open charm and beauty production in Pb–Pb collisions at \( \sqrt{s_{NN}} = 5.5 \) TeV will allow to investigate the mechanisms of heavy-quark production, propagation and hadronization in the hot and dense QCD medium formed in high-energy heavy-ion collisions. Heavy-quark production measurements in pp collisions at \( \sqrt{s} = 10–14 \) TeV, besides providing the necessary baseline for the study of medium effects in Pb–Pb collisions, are interesting \( \text{per se} \), as a test of QCD in a new domain, 5–7 times above the present energy frontier at the Tevatron.

The \( \bar{c}c \) and \( \bar{b}b \) production yields assumed as the baseline for ALICE simulation studies are: for pp collisions at 14 TeV, 0.16 and 0.007, respectively [2] (and lower by about 25% at 10 TeV, the envisaged energy of the first long pp run); for the 5% most central Pb–Pb collisions at 5.5 TeV, 115 and 4.6, respectively. These numbers are obtained from pQCD calculations at NLO [3] with a reasonable set of parameters [2], including nuclear shadowing. An illustration of the theoretical uncertainty bands, spanning over a factor about 2, for the D and B meson cross sections will be shown in Section 2.2 along with the expected ALICE sensitivity.

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 decreasing suppression when going from the mostly gluon-originated light-flavour hadrons (\( h^\pm \) or \( \pi^0 \)) to D and B mesons. In terms of the Pb–Pb-to-pp nuclear modification factors of the \( p_t \)-differential yields: \( R_{AA}^A(p_t) \lesssim R_{AA}^D(p_t) \lesssim R_{AA}^B(p_t) \) [5].

2. Heavy-flavour measurements in preparation

The ALICE experimental setup, described in detail in [1, 6], allows for the detection of open charm and beauty hadrons 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) \[7\], the Time Projection Chamber (TPC) \[8\] and the Transition Radiation Detector (TRD) \[9\], embedded in a magnetic field of 0.5 T, allow for track reconstruction in the pseudorapidity range \(|\eta| < 0.9\) with a \(p_t\) resolution better than 2% up to 20 GeV/c and a transverse impact parameter resolution better than 60 \(\mu m\) 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 in the TOF detector; electrons are separated from charged hadrons in the dedicated TRD, in the TPC, and in the electromagnetic calorimeter (EMCAL); muons are identified in the muon spectrometer covering the pseudo-rapidity range \(-4 < \eta < -2.5\).

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

- Open charm: fully reconstructed hadronic decays \(D^0 \rightarrow K^-\pi^+, D^+ \rightarrow K^-\pi^+\pi^+, D^{*+} \rightarrow D^\pi^+, D^0 \rightarrow K^-\pi^+\pi^-, D^+_s \rightarrow K^-K^+\pi^+, \Lambda^+_c \rightarrow pK^-\pi^+\) (under study) in \(|\eta| < 0.9\); single muons and di-muons in \(-4 < \eta < -2.5\).
- Open beauty: 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); b-tagging of jets reconstructed in the tracking detectors and in the EMCAL (under study).

2.1. Commissioning of the hardware and software tools

At present, the installation of most of the ALICE detector is completed and, since December 2007, the different sub-systems are being commissioned and calibrated with cosmic-ray tracks (atmospheric muons) \[10\]. In view of the heavy-flavour measurements, a crucial part of the commissioning is represented by the alignment of the ITS, that is the determination of the actual position and orientation in space of its 2198 Silicon sensors. The alignment, which has to reach a precision well below 10 \(\mu m\) in order to guarantee a close-to-design tracking resolution, will be performed using tracks from cosmic rays and first pp collisions. The first results \[7\], obtained with cosmic rays collected during summer 2008, indicate that the target precision is within reach.

On the offline software side, an intense activity for the preparation and refinement of all the analysis tools is ongoing. In particular, the analysis model using the Grid distributed computing environment is being tested. As an example, in a recent campaign, more than \(10^8\) pp events, corresponding to about 1/10 of the expected yearly statistics, have been simulated by running up to 15,000 simultaneous processes at almost 100 centres worldwide. The simulated data are now being analyzed remotely by several tens of single users. In the following Sections, we report on a selection of results extrapolated to the expected statistics collected by ALICE per LHC year\[3\].

2.2. Charm and beauty measurements at central rapidity

Among the most promising channels for open charm detection are the \(D^0 \rightarrow K^-\pi^+\) (\(c\tau \approx 120\ \mu m\), branching ratio \(\approx 3.8\%\)) and \(D^+ \rightarrow K^-\pi^+\pi^+\) (\(c\tau \approx 300\ \mu m\), branching ratio \(\approx 9.2\%\)).

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1 \(d_0\), defined as the track distance of closest approach to the interaction vertex, in the plane transverse to the beams.
2 \(10^7\) central (0–5% \(\rho^{\text{inel}}\)) Pb–Pb events in 1 month at \(\mathcal{L}_{\text{Pb-Pb}} = 10^{23}\ \text{cm}^{-2}\text{s}^{-1}\) and \(10^8\) pp events in 8 months at \(\mathcal{L}^{\text{ALICE}} = 5 \times 10^{30}\ \text{cm}^{-2}\text{s}^{-1}\), in the barrel detectors; the forward muon arm will collect about 40 times larger samples of muon-trigger events (i.e. \(4 \times 10^8\) central Pb–Pb events); safety factors are included.
decays, reconstructed in the TPC and ITS, in the rapidity range $|y| < 1$. 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 of the decay tracks from the primary vertex and good alignment between the reconstructed D meson momentum and flight direction. 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 at central rapidity, $|y| < 1$, can be studied by detecting the semi-electronic decays of $b$-hadrons (branching ratio $\approx 10\%$). Given that electrons from beauty have an average impact parameter $d_0 \approx 500 \mu m$, it is possible to obtain a high-purity sample with a strategy that relies on electron identification (TPC and TRD) and impact parameter cut (to reduce the semi-electronic charm-decay component and reject misidentified $\pi^\pm$ and $e^\pm$ from Dalitz decays and $\gamma$ conversions). As an example, with $10^7$ central Pb–Pb events, this strategy is expected to allow for the measurement of the $b$-decay electron $p_t$-differential cross section in the range $2 < p_t < 20$ GeV/$c$ with statistical errors lower than 15% at high $p_t$. Similar performance figures are expected for pp collisions. In Fig. 1 we superimpose the simulated results for $D^0$ $d^2\sigma/dp_t dy$ and $B$ $d\sigma(p_t > p_t^{\text{min}})/dy$ in pp collisions to the predictions from the MNR and FONLL calculations. The comparison shows that ALICE will be able to perform a sensitive test of the pQCD predictions for $c$ and $b$ production at LHC energy.

By comparing to theoretical predictions the expected ALICE precision for the measurement of the nuclear modification factors $R_{AA}^D$ and $R_{AA}^B$ from $B$, and for the heavy-to-light ratio $R_{\Lambda}^D$ from $B / R_{\Lambda}^D$ from $D$, has been shown that the charm and beauty measurements described above can be used to test the expected colour-charge and mass dependence of parton energy loss.

2.3. Charm and beauty measurements at forward rapidity

Charm and beauty production can be measured also in the forward muon spectrometer ($-4 < \eta < -2.5$) by analyzing the single-muon $p_t$ and di-muon invariant-mass distributions. The main background to the ‘heavy-flavour muon’ signal is $\pi^\pm$ and $K^\pm$ decays. The cut $p_t > 1.5$ GeV/$c$ is applied in order to increase the signal-to-background ratio. Then, a technique that performs a
Figure 2: Charm (left) and beauty (right) production measurements in $-4 < y < -2.5$, using single muons and di-muons, in pp at $\sqrt{s} = 14$ TeV. Boxes represent the systematic uncertainties. Error bars represent the statistical uncertainties.

simultaneous fit of the single-muon and di-muon distributions with the charm and beauty components, using the predicted shapes as templates, allows to extract a $p_T^{\text{min}}$-differential cross section for D and B mesons. The expected performance for pp collisions is shown in Fig. 2. Since only minimal cuts are applied, the statistical errors are expected to be lower than 5% up to muon $p_T \approx 30$ GeV/c. The systematic errors, mainly due to the fit assumptions, are expected to be lower than 20%. High-$p_T$ single muons could provide the first observation of b-quark energy loss at LHC. Indeed, the single-muon $p_T$ distribution at LHC energies is expected to be dominated by b decays in the range $3 < p_T < 25$ GeV/c and by W-boson decays above this range. Therefore, the central-to-peripheral muon nuclear modification factor of $R_{CP}(p_T)$ would be suppressed in the region dominated by beauty, due to parton energy loss, and would rapidly increase to about one (binary scaling), where the medium-blind muons from W decays dominate [12].

3. Summary

Heavy quarks will provide ways to test different aspects of QCD under extreme conditions at the LHC: from the predictions of pQCD at a new energy scale, in pp collisions, to the mechanism of energy loss in a QCD medium, in Pb–Pb. The ALICE detectors and analysis tools are being commissioned, with the aim of achieving the excellent tracking, vertexing and particle identification performance that will allow to accomplish the rich heavy-flavour physics program.

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