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ALICE commissioning and prospects for beauty and quarkonia measurements

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The ALICE experiment at LHC has been commissioned with cosmic-ray particles during 2008 and 2009. ALICE looks forward to the high-energy proton-proton run in 2010 and, as the dedicated heavy-ion detector at the LHC, to the pilot Pb–Pb run before the end of 2010. In this report, we focus on heavy flavour and quarkonia measurements, which constitute, as we will explain, one of the main items of the ALICE physics program in proton–proton and heavy-ion collisions. After describing some aspects of the detector commissioning with cosmics that are closely related to the preparation for these measurements —namely, the detector alignment— we will review the expected performance for beauty and quarkonia production studies in the first years.

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1. Introduction

ALICE [1] 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 GeV/fm^3) and high temperature ($\gg 0.2$ GeV), expected to be reached in central Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.5$ 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.

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.

Heavy-quark production measurements in proton–proton collisions at LHC energies, $\sqrt{s} = 7$–14 TeV, besides providing the necessary baseline for the study of medium effects in nucleus–nucleus collisions, are interesting *per se*, as a test of QCD in a new energy domain.

2. Heavy-flavour phenomenology at the LHC: from pp to nucleus–nucleus

The expected $\rm c\overline{c}$ and $\rm b\overline{b}$ production yields for pp collisions at the design LHC energy, $\sqrt{s} = 14$ TeV, are 0.16 and 0.0072, respectively [2]. The values become 0.10 and 0.0035, respectively, at the 2010 energy, $\sqrt{s} = 7$ TeV. For the 5% most central Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.5$ 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. An illustration of the theoretical uncertainty bands for the B meson cross section will be shown in section 5, along with the expected sensitivity of the ALICE experiment.

Experiments at the Relativistic Heavy Ion Collider (RHIC) have shown that the nuclear modification factor, $R_{\rm AA}(p_{\rm t},\eta) = \frac{1}{\langle N_{\rm coll}\rangle} \cdot \frac{{\rm d}^2N_{\rm AA}/{\rm d}p_{\rm t}{\rm d}\eta}{{\rm d}^2N_{\rm pp}/{\rm d}p_{\rm t}{\rm d}\eta}$, 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 progressively decreasing $R_{\rm AA}$ suppression when going from the mostly gluon-originated light-flavour hadrons ($h^\pm$ or π^0) to D and to B mesons: $R^h_{\rm AA} \lesssim R^{\rm D}_{\rm AA} \lesssim R^{\rm B}_{\rm AA}$ [5]. 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 $c\overline{c}$ 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. Beauty and quarkonia detection in ALICE

The ALICE experimental setup, described in detail in [1], allows for the detection of open beauty (and charm) 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:

- Central 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[1] 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 $\mathrm{d}E/\mathrm{d}x$ 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), in the TPC, and in the electromagnetic calorimeter (EMCAL).

- Muon spectrometer; muons are reconstructed and identified in the forward muon spectrometer covering the pseudo-rapidity range $-4 < \eta < -2.5$; this detector contains a set of absorbers to suppress hadron and electron background, five tracking stations, and two trigger stations for the selection of muon events; a dipole magnet with a field integral of 3 Tm along the beam axis provides the bending power to measure the momenta of muons.

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

- Open beauty (section 5): inclusive single leptons $\mathrm{B} \to \mathrm{e} + X$ in $|\eta| < 0.9$ and $\mathrm{B} \to \mu + X$ in $-4 < \eta < -2.5$; inclusive displaced charmonia $\mathrm{B} \to \mathrm{J}/\psi\,(\to \mathrm{e}^+\mathrm{e}^-) + X$ (under study).

- Quarkonia (section 6): $c\overline{c}$ (J/ψ, ψ') and $b\overline{b}$ (Υ, Υ', Υ'') states in the $\mathrm{e}^+\mathrm{e}^-$ ($|\eta| < 0.9$) and $\mu^+\mu^-$ ($-4 < \eta < -2.5$) channels.

In addition, charm production will be measured in the central rapidity region, via fully-reconstructed hadronic decays of D^0, D^+, D_s^+, D^{*+}, Λ_c^+ (and charge conjugates), and in the forward rapidity region via semi-muonic decays.

[1] The 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.

4. ALICE commissioning with cosmic-ray particles

The installation of most of the ALICE detectors is completed and the experiment is ready for data taking with both proton and heavy-ion beams. Partially installed are the TRD (25%, to be completed 2010), the photon spectrometer PHOS (60%, to be completed 2010) and the electromagnetic calorimeter EMCAL (to be completed 2011). The central tracking system (ITS and TPC), the time of flight system (TOF) and the forward muon spectrometer are fully installed. Therefore at start-up ALICE has full hadron and muon identification capabilities and partial photon and electron identification capabilities.

Since December 2007, the different sub-systems are being commissioned and calibrated with cosmic-ray tracks [6]. In particular, after two short hardware-commissioning runs in December 2007 and in March 2008, two long cosmic-ray runs for detector calibration and software tuning have been performed in summer 2008 and in summer 2009, using the trigger signals provided by the pixel layers, by the TOF detector, and by the ACORDE scintillator array placed above the central magnet.

Due to its large volume, the TPC could collect more than 10^6 cosmic muon and particle shower events. The momentum resolution was studied by separating the cosmic tracks into two halves and comparing the reconstructed momenta. Already after the first calibration, a momentum resolution of 6% at 10 GeV$/c$ is achieved, reassuringly close to the design value of 4.5% [6].

In view of the heavy-flavour measurements, a crucial part of the commissioning is represented by the alignment of the tracking detectors, that is the determination of the actual position and orientation in space of all single detection elements. Alignment is particularly critical for the Inner Tracking System and for the Muon Spectrometer. For the ITS, an alignment precision well-below 10 μm is needed to achieve a track impact parameter resolution within 20% of the ideal resolution without misalignment; this is necessary to separate from the main interaction vertex the displaced tracks from beauty and charm decays. The first ITS alignment is described in the next paragraph. For the Muon Spectrometer, the residual misalignments have to be contained within 50 μm in order not to spoil the di-muon mass resolution and achieve a good separation of the various Υ states. The muon spectrometer has collected a small sample of nearly-horizontal cosmic muons that gave a first indication of the internal alignment of the chambers and allowed to start exercising the track-based alignment methods. Clearly, the alignment will be obtained using muon tracks from pp collisions: with a sample of 10^5 tracks a precision below 20 μm is expected [7].

Alignment of the Inner Tracking System

The ALICE ITS consists of six cylindrical layers of silicon detectors with three different technologies: pixels in the two innermost layers (SPD), drifts in the two intermediate layers (SDD), and strips in the two outer ones (SSD). The number of parameters to be determined in the ITS alignment is about 13,000 and the target precision, as mentioned above, is better than 10 μm.

The first alignment of the ITS [8] was performed using about 10^5 charged tracks from cosmic-rays that have been collected during summer 2008 with the ALICE magnetic field switched off, using the FastOR trigger provided by the pixel layers. The initial step of the alignment procedure consisted in the validation of the survey measurements for the SSD, which indicates that the residual misalignment for modules on ladders is within 5 μm, while the residual misalignment for the

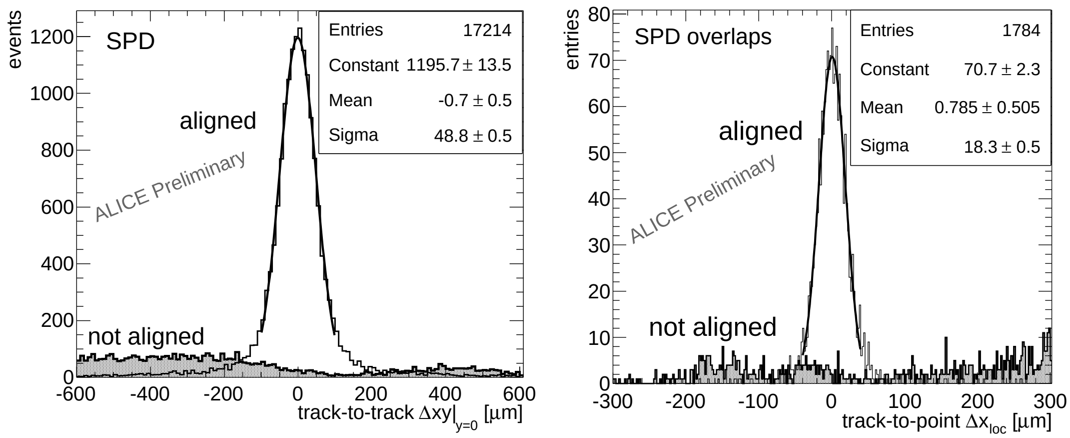

Figure 1: ITS alignment with cosmic-ray tracks. Left: distribution of $\Delta xy|_{y=0}$ for SPD, without alignment and with the Millepede alignment corrections. Right: SPD track-to-point $\Delta x_{\rm loc}$ for "extra" points in acceptance overlaps before and after alignment.

ladders with respect to the support cones amounts to about 20 μm. The next step uses track-based software alignment algorithms, that minimize track-to-measured-points residuals. The main algorithm is Millepede [9], also used for the Muon Spectrometer, where a global fit to all residuals is performed, extracting all the alignment parameters simultaneously. We use mainly two observables to assess the quality of the obtained alignment: the matching of the two half-tracks produced by a cosmic-ray particle in the upper and lower halves of the ITS barrel, and the residuals between double points produced in the geometrical overlaps between adjacent modules. For the SPD, both observables (shown in Fig. 1) indicate an effective space point resolution of about 14 μm in the most precise direction, to be compared to about 11 μm extracted from the Monte Carlo simulation without misalignments. This difference of $\approx 25\%$ (from 11 to 14 μm) is already quite close to 20%, which is the target of the alignment.

For all six layers, the completion of the alignment for all modules will require tracks from proton–proton collisions; a few 10^6 events (collected in a few days) should allow us to reach a uniform alignment level over the entire detector.

5. Prospects for beauty measurements

The production of open beauty at central rapidity, $|y| < 1$, can be studied by detecting the semi-electronic decays of b-hadrons (branching ratio $\simeq 10\%$). Given that electrons from beauty have an average transverse impact parameter $d_0 \simeq 500$ μm, 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 γ conversions). As an example, with 10^7 central Pb–Pb events, this strategy is expected to allow for the measurement of the $p_{\rm t}$-differential cross section of electrons from B decays in the electron $p_{\rm t}$ range 2–20 GeV/c with statistical errors lower than 15% at high $p_{\rm t}$. Similar performance figures are expected for pp collisions. In Fig. 2 (left) we superimpose the

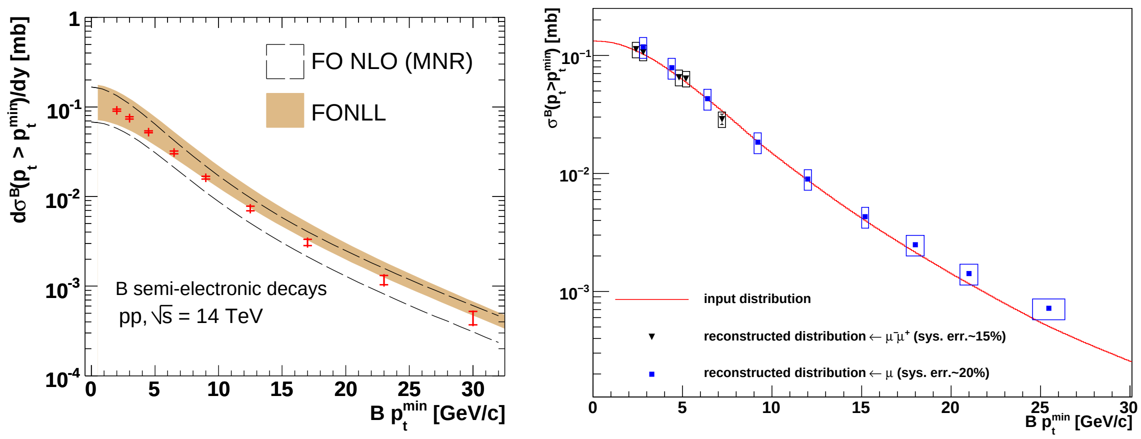

Figure 2: Expected performance for beauty production measurement in pp collisions at 14 TeV in the central and forward rapidity regions. Left: B p_t^{min}-differential production cross section in $|y| < 1$ using displaced single electrons, compared to NLO pQCD predictions (MNR [3] and FONLL [10]). Inner error bars represent the statistical errors, outer error bars represent the quadratic sum of statistical and systematic errors. A normalization error of 5% is not shown. Right: B p_t^{min}-differential production cross section in $-4 < y < -2.5$ using single muons and di-muons. Error bars represent the statistical errors, boxes represent the systematic errors.

simulated results for B $d\sigma(p_t > p_t^{min})/dy$ in pp collisions to the predictions from the MNR [3] and FONLL [10] calculations. The comparison shows that ALICE will be able to perform a sensitive test of the pQCD predictions for beauty 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 $R_{AA}^{e\text{ from B}}$, and for the heavy-to-light ratio $R_{AA}^{e\text{ from B}}/R_{AA}^{e\text{ from D}}$, it has been shown [11] that the charm and beauty measurements in the central barrel can be used to test the expected colour-charge and mass dependence of parton energy loss.

Beauty (and charm) 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 [2]. The main background to the 'heavy-flavour muon' signal is $\pi^{\pm}$ and $K^{\pm}$ decays. A cut $p_t > 1.5$ GeV$/c$ is applied in order to increase the signal-to-background ratio. Then, a technique that performs a 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^{min}-differential cross section for B and D hadrons [12]. The expected performance for pp collisions is shown in Fig. 2 (right). 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 $3 \lesssim p_t \lesssim 25$ 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 [13].

6. Prospects for quarkonia measurements

ALICE can detect quarkonia in the di-electron channel at central rapidity ($|y| \lesssim 1$) and in the di-muon 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 electron and muon identification is about 1 GeV$/c$. The high-p_t reach is expected to be 10 (20) GeV$/c$ for the J/ψ in $\mathrm{e}^+\mathrm{e}^-$ ($\mu^+\mu^-$), for a Pb–Pb run of one month and for a pp run of about seven months at nominal luminosity. During the initial pp run at 7 TeV in 2010, a measurement of the p_t-differential J/ψ cross section up to about 10 GeV$/c$ is expected to be available after about two–three months of data-taking. In the bottomonium sector, the mass resolution of about 90 MeV at $M_{\ell^+\ell^-} \sim 10$ GeV, for both di-electrons and di-muons, 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 hot and dense QCD medium formed in Pb–Pb collisions.

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 in the central barrel by studying the separation of the di-electron 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 in the range $0 \lesssim p_\mathrm{t} \lesssim 10$ GeV$/c$.

7. Summary

Heavy quarks, abundantly produced at LHC energies, will allow to address several issues at the heart 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. The excellent tracking, vertexing and particle identification performance of ALICE will allow to fully explore this rich phenomenology.

Extensive calibration and alignment activities are ongoing, using the data collected during the commissioning runs with cosmic-ray particle triggers. The first results indicate that the excellent design performance mentioned above is within reach.

Already in September 2008, the experiment was fully ready, from the hardware and software point of view, to obtain physics results from the first pp collisions provided by the LHC. This is well-exemplified by the first beam-induced event that was recorded and reconstructed on September 11, 2008, shown in Fig. 3.

References

[1] K. Aamodt et al. [ALICE Collaboration], JINST 3 (2008) S08002.

[2] B. Alessandro et al. [ALICE Collaboration], J. Phys. G 32 (2006) 1295.

[3] M.L. Mangano, P. Nason and G. Ridolfi, Nucl. Phys. B 373 (1992) 295.

[4] Yu.L. Dokshitzer and D.E. Kharzeev, Phys. Lett. B 519 (2001) 199.

[5] N. Armesto et al., Phys. Rev. D 71 (2005) 054027.

[6] P. Kujer [ALICE Collaboration], Nucl. Phys. A 830 (2009) 81c.

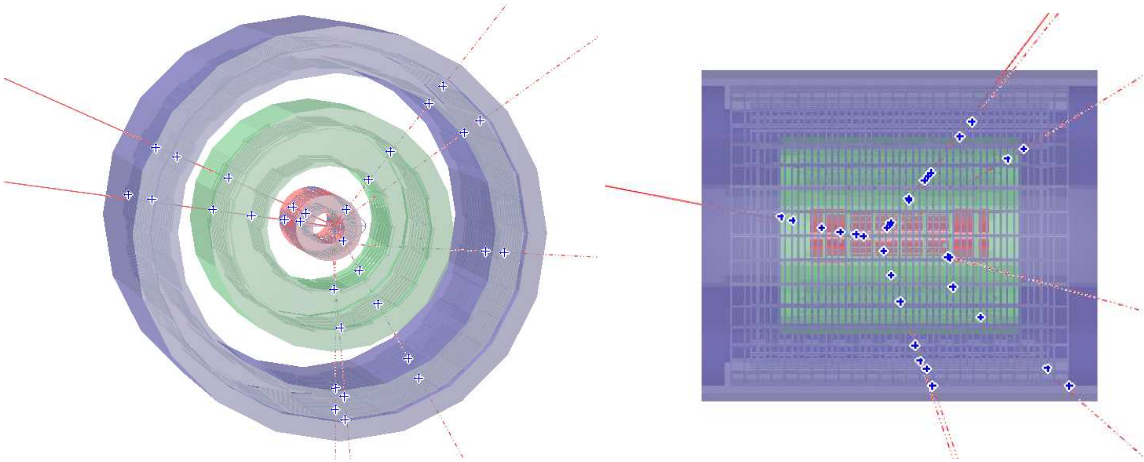

Figure 3: First beam-induced interaction observed in the ITS (September 11, 2008). The reconstructed event contains an interaction between a stray particle from the beam and a silicon pixel detector in the innermost ITS layer. Seven tracks are reconstructed, as well as their common production vertex.

[7] L. Aphecetche et al., ALICE Internal Note 2009-044 (2009);
J. Castillo [ALICE Collaboration], in CERN-2007-004 (2007).

[8] K. Aamodt et al. [ALICE Collaboration], arXiv:1001.0502;
C. Bombonati et al., ALICE Internal Note 2009-035 (2009).

[9] V. Blobel, in CERN-2007-004 (2007).

[10] M. Cacciari et al., JHEP 0407 (2004) 033; M. Cacciari, private communication.

[11] A. Dainese [ALICE Collaboration], J. Phys. G 35 (2008) 044046; Nucl. Phys. A 783 (2007) 417.

[12] L. Manceau [ALICE Collaboration], Eur. Phys. J. C 62 (2009) 9.

[13] Z. Conesa del Valle et al., Phys. Lett. B 663 (2008) 202.