Measurements of quarkonium production with ALICE at the LHC

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Abstract. ALICE is the LHC experiment dedicated to the study of heavy-ion collisions. The main purpose of ALICE is to investigate the properties of a new state of deconfined nuclear matter, the quark gluon plasma. Quarkonium measurements are very promising tools to unveil the properties of the quark gluon plasma. We will review the capabilities of the ALICE detectors to measure heavy quarkonia at both mid and forward-rapidity regions, and discuss the related physics programme.

1. Introduction

In ultra-relativistic heavy ion collisions, we aim to investigate the properties of nuclear matter under extreme conditions of temperature and pressure which are expected to lead to the creation of deconfined partonic matter, the Quark Gluon Plasma (QGP). With the objective of studying the QGP, heavy ion collisions were studied at the CERN SPS and are currently under investigation at RHIC at BNL. The Large Hadron Collider (LHC) at CERN, which delivered its first proton-proton (p-p) collisions in November 2009, will collide Lead to Lead (Pb-Pb) ions at $\sqrt{s_{NN}}$=5.5 TeV providing so far unprecedented conditions to study the QGP.

While several observables have been proposed to characterize the QGP, the study of heavy quark (c and b) production is thought to be one of the most powerful probes. The study of the production of heavy quark and anti-quark bound states (quarkonia), J/ψ , Ψ' ($c\bar{c}$), Υ (1S), Υ (2S) and Υ (3S) ($b\bar{b}$) is particularly interesting. It was first proposed that quarkonium resonances will dissociate by color screening in the QGP [1], thus a suppression of quarkonium production in nucleus-nucleus collisions compared to proton-nucleus collisions was predicted as a signature of the QGP formation. Later, it was also proposed that additional quarkonium production mechanisms, such as quark and anti-quark recombination in the QGP [2] or statistical hadronization [3], could add to the prompt production by initial hard scattering. In this case an enhanced production of quarkonium resonances will be observed in nucleus-nucleus collisions. The recombination scenarios are expected to be important for the charmonium states at RHIC energies and even more at LHC energies.

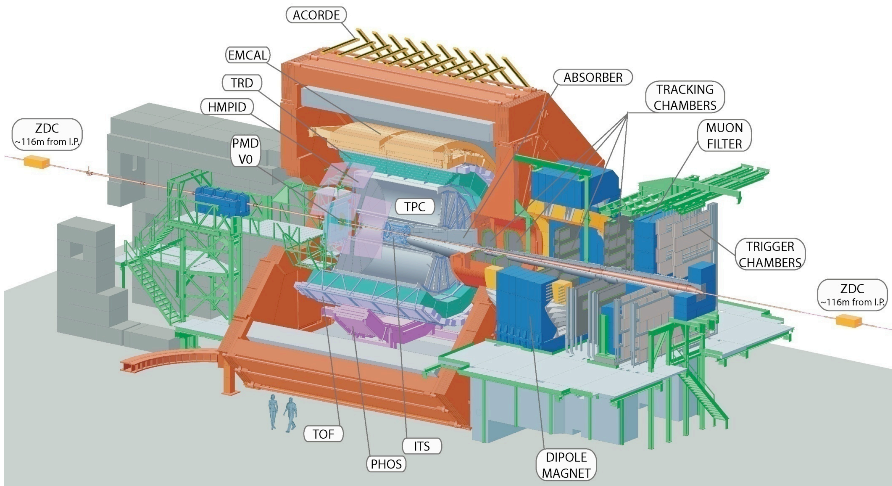

Figure 1. General layout of the ALICE detector.

2. The ALICE experiment at the LHC

ALICE is a general-purpose heavy-ion experiment designed to study the physics of strongly interacting matter and the QGP in nucleus-nucleus collisions at the LHC. The detector is designed to cope with the highest particle multiplicities anticipated for Pb-Pb collisions (dN_{ch}/dy up to 8000) and was operational for the first p-p collisions at the LHC in November 2009. In addition to heavy systems, ALICE will study collisions of lower-mass ions and protons (both p-p and p-A), which primarily provide reference data for the nucleus-nucleus collisions. In addition, the p-p and p-A data will allow for a number of genuine physics studies. The first p-p physics result was produced just one week after the first ever LHC collision [4].

The detector consists of a central part, which measures hadrons, electrons and photons, and of a forward spectrometer to measure muons. The central part, which covers polar angles from 45° to 135° over the full azimuth, is embedded in the L3 solenoidal magnet. It consists of various tracking detectors and particle identification arrays among which are the Inner Tracking System (ITS) of high resolution silicon detectors, a cylindrical Time-Projection Chamber (TPC) and a Transition Radiation Detector (TRD). The forward muon arm (covering polar angles $171° - 178°$) consists of a complex arrangement of absorbers, a large dipole magnet, and fourteen planes of tracking and triggering chambers. Several smaller detectors (ZDC, FMD, V0...) for global event characterization and triggering are located at forward angles. The general layout of the ALICE detector is shown in figure 1. More details can be found in [5].

3. Quarkonia detection capabilities

ALICE has good capabilities to measure quarkonium production in two rapidity domains, at mid rapidity through their dielectron decay and at forward rapidity via

Table 1. Expected mass resolution (σ_m), signal rate (S), signal-to-background ratio and significance for J/ψ and Υ in the dielectron channel within $\pm 1.5\sigma$ around each resonance mass for 10% most central Pb-Pb collisions. All yields correspond to a nominal year (see text) of data taking.

state	σ_m(MeV)	S(x10^3)	S/B	S/$\sqrt{S+B}$
J/ψ	33	121.1	1.4	265
Υ	90	1.3	1.6	21

their dimuon decay.

3.1. At mid rapidity in the dielectron channel

Electron pairs will be measured in the ALICE central barrel in the $|y| < 0.9$ rapidity domain. Electrons are tracked and identified by the following detectors, as seen by a particle travelling out from the interaction point:

- ITS [6] allows track finding, primary vertex reconstruction and secondary vertex finding. It is composed of three subsystems of two layers each: the Silicon Pixel Detector, the Silicon Drift Detector and the Silicon Strip Detector.
- TPC [7], optimized for large multiplicity environments, allows track finding, momentum measurement, and charged hadron identification via dE/dx. The track momentum resolution, including TPC and ITS information, is expected to be better than 2% for transverse momentum $p_\perp < 20$ GeV/c.
- TRD [8] allows electron identification for momenta larger than 1 GeV/c.

The invariant mass resolution for the quarkonia was studied using detailed geant simulations. The reconstructed peaks were fitted by a Gaussian and the invariant mass resolution for the J/ψ and Υ were found to be $\sigma_m^{J/\Psi} = 33$ MeV/c^2 and $\sigma_m^{\Upsilon} = 90$ MeV/c^2 respectively. The expected number of J/ψ and Υ to be reconstructed by the central barrel in a nominal year are summarized in Table 1. A nominal year is defined by a 10^6 s data taking period of Pb-Pb collisions at a luminosity of 5×10^{26} cm^{-2}s^{-1} and for a charged particle multiplicity density dN$_{ch}$/d$y = 3000$. Our simulations showed that the J/ψ can be reconstructed up to $p_\perp \sim 10$ GeV/c.

3.2. At forward rapidity in the dimuon channel

Muon pairs will be reconstructed by the ALICE forward muon spectrometer [9] in an acceptance region of $-4 < y < -2.5$ and with full azimuthal coverage. It consists of

- a front absorber to stop most hadrons, electrons and photons coming from the interaction point,
- an inner beam shield to stop re-scattered particles from the beam pipe,
- 10 tracking planes to allow particle trajectory reconstruction,

Table 2. Expected mass resolution (σ_m), signal rate (S), signal-to-background ratio and significance for J/ψ and Υ in the dimuon channel with an interval of $\pm 2.0\sigma$ around each resonance mass for minimum-bias Pb-Pb collisions. All yields correspond to a nominal year (see text) of data-taking.

state	σ_m(MeV)	S(x10^3)	S/B	S/$\sqrt{S+B}$
J/ψ	70	676.7	0.3	410
Υ	100	6.8	2.7	71

- a large area warm 3.0 Tm dipole magnet for momentum determination from the track bending,
- and a passive muon filter wall followed by 4 trigger planes that will provide single muon and muon pair triggers.

Like for the dielectron channel we use full simulations to study the muon spectrometer performances for the quarkonium reconstruction. We found the invariant mass resolution for the J/ψ and Υ to be $\sigma_m^{J/\Psi} = 70$ MeV/c^2 and $\sigma_m^{\Upsilon} = 100$ MeV/c^2 respectively.

The expected numbers of J/ψ and Υ to be reconstructed by ALICE in the muon spectrometer in a nominal year are summarised in Table 2. It is worth noting that the statistics for a nominal year will enable detailed differential studies of J/ψ production in Pb-Pb collisions. We expect to be able to reconstruct the J/ψ down from $p_\perp = 0$ GeV/c up to $p_\perp \sim 20$ GeV/c. It is also important to note that the expected mass resolution and statistics are sufficient to separate the three states of the Υ family.

More details on the ALICE capabilities to measure quarkonia production at both mid and forward rapidity and on the expected rates in both p-p and Pb-Pb collisions can be found in reference [10].

4. Quarkonium observables

4.1. Suppression or enhancement studies

The *bread and butter* of the quarkonium production studies are the J/ψ suppression, or enhancement, measurements. Our simulations showed that ALICE can perform them in two rapidity domains ($|y| < 0.9$ and $-4 < y < -2.5$) differentially in at least five centrality classes and as a function of $p_\perp$ [10]. Concerning the normalisation of the J/ψ yields in Pb-Pb collisions several options are being investigated. First, we can measure the R_{CP}, *i.e.*, the centrality dependence of the J/ψ yields compared to the most peripheral collisions, respectively normalized by their number of binary collisions (N_{coll}). This will be particularly meaningful if the regeneration mechanism dominates the J/ψ production.The second option is a R_{AA} measurement, *i.e.*, the yields in Pb-Pb collisions compared to those in p-p collisions normalized by N_{coll}. Since the reference for R_{AA}, p-p collisions, is cleaner than the one for R_{CP}, R_{AA} is expected to be more educating than R_{CP}. However, it has the drawback that p-p collisions will be initially measured at a higher centre of mass energy. Third, we can normalise with respect to beauty production. In the muon spectrometer beauty production can be measured from the low-mass and high-mass dimuons originating from correlated $B\bar{B}$ pair decays.

4.2. Secondary J/ψ *production*

A good knowledge of the sources of secondary J/ψ is crucial for the interpretation of the suppression results. This knowledge is poor, the commonly accepted understanding is that $\sim 40\%$ of the produced J/ψ come from the decay of the excited states ψ' ($\sim 10\%$) and χ_c ($\sim 30\%$), both at SPS and RHIC. At LHC the situation will be even worse. Indeed, in addition to the above ones, the contribution from B hadron decays will also be important. At the LHC this contribution is expected to be $\sim 20\%$. ALICE can measure the J/ψ from B decays in the central barrel by measuring the displaced secondary vertex. A technique to statistically measure J/ψ from B decays in the muon spectrometer, based on J/ψ-muon correlations, is also under investigation. The number of J/ψ originating from ψ' decays will be estimated from the direct ψ' yield measured in the dimuon channel. At mid-rapidity, a technique to measure the secondary J/ψ coming from the radiative χ_c decays is under study [11]. The J/ψ is measured in its dielectron channel thanks to the ITS, TPC and TRD while the photon is measured by conversion with the e^+ and e^- being measured in the TPC.

4.3. Quarkonium polarization

Quarkonium polarization measurements should allow to distinguish different production mechanisms, since different models predict different polarizations. Quarkonium polarization can be reconstructed from the angular distribution of the decay products (dimuons or dielectrons). It has been predicted that an increase of J/ψ polarization may be expected if the QGP is formed [12]. Our simulations have shown that for both p-p and Pb-Pb collisions differential measurements of J/ψ polarization versus $p_\perp$ and centrality will be possible after a nominal year of data taking while for the Υ polarization integrated measurements will be performed. A nominal year of p-p collisions is defined by a 10^7 s data taking period at a luminosity of 5×10^{30} cm^{-2}s^{-1}.

4.4. Υ *measurements*

The high luminosity and energy conditions at the LHC will enable the measurements of the Υ family. Of special interest will be the measurement of the Υ' over Υ ratio, which is expected to be particularly sensitive to the QGP suppression mechanism. Figure 2 shows the expected Υ'/Υ ratio as a function of the collision centrality for three different QGP suppression scenarii, one (closed triangles) characterized by a high deconfinement temperature $T_d = 270$ MeV [13], another one (open circles) using $T_d = 190$ MeV [14] and

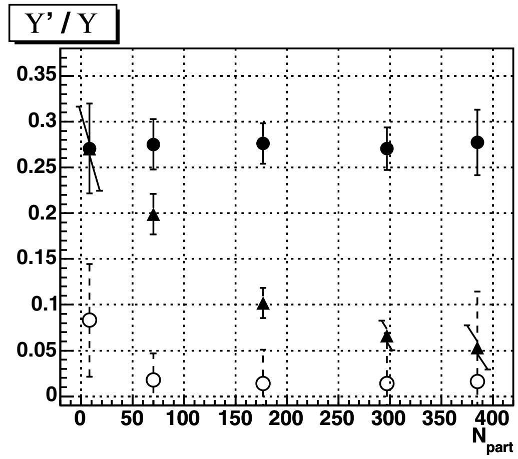

Figure 2. Υ'/Υ ratio as a function of the collision centrality for a no suppression scenario (closed circles), one with high deconfinement temperature T_d = 270 MeV (closed triangles) and one with T_d = 190 MeV (open circles). See text for details.

a no suppression scenario (closed circles). The statistics correspond to a nominal year of data taking as defined previously. We observe that the Υ'/Υ has a good discriminating power between the different suppression scenarii.

5. Conclusion

We summarized the expected performances of ALICE to investigate quarkonium physics. We showed that ALICE has good potential to contribute to the understanding of quarkonium physics in heavy ion collisions and to help investigate the properties of the quark gluon plasma. The ALICE experiment has successfully entered the data-taking era and the detector is ready to continue.

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