Quarkonium in A–A collisions with the ALICE experiment

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Abstract. Quarkonia, i.e. bound states of heavy quarks (charm/bottom), provide remarkable probes of the hot and strongly-interacting medium, the quark gluon plasma (QGP), which is created during heavy-ion collisions. Heavy quarks are produced during initial hard-scattering processes prior to the QGP formation and their number is conserved throughout the partonic and hadronic phases of the collision. At LHC, experimental observations of quarkonium states in A-A collisions are reproduced through two antagonist mechanisms: the sequential suppression and quarkonium production by (re)combination of deconfined quarks. Recent measurements of a significant J/ψ elliptic flow ($v_2$) in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV suggest a participation of the charm quarks to the collectivity of the medium. However, quarkonium interactions in the medium are not yet fully understood and several points should still be clarified. The ALICE experiment at the LHC measures quarkonia at mid-rapidity in the dielectron decay channel and at forward rapidity in the dimuon one, both down to zero transverse momentum. Latest measurements of quarkonium nuclear modification factor and elliptic flow in Pb-Pb collisions will be presented and compared to lower energy results and theoretical predictions.

1. Introduction
Measurements of quarkonia in heavy-ion collisions have been performed for several decades. Heavy quarks are produced prior to the formation of the QGP and experience the full medium evolution, providing crucial probes of the QGP properties. Quarkonium mesons formed of either a charm and anti-charm pair (J/ψ, ψ(2S)) or a beauty and anti-beauty pair (ϒ(1S),ϒ(2S),ϒ(3S)) can be experimentally measured through their dilepton decay. In the QGP they experience a suppression mechanism by color-screening in the medium and (re)generation by quark (re)combination at a later stage of the collision. The relative extent of both mechanisms depends on the system energy density, the heavy quark density and the specific bound state. Whereas light quarks typically reflect medium thermalization and expansion properties, heavy quarks carry information about their early interactions in the medium. Since the thermalization time of heavy quarks is longer, a relevant question is their degree of thermalization in the QGP. Substantial anisotropies are observed in the heavy-flavour sector and if charm quarks interact in the medium, their flow should be transmitted to quarkonium states formed through (re)combination.
2. Apparatus
The ALICE detector [1] measures quarkonium down to zero transverse momentum in two rapidity ranges: at mid-rapidity \(|y| < 0.9\) with the central barrel through the dielectron decay channel and at forward rapidity \((2.5 < y < 4)\) with the muon arm through the dimuon decay channel. Other detectors [2] are involved in the presented results for triggering, centrality determination and luminosity measurement. The 2015 Pb–Pb data campaign provided unprecedented statistics for quarkonium measurements, with an integrated luminosity reaching \(\sim 13 \text{ mb}^{-1}\) in the central barrel and \(\sim 225 \text{ mb}^{-1}\) in the muon spectrometer. All quarkonium measurements are inclusive, i.e. they include direct production and contributions from heavier charmonium states and B decays.

3. Quarkonium production in Pb–Pb collisions
The measurement of quarkonium suppression with respect to the corresponding pp yield is quantified through the nuclear modification factor \(R_{AA}\). Results for \(J/\psi\) are presented on Fig.1 as a function of the number of participants in the collision. Compatible \(R_{AA}\) values are observed between both \(J/\psi\) decay channels. After a strong decrease in peripheral collisions, the \(J/\psi\) production reaches a plateau around \(R_{AA} \sim 0.6\) [3]. Mid-rapidity results exhibit a hint of production enhancement for the most central collisions, in compliance with theoretical expectations including a \((\text{re})\)generation contribution dominant at mid-rapidity for most central events. The results are compatible with previous observations at \(\sqrt{s_{NN}} = 2.76\) TeV but benefit from an increased precision. These observations are interpreted as an indication of the interplay between the suppression and \((\text{re})\)combination mechanisms. A precise discrimination based on theory models [4, 5, 6, 7] is not possible because of substantial uncertainties on the determination of charm cross-section and the estimation of cold nuclear matter effects [8, 9]. The \(J/\psi\) \(R_{AA}\) is enhanced at low transverse momentum \(p_T\) for the most central collisions, this effect being expected from the \((\text{re})\)combination contribution, while a stronger suppression is observed as the \(J/\psi\) \(p_T\) increases, for both forward and mid-rapidity results. Available predictions [4] from a transport model predict a similar trend.

![Figure 1](image1.png)

**Figure 1.** Comparison of \(J/\psi\) \(R_{AA}\) measurements as a function of the number of participants in Pb–Pb collisions at \(\sqrt{s_{NN}} = 5.02\) TeV in the dielectron and dimuon decay channels

![Figure 2](image2.png)

**Figure 2.** Double ratio of \(\psi(2S)\) and \(J/\psi\) \(R_{AA}\) as a function of the number of participants in Pb–Pb collisions at \(\sqrt{s_{NN}} = 5.02\) TeV

More statistics is required to better study \(\psi(2S)\) production in A–A collisions. A relative suppression to \(J/\psi\) measurement is observed at forward rapidity (as seen on Fig. 2), as expected from the sequential suppression picture since the \(\psi(2S)\) is more loosely bound. Data show a
stronger suppression in semi-central and central collisions. An upper limit with a confidence level of 95% was calculated for low signal significances. More precise (semi-)peripheral measurements would greatly contribute to describe the suppression and (re)combination mechanisms for charmonium states. An overall improved measurement of the $\psi(2S)$ over $J/\psi$ ratio would particularly help model discrimination. During the LHC run 3 a substantial improvement of the collected statistics and of the signal over background ratio is expected for this challenging measurement.

Inclusive measurements of $\Upsilon(1S)$ are also available at forward rapidity in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Because of the high mass of the bottom quark, a lower density of bottom quarks is expected in medium compared to charm. $R_{AA}$ values around $\sim 0.5$ [10] are observed, similar to $\sqrt{s_{NN}} = 2.76$ TeV results [11]. The centrality dependence is more pronounced than in the charmonium case and results exhibit almost no variation with $p_T$.

4. Quarkonium azimuthal anisotropy in Pb–Pb collisions

The elliptic shape of the medium created in non-central collisions causes an anisotropic matter distribution, passed to the particle momentum distribution if the system is interacting. The decomposition of particle momentum distribution into a Fourier series [12] allows for a precise study of each harmonic. The second coefficient, the elliptic flow ($v_2$), reflects the anisotropy in the transverse plane and is very sensitive to the early times of the collision. Because of their large mass, the thermalization degree of heavy quarks might be partial and needs to be ascertained. Heavy flavour hadrons and in particular recent D mesons measurements of ALICE [13] exhibit significant azimuthal anisotropies. Event shape engineering results give strong hints that charm follows the collective expansion of the medium.

Previous studies at RHIC energies [15, 16] of quarkonium elliptic flow led to small anisotropies compatible with zero but dominated by large uncertainties. LHC first collisions at $\sqrt{s_{NN}} = 2.76$ TeV revealed first positive $J/\psi$ $v_2$ values measured both by CMS [17] and ALICE [10] in different kinematic ranges. The analysis at $\sqrt{s_{NN}} = 5.02$ TeV [18] features a sizeable azimuthal anisotropy for several transverse momentum and centrality ranges. For the first time, mid-rapidity measurements are also performed. The comparison to open heavy flavour on Fig.3 reveals similar amplitudes, pointing towards charm thermalization in the medium.
Theoretical calculations reproducing $R_{AA}$ measurements can reproduce the measured amplitude of the elliptic flow if a strong (re)combination component is included (Fig.4). Therefore $J/\psi$ elliptic flow measurements weight in favour of quarkonium formation through charm quark (re)combination before or during the hadronization stage. At high $p_T$ a small anisotropy is expected from primordial $J/\psi$, arising from path length differences through the elliptic shape of the fireball. A second contribution is considered by [7] from the early magnetic field [19]. However the measured amplitude lies far above theory predictions. A missing mechanism should possibly be invoked explain this discrepancy.

5. Conclusion
ALICE measurements in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV provide deeper understanding of quarkonium physics. The study of the nuclear modification factor allows an investigation of the interplay between suppression and (re)combination mechanisms. $J/\psi$ $R_{AA}$ and elliptic flow require that a significant proportion of $J/\psi$ are produced through charm quark (re)combination. The $J/\psi$ azimuthal anisotropy is a sign of charm interaction with the medium constituents but the unexpected amplitude at high $p_T$ has not been explained yet. Bottomonium results show a suppression which increases towards most central collisions, with a negligible $p_T$ dependence and little room for a (re)generation contribution. The additional statistics of the next LHC run, also thanks to the ALICE detector upgrade, should bring new insights to quarkonium formation and evolution in the QGP.

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