Measurement of $J/\psi$ production in Pb–Pb and pp collisions at the LHC with the ALICE experiment

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Abstract. ALICE (A Large Ion Collider Experiment) aims to study the behaviour of nuclear matter at high energy densities and the transition to Quark Gluon Plasma (QGP), expected to occur in relativistic heavy ion collisions. Quarkonia are important probes of nuclear matter and QGP, through the modification of their yield in the hot and dense medium formed in heavy ion collisions. Their measurement in pp collisions is also crucial to the ALICE physics program. ALICE measures quarkonium production at both forward (in the dimuon channel) and mid-rapidity (in the dielectron channel). In 2010 and 2011 the Large Hadron Collider has provided pp collisions at $\sqrt{s} = 7$ TeV and 2.76 TeV and Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The ALICE results on $J/\psi$ production in both Pb–Pb and pp collisions are presented.

1. Introduction
The ALICE [1] experiment at the Large Hadron Collider [2] was designed to study strongly interacting matter in ultra-relativistic heavy-ion collisions at energy densities orders of magnitude higher than that of ordinary nuclear matter. Under these conditions, finite temperature QCD calculations on the lattice (see e.g. [3]) predict a transition to a deconfined state of matter known as Quark-Gluon Plasma (QGP). Heavy flavour production is modified by the presence of this medium. In particular, quarkonium suppression by colour screening was one of the first proposed signatures for QGP formation [4]. Charmonium regeneration due to the recombination of initially uncorrelated $c$ and $\bar{c}$ quarks may also become relevant at LHC energies [5]. A detailed description of the physics motivations for charmonium measurements in heavy-ion collisions can be found in [6]. Further discussion on this topic can be found elsewhere in these Proceedings[7, 8]. $J/\psi$ production in pp collisions is also part of the ALICE program, as a reference for Pb-Pb data as well as in its own right, with the aim of understanding the quarkonium production mechanism.

2. $J/\psi$ detection in ALICE
A complete description of the ALICE experiment can be found in [1]. The $J/\psi$ measurement at mid-rapidity is performed by detecting its dielectron decay with the ALICE central detectors ($|\eta| < 0.9$, where $\eta$ denotes the particle pseudorapidity). The analysis presented here is based on the Inner Tracking System (ITS) for vertexing and tracking, the Time Projection Chamber [9] (TPC) for tracking and particle identification, the Time of Flight (TOF) for particle identification. Other detectors such as the Transition Radiation Detector and the Electromagnetic Calorimeter, not used in this analysis, are expected to greatly improve
the ALICE electron identification capabilities in the near future. At forward rapidity, J/ψ production is measured in the dimuon channel with a dedicated muon spectrometer (-4 < η < -2.5). The muon spectrometer is equipped with a dipole magnet, a set of absorbers, five tracking stations based on multiwire proportional chambers with pad readout, and a muon trigger system. In both the mid- and forward rapidity analysis, the VZERO scintillators (-3.7 < η < -1.7, 2.8 < η < 5.1) are used for triggering and for luminosity (in pp) and centrality (in Pb–Pb) determination.

3. Results from pp collisions
The results presented in this section have been obtained from pp collision data samples collected in 2010 (at $\sqrt{s} = 7$ TeV) and 2011 (at $\sqrt{s} = 2.76$ TeV). The mid-rapidity data have been collected using a minimum bias trigger based on the VZERO detector and on the two innermost layers of the ITS (Silicon Pixel Detector, SPD). For forward rapidity data, in addition to the minimum bias condition, the detection of a muon with transverse momentum $p_T > 0.5$ GeV/c was required by the muon trigger.

3.1. Inclusive and prompt cross section
ALICE measured the inclusive J/ψ cross section down to zero transverse momentum, at the energies of 7 TeV [10] and 2.76 TeV [11], in the rapidity ranges $|y| < 0.9$ and $2.5 < y < 4$. We denote as inclusive cross section the sum of the prompt\(^\dagger\) and non-prompt (from B meson decays) cross sections. The integrated luminosity corresponding to the mid- (forward) rapidity data sample used for the cross section measurement is 5.6 nb\(^{-1}\) (15.6 nb\(^{-1}\)) at $\sqrt{s} = 7$ TeV and 1.1 nb\(^{-1}\) (19.9 nb\(^{-1}\)) at $\sqrt{s} = 2.76$ TeV. The inclusive differential cross sections are shown in Fig. 1. The $p_T$ distributions are reasonably well reproduced by NLO calculations with Non Relativistic QCD (NRQCD) factorisation [12, 13]. At mid-rapidity, due to the ITS vertexing capabilities (the impact parameter resolution in the $r\varphi$ plane is about 75 µm for $p_T > 1$ GeV/c), it is possible to separate the non-prompt from the prompt component of the J/ψ yield via the

\(^\dagger\) The prompt component is in turn made of a direct and a non-direct component, the latter arising from decays of higher charmonium resonances such as ψ′ and χc.
displacement of the production vertex (pseudo-proper time), as described in [14]. The fraction of the total J/$\psi$ yield coming from decays of B-mesons at $\sqrt{s} = 7$ TeV was measured for $p_T > 1.3$ GeV/c and $|y| < 0.9$. The result is shown in Fig. 2, as a function of $p_T$. It is compatible with the results obtained by the ATLAS and CMS collaborations [15, 16].

![Figure 2. Fraction of J/$\psi$ from B meson decays as a function of $p_T$ in $|y| < 0.9$, compared to the ATLAS [15] and CMS [16] results. Superimposed is a semi-phenomenological function used to extrapolate to $p_T = 0$. This figure is taken from [14].](image)

3.2. Polarisation
J/$\psi$ polarisation is a crucial observable for the comparison between data and models (see e.g. [17]). ALICE measured polarisation at forward rapidity for $2 < p_T < 8$ GeV/c at $\sqrt{s} = 7$ TeV [18], via the polar ($\theta$) and azimuthal ($\phi$) angular distribution of decay muons. The distributions are fitted as

$$W(\theta, \phi) \propto \lambda_\theta \cos^2 \theta + \lambda_\phi \sin^2 \theta \cos 2 \phi + \lambda_{\theta,\phi} \sin 2 \theta \cos \phi$$

and the $\lambda_\theta$ and $\lambda_\phi$ parameters are extracted. The $\lambda_\theta$ parameter is the most directly related to the polarisation: $\lambda_\theta = 0$ means no polarisation, while $\lambda_\theta = 1(-1)$ means transverse (longitudinal) polarisation. The measurement was performed in two different reference frames: Collins-Soper and helicity. The obtained parameters for the two reference frames are shown as a function of $p_T$ in Fig. 3, together with the corresponding NRQCD predictions [19]: the data suggest weak or no polarisation. Extension of the measurement to higher $p_T$ is foreseen in the near future, in order to provide a more stringent test of theoretical predictions.

3.3. Multiplicity dependence
ALICE has measured the inclusive J/$\psi$ yield as a function of the charged particle pseudorapidity density $dN_{ch}/d\eta$ in pp collisions$^2$ at $\sqrt{s} = 7$ TeV [20]. The interesting aspect of such a measurement is the interplay between soft and hard regimes in particle production at LHC energies, especially in the frame of multi-partonic interactions. The result is reported in Fig. 4; both the multiplicity and the J/$\psi$ yield have been divided by their average values. A linear increase of the yield as a function of multiplicity is observed at both mid- and forward rapidity. Such behaviour is not reproduced by PYTHIA 6.4, which predicts a slight decrease of the yield.

$^2$ The maximum value of $dN_{ch}/d\eta$ in the used data sample is about 30, a value similar to the multiplicity reached in semi-central Cu–Cu collisions at RHIC.
4. Pb–Pb collisions: data analysis and results

$J/\psi$ production in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV was measured by ALICE at both mid- and forward rapidity. At mid-rapidity, we report results obtained with a data sample, corresponding to an integrated luminosity of $1.7 \mu b^{-1}$, collected in 2010 using a minimum bias trigger based on VZERO and SPD. At forward rapidity, we report results obtained with a data sample, corresponding to an integrated luminosity of $70 \mu b^{-1}$, collected in 2011 using a trigger requiring, in addition to the minimum bias condition, the detection of an opposite-sign pair of muons with $p_T > 1$ GeV/c. The centrality of Pb–Pb collisions is determined event by event, based on the signal amplitude in the VZERO detector, as described in [21].
4.1. Data analysis

4.1.1. Track selection At mid-rapidity, electrons are identified via their energy-loss in the TPC: an inclusion cut of three standard deviations around the electron expectation value for a given momentum is performed, together with an exclusion cut of 3.5 standard deviations around the proton and the pion expectation values. Electron pairs with $|y^{ee}| < 0.9$ are retained in the analysis. At forward rapidity, track selection is performed by requiring all reconstructed muon tracks to have hits in the trigger chambers, the trigger system being located downstream of a 1.2 m thick iron wall (corresponding to 7 interaction lengths), which efficiently absorbs hadrons and low momentum muons. Muon pairs with $2.5 < y^{\mu\mu} < 4$ are retained in the analysis.

4.1.2. Signal extraction In the mid-rapidity analysis, the $J/\psi$ signal is extracted from the opposite-sign electron pair invariant mass spectrum (Fig. 5, left) by first subtracting the background, then integrating the spectrum in the dielectron mass region $2.92 \text{ GeV}/c^2 < m_{e^+e^-} < 3.16 \text{ GeV}/c^2$ and extrapolating the yield to the full mass range. The background shape is determined via event-mixing and scaled to the tails of the same-event spectrum. The resulting $J/\psi$ yield is about 2000. In the forward rapidity analysis, a simultaneous fit of signal and background is performed (Fig. 5, right). A modified Crystal-Ball function [22] is used for the signal, while a Gaussian with width varying with the mass is used for the background. The resulting $J/\psi$ yield is about 40000.

![Figure 5. Invariant mass spectra of opposite-sign electron pairs in $|y^{ee}| < 0.9$ (left) and muon pairs in $2.5 < y^{\mu\mu} < 4$ (right).](image)

4.1.3. Acceptance and efficiency correction The acceptance and efficiency are computed, as a function of centrality, via Monte Carlo simulations with a realistic detector configuration. In the mid-rapidity analysis, HIJING events enriched with $J/\psi$ dielectron decays are used. In the forward rapidity analysis, $J/\psi$ dimuon decays are embedded into real Pb–Pb events. The resulting efficiencies are shown, as a function of centrality, in Fig. 6. The efficiency in the dielectron (dimuon) channel decreases from 8.9% to 7.8% (14.5% to 13.3%) from the most peripheral to the most central bin: in both cases, the relative efficiency loss from peripheral to central is not larger than 10%.
4.2. Results

4.2.1. Nuclear modification factor  The nuclear modification factor $R_{AA}$ is used to quantify the effect of the medium on $J/\psi$ production. It is defined as

$$R_{AA,i} = \frac{Y_{J/\psi}}{T_{AA,i} \sigma_{J/\psi}^{pp}}$$

where: the index $i$ denotes different centrality classes; $Y_{J/\psi}$ is the (branching ratio and efficiency-corrected) $J/\psi$ yield per Pb–Pb collision; $T_{AA}$ is the nuclear thickness function; $\sigma_{J/\psi}^{pp}$ is the $J/\psi$ cross section in pp collisions at $\sqrt{s} = 2.76$ TeV, measured by ALICE as discussed in 3.1. The centrality-integrated nuclear modification factors are 0.497 ± 0.006(stat.) ± 0.078(syst.) at forward rapidity and 0.66 ± 0.10(stat.) ± 0.24(syst.) at mid-rapidity. The systematic uncertainties are dominated by $\sigma_{J/\psi}^{pp}$ and, for the mid-rapidity analysis, by the signal extraction. The nuclear modification factor as a function of centrality (centrality is here quantified by the number of participant nucleons, $N_{\text{part}}$) is shown in Fig. 7 (left), for both mid- and forward rapidity. At forward rapidity we observe clear $J/\psi$ suppression ($R_{AA} < 1$). The data show weak centrality dependence for $N_{\text{part}} > 150$. Similar conclusions, although with larger uncertainties, can be drawn from the mid-rapidity data. In Fig. 7 (right), the forward rapidity data are compared to the predictions of transport[23, 24] and statistical hadronisation[25] models, all of which assume that a substantial fraction ($> 50\%$) of the $J/\psi$ yield is "regenerated". Within uncertainties, the models are able to reproduce the data. In Fig. 8 the forward rapidity data are compared to measurements [26, 27] by PHENIX at RHIC ($\sqrt{s} = 200$ GeV) and CMS at the LHC. The ALICE $R_{AA}$ above $N_{\text{part}} \approx 150$ is larger than the values reported by CMS and PHENIX. We note that our results are from much higher $\sqrt{s}$ than PHENIX, and cover a lower $p_T$ range than CMS.

At forward rapidity, $R_{AA}$ was also measured as a function of $p_T$, in the centrality range 0-90%. The result is shown in Fig. 9, compared to the measurements by PHENIX [26] in 0-20% and CMS [27] in 0-100%, and to transport model predictions [28]. We observe that: $R_{AA}$ is relatively large at low $p_T$; it decreases with $p_T$: the dependency becomes very weak for transverse momenta above $\approx 4$ GeV/c. The $p_T$ dependence at low $p_T$ differs significantly from that observed at lower energy by PHENIX (although the comparison may be biased by the different centrality selection). The ALICE and CMS data are compatible in the common $p_T$ region. We observe that transport models with regeneration are able to reproduce the ALICE data within uncertainties. The nuclear modification factor measurement at forward rapidity was also performed as a function of rapidity. The results are shown in Fig. 10, together with the mid-rapidity data point. We observe that $R_{AA}$ decreases by $\approx 40\%$ from $y = 2.5$ to $y = 4$. More
Figure 7. Left: $J/\psi$ nuclear modification factor as a function of the number of participant nucleons at mid-$(|y| < 0.9)$ and forward $(2.5 < y < 4)$ rapidity. Right: the forward rapidity data are compared to the predictions of transport [23, 24] and statistical hadronization [25] models (right).

Figure 8. $J/\psi$ nuclear modification factor as a function of the number of participant nucleons at forward rapidity, compared to the PHENIX [26] (left) and CMS [27] (right) data.

Figure 9. $J/\psi$ nuclear modification factor at forward rapidity as a function of $p_T$, compared to the PHENIX [26] and CMS [27] data (left) and to transport model predictions [28] (right).
4.2.2. Elliptic flow

Pressure gradients in a thermalised medium convert initial spatial anisotropy in momentum anisotropy with respect to the reaction plane $\phi_{RP}$. The momentum anisotropy of a given probe is quantified by $v_2$, defined as the second harmonic coefficient of the distribution of the azimuthal angle with respect to the reaction plane:

$$dN/d\Delta \phi \propto 1 + v_2 \cos(2\Delta \phi)$$

with $\Delta \phi = \phi - \phi_{RP}$. The $v_2$ of $J/\psi$ at LHC energies may tell us about regeneration: if the $J/\psi$ arise via this mechanism, one expects a non-zero flow at low and intermediate $p_T$. The $J/\psi$ signal was extracted in bins of $\Delta \phi$ and $p_T$. The $v_2$ coefficient was extracted from the measured $\Delta \phi$ distributions (an example is given in Fig. 11, left); the results are shown as a function of $p_T$ in Fig. 11 (right), compared to the preliminary STAR measurement [31] at $\sqrt{s} = 200$ GeV and to transport model predictions [32]. We observe a hint of non-zero $v_2$ at $2 < p_T < 4$ GeV/c: the

Figure 10. $J/\psi$ nuclear modification factor as a function of rapidity.

details on the nuclear modification factor measurement and its implications can be found in [29] and [30].

Figure 11. Left: example of $J/\psi$ $v_2$ extraction from the $\Delta \phi$ distribution. Right: $J/\psi$ $v_2$ as a function of transverse momentum, compared to the preliminary STAR results [31] and to the predictions of transport models [32] with $J/\psi$ regeneration.
measured value differs from zero by 2.2 standard deviations. Such behaviour was not observed by STAR. The transport model predictions, which assume $J/\psi$ regeneration from $c\bar{c}$ pairs, are compatible with the data. More details on the elliptic flow measurement can be found in [33].

5. Conclusions
The ALICE results on $J/\psi$ production in pp collisions include: the inclusive cross section down to zero $p_T$; the measurement of the beauty feed-down contribution at mid-rapidity; a weak or null polarisation; a linear increase of the $J/\psi$ yield with multiplicity.

The ALICE results on $J/\psi$ production in Pb–Pb collisions include: weak or no centrality dependence of $R_{AA}$ at large number of participants; an $R_{AA}$ larger than RHIC at low $p_T$; a significant decrease of $R_{AA}$ at large rapidities; a hint of non-zero $v_2$ at intermediate $p_T$.

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