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J/ψ production measurements in pp and Pb-Pb collisions with ALICE at the LHC

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ALICE at the LHC has measured the inclusive J/ψ production in proton-proton collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 2.76$ TeV as well as in ion-ion collisions at $\sqrt{s_{NN}} = 2.76$ TeV. ALICE is able to detect J/ψ resonances, down to p_{T} =0, both in the dielectron (at mid-rapidity, $|y| < 0.9$) and dimuon (at forward-rapidity, $-4 < y < -2.5$) decay channels. The results on the differential (p_{T} and y) cross-sections for inclusive J/ψ production in pp collisions at the two energies are discussed. Finally, the first results on the J/ψ nuclear modification factor (R_{AA}) in Pb-Pb collisions is presented.

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1. Introduction

High energy heavy-ion collisions are used to study strongly interacting matter under extreme conditions. At sufficiently high collision energies, it is believed that hot and dense deconfined matter, commonly referred to as the Quark-Gluon Plasma (QGP), is formed [1].

Among the other observables for the study of QGP formation, heavy flavour particles deserve more and more attention since their large production rate at the LHC energies allows detailed studies of their characteristics. The J/ψ meson has been proposed [2] as a probe of the formation of a hot coloured medium through its disappearance via Debye screening, while, in the new energy domain accessed at the LHC, the large number of charm quark produced could give the possibility of observing new phenomena such as the regeneration of the charmonium bound states due to recombination of c and $\bar{c}$ quarks.

The measurement of heavy quarkonium in p–p collisions has a double intent. On the one hand, the measurement in nuclear collisions needs a reference to quantify the medium induced modification to the measured yields. On the other hand, the interest is driven by the fact that the production mechanism of a bound state is governed by both perturbative and non-perturbative aspects of Quantum Chromodynamics. The models currently available (such as the colour evaporation, colour singlet and the non relativistic QCD models) [3, 4] are unable to reproduce, at the same time, the production cross section, the distributions in the kinematical variables and the polarization of the heavy quarkonium. Promising new NRQCD developments [5] seem to better describe the production cross section in very different energy domains. Therefore, measurements in a new energy domain, such as the one reachable at LHC, may provide new clues for the understanding of the hadroproduction process.

2. Experimental apparatus and analysis conditions.

ALICE [6] is able to measure heavy quarkonia through their leptonic decays. In the central rapidity region ($|y| < 0.9$), this measurement is carried out through the detection of the e^+e^- pair. Various detector systems are embedded in a large solenoid magnet, that provides a magnetic field of 0.5 T. The subdetectors involved in the analysis described here are the Inner Tracking System (ITS) [7] and the Time Projection Chamber (TPC) [8]. The ITS is composed of six cylindrical layers of silicon pixels detectors based on three different technologies (pixel, strip and drift detectors), with a radius varying from 4 to 44 cm. The ITS is designed to localize the primary vertex with a resolution better than 100 μm, to reconstruct the secondary vertices from the decays of heavy flavour hadrons, to track and identify low momentum particles. The TPC is a large volume gaseous detector ($85 < r < 247$ cm in the radial direction and 5 m in the longitudinal direction) that is crucial both for the tracking and for the particle identification via specific energy loss measurements.

The forward rapidity region ($-4 < y < -2.5$) is covered by a muon spectrometer [9]. It consists of a front absorber that stops the hadrons coming from the interaction point, a 3 T · m dipole magnet coupled with five tracking stations of Cathode Pad Chambers (CPC) and, after an iron wall about 1.2 m thick, two stations of Resistive Plate Chambers (RPC) form the trigger system. Throughout its full length, the spectrometer is shielded against secondary particles produced in the beam pipe by a conical absorber ($\theta < 2^o$). The spectrometer is able to detect muons with a momentum larger than 4 GeV/c. At the trigger level, L0 decisions are delivered if tracks pass a p_T cut, where the p_T thresholds are programmable.

One of the L0 trigger detectors also used for this analysis is the VZERO. It consists of two scintillator arrays covering the range $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$ positioned respectively at $z = 340$ and $z = -90$ cm. This detector provides timing information with a resolution better than 1 ns. It is crucial in the offline rejection of beam-halo and beam-gas events.

In 2010 and 2011, the LHC provided pp collisions at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 7$ TeV, as well as Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

The analysed events were collected in a minimum bias trigger configuration. In proton-proton collisions, this trigger is defined as a logical OR between at least one readout chip fired in the pixel layers of the ITS and at least one of the two VZERO detectors fired. It requires a coincidence of the beam pick-up counters signals, indicating the passage of proton bunches. In Pb-Pb collisions, the logic applied is an AND between the above mentioned trigger signals. For the muon analysis an additional requirement of at least one triggered muon is applied for the proton data analyis.

For the dielectron analysis, a constraint on the reconstructed vertex position of 10 cm around the nominal position is applied. The tracks have to fulfill requirements on the transverse momentum ($p_T > 1$GeV/c), on the number of TPC clusters ($n_{clusters} > 70$ out of 159), on the χ^2 per point after the global track fit ($\chi^2 < 4$) and on the rapidity ($|y| < 0.9$) in order to be accepted in the analysis. A further constraint on the rapidity of the reconstructed J/ψ is applied ($|y_{J/\psi}| < 0.9$). For the Pb-Pb data, the rapidity window is slightly reduced to $|y| < 0.8$ both for the single track and for the reconstructed dilepton.

For the dimuon analysis, the events are required to have at least a vertex reconstructed by the pixel detector of the ITS and to have at least one of the two muon candidates that matches a tracklet in the muon trigger system. A cut on the track position at the end of the absorber was applied in order to get rid of small angle muons. Events on the edge of the acceptance were removed requiring that the rapidity of the muon pair is $-4 < y < -2.5$. In Pb-Pb collisions, the request of having both the muon matching the trigger is applied.

3. Inclusive J/ψ production in proton-proton collisions at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 7$ TeV

J/ψ production is being extensively studied in ALICE as a function of the centre of mass energy, transverse momentum and rapidity. Furthermore, the J/ψ production has been studied as a function of the charged particle density [18] as well as its polarisation [14] and the contribution from B meson decay.

For the measurement of the inclusive J/ψ production cross section, the integrated luminosity used for the analysis at $\sqrt{s} = 7$ TeV ($\sqrt{s} = 2.76$ TeV) is of $L_{\mathrm{int}} = 5.6$ nb^{-1} (1.1 nb^{-1}) for the dielectron analysis and $L_{int} = 15.6$ nb^{-1} (20.2 nb^{-1}) for the dimuon one.

The opposite sign (OS) invariant mass spectrum in the electron analysis, left Fig. 1, is obtained combining identified electron tracks and partly subtracting the γ conversion background. The TPC is used for the particle identification: $\pm 3\sigma$ inclusion cut for electrons and $\pm 3.5\sigma(3\sigma)$ exclusion cut for pions (protons) were used. In the plot is also shown the like sign (LS) scaled to match the integral of the OS spectrum in the mass interval $3.2 - 5$ GeV$/c^2$. The necessity of a scale factor

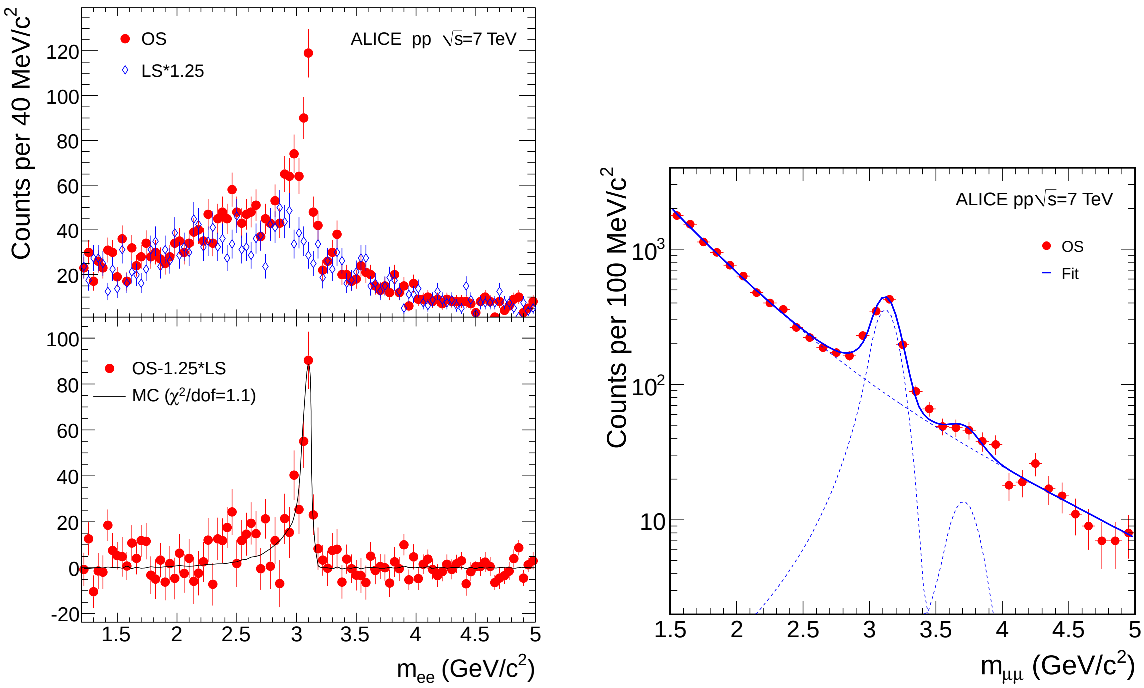

Figure 1: Invariant mass spectra at $\sqrt{s} = 7$ TeV. (left figure): signal extraction in the electron decay channel. In the top panel the invariant mass distribution for LS and OS electron pairs is shown. In the bottom panel: the difference between these two distributions with the Monte Carlo signal superimposed is shown. Right figure: signal extraction in the muon decay channel. The invariant mass plot has been fitted with a combination of Crystal-Ball functions for the signal and two exponential for the background.

is due to misidentified electrons and correlated background. The signal is obtained by subtracting the LS from the OS spectrum. As shown in the bottom panel, there is a good agreement between data and Monte Carlo simulations. For the muon decay channel, the opposite sign invariant mass spectrum (right Fig. 1) was fitted with Crystal Ball functions [10] for the signal of the J/ψ and the ψ' plus a sum of two exponentials for the underlying continuum. The parameters of the fit were tuned by fitting MC simulations of pure signal.

The acceptances and the efficiencies of the apparatus have been estimated via realistic Monte Carlo simulations. The real conditions of the detectors are plugged in simulations based on realistic J/ψ p_T and y distributions. The $A \times \varepsilon$ obtained for J/ψ measurement at $\sqrt{s} = 7$ TeV ($\sqrt{s} = 2.76$ TeV) of 10% (9%) for the dielectron channel and 33% (35%) for the dimuon one.

For the determination of the production cross sections, the number of J/ψs are normalized to the measured cross section of the occurrence of the minimum bias condition itself.

$$\sigma_{J/\psi} = \frac{1}{BR(J/\psi \to l^+l^-)} \frac{N_{J/\psi}}{A \times \varepsilon} \times \frac{\sigma_{MB}}{N_{MB}}$$

The minimum bias cross sections (σ_{MB}) were obtained relative to the cross section measured in the Van der Meer scan [11], of the coincidence between signals in the two V0 detectors.

Results at $\sqrt{s}$=7 TeV are: $\sigma_{J/\psi}(|y| < 0.9) = 10.7 \pm 1.2(\text{stat}) \pm 1.7(\text{syst})\ ^{1.6}_{-2.3}(\text{polar})\ \mu$b and $\sigma_{J/\psi}(-4 < y < 2.5) = 6.31 \pm 0.25(\text{stat}) \pm 0.80(\text{syst})\ ^{0.95}_{-1.96}(\text{polar})\ \mu$b.

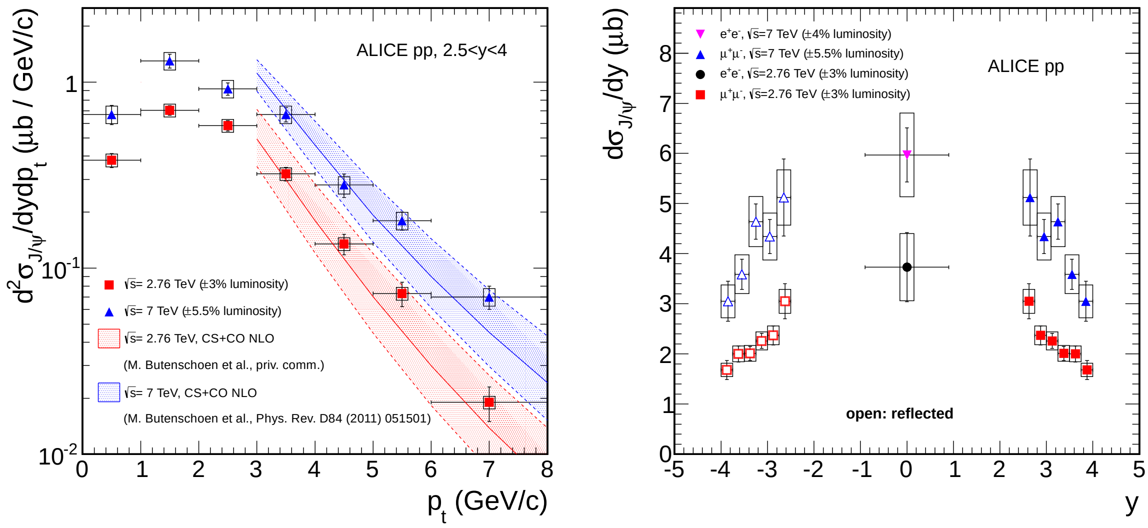

Figure 2: J/ψ differential distributions at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 7$ TeV [15]: the $\mathrm{d}^2\sigma_{J/\psi}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y$ at forward rapidity are compared to the NRQCD predictions (left figure); in the right figure, the $\mathrm{d}\sigma_{J/\psi}/\mathrm{d}y$ is shown.

While results at $\sqrt{s} = 2.76$ TeV are:

$$\sigma_{J/\psi}(|y| < 0.9) = 6.71 \pm 1.24(\mathrm{stat}) \pm 1.22(\mathrm{syst})\ {}^{1.01}_{-1.41}(\mathrm{polar})\ \mu\mathrm{b}$$

and

$$\sigma_{J/\psi}(-4 < y < 2.5) = 3.34 \pm 0.13(\mathrm{stat}) \pm 0.28(\mathrm{syst})\ {}^{0.53}_{-1.07}(\mathrm{polar})\ \mu\mathrm{b}.$$

The systematic uncertainties were obtained considering: the uncertainty on the signal extraction, varying the background calculation and the mass range in the dielectron channel while different signal and background shapes were considered for the fit in the dimuon channel; the uncertainty on the acceptance evaluation, estimated varying the input kinematical distributions; the uncertainty on the efficiency reconstruction, evaluated from residual mismatches between data and MC simulations in track quality and particle identification cuts for the dielectron channel and chamber efficiencies in the muon channel; the uncertainty on the muon trigger efficiency, as the difference between $N_{J/\psi}$ collected asking that one or both muons fire the trigger; and the uncertainty on the determination of σ_{MB}, that is mainly due to the beam intensity measurement and the analysis procedure of the VZERO coincidences in the Van der Meer scan. The unknown polarization of the J/ψ affects the acceptance values. These were calculated doing MC simulations of pure signal fully transverse or longitudinally polarized in the Collins-Soper and helicity reference frames. The uncertainties are quoted for the frame in which they are largest.

Following the same approach adopted for the evaluation of the integrated cross section, also the differential distributions are studied.

In the left Fig. 2 the $\mathrm{d}^2\sigma_{J/\psi}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y$ measured in $\mu^+\mu^-$ channel at the two energies is shown. The NRQCD NLO [12] well reproduce the experimental data. In the right Fig. 2, the $\mathrm{d}\sigma_{J/\psi}/\mathrm{d}y$ for both mid rapidity and forward analysis is shown.

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The J/ψ production yield at $\sqrt{s} = 7$ TeV has also been measured as a function of the charged particle pseudo-rapidity density measured in the ITS ($|y| < 1.6$) both in the e^+e^- and $\mu^+\mu^-$ channels. The high-multiplicity p-p collisions at LHC energies may exhibit features present in lower energy ion-ion interactions. Results show a linear increase of the J/ψ yield as a function of the charged particle multiplicity at mid-rapidity [13].

The inclusive J/ψ polarization measurement results at $\sqrt{s} = 7$ TeV are going to be published [14]. The J/ψ polarization has been studied in two reference frames (Collins-Soper and helicity) and the results show that, for the inclusive J/ψ production, is compatible with null polarisation except for lowest measured p_{T} bin (2-3 GeV/c) in the helicity frame where a longitudinal polarization is measured.

At mid-rapidity, thanks to the good resolution on the impact parameter, ALICE can identify J/ψ from decays of beauty hadrons via the measurement of the pseudo-proper decay length [16]. ALICE can extend at lower p_{T} values the measurement of the other LHC experiments. Preliminary results on the fraction of J/ψ from b-decay show the agreement of the ALICE measurement with the other experiment and also with the fraction measured at Tevatron. This fraction is $F_B = 0.137 \pm 0.054(\mathrm{stat}) + 0.025 - 0.018(\mathrm{syst})^{+0.040}_{-0.021}(\mathrm{pol})$ for $1.3 < p_T < 7$ GeV/c.

4. Inclusive J/ψ production in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

The nuclear modification factor R_{AA} and the centre-to-peripheral modification factor R_{CP} can be used to quantify medium induced modifications of the production of inclusive J/ψ . ALICE measured the R_{AA} and the R_{CP} at forward rapidity with the muon spectrometer in the centrality bins 0-10%, 10-20%, 20-40% and 40-80% [17], while at mid-rapidity only an estimate of the R_{CP} has been worked out in two rapidity bins 0-40% and 40-80%. The results here presented refer to an integrated luminosity of 2.7 $\mu\mathrm{b}^{-1}$ in the centrality interval 0-80%. The centrality determination is based on a fit on the VZERO signal amplitude distribution described in [18].

The analysis techniques used for the signal extraction are similar to those adopted in the p-p data analysis. For the dimuon analysis, both the reconstructed muons are required to match a muon trigger tracklet. The raw J/ψ yield has been estimated as the average of various approaches: Crystal-Ball plus a double exponential or a third-order polynomial for the background, the mixing event technique and other fit functions. The double of the RMS of these results has been taken as the systematic uncertainty on the signal extraction. The estimation of the $A \times \varepsilon$, for the correction of the raw yield, has been performed via MC simulations of realistic J/ψ p_{T} and y distributions interpolated from existing measurements [19] and the stability of the efficiency with the centrality has been checked with the embedding technique: in the most central bin (0-10%) a small reduction has been noted ($\sim 2\%$). The reference value $\sigma_{pp}^{J/\psi}$ is the one measured at $\sqrt{s} = 2.76$ TeV, described in the previous section.

The inclusive J/ψ R_{AA} at forward rapidity ($p_{\mathrm{T}} > 0$) is shown in Fig. 3 as a function of the average number of nucleons participating to the collisions $\langle N_{part} \rangle$ calculated using the Glauber model. This result shows no significant dependence on centrality, and the centrality integrated values is $R_{AA}^{0-80\%} = 0.545 \pm 0.032(\mathrm{stat.}) \pm 0.084(\mathrm{syst.})$. The comparison with the PHENIX R_{AA} measurements at $\sqrt{s} = 200$ GeV [20] (left Fig. 3) shows that the ALICE results are clearly above the one measured by PHENIX at forward rapidity (1.2< $|y|$ <2.2). The comparison with CMS

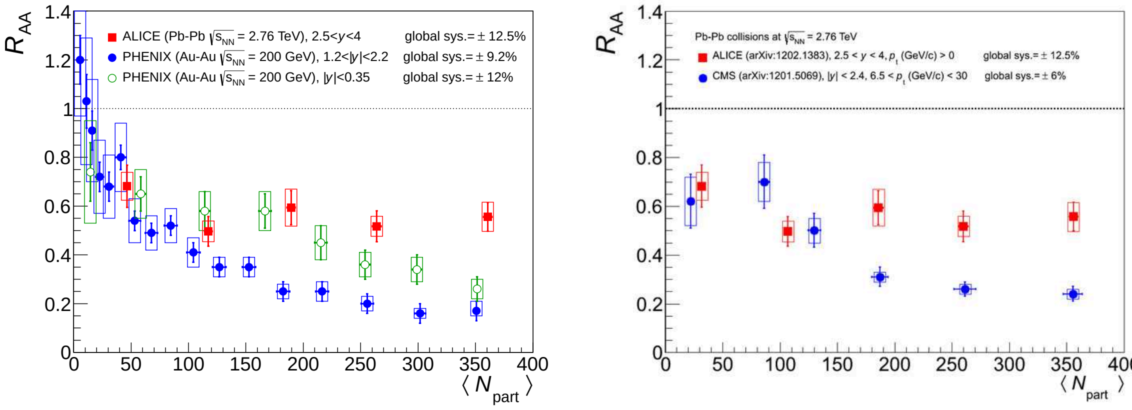

Figure 3: Forward rapidity J/ψ R_{AA} in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV as a function of $\langle N_{part} \rangle$ compared with PHENIX resulst in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV (left figure) and CMS results at mid-rapidity (right figure)

results at mid-rapidity (right Fig. 3) seems to show lesser suppression at forward rapidity, but the different kinematical domains (CMS measured J/ψ with p_{T} larger than 6.5 GeV/c) make difficult a direct comparison.

5. Conclusions

J/ψ measurements in p-p collisions at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 7$ TeV and in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV have been presented. The ALICE measurements are unique at the LHC for the rapidity coverage and the low p_{T} values reached. In proton-proton collisions, the inclusive J/ψ differential p_{T} distributions are well reproduced by NRQCD NLO calculations. Moreover, the J/ψ polarisation at forward rapidity has been measured and a linear dependence of the J/ψ yield to the charged particle density at mid-rapidity has been measured. At mid-rapidity, ALICE can extend the p_{T} region of the other LHC experiments to lower values in the measurement of J/ψ from b-decays. The 2011 statistics will give the possibility of more precise measurements.

In Pb-Pb collisions, a significant suppression has been observed and the comparison with the PHENIX results at 200 GeV, intriguing hints of possible J/ψ regeneration seem to appear, but, for a better understanding of the role played by the cold nuclear matter and parton distribution functions in nuclei, the J/ψ measurement has to be performed also in p-Pb collisions. The first run of p-Pb collisions at the LHC is foreseen at the end of 2012.

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