J/ψ Measurements with the ALICE Experiment at the LHC

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Abstract. The ALICE detector is the dedicated heavy-ion experiment at the Large Hadron Collider (LHC) at CERN. It provides excellent capabilities to study quarkonium production in proton-proton (pp) and heavy-ion (A-A) collisions in the kinematic range of $|y| < 0.9$ and $2.5 < y < 4.0$ down to a transverse momentum of zero. Quarkonia, bound states of heavy (charm or bottom) quark anti-quark pairs such as the J/ψ, are expected to be produced by hard processes. Thus they will provide insights into the earliest and hottest stages of A-A collisions where the formation of a Quark-Gluon Plasma is expected. Results of the inclusive and prompt J/ψ production cross section in pp collisions at $\sqrt{s} = 2.76$ and 7 TeV will be presented. A polarization measurement in the forward region and the dependence of the J/ψ yield on the charged particle multiplicity in pp collisions will be discussed. The nuclear modification factor ($R_{AA}$) at forward rapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV will be shown and its implications discussed.

1. Introduction

J/ψ suppression was proposed as a signature for a deconfined state of strongly interacting matter, called the Quark-Gluon-Plasma (QGP), that is expected to be created in realtivistic heavy-ion collisions [1]. There are several medium induced effects that can play a role on the production yield of J/ψ under the externe conditions of such a hot and dense phase. The melting of the $c\bar{c}$ due to Debye-screening, known from QED, can lead to a reduced production rate, while there might be contributions enhancing the yields such as random combinations of uncorrelated charm and anti-charm quark at high charm quark densities or even a thermal production of $c\bar{c}$ at LHC energies.

In the past, many experiments [2, 3, 4] have measured the J/ψ production in heavy-ion, proton-proton and proton-ion collisions to understand the production mechanisms and the behaviour of quarkonia under different conditions. The NA50 experiment at the CERN SPS observed a suppression of J/ψ and $\psi'$ in central Pb-Pb and in p-A collisions, while the NA60 collaboration measured p-A and In-In collisions with the outcome that a large fraction (70-80%) of the suppression in most central Pb-Pb collisions, seen by NA50, is due to cold nuclear matter effects (CNM). Some years later at RHIC the PHENIX experiment observed in Au-Au and d-Au collisions at ten times higher centre-of-mass energies than at SPS a similar suppression at midrapidity but larger suppression at forward rapidities, see Ref. [5]. Finally, the STAR collaboration has reported a smaller suppression at high transverse momentum ($p_T \gtrsim 5$ GeV/c) at midrapity.
2. Experimental setup

ALICE [6] is the dedicated heavy-ion experiment at the LHC. Quarkonia can be measured in two different parts, the central barrel with a pseudo rapidity coverage of $|\eta| < 0.9$ and the muon spectrometer located at $-4.0 < \eta < -2.5$. $J/\psi$ can be reconstructed down to $p_T=0$ in both decay channels, $J/\psi \rightarrow e^+e^-$ at midrapidity and $J/\psi \rightarrow \mu^+\mu^-$ at forward rapidity.

The main detectors used for the $J/\psi$ reconstruction are the Inner Tracking System (ITS) and the Time Projection Chamber (TPC) in the dielectron analyses and will be complemented by the ElectroMagnetic CALorimeter (EMCAL) and the Transition Radiation Detector (TRD) in future analyses. The large-volume TPC serves as the main tracking device and provides Particle IDentification (PID) via the specific energy-loss of the particles in the detector gas. The ITS, consisting of six layers of silicon (two layers of pixel, strip and drift), provides excellent vertex reconstruction and improves the momentum resolution by its tracking capabilities. The muon spectrometer, used in the studies of $J/\psi$ decaying into two muons, consists of a tracking system behind a ten interaction length thick absorber and is completed by a triggering system behind a 1.2 m thick iron wall.

3. Inclusive $J/\psi$ cross sections in proton-proton collisions at 2.76 and 7 TeV

A detailed measurement of $J/\psi$ production in pp collisions is performed as a function of the centre-of-mass energy, transverse momentum, rapidity and the charged particle density. In addition, preliminary results on the fraction of $J/\psi$ coming from B-hadron decays are obtained. Furthermore, a polarization measurement of $J/\psi \rightarrow \mu^+\mu^-$ has been performed in two different reference frames. Data sets with an integrated luminosity of 15.6 (19.9) nb$^{-1}$ at $\sqrt{s}=7$ (2.76) TeV in the dimuon decay channel and 5.6 (1.1) nb$^{-1}$ in the dielectron analysis have been collected in 2010(11). The $J/\psi$ signal of the dimuon and dielectron analysis have been divided into several rapidity ($y$) and transverse momentum ($p_T$) bins at both energies. Good agreement is found with the results by the LHCb collaboration at forward rapidity and with the other LHC experiments (CMS and ATLAS) at midrapidity, see Fig. 1. Furthermore ALICE has the unique capability to measure the inclusive $J/\psi$ production in a large rapidity range down to $p_T=0$ (see Fig. 2).

![Figure 1](image1.png)  
**Figure 1.** The differential inclusive $J/\psi$ cross section $d^2\sigma_{J/\psi}/dp_Tdy$ at $\sqrt{s}=7$ TeV compared to results from other LHC experiments with similar rapidity ranges [7, 8, 9, 10].

![Figure 2](image2.png)  
**Figure 2.** $d\sigma_{J/\psi}/dy$ for centre-of-mass energies of 2.76 and 7 TeV with a transverse momentum reach down to 0 [11].
A completely new study of quarkonia was performed, where the inclusive J/ψ yield was measured in dependence of the charged particle density \(dN_{ch}/d\eta\) in proton-proton collisions at \(\sqrt{s}=7\) TeV. The charged particle densities were obtained by the ITS silicon pixel detector in the pseudo rapidity range \(|\eta|<1.0\). An approximately linear increase with the midrapidity \(dN_{ch}/d\eta\) was seen in both rapidity regions (see Fig. 3). Even with a rapidity gap of 3.25 the correlation stays, which is a very intriguing observation. An enhancement relative to the minimum bias yield up to a factor 5 (8) at forward (midrapidity) was found. Details of this analysis can be found in [12].

Figure 3. The midrapidity charged particle density dependence of the inclusive J/ψ yield in \(|y|<0.9\) and \(2.5<y<4.0\) in pp collisions at \(\sqrt{s}=7\) TeV. The vertical (horizontal) axis shows values relative to the minimum bias yield (charged particle density).

ALICE is the first experiment at LHC, that has measured the polarisation of J/ψ decaying into two muons. This analysis was performed in pp collisions at \(\sqrt{s}=7\) TeV[13]. The distribution of the J/ψ decay products can be expressed as,

\[
W(\Theta, \phi) = \frac{1}{3 + \lambda_\Theta}(1 + \lambda_\Theta \cos^2 \Theta + \lambda_\phi \sin^2 \Theta \cos 2\phi + \lambda_{\Theta \phi} \sin 2\Theta \cos \phi)
\]

(1)

where \(\Theta(\phi)\) are the polar (azimuthal) angles in a given reference frame (Collins-Soper (CS) or helicity (HE)) and \(\lambda_\Theta, \lambda_\phi, \lambda_{\Theta \phi}\) are the polarization parameters. It was found that the polarization of the J/ψ in the forward region is consistent with very little or no polarisation and shows a weak \(p_T\) dependence in the HE frame, see Fig. 4.

With the excellent resolution of the ITS it was possible to study the fraction of J/ψ coming from B-hadrons in the central part of the experiment. The fraction was obtained to be 13.7\%±5.4(stat.)\(^{+2.5}_{-1.8}\)(syst.)\(^{+2.2}_{-2.7}\)(syst.polar.) and agrees with other LHC results [8, 9, 10].

4. Nuclear modification factor \((R_{AA})\) in Pb-Pb collisions at \(\sqrt{s_{NN}}=2.76\) TeV

The inclusive J/ψ production was studied in Pb-Pb collisions at \(\sqrt{s_{NN}}=2.76\) TeV with the muon spectrometer [14]. The data sample collected end of 2010 belongs to an integrated luminosity of 2.88 \(\mu\)b\(^{-1}\). 2350±139(stat.)±189(syst.) J/ψ have been reconstructed in the region 2.5 < y < 4.0
Figure 4. The polarization parameter $\lambda_\Theta$ and $\lambda_\phi$ as a function of $p_T$ for inclusive $J/\psi$ in $2.5 < y < 4.0$ [13].

with a invariant mass resolution of 75 MeV/$c^2$. The pp results shown in Fig. 2 at the same energy ($\sqrt{s}$=2.76 TeV) serve as a reference for the determination of the inclusive $J/\psi$ nuclear modification factor $R_{AA} = Y_{\text{Pb-Pb}} / \langle N_{\text{coll}} \rangle Y_{\text{pp}}$. $\langle N_{\text{coll}} \rangle$ corresponds to the average number of binary nucleon-nucleon collisions in a given centrality class. $Y_{\text{Pb-Pb}}$ and $Y_{\text{pp}}$ are the corrected yields with equal kinematics at the given system. Figure 5 compares our results to several theoretical predictions [15, 16, 17] that include a $J/\psi$ regeneration component from deconfined charm quarks in the medium or generation at the QCD phase boundary (hadronization). The data compared to PHENIX results at central and forward rapidity, see Fig. 6, show a smaller suppression than at RHIC. Of course, cold nuclear matter effects are expected to be different at the two energies and have to be taken into account.

Figure 5. The inclusive $J/\psi$ nuclear modification factor as a function of the average number of participating nucleons measured in $\sqrt{s_{\text{NN}}}$=2.76 TeV Pb-Pb collisions and compared to theoretical predictions.

Figure 6. Comparison of the inclusive $J/\psi$ $R_{AA}$ to results at central and forward rapidity obtained by the PHENIX collaboration for Au-Au collisions at $\sqrt{s_{\text{NN}}}$=200 GeV [5, 18].
5. Conclusions
The ALICE $J/\psi$ measurements in pp at $\sqrt{s}=2.76$ and 7 TeV and in Pb-Pb at $\sqrt{s_{NN}}=2.76$ TeV have been presented. The results cover a large rapidity and transverse momentum range down to $p_T=0$. In pp collisions the $J/\psi$ yield in $|y|<0.9$ and $2.5<y<4.0$ was found to increase approximately linear with the charged particle multiplicity in the range of $|\eta|<1.0$. For the first time at the LHC the $J/\psi$ polarization was measured and is compatible with 0 in the measured $p_T$ range (2 < $p_T$ < 8 GeV/c). The inclusive $J/\psi$ nuclear modification factor in Pb-Pb collisions is larger than that observed at RHIC energies in central Au-Au collisions. Theoretical (re)generation models are able the describe the observed shape and amount of suppression within their uncertainties. This might be a hint for a $J/\psi$ regeneration in hot matter or at the chemical freeze-out at LHC energies. However, effects related to cold nuclear matter remain unknown at LHC energies and need to be studied with the data of the upcoming p-Pb run.

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