ATLAS results on heavy flavour production and its relation to quark matter

Marisilvia Donadelli on behalf of the ATLAS Collaboration
University of Sao Paulo, Brazil
E-mail: marisilvia.donadelli@cern.ch

Abstract. We present measurements of $J/\psi$ and $\psi(2S)$ production in proton-lead collisions at a centre of mass energy per nucleon-nucleon interaction of $\sqrt{s_{NN}} = 5.02$ TeV and in proton-proton collisions at $\sqrt{s} = 2.76$ TeV, with integrated luminosities of 28.1 $nb^{-1}$ and 4.0 $pb^{-1}$, respectively. Both measurements are based on data recorded by the ATLAS detector in 2013 and are performed in the dimuon decay channel. Prompt components of $J/\psi$ and $\psi(2S)$ are separated from the nonprompt components resulting from $b$-hadron decays through an analysis of the distance between the $J/\psi$ and $\psi(2S)$ decay vertexes and the event primary vertex. The measurements of nuclear modification factors and self-normalized yields for the $J/\psi$ and $\psi(2S)$ are performed in the following ranges: $8.5 < p_{T}^{\mu\mu} < 30$ GeV in transverse momentum, $-1.5 < y^{*}_{\mu\mu} < 1.5$ in centre-of-mass rapidity and $0 - 90\%$ in centrality. The differential cross section for production of nonprompt $J/\psi$ is compared to a FONLL calculation which does not include nuclear effects for the ranges of $8 < p_{T}^{\mu\mu} < 30$ GeV in transverse momentum, and for $|y^{*}|_{\mu\mu} < 1.94$ in centre-of-mass rapidity. Forward-backward production ratios are presented and compared to theoretical predictions.

1. Introduction

Intense theoretical and experimental efforts have been deployed in the ultra-relativistic heavy ion physics field [1, 2] since Matsui and Satz first suggested that quarkonium ($Q\bar{Q}$) suppression could be a signal of the quark gluon plasma (QGP) formation in nucleus-nucleus (A+A) collisions [3]. With the idea that color screening would prevent the formation of $Q\bar{Q}$ states when the screening length becomes shorter than the $Q\bar{Q}$ size and given the fact that this length is directly related to the temperature, a measurement of a suppressed quarkonium yield would thus provide direct experimental sensitivity to the temperature of the medium created in high energy nuclear collisions. However, before using the suppression of quarkonium yields in A+A collisions relative to $pp$ collisions as a probe to study QGP, it is important to measure the quarkonium production also in $p(d)+A$ interaction where no QGP effect is expected. Quarkonium suppression has also been observed in $p(d)+A$ collisions [4, 5, 6, 7], where the so-called cold nuclear matter (CNM) effects take place, with several phenomenological interpretations. The CNM effects not only affect quarkonia production but can also affect $b$-quark production. For instance, the effects of gluon saturation and shadowing are expected to be similar to those for charmonium production however, nuclear absorption and parton energy loss are expected to be less pronounced. Therefore, additional constraints can be obtained by measuring $b$-quark production, which can be accomplished by measuring the cross sections for $J/\psi$ and $\psi(2S)$ production in the decay chains of $b$-hadrons.
2. The ATLAS detector
The ATLAS detector [8] at the LHC covers nearly the entire solid angle around the collision point, and it is designed to measure the properties of a wide range of physics processes in \( p + p \), \( p + \text{Pb} \) and \( \text{Pb} + \text{Pb} \) interactions. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three superconducting toroid magnet systems. The inner-detector system (ID) is immersed in a 2 T axial magnetic field and provides charged particle tracking in the pseudorapidity range \( |\eta| < 2.5 \). The high-granularity silicon pixel detector covers the vertex region and is surrounded by the silicon microstrip tracker and transition radiation tracker. The calorimeter system covers the range \( |\eta| < 4.9 \). Within the region \( |\eta| < 3.2 \), electromagnetic calorimetry is provided by barrel and endcap high-granularity lead-liquid-argon (LAr) calorimeters, with an additional thin LAr presampler covering \( |\eta| < 1.8 \). Forward calorimeters (FCal) are located in the range \( 3.1 < |\eta| < 4.9 \). The muon spectrometer comprises separate trigger and high-precision tracking chambers that measure the deflection of muons in a magnetic field generated by superconducting air-core toroids. The precision tracking chamber system covers the region \( |\eta| < 2.7 \), with trigger coverage in the range \( |\eta| < 2.4 \).

3. \( J/\psi \) and \( \psi(2S) \) production in \( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \) \( p + \text{Pb} \) and \( \sqrt{s} = 2.76 \text{ TeV} \) \( pp \) collisions

3.1. Signal extraction
\( J/\psi \) and \( \psi(2S) \) production measurements were performed in the dimuon decay channel in \( p + \text{Pb} \) collisions at \( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \) with an integrated luminosity of 28.1 \( nb^{-1} \), and in \( pp \) collisions at \( \sqrt{s} = 2.76 \text{ TeV} \) with an integrated luminosity of 4.0 \( pb^{-1} \) [9]. The \( p + \text{Pb} \) collisions were produced from a 4 TeV proton beam and a 1.57 TeV per nucleon lead beam. The asymmetric energy of the beams resulted in a shift of the centre of mass by 0.465 units of rapidity relative to the laboratory frame. The centre-of-mass rapidity, \( y^* = y_{\text{lab}} - 0.465 \), is defined to be positive in the proton-going side. The number of produced \( J/\psi \) and \( \psi(2S) \) mesons and the relative fraction of nonprompt\(^1\) \( J/\psi \) and \( \psi(2S) \) with respect to inclusive production are determined using a two-dimensional likelihood fit of the dimuon invariant mass and pseudoproper time\(^2\) \((m_{\mu\mu}, \tau)\) spectrum of weighted \( J/\psi \) and \( \psi(2S) \) candidates. The probability density function for the fit follows the method described in [10]. From vertices reconstruction, it is possible to obtain the pseudoproper time to disentangle prompt and nonprompt components. Figure 1 shows the distributions of dimuon invariant mass (upper panels) and pseudoproper time (bottom panels) of weighted \( J/\psi \) and \( \psi(2S) \) candidates in the range of \( 8.5 < p_T < 30 \text{ GeV} \) and \(-1.5 < y^* < 1.5 \) [9].

3.2. Self-normalized yields and nuclear modification factors
In order to characterize the \( p + \text{Pb} \) collision impact parameter, each event is assigned to a centrality class based on the total transverse energy measured in the FCal on the Pb-going side \((-4.9 < \eta < -3.2 \) with the negative \( \eta \) being defined as Pb-going side), \( E_T^{\text{FCal}} \) [11]. Each centrality class corresponds to a fixed percentile in the \( E_T^{\text{FCal}} \) distribution. The standard Glauber model [12] is used to calculate the mean number of participant nucleons, \( \langle N_{\text{part}} \rangle \), and the mean nuclear thickness function, \( \langle T_{\text{pp}} \rangle \), for each centrality class. Based on the observed centrality dependence of charged particle multiplicity [11], the Glauber-Gribov Color Fluctuation (GGCF) model [13, 14], an extension to the Glauber model which allows event-by-event fluctuations of the nucleon-nucleon cross section, is also considered. Recently, calculations of a centrality bias have

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1 Nonprompt component originates from decays of \( b \)-hadrons.

2 The pseudoproper time is defined as \( \tau = L_{xy} \frac{m_{\mu\mu}}{p_T} \), where \( m_{\mu\mu} \) is the invariant mass of the dimuon, \( p_T \) is its transverse momentum and \( L_{xy} \) is the signed transverse distance between the primary interaction vertex and the \( J/\psi \rightarrow \mu^+\mu^- \), or the \( \psi(2S) \rightarrow \mu^+\mu^- \) vertex.
been made in which the average yield from hard scattering processes in each nucleon-nucleon collision is taken to be proportional to the contribution from that collision to the \( E_T \), which determines the centrality \( (E_T^{FCal}) [15] \). This model is applied to the ATLAS \( p+Pb \) centrality classification for both the standard Glauber model and the GGCF model.

The yields of \( J/\psi \) and \( \psi(2S) \) per event in each centrality class can be normalized to the yield per event measured in all centrality classes (0-90% centrality). These quantities are called self-normalized yields, \( \langle \psi \rangle / \langle \psi \rangle \). The correlation of charmonium production with the size of the underlying event activity is done by comparing the self-normalized charmonium yields with the similar self-normalized transverse energy, \( E_T^{FCal}/\langle E_T^{FCal} \rangle \), measured in the Pb-going side of the FCal. \( \langle \psi \rangle \) and \( E_T^{FCal}/\langle E_T^{FCal} \rangle \) are defined as:

\[
\frac{\psi}{\langle \psi \rangle} = \frac{N_\psi/N_{evt}}{N_\psi^{0-90%}/N_{evt}^{0-90%}},
\]

(1)

\[
\frac{E_T^{FCal}}{\langle E_T^{FCal} \rangle} = \frac{\langle E_T^{FCal} \rangle}{\langle E_T^{FCal} \rangle} \bigg|_{cent}^{0-90%},
\]

(2)

where \( N_\psi \) is the yield extracted from the fit for one centrality class. The yield is divided by
\( \langle T_pPb \rangle \) in the case of bias-corrected self-normalized ratios.

The prompt \( J/\psi \), nonprompt \( J/\psi \) and prompt \( \psi(2S) \) self-normalized yields, \( \psi/\langle \psi \rangle \), in bins of self-normalized FCal \( E_T \), \( E_T^{\text{FCal}}/\langle E_T^{\text{FCal}} \rangle \), are shown in Figure 2 [9]. The self-normalized ratios without centrality bias corrections are compared with CMS results [16]. The uncorrected results are consistent with unity in the slope of the line as well as CMS results at small \( E_T^{\text{FCal}}/\langle E_T^{\text{FCal}} \rangle \). However, at large \( E_T^{\text{FCal}} \) region \( E_T^{\text{FCal}}/\langle E_T^{\text{FCal}} \rangle > 3 \), significant deviations from the linear scaling were observed for all three resonances. The deviations become more significant when the centrality bias correction is applied. This deviation at large \( E_T^{\text{FCal}} \) is also observed for \( Z \) and thus it has probably no relation with quarkonium suppression but it could rather be due to a kinematic effect.

![Figure 2](image-url)

**Figure 2.** Self-normalized ratio for prompt \( J/\psi \), nonprompt \( J/\psi \) and prompt \( \psi(2S) \) with no centrality bias corrections (top) and with bias corrections for the standard Glauber (bottom left) and GGCF (bottom right) configurations. The x-axis variables are normalized by their corresponding \( E_T^{\text{FCal}} \) integrated values. For all points, the abscissae are at the mean value in each \( E_T^{\text{FCal}} \) bin. The dotted line is a linear function with a slope equal to unity. The error bars indicate only the statistical uncertainties, and the boxes represent the systematic uncertainties. The \( E_T/\langle E_T \rangle \) value of CMS results shown in the top plot was measured at \( 4 < |\eta| < 5.2 \) [9].

The nuclear modification factor, \( R_{pPb} \), is used to compare the production of \( J/\psi \) and \( \psi(2S) \) in \( p+Pb \) collisions to the same processes in \( pp \) collisions:

\[
R_{pPb} = \frac{1}{A_{Pb}} \frac{d^2\sigma_{pPb}^{pPb}/dyd\eta}{d^2\sigma_{\psi}^{pp}/dyd\eta_p} \tag{3}
\]
where $\psi$ refers to either prompt or nonprompt $J/\psi$ or prompt $\psi(2S)$ and $A_{\text{Pb}}^{\text{Pb}} = 208$. The nuclear modification factor may also be defined for a given centrality class as:

$$R_{p\text{Pb}} = \frac{1}{\langle T_{p\text{Pb}} \rangle_{\text{cent}}} \frac{1/N_{\text{evt}}}{d^2N_{\psi^{+\text{Pb}}}/dy^*dp_T} \bigg|_{\text{cent}}$$

where $N_{\text{evt}}$ is the total number of minimum bias $p+\text{Pb}$ events, $\langle T_{p\text{Pb}} \rangle_{\text{cent}}$ is the mean nuclear thickness function in the centrality class, and $N_{\psi^{+\text{Pb}}}$ is the number of charmonium signal events in the same centrality class. In the absence of a measured $pp$ reference cross section at $\sqrt{s} = 5.02$ TeV, an interpolation of the cross sections measured at nearby energies is used. The interpolation is based on the cross section measured at $\sqrt{s} = 2.76$ TeV [9] and the cross sections measured at $\sqrt{s} = 7$ and 8 TeV [10]. For that, three functional forms in $\sqrt{s}$ (linear, power law and exponential) were used for the interpolation, with the central value of the cross section at $\sqrt{s} = 5.02$ TeV derived from the power law form. The other functions are used in the calculation of the uncertainty associated with the interpolation [9]. The prompt $\psi(2S)$ to $J/\psi$ production ratio in $p+\text{Pb}$ collisions is shown in Figure 3 in bins of $E_{\text{FCal}}^T$ along with the same ratio in $pp$ collisions at 2.76 TeV.

![Figure 3. Prompt $\psi(2S)$ to $J/\psi$ production ratio as a function of total FCal $E_T$ for $p+\text{Pb}$ collisions. The error bars indicate only the statistical uncertainties, and the boxes represent the systematic uncertainties. As a reference, the ratio of $pp$ collisions at 2.76 TeV is also shown in the square green point [9].](image)

Prompt $\psi(2S)$ to $J/\psi$ double ratios $R_{p\text{Pb}}(\psi(2S))/R_{pp}(J/\psi)$ in bins of $y^*$ and in bins of $E_{\text{FCal}}^T$ are shown in Figure 4. The prompt production ratios at 2.76 TeV $pp$ collisions are used as the reference, since the single production ratios in $pp$ collisions do not depend significantly on $\sqrt{s}$. The right panel of Figure 4 is the single prompt excited-to-ground state ratio measured in $p+\text{Pb}$ collisions in Figure 3 divided by the $pp$ point for $\sqrt{s} = 2.76$ TeV with the errors convolved. The prompt $\psi(2S)$ to $J/\psi$ double ratios show no obvious rapidity dependence but a decreasing trend as the event activity increases.

4. Differential $J/\psi$ production cross section and forward-backward ratio in $\sqrt{s_{NN}} = 5.02$ TeV $p+\text{Pb}$ collisions

4.1. Forward-backward ratio

Using the same data set of $p+\text{Pb}$ collisions with an integrated luminosity of 28.1 nb$^{-1}$, $J/\psi$ mesons were reconstructed in the dimuon decay channel over the transverse momentum range...
Figure 4. Prompt \( \psi(2S) \) to \( J/\psi \) double ratio in bins of center-of-mass rapidity, \( y^* \) (left) and total FCal \( E_T \) (right). The error bars indicate only the statistical uncertainties, and the boxes represent the systematic uncertainties. The horizontal size of box represents bin width. Prompt production ratios at 2.76 TeV \( pp \) collisions are used as the reference when calculating the double ratio [9].

The number of produced \( J/\psi \) mesons and the nonprompt fraction are determined through similar procedure as already described in Section 3.1. Considering that previous measurements in \( p+Pb \) collisions at the LHC [18, 19] show that the differential cross section for \( J/\psi \) production at forward \( y^* \) (proton direction) are significantly smaller than at backward \( y^* \) (heavy-ion direction), an observable to quantify this asymmetry is proposed, namely, the forward-backward ratio, \( R_{FB} \):

\[
R_{FB}(p_T, y^*) = \frac{d^2\sigma(p_T, y^* > 0)/dp_T/dy^*)}{d^2\sigma(p_T, y^* < 0)/dp_T/dy^*}
\]

which has the advantage of not depending on the knowledge of the \( J/\psi \) production cross section in \( pp \) collisions, not to mention that the experimental and theoretical uncertainties partially cancel in the ratio. Figure 5 shows \( R_{FB} \) as a function of transverse momentum in the range \( 8 < p_T < 30 \) GeV for prompt \( J/\psi \) (upper panel) and for nonprompt \( J/\psi \) (bottom panel). Figure 5 shows \( R_{FB} \) as a function of \( y^* \) in the range \( |y^*| < 1.94 \) for prompt \( J/\psi \) (upper panel) and for nonprompt \( J/\psi \) (bottom panel). These results are consistent with unity within experimental uncertainties, with no significant \( p_T \) or \( y^* \) dependence, for both prompt and nonprompt \( J/\psi \) [17]. These results differ from measurements at more forward \( y^* \) and lower \( p_T \) performed by ALICE and LHCb Collaborations, suggesting a strong kinematic dependence of the CNM effects on both charmonium and \( b \)-quark production. The \( R_{FB} \) ratio for prompt \( J/\psi \) agrees with theoretical predictions [20, 21] that include shadowing effects based on the EPS09 nuclear parton distribution functions [22].

4.2. Differential cross sections and comparison with FONLL calculation

The differential cross sections of nonprompt \( J/\psi \) production are compared to a scaled \( pp \) reference based on FONLL calculations [23]. They are multiplied by a factor of 208 to account for the number of nucleons in the Pb ion. The FONLL calculations are performed using CTEQ6.6 [24] parton distribution functions that do not include any nuclear modification. As can be seen in Figure 7, the measured cross sections are found to be consistent with FONLL calculation within uncertainties.
5. Conclusions

ATLAS has performed measurements of prompt and nonprompt components of $J/\psi$ and $\psi(2S)$ production in $p+Pb$ collisions at 5.02 TeV and in $pp$ collisions at 2.76 TeV. Results were presented for differential cross sections, forward-backward ratio for $J/\psi$, $R_{pPb}$, and self-normalized yields for $J/\psi$ and $\psi(2S)$ via $pp$ interpolation. CNM effects were seen in a number of observables.

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Figure 7. Differential cross section for production of nonprompt $J/\psi$ as a function of $J/\psi$ centre-of-mass rapidity (upper panel) and transverse momentum (bottom panel) compared with a FONLL calculation for $pp$ collisions scaled by the number of nucleons in the Pb ion [17].

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