Abstract

The suppression of heavy charmonia states in heavy-ion collisions is a phenomenon understood as a consequence of quark gluon plasma formation in the hot, dense system formed in heavy ion collisions at the LHC. In addition to hot matter effects in heavy-ion collisions, so-called cold nuclear effects that modify heavy charmonia production are also present. Therefore, a full assessment requires detailed studies in both A+A and p+A collisions. Based on p+Pb data collected in 2013 and pp and Pb+Pb data collected in 2015 at the LHC, the ATLAS experiment has studied prompt and non-prompt J/ψ and ψ(2S) production via the dimuon decay final states. The production and excited-to-ground state ratios of heavy charmonia measured in both p+Pb and Pb+Pb collision data with respect to that measured in pp collision data is presented in intervals of transverse momentum, rapidity and centrality.

Keywords: Quarkonia, AA collisions, QCD, QGP, ATLAS, LHC

1. Introduction

Charmonia, bound states of charm and anti-charm quarks, are excellent probes for study of the hot and dense system created in ion-ion collisions. Those states produced from the hard scattering or coming from very short time decays are denominated prompt, while those originating from longer decays are denominated non-prompt. Both production mechanisms experience the collision environment differently, thus the separation of prompt and non-prompt components allows the disentangling of two kinds of physics due to the nature of both production mechanisms. Non-prompt states predominantly arise from b-quark decays, allowing the testing of their interactions with the medium, so their suppression is usually attributed to the energy loss of the propagating b-quark. On the other hand, the suppression of prompt states is related to the interactions of the c̅c composite with the surrounding medium. Besides these two aspects, there are many related effects that modify the charmonium production in proton-ion and ion-ion collisions, giving rise to cold and hot nuclear matter effects. Examples of these include parton density function modification due to the nuclear medium, initial stage energy loss, nuclear absorption, suppression by color screening, regeneration, medium induced energy loss, and feed-down from excited states or B-hadrons. A clear understanding of the charmonium production requires the analysis of different colliding systems; such analysis should shed
light on the different effects. This has been achieved by the ATLAS experiment [1], which has measured the production of prompt and non-prompt $J/\psi$ and $\psi(2S)$ in $pp$, $p+\text{Pb}$ and $\text{Pb}+\text{Pb}$ collisions [2, 3, 4].

2. Experimental methods

The measurement was performed using the dimuon decay channel. Interesting events were selected using triggers involving at least two muons. Muon pairs with unlike charge and coming from a common decay vertex are identified as candidates. For each candidate, the invariant mass, $m_{\mu\mu}$, and the pseudo-proper lifetime are computed for $p_{T}^\mu > 8.5$ GeV and center-of-mass rapidity of the proton-nucleon system, $|y| < 1.94$ in $p+\text{Pb}$; $p_{T}^\mu > 9$ GeV and $|y| < 2$ in $\text{Pb}+\text{Pb}$. In both cases, the invariant mass range is $2.0 < m_{\mu\mu} < 4.2$ GeV. The pseudo-proper lifetime, $\tau$, is defined as $\tau = L_{xy} m_{\mu\mu} / p_{T}^\mu$ where the length, $L_{xy}$, is the signed projection of the decay length on the transverse plane. Each event is weighted to consider trigger and reconstruction efficiencies and detector acceptance. The kinematic cuts are chosen to minimize the variations on the size of the full weight and thus reduce systematic uncertainties. A maximum likelihood, weighted simultaneous fit to the invariant mass and pseudo-proper lifetime using a fit model was performed to extract the prompt and non-prompt signals. The lineshape is described by a probability density function with seven terms in total, involving prompt and non-prompt $J/\psi$ and $\psi(2S)$ and also prompt and non-prompt terms for the background.

Each signal term is described by the weighted sum of a Crystal Ball and a Gaussian distribution multiplied by a term depending on the pseudo-proper lifetime. The time signal is modeled by a delta function for prompt candidates, and by an exponential decay for non-prompt candidates. Both terms are convolved with a Gaussian responsible for describing the detector resolution of the decay vertex. Sensitivity of the model constitutes an important source of systematic uncertainties in the $p+\text{Pb}$ analysis. This sensitivity was quantified by varying the choice of model, and the systematic uncertainties were determined to range from 2% to 10% for $J/\psi$ and up to 80% for $\psi(2S)$; for $\text{Pb}+\text{Pb}$, they are approximately 2% for $J/\psi$ and 10% for $\psi(2S)$.

Different datasets were analyzed. First, $pp$ collisions at $\sqrt{s} = 2.76$ were analyzed and the results interpolated to 5.02 TeV using samples at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8.16$ TeV, to have the equivalent cross section for $pp$ at 5.02 TeV. The systematic uncertainty of this interpolation was studied in detail. Data from the $p+\text{Pb}$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV were analyzed and compared to the interpolated $pp$ data. The $\text{Pb}+\text{Pb}$ dataset from $\sqrt{s_{NN}} = 5.02$ TeV collisions was compared to newer $pp$ reference data taken at $\sqrt{s} = 5.02$ TeV.

![Fig. 1](image.png)

Fig. 1. (Left) Non-prompt fraction of $J/\psi$ production in 5.02 TeV $pp$ collision data for different rapidity regions. The vertical error bars are the combined systematic and statistical uncertainties. (Middle) Non-prompt fraction as a function of $J/\psi$ transverse momentum $p_T$. Positive $y^*$ is defined in the proton beam direction. The error bars show the statistical uncertainty, and the shaded boxes show the sum in quadrature of statistical and systematic uncertainties. (Right) Non-prompt fraction of $J/\psi$ production in 5.02 TeV $\text{Pb}+\text{Pb}$ collision data as a function of $p_T$ for different centrality slices in the rapidity range $|y| < 2$.

3. Results

The $J/\psi$ non-prompt fraction is shown in Fig. (1), for $pp$, $p+\text{Pb}$, and $\text{Pb}+\text{Pb}$ collisions, as a function of $p_T$, for several rapidity slices for $pp$ and $p+\text{Pb}$, and centrality slices for $\text{Pb}+\text{Pb}$. The trend is similar, and there is no visible dependence on rapidity in $pp$ and $p+\text{Pb}$. In $\text{Pb}+\text{Pb}$, no centrality dependence is observed, and the fraction indicates some enhancement at low $p_T$ with respect to $pp$ and $p+\text{Pb}$.
Fig. 2. The nuclear modification factor, $R_{pPb}$, as a function of $p_T$ for prompt (A) and non-prompt (B) $J/\psi$. The error bars indicate only the statistical uncertainties, and the boxes represent the systematic uncertainties. The nuclear modification factor, $R_{AA}$, is shown as a function of $p_T$ for prompt (C) and non-prompt (D) $J/\psi$, for $|y| < 2$ and centrality from 0 to 80%. The statistical uncertainty for each point is indicated by a narrow vertical error bar which is smaller than the plotting symbol for most points. The error box plotted with each point represents the systematic uncertainty, while the error band represents the correlated scale uncertainties.

The nuclear modification factor $R_{pPb}$, defined as the ratio of the yield in $p+$Pb to 208 times the yield in $pp$, is shown in Fig. (2) (A and B) for prompt and non-prompt $J/\psi$. To compare to the production of charmonia in Pb+Pb with respect to $pp$, the nuclear modification factor $R_{AA}$ is computed. In Fig. (2) (C and D), the $R_{AA}$ is shown as a function of $p_T$ for prompt and non-prompt $J/\psi$ production. Prompt production exhibits an increasing behavior with $p_T$, whereas non-prompt is flat. The kinematic cuts are very similar for $p+$Pb and Pb+Pb, allowing comparison between $R_{pPb}$ and $R_{AA}$.

The centrality dependence is shown in Fig. (3) as a function of the number of participants, where both production mechanisms show strong suppression with a similar trend. The rapidity dependence is not included in this note but the results are essentially constant in rapidity for both production mechanisms [4].

The last observable presented is the ratio of $\psi(2S)$ to $J/\psi$ production, expressed as $R_{AA}'^{\psi(2S)}/R_{AA}'^{J/\psi}$. The result is presented as a function of centrality in Fig. (4) for prompt and non-prompt production mechanisms. Prompt production shows a value less than one, while the non-prompt component is compatible with unity.

Fig. 3. The nuclear modification factor, $R_{AA}$, as a function of centrality expressed as the number of participants $N_{\text{part}}$ for the prompt (left) and non-prompt (right) $J/\psi$ for $9 < p_T < 40$ GeV and for rapidity $|y| < 2$. The statistical uncertainty on each point is indicated by a narrow vertical error bar. The error box represents the point-to-point systematic uncertainty, while the error bands represent correlated scale uncertainties.
4. Conclusions

Charmonia states have been measured by ATLAS in $p$+Pb and Pb+Pb and compared to $pp$ collisions. Nuclear modification factors and the double ratios quantify the effect of cold and hot nuclear environments on the charmonium production. The values of $R_{pPb}$ are consistent with unity and are constant along transverse momentum and center-of-mass rapidity. For hot matter, the $R_{AA}$ is presented as a function of $p_T$, rapidity, and centrality. This quantity shows interesting features like the increasing behavior in $p_T$ for prompt $J/\psi$ and the same trend in the prompt and non-prompt suppression as a function of centrality, which drops as low as 0.2 in the most central collisions. As anticipated, suppression was also observed for non-prompt mesons, which are produced by decays of $b$-quark systems that experience the hot and dense medium.

The double ratio $R^{\psi(2S)}_{AA}/R^{J/\psi}_{AA}$ has been measured, comparing the production of $\psi(2S)$ with $J/\psi$. This ratio is equal to unity for non-prompt production and is less than unity for prompt production. The result is compatible with the idea of $b$-quarks decaying into $c\bar{c}$-states outside the nuclear medium, leaving the charmonia state unaffected by the medium, while mesons formed within the medium are more suppressed. Also, the result is consistent with the $\psi(2S)$ being more suppressed than the $J/\psi$, which supports the hypothesis of a sequential melting of the excited states with lower binding energy.

References