Charmonium production in pp, pPb and PbPb collisions with CMS

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Abstract.
The LHC Run 1 results of the analysis of charmonium production in pp, pPb and PbPb collisions with the CMS experiment are reported. The coherent $J/\psi$ photoproduction cross section is measured as a function of rapidity in ultra-peripheral PbPb collisions at 2.76 TeV. The forward-backward ratio of prompt $J/\psi$ yields in pPb collisions at 5.02 TeV is presented as a function of the event activity and $p_T$. The nuclear modification factor of prompt $J/\psi$ in PbPb collisions at 2.76 TeV is shown as a function of rapidity, centrality and $p_T$. Finally, the ratio of $\psi(2S)$ to $J/\psi$ yields in PbPb collisions with respect to pp collisions at 2.76 TeV is analysed in different rapidity and centrality bins.

1. Introduction
Charmonium states constitute an important probe of the Quark-Gluon Plasma (QGP), since they are produced in the early stage of heavy ion collisions and their yields are sensitive to the evolution of the medium. It has been predicted that the charmonium production can be suppress in QGP due to the Debye screening of the strong interaction between quarks [1]. Since the binding energy of charmonia decreases for higher excited states, it is expected that charmonium states dissociate sequentially in the QGP [1]. Moreover, a large amount of charm quarks are produced in PbPb collisions at LHC energies, and it becomes possible that uncorrelated charm and anticharm quarks recombine to form charmonium mesons during hadronization, enhancing their measured yields compared to those in proton-proton (pp) collisions [3]. Apart from the presence of QGP, the production of charmonium states can be altered by nuclear matter effects such as parton energy loss due to multiple scattering in the nucleus [2], or nuclear modification of the parton distribution functions (PDF) [4]. These nuclear matter effects can be studied more precisely in proton-lead (pPb) collisions and ultra-peripheral PbPb collisions (UPC), where the formation of QGP is not expected.

2. Analysis procedure and results
2.1. $J/\psi$ in Ultra Peripheral PbPb collisions
The gluon nuclear PDF can be probed, in the range of Bjorken-x values from $10^{-5}$ to $10^{-2}$, by photon-nucleus interactions in ultra-peripheral PbPb collisions at 2.76 TeV [6]. The photon-induced reactions can be classified as coherent if the photon interacts with the whole nucleus, or incoherent if the photon interacts with a single nucleon. Coherent and incoherent photoproduction can be accompanied by the emission of forward neutrons produced by the
strong electromagnetic fields present in UPC events and the break up of the nucleus [6]. The UPC events were selected by requiring low activity in the hadron forward calorimeter, the presence of at least one neutron in the zero degree calorimeters, and two muon tracks within the invariant mass region \(2.6 < m_{\mu\mu} < 3.5\) GeV/c\(^2\). In order to extract the coherent signal contribution from background (\(\gamma\gamma \rightarrow \mu^+\mu^-\) interactions and incoherent \(J/\psi\) production), the dimuon invariant mass and \(p_T\) spectra were simultaneously fitted using an unbinned maximum likelihood fit.

![Figure 1: Differential cross section as a function of rapidity for coherent \(J/\psi\) photoproduction measured by CMS [6] (red) and ALICE [7, 8] (black), in ultra-peripheral PbPb collisions at 2.76 TeV [6]. The horizontal bars represent the size of the measured rapidity bins, and the vertical error bars display the statistical and systematic uncertainties. The impulse approximation (blue) and the leading twist approximation predictions (yellow) are also included.](image)

The CMS cross section measurement for coherent \(J/\psi\) photoproduction using 159 \(\mu b^{-1}\) PbPb data [6], is compared in Fig. 1 to the ALICE measurements [7, 8], and to theoretical predictions. The impulse approximation model neglects all nuclear effects by estimating the coherent photoproduction in \(\gamma+Pb\) collisions using data from \(\gamma+p\) collisions [9], while the leading twist approximation model describes an effective nuclear gluon shadowing by implementing a gluon recombination mechanism at the partonic level using as input a diffractive proton PDF [10]. Experimental results from CMS and ALICE show a continuous decrease with rapidity, favouring the leading twist approximation.

2.2. \(J/\psi\) in \(pPb\) collisions

The prompt \(J/\psi\) production was measured in \(pPb\) collisions at 5.02 TeV [12]. Since B-mesons traverse a measurable pathlength before decaying, the prompt and non-prompt \(J/\psi\) can be separated by the pseudo-proper decay length, \(l_{J/\psi} = L_{xy}m_{J/\psi}/p_T\), where \(L_{xy}\) is the transverse distance between the primary vertex and the \(\mu^+\mu^-\) vertex computed in the laboratory frame. The prompt and non-prompt \(J/\psi\) were extracted by performing an extended unbinned maximum likelihood fit simultaneously to the invariant-mass and \(l_{J/\psi}\) distributions of dimuons [12]. The forward-to-backward ratio \((R_{FB})\) of prompt \(J/\psi\) cross sections, where the forward (backward) region is defined by the \(p\)-going (Pb-going) direction, is used to analyse the \(p_T\) and rapidity dependence of nuclear effects.

In Figure 2, the \(p_T\) dependence of the prompt \(J/\psi\) \(R_{FB}\) is compared, in three different rapidity regions, to the next-to-leading order (NLO) EPS09 shadowing calculation based on the Color Evaporation Model (CEM) [13]. The results, using 34.6 \(nb^{-1}\) pPb data, shows \(R_{FB}\) values approaching unity at high \(p_T\), but lower than the model calculations at low \(p_T\) suggesting the presence of other nuclear effects apart from just nPDF modifications. Moreover, the transverse energy deposited in the forward hadronic calorimeter at \(4 < |\eta| < 5.2\) is used to determine the dependence of the \(R_{FB}\) with the event activity. Fig. 3 shows a decreasing pattern of the \(R_{FB}\) with increasing \(E_T\) over all \(p_T\) and rapidity intervals.
2.3. $J/\psi$ and $\psi(2S)$ in PbPb collisions

The enhancement or suppression of charmonia due to QGP can be quantified with the nuclear modification factor ($R_{AA}$), which represents the ratio of yields in heavy ion collisions with respect to pp collisions scaled by the number of binary nucleon-nucleon interactions. The $R_{AA}$ of prompt $J/\psi$ was measured using pp and PbPb data at 2.76 TeV [11]. The prompt $J/\psi R_{AA}$ distributions versus rapidity, centrality and $p_T$, are shown in Fig. 4. A strong suppression of prompt $J/\psi$ yields in PbPb collisions compared to pp collisions, with no significant dependence on $p_T$ and rapidity, is observed for more central events, suggesting the presence of hot medium effects.

Figure 4: Prompt $J/\psi$ nuclear modification factor with respect to rapidity (left), centrality (middle), and $p_T$ (right) in PbPb collisions at 2.76 TeV [11]. The horizontal lines display the range of the measured bins and the gray boxes represent the magnitude of the global uncertainties.
The variation between the production of $\psi(2S)$ and $J/\psi$ in PbPb compared to pp collisions is determined by the double ratio $(N_{\psi(2S)}/N_{J/\psi})_{\text{PbPb}}/(N_{\psi(2S)}/N_{J/\psi})_{\text{pp}}$. This double ratio was measured by CMS using PbPb and pp data at 2.76 [14]. The centrality dependence of the double ratio is presented in Fig. 5. At mid rapidity and high $p_T$ ($|y| < 1.6$ and $6.5 < p_T < 30$ GeV/c), the $\psi(2S)$ production is more suppressed than $J/\psi$ production in all measured centrality bins. Moreover, the opposite trend is observed at forward rapidity and intermediate $p_T$ ($1.6 < |y| < 2.4$ and $3 < p_T < 30$ GeV/c), where the $\psi(2S)$ production is less suppressed than $J/\psi$ in central PbPb collisions, implying the existence of other medium effects apart from sequential melting.

3. Summary
The coherent $J/\psi$ photoproduction cross section in PbPb UPC is in good agreement with the leading twist approximation, indicating that shadowing effects are needed to describe the data. The $R_{FB}$ of $J/\psi$ in pPb collisions is consistent with unity at high $p_T$ and decreases at low $p_T$, suggesting the existence of additional nuclear effects apart from just nPDF modifications. The prompt $J/\psi R_{AA}$ is shown to be lower than unity and has a decreasing centrality dependence, expected from QGP. The double ratio of prompt $\psi(2S)$ to $J/\psi$ yields is observed to be above unity for central PbPb collisions in the low $p_T$ and forward rapidity region, implying the presence of physics processes beyond the sequential melting scenario.

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