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/ψ 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/ψ 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/ψ 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/ψ 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/ψ 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/ψ production), the dimuon invariant mass and p_T spectra were simultaneously fitted using an unbinned maximum likelihood fit.

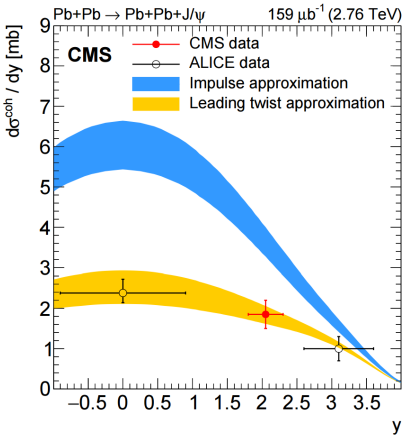

Figure 1: Differential cross section as a function of rapidity for coherent J/ψ photoproduction measured by CMS [6] (red) and ALICE [7, 8] (black), in ultra-peripheral PbPb collisions at 2.76 TeV [6]. The horizontal bars represent the size of the measured rapidity bins, and the vertical error bars display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

The CMS cross section measurement for coherent J/ψ photoproduction using 159 μb^{-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 γ+Pb collisions using data from γ+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/ψ in pPb collisions

The prompt J/ψ 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/ψ can be separated by the pseudo-proper decay length, $l_{J/\psi} = L_{xy} m_{J/}/p_T$, 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/ψ 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/ψ 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.

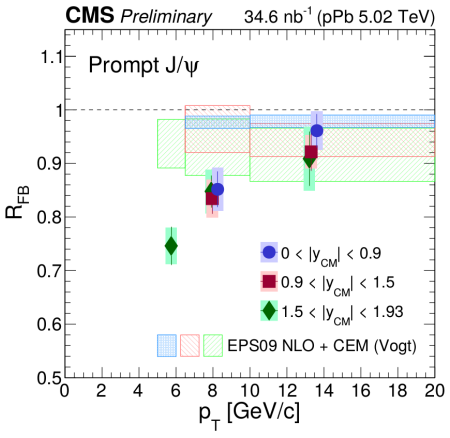

Figure 2: Prompt J/ψ R_{FB} versus p_T in three rapidity ranges [12]. The statistical (systematic) uncertainties are represented by the vertical bars (shaded boxes). The EPS09 (NLO) shadowing calculation is also shown.

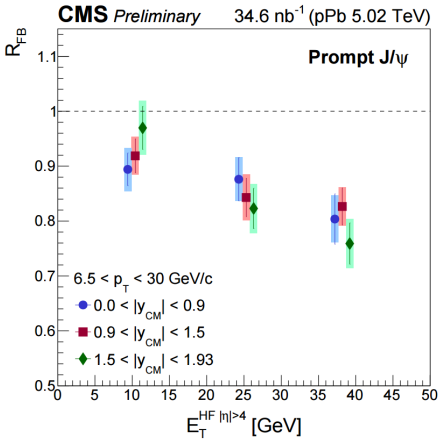

Figure 3: Prompt J/ψ R_{FB} versus E_T in three rapidity ranges [12]. The statistical (systematic) uncertainties are represented by the vertical bars (shaded boxes). Data points are slightly shifted to avoid overlaps between each other.

2.3. J/ψ 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/ψ was measured using pp and PbPb data at 2.76 TeV [11]. The prompt J/ψ R_{AA} distributions versus rapidity, centrality and p_T, are shown in Fig. 4. A strong suppression of prompt J/ψ 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.

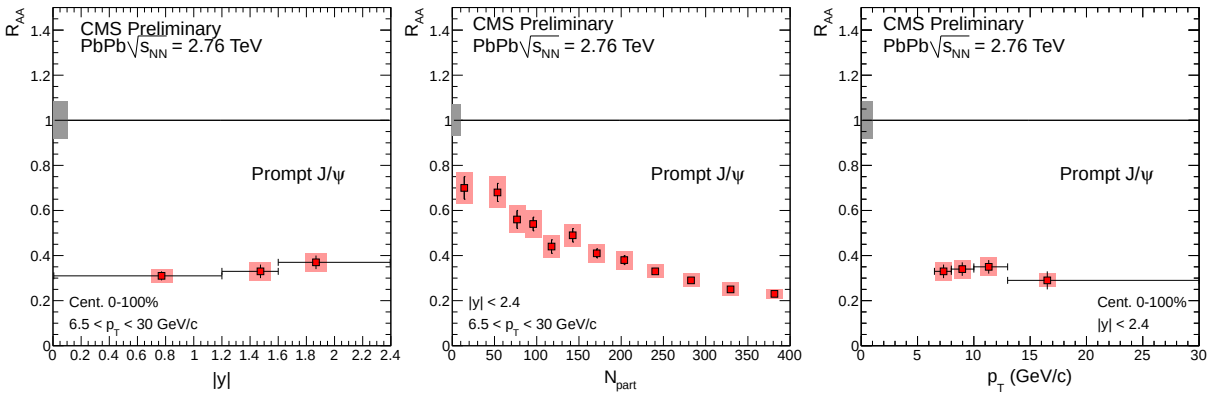

Figure 4: Prompt J/ψ nuclear modification factor with respect to rapidity (left), centrality (middle), and p_T (right) in PbPb collisions at 2.76 TeV [11]. The horizontal lines display the range of the measured bins and the gray boxes represent the magnitude of the global uncertainties.

The variation between the production of $\psi\,(2S)$ and J/ψ in PbPb compared to pp collisions is determined by the double ratio $(N_{\psi(2S)}/N_{J/\psi})_{PbPb}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$. 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/ψ 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/ψ in central PbPb collisions, implying the existence of other medium effects apart from sequential melting.

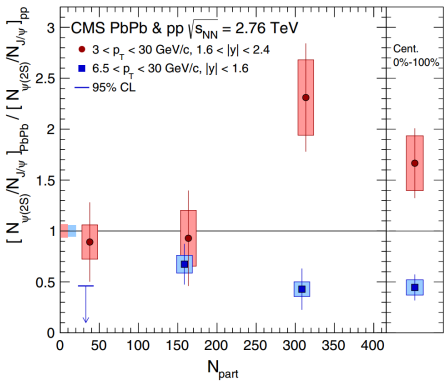

Figure 5: Double ratio of $\psi\,(2S)$ over J/ψ yields as a function of centrality at forward rapidity (red) and mid rapidity (blue) [14]. The pp uncertainties are shown by boxes at unity while the statistical uncertainties are displayed by bars. The centrality-integrated results are presented in the right panel.

3. Summary

The coherent J/ψ 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/ψ 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/ψ 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/ψ 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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