Forward rapidity $\psi(2S)$ meson production in pp, p-Pb and Pb-Pb collisions with ALICE at the LHC

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Abstract. The ALICE Collaboration has studied the inclusive $\psi(2S)$ meson production in pp, p-Pb and Pb-Pb collisions at the CERN LHC. The $\psi(2S)$ is detected through its decay to a muon pair, using the forward Muon Spectrometer, which covers the pseudo-rapidity range $-4 < \eta < -2.5$. The $\psi(2S)$ production cross sections in pp collisions are presented as a function of rapidity (y) and transverse momentum (p_T). In p-Pb collisions, $\psi(2S)$ results are compared to the J/ψ ones by the ratio of their production cross sections as a function of rapidity, transverse momentum and event activity. The $\psi(2S)$ nuclear modification factor, R_{pA}, is also discussed. The results show a $\psi(2S)$ suppression compared to the one observed for the J/ψ meson and are not described by theoretical models including cold nuclear matter effects as nuclear shadowing and energy loss. Finally, the preliminary results of $\psi(2S)$ meson production in Pb-Pb collisions are shown in two p_T ranges as a function of the collision centrality.

1. Introduction

The study of charmonia (bound states of c and $\bar{c}$ quarks), in different collision systems, is the object of intense theoretical and experimental investigations [1]. Proton-proton (pp) collisions are fundamental to evaluate the production cross section and to test production models. In proton-nucleus (p-A) collisions, several initial and final state effects, related to the presence of cold nuclear matter (shadowing, energy loss and nuclear absorption) can influence the observed charmonium yields [2, 3]. Finally, in nucleus-nucleus (A-A) collisions, a deconfined phase of quarks and gluons (QGP) is expected to play an important role on the charmonium production [4]. Among the charmonium the $\psi(2S)$ meson is receiving a lot of attention since it is more weakly-bound than the J/ψ and intriguing results have been already obtained at lower collision energies [5]. ALICE data can improve the understanding of $\psi(2S)$ production in hadronic collisions.

2. ALICE detector and data samples

The ALICE detector consists of a central barrel dedicated to particle tracking and identification (in the pseudo-rapidity range of $|\eta| < 0.9$) and a forward spectrometer for the detection of muons (in the interval of $-4 < \eta < -2.5$). More details about the experimental setup can be found in [6]. Charmonium states are detected in the dimuon decay channel using the Muon Spectrometer. The pp analysis is performed in the rapidity interval of $-4 < y_{\rm lab} < -2.5$ using a data sample obtained at the center of mass energy of $\sqrt{s}$=7 TeV and corresponding to an integrated luminosity of $L^{pp}_{\rm int} = 1.35 \pm 0.07\ {\rm pb}^{-1}$. In p-Pb collisions data have been collected at $\sqrt{s_{NN}}$=5.02 TeV in two configurations with inverted beam directions, with the following rapidity coverages: $-4.46 < y_{\rm cms} < -2.96$ ($L_{\rm int}^{\rm Pbp} = 5.81 \pm 0.18$ nb^{-1}, Pb-going direction) at backward rapidity and $2.03 < y_{\rm cms} < 3.53$ ($L_{\rm int}^{\rm pPb} = 5.01 \pm 0.19$ nb^{-1}, p-going direction) at forward rapidity. Finally, the ψ(2S) production in Pb-Pb collisions is studied at $\sqrt{s_{NN}}$=2.76 TeV ($L_{\rm int}^{\rm PbPb} = 68.8 \pm 0.9\ \mu$b^{-1}) in the rapidity region of $-4 < y_{\rm lab} < -2.5$.

3. Results

The ψ(2S) cross section is obtained as: $\sigma^{\psi(2S)} = N^{\psi(2S)}/(L_{\rm int} \cdot {\rm BR}_{\mu^+\mu^-} \cdot \langle A\epsilon \rangle)$, where $N^{\psi(2S)}$, the number of reconstructed ψ(2S), is divided by the branching ratio $BR_{\mu^+\mu^-}$, the detector mean acceptance times efficiency $\langle A\epsilon \rangle$ and finally normalized to the integrated luminosity $L_{\rm int}$.

3.1. pp collisions

The results in pp collisions [7] are shown in Fig.1: the $p_{\rm T}$-differential cross section is compared to LHCb results [8]. A good agreement is observed between the two experiments (small differences are visible at low $p_{\rm T}$, but the comparison is not trivial because of the different rapidity coverage of the two detectors).

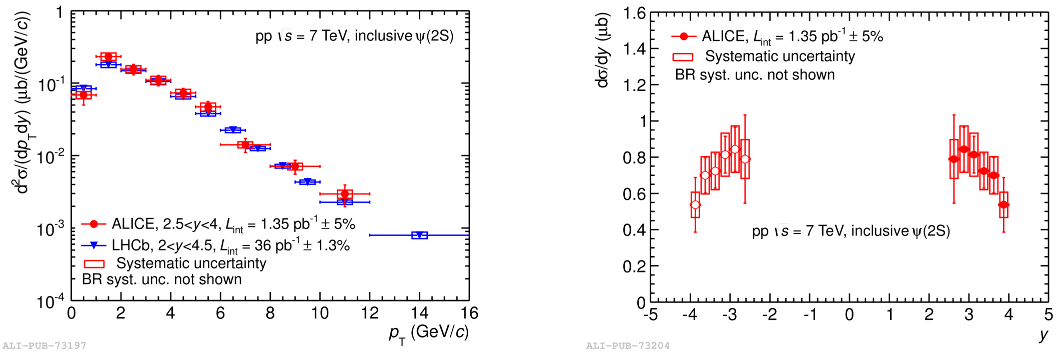

Figure 1. Differential ψ(2S) production cross section as a function of $p_{\rm T}$ (left) and y (right). The $p_{\rm T}$ differential results are compared to LHCb measurements [8].

3.2. p-Pb collisions

The cross section ratio between the tightly bound J/ψ and the loosely bound ψ(2S) charmonium states, ${\rm B.R.}_{\psi(2S)\to\mu^+\mu^-}\sigma_{\psi(2S)}/{\rm B.R.}_{J/\psi\to\mu^+\mu^-}\sigma_{J/\psi}$ is shown in the left panel of Fig.2. These ratios are significantly lower than the ones in pp, both at forward and backward rapidity, pointing to a bigger ψ(2S) suppression (compared to the J/ψ) in p-Pb collisions than in pp.
The double ratios together with that of PHENIX, $[\sigma_{\psi(2S)}/\sigma_{J/\psi}]_{\rm pPb}/[\sigma_{\psi(2S)}/\sigma_{J/\psi}]_{\rm pp}$ is shown in the right panel of Fig.2. These results indicate thate the ψ(2S) suppression is more than the J/ψ to a level of 2.1σ at forward-rapidity and 3.5σ at backward-rapidity. At midrapidity, PHENIX results [9], from $\sqrt{s_{\rm NN}}$ = 200 GeV d-Au collisions, are in qualitative agreement with ALICE data [10].
The nuclear modification factor $R_{\rm pA}$, i.e. the ratio of the ψ(2S) production yield in p-A to the one in pp scaled by the number of binary collisions, is another useful quantity to study the effects of nuclear matter on the ψ(2S) production. The $R_{\rm pA}$ of ψ(2S) and J/ψ, are shown in Fig.3, left, in the two rapidity intervals, indicating a stronger ψ(2S) suppression than that of the J/ψ, both at backward and forward rapidity.

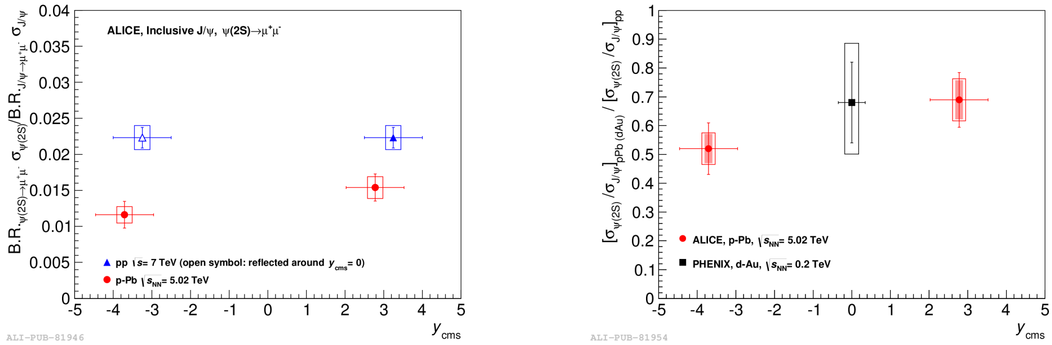

Figure 2. Left: the cross section ratios compared with the corresponding pp results at $\sqrt{s} = 7$ TeV. Right: the double ratios compared to the corresponding PHENIX result [9].

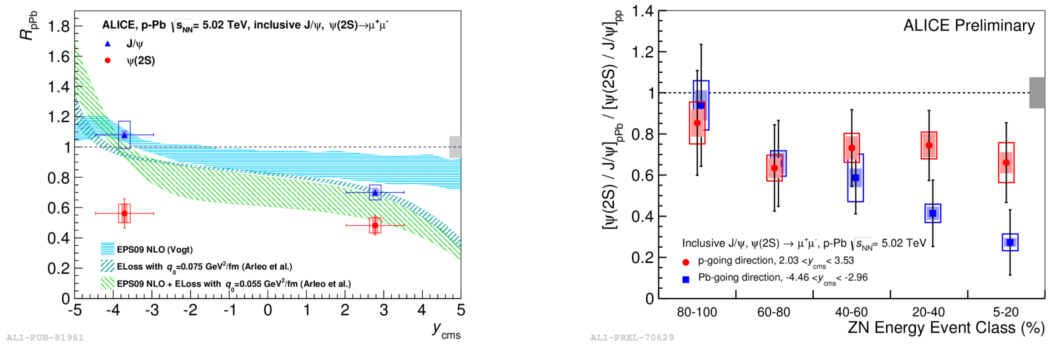

Figure 3. Left: the nuclear modification factor for $\psi(2\mathrm{S})$ compared to the corresponding J/ψ one. Model calculations tuned on J/ψ and including nuclear shadowing and coherent energy loss are also shown. Right: double ratios as a function of the event activity in p-Pb and Pb-p collisions.

ALICE results are compared with theoretical predictions including shadowing only [11] or coherent energy loss, with or without a shadowing contribution [12]. These calculations correspond to the ones performed for the J/ψ: shadowing effects are expected to be similar (within 2-3%), because of the similar gluon distributions that produce the $c\bar{c}$ state, while no dependence on the final state is expected for coherent energy loss. The predictions are in disagreement with the $\psi(2\mathrm{S})$ data and indicate that other final state effects should be considered to explain the observed $\psi(2\mathrm{S})$ suppression. The break-up of the resonance in the nuclear medium depends on the binding energy of the charmonium states and could be considered a cause of the larger $\psi(2\mathrm{S})$ suppression. However, the break-up is relevant only if the charmonium formation time τ_f is smaller than the time τ_c spent by the $c\bar{c}$ pair in the nucleus. Estimates for τ_f [13] are in the range 0.05-0.15 fm/c, while $\tau_c = \langle L \rangle / (\beta_z \gamma)$ [14] (where $\langle L \rangle$ is the average length of nuclear matter crossed by the pair, $\beta_z = \tanh y^{rest}_{c\bar{c}}$ and $\gamma = E_{c\bar{c}}/m_{c\bar{c}}$) is about 10^{-4}fm/c at forward rapidity and about $7 \cdot 10^{-2}$fm/c at backward rapidity. In this situation, the strong $\psi(2\mathrm{S})$ suppression cannot be explained in terms of the $c\bar{c}$ pair break-up (expecially at backward rapidity where the difference between the J/ψ and $\psi(2\mathrm{S})$ R_{pA} is bigger). Finally, the double ratio $[\sigma_{\psi(2\mathrm{S})}/\sigma_{\mathrm{J}/\psi}]_{\mathrm{pPb}}/[\sigma_{\psi(2\mathrm{S})}/\sigma_{\mathrm{J}/\psi}]_{\mathrm{pp}}$ is presented as a function of the event activity (i.e. the event multiplicity based on a measurement from the Zero Degree Calorimeters) in the two rapidity intervals (see Fig.3, right panel). When compared to the J/ψ, the $\psi(2\mathrm{S})$ is more suppressed with increasing event activity, in particular at backward rapidity. This could be another hint of final state effects that can affect the $\psi(2\mathrm{S})$ production, in particular at backward rapidity.

3.3. *Pb-Pb collisions*

The double ratio $[\sigma_{\psi(2S)}/\sigma_{J/\psi}]_{PbPb}/[\sigma_{\psi(2S)}/\sigma_{J/\psi}]_{pp}$ has been studied by ALICE as a function of the collision centrality in two p_T intervals (see Fig.4). In the interval $0 < p_T < 3$ GeV/c, the ψ(2S) signal can be extracted in three centrality classes, while, in the interval $3 < p_T < 8$ GeV/c the upper limit at 95% confidence level is shown for the most central collisions. ALICE results are compared with the CMS double ratios presented in two p_T intervals corresponding to two different rapidity ranges. However, the large statistical and systematic uncertainties of the ALICE results prevent a firm conclusion on the ψ(2S) behaviour in Pb-Pb and the comparison with the CMS values [15] is not straightforward, given also the different kinematic coverage.

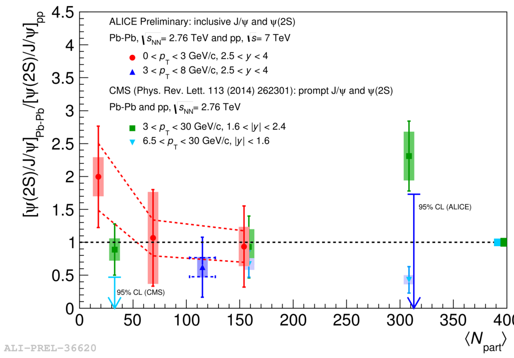

Figure 4. Double ratios $[\sigma_{\psi(2S)}/\sigma_{J/\psi}]_{PbPb}/[\sigma_{\psi(2S)}/\sigma_{J/\psi}]_{pp}$ as a function of the event centrality, in two p_T intervals. CMS measurements [15], in two p_T intervals corresponding to two different rapidity coverages, are also shown.

4. Conclusions

In summary, ALICE collaboration has studied the ψ(2S) production in pp, p-Pb and Pb-Pb collisions. In pp collisions the ψ(2S) production cross sections have been obtained as a function of p_T and y, and are in good agreement with the LHCb measurements. In p-Pb collisions the ψ(2S) is more suppressed than the J/ψ at both forward and backward rapidity. Theoretical models based on shadowing and/or energy loss are in disagreement with data and the break-up of the $c\bar{c}$ pair can hardly explain the strong ψ(2S) suppression, indicating that other final state effects are required. Finally, preliminary results in Pb-Pb collisions have been shown: large uncertainities prevent to make definitive conclusions.

5. References

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