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 $J/\psi$ 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 $J/\psi$ 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.
at $\sqrt{s_{NN}}=5.02$ TeV in two configurations with inverted beam directions, with the following rapidity coverages: $-4.46 < y_{\text{cms}} < -2.96$ ($L_{\text{int}}^{\text{PbPb}} = 5.81 \pm 0.18 \text{ nb}^{-1}$, Pb-going direction) at backward rapidity and $2.03 < y_{\text{cms}} < 3.53$ ($L_{\text{int}}^{\text{PbPb}} = 5.01 \pm 0.19 \text{ nb}^{-1}$, p-going direction) at forward rapidity. Finally, the $\psi(2S)$ production in Pb-Pb collisions is studied at $\sqrt{s_{NN}}=2.76$ TeV ($L_{\text{int}}^{\text{PbPb}} = 68.8 \pm 0.9 \mu\text{b}^{-1}$) in the rapidity region of $-4 < y_{\text{lab}} < -2.5$.

3. Results
The $\psi(2S)$ cross section is obtained as: $\sigma(2S) = N(2S)/\left(L_{\text{int}} \cdot BR_{\mu^+\mu^-} \cdot \langle A\epsilon \rangle \right)$, where $N(2S)$, the number of reconstructed $\psi(2S)$, 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 $L_{\text{int}}$.

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

3.2. p-Pb collisions
The cross section ratio between the tightly bound $J/\psi$ and the loosely bound $\psi(2S)$ charmonium states, $B.R.\psi(2S)_{\rightarrow \mu^+\mu^-}/\sigma(2S)/B.R.\ J/\psi_{\rightarrow \mu^+\mu^-}/\sigma(1S)$ 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 $\psi(2S)$ suppression (compared to the $J/\psi$) in p-Pb collisions than in pp.

The double ratios together with that of PHENIX, $\sigma(2S)/\sigma(1S)$, is shown in the right panel of Fig.2. These results indicate that the $\psi(2S)$ suppression is more than the $J/\psi$ to a level of $2.1\sigma$ at forward-rapidity and $3.5\sigma$ at backward-rapidity. At midrapidity, PHENIX results [9], from $\sqrt{s_{NN}} = 200$ GeV d-Au collisions, are in qualitative agreement with ALICE data [10].

The nuclear modification factor $R_{pA}$, i.e. the ratio of the $\psi(2S)$ 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 $\psi(2S)$ production. The $R_{pA}$ of $\psi(2S)$ and $J/\psi$, are shown in Fig.3, left, in the two rapidity intervals, indicating a stronger $\psi(2S)$ suppression than that of the $J/\psi$, 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 $\psi(2S)$ compared to the corresponding $J/\psi$ one. Model calculations tuned on $J/\psi$ 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 $J/\psi$: 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 $\psi(2S)$ data and indicate that other final state effects should be considered to explain the observed $\psi(2S)$ 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 $\psi(2S)$ suppression. However, the break-up is relevant only if the charmonium formation time $\tau_f$ is smaller than the time $\tau_c$ spent by the $c\bar{c}$ pair in the nucleus. Estimates for $\tau_f$ [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, $\beta_z = \tanh \gamma_{c\bar{c}}$ 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 $\psi(2S)$ suppression cannot be explained in terms of the $c\bar{c}$ pair break-up (especially at backward rapidity where the difference between the $J/\psi$ and $\psi(2S)$ $R_{pA}$ is bigger). Finally, the double ratio $[\sigma_{\psi(2S)/\sigma_{J/\psi}}]_{p\bar{p}}/[\sigma_{\psi(2S)/\sigma_{J/\psi}}]_{pp}$ 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 $J/\psi$, the $\psi(2S)$ 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 $\psi(2S)$ 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 $\psi(2S)$ 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 $\psi(2S)$ behaviour in Pb-Pb and the comparison with the CMS values [15] is not straightforward, given also the different kinematic coverage.

![Figure 4.](image.png)

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 $\psi(2S)$ production in pp, p-Pb and Pb-Pb collisions. In pp collisions the $\psi(2S)$ 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 $\psi(2S)$ is more suppressed than the $J/\psi$ 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 $\psi(2S)$ suppression, indicating that other final state effects are required. Finally, preliminary results in Pb-Pb collisions have been shown: large uncertainties prevent to make definitive conclusions.

5. References

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