

$\psi(2S)$ Production at the LHC

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Abstract. We calculate the production of $\psi(2S)$ and the pertinent double ratio of its nuclear modification factor (R_{AA}) over that of the J/ψ in Pb-Pb collisions at the LHC. Based on a transport model with temperature dependent reaction rates, a sequential regeneration pattern emerges: the larger $\psi(2S)$ width, relative to the J/ψ , around and below the critical temperature, implies that most of the $\psi(2S)$ states are regenerated later in the evolution of the fireball. This has noticeable consequences for the transverse-momentum (p_T) spectra of the regenerated charmonia. While the total yield of $\psi(2S)$ meson remains smaller than those of J/ψ 's, their harder p_T spectra can produce a double ratio above unity for a $p_T > 3$ GeV cut, as applied by the CMS collaboration. A significant uncertainty in our calculations is associated with the values of the temperature where most of the $\psi(2S)$ regeneration occurs, *i.e.*, the quantitative temperature dependence of its inelastic width.

1. Introduction

Intense experimental efforts are ongoing to measure the production systematics of heavy quarkonia in heavy-ion collisions (HICs), to establish a robust benchmark for studying their modifications in hot and dense QCD matter [1, 2, 3, 4]. The sequence of bound states in the vacuum spectrum of heavy quarkonia provides a unique probe of how the basic QCD force evolves in the medium. In the charmonium sector, where extensive measurements of J/ψ production have revealed important information about its in-medium kinetics, the $\psi(2S)$ state is now becoming a rather hot topic. A strong $\psi(2S)$ suppression relative to the J/ψ has been observed both in proton-nucleus (pA) collisions at RHIC and the LHC [5, 6], and in nucleus-nucleus collisions [7] at the SPS, generally associated with final-state interactions together with a much smaller binding energy of the $\psi(2S)$. It was therefore rather intriguing when the CMS collaboration found an enhancement of the $\psi(2S)/J/\psi$ ratio in central Pb-Pb(2.76 TeV) collisions, relative to pp collisions [8]. More precisely, this enhancement was found in the kinematic range of forward-rapidities ($1.6 < |y| < 2.4$) and transverse momenta $p_T > 3$ GeV, while it turns out to be suppressed around mid-rapidity and $p_T > 6.5$ GeV. In Ref. [9] we suggested a sequential regeneration of J/ψ and $\psi(2S)$ states as a potential mechanism to understand this phenomenon within schematic model scenarios. In the present paper we expand on this work by revisiting the results within a more quantitative rate equation approach [10, 11, 12] (Sec. 2), discussing the double ratio and its main uncertainties in Pb-Pb(2.76 TeV) collisions (Sec. 3), and providing predictions at 5.02 TeV (Sec. 4). We conclude in Sec. 5.

2. Transport model for charmonia production

Our approach for quarkonium kinetics in HICs utilizes a rate equation,

$$\frac{dN_{\Psi}}{d\tau} = -\Gamma_{\Psi}(T) [N_{\Psi} - N_{\Psi}^{\text{eq}}(T)] , \quad (1)$$

which evolves the charmonium yields, N_{Ψ} ($\Psi=J/\psi, \psi(2S), \chi_c(1P)$) through an expanding fireball. The pertinent transport coefficients are: (a) the inelastic reaction rate $\Gamma_{\Psi}(T)$ in the quark-gluon plasma (QGP) and in hadronic matter. ‘‘Quasifree’’ dissociation is adopted as the dominant mechanism to break up J/ψ and $\psi(2S)$ states in the QGP where both have relatively small binding energies, $E_B \leq T$, while hadronic dissociation rate is calculated from a meson exchange model with $SU_f(4)$ flavor symmetry; (b) the thermal equilibrium limit $N_{\Psi}^{\text{eq}}(T)$ which controls the rate of regeneration. It is evaluated from the statistical model on either partonic or hadronic basis and includes non-equilibrium corrections due to a finite correlation volume and incomplete charm-quark thermalization [10].

To compute p_T spectra, we decompose the solution of the rate equation into two parts, one characterizing the primordial (direct) production and the other from regeneration of Ψ states. The Boltzmann equation is used to calculate the p_T -spectra of the primordial part via

$$\frac{\partial f(\vec{x}, \vec{p}, t)}{\partial t} + \vec{v} \cdot \frac{\partial f}{\partial \vec{x}} = -\Gamma_{\Psi}(\vec{p}, T) f(\vec{x}, \vec{p}, t) \quad (2)$$

where f is the phase space distribution of charmonia and $\vec{v} = \vec{p}/E_p$ their velocity. Escape effects are included by setting the rate to zero if a state exits the fireball boundary. The p_T -spectra of the regeneration component are evaluated from a blastwave description assuming thermal equilibrium,

$$\frac{dN}{p_T dp_T} \simeq m_T \int_0^R r dr K_1 \left(\frac{m_T \cosh(\rho(r))}{T} \right) I_0 \left(\frac{p_T \sinh(\rho(r))}{T} \right) \quad (3)$$

where $m_T = \sqrt{p_T^2 + m^2}$ is the transverse mass and $\rho(r) = \tanh^{-1}(v(r, t, b))$ the transverse-flow profile of the fireball. Later times in the evolution lead to a harder spectra, as lower temperatures are overcompensated by the blue-shift due to larger flow. The blastwave spectra are normalized to the regeneration yield obtained from the p_T -independent rate equation. The pertinent R_{AA} ’s are computed in the usual way as a ratio of AA and pp spectra, $R_{AA} = (N^{AA})/(N_{\text{coll}}N^{\text{pp}})$, scaled by the binary collision number, N_{coll} , obtained from the optical Glauber model.

The space-time evolution of the temperature is constructed from a simple ansatz for an iso- and isentropically expanding fire cylinder volume, $V_{\text{FB}}(t)$. Using conservation of total entropy,

$$S_{\text{tot}} = s(T)V_{\text{FB}}(t) , \quad (4)$$

together with a suitable equation of state for the entropy density, $s(T)$ (for which we use a QGP quasi-particle and hadron-resonance gas connected through a mixed phase at $T_c=180$ MeV), the time-dependent temperature is obtained for a given centrality by matching S_{tot} to the final-state hadron multiplicities.

3. Sequential regeneration in Pb-Pb(2.76 TeV)

Our results for the centrality dependence of the R_{AA} ‘‘double ratio’’, $R_{AA}(\psi(2S))/R_{AA}(J/\psi)$, as obtained from the kinetic rate equation are displayed in Fig. 1. They confirm the results of our previously published schematic-model study [9]; moderate quantitative deviations arise from the more restrictive model approach which intimately couples the suppression and regeneration yields. The basic trends of the CMS data in Pb-Pb(2.76 TeV) collisions for the two p_T cuts are still reproduced (left panel of Fig. 1), although the maximal enhancement in central collisions is

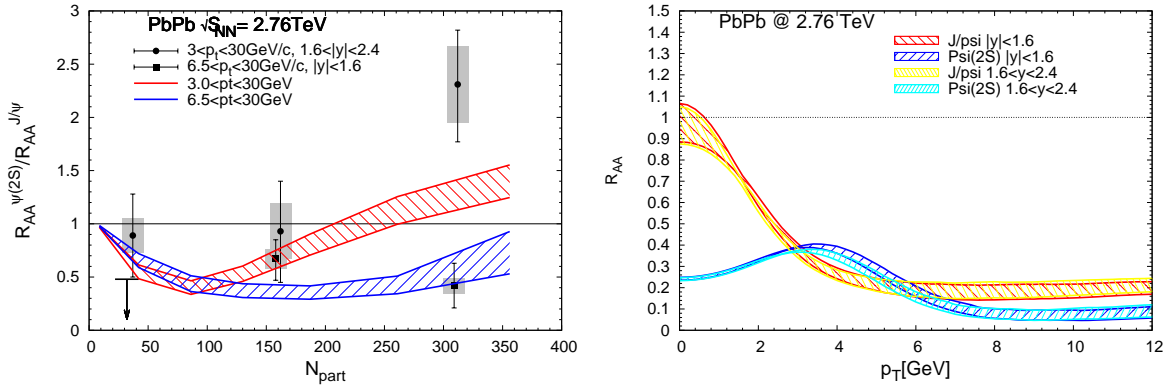


Figure 1. Charmonium production in Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV within the kinetic rate equation approach. Left panel: centrality dependence of the double ratio $R_{AA}(\psi(2S))/R_{AA}(J/\psi)$ for $p_T > 6.5$ GeV and $|y| < 1.6$ (blue band) as well as $p_T > 3$ GeV and $1.6 < |y| < 2.4$ (red band), compared to CMS data (points with error bars) [8]. Right panel: p_T dependence of the individual J/ψ and $\psi(2S)$ R_{AA} 's for central collisions. A 10% shadowing is assumed.

not fully reproduced. Nevertheless, the marked increase of the double ratio beyond one remains a key signature of the *sequential regeneration* mechanism, whereby most of the $\psi(2S)$ are formed later in the evolution, thus being blue-shifted to p_T above 3 GeV (red band). The regenerated J/ψ are mostly concentrated at momenta $p_T \leq 3$ GeV, consistent with ALICE data [13]. On the other hand, for $p_T > 6.5$ GeV (blue band), the regeneration component has essentially faded away (being exponentially suppressed relative to the primordial power-law spectra), and the stronger suppression of the primordial $\psi(2S)$ relative to the J/ψ leads to a double ratio below one. The explicit p_T dependence of the $\psi(2S)$ and J/ψ R_{AA} s for central Pb-Pb is depicted in the right panel of Fig. 1.

The largest contribution to the uncertainty bands in Fig. 1 is due to the choice of the average temperature, \bar{T}_{reg} , at which the blast-wave expression is evaluated, representing the window where most of the regeneration occurs. From the time dependence of the regeneration yields we estimate $\bar{T}_{reg} \simeq 160$ -165 MeV for the $\psi(2S)$ and $\bar{T}_{reg} \simeq 180$ -200 MeV for the J/ψ [9] which can describe the ALICE data for $R_{AA}^{J/\psi}(p_T)$ at 2.76 TeV [14]. We also varied the initial spectra by inclusion of a moderate Cronin effect with a broadening parameter of up to $a_{qN} = 0.2 \text{ GeV}^2/\text{fm}$.

4. Predictions for 5.02 TeV

For our predictions at $\sqrt{s_{NN}}=5.02$ TeV, we implement the following changes. The charged particle multiplicity, *i.e.*, S_{tot} , is increased by 22.5% [15], yielding an increase of $\sim 7\%$ for the initial temperature. Using experimental [16] and theoretical [17] results as guidance, the charm cross section in pp, $\frac{d\sigma_{c\bar{c}}}{dy}$, is increased by $\sim 40\%$, from 0.65(0.59) mb to 0.92(0.84) mb at mid-(forward) rapidity, and likewise for charmonia. Their initial p_T spectra in pp are updated (somewhat harder than at 2.76 TeV), and a 10% additional shadowing is assumed. Finally, for the J/ψ blast-wave spectra, we found that a somewhat lower temperature range of $T=179$ -181 MeV (representing a time window around the mixed phase) better describes the preliminary ALICE dimuon data for the J/ψ $R_{AA}(p_T)$ at 5.02 TeV as presented at this meeting [18].

The resulting R_{AA} double ratios for the different p_T cuts show a trend of moving closer together (see left panel of Fig. 2). Due to the increase in transverse flow, more regenerated J/ψ are pushed beyond the $p_T > 3$ GeV thus suppressing the red band, while more $\psi(2S)$ are pushed

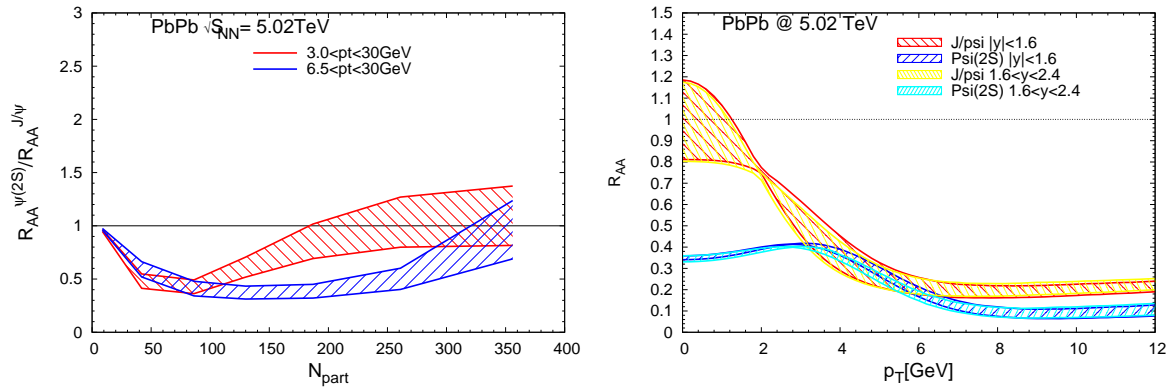


Figure 2. Same as Fig. 1 but for Pb-Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV.

beyond $p_T > 6.5$ GeV thus enhancing the blue band, cf. also the individual $R_{AA}(p_T)$'s in the right panel of Fig. 2.

5. Conclusions

In summary, the application of a kinetic rate equation approach to charmonium production in HICs suggests a scenario where $\psi(2S)$ states are regenerated significantly later in the fireball evolution than J/ψ mesons. This emerges from inelastic reaction rates which are significantly larger for the $\psi(2S)$ than the J/ψ in the later (hadronic) stages of the fireball. This “sequential regeneration” is a direct consequence of sequential suppression plus detailed balance. We have found that the phenomenological implications of this scenario can help to explain the puzzling observation of the CMS $\psi(2S)$ -to- J/ψ R_{AA} double ratio.

Acknowledgments

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