ψ(2S) Production at the LHC

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Abstract. We calculate the production of ψ(2S) and the pertinent double ratio of its nuclear modification factor ($R_{AA}$) over that of the $J/\psi$ in Pb-Pb collisions at the LHC. Based on a transport model with temperature dependent reaction rates, a sequential regeneration pattern emerges: the larger ψ(2S) width, relative to the $J/\psi$, around and below the critical temperature, implies that most of the ψ(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 ψ(2S) meson remains smaller than those of $J/\psi$’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 ψ(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]. 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 $J/\psi$ production have revealed important information about its in-medium kinetics, the ψ(2S) state is now becoming a rather hot topic. A strong ψ(2S) suppression relative to the $J/\psi$ has been observed in both proton-nucleus (pA) collisions at RHIC and the LHC [4, 5], and in nucleus-nucleus collisions [6] at the SPS, generally associated with final-state interactions together with a much smaller binding energy of the ψ(2S). It was therefore rather intriguing when the CMS collaboration found an enhancement of the ψ(2S)/$J/\psi$ ratio in central Pb-Pb(2.76 TeV) collisions, relative to pp collisions [7]. 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. [8] we suggested a sequential regeneration of $J/\psi$ and ψ(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 [9, 10, 11] (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,

\[ \frac{dN_\Psi}{d\tau} = -\Gamma_\Psi(T) [N_\Psi - N_{eq}(T)] , \]

which evolves the charmonium yields, \( N_\Psi (\Psi=J/\psi, \psi(2S), \chi_c(1P)) \) 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 \( J/\psi \) 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 \( N_{eq}(T) \) which controls the rate of regeneration. It is evaluated from the statistical model in either partonic or hadronic basis and includes non-equilibrium corrections due to a finite correlation volume and incomplete charm-quark thermalization [9].

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 \( \Psi \) states. The Boltzmann equation is used to calculate the \( p_T \)-spectra of the primordial part via

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

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,

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

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, \( R_{AA} = (N_{AA})/(N_{coll}N_{pp}) \), 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, \( V_{FB}(t) \). Using conservation of total entropy,

\[ S_{tot} = s(T)V_{FB}(t) \]

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 \( T_c=180 \text{ MeV} \)), 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 [7]. Right panel: $p_T$ dependence of the individual $J/\psi$ and $\psi(2S)$ $R_{AA}$’s for central collisions. A 10% shadowing is assumed in the $p_T$-spectra according to EPS09 NLO [12].

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 $J/\psi$ 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 $J/\psi$ leads to a double ratio below one. The explicit $p_T$ dependence of the $\psi(2S)$ and $J/\psi$ $R_{AA}$’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, $T_{\text{reg}}$, 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 $T_{\text{reg}} \simeq 160-165$ MeV for the $\psi(2S)$ and $T_{\text{reg}} \simeq 180-200$ MeV for the $J/\psi$ [8] which can describe the ALICE data for $R_{AA}(J/\psi)$ 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 $a_{gN}=0.2$ GeV$^2$/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., $S_{\text{tot}}$, is increased by 22.5% [15], yielding an increase of ~7% for the initial temperature. Using experimental [16] and theoretical [17] results as guidance, the charm cross section in pp, $d\sigma_c/dy$, is increased by ~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 $J/\psi$ 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 $R_{AA}(J/\psi)$ 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 $J/\psi$ are pushed beyond the $p_T>3$ GeV thus suppressing the red band, while more $\psi(2S)$ are pushed
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 $J/\psi$ mesons. This emerges from inelastic reaction rates which are significantly larger for the $\psi(2S)$ than the $J/\psi$ 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-$J/\psi$ $R_{AA}$ double ratio.

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