# $\psi(2S)$ Transport in heavy-ion collisions at the LHC

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## I. Introduction

The production of charmonia in ultra-relativistic heavy-ion collisions (URHICs) has been an active area of research for four decades. The initially proposed $J/\psi$ suppression signature of quark–gluon plasma (QGP) formation [1] has developed into more comprehensive transport models that account for regeneration mechanisms as dictated by the principle of detailed balance. This ensures that the abundances of charmonia approach their pertinent equilibrium limits, see, e.g., Refs. [2, 3] for reviews. Recent pioneering ALICE measurements [4] of $\psi(2S)$ production at low transverse momenta ($p_T$) are providing critical constraints to model calculations and can be used to test a "sequential regeneration" of $J/\psi$ and $\psi(2S)$ mesons [5].

## II. Methods

We provide an update of our semi-classical transport approach [6, 7] for quarkonium production in URHICs, focusing on $J/\psi$ and $\psi(2S)$ mesons in 5.02 TeV Pb-Pb collisions at the Large Hadron Collider (LHC) [8]. We have employed the most recent charm-production cross sections reported in pp collisions, which are pivotal for the magnitude of the regeneration contribution, and their modifications due to cold-nuclear-matter (CNM) effects. We have also utilized an improved input for the in-medium charmonium binding energies to ensure an approximately constant $J/\psi$ mass, consistent with our bottomonium calculations [9]. This update was rather mild and has a very small net effect on the total production. We have further reassessed the relevance of inelastic-scattering versus gluo-dissociation mechanisms, confirming them to be rather negligible.

## III. Results

In our applications to phenomenology, we specifically elaborate on predictions for recent ALICE data on $\psi(2S)$ production in 5.02 TeV Pb-Pb collisions at the LHC [4]. Multi-differential observables are calculated in terms of nuclear modification factor ($R_{\mathrm{AA}}$) as a function of centrality, transverse momentum, and rapidity, including the contributions from feeddown from bottom hadron decays. Our predictions for $\psi(2S)$ production, both in terms of the nuclear modification and the ratio relative to $J/\psi$ production, are in good agreement with the data, see Fig. 1. Specifically, the $\psi(2S)/J/\psi$ ratio is significantly larger than what one would expect from the equilibrium values at a given temperature. This originates from the fact that the $\psi(2S)$ is regenerated much later in the fireball evolution than the more strongly bound the $J/\psi$, due to its much smaller binding energy. The mechanism of sequential regeneration relative to the more strongly bound $J/\psi$ meson thus plays an important role in interpreting recent ALICE data.

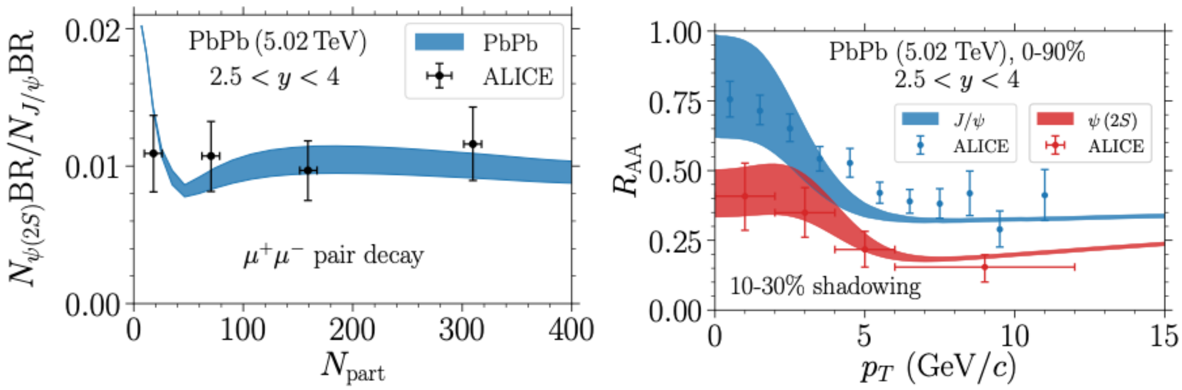


FIG. 1. Left: the ratio of $\psi(2S)$ over $J/\psi$ as a function of centrality ($N_{part}$) in Pb-Pb (5.02 TeV) collisions at forward rapidity, compared to ALICE data [4]. The bands indicate the uncertainty of the $\psi(2S)$ dissociation temperature around the mixed phase, $T_{diss}$ =179–180 MeV. Right: nuclear modification factor ($R_{AA}$) as a function of transverse momentum ($p_T$) for inclusive $J/\psi$ (blue) and $\psi(2S)$ (red) production at forward rapidity in 0–90% Pb-Pb (5.02 TeV) collisions, compared to ALICE data [4]. The bands indicate the uncertainty due to nuclear shadowing.

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