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Charmonium production measurements from small to large systems at LHCb

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Abstract. Modifications of quarkonium production in hadronic collisions provide key experimental observables to probe the interaction of heavy quarks with nuclear matter. The excited $\psi(2S)$ charmonium state, with its relatively low binding energy, is especially sensitive to such effects. New LHCb measurements on the $\psi(2S)/J/\psi$ production ratio in pp, pPb, and PbPb collisions, together with prospects for forthcoming measurements using Run 3 data are presented here compared to the latest theory predictions.

1 Introduction

The production of charmonia, in particular the J/ψ and $\psi(2S)$ states, has long been considered a key probe for understanding the properties of the quark–gluon plasma (QGP). Due to their large masses and short formation times, they are produced early in the collision and experience the entire evolution of the medium. The idea that charmonium suppression is an indicator of QGP formation was first introduced by T. Matsui and H. Satz [1], who proposed that in deconfined nuclear matter, $c\bar{c}$ pairs become unbound under the effect of colour screening, with different yields for different states depending on their binding energy. More recently, regeneration mechanisms, either inside the QGP or at the phase boundary, have been considered an important ingredient in the description of J/ψ yields at the LHC and RHIC energies [2]. To quantify the suppression, the production of charmonia in nucleus–nucleus collisions is compared to that in proton–proton (pp) and proton–nucleus (pA) collisions, which serve as essential baselines. The degree of suppression, and in particular the comparisons between different collision systems and charmonium states, provide insights into the properties of the QGP. Excited states like the $\psi(2S)$, which are more weakly bound than the J/ψ, are expected to melt at lower temperatures, leading to sequential suppression patterns. This makes the measurement of the $\psi(2S)/J/\psi$ ratio across different collision systems, and especially in PbPb, a sensitive probe of QGP dynamics.

In the following, the most recent LHCb measurements of the charmonium production ratio in pp and pPb collisions as a function of event multiplicity, and in PbPb collisions as a function of centrality, are presented. Moreover an outlook on upcoming Run 3 results is provided.

The results shown below are obtained using data collected by the LHCb detector. It is a single-arm forward spectrometer with a pseudorapidity coverage, $2 < \eta < 5$, unique at

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the LHC [3, 4]. The detector includes a high-precision tracking system providing excellent vertex and momentum resolution, two ring-imaging Cherenkov detectors for charged-particle identification, a calorimeter system to identify photons, electrons and hadrons, and a muon system. During Run 2, LHCb collected data in all available collision systems: pp, pPb (and Pbp), PbPb, as well as fixed-target interactions between the circulating beams and noble gases injected into the interaction region via the SMOG device [5].

2 Multiplicity dependence of $\sigma(\psi(2S))/\sigma(J/\psi)$ in pp collisions at $\sqrt{s} = 13$ TeV

The production of charmonia in pp collisions represents the essential reference for interpreting heavy-ion results, and is also of intrinsic interest to test NRQCD predictions on the relative contributions of color-singlet and color-octet mechanisms in quarkonium production. LHCb has recently measured the $\psi(2S)/J/\psi$ production ratio as a function of the event multiplicity at forward rapidity, exploiting 13 TeV pp data [6]. The measurement is performed separately for nonprompt charmonia originating from b-hadron decays and for prompt production, the latter most interesting to compare with theory predictions. The multiplicity of the event is estimated by the number of tracks in the LHCb VErtex LOcator (VELO) for each primary vertex.

The left plot of Fig. 1 shows that the ratio from b-hadron decays exhibits no significant dependence on the event activity. In contrast, a clear decreasing trend of the prompt $\psi(2S)/J/\psi$ ratio is observed with increasing multiplicity. This behaviour is well described by the comovers interaction model [7], suggesting that final-state interactions with the produced medium already play a role in high-multiplicity pp collisions.

3 Multiplicity dependence of $\sigma(\psi(2S))/\sigma(J/\psi)$ in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

Proton–nucleus collisions provide crucial insight into cold nuclear matter (CNM) effects and allow one to disentangle them from the hot-medium effects observed in nucleus–nucleus collisions. LHCb has measured the $\psi(2S)/J/\psi$ production ratio as a function of the event multiplicity using pPb collisions collected at $\sqrt{s_{NN}} = 8.16$ TeV in 2016. The measurement has been performed in both forward (pPb) and backward (Pbp) rapidity regions [8], corresponding to center-of-mass rapidity of $1.5 < y^* < 4.0$ and $-5.0 < y^* < -2.5$, respectively. As previously defined the multiplicity is estimated by the number of tracks in the VELO for each primary vertex, using simulation it is translated in density of charged primary tracks per unit of pseudorapidity ($dN_{ch}/d\eta$) to allow comparison with other collision systems and experiments.

As in pp collisions, the ratio from b-hadron decays remains flat with multiplicity. For prompt production, as shown in the right plot of Fig. 1, a decreasing trend with multiplicity is found in the pPb (forward) configuration, consistent with the behavior observed in pp collisions. On the other hand, the Pbp (backward) configuration shows a stronger suppression with a flatter dependence, especially at higher multiplicities. The forward results support the comovers scenario, while the backward ones exhibit features in agreement with ALICE PbPb results [9], pointing to stronger final-state effects at play.

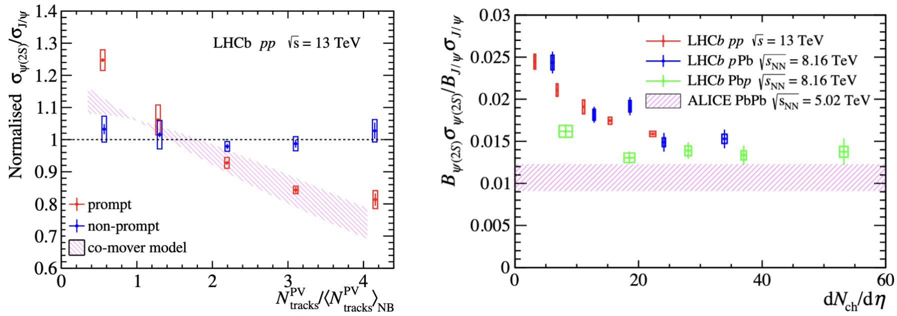

Figure 1. Left plot: $\sigma(\psi(2S))/\sigma(J/\psi)$ ratio as a function of the event multiplicity for nonprompt (blue dots) and prompt (red dots) production, compared to comover predictions [7] (pink band). Right plot: Ratio of prompt $\sigma(\psi(2S))/\sigma(J/\psi)$ as a function of the event multiplicity in pPb (blue dots) and Pbp (green dots) collisions at $\sqrt{s_{NN}}$ = 8.16 TeV compared to pp (red dots) and ALICE PbPb results [9] (orange band).

4 Centrality dependence of $\sigma(\psi(2S))/\sigma(J/\psi)$ in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

The first measurement of the prompt $\psi(2S)/J/\psi$ production ratio in PbPb collisions at forward rapidity has been performed by LHCb [10]. The ratio has been measured as a function of the event centrality, whose classes are determined using a Glauber model approach [11].

The results shown in Fig. 2 indicate a suppression of the $\psi(2S)$ relative to the J/ψ, with a rather flat centrality dependence. As shown in the left plot of the figure, the measurement is in agreement with previous measurements of the same quantity. Comparisons with theoretical models, shown in the right plot, demonstrate that the TAMU transport model [12] provides a better description of the data, while the Statistical Hadronization Model (SHMc) [13] underestimates the ratio, although it captures the flat trend.

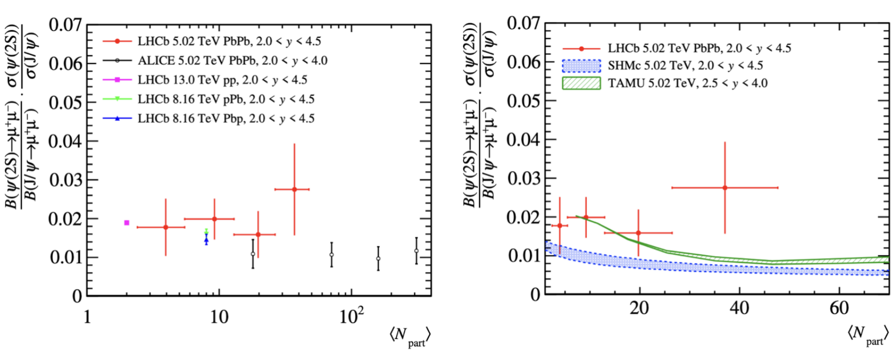

Figure 2. Ratio $\sigma(\psi(2S))/\sigma(J/\psi)$ as a function of centrality in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV (red dots). The measurement is compared with previous measurements (left) and theoretical predictions (right).

5 Run 3 outlook

LHCb has already collected its largest PbPb sample in 2024, corresponding to an integrated luminosity of about 0.43 nb^{-1}. Thanks to the Upgrade I detector [14], improved reconstruction efficiencies and extended centrality reach up to $\sim 30\%$ are achieved. Preliminary studies indicate the possibility of precisely separating prompt and nonprompt charmonium production in forward PbPb collisions, using a fit on the pseudo-proper time (t_z) distribution, as observed in the left plot of Fig. 3.

In addition, the upgraded fixed-target system SMOG2 has been successfully operated, providing high-quality data for pA and PbA collisions in 2024. These samples will enable complementary studies of charmonium production in cold and hot nuclear matter, thereby strengthening the interpretation of heavy-ion results. The right plot of Fig. 3 shows the dimuon invariant mass distribution and fit obtained with about 40 hours of pH_2 data-taking in 2024.

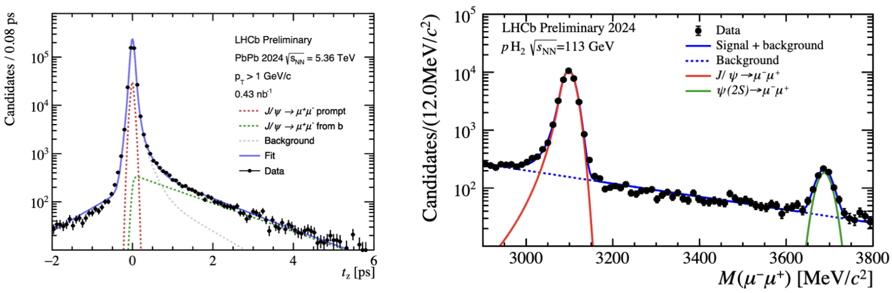

Figure 3. Preliminary Run 3 results from LHCb. Separation of prompt and nonprompt J/ψ candidates in PbPb collisions at $\sqrt{s_{NN}} = 5.36$ TeV (left). Charmonium invariant mass distribution for dimuon candidates in pH_2 fixed-target collisions collected in 2024 (right).

6 Conclusions

Charmonium production has been studied at LHCb across different collision systems, from pp to pPb and PbPb. The prompt $\psi(2S)/J/\psi$ ratio exhibits a decreasing trend with multiplicity in pp and forward pPb collisions, consistent with the comovers scenario, while backward pPb collisions display stronger suppression compatible with PbPb results. The first forward-rapidity PbPb measurement shows a flat centrality dependence, in agreement with theoretical models incorporating regeneration mechanisms.

Looking ahead, the unprecedented statistics from Run 3 and the new SMOG2 capabilities will allow LHCb to provide decisive input on charmonium production and its modification in nuclear matter effects, contributing significantly to the understanding of QGP properties.

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