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Charmonium production from small to large systems at LHCb

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Quarkonium production is a powerful probe of heavy-quark interactions with nuclear matter, and one of the proposed observables for this purpose is the $\psi(2S)$-to-J/ψ cross-section ratio. LHCb has recently measured this ratio in Run 2 data as a function of multiplicity in pp and pPb collisions, and as a function of centrality in PbPb collisions. Results in pp and forward pPb show a multiplicity dependence consistent with co-movers, while backward Pbp is flat. The cross-section ratio in PbPb is in agreement with previous results and best described by TAMU transport model. With its Run 3 upgrades, including the SMOG2 fixed-target system, LHCb can now perform higher-precision PbPb studies, explore new collision systems, and thereby improve our understanding of the medium created in heavy-ion collisions.

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1. Introduction

The production of charmonia (bound states of $c\bar{c}$) was early identified as a key probe for studying the properties of the quark–gluon plasma (QGP): since these states are formed early in the collision, they are sensitive to the entire evolution of the medium.

Among the proposed signatures of the QGP in charmonium production, one of the earliest and most prominent is the suppression of these states due to colour screening [1]. In this scenario, the deconfined colour charges in the QGP screen the interaction between the $c\bar{c}$, preventing them from binding. The amount of suppression is related to the temperature of the QGP and the binding energy of the state (the more weakly bound $\psi(2S)$ is expected to be more suppressed than J/ψ). More recently it was proposed [2] that at the high energies reached at the LHC, c and $\bar{c}$ are produced so abundantly that they can recombine and form charmonium states, leading to an enhancement in their production.

Experimentally, in nucleus–nucleus (A–A) collisions, the relative yields between different charmonium states are expected to change with the centrality of the collision as it is closely related to the temperature of the medium. To quantify the modification of particle production in A–A collisions, the results need to be compared to those from proton–proton (pp) and proton–nucleus (pA) collisions, which serve as baselines. In particular, pA collisions provide a handle to disentangle Cold Nuclear Matter (CNM) effects from hot-medium effects.

The LHCb collaboration has recently published new Run 2 results on the $\psi(2S)$-to-J/ψ production ratio as a function of event multiplicity in pp [3] and pPb [4] collisions, and as a function of centrality in PbPb [5] collisions, which are presented in Secs. 2, 3 and 4, respectively.

The LHCb detector [6, 7] is a forward single-arm spectrometer with a unique pseudorapidity coverage of $2 < \eta < 5$. Thanks to its unique forward experimental setup, the LHCb detector geometry allows the study of two centre-of-mass rapidity (y^*) regions in proton-lead collisions: forward (pPb) and backward (Pbp), corresponding to $1.5 < y^* < 4.0$ and $-5.0 < y^* < -2.5$, respectively. The detector is equipped with state-of-the-art vertexing, tracking and particle identification. Vertex reconstruction is performed by the VErtex LOcator (VELO), which provides excellent spatial resolution close to the interaction point. The detector was upgraded for Run 3, and Sec. 5 presents the main upgrades as well as the prospects for forthcoming results and physics opportunities.

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

The LHCb collaboration has measured the $\psi(2S)$-to-J/ψ cross-section ratio as a function of event multiplicity in pp collisions at $\sqrt{s} = 13$ TeV [3]. These kind of measurements serve a threefold purpose. First, they provide a baseline for interpreting results in systems subject to nuclear effects. Second, they offer insight into the still not fully understood mechanisms of charmonium production. Third, the dependency on multiplicity yields valuable information to help understand the QGP-like signatures observed at high multiplicities in small systems.

Fig. 1 shows the results for prompt and non-prompt normalised $\psi(2S)$-to-J/ψ cross-section ratio, where the two components were separated using the distance between the primary vertex (PV) and the dimuon decay vertex. The event multiplicity is estimated from the number of VELO tracks used to reconstruct the PV, $N^{\mathrm{PV}}_{\mathrm{tracks}}$, and is normalized by its mean value in no-bias collisions,

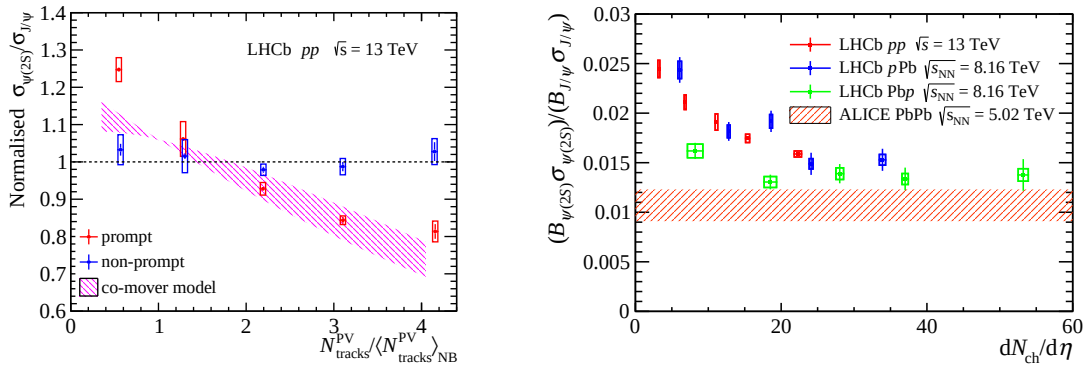

Figure 1: *Left*: Normalised $\psi(2S)$-to-J/ψ cross-section ratio as a function of multiplicity for non-prompt (blue) and prompt (red) production [3] compared to co-mover predictions [8] (magenta band). *Right*: $\psi(2S)$-to-J/ψ cross-section ratio as a funciton track density in pPb (blue) and Pbp (green) [4] compared to pp (red) [3] and ALICE PbPb results (orange band) [9].

$\langle N^{\rm PV}_{\rm tracks}\rangle^{\rm NB}$. Non-prompt ratio shows no dependence on multiplicity. On the contrary, prompt results show an evident decrease with multiplicity.

Predicitions from the co-movers model [8] are also shown in Fig. 1. In this model, charmonium suppression arises from final-state interactions with soft particles, or co-movers, produced in the same collision. The suppression grows with the medium density and is stronger for states with smaller binding energies. The prompt cross-section ratio presented here is consistent with the co-mover predictions at high multiplicities, 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 $\sqrt{s} = 8.16$ TeV

The same observable as in pp has also been measured by LHCb in proton–lead collisions at $\sqrt{s_{NN}} = 8.16$ TeV in both forward (pPb, $1.5 < y^* < 4.0$) and backward (Pbp, $-5.0 < y^* < -2.5$) configurations [4]. The prompt $\psi(2S)$-to-J/ψ cross-section ratio (normalized by the respective branching fractions) is shown in Fig. 1, together with the pp results [3] and the PbPb measurement from ALICE at $\sqrt{s_{NN}} = 5.02$ TeV [9]. To enable comparison across different collision systems, the results are presented as a function of the charged-particle multiplicity density, $\mathrm{d}N_{ch}/\mathrm{d}\eta$.

As shown, the pPb ratio is consistent with the pp result, suggesting that both systems create a similar final-state environment where suppression is dominated by co-movers, as discussed in Sec. 2. In contrast, the Pbp ratio agrees with the PbPb result from ALICE, indicating that a similar physical mechanism is at play in both systems, possibly involving additional suppression effects such as the formation of a QGP.

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

The $\psi(2S)$-to-J/ψ cross-section ratio has been measured at LHCb for the first time in forward rapidities in PbPb collisions at $\sqrt{s} = 5.02$ TeV as a function of centrality [5].

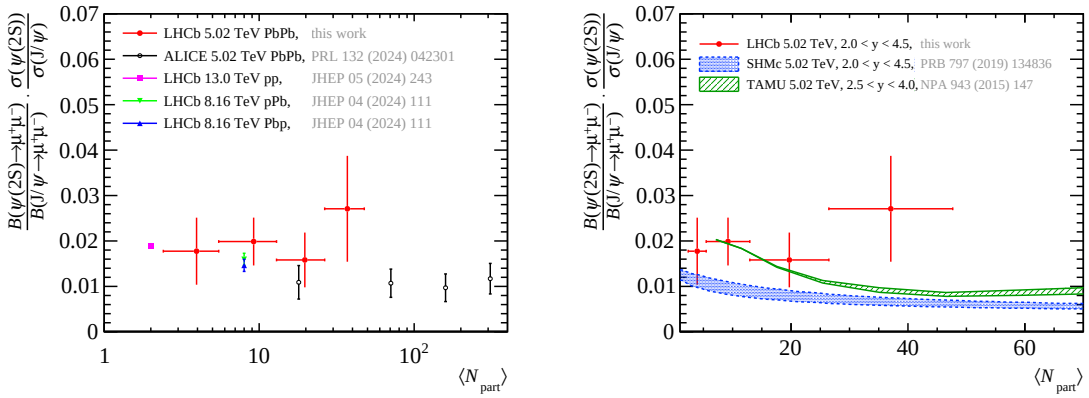

Figure 2: *Left*: Comparison of LHCb PbPb results (red) [5] with pp (magenta) [3], pPb (green) and Pbp (blue) [4] and ALICE PbPb (black) [9], as a function of centrality. *Right*: LHCb PbPb results (red) [5] as a function of centrality, compared with SHMc (blue band) [11] and TAMU (green band) [12] predictions.

The results are shown in Fig. 2 versus the mean number of participating nucleons, $\langle N_{\rm part}\rangle$, obtained from a Glauber model [10]. The left panel compares the LHCb PbPb results with an ALICE measurement with the same collision system and energy and the previously presented LHCb results. All the results are consistent within uncertainties. LHCb PbPb results show no centrality dependence. The right panel compares the data with two theoretical predictions: the Statistical Hadronization Model (SHMc) [11] and the TAMU transport model [12]. The TAMU model, which includes charmonium regeneration, provides the better description of the data.

5. Run 3 outlook

LHCb underwent Upgrade I [13] before Run 3. Thanks to the upgraded detectors, the experiment has extended its centrality coverage in A–A collisions up to $\sim 30\%$. In addition, the higher LHC luminosity enabled LHCb to record an unprecedented integrated luminosity of 0.43 nb^{-1} in PbPb collisions in 2024. Preliminary studies on this sample have showed the possibility to separate prompt and non-prompt production, as seen in Fig. 3 for J/ψ, where the distribution of the pseudo-proper time t_z, determined from the distance between the PV and the decay vertex, is displayed.

The *System for Measuring Overlap with Gas* (SMOG), LHCb's fixed-target system during Run 2, was upgraded to SMOG2 for Run 3 [14]. A key feature of SMOG2 is the use of a gas storage cell located 20 cm upstream of the LHCb interaction point, which enables simultaneous data taking in fixed-target and collider modes.

The year 2024 marked a highly successful period of fixed-target data taking, during which substantial datasets were collected using newly introduced gas species (pH$_2$, pD$_2$, PbNe, and PbAr), opening new opportunities for charmonium studies. Starting in July 2025, a light-ion run with oxygen and neon was conducted, during which LHCb recorded fixed-target OH$_2$, OO, and NeNe collisions at $\sqrt{s_{NN}} = 5.35$ TeV, as shown in Fig. 3. These datasets offer a unique opportunity to explore different stages of QGP formation.

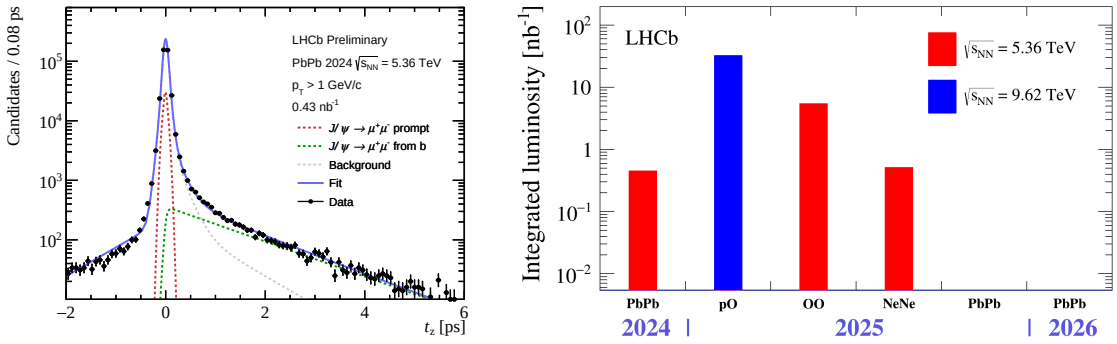

Figure 3: *Left*: Preliminary fit (solid blue) to the pseudo-proper time spectrum of J/ψ meson in PbPb 2024 data at $\sqrt{s_{NN}}$ = 5.36 TeV with prompt (red), non-prompt (green) and background (gray) components. *Right*: Integrated luminosity and energies of PbPb and light ion data samples in 2024 and 2025 so far.

6. Conclusions

We have reviewed recent LHCb results on charmonium production through the cross-section ratio $\sigma(\psi(2S))/\sigma(J/\psi)$ in pp, pPb, and PbPb collisions, which together provide a comprehensive picture of charmonium production from small to large collision systems. In pp and forward pPb collisions, the ratio decreases with increasing multiplicity, consistent with the co-mover interaction model. In contrast, backward Pbp results show no clear multiplicity dependence but exhibit a stronger suppression overall. Finally, the forward PbPb measurements show no centrality dependence and are better described by the TAMU transport model, which includes charmonium regeneration.

As shown, Run 3 upgrades have significantly strengthened the heavy-ion physics potential of LHCb. The extended centrality coverage in A–A collisions and the unprecedented PbPb statistics collected in 2024 enable more precise as well as differential measurements, including the separation of prompt and non-prompt charmonium production. In parallel, the SMOG2 upgrade has opened a new era for fixed-target physics, allowing simultaneous fixed-target and collider data taking which provided large datasets with various gas species. Finally, the light-ion programme offers a unique opportunity to bridge the gap between small and large systems and to explore different stages of QGP formation. Together, these developments position LHCb to deliver a rich charmonium physics programme in the coming years.

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