Recent conventional and exotic charmonia results from LHCb

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Abstract. Quarkonia production in heavy-ion collisions is an important experimental probe that sheds light on the heavy quark interaction with the nuclear medium. The bound quarkonium states undergo dissociation and recombination in PbPb collisions, where they can also experience the initial and final state effects such as shadowing and co-mover breakup. With the large datasets of pp and pPb collisions, and excellent vertexing capabilities allowing separation of the prompt and b-decay components, LHCb performs precise measurements of J/ψ, $\psi(2S)$ and, for the first time at the LHC, χ_c production and modification in small collision systems. This contribution will discuss these results, along with the first measurement of the nuclear modification factor of the exotic $\chi_{c1}(3872)$.

1 Introduction

In ultra-relativistic heavy-ion collisions, quarkonium production is suppressed when the temperature exceeds its binding energy. Above the critical temperature of deconfinement, Debye color screening prevents quarks and anti-quarks from forming quarkonium in Quark-Gluon Plasma (QGP) [1]. The quarkonium can also go through a collisional dissociation and regeneration process inside QGP [2]. While in small collision systems like pp and pPb collisions, in the absence of Hot Nuclear Matter (HNM) effect, quarkonium can also dissociate by interacting with co-moving particles in the final state [3]. The excited quarkonium states are loosely bound compared to the ground state, leading to preferential suppression, especially in a high-multiplicity environment. The investigation of conventional and exotic charmonia production across different collision systems helps us understand the production mechanism of quarkonium, and study as well the evolution of medium properties with system size.

The LHCb detector [4] is a single-arm spectrometer with a forward pseudorapidity coverage ($2 < \eta < 4.8$). Its tracking system is comprised of the VErtex LOcator (VELO) and four planar tracking stations. The VELO provides precise measurements of track coordinates close to the interaction region. The number of tracks reconstructed by the VELO is often used as a proxy for charged particle multiplicity. The LHCb detector has recorded pp and pPb collisions data at $\sqrt{s} = 13$ TeV for pp collisions and $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV in both the proton-going (forward) and lead-going (backward) pPb collisions, providing a transition environment from small collision systems to heavy-ion collisions.

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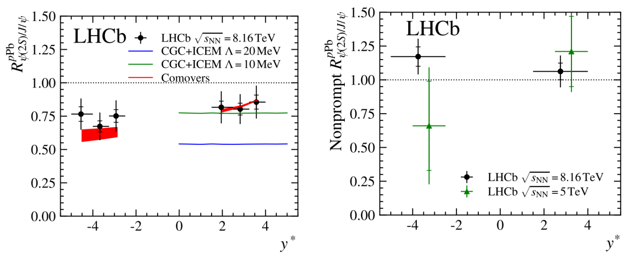

Figure 1. Cross section double ratios $R^{p\mathrm{Pb}}_{\psi(2S)/J/\psi}$ as a function of rapidity in center-of-mass frame y^*, for (left) prompt and (right) nonprompt production. The horizontal bars are bin widths, vertical error bars represents statistical and total uncertainties.

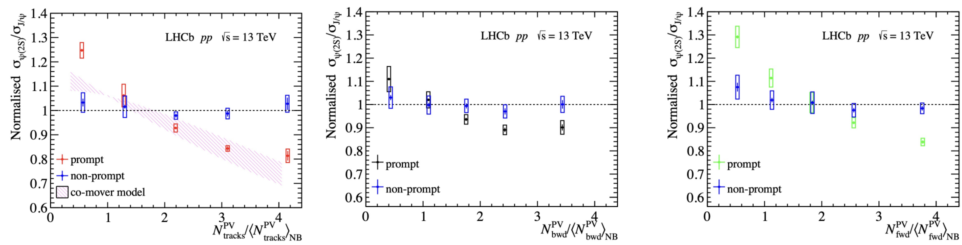

Figure 2. Self-normalized production ratio as a function of (left) charged-tracks density $N^{\mathrm{PV}}_{\mathrm{tracks}}/\langle N^{\mathrm{PV}}_{\mathrm{tracks}}\rangle_{NB}$, (middle) forward charged-tracks density $N^{\mathrm{PV}}_{\mathrm{fwd}}/\langle N^{\mathrm{PV}}_{\mathrm{fwd}}\rangle_{NB}$ and (right) backward charged-tracks density $N^{\mathrm{PV}}_{\mathrm{bwd}}/\langle N^{\mathrm{PV}}_{\mathrm{bwd}}\rangle_{NB}$. The error bars represent statistical uncertainties and heights of the boxes represent systematic uncertainties.

2 Conventional charmonium production

The LHCb collaboration measured the cross-section double ratio $R^{p\mathrm{Pb}}_{\psi(2S)/J/\psi} = \frac{(\sigma_{\psi(2S)}/\sigma_{J/\psi})_{p\mathrm{Pb}}}{(\sigma_{\psi(2S)}/\sigma_{J/\psi})_{pp}}$ in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV [5], as shown in the Fig 1. The reference $\psi(2S)$ to J/ψ cross-section ratio is measured in 7 TeV pp collisions at LHCb [6]. The prompt and nonprompt production are separated using pseudo-proper time $t_z = \frac{z_X - z_{\mathrm{PV}}}{p_z}$, where z_X and z_{PV} are the coordinates of charmonium and primary vertex (PV) along the beam axis. The ratio of nonprompt $\psi(2S)$ and J/ψ nuclear modification factors are compatible with one as expected since the nuclear matter effects affect $b-$hadron production but not their decays. The prompt double ratio is lower than one, especially in the backward rapidity where a higher multiplicity is achieved. The $\psi(2S)$ has a larger radius and lower binding energy, leading to a preferential dissociation when interacting with co-moving particles. The results agree with co-mover model calculations [3] and the predictions from Color-Glass Condensate (CGC) with Improved Color Evaporation Model (ICEM) models [7].

The LHCb Collaboration also measured the multiplicity-dependent self-normalized cross-section ratio of $\psi(2S)$ to J/ψ production $\frac{(\sigma_{\psi(2S)}/\sigma_{J/\psi})_n}{(\sum_n \sigma_{\psi(2S)}/\sum_n \sigma_{J/\psi})_n}$ at 13 TeV pp collisions [8], n stands for the multiplicity bin index. The prompt ratio decreases with increasing charged track multiplicity $N^{\mathrm{PV}}_{\mathrm{tracks}}$, as shown in the Fig 2, measured by the number of tracks used in PV reconstruction and normalized by that in No-Bias data, which is selected with a random trigger. The prompt ratio shows a decreasing trend as a function of forward charged track multiplicity while decreasing much slower as a function of backward-charged track multiplicity. This is consistent with expectation that charmonium can dissociate due to interactions with co-moving particles in the same direction.

The LHCb collaboration measured the fraction of χ_c (including χ_{c1} and χ_{c2}) decays in the prompt J/ψ yield $F_{\chi_c \to J/\psi} = \frac{\sigma_{\chi_c \to J/\psi}}{\sigma J/\psi}$ in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV [9]. The $F_{\chi_c \to J/\psi}$ results in pPb collisions have an overall consistency with the results in 7 TeV pp

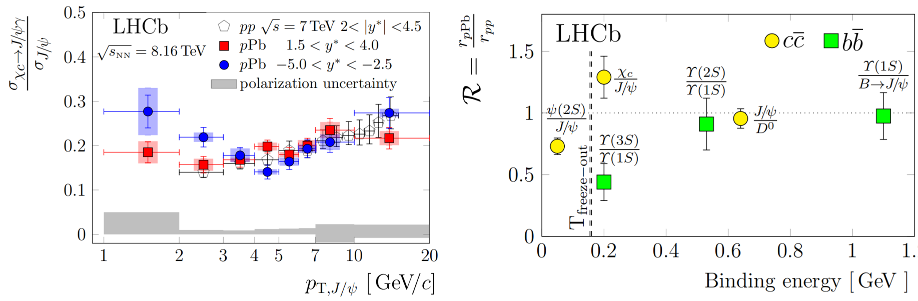

Figure 3. The (left) Fraction of χ_c decays to prompt J/ψ as a function of $p_{T,J/\psi}$, where the error bars (boxes) show the statistical (systematic) uncertainties and gray band is uncertainty from polarization effects, and (right) double ratio between quarkonium states vs. binding energy along with the estimated freeze-out temperature [11] in pPb collisions.

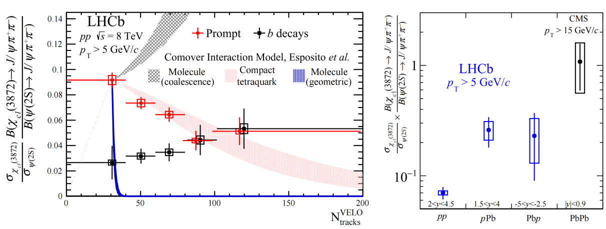

Figure 4. The $\chi_{c1}(3872)$ to $\psi(2S)$ cross-section ratio (left) as a function of number of VELO tracks in pp collisions, and (right) as a function of system sizes of collisions. The vertical error bars (boxes) are statistical (systematic) uncertainties. The horizontal error bars in the left plot are bin widths.

collisions [10], as shown in the Fig 3, suggesting that neither the prompt J/ψ mesons nor χ_c dissociate in the pPb collisions. The non-dissociation of χ_c states suggests a constraint on the temperature of pPb collision system of no more than 180 MeV, which is the smallest binding energy of χ_c states. This temperature is close to the estimated freeze-out temperature, 155-160 MeV, in pPb collisions [11]. The double ratio for quarkonium states in the backward pPb collisions is shown in Fig 3. The only quarkonium with binding energy higher than freeze-out temperature suppressed is $\Upsilon(3S)$. With similar binding energy, $\Upsilon(3S)$ is 2.9 times heavier than χ_c, which could favor its dissociation by interaction with co-moving particles.

3 Exotic charmonium

The LHCb collaboration measured the cross-section ratio of exotic state $\chi_{c1}(3872)$ to the conventional charmonium state $\psi(2S)$ with similar mass in 8.16 TeV pPb collisions and 8 TeV pp collisions, as shown in the Fig. 4 [12, 13]. The result in pp collisions [13] shows a decreasing trend with increasing multiplicity for prompt $\chi_{c1}(3872)$ to $\psi(2S)$ cross-section ratio. Predictions from the co-mover interaction model suggest that, if $\chi_{c1}(3872)$ is a pure molecular with a corresponding higher radius, it will quickly dissociate with increasing multiplicity [3]. If coalescence provides an additional formation mechanism, the cross-section ratio will increase with increasing multiplicity. Neither of these calculations matches the data. If $\chi_{c1}(3872)$ is a compact tetraquark with a radius slightly larger than $\psi(2S)$, it will go through a slightly preferential suppression which matches the measured trend. The comparison between the pp and pPb results from LHCb, together with the PbPb result from CMS [14], shows an increasing trend in the prompt $\chi_{c1}(3872)$ to $\psi(2S)$ cross-section ratio with increasing size of collisions, which can result from a combination of effects. Given that the $\chi_{c1}(3872)$ to

$\psi(2S)$ cross-section ratio decreases with increasing multiplicity in pp collisions, the increasing trend with collision size may indicate that the hadronic density in pPb collisions allows the quark coalescence to be a dominant mechanism for $\chi_{c1}(3872)$ production.

4 Conclusion

The LHCb collaboration measured the $\psi(2S)$ to J/ψ cross-section double ratio in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV with a reference of cross-section ratio in 7 TeV pp collisions, and the self-normalized cross-section ratio in pp collisions. Results agree that $\psi(2S)$ is preferentially suppressed in high-multiplicity events. In pPb collisions, $\psi(2S)$ is more suppressed than in pp collisions. The relatively larger radius and lower binding energy for $\psi(2S)$ leads to an easier dissociation by interaction with final-state particles. The measurement of the fraction of χ_c decaying to prompt J/ψ in 8.16 TeV pPb collisions and 7 TeV pp collisions suggest that neither χ_c nor J/ψ are suppressed in pPb collisions, indicating that the temperature reached in 8.16 TeV pPb collisions is not able to inhibit the formation of quarkonium states with binding energy as small as 180 MeV.

The LHCb collaboration measured the relative production of exotic $\chi_{c1}(3872)$ to $\psi(2S)$ in 8 TeV pp collisions and 8.16 TeV pPb collisions. An increasing cross-section ratio with increasing size of collisions is observed, indicating the exotic $\chi_{c1}(3872)$ production modification in pPb and PbPb collisions is different from that of the $\psi(2S)$.

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