PROCEEDINGS OF SCIENCE

Quarkonia and exotic hadron production in pPb collisions at LHCb

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Quarkonia production in hadronic collisions is an important experimental observable that sheds light on the heavy quark interaction with the nuclear medium. While the bound quarkonium states undergo dissociation and recombination in PbPb collisions, in pPb collisions they can suffer from a combination of initial and final state effects such as shadowing and comover breakup. The exotic hadron $\chi_{c1}(3872)$, which likely contains a $c\bar{c}$ pair plus two light quarks, may be affected by similar phenomena plus modifications of the hadronization process that emerge in dense systems. This document will discuss recent results on conventional charmonia from LHCb, and the first measurement of $\chi_{c1}(3872)$ production in pPb collisions.

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1. Introduction: pPb collisions at the LHCb Experiment.

The LHCb experiment was conceived to study heavy flavour physics at the Large Hadron Collider (LHC) [1]. It is a single-arm spectrometer composed of several subdetectors, with a forward pseudorapidity coverage ($2 \lesssim \eta \lesssim 4.5$). It counts with excellent reconstruction performance of heavy flavour hadrons down to low transverse momentum. Its tracking system consists 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 ($N_{\text{tracks}}^{\text{VELO}}$) is often used as a proxy for charged particle multiplicity. Particle identification in LHCb is provided by a calorimeter, two Cherenkov detectors (RICH) and four muon stations.

In proton-^{208}Pb ion collisions, the forward acceptance of LHCb, complementary to other LHC experiments, allows for the study of nPDFs at low longitudinal momentum fractions (high rapidity), close to saturation. The kinematic reach is extended by reversing the direction of the proton and the lead beams, accessing forward ($1.5 \lesssim \eta \lesssim 4$) and backward ($-5 \lesssim \eta \lesssim -2.5$) pseudo-rapidities[1]. The pPb collision data was acquired during two LHC heavy-ion runs, the first in 2013, at $\sqrt{s_{\text{NN}}} = 5.02\,\text{TeV}$, with an integrated luminosity of $1.1\,\text{nb}^{-1}$ ($0.4\,\text{nb}^{-1}$) for forward (backward) collisions, and the second run in 2016 at $\sqrt{s_{\text{NN}}} = 8.16\,\text{TeV}$, with $12.5\ \text{nb}^{-1}$ ($19.3\,\text{nb}^{-1}$).

2. LHCb measurements on quarkonia production in pPb collisions

Quarkonia ($\text{c}\bar{\text{c}}$,$\text{b}\bar{\text{b}}$) suppression with respect to pp collisions has long been considered to be a probe for the formation of the Quark Gluon Plasma (QGP) in collisions of heavy nuclei [2]. The study of quarkonia production in pPb collisions is primarily motivated by the study of the so-called cold nuclear matter (CNM) because the energy density is not expected to be sufficient to form the QGP. In CNM, however, there are certain effects that affect quarkonia production in pPb collisions and can lead to suppression with respect to pp collisions. These include: nuclear modifications on partonic densities, parameterised by nuclear parton distribution functions (nPDFs) [3, 4]; parton saturation, described by Colour Glass Condensate [5]; coherent energy loss [6] and interactions with comovers in the final state [7, 8]. Nevertheless, over recent years there have been observations that appear to be evidence for the formation of a QGP-like medium in pPb collisions [9, 10]. If a thermalised medium was formed, the modification of quarkonia production would be affected by different mechanisms than in CNM.

The prompt and non-prompt contributions to the production of all the $\text{c}\bar{\text{c}}$ resonances measured at LHCb are separated using the pseudo-proper time, defined as $t_z = \frac{(z_X - z_{PV}) \times M_X}{p_z}$, where z_X and z_{PV} are the coordinates along the beam axis of the $\text{c}\bar{\text{c}}$ resonance decay vertex position and of the primary vertex (the interaction point of the two beams), p_z is the z component of the meson momentum and M_X its known mass.

The main observable used to quantify nuclear effects in pPb collisions is the nuclear modification factor, $\text{R}_{p\text{Pb}}(y, p_{\text{T}}) = \frac{1}{208} \left(\frac{\text{d}^2\sigma_{p\text{Pb}}}{\text{d}y\text{d}p_{\text{T}}} \middle/ \frac{\text{d}^2\sigma_{pp}}{\text{d}y\text{d}p_{\text{T}}} \right)$. The results for the $\text{R}_{p\text{Pb}}$ of the promptly-produced

[1]Since the energy per nucleon is larger in the proton than in the lead beam, the nucleon-nucleon centre-of mass system has a rapidity in the laboratory frame of 0.465 (-0.465) for pPb (Pbp) collisions. In the following, all rapidity values will be quoted in the centre-of-mass reference frame.

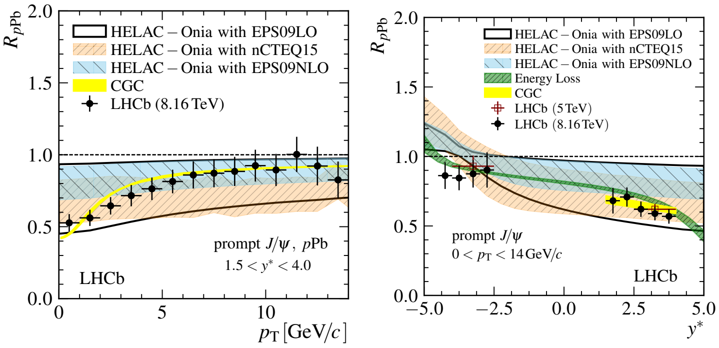

Figure 1: Prompt J/ψ $R_{p\mathrm{Pb}}$ at $\sqrt{s_{\mathrm{NN}}} = 8$ TeV [11] (5 TeV [12]), shown in black circles (red squares) and initial-state CNM calculations. Left: y-integrated ($1.5 < y < 4.0$). Right: p_{T}-integrated.

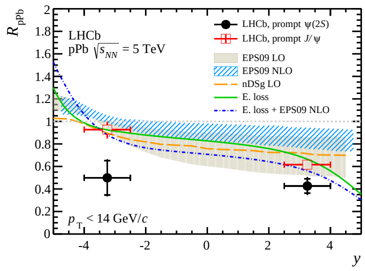

Figure 2: Prompt ψ(2S) (J/ψ) $R_{p\mathrm{Pb}}$ as a function of y [13], shown in black points (red squares). Several theoretical calculations that include initial-state CNM effects are represented.

J/ψ at $\sqrt{s_{\mathrm{NN}}} = 8$ TeV [11] are shown in Figure 1. It is significantly lower than 1 at low p_{T} for forward rapidities, indicating a suppression of J/ψ production with respect to pp collisions. Theoretical calculations accounting for CNM initial state effects show good agreement with the data. The results for J/ψ production serve as a benchmark for higher-energy states. The $R_{p\mathrm{Pb}}$ was measured for ψ(2S) at $\sqrt{s_{\mathrm{NN}}} = 5$ TeV [13]. The prompt production of ψ(2S) shows a stronger suppression than the J/ψ, particularly at $y < 0$, no longer compatible with initial state effects (Figure 2). The χ_{c1} and χ_{c2} resonances were measured at $\sqrt{s_{\mathrm{NN}}} = 8$ TeV [14] through their $\chi_{ci} \to \mathrm{J}/\psi\gamma$ decay. Photons reconstructed through the energy deposited in the calorimeters (calorimetric photons) and through the $\gamma \to e^+e^-$ decay (converted photons) were used to obtain two independent measurements. The resulting cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ is compatible with previous results from pp collisions at $\sqrt{s} = 7$ TeV [15], measured using converted photons.

From the aforementioned results for $c\bar{c}$ production, it is concluded that resonances of similar mass are similarly affected by the nuclear effects that arise in pPb collisions. For the J/ψ, initial CNM effects are sufficient to interpret the suppression with respect to pp. However, for the lower binding energy states, additional effects are necessary.

The $b\bar{b}$ resonances Υ(1S), Υ(2S) and Υ(3S) are measured for pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8$ TeV [16]. The y-dependence of the $R_{p\mathrm{Pb}}$ for Υ(1S) and Υ(2S) is shown in Figure 3. The results for Υ(1S) do not differ significantly from those of the J/ψ, but the excited state Υ(2S) shows a stronger suppression at $y < 0$, similarly to the ψ(2S). The theoretical calculations that account only for initial-state CNM effects are in disagreement with the data at backward rapidities. However, final-state interactions with comovers can explain the suppression at $y < 0$. A new model that includes the formation of a thermalised medium [18] also succeeds in reproducing the data.

For Υ(3S), only an integral ratio could be measured, $\mathfrak{R}_{p\mathrm{Pb}}^{\Upsilon(3S)} = \mathrm{R}_{p\mathrm{Pb}}^{\Upsilon(3S)} \Big/ \mathrm{R}_{p\mathrm{Pb}}^{\Upsilon(1S)}$, shown in Figure 4. A stronger suppression of the excited state over the ground state is observed, especially at backward rapidities. These results can be described through final-state interactions with comovers.

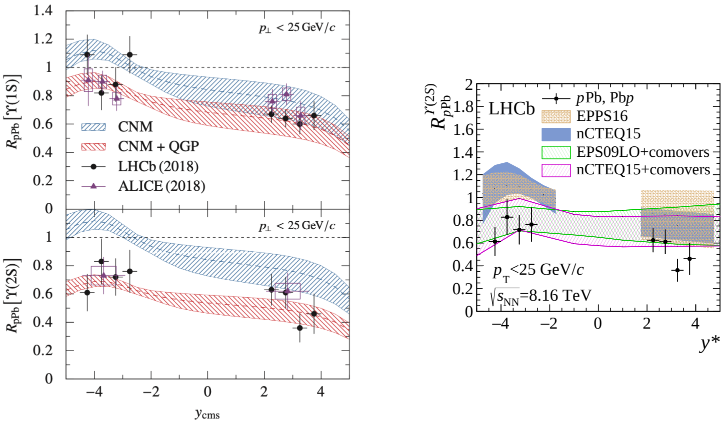

Figure 3: p_T-integrated R_{pPb}, for $\Upsilon(1S)$ (top left) and $\Upsilon(2S)$ (bottom left, right). The black points (purple triangles) are LHCb [16] (ALICE [17]) results. A model with QGP [18] is shown on the left.

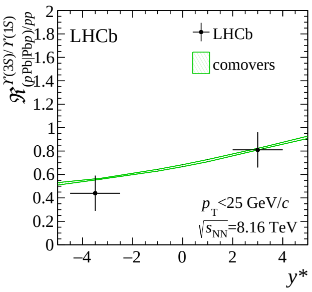

Figure 4: Results for the p_T-integrated ratio of the R_{pPb} for $\Upsilon(3S)$ over $\Upsilon(1S)$ [16], at forward and backward rapidities.

3. Cross section ratio $\sigma(\chi_{c1}(3872))/\sigma(\psi(2S))$ production at $\sqrt{s_{NN}}$ = 8 TeV.

The exotic state $\chi_{c1}(3872)$ is believed to be composed of a $c\bar{c}$ pair and two light quarks. In order to comprehend its nature, it is useful to compare its production with that of the $\psi(2S)$, of similar mass. Previous LHCb pp results [19] suggest a decrease of the relative prompt-production of $\chi_{c1}(3872)$ with respect to $\psi(2S)$ with increasing charged-particle multiplicity, which would hint at a suppression effect due to the medium. However, the new LHCb measurements on the $\sigma(\chi_{c1}(3872))/\sigma(\psi(2S))$ prompt-production ratio in pPb and Pbp collisions [20], together with the CMS result for PbPb collisions [21], show an increase of the ratio with the size of the collision system. This can be due to a larger relative suppression of the $\psi(2S)$, or a medium-assisted enhancement of the $\chi_{c1}(3872)$. In the latter case, the enhancement mechanism could be due to the rise of coalescence hadronisation or interactions with co-moving quarks/antiquarks [22].

4. Conclusion

The LHCb Collaboration has measured the production of several quarkonia states in pPb collisions, including $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ and prompt J/ψ at $\sqrt{s_{NN}}$ = 5 and 8 TeV, and prompt $\psi(2S)$ at $\sqrt{s_{NN}}$ = 5 TeV. The prompt-production cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ has been measured at $\sqrt{s_{NN}}$ = 8 TeV. From results in pPb, it is concluded that in this collision system, the production of these hadrons is suppressed with respect to pp collisions. This suppression is similar for resonances of similar mass but larger for the lower binding-energy states at backward rapidities. In order to reproduce these results with theoretical calculations, final-state interactions should be accounted for. The formation of a QGP droplet could also explain the suppression pattern.

The LHCb Collaboration has produced the first measurement of the exotic hadron $\chi_{c1}(3872)$ in pPb collisions. The increase of the ratio of cross-sections $\sigma(\chi_{c1}(3872))/\sigma(\psi(2S))$ from pp to pPb to PbPb collisions may indicate that this hadron experiences different dynamics in the nuclear medium than the conventional $c\bar{c}$ state.

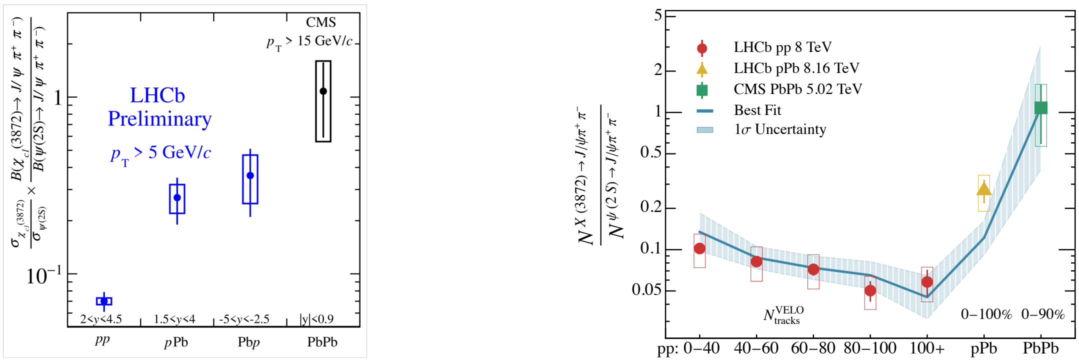

Figure 5: Left: Ratio of $\chi_{c1}(3872)$ to $\psi(2S)$ integrated cross-sections in the $J/\psi\pi^+\pi^-$ channel, measured in pp [19], pPb, Pbp [20] and PbPb [21] collisions. Right: Medium-assisted enhancement model [22]. The pp yields are divided into bins of $N^{\text{VELO}}_{\text{tracks}}$ tracks.

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