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Quarkonia production in pPb and PbPb collisions at LHCb

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We present LHCb results on quarkonia production in proton-lead collisions, using the data collected at 5.02 and 8.16 TeV nucleon-nucleon centre-of-mass energies, covering forward and backward rapidities. Measurements include charmonia, where the prompt and from-b-decay components are disentangled, and bottomonia states. The large increase in size of the heavy flavour sample collected at 8.16 TeV with respect to the 5.02 TeV sample allows a remarkable improvement in the accuracy of the studies of nuclear matter effects. Coherent production of J/Psi in PbPb collisions are also presented.

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1. Heavy ions in LHCb

The LHCb experiment [1] has been conceived with the main goal of studying heavy flavour physics in pp collisions at the LHC, exploiting the unprecedented yield of b-quark pairs, which are mainly produced at small angles with respect to the direction of the colliding proton beams. The detector is therefore designed as a forward spectrometer covering the pseudorapidity region $2 < \eta < 5$ and providing excellent vertexing, tracking and particle identification capabilities for the reconstruction of heavy flavour decays. Another key feature is the online selection system, consisting of a hardware level with high output bandwidth (up to 1 MHz), followed by a software level providing high flexibility.

Though heavy ion physics was not among the original motivations for the experiment, the detector capabilities offer some unique possibilities also for this field. The forward acceptance provides high complementarity to the other LHC experiments and is fully instrumented, offering excellent reconstruction performance, unrivaled at the LHC, for exclusive heavy flavour states down to null transverse momentum (p_{T}), disentangling charmed particles produced promptly from those coming from b-hadron decays.

A comparison among the kinematic reaches of LHCb and the other LHC experiments in pA collisions, in terms of the Bjorken-x value of the nucleon in the nuclear target and the squared parton-parton invariant mass Q^2, is shown in Figure 1. Two regions are covered in proton-lead collisions, depending on the orientation of the proton and lead beams. The so-called *forward* (or pPb) configuration, when the proton beam points toward the detector (i.e., it enters the detector region from its vertex detector), corresponds to values of x down to 10^{-5}, where gluon saturation is expected to occur. In the *backward* (Pbp) configuration, when the Pb beam points toward the

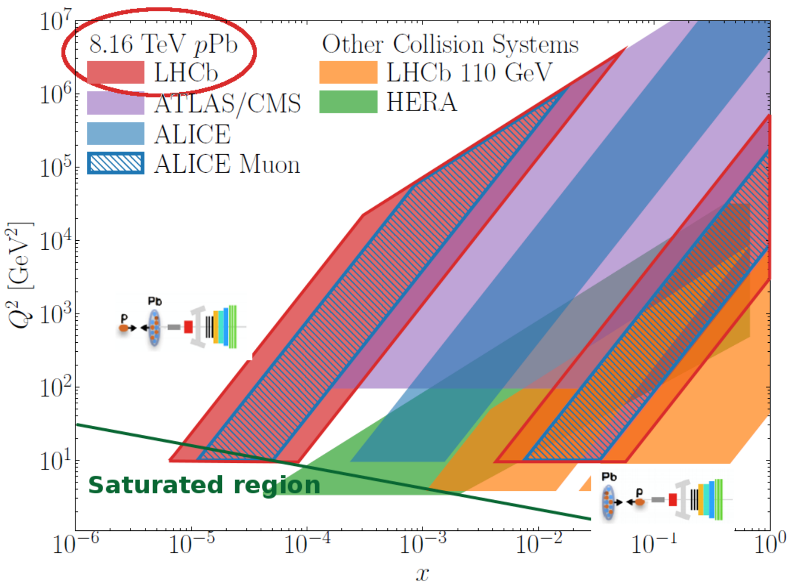

Figure 1: Kinematic reach corresponding to the acceptance of the four LHC experiments in pPb collisions. The kinematic regions accessible in the fixed-target configuration at LHCb and in e-p collisions at HERA are also shown.

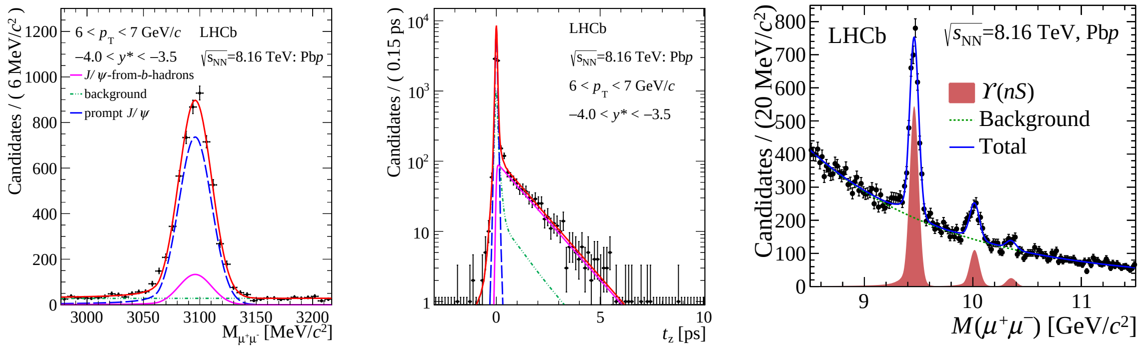

Figure 2: Distributions of (left) reconstructed mass and (middle) pseudo-proper time $t_z \equiv (z_{J/\psi} - z_{PV}) \times (M/p_z)_{J/\psi}$ for the $J/\psi \to \mu^+\mu^-$ decay candidates from the 8 TeV Pbp sample [2] in the rapidity bin $-4.0 < y^* < -3.5$ ($z_{J/\psi}$ and z_{PV} are the reconstructed longitudinal position of the J/ψ decay vertex and the interaction primary vertex, respectively). The result of a fit to determine prompt signal, from-b signal and background fractions is overdrawn. In the right plot. mass distribution for the $\Upsilon(nS)$ candidates from the same sample in $-5.0 < y^* < -2.5$ [3].

detector, measurements are sensitive to the anti-shadowing region up to $x \sim 0.1$.

On the other hand, the most central PbPb collisions can't be properly reconstructed due to the high track density in the forward region. LHCb is therefore more suited for smaller collision systems like pPb, but can contribute to the understanding of peripheral and PbPb ultra-peripheral collisions (UPC).

In this contribution we focus on quarkonia production studies in pPb collisions and PbPb UPC.

2. Quarkonia in pPb collisions

The experiment collected a first dataset of pPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV in 2013, corresponding to integrated luminosities of 1.1 and 0.5 nb^{-1} in the forward and backward configuration, respectively. After this succesfull experience, larger luminosities were delivered to LHCb during the 2016 pPb run at $\sqrt{s_{\text{NN}}} = 8.16$ TeV, with 13.6 and 30.8 nb^{-1} recorded.

The modification of quarkonia production with respect to pp collisions constitutes a major probe for the hot and dense matter, known as quark-gluon plasma (QGP), produced in PbPb collisions at LHC. In pPb collisions QGP is not expected to be formed and the system is considered to be a reference for the understanding of cold nuclear matter (CNM) effects.

Figure 2 illustrates the ability to distinguish promptly produced J/ψ mesons from those produced in b-hadron decays in reconstructed $J/\psi \to \mu^+\mu^-$ decays. The nuclear modification factor $R_{pPb} \equiv \sigma_{p\text{Pb}}/(A_{\text{Pb}}\ \sigma_{pp})$, where $\sigma_{p\text{Pb}}$ and σ_{pp} are the production cross-sections in the two collision systems and $A_{\text{Pb}} = 208$ is the lead mass number, can be measured separately for the two components. The result for the prompt component obtained from the 8 TeV sample [2] is shown in Figure 3 as a function of p_{T} and the c.m. rapidity y^*. A clear suppression with respect to pp collisions is observed at forward rapidity and low p_{T}, compatible with the expected effect from nuclear PDF modifications (shadowing) as computed in the framework of NRQCD factorisation using several collinear nuclear PDF sets with the HELAC-Onia package [4, 5]. However, the ra-

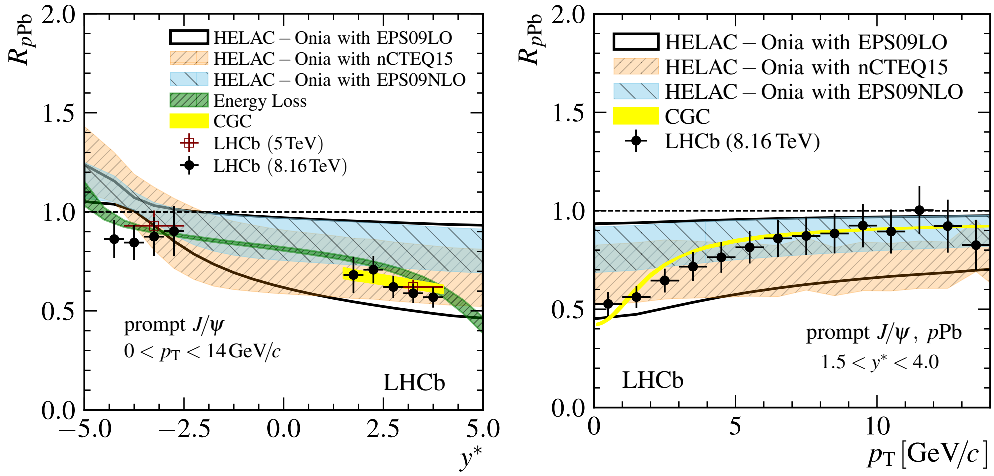

Figure 3: Nuclear modification factor R_{pPb} for prompt J/ψ production as a function of (left plot) y^* and (right plot) p_T for the forward configuration [2].

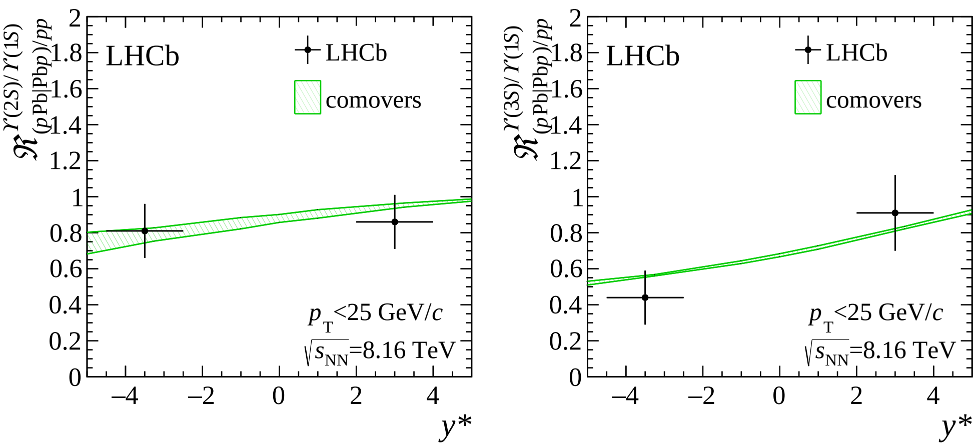

Figure 4: Ratio between Υ nuclear modification factors as a function of rapidity for (left plot) $\Upsilon(2S)/\Upsilon(1S)$ and (right plot) $\Upsilon(3S)/\Upsilon(1S)$ [3].

pidity dependence can also be well explained by the coherent energy loss model [6]. The result at forward rapidity is also compatible with the latest calculations based on the Color Glass Condensate model [7]. More measurements, notably on Drell-Yan production, are needed to disentangle these physical effects [8].

If final-state effects in CNM can't be excluded from the J/ψ result, they are definetely needed to explain the different modifications of quarkonia states. The first measurement of $\psi(2S)$ production in the 5 TeV sample [9] indicated a larger suppression with respect to J/ψ, in agreement with results from the other LHC experiments [10, 11, 12, 13]. A more recent result [3] shows evidence for different suppression among the three $\Upsilon(nS)$ states, which are cleanly observed in the 8 TeV sample (see Figure 2). The result, shown in Figure 4, agrees well with the pattern predicted in the framework of the "comovers" model [14], where dissociation of the quarkonia states is attributed to interaction with final-state particles which are close in phase-space. This relatively large ef-

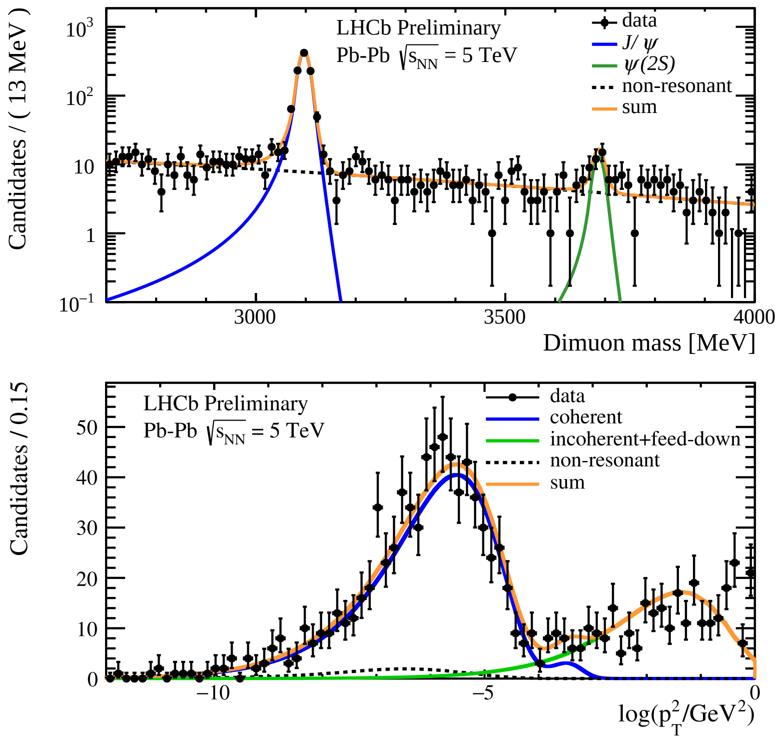

Figure 5: Candidates for J/ψ exclusive production in PbPb collisions at 5 TeV [16], reconstructed from $J/\psi \to \mu^+\mu^-$ decays. In the upper plot, the reconstructed mass distribution is shown in an extended mass range where, beside the clean J/ψ peak, a small signal for $\psi(2S)$ can also be seen. In the lower plot, the $\log(p_T^2)$ distribution in the J/ψ mass range (3096.9 ± 65 MeV) is fitted with templates for coherent and incoherent production.

fect needs to be taken into account in the interpretation of the spectacular suppression of Υ states recently observed by CMS in PbPb collisions [15].

3. Quarkonia in PbPb collisions

A first small sample of PbPb collisions was recorded by LHCb during the 2015 run, corresponding to about 10 μb^{-1}. The tracking detector performance in this challenging environment was found to be satisfactory for events of centrality above 50%.

The first preliminary physics result [16] has been obtained from ultra-peripheral collisions, where hadron photoproduction is enhanced by the large photon flux from the lead nuclei. The observation of photoproduction of heavy flavour states, providing a hard scale for perturbative QCD calculations, is particularly interesting to explore the gluon density down to the saturation region at $x \sim 10^{-5}$. The exclusive production of J/ψ is cleanly observed (see Figure 5). The excellent p_T resolution allows to distinguish coherent and incoherent production, whose p_T distributions are found to be well described by templates obtained with the STARlight generator [17].

The accuracy of the result is limited by the size of the data sample, but this analysis demonstrates the LHCb potential for physics in PbPb UPC. During the run performed in november 2018, an integrated luminosity of 210 μb^{-1} was collected, providing the possibility for a precision measurement of exclusive J/ψ and $\psi(2S)$ production.

4. Prospects

The results obtained so far by the LHCb collaboration from heavy ion collisions demonstrate the capability of the experiment to provide unique contributions to this field, notably on quarkonia production, where exclusive final states can be reconstructed with high efficiency and purity in an unique kinematic region. The size of the sample collected in 2018 at 8 TeV is expected to provide access to new channels, as χ_c and η_c quarkonia states and Drell-Yan dimuon events. Studies of flow and correlations with quarkonia in the unique forward acceptance region covered by LHCb are also planned.

The largely unknown parton distribution functions of nuclei and the similarities observed between high-multiplicity pp and pPb events compared to PbPb, often described by means of hydrodynamic models, are the main motivations for an extended pPb data taking program during LHC Run 3 and Run 4. The future increase in luminosity, combined with the improved detector capabilities of the upgraded detector [18], which includes a new vertex detector with improved granularity, will allow new and precise measurements to be performed with access to more central PbPb collisions. The proposed plans for future heavy ion running, discussed in detail in Reference [19], foresee an increase in integrated luminosity for pPb and PbPb collisions by more than an order of magnitude during the LHC Runs 3 and 4 (2021-2029). This will open novel possibilities, as precision studies using Drell-Yan events and correlations in heavy flavour production. A proposal for a second detector upgrade for the LHC Run 5 (starting 2031) has been put forward [20, 21]. The granularity of such detector, conceived to take profit of the full potential of LHC luminosity in pp collisions, would make it possible to reconstruct even the most central PbPb collisions.

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