STUDIES OF LOW-x PHENOMENA WITH THE LHCb DETECTOR*

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With a unique geometry covering the forward rapidity region, the LHCb detector provides unprecedented kinematic coverage at low Bjorken-x down to 10^{-5} or lower. The excellent momentum resolution, vertex reconstruction, and particle identification allow for precision measurements down to very low hadron transverse momentum. In this contribution, the latest studies of the relatively unknown low-x region are reported, including recent measurements of charged and neutral light hadron production in proton–lead and proton–proton collisions. Comparisons to various theoretical model calculations are also discussed. Finally, prospects for future measurements are outlined.

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1. Introduction

Light hadrons, such as π, K, and p, are copiously produced in high-energy proton–proton (pp) and proton–ion (pA) collisions at high nucleon–nucleon centre-of-mass energies ($\sqrt{s_{NN}}$). In pA collisions, their production rate is affected by nuclear or collective behaviour manifested as deviations from a simple binary scaling of the production in pp. These modifications are known as Cold Nuclear Matter (CNM) effects. In general, they may have different origins and occur at different stages of the collisions. Initial-state effects are described by modifications of the parton distribution functions (PDF) in a nucleus with respect to a proton [1]. Another approach, specific for the low-x region, considers that the gluon density is expected to saturate, allowing the QCD dynamics to be described by the colour glass condensate (CGC) effective field theory [2]. The CGC framework can be used to predict

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hadron-production rates in hadronic collisions in the forward region [3, 4]. In addition, other effects associated either with initial- or final-state processes might also emerge and produce additional modifications.

The CNM effects can be tested with the high transverse momentum (p_{T}) part of the spectrum. Here, perturbative QCD approaches [3, 5, 6] can be applied. For this reason, experimental data of the hard part of the hadron spectrum may help to better understand the origin of CNM effects by constraining the different phenomenological models. The low-p_{T} part of the spectrum is also very relevant. This production is mainly driven by soft-QCD processes, and quantitative first-principles predictions of the hadron production rate are currently not possible. The Monte Carlo event generators are generally used for predictions, but the lack of hadron production data at forward rapidity complicates their tuning. This has an impact in experimental high-energy physics at LHC, but also in cosmic-ray physics, where these models are fundamental to study the atmospheric evolution of hadronic cascades from high-energy cosmic rays [7].

Since low-x partons are accessed with high $\sqrt{s_{NN}}$ and hadrons produced at forward rapidities, the LHCb experiment [8, 9], located at the Large Hadron Collider (LHC) at CERN, is in a unique position to study saturation phenomena. The LHCb is the only LHC detector fully instrumented between 2 and 5 units of pseudorapidity (η). The detector is equipped with a tracking system that detects charged hadron trajectories with a momentum resolution ranging from 0.5 to 1%. Also, it counts with a calorimeter system that permits photon identification. The LHCb has recorded data from pA and pp collisions at different energies, which have been used to perform measurements of charged hadron production [10, 11] and π^0 production [12].

2. Charged hadron production in pPb and pp collisions

The LHCb has measured prompt charged hadron production at $\sqrt{s_{NN}} =$ 5 TeV in pPb and pp collisions [10] and in pp collisions at $\sqrt{s_{NN}}=13$ TeV [11]. Hadron production can be studied by measuring prompt charged particles, defined as long-lived particles produced in the primary interaction or without long-lived ancestors. Long-lived charged particles, mostly π, K, and p, are detected using the LHCb tracking system. Raw track yields need to be corrected with reconstruction and selection efficiencies. Additionally, background contributions originating from fake tracks not corresponding to real particles and non-prompt particles are determined to correct the yields. Double-differential production cross sections are computed with respect to p_{T} and η. The measurement corresponds to $p > 2$ GeV/c and $0.2 < p_{\mathrm{T}} < 8.0$ GeV/c prompt charged particles with $2.0 < \eta < 4.8$ in pp and $-5.2 < \eta < -2.5$ (backward region) and $1.5 < \eta < 4.3$ (forward region) in pPb collisions.

The measured cross sections allow the nuclear modification factor $R_{p\mathrm{Pb}} \equiv \sigma_{p\mathrm{Pb}}/(A\sigma_{pp})$ for charged particles to be computed for the first time in the forward and backward regions at the LHC. The probed values of the parton momentum fraction x in the lead nucleus range approximately between $[10^{-6}, 10^{-4}]$ and $[10^{-3}, 10^{-1}]$ for the forward and backward regions, respectively. The $R_{p\mathrm{Pb}}$ result is shown in Fig. 1 along with several phenomenological predictions. In the forward region, $R_{p\mathrm{Pb}}$ shows suppression of charged particle production, in general agreement with expectations from nuclear PDFs [5]. The saturation model tends to overestimate $R_{p\mathrm{Pb}}$ in the low-p_{T} region [3], however, more recent NLO calculations are able to describe the data better [4]. In the backward region, a Cronin enhancement [13] is seen for $p_{\mathrm{T}} > 1.5$ GeV$/c$. This feature is not well described by nuclear PDFs [5] or by a pQCD calculation considering parton multiple scattering [14], which reproduced the enhancement observed by the PHENIX Collaboration in the backward region of proton–gold collisions [6]. The measurement places stringent constraints to the nuclear PDFs and saturation models over a wide x range with a total relative uncertainty in the $R_{p\mathrm{Pb}}$ determination down to 4.2%.

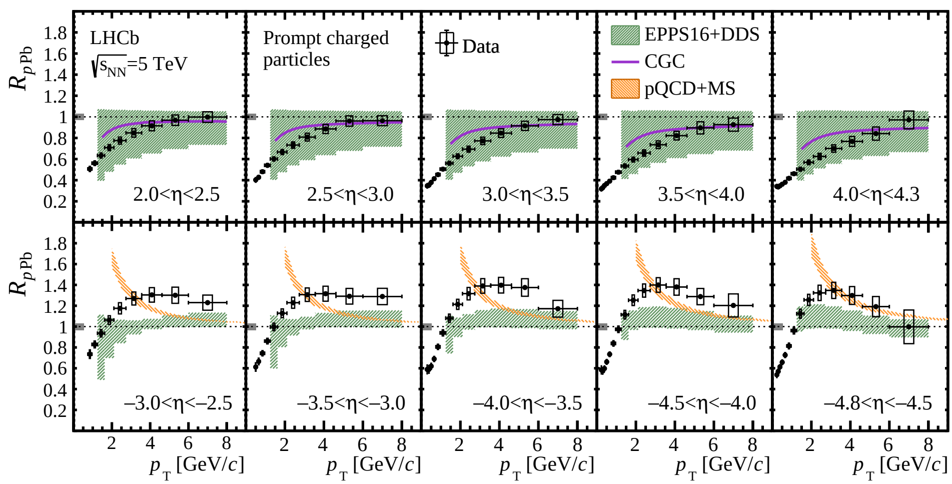

Fig. 1. Nuclear modification factor for charged hadrons as a function of p_{T} in different η intervals for the (top) forward and (bottom) backward regions, compared with theoretical predictions. Vertical error bars correspond to statistical uncertainties, open boxes to uncorrelated systematic uncertainty, and the filled box at $R_{p\mathrm{Pb}} = 1$ to the correlated uncertainty from the luminosity.

2.1. Neutral pion production in pPb and pp collisions

The neutral hadron production provides complementary information to that of charged hadrons for the study of CNM effects. The LHCb has measured the inclusive production of π^0 mesons in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV and pp collisions at $\sqrt{s_{NN}} = 5$ and 13 TeV [12]. Since the measurement involves only one hadron type, it provides additional information to the previously reported results from charged hadrons assuming that the nuclear modification is similar for charged and neutral pions. An additional motivation is that π^0 cross-section measurements are an input for global analyses constraining the fragmentation functions [15] to describe the hadronisation process.

The π^0 mesons are measured with the decay into two photons, which are reconstructed either in the electromagnetic calorimeter or through the reconstruction of an electron–positron pair produced in interactions with the detector material. Yields of π^0 are extracted with a fit to the invariant-mass spectrum of the two reconstructed photons in different p_{T} intervals over the $1.5 < p_{\mathrm{T}} < 10.0$ GeV/c range. These yields are the input to an iterative

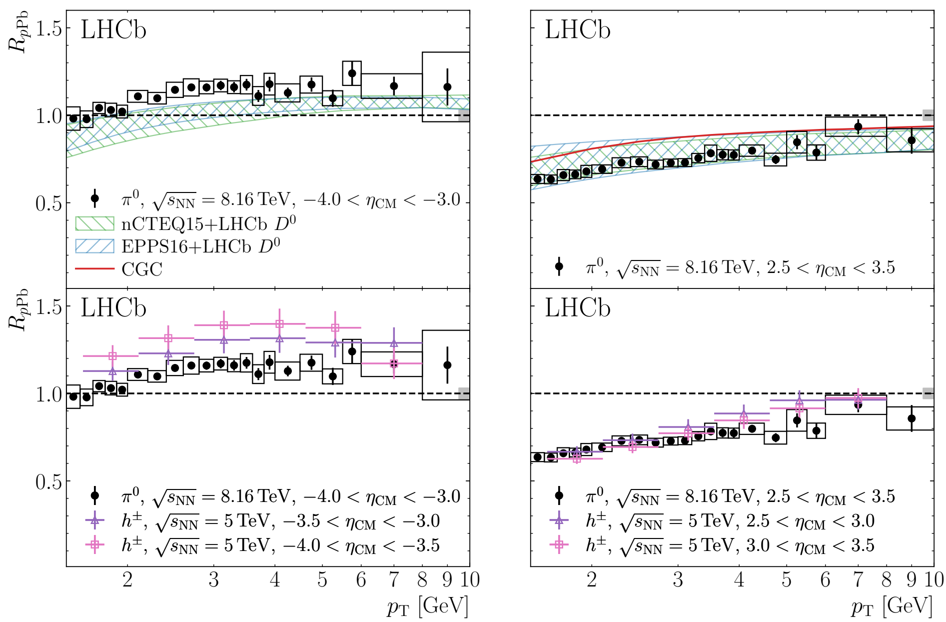

Fig. 2. Nuclear modification factor for π^0 as a function of p_{T} in different η intervals for the (left) backward and (right) forward regions, compared with (top) theoretical predictions and (bottom) the charged hadron results. Vertical error bars correspond to statistical uncertainties, open boxes to uncorrelated systematic uncertainty, and the filled boxes at $R_{p\mathrm{Pb}} = 1$ to the correlated uncertainty.

unfolding technique that corrects detector efficiency and resolution effects. Finally, differential cross sections with respect to $p_{\rm T}$ are computed for pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV and pp collisions at $\sqrt{s_{NN}} = 5$ and 13 TeV.

The nuclear modification factor $R_{p\rm Pb}$ is also computed. The pp reference at $\sqrt{s_{NN}} = 8.16$ TeV is constructed by interpolating the cross section measured at 5 TeV and 13 TeV. The results for $R_{p\rm Pb}$ are shown in Fig. 2, where they are compared with theoretical predictions and the previously reported charged hadron results. In the forward region, suppression of π^0 production is observed, compatible with that observed for charged hadrons and the predictions from nuclear PDFs [16]. This indicates that the effects affect similarly the different hadron species. The CGC prediction [3] underestimates the suppression as in the case of charged hadrons. In the backward region, an enhancement of π^0 production is observed, although less pronounced than for the charged hadron result. This indicates a mass dependency of the Cronin enhancement or that the mechanism affects differently mesons and baryons. This would favour explanations of this effect in terms of radial flow [17] or baryon enhancement from the final-state recombination [18]. The observed enhancement is also larger than predicted by nuclear PDF calculations [16], leaving room for contributions from additional effects.

3. Conclusions and outlook

The presented studies demonstrate the capabilities of the LHCb experiment to perform precise measurements of light-hadron production. The first measurements of the $R_{p\rm Pb}$ in the forward and backward regions at the LHC for charged hadrons and π^0 constitute crucial inputs to investigate the mechanisms behind CNM effects constraining phenomenological models. Also, the measurements provide data in kinematic regions not previously covered by other experiments and are useful to constrain Monte Carlo generators.

Future measurements at the LHCb will provide additional input to investigate CNM effects and, in particular, the saturation region. The particle identification system at the LHCb can cleanly separate the contribution of the different light hadrons, making a precise measurement of (π, K, p) production cross sections viable. The measurement of other light neutral hadrons (η, η') is also possible. Additionally, the π^0 measurement is an input for a measurement of direct photon production where photons from π^0 decays are the main background. This measurement would cleanly probe the saturation region since photons do not interact strongly and therefore are not subject to final-state effects. Also, the measurement of azimuthal photon–hadron correlations can be used to extract photons produced in a Compton process which probes directly the nuclear structure giving direct access to the saturation region.

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