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Abstract. It is believed that the Color Glass Condensate (CGC) can describe the increase of parton density at very high energies or small values of the Bjorken-x. In this paper, the principal features of the CGC framework are outlined. Special attention is given to the prospects of observing gluon saturation effects at the LHC. In particular, heavy flavour and charmonium production are discussed in terms of physics performance studies of the ALICE Forward Muon Spectrometer.

1. Introduction

By colliding heavy nuclei at high energy the CERN Large Hadron Collider (LHC) is expected to create a new phase of hadronic matter, known as the Quark Gluon Plasma (QGP). Charmonium suppression was one of the main pieces of evidence for CERN's claim to have produced a deconfined matter state of quarks and gluons at SPS energies [1, 2]. By studying QGP signatures such as this, it was soon realised that a good description of less complex systems (p+p and p+A) is essential. Cold nuclear matter effects such as initial state energy loss and shadowing have been studied to quantify whether absorption is also present [3]; it has been suggested that initial state effects have been observed at RHIC energies [4, 5]. At the LHC several colliding systems can be studied in a new energy regime. Additionally, the large predicted $c\bar{c}$ and $b\bar{b}$ cross sections promise a systematic study of their production mechanism. Moreover, the range of Bjorken-x values to be reached is unique. In particular, ALICE (A Large Ion Collider Experiment) [6] will probe deep into novel x values, as low as about 10^{-6} for the J/ψ. As the ALICE experiment can measure heavy flavour decays and quarkonia at both central and forward rapidity regions [6], a comparison between these measurements is foreseen during the forthcoming years. In this paper only results in the forward region are described.

Small-x physics is connected to the subject of gluon saturation. In the absence of gluon saturation, QCD evolution equations (DGLAP [8] and BFKL [9]) are applied to the gluonic parton distribution. The Color Glass Condensate (CGC) effective theory [10] takes saturation effects explicitly into account. It imposes non-linear corrections to these equations leading to the JIMWLK [11, 12] or the BK ones [13, 14]. Ultimately, a systematic study of small-x physics might provide, for a given colliding system, an experimental estimate of the saturation scale $Q_s^2(x)$ [10] which is believed to be responsible for controlling initial cold matter effects.

In this paper, the prospects of observing gluon saturation effects via the measurements of heavy flavour decays and charmonium will be discussed. In particular, simulations based on the CGC are presented, compared to those given by a version of the PYTHIA [15] event generator tuned for NLO pQCD predictions [16], with the inclusion of shadowing. Unless otherwise stated, such a tuning will be referred to as MNR+EKS98 (for more details see [6, 7]).

2. Prepared simulations and models used

In brief, the CGC description described in [17, 18] is used. In such an approach, the heavy quark pair cross-section in a p+Pb collision can be written as:

$$\frac{dN^{pPb}_{Q\overline{Q}}}{dyd^2\boldsymbol{p}_{\rm t}} = f_g^{(p)}(x_1) \otimes \varphi(x_2) \otimes \frac{dN^{\rm sat}_{{\rm gg}\to Q\overline{Q}}}{dyd^2\boldsymbol{p}_{\rm t}} \ , \tag{1}$$

where $f_g^{(p)}$ is the standard gluon distribution in the proton as a function of the momentum carried by the parton (x_1 or x_2), for which the CTEQ6L0 parameterisations [19] are used. $\varphi(x_2)$ is a function that encodes the necessary information about the gluon distribution in a saturated nucleus. The evolution of this object with x_2 is determined by solving numerically the BK equation, and its initial condition (at the moderate value of $x_0 = 10^{-2}$) is taken from the McLerran-Venugopalan model [10]. $dN^{\rm sat}_{{\rm gluons}\to Q\overline{Q}}/dyd^2\boldsymbol{p}_{\rm t}$ is the heavy quark spectrum resulting from gluon fusion processes into heavy quark $Q\overline{Q}$ pairs, evaluated by taking into account the re-scattering effects that are relevant in a saturated regime. It is important to keep in mind that this formula is valid only when $x_2 \ll x_1$, since any possible high density effect in the proton has been ignored. Additionally, as described in the references given, the region of large $x_2(> 10^{-2})$ should be avoided. The convention used is that the projectile and the target represent hadrons coming from the positive and negative rapidity, respectively. The values for c and b quark masses are set to 1.2 GeV/c^2 and 4.75 GeV/c^2, respectively.

Furthermore, the collision geometry has been simplified by omitting effects due to the impact parameter; this approximation amounts to considering a nucleus of constant thickness, which may not affect any hard probe production. α_s is treated as a constant having the value of 0.15. $Q^2_{s,p}$, $Q^2_{s,A}$ are evaluated at $x_0(= 10^{-2})$, taking the following values: 0.33 GeV^2, 1.93 GeV^2, respectively. A number of constant pre-factors are also missing in the code used for obtaining the heavy quark yield in the CGC approach. For this reason, our spectra were normalised using the total yield of p+p collisions at $\sqrt{s}$= 8.8 TeV as given by the MNR+EKS98. In the future, a proper normalisation will be taken into account. Despite the large spread of the absolute cross-section values for different sets of inputs, the ratios obtained using MNR+EKS98 calculations depend significantly less on the choice of the parameters. Therefore, they provide a baseline reference for making comparisons to CGC results.

3. Heavy flavour decays

In this paper, the approximation just described is studied in the context of the ALICE experiment. In particular, heavy quark pairs produced in the Forward Muon Spectrometer [20] acceptance originate from the interaction of a low-x parton from the projectile and a higher-x parton from the target. Thus, all quark pairs produced within the detector acceptance are not very sensitive to the large-x extrapolation of the projectile gluon distribution. The rapidity was defined in the laboratory frame. The centre-of-mass-frame shift with respect to the laboratory, of $\delta y = -0.47$ for Pb+p collisions, was taken into account. Notice that it constrains the rapidity window where the R_{Pb-p} can be measured; the ratio will correspond to muons with $y \in$ [-2.97,-4] for p+p collisions and muons with $y \in$ [-2.5,-3.53] for Pb+p collisions. Nuclear modification factors (R_{A-p}) are defined as the ratio between the yield in p+A collisions to the yield in p+p collisions, normalised by the number of binary collisions ‡.

To obtain the results presented in this section, the AliRoot [21] coding

‡ Although not discussed here, the study of multiple scattering effects is also envisaged by measuring the R_{p+Pb} ratio.

implementation of generated c and b quarks, as given by the CGC, was required. Only heavy quarks have been generated, thus the following results do not take any background into account, e.g. from muons originating from hadronic sources (pions and kaons). We acknowledge that these decays should be taken into account in our analysis to make it somewhat more realistic; this background contributes mostly to the low p_{t} region (p_{t} <1.5 GeV/c) [7]. Both the quark fragmentation processes and the heavy hadron decays were computed through their semi-muonic channels. Notice also that the frontal absorber of the spectrometer does not allow low momentum muons to be detected ($\sim$ p<3-4 GeV/c). Transverse momentum and rapidity distributions of muons from c and b quarks were calculated for both models (MNR+EKS98 and CGC) in p+p and Pb+p collisions at $\sqrt{s}$ = 8.8 TeV [22]. As is shown in Figure 1, the R_{Pb-p} ratio was obtained for muons coming from beauty; from charm, and for their sum. For a p_{t} below 2.5 GeV/c, muons from charm dominate in both models. Figure 1 shows that a depletion in the R_{Pb-p} ratio versus p_{t} is more pronounced for the CGC than in MNR+EKS98 simulations. This is due to saturation effects. A full physics performance study is needed as a next step in this analysis.

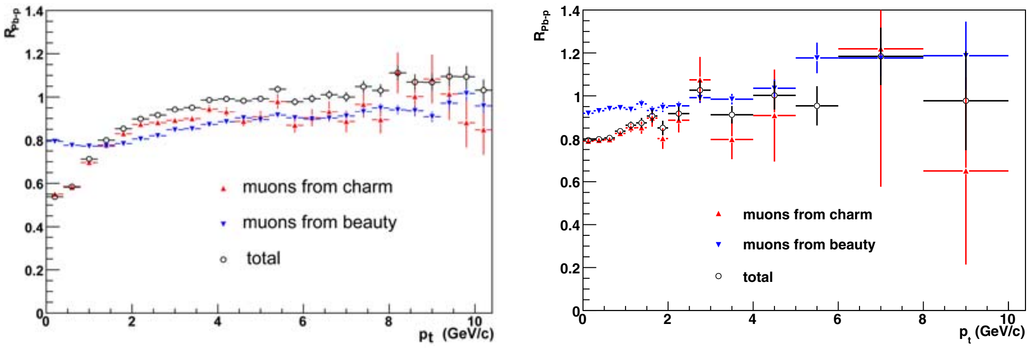

Figure 1. The nuclear modification factor R_{Pb-p} is presented for both CGC and MNR+EKS98 calculations on the left and right hand side, respectively. These results are obtained at the generation level only. See text for more details.

4. The J/ψ meson

The $Q\overline{Q}$ production is given by the CGC. The J/ψ production cross-section was calculated following the Color Evaporation Model [23] approach. As in Section 3, only numerical simulations are presented without discussing full simulation results. $Q^2_{s,p}$, $Q^2_{s,A}$ have taken the following values: 0.17 GeV^2 and 2.0 GeV^2, respectively. Notice that the values for $Q^2_{s,p}$ and $Q^2_{s,A}$ are different from those presented in the previous section. New saturation values were estimated from analysing recent RHIC data [24]. It was not possible to use these new values in the earlier sections because these fine-tuned parameters were not available at the time that study was carried out. These model parameters were varied systematically (not shown) observing no major changes. As expected these results are α_s dependent, as this variable is proportional to the degree of gluon saturation. Figure 2 shows the R_{Pb+p} ratio versus rapidity for different values of transverse momentum: 2.5 GeV/c (dashed line), 5 GeV/c (dotted line) and 10 GeV/c (dash-dotted line). A large suppression is expected for all momenta, and, at low $p_{\rm t}$, all predictions are lower than those from EPS09 [25] calculations (~ 0.8) [26]. Notice that an increase of R_{p+Pb} at large values of rapidity is expected due to multiple scattering, resulting from the small c quark mass. As mentioned before, these results are not valid for $x_2(Pb) > 0.01$; further theoretical developments might also be considered to verify the validity of $Q\overline{Q}$ production at small-x values (see [27]).

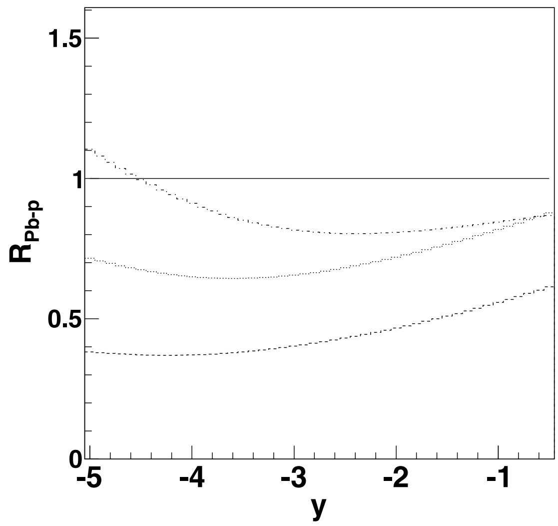

Figure 2. J/ψ's R_{Pb+p} ratio versus rapidity for different values of transverse momentum: 2.5 GeV/c (dashed line), 5 GeV/c (dotted line) and 10 GeV/c (dash-dotted line). These results are obtained from numerical CGC simulations only and were calculated at $\sqrt{s}$ = 8.8 TeV.

5. Summary

Both CGC and MNR+EKS98 numerical results on single muon production were obtained in p+p and Pb+p interactions at $\sqrt{s}$=8.8 TeV. At low p_t, the CGC model shows a stronger suppression for charm quarks than for beauty, owing to the saturation itself. By performing numerical CGC simulations alone it was also discussed that the J/ψ meson offers an additional and very promising way to study small-x physics at the LHC. Further work is being carried out to study full detector performance effects for these analyses.

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