Momentum space dipole amplitude for DIS and inclusive hadron production

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Abstract.
We show how the AGBS model, originally developed for deep inelastic scattering applied to HERA data on the proton structure function, can also describe the RHIC data on single inclusive hadron yield for $d+Au$ and $p+p$ collisions through a new simultaneous fit. The single inclusive hadron production is modeled through the color glass condensate, which uses the quark(and gluon) condensate amplitudes in momentum space. The AGBS model is also a momentum space model based on the asymptotic solutions of the BK equation, although a different definition of the Fourier transform is used. This description entirely in transverse momentum of both processes arises for the first time. The small difference between the simultaneous fit and the one for HERA data alone suggests that the AGBS model describes very well both kind of processes and thus emerges as a good tool to investigate the inclusive hadron production data. We use this model for predictions at LHC energies, which agree quite well with available experimental data.

PACS: 12.38.Bx, 13.60.Hb, 13.85.Ni

COLOR DIPOLE PICTURE OF DIS

At small-x, electron-proton deep inelastic scattering (DIS) can be seen in a particular frame, called *dipole frame*, which allows the factorization of the virtual photon-proton cross section. In this frame, the proton carries most of the total energy, but the photon has enough energy to split into a quark-antiquark pair, or a dipole. This $q\bar{q}$ pair then interacts with the proton. The virtual photon-proton cross section can be written as

$$\sigma_{T,L}^{\gamma^* p}(Q^2,Y) = \int d^2r \int_0^1 dz \left|\Psi_{T,L}(\boldsymbol{r},z;Q^2)\right|^2 \sigma_{\rm dip}(\boldsymbol{r},Y), \tag{1}$$

where the labels T and L refer, respectively, to the transverse and longitudinal parts of the cross section, $\boldsymbol{r}=\boldsymbol{x}-\boldsymbol{y}$ is the vector which gives the transverse size of the dipole, $\boldsymbol{x}$ and $\boldsymbol{y}$ being the transverse coordinates of the quark and the antiquark; z is the fraction of the momentum of the photon carried by the quark and $\Psi_{T,L}(\boldsymbol{r},z;Q^2)$ are the transverse and longitudinal wavefunctions for the photon in the dipole description. Using Eq.(1) one can obtain the expression for the F_2 proton structure function through the formula

$$F_2(x,Q^2) = \frac{Q^2}{4\pi^2\alpha_{em}}\left[\sigma_T^{\gamma^* p}(x,Q^2)+\sigma_L^{\gamma^* p}(x,Q^2)\right]. \tag{2}$$

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AIP Conf. Proc. 1520, 148-153 (2013); doi: 10.1063/1.4795948

The quantity σ_{dip} in Eq.(1) is the dipole-proton cross section which can be expressed as

$$\sigma_{dip}^{\gamma^* p}(r,Y) = 2\pi R_p^2 \mathcal{N}(r,Y). \tag{3}$$

where $\mathcal{N}(r,Y)$ is the dipole scattering amplitude.

AGBS PARAMETRIZATION

A parametrization of dipole-proton scattering amplitude in momentum space has been proposed by de Santana Amaral, Gay Ducati, Betemps, and Soyez (AGBS) [2]. The F_2 structure function takes the form:

$$F_2(x,Q^2) = \frac{Q^2 R_p^2 N_c}{4\pi^2} \int_0^\infty \frac{dk}{k} \int_0^1 dz\, |\tilde{\Psi}(k^2,z;Q^2)|^2 N(k,Y) \tag{4}$$

where now the photon wavefunction is expressed in momentum space and $N(k,Y)$ is the scattering amplitude in momentum space. The AGBS model analytically interpolates between the behavior of the Balitsky-Kovchegov (BK) [1] evolution equantion solutions in the dilute regime and the saturation one, in which it behaves like

$$N(k,Y) \overset{k \ll Q_s}{=} c - \log\left(\frac{k}{Q_s(Y)}\right). \tag{5}$$

The expression for the dilute tail of the scattering amplitude reads

$$N(k,Y) \overset{k \gg Q_s}{\approx} \left(\frac{k^2}{Q_s^2(Y)}\right)^{-\gamma_c} \log\left(\frac{k^2}{Q_s^2(Y)}\right) \exp\left[-\frac{\log^2\left(k^2/Q_s^2(Y)\right)}{2\bar{\alpha}\chi''(\gamma_c)Y}\right], \tag{6}$$

where $\lambda = \min \bar{\alpha}\frac{\chi(\gamma)}{\gamma} = \bar{\alpha}\frac{\chi(\gamma_c)}{\gamma_c} = \bar{\alpha}\chi'(\gamma_c)$.

Interpolation in the AGBS model is done through the following expression for the scattering amplitude ($\rho \equiv \ln(k^2/k_0^2)$)

$$\tilde{T}^{\text{AGBS}}(\rho,Y) = L_F\left(1 - e^{-T_{\text{dil}}}\right), \tag{7}$$

where

$$T_{\text{dil}} = \exp\left[-\gamma_c(\rho-\rho_s) - \frac{\mathcal{L}^2 - \log^2(2)}{2\bar{\alpha}\chi''(\gamma_c)Y}\right], \tag{8}$$

$$\mathcal{L} = \ln\left[1 + e^{(\rho-\rho_s)}\right] \qquad \text{with} \quad Q_s^2(Y) = k_0^2 e^{\lambda Y}, \tag{9}$$

and

$$L_F = 1 + \ln\left[e^{\frac{1}{2}(\rho-\rho_s)} + e^{-\frac{1}{2}(\rho-\rho_s)}\right]. \tag{10}$$

This model describe quite well the HERA data on F_2^p with heavy quarks included [2] and was also used to study whether the possible effects of pomeron loops on the high energy QCD evolution were already present at HERA energies [3].

HERA AND RHIC DATA SIMULTANEOUS FIT

Both HERA proton structure function F_2^p (4) and RHIC hadron yield

$$\frac{dN}{dy_h d^2 p_t} = \frac{K}{(2\pi)^2} \int_{x_F}^{1} \frac{dz}{z} \left[x_1 f_{q/p}(x_1, p_t^2) \tilde{N}_F \left(\frac{p_t}{z}, x_2 \right) D_{h/q} \left(z, p_t^2 \right) + x_1 f_{g/p}(x_1, p_t^2) \tilde{N}_A \left(\frac{p_t}{z}, x_2 \right) D_{h/g} \left(z, p_t^2 \right) \right], \tag{11}$$

data were used to simultaneously fit the AGBS model to DIS and heavy ion processes. In (11), p_t and y_h are the transverse momentum and rapidity of the produced hadron while $f_{i/p}$ and $D_{h/i}$ refer to the parton distribution function of the incoming nucleon and to the hadron fragmentation function respectively, which are considered at the scale $Q^2 = p_t^2 > 1$ GeV^2. Here we will use the CTEQ6 LO p.d.f's [8] and the LO KKP fragmentation functions [9]. $N_{A,F}$ denote the scattering amplitudes in the adjoint and fundamental representations, respectively. They are obtained from the AGBS amplitudes through [4]

$$\tilde{N}_{A,F} = 2\pi \nabla_{\boldsymbol{k}}^2 T_{A,F}^{\mathrm{AGBS}}. \tag{12}$$

For light hadrons the finite mass effects can be neglected, so that the pseudorapidity η and rapidity y_h of the produced hadrons are similar $\eta \approx y_h$, giving the following kinematics: $x_F = \sqrt{m_h^2 + p_t^2} \exp(\eta_h)/\sqrt{S_{NN}} \approx p_t \exp(y_h)/\sqrt{S_{NN}}$, $x_2 = x_1 \exp(-2y_h)$ and $x_1 = x_F/z$.

In this analysis, all the last combined HERA data measurements of the proton structure function from H1 and ZEUS Collaborations [5] are fitted, within the kinematic range: $x \leq 0.01$ and $0.1 \leq Q^2 \leq 150\,\mathrm{GeV}^2$.The RHIC data on single inclusive hadron production from BRAHMS [6] and STAR [7] collaborations were also fitted. They were considered in the p_t range higher than 1 GeV to allow that perturbative theory can be applied. To avoid contribution of large-x in the target, we have focused our study in the forward ($y_h \geq 2$) rapidity region, although we also made the fit to the and mid-rapidity ($y_h = 1$) region. Concerning the parameters, we keep fixed $\bar{\alpha} = 0.2$ and $\gamma_c = 0.6275$, whose value corresponds to the one obtained from the LO BFKL kernel. The other parameters in the amplitude—λ, k_0^2 and $\chi''(\gamma_c)$—are left to be free, as well as the proton radius R_p, which fixes the normalization of the dipole–proton cross section with respect to the dipole–proton amplitude for DIS at HERA, and the rapidity–dependent K factors. Only light quarks were considered and the values used for their masses were $m_{u,d,s} = 140$ MeV.

TABLE 1. Parameters extracted from the fit to H1 and ZEUS combined data [5] on the proton structure function F_2 at HERA.

χ^2/d.o.f.	k_0^2 ($\times 10^{-3}$)	λ	$\chi''(\gamma_c)$	R(GeV^{-1})
0.903	1.13 ± 0.024	0.165 ± 0.002	7.488 ± 0.081	5.490 ± 0.039

First of all we performed a fit to DIS data, in order to verify the behavior of the AGBS model to the new combined H1 and ZEUS data [5]. The values of the parameters, shown in the table 1, are close to those obtained in the original AGBS fit to the HERA data.

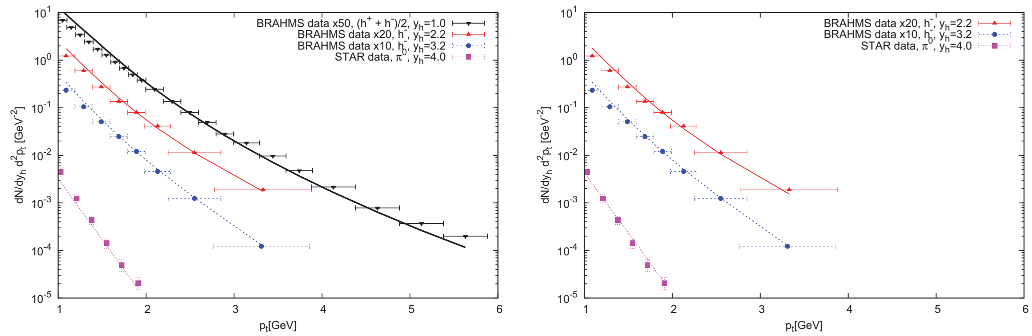

FIGURE 1. Results for the RHIC charged hadron and π^0 yield for $d+Au$ collisions from the simultaneous fit of AGBS to RHIC [6, 7] and HERA [5] data. *Left* plot incudes the midrapidity region $y_h \geq 1.0$

TABLE 2. Parameters extracted from the simultaneous fit to HERA F_2 (H1 and ZEUS combined data [5]) and to the RHIC hadron yield for the $d+Au$ collisions (BRAHMS and STAR data [6, 7]). The *second column* corresponds to the fit with the forward rapidity region of the RHIC data included, while in the *third column* the mid-rapidity region of the RHIC data set was also considered.

	$y_h \geq 2.2$	$y_h \geq 1.0$
χ^2/d.o.f.	0.799	1.056
k_0^2 $(\times 10^{-3})$	2.760 ± 0.130	1.660 ± 0.137
λ	0.190 ± 0.003	0.186 ± 0.003
$\chi''(\gamma_c)$	5.285 ± 0.123	6.698 ± 0.223
$R(\mathrm{GeV}^{-1})$	4.174 ± 0.053	4.695 ± 0.112
$K(y_h = 1.0)$	–	6.172 ± 0.379
$K(y_h = 2.2)$	2.816 ± 0.110	3.783 ± 0.259
$K(y_h = 3.2)$	2.390 ± 0.098	3.256 ± 0.226
$K(y_h = 4.0)$	0.7	0.7

This fit will serve as a guideline for our simultaneous fit, once DIS processes are free from model dependent PDF's and fragmentation functions that can interfere on the best values for the model parameters. The simultaneous fit to DIS and hadron production in $d+Au$ collisions has shown a good agreement with the data set, mainly when only forward RHIC data were considered, as seen in the χ^2 values of the table 2. In the Fig. 1 we see the description of the RHIC hadron yield for both lines of table 2. The poorer description of the mid-rapidity region occurs because the target has not reached its gluon condensate state, when neither our amplitude nor the CGC formulation entering the Eq. (11) are valid. The parameters values—even those got when the mid-rapidity data was included—show that the AGBS model describes equally well the HERA and RHIC data, and the last improves the AGBS model.

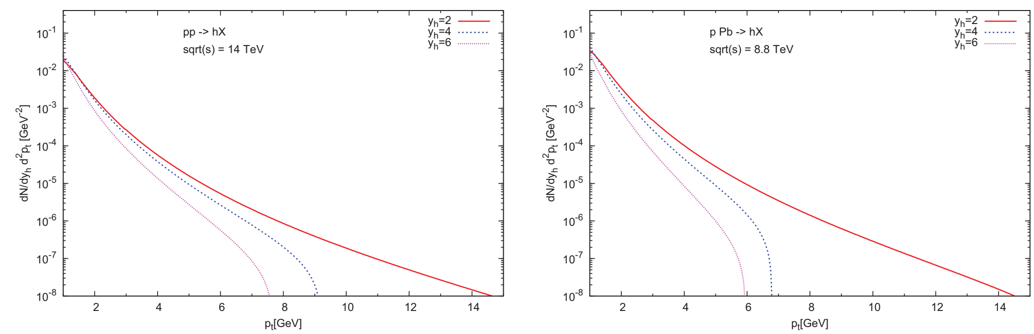

FIGURE 2. Predictions of the AGBS model to the LHC charged hadron yield for $p+p$ (*left*) and $p+Pb$ (*right*) collisions. Parameters from the simultaneous fit of AGBS to forward rapidity RHIC and HERA data (first line of table 2). We have used $A_{\rm eff} = 20$ for lead target.

LHC PREDICTIONS

In this section we present predictions of the AGBS model for $p+p$ and $p+Pb$ collisions at LHC energies of 14 and 8.8 TeV, respectively. We use the parameters obtained from the simultaneous fit in the case of forward rapidity region of RHIC data (first line of the table 2) as explained above and our results are shown in the Figs. 2. Fig. 3 shows the description of the recent LHC CMS [10] p_t distribution data for proton–proton collisions using our model. Surprisingly, a very good description was obtained, although the K factors are large. This could be explained as an uncertainty of the AGBS model in the comparison with the pseudorapidity averaged data performed by the CMS collaboration. As the AGBS model is not supposed to describe the central rapidity region since it is a model for the low-x part of the target (projectile), we used an averaged value $\eta = 1.4$ so that the description of the pseudorapidity averaged data over the region $|\eta| < 2.4$ should imply some disagreements, which are in the K factor. Standing for NLO corrections, the K factors account for the qq and gq interactions, while Eq. (11) considers only gluons in the target. Thus, as expected, the K values decrease with the energy, because the target (projectile) gluon wavefunction is more important when compared with the quark density as the energy increases. In other words, Eq. (11) should receive less quark corrections in the target for higher energies.

CONCLUSIONS AND DISCUSSION

We have shown in this work the compatibility of the AGBS model with both the single inclusive hadron yield at RHIC and the small-x DIS at HERA. Through Eq. (12) one could write analytically the AGBS model in the appropriate Fourier space used to describe the single inclusive hadron yield from the Color Glass Condensate. We have performed a new simultaneous fit of the AGBS model to the F_2^p at HERA and hadron yield at RHIC, which results agreed with the one performed to HERA data alone, meaning that our expression correctly describes the AGBS in the standard Fourier space of the CGC formalism applied to hadron production.

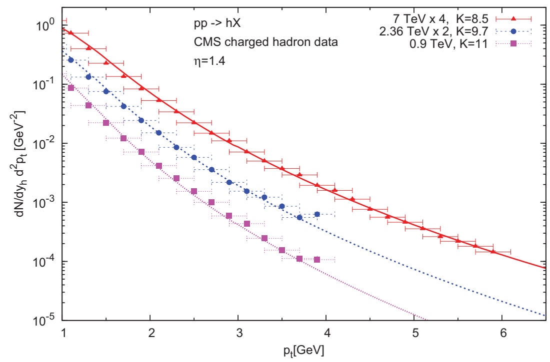

FIGURE 3. Predictions of the AGBS model to the LHC CMS charged hadron yield for $p+p$ collisions at $\sqrt{s} = 0.9, 2.36$ and 7 TeV. The experimental points are from CMS for $|\eta| < 2.4$ [10]. Parameters extracted from the simultaneous fit of AGBS to forward rapidity RHIC and HERA data (first line of table 2).

The model describes well the forward rapidity region of the RHIC data for $d+Au$ and $p+p$ collisions, but fails at mid-rapidities as expected. Thus, being a model for the small-x dipole amplitude, the parameters from the fit for the forward rapidities should be used to further employ of the AGBS model in inclusive hadron production. The same formulation was used to make predictions to the LHC $p+p$ and $p+Pb$ collisions at 14 and 8.8 TeV, respectively. As a matter of data comparison, the model was also used to describe the CMS data on the hadron yield for $p+p$ collisions [10] at different energies.

ACKNOWLEDGMENTS

This work is supported by CNPq (Brazil). E.G.O. is supported by FAPESP under contract 2011/50597-8.

REFERENCES

1. I. Balitsky, Nucl. Phys. B **463**, 99 (1996); Y. V. Kovchegov, Phys. Rev. D **60**, 034008 (1999); Phys. Rev. D **61**, 074018 (2000).
2. J. T. de Santana Amaral, M. B. Gay Ducati, M. A. Betemps and G. Soyez, Phys. Rev. D **76**, 094018 (2007)
3. E. Basso, M. B. Gay Ducati, E. G. de Oliviera, and J. T. de Santana Amaral, Eur. Phys. J. C **58**, 9 (2008); E. Basso, M. B. Gay Ducati, E. G. de Oliviera, and J. T. de Santana Amaral, Braz. J. Phys. v. **38**, 483 (2008).
4. E. A. F. Basso, M. B. Gay Ducati and E. G. de Oliveira, Phys. Rev. D **84**, 034024 (2011).
5. F. D. Aaron *et al.* (H1 and ZEUS Collaborations), JHEP **0110** 109 (2010).
6. I. Arsene *et al.* (BRAHMS Collaboration), Phys. Rev. Lett. **93**, 242303 (2004).
7. J. Adams *et al.* (STAR collaboration), Phys. Rev. Lett. **97**, 152302 (2006).
8. J. Pumplin *et al.*, JHEP **07** 12 (2002).
9. B. A. Kniehl, G. Krammer and B. Pötter, Nucl. Phys. **B582**, 514 (2000).
10. V. Khachatryan *et al.* (CMS Collaboration), JHEP **0210**, 041 (2010) [arXiv:hep-ex/1002.0621]; Phys. Rev. Lett. **105**, 022002 (2010).