Pseudo-rapidity distributions of charged hadrons in pp and pA collisions at the LHC*

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Abstract: In the framework of the Color Glass Condensate, the pseudo-rapidity distributions of charged hadrons in pp and pA collisions at the LHC are studied with the UGD function from the GBW model. With a χ^2 analysis of the CMS data in pp collisions at $\sqrt{s}$=0.9, 2.36, 7 TeV, the normalization factor is obtained and the theoretical results are in good agreement with the experimental data. Then, considering the influence of nucleon hard partons transverse distribution on the number of participants in pA collisions by using a Glauber Monte Carlo method, we also give the predictive results for the multiplicity distributions in pPb collisions at $\sqrt{s}$=4.4 TeV.

Key words: Color Class Condensate, hadron multiplicities, Glauber Monte Carlo method

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1 Introduction

At small-x in super high energy collisions, perturbative Quantum Chromodynamics (pQCD) has predicted that the gluons in a hadron wave function should form a Color Glass Condensate (CGC) [1], which is characterized by strong coherent gluon fields leading to parton saturation. After that, signals of parton saturation have already been observed both in electron-proton (ep) deep inelastic scattering at HERA [2] and in deuteron-gold collisions at Relativistic Heavy-Ion Collisions (RHIC) [3, 4]. However, the research of the nature of CGC needs more confirmation, so it is still an active subject on both theoretical and experimental sides. Recently, the data for charge hadron multiplicities in pp collisions were probed by the Large Hadron Collider (LHC) [5, 6], and soon the first data on pPb collisions at $\sqrt{s} = 4.4$ TeV will also be given. The data at the LHC will allow us to probe the nuclear gluon distributions at a very small Bjorken x domain (10^{-6}–10^{-4}). Thus, these measurements are very important for testing the nature of the CGC. In this paper, based on the CGC formalism, we will investigate the charge hadron multiplicity distributions in pp collisions and give the predictive results for pPb collisions.

In the CGC formalism, the cross section for inclusive hadron production can be given by the convolution of the unintegrated gluon distribution (UGD) of the proton (or nucleus) from the projectile and the target [1, 7]. For the charge hadron pseudo-rapidity distributions, the cross section can be obtained by integrating the inclusive production over $p_{\rm t}$ and a Jacobian transformation [7, 8]. Correspondingly, the UGD function of the proton can be obtained from the dipole-proton scattering amplitude by a Fourier transform. In this paper, the simple UGD function from the Golec-Biernat and Wüsthoff (GBW) model [9], which has successfully described both the HERA and RHIC data, is used for pp collisions. Through a χ^2 analysis of the CMS data for pp collisions, the normalization factor K that describes the conversion of partons to hadrons can be obtained.

In pA collisions, the number of participating nucleons in the collisions must be considered, and the simple and appropriate method to calculate this number is the Glauber Monte-Carlo (GMC) approach [10]. At super high energy domain, the contribution from small-x gluons dominates the mechanism of inelastic hadronic collisions and the influence of the transverse spatial distribution of hard partons in the nucleon must be considered in the GMC approach [11–13]. The most simple and popularly used method to consider the hard partons transverse distribution is considered the nucleon as a hard sphere. In this paper, in order to give a accurate predictive results for pA collisions, the transverse distri-

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bution derived from the J/Ψ photo-production data in the nucleon is used [11].

2 Method

In the CGC formalism [1, 7], the formula for the inclusive production in pp collisions can be given by

$$E\frac{\mathrm{d}\sigma}{\mathrm{d}^3p} = K\frac{2}{C_\mathrm{F}}\frac{1}{p_\mathrm{t}^2}\int^{p_\mathrm{t}}\mathrm{d}k_\mathrm{t}^2\alpha_\mathrm{s}\varphi_{\mathrm{p}_1}(x_1,k_\mathrm{t}^2)\varphi_{\mathrm{p}_2} \times(x_2,(p-k)_\mathrm{t}^2), \tag{1}$$

where $C_\mathrm{F}=(N_\mathrm{c}^2-1)/(2\pi N_\mathrm{c})$, $x_{1,2}=(p_\mathrm{t}/\sqrt{s})\exp(\pm y)$ and $\sqrt{s}$ is the center of mass energy. φ_p is the unintegrated gluon distribution of a proton. The normalization factor K can be determined by a global fit to pp data at various energies.

The multiplicity distribution per unit rapidity can be given by integrating Eq. (1) over p_t

$$\frac{\mathrm{d}N}{\mathrm{d}y}=\frac{1}{S}\int\mathrm{d}^2p_\mathrm{t}E\frac{\mathrm{d}\sigma}{\mathrm{d}^3p},$$

where S is either the inelastic cross section for the minimum bias multiplicity, or a fraction of it corresponding to a specific centrality cut. For the main contribution to Eq. (1) is given by two regions of integration over k_t: $k_\mathrm{t}\ll p_\mathrm{t}$ and $|\vec{p}_\mathrm{t}-\vec{k}_\mathrm{t}|\ll p_\mathrm{t}$, it can be rewritten as

$$\frac{\mathrm{d}N}{\mathrm{d}y} = \frac{K}{S}\frac{2\alpha_\mathrm{S}}{C_\mathrm{F}}\int\frac{\mathrm{d}p_\mathrm{t}^2}{p_\mathrm{t}^2}[\varphi_{\mathrm{p}_1}(x_1,p_\mathrm{t}^2)\int^{p_\mathrm{t}}\mathrm{d}k_\mathrm{t}^2\varphi_{\mathrm{p}_2}(x_2,k_\mathrm{t}^2) +\varphi_{\mathrm{p}_2}(x_2,p_\mathrm{t}^2)\int^{p_\mathrm{t}}\mathrm{d}k_\mathrm{t}^2\varphi_{\mathrm{p}_1}(x_1,k_\mathrm{t}^2)]. \tag{2}$$

Here, for the unintegrated gluon distribution, φ_p, the one from the GBW model will be used [9, 14]

$$\varphi_\mathrm{p}(x,p_\mathrm{t}^2)=\frac{3\sigma_0}{4\pi^2\alpha_\mathrm{s}(Q_\mathrm{s,p})}\frac{p_\mathrm{t}^2}{Q_\mathrm{s,p}^2(x)}\exp\left(-\frac{p_\mathrm{t}^2}{Q_\mathrm{s,p}^2(x)}\right), \tag{3}$$

where the saturation scale is taken as [15]

$$Q_\mathrm{s,p}^2(y)=Q_0^2\left(x_0\frac{\sqrt{s}}{Q_0}\exp(\pm y)\right)^{\bar{\lambda}}, \tag{4}$$

with the parameters $\sigma_0=23$ mb, $Q_0=0.6$ GeV, $x_0=0.01$ and $\bar{\lambda}=0.205$. The running coupling constant α_s, is assumed to freeze at $\alpha_\mathrm{max}=0.52$ [16]

$$\alpha_\mathrm{s}(Q^2)=\min\left[\frac{12\pi}{27\ln\frac{Q^2}{\Lambda^2}},\alpha_\mathrm{max}\right], \tag{5}$$

where $\Lambda=0.226$. In order to account for large-x effects in the gluon distribution, the distribution function is always multiplied by $(1-x)^4$.

To calculate the distribution verse pseudo-rapidity, one should express rapidity y in terms of pseudo-rapidity η

$$y(\eta)=\frac{1}{2}\ln\frac{\sqrt{\cosh^2\eta+\mu^2}+\sinh\eta}{\sqrt{\cosh^2\eta+\mu^2}-\sinh\eta}, \tag{6}$$

and the Jacobian can be obtained by

$$J(\eta)=\frac{\partial y}{\partial\eta}=\frac{\cosh\eta}{\sqrt{\cosh^2\eta+\mu^2}}, \tag{7}$$

where the scale $\mu\left(\sqrt{s}\right)=0.24/(0.13+0.32\sqrt{s}^{0.115}\Big)$ with $\sqrt{s}$ expressed in units of TeV [15].

For pA collisions, the saturation scale of the nucleus can be given as

$$Q_{\mathrm{s},A}^2(y)=N_{\mathrm{part},A}Q_\mathrm{s,p}^2(y), \tag{8}$$

where $N_{\mathrm{part},A}$ is the number of participating nucleons in the collisions. In the GMC approach, the number of participants can be given by [10]

$$N_{\mathrm{part},A}(\vec{b})=\sum_{i=1,2\ldots A}P(|\vec{b}-\vec{r}_i|), \tag{9}$$

where $\vec{b}$ is the impact parameter of the pA collisions, and the set $\vec{r}_i$, which corresponds to the coordinates of the nucleons in the target, can be picked randomly according to a Woods-Saxon distribution [10, 17]

$$\rho(r)=\rho_0\frac{1}{1+\exp\left(\frac{r-R}{a}\right)},$$

where ρ_0 corresponds to the nucleon density in the center of the nucleus, R corresponds to the nuclear radius and a corresponds to the "skin depth". In the GMC framework, the nucleons are always simply considered as a "hard sphere" (HS), and the function

$$P^\mathrm{HS}(|\vec{b}-\vec{r}_i|)=\Theta(|\vec{b}-\vec{r}_i|-d_\mathrm{max}), \tag{10}$$

where

$$d_\mathrm{max}=\sqrt{\frac{\sigma_\mathrm{in}(\sqrt{s})}{\pi}}$$

with $\sigma_\mathrm{in}(\sqrt{s})$=52, 60, 65.75, 70.45 mb at $\sqrt{s}$=0.9, 2.36, 4.4, 7 TeV, respectively. Here, the nucleon partons transverse distribution derived from the J/ψ photo-production data is used, and this transverse distribution can be described by a dipole (D) form [13]

$$P^\mathrm{D}(|\vec{b}-\vec{r}_i|)=m_\mathrm{g}^2/(4\pi)(m_\mathrm{g}|\vec{b}-\vec{r}_i|)K_1(m_\mathrm{g}|\vec{b}-\vec{r}_i|)\sigma_\mathrm{in}, \tag{11}$$

where K_1 denotes the modified Bessel function and the

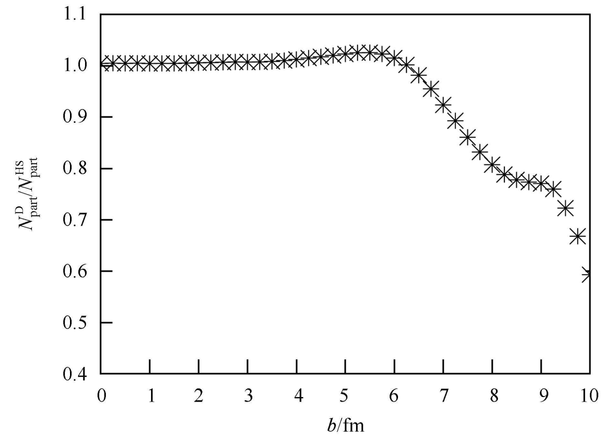

Fig. 1. The ratio of $N_{\mathrm{part},A}$ with the dipole model to that with the hard sphere model.

mass parameter $m_{\mathrm{g}}\sim 1.1\ \mathrm{GeV}^2$. The ratio of $N_{\mathrm{part},A}$ with the dipole model to that with the hard sphere model is shown in Fig. 1. It is shown that a clearly downward trend can be seen in the domain $b>6$ fm.

3 Results and discussion

In order to obtain the normalization factor from the data in pp collisions, we must introduce the χ^2 analysis method [18, 19]

$$\chi^2=\sum_{j}^{n}\frac{\left(\left.\frac{\mathrm{d}N}{\mathrm{d}\eta}\right|_{\mathrm{pp},j}^{\mathrm{data}}-\left.\frac{\mathrm{d}N}{\mathrm{d}\eta}\right|_{\mathrm{pp},j}^{\mathrm{theo}}\right)^2}{\left(\left.\frac{\mathrm{d}N}{\mathrm{d}\eta}\right|_{\mathrm{pp},j}^{\mathrm{err}}\right)^2}, \tag{12}$$

where

$$\left.\frac{\mathrm{d}N}{\mathrm{d}\eta}\right|_{\mathrm{pp},j}^{\mathrm{data}}\left(\left.\frac{\mathrm{d}N}{\mathrm{d}\eta}\right|_{\mathrm{pp},j}^{\mathrm{theo}}\right)$$

indicates the experimental data (theoretical values) for the charge hadron pseudo-rapidity distributions in pp collisions, and $\left.\frac{\mathrm{d}N}{\mathrm{d}\eta}\right|_{\mathrm{pp},j}^{\mathrm{err}}$ denotes the systematic errors in the experiment. With $\chi^2_{\min}/$ (degree of freedom)=0.2597, we find that the normalization factor $k(=K/S_{\mathrm{pp}})$ is equal to 0.098. The theoretical results in pp collisions at $\sqrt{s}$=0.9 (a), 2.36 (b), 7 (c) TeV are shown in Fig. 2. As a contrast, the results with the KLN model is also given [7], and the solid and dashed curves are the results with the GBW model and the KLN model, respectively. It is shown that the theoretical results with both of them are in good agreement with the experimental data [5, 6]. Fig. 2 also shows that the theoretical results with the GBW model are lower than those with the KLN model at larger η.

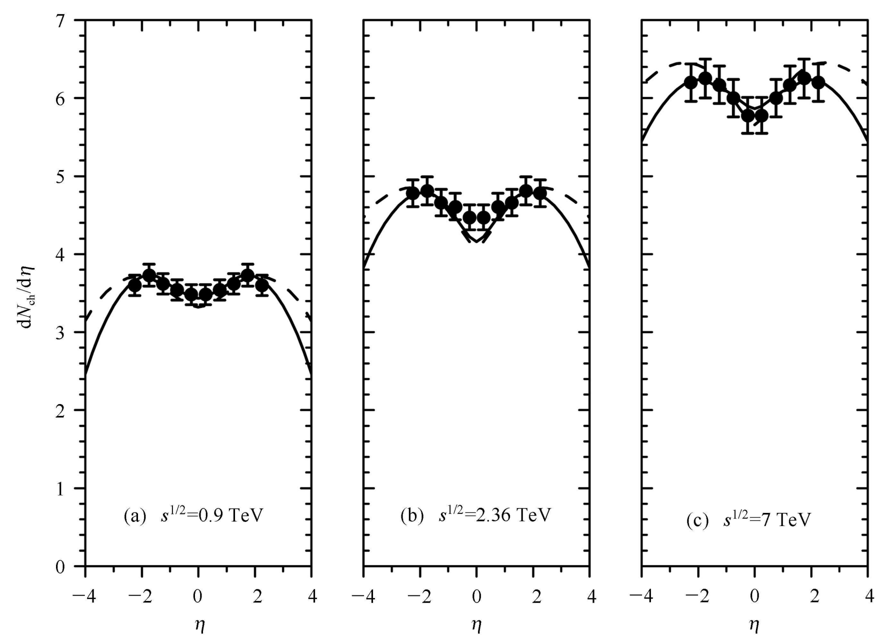

Fig. 2. Pseudo-rapidity distribution of charged hadrons in pp collisions at $\sqrt{s}$=0.9 TeV (a), 2.36 TeV (b) and 7 TeV (c). The solid and dashed curves are the results of the GBW model and the KLN model, respectively. The data come from CMS [5, 6].

For pA collisions, the average hadron multiplicities can be obtained by

$$\frac{\mathrm{d}N}{\mathrm{d}\eta}\Big|_{\mathrm{pA}}=\frac{\displaystyle\int_{b_1}^{b_2}\mathrm{d}b2\pi b\frac{\mathrm{d}N}{\mathrm{d}\eta}\Big|_{\mathrm{pA}}(b)}{\displaystyle\int_{b_1}^{b_2}\mathrm{d}b2\pi b\{1-[1-\sigma_{\mathrm{in}}^{\mathrm{pp}}\hat{T}_A(b)]^A\}},\qquad(13)$$

where $\hat{T}(b)$ is the thickness function [13], and the pseudo-rapidity distributions in pA collisions, $\frac{\mathrm{d}N}{\mathrm{d}\eta}\Big|_{\mathrm{pA}}(b)$, can be obtained from that in pp collisions by changing $Q^2_{\mathrm{S,p}}$ to $Q^2_{\mathrm{S},A}$. Fig. 3 shows the predictive results for pPb collisions at $\sqrt{s}$=4.4 TeV for different centrality: 0–100% (solid curve), 0–50% (dashed curve), 50%–100% (dotted curve). The results will be verified by the LHC experiments in the near future.

In summary, according to the CGC formalism, we have calculated the hadron pseudo-rapidity distribution at the LHC. With the χ^2 analysis of the experimental data in pp collisions, the normalization factor is obtained and the theoretical results are in good agreement with the experimental data. In order to give a accurate predictive results for pA collisions, the hadron partons transverse distribution in a nucleon is also considered in the GMC approach, and the predictive results will be validated by future LHC experiments.

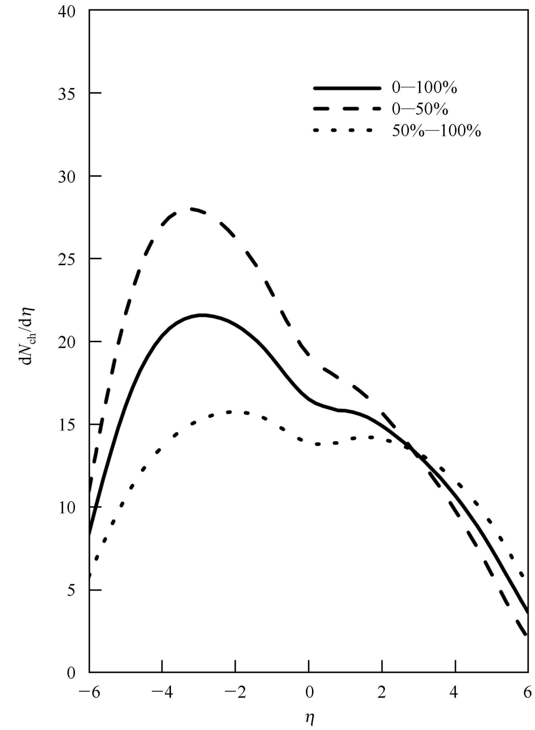

Fig. 3. Pseudo-rapidity distribution of charged particles in minimum bias pPb collisions at $\sqrt{s}$= 4.4 TeV with the GBW model for different centrality cuts.

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