Baryon stopping as a test of geometric scaling

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Abstract

We suggest to use net-proton rapidity distributions in central relativistic heavy-ion collisions at SPS, RHIC and LHC energies in order to probe saturation physics. Within the color glass condensate framework based on small-coupling QCD, net-baryon rapidity distributions are shown to exhibit geometric scaling. Excellent agreement with RHIC data in Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV is found. Predictions for net-proton rapidity spectra in central Pb + Pb collisions at LHC energies of $\sqrt{s_{NN}}$ = 5.5 TeV are made.

Baryon stopping in relativistic heavy-ion collisions as a probe of QCD-matter at high parton density is of great current interest [1–4]. Theoretical QCD-based approaches usually focus on charged-hadron production. In the central rapidity region a reasonable understanding has been achieved in the color glass condensate (CGC) framework [5–8] through inclusive gluon production [9,10]. In this theory, due to the self-interaction of gluons, the number of gluons in the nuclear wave function increases with increasing energy and decreasing longitudinal momentum fraction x carried by the parton.

Unitarity requires that the gluon density saturates below a characteristic momentum scale, the so-called saturation scale Q_s. In this regime gluons form a coherent state. Presently the evidence for the existence of this state of matter is, however, not yet clear. Due to the dependence of the saturation scale on rapidity and mass number, it has been proposed that saturation effects should be studied with heavy nuclei and large rapidities at RHIC energies and beyond.

We have suggested in [11] to use the rapidity distribution of net protons ($p - \bar{p}$) in central heavy-ion collisions as a testing ground for saturation physics, cf. Fig. 1. In $A+A$ collisions, two distinct and symmetric peaks with respect to rapidity y occur at SPS energies [12] and beyond. The rapidity separation between the peaks increases with energy, and decreases with increasing mass number A reflecting larger baryon stopping for heavier nuclei, as has been investigated phenomenologically in the relativistic diffusion model [13].

The net-baryon number is essentially transported by valence quarks. During the collision the fast valence quarks in one nucleus scatter in the other nucleus by exchanging soft gluons, leading to their redistribution in rapidity space. Here we do not address the issue of the baryon transport mechanism in the fragmentation process [14] that is relevant for identified baryons.

We take advantage of the fact that the valence quark parton distribution is well known at large x, which corresponds to the forward and backward rapidity region, to access the gluon distribution at small x in the target nucleus. Therefore, this picture provides a clean probe of

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the unintegrated gluon distribution $\varphi(x, p_T)$ at small x in the saturation regime. Here p_T is the transverse momentum transfer.

We have two symmetric contributions, coming from the two beams. The contribution of the fragmentation of the valence quarks in the forward moving nucleus is given by the simple formula [15] for the rapidity distribution of hadrons:

$$\frac{dN}{dy} = \frac{C}{(2\pi)^2} \int \frac{d^2 p_T}{p_T^2}\, x_1 q_v(x_1, Q_f)\, \varphi\left(x_2, p_T\right), \tag{1}$$

where $x_1 = p_T/\sqrt{s}\exp(y)$, $x_2 = p_T/\sqrt{s}\exp(-y)$ are the longitudinal momentum fractions carried, respectively, by the valence quark in the projectile and the soft gluon in the target. The factorization scale is set equal to the transverse momentum, $Q_f \equiv p_T$. The contribution of valence quarks in the other beam nucleus is added incoherently by changing $y \to -y$. The gluon distribution is related to the forward dipole scattering amplitude $\mathcal{N}(x, r_T)$, for a quark dipole of transverse size r_T, through the Fourier transform

$$\varphi(x, p_T) = 2\pi p_T^2 \int r_T dr_T \mathcal{N}(x, r_T) J_0(r_T p_T). \tag{2}$$

In the fragmentation region of the projectile the valence quark parton distribution function (PDF) is dominated by large values of x_1. We integrate out the fragmentation function such that the hadron rapidity distribution is proportional to the parton distribution. The overall constant C depends on the nature of the produced hadron.

One important prediction of the color glass condensate theory is geometric scaling: the gluon distribution depends on x and p_T only through the scaling variable $p_T^2/Q_s^2(x)$, where $Q_s^2(x) = A^{1/3} Q_0^2\, x^{-\lambda}$, A is the mass number and Q_0 sets the dimension. This has been confirmed experimentally at HERA [16]. The fit value $\lambda = 0.2 - 0.3$ agrees with theoretical estimates based on next-to-leading order Balitskii-Fadin-Kuraev-Lipatov (BFKL) results [17, 18]. To show that the net-baryon distribution reflects the geometric scaling of the gluon distribution, we perform the following change of variables:

$$x \equiv x_1, \;\; x_2 \equiv x\, e^{-2y}, \;\; p_T^2 \equiv x^2 s\, e^{-2y}. \tag{3}$$

Thus, we rewrite Eq. (1) as

$$\frac{dN}{dy}(\tau) = \frac{C}{2\pi} \int_0^1 \frac{dx}{x}\, x q_v(x)\, \varphi(x^{2+\lambda} e^{\tau}), \tag{4}$$

where $\tau = \ln(s/Q_0^2) - \ln A^{1/3} - 2(1+\lambda)\, y$ is the corresponding scaling variable. Hence, the net-baryon multiplicity in the peak region is only a function of a single scaling variable τ, which relates the energy dependence to the rapidity and mass number dependence. In the fragmentation region, the valence quark distribution is only very weakly dependent on Q_f. From the equation for the isolines, $\tau =$ const, one gets the evolution of the position of the fragmentation peak in the forward region with respect to the variables of the problem, $y_{\text{peak}} = 1/(1+\lambda)[(y_{\text{beam}} - \ln A^{1/6}] + \text{const}$, where $y_{\text{beam}} = 1/2 \cdot \ln[(E+p_L)/(E-p_L)] \simeq \ln\sqrt{s}/m_0$ is the beam rapidity at beam energy E and longitudinal momentum p_L with the nucleon mass m_0.

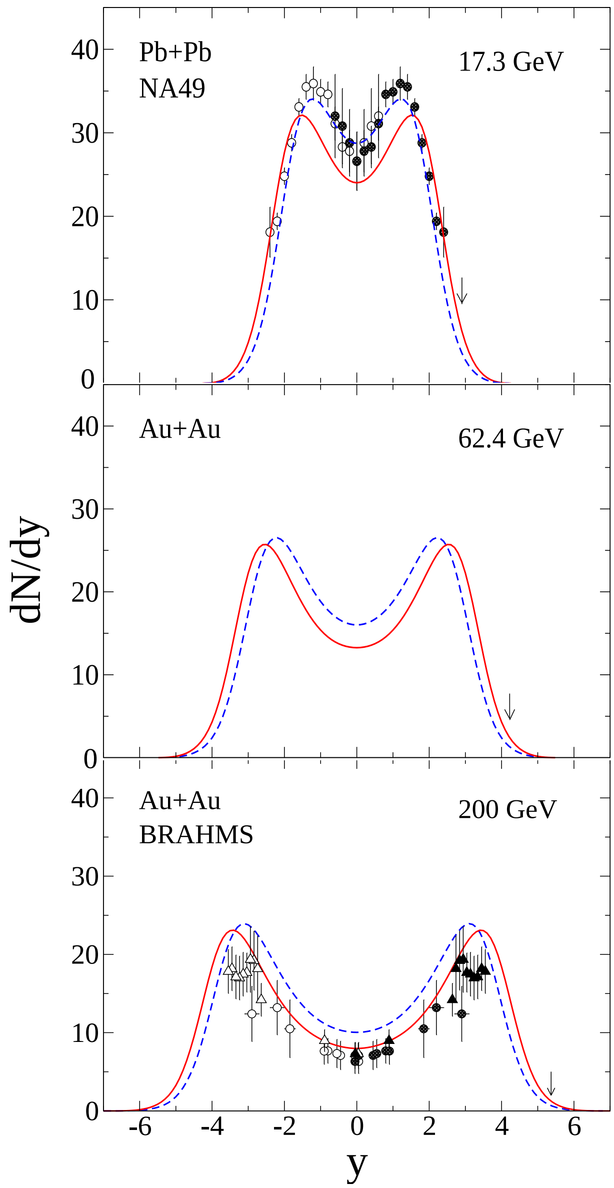

Fig. 1: Rapidity distribution of net protons in central (0 – 5%) Pb + Pb collisions at SPS energies of $\sqrt{s_{NN}}$ = 17.3 GeV (top frame). The theoretical results are compared with NA49 data [12]. Solid curves are for $Q_0^2 = 0.034$ GeV^2 and $\lambda = 0.288$, dashed curves are for $Q_0^2 = 0.068$ GeV^2, producing more stopping. At RHIC energies of $\sqrt{s_{NN}}$ = 62.4 GeV (middle frame) and 200 GeV (bottom frame) for central (0 - 5%) Au + Au, our corresponding theoretical results are shown, and compared with BRAHMS data at 200 GeV [1] (circles, 0 – 5%). Triangles are preliminary BRAHMS data points for 0 – 10% [19]. Arrows indicate the beam rapidities. From Y. Mehtar-Tani and G. Wolschin, arXiv:0811.1721 (2008).

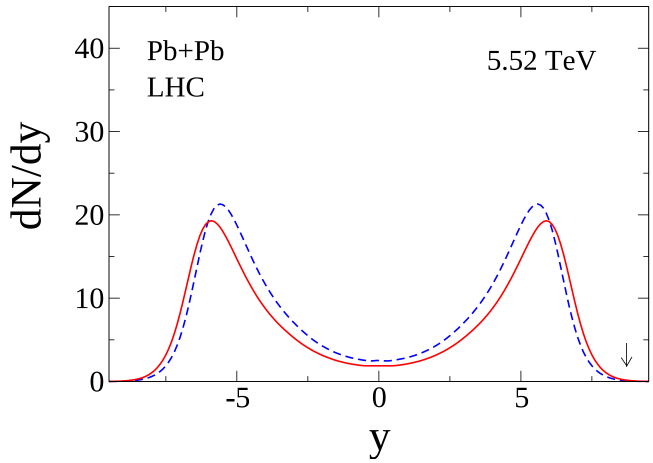

Fig. 2: Rapidity distribution of net protons in central Pb + Pb collisions at LHC energies of $\sqrt{s_{NN}}$ = 5.52 TeV. The theoretical distribution is shown for two values of the saturation scale as in Fig. 1.

To take into account saturation effects in the target we choose the Golec-Biernat-Wüsthoff model [20] for the forward dipole scattering amplitude $\mathcal{N}$. The valence quark parton distribution of the nucleus is taken to be equal to the valence quark PDF in a nucleon times the number of participants in the nucleus. We are focusing here on the forward rapidity region, and interpolate to mid-rapidity where small-x quarks are dominant, by matching the leading-order distributions and the Regge trajectory, $xq_v \propto x^{0.5}$, at $x = 0.01$ [3].

Our results for net-proton rapidity distributions in central Pb + Pb and Au + Au collisions are shown in Fig. 1. Solid curves are for $Q_0^2 = 0.034$ GeV^2 and $\lambda = 0.288$ [20]. Dashed curves are for twice the value of Q_0^2 producing slightly more stopping, as would also be the case for a larger value of A. These two values correspond to $Q_s^2 = 0.77$ GeV^2 and 1.54 GeV^2 at $x = 0.01$, respectively. We compare with SPS NA49 Pb + Pb data at $\sqrt{s_{NN}} = 17.3$ GeV [12], and BRAHMS Au + Au data at 200 GeV [1, 2]. Our prediction for central Pb + Pb at 5.52 TeV LHC energies is shown in Fig. 2, again for the above two values of the saturation scale. Here we have normalized the total yield to the number of proton participants, $N_p \simeq 140$ for both, central Au + Au and Pb + Pb. At LHC energies the mid-rapidity region is almost charge (baryon) free, and we obtain $dN/dy(y = 0) \simeq 1 - 3$ for net protons.

To summarize, we have presented a saturation model for net-baryon distributions that successfully describes net-proton rapidity distributions and their energy and mass dependence. The remarkable feature of geometric scaling predicted by the CGC is reflected in the net-baryon rapidity distribution, providing a direct test of saturation physics.

In particular, we have shown that the peak position in net-proton rapidity distributions of centrally colliding heavy ions at ultra-relativistic energies obeys a scaling law involving the mass number and the beam energy. Our result for the mean rapidity loss in $\sqrt{s_{NN}}$ = 200 GeV Au + Au [11] is significantly larger than the BRAHMS result, which contains an extrapolation to the unmeasured region. This emphasizes the importance of a detailed analysis at LHC energies.

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