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Rapidity distributions of net protons from AGS to LHC energy regions[*]

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Abstract Taking the conservation of baryon number into account in a non-uniform flow model, the rapidity distribution of the net protons at the LHC is predicted. The energy dependence of the rapidity distribution, baryon stopping and collective flow from BNL/AGS to CERN/LHC are systematically investigated.

Key words relativistic heavy ion collisions, LHC, collective flow, baryon stopping

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1 Introduction

The LHC will reach a center of mass energy of $\sqrt{s_{\rm NN}}$=5.5 TeV with Pb-Pb collisions: a factor of 27 higher than the maximal energy explored at the relativistic heavy-ion collider RHIC so far. This is an even larger increase in center of mass energy than the factor 10 in going from the CERN SPS to the BNL RHIC. It leads to a significant extension of the kinematic range in longitudinal rapidity and transverse momentum. The collectivity of high energy density matter is one of the important properties to understand high-energy heavy-ion collisions [1]. It is also challenging to understand how collectivity is generated during collisions. An other challenge is how to connect the experimentally observed collectivity and its origin.

Bjorken [2] postulated that the rapidity distribution of the produced particles establishes a plateau at mid-rapidity when the collision energies reach asymptotically high energies. It is well known that collisions at the available heavy-ion energy regions of AGS, SPS and RHIC are neither fully stopped nor fully transparent [3–11], although a significant degree of transparency is observed. But the central plateau structure becomes more and more obvious as the collision energy increases to those of SPS and RHIC. The fact that the observed distributions are flatter at mid-rapidity and wider than those predicted by the thermal isotropic model [12–14] may point in this direction. It is obvious from the experimental data that the central dips of the baryon rapidity distributions appear especially at SPS and RHIC energy regions.

Investigations with the NUFM (Non-Uniform Flow Model) [15–18] showed that the fireballs keep some memory of the motion of the incident nuclei. Therefore, the distribution of fireballs, instead of being uniform in the longitudinal direction, is more concentrated in the motion direction of the incident nuclei, i.e. more dense at larger absolute values of the rapidity. This will not only lead to an anisotropy in the longitudinal-transverse directions but also render the fireballs (especially for those baryons) distributing non-uniformly in the longitudinal direction.With the NUFM [15–18] one may analyze the central dip of the baryon rapidity distribution by assuming that the centers of the fireballs are distributed non-uniformly in the longitudinal phase space.

2 Motivations

We have always used the NUFM to study the net proton rapidity in the AGS, SPS and RHIC energy

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regions [16]. But for the RHIC energy regions, we made a mistake in Ref. [16] in the prediction of the net proton distributions since we neglected the effects of the baryon number conservation. Therefore, it is necessary to reanalyze the features of net proton rapidity distributions occuring in the AGS to RHIC energy region by taking the baryon number conservation into account. It is found that, when we consider the baryon number conservation, the features of the distributions at RHIC are completely different from the results given before Ref. [16], especially in the large absolute rapidity region. On the other hand, with the forthcoming operation of the LHC, the predictions of the features of net proton rapidity distributions at the LHC are also important. We will restudy the features of net proton rapidity distributions occuring in the AGS to RHIC energy region by using the NUFM, and make predictions for the features of the forthcoming LHC data in this paper. In the following we will give a simple introduction to the NUFM.

A parametrization of such a non-uniform distribution can be obtained by using an ellipse-like picture on the emission angle distribution. In this scenario, the emission angle is given by

$$\theta = \tan^{-1}(e \tan\Theta). \tag{1}$$

Here, the induced parameter $e (0 \leqslant e \leqslant 1)$ represents the ellipticity of the introduced ellipse, which describes the non-uniformity of the fireball distribution in the longitudinal distribution. Detailed discussions about the NUFM were given in Ref. [15–18]. The rapidity distribution in the NUFM is given by

$$\frac{n_{\mathrm{NUFM}}}{y} = eKm^2T \int_{-y_{\mathrm{e0}}}^{y_{\mathrm{e0}}} \rho(y_{\mathrm{e}}) \mathrm{d}y_{\mathrm{e}} (1 + 2\Gamma + 2\Gamma^2) \mathrm{e}^{-1/\Gamma}, \tag{2}$$

where y_{e0} is the rapidity limit, which confines the rapidity interval of the longitudinal flow. In Eq. (2),

$$\Gamma = T/m \cosh(y - y_{\mathrm{e}}), \tag{3}$$

where y_{e} is the rapidity of the collective flow, m is the mass of the produced particle and T is the temperature parameter. The physical meaning of the parameters e and y_{e0} will be discussed in this paper.

$$\rho(y_{\mathrm{e}}) = \sqrt{\frac{1 + \sinh^2(y_{\mathrm{e}})}{1 + e^2 \sinh^2(y_{\mathrm{e}})}} \tag{4}$$

is the flow distribution function in the longitudinal direction.

3 The net proton distributions in the AGS to LHC energy regions

Based on the applicability of the NUFM to relativistic heavy-ion collisions, we reanalyze and predict the rapidity distribution features of the net proton yield in the whole AGS, SPS, RHIC and LHC energy regions. Compared with the previous NUFM calculation [16], we consider now the influence of baryon number conservation when discussing the distributions. The obtained rapidity distributions from AGS to the LHC are provided in Fig. 1.

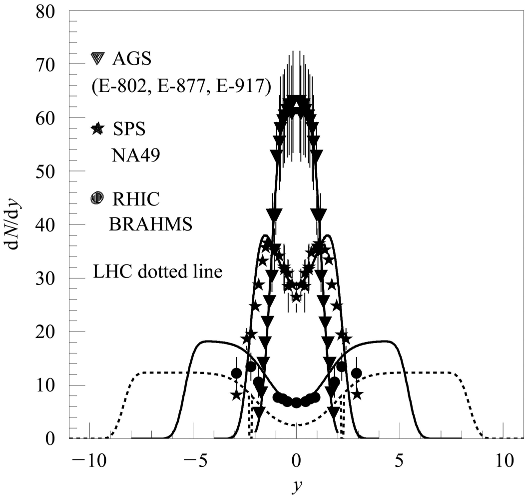

Fig. 1. The net proton distributions at AGS, SPS, RHIC and the LHC; the experimental results are from Refs. [3–11], the dotted line is the NUFM prediction for the LHC.

Figure 1 shows the net-proton rapidity distributions measured at AGS, SPS and RHIC from the top 5% central collisions, respectively. The triangles, stars and circles stand for the AGS, SPS and RHIC experimental results, respectively. The solid lines are our NUFM calculations for the AGS to RHIC region and the dotted line is the calculation for the LHC. It can be seen from Fig. 1 that the NUFM model can reproduce the central dip of the rapidity distribution of the protons for SPS and RHIC in agreement with the experimental findings. y_{e0} is approximately equal to the half width of the fit distribution. In this sense, parameter y_{e0} can represent the kinetic region of collective flow in the longitudinal direction. Parameter T is chosen to be 0.12 GeV.

The features of the non-uniform flow distributions show a strong energy dependence when going from AGS to the LHC. For example, at AGS ($e = 0.82$, E_{lab}=10.8 GeV), the net proton distribution has a peak at mid-rapidity, but the distribution is narrower than that at the other three energies. The collective flow is approximately uniform at AGS, while at SPS ($e=0.61$) a dip begins to show in the middle of rapidity distribution. By comparison with AGS, the collective flow at $y\approx 0$ is diluted at SPS, RHIC and the LHC. At the LHC, a broad dip in the middle of the rapidity region has developed, spanning several units of rapidity, indicating that the collisions are quite transparent in the LHC energy region. According to our study, $e=0.19$ at the LHC gives the most obvious non-uniform feature at the four energy regions. By reanalyzing RHIC, we obtain a wider rapidity distribution than that given by Ref. [16]. From Eq. (1) and Eq. (4), we know that e is a parameter that represents the ellipticity of the introduced ellipse, describing the non-uniformity of the fireball distribution in the longitudinal direction. It can be figured out from Eq. (4) that the larger parameter e, the flatter the distribution function, the more uniform is the longitudinal flow distribution. For $e\Rightarrow 1$ ($\rho(y)\Rightarrow 1$), the longitudinal flow distribution becomes completely uniform and one returns to a uniform flow. From Fig. 2 we see that, as the incident energy increases, the longitudinal flow distribution becomes more non-uniform. $e=0.19$ at the LHC is smaller than that of $e=0.31$ at RHIC, $e=0.61$ at SPS and $e=0.82$ at AGS. The non-uniformity at the LHC is the largest in the whole AGS, SPS, RHIC and LHC energy region, as shown in Fig. 2.

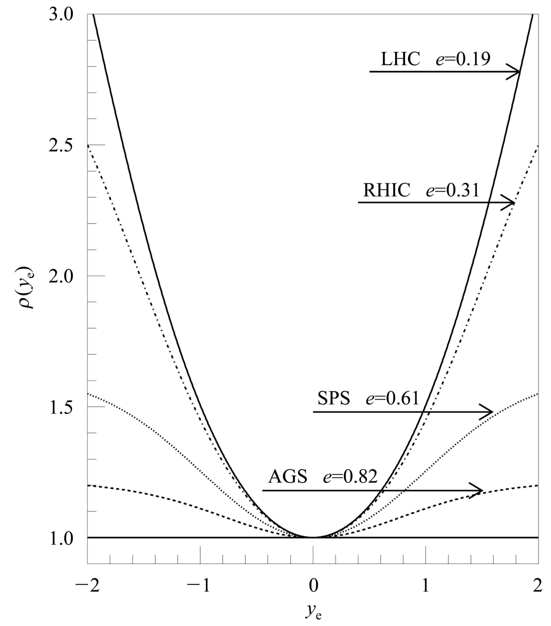

Fig. 2. The phase space distribution function of the net protons in the longitudinal direction in the whole AGS, SPS, RHIC and LHC energy region.

It is found from the calculation that y_{e0} determines the width of the distribution and confines the kinetics region of the collective flow. In order to discuss the dependence of the velocity of the collective flow on collision energy in the center of mass system, we give a calculation of the average velocity in the longitudinal direction as $\langle\beta_L\rangle=\langle\tanh(y_{e0}/2)\rangle$ and $\langle\beta\gamma\rangle_L$, where $\gamma=1/\sqrt{1-\beta_L^2}$ is the Lorenz factor.

The stopping may be estimated from the rapidity loss experienced by the baryons in the colliding nuclei. If the incoming beam baryons have the rapidity y_p relative to the CM, the average rapidity loss of net protons is

$$\langle\delta y\rangle=y_p-\langle y\rangle, \tag{5}$$

where $\langle y\rangle$ is the average rapidity of net protons.

$$\langle y\rangle=\frac{2}{N_{\rm part}}\int_0^{y_p} y\mathrm{d}y\frac{\mathrm{d}N_{\rm B-\bar{B}}(y)}{\mathrm{d}y}, \tag{6}$$

where $N_{\rm part}$ is participant nucleon number. y_p is the rapidity of the incoming beam baryons relative to the CM . $\langle y\rangle$ calculation in our calculation is given by

$$\langle y\rangle=\frac{\int_0^{y_p} y\mathrm{d}y\frac{\mathrm{d}n}{\mathrm{d}y}}{\int_0^{y_p}\mathrm{d}y\frac{\mathrm{d}n}{\mathrm{d}y}}, \tag{7}$$

where $\mathrm{d}n/\mathrm{d}y$ is given by the NUFM.

From Fig. 3 and Table 1, we see that, from AGS to SPS, the average rapidity loss $\langle\delta y\rangle$ increases linearly

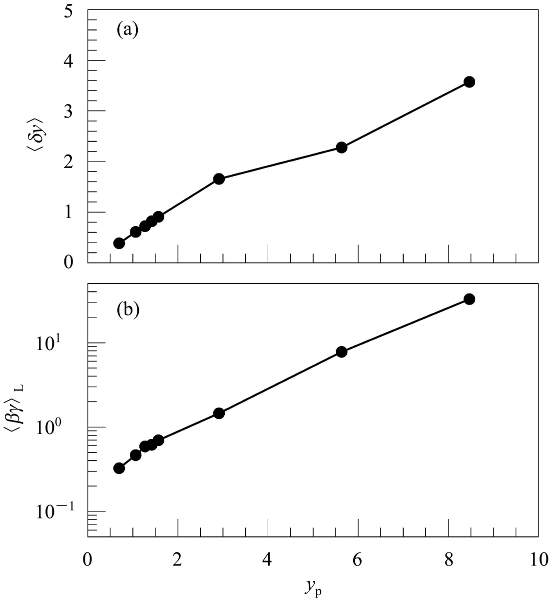

Fig. 3. The dependencies of the average rapidity loss $\langle\delta y\rangle$ (a) and $\langle\beta\gamma\rangle_L$ (b) on the incident proton rapidity in the whole AGS, SPS, RHIC and LHC energy regions.

with $y_{\rm p}$ near the origin, but begins to increase more slowly and then stars to deviate from the linear relationship in the RHIC and LHC region. This may suggest a difference in the interaction mechanism in RHIC and the LHC from that in AGS and SPS.

Table 1. The different parameters of the net proton distribution by using the NUFM from AGS to LHC.

$E_{\rm lab}$ or $\sqrt{s_{\rm NN}}$/GeV	$y_{\rm p}$	$\langle\delta y\rangle$	$\langle\beta\gamma\rangle_{\rm L}$	e
$E_{\rm lab}=2$ (AGS)	0.6951	0.3519	0.3255	1.0
$E_{\rm lab}=4$ (AGS)	1.0647	0.5391	0.4653	1.0
$E_{\rm lab}=6$ (AGS)	1.2714	0.6332	0.5897	1.0
$E_{\rm lab}=8$ (AGS)	1.4166	0.6997	0.6189	1.0
$E_{\rm lab}=10.8$ (AGS)	1.5674	0.9499	0.6967	0.82
$E_{\rm lab}=200$ (SPS)	2.9112	1.6774	1.4558	0.61
$\sqrt{s_{\rm NN}}=200$ (RHIC)	5.36	2.3021	7.7894	0.31
$\sqrt{s_{\rm NN}}=5500$ (LHC)	8.4669	3.5724	32.7912	0.19

4 Summary and conclusion

The LHC will open a new era in the investigation of nucleus-nucleus collisions at ultra-relativistic energies and will greatly expand the range of conditions under which it is possible to study the properties of QCD matter. So it is important to predict the features of baryon stopping and collective flow. Net proton rapidity distributions have been measured in several experiments at different energies, ranging from AGS to RHIC. The compiled data are shown in Fig 1. The NUFM enables us to estimate multiplicity distribution in future high-energy heavy-ion collisions at the LHC. A detailed energy dependence of the net baryon distributions among AGS, SPS and RHIC shows a clear transition from the baryon stopping region to the baryon transparent region. The detailed study of net proton rapidity distributions from AGS to the LHC will deepen our understanding of the relativistic heavy-ion collisions.

In relativistic heavy ion collisions, a large amount of energy is lost that is deposited in the region of central rapidity. Soft hadronic observances measure directly the final "freeze-out" stage of the collision, when hadrons decouple from the bulk and free-stream to the detectors. Freeze-out may correspond to a complex configuration in the combined coordinate-momentum space, with collective components (called flow). A detailed experimental-driven understanding of the freeze-out configuration is the crucial first step in understanding the system's prior evolution and the physics of hot colored matter. The isotropic thermal model and cylindrical symmetric longitudinal flow model [12–14] have discussed the particle distribution feature at freeze-out, but they cannot exhibit the central dip distribution, especially at higher collision energy when the nuclear medium has more transparency. The Non-Uniform Flow Model (NUFM) can express the dip distribution feature at the higher RHIC energy region at freeze-out. The predicted central dip of the features of the net proton distribution of the forthcoming LHC will be checked by the LHC experimental results. According to our calculation, it is found that the appearance or disappearance of the central dip is insensitive to the rapidity limit but depends strongly on the magnitude of the ellipticity e for the net proton distribution. From this we can infer that the central dip strongly relates to the non-uniformity of longitudinal flow distributions for the net proton distributions. On the other hand, the second parameter $y_{\rm e0}$ in the NUFM determines the width of the rapidity distributions. The larger the distribution limit of emission source $y_{\rm e0}$, the wider are the rapidity distributions.

By analyzing the proton rapidity distribution, it is found that the transparency of relativistic heavy-ion collisions increases as the collision energy increases, i.e. the higher the collision energy, the more transparent is the collision system. The phase space of the heavy collision system is nearly completely uniform in the longitudinal direction for AGS. The phase space of the protons is populated non-uniformly in the longitudinal direction at SPS and RHIC. At the LHC, a broad dip in the middle of the rapidity region has developed, spanning several units of rapidity, indicating that the collisions are quite transparent in the LHC energy region. According to our study, $e=0.19$ at the LHC gives a more obvious non-uniform feature than that of the AGS, SPS and RHIC energy regions. By reanalyzing RHIC, we obtain a wider rapidity distribution than that of Ref. [16].

It is found that, from AGS to SPS, the average rapidity loss $\langle \delta y \rangle$ increases linearly with $y_{\rm p}$, but begins to increase more slowly and deviates from the linear relationship for RHIC and the LHC. This suggests the occurence of a difference in the interaction mechanism in RHIC and the LHC from that in AGS and SPS.

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