Extended longitudinal scaling and the thermal model

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The property of extended longitudinal scaling of rapidity distributions was noticed recently over a broad range of beam energies. It is shown here that this property is consistent with predictions of the statistical thermal model up to the highest BNL Relativistic Heavy Ion Collider (RHIC) beam energies; however, we expect that at CERN Large Hadron Collider (LHC) energies the rapidity distribution of produced particles will violate extended longitudinal scaling.

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I. Introduction. It was widely expected [1] that the rapidity distribution of particles produced in relativistic heavy-ion collisions would show a plateau around central rapidities. Although it was not observed at CERN Super Proton Synchrotron (SPS) energies, there was a rather general belief about its existence in BNL Relativistic Heavy Ion Collider (RHIC) experiments. Now, as the final countdown [2] to CERN Large Hadron Collider (LHC) has started, expectations are much more cautious [3]. Recent results about the rapidity of charged mesons [4] and pseudorapidity distributions [5,6] do not allow for any firm prediction concerning the existence of a plateau at LHC energies. Instead of this, a new property is emerging—extended longitudinal scaling in rapidity distributions. The shape of the pseudorapidity distribution scales according to the limiting fragmentation hypothesis. The distributions of particle yields are largely independent of energy over a broad region of rapidity when viewed in the rest frame of one of the colliding particles. In this kinematic region it is allowed to neglect differences between pseudorapidity and rapidity distribution.

Extended longitudinal scaling was observed in high energy *pp* collisions [7] and is also a property of ultrarelativistic heavy-ion collisions. In this article we show that the extended longitudinal scaling feature of the shifted rapidity distribution also arises within the thermal model up to the highest RHIC energies. However, when an extrapolation is made to LHC energies the extended longitudinal scaling effect vanishes. This would violate some of LHC's predictions based on the extended longitudinal scaling feature [8].

II. Rapidity distributions. The statistical thermal model has been recently extended [9,10] to allow for the description of the rapidity distribution of produced particles in heavy-ion collisions. Chemical potentials and the temperature become rapidity dependent quantities. This property corresponds to the changing nature of the expanding fireball.

An extension of the thermal model [9] is used to calculate the rapidity distributions. The model uses a Gaussian distribution of fireballs centered at zero and described by

$$\rho(y_{\rm FB}) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{y_{\rm FB}^2}{2\sigma^2}\right). \qquad (1)$$

The rapidity distribution of particle i is then calculated by

$$\frac{dN^i}{dy} = \int_{-\infty}^{+\infty}\rho\,(y_{\rm FB})\,\frac{dN_1^i\,(y-y_{\rm FB})}{dy}dy_{\rm FB}, \qquad (2)$$

where $\frac{dN_1^i}{dy}$ is obtained from the thermal distribution of hadrons from a single fireball. It is necessary to assume universality of the chemical freeze-out conditions. This means that the temperature and the baryonic chemical potential are related via the freeze-out curve deduced from particle yields at varying beam energies. A parametrization of the universal freeze-out curve is given by [11]

$$T = 0.166 - 0.139\mu_B^2 - 0.053\mu_B^4. \qquad (3)$$

The extension of the thermal model introduces a new energy dependent parameter, the width of the Gaussian distribution, σ. This parameter is readily determined by fitting the generated distribution to the one found at various experimental energies. We consider specifically the pion rapidity distributions at SPS and RHIC energies.

The most abundantly produced particles in nuclear collisions are pions. The pion rapidity distribution should then display the same features as the total charged particle rapidity distribution. Because the baryon chemical potential has only a minimal influence on the rapidity distribution of pions, this distribution is also an excellent candidate to determine the fireball width. The experimental pion distributions were used to find the best fit to σ and these were then used to calculate the rapidity spectra coming from the extended thermal model.

The results of the fits for the rapidity spectra are shown in Fig. 1 [4]. The experimental distribution width has been proposed to change with collision energy like $\sigma^2 = \ln\frac{\sqrt{s_{NN}}}{2m_p}$. This is also shown in Fig. 2 and it can be seen that the two distribution widths have a similar energy dependence. It is a remarkable property that this simple analytical $\sqrt{s_{NN}}$ fit is applicable to heavy-ion collisions over such a wide range of beam energies. It appeared for the first time in the classic paper by Landau [12] where the notion of hydrodynamical

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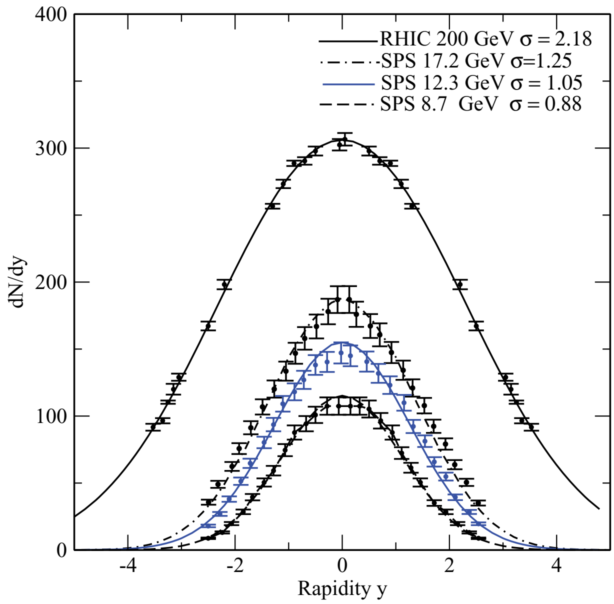

FIG. 1. (Color online) The pion rapidity spectra used to fit the Gaussian fireball distribution width σ to the experimental data from SPS and BRAHMS are shown.

evolution of a hadronic system was introduced. This concept was later successfully used for the description of high energy multiparticle production in pp collisions [13–15].

The differences seen in Fig. 2 could be attributed to specific heavy-ion processes such as the cooling, freezing, and evaporation of the primary highly excited blob of dense hadronic matter.

For a comparison with LHC predictions, $\frac{dN_\pi}{dy}/\frac{\langle N_{\rm part}\rangle}{2}$ is plotted in Fig. 3. Here we can clearly see the similar tails

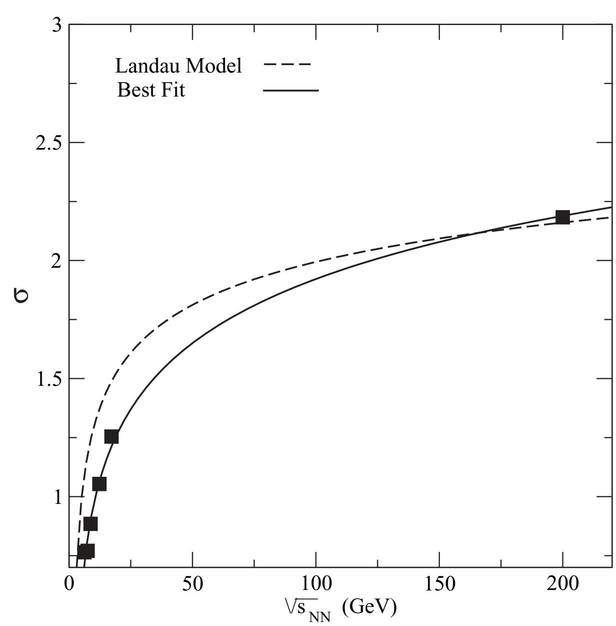

FIG. 2. Energy dependence of the distribution width. The data points shown are the σ's in the thermal model fitted to experimental data. The short-dashed line is the prediction based on the Landau model ($\sigma^2 \approx \ln \sqrt{s_{NN}}/2m_P$).

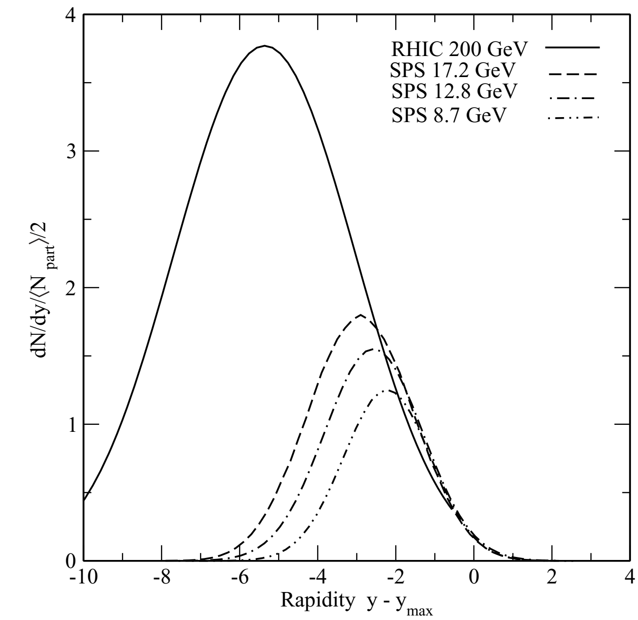

FIG. 3. Longitudinal scaling at the lower energies. The values of $y_{\rm max}$ are 5.36, 2.9, 2.569, and 2.222 at RHIC 200 GeV, SPS 17.2 GeV, SPS 12.3 GeV, and SPS 8.7 GeV, respectively.

of the four rapidity distributions for the higher SPS energies and for RHIC. This is also seen in the experimental data in Ref. [8].

By extrapolating the results for σ to LHC energies, we can make an extrapolation based on the thermal model for the rapidity distribution. Using the fitted curve we obtain $\sigma_{\rm LHC} = 3.45$. Following the prediction based on the Landau model curve one would obtain for LHC $\sigma = 2.82$. The extrapolation

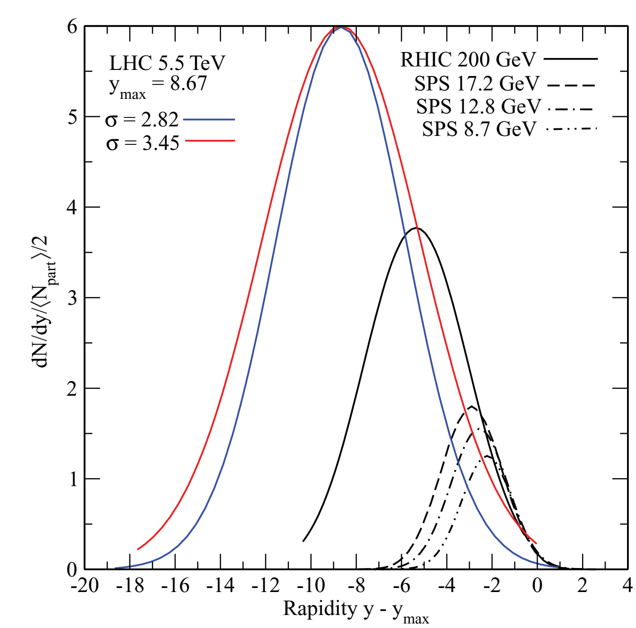

FIG. 4. (Color online) Extrapolating to LHC energies gives the highest curves in the figure above ($\sigma = 3.45$ and $\sigma = 2.82$). The values of $y_{\rm max}$ at RHIC and SPS are the same as those given in Fig. 3.

is over a large energy range and thus both values of σ are shown in Fig. 4 for comparison.

It can clearly be seen that extended longitudinal scaling does not occur at LHC energies. Thus the extension of the thermal model to describe rapidity distributions is consistent with the concept of extended longitudinal scaling at SPS and RHIC energies but not at LHC energies.

A violation of extended longitudinal scaling at LHC energies is also predicted in the string percolation model [16].

III. Conclusions. About 35 years ago it was noted in Ref. [13] that the "possible experimental fact of a Gaussian rapidity distribution of produced particle is significant independently of the Landau model. Only further detailed calculations of correlations and other fine structure can be expected to establish or disprove the hydrodynamic picture of particle production."

This statement was made to describe the pending $p - \bar{p}$ experiments at $\sqrt{s_{NN}} = 53$ GeV at that time. The outcome is still pending concerning the $\sqrt{s_{NN}} = 5.5$–14 TeV present day experiments.

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