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Centrality dependence of midrapidity density from GeV to TeV heavy-ion collisions in the effective-energy universality picture of hadroproduction

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The dependence on centrality, or on the number of nucleon participants, of the midrapidity density of charged particles measured in heavy-ion collisions at the collision energy of about 20 GeV at RHIC to the highest LHC energy of 5 TeV is investigated within the recently proposed effective-energy approach. This approach relates multihadron production in different types of collisions by combining, under the proper scaling of the collision energy, the constituent quark picture with Landau relativistic hydrodynamics. The measurements are shown to be well described based on the similarity of multihadron production process in (anti)proton-proton interactions and heavy-ion collisions driven by the centrality-dependent effective energy of participants.

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Recently, we have shown that the multiplicity [1] and midrapidity density [2] data from heavy-ion collisions in the collision energy range of several orders of magnitude are well described in the framework of the picture of the dissipating effective energy of constituent quark participants [3,4], or, for brevity, the effective-energy approach. In this paper, we show that the recent measurements of the centrality dependence of the pseudorapidity midrapidity density of charged particles in PbPb collisions by ALICE [5], at the highest center-of-mass (c.m.) energy per nucleon, $\sqrt{s_{NN}}$, ever reached, namely at $\sqrt{s_{NN}} = 5.02$ TeV, are also well described using the effective-energy approach.

This approach interrelates the particle production process in different types of collisions [3], as briefly described below. Within such a picture, the process of particle production is quantified in terms of the amount of *effective* energy deposited by interacting constituent quark participants into the small Lorentz-contracted volume formed at the early stage of a collision. The approach considers the Landau relativistic hydrodynamic approach to multiparticle production [6] employed in the framework of constituent (or dressed) quarks, in accordance with the additive quark model [7,8]. Then, in $pp/\bar{p}p$ collisions, a single constituent quark from each nucleon is assumed to contribute in a collision. The remaining quarks are treated as spectators resulting in formation of leading particles carrying away a significant part of the collision energy. On the contrary, in the head-on heavy-ion collisions, all three constituent quarks from each of the participating nucleons are considered to contribute so that the whole energy of the nucleons becomes available for the particle production. Thus, the bulk measurements in head-on heavy-ion collisions at $\sqrt{s_{NN}}$ are treated to be similar to those from $pp/\bar{p}p$ collisions at the properly scaled c.m. energy $\sqrt{s_{pp}}$, i.e., at $\sqrt{s_{pp}} \simeq 3\sqrt{s_{NN}}$.

All together, the above-discussed ingredients lead to the relationship between charged particle (pseudo)rapidity density per participant pair at midrapidity, $\rho(\eta) = (2/N_{\rm part})dN_{\rm ch}/d\eta$ $(\eta \approx 0)$, in heavy-ion collisions and in $pp/\bar{p}p$ interactions:

$$\frac{\rho(0)}{\rho_{pp}(0)} = \frac{2N_{\rm ch}}{N_{\rm part}N_{\rm ch}^{pp}}\sqrt{\frac{L_{pp}}{L_{NN}}}, \qquad \sqrt{s_{pp}} = 3\sqrt{s_{NN}}. \tag{1}$$

Here, $N_{\rm ch}$ and $N_{\rm ch}^{pp}$ are the (total) mean multiplicities in nucleus-nucleus and nucleon-nucleon collisions, respectively, and $N_{\rm part}$ is the number of nucleon participants. The relation of the pseudorapidity density and the mean multiplicity is applied in its Gaussian form as obtained in Landau hydrodynamics. The factor L is defined as $L = \ln(\sqrt{s}/2m)$. According to the approach considered, m is the proton mass, m_p, in nucleus-nucleus collisions and the constituent quark mass in $pp/\bar{p}p$ collisions set to $\frac{1}{3}m_p$. Such universality was found to correctly predict [4] the value of the midrapidity density in pp interactions measured at LHC TeV energies [9].

In the further development [2], one considers the obtained relation, Eq. (1), in terms of centrality. The centrality is regarded as the degree of the overlap of the volumes of the two colliding nuclei, characterized by the impact parameter,

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and is closely related to the number of nucleon participants. Hence, the centrality is related to the amount of the energy released in the collisions, i.e., to the effective energy, ε_{NN}. In the framework of the proposed approach, the effective energy can be defined as a fraction of the c.m. energy available in a collision according to the centrality, α:

$$\varepsilon_{NN} = \sqrt{s_{NN}}(1-\alpha). \tag{2}$$

Then, after taking into account the energy scaling, Eq. (1) reads for the effective c.m. energy ε_{NN},

$$\begin{aligned} \rho(0) &= \rho_{pp}(0)\frac{2N_{\mathrm{ch}}}{N_{\mathrm{part}}N_{\mathrm{ch}}^{pp}}\sqrt{1-\frac{2\ln 3}{\ln(2m_p/\varepsilon_{NN})}}, \\ \varepsilon_{NN} &= \sqrt{s_{pp}}/3, \end{aligned} \tag{3}$$

where N_{ch} is the multiplicity in central nucleus-nucleus collisions measured at $\sqrt{s_{NN}} = \varepsilon_{NN}$, and $\rho_{pp}(0)$ and N_{ch}^{pp} are taken at $\sqrt{s_{pp}} = 3\varepsilon_{NN}$.

In Fig. 1, the N_{part} dependence of the charged particle pseudorapidity density $\rho(0)$, measured in heavy-ion collisions at $\sqrt{s_{NN}}$ from GeV c.m. energies by the PHOBOS experiment at RHIC [10] to a few TeV c.m. energies by the ALICE [5,11], ATLAS [12], and CMS [13] experiments at LHC, is compared with the calculations of Eq. (3). According to the consideration, the calculations are made at $\sqrt{s_{pp}} = 3\varepsilon_{NN}$. The midrapidity density $\rho_{pp}(0)$ and the multiplicity N_{ch}^{pp} are taken from the existing $pp/\bar{p}p$ data [14,15], and the N_{ch} values are taken from the heavy-ion collision data [1,16] where available, while otherwise the corresponding experimental c.m. energy fits are applied. The calculations use the power-law s_{pp}-fits for N_{ch}^{pp} [14] and for ρ_{pp} at $\sqrt{s_{pp}} > 53$ GeV [13], the linear-log fit [14] for ρ_{pp} at $\sqrt{s_{pp}} \leq 53$ GeV, and the "hybrid" s_{NN}-fit [2] for N_{ch}.

One can see that, within this approach, where the collisions are derived by the centrality-defined effective c.m. energy ε_{NN}, the calculations are in very good overall agreement with the measurements independent of the collision energy. Similar results are obtained as the N_{part} dependence of the PHENIX [17], STAR [18], or CuCu PHOBOS [10] measurements from RHIC are used (not shown). Some slightly lower values seen in the predictions compared to the data for some low-N_{part}, i.e., for the most peripheral collisions, at $\sqrt{s_{NN}} = 19.6$ GeV, look to be due to the experimental limitations and the extrapolation used in the reconstruction for the measurements in this region of very low multiplicity [10]. This may also explain the N_{part} scaling of the data at $\sqrt{s_{NN}} = 19.6$ GeV in the most peripheral region which does not follow the common trend of decreasing observed at higher energies. The calculations obtained to be lower than the data for a few most central collisions at the LHC energy at $\sqrt{s_{NN}} = 2.76$ TeV and some slight deviations seen for the 5.02 TeV predictions can be explained by yet to come measurements of N_{ch}^{pp} at energies above the top Tevatron energy of $\sqrt{s_{pp}} = 1.8$ TeV.

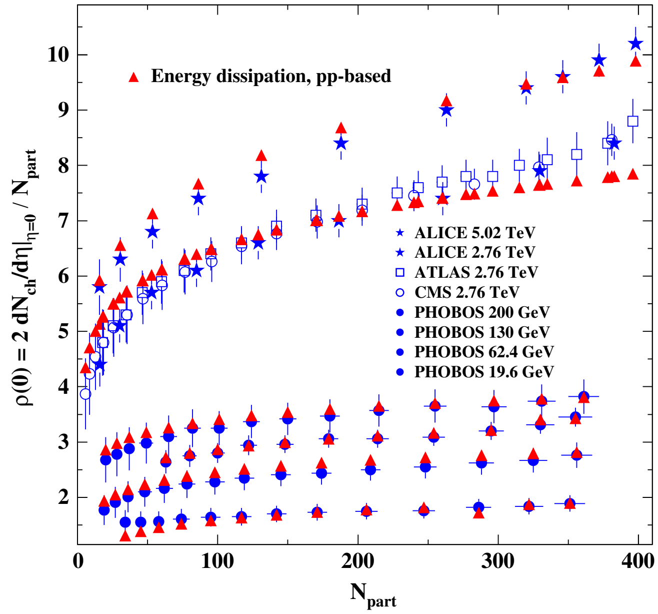

FIG. 1. The charged particle pseudorapidity density at midrapidity per participant pair as a function of the number of participants, N_{part}. The solid circles show the measurements from AuAu collisions at RHIC by PHOBOS at $\sqrt{s_{NN}} = 19.6$ to 200 GeV [10] (bottom to top). The LHC measurements are from PbPb collisions by ALICE at $\sqrt{s_{NN}} = 2.76$ TeV [11] and $\sqrt{s_{NN}} = 5.02$ TeV [5] (solid stars) and by ATLAS [12] (open squares) and CMS [13] (open circles) at $\sqrt{s_{NN}} = 2.76$ TeV. The solid triangles show the calculations by Eq. (3) using $pp/\bar{p}p$ data.

Recently, we have shown that, within the effective-energy approach, one describes as well the mean multiplicity data from heavy-ion collisions up to $\sqrt{s_{NN}} = 2.76$ TeV [1]. Moreover, the pseudorapidity distribution in the *full*-η range, and not only the midrapidity density, are shown to be reproduced. The findings and a new energy-balanced limiting fragmentation scaling introduced in [1] elucidate the differences observed in the multiplicity and the midrapidity density centrality dependence as measured at RHIC and LHC. The description of the observed dependences suggest a possible change of the multihadron production mechanism in heavy-ion collisions when one moves to TeV energy heavy-ion collisions, where the collisions seem to obey a head-on collision regime for all centralities. The midrapidity density is expected to increase with the number of participants both at RHIC and LHC as soon as the central-η region is formed by considered to be centrally-colliding participants at the c.m. energy of ε_{NN}. This increase is shown by the measurements, see Fig. 1, and is well described by the approach discussed here. Similar to the midrapidity density, the multiplicity is also expected to demonstrate the increase with the number of participants. Such a behavior, observed at the TeV LHC energies, is shown to be well described by the effective-energy approach and then treated to indicate the central collision regime independent of centrality. However, at RHIC, the multiplicity measurements show a constancy with the centrality, in contrast to the midrapidity behavior at the same energies. This effect is shown to be due to the fact that, at RHIC energies, the multiplicity gets an additional contribution because of the difference between the collision energy and the effective energy shared by the interacting participants. This contribution is taken into account by the proposed energy-balanced limiting fragmentation within the effective-energy approach by considering the limiting fragmentation scaling in terms of the effective energy ε_{NN}. This allows us to well describe the multiplicity and the pseudorapidity distribution for all energies independent of centrality [1]. Additionally, in [2] the transverse-energy midrapidity densities are shown to demonstrate the complementarity of the head-on data and the centrality data in terms of the effective energy, similar to that obtained for the midrapidity densities [2] and the mean multiplicities [1].

Interestingly, this picture is shown as well to successfully explain [3,4] the similarity of the measurements in other collisions, such as the scaling between the charged particle mean multiplicity in e^+e^- and $pp/\bar{p}p$ collisions [19] and the universality of both the multiplicity and the midrapidity density measured in the most central nuclear collisions and in e^+e^- annihilation [20]; see [21] for discussion. In the latter case, colliding leptons are considered to be structureless and deposit their total energy into the Lorentz-contracted volume, similarly to nucleons in head-on nuclear collisions [4]. This is shown to be supported by the observation made in [14], where the multiplicity measurements in $pp/\bar{p}p$ interactions up to TeV energies are shown to be well reproduced by e^+e^- data as soon as the inelasticity is set to ≈ 0.35, i.e., effectively $1/3$ of the hadronic interaction energy. For recent discussion on the universality of hadroproduction up to LHC energies, see [15]; see also [21,22].

To summarize, the effective-energy dissipation approach based on the picture which combines the constituent quark model together with Landau relativistic hydrodynamics in view of the universality of the multihadron production in hadronic and nuclear collisions is shown to well describe the data from heavy-ion collisions within the c.m. energy of several orders of magnitude; in particular the centrality dependence of the midrapidity density of charged particles measured in heavy-ion collisions up to 5.02 TeV is shown to be well reproduced. Future measurements at higher energies in different types of collisions are crucial in order to clarify the underlying features of hadroproduction mechanism.

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