Hydrodynamic extension of the two component model for hadroproduction in heavy-ion collisions.

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The dependence of the spectra shape of produced charged hadrons on the size of a colliding system is discussed using a two component model. As a result, the hierarchy by the system-size in the spectra shape is observed. Next, the hydrodynamic extension of the two component model for hadroproduction using recent theoretical calculations is suggested to describe the spectra of charged particles produced in heavy-ion collisions in the full range of transverse momenta, $p_T$. Data from heavy-ion collisions measured at RHIC and LHC are analyzed using the introduced approach and are combined in terms of energy density. The observed regularities might be explained by the formation of QGP during the collision.

I. INTRODUCTION

Recently, a unified approach to describe charged particle production in high-energy collisions and describing two distinct mechanisms of hadroproduction has been proposed [1]. It was suggested to approximate the spectra of charged hadrons in heavy-ion collisions in the full range of transverse momenta, $p_T$.

According to this approach, the exponential part of the spectra shape is observed. Next, the hydrodynamic extension of the two component model for hadroproduction using recent theoretical calculations is suggested to describe the spectra of charged particles produced in heavy-ion collisions in the full range of transverse momenta, $p_T$.

Thus, it is interesting to compare the shapes of charged particles produced in these two types of interactions ($\gamma \gamma$ and $pp$) with a more complex case of heavy-ion collisions.

II. HIERARCHY IN HADROPRODUCTION DYNAMICS

It is suggested to look at the recent data on lead-lead collisions measured by the ALICE Collaboration [3] in the range of transverse momentum $p_T$ up to 50 GeV. Figure 1 shows experimental data on $\gamma \gamma$ [4], $pp$ [5] and lead-lead [3] collisions fitted with the parameterization introduced [1]. One can notice, that this parameterization can not describe the shape of the spectra in lead-lead collisions for the very high-$p_T$ values and an additional power-law term is needed:

$$\frac{d\sigma}{p_T dp_T} = A_\epsilon \exp \left(-\frac{E_{T_{\text{kin}}}}{T_\epsilon}\right) + \frac{A}{(1 + \frac{p_T^2}{T_1^2 N_1})^N}$$



1. The bulk of low-$p_T$ particles originates from the 'quark-gluon soup' formed in the heavy-ion collision and has an exponential $p_T$ distribution, as shown by the red dashed line in figures 1 and 2.

2. The high-$p_T$ tail (shown by the green solid line in figures 1 and 2) accounts for the mini-jets that pass through the nuclei, the process that can be described in pQCD [6]. When these jets hadronize into final state particles outside the nuclei, we get the same power-law term as in $pp$-collisions (figures 1 b) and c), resulting in a constant suppression ($R_{AA}$) of high-$p_T$ ($> 20$ GeV) particles (figure 2). Note, that while passing through the nuclei these jets should loose about $\frac{dE}{dz} \cdot R_A \sim 7$ GeV [6], where $R_A$ is the radius of the nuclei. Therefore, hadrons with $p_T < 7$ GeV produced from these jets will be largely suppressed, as it seen in the figure 2.
3. On the other hand, mini-jet fragmentation into final state hadrons can also occur before the jet leaves the nuclei volume. The produced particles have to wade out through the nuclei, being affected by multiple rescatterings, and thus their distribution (blue dash-dot line in figures 1 and 2) becomes more close to the exponent, resulting in higher values of $N_1$ and $T_1$ of the power-law term, and dominates the mid-$p_T$ region. This process can't be described in pQCD, however.

- heavy-ion collision: due to the quenching of charged hadrons inside the nuclei the power-law term 'splits' into two distributions with different parameters (the second closer to the exponent). Therefore, we need a sum of exponential and 2 power-law terms to describe the spectra.

III. HYDRODYNAMIC EXTENSION OF THE MODEL

Though, the parameterisation using an exponential and two power-law terms (2) gives a rather perfect description of the experimental data (3) (Figure 1 c), it is known that Boltzmann thermodynamics is not applicable for heavy-ion collisions. When a large colliding system is formed, one should also take effects of the 'collective motion' into account [7]. Thus, in heavy-ion collisions the multiparticle production is usually considered in terms of relativistic hydrodynamics, contrary to widely used thermodynamic approaches [8, 9] for $pp$, $\gamma p$ and $\gamma\gamma$-collisions. Therefore, it is suggested to modify the introduced approach (1) using recent theoretical calculations [7].

The idea of hydrodynamic approach is that the thermalized system expands collectively in longitudinal direction generating the transverse flow by the high pressure in the colliding system. According to this approach the radiation of thermalized particles can be parameterized by the following formula:

$$\frac{dN}{dp_T dp_T} \propto \int_0^R r dr m_T I_0 \left( \frac{p_T}{T_c} \sinh \rho \right) K_1 \left( \frac{m_T \cosh \rho}{T_c} \right),$$

where $\rho = \tanh^{-1} \beta_s$ and $\beta_s(r) = \beta_s \left( \frac{r}{R} \right)$, with $\beta_s$ standing for the surface velocity. In this analysis we take $\beta_s = 0.5c$ which is consistent with previous observations [7]. Thus, one have to substitute the exponential term in (1) by (3).

Note, that the power-law term in (1) stands for the point-like pQCD interactions that occur in the early stage of the collision, with the hadrons produced from the mini-jet fragmentation leave the interaction area before reaching the thermal equilibrium. Therefore, we assume this term to be considered without taking the 'collective motion' into account.
Now one can use this hydrodynamic approach to fit the recent experimental data on lead-lead collisions measured by the Alice Collaboration \(^3\) at \(\sqrt{s} = 2.76\) TeV.

\[
\frac{dn}{d\eta d\rho_T} = A_e \cdot \int_0^R r \, dr \, m_T \cdot I_0 \left( \frac{\rho_T \sinh \rho}{T_e} \right) K_1 \left( \frac{m_T \cosh \rho}{T_e} \right) \frac{A}{(1 + \frac{p_T^2}{T_e^2} N_C)} + \frac{A_1}{(1 + \frac{p_T^2}{T_1^2} N_I)}
\]

These data are shown in figure 3 together with the fit at LHC differ significantly, the energy density in central collisions at RHIC might be of the same order with that in peripheral collisions at LHC.

In this paper we consider the experimental data measured in AuAu collisions at \(\sqrt{s} = 200\) GeV/N and \(\sqrt{s} = 130\) GeV/N by PHENIX \(^{11,12}\) and PbPb collisions at \(\sqrt{s} = 2.76\) TeV/N by ALICE \(^3\). The energy density \(\varepsilon\) for central collisions can be determined from the experimental data by the formula \(^{13}\):

\[
dE_T/d\eta (\eta \sim 0) = \pi R^2 \varepsilon f_0,
\]

where \(\varepsilon_f\) is the energy density averaged over the transverse area, and \(R\) is the nuclear radius.

However, for non-central collisions it is more convenient to estimate it using a simple parameterization \(^{13}\):

\[
\varepsilon = \varepsilon_0 \left( \frac{8}{s_0} \right)^{\alpha/2} N_{\text{coll}}^\beta,
\]

with \(\varepsilon_0\) calculated for the most central collisions, \(\alpha \approx 0.3\) \(^{14}\), \(\beta \approx 0.5\) \(^{15}\) and \(\sqrt{s_0} = 200\) GeV \(^{13}\). Here the second factor is responsible for the incident energy dependence, \(\sqrt{s}\) is the c.m.s collision energy, and the third one shows the dependence on the number of binary parton-parton collisions \(N_{\text{coll}}\) which is related to the centrality of the collision. Note, that in this analysis \(\varepsilon_0\) turned out to be the same for PHENIX and ALICE data, thus confirming the \(\alpha = 0.3\) value proposed in \(^{14}\).

Having calculated the energy density \(\varepsilon\) using the formula \(^{6}\), one can plot the temperature \(T_e\) extracted from \(^4\) as a function of it, as shown in figure 5. First of all, as it was expected, the energy density obtained in central collisions at RHIC is similar to those in peripheral collisions at LHC, and, remarkably, a smooth transition in the \(T_e\) values between these three measurements is also observed. Note, that as one could naively expect, the value of \(T_e\) (as well as \(N\) and \(T\) of the power-law term in \(^{4}\)) for peripheral lead-lead collisions turns out to be practically identical with that obtained for pp-collisions at the same c.m.s. energy \(^5\).

Next, one can notice rather interesting behavior of the temperature \(T_e\) as a function of energy density \((\varepsilon \propto T_e^4 + B)\), which is in a good agreement with the Bag model \(^{18}\), with \(B = 0.25\) GeV/fm\(^3\), as determined from the fit in figure 4. Another remarkable observation on the temperature \(T_e\) of the final state particles is that

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\(^1\) Compare figure 4 with one in \(^{10}\).
FIG. 4. Temperature of the final state hadrons coming from the 'thermalized' part of the spectra in heavy-ion collisions as a function of energy density. Solid line stands for the $T_e \propto (\varepsilon - B)^{0.25}$ fit and dashed line shows $T_e \rightarrow \text{const}$ behavior for high energy densities it reaches a certain limit. This might be explained from QGP theory that considers the phase transition temperature $T_c$ from QGP to final state hadrons: the expanding system cools down until it reaches the freeze-out stage, thus, the temperature of the final state particles should be always below $T_c$. Indeed, for high values of $\varepsilon$ one can notice, that the observed freeze-out temperature is $T_{fo} \approx 145$ MeV, and (as one can expect) is slightly below the critical temperature $T_c \sim 155 - 160$ MeV for QGP obtained in different calculations [17, 18].

V. CONCLUSION

The spectra of charged hadron production in heavy-ion collisions have been compared with those measured in $pp$ and $\gamma\gamma$ interactions using the recently introduced two component model. The observed hierarchy on the size of the colliding system has been discussed and the qualitative picture for hadroproduction in heavy-ion collisions explaining the peculiar shape of nuclear modification factor, $R_{AA}$, has been introduced. Next, the hydrodynamic extension of this parameterization accounting for the collective motion in heavy-ion collisions was suggested. This approach allowed to extract the 'thermalized' production of charged hadrons from the whole statistical ensemble and to study it separately. Thus, the variations of the temperature of the final state hadrons coming from the 'thermalized' part of the spectra have been studied as a function of energy density using both RHIC and LHC data and the behavior that might be explained in terms of QGP formation has been observed.

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