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Research Article

Speed of Sound Parameter from RHIC and LHC Heavy-Ion Data

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In framework of combing the participant-spectator model and the Landau hydrodynamic model, the pseudorapidity distributions of charged particles produced in heavy-ion (or nucleus-nucleus) collisions at RHIC and LHC energies are described by a modified Landau hydrodynamic model, where the Landau hydrodynamic model is applied to the target/projectile spectators and the target/projectile participants, respectively. The modeling results are in agreement with the PHOBOS and ALICE experimental data. Then, the values of square speed of sound (c_s^2) for the participants and spectators can be obtained from the widths of charged particle pseudorapidity distributions. Some features of c_s^2 for different centralities and center-of-mass energies are obtained too.

1. Introduction

High energy collisions are an important research topic in fields of particle and nuclear physics. Many charged and neutral particles are produced in the collisions. Particularly, the Relativistic heavy ion collider (RHIC) and the large hadron collider (LHC) have been opening a new epoch for high energy heavy-ion collider. Many experimental results are reported and many theoretical models are proposed to describe the data.

Among the theoretical models, the Landau hydrodynamic model [1–4] is one of the most useful treatment methods in high energy heavy-ion (or nucleus-nucleus) collisions [5–13]. We hope to use the Landau hydrodynamic model to analyze experimental data measured in nucleus-nucleus collisions at RHIC [6, 14–18] and LHC energies [19–21]. The Landau hydrodynamic model was proposed at lower energy. In [13], the model is revised for RHIC energies. In [22, 23], it is shown that the model in the frame of quark participants works well from the alternating gradient synchrotron (AGS) to the RHIC energies. We notice that these revision and application of the Landau hydrodynamic model are in a narrow or central rapidity region. Contributions of leading nucleons are not included in these studies [13, 22, 23].

To analyze a wider pseudorapidity distribution, we need to consider the contributions of leading nucleons. In the framework of participant-spectator model [24], the spectators are one of the main sources of leading nucleons. We may apply Landau hydrodynamic model to the target/projectile spectators and the target/projectile participants, respectively. Then, we can use a modified Landau hydrodynamic model which contains four components to describe wider pseudorapidity distributions of charged particles produced in Au-Au and Cu-Cu collisions at RHIC energy [25–27] and Pb-Pb collisions at LHC energy [19–21]. Because the square speed of sound parameter (c_s^2) is related to the width of pseudorapidity distribution, we can obtain naturally the values of c_s^2.

In this paper, to extract the parameter c_s^2, a modified Landau hydrodynamic model is introduced in Section 2. Comparisons of modeling results with experimental data of PHOBOS [27] and ALICE Collaborations [21] and the obtained parameter values are given in Section 3. Finally, we give conclusions of the present work in Section 4.

2. The Model

According to the participant-spectator model [24], the overlapping regions between the target and projectile nuclei in collisions are called the participants, and the other parts outside the overlapping regions are called the spectators. Then, we divide the interacting system of nucleus-nucleus collisions into four parts (sources). From low rapidity region to a high one, the four sources are a target spectator, a target participant, a projectile participant, and a projectile spectator. Because leading nucleons in the overlapping regions contribute large pseudorapidities, we may consider these leading nucleons not belonging to the participants. Instead, they belong to the spectators. The participants contain only the nonleading nucleons in the overlapping regions. The spectators contain in fact the other parts outside the overlapping regions and the leading nucleons in the overlapping regions.

For each source, we can use the Landau hydrodynamic model to describe rapidity (y) or pseudorapidity (η) distribution. Generally speaking, the rapidity distribution and the pseudorapidity distribution are not exactly equal to each other. From the rapidity/pseudorapidity distribution to pseudorapidity/rapidity distribution, we need a conversion. However, at very high energy such as RHIC and LHC energies, we use approximately $y \approx \eta$ which renders a small dispersion in analyzing the experimental data [28].

According to the Landau hydrodynamic model [1–4], the evolvement of interacting system in nucleus-nucleus collisions can be described by the hydrodynamic method. After a series of calculated treatments, the pseudorapidity distribution of charged particles produced in the collisions can be described by a Gaussian function [3, 12, 13, 29–31]:

$$\frac{dN_{\mathrm{ch}}}{d\eta} = \frac{K s_{NN}^{1/4}}{\sqrt{2\pi}\sigma_\eta} \exp\left(-\frac{\eta^2}{2\sigma_\eta^2}\right), \quad (1)$$

where

$$\sigma_\eta^2 = \frac{8}{3} \frac{c_s^2}{1-c_s^4} \ln\left(\frac{\sqrt{s_{NN}}}{2m_N}\right), \quad (2)$$

denotes the square of distribution width, K is a normalization constant, $\sqrt{s_{NN}}$ is the center-of-mass energy per nucleon pair in the units of GeV, m_N is the mass of a proton in the units of GeV, and c_s^2 is the square speed of sound.

It should be noticed that Landau considered originally pseudorapidity, and the "modified" form by Shuryak introduced rapidity instead [3, 29]. The rapidity was also introduced by Milekhin [32] in the form of $\sigma_\eta^2 = 0.56 \ln[(E_{\mathrm{lab}}/2m_N)+2]$, where E_{lab} is the beam energy in the units of GeV in fixed target experiments. Considering $y \approx \eta$ at very high energy, we do not need to distinguish between y and η at RHIC and LHC energies. The Gaussian function is not only an approximation of the original Landau distribution [29–31], but also a close representation of the modified distribution discussed in [13].

Substituting (2) in (1), we have

$$\frac{dN_{\mathrm{ch}}}{d\eta} = \frac{K s_{NN}^{1/4}}{\sqrt{(16\pi/3)\left(c_s^2/\left(1-c_s^4\right)\right)\ln\left(\sqrt{s_{NN}}/2m_N\right)}} \times \exp\left(-\frac{\eta^2}{(16/3)\left(c_s^2/\left(1-c_s^4\right)\right)\ln\left(\sqrt{s_{NN}}/2m_N\right)}\right). \quad (3)$$

Then, we can use (3) to describe the pseudorapidity distribution of charged particles produced in a given source. For a distribution in the full phase space, we need a modified Landau hydrodynamic model which contains four components corresponding to four sources in collisions [33]. The four sources are the target spectator/participant and projectile participant/spectator, respectively. The participants contain the nonleading nucleons in the overlapping regions, and the spectators contain the nucleons outside the overlapping regions and the leading nucleons in the overlapping regions.

As a main free parameter, the (square) speed of sound is related to the width of pseudorapidity distribution due to (2). If we can describe the particle pseudorapidity distribution corresponding to a given source, then the square speed of sound of the source can be obtained. In fact,

$$c_s^2 = -\frac{4}{3\sigma_\eta^2} \ln\left(\frac{\sqrt{s_{NN}}}{2m_N}\right) + \sqrt{\left[\frac{4}{3\sigma_\eta^2} \ln\left(\frac{\sqrt{s_{NN}}}{2m_N}\right)\right]^2 + 1}. \quad (4)$$

3. Comparison with Experimental Data

The pseudorapidity distributions of charged particles produced in Au-Au collisions at $\sqrt{s_{NN}}$ = 19.6, 62.4, 130, and 200 GeV are presented in Figures 1, 2, 3, and 4, respectively. The circles represent the experimental data with different centralities measured by the PHOBOS collaboration [27], and the curves are our results calculated by the modified Landau hydrodynamic model. In the calculation, the values of c_s^2 are obtained by fitting the experimental data. The obtained values of c_s^2 and χ^2/dof (χ^2 per degree of freedom) are given in Table 1. One can see that the model describes the experimental data at RHIC energies. In the range of errors, the values of c_s^2 for the participants (P) and spectators (S) are the same. Both values of c_s^2 for the participants and spectators do not depend obviously on the centrality and $\sqrt{s_{NN}}$ in the considered energy range.

The pseudorapidity distributions of charged particles produced in Cu-Cu collisions at $\sqrt{s_{NN}}$ = 22.4, 62.4, and 200 GeV are presented in Figures 5, 6, and 7, respectively. The circles represent the experimental data with different centralities measured by the PHOBOS collaboration [27], and the curves are our results calculated by the modified Landau hydrodynamic model. The obtained values of c_s^2 and χ^2/dof are given in Table 2. One can see again that the model describes the experimental data. The values of c_s^2 for the participants and spectators are the same in the range of errors. Both values of c_s^2 for the participants and spectators do not depend obviously on the centrality and $\sqrt{s_{NN}}$ at RHIC energies.

Figure 8 shows the pseudorapidity distributions of charged particles produced in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV. The circles represent the experimental data of the ALICE collaboration [21], and the curves are our results calculated by the modified Landau hydrodynamic model. The obtained values of c_s^2 and χ^2/dof are given in Table 3. Once more the model describes the experimental data. The values of c_s^2 for the participants and spectators at LHC energy are the

TABLE 1: Values of c_s^2 for the participants (P) and spectators (S) as well as χ^2/dof for the curves in Figures 1–4 which represent Au-Au collisions at RHIC energies.

Bin (%)	c_s^2 (P)	c_s^2 (S)	χ^2/dof
	19.6 GeV		
0–3	0.25 ± 0.13	0.25 ± 0.13	0.431
3–6	0.25 ± 0.13	0.25 ± 0.13	0.489
6–10	0.25 ± 0.13	0.25 ± 0.13	0.555
10–15	0.25 ± 0.13	0.25 ± 0.13	0.602
15–20	0.25 ± 0.13	0.25 ± 0.13	0.399
20–25	0.25 ± 0.13	0.25 ± 0.13	0.090
25–30	0.25 ± 0.13	0.25 ± 0.13	0.145
30–35	0.25 ± 0.13	0.25 ± 0.13	0.108
35–40	0.25 ± 0.13	0.25 ± 0.13	0.075
40–45	0.25 ± 0.13	0.25 ± 0.13	0.183
	62.4 GeV		
0–3	0.24 ± 0.12	0.18 ± 0.09	0.983
3–6	0.24 ± 0.12	0.18 ± 0.09	0.610
6–10	0.24 ± 0.12	0.18 ± 0.09	0.199
10–15	0.25 ± 0.12	0.18 ± 0.09	0.205
15–20	0.25 ± 0.12	0.18 ± 0.09	0.146
20–25	0.25 ± 0.12	0.18 ± 0.09	0.155
25–30	0.25 ± 0.12	0.18 ± 0.09	0.139
30–35	0.25 ± 0.12	0.18 ± 0.09	0.128
35–40	0.27 ± 0.14	0.18 ± 0.09	0.114
40–45	0.27 ± 0.14	0.18 ± 0.09	0.127
45–50	0.27 ± 0.14	0.18 ± 0.09	0.074
	130 GeV		
0–3	0.23 ± 0.12	0.25 ± 0.13	0.295
3–6	0.23 ± 0.12	0.25 ± 0.13	0.243
6–10	0.23 ± 0.12	0.25 ± 0.13	0.351
10–15	0.26 ± 0.13	0.21 ± 0.11	0.250
15–20	0.26 ± 0.13	0.21 ± 0.11	0.101
20–25	0.26 ± 0.13	0.21 ± 0.11	0.066
25–30	0.28 ± 0.14	0.23 ± 0.12	0.181
30–35	0.28 ± 0.14	0.23 ± 0.12	0.137
35–40	0.28 ± 0.14	0.23 ± 0.12	0.092
40–45	0.28 ± 0.14	0.23 ± 0.12	0.092
45–50	0.28 ± 0.14	0.23 ± 0.12	0.183
	200 GeV		
0–3	0.23 ± 0.12	0.13 ± 0.07	0.128
3–6	0.23 ± 0.12	0.13 ± 0.07	0.048
6–10	0.23 ± 0.12	0.13 ± 0.07	0.029
10–15	0.23 ± 0.12	0.13 ± 0.07	0.214
15–20	0.23 ± 0.12	0.13 ± 0.07	0.057
20–25	0.23 ± 0.12	0.13 ± 0.07	0.192
25–30	0.23 ± 0.12	0.13 ± 0.07	0.239
30–35	0.23 ± 0.12	0.13 ± 0.07	0.144
35–40	0.23 ± 0.12	0.13 ± 0.07	0.099
40–45	0.23 ± 0.12	0.13 ± 0.07	0.087
45–50	0.23 ± 0.12	0.13 ± 0.07	0.081

Table 2: Values of c_s^2 for the participants and spectators as well as χ^2/dof for the curves in Figures 5–7 which represent Cu-Cu collisions at RHIC energies.

Bin (%)	c_s^2 (P)	c_s^2 (S)	χ^2/dof
	22.4 GeV		
0–3	0.21 ± 0.11	0.15 ± 0.08	0.340
3–6	0.23 ± 0.12	0.15 ± 0.08	0.376
6–10	0.23 ± 0.12	0.15 ± 0.08	0.748
10–15	0.23 ± 0.12	0.15 ± 0.08	0.184
15–20	0.24 ± 0.12	0.21 ± 0.11	0.088
20–25	0.24 ± 0.12	0.21 ± 0.11	0.095
25–30	0.21 ± 0.11	0.21 ± 0.11	0.089
30–35	0.24 ± 0.12	0.22 ± 0.11	0.120
35–40	0.24 ± 0.12	0.22 ± 0.11	0.123
40–45	0.24 ± 0.12	0.22 ± 0.11	0.180
45–50	0.24 ± 0.12	0.22 ± 0.11	0.193
50–55	0.24 ± 0.12	0.22 ± 0.11	0.225
	62.4 GeV		
0–3	0.23 ± 0.12	0.13 ± 0.07	0.102
3–6	0.23 ± 0.12	0.13 ± 0.07	0.143
6–10	0.23 ± 0.12	0.13 ± 0.07	0.141
10–15	0.23 ± 0.12	0.13 ± 0.07	0.189
15–20	0.23 ± 0.12	0.15 ± 0.08	0.114
20–25	0.23 ± 0.12	0.15 ± 0.08	0.081
25–30	0.25 ± 0.13	0.17 ± 0.09	0.093
30–35	0.25 ± 0.13	0.17 ± 0.09	0.049
35–40	0.25 ± 0.13	0.17 ± 0.09	0.060
40–45	0.25 ± 0.13	0.17 ± 0.09	0.067
45–50	0.25 ± 0.13	0.17 ± 0.09	0.042
50–55	0.27 ± 0.14	0.17 ± 0.09	0.057
	200 GeV		
0–3	0.25 ± 0.13	0.18 ± 0.09	0.141
3–6	0.25 ± 0.13	0.15 ± 0.08	0.078
6–10	0.25 ± 0.13	0.15 ± 0.08	0.066
10–15	0.25 ± 0.13	0.15 ± 0.08	0.054
15–20	0.25 ± 0.13	0.15 ± 0.08	0.064
20–25	0.25 ± 0.13	0.15 ± 0.08	0.071
25–30	0.27 ± 0.14	0.15 ± 0.08	0.046
30–35	0.27 ± 0.14	0.15 ± 0.08	0.051
35–40	0.27 ± 0.14	0.15 ± 0.08	0.063
40–45	0.27 ± 0.14	0.15 ± 0.08	0.056
45–50	0.27 ± 0.14	0.15 ± 0.08	0.038
50–55	0.27 ± 0.14	0.15 ± 0.08	0.078

Table 3: Values of c_s^2 for the participants and spectators as well as χ^2/dof for the curves in Figure 8 which represent Pb-Pb collisions at 2.76 TeV (LHC energy).

Bin (%)	c_s^2 (P)	c_s^2 (S)	χ^2/dof
0–5	0.17 ± 0.03	0.16 ± 0.08	0.093
5–10	0.17 ± 0.03	0.16 ± 0.08	0.082
10–20	0.16 ± 0.03	0.17 ± 0.08	0.067
20–30	0.16 ± 0.03	0.17 ± 0.08	0.054

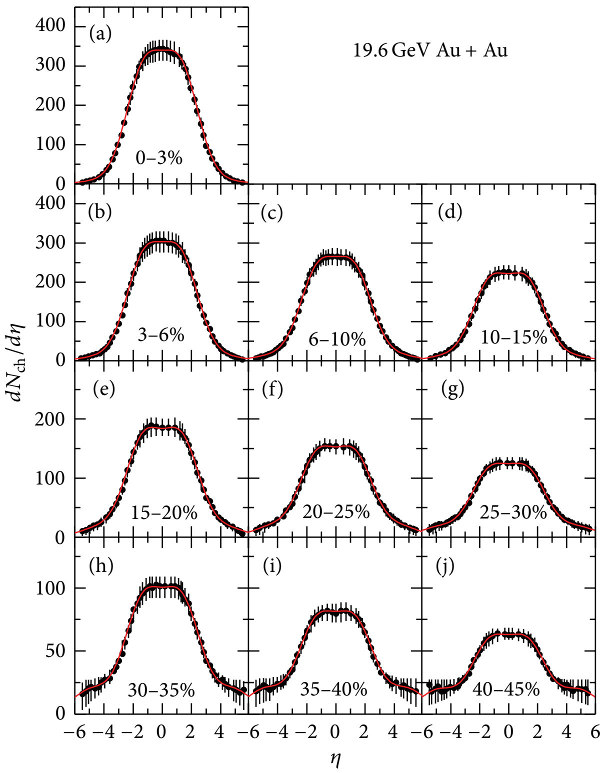

FIGURE 1: $dN_{ch}/d\eta$ versus η for different centrality bins in Au-Au collisions at $\sqrt{s_{NN}}$ = 19.6 GeV. The circles and curves represent the experimental data of the PHOBOS collaboration [27] and our calculated results, respectively.

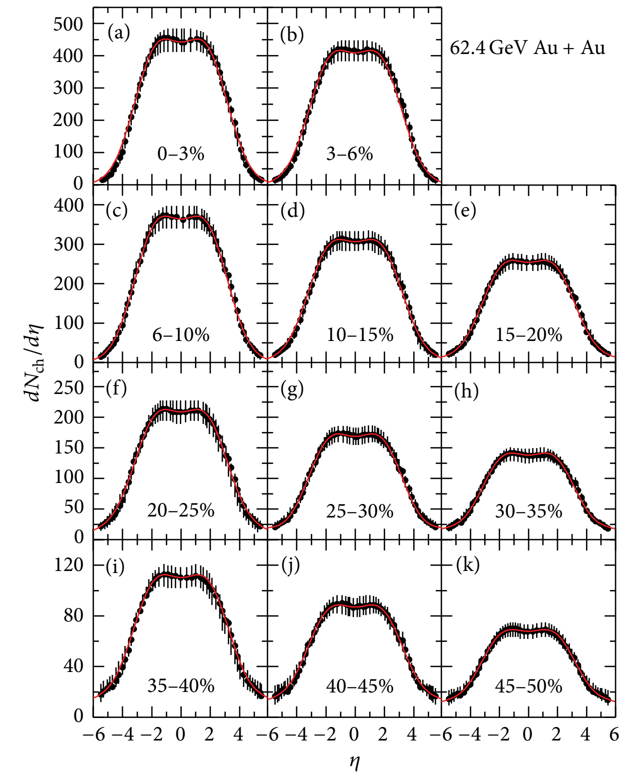

FIGURE 2: As Figure 1 but showing the results in Au-Au collisions at $\sqrt{s_{NN}}$ = 62.4 GeV.

same, and they are the same as those at RHIC energies in the range of errors. Both the values of c_s^2 for the participants and spectators do not depend obviously on the centrality.

From Figures 1–8, one can see that the modified Landau hydrodynamic model proposed by us is in agreement with the experimental data at RHIC and LHC energies. In the model, both the contributions of participants and spectators (or nonleading nucleons and leading nucleons) are included. We notice that in recent works [21, 34] both the Landau-Carruthers Gaussian [11, 12] and the Landau-Wong function [13] overestimate/underestimate the distributions in central/forward rapidity regions. If we consider the contributions of leading nucleons in the Landau-Carruthers Gaussian [11, 12] and in the Landau-Wong function [13], respectively, both the situations will change to be better.

The values of c_s^2 obtained by us are in agreement with the hadron resonance (HRG) gas model [35, 36]. According to the HRG model, the existing region of hadron resonances including the pions has a large c_s^2 (~0.23), and the existing region of hadron resonances excluding the pions has a small c_s^2 (~0.12) at low temperature (~85 MeV). The two regions trend approximately the same one (~0.14–0.15) at high temperature (~190 MeV). In [37], based on the lattice quantum chromodynamics (QCD) theory, the values of c_s^2 and other parameters are obtained in the temperature range from 125 MeV to 400 MeV. According to [37], the values of c_s^2 are 0.12–0.16 at 125 MeV and 0.31 at 400 MeV. One can see that these values are in agreement with our results in the range of errors.

We notice that the errors for c_s^2 in the present work are universally large. This renders that c_s^2 is not a sensitive quantity. As an intensive quantity, c_s^2 is a reflection of the ratios of pressure to energy density or entropy to specific heat in the participant and spectator regions and is related to the pseudorapidity distribution width which depends on the rapidity shifts of the participants and spectators.

The same c_s^2 for the participants and spectators and for different centrality bins at RHIC and LHC energies reflect the same matter density at the freeze-out stage of particle production. In collisions, the spectators have nearly a normal nuclear density, and the participants have a much larger density than the normal nuclear one. After collisions, the participants expand rapidly in volume and reach the normal nuclear density. Then, the participants produce many final-state particles. For the participants, to expand to the normal nuclear density and then to produce final-state particles are a fact that does not depend on centrality and energy at RHIC and LHC energies.

4. Conclusions

From the above discussions, we obtain following conclusions.

(a) The pseudorapidity distributions of charged particles produced in nucleus-nucleus collisions at RHIC and

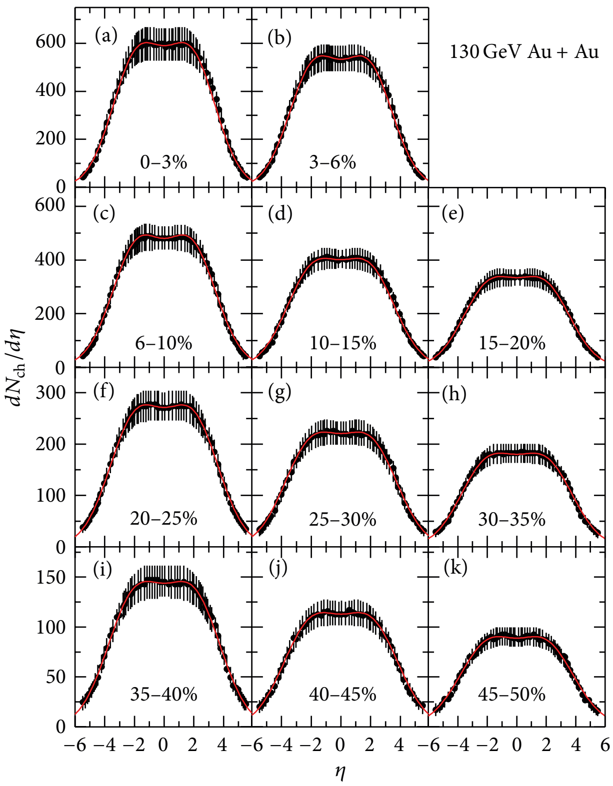

Figure 3: As Figure 1 but showing the results in Au-Au collisions at $\sqrt{s_{NN}} = 130$ GeV.

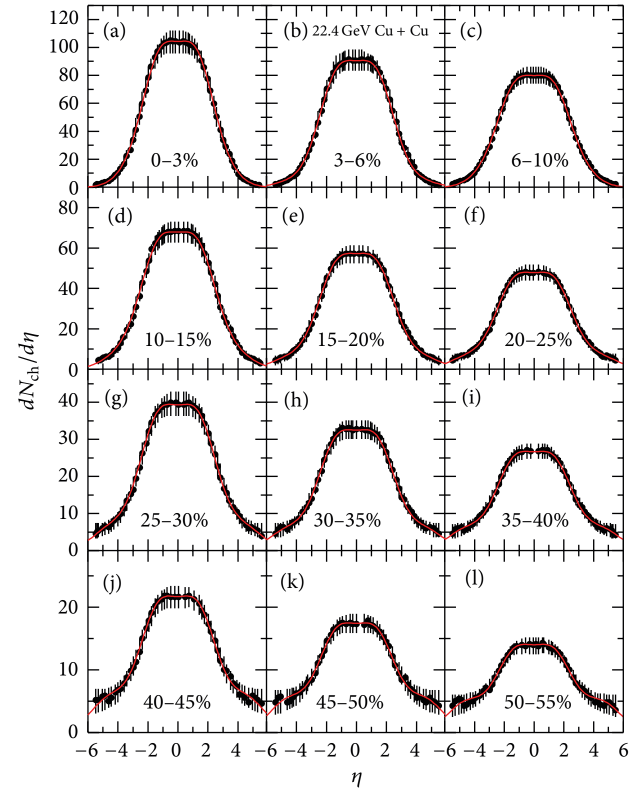

Figure 5: As Figure 1 but showing the results in Cu-Cu collisions at $\sqrt{s_{NN}} = 22.4$ GeV.

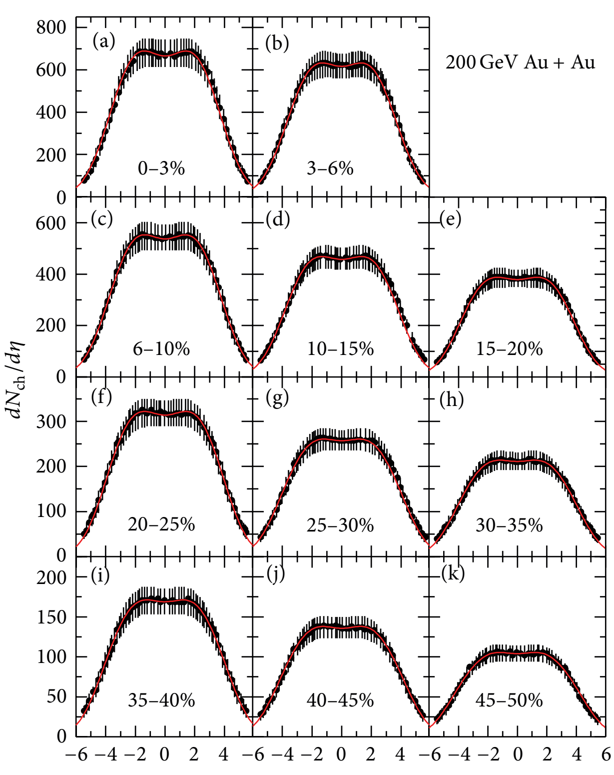

Figure 4: As Figure 1 but showing the results in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

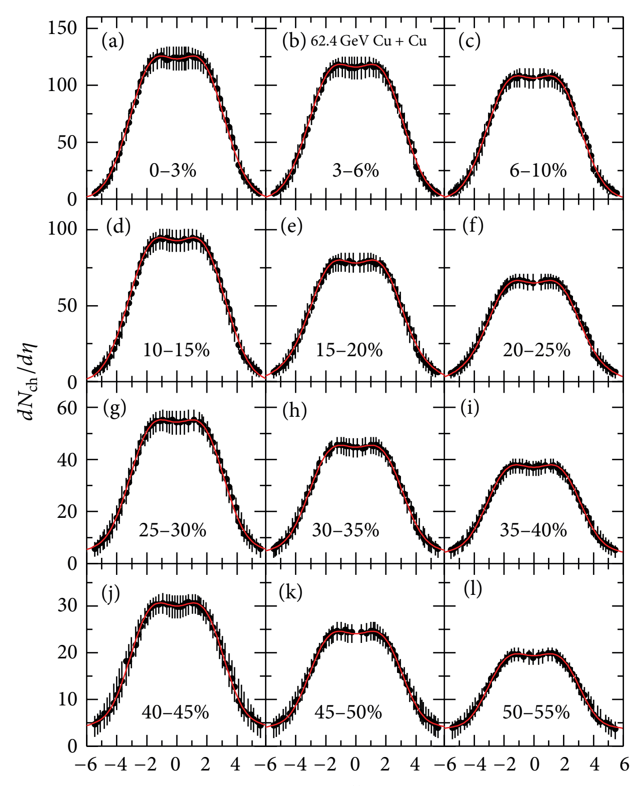

Figure 6: As Figure 1 but showing the results in Cu-Cu collisions at $\sqrt{s_{NN}} = 62.4$ GeV.

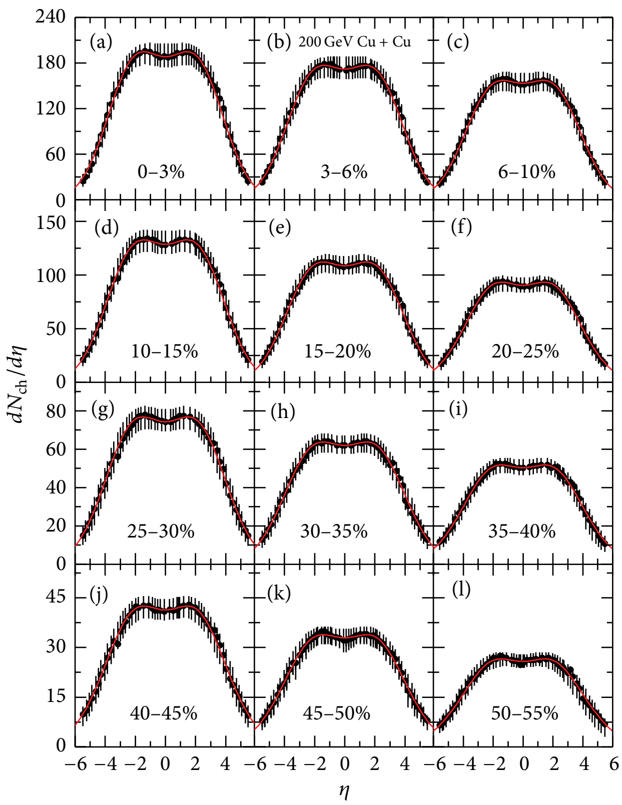

FIGURE 7: As Figure 1 but showing the results in Cu-Cu collisions at $\sqrt{s_{NN}}$ = 200 GeV.

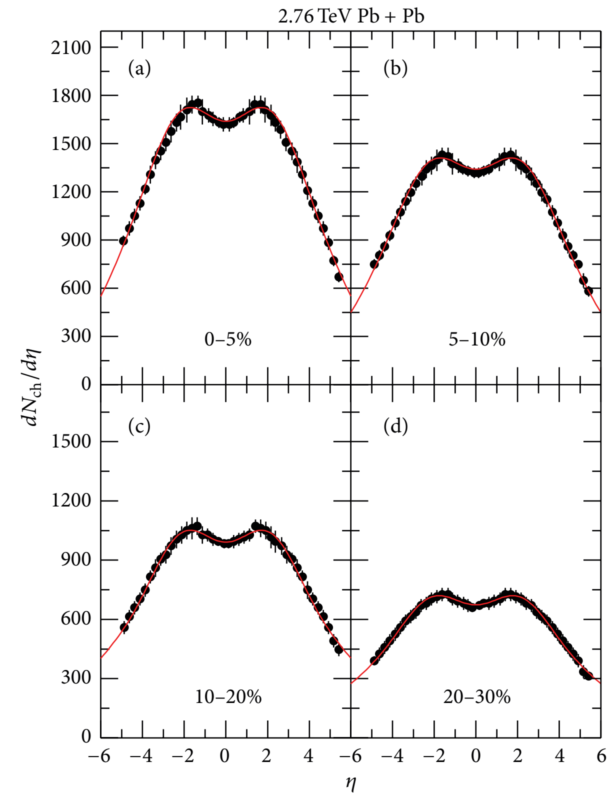

FIGURE 8: $dN_{ch}/d\eta$ versus η for different centrality bins in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV. The circles and curves represent the experimental data of the ALICE collaboration [21] and our calculated results, respectively.

LHC energies can be described by the modified Landau hydrodynamic model. The modeling results are in agreement with the PHOBOS experimental data of Au-Au collisions at $\sqrt{s_{NN}}$ = 19.6, 62.4, 130, and 200 GeV and Cu-Cu collisions at $\sqrt{s_{NN}}$ = 22.4, 62.4, and 200 GeV, as well as ALICE experimental data of Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV.

(b) In the concerned energy range from 19.6 GeV to 2.76 TeV, the values of c_s^2 for the participants and spectators are the same in the range of errors and do not depend obviously on the centrality and $\sqrt{s_{NN}}$.

(c) The values of c_s^2 obtained in the present work are in agreement with the results of the HRG model and the lattice QCD theory. To extract c_s^2 of interacting system, our work provides a new method which bases on the width of particle pseudorapidity distribution.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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