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Research Article

Can Tsallis Distribution Fit All the Particle Spectra Produced at RHIC and LHC?

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The Tsallis distribution has been tested to fit all the particle spectra at mid-rapidity from central events produced in d + Au, Cu + Cu, and Au + Au collisions at RHIC and p + Pb, Pb + Pb collisions at LHC. Even though there are strong medium effects in Cu + Cu and Au + Au collisions, the results show that the Tsallis distribution can be used to fit most of particle spectra in the collisions studied except in Au + Au collisions where some deviations are seen for proton and Λ at low p_T. In addition, as the Tsallis distribution can only fit part of the particle spectra produced in Pb + Pb collisions where p_T is up to 20 GeV/c, a new formula with one more fitting degree of freedom is proposed in order to reproduce the entire p_T region.

1. Introduction

The heavy-ion collision experiments at RHIC and LHC give us the opportunity to study the phase transition from nuclear matter to quark gluon plasma (QGP), the collective motion, the nuclear medium effects, and so on. The particle spectrum is one of the basic quantities measured in experiments to address the questions raised in such studies. Recently, the Tsallis distribution has attracted the attention of many theorists and experimentalists in high energy heavy-ion collisions [1–25]. It has been applied to particle spectra produced in different reaction systems, from pp, pA to AA, to understand the particle production mechanism and extract physical quantities, for example, temperature [2–4, 7, 12–14, 17–21, 24] and chemical potential [26]. In pp collisions, the excellent ability to fit the spectra of identified hadrons and charged particles in a large range of p_T up to 200 GeV/c is quite impressive [2, 23–25]. A systematic investigation of particle spectra in p + p collisions at RHIC and LHC has been conducted in [2]. The results show that the Tsallis distribution can fit all the particle spectra at different energies in p + p collisions. A possible cascade particle production mechanism is proposed. Recently, a Tsallis distribution scaling function was found for charged hadron spectra in p + p and p + $\overline{\text{p}}$ collisions [1]. Comparing to nucleus-nucleus collisions, the pp collision is very simple. It has been used as a baseline for nucleus-nucleus collisions. A nuclear modification factor R_{pA} or R_{AA} was proposed to show the nuclear medium effects in pA or AA collisions referring to pp collisions [5, 10–12, 27–34]. The nuclear modification factor different from unity is a manifestation of medium effects. Many authors have successfully applied Tsallis distribution to fit particle spectra in pA and AA collisions even though the spectra were affected by nuclear medium modification [3–8, 10, 11, 18, 21]. We also notice that many works only show the small p_T part of the particle spectra, while the exponential distribution also can fit the low p_T region [11, 35]. It should cover all p_T regions of particle spectra, available in experiment, in order to show the advantage and/or the fitting power of the Tsallis distribution. In recent years, the experimental groups at RHIC and LHC have published the wide p_T range of particle spectra for different particles in different reaction systems. Such data allow us to conduct the systematic study of particle spectra in

heavy-ion collisions at RHIC and LHC using the Tsallis distribution, as we have done for p + p collisions [2].

In this work, we would like to test whether the Tsallis distribution can fit all the particle spectra produced at RHIC and LHC, which can help us to understand the particle production mechanism. Before we start to conduct our investigation, we can get some clues to estimate whether it can fit the particle spectrum or not from the nuclear modification factor. If R_{pA} or R_{AA} is flat for the whole p_T region, according to its definition, this means that the particle spectrum is similar in shape and only differs in magnitude to the one in p + p collisions. Based on the previous studies [1, 2], we are sure that the Tsallis distribution can fit the particle spectrum since it can fit all the particle spectra produced in p + p collisions, especially up to extremely high p_T [2, 23–25]. In the pA reactions, R_{pA} are flat and very close to 1 for most of the produced particles at different centralities [5, 10, 11, 27, 29, 34], while in the AA collisions the nuclear medium effects play an important role. R_{AA} increases from the most central collisions to peripheral collisions [11, 12, 28, 30–33]. Since the nuclear modification factors of different particles are almost 1 in peripheral heavy-ion collisions [5, 10–12, 27–34], as we discussed, Tsallis distribution should be able to fit the particle spectra. Therefore we will only focus on the particle spectra at the most central collisions where the Tsallis distribution may not fit all of them. We have collected data of particle spectra from d + Au, Cu + Cu, and Au + Au collisions at RHIC and p + Pb, Pb + Pb collisions at LHC and select the data for most of the particles with the highest $p_T > 5$ GeV to conduct this study.

The paper is organized as follows. In Section 2, we show different versions of the Tsallis distribution used in the literature. More details can be found in [2]. We also give the form of Tsallis distribution used in our analysis. In Section 3, we show our results of particle spectra from d + Au, p + Pb, Cu + Cu, Au + Au, and Pb + Pb. Another distribution is proposed to fit the particle spectra in Pb + Pb collisions since Tsallis distribution can only fit part of the particle spectra in the case. A brief conclusion is given in Section 4.

2. Tsallis Distributions

In the literature, several versions of Tsallis distribution with different arguments can be found [2–25]. The asymptotic behaviors of these distributions at low and high p_T limits can be found in [2]. We only briefly show them here.

The STAR [9] and PHENIX [5, 12] Collaborations at RHIC along with ALICE [13, 14] and CMS [15] Collaborations at LHC adopted this form of Tsallis distribution:

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi p_T}\frac{d^2N}{dydp_T} = \frac{dN}{dy}\frac{(n-1)(n-2)}{2\pi nC[nC+m(n-2)]}\left(1+\frac{m_T-m}{nC}\right)^{-n}, \tag{1}$$

where $m_T = \sqrt{p_T^2+m^2}$ is the transverse mass and m is the mass of the particle. dN/dy, n, and C are fitting parameters.

In [8, 19–22, 36], the following Tsallis form is used:

$$E\frac{d^3N}{dp^3} = gV\frac{m_T\cosh y}{(2\pi)^3}\left[1+(q-1)\frac{m_T\cosh y-\mu}{T}\right]^{q/(1-q)}, \tag{2}$$

based on thermodynamic consistency arguments. Where g is the degeneracy of the particle, V is the volume, y is the rapidity, μ is the chemical potential, T is the temperature, and q is a parameter. In (2), there are four parameters V, μ, T, and q. μ was assumed to be 0 in [19–21, 36] which is a reasonable assumption because the energy is high enough and the chemical potential is small compared to temperature. In the mid-rapidity $y = 0$ region, (2) is reduced to

$$E\frac{d^3N}{dp^3} = gV\frac{m_T}{(2\pi)^3}\left[1+(q-1)\frac{m_T}{T}\right]^{q/(1-q)}. \tag{3}$$

In [4, 21], (2) has been rewritten as

$$\frac{dN}{m_T dm_T} = C\int_{-Y}^{Y}\cosh y dy m_T\left[1+(q-1)\frac{m_T\cosh y}{T}\right]^{q/(1-q)}, \tag{4}$$

to take into account the width of the corresponding rapidity distribution of the particles.

In [17], Sena and Deppman applied the nonextensive formalism to obtain the probability of particle with momentum p_T as

$$\frac{1}{\sigma}\frac{d\sigma}{dp_T} = cp_T\int_0^{\infty}dp_L\left[1+(q-1)\beta\sqrt{p_L^2+p_T^2+m^2}\right]^{-q/(q-1)}, \tag{5}$$

where c is the normalization constant, q is a parameter, $\beta = 1/T$, and m is the mass of particle. With the approximation p_T very large compared to p_L and m [37], (5) can be rewritten as

$$\frac{1}{\sigma}\frac{d\sigma}{dp_T} = c\left[2(q-1)\right]^{-1/2}B\left(\frac{1}{2},\frac{q}{q-1}-\frac{1}{2}\right)\cdot u^{3/2}\left[1+(q-1)u\right]^{-q/(q-1)+1/2}, \tag{6}$$

where $u = p_T/T$ and $B(x, y)$ is the beta-function.

In [24], Wong and Wilk proposed a new form of the Tsallis distribution function to take into account the rapidity cut:

$$\left(E\frac{d^3N}{dp^3}\right)_{|\eta|<a} = \int_{-a}^{a}d\eta\frac{dy}{d\eta}\left(\frac{d^3N}{dp^3}\right), \tag{7}$$

where

$$\frac{dy}{d\eta}(\eta, p_T) = \sqrt{1 - \frac{m^2}{m_T^2 \cosh^2 y}}, \tag{8}$$

with

$$y = \frac{1}{2} \ln \left[\frac{\sqrt{p_T^2 \cosh^2 \eta + m^2} + p_T \sinh \eta}{\sqrt{p_T^2 \cosh^2 \eta + m^2} - p_T \sinh \eta} \right],$$
$$\frac{d^3N}{dp^3} = C \frac{dN}{dy} \left(1 + \frac{E_T}{nT}\right)^{-n}, \quad E_T = m_T - m, \tag{9}$$

where $C(dN/dy)$ is assumed to be a constant.

In [2], we have obtained

$$\left(E \frac{d^3N}{dp^3}\right)_{|\eta|<a} = A \left(1 + \frac{E_T}{nT}\right)^{-n}, \tag{10}$$

where A, n, and T are the fitting parameters. This is equivalent to (1) but in a simpler form. We adopt (10) to do the analysis here. We notice that (10) has been used by the CMS Collaboration [16, 38] and by Wong et al. in their recent paper [25]. The STAR Collaboration has also applied a formula which is very close to (10) [29].

3. Results

We have selected the data of particle spectra from the most central collisions with the highest $p_T > 5$ GeV for most of the particles in d + Au, p + Pb, Cu + Cu, A u + Au, and Pb + Pb at RHIC and LHC. We fit the center values of the experimental points. The fit metric used is defined by

$$M^2 = \sum_i \left[1 - \frac{y_i\,(\text{fit})}{y_i\,(\text{data})}\right]^2. \tag{11}$$

As we discussed before, the Tsallis distribution should be able to fit the particle spectra from d + Au and p + Pb. One good example has been shown in [4, 5] for K_S^0 and K^{0*} in d + Au at $\sqrt{s_{NN}} = 200$ GeV where their spectra can be obtained by multiplying the particle spectra in p + p collisions with N_{coll}. In Figures 1 and 2, our results for d + Au at $\sqrt{s_{NN}} = 200$ GeV and p + Pb at $\sqrt{s_{NN}} = 5.02$ TeV using (10) have been shown. In order to see the agreement between the data and the Tsallis distribution in linear scale, a ratio data/fit is defined. As shown in Figures 1 and 2, the fits for all particles are good. For the left collision systems, we also do the same comparisons. We would like to emphasize that p_T of charged particle spectrum is up to 45 GeV/c.

Now let us turn to the AA collisions. First we use Tsallis distribution Equation (10) to fit the particle spectra in Au + Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV in Figure 3. All the particle spectra are well fitted except the proton spectrum at $p_T < 1$ GeV/c. This makes a little difference of AA collisions from p + p collisions. We want to check whether this deviation will

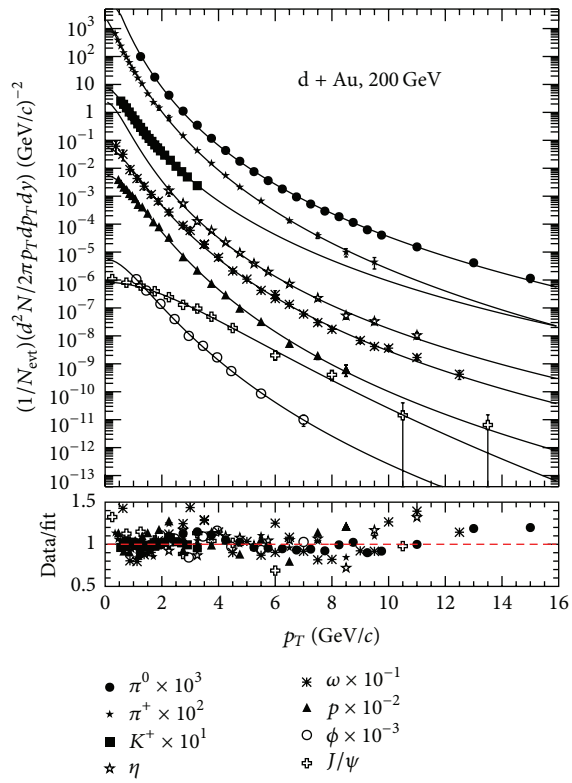

Figure 1: The data are from [10, 11, 27, 39–42] for d + Au at $\sqrt{s_{NN}} = 200$ GeV. The curves are the analytical results with Tsallis distribution Equation (10). The corresponding fitting parameters and χ^2/ndf are given in Table 1. For a better visualization both the data and the analytical curves have been scaled by a constant as indicated. The ratios of data/fit are shown at the bottom.

become larger at higher colliding energy in AA collisions. We considered the particle spectra from Cu + Cu collisions at $\sqrt{s_{NN}} = 200$ GeV. The results are shown in Figure 4. The fitting with (10) for different particle spectra is very well. But we do not know whether there is deviation or not for proton at low p_T since the data for $p_T < 3$ GeV/c are not available. Fortunately, the data for different particle spectra at low p_T in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV are given. In Figure 5, one can see the deviations of particle spectra of proton and Λ at low p_T from the Tsallis distribution Equation (10). While a deviation is observed for proton at $p_T < 2$ GeV/c which becomes a little larger than the one in Au + Au at $\sqrt{s_{NN}} = 62.4$ GeV, all other particle spectra are well fitted. This makes us curious to fit the particle spectra in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. With the successful running at LHC, the identified hadron particle spectra data in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are available up to 20 GeV/c. The data satisfy two criteria. One is that there are strong nuclear medium effects in Pb + Pb collisions which can be seen from R_{PbPb} and the other is that the transverse momenta of the particles reach high values. This gives us an opportunity to test the fitting power of the Tsallis distribution. When we use Tsallis distribution Equation (10) to fit pion spectrum, we

Table 1: The fitting parameters and the corresponding χ^2/ndf for various particles in different collision systems with Tsallis distribution Equation (10).

System	Particle	Centrality	A	T (GeV)	n	χ^2/ndf
d + Au $\sqrt{s_{NN}}$ = 200 GeV	γ	Minimum bias	1274.39	0.108	7.48	30.66/21
	π^0	0–20%	54.08	0.130	9.70	15.46/18
	π^+	0–20%	21.60	0.173	11.56	10.74/21
	K^+	0–20%	0.776	0.214	8.89	1.54/18
	η	0–20%	2.403	0.163	9.57	6.75/10
	ω	0–20%	0.565	0.224	10.53	18.08/24
	p	0–20%	0.568	0.221	11.97	11.60/20
	ϕ	0–20%	0.0563	0.270	13.63	3.57/7
	J/ψ	0–20%	$8.30E-7$	0.582	26.91	15.67/10
p + Pb $\sqrt{s_{NN}}$ = 5.02 TeV	Charged	Minimum bias	33.32	0.182	7.00	501.03/57
	K_s^0	0–5%	1.537	0.302	9.16	15.12/31
	p	0–5%	0.536	0.449	22.49	6.53/36
	Λ	0–5%	0.323	0.469	19.47	21.13/17
Au + Au $\sqrt{s_{NN}}$ = 62.4 GeV	π^+	0–10%	551.14	0.171	16.80	20.80/20
	K_s^0	0–5%	20.03	0.264	40.88	12.95/12
	p	0–10%	21.37	0.226	22.64	305.47/16
	Λ	0–5%	6.83	0.295	11039.30	7.26/9
	Ξ	0–5%	0.352	0.315	7811.73	6.94/8
	Ω	0–20%	$4.35E-2$	0.308	3064.05	2.57/2
Cu + Cu $\sqrt{s_{NN}}$ = 200 GeV	π^0	0–10%	304.12	0.128	9.42	38.83/21
	π^+	0–10%	1016.57	0.111	9.45	7.16/8
	K_s^0	0–10%	15.89	0.198	12.19	51.37/19
	ω	0–20%	51.79	0.139	9.48	1.21/4
	p	0–10%	242.07	0.107	9.90	0.12/5
	ϕ	0–10%	1.09	0.226	12.08	7.02/8
	Λ	0–10%	2.04	0.297	35.35	121.47/16
	Ξ	0–10%	0.199	0.326	42.47	6.25/7
	J/Ψ	0–20%	$7.98E-6$	0.399	8.16	3.60/7
Au + Au $\sqrt{s_{NN}}$ = 200 GeV	γ low p_T	0–20%	109.59	0.184	19.24	4.10/8
	γ high p_T	0–5%	4.64	0.187	7.85	15.44/14
	π^0	0–10%	18.68	0.191	9.06	12.36/12
	π^+	0–10%	1165.01	0.138	10.50	251.34/28
	K_s^0	0–5%	49.56	0.213	13.99	153.73/18
	η	0–20%	4978.81	0.066	8.16	4.03/7
	p	0–12%	312.81	0.118	9.50	54866.3/26
	ϕ	0–10%	3.44	0.236	13.70	7.85/7
	Λ	0–5%	31.74	0.215	18.91	2739.02/18
	J/Ψ	0–20%	$3.576E-4$	0.221	7.88	0.83/3

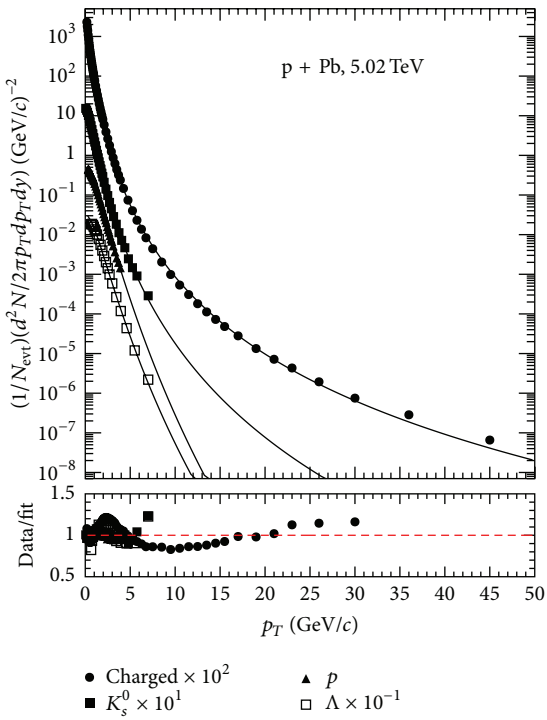

FIGURE 2: The data are from [34, 43] for p + Pb at $\sqrt{s_{NN}} = 5.02$ TeV. The curves are the analytical results with Tsallis distribution Equation (10). The corresponding fitting parameters and χ^2/ndf are given in Table 1. For a better visualization both the data and the analytical curves have been scaled by a constant as indicated. The ratios of data/fit are shown at the bottom.

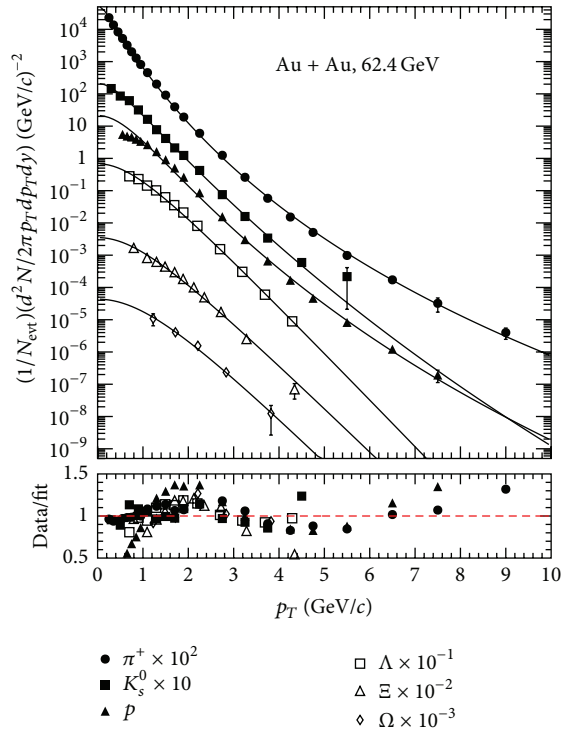

FIGURE 3: The data are from [30, 44] for Au + Au at $\sqrt{s_{NN}} = 62.4$ GeV. The curves are the analytical results with Tsallis distribution Equation (10). The corresponding fitting parameters and χ^2/ndf are given in Table 1. For a better visualization both the data and the analytical curves have been scaled by a constant as indicated. The ratios of data/fit are shown at the bottom (Color online).

find that (10) can only fit part of it. If we choose to fit the low p_T region, (10) can fit the particle spectrum up to 10 GeV/c, as shown in Figure 6 with red dashed line. The blue dotted-dashed line shows the fit for high p_T region which starts from 4 GeV/c.

The exponential form equation was used to fit the particle spectra at RHIC when only the low p_T data are available [11, 35]. With the upgrade of detectors, we have a better ability to measure the particle spectra. When the intermediate p_T data are available, the Tsallis distribution is used to understand the particle spectra and extract physical information. The two-Boltzmann distribution was also used in [7]. But in both cases the number of free fitting parameters increases from 2 to 3. One fitting degree of freedom is increased in this transition. In [6], a double Tsallis formula was proposed to fit particle spectra obtained from central events in Pb + Pb collisions. In this case, three fitting degrees of freedom are increased. Here we will follow the same logic of the transition from exponential distribution to Tsallis distribution to propose a new form equation to fit the particle spectra in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV by only increasing one fitting degree of freedom. We increase the number of free fitting parameters from 3 to 4 and the proposed formula is

$$\left(E\frac{d^3N}{dp^3}\right)_{|\eta|<a} = A\frac{e^{-(b/T)\arctan(E_T/b)}}{\left[1+\left(E_T/b\right)^4\right]^c}. \tag{12}$$

There are four parameters A, b, T, and c. We are inspired by the solution of Fokker-Planck equation [56]. We change the power from 2 in [56] to 4 in (12) in order to fit well all the particle spectra with one equation. Figure 6 shows that the fits with (12) are excellent. We would like to mention that when $E_T/b \ll 1$, (12) becomes

$$\left(E\frac{d^3N}{dp^3}\right)_{|\eta|<a} \propto e^{-E_T/T} \tag{13}$$

and when $E_T/b \gg 1$,

$$\left(E\frac{d^3N}{dp^3}\right)_{|\eta|<a} \propto p_T^{-4c}. \tag{14}$$

Equation (12) has the same asymptotic behaviors as (10).

4. Conclusions

In this paper, we have tested the fitting ability of Tsallis function by fitting different particle spectra produced at the most central collisions in d + Au, p + Pb, Cu + Cu, Au + Au, and Pb + Pb at RHIC and LHC. The Tsallis distribution is able to fit all the particle spectra in d + Au and p + Pb collisions where the medium effects are very weak. This information can be obtained by the nuclear modification

Table 2: The fitting parameters and the corresponding χ^2/ndf for different particles in Pb + Pb at $\sqrt{s_{NN}}$ = 2.76 TeV with (12).

System	Particle	Centrality	A	T (GeV)	b	c	χ^2/ndf
Pb + Pb $\sqrt{s_{NN}}$ = 2.76 TeV	Charged π	0–5%	2049.91	0.252	2.195	0.886	174.54/59
	Charged K	0–5%	112.68	0.346	1.776	1.150	35.37/54
	Charged p	0–5%	10.55	0.710	1.845	1.605	42.29/45
	ϕ	0–5%	2.11	0.749	1.281	1.080	1.84/4
	Λ	0–5%	3.525	0.761	1.907	1.679	23.15/27
	Ξ	0–10%	0.376	0.774	2.003	1.665	32.95/23
	Ω	0–10%	0.0615	0.658	2.098	1.324	2.41/9

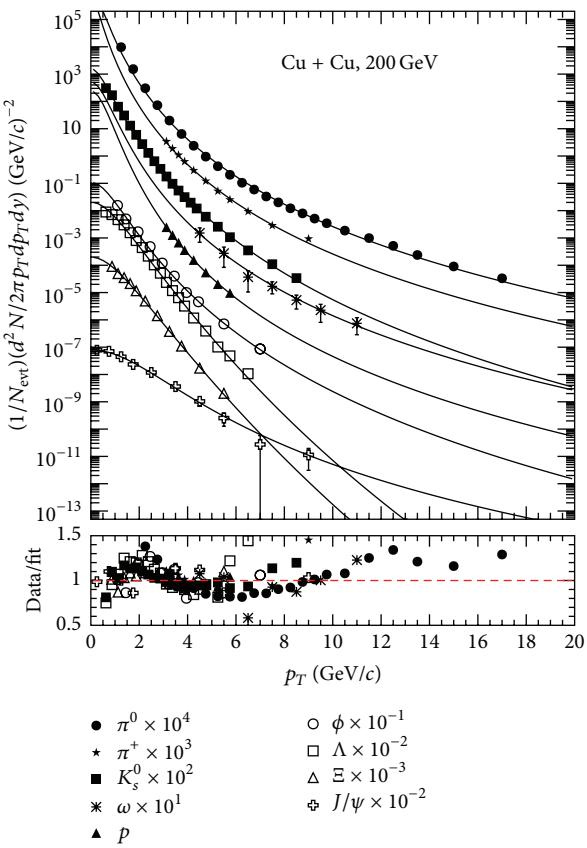

Figure 4: The data are from [11, 31, 40, 45–47] for Cu + Cu at $\sqrt{s_{NN}}$ = 200 GeV. The curves are the analytical results with Tsallis distribution Equation (10). The corresponding fitting parameters and χ^2/ndf are given in Table 1. For a better visualization both the data and the analytical curves have been scaled by a constant as indicated. The ratios of data/fit are shown at the bottom.

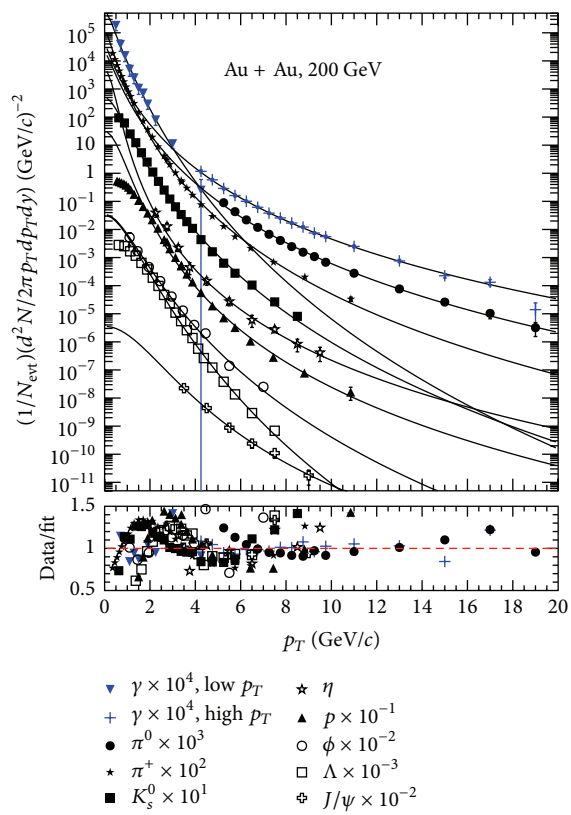

Figure 5: The data are from [11, 32, 46, 48–52] for Au + Au at $\sqrt{s_{NN}}$ = 200 GeV. The curves are the analytical results with Tsallis distribution Equation (10). The corresponding fitting parameters and χ^2/ndf are given in Table 1. For a better visualization both the data and the analytical curves have been scaled by a constant as indicated. The ratios of data/fit are shown at the bottom.

factor. In the AA collisions, the Tsallis distribution can fit all the particle spectra very well at RHIC energies except the little deviation observed for proton and Λ at low p_T. However the Tsallis distribution can only fit part of the particle spectra in Pb + Pb at $\sqrt{s_{NN}}$ = 2.76 TeV, either in the low or in the high p_T region. We have proposed a new formula in order to fit all the particle spectra in Pb + Pb by increasing one fitting degree of freedom from Tsallis distribution. This follows the same idea of the transition from the exponential distribution to Tsallis distribution when intermediate p_T data are available in experiments.

According to the results in this paper and [2], we conclude that we can do the systematic analysis of particle spectra with Tsallis distribution in p + p, pA at RHIC and LHC. In the AA collisions at p_T < 10 GeV/c, we can do the same analysis as in p + p and pA at RHIC and LHC. But when we consider Pb + Pb collisions, the Tsallis distribution fails.

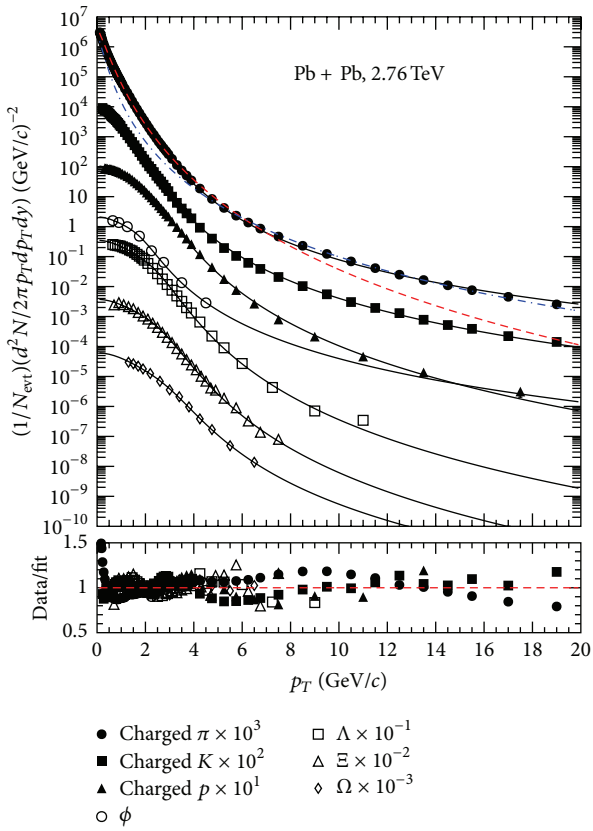

Figure 6: The data are from [33, 53–55] for Pb + Pb at $\sqrt{s_{NN}}$ = 2.76 TeV. The red dashed line is the results fitting the low p_T region and the blue dotted-dashed line is the results fitting the high p_T region using (10). The solid curves are the analytical results with (12). The corresponding fitting parameters and χ^2/ndf are given in Table 2. For a better visualization both the data and the analytical curves have been scaled by a constant as indicated. The ratios of data/fit are shown at the bottom.

Conflict of Interests

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

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