Study of the particle transverse momentum spectra in relativistic heavy ion collisions using the Tsallis statistics

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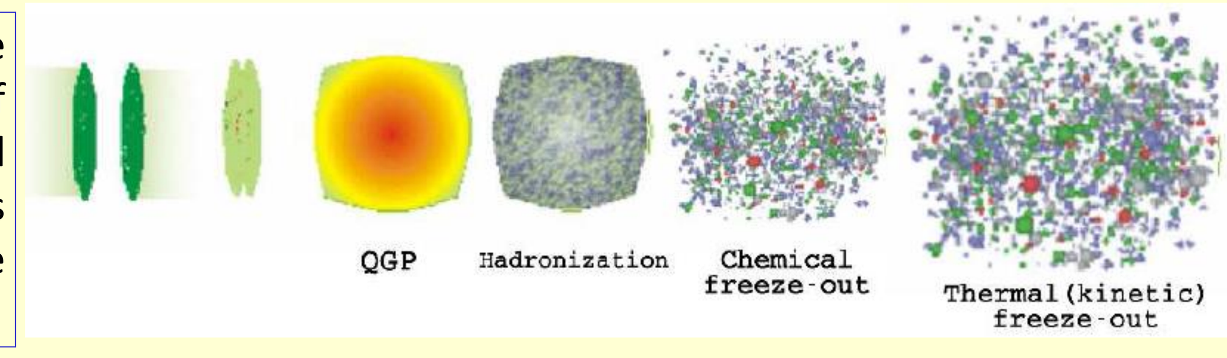
Introduction

High-energy heavy ion collisions provide a unique opportunity to study the nuclear matter under extreme conditions. The hot and dense matter produced in these collisions may evolve through the following scenario: pre-equilibrium, possible formation of QGP, a QGP-hadron gas mixted state, a gas of interacting hadrons, a chemical freeze-out state when the inelastic processes cease and the particle ratios become fixed and, finally, a thermal freeze-out state when the elastic interactions among the produced hadrons cease and the particles stream freely to detectors. Thermal freeze-out conditions (i.e. temperature and transverse flow velocity) can be obtained from the analysis of the transverse momentum distributions for the identified charged hadrons.



The transverse momentum spectra can be described by the Tsallis distribution [1] characterized by a nonextensivity parameter q, which for q → 1 becomes the usual exponential Boltzmann-Gibbs (BG) distribution:

$$h_q(p_T) = C_q \cdot \left[1-(1-q)\frac{p_T}{T}\right]^{\frac{1}{1-q}} \quad \overset{q\to 1}{\Longrightarrow} \quad h(p_T) = C_1 \cdot \exp\left(-\frac{p_T}{T}\right)$$

where Cq is a normalization constant. It is considered that the system formed in the collision is far from thermal equilibrium and the temperature of the fireball fluctuates from event to event (or also in the same event). Such a situation is described by this nonextensive Tsallis statistics.

- q = 1 ➔ no temperature fluctuations
- q > 1 ➔ presence of fluctuations

These fluctuations could be caused mainly by the possible energy transfer between the central fireball (participants) and nuclear fragments passing by without interaction (spectators). Therefore, the effective temperature can be expressed as:

$$T \to T_{eff} = T_0 + (q-1)T_v$$

Where Tv is a new parameter characterizing such an energy transfer (due to the presence of fluctuations) and To is the system temperature.

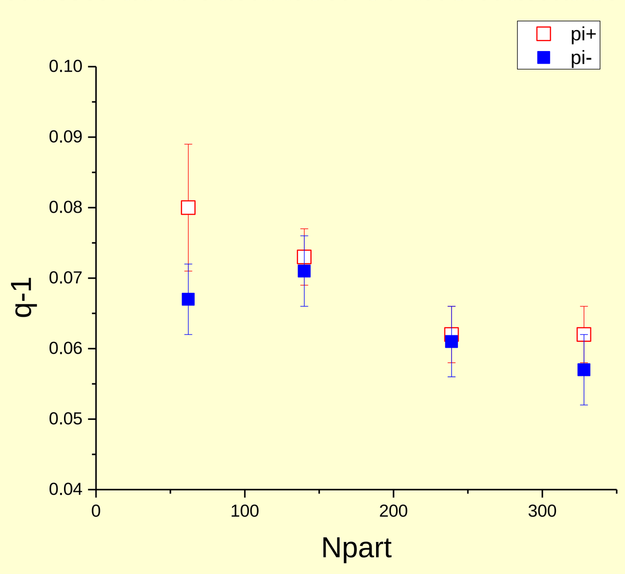
The **Tsallis Blast-Wave (TBW)** [2] modify the standard Blast-Wave model to utilize Tsallis statistics instead of the conventional Boltzmann-Gibbs statistics (the authors changed sources of particle emission from a Boltzmann distribution to a Tsallis distribution)

$$\frac{dN}{m_T dm_T} \propto m_T \int_{-Y}^{+Y} \cosh(y)dy \int_{-\pi}^{+\pi} d\phi \times \int_0^R r dr \left(1+\frac{q-1}{T}(m_T\cosh(y)\cosh(\rho) - p_T\sinh(\rho)\cos(\phi)\right)\right)^{-1/(q-1)}$$

where the left-hand side is invariant differential particle yield at mid-rapidity, m_T and p_T are transverse mass and transverse momentum of the produced particle, q is the parameter characterizing the degree of non-equilibrium, and ρ is the flow profile growing as n-th power along the transverse radial direction (r) from zero at the center of the collisions to βs at the hard-spherical edge (R). Maximum flow velocity is βs= <β> (1+n/2), where n=1 and <β> is the average flow velocity.

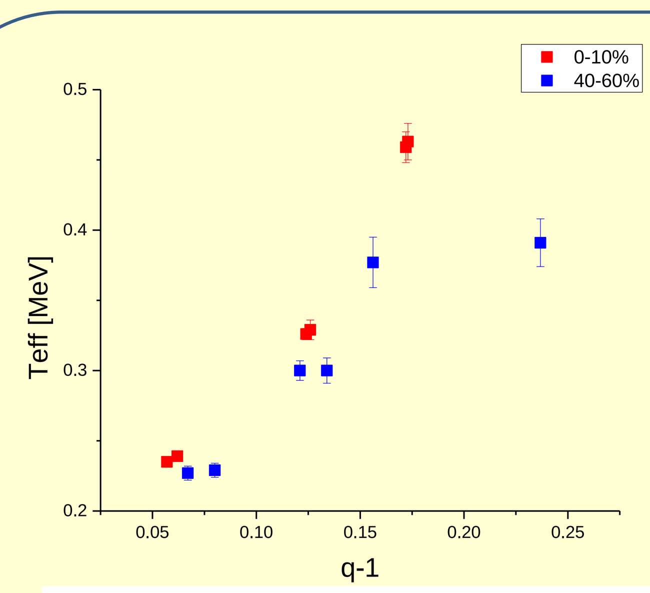
Results

Transverse momentum spectra of charged pions produced in Au+Au collisions at 200 GeV and measured by the BRAHMS experiment [3,4] were fitted using formula 1 and the fit parameter (q-1) is shown as a function of the number of participants.



The non-extensivity parameter is smaller in central AuAu collisions and increases going to peripheral collisions.

The results suggest that the degree of non-equilibrium is higher in peripheral collisions.



The figure shows the effective temperatures as a function of non-extensivity parameter, q-1 (red for 0-10% centrality and blue for 40-60% centrality). The fit results using the formula (2) are shown in the Table 1.

To, the system temperature, is similar within errors for 0-10% and 40-60% centrality and the energy transfer parameter, Tv, is higher in central collisions.

Positive particles

Centrality	To [MeV]	Tv
0-10%	139.6 +/- 26.1	1.65+/-0.18
40-60%	140.5 +/- 27.6	1.28+/-0.22

Negative particles

To [MeV]	Tv
136.3 +/- 21.9	1.62+/-0.14
142.6 +/- 26.6	1.16+/-0.17

Transverse momentum spectra of charged pions from UrQMD code [5] in Au+Au collisions at two energies (plab = 5 GeV/c and 11 GeV/c) were fitted using formula 1 considering different system temperatures . The fit parameter (q-1) for negative and positive pions is shown in Table 2.

P_{lab} = 11 GeV/c

T [MeV]	$(q-1)_{\pi+}$	$(q-1)_{\pi-}$
120	0.162 +/- 0.008	0.182 +/- 0.014
130	0.148 +/- 0.007	0.169 +/- 0.010
140	0.133 +/- 0.006	0.155 +/- 0.010

P_{lab} = 5 GeV/c

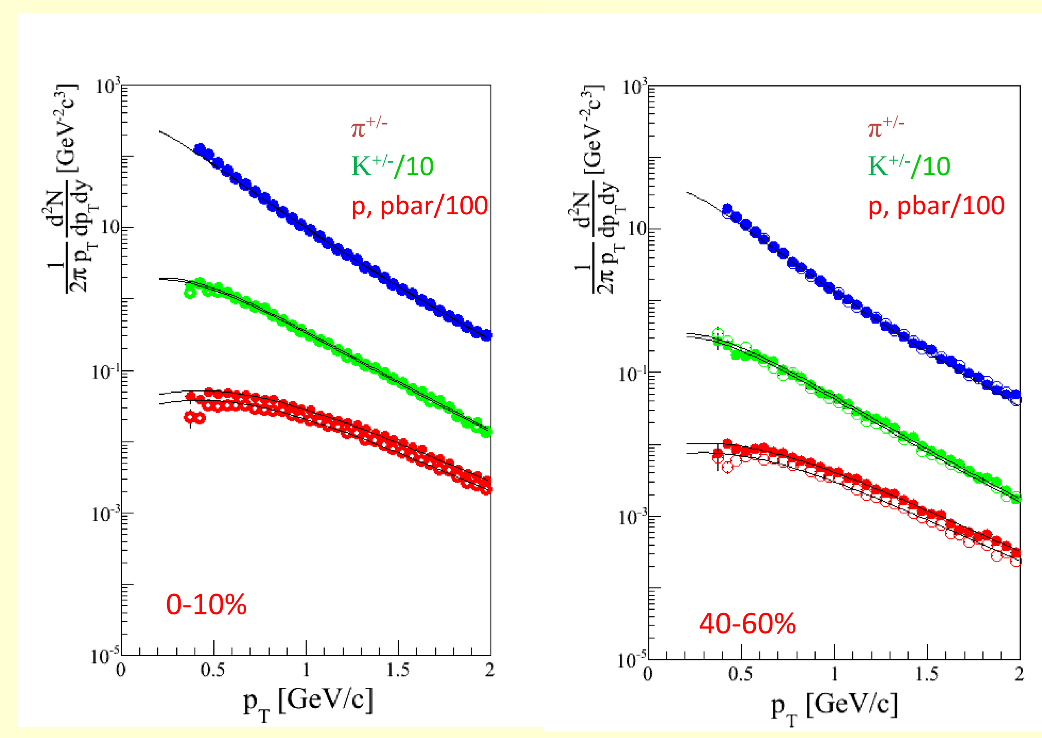
T [MeV]	$(q-1)_{\pi+}$	$(q-1)_{\pi-}$
120	0.171 +/- 0.015	0.198 +/- 0.019
130	0.153 +/- 0.010	0.171 +/- 0.011
140	0.132 +/- 0.009	0.154 +/- 0.011

❑ The non-equlibrium parameter q-1 is smaller for positive pions than the values obtained for negative pions for all the temperatures.

❑(q-1) increases as compared to experimental data Au-Au collisions from RHIC indicating a very non-equilibrated system indicating that the system produced in nucler collisions at lower energies than RHIC top energy is far away from its thermal equilibrim.

Tsallis Blast-Wave fits:

Identified particle transverse momentum spectra in 0-10% central (left) and 40-60% peripheral Au+Au collisions at 200 GeV. The solid lines are the Tsallis BlastWave fits.



TBW Fit parameters:

0-10% T=93+/-2 MeV <β>=0.46+/-0.01 βs=0.69+/-0.01 q-1=0.022+/-0.004

40-60% T=90+/-3 MeV <β>=0.31+/-0.01 βs=0.46+/-0.04 q-1=0.068+/-0.005

❑ The non-equlibrium parameter q-1 is small in central 0-10% Au-Au collisions at 200 GeV suggesting that produced particles approach thermal equilibrium.

❑(q-1) increases by a factor of ~3 from 0.0022 to 0.068 in 40-60% peripheral Au-Au collisions indicating a very non-equilibrated system.

❑ The obtained <β> for produced hadrons (pi, K and p) is about ~0.45c, much smaller than that we obtained from the standard BW (~0.66c).

❑ No centrality dependence of the freeze-out temperature from TBW fits. This trend is in contrast to the conventional BW , where a decrease of temperature was observed.

Conclusions:

- The high value of q reflects high fluctuations in temperature, To. And a system with a higher fluctuation in temperature means the system is far away from its thermal equilibrium. The q parameter obtained from Tsallis fits to the pT spectra is smaller in central 0-10% Au+Au collisions at 200 GeV than in peripheral (40-60% centrality) collisions.
- The system temperature To is similar for the two centralities, but the energy transfer parameter Tv is higher in central collisions.
- The simulated UrQMD data for Au+Au collisions at plab = 5 GeV/c and 11 GeV/c shows that the q parameter increases as the energy decreases.
- Identified particle spectra at RHIC have been analyzed with using Tsallis statistics in Blast-wave description. The results show that in central 0-10% Au-Au collisions at 200 GeV the produced particles approach thermal equilibrium and in 40-60% peripheral Au-Au collisions is formed a very non-equilibrated system.

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