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Hint of pion condensation in proton-proton collisions at the LHC using non-extensive Tsallis statistics

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A study is performed on the possible Bose-Einstein Condensation (BEC) of pions in proton-proton (pp) collisions at $\sqrt{s} = 7$ TeV at the Large Hadron Collider. To have a better understanding, the results of pp systems have been contrasted with the systems produced in Pb-Pb collisions. We studied the temperature and final state multiplicity dependence of the number of particles in the pion condensates. A wide range of multiplicity is considered, covering the hadronic and heavy-ion collisions, using experimental transverse momentum spectra inputs. We observe a clear dominancy of non-extensive parameter q, which measures the degree of non-equilibrium, on the critical temperature and number of particles in the pion condensates.

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1. Introduction

In the final state of the ultra-relativistic collisions, a multitude of particles are produced. Due to the overpopulation of pions in the low momentum region in the final state, the formation of pion Bose-Einstein condensate is a high possibility. However, it is nontrivial to experimentally observe BEC, as the pion spectra get contaminated by resonance decays and a very low $p_{\rm T}$ measrement is a difficult task. Nonetheless, theoretical and phenomenological studies can be done to understand the possible formation of BEC in high-energy collisions. High-temperature BEC is very different from the traditional low-temperature BEC, dealing with extremely high density and different types of interactions. Nevertheless, it is still highly probable that a BEC may form during ultra-relativistic collisions. Several studies have been conducted to explore the formation of BEC in high-energy collisions. In this article, we do a systematic study by taking the pp collision system at $\sqrt{s} = 7$ TeV and estimate the ratio of pions in the BEC to the total number of pions [1].

It has been observed that the transverse momentum spectra in pp collision deviate from the thermalized Boltzmann distribution in the high $p_{\rm T}$ region. However, the Tsallis non-extensive distribution function can fit the $p_{\rm T}$-spectra very well for all $p_{\rm T}$ range. In view of this, we have considered the Tsallis non-extensive statistics to study the pions produced in high energy pp collisions. In Tsallis statistics, the non-extensive parameter (q) denotes the deviation of the system from equilibrium.

2. Formulation

Moving forward, the particle multiplicities can be estimated by the following equation [2],

$$N = \int \frac{d^3x d^3p}{h^3} \frac{g}{exp\left(\frac{\sqrt{p^2+m^2}-\mu}{T}\right) - 1} \simeq V \int \frac{d^3p}{(2\pi)^3} \frac{g}{exp\left(\frac{\sqrt{p^2+m^2}-\mu}{T}\right) - 1}, \tag{1}$$

where g is the degeneracy of the particle, p is the momentum, m is the mass, μ is the chemical potential, T is the temperature, and V is the system's volume.

In the thermodynamic limit [3], $V \longrightarrow \infty$, we can write the above equation with separate terms for $p = 0$ and $p > 0$,

$$N \simeq \frac{g}{exp\left(\frac{m-\mu}{T}\right) - 1} + V \int \frac{d^3p}{(2\pi)^3} \frac{g}{exp\left(\frac{\sqrt{p^2+m^2}-\mu}{T}\right) - 1}$$

$$\Rightarrow N_{\rm total} = N_{\rm condensation} + N_{\rm excited}. \tag{2}$$

Under Tsallis non-extensivity [4], the BE-distribution function changes to,

$$f = \frac{1}{exp_{\rm q}\left(\frac{E-\mu}{T}\right) - 1}. \tag{3}$$

where,

$$\exp_q(x) \equiv \begin{cases} [1 + (q-1)x]^{\frac{1}{q-1}} & \text{if } x > 0 \\ [1 + (1-q)x]^{\frac{1}{1-q}} & \text{if } x \leq 0 \end{cases} \tag{4}$$

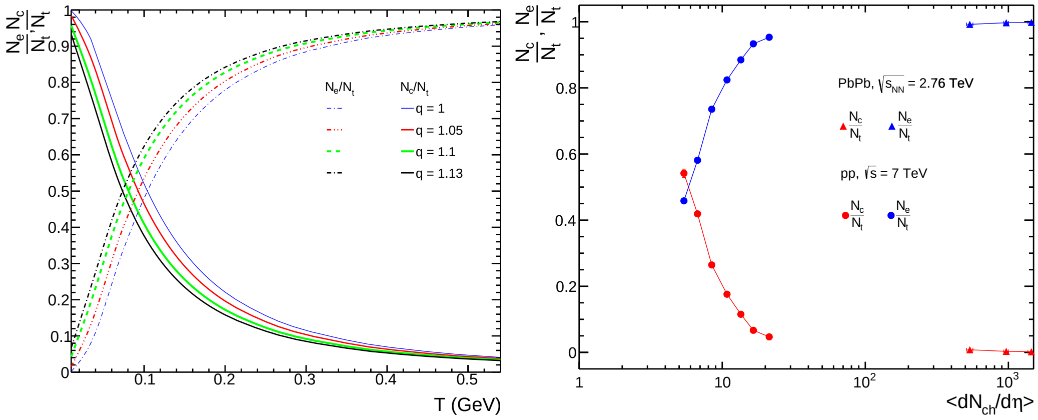

Figure 1: Ratios of number of pions in the condensate to the total number of pions and number of pions in the excited states to the total number of pions as functions of temperature for certain values of non-extensive parameters (left panel) and charged particle multiplicity for pp collision for $\sqrt{s}$ = 7 TeV and for Pb-Pb collision system at $\sqrt{s_{NN}}$ = 2.76 TeV (right panel) [1].

where $x = (E - \mu)/T$, E is the energy of the particle given by $E = \sqrt{p^2 + m^2}$.

Thus, under thermodynamically consistent non-extensivity, Eq. 2 modifies as follows [1];

$$N \simeq \frac{g}{\left[exp_q\left(\frac{m-\mu}{T}\right) - 1\right]^q} + V \int \frac{d^3p}{(2\pi)^3} \frac{g}{\left[exp_q\left(\frac{\sqrt{p^2+m^2}-\mu}{T}\right) - 1\right]^q}. \tag{5}$$

For LHC energies, the chemical potential can be taken as zero. In the limit, $q \longrightarrow 1$, Eq. (3) reduces to the standard Maxwell-Boltzmann distribution function. The Tsallis parameter, T and q appearing in Eq. 4 are extracted from the p_T-spectra of the particle by using Tsallis distribution as a fitting function.

3. Results and discussion

Firstly, we take a theoretical approach to understand the pion BEC. In the left panel of fig.1, we have plotted the ratio of pions in the condensate to the total number of pions and the ratio of pions in the excited states to the total number of pions for certain q values. We see a significant dependency on the non-extensive parameter, q. At a temperature lower than nearly 100 MeV, the number of pions in the condensate dominates. In any case, it is highly feasible that a pion BEC can be formed in the final state of the ultra-relativistic collision, which can have significant consequences on the system dynamics. For a detailed description, please see ref. [1].

Further, by fitting the pion p_T spectra, the Tsallis parameters are extracted [5], which are then used in Eq.5 to estimate the number of pions in the condensate and excited states. In the right panel of fig.1, we have plotted the ratio of pions in the condensate to the total number of pions and the ratio of pions in the excited states to the total number of pions for the pp collision system at $\sqrt{s}$ = 7 TeV and for Pb-Pb collision system at $\sqrt{s_{NN}}$ = 2.76 TeV. We observe a significant fraction of pions is under BEC. In addition, pions dominate the condensate below a charged particle multiplicity $dN_{ch}/d\eta \simeq 6$.

4. Summary

We have attempted to study the possibility of BEC in high energy collisions at TeV energies at the LHC by taking the information from pion transverse momentum spectra. A significant number of pions are found to be in the condensate in the final state of pp collision at $\sqrt{s} = 7$ TeV. Moreover, from the theoretical study, the BEC formation probability is seen to be higher for a system away from equilibrium ($q \neq 1$). Moreover, measurements close to $p_{\mathrm{T}} = 0$ GeV/c with the LHC upgrades would be of greater importance to explore BEC in TeV collisions.

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