Decoding Chemical Potential Effects at the Kinetic Freeze-Out through Tsallis Non-Extensive Statistics at the LHC

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Introduction

At the LHC energies near chemical freeze-out, the chemical potential is expected to be zero due to particles and antiparticles being produced almost in equal numbers. However, considering the same case at the kinetic freeze-out temperature is not trivial. The kinetic freeze-out of particles is a highly complex phenomenon. We argue that there can be a finite total chemical potential at the kinetic freeze-out, and its importance cannot be ignored. Primarily, this study considers the importance of chemical potentials at the kinetic freeze-out stage. During the hadronic phase, several processes may occur, contributing to an imbalance in particle-antiparticle, giving rise to a finite chemical potential (μ). This prompts us to look into the effect of chemical potential in TeV pp collisions at the kinetic freeze-out using the non-extensive Tsallis distribution function. The thermodynamically consistent form of the Tsallis distribution function for non-zero μ is given by [1],

$$\left.\frac{d^2N}{dp_Tdy}\right|_{y=0} = gV\frac{p_Tm_T}{(2\pi)^2}\left[1+(q-1)\frac{m_T-\mu}{T}\right]^{-\frac{q}{q-1}} \tag{1}$$

The four parameters T, V, q and μ in Eqn. 1 have a redundancy for $\mu \neq 0$ .The redundancy is not present when $\mu = 0$. Then, the transverse momentum distribution in terms of modified variables can be written as,

$$\frac{d^2N}{dp_Tdy} = gV_0\frac{p_Tm_T}{(2\pi)^2}\left[1+(q-1)\frac{m_T}{T_0}\right]^{-\frac{q}{q-1}} \tag{2}$$

Please refer to Ref. [1] for a more detailed discussion.

Results and Discussion

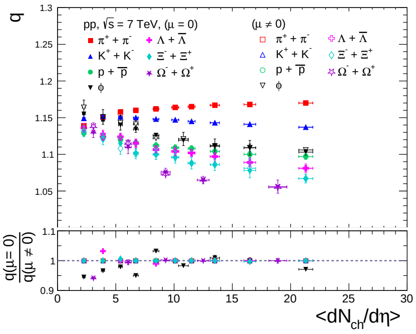

FIG. 1: Comparison of the non-extensive parameter (q) at ($\mu = 0$) and ($\mu \neq 0$) for pp collisions at $\sqrt{s} = 7$ TeV for different final state particles as a function of final state multiplicity [1].

Fig. 1 demonstrates the variation of non-extensive parameter (q) for both the cases $i.e.$ ($\mu = 0$) and ($\mu \neq 0$) as a function of charged particle multiplicity for pp collisions at $\sqrt{s} =$ 7 TeV for different final state particles. The bottom panel depicts a ratio indicating a near-independency of the q-parameter on the chemical potential of the system.

In the left panel of figure 2, we observe that the temperature for all the hadrons increases with increasing charged-particle multiplicity. A mass-ordering trend is observed with

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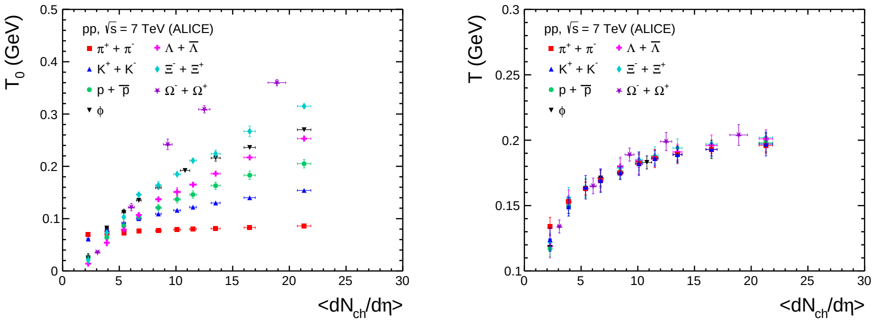

FIG. 2: The left and right panels represent the temperature parameters $T_0(\mu = 0)$ and $T(\mu \neq 0)$ as a function of charged-particle multiplicity for *pp* collisions at $\sqrt{s} = 7$ for different final state particles [1].

systems with heavier mass particles having a higher temperature than lighter mass particles at all charged-particle multiplicities. This corresponds to a mass-dependent differential freeze-out scenario, where particles freeze out at different times, corresponding to different volumes and temperatures for different particle species. However, in the right panel of figure 2, we observe that the kinetic freeze-out temperature for all the particle species investigated in this study seems to be the same when considering a finite chemical potential at the kinetic freeze-out of the produced fireball.

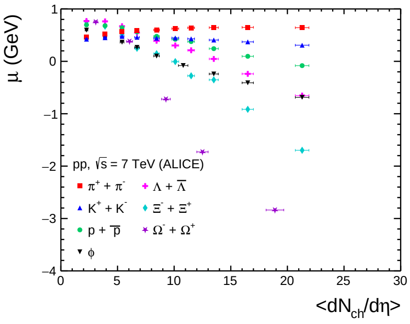

FIG. 3: Chemical potential (μ) as a function of charged-particle multiplicity for *pp* collisions at $\sqrt{s} = 7$ for different final state particles [1].

In figure 3, a non-zero value of the chemical potential at kinetic freeze-out temperature is observed for all the considered particle species. As we move towards systems with massive particles, the chemical potentials move towards a negative value. However, we observe positive chemical potentials for all the charged-particle multiplicity for lighter particles such as π, K, and p. However, in the case of more massive particles, such as baryons, the chemical potential transits from positive to negative as the rate of change of particle multiplicity with respect to pseudo-rapidity increases. As we advance towards higher massive particles, the chemical potential shifts towards a -ve value, which suggests that heavy mass particle production is less favorable.

Acknowledgments

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References

[1] G. S. Pradhan, D. Sahu, R. Rath, R. Sahoo and J. Cleymans, arXiv:2301.04038 [hep-ph].