OPEN ACCESS INTERNATIONAL JOURNAL OF SCIENCE & ENGINEERING

ANALYSING Λ −SPECTRA AT LHC ENERGY 2.76 TeV IN THE LIGHT OF NON-EXTENSIVE STATISTICS

Bhaskar DE
Assistant Professor, Department of Physics, Taki Government College, Taki, West Bengal-743429, India
bhaskar.de@gmail.com

Abstract: **The transverse momentum spectra of secondary heavy and strange baryon, Λ, produced in different central Lead-Lead interactions at 2.76 TeV per nucleon at Large Hadron Collider, have been systematically analyzed theoretically with the help of Tsallis generalized non-extensive statistics to understand various thermodynamical properties of the evolving partonic medium. The findings have been discussed in detail which indicate at the possible formation of a weakly coupled partonic state called, quark-gluon-plasma(QGP).**

Keywords: *Heavy ion collisions, inclusive cross-section.*

I INTRODUCTION

One of the main goals of the nuclear collisions at ultra-relativistic energies is to create a deconfined phase of hadronic constituents, namely partons(quarks and gluons), for a very brief period. As the life-time of such a deconfinedpartonic state is of the nuclear characteristic time (10^{-23} seconds), one has to depend on various indirect signatures to extract different information on the evolution process of such fireball media. The initial nuclear matter consists of mainly the valence quarks --- up and down quarks. But, the nuclear collisions at high energies, produce strange quarks and anti-quarks which subsequently recombine with neighboring quarks and anti-quarks to produce bound states of strange hadrons. As these strange quarks travel through and interact with the hot and dense fireball media before formation of the bound states, the strange hadrons carry significant information on the thermodynamical characteristics of the media and, hence, can be treated as an important indirect probe.

On the other hand, Tsallis generalized statistics[1] has been proven, over the years, a good statistical tool to analyse experimental data emanated from a system which is yet to reach it's equilibrium with properties of presence of long-range correlation and/or presence of event-by-event fluctuations[2-11]. Earlier we had dealt with systematic analyses of lighter mesons and baryons like pi-meson, K-meson, protons/anti-proton etc. produced in Lead-Lead (Pb-Pb) collisions at centre-of-mass energy 2.76 TeV per nucleon with a theoretical approach based on Tsallis non-extensive statistics. However, all those analyses were confined mainly to low and intermediate transverse momentum-region. Now-a-days, lots of data from high transverse momenta have started pouring in, which is actually the regime of perturbative Quantum Chromodynamics (pQCD). In the present study, we have taken up the task to verify the applicability of Tsallis non-extensive statistics to heavier baryons in this regime. So, we will be, systematically, analyzing here, the transverse momentum spectra of one of the heavier baryons, lambda hyperon (Λ), produced in different central Pb-Pb interactions at LHC energy 2.76 TeV per nucleon.

The organization of the present work is as follows: In the next section(Section II) we will present a brief sketch of the present theoretical approach whereas in Section III we will deliver the results and a detailed discussion on the outcome of our analysis. The last section will be preserved for concluding remarks.

II OUTLINE OF THE THEORETICAL APPROACH

The generalized expression for number of states, n_i, available for energy E_i in a non-equilibrated system is given by inTsallis-Boltzmann(TB) distribution (neglecting the chemical potential)

$$n_i(E_i) = \left[1 + (q-1)\frac{E_i}{T}\right]^{\frac{1}{1-q}} \quad (1)$$

Where T is the local effective temperature of the system and q is the non-extensive index. As $q \to 1$ the above equation yields the usual Boltzmann distribution for equilibrated system

$$n_i(E_i) = e^{-\frac{E_i}{T}} \quad (2)$$

The non-extensive distribution for a system having fermions(+) or bosons(-) is given by

$$n_i(E_i) = \left[\left(1 + (q-1)\frac{E_i}{T}\right)^{\frac{1}{q-1}} \pm 1\right]^{-1} \quad (3)$$

However, for high energy the difference between eqn.(1) and eqn.(3) becomes negligible. So, we can use eqn.(1) for all the varieties.

For thermodynamical consistencies, the generalized distribution, given in eqn.(1), is to be constrained by[5]

$$\sum_i n_i^q = N \quad (4)$$

where N is the total number of the particles. In the large volume limit the summation on the left hand side of the last equation is replaced by

$$\sum_i \to V \int \frac{d^3p}{(2\pi)^3}$$

where V is the volume of the system and p is the momentum of the particle.

Hence, the expression for total number of particles is given by

$$N = gV \int \frac{d^3p}{(2\pi)^3}\left[1 + (q-1)\frac{E}{T}\right]^{\frac{q}{1-q}} \quad (5)$$

with g being the degeneracy factor.

Now, the Lorentz invariant momentum distribution of the particles will be of the form

$$E\frac{dN}{d^3p} = \frac{gV}{(2\pi)^3} E\left[1 + (q-1)\frac{E}{T}\right]^{\frac{q}{1-q}} \quad (6)$$

And, the energy, E, of the particle is given by

$$E = m_T \cosh y \quad (7)$$

with $m_T = \sqrt{m_0^2 + p_T^2}$ being the transverse mass where m_0 is the rest mass and p_T is the transverse momentum; whereas $y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$ is a Lorentz invariant entity, called rapidity, with p_z being the longitudinal momentum. In the non-relativistic limit, y gives simply the velocity of the particle. Since, $d^3p = 2\pi p_T\, dp_T\, dy$, the invariant yield will have the form

$$\frac{dN}{dy\, p_T\, dp_T} = \frac{gV}{(2\pi)^2} m_T \cosh y \left[1 + (q-1)\frac{m_T \cosh y}{T}\right]^{\frac{q}{1-q}} \quad (8)$$

If the analysis is confined in the central rapidity region $(y = 0)$, the last equation will be of the form

$$\frac{dN}{dy\, p_T\, dp_T} = \frac{gV}{(2\pi)^2} m_T \left[1 + (q-1)\frac{m_T}{T}\right]^{\frac{q}{1-q}} \quad (9)$$

Further, the local effective temperature is correlated with the non-extensive parameter, q, and the empirical relationship of the correlation is given by[3]

$$T = T_0[1 - c(q-1)] \quad (10)$$

where T_0 is the critical temperature for phase transition, called Hagedorn temperature and the parameter c depends on (i) the fluctuation of the temperature around T_0 due to a stochastic process in any selected region of the system and (ii) some energy transfer between the selected region and the rest of the system.

Combining equation (9) along with equation(10) we get the final working formula to analyze the experimental data on transverse momentum spectra and it is given by

$$\frac{dN}{dy\, p_T\, dp_T} = C\, m_T \left[1 + (q-1)\frac{m_T}{T_0(1 - c(q-1))}\right]^{\frac{q}{1-q}} \quad (11)$$

with $C = \frac{gV}{2\pi^2} = \text{constant}$.

III RESULTS AND DISCUSSION

The working formula (eqn. 11) has been fitted with experimental data on transverse momentum spectra of secondary lambda hyperons produced in different central Pb-Pb collisions at centre-of-mass energy 2.76 TeV per nucleon. The entire analysis was confined to the high-p_T region. The values of different parameters obtained from fits have been provided in tabular form in Table 1 whereas the fits have been presented in pictorial form in Fig. 1.

Table 1 : Values of different parameters obtained from fits

Centrality	Number of Participant Nucleons	Non-extensive Index (q)	Haggedorn Temperature (T_0 in MeV)	c	Local Effective Temperature (T in MeV)	Reduced chi-square
0-5%	382.8	1.090 ± 0.003	181 ± 16	0.259 ± 0.009	177	1.615
5-10%	329.7	1.094 ± 0.002	178 ± 10	0.425 ± 0.007	171	1.148
10-20%	260.5	1.095 ± 0.002	186 ± 23	0.825 ± 0.006	172	1.174
20-40%	157	1.105 ± 0.006	183 ± 17	1.20 ± 0.08	160	1.053
40-60%	69	1.109 ± 0.006	183 ± 18	1.6 ± 0.3	151	0.488
60-80%	23	1.125 ± 0.003	180 ± 11	2.2 ± 0.2	131	0.463
80-90%	7.5	1.126 ± 0.002	176 ± 15	2.7 ± 0.4	115	0.171

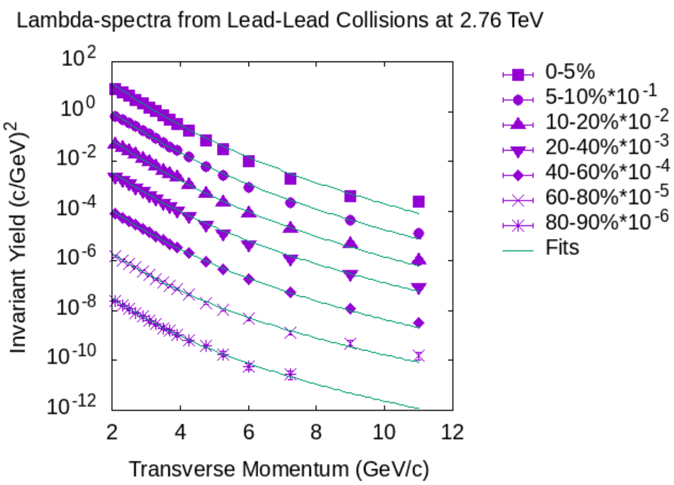

Figure 1 Plots of transverse momentum spectra of Λ produced in Lead-Lead interactions at centre-of-mass-energy 2.76 TeV/nucleon. The experimental data are taken from Ref.[12]. The solid lines are the fits obtained on the basis of equation (11).

The centrality of nuclear interactions is measured as a function of impact parameter which is the distance between the centers of the two nuclei. So, viewing from the transverse plane, the overlapped region between two nuclei will be almost circular for most central collisions whereas this shape will be deformed to nearly elliptical or almond shaped for non-central interactions. The number of participant nucleons (N_{part}) or the number of wounded nucleons will also decrease from central to peripheral collisions since the volume of the overlapped region decreases gradually from most central to peripheral collisions. Those nucleons, which do not take part in the interactions, are called spectator nucleons. The average values of N_{part} for various centrality classes are also provided in Table I which have been obtained from Ref.[8].

The fits can be treated as successful from the moderate values of reduced chi-square given in the last column of Table 1. The nature of the variation of different parameters with respect to centralities in terms of number of participant nucleons are provided graphically in Fig. 2 to Fig. 5.

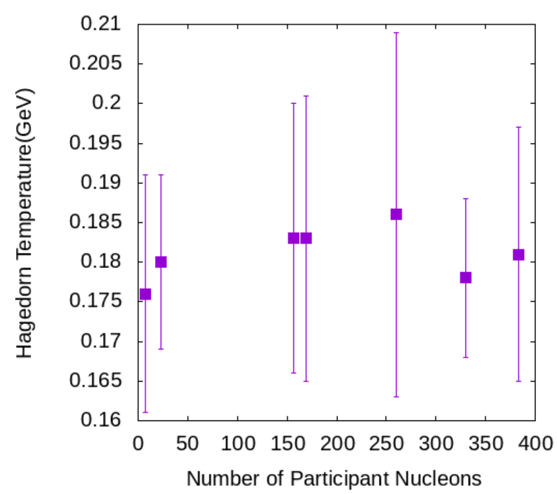

Figure 2 The plot of the Hagedorn Temperature, obtained from fits, as a function of number of participant nucleons.

The obtained values of Hagedorn temperature (Figure 2) or the Critical temperature for phase transition exhibit nearly constant behavior with respect to centralities and the average value, from the present analysis, is around 180 MeV. This value is in close vicinity of the expected theoretical value around 140 MeV(mass of the pi-meson) and is in agreement with the findings of the different previous analyses[10,11,13,14].

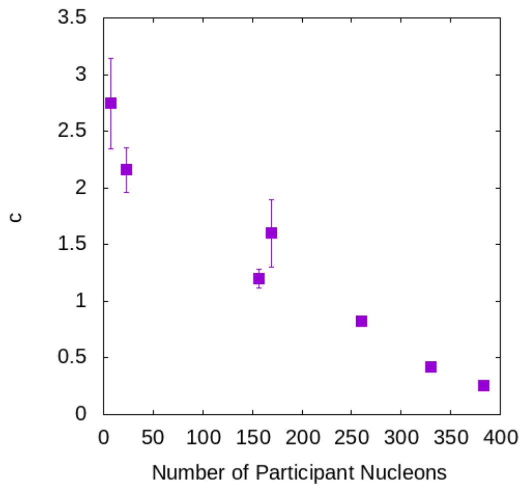

Figure 3 The variation of the parameter, c, ***with respect to centrality.***

Figure 3 depicts the variation of the parameter, c, with respect to number of participant nucleons. It is observed that this particular parameter decreases with increment in number of participant nucleons. As the number of participant nucleons increases from peripheral to central regions, the number of spectator nucleons gradually decreases. Hence, the probability of transfer of energy from the interaction zone to the non-interacting spectator nucleons gradually decreases. This effect is reflected in the decreasing trend of c with respect to number of participant nucleons.

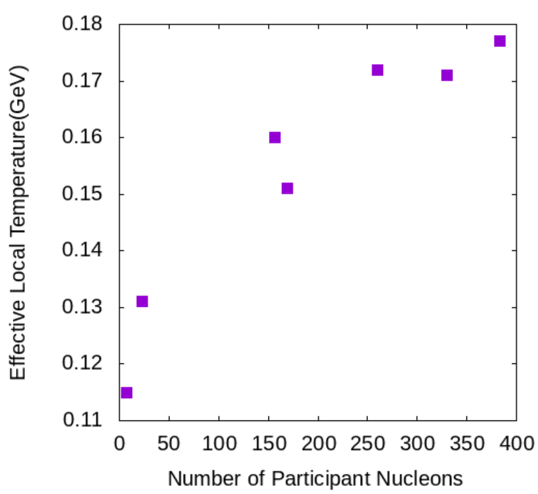

Figure 4Thevariation of the effective local temperature with respect to centrality.

The values of effective local temperature of the interaction zone, from where the detected particles have been emitted, can be calculated using equation (10). The same has been pictorially presented in Fig. 4 as a function of centralities. It is observed that the local temperature increases with centrality. As the centrality increases, the loss of energy due to transfer from interaction zone to spectator nucleons reduces; and hence more energy is available in the interaction region which subsequently increases the local temperature and for most central collisions it is in close vicinity of the critical value for phase transition as is evidenced from the comparison of Fig. 2 and Fig. 4.

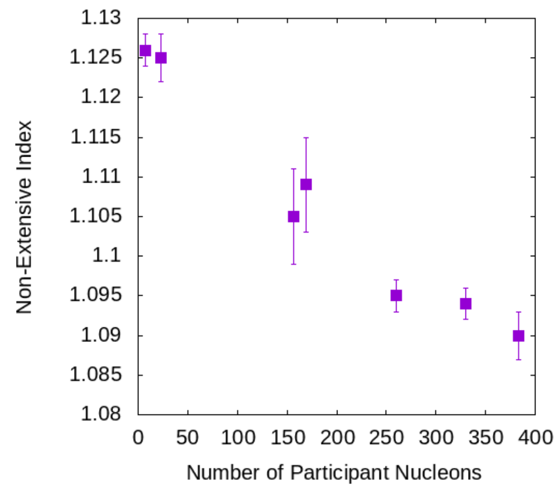

Figure 5Thevariation of the non-extensive index with respect to centrality.

The nature of centrality dependence of the non-extensive index,q, has graphically been provided in Fig. 5. $q$decreases as number of participant nucleons increases and is in anti-correlation with the local temperature. The non-extensive index is inversely proportional to the heat capacity at constant volume for a thermal system, and this heat capacity is directly proportional to the number of participant nucleons[3]. Hence, increment in number of participant nucleons ensure more equilibrated thermal system as it is evidenced from Figure 4 where the local temperature approaches the critical temperature for phase transition in central collisions where the numbers of participant nucleons are quite high. However, despite the local temperature lies very near to critical temperature for central collisions, the value of q still lies away from it's equilibrium value 1. This is because of the fact that the present analysis have been confined to high transverse momentum region where perturbative Quantum Chromodynamics dominates the particle mechanism process as the highly energetic partons experience hard scatterings while travelling through the produced medium followed by fragmentation and hadronization. Besides, multigluon fluctuations also contribute to the high value of q[15,16]. And all these features can be treated as the evidence of formation of weakly coupled partonic state, namely quark gluon plasma(QGP) in central Pb-Pb interactions at LHC energy 2.76 TeV per nucleon.

V CONCLUSIONS

In the present analysis we have dealt, systematically, with$\Lambda-$spectra produced in various central Pb-Pb interactions in high transverse momentum region at LHC energy 2.76 TeV/nucleon in the light of Tsallis non-extensive statistics. It is observed that the adopted theoretical approach reproduces the experimental data quite successfully which indicates at the applicability of Tsallis generalized statistics even in the high transverse momentum region where pQCD dominates the particle production mechanism. It is also observed from the behavior of different parameters that in central collisions, the local temperature reaches nearly to the critical temperature for phase transition from bound hadrons to a soup of hadronic constituents. However, the non-extensive index does not reach to it's equilibrium value, and this can be attributed to the presence of a deconfined QCD matter called QGP, which in course of it's interaction with the highly energetic partons gives rise to non-extensivity to the evolving thermal system.

REFERENCES

[1] C. Tsallis, "Possible Generalization of Boltzmann-Gibbs Statistics", Jour. Stat. Phys. (479) , Volume 52,1988.

[2] C. Beck, "Nonextensive methods in turbulence and particle physics",Physica A (209), Volume 305, 2002.

[3] G. Wilk and Z. Wlodarczyk, "Multiplicity fluctuations due to the temperature fluctuations in high-energy nuclear collisions", Phys. Rev. C (054903), Volume 79, 2009.

[4] T. S. Biro and E. Molnar, "Non-extensive statistics, relativistic kinetic theory and fluid dynamics", Eur. Phys. Jour. A (172), Volume 48, 2012.

[5] J. Cleymans and D. Worku, "The Tsallis distribution in proton–proton collisions at $\sqrt{s}$= 0.9 TeV at the LHC", Jour. Phys. G (025006), Volume 39, 2012.

[6] B. De et al, "Non-Extensive thermodynamics, heavy ion collisions and particle production at RHIC energies", Int. Jour. Mod. Phys. E (1687), Volume 16, 2007.

[7] B. De et al, "Analyzing nonextensivity of η-spectra in relativistic heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV ", Int. Jour. Mod. Phys. A (1239), Volume 25, 2010.

[8] B. De, "Non-extensive statistics and a systematic study of meson-spectra at LHC energy $\sqrt{s_{NN}} = 2.76$ TeV" , Eur. Phys. Jour. A (70), Volume 50, 2014.

[9] B. De, "Non-extensive statistics and understanding particle production and kinetic freeze-out process from p_T-spectra at 2.76 TeV" , Eur. Phys. Jour. A (138), Volume 50, 2014.

[10] G. Wilk and Z. Wlodarczyk, "Power laws in elementary and heavy-ion collisions - A story of fluctuations and nonextensivity?", Eur. Phys. Jour. A (299), Volume 40, 2009.

[11] I. Sena and A. Deppman, "Systematic analysis of p_T-distributions in $p + p$collisions", Eur. Phys. Jour. A (17), Volume 49,2013.

[12] B. Abelev et al (ALICE Collaboration), " K_s^0 and Λ production in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV", Phy. Rev. Lett. (222301), Volume 111,2013.

[13] S. Ejiri, "Lattice QCD at finite temperature", Nucl. Phys. B Proc. Suppl. (19), Volume 94, 2001.

[14] K. Miura et al, "Phase diagram evolution at finite coupling in strong coupling lattice QCD", Phys. Rev. D (074034), Volume80,2009.

[15] S. Dash and D. P. Mahapatra, "Transverse Momentum Distribution in Heavy Ion Collision using q-Weibull Formalism" , arXiv:1611.04025, 2016

[16] I. Vitev, "Testing the theory of QGP-induced energy loss at RHIC and the LHC ", Phys. Lett. B (38), Volume 639, 2006.