

Insights into the Transverse Spectra of Jets at LHC: A Particle Collision Study

Emma Williams

Department of Biochemistry, University of Oxford, Oxford, United Kingdom

ABSTRACT

Transverse momentum spectra of charged jets from two different experiments --- proton-lead collisions at 5.02 TeV and lead-lead collisions at 2.76 TeV --- have been analysed systematically, alongwith a feedback from proton-proton collisions, in the light of Tsallis non-extensive statistics and multiplicity as well as temperature fluctuations. The analytical results hint at possible occurrence of a deconfined or weakly coupled partonic state in systems having relatively high participant nucleons.

KEYWORDS: Relativistic Heavy Ion Collision, Inclusive Cross Section.

I. INTRODUCTION

The high energy nuclear collisions produce a system of high temperature and density where a state of deconfined elementary hadronic constituents is believed to exist for a very brief period ($\sim 10^{-23}$ seconds). However, there is no direct or external tool to probe such a short-living system. Partons, which are formed at the early stage of the collision through hard scatterings, propagate through such a hot and dense expanding system. Ultimately they fragment into jets of hadrons. However, these fragmentation processes get modified due to presence of parton-medium interactions during the partonic course of motion through the rest of the medium. Hence, these hadronic jets provide an indirect probe to get insights of the properties of the thermalized fireball produced in such high energy nuclear collisions.

Tsallis generalized non-extensive statistics [1, 2] is, now-a-days, being applied to understand various thermodynamical aspects of such a system having non-markovian nature due to possible presence of long-range correlations and/or having signatures of event-by-event fluctuations [3-31]. We, in our earlier endeavours, had utilised a theoretical approach, inspired by non-extensive statistics, to extract information from different particle-spectra at RHIC as well as at LHC energies [32-35]. This particular phenomenological approach differs from other existing models/approaches in the sense that it requires some feedback, in terms of multiplicity fluctuations, from nucleon-nucleon collisions to understand nucleon-nucleus and nucleus-nucleus interactions.

In the present study, the same approach has, once again, been employed for a systematic analysis of transverse momentum spectra of charged jets produced at LHC energies. In our previous analyses, the studies were confined only to a single energy [34,35]. But, in the present work, the data from lead-lead(Pb+Pb) collisions at $\sqrt{s_{NN}} = 2.76$ TeV ($\sqrt{s_{NN}}$ is the colliding energy per nucleon in the center of mass frame) well as those from proton-lead(P+Pb) collisions at 5.02 TeV have been taken into account.

The organization of the present work is as follows: a brief outline of the theoretical approach, to be used in the present study, has been presented in next section. The obtained results and a detailed discussion on it have been provided in Section 3. And the last section is preserved for the concluding remarks.

II. OUTLINE OF THE THEORETICAL APPROACH

The main working formula, inspired by Tsallis non-extensive statistics, to analyse the transverse momentum spectra of a particular detected secondary is given by [35]

$$\frac{d^2N}{p_T dp_T dy} = \frac{dN}{dy} \frac{1}{\int_0^\infty \frac{\gamma(m_T - v_T p_T)}{\left[1 + (q-1) \frac{\gamma(m_T - v_T p_T)}{T_{eff}}\right]^{\frac{q}{q-1}} \pm 1} p_T dp_T} \frac{\gamma(m_T - v_T p_T)}{\left[1 + (q-1) \frac{\gamma(m_T - v_T p_T)}{T_{eff}}\right]^{\frac{q}{q-1}} \pm 1} \quad (1)$$

where dN/dy is the particle-yield per unit rapidity in the rapidity interval Δy , $m_T = \sqrt{m_0^2 + p_T^2}$ is the transverse mass with m_0 being the rest mass of the detected secondary, p_T being the transverse momentum, v_T is the average transverse velocity, $\gamma = \frac{1}{\sqrt{1-v_T^2}}$ and T_{eff} is the effective temperature of the interaction region and q

is the non-extensive index. Besides, the - sign is for bosons and the + sign is for fermions.

If the distribution is given in pseudo-rapidity interval ($\Delta\eta$), the last equation will be of the form

$$\frac{d^2N}{p_T dp_T d\eta} = \frac{dN}{d\eta} \frac{p_T}{m_T} \frac{1}{\int_0^\infty \frac{\gamma(m_T - v_T p_T)}{\left[1 + (q-1) \frac{\gamma(m_T - v_T p_T)}{T_{eff}}\right]^{\frac{q}{q-1}} \pm 1} p_T dp_T} \times \frac{\gamma(m_T - v_T p_T)}{\left[1 + (q-1) \frac{\gamma(m_T - v_T p_T)}{T_{eff}}\right]^{\frac{q}{q-1}} \pm 1} \quad (2)$$

Further, it was observed earlier that the parameters T_{eff} and q are strongly correlated, even if they were set free [5, 32]. So, these two parameters along with the average multiplicity can phenomenologically be correlated by the following relationships [5, 33-35]:

$$T_{eff} = T_{kin}(1 - c(q - 1)) \quad (3)$$

$$\frac{\langle N \rangle - n_0 N_{part}}{\langle N \rangle} = c(q - 1) \quad (4)$$

where T_{kin} is the kinetic freeze-out temperature, $\langle N \rangle$ is the average multiplicity of the detected secondary produced in nucleus-nucleus(A+A) interactions and n_0 is the same for P + P interactions, and N_{part} is the number of participant nucleons for a particular central nuclear interactions. However, in case of proton-nucleus(P+A) collisions, the multiplicity is not linearly dependent on N_{part} , rather there is a clear indication of logarithmic dependence [36-38]. So, to deal with P+A collisions, the modified expression for multiplicity fluctuation will be

$$\frac{\langle N \rangle - n_0 \ln N_{part}}{\langle N \rangle} = c(q - 1) \quad (5)$$

If the studied rapidity regions and it's widths($\Delta\eta$) are same or nearly same for both the cases, one can replace $\langle N \rangle$ and n_0 with the corresponding rapidity yields($\frac{dN}{d\eta}$). In the present study, the data, under consideration for all the systems, are available from the central rapidity region($|\eta| < 0.5$ with $\Delta\eta = 1$); and hence, we can set $\langle N \rangle = \frac{dN}{d\eta}$.

Here, equation (3) takes into account the fluctuation in effective temperature while that in multiplicity by equation(4) for A+A collisions and by equation(5) for P+A interactions. These two types of fluctuations are mutually correlated through the factor $c(q - 1)$ where c is the parameter which takes care of the fluctuations of the system arising out of a stochastic process in any selected region of the system and/or of some energy transfer between the selected region and the rest of the system [5]. However, for the sake of calculational simplicity it is assumed that c is independent of any flow-velocity.

Furthermore, in our previous study [34], it was observed that, in some cases, the product term($n_0 N_{part}$), in eqn.(4), exceeds $\langle N \rangle$ which makes c negative. But, negativity of c violates the assumption that the transfer of energy takes place only from the interaction region to the spectators of the non-interacting nucleons [5]. Hence, to keep the physical assumptions, associated with the above constraints, valid, the ‘-’ sign was replaced with ‘~’ in our previous works [34, 35], so that only the magnitude of the fluctuation between $\langle N \rangle$ and $n_0 N_{part}$ or $n_0 \ln N_{part}$ could be taken into account; and the modified forms of the second constraint are given by,

$$\frac{\langle N \rangle \sim n_0 N_{part}}{\langle N \rangle} = c(q - 1) \quad (6)$$

$$\frac{\langle N \rangle \sim n_0 \ln N_{part}}{\langle N \rangle} = c(q - 1) \quad (7)$$

Equation(2) along with equations(3) & equation(6) or equation(7) forms the basis of our theoretical analysis of the transverse momentum spectra from nucleus-nucleus and nucleon-nucleus collisions.

III. RESULTS AND DISCUSSION

Table 1: Values of fitted parameters with respect to the experimental data on charged jet-spectra produced in

P + P collision at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ & 5.02 TeV

$\sqrt{s_{NN}}$ (TeV)	n_0	q	T_{eff} (GeV)	v_T (in units of velocity of light)	Reduced χ^2
2.76	2.2±0.3	1.151±0.002	0.080±0.003	0.11±0.02	0.252
5.02	14±1	1.162±0.003	0.079±0.002	0.18±0.02	0.020

Table 2: Values of fitted parameters with respect to the experimental data on charged jet-spectra at different centralities of Pb + Pb collisions at LHC energy $\sqrt{s_{NN}} = 2.76 \text{ TeV}$

Centrality	N_{part}	$\langle N \rangle$	v_T (in units of velocity of light)	T_{kin} (GeV)	c	q	T_{eff} (GeV)	Reduced χ^2
0-10%	356	985±17	0.49±0.07	0.116±0.004	1.332±0.006	1.154	0.092	0.206
10-30%	223	635±12	0.38±0.06	0.113±0.005	1.418±0.005	1.160	0.087	0.094
30-50%	107	304±8	0.34±0.03	0.111±0.003	1.394±0.005	1.162	0.086	0.032
50-80%	32.5	93±6	0.29±0.03	0.109±0.002	1.419±0.003	1.163	0.084	0.049

Table 3: Values of fitted parameters with respect to the experimental data on charged jet-spectra at different centralities of P + Pb collisions at LHC energy $\sqrt{s_{NN}} = 5.02 \text{ TeV}$

Centrality	N_{part}	$\langle N \rangle$	v_T (in units of velocity of light)	T_{kin} (GeV)	c	q	T_{eff} (GeV)	Reduced χ^2
0-20%	13.8	31±1	0.20±0.03	0.106±0.002	1.162±0.004	1.160	0.086	0.042
20-40%	10.4	25.2±0.4	0.20±0.02	0.108±0.002	1.850±0.003	1.163	0.075	0.013
40-60%	7.42	18.3±0.3	0.19±0.02	0.118±0.004	3.098±0.006	1.172	0.055	0.064
60-80%	4.81	13.0±0.3	0.22±0.03	0.129±0.003	3.853±0.005	1.176	0.041	0.092
80-100%	2.94	8.8±0.1	0.20±0.02	0.132±0.005	4.033±0.003	1.177	0.038	0.142

Figure-1(a) is the graphical representation of charged jet spectra produced in P +P interactions at 2.76 & 5.02 TeV fitted with basic working formula given in eqn.(2) without the constraints given in eqn.(3) and eqn.(6)/eqn.(7). The values of different parameters obtained from the fits are presented in Table-1, where n_0 denotes the average multiplicity per unit rapidity in P+P interactions. Generally, pi-mesons are the most abundant variety among the different secondaries produced in high energy nuclear interactions. So, for simplicity, we have used $m_0 = 0.14 \text{ GeV}$ throughout our present analysis along with choosing the proper sign for bosonic variety in the final working formula.

A point is to be noted here. The directly measured data on charged jet spectra for P+P interactions at 5.02 TeV is not readily available. So, we have used the data provided in Ref. [39] as reference P+P spectrum for 5.02 TeV which were obtained by scaling down the measured charged jets at 7 TeV. Besides, to maintain uniformity, we have used only those data which were obtained with the resolution parameter $R = 0.2$ for all the interactions throughout our present study.

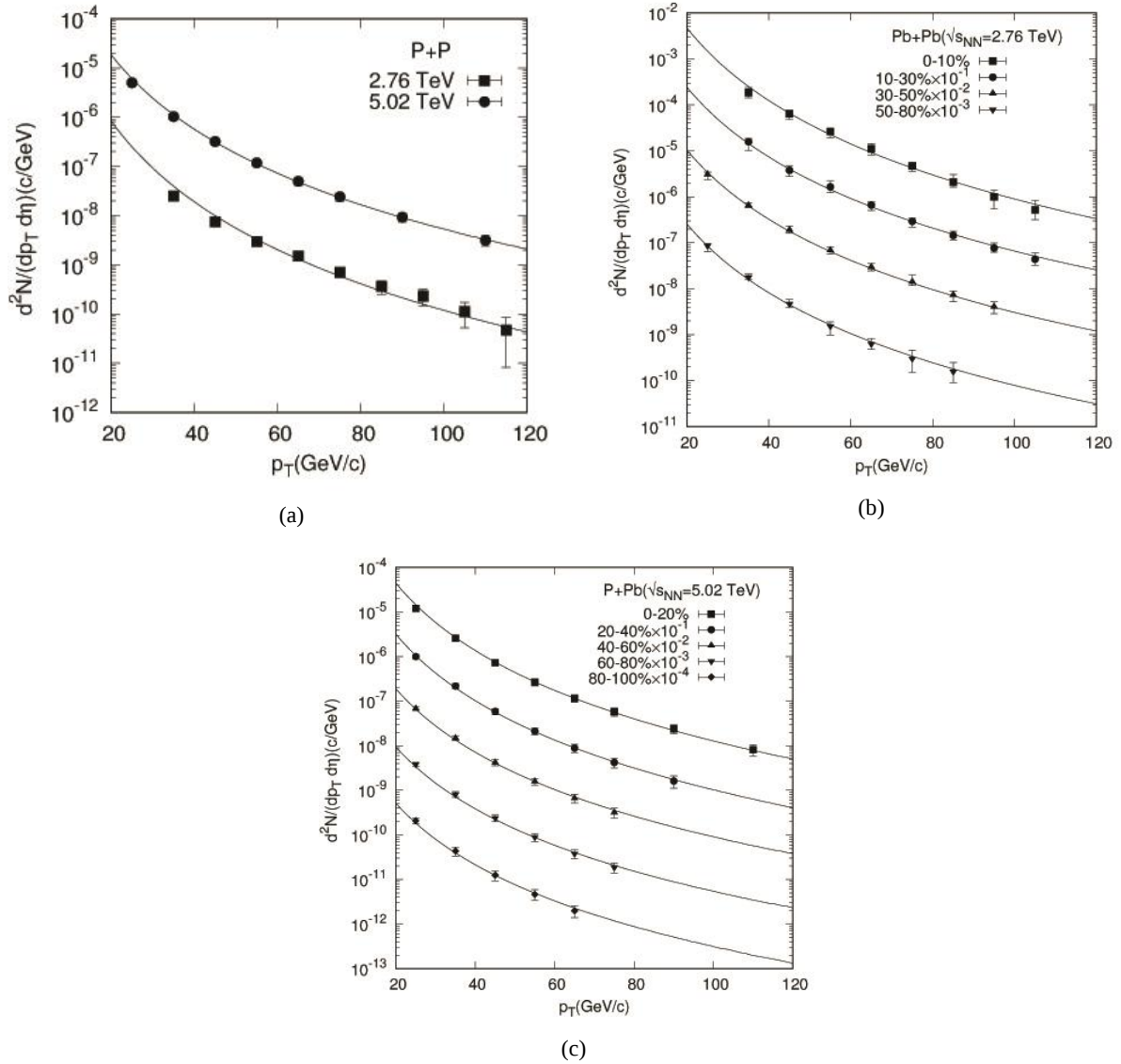


Figure 1: Plots of transverse momentum spectra of charged jets produced in P+P, P+Pb and Pb+Pb collisions at LHC energies. The filled symbols represent the experimental data points [39-41] while the solid curves provide the fits on the basis of nonextensive approach (eqn.(2)).

Fig.1(b)-Fig.1(c) depict the fits to the experimental data on charged jet spectra as a function of transverse momentum in different central Pb+Pb collisions at 2.76 TeV and P+Pb collisions at 5.02 TeV at LHC. All these fits have, now, been obtained on the basis of equation(2) along with the constraints given in eqn(3) & eqn.(6) or equation(7). Table-2-Table-3 represent the values of various parameters obtained from the fits. The performance of the chosen approach can be treated as quite satisfactory on the basis of obtained values of reduced-chi-square given in Table-1-Table-3.

The behaviour of four parameters, which carry very important information on the dynamical properties of the fireballs produced in nuclear interactions, have been depicted graphically in Figure-2. The behaviour of kinetic freeze-out temperature, T_{kin} , obtained for different collision systems is given in Fig.2(a). It exhibits weak dependence on system-size for $N_{part} \geq 10$, but, for $N_{part} < 10$, it shows an increasing tendency when one goes from central to peripheral collisions. A constant T_{kin} at higher N_{part} -regions may be regarded as the occurrence of a common phase state, namely quark-gluon plasma, for different interacting systems [27]. In one of our previous studies, T_{kin} was found to execute a bit constant behaviour for production of some of the secondaries like $K^\pm$ (K-mesons) and $P/\bar{P}$ at 2.76 TeV with respect to N_{part} , although, the magnitude had a strong dependence on mass of the detected secondary [35]. But, such a constant behaviour was absent while pi-mesons were under consideration, where it had exhibited a decreasing pattern with increasing N_{part} . However, if the effect of the transverse flow was neglected, the constant behaviour was visible even for pi-mesons [34].

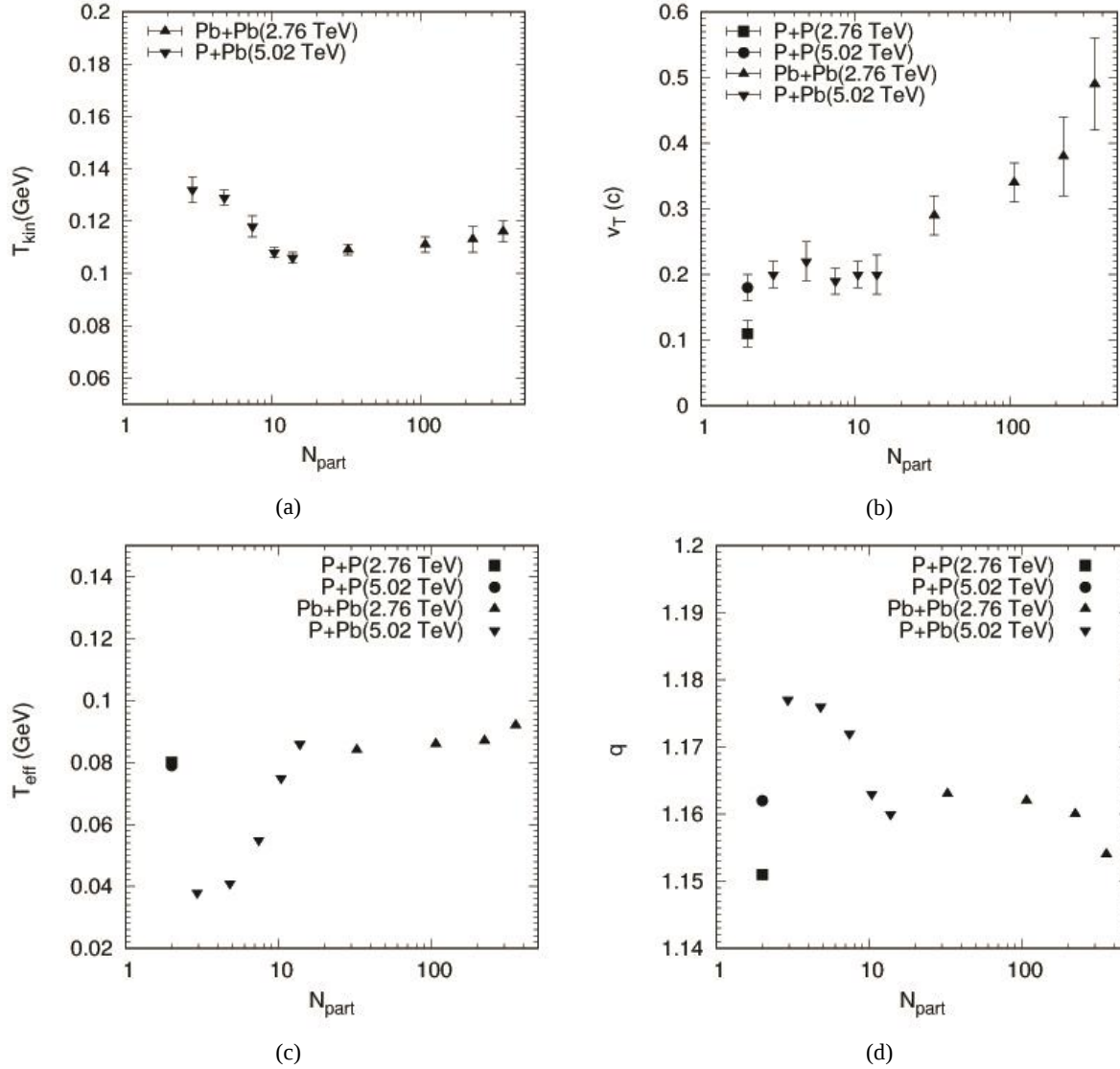


Figure 2: Plots of the kinetic freeze-out temperature, T_{kin} , average transverse flow, v_T , effective Temperature, T_{eff} , and the nonextensive parameter, q , obtained from the fits of charged jet-spectra for various centralities of P+Pb and Pb+Pb collisions at two different LHC energies.

The nature of average transverse flow v_T as a function of number of participant nucleons has been graphically depicted in Fig.2(b). It appears that v_T has a relatively weaker dependence on N_{part} for P+Pb interactions whereas a strong centrality dependence is observed for Pb+Pb collisions. Besides, the magnitude of v_T is high for Pb+Pb systems compared to those for P+Pb systems. The findings for Pb+Pb interactions at 2.76 TeV are in accordance with our previous work [35] where identified hadron spectra for the same were dealt with. However,

the presence of transverse flow is quite prominent in P+P collisions compared to our previous study [35]. Somewhat similar observation was made in [42] while dealing with identified hadron spectra of high multiplicity from P+P collisions at an wide range of LHC energy with a variant of Blast Wave model.

The graphs in Fig.2(c)-2(d) provide the dependence of the effective temperature T_{eff} and the non-extensive parameter q on the number of participant nucleons. There is a sharp rise in the value of T_{eff} when one goes from peripheral to central P+Pb collisions whereas a steep fall is observed for q in that region ($N_{part} < 10$). However, for $N_{part} \geq 10$, the variations in T_{eff} and q are less prominent, just like T_{kin} . So, once again, all these observations point toward the possible existence of a common phase state of weakly coupled partons in different central Pb+Pb collisions. However, there is a slight decrement in the q -value for most central Pb+Pb collisions. In central Pb+Pb collisions, jet quenching suppresses the multiplicity at high p_T -region due to loss of energy of the energetic partons, associated with jet, moving through the rest of the medium [40].

If we assume $\langle N' \rangle$ is the multiplicity in absence of jet quenching and $\langle N \rangle$ in presence of that, then the ratio of the multiplicity fluctuations for these two systems will be

$$\frac{\frac{\langle N' \rangle - n_0 N_{part}}{\langle N' \rangle}}{\frac{\langle N \rangle - n_0 N_{part}}{\langle N \rangle}} = \frac{c'(q' - 1)}{c(q - 1)} \quad (8)$$

where q' and q are the non-extensive parameters for the systems without jet-quenching and with jet-quenching respectively. Hence, as $\langle N' \rangle > \langle N \rangle$, $c(q - 1) < c'(q' - 1)$. So, in the presence of the medium-effect, i.e. jet quenching, either or both the parameters q and c may exhibit low values along with high T_{eff} and low multiplicity at high transverse momenta.

From the behaviours of all the four parameters, depicted in Figure 2, one common scenario has emerged and that is the sudden change in the pattern of the N_{part} -dependence of the parameters when one moves from P+P to Pb+Pb via P+Pb colliding systems. The lack of existence of a general systematic trend of the parameters over the entire N_{part} -interval indicates at the different underlying physics associated with different colliding systems and a discussion in this regard is presented below:

The modification of jet-spectra(jet-quenching) in A+A collisions at large- p_T is the result, in main, of the interaction between the moving jet and the 'hot' partonic medium formed due to heavy ion collisions. The highly energetic moving color charge in a jet can lose energy, in two ways, while travelling through a thermal QCD medium having a characteristic energy scale of the order of local equilibrium temperature(~ 100 - 200 MeV) : (i) Elastic collisions with the constituents of the plasma and (ii) Medium-induced emission of multiple gluons or gluon Bremsstrahlung [43-46]. The latter one plays the dominant role at extremely high energy, like LHC, and at high- p_T regime [43-52]. This radiative energy loss effectively reduces the energy of the parton moving through the QGP. The lost energy is redistributed in small- and medium- p_T hadrons [52, 53], which, subsequently, broaden and soften the hadron-spectra. The fractional energy loss by the jet, due to medium-induced radiation, has a sub-linear-dependence on number of participant nucleons and, hence, is more prominent in central collisions [52, 54, 55]. This energy loss of the partonic jets, before fragmentation into bunch of hadrons, leaves its traits on the hadronic spectra at high p_T -region($p_T \geq 20$ GeV/c) through (i) high- p_T hadron suppression and (ii) imbalance in back-to-back high- p_T dijet azimuthal correlation [43, 56-62]. Besides, it was observed in the studies of gold-gold(Au+Au) interactions at RHIC energy that the fluctuation in induced-gluon multiplicity reduces the attenuation due to jet quenching [63].

Apart from the radiative loss due to presence of hot QCD matter, high- p_T regime of the hadron spectra in A+A collisions experiences another attenuation from the Cold Nuclear Matter(CNM) energy loss, excluding other types of CNM effects like dynamical nuclear shadowing, Cronin Effect, etc. which have significance at low- and intermediate- p_T regions [64, 65]. The CNM effect arises, mainly, due to (i) modified parton distribution function of the colliding heavy ions and (ii) initial-state and final-state radiative losses of the jets before and after the hard collisions respectively. This final-state radiative energy loss is similar to that of final-state loss in QGP, though, the magnitude is small compared to latter one [66]. The collision between a light nucleus and a heavy ion, like P+Pb at LHC and D+Au at RHIC, provide a good probe to understand the detailed mechanism and the effect of CNM, where the presence of a hot final state effect is quite unlikely. Hence, the physical scenario, in such experiments, is expected to be completely different from that in A+A interactions. This is reflected in the different subfigures of Figure 2, which are pictorial representation of centrality-dependence of different parameters obtained from the present analyses. The parameters like T_{kin} , T_{eff} and q exhibit strong centrality dependencies, whereas, the transverse flow(v_T) has relatively weaker centrality dependence for P+Pb interactions at 5.02 TeV compared to Pb+Pb interactions at 2.76 TeV. Besides, in the present analysis, we found that the values of T_{kin} , T_{eff} and q for most central P+Pb interactions(0-20% and 20-40%) are in close vicinity of those for Pb+Pb interactions. This is somewhat in agreement with the views that a thermalized medium might have been formed in P+Pb interactions at LHC energy due to observation of some sort of collective effects similar to those observed in ultrarelativistic nuclear-nuclear collisions [67, 68].

No such medium-effect is expected to affect the spectra in P+P interactions as the environment, here, can be treated as nearly vacuum. But, as far as the formation of a deconfined phase is concerned, there are predictions in support of a occurrence of a possible phase transition in high multiplicity P+P interactions at very high energy($\sim$ TeV) from the signatures like enhanced production of multi-strange hadrons, multiplicity-dependence of p_T -spectra, transverse baryon flow, near-side long-range angular correlations etc. [69-76]. In the present work, the obtained values of the parameters, T_{eff} and q for P+P collisions at studied LHC energies lie in the neighbourhood of those for Pb+Pb and most central P+Pb interactions which may indicate at some sort of similarities between the systems evolved from different kind of interactions. However, on the basis of present formalism, there is not much scope to throw light on this particular aspect.

The values of another parameter, c , have been given in Table-2-Table-3. It is observed that c , on an average, increases as N_{part} decreases for a particular interaction at a definite energy. Similar tendency was observed for the meson-spectra while going from central to peripheral collisions at 2.76 TeV [35]. A possible explanation for

this particular behavior is as follows: The parameter c is directly proportional to the amount of energy transferred from the interaction region to the non-interacting spectators nucleons [5]. As one goes from central to peripheral interactions, the number of spectator nucleons increases as well as the amount of energy absorbed by them also increases. Hence, this increment in c -values from central to peripheral collisions. Furthermore, as discussed earlier in this section, the absence of hot-medium-effect in P+Pb interactions at 5.02 TeV [39] may be reflected in high values of c compared to those obtained for Pb + Pb interactions. However, the difficulties in proper identification of c still remain.

IV. CONCLUSION

In the present study, we have dealt with, systematically, charged jet spectra produced in different central Pb+Pb and P+Pb interactions at 2.76 TeV and 5.02 TeV respectively along with P+P collisions on the same footing. A variant of Tsallis non-extensive statistics is in use in the current analysis along with incorporation of temperature as well as multiplicity-fluctuations in the main working formula. Earlier this phenomenological approach was applied to analyse identified hadron-spectra at 2.76 TeV with moderate success [34, 35]. In the present case, the numbers of data-points, at times, are too sparse, especially for peripheral collisions. Still, the low values of reduced-chi-square indicate that the present approach can be treated as compatible to reproduce the data even at high transverse momenta region, and, hence, to extract important information on the thermodynamical state of the system.

The charged jet spectra, on the basis of present analyses, indicates at the presence of stronger transverse flow for P+P interactions compared to our earlier studies on identified hadron-spectra [35]. Besides, the systematic analyses also reveal that the effect of transverse flow increases if more and more nucleons involve in the interaction region. The parameters T_{eff} and q exhibit expected anticorrelation. However, both the parameters alongwith T_{kin} show, on an average, weak dependence on N_{part} and, hence, on system size for $N_{part} \geq 10$. This could be treated as the signal for occurrence of a weakly-coupled or deconfined partonic state. However, for $N_{part} < 10$, such an observation could not be made. This region belongs to mostly different central P+Pb collisions. The relatively high values of non-extensive parameter, in this region, indicate that the system is far away from thermal equilibrium and hence involve large degree of fluctuations as the number of participant nucleons is significantly low here. Besides, the jet-quenching, caused due to medium-induced gluon radiation and/or Cold Nuclear Matter energy loss by the partonic jets, may leave its traits on the parameters q and c by lowering them in central Pb + Pb interactions. Moreover, despite the absence of any general trend of the parameters with respect to N_{part} , some sort of similarities are observed between most central P+Pb interactions and Pb+Pb interactions in mid-central to peripheral regions along with P+P interactions at LHC energies. However, we are dealing with a 4-parameter working formula and the data available, at times, cannot be treated as sufficient enough. So, it will be hard to draw any conclusion on the basis of the present observations. Once sufficient data on jet-spectra over the entire high- p_T region for central as well as peripheral collisions are available, a more rigorous study can be made with the present formalism to obtain further insights, in detail, on the characteristics of the media evolved in P+P, P+A and A+A interactions.

V. REFERENCES

- [1] C. Tsallis, "Possible Generalization of Boltzmann-Gibbs Statistics", Jour. Stat. Phys., vol. 52, pg. 479, 1988
- [2] C. Tsallis, Lecture Notes on Physics - Nonextensive Statistical Mechanics and It's Applications 560/2001, 3 (Springer, 2001).
- [3] C. Beck, "Nonextensive methods in turbulence and particle physics", Physica A, vol. 305, pg.209, 2002.
- [4] G. Wilk and Z. Wlodarczyk, "Interpretation of the Nonextensivity Parameter q in Some Applications of Tsallis Statistics and Lévy Distributions", Phys. Rev. Lett., vol. 84, pg. 2770, 2000.
- [5] G. Wilk and Z. Wlodarczyk, "Multiplicity fluctuations due to the temperature fluctuations in high-energy nuclear collisions", Phys. Rev. C, vol. 79, pg. 054903, 2009.
- [6] T. S. Biro, K. Urmosy and Z. Schram, "Thermodynamics of composition rules", Jour. Phys. G, vol. 37, pg. 094027, 2010.
- [7] T. S. Biro and E. Molnar, "Non-extensive statistics, relativistic kinetic theory and fluid dynamics", Eur. Phys. Jour. A, vol. 48, pg.172, 2012.
- [8] M. Biyajima et al, "Modified Hagedorn formula including temperature fluctuation: Estimation of temperatures at RHIC experiments", Eur. Phys. Jour. C, vol. 48, pg. 597, 2006.
- [9] W. M. Alberico and A. Lavagno, "Non-extensive statistical effects in high-energy collisions", Eur. Phys. Jour. A, vol. 40, pg. 313, 2009.
- [10] A. Lavagno, P. Quarati and A. M. Scarfone, "Consistent nonadditive approach and nuclear equation of state", Braz. Jour. Phys., vol. 39, pg. 457, 2009.

- [11] G. Kaniadakis, “Relativistic entropy and related Boltzmann kinetics”, Eur. Phys. Jour. A, vol. 40, pg. 275, 2009.
- [12] T. Kodama and T. Koide, “Dynamical origin of power spectra”, Eur. Phys. Jour. A, vol. 40, pg. 289, 2009.
- [13] T. Wibig, “Constraints for non-standard statistical models of particle creations by identified hadron multiplicity results at LHC energies”, Eur. Phys. Jour. C, vol. 74, pg. 2966, 2014.
- [14] G. Ran & D. Jiulin, “Energy distribution and energy fluctuation in Tsallis statistics”, Physica A, vol. 391, pg. 2853, 2012.
- [15] P. Van, G. G. Barnafoldi, T. S. Biro and K. Urmossy, “Nonadditive thermostatics and thermodynamics”, Jour. Phys. Conf. Ser. Vol. 394, pg. 012002, 2012.
- [16] K. Urmossy, T. S. Biro, G. G. Barnafoldi and Z. Xu, “ v_2 of charged hadrons in a ‘soft + hard’ model for PbPb collisions at $\sqrt{s} = 2.76$ A TeV”, arXiv:hep-ph/1501.05959.
- [17] I. Sena and A. Deppman, “Systematic analysis of p_T -distributions in p+p collisions”, Eur. Phys. Jour. A, vol. 49, pg. 17, 2013.
- [18] L. Marques, E. Andrade-II and A. Deppman, “Nonextensivity of hadronic systems”, Phys. Rev. D, vol. 87, pg. 114022, 2013.
- [19] A. Deppman, “Thermodynamics with fractal structure, Tsallis statistics, and hadrons”, Phys. Rev. D, vol. 93, pg. 054001, 2016.
- [20] J. Cleymans, “Systematic properties of the Tsallis distribution: Energy dependence of parameters in high energy p-p collisions”, Phys. Lett. B, vol. 723, pg. 351, 2013.
- [21] M. D. Azmi and J. Cleymans, “The Tsallis distribution at large transverse momenta”, Eur. Phys. Jour. C, vol. 75, pg. 430, 2015.
- [22] T. Bhattacharyya et al, “Radial flow in non-extensive thermodynamics and study of particle spectra at LHC in the limit of small ($q - 1$)”, Eur. Phys. Jour. A, vol. 52, id 30, 2016.
- [23] M. Rybczynski, Z. Włodarczyk and G. Wilk, “On the possibility of q-scaling in high energy production processes” Jour. Phys. G, vol. 39, pg. 095004, 2012.
- [24] O. Ristea et al, “Study of the freeze-out process in heavy ion collisions at relativistic energies”, Jour. of Phys. Conf. Ser., vol. 420, pg. 012041, 2013.
- [25] P. K. Khandai et al, “System size dependence of hadron p_T spectra in p+p and Au+Au collisions at $\sqrt{s} = 200$ GeV”, Jour. of Phys. G, vol. 41, pg. 025105, 2014.
- [26] D. Thakur et al, “Indication of a Differential Freeze-Out in Proton-Proton and Heavy-Ion Collisions at RHIC and LHC Energies”, Adv. High Ener. Phys., vol. 2016, id 4149352, 2016.
- [27] H. R. Wei, F. H. Liu and R. A. Lacey et al, “Disentangling random thermal motion of particles and collective expansion of source from transverse momentum spectra in high energy collisions”, Jour. Phys. G, vol. 43, pg. 125102, 2016.
- [28] H. R. Wei, F. H. Liu and R. A. Lacey et al, “Kinetic freeze-out temperature and flow velocity extracted from transverse momentum spectra of final-state light flavor particles produced in collisions at RHIC and LHC”, Eur. Phys. Jour. A, vol. 52, pg. 102, 2016.
- [29] A. Parvan, “Ultrarelativistic transverse momentum distribution of the Tsallis statistics”, Eur. Phys. Jour. A, vol. 53, id 53, 2017.
- [30] A. Parvan et al, “Systematic comparison of Tsallis statistics for charged pions produced in pp collisions”, Eur. Phys. Jour. A, vol. 53, pg. 102, 2017.
- [31] A. Bialas, “Tsallis $p_\perp$ distribution from statistical clusters”, Phys. Lett. B, vol. 747, pg. 190, 2015.
- [32] B. De et al, “Non-Extensive thermodynamics, heavy ion collisions and particle production at RHIC energies”, Int. Jour. Mod. Phys. E, vol. 16, pg. 1687, 2007.
- [33] 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, vol. 25, pg. 1239, 2010.
- [34] 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, vol. 50, pg. 70, 2014.
- [35] 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 vol. 50, 138, 2014.
- [36] Y. V. Kovchegov and A. H. Mueller, “Gluon production in current-nucleus and nucleon-nucleus collisions in a quasi-classical approximation”, Nucl. Phys. B, vol. 529, pg. 451, 1998.
- [37] A. Dumitru and L. D. McLerran, “How protons shatter colored glass”, Nucl. Phys. A, vol. 700, pg. 492, 2002.
- [38] L. D. McLerran and M. Praszalowicz, “Fluctuations and the rapidity dependence of charged particles spectra in fixed centrality bins in pA collisions”, Annal. Phys., vol. 372, pg. 215, 2016.
- [39] J. Adam et al (ALICE Collaboration), “Centrality dependence of charged jet production in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, Eur. Phys. Jour. C, vol. 76, pg. 271, 2016.

- [40] J. Adam et al (ALICE Collaboration), “Measurement of jet suppression in central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV”, Phys. Lett. B, vol. 746, pg. 1, 2015.
- [41] B. Abelev et al (ALICE Collaboration), “Measurement of charged jet suppression in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV”, Jour. High. Ener. Phys., vol. 03, pg. 013, 2014.
- [42] P. Ghosh et al, “Indication of transverse radial flow in high-multiplicity proton–proton collisions at the Large Hadron Collider”, Jour. Phys. G, vol. 41, pg. 035106, 2014.
- [43] D. d’Enterria, “Jet Quenching”, arXiv: nucl-ex/0902.2011.
- [44] N. Armesto et. al., “Comparison of jet quenching formalisms for a quark-gluon plasma “brick”” Phys. Rev. C, vol. 86, pg. 064904, 2012.
- [45] G. Y. Qin, “Theory of jet quenching in ultra-relativistic nuclear collisions”, Nucl. Phys. A, vol. 931, pg. 165, 2014.
- [46] J. Ghiglieri, G. D. Moore & D. Teaney, “Jet-medium interactions at NLO in a weakly-coupled quark-gluon plasma”, Jour. High. Ener. Phys., vol. 2016, issue 03, id 095, 2016.
- [47] M. Gyulassy & X. N. Wang, “Multiple collisions and induced gluon bremsstrahlung in QCD”, Nucl. Phys. B, vol. 420, pg. 583, 1994.
- [48] R. Baier et al, “Radiative energy loss of high energy quarks and gluons in a finite-volume quark-gluon plasma”, Nucl. Phys. B, vol. 483, 291, 1997.
- [49] R. Baier et al, “Radiative energy loss and $p_{\perp}$ -broadening of high energy partons in nuclei”, Nucl. Phys. B, vol. 484, 265, 1997.
- [50] B. G. Zakharov, “Fully quantum treatment of the Landau-Pomeranchuk-Migdal effect in QED and QCD”, JETP Lett., vol. 63, pg. 952, 1996.
- [51] B. G. Zakharov, “Radiative energy loss of high-energy quarks in finite-size nuclear matter and quark-gluon plasma”, JETP Lett., vol. 65, pg. 615, 1997.
- [52] I. Vitev, “Testing the theory of QGP-induced energy loss at RHIC and the LHC”, Phys. Lett. B, vol. 639, pg. 38, 2006.
- [53] I. Vitev, “Large angle hadron correlations from medium-induced gluon radiation”, Phys. Lett. B, vol. 630, pg. 78, 2005.
- [54] M. Gyulassy, “The QGP Discovered at RHIC”, arXiv:nucl-th/0403032.
- [55] I. Vitev, “Theoretical developments in heavy and light flavor energy loss”, Jour. Phys. G, vol. 30, pg. S791, 2004.
- [56] M. Gyulassy & M. Plumer, “Jet quenching in dense matter”, Phys. Lett. B, vol. 243, pg. 432, 1990.
- [57] X. N. Wang & M. Gyulassy, “Gluon shadowing and jet quenching in A+A collisions at $\sqrt{s} = 200A$ GeV”, Phys. Rev. Lett, vol. 68, pg. 1480, 1992.
- [58] D. A. Appel, “Jets as a probe of quark-gluon plasmas”, Phys. Rev. D, vol. 33, pg. 717, 1986.
- [59] J. P. Blaizot & L. D. McLerran, “Jets in expanding quark-gluon plasmas”, Phys. Rev. D, vol. 34, pg. 2739, 1986.
- [60] G. Aad et al [ATLAS Coll.], “Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS Detector at the LHC”, Phys. Rev. Lett., vol. 105, pg. 252303, 2010.
- [61] S. Chatrchyan et al [CMS Coll.], “Observation and studies of jet quenching in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV”, Phys. Rev. C, vol. 84, pg. 024906, 2011.
- [62] Y. J. Lee, “Jet Quenching at RHIC and the LHC”, Jour. of Phys. Conf. Series, vol. 446, pg. 012001, 2013.
- [63] M. Gyulassy, P. Levai & I. Vitev, “Jet tomography of Au+Au reactions including multi-gluon fluctuations”, Phys. Lett. B, vol. 538, pg. 282, 2002.
- [64] C. G. Yaldo, ‘Estimating Cold Nuclear Matter Effects Using Jets In P-Pb Collisions At $\sqrt{s_{NN}} = 5.02$ TeV With The Alice Detector’ (2015). Wayne State University Dissertations.1302. http://digitalcommons.wayne.edu/oa_dissertations/1302.
- [65] Z. B. Kang, I. Vitev & H. Xing, “Effects of cold nuclear matter energy loss on inclusive jet production in p+A collisions at energies available at the BNL Relativistic Heavy Ion Collider and the CERN Large Hadron Collider”, Phys. Rev. C, vol. 92, pg. 054911, 2015.
- [66] I. Vitev, “Non-Abelian energy loss in cold nuclear matter” Phys. Rev. C, vol. 75, pg. 064906, 2007.
- [67] K. Tywoniuk, “Is there jet quenching in pPb?”, Nucl. Phys. A, vol. 926, pg. 85, 2014.
- [68] J. Kamin, “Hot and cold nuclear matter effects in p–Pb collisions at the LHC”, Eur. Phys. Jour. Web of Conf., vol. 95, pg. 03018, 2015.
- [69] ALICE Collb., “Enhanced production of multi-strange hadrons in high-multiplicity proton–proton collisions”, Nature Phys., vol. 13, pg. 535, 2017.
- [70] ALICE Collb., “Femtoscropy of pp collisions at $\sqrt{s} = 0.9$ and 7 TeV at the LHC with two-pion Bose-Einstein correlations”, Phys. Rev. D, vol. 84, pg. 112004, 2011.

- [71] CMS Collb., “Observation of long-range, near-side angular correlations in proton-proton collisions at the LHC” Jour. High Ener. Phys., vol. 2010, issue 09, id 091, 2010.
- [72] CMS Collb., “Measurement of Bose-Einstein correlations in pp collisions at $\sqrt{s} = 0.9$ and 7 TeV”, Jour. High Ener. Phys., vol. 2011, issue. 05, id 029, 2011.
- [73] T. Alexopoulos et al, “Evidence for hadronic deconfinement in $\bar{p}$ -p collisions at 1.8 TeV”, Phys. Lett. B, vol. 528, pg. 43, 2002.
- [74] P. Levai & B Muller, “Transverse baryon flow as possible evidence for a quark-gluon-plasma phase”, Phys. Rev. Lett., vol. 67, pg. 1519, 1991.
- [75] L. Van Hove, “Multiplicity dependence of p_t spectrum as a possible signal for a phase transition in hadronic collisions”, Phys. Lett. B, vol. 118, pg. 138, 1982.
- [76] J. D. Bjorken, “Energy Loss of Energetic Partons in Quark - Gluon Plasma: Possible Extinction of High p_T Jets in Hadron - Hadron Collisions” FERMILAB-Pub-82/59-THY, 1982.