ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

IJESRT

INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY

# A SYSTEMATIC STUDY OF TRANSVERSE SPECTRA OF JETS AT LHC ENERGIES

**Bhaskar De**
Department of Physics, Taki Government College, Taki-743429, West Bengal, India

**DOI**: 10.5281/zenodo.1207003

## 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, along with 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]

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

where $^{dN}/_{dy}$ is the particle-yield per unit rapidity in the rapidity interval $\Delta y$, $m_T=\sqrt{m_0^2+p_T^2}$ 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

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

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]:

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

$$\frac{<N>\ -n_0\,N_{part}}{<N>}=c(q-1) \quad (4)$$

where $T_{kin}$ is the kinetic freeze-out temperature, $<N>$ 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

$$\frac{<N>\ -n_0\,\ln N_{part}}{<N>}=c(q-1) \quad (5)$$

If the studied rapidity regions and it's widths($\Delta\eta$) are same or nearly same for both the cases, one can replace $<N>$ 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 $<N>=\frac{dN}{d\eta}$.

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($n_0N_{part}$), in eqn.(4), exceeds $<N>$ 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 $< N >$ 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,

$$\frac{< N > \sim n_0\, N_{part}}{< N >} = c(q-1) \tag{6}$$

$$\frac{< N > \sim n_0\, \ln N_{part}}{< N >} = c(q-1) \tag{7}$$

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 TeV & 5.02 TeV***

| $\sqrt{s_{NN}}$ (TeV) | $n_0$ | $q$ | $T_{eff}$(GeV) | $v_T$ (in units of velocity of light) | Reduced $\chi^2$ |
|---|---|---|---|---|---|
| 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 TeV***

| Centrality | $N_{part}$ | $< N >$ | $v_T$ (in units of velocity of light) | $T_{kin}$ (GeV) | $c$ | $q$ | $T_{eff}$ (GeV) | Reduced $\chi^2$ |
|---|---|---|---|---|---|---|---|---|
| 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 |

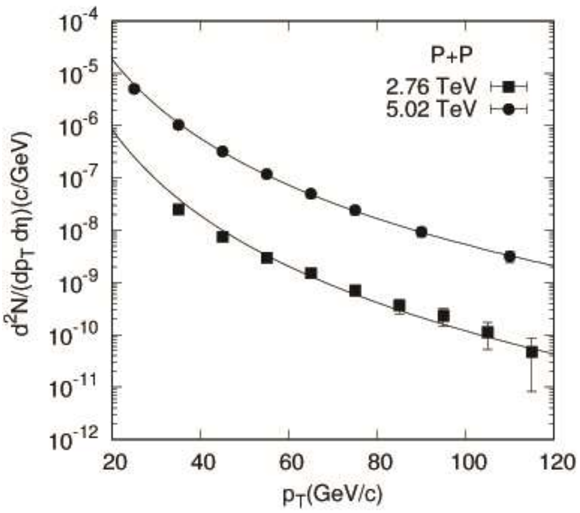
***Table 3: Values of fitted parameters with respect to the experimental data on charged jet-spectra at different centralities of P + Pb collisions at LHC energy $\sqrt{s_{NN}}$ = 5.02 TeV***

| Centrality | $N_{part}$ | $< N >$ | $v_T$ (in units of velocity of light) | $T_{kin}$ (GeV) | $c$ | $q$ | $T_{eff}$ (GeV) | Reduced $\chi^2$ |
|---|---|---|---|---|---|---|---|---|
| 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 |

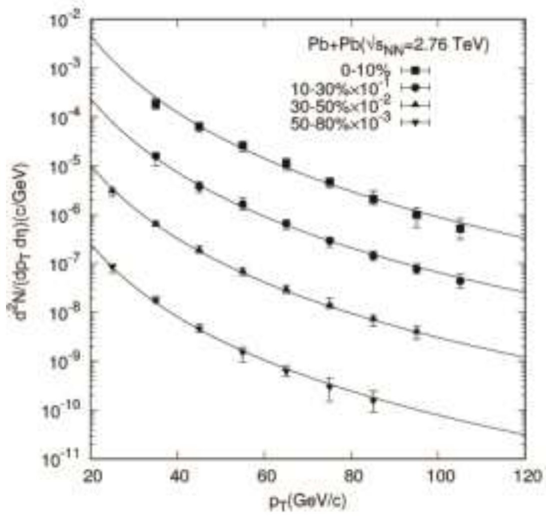
Figure-1(a) is the graphical representation of charged jet spectra produced in P +P interactions at 2.76 & 5.02 TeV fitted with basic working formula given in eqn.(2) without the constraints given in eqn.(3) and eqn.(6)/eqn.(7). The values of different parameters obtained from the fits are presented 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 $m_0 = 0.14$ 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

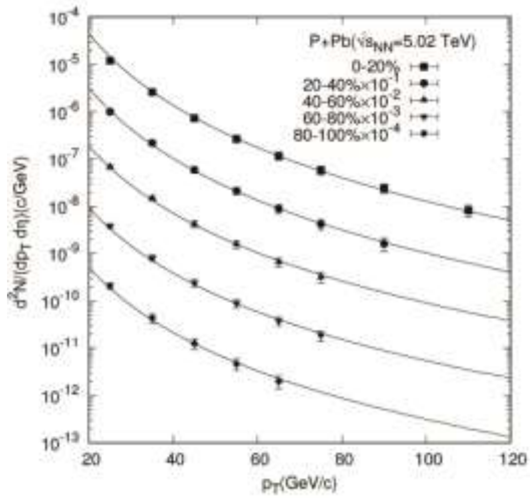
TeV which were obtained by scaling down the measured charged jets at 7 TeV. Besides, to maintain uniformity, we have used only those data which were obtained with the resolution parameter R = 0.2 for all the interactions throughout our present study.




(a)




(b)




(c)

***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

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

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].

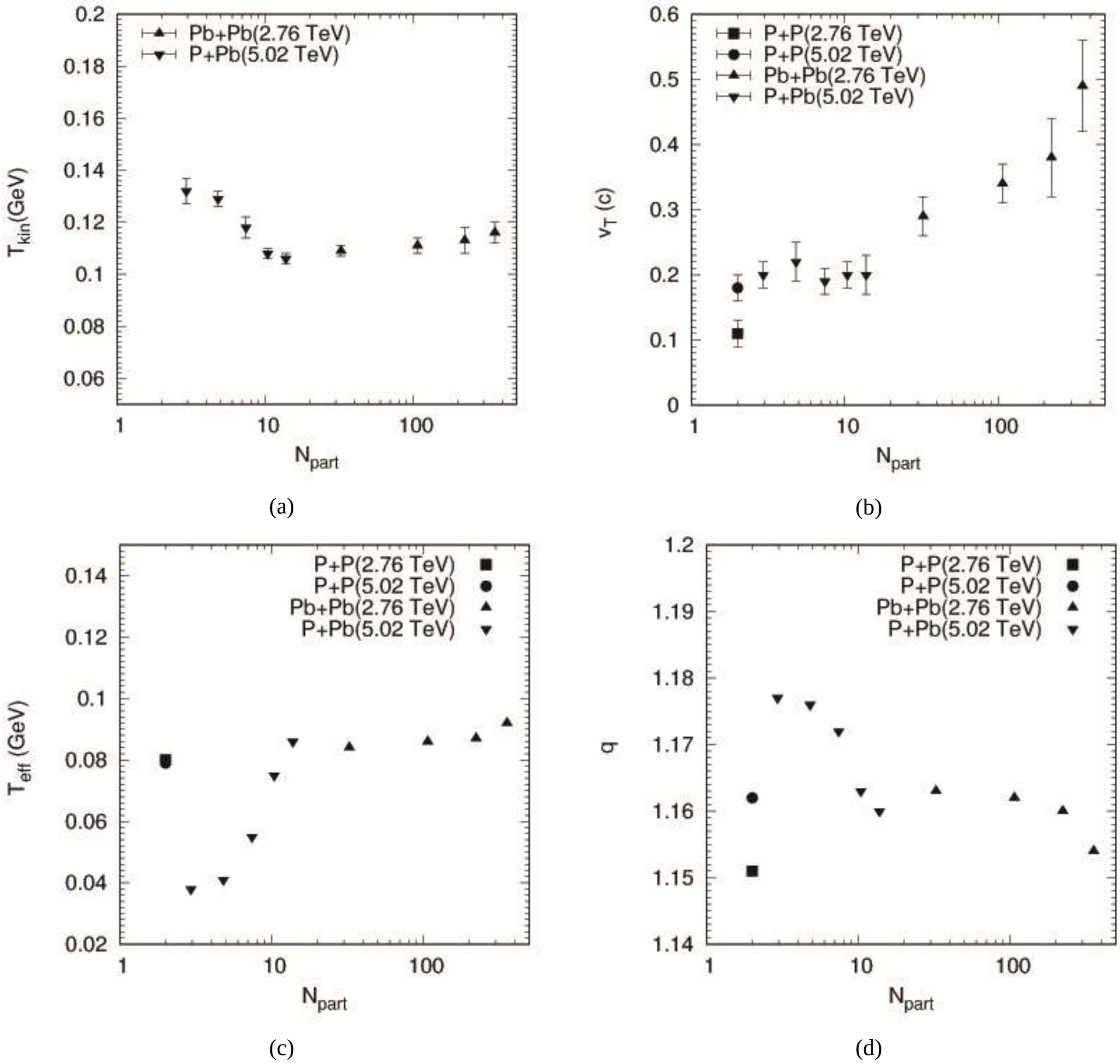



***Figure 2: Plots of the kinetic freeze-out temperature, $T_{kin}$ , average transverse flow, $v\_T$ , effective Temperature, $T_{eff}$ , and the nonextensive parameter, $q$ , obtained from the fits of charged jet-spectra for various centralities of P+Pb and Pb+Pb collisions at two different LHC energies.***

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

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

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 $< N' >$ is the multiplicity in absence of jet quenching and $< N >$ in presence of that, then the ratio of the multiplicity fluctuations for these two systems will be

$$\frac{\frac{< N' > - n_0 N_{part}}{< N' >}}{\frac{< N > - n_0 N_{part}}{< N >}} = \frac{c'(q'-1)}{c(q-1)} \tag{8}$$

where $q'$ and $q$ are the non-extensive parameters for the systems without jet-quenching and with jet-quenching respectively. Hence, as $< N' > > < N >$, $c(q-1) < c'(q'-1)$. 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(~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.

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## CITE AN ARTICLE

De, B. (2018). A SYSTEMATIC STUDY OF TRANSEVERSE SPECTRA OF JETS AT LHC ENERGIES. *INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY*, *7*(3), 600-609.