Radial Flow and Differential Freeze-out in Proton-Proton Collisions at \( \sqrt{s} = 7 \) TeV at the LHC

Arvind Khuntia, Himanshu Sharma, Swatantra Kumar Tiwari, and Raghunath Sahoo*

Discipline of Physics, School of Basic Sciences, Indian Institute of Technology Indore, Indore-433552, India.

Jean Cleymans

UCT-CERN Research Centre and Department of Physics, University of Cape Town, Rondebosch 7701, South Africa

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We analyse the transverse momentum (\( p_T \))-spectra as a function of charged-particle multiplicity at midrapidity (\(|y| < 0.5\)) for various identified particles such as \( \pi^\pm \), \( K^\pm \), \( K_S^0 \), \( p + \bar{p} \), \( \phi \), \( K^{*0} + \bar{K}^{*0} \), and \( \Lambda + \bar{\Lambda} \) in proton-proton collisions at \( \sqrt{s} = 7 \) TeV using Boltzmann-Gibbs Blast Wave (BGBW) model and thermodynamically consistent Tsallis distribution function. We obtain the multiplicity dependent kinetic freeze-out temperature (\( T_{\text{kin}} \)) and radial flow (\( \beta \)) of various particles after fitting the \( p_T \)-distribution with BGBW model. Here, \( T_{\text{kin}} \) exhibits mild dependence on multiplicity class while \( \beta \) shows almost independent behaviour. The information regarding Tsallis temperature and the non-extensivity parameter (\( q \)) are drawn by fitting the \( p_T \)-spectra with Tsallis distribution function. The extracted parameters of these particles are studied as a function of charged particle multiplicity density (\( dN_{ch}/d\eta \)). In addition to this, we also study these parameters as a function of particle mass to observe any possible mass ordering. All the identified hadrons show a mass ordering in temperature, non-extensive parameter and also a strong dependence on multiplicity classes, except the lighter particles. It is observed that as the particle multiplicity increases, the \( q \)-parameter approaches to Boltzmann-Gibbs value, hence a conclusion can be drawn that system tends to thermal equilibrium. The observations are consistent with a differential freeze-out scenario of the produced particles.

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I. INTRODUCTION

High multiplicity \( pp \)-collisions at LHC give us the opportunity to study matter under extreme conditions i.e. at high temperature and/or energy density. Initial energy density results in high pressure gradient, which leads to expansion of the fireball. The interactions among the produced particles are both elastic as well as inelastic, further, depend upon the mean free path of these particles. Recent results on suppression of \( K^{*0}/K \) ratio as a function of charged particle multiplicity in \( pp \)-collisions signifies a presence of hadronic phase in high multiplicity \( pp \)-collisions with non-zero lifetime [1]. This hadronic phase is defined as the phase between the chemical freeze-out and kinetic freeze-out. The freeze-out hypersurface, where the inelastic process ceases, known as chemical freeze-out. After chemical freeze-out, elastic collisions are continued till the kinetic freeze-out, where the mean free path of the particles are larger than the system size. This kinetic freeze-out hypersurface can be determined by studying the transverse momentum spectra (\( p_T \)) of the produced particles. The freeze-out processes are complicated and show a hierarchy, where formation of different types of particles and reactions cease at different time scales. From the kinetic theory perspective, reactions with lower interaction cross section switch off early compared to reaction with higher interaction cross section. So, strange and multi-strange particles should freeze-out early as compared to the light flavored hadrons, which leads to a differential freeze-out hypersurfaces.

Higher probability of multi-partonic interactions at higher collision energies lead to multiple interactions in the produced system, which results in high-multiplicity \( pp \)-collisions. This multi-partonic interactions might lead to thermalisation in high multiplicity \( pp \)-collisions, which can be described by a statistical models.

Such a statistical description of transverse momentum (\( p_T \)) of final state particles produced in high-energy collisions has been proposed to follow a thermalised Boltzmann type of distribution as given by [2]

\[
E \frac{d^3 \sigma}{dp_T} \simeq C \exp \left( - \frac{p_T}{T_{\text{exp}}} \right) . \tag{1}
\]

The identified particle spectra at RHIC and LHC do not follow Boltzmann-Gibbs distribution due to the possible QCD contributions at high-\( p_T \). However, one can describe the low-\( p_T \) particle production at high multiplicity classes in \( pp \)-collision by incorporating the radial flow (\( \beta \)) into Boltzmann-Gibbs distribution function, which is known as Boltzmann-Gibbs Blast Wave (BGBW) model [3]. The particles in the system are boosted by this radial flow. We can extract \( T_{\text{kin}} \) and
radial flow ($\beta$) by fitting the identified transverse momentum spectra at low-$p_T$.

To describe the complete transverse spectra of identified particles, one has to account for the power-law contribution at high $p_T$ [4–6] and this empirically takes care for the possible QCD contributions.

A combination of both of these aspects has been proposed by Hagedorn, which describes the experimental data over a wide $p_T$-range [7] and is given by

$$E \frac{d^3\sigma}{d^3p} = C \left(1 + \frac{p_T}{p_0}\right)^{-n} \exp\left(-\frac{np_T}{p_0}\right) \quad \text{for } p_T \to 0,$$

$$\left(\frac{p_T}{p_0}\right)^n \quad \text{for } p_T \to \infty,$$

(2)

where $C$, $p_0$, and $n$ are fitting parameters.

For small $p_T$, the resultant function acts as an exponential function and a power-law function for large $p_T$. A finite degree of deviation from the equilibrium statistical description of identified particle $p_T$-spectra has already been observed by experiments at RHIC [8, 9] and LHC [10–13]. For a thermalised system, the mean transverse momentum ($\langle p_T \rangle$) is associated with the temperature of the hadronizing matter, but for systems which are far from thermal equilibrium one fails to make such a connection. In the latter systems, either the temperature fluctuates event-by-event or within the same event [14]. This creates room for a possible description of the $p_T$-spectra in high-energy hadronic and nuclear collisions, using the non-extensive Tsallis statistics [15–17]. A thermodynamically consistent non-extensive distribution function is given by [18]

$$f(m_T) = C_q \left[1 + (q - 1) \frac{m_T}{T}\right]^{-\frac{1}{q-1}}.$$  

(3)

Here, $m_T$ is the transverse mass and $q$ is called the non-extensive parameter - a measure of the degree of deviation from equilibrium. Eqs. 2 and 3 are related through the following transformations for large values of $p_T$:

$$n = \frac{1}{q - 1}, \quad p_0 = \frac{T}{q - 1}. \quad \text{(4)}$$

In the limit $q \to 1$, one recovers the standard Boltzmann-Gibbs distribution (Eq. 1) from the Tsallis distribution (Eq. 3).

Tsallis non-extensive statistics is used widely to explain the particle spectra in high-energy collisions [14, 19–22] starting from elementary $e^+ - e^-$, hadronic and heavy-ion collisions [23–38]. The criticality in the non-extensive $q$-parameter is also shown for speed of sound in a hadron resonance gas using non-extensive statistics [39]. A comprehensive analysis of $\pi^-\pi^+$ and heavy quarkonium states has recently been done in Ref. [40, 41].

The paper is organized as follows. In section II A, we present the BGBW to describe the identified particle spectra up to $p_T \approx 3$ GeV/c and also discuss about $T_{kin}$ and radial flow ($\beta$) as a function of charged particle multiplicity and particle mass. Similarly, in section II B, we use a thermodynamically consistent Tsallis distribution function to describe the identified particle spectra for the complete range of $p_T$. Also we discuss the results in view of the non-extensive statistical description of the identified particles as a function of charged particle multiplicity and particle mass. Finally, in section III we present the summary of our results.

II. TRANSVERSE MOMENTUM SPECTRA OF IDENTIFIED HADROMS

In this section, we analyse the transverse momentum spectra of $\pi^\pm$, $K^{\pm}$, $K^{0}_{S}$, $p + p$, $\phi$, $K^{*0} + \bar{K}^{*0}$, and $\Lambda + \bar{\Lambda}$ produced in $pp$-collisions at $\sqrt{s} = 7$ TeV at the LHC, measured by the ALICE [42, 43]. This $p_T$-spectra is analysed by using Boltzmann-Gibbs Blast Wave (BGBW) model and a thermodynamically consistent Tsallis non-extensive statistics.

A. Boltzmann-Gibbs Blast Wave (BGBW) Model

In this subsection, we employ BGBW model to fit the transverse momentum spectra of various identified light flavor hadrons measured at $\sqrt{s} = 7$ TeV. For this study, we do not include multistrange particles because statistical uncertainties forbids us in drawing any physics conclusion. The expression for invariant yield in the framework of BGBW is given as follows [3]:

$$E \frac{d^3N}{d^3p} = D \int d^3\sigma_\mu p^\mu \exp\left(-\frac{p^\mu u_\mu}{T}\right), \quad \text{(5)}$$

where the particle four-momentum is,

$$p^\mu = (m_T \cos\phi, p_T \cos \phi, p_T \sin \phi, m_T \sinh y), \quad \text{(6)}$$

the four-velocity is given by,

$$u^\mu = \cosh \rho \left(\cosh \eta, \frac{\cosh \eta}{\tanh \rho}, \tanh \rho \sin \phi, \sinh \eta \right), \quad \text{(7)}$$

while the kinetic freeze-out surface is parametrised as,

$$d^3\sigma_\mu = \left(\cosh \eta, 0, 0, -\sinh \eta \right) \tau r \, dr \, d\eta \, d\phi, \quad \text{(8)}$$

Here, $\eta$ is the space-time rapidity. With simplification assuming Bjorken correlation in rapidity, i.e. $y = \eta$ [53],
Eq. 5 can be expressed as:

\[
\frac{d^2N}{dp_T dy} \bigg|_{y=0} = D \int_0^{R_0} r dr K_1 \left( \frac{m_T \cosh \rho}{T_{kin}} \right) I_0 \left( \frac{p_T \sinh \rho}{T_{kin}} \right),
\]

where \( D \) is the normalisation constant. Here \( g \) is the degeneracy factor and \( m_T = \sqrt{p_T^2 + m^2} \) is the transverse mass. \( K_1 \left( \frac{m_T \cosh \rho}{T_{kin}} \right) \) and \( I_0 \left( \frac{p_T \sinh \rho}{T_{kin}} \right) \) are the modified Bessel’s functions and are given by,

\[
K_1 \left( \frac{m_T \cosh \rho}{T_{kin}} \right) = \int_0^\infty \cosh \exp \left( - \frac{m_T \cosh \rho}{T_{kin}} \right) dy,
\]

\[
I_0 \left( \frac{p_T \sinh \rho}{T} \right) = \frac{1}{2\pi} \int_0^{2\pi} \exp \left( \frac{p_T \sinh \rho \cos \phi}{T_{kin}} \right) d\phi,
\]

where \( \rho \) in the integrand is a parameter given by \( \rho = \tanh^{-1} \beta \), with \( \beta = \beta_s \left( \xi \right)^n \) \([3, 44-46]\) is the radial flow. \( \beta_s \) is the maximum surface velocity and \( \xi = (r/R_0) \), with \( r \) as the radial distance. In the blast-wave model the particles closer to the center of the fireball move slower than the ones at the edges. The average of the transverse velocity can be evaluated as \([47]\),

\[
< \beta > = \frac{\int \beta_s \xi^n d\xi}{\int \xi d\xi} = \left( \frac{2}{2 + n} \right) \beta_s. \quad (10)
\]

In our calculation, we use a linear velocity profile, \( n = 1 \) and \( R_0 \) is the maximum radius of the expanding source at freeze-out \( (0 < \xi < 1) \).

In figure 1, we show the fitting of \( p_T \)-spectra of pion \((\pi^\pm)\), kaon \((K^\pm)\) and proton \((p + p)\) \([42]\) measured in \( pp \)-collisions at \( \sqrt{s} = 7 \) TeV in various multiplicity classes. Here, we have used BGBW function to fit the spectra given by Eq. 9, where \( T_{kin} \) and radial flow \( \beta \) are the free parameters. We perceive that BGBW function explains the experimental data very well for all the particles at lower \( p_T \) (\( \sim 3 \) GeV/c) with a good \( \chi^2/ndf \). However, a higher \( \chi^2/ndf \) is obtained in case of \( \pi^\pm \) due to the underestimation of experimental data at lower \( p_T \), as we are not considering the contributions from resonances.

We have extracted the kinetic freeze-out temperature and radial flow velocity for all the hadrons considered here. Figure 2 represents the extracted \( T_{kin} \) as a function of charged particle multiplicity for identified hadrons. We notice that, \( T_{kin} \) is higher for massive particles in comparison to lighter ones which supports the differential freeze out scenario and that massive particles freeze-out earlier from the system. However, \( K^0_S \) behaves differently in the system. It is also evident from the figure that the particles having similar masses are coming from the same freeze-out hypersurface at highest multiplicity class. Further, we observe multiplicity independent behaviour of \( T_{kin} \) particularly for lighter hadrons.

In figure 3, we have demonstrated the extracted radial flow velocity for the identified particles as a function of multiplicity class. We find that \( \beta \) value reduces as the particle mass increases in all the multiplicity classes except for proton. Again, \( K^0_S \) behaves in a different manner which is not understood in the present work. Further, al-
most equal magnitude of radial flow is observed for $K^{*0}$ and $\phi$, which have similar masses. Furthermore, we observe that $p$ has mass similar to $K^{*0}$ and $\phi$ but the radial flow of $p$ is closer to $\Lambda$, as both are baryons, which advocates that baryons like $p$ and $\Lambda$ freeze-out from the same hypersurface while mesons such as $\phi$ and $K^{*0}$ freeze-out from a different hypersurface.

FIG. 2: (color online) Multiplicity dependence of $T_{kin}$ for $pp$-collisions at $\sqrt{s} = 7$ TeV using Eq. 9 as the fitting function.

FIG. 3: (color online) Multiplicity dependence of the radial flow, $\beta$ for $pp$-collisions at $\sqrt{s} = 7$ TeV using Eq. 9 as the fitting function.

FIG. 4: (Color online) Experimentally measured $p_T$-spectra of pion ($\pi^\pm$), kaon ($K^\pm$) and proton ($p+\bar{p}$) [42], fitted with Tsallis distribution for $pp$-collisions at $\sqrt{s} = 7$ TeV using Eq. 12 for various multiplicity classes. The extracted parameters are given in table I.
for LHC energies, where \( \sqrt{s} \) is given by,

\[
K \text{ and } \Lambda + \bar{\Lambda} \quad \text{fitted with Tsallis distribution parameters in the context of non-extensive statistics. After fitting we found that, } \chi^2/\text{ndf} \text{ is below 1 for all the considered particles for highest multiplicity while it increases as the multiplicity decreases. This shows that the spectra are very well described by the non-extensive statistics particularly at highest multiplicity class.}
\]

Figure 6 represents the temperature parameter, \( T \) extracted in the fitting as a function of event multiplicity for all the considered particles. We notice a monotonic increase in \( T \) with the increase in particle multiplicity for all the hadrons. For heavier particles, the temperature is observed to be higher, which indicates an early freeze-out of the these particles. We also find that the temperature for lighter particles does not change appreciably with multiplicity but for heavier particles it shows a significant variation of \( T \) with charged particle multiplicity. We have also shown the variation of the non-extensive parameter, \( q \) with charged particle multiplicity in Fig. 7. The value of \( q \) decreases monotonically for higher multiplicity classes for all the particles discussed in this work. Theses findings suggest that the system formed in higher multiplicity class is close to thermal equilibrium. However for \( \pi^\pm \), \( K^\pm \) and \( K_S^0 \), \( q \) is almost independent of the charged particle multiplicity density. The fact that the \( q \)-values go on decreasing with multiplicity is an indicative of the tendency of the produced systems towards thermodynamic equilibrium. This goes inline with the naive expectations while understanding the microscopic view of systems approaching thermodynamic equilibrium. A similar tendency of \( q \) decreasing with number of participating nucleons for Pb+Pb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \) has been observed for the bulk part (\( p_T < 6 \text{ GeV/c} \)) of the charged hadron spectra [55, 57]. The present study is useful in understanding the microscopic features of degrees of equilibration and their dependencies on the number of particles in the system.

FIG. 5: (Color online) The \( p_T \)-spectra of neutral kaon (\( K^{*0} + K^0 \)) and lambda (\( \Lambda + \bar{\Lambda} \)) [42] fitted with Tsallis distribution for \( pp \)-collisions at \( \sqrt{s} = 7 \text{ TeV} \) using Eq. 12 for various multiplicity classes. The extracted parameters are given in table I.

B. Non-extensivity and \( p_T \)-spectra

The Tsallis distribution function at mid-rapidity, with finite chemical potential [48] is given by,

\[
1 \frac{d^2N}{dp_T dp_T dy}_{y=0} = \frac{g V m_T}{(2\pi)^2} \left[ 1 + (q - 1) \frac{m_T - \mu}{T} \right]^{-\frac{q}{q-1}} \quad (11)
\]

where, \( m_T \) is the transverse mass of a particle given by \( \sqrt{p_T^2 + m^2} \), \( g \) is the degeneracy, \( V \) is the system volume and \( \mu \) is the chemical potential of the system. At the LHC energies, where \( \mu \approx 0 \), the transverse momentum distribution function [49] reduces to:

\[
1 \frac{d^2N}{dp_T dp_T dy}_{y=0} = \frac{g V m_T}{(2\pi)^2} \left[ 1 + (q - 1) \frac{m_T}{T} \right]^{-\frac{q}{q-1}}. \quad (12)
\]

Now, we use Eq. 12 to fit the transverse momentum spectra of various particles measured experimentally for different multiplicity classes at \( \sqrt{s} = 7 \text{ TeV} \). The fittings are shown in Figs. 4 and 5. We have listed the definitions of the multiplicity classes in Table 1. The fitting is performed using the TMinuit class available in ROOT library keeping all the parameters free. Here, we follow the notion of a mass dependent differential freeze-out scenario [50, 54], where particles freeze-out at different times, which correspond to different system volumes and temperatures. Henceforth, we study the thermodynamic parameters in the context of non-extensive statistics. After fitting we found that, \( \chi^2/\text{ndf} \) is below 1 for all the considered particles for highest multiplicity while it increases as the multiplicity decreases. This shows that the spectra are very well described by the non-extensive statistics particularly at highest multiplicity class.
TABLE I: Number of mean charged particle multiplicity density corresponding to different event classes [42, 43].

| Classname | Mult1 | Mult2 | Mult3 | Mult4 | Mult5 | Mult6 | Mult7 | Mult8 | Mult9 | Mult10 |
|-----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 0.5πch   | 21.3±0.6 | 16.5±0.5 | 13.5±0.4 | 11.5±0.3 | 10.1±0.3 | 8.45±0.25 | 6.72±0.21 | 5.40±0.17 | 3.90±0.14 | 2.26±0.12 |

TABLE II: The extracted Tsallis parameters as well as the χ²/ndf for all the multiplicity classes. For Ω− + Ω+, multiplicity classes are combined to deal with the statistics [43]. For Κ°, Λ + ¯Λ, Ξ− + ¯Ξ− and Ω− + Ω+, the parameters are taken from our earlier work [58].

![FIG. 6](color online) Multiplicity dependence of T for pp-collisions at √s = 7 TeV using Eq. 12 as a fitting function.

![FIG. 7](color online) Multiplicity dependence of the non-extensive parameter, q for pp-collisions at √s = 7 TeV using Eq. 12 as a fitting function.
III. SUMMARY

The high-multiplicity events in pp-collisions at the LHC energies have become a matter of special attention to the research community, as it has shown heavy-ion like properties e.g., enhancement of strange particles, which are not yet understood from the existing theoretical models. Understanding the microscopic properties of such events are of paramount importance in order to have a complete understanding of the matter created in these collisions. In this paper, we have tried to understand these events from their thermodynamics point of view. The information regarding kinetic freeze-out hypersurface of the identified particles at this energy is estimated by fitting BGBW function upto low-p_T. To address the high p_T, which has pQCD inspired power-law contribution become customary to use a thermodynamically consistent Tsallis non-extensive statistics to describe the complete spectra.

We have analysed the multiplicity dependence of the p_T-spectra of identified hadrons in pp-collisions at √s = 7 TeV measured by the ALICE experiment at the LHC, using BGBW model and thermodynamically consistent non-extensive statistics. The extracted thermodynamic parameters i.e. the kinetic freeze-out parameter (T_{kin}) and radial flow (β) are studied as a function of charged particle multiplicity in BGBW formalism. Similarly, we have studied the Tsallis temperature parameter (T) and the non-extensive parameter (q) as a function of charged particle multiplicity using Tsallis statistics. In addition to this, we have also studied these parameters as a function of particle mass. In summary,

- It is observed that BGBW model explains the experimental data upto p_T ≃ 3 GeV/c with an appreciable χ^2/ndf. The multistrange particles are not included in the fitting due to large statistical uncertainties.
- We have extracted the kinetic freeze-out temperature for all the identified hadrons. It is discovered that T_{kin} follows a mass dependent pattern and acquires higher values for lighter particles. This goes inline with the fact that heavier particles freezeout earlier in time. However, we notice multiplicity independent behaviour of T_{kin} particularly for lighter hadrons.
- The radial flow (β) parameter is also extracted in this study, which is observed higher for lighter particles. This observation reveals hydrodynamic behaviour of particles.
- The near-multiplicity independent behaviour of radial flow velocity, β is an important observation and this needs further investigations.
- It has been manifested in the present paper, the Tsallis distribution provides a complete description of identified particle spectra produced in pp-collisions at √s = 7 TeV upto very high-p_T.
- The variable T shows a systematic increase with multiplicity, the heaviest baryons showing the steepest increase. This is an indication of a mass hierarchy in particle freeze-out.
- The obtained parameters show variations with the event multiplicity. The notable variation of the non-extensive parameter, q which decreases towards the value 1 as the multiplicity increases and this effect is more significant for heavy mass particles. This shows the tendency of the produced system to equilibrate with higher multiplicities. This goes inline with the expected multi-partonic interactions, which increase for higher multiplicities in pp-collisions and are thus responsible for bringing the system towards thermodynamic equilibrium [59].

Conclusively, we find that BGBW explains the transverse momentum spectra upto ≃ 3 GeV/c for high multiplicity pp-collisions with an appreciable χ^2/ndf, while the Tsallis statistics describe the complete spectra for all the event classes.

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