Understanding partonic energy loss from measured light charged particles and jets in PbPb collisions at LHC energies

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Abstract.

We perform a comprehensive study of partonic energy loss reflected in the nuclear modification factors of charged particles and jets measured in PbPb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ and 5.02 TeV in wide transverse momentum ($p_T$) and centrality range. The $p_T$ distributions in pp collisions are fitted with a modified power law and the nuclear modification factor in PbPb collisions can be obtained using effective shift ($\Delta p_T$) in the spectrum measured at different centralities. Driven by physics consideration, the functional form of energy loss given by $\Delta p_T$ can be assumed as power law with different power indices in three different $p_T$ regions. The power indices and the boundaries of three $p_T$ regions are obtained by fitting the measured nuclear modification factor as a function of $p_T$ in all collision centralities simultaneously. The energy loss in different collisions centralities are described in terms of fractional power of number of participants. It is demanded that the power law functions in three $p_T$ regions and their derivatives are continuous at the $p_T$ boundaries. The $\Delta p_T$ for light charged particles is found to increase linearly with $p_T$ in low $p_T$ region below $\sim 5-6$ GeV/c and approaches a constant value in high $p_T$ region above $\sim 22-29$ GeV/c with an intermediate power law connecting the two regions. The method is also used for jets and it is found that for jets, the $\Delta p_T$ increases approximately linearly even at very high $p_T$. 
1. Introduction

The collisions of heavy ions at ultra relativistic energies are performed to create and study bulk strongly interacting matter at high temperatures. The data from RHIC and LHC provide strong evidences of formation of a new state of matter known as quark gluon plasma (QGP) in these collisions [1].

The light charged hadrons and jets transverse momentum ($p_T$) spectra give insight into the particle production mechanism in pp collisions. The partonic energy energy loss is reflected in these particles when measured in heavy ion collisions due to jet-quenching [2] which measures the opacity of the medium. A modified power law distribution [3, 4, 5] describes the $p_T$ spectra of the hadrons in pp collisions in terms of a power index $n$ which determines the initial production in partonic collisions. In Ref. [6], the power law function is applied to heavy ion collisions as well which includes the transverse flow in low $p_T$ region and the in-medium energy loss (also in terms of power law) in high $p_T$ region.

The spectra of hadrons are measured in both pp and AA collisions and nuclear modification factor ($R_{AA}$) is obtained. The energy loss of partons can be connected to horizontal shift in the scaled hadron spectra in AA with respect to pp spectra as done by PHENIX measurement [7]. Their measurements of neutral pions up to $p_T \sim 10 \text{ GeV}/c$ are consistent with the scenario where the momentum shift $\Delta p_T$ is proportional to $p_T$. In similar approach, the authors in Ref. [8], extracted the fractional energy loss from the measured nuclear modification factor of hadrons as a function of $p_T$ below 10 GeV/c in AuAu collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$. They also considered that the energy loss increases linearly with $p_T$. In recent PHENIX work [9], fractional energy loss was obtained in the hadron spectrum measured up to $p_T = 20 \text{ GeV}/c$ in heavy ions collisions at RHIC and LHC energy and is not found to be constant. This means that a constant fractional energy loss (energy loss varying linearly with $p_T$) can be applicable only to low $p_T$ RHIC measurements.

There are many recent studies which use so-called shift formalism to study the energy loss. The work in Ref. [10] is based on shift formalism and describes the transverse momentum ($p_T$), rapidity ($y$) and centrality dependences of the measured jet nuclear modification factor ($R_{AA}$) in PbPb collisions at LHC. They assume that the energy loss is given by a power law in terms of $p_T$, the value of power index is obtained between 0.4 to 0.8 by fitting the $R_{AA}$ as a function of $p_T$ and centralities. They also found that the energy loss linearly increases with number of participants. Using the same method they study the magnitude and the colour charge dependence of the energy loss in PbPb collisions at LHC energies using the measured data of the inclusive jet suppression [11]. The authors of the Ref. [12] work on inclusive charged particle spectra measured in the range ($5 < p_T < 20 \text{ GeV}/c$) in heavy ion collisions at RHIC and LHC. They assume that the energy loss linearly increases with $p_T$ and pathlength.

There are detailed calculations of energy loss of partons in the hot medium [see e.g. Refs. [13, 14]. Phenomenological models tend to define simple dependence of the
Understanding partonic energy loss ... radiative energy loss of the parton on the energy of the parton inside the medium [for a discussions see Ref. [15]]. The energy loss can be characterized in terms of coherence length $l_{\text{coh}}$, which is associated with the formation time of gluon radiation by a group of scattering centres. If $l_{\text{coh}}$ is less then the mean free path $\langle \lambda \rangle$ of the parton, the energy loss is proportional to the energy of the parton. If $l_{\text{coh}}$ is greater than $\lambda$ but less than the path length ($L$) of the parton ($\lambda < l_{\text{coh}} < L$), the energy loss is proportional to the square root of the energy of the parton. In the complete coherent regime, $l_{\text{coh}} > L$, the energy loss per unit length is independent on energy but proportional to the parton path length implying that $\Delta p_T$ is proportional to square of pathlength. There is a nice description of charged particle spectra at RHIC and LHC using such a prescription by dividing the $p_T$ spectra in three regions [16, 17]. For low and intermediate energy partons, $\Delta p_T$ is assumed to be linearly dependent on $L$ [18]. The work in Ref. [19] studies the energy loss of jets in terms of exponent of the number of participants. It should be remembered that the fragmentation changes the momentum between the partonic stage (at which energy is lost) and hadron formation. There are models which say that softening occurs at fragmentation stage due to color dynamics [See e.g. Ref. [20]].

In general, one can assume that the energy loss of partons in the hot medium as a function of parton energy is in the form of power law where the power index ranges from 0 (constant) to 1 (linear). Guided by these considerations, in the present work, the $p_T$ loss has been assumed as power law with different power indices in three different $p_T$ regions. The energy loss in different collisions centralities are described in terms of fractional power of number of participants. The $p_T$ distributions in pp collisions are fitted with a modified power law and $R_{AA}$ in PbPb collisions can be obtained using effective shift ($\Delta p_T$) in the $p_T$ spectrum measured at different centralities. The power index and the boundaries of three $p_T$ regions are obtained by fitting the measured $R_{AA}$ of charged particles and jets in PbPb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ and 5.02 TeV in large transverse momentum ($p_T$) and centrality range. The shift $\Delta p_T$ includes the medium effect, mainly energy loss of parent quark inside the plasma. The shift $\Delta p_T$ can be approximatively understood as the partonic energy loss in the case of jets while in case of hadrons it is not simple due to complicated correlations. Often we refer to the shift $\Delta p_T$ as the energy loss.

2. Nuclear Modification Factor and Energy Loss

The nuclear modification factor $R_{AA}$ of hadrons is defined as the ratio of yield of the hadrons in AA collision and the yield in pp collision with a suitable normalization

$$R_{AA}(p_T, b) = \frac{1}{T_{AA}} \frac{d^2 N^{AA}(p_T, b)}{dp_T dy} / \frac{d^2 \sigma^{pp}(p_T, b)}{dp_T dy}.$$  (1)

Here, $T_{AA}$ is the nuclear overlap function which can be calculated from the nuclear density distribution. High $p_T$ partons traversing the medium loose energy and cause the suppression of hadrons at high $p_T$ indicated by value of $R_{AA}$ which is less than one.
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The transverse momentum distribution of hadrons in pp collisions can be described by the Hagedorn function which is a QCD-inspired summed power law [21] given as

\[
\frac{d^2\sigma_{pp}}{dp_T^2dy} = A_n \frac{2\pi p_T}{p_0} \left( 1 + \frac{p_T}{p_0} \right)^{-n}.
\]  

(2)

where \( n \) is the power and \( A_n \) and \( p_0 \) are other parameters which are obtained by fitting the experimental pp spectrum. The yield in the AA collision can be obtained by shifting the spectrum by \( \Delta p_T \) as

\[
\frac{d^2N_{AA}}{dp_T^2dy} = \frac{d^2\sigma_{pp}}{dp_T^2dy} \left( 1 + \frac{d(\Delta p_T)}{dp_T} \right) \left( p_T + \Delta p_T \right) \left( \frac{p_T + \Delta p_T}{p_T} \right)^{-n}.
\]  

(3)

The reasoning behind writing Eq. 3 lies in the assumption that particle yield at a given \( p_T \) in AA collisions would have been equal to the yield in pp collisions at \( p_T + \Delta p_T \). The shift \( \Delta p_T \) includes the medium effect, mainly energy loss of parent quark inside the plasma.

The nuclear modification factor \( R_{AA} \) can be obtained as

\[
R_{AA} = \left( 1 + \frac{\Delta p_T}{p_0 + p_T} \right)^{-n} \left( \frac{p_T + \Delta p_T}{p_T} \right) \left( 1 + \frac{d(\Delta p_T)}{dp_T} \right).
\]  

(4)

The energy loss given by \( p_T \) loss, \( \Delta p_T \) can be extracted by fitting the experimental data on \( R_{AA} \) with Eq. 4. The \( \Delta p_T \) and its derivative will go as input in the above equation and can be assumed to be in the form of the power law with different values of power indices in three different \( p_T \) regions as follows

\[
\Delta p_T = \begin{cases} 
  a_1 \left( p_T - C_1 \right)^{\alpha_1} & \text{for } p_T < p_{T_1}, \\
  a_2 \left( p_T - C_2 \right)^{\alpha_2} & \text{for } p_{T_1} \leq p_T < p_{T_2}, \\
  a_3 \left( p_T - C_3 \right)^{\alpha_3} & \text{for } p_T \geq p_{T_2}.
\end{cases}
\]  

(5)

The parameter \( a_1 \) in our work contains the pathlength dependence. The pathlength \( L \) scales as the square root of number of participants as \( \sqrt{N_{\text{part}}} \). For low and intermediate energy partons, \( \Delta p_T \) can be assumed to be linearly dependent on \( L \) [18]. If the scattering happens in complete coherent regime where the whole medium acts as one coherent source of radiation, the \( \Delta p_T \) approaches quadratic dependence on \( L \). The work in Ref. [19] studies the energy loss of jets in terms of exponent of the number of participants. Without complicating the calculations we can assume that \( a_1 = M \left( N_{\text{part}}/(2A) \right)^\beta \). The exponent \( \beta \) is obtained separately for each dataset. The parameter \( M \) relies on the energy density of the medium depending on the collision energy but has a same value for all centralities. The boundaries of the \( p_T \) regions \( p_{T_1}, p_{T_2} \) and the power indices \( \alpha_1, \alpha_2 \) and \( \alpha_3 \) in the three different regions are used as free parameters while fitting the \( R_{AA} \) measured at different centralities simultaneously. The parameter \( C_1 \) is fixed to a suitable value to choose a lower \( p_T \) cutoff and the
parameters $C_2$, $C_3$, $a_2$ and $a_3$ are obtained by assuming the function and its derivative to be continuous at boundaries.

Demanding that the function in Eq. (5) to be continuous at $p_T = p_{T1}$ and at $p_T = p_{T2}$ we obtain

$$a_2 = a_1 \frac{(p_{T1} - C_1)^{\alpha_1}}{(p_{T1} - C_2)^{\alpha_2}} .$$

(6)

$$a_3 = a_2 \frac{(p_{T2} - C_2)^{\alpha_2}}{(p_{T2} - C_3)^{\alpha_3}} .$$

(7)

Demanding that at $p_T = p_{T1}$, the derivative of Eq. (5) is continuous.

$$a_1 \alpha_1 (p_{T1} - C_1)^{\alpha_1 - 1} = a_2 \alpha_2 (p_{T1} - C_2)^{\alpha_2 - 1} ,$$

(8)

Using the value of $a_2$ from Eq. (6)

$$\frac{\alpha_1}{(p_{T1} - C_1)} = \frac{\alpha_2}{(p_{T1} - C_2)} ,$$

(9)

$$C_2 = p_{T1} - \frac{\alpha_2}{\alpha_1} (p_{T1} - C_1) .$$

(10)

Similarly, demanding the derivative to be continuous at $p_T = p_{T2}$, we get $C_3$

$$C_3 = p_{T2} - \frac{\alpha_3}{\alpha_2} (p_{T2} - C_2) .$$

(11)

In case of jets we consider only one region as the data starts from very high $p_T$ above 40 GeV/c.

3. Results and Discussions

Figure 1 shows the invariant yields of the charged particles as a function of the transverse momentum $p_T$ for pp collisions at $\sqrt{s} = 2.76$ TeV measured by the ALICE experiment [22]. The solid curve is the Hagedorn distribution fitted to the $p_T$ spectra with the parameters given in Table 1.

| Parameters | Charged particles | Jets |
|------------|-------------------|------|
| $\sqrt{s_{NN}}$ (GeV/c) | $\sqrt{s_{NN}} = 2.76$ TeV | $\sqrt{s_{NN}} = 5.02$ TeV | $\sqrt{s_{NN}} = 2.76$ TeV | $\sqrt{s_{NN}} = 5.02$ TeV |
| $n$ | 7.26 $\pm$ 0.08 | 6.70 $\pm$ 0.14 | 8.21 $\pm$ 1.55 | 7.90 $\pm$ 0.50 |
| $p_0$ (GeV/c) | 1.02 $\pm$ 0.04 | 0.86 $\pm$ 0.16 | 18.23 $\pm$ 1.69 | 19.21 $\pm$ 3.20 |
| $\chi^2$/NDF | 0.15 | 0.06 | 0.23 | 0.95 |

Figure 2 shows the nuclear modification factor $R_{AA}$ of the charged particles as a function of the transverse momentum $p_T$ for different centrality classes in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV measured by the ALICE experiment [23]. The solid lines are the function given by Eq. (4). The modeling of centrality dependence using $N_{\text{part}}$ with
\[ \beta = 0.58 \text{ gives a very good description of the data. The extracted parameters of the shift } \Delta p_T \text{ obtained by fitting the } R_{AA} \text{ measured in different centrality classes of PbPb collisions at } \sqrt{s_{NN}} = 2.76 \text{ TeV are given in Table 2 along with value of } \chi^2/\text{NDF. It shows that the } \Delta p_T \text{ increases almost linearly (} p_T^{0.97} \text{) upto } p_T \simeq 5 \text{ GeV}/c \text{ in confirmation with earlier studies. After that it increases slowly with power } \alpha = 0.224 \text{ upto a } p_T \text{ value 29 GeV}/c \text{ and then becomes constant for higher values of } p_T. \]

**Table 2.** The extracted parameters of the shift \( \Delta p_T \) obtained by fitting the charged particles \( R_{AA} \) measured in different centrality classes of PbPb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ and 5.02 TeV}. \)

| Parameters | \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \) | \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) |
|------------|---------------------------------|---------------------------------|
| \( M \)    | \( 0.75 \pm 0.02 \)              | \( 0.80 \pm 0.038 \)            |
| \( p_{T1} (\text{GeV}/c) \) | \( 5.03 \pm 0.15 \)              | \( 5.10 \pm 0.22 \)            |
| \( p_{T2} (\text{GeV}/c) \) | \( 29.0 \pm 0.1 \)               | \( 22.2 \pm 4.1 \)             |
| \( C_1 (\text{GeV}/c) \) | \( 1.0 \text{ (fixed)} \)        | \( 1.0 \)                      |
| \( \alpha_1 \) | \( 0.97 \pm 0.02 \)              | \( 0.95 \pm 0.04 \)            |
| \( \alpha_2 \) | \( 0.22 \pm 0.02 \)              | \( 0.22 \pm 0.03 \)            |
| \( \alpha_3 \) | \( 0.05 \pm 0.13 \)              | \( 0.05 \pm 0.10 \)            |
| \( \chi^2/\text{NDF} \) | \( 0.35 \)                       | \( 0.38 \)                     |
Figure 2. The nuclear modification factor $R_{AA}$ of the charged particles as a function of transverse momentum $p_T$ for various centrality classes in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV measured by the ALICE experiment. The solid curves are the $R_{AA}$ fitting function (Eq. [4]).
Figure 3 shows the energy loss $\Delta p_T$ of the charged particles as a function of the transverse momentum $p_T$ for different centrality classes in PbPb collision at $\sqrt{s_{NN}} = 2.76$ TeV. The $\Delta p_T$ is obtained from Eq. 5 with parameters given in Table 2. The $\Delta p_T$ increases from peripheral to the most central collision regions as per $N_{\text{part}}^{0.58}$. The figure shows that the $\Delta p_T$ increases almost linearly up to $p_T \sim 5$ GeV/c. After that it increases slowly up to a $p_T$ value 29 GeV/c and then becomes constant for higher values of $p_T$.

Figure 4 shows the invariant yields of the charged particles as a function of the transverse momentum $p_T$ in pp collisions at $\sqrt{s} = 5.02$ TeV measured by the CMS experiment [24]. The solid lines are the Hagedorn function fitted to the measured $p_T$ spectra the parameters of which are given in Table 1.

Figure 5 shows the nuclear modification factor $R_{AA}$ of the charged particles as a function of the transverse momentum $p_T$ for different centrality classes in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV measured by the CMS experiment [24]. The solid curves are the $R_{AA}$ fitting function (Eq. 4). Here also the modeling of centrality dependence using $N_{\text{part}}^\beta$ with $\beta = 0.58$ gives a good description of the data. The extracted parameters of the shift $\Delta p_T$ obtained by fitting the $R_{AA}$ measured in different centrality classes of PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are given in Table 2 along with the value of $\chi^2/N_{\text{D.F.}}$. It shows that the $\Delta p_T$ increases almost linearly ($p_T^{0.96}$) similar to the case at 2.76 TeV for $p_T$ up to 5.1 GeV/c. After that it increases slowly with power $\alpha = 0.22$ up to a $p_T$ value 22.2 GeV/c and then becomes constant for higher values of $p_T$ right up to 160 GeV/c.

Figure 6 shows the energy loss $\Delta p_T$ of the charged particles as a function of the
transverse momentum $p_T$ for different centrality classes in PbPb collision at $\sqrt{s_{NN}} = 5.02$ TeV. The $\Delta p_T$ is obtained from Eq. 5 with the parameters given in Table 2. The $\Delta p_T$ becomes constant for $p_T$ in the range 22 GeV/c to 160 GeV/c and increases as the collisions become more central.

Figure 7 shows the comparison of energy loss $\Delta p_T$ of the charged particles as a function of the transverse momentum $p_T$ for 0 - 5 % centrality class in PbPb collision at $\sqrt{s_{NN}} = 2.76$ and at 5.02 TeV. The $\Delta p_T$ at 5.02 TeV is similar but slightly more than that at 2.76 TeV.

Figure 8 shows the yields of the jets as a function of the transverse momentum $p_T$ for pp collisions at $\sqrt{s} = 2.76$ TeV measured by the ATLAS experiment [25]. The solid curve is the Hagedorn distribution fitted to the $p_T$ spectra, the parameters of which are given in Table 1.

Figure 9 shows the nuclear modification factor $R_{AA}$ of the jets as a function of the transverse momentum $p_T$ for different centrality classes in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV measured by the ATLAS experiment [25]. The solid curves are the $R_{AA}$ fitting function (Eq. 4). Here the modeling of centrality dependence using $N_{\text{part}}^\beta$ with $\beta = 0.60$ gives a good description of the data. The extracted parameters of the energy loss obtained by fitting the $R_{AA}$ measured in different centrality classes of PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are given in Table 3 along with the value of $\chi^2$/NDF. It shows that the $\Delta p_T$ increases as $p_T^{0.76}$ at all the values of $p_T$ measured for jets.

Figure 10 shows the shift $\Delta p_T$ of the jets as a function of the transverse momentum
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Figure 5. The nuclear modification factor $R_{AA}$ of the charged particles as a function of transverse momentum $p_T$ for various centrality classes in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV measured by the CMS experiment [24]. The solid lines are the $R_{AA}$ fitting function (Eq. 4).

$p_T$ for different centrality classes in PbPb collision at $\sqrt{s_{NN}} = 2.76$ TeV. The $\Delta p_T$ is obtained from Eq. 5 using the parameters given in Table 3. The $\Delta p_T$ increases from peripheral to the most central collision regions. The figure shows that the $\Delta p_T$ increases almost linearly at all the values of $p_T$ measured for jets.

Figure 11 shows the yields of the jets as a function of the transverse momentum $p_T$ for pp collisions at $\sqrt{s} = 5.02$ TeV measured by the ATLAS experiment [26]. The solid curve is the Hagedorn distribution with the parameters given in Table 1.

Figure 12 shows the nuclear modification factor $R_{AA}$ of the jets as a function of the transverse momentum $p_T$ for different centrality classes in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV measured by the ATLAS experiment [26]. The solid curves are the $R_{AA}$ fitting function.
Figure 6. The energy loss $\Delta p_T$ of the charged particles as a function of transverse momentum $p_T$ in PbPb collision at $\sqrt{s_{NN}} = 5.02$ TeV for different centrality classes.

Figure 7. The energy loss $\Delta p_T$ of the charged particles as a function of transverse momentum $p_T$ in PbPb collision at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV for 0 - 5 % centrality.
Figure 8. The yields of the jets as a function of transverse momentum $p_T$ for pp collision at $\sqrt{s} = 2.76$ TeV measured by the ATLAS experiment [23]. The solid curve is the fitted Hagedorn distribution.

Table 3. The extracted parameters of the shift $\Delta p_T$ obtained by fitting the jet $R_{AA}$ measured in different centrality classes of PbPb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV.

| Parameters | $\sqrt{s_{NN}} = 2.76$ TeV | $\sqrt{s_{NN}} = 5.02$ TeV |
|------------|-----------------|-----------------|
| $M$        | 0.33 ± 0.1      | 0.40 ± 0.12     |
| $C$ (GeV/c)| -55.1 ± 22.7    | -119 ± 15       |
| $\alpha$   | 0.76 ± 0.08     | 0.72 ± 0.01     |
| $\chi^2$/NDF | 0.30            | 0.25            |

function (Eq. 4). The modeling of centrality dependence is done with $N_{\text{part}}^\beta$ and the value of exponent is obtained as $\beta = 0.75$. The extracted parameters of the energy loss obtained by fitting the $R_{AA}$ measured in different centrality classes of PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are given in Table 3 along with the value of $\chi^2$/NDF. It shows that the $\Delta p_T$ increases as $p_T^{0.72}$ at all the values of $p_T$ measured for jets similar to the case of jets at $\sqrt{s_{NN}} = 5.02$ TeV.

Figure 13 shows the energy loss $\Delta p_T$ of the jets as a function of the transverse momentum $p_T$ for different centrality classes in PbPb collision at $\sqrt{s_{NN}} = 5.02$ TeV. The $\Delta p_T$ is obtained from Eq. 5 with the parameters given in Table 3. The $\Delta p_T$ increases from peripheral to the most central collision regions. The figure shows that the $\Delta p_T$ increases almost linearly at all the values of $p_T$ measured for jets.
Figure 9. The nuclear modification factor $R_{AA}$ of jets as a function of transverse momentum $p_T$ for various centrality classes in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV measured by the ATLAS experiment [25]. The solid curves are the $R_{AA}$ fitting function given by Eq. [4].
Figure 10. The shift $\Delta p_T$ of the jets as a function of transverse momentum $p_T$ in PbPb collision at $\sqrt{s_{NN}} = 2.76$ TeV for different centrality classes.

Figure 11. The yields of the jets as a function of transverse momentum $p_T$ for pp collision at $\sqrt{s} = 5.02$ TeV measured by the ATLAS experiment [26]. The solid curve is the fitted Hagedorn distribution.
Figure 12. The nuclear modification factor $R_{AA}$ of the jets as a function of transverse momentum $p_T$ for various centrality classes in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV measured by the ATLAS experiment [26]. The solid curves are the $R_{AA}$ fitting function given by Eq. [4].
Figure 13. The energy loss $\Delta p_T$ of the jets as a function of transverse momentum $p_T$ in PbPb collision at $\sqrt{s_{NN}} = 5.02$ TeV for different centrality classes.

Figure 14 shows the energy loss $\Delta p_T$ of the jets as a function of the transverse momentum $p_T$ in the most central (0-10%) PbPb collision at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV. These are compared with the $\Delta p_T$ obtained for charged particles in the 0-5% centrality class of PbPb collision at $\sqrt{s_{NN}} = 5.02$ TeV. The energy loss $\Delta p_T$ in case of jets for both the energies increases with $p_T$. The values of $\Delta p_T$ for jets at 5.02 TeV is more than that at 2.76 TeV. This behaviour at high $p_T$ is very different from the energy loss of charged particles which becomes constant in these $p_T$ regions. The modeling of centrality dependence of energy loss has been done using $N_{\text{part}}^3$. For charged particles, the centrality dependence of $p_T$ shift is found to be $N_{\text{part}}^{0.58}$ which corresponds to $L^{1.18}$. The centrality dependence for jets at $\sqrt{s_{NN}} = 2.76$ TeV is found to be $N_{\text{part}}^{0.60}$. In case of jets at 5 TeV, the centrality dependence of energy loss is found to be $N_{\text{part}}^{0.75}$ corresponding to $L^{1.5}$ which means that the jets even at very high energy are still away from complete coherent regime.
Figure 14. The energy loss $\Delta p_T$ of the jets as a function of transverse momentum $p_T$ in the most central PbPb collision at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV. The $\Delta p_T$ obtained for charged particles in the most central PbPb collision at $\sqrt{s_{NN}} = 5.02$ TeV is also shown.
4. Conclusions

We presented a study of partonic energy loss with $p_T$ shift extracted from the measured $R_{AA}$ of charged particles and jets in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV in wide transverse momentum and centrality range. The functional form of energy loss given by $\Delta p_T$ has been assumed as power law with different power indices in three different $p_T$ regions driven by physics considerations. The power indices and the boundaries of three $p_T$ regions are obtained by fitting the experimental data of $R_{AA}$ as a function of $p_T$ and centrality. The energy loss for light charged particles is found to increase linearly with $p_T$ in low $p_T$ region below 5-6 GeV/$c$ and approaches a constant value in high $p_T$ region above 25 GeV/$c$ with an intermediate power law connecting the two regions. The $\Delta p_T$ at 5.02 TeV is similar but slightly more than that at 2.76 TeV. In case of jets we consider only one $p_T$ region and it is found that for jets, the energy loss increases almost linearly even at very high $p_T$. The modeling of centrality dependence of energy loss has been done using $N_{part}^\beta$. For charged particles, the centrality dependence of $p_T$ shift is found to be $N_{part}^{0.58}$ which corresponds to $L^{1.18}$. The centrality dependence for jets at $\sqrt{s_{NN}} = 2.76$ TeV goes as $N_{part}^{0.60}$. In case of jets at 5 TeV, the centrality dependence of energy loss is found to be $N_{part}^{0.75}$ corresponding to $L^{1.5}$ which means that the jets even at very high energy are still away from complete coherent regime.

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