MULTIPARTONIC CASCADES IN EXPANDING MEDIA*

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In this work, we introduce both gluon and quark degrees of freedom for describing the partonic cascades inside the medium. We present numerical solutions for the set of coupled evolution equations with splitting kernels calculated for the static, exponential, and Bjorken expanding media to arrive at medium-modified parton spectra for quark- and gluon-initiated jets, respectively. We discuss novel scaling features of the partonic spectra between different types of media. Next, we study the inclusive jet R_{AA} by including phenomenologically driven combinations of quark and gluon fractions inside a jet. In addition, we have also studied the effect of the nPDF as well as vacuum-like emissions on the jet R_{AA}. Differences among the estimated values of quenching parameter for different types of medium expansions are noted. Next, the impact of the expansion of the medium on the rapidity dependence of the jet R_{AA} as well as jet v_2 is studied in detail. Finally, we present qualitative results comparing the sensitivity of the time for the onset of the quenching for the Bjorken profile on these observables. All the quantities calculated are compared with the recent ATLAS data.

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1. Theoretical background

The study of hard probes such as jets and their quenching features inside the hot and dense QCD medium formed in heavy-ion collisions such as the LHC and the RHIC can reveal interesting properties of the evolving medium. The effects of energy loss (quenching of jets) are studied using rate equations describing parton splittings in the medium. The rate itself is derived within the approximation of multiple-soft scattering in expanding media [1], and the in-medium distributions are found using a numerical solution of the coupled evolution equations [2, 3]. Our aim is to study the impact of the medium expansion on the jet quenching observables. To compare them to experimental data on jet production in heavy-ion collisions, we have included both gluon and quark degrees of freedom in the description of partonic cascades and emphasize the importance of precise modelling of the input parton spectra. In comparison to recent works on gluonic cascades [1, 4], we have included both the gluon and quark degrees of freedom for partonic cascades into the evolution equations for a more realistic description of medium evolved parton spectra for an expanding medium [3]. Therefore, we are able to provide the more precise study of the R_{AA} and estimate the quenching parameter, $\hat{q}$, to be extracted from the data. We shall use the optimized values of the jet quenching parameter which minimizes the differences in the inclusive R_{AA} among different medium profiles to study the inclusive jet suppression in a more differential way. Namely, we evaluate the rapidity dependence of the R_{AA} where experiment hints at a non-trivial behavior and then we evaluate the jet v_2 constructed from the path-length-dependent R_{AA}. This will allow us to quantify the impact of the way how the medium expands on these more differential observables which are being measured by experiments.

In order to describe the in-medium parton cascades, we start from the coupled evolution equations for the in-medium inclusive fragmentation function [2, 3, 5]

$$
\begin{aligned}
\frac{\partial}{\partial\tau} D_g\left(x,\tau\right) &= \int_0^1 \mathrm{d}z\, \mathcal{K}_{gg}(z) \left[\sqrt{\frac{z}{x}} D_g\left(\frac{x}{z},\tau\right) \Theta(z-x) - \frac{z}{\sqrt{x}} D_g(x,\tau)\right] \\
&\quad - \int_0^1 \mathrm{d}z\, \mathcal{K}_{qg}(z) \frac{z}{\sqrt{x}}\, D_g\left(x,\tau\right) + \int_0^1 \mathrm{d}z\, \mathcal{K}_{gq}(z) \sqrt{\frac{z}{x}}\, D_S\left(\frac{x}{z},\tau\right) , \\
\frac{\partial}{\partial\tau} D_S\left(x,\tau\right) &= \int_0^1 \mathrm{d}z\, \mathcal{K}_{qq}(z) \left[\sqrt{\frac{z}{x}} D_S\left(\frac{x}{z},\tau\right) \Theta(z-x) - \frac{1}{\sqrt{x}} D_S(x,\tau)\right]
\end{aligned}
\tag{1}
$$

$$+\int_0^1 \mathrm{d}z\,\mathcal{K}_{qg}(z)\sqrt{\frac{z}{x}}D_g\left(\frac{x}{z},\tau\right). \tag{2}$$

where $D_g(x)$ and $D_S(x) \equiv \sum_f \left[D_{q_f}(x) + D_{\bar{q}_f}(x)\right]$ are the gluon and quark singlet distributions, respectively. We define $\tau = \sqrt{\hat{q}_0/E}\,t$ as the evolution variable, $\hat{q}_0$ as the jet quenching coefficient in static medium, and t as the distance traversed in the medium. For our medium modelling, we consider three scenarios as follows:

— Static medium: For a static medium of finite medium length L, we have $\hat{q}(t) = \hat{q}_0\Theta(L-t)$. The splitting rate is defined as [1, 3, 6]

$$\mathcal{K}_{ij}(z,\tau) = \frac{\alpha_\mathrm{s}}{2\pi}P_{ij}(z)\kappa_{ij}(z)\,\mathrm{Re}\left[(i-1)\tan\left(\frac{1-i}{2}\kappa_{ij}(z)\tau\right)\right]. \tag{3}$$

In the above equation, $P_{ij}(z)$ is the (unregularised) Altarelli–Parisi splitting functions and $\kappa_{ij}(z)$ is enlisted in Appendix A of [3]. We shall also use the case of soft gluon emissions, *i.e.* $1-z, z \ll 1$ for the static medium.

— Exponential expanding medium: For exponentially expanding media, the splitting rate can be derived as [1, 3, 6]

$$\mathcal{K}_{ij}(z,\tau) = \frac{\alpha_\mathrm{s}}{\pi}P_{ij}(z)\kappa_{ij}(z)\,\mathrm{Re}\left[(i-1)\frac{J_1\big((1-i)\kappa_{ij}(z)\tau\big)}{J_0\big((1-i)\kappa_{ij}(z)\tau\big)}\right], \tag{4}$$

where $\hat{q}(t) = \hat{q}_0\,\mathrm{e}^{-t/L}$ is the jet quenching co-efficient.

— Bjorken expanding medium: The jet quenching parameter for the Bjorken expanding medium is defined as

$$\hat{q}(t) = \begin{cases} 0 & \text{for} \quad t < t_0\,, \\ \hat{q}_0(t_0/t) & \text{for} \quad t_0 < t < L + t_0\,, \\ 0 & \text{for} \quad L + t_0 < t\,. \end{cases} \tag{5}$$

The splitting rate is written as [1, 3, 6]

$$\begin{aligned}\mathcal{K}_{ij}(z,\tau,\tau_0) &= \frac{\alpha_\mathrm{s}}{2\pi}P_{ij}(z)\kappa_{ij}(z)\sqrt{\frac{\tau_0}{\tau+\tau_0}} \\ &\quad\times\mathrm{Re}\left[(1-i)\frac{J_1(z_L)Y_1(z_0) - J_1(z_0)Y_1(z_L)}{J_1(z_0)Y_0(z_L) - J_0(z_L)Y_1(z_0)}\right],\end{aligned} \tag{6}$$

where

$$\begin{aligned} z_0 &= (1-i)\kappa_{ij}(z)\tau_0\,, &(7)\\ z_L &= (1-i)\kappa_{ij}(z)\sqrt{\tau_0(\tau+\tau_0)}\,, &(8)\end{aligned}$$

with $\tau_0 = \sqrt{\hat{q}_0/E}t_0$.

Next, we shall use these medium-modified parton splitting functions for all possible combinations of parton splittings to numerically solve the medium evolved parton spectra [3] to arrive at a quenching factor of the jets in medium.

Thus, the quenching factor can be written as

$$\mathcal{Q}_{\{i=q/g\}}(p_\mathrm{T}) = \int\limits_0^1 \mathrm{d}x\, x^{n_i(p_\mathrm{T},y)-1} D\left(x, \sqrt{x}\tau; \{i\}\right)\,. \tag{9}$$

Subsequently, combining the contributions from the quark and gluons, the nuclear modification factor R_{AA} is written as [3]

$$\begin{aligned} R_{AA} &= \frac{\sigma_q^{0,\mathrm{med}}(p_\mathrm{T},y,R)}{\sigma_q^0(p_\mathrm{T},y,R)+\sigma_g^0(p_\mathrm{T},y,R)}\,\mathcal{Q}_q(p_\mathrm{T},R)\\ &\quad+\frac{\sigma_g^{0,\mathrm{med}}(p_\mathrm{T},y,R)}{\sigma_q^0(p_\mathrm{T},y,R)+\sigma_g^0(p_\mathrm{T},y,R)}\,\mathcal{Q}_g(p_\mathrm{T},R)\,, \end{aligned}\tag{10}$$

where $\sigma_i^{0,\mathrm{med}}$ is vacuum cross section with nPDF effects and jet cone-size R.

Finally, the path-length dependence of the jet quenching phenomena can be explored through the jet v_2 as [7]

$$v_2 = \frac{1}{2}\frac{R_{AA}\left(L^\mathrm{in}\right)-R_{AA}\left(L^\mathrm{out}\right)}{R_{AA}\left(L^\mathrm{in}\right)+R_{AA}\left(L^\mathrm{out}\right)}\,, \tag{11}$$

where L are the medium lengths traversed by the jet particle in the direction along (in) or perpendicular (out) to the event plane. The values of L^in and L^out are listed in Ref. [3].

2. Results and conclusions

We present the comparisons among different medium profiles for the R_{AA} as a function of p_T and R_{AA} ratio as a function of rapidity in Fig. 1. We have used the optimised values of $\hat{q}_0$ as outlined in Table 2 of [3]. For our purpose, we have included both the nPDF as well as vacuum-like emissions

(VLE) effects for the input parton spectra for all the medium profiles [3]. In Fig. 1 (left), although the differences in the magnitude and shape of R_{AA} among different medium profiles are small, they differ considerably in the optimised $\hat{q}_0$ values. Inclusion of the quark along with the gluon jets improves the level of completeness of the jet energy loss prescription for all the medium profiles. The extracted $\hat{q}_0$ values differ from the ones in [1] leading to the breakdown of the effective scaling laws observed in [1]. Next,

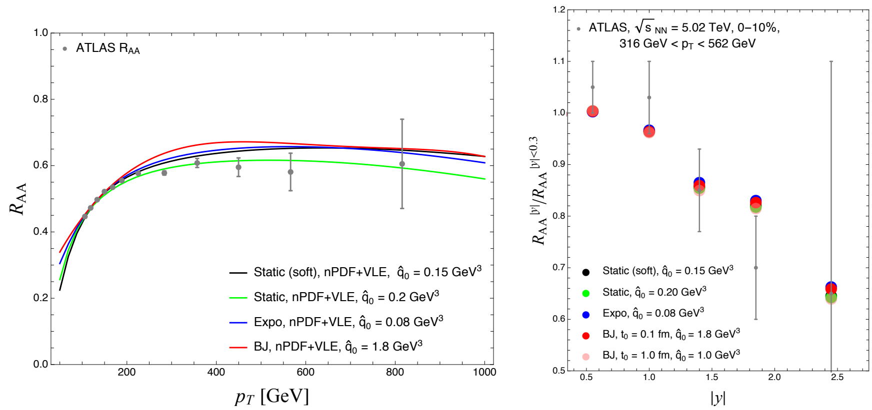

Fig. 1. (Left panel) The comparison of the jet R_{AA} for four medium profiles with the ATLAS data (in gray) [8]. (Right panel) The rapidity ratio of R_{AA} in different $|y|$ bins and R_{AA} in $|y| < 0.3$ for $p_{\mathrm{t}} = 316 - 512$ GeV.

in Fig. 1 (right), we plot the R_{AA} ratio for different medium profiles as a function of rapidity and compare with the ATLAS data [8]. Thus, we see that the rapidity dependence does not allow to distinguish between static, exponential, and Bjorken medium profiles [3]. The trends seen in the ratio of R_{AA} in rapidity are the same for all the medium profiles. We conclude that the rapidity dependence is due to a change in the steepness of input parton spectra [3]. Next, in Fig. 2, we study the jet v_2 with p_{T} for different medium profiles compared with measurements from Refs. [9, 10]. We note a difference in the Bjorken profile with $t_0 = 0.1$ fm with the static and exponential profiles. A factor of two difference can also be observed between the two Bjorken profiles implying that the jet v_2 is sensitive to the choice of t_0 [3, 11]. These results of jet rapidity dependence and v_2 presented highlight the sensitivity of the medium expansion on the observed phenomena of jet quenching in heavy-ion collisions.

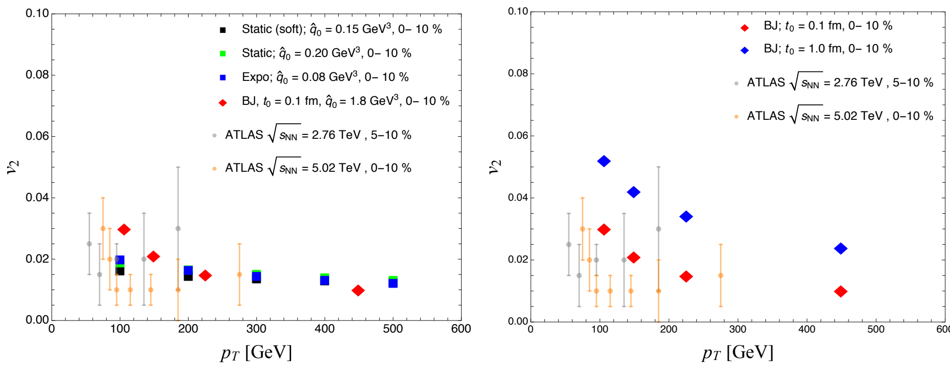

Fig. 2. Comparison of the jet v_2 for the static medium, exponential medium, and the Bjorken medium with $t_0 = 0.1$ fm (left panel). Similar comparison (right panel) for Bjorken media for $t_0 = 0.1$ fm (early quenching) and $t_0 = 1.0$ fm (late quenching). ATLAS data from [9, 10].

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