PARTON ENERGY LOSS AND CHARMONIA SUPPRESSION IN HEAVY-ION COLLISIONS*

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Understanding the energy loss of partons traversing the strongly interacting matter created in heavy-ion collisions is one of key goals of the heavy-ion physics program. We present results of phenomenological analyses of various recent jet quenching data and data on charmonia suppression. The core of the model used in these analyses is based on the shift formalism which allows for an extraction of the magnitude of parton energy loss from the data with minimal assumptions on the underlying physics mechanisms.

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1. Suppression of jets and charmonia

The basic motivation for studying jets and quarkonia in heavy-ion collisions is to understand the properties of hot and dense deconfined matter created in those collisions, which is often called quark–gluon plasma [1]. Quarks and gluons with large transverse momentum (p_{T}) can be produced in hard scattering processes in both pp collisions and heavy-ion collisions. When produced in pp collisions, these high-p_{T} quarks and gluons shower and form observed jets. When produced in a collisions of two heavy ions, the parton shower or its constituents propagate through the QGP and interact with it [2–4]. The baseline result of that interaction can be quantified by the measurement of nuclear modification factor which is defined as

$$R_{AA} = \frac{\left.\frac{1}{N_{\mathrm{evt}}^{\mathrm{tot}}} \frac{\Delta^2 N_{\mathrm{jet}}}{\Delta p_{\mathrm{T}} \Delta y}\right|_{\mathrm{centrality}}}{\left. T_{AA} \frac{\Delta^2 \sigma_{\mathrm{jet}}}{\Delta p_{\mathrm{T}} \Delta y}\right|_{pp}} . \tag{1}$$

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Here, $N_{\mathrm{evt}}^{\mathrm{tot}}$ is the total number of Pb+Pb collisions within a chosen centrality bin, T_{AA} is the nuclear thickness function (that accounts for the geometric enhancement of per-collision nucleon–nucleon luminosity), and N_{jet} and σ_{jet} is the number of jets and the inclusive jet cross section, respectively.

The R_{AA} of jets [5,6] and charged particles [7–10] was studied in details in heavy-ion collisions at $\sqrt{s_{NN}} = 2.76$ TeV at the LHC. The R_{AA} of jets was observed to exhibit only mild dependence on jet p_{T} with values near 0.5 in 0–10% central heavy-ion collisions in the p_{T} region of 50–300 GeV. The R_{AA} of charged particles at high-p_{T} ($p_{\mathrm{T}} \gtrsim 20$ GeV) was observed to steeply increase and eventually to plateau near $p_{\mathrm{T}} = 100$ GeV. Both the R_{AA} of jets and the R_{AA} of charged hadrons were observed not to exhibit any strong dependence on rapidity (y) of the jet or rapidity of the charged hadron, respectively. Both the relative flatness with p_{T} and the absence of rapidity dependence are features that are *a priori* not expected given a difference in the initial parton spectra and flavor composition at different rapidities. Complementary to those measurements is a measurement of fragmentation functions [11–13] where a fragmentation function is defined *e.g.* as

$$D(z) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{\Delta N_{\mathrm{ch}}}{\Delta z} \,. \tag{2}$$

Here, N_{ch} is the number of charged particles and N_{jet} is the number of jets under consideration, and $z \equiv p_{\mathrm{T}}^{\mathrm{trk}} \cos \Delta R / p_{\mathrm{T}}^{\mathrm{jet}}$ is the longitudinal momentum fraction of particles inside the jet. In order to quantify any differences between Pb+Pb and pp collisions, the ratios of the fragmentation functions are measured

$$R_{D(z)} \equiv \frac{D(z)_{\mathrm{PbPb}}}{D(z)_{pp}} \,. \tag{3}$$

The $R_{D(z)}$ distributions measured in 2.76 TeV collisions exhibit an enhancement in fragment yield in central collisions for $0.01 < z < 0.04$, a reduction in fragment yields for $0.04 < z < 0.2$, and an enhancement in the fragment yield for $z > 0.2$. The magnitude of these modifications decreases in more peripheral collisions.

Suppression of charmonia in $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions was also quantified by the measurement of the nuclear modification factor. The R_{AA} of J/Ψ was measured in mid-rapidity by the CMS Collaboration [14] in the p_{T} interval of 6.5–30 GeV and it reaches a value of ≈ 0.2 in 0–5% central collisions with only weak (if any) dependence on the J/Ψ momentum. The rapidity dependence of the modification is also weak. Further, the measurements showed that $\Psi(2S)$ yields are suppressed by a factor of ≈ 2 with respect to J/Ψ in the range of $|y| < 1.6$ [15].

The strong suppression of jets and charmonia exhibiting the above described features calls for the understanding. In the next section, we will discuss one particular approach how to understand some of the basic features seen in the data.

2. Modeling the parton energy loss

Interpretation of the inclusive jet suppression and fragmentation data is complicated by the flavor admixture of the primordial partons. To address this primary complication, we proposed a model [16] which is based on parameterizations of initial parton spectra and the parton energy loss. The only assumption on the physics of the jet quenching in this model is the functional form for the parton energy loss which is assumed to be of the power-law form — the total transverse momentum lost by the parton is

$$\Delta p_{\mathrm{T}} = c_{\mathrm{F}}\, s \left(\frac{p_{\mathrm{T,ini}}}{p_{\mathrm{T,0}}}\right)^{\alpha} . \tag{4}$$

Here, s, α, and c_{F} are free parameters of the model, $p_{\mathrm{T,ini}}$ is the transverse momentum of a parton initiating a jet and $p_{\mathrm{T,0}}$ is an arbitrary scale (set to 40 GeV). Parameter c_{F} represents a color factor which quantifies the difference between the in-medium radiation of quark-initiated jets and gluon-initiated jets. While this model was labeled Effective Quenching (EQ) model, it could very well be called the *model-independent method* which allows to extract basic properties of the *average* parton energy loss.

The model is capable of describing the full p_{T}, rapidity, and centrality dependence of the measured jet nuclear modification factor using three independent parameters as follows [17]:

$s = x\, N_{\mathrm{part}} + y$	$x = (12.3 \pm 1.4) \times 10^{-3}$ GeV $y = 1.5 \pm 0.2$ GeV
α	0.52 ± 0.02
c_{F}	1.78 ± 0.12

This implies that, for example, jet initiated by a quark with $p_{\mathrm{T}} =$ 100 GeV loses approximately 12 GeV. This also implies that the absence of the rapidity dependence seen in the jet R_{AA} is a consequence of a cancellation between two competing effects which evolve with increasing rapidity: steepening of initial parton spectra and enhancing the fraction of quark initiated jets. While the former alone generally leads to a smaller R_{AA}, the latter alone generally leads to a larger R_{AA}. It is also important to note that the extracted value of c_{F} is consistent with the value calculated and measured in the vacuum which is ≈ 1.8 at the jet hardness $Q \simeq$ 20–100 GeV [18, 19].

The analysis done using this model can be used to understand the modification of fragmentation functions at high and intermediate z observed in the data as well as the relation between the magnitude of the nuclear modification factor of jets and charged particles. The main principle of the modeling is following: subtract the energy from the initial parton and then let it fragment as in the vacuum. The modifications seen in $R_D(z)$, excluding the enhancement at low-z, are described by the model. An example is shown in Fig. 1. Thus, it may be concluded that these modifications result primarily from the different quenching of the quark and gluon jets. The assumption on the fragmentation of the quenched parton used here reflects a physics scenario in which the parton shower looses the energy coherently which was previously recognized in detailed theory calculations to play an important role in the jet quenching process [20–23].

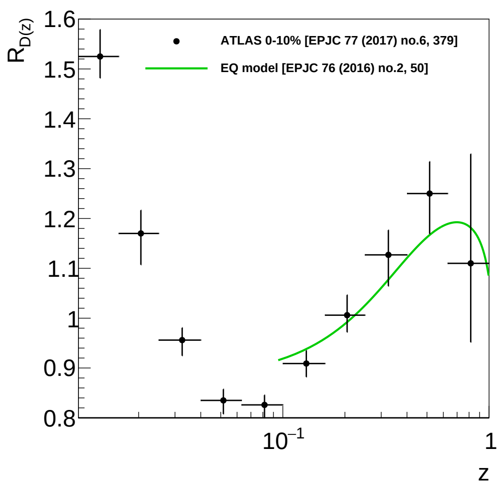

Fig. 1. Comparison of the model with $R_{D(z)}$ measured by ATLAS in 0–10% Pb+Pb collisions.

The charged particle R_{AA} and jet R_{AA} can, in principle, be connected using fragmentation functions since each charged particle with sufficiently high-p_{T} which does not come from the underlying event has to be found in a jet. Indeed, the model can reasonably well reproduce the R_{AA} of inclusive charged particles at $p_{\mathrm{T}} \gtrsim 20$ GeV [16].

The ability of EQ model to successfully describe jet R_{AA} in all measured rapidity bins, inclusive charged particle R_{AA} at high-p_{T}, and details seen in the inclusive jet fragmentation functions speaks strongly in favor of a physics picture in which parton shower or its large part looses the energy coherently. If this is the case, one can ask if it is possible to find some similarities between the suppression of jets and a suppression of other objects with an internal structure such as, for example, charmonia. The similarity between the jet suppression and charmonia suppression was explored in Ref. [17]. The EQ model was used to explore charmonia suppression having in the input $p_{\rm T}$ spectra of J/Ψ and $\Psi(2S)$ from PYTHIA 8 [24] reweighted to reproduce the data measured in pp collisions at the 2.76 TeV [25]. A very good agreement of the model with the data for the case of the light-quark energy loss was seen. The $N_{\rm part}$, $p_{\rm T}$ and rapidity dependence of the R_{AA} of J/Ψ were reproduced. Remarkably, the model was also able to reproduce the larger suppression of $\Psi(2S)$ with respect to J/Ψ.

The striking similarity between the measured J/Ψ and $\Psi(2S)$ suppression and the energy loss of jets suggests that the radiative energy loss may be a dominant contribution to the energy loss of charmonia in the studied kinematic region.

3. Summary

Various aspects of the jet quenching can be understood as resulting from the difference between the suppression of quark-initiated and gluon-initiated jets. Generally, jet quenching and charmonia suppression can provide important information about the properties of QGP, however, not only that. They can also help to understand some aspects of the hadron formation: space-time scales of the hadron formation via well-defined space-time scales of QGP; role of color such as the color-octet *versus* color-singlet production of charmonia.

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