

Physics probed by the P_T dependence of the nuclear suppression factor

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The nuclear suppression factor R_{AA} of single inclusive hadrons measured in ultrarelativistic heavy-ion collisions was the first observable to study jet quenching, i.e., the final state interaction of hard parton showers with the surrounding bulk matter. While its transverse momentum (P_T) dependence of R_{AA} observed at RHIC was weak and hence never decisive in constraining models, there is now a strong and nontrivial P_T dependence observed at the LHC. This has been a challenge for several models which worked well at RHIC kinematics. However, in more general terms it is also of importance to understand what physical properties of the hard process and the parton-medium interaction are reflected in $R_{AA}(P_T)$. The results of the work presented here suggest that the two main effects underlying the P_T dependence are the Quantum-Chromodynamics scale evolution of the fragmentation function and the limited distance (set by the typical medium length scale) for which a shower evolves in the medium.

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I. INTRODUCTION

The single inclusive hadron nuclear suppression factor R_{AA} is defined as the hadron yield in heavy-ion (A-A) collisions of given centrality, divided by the yield in p-p collisions, scaled with the number of binary nucleon-nucleon collisions occurring in the heavy-ion case,

$$R_{AA}(P_T, y) = \frac{dN_{AA}^h/dP_T dy}{T_{AA}(\mathbf{b})d\sigma^{pp}/dP_T dy}. \quad (1)$$

It is by construction unity if there are neither initial nor final state interactions affecting hard Quantum-Chromodynamics (QCD) processes in A-A collisions. Experimentally, the indication of $R_{AA} \ll 1$ was taken as one of the crucial verifications of the collective nature of A-A collisions, as such an observation indicates significant final state interaction of hard partons with hot and dense matter.

Results for R_{AA} were the first indication of jet quenching in the RHIC era [1] and among the first reported findings at the start of the LHC heavy-ion program [2]. Unlike at RHIC, the first results from LHC showed a strong rise of R_{AA} with P_T with a minimum well below the RHIC value. Later results from the CMS collaboration out to 100 GeV [3] then showed that the rise does not continue but rather appears to level off from about 40 GeV onward at a value of ~ 0.6 .

The strong rise of R_{AA} was unexpected for a number of models which tended to overestimate the expected suppression at the LHC [for instance, [4,5] indicated that the Armesto-Salgado-Wiedemann (ASW) formalism [6] underpredicted the measured R_{AA} , [7] showed the same thing for the Wicks-Horowitz-Djordjevic-Gyulassy (WHDG) formalism, [8] for the Arnold-Moore-Yaffe (AMY) formalism, and [5] also demonstrated the failure of an AdS/CFT motivated framework [9]] but could be reproduced in others, in particular the higher twist framework [10,11]. The P_T dependence of R_{AA}

has consequently been recognized as an important tool to distinguish models which yield near-identical results at RHIC kinematics [5,12].

There is, however, significantly less information available on what physics drives the P_T dependence of R_{AA} in various models and what particular scenarios are supported or disfavored by the data. It is the aim of this work to illustrate the rich combination of various effects leading to the observed P_T dependence using the example of the in-medium shower evolution code YaJEM [13–15].

II. QUALITATIVE ESTIMATES

A. Simple considerations

Following the discussion in [12], the most general representation of the partonic final state interaction in a hot medium is the medium-modified fragmentation function (MMFF) $D_{i \rightarrow h}(z, E_i, Q_i^2 | T_1(\zeta), T_2(\zeta), \dots, T_n(\zeta))$, i.e., the distribution of hadrons h given a parton i with initial energy E_i and initial virtuality Q_i^2 where the hadron energy $E_h = zE$ and the parton has traversed a medium along the path ζ where $T_i(\zeta)$ are the medium transport coefficients relevant for the process. If the MMFF can be computed, its convolution with the perturbatively calculable parton spectrum gives the medium-modified hadron yield.

A frequently used simplification in the case of leading hadron observables is the so-called energy loss approximation,

$$D_{i \rightarrow h}(z, E, Q_i^2 | T_i(\zeta)) \approx P(\Delta E, E | T_i(\zeta)) \otimes D_{i \rightarrow h}(z, Q_i^2), \quad (2)$$

where the MMFF is replaced by an energy loss probability distribution $P(\Delta E, E | T_i(\zeta))$ for the leading parton which is convoluted with the vacuum fragmentation function $D_{i \rightarrow h}(z, Q_i^2)$ which only depends on the momentum fraction z and the scale at which the process takes place.

Using a very simple constant energy loss assumption, a qualitative argument why R_{AA} should generically increase

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with P_T can be made as follows [16]: Parton spectra in pQCD can be approximated by a power law as $dN/dp_T = \text{const.}/p_T^n$ where $n \approx 7$ for RHIC kinematics and $n \approx 5$ at LHC. Assuming that one can approximate the effect of the medium by the mean value energy loss $\langle \Delta E \rangle$ (for realistic energy loss models, this is not a good approximation, as fluctuations around the mean turn out to be large), the energy loss corresponds to a shift in the parton spectrum prior to fragmentation (note that this does not correspond to a realistic space-time picture of the reaction—the uncertainty relation suggests that the scale evolution of the fragmentation function takes place in medium).

The shift can be taken into account by the replacement $p_T \rightarrow p_T + \langle \Delta E \rangle$ in the expression for the parton spectrum. $R_{AA}(p_T)$ can then be approximated by the ratio of the parton spectra before and after energy loss as

$$R_{AA}(p_T) \approx \left(\frac{p_T}{p_T + \langle \Delta E \rangle} \right)^n = \left(1 - \frac{\langle \Delta E \rangle}{p_T + \langle \Delta E \rangle} \right)^n, \quad (3)$$

and it is easily seen that this expression approaches unity for $p_T \gg \langle \Delta E \rangle$ and that n governs how fast this limit is approached.

In contrast, assuming a constant fractional energy loss $\Delta E = zp_T$ leads to a suppression factor independent of p_T in a power law approximation, as

$$R_{AA}(p_T) \approx \left(\frac{p_T}{p_T + zp_T} \right)^n = \left(\frac{1}{1+z} \right)^n. \quad (4)$$

However, in reality the perturbative QCD (pQCD) parton spectrum is only locally approximated by a power law and the power n of a local fit to the spectrum increases with p_T in the kinematically accessible range. This implies that the constant energy loss scenario approaches unity more slowly for a real spectrum than for a simple power law approximation and that constant fractional energy loss leads to a *decrease* of R_{AA} with P_T in the realistic case (see, e.g., [17] for an explicit calculation).

It follows that the P_T dependence of R_{AA} is always determined from a *combination* of parton-medium interaction physics and shape of the primary parton spectrum.

B. The role of in-medium shower evolution

As indicated above, a more realistic treatment of parton-medium interaction involves computing the MMFF. In the following, we illustrate the chief additional mechanisms generating P_T dependence of R_{AA} using the example of the in-medium shower evolution Monte Carlo (MC) code YaJEM [13–15].

In the absence of a medium, YaJEM is identical to the PYSHOW algorithm [18] which evolves partons as a series of $a \rightarrow bc$ branchings in the energy fraction $z = E_b/E_a$ and the virtuality $t = \ln(Q_a^2)/\Lambda_{\text{QCD}}^2$ with $\Lambda_{\text{QCD}} = O(300)$ MeV, starting from an initial virtuality scale Q_i which is given by the momentum scale of the hard process. This series of branchings terminates at a lower scale Q_0 , at which point nonperturbative dynamics is assumed to dominate and the Lund hadronization model [19] is used.

In YaJEM, it is assumed that the virtuality Q_a^2 and energy E_a of any intermediate shower parton a is modified by the medium via two transport coefficients, \hat{q} and \hat{e} as

$$\Delta Q_a^2 = \int_{\tau_a^0}^{\tau_a^0 + \tau_a} d\zeta \hat{q}(\zeta), \quad (5)$$

and

$$\Delta E_a = \int_{\tau_a^0}^{\tau_a^0 + \tau_a} d\zeta \hat{e}(\zeta) \quad (6)$$

as the parton propagates along the path ζ . To evaluate these equations requires a mapping of the shower evolution of PYSHOW in momentum space to the hydrodynamical evolution in position space and a model of the transport coefficients as a function of thermodynamical properties of the medium.

The temporal structure of the shower evolution can be parametrically recovered by uncertainty arguments. The mean lifetime of a virtual parton b coming from a parent a is hence given as

$$\langle \tau_b \rangle = \frac{E_b}{Q_b^2} - \frac{E_b}{Q_a^2}. \quad (7)$$

In the MC simulation of the shower, the actual lifetime is determined from this mean value according to the probability distribution

$$P(\tau_b) = \exp \left[-\frac{\tau_b}{\langle \tau_b \rangle} \right], \quad (8)$$

(for a detailed derivation of the time ordering in a MC shower; see [20]).

Two important observations follow: Medium-induced changes of the shower kinematics are not significant if $Q^2 \gg \Delta Q^2$ (or $E \gg \Delta E$). Probing R_{AA} at higher P_T corresponds to probing higher values of the initial virtuality scale Q_i and to higher values of parton energies E_i , and thus both the partonic shower evolution as well as the part of the shower evolution in which $Q^2 \gg \Delta Q^2$ grow with P_T (this is the MC shower equivalent of the QCD scale evolution of the fragmentation function). As a result, vacuum and in-medium shower evolution become progressively similar at high P_T with the implication $R_{AA} \rightarrow 1$ (see [16] for an explicit computation)—the QCD scale evolution thus has a generic tendency to increase R_{AA} .

At the same time, effects at the lower scale Q_0 also influence R_{AA} . As Eq. (7) indicates, at sufficiently high E the formation length of a branching eventually exceeds the dimensions of the medium. If the medium is characterized by a length scale L , the in-medium evolution of the shower will thus proceed only down to a scale $Q_0 = \sqrt{E/L}$ [21,22]. This in turn implies that for jets with large E the intermediate virtuality Q will never be small while the jet is still in medium and hence $Q^2 \gg \Delta Q^2$ will always be realized. In essence, the fact that the length scale for shower evolution can exceed the medium dimensions also implies $R_{AA} \rightarrow 1$ for sufficiently large P_T [15].

While these two mechanisms have been discussed here in the specific context of YaJEM, they are in fact more generic. The lower scale being set by the medium dimensions is a

consequence of the uncertainty principle and thus difficult to avoid in any model, while the weakening influence of the medium for longer QCD scale evolution is based on a scale comparison and closely analogous to the loss of sensitivity to the low Q^2 nonperturbative parton distributions when an initial scale evolution is carried out to a high virtuality (see, for instance, [23]).

C. Minor effects

There are yet more effects which shape the P_T dependence of R_{AA} to some degree. One of them is the composition of the primary parton spectrum. Because gluons carry a color charge different from quarks and interact with a factor $C_F = 9/4$ more strongly, gluons also experience stronger medium-induced suppression than quarks. However, the ratio of quarks to gluons in the pQCD parton spectrum varies as a function of p_T ; while the low p_T part is dominated by gluon production, at high p_T quark production takes over. Corresponding to this transition, there is a slight rise in R_{AA} reflecting the lower interaction strength of quarks [16].

Similarly, while one usually attributes the modification of inclusive hard hadron spectra to the final state interaction with the hot and dense medium which is not present in the case of p-p collisions, there is also a modest change of the initial state comparing p-p with A-A collisions, which is parametrized by the nuclear parton distribution functions (nPDFs), e.g., [23–25]. The x dependence of the nPDFs, mapped to a p_T dependence in the parton spectrum after convolution of the initial state parton distributions with the perturbative hard scattering cross section, leads to a nontrivial P_T dependence of R_{AA} even in the absence of final state interactions and, e.g., a sizable enhancement of A-A over p-p near the kinematic limit [16].

In the kinematic range of current LHC measurements of R_{AA} , however, both the transition of the dominant parton type and the nuclear initial state effects change R_{AA} by less than 5%; hence we will in the following take the effects consistently into account but not discuss them in further detail.

III. DETAILED MODELING

A. Embedding into fluid dynamics

To obtain the medium-modified hadron yield, the MMFF must be averaged over the medium geometry. In this work, the medium evolution is taken to be a constrained 2 + 1D hydrodynamics evolution, extrapolated from RHIC to LHC kinematics using the EKRT model [5]. It is of some importance that a realistically evolving medium is utilized as a background, because embedding into, e.g., a static background can lead to a core-corona scenario [26] in which partons inside a certain geometrical region are strongly suppressed whereas partons produced in the corona escape the medium unmodified. Such a geometrical suppression picture can alter the P_T dependence of R_{AA} [17], however, this is an unphysical artefact of unrealistic modeling.

The probability density $P(x_0, y_0)$ for finding a hard vertex at the transverse position $\mathbf{r}_0 = (x_0, y_0)$ and impact parameter

\mathbf{b} is in leading order pQCD given by the product of the nuclear profile functions as

$$P(x_0, y_0) = \frac{T_A(\mathbf{r}_0 + \mathbf{b}/2)T_A(\mathbf{r}_0 - \mathbf{b}/2)}{T_{AA}(\mathbf{b})}, \quad (9)$$

where the thickness function is given in terms of Woods-Saxon, the nuclear density $\rho_A(\mathbf{r}, z)$ as $T_A(\mathbf{r}) = \int dz \rho_A(\mathbf{r}, z)$, and $T_{AA}(\mathbf{b})$ is the standard nuclear overlap function $T_{AA}(\mathbf{b}) = d^2\mathbf{s} T_A(\mathbf{s})T_A(\mathbf{s} - \mathbf{b})$.

If the angle between outgoing parton and the reaction plane is ϕ , the path of a given parton through the medium $\zeta(\tau)$, i.e., its trajectory ζ as a function of proper medium evolution time τ is determined in an eikonal approximation by its initial position \mathbf{r}_0 and the angle ϕ as $\zeta(\tau) = (x_0 + \tau \cos(\phi), y_0 + \tau \sin(\phi))$ where the parton is assumed to move with the speed of light $c = 1$ and the x direction is chosen to be in the reaction plane.

The transport coefficients used in YaJEM are then obtained from the hydrodynamical energy density ϵ as

$$\hat{q}(\zeta) = K \cdot 2 \cdot \epsilon^{3/4}(\zeta)(\cosh \rho - \sinh \rho \cos \alpha), \quad (10)$$

and

$$\hat{e}(\zeta) = K_E \cdot 2 \cdot \epsilon^{3/4}(\zeta)(\cosh \rho - \sinh \rho \cos \alpha), \quad (11)$$

where K and $K_E = 0.08K$ are parameters determining the overall normalization of the coefficients, ρ is the local flow velocity of the medium, and α is the angle between parton propagation direction and flow direction. In the following, to focus on the P_T dependence of R_{AA} and make the various influences discussed below comparable, K is always adjusted such that R_{AA} at 10 GeV reproduces the data.

If $D_{i \rightarrow h}(z, E_i, Q_i | \zeta)$ is the MMFF as computed in YaJEM for the path ζ , then the medium-averaged MMFF is obtained as

$$\begin{aligned} \langle D_{i \rightarrow h}(z, E_i, Q_i) \rangle_{T_{AA}} \\ = \frac{1}{2\pi} \int_0^{2\pi} d\phi \int_{-\infty}^{\infty} dx_0 \int_{-\infty}^{\infty} dy_0 P(x_0, y_0) D_{i \rightarrow h}(z, E_i, Q_i | \zeta). \end{aligned} \quad (12)$$

From this, the medium-modified production of hadrons is obtained from

$$d\sigma_{\text{med}}^{AA \rightarrow h+X} = \sum_i d\sigma_{\text{vac}}^{AA \rightarrow i+X} \otimes \langle D_{i \rightarrow h}(z, E_i, Q_i) \rangle_{T_{AA}}, \quad (13)$$

from where R_{AA} can be obtained.

B. The role of the evolution scales

As discussed above, the MMFF is obtained from a partonic shower evolution in medium starting from a virtuality scale Q_i and extending down to a scale $Q_0 = \sqrt{E/L}$, followed by a further evolution in vacuum down to the nonperturbative hadronization scale Q_h , taken to be 1 GeV in the following. To study the importance of the evolution of these scales with P_T , let us first consider the outcome of a calculation where the scales are held fixed.

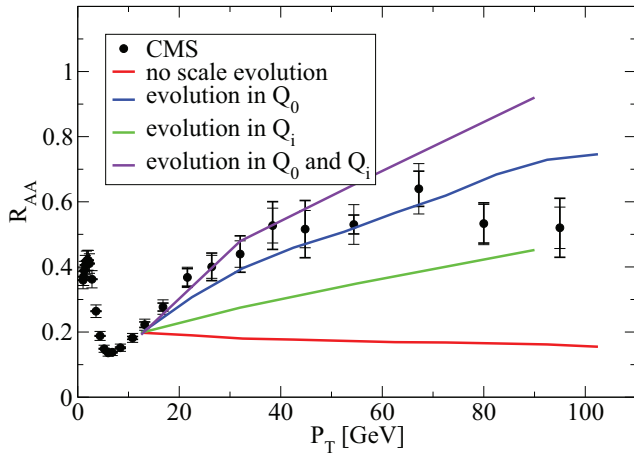


FIG. 1. (Color online) P_T dependence of R_{AA} as obtained by the CMS collaboration [3] in comparison with YaJEM results with different treatment of upper and lower partonic evolution scale.

Using $Q_i = 20$ GeV, $Q_0 = Q_h = 1$ GeV, we generate an MMFF without scale dependence which is used throughout the kinematic range considered. Because this resulting MMFF, once averaged over the medium, retains only a dependence on the fractional momentum z , all medium modification is necessarily formulated as a function of z as well. The alert reader will realize that this corresponds closely to a constant fractional energy loss scenario in which a *decrease* of R_{AA} is expected after folding with a pQCD parton spectrum. As Fig. 1 shows, this is indeed the case, resulting in a curve in striking disagreement with the data (note that the earliest YaJEM results did not include scale evolution and thus showed this trend [13]).

If the in-medium evolution is not terminated at $Q_0 = 1$ GeV but rather at the scale $Q_0 = \sqrt{E/L}$ as dynamically computed given the parton initial position, path and energy in the MC simulation, with the initial scale Q_i still held fixed at 20 GeV and vacuum evolution carried out between Q_0 and Q_h , the trend reverts to a rise with P_T and reasonable agreement with the data is found.

Likewise, if the lower scale is fixed to $Q_0 = 1$ GeV but Q_i is allowed to vary with initial parton energy E (corresponding to the usual QCD scale evolution of the fragmentation function), the decreasing trend reverts to a rising trend, albeit a weaker one as in the previous case which is not in agreement with the data.

Finally, in the realistic case in which both scales are allowed to vary, a strong rise of R_{AA} with P_T is observed, overshooting the data in the region beyond 40 GeV (note that this corresponds to the curve published in [5]).

While these results establish that the treatment of the shower evolution scales is a crucial influence on the P_T dependence of R_{AA} , the outcome that the most realistic evolution scenario overshoots the data is somewhat unsatisfactory.

C. A closer look at the lower evolution scale

While the QCD evolution of the MMFF in terms of Q_i is a concept which is well understood in vacuum QCD, the

determination of the lower scale Q_0 is not on the same level or rigor. The expression $Q_0 = \sqrt{E/L}$ is parametrically set by the uncertainty relation, but this implies that the expression is valid up to a factor $O(1)$ and hence begs the question of precisely what E and what L should be inserted into it.

For instance, rather than estimating the lower scale for the whole jet (using the shower-initiating parton energy E) we might also take the leading subjet based on the argument that we are considering an observable which is predominantly sensitive to the fragmentation of leading partons, and thus what determines the medium modification of these is only the subjet in which the leading parton is found. This would argue for a relation $Q_0 = \sqrt{fE/L}$ with $f \approx 0.7$ at RHIC and $f \approx 0.5$ at LHC.

Likewise, the in-medium distance is typically taken as the distance of the hard reaction vertex to the Cooper-Frye surface of the hydrodynamically evolving medium. However, as discussed in [27], there is no compelling reason to use precisely the Cooper-Frye surface. In the context of fluid dynamics, the Cooper-Frye surface is usually taken to be an isothermal surface representing an idealized separation of matter which is interacting so strongly that fluid dynamics is justified and matter interacting so weakly that free streaming is valid. In contrast, jet-medium interactions do not require medium particles to interact, they merely require the presence of scattering centers, and hard partons would interact also with a free streaming hadronic medium. This may indicate that a realistic L would be somewhat larger than the distance to the Cooper-Frye surface.

Estimating the decoupling of the jet to be on average 20% beyond the Cooper-Frye surface and taking only the subjet of the leading parton into account results in a plausible scenario with $f = 0.4$ which we explore in Fig. 2.

It is apparent from the figure that using $f = 0.4$ is just enough to compensate the effect of the QCD scale evolution in the kinematic range considered, resulting in a scenario which is in agreement with the data up to 70 GeV while still overshooting the last two data points. Thus, within plausible

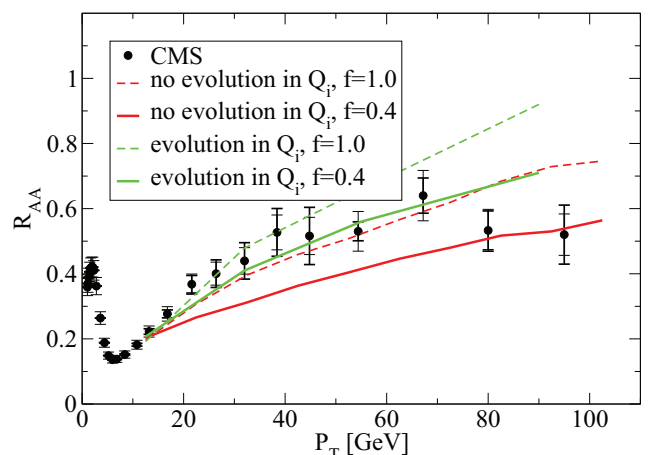


FIG. 2. (Color online) P_T dependence of R_{AA} as obtained by the CMS collaboration [3] in comparison with YaJEM results varying the parametric estimate for the lower scale.

variations of the parametric expression for the lower scale, the realistic computation gives a fair account of the data.

D. The plateau region

The question remains whether the trend indicated by the data is a plateau at high P_T or not. There is no easy theoretical argument why R_{AA} should reach a plateau at around 40–60 GeV. Both upper and lower scale evolution arguments asymptotically imply $R_{AA} \rightarrow 1$. The increasing power $n(p_T)$ of local power law fits to the pQCD spectrum imply also a decreasing sensitivity to parton energy loss at least up to $\sqrt{s}/4$ (beyond phase space restrictions become important [16]). Neither a constant energy loss nor a constant fractional energy loss would thus result in a constant R_{AA} , rather achieving a constant R_{AA} would require fine tuning of the parton-medium interaction strength to just compensate for the effects from the shape of the parton spectrum and the scale evolutions.

One idea which could provide such a mechanism is the energy dependence of the transport coefficient \hat{q} as suggested in [28]. To explore this idea, we parametrize the result of $\hat{q}(E)$ for a temperature of 400 MeV from Fig. 9 in [28] as

$$\hat{q}(E) = \hat{q}(10 \text{ GeV}) \cdot \left(1.8 \frac{E}{1 \text{ GeV}} - 1.8\right), \quad (14)$$

(note that this neglects the temperature dependence of the evolution of the transport coefficient) and use this expression to compute again hadron R_{AA} . The result is shown in Fig. 3.

The factor ~ 2 increase in \hat{q} over the kinematic range leads to better agreement with the data points in the ‘‘plateau’’ region above 80 GeV, however, the overall shape agreement between data and calculation worsens (note again that both curves are normalized to the data at $P_T = 10$ GeV). This indicates again that generating a plateau in single inclusive R_{AA} is in essence a fine-tuning problem.

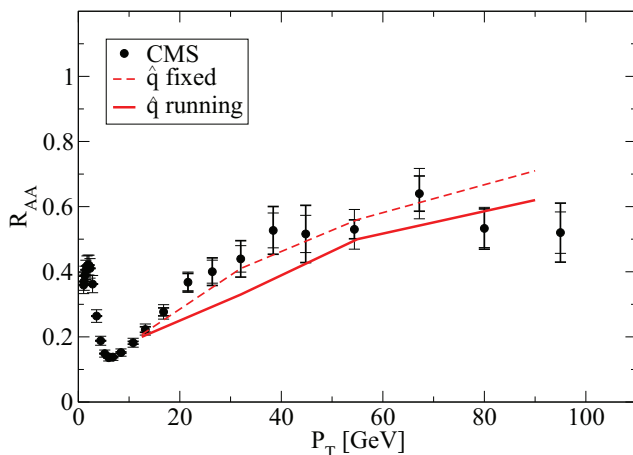


FIG. 3. (Color online) P_T dependence of R_{AA} as obtained by the CMS collaboration [3] in comparison with YaJEM results varying the parametric estimate for the lower scale.

IV. CONSIDERING JET R_{AA}

The CMS collaboration has also measured the nuclear suppression factor of jets (defined via clustering with anti- k_T with a radius parameter of $R = 0.3$) and observed a result fairly independent of P_T in a kinematic region comparable to the parton kinematics underlying the hadronic R_{AA} . This was taken as independent confirmation of the existence of a plateau [29].

One has to realize, however, that the physics underlying the suppression of single inclusive hadrons is quite different from the suppression of clustered jets. Fundamentally, jets are much more robust against medium-induced radiation (or indeed any radiation process) because close-to-collinear radiation is always clustered back into the jet and only large-angle radiation processes outside the cone radius lead to a suppression of the jet rate [30]. There is thus no *a priori* reason to expect that the mechanisms discussed above affect jet R_{AA} in the same way.

A. Modeling

Jet R_{AA} is obtained using the same medium evolution scenario and the same pQCD calculation for the hard process itself as described above and used to compute hadronic R_{AA} . In the following, the parameter K describing the overall medium quenching strength [see Eq. (10)] is taken directly from the corresponding hadron suppression scenario and no additional fit procedure for jet R_{AA} is used.

The only difference is that in the following the output of YaJEM is clustered using the anti- k_T algorithm of the FASTJET package [31] to obtain the probability distribution $P(z, E_i, Q_i^2 | \hat{q}(\zeta), \hat{\epsilon}(\zeta))$ to cluster the shower from a parton with initial energy E_i and virtuality Q_i into a jet with energy $E_{\text{jet}} = zE_i$ rather than the MMFF. This probability distribution can then be averaged over the geometry and convoluted with the spectrum in the same way as the MMFF.

B. Results

The different scenarios with upper and lower evolution scale held fixed or determined by the kinematics and space-time position in the MC event are plotted in Fig. 4 in comparison with preliminary CMS data [29].

A striking difference to Fig. 1 is that jet R_{AA} is almost insensitive to the lower evolution scale. The very purpose of a clustering procedure is, however, to suppress physics at soft, nonperturbative scales and be sensitive only to hard, perturbative physics, thus such an insensitivity is to be expected. The remaining P_T dependence is chiefly driven by the pQCD scale evolution, i.e., the initial virtuality scale Q_i as well as the fact that with increased jet energy jets become kinematically more and more collimated (cf. [32] for a discussion of the role of collimation for the dijet imbalance), implying that it becomes increasingly difficult to radiate energy out of the jet cone and leading again to a trend $R_{AA} \rightarrow 1$ asymptotically. The growth is somewhat slower than in the hadron R_{AA} case.

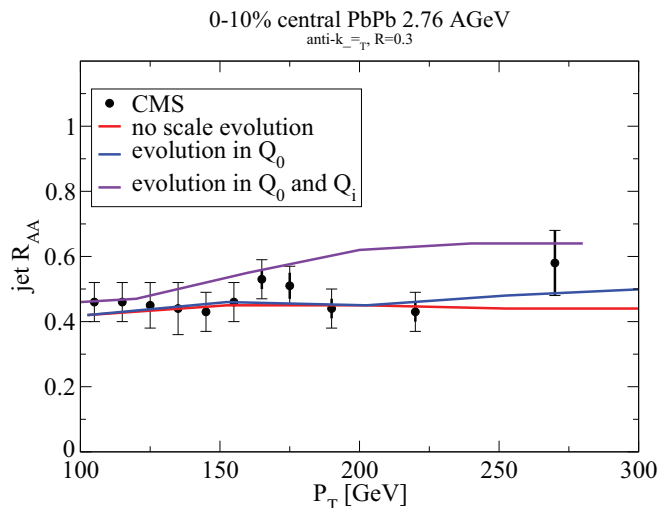


FIG. 4. (Color online) P_T dependence of jet R_{AA} as obtained by the CMS collaboration [29] in comparison with YaJEM results with different treatment of upper and lower partonic evolution scale.

Another crucial observation is that a plateaulike shape with a very weak P_T dependence over the kinematic range considered arises naturally for jet R_{AA} , thus unlike in the hadron R_{AA} case there is no fine-tuning problem, and thus one cannot take the lack of strong P_T dependence in jet R_{AA} as an indication that hadronic R_{AA} would level to a plateau.

No attempt to do a simultaneous global fit of hadron and jet R_{AA} to the data was made, but it is clear from the results presented here that such a fit would result in a reasonably good agreement between model and data even without novel physics like an additional energy evolution of \hat{q} .

V. CONCLUSIONS

The P_T dependence of the nuclear suppression factor R_{AA} is a consequence of a nontrivial interplay of several effects, chief among them the curvature of the primary pQCD spectrum, the QCD scale evolution of the MMFF, and the fact that

the in-medium evolution of showers is restricted to a length scale set by the medium size. Subleading effects include the change in the dominant parton type with P_T as well as effects from the nuclear initial state. Many of these effects are fairly generic and do not depend on specific assumptions about the nature of parton-medium interaction (but approximation schemes such as the energy loss approximation dropping the virtuality evolution of the shower in medium have been made in practice).

The measured P_T dependence poses significant and non-trivial constraints for models, and in particular identify approximations which cannot be safely made (for instance, dropping the QCD evolution of the MMFF is clearly not a justified approximation).

Within a reasonable parameter space of the precise details of embedding the shower evolution into a hydrodynamically evolving medium, fair agreement of the most realistic modeling case with both the measured single inclusive hadron and jet R_{AA} can be obtained. However, if one interprets the data as exhibiting a P_T -independent plateau of suppression beyond 40 GeV, then conventional pQCD mechanisms such as the scale evolution and the finite length effect are insufficient to account for the data, and novel physics beyond what is discussed in this work is required. Even in this case, P_T independence requires the cancellation of the known P_T dependence of QCD effects and results in essence in a fine-tuning problem. Jet R_{AA} is expected to have a generically weaker P_T dependence and is hence no strong indicator for the presence or absence of a plateau. In this context, it should be kept in mind that no measured p-p baseline at 2.76 GeV was available at high P_T for the CMS publication [3].

Future measurements with higher statistics and higher reach in P_T will reveal if R_{AA} can be completely described by known pQCD effects or if novel physics mechanisms are indicated by the data.

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