

Quenching of Hadron Spectra in Heavy Ion Collisions at the LHC

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The p_{\perp} dependence of the nuclear modification factor R_{AA} measured in PbPb collisions at the LHC exhibits a universal shape, which can be very well reproduced in a simple energy loss model based on the Baier-Dokshitzer-Mueller-Peigné-Schiff medium-induced gluon spectrum. The scaling is observed for various hadron species (h^{\pm} , D , J/ψ) in different centrality classes and at both colliding energies, $\sqrt{s} = 2.76$ and $\sqrt{s} = 5.02$ TeV. Results indicate a 10%–20% increase of the transport coefficient from $\sqrt{s} = 2.76$ to $\sqrt{s} = 5.02$ TeV, consistent with that of particle multiplicity. Based on this model, a data-driven procedure is suggested, which allows for the determination of the first and second moments of the quenching weight without any prior knowledge of the latter.

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Since its discovery [1,2], jet quenching has almost become an iconic symbol for quark-gluon plasma (QGP) formation in high-energy heavy ion collisions. The depletion, with respect to pp collisions, of high transverse momentum particle production observed in AuAu and CuCu collisions at RHIC ($\sqrt{s} = 130, 200$ GeV) [3–6] and more recently in PbPb collisions at the LHC ($\sqrt{s} = 2.76, 5.02$ TeV) [7–10], indeed, signals the early formation of a dense medium in these collisions. Today, there is a general consensus in the community that the physical origin of jet quenching is the energy loss of quarks and gluons due to multiple scattering in QGP, as predicted long ago [11,12].

The wealth of measurements presently available, from single particle spectra (identified and all charged hadrons, heavy-quark mesons, quarkonia, jets) to double inclusive particle production (e.g., jet-tagged or photon-tagged correlations) at RHIC and LHC has allowed for a sophisticated phenomenology on jet quenching; see Refs. [13–16] for reviews. Most studies which aim at explaining data are based on a perturbative picture for medium-induced gluon radiation, however, within a variety of theoretical frameworks and underlying assumptions. The description of the hot medium, often within (ideal or viscous) hydrodynamics, may also vary significantly from one study to another. Often, these approaches are based on Monte Carlo event generators, which allow for the inclusion of different physical processes as well as for the computation of different observables within a consistent framework [17–21]. This versatility is certainly appealing. However, the complexity of these approaches could also make the interpretation of the experimental results delicate.

In this Letter, I would like to explore a somewhat different strategy by assuming only a single physical process—radiative parton energy loss—to describe the quenching of single inclusive hadron spectra at large transverse momentum ($10 \text{ GeV} \lesssim p_{\perp} \lesssim 300 \text{ GeV}$) within

a simple analytic model. The goal is to extract, using the least number of assumptions, the amount of energy lost by the partons inside the medium from the quenching of light hadrons, D and J/ψ mesons. The results are also compared to an independent data-driven approach, based on the Taylor expansion of the pp production cross section, which allows for computing the first moments of the energy loss probability distribution. No attempt to model the produced medium is performed, here characterized by a single energy loss scale extracted from the high-precision measurements. In particular, I will not investigate the relationship between energy loss scales and medium properties, such as the local transport coefficient $\hat{q}(\mathbf{x}, \tau)$. This has been performed in a series of studies which show a systematic deviation from the extracted transport coefficient and its perturbative estimate [22–27]; other approaches, nevertheless, claim that RHIC or LHC data are consistent with perturbative expectations [28,29].

There are many reasons to focus on particle production at large p_{\perp} . First of all, cold nuclear matter effects (nuclear parton distributions, energy loss in cold nuclear matter, or the Cronin effect due to multiple scattering) vanish as soon as the hard scale of the process exceeds the saturation scale(s) of the incoming nuclei, $Q = \mathcal{O}(p_{\perp}) \gg Q_s^A$, where $Q_s^A \approx 1 - 2 \text{ GeV}$ at the LHC (see the discussion in [30]). In addition, various hot medium effects which could affect the production of particles at low p_{\perp} , say $p_{\perp} \lesssim 10 \text{ GeV}$, are also expected to fade out when p_{\perp} gets larger. This is the case of possible coalescence processes in QGP [31] or the role of power-suppressed direct processes [32,33], to mention only two. The quenching of particle production due to parton energy loss also becomes much simpler at large p_{\perp} . In the high-energy limit, radiative energy loss becomes independent of the parton energy (up to logarithms) [34–37] and significantly larger than collisional energy loss [38,39]. Perhaps more importantly, the power law behavior of the pp production cross section expected at

large p_\perp leads to a simple scaling property for R_{AA} discussed below. Finally, thanks to the considerable integrated luminosity acquired at the LHC, the measurement of R_{AA} is now performed up to $p_\perp \simeq 300$ GeV [10,40], making possible the study of its p_\perp dependence over 2 orders of magnitude.

The usual way to model energy loss effects on the production of particle i in heavy-ion collisions is to rescale its pp production cross section, $d\sigma_{pp}^i/dydp_\perp$. Thus, the minimum bias (centrality integrated) heavy-ion production cross section reads [41]

$$\frac{d\sigma_{AA}^i(p_\perp)}{dydp_\perp} = A^2 \int_0^\infty d\epsilon \frac{d\sigma_{pp}^i(p_\perp + \epsilon)}{dydp_\perp} P_i(\epsilon, E), \quad (1)$$

where the so-called quenching weight, P_i , represents the probability density for the particle i with energy E to lose the energy ϵ while traversing the hot medium [41,42]. It is characterized by the scale $\omega_c = 1/2\hat{q}L^2$, where \hat{q} is the transport coefficient of the medium and L its length. In the high energy limit, $\omega_c/E \rightarrow 0$, medium-induced gluon radiation becomes independent of the parton energy, up to logarithmic corrections. As a consequence, the quenching weight becomes a function of ϵ/ω_c only, $P(\epsilon, E \gg \omega_c) \equiv 1/\omega_c \bar{P}(x \equiv \epsilon/\omega_c)$. Once ω_c is known, the mean energy loss $\langle \epsilon \rangle = \langle x \rangle \omega_c$ can be determined, where $\langle x \rangle$ is the first moment of \bar{P} ; $\langle x \rangle = 1/2\alpha_s C_R$ for a propagating parton in color representation R [43].

In practice, however, the detected particle (typically a hadron) is not the particle that experiences the energy loss, a quark or a gluon. Introducing the fragmentation function of parton k into the hadron h , the heavy-ion cross section can be written as (with $x \equiv z\epsilon/\omega_c$)

$$\begin{aligned} \frac{d\sigma_{AA}^h(p_\perp)}{dydp_\perp} &= A^2 \sum_k \int_0^1 dz D_k^h(z) \int_0^\infty dx \\ &\times \frac{d\hat{\sigma}_{pp}^k(p_\perp/z + \omega_c x/z)}{dydp_\perp} \frac{1}{z} \bar{P}_k(x/z), \quad (2) \end{aligned}$$

where z is the momentum fraction carried away by the hadron. Equation (2) involves the weighted sum over the flavor of the partons fragmenting into the detected hadron, in pp and AA collisions. In the massless scheme, the relative contributions to this incoherent sum depend essentially on the product of parton distribution functions, hidden in the cross section, $d\hat{\sigma}_{pp}^k/dydp_\perp$, and on the fragmentation functions. I shall assume, here, that only one partonic channel dominates the production of the measured hadrons. This approximation should be appropriate at the LHC where the production of light hadrons is dominated by gluon fragmentation [44], although at very large p_\perp , say $p_\perp \gtrsim 100$ GeV, quark fragmentation processes are no longer negligible. Regarding D meson production, it is dominated by charm-quark fragmentation

[45], while at large p_\perp heavy-quarkonia are likely to be produced by the fragmentation of a gluon or color octet $[Q\bar{Q}]_8$ states [46]. Assuming $1/z\bar{P}(x/z)$ to be a smooth function of z compared to the rest of the integrand, this term is evaluated at a typical $\langle z \rangle$ and taken out of the z integral, leading to

$$\frac{d\sigma_{AA}^h(p_\perp)}{dydp_\perp} \simeq A^2 \int_0^\infty dx \frac{d\sigma_{pp}^h(p_\perp + \bar{\omega}_c x)}{dydp_\perp} \bar{P}(x), \quad (3)$$

with $\bar{\omega}_c \equiv \langle z \rangle \omega_c$. From (3), the nuclear modification factor,

$$R_{AA}^h(p_\perp) \equiv \frac{1}{A^2} \frac{d\sigma_{AA}^h(p_\perp)}{dydp_\perp} \Big/ \frac{d\sigma_{pp}^h(p_\perp)}{dydp_\perp}, \quad (4)$$

can be determined. When p_\perp is large with respect to any other scale in the process (say, Λ_{QCD} or the heavy-quark mass m_Q), the single inclusive hadron spectrum in pp collisions exhibits a power law behavior, $d\sigma_{pp}^h/dydp_\perp \propto p_\perp^{-n}$ where n depends, in principle, on the hadron species and on the center-of-mass energy of the collision, $n = n(h, \sqrt{s})$. Thus, according to this simple energy loss model, the nuclear modification factor at large p_\perp ,

$$R_{AA}^h(p_\perp) = \int_0^\infty dx \left(1 + x \frac{\bar{\omega}_c}{p_\perp}\right)^{-n} \bar{P}(x), \quad (5)$$

becomes a scaling function of $p_\perp/\bar{\omega}_c$ for a given power law index n . Such a scaling behavior can be observed from the centrality dependence (corresponding to different energy loss scales $\bar{\omega}_c$) of $R_{AA}^h(p_\perp)$ at a given energy \sqrt{s} . Performing the replacement $(1 + x\bar{\omega}_c/p_\perp)^{-n}$ by $\exp(-xn\bar{\omega}_c/p_\perp)$, as suggested by Baier *et al.* (BDMS) [41], leads to an approximate scaling in the variable $p_\perp/n\bar{\omega}_c$, which now allows for comparing the values of R_{AA} at different center-of-mass energies and/or for different hadron species. Note that, within the BDMS approximation, the p_\perp dependence of R_{AA} is directly connected to the medium-induced gluon spectrum ($u = \omega/\omega_c$) [41]

$$R_{AA}(y \equiv p_\perp/n\bar{\omega}_c) \simeq \exp \left[- \int_0^\infty du \frac{dI'(u)}{du} (1 - e^{-u/y}) \right], \quad (6)$$

with $dI'(u)/du = \omega_c dI(\omega)/d\omega$. In the present Letter, $R_{AA}(p_\perp/\bar{\omega}_c)$ is computed numerically from (5) using the quenching weight computed in [47] from the BDMS medium-induced gluon spectrum [34,48]. It has been checked, for consistency, that the BDMS analytic approximation, Eq. (6), reproduces Eq. (5) well when $p_\perp/n\bar{\omega}_c$ gets large.

Thus, in this simple energy loss model, the shape of R_{AA} as a function of p_\perp is fully predicted once the exponent n is known, obtained from a fit to the pp data at the

corresponding center-of-mass energy. What remains to be determined is the energy loss scale $\bar{\omega}_c$, which is, in principle, a complicated (and virtually unknown) function of the space-time evolution of the QGP energy density and the geometry of the heavy ion collision. Rather than modeling the hot medium, the value of $\bar{\omega}_c$ is obtained from an “agnostic” one-parameter fit to each data set (summing statistical and systematic uncertainties in quadrature), in a given centrality class and at a given \sqrt{s} . Measurements include charged hadrons measured by CMS in five centrality classes [49] at both colliding energies [9,10], J/ψ and D mesons measured, respectively, by ATLAS [50] and CMS [51] at $\sqrt{s} = 5.02$ TeV in one centrality class, for a total number of 12 data sets. Data from ALICE [7,52,53] are not included here as I focus on measurements with largest p_\perp ; however, these results will be included in the more detailed analysis [54].

The comparison of the fits to the individual data sets will be shown in a forthcoming publication [54]. Instead, Fig. 1 shows all data points [55] plotted as a function of the scaling variable, $p_\perp/n\bar{\omega}_c$, together with the shape of R_{AA} computed from Eq. (5). Clearly, all data exhibit an almost perfect scaling, lining up into a single “universal” shape. This feature, predicted in the energy loss model and observed in data, supports the interpretation of a unique process responsible for the nuclear modification factors of all hadrons above a given p_\perp in heavy-ion collisions at the LHC. In particular, I find it interesting that the quenching of heavy mesons (D and J/ψ) obeys the same pattern, suggesting, again, that at large p_\perp , the same process affects all hadron species similarly, including bound states like heavy quarkonia [56]. Also worth noting are the scaling

violations observed for lower p_\perp particles. The lack of scaling emerges below $p_\perp \approx 10$ GeV, for all centralities, which may signal the appearance of other phenomena below this energy scale. Another remarkable fact is how well the shape observed in data coincides with that given by the energy loss model, based on the BDMPS medium-induced gluon spectrum. However, I checked that computing R_{AA} using the Gyulassy-Lévai-Vitev spectrum [35,36] also reproduces the shape of the data very well. Thus, the current data precision does not yet allow one or another gluon spectrum to be favored. Smaller systematic uncertainties at lower p_\perp and improved statistics in the largest p_\perp bins will help reach that goal.

Apart from investigating the scaling of R_{AA} for different hadron species or collision systems, this procedure allows for extracting the mean energy loss (times the mean fragmentation variable), $\langle \bar{\epsilon} \rangle \equiv \langle z \rangle \times \langle \epsilon \rangle$, experienced by the fast parton in the QGP, as a function of centrality. Here, $\langle \epsilon \rangle$ has to be understood as the mean energy loss of the fragmenting parton, averaged over its production point and directions of propagation in the hot medium. Note that the error bars on $\langle \bar{\epsilon} \rangle$, determined from the χ^2 minimization procedure (with a usual tolerance criterion of $\Delta\chi^2 = 1$), are strongly correlated from one centrality class to another, since they arise mostly from the correlated systematic uncertainties of the data. By changing the color prefactor of the induced spectrum from C_F to C_A , I checked that the values of $\langle \bar{\epsilon} \rangle$ do not change significantly when the fragmenting parton is assumed to be a quark or a gluon. The mean parton energy loss $\langle \epsilon \rangle$ can be deduced from $\langle \bar{\epsilon} \rangle$ once $\langle z \rangle$ is known. It can be estimated from the (fractional) moments of the relevant fragmentation

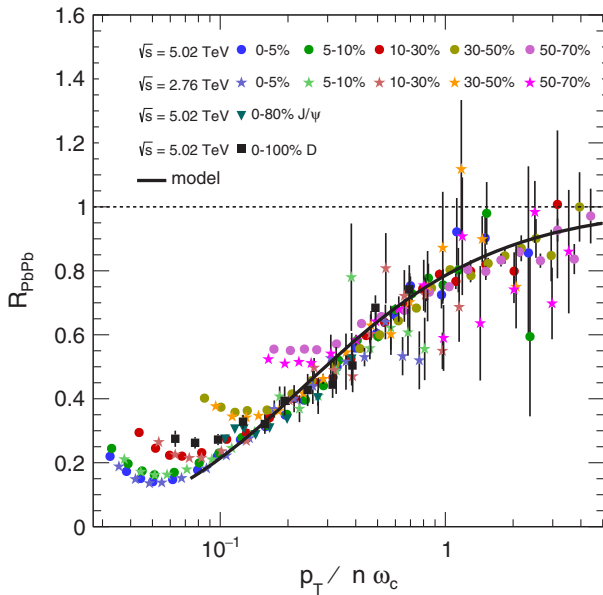


FIG. 1. R_{AA} of h^\pm , D , and J/ψ as a function of $p_\perp/n\bar{\omega}_c$ in PbPb collisions at $\sqrt{s} = 2.76$ and $\sqrt{s} = 5.02$ TeV in different centrality classes.

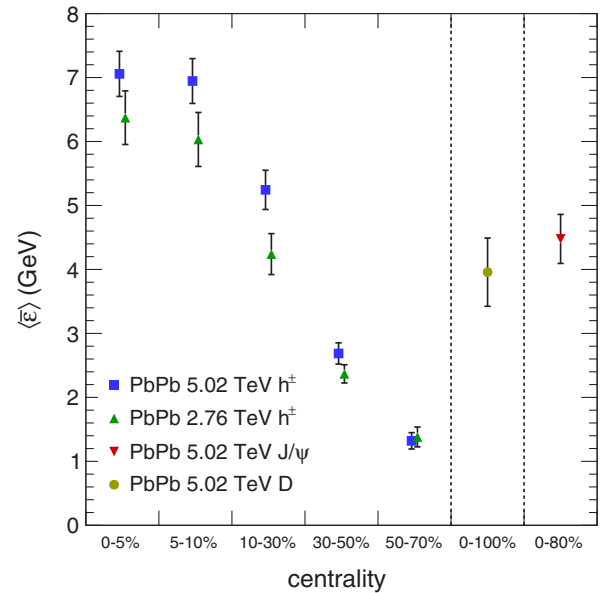


FIG. 2. Mean energy loss extracted in PbPb collisions at $\sqrt{s} = 2.76$ TeV (triangles) and $\sqrt{s} = 5.02$ TeV (squares) from the quenching of h^\pm , D , and J/ψ .

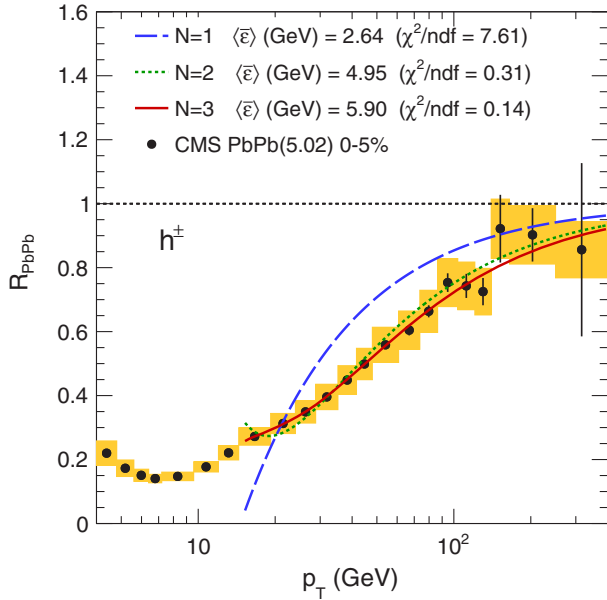


FIG. 3. Taylor expansion fits at first (dashed line), second (dotted line) and third order (solid line) to the CMS measurements.

function, $\langle z \rangle \simeq \int dz z^{n+1} D_k^h(z) / \int dz z^n D_k^h(z)$, where n is the power law exponent of the pp cross section. At the LHC, next-to-leading order calculations indicate that $\langle z \rangle \simeq 0.5$ for light hadron production [44].

As can be seen in Fig. 2, $\langle \bar{\epsilon} \rangle$ is (as expected) maximal in the most central bins and of the order of 6–7 GeV. It starts to drop in the more peripheral classes, to reach $\langle \bar{\epsilon} \rangle \simeq 1$ GeV in the 50%–70% centrality class. It is particularly interesting to note that the mean energy loss in PbPb collisions at $\sqrt{s} = 5.02$ TeV is roughly 10%–20% larger than at $\sqrt{s} = 2.76$ TeV. This is nicely consistent with the measurements of ALICE [58] which show that the multiplicity distribution, $dN/dy \propto \hat{q} \propto \langle \epsilon \rangle$, increases by roughly the same amount. The present approach, however, does not allow one to extract \hat{q} from the sole knowledge of $\langle \epsilon \rangle$. In particular, a longer lived medium at the highest collision energy might as well explain the increase of $\langle \bar{\epsilon} \rangle$ observed in Fig. 2. Including finite energy corrections in the quenching weight [see Eq. (1)] slightly affects the shape of R_{AA} at small values of $p_{\perp}/\omega_c \lesssim 1$; as a result, the values of $\langle \bar{\epsilon} \rangle$ increase by approximately 10% to 15%, from more peripheral to more central collisions, when these are taken into account [54].

The values of $\langle \bar{\epsilon} \rangle$ extracted from the quenching of D and J/ψ are also displayed in Fig. 2, in similar centrality bins (0%–100% and 0%–80%, respectively). Perhaps a bit surprisingly at first glance, no genuine difference between these two channels is observed. Assuming that D and J/ψ production at large p_{\perp} come from charm quark and gluon fragmentation, respectively, a naive estimate would lead to $\langle \epsilon \rangle_{J/\psi} / \langle \epsilon \rangle_D = C_A / C_F = 9/4$. The typical values of $\langle z \rangle$ for both particles could, of course, be different, although not significantly since the $c \rightarrow D$ and $g \rightarrow J/\psi$ (or $[c\bar{c}]_8 \rightarrow J/\psi$) fragmentation functions are hard [59–61]. However, as noted in [45], the gluon fragmentation component into D mesons is not negligible, of the order of 30% at the Tevatron. Also, the presence of color singlet states $[c\bar{c}]_1$ fragmenting into J/ψ , unaffected by the medium, could reduce the value of $\langle \epsilon \rangle$ extracted from $J/\psi R_{AA}$. This might explain, at least partly, why the estimates from D and J/ψ are similar.

The above estimates of the mean energy loss rely on a model using a specific quenching weight. The success of a simple model, which rightfully predicts the shape of $R_{AA}(p_{\perp})$ observed in data, gives some confidence on the robustness of these estimates. Nevertheless, it is legitimate to question the model dependence of these results. In the following, I suggest extracting the first moments of the quenching weight, without any prior knowledge of the latter.

At the LHC, for the first time, measurements of R_{AA} extend at transverse momenta significantly larger than the typical energy loss scale, $p_{\perp} \gg \langle \epsilon \rangle \simeq 5 - 10$ GeV even in the most central collisions (see Fig. 2). From the Taylor expansion of (5), R_{AA} is conveniently approximated at large p_{\perp} by

$$R_{AA}^{(N)}(p_{\perp}, \{\langle \bar{\epsilon}^j \rangle\}) = \sum_{i=0}^N (-1)^i \frac{\Gamma(n+i)}{\Gamma(i+1)\Gamma(n)} \frac{\langle \bar{\epsilon}^i \rangle}{p_{\perp}^i}. \quad (7)$$

The first N moments $\langle \bar{\epsilon}^j \rangle$ can, therefore, be determined from a fit to R_{AA} data, without any specific assumption on the quenching weight. In order to check this procedure, R_{AA} toy data were generated according to a known quenching weight (in this case, that based on the BDMPS gluon spectrum) and then fitted using (7) at orders $N = 1, 2, 3$. This study shows that the first and second moments of the known quenching weight can be retrieved with a good accuracy from $R_{AA}^{(N=3)}$ [54]. Based on this result, the mean energy loss $\langle \bar{\epsilon} \rangle$ has been determined for each LHC data set

TABLE I. Values of $\langle \bar{\epsilon} \rangle$ (in GeV) extracted from the BDMPS model and from the Taylor expansion method (using $N = 3$).

Centrality	0%–5%	5%–10%	10%–30%	30%–50%	50%–70%
BDMPS	7.1 ± 0.4	6.9 ± 0.4	5.2 ± 0.3	2.7 ± 0.2	1.3 ± 0.1
Taylor expansion	5.9 ± 0.7	5.8 ± 0.7	4.9 ± 0.7	2.8 ± 0.4	1.8 ± 0.5

discussed here. Figure 3 shows the result of the fits to the charged hadron R_{AA} measured in the 0%–5% most central PbPb collisions. As can be seen, the quality of the fits improves as N is getting larger. These totally agnostic estimates of the mean energy loss (taking $N = 3$) are compared in Table I to the results based on the BDMPS model. Both approaches yield consistent values, yet the uncertainties using the Taylor series tend to be larger because of the higher number of parameters used.

In summary, I discussed the quenching of single hadron spectra in heavy-ion collisions at the LHC within a simple energy loss model. It is shown that the R_{AA} of charged hadron, charmed mesons and heavy quarkonia, measured at different \sqrt{s} and in various centrality classes scale on a single curve which is nicely predicted by the model. This allows for the extraction of the mean parton energy loss. Finally, I also suggest a model-independent procedure for extracting this quantity (and its variance), which gives consistent results.

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