Parton energy loss at LHC tests for a strongly coupled medium

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We construct a measure of transverse momentum loss of jets in nuclear collisions at LHC directly using measurements of jet cross sections in PbPb and pp collisions. The proposal is shown to be equivalent to $R_{AA}$ and is equally straightforward to construct. Using data from the ATLAS collaboration at two different collision energies, we show that the proposed measure has small statistical uncertainties. We argue that systematic errors can be easily improved over our estimates by the experimental collaboration to such an extent that it directly probes whether the jet-medium interaction is due to a strongly interacting medium or a weakly interacting plasma. We argue that the current data may marginally favour a strongly interacting medium. On the other hand, assuming that the medium is weakly interacting, we are able to provide estimates of the jet quenching parameter $\hat{q}$ which are in rough agreement with previously reported estimates.

Fast particles moving through matter lose energy and momentum by bremsstrahlung. This principle is used in particle detectors. Results from RHIC and LHC show unambiguously that jets produced in nuclear (AA) collisions differ from their counterparts in proton-proton (pp) collisions [1]. This is interpreted as evidence that fast particles also lose energy to matter through the strong interactions, as was first hypothesized in [2–4] and observed at RHIC through the suppression of hadrons at high momenta [1, 2].

At the LHC the reconstruction of jets is routine and results for jet quenching were presented very soon after the initial runs [6]. In this case $R_{AA}$ can be defined through the ratio of differential jet cross sections,

$$R_{AA} = \frac{d\sigma_{AA}}{dpT\,dy} / \frac{d\sigma_{pp}}{dpT\,dy} \text{ where } \frac{d\sigma_{AA}}{dpT\,dy} = \frac{1}{N_{\text{evt}}\,T_{AA}} \frac{dN_{\text{jet}}}{dpT\,dy},$$

with $N_{\text{jet}}$ being the number of jet events out of a total $N_{\text{evt}}$ events in a given $p_T$ and $y$ bin for a fixed bin of centrality, and $T_{AA}$ being the thickness function in PbPb collisions [7]. In this paper we explore another representation of this difference. From the same jet cross sections, we may obtain a transverse momentum shift, $\Delta p_T$ defined by setting

$$\left. \frac{d\sigma_{AA}}{dpT\,dy} \right|_{p_T} = \left. \frac{d\sigma_{pp}}{dpT\,dy} \right|_{p_T+\Delta p_T}$$

As long as $R_{AA}$ is less than unity over a large enough range of $p_T$, $\Delta p_T$ must be positive in most of this range, since the cross sections on both sides of the equation fall with increasing $p_T$. $\Delta p_T$ is a direct measure of jet energy loss, the two being linearly related. The jet $p_T$ and $\Delta p_T$, averaged over the rapidity acceptance and azimuthal angle, are easily computable fractions of the jet energy $E$ and the energy loss $\Delta E$. The relations between them is easily incorporated into an experimentalist’s jet Monte Carlo. So we hope that the construction that we outline here is used in future to report $\Delta p_T$, or even the Monte Carlo-derived quantity $\Delta E$, as a direct output from the LHC experiments. Finally, we note that this proposal for the construction of $\Delta p_T$ differs from that proposed several times earlier, namely through the mismatch in $p_T$ between multiple objects in the final state [8–10], either multiple jets or a $\gamma/Z$ and its recoil jet. The earlier proposals have theoretically smaller systematic uncertainties, but have significantly larger statistical uncertainties because they use rarer events. Another approach which differs from ours proceeds by parametrizing the jet spectra in terms of a few parameters [11, 12].

All of the experiments at LHC report cross sections from fully reconstructed jets. The ATLAS experiment, for example, clusters calorimeter tracks using the anti-$k_T$ algorithm with different jet opening angles $R$. For jet energy determination the subtraction of the underlying event is done carefully including effects due to flow. ATLAS reports a study of the change in $R_{AA}$ with CM energy using $\sqrt{S} = 2760$ GeV [13] and $\sqrt{S} = 5020$ GeV [14]. ALICE [15] and CMS [17] report no statistically significant variation of $R_{AA}$ over a large range of $R$. Since all experiments report jet data for $R = 0.4$, we choose this jet definition for our analysis of the ATLAS data. The results can then be cross validated by the other experiments.

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FIG. 1: $\Delta p_T$ inferred from the observations of the ATLAS experiment at $\sqrt{S} = 2.76$ TeV [13] in two centrality bins and at $\sqrt{S} = 5.02$ TeV [14]. The errors shown here come only from statistical errors.

At the lower energy ATLAS reports statistical errors of jet cross sections in PbPb collisions to be 1.5–2.5% over the energy range up to $p_T = 200$ GeV, growing to almost 10% in the bin with $p_T > 350$ GeV in all centrality bins. The systematic uncertainties vary from about 15–20%. Statistical errors for jets in pp collisions are smaller by a factor of 3, and systematic uncertainties are around 3%. At the higher energy the systematic uncertainties in pp collisions decrease marginally to about 2%, but the statistical errors are currently larger, being between about 10–15%. At this energy, in PbPb collisions systematic uncertainties are similar, and statistical errors range from 2–5% for $p_T \leq 200$ GeV but rise from 10–80% at higher energy, depending on the centrality. Clearly, the luminosity available at this energy is insufficient to make a quantitative statement about jets in PbPb collisions for $p_T > 400$ GeV.

In Figure 1 we show the results for $\Delta p_T$ inferred from the cross sections reported by the ATLAS experiment at some sample centrality bins at two different collider energies. Similar results are obtained in all centrality bins. We discuss later how the shapes of these curves can be used to distinguish between a strongly and a weakly coupled plasma, and extract the jet energy loss parameters, $\hat{q}$, if the latter is the case. Errors in the jet cross sections in both PbPb and pp collisions propagate into errors in determining $\Delta p_T$ through the definition in eq. (2). In the figure we show the error propagated into $\Delta p_T$ from the statistical errors in the cross sections.

The jet cross section in pp collisions shows a fairly steep fall for $p_T < 300$ GeV, and a slightly smaller logarithmic slope at higher $p_T$. Unfortunately, this means that the large systematic uncertainty, especially in PbPb collisions will translate into a large uncertainty in $\Delta p_T$. We may add these uncertainties in quadrature. The justification is based on independent normal distributions of errors. While this may be accurate for statistical errors, it is likely to be far from correct for systematic uncertainties. Especially if there are covariances between different sources, these need to be taken into account. Since the correlation matrix between errors is not published, it is hard for an independent analysis like ours to do full justice to the error analysis.

One example of such a covariance in the systematic uncertainty which can be corrected easily by the collaboration is that coming from uncertainties in the luminosity. This affects the cross sections in both PbPb and pp collisions, and therefore has a smaller effect on $\Delta p_T$. However, since this is folded into the published tables of systematic errors, in our analysis we have been forced to add them twice. There are similar cancellations possible between some parts of the other systematic errors, which can only be evaluated by the experimental collaboration.

We can try a crude estimation of the effect of covariances between different components of the systematic uncertainties as follows. With the $\Delta p_T$ determined through eq. (2) we can reconstruct $R_{AA}$ through the definition

$$R'_{AA}(p_T) = \left. \frac{d\sigma_{pp}}{dp_T dy} \right|_{p_T+\Delta p_T} / \left. \frac{d\sigma_{pp}}{dp_T dy} \right|_{p_T}$$

This reconstructed quantity $R'_ {AA}$ is given its uncertainty band through the usual error propagation algorithms. Comparing the propagated error with the error in $R_{AA}$ reported by the ATLAS collaboration gives us a rough idea of the correction factor required from the covariance of systematic uncertainties. In the left panel of Figure 2 we compare
is radiated away by emitting a gluon, the coupling must be determined at the scale the jet-medium coupling is \( \alpha \). The contribution to the virtuality of the jet is then \( E \approx E_T \) for the \( p_T \) perpendicular direction, \( p_{\perp} = O(T) \) changing the momentum to \( P + p_{\perp} \approx (E, T, 0, E) \), for example. The virtuality of the jet is then \( Q^2 \approx T^2 \). However, any component of momentum added in the longitudinal direction gives a contribution to the virtuality of \( O(ET) \). Since \( E \gg T \), then it is more likely that \( Q^2 \approx ET \). When this virtuality is radiated away by emitting a gluon, the coupling must be determined at the scale \( Q^2 \). Even though the jet energy, \( E \), is large, its interaction with the medium is controlled by a strong coupling at a smaller scale. For example, if \( E \approx 100 \text{ GeV} \), then the jet cross section is controlled by \( \alpha_s \approx 0.1 \). However, if \( T \approx 0.2 \text{ GeV} \), then \( Q \ll 5 \text{ GeV} \), so that the jet-medium coupling is \( \alpha_s \approx 0.2 \). The domain of \( \alpha_s \leq 0.15 \) is definitely in the realm of weak coupling.

\[ R_{AA} \] and \( R'_{AA} \). Two results follow immediately. First, the estimates agree, showing that \( \Delta p_T \) and \( R_{AA} \) reported by the ATLAS collaboration are equivalent measures of the difference between PbPb and pp jet cross sections. Before making the second inference, note that the bars shown here represent the statistical and systematic uncertainties added in quadrature. For \( R_{AA} \), the uncertainty bars are reduced by a factor of five. As one can see from the figure, this brings the two sets of uncertainties into rough agreement at the highest \( p_T \). This is an indication that systematic uncertainties in \( \Delta p_T \) that we can estimate using published data are an overestimate. Covariances between systematic uncertainties are available to experimental collaborations and can lead to a reduction of our naive computation of uncertainties by a factor of five or more.

The construction of \( R'_{AA} \) can also be used to test that \( \Delta p_T \) from different experiments agree. For this we construct \( R'_{aa} \) using the pp jet cross sections measured by the CMS along with the \( \Delta p_T \) that we extracted from the ATLAS measurements. The latter are taken in the bin of 0–10% centrality. The results agree with \( R_{AA} \) reported by the CMS collaboration in the bins of 0–5% and 5–10% centrality. A similar test is possible for the data from the ALICE collaboration. However, the cross sections reported are binned in the pseudo-rapidity \( \eta \) instead of \( y \), and with somewhat more stringent cuts on \( \eta \). In view of this, we do not show comparisons using these cross sections.

The results shown in Figure 4 are a demonstration that \( R_{AA} \) and \( \Delta p_T \) are just two different ways of reporting the experimentally observed differences between fully reconstructed jets in pp and AA collisions. We claim that each representation has its strengths. More than a decade of work has shown how useful \( R_{AA} \) is. In the remainder of this letter we show that \( \Delta p_T \) allows us to clearly test very interesting physics, such as whether the fireball is strongly or weakly coupled, and, in either case, answer more detailed questions about the basic underlying theory. These demonstrations are made in order to persuade experimental collaborations to extract and report \( \Delta p_T \).

Jets are produced at the very earliest instants of the collisions, and since they travel at the speed of light, \( c \), they outstrip any hydrodynamical disturbance, which can only travel at the speed of sound, \( v_s \). As a result, jets leave the fireball early, before a rarefaction pulse can set fireball into collective transverse motion. So they are a good primordial probe of matter in the fireball. A direct experimental determination of the energy loss probes both thermal and pre-equilibrium matter in the fireball, in principle. In some of the analysis presented in this paper we will assume that soft effects from the pre-equilibrium system are negligible, and \( \Delta p_T \) is largely due to the interaction of the jet with thermalized matter. Nevertheless the ability of \( \Delta p_T \) to probe pre-equilibrium physics must not be forgotten. Possible tests of their importance could be to compare experimental determinations with model results.

If the jet energy is \( E \), then the 4-momentum of the parton, \( P \), may be written as \( P = (E, 0, 0, E) \) when we choose the \( z \)-axis to be aligned with the initial direction of motion of the hard parton in the final state, and not the beam direction. Any interaction with thermal matter (at temperature \( T \)) can push \( P \) off-shell by adding momenta in a perpendicular direction, \( p_{\perp} = O(T) \) changing the momentum to \( P + p_{\perp} \approx (E, T, 0, E) \), for example. The virtuality of the jet is then \( Q^2 \approx T^2 \). However, any component of momentum added in the longitudinal direction gives a contribution to the virtuality of \( O(ET) \). Since \( E \gg T \), then it is more likely that \( Q^2 \approx ET \). When this virtuality is radiated away by emitting a gluon, the coupling must be determined at the scale \( Q^2 \). Even though the jet energy, \( E \), is large, its interaction with the medium is controlled by a strong coupling at a smaller scale. For example, if \( E \approx 100 \text{ GeV} \), then the jet cross section is controlled by \( \alpha_s \approx 0.1 \). However, if \( T \approx 0.2 \text{ GeV} \), then \( Q \ll 5 \text{ GeV} \), so that the jet-medium coupling is \( \alpha_s \approx 0.2 \). The domain of \( \alpha_s \leq 0.15 \) is definitely in the realm of weak coupling.

FIG. 2: Comparison of the reconstructed \( R'_{AA} \) of eq. 4 with direct experimental measurements of \( R_{AA} \) from ATLAS (left) and CMS (right). The error bars shown are statistical and systematic uncertainties added in quadrature. The errors shown on \( R'_{AA} \) are one fifth of that obtained through error propagation on \( \Delta p_T \) inferred from ATLAS observations at \( \sqrt{s} = 2.76 \text{ TeV} \) for the most central 0–10% of events. Experimental data are displaced slightly from the center of the \( p_T \) bins for visibility.
and of $\alpha_s > 0.5$ is often considered to be strongly coupled.

In view of this a first question is whether the medium can be considered as weakly coupled or not. If it is weakly coupled, then gluon radiation is modeled as being created by a series of coherent collisions with quasi-particles in the plasma [21, 22] giving $\Delta p_T \propto L^2$, where $L$ is the path length of the jet in the fireball (we mention a possible caveat later). On the other hand, if the medium is strongly coupled, then it is modeled as exerting a retarding force which causes gluon bremsstrahlung [23] giving $\Delta p_T \propto L^3$. Tests of these scalings have been attempted before [24–26]. We argue that direct experimental access to $\Delta p_T$ allows us to make such and more detailed tests, as we demonstrate.

Clearly, an important ingredient in all studies of the interaction of hard probes with matter is the path length $L$. In a material whose volume has a well-defined surface, $\Sigma$, this notion in simple. For a jet produced at a point $P$ inside $\Sigma$, with momentum pointing in the direction $P$, walk along the ray $P \pm sP$. The distance $s$ at which the ray intersects $\Sigma$ is the path length $L(P, P')$. The mean path length, $L$, is obtained by averaging over $P$ and $P'$ for each impact parameter $b$. Since a jet leaves the fireball before transverse expansion sets in, one may examine the path length in a longitudinally expanding plasma [27]. This may be modelled as a boost-invariant cylindrical region whose transverse shape is essentially given by the initial collision geometry. Since matter interactions change the jet-rapidity by an angle of order $T/E \ll 1$, we may take its rapidity to be fixed. Due to longitudinal boost invariance, it can then only leave the fireball through the transverse surface $\Sigma$.

This simple model is complicated by two factors. One is that the nuclear density is taken to be continuous in computing $T_{AA}$, and one has to take the same Wood-Saxon density [28] in this computation. The other is that during longitudinal expansion, matter begins to diffuse outwards in the transverse direction. In this case one has to estimate when the matter density is small enough that the probability of a jet scattering with matter after travelling distance $L$ is less than some pre-assigned value, $\epsilon$. Causal diffusion equations are needed at such early times, and there are no quantitative estimates of the two transport coefficients required [24]. In view of this uncertainty, we may place the surface where 99% of the matter is inside $\Sigma$. We find this radius $R_{99} = 1.53 R_{RMS}$, where the symbol on the right denotes the RMS radius. This is, of course, a very generous over-estimate. Even in this extreme scenario, we find that $L$ is 4.9 fm in the most central 0–10% of events in PbPb collisions, which is before transverse expansion is well developed. Since $L$ decreases as one goes to more peripheral events, jets can escape matter even earlier in these events.

Although the simple hydrodynamical model that we have used is serviceable enough, alternative initial conditions should be examined in future, along with the hydrodynamic expansion of the fireball. We adopt this simplified model for $L$ here because our treatment of experimental systematic uncertainties currently dominate the errors in our treatment. Once that is brought under better control, then one needs to improve the computation of $L$, possibly by using a transport model.

In the remainder of our analysis, we suppose that non-radiative collisional energy loss is a subdominant mechanism in the fireballs at LHC. This has been tested in several publications [30, 31]. Alternative explanations of the observed jet energy loss, namely through modification of parton densities and shadowing, have also been quantified and found to
be small \(^{32,33}\). If the radiative energy loss, \(i.e.,\) bremsstrahlung, is the primary mechanism of jet-matter interactions, then the centrality dependence of \(\Delta p_T\) must come from the dependence of \(L\) on the impact parameter \(b\). This provides an easy test of whether or not matter is strongly coupled. If it is, then \(\Delta p_T/L^3\) should be independent of centrality. On the other hand, if matter is weakly coupled, then \(\Delta p_T/L^2\) should be seen not to depend on centrality. We show these tests in Figure \(\text{3}\). In the first panel one sees a test of whether the medium is strongly coupled. At each \(p_T\) we find that \(\Delta p_T/L^3\) is independent of centrality with good accuracy within the statistical uncertainties. The alternate hypothesis, of centrality independence of \(\Delta p_T/L^2\) is certainly ruled out if only statistical uncertainties were taken into account. However, if one takes into account systematic uncertainties, then it may seem that this hypothesis cannot be ruled out. At \(\sqrt{S} = 5020\) GeV the statistical errors are larger and the systematic errors are similar in magnitude. As a result, this test again seems to be inconclusive unless correlations between systematic uncertainties are taken into account.

Our previous discussion of the systematic uncertainties in \(R_{AA}\) indicate that the situation can be improved by the LHC experimental collaborations. Indeed, the simple prescription shown in Figure \(\text{2}\) which seems to tell us that covariances between uncertainties can be roughly accounted for by reducing the uncertainties by a factor of 5. In that case it is already clear that a test such as that shown in Figure \(\text{4}\) could disfavour the weakly coupled model of the fireball. Although such a conclusion is currently premature, it strongly indicates that if ATLAS, and other LHC collaborations, perform the analysis shown, then they would easily be able to discriminate between a strongly and weakly coupled medium.

Two further remarks are in order. First, that in strongly coupled matter the ratio \(\Delta p_T/L^3\) must be given by \(\zeta T^4\). There is no prediction of \(\zeta\) for QCD, only for its conformal cousins \(^{34,37}\) (see however, \(^{38}\) for an attempt to parametrize the computation for QCD). It could depend on the 't-Hooft coupling, which is formally \(N_c \alpha_s(Q)\), and for QCD, \(\text{i.e.,}\) with \(N_c = 3\), may be of order unity. If the complete treatment of systematic uncertainties do favour the strong coupling picture, then certainly the sub-leading corrections in \(N_c\) will have to be investigated. The figure shows that over a large range of \(p_T\) the result is compatible with \(T \simeq 0.350-0.4\) GeV, if \(\sqrt{T}\) is of order unity. The minor variation seen in \(\Delta p_T/L^3\) could come from the change in \(Q \simeq \sqrt{T \hat{E}}\) and the logarithmic change it induces in \(\alpha_s\).

On the other hand, if matter is weakly coupled, then \(\Delta p_T/L^2\) is clearly dependent on \(p_T\). The treatment of BDMPS-Z \(^{39}\) shows that this is captured in the relation

\[
\Delta p_T = \kappa L^2 \log \left( \frac{p_T}{\omega^2 L} \right),
\]

where \(\kappa \propto T^3\) and \(\omega \propto T\). Further, one may write \(\kappa = C \alpha_s \tilde{q}/4\) where \(\alpha_s\) is the strong coupling at the appropriate scale, and \(C\) is given by the quadratic Casimir \(C_F = 4/3\) for quark initiated jets and \(C_A = 3\) for gluon initiated ones. For jets at \(y = 0\), one finds that the gluon-gluon luminosity, \(g^2(2p_T/\sqrt{S})\) dominates for \(p_T < 150\) GeV (for \(\sqrt{S} = 2.76\) TeV), beyond which the quark gluon luminosity \(g(2p_T/\sqrt{S})\tilde{q}(2p_T/\sqrt{S})\) is larger. The jet cross sections due to these

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**FIG. 4:** The values of \(\kappa\) and \(\omega\) obtained by fits to data from \(^{13}\) and \(^{13}\). The centrality and \(\sqrt{S}\) for each set is indicated. Since the parameters are proportional to powers of \(T\), the value of \(\omega\) in any bin should be fixed by \(\kappa\) in that bin and independent estimations of the two parameters in any one bin. The boxes in the panel on the right show a test of this hypothesis, with the uncertainty taken from the parameter uncertainty at the input 0–10% centrality bin at \(\sqrt{S} = 2760\) GeV.
two parton subprocesses are in the ratio $C_A/C_F = 9/4$. The $gg$ subprocess contains $s$, $t$, and $u$ channel exchanges, whereas the $qg$ subprocess contains only $s$ channel exchange. This causes another enhancement of the $gg$ subprocess by a factor of about 8. As a result, for jets with $p_T < 400$ GeV, one may take the $gg$ subprocess to dominate. So one may take $C = C_A$. Then taking $\alpha_s \simeq 0.15 - 0.25$, as discussed earlier, one has $\hat{q} = (5 - 9)\kappa$.

It is possible to extract the two parameters $\kappa$ and $\omega$ from the values of $\Delta p_T$ at each centrality separately for each of the two values of $\sqrt{S}$. In performing these fits we have added the systematic and statistical uncertainties in quadrature. As discussed earlier, this is an oversimplification, and direct access to the results of detector Monte Carlos could allow a better treatment of the systematic errors. The results are shown in Figure 4. There is no statistically significant dependence of the parameters from one bin to another. The minor variations are entirely accounted for by assuming that there are small changes in $T$ as the centrality and $\sqrt{S}$ change.

We can extract an estimate for $\hat{q}$ given the range of $\kappa$ shown. This gives $\hat{q} = 1 - 4$ GeV/fm$^2$ (which is 0.2 - 0.8 GeV$^2$/fm in units which have also been used in the literature). There are a few previous estimates of $\hat{q}$ from jets at LHC. Among them we find estimates ranging from $\hat{q} \simeq 10 \pm 4$ GeV/fm$^2$ (at $T = 470$ MeV for $\sqrt{S} = 2.76$ GeV) [40], $\hat{q} \simeq 12.4$ GeV/fm$^2$ [41], and $\hat{q} \simeq 3 - 7$ GeV/fm$^2$ (for $T = 470$ MeV) [42]. This last range, in particular, is a 90% CR range, whereas we quote the more common 1-sigma errors, i.e., the 68% CL. Although our quoted range of $\hat{q}$ is on the lower side of the band, it is consistent with the current spread of values, assuming that the medium is weakly coupled. We note that if we had used $R_{RMS}$ to estimate $L$ we would have found $\hat{q} = 2.3 - 9.4$ GeV/fm$^2$, which is in complete agreement with the results of [40, 42].

It is clear that more accurate results can be obtained not only through better control of experimental systematic errors, but also by better control of theoretical systematics on $L$. There is also the caveat that we mentioned earlier. A possible correction to the formula in eq. (1) would be to average $\kappa$ using the instantaneous temperature, which changes as the system expands. If one assumed Bjorken expansion, with $v_s = 1/\sqrt{3}$, then one finds $\kappa$ should be replaced by $\kappa_0 \log(L/\tau_0)/(L/\tau_0 - 1)$, where $\tau_0$ is the time at which we can expect Bjorken expansion to set in and $\kappa_0$ is the value of $\kappa$ at that time. When $L \gg \tau_0$ this could change the $L$ dependence in eq. (4). In particular, in this model, when $L$ is large one finds that the $L^2$ factor could change to $L \log L$. This weaker dependence on $L$ would further reduce support for the weak coupling picture, of course. However, this argument is approximate, since a softer equation of state will make less of a difference, the fuzzy borderline between pre-equilibrium and equilibrium expansion could change the results, and there is always the question of how to separate the scale of hydrodynamical expansion and the scale of coherence between successive emissions that leads to the LPM effect. This last point is clearly crucial since $T L$ is not much larger than unity, showing that the scale separation is hard, and the assumption that $\hat{q}$ can be replaced by its instantaneous value during hydrodynamic averaging could be false. Clearly, answering the first question requires a hydro+transport computation, whereas addressing this last requires a more careful analysis of the transition between microscopic dynamics and bulk transport. These interesting issues we leave to the future.

To summarize, we have introduced a measure $\Delta p_T$, the transverse momentum loss of a hard jet in a medium, and shown that it can be easily extracted from experimental measurements using eq. (3). We demonstrated that this although this information is exactly equivalent to the widely used measure $R_{AA}$, it can be used to directly distinguish between weakly and strongly coupled plasmas. We have argued that the presence of correlated systematic uncertainties makes it hard for people outside the experimental LHC collaborations to get an accurate estimate of errors in $\Delta p_T$. However, very rough corrections for these correlations/covariances shows that the data mildly supports a strongly coupled fireball over one which is weakly coupled. We have further shown how one can extract medium properties from $\Delta p_T$. In particular, we showed that assuming that the fireball is weakly coupled, one can extract a value of $\hat{q}$ which is consistent with current estimates.

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