Jet shape modifications in holographic dijet systems

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We present a coherent model that combines jet production from perturbative QCD with strongly-coupled jet-medium interactions described in holography. We use this model to study the modification of an ensemble of jets upon propagation through a quark-gluon plasma resembling central heavy ion collisions. Here the modification of the dijet asymmetry depends strongly on the subleading jet width, which can therefore be an important observable for studying jet-medium interactions. We furthermore show that the modification of the shape of the leading jet is relatively insensitive to the dijet asymmetry, whereas the subleading jet shape modification is much larger for more imbalanced dijets. Finally, we compare the results of our holographic model to a recent CMS measurement.

Introduction - The discovery that the quark-gluon plasma (QGP) produced in heavy ion collisions (HIC) at RHIC and the LHC is strongly coupled makes it both interesting and difficult to understand [1, 2]. One excellent way to probe this plasma is to make use of highly energetic quarks and gluons that are naturally produced during the collision and study their properties after they traverse the medium [3]. The production of such energetic sprays of particles, called jets, in elementary collisions is well understood within a perturbative QCD (pQCD) framework, but the interaction of these jets with QGP is theoretically more challenging since the physics of the plasma itself is strongly coupled. Here we will start with an ensemble of jets where the energies, widths and dijet asymmetry of the produced jets are fixed from pQCD computations, but the subsequent evolution through QGP is fully determined from holography [4, 5].

One of the most famous observables showing the strongly interacting nature of the QGP is the increased imbalance of jet energies in a dijet system. This is characterized by the modification of the dijet asymmetry $A_1 = (p_1 - p_2)/(p_1 + p_2)$, with $p_{1,2}$ the transverse momentum of the leading and subleading jet. The energy loss of jets depends on the path length through the medium, but even for a constant path length the energy loss fluctuates from jet to jet. Recent work found that solely including fluctuations in the energy loss distribution of centrally-produced dijets can explain the dijet asymmetry observed in HIC, even though in this case both jets have equal path lengths [6]. Indeed, the fluctuations in energy loss for fixed path lengths can be comparable to the energy loss itself [7].

We confirm these studies by showing that the dijet asymmetry in our model is insensitive to the starting position of the dijet, provided that the jet widths of each jet fluctuate independently (in our model the jet width is crucial for the energy loss). In the theoretical case where both jets are restricted to have the same jet width we find that the position and hence the path length imbalance is important to modify the dijet asymmetry. Curiously, either the path length variation or the energy loss fluctuation results in an almost equal dijet asymmetry distribution. However, a coherent picture with appropriate nuclear modification factor and jet shape modifications can only be obtained when both effects are included.

The width of a jet, the energy loss and the dijet asymmetry have an interesting interplay in holography. Every jet widens and wider jets lose more energy [4, 8]. The steeply falling spectrum of jets together with the $p_T$ cut can however act as a selection mechanism for narrower jets, which lose less energy. We will see that this mechanism is especially relevant for leading jets, but for subleading jets the energy loss simply moves the dijet to a more asymmetric dijet bin, since the subleading jet already passes the $p_T$ cut by virtue of the leading jet $p_T$.

Our analysis suggests two new observables that can be particularly informative for the interaction of jets and QGP. We first highlight the dependence of the dijet asymmetry on the subleading jet width and show that wide subleading jets lead to imbalanced dijets. Secondly, we show the jet shape modifications of subleading and leading jets binned for different values of the dijet asymmetry. Our model suggests that the leading jet is strongly modified independent of $A_1$, whereas the most imbalanced dijets have the widest subleading jets. This observation matches qualitatively with simulations done in JEWEL, but the effect of the subleading jet shapes on the dijet asymmetry is stronger in our holographic model. For related recent works on the jet substructure see also [9–20] and references therein.

The aim of this work is to qualitatively study the effects of energy loss from holography and to use those insights to identify observables that capture the physics of jet-medium interactions. We do not attempt to model all aspects of jet physics in the holographic calculation and specifically do not include third jets, incoherent substructure inside the subleading jet, hadronization or a jet finding algorithm. All of these effects can have important contributions, particularly on the subleading jet shape far from the jet axis as we discuss later. Finally, this work
Figure 1. (left) Jet nuclear modification factor $R_{AA}^{jet}$ for different starting positions of jets in the transverse plane and the physical value (black). (middle) The corresponding dijet asymmetry distribution is surprisingly insensitive to the starting position, even though central starting positions have balanced path lengths [6]. Jets produced at the center do lose more energy (as evident from the $R_{AA}^{jet}$), and are also more heavily modified (see also Fig. 2). (right) When (artificially) demanding that both jets in a dijet system have the same jet width the dijet distribution does depend on the path length imbalance. Interestingly the average dijet imbalance for jets with the same width (solid black) is almost equal to the physical case where both jet widths fluctuate independently (dashed black). The overlayed data points show the input $A_J$ distribution (black circles) from Pythia+Hydjet simulations and the modified distribution (blue squares) measured by CMS in [21].

has become especially relevant as CMS recently published results similar to our proposed measurement [22]. In the discussion we comment on a comparison with our model predictions.

The model - In holographic models the propagation of a quark-antiquark pair at large coupling is described by the dynamics of a classical string in Anti-de-Sitter space (AdS) [23]. In the dual picture a falling string corresponds to a cone of energy propagating along its axis with an opening angle proportional to the downward angle $\sigma_0$ of the string endpoint [8, 24]. Such strings can be used as holographic proxies for jets, if supplied with the required energy and if the string endpoints are chosen to be moving apart in the center of energy frame.

We use the model introduced in [4, 5], which includes input from pQCD to construct an ensemble of initial string conditions that is realistic from a QCD perspective. In this model, the distribution of holographic jet widths is fixed to the pQCD calculation of the variable $C_1^{(1)}$ in [25]. A result of [5] is the distribution of energy along strings at late times, which with the width fixes the jet shape completely. This shape matches the measured inclusive jet shape in $p+p$ collisions well. Note that this model results in null strings, which have the property that the energy distribution within the jet cone stays fixed in vacuum and hence the jet shape in $p+p$ does not evolve. For the case with plasma each individual jet widens, but note that this does not necessarily imply that the entire ensemble after applying a transverse momentum cut widens as well [4]. For null strings quark and gluon jets are the same, except that they have different $C_1^{(1)}$ distributions [25], with gluon jets being wider. We take a 50% estimate of quark jets for the $p_T$ range studied in this work. We use the $C_1^{(1)}$ distribution to describe the widths of both leading and subleading jets, however we note that the resulting subleading jet shape in vacuum is narrower than measurements [26], presumably due to the presence of third jets.

We fix the initial vacuum dijet asymmetry as in [5] from a (smeared) Pythia+Hydjet simulation from [21], which used transverse momentum cuts $(p_T^1, p_T^2) > (120, 30)$ GeV. This initial dijet distribution is realistic in asymmetry, but it is important to note that the system is hence not balanced in transverse momentum. Realistically the subleading jet is often accompanied by a smaller third jet such that the total transverse momentum is balanced. In our study we choose to ignore these third jets, which could have a significant contribution for high $p_T$ particles away from the subleading jet axis.

As in [5] we use a simple blast-wave model for the temperature profile (see [5] for details). Jets are produced according to a binary scaling distribution in the transverse plane and the normalization of the temperature is chosen to lead to reasonable jet suppression. Here we include transverse velocity effects using the fluid-gravity metric. As a simple model for the transverse fluid velocity we take $u_i = -\tanh \left( \frac{p_T}{T} \frac{\nabla_i T}{T} \right)$, which works well for small times [27, 28] and gives a realistic magnitude at late times. Here we neglect all gradient terms in the hydrodynamic expansion. It is possible to use a more complete analysis of string propagation in general metrics, including far-from-equilibrium dynamics and viscous hydrodynamics, see e.g. [29], but these corrections do not have significant effects on the results presented here.

We start our strings near the boundary at proper time $\tau_0 = 0.5$ fm/c. For each jet we compute the evolution of a collection of null geodesics, which we translate into an energy momentum flow when the plasma reaches the freeze-out temperature of 175 MeV [8, 30]. The segments that have not fallen in the black hole have new AdS angles, which lead to a new jet shape and new jet $p_T$ defined...
Dijets and jet shapes - The energy loss of dijets in HIC has particularly rich and interesting physics. Depending on the production point of the dijet the two jets traverse a different part of the medium. Both jets may also lose energy differently, depending on their width in the holographic picture or on the particular structure of the particle shower in a weakly coupled picture.

Fig. 1 (left) shows the resulting suppression of jets of a given $p_T$ relative to the initial ensemble (the jet nuclear modification factor $R_{AA}^J$), for all jets in the ensemble separated by their initial positions. Jets produced at the center lose much more energy on average than jets produced at the edge and hence are more suppressed. In order to quantify the effects of the path length imbalance and the jet width fluctuations on the $A_J$ distribution we show the distribution for the ensemble separately for different initial positions (dijets originating at the center always have balanced path lengths), see Fig. 1 (middle), and subsequently for the subset of these dijets where the two jets have the same jet width, see Fig. 1 (right). In this case the jets in a dijet system do not have independent energy loss fluctuations. When the dijets have both widths varying independently the asymmetry does not depend strongly on the path length, confirming results of [6]. However, for the theoretical case that both jets in a dijet have the same width the path length imbalance is crucial to obtain the dijet imbalance. It is surprising to note that on average the final $A_J$ distribution is almost identical regardless of whether the jet widths fluctuate independently or not, and furthermore that the fluctuating dijets created at the edge ($x = 6.5$ fm) are in fact less asymmetric than the fluctuating ones. The dijet asymmetry is also almost identical to the one obtained for centrally-produced dijets. This surprising finding in particular implies that the dijet distribution is rather robust and that describing energy loss fluctuations is not crucial for obtaining the correct dijet asymmetry distribution. However, this is not the case for more sophisticated observables discussed below.

To study both effects more closely we show the jet shape modifications for both subleading and leading jets in Fig. 2 (left), where $\rho_{AA,pp}(r)$ are the normalized transverse momentum distributions as a function of the angular distance $r$ to the average direction of the jet for $AA$ and $pp$ collisions respectively. Clearly, jets produced at the center also have their shapes more strongly modified, which in the case of independent energy loss makes them more imbalanced. This gives an extra explanation why the path length is not crucial for the dijet asymmetry distribution [6]: jets that have the same path length often are jets that are modified most which makes them more unbalanced for that reason.

Our main result is to select jets on their final width (defined here as $w = \int_0^{R_{AA}^J=0.3} r \rho_r(r)dr$), which unlike selecting on starting positions is also possible experimentally. Fig. 2 (middle) shows the $A_J$ distribution binned for different widths of the subleading jet. Clearly, the width of the subleading jet is essential in the dijet asymmetry: wider subleading jets lead to asymmetric dijets, whereas the narrowest subleading jets even lead to a distribution that is more symmetric than the original $pp$ asymmetry. In Fig. 2 (right) we compare our result with results from the JEWEL Monte Carlo generator, which is based on a weakly-coupled kinetic theory with scattering centers in the QGP [31]. We generate events at 2.76 TeV with the default medium model chosen to match hydrodynamic simulations at this energy and reconstruct anti-$k_t$ jets using FastJet. We turn off medium recoils in JEWEL.

Figure 2. (left) Leading (solid) and subleading (dashed) jet shapes are more heavily modified for centrally produced jets. The average jet shape modification for leading and subleading jets is shown in black solid and dashed and for inclusive jets in dotted black. (middle) Our main result is the dijet asymmetry binned for different widths of the subleading jets, which shows a strong qualitative difference for wide and narrow subleading jets (corresponding to unbalanced and balanced dijets, respectively). The dijets with the most narrow subleading jets are even more balanced than vacuum dijets. (right) In JEWEL dijets with a wider subleading jet also have a more imbalanced dijet asymmetry distribution, but for wide subleading jets the distribution is broader in $A_J$ and for narrow subleading jets it is narrower. The errors are statistical only.
so that medium back reaction is ignored as in the holographic calculation. Wider subleading jets are also more imbalanced on average in JEWEL, but for larger $C_1^{(1)}$ values the distribution is wider than in the holographic case.

The jet shapes in the leftmost panel of Fig. 2 are ‘theoretical’, in the sense that experimentally it is impossible to assign a starting location $x_1$ to an individual jet. It is however possible to see a similar effect experimentally by selecting dijets according to their transverse momentum (Fig. 3, left) or their asymmetry (Fig. 3, middle). Quite curiously, the leading jet shape does not depend strongly on either $p_T$ or $A_J$ (an experimental indication that this is correct can be found in [26], see also our discussion section below). However, we find that the subleading jet shapes strongly depend on both the transverse momentum and the dijet asymmetry, with more unbalanced dijets having wider subleading jets. The narrowing of leading jets and widening of the subleading jets is in agreement with the two competing effects studied in [4], where every jet gets wider, but the average shape of the ensemble of jets can narrow due to the steeply falling jet production spectrum. For the leading jets the second effect is dominant, but for subleading jets the first effect dominates, since the subleading $p_T$ cut is much lower than the typical $p_T$ of a subleading jet. Subleading jets therefore usually stay within the sample and especially for larger dijet asymmetries gain considerably in width. For qualitative illustration, we show in grey in Fig. 3 regions where our results are only partial, since in those regions both medium backreaction (for low $p_T$ hadrons) and third jets for the subleading jets (high $p_T$ hadrons) can significantly modify the jet shapes.

The JEWEL analysis (Fig. 3, right) confirms the jet shape dependence on $A_J$ qualitatively, except that at large $r$ the subleading jet shapes in JEWEL are narrower. One advantage of JEWEL is that it contains a full Monte Carlo, and hence incorporates 3rd jets, or incoherent partons at relatively large $r$ that lose energy to QGP independently (see i.e. [32, 33]). These type of partons are a rather typical contribution to subleading jet shapes at large $r$, and the quenching of such partons will lead to narrower subleading jet shapes. Since this is not taken into account in the holographic model the subleading jet shape at large $r$ cannot be accurately compared with experimental data. The JEWEL analysis, on the other hand, compares quite well with CMS jet shape data [26], when restricting to $p_T > 3$ GeV (this leaves out the thermal particles that we did not take into account). This effect is likely also related to the reason that JEWEL has wider distributions in Fig. 2 (right), since incoherent partons do not give rise to subleading jets as wide as in the holographic model. However, the width of the jet is less sensitive to the large $r$ part of the jet shape, so that the middle of Fig. 2 is more robust than the subleading jet shape at large $r$.

Qualitatively the dependence on the subleading jet width is intuitive: a wider jet generically loses more energy than a narrow jet, and hence will likely end up with significantly less energy than the other jet. The full story is however more complicated: the combination of the steeply falling jet spectrum and momentum cuts biases the interpretation of jet modification observables and necessitates considering an ensemble of jets [4, 5]. Furthermore in both JEWEL and holography the modified jet width can deviate substantially from the initial jet width. Nevertheless, both the holographic model and JEWEL agree with the naive intuition, although the holographic model produces significantly wider subleading jets. This suggests either a stronger influence of the jet width on the energy loss in holography, or a stronger jet width evolution while the jet traverses the plasma.

**Discussion** - In this work we take input from pQCD to model dijet evolution through a holographic plasma. This suggests two interesting observables requiring further study: the $A_J$ distribution binned for different subleading jet widths (Fig. 2, middle) and the jet shape modifications of leading and subleading jets binned for different $A_J$ (Fig. 3, middle). The former showed simi-
Subleading jet shapes, $1 < p_T < 2$ GeV

![Subleading jet shapes, $1 < p_T < 2$ GeV](image)

Leading jet shapes, $1 < p_T < 2$ GeV

![Leading jet shapes, $1 < p_T < 2$ GeV](image)

Subleading jet shapes, $4 < p_T < 8$ GeV

![Subleading jet shapes, $4 < p_T < 8$ GeV](image)

Leading jet shapes, $4 < p_T < 8$ GeV

![Leading jet shapes, $4 < p_T < 8$ GeV](image)

Figure 4. We show the leading (top) and subleading (bottom) jet shape modifications derived from CMS data [22] binned for different dijet asymmetries $x_l = p_T/\gamma /p_T$ for charged hadrons with $p_T$ within $(1, 2)$ GeV (left) and $(4, 8)$ GeV (right). Unbalanced jets (blue) lead to more low $p_T$ particles for subleading jets, whereas both leading and subleading jets have a reduced number of high $p_T$ hadrons at large angles.

Lar qualitative features to the results from JEWEL Monte Carlo, while the jet shapes agreed qualitatively for the leading jet shapes and for small $r$. Both experimental measurements and different model results of these observables (including pQCD computations, for example [34]) will shed light on the interplay of path lengths, jet energy loss fluctuations, jet structure and substructure.

The model presented requires many future improvements, and for that reason the results presented should be seen as qualitative. We only consider back-to-back dijets without considering third jets [35], and we do not treat the back reaction of jets on the medium or include any hadronization procedure. All of these can potentially be improved by incorporating the model in a Monte Carlo framework such as JETScape [36] (see also [10]). We stress in particular that third jets can affect the subleading jet shapes at intermediate to large $r$, which likely contributes to the difference between our result (Fig. 3 middle) and JEWEL (Fig. 3 right). We note that the averaged subleading jet shape of JEWEL agreed quite well with the result of CMS when including particles with $p_T > 3$ GeV. This cut in transverse momentum is important to separate the jet from the medium (also done in [37]). However it is known that recoils have a large effect on jet shapes when lower $p_T$ particles are included [11], and they may have some impact on the jet shapes for $p_T > 3$ GeV especially at large $r$. Finally, it would also be interesting to extend this analysis to $\gamma$–jet events, where it is possible to use the photon as a probe of the initial jet energy and directly study how the shape modification of a jet depends on its energy loss.

Even though as argued our results have to be taken qualitatively, it is still interesting to compare our model predictions with the recent measurements by CMS [22]. Though a preprint of this work appeared before the data was taken, for completeness we show in Fig. 4 ratios derived from the recent measurements by CMS [22] of the leading and subleading jet shapes of low and high $p_T$ particles as a function of the dijet asymmetry. Note that this CMS measurement measures the absolute shapes $P(r)$ instead of the self-normalised shapes $p(r)$ as in Fig. 3, which in particular means that the $P(r)$ ratios do not necessarily cross unity. Error bars shown are the quadratic sum of statistical and systematic uncertainties, which in this case are dominated by systematics. These $p_T$-binned ratios can give more insights than the $p_T$-integrated results of [22], since the different physical scales can separate medium backreaction and the quenching of hard partons (including third jets).

Optimistically, the high $4 < p_T < 8$ bin behaves qualitatively similarly to our leading jet shape predictions and those from JEWEL shown in Fig. 3, whereas the subleading jet shapes at $1 < p_T < 2$ GeV also qualitatively follow the trend predicted in holography. Indeed, at high $p_T$ the leading jet shapes become narrower and depend only weakly on the dijet asymmetry, while the subleading jet shapes at low $p_T$ are ordered in the same way as in Fig. 3 – more unbalanced dijets (smaller $x_l$) correspond to wider subleading jets. It is reasonable that the subleading jet broadening in Fig. 3 shows up at low $p_T$, but we note that this is also the regime where we can expect effects from medium response that we do not include here. Contrary to our expectations from Fig. 3, it is interesting that the subleading jet shapes at high $p_T$ do not depend significantly on the asymmetry and become narrower. At large $r$, the subleading jet shapes in JEWEL also become narrower. We expect that third jets may be crucial for understanding the lack of dependence of the subleading jet shape on the asymmetry for high-$p_T$ particles.

At the moment both the holographic model (which is more strongly coupled) and JEWEL (which is based on weak coupling) are too simple to fully describe the experimental data. The fact that for these two theories this observable is much more difficult to obtain than the dijet asymmetry distribution by itself (see Fig. 1) makes it of special interest for future work, since it could be used to differentiate between the regimes.

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