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Sensitivity of jet substructure to jet-induced medium response

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ABSTRACT

Jet quenching in heavy ion collisions is expected to be accompanied by recoil effects, but unambiguous signals for the induced medium response have been difficult to identify so far. Here, we argue that modern jet substructure measurements can improve this situation qualitatively since they are sensitive to the momentum distribution inside the jet. We show that the groomed subjet shared momentum fraction z_g, and the girth of leading and subleading subjets signal recoil effects with dependencies that are absent in a recoilless baseline. We find that recoil effects can explain most of the medium modifications to the z_g distribution observed in data. Furthermore, for jets passing the Soft Drop Condition, recoil effects induce in the differential distribution of subjet separation ΔR_{12} a characteristic increase with ΔR_{12}, and they introduce a characteristic enhancement of the girth of the subleading subjet with decreasing z_g. We explain why these qualitatively novel features, that we establish in JEWEL+PYTHIA simulations, reflect generic physical properties of recoil effects that should therefore be searched for as telltale signatures of jet-induced medium response.

High momentum transfer processes with hadronic final states are generically and strongly modified when occurring within the dense environment produced in nucleus–nucleus collisions. This jet quenching phenomenon is being studied systematically at the LHC for jet $p_\perp$-spectra, dijet asymmetries, jet fragmentation functions, jet shapes and, most recently, for a large class of increasingly refined jet substructure observables. Jet quenching implies jet-medium interactions. If the medium is close to a perfect liquid, medium recoil propagates in the form of hydrodynamic excitations [1], but it is expected to show signs of large angle scattering if jet-medium interactions were to resolve partonic degrees of freedom in the medium [2–4]. Beyond confirming the assumed dynamics of jet-medium interactions, the observation of recoil distributions is thus of great interest for characterizing the nature of the medium.

However, the characterization of jet recoil distributions has remained elusive so far for several reasons. In particular, recoil effects are expected to contribute mainly to the soft large-angle hadronic activity, but there are experimental and theoretical uncertainties in establishing soft recoil remnants on top of a large and fluctuating background that need to be controlled. Also, many of the measurements used to characterize jet quenching are remarkably insensitive to soft large-angle activity. For instance, quenched hadron spectra are by construction insensitive to how the lost energy is distributed, and traditional jet quenching observables constructed from jet $p_\perp$ and jet axis (such as the jet nuclear modification factor) are dominated by hard contributions. One may expect that jet shape observables are more sensitive to the jet medium response since they are sensitive to momentum distributions inside the jet. Our main result will be to establish a first example for a combination of jet substructure observables — namely measurements of the subjet shared momentum fraction z_g and of girth — that allow for the separation of recoil effects from alternative interpretations with both characteristic quantitative and qualitative features in the data.

In contrast to jet quenching models that parametrize (e.g., in terms of the quenching parameters $\hat{q}$ and $\hat{e}$) the recoil carried away from the jet, fully dynamical event generators of jet quenching are better suited to study recoil effects as they can propagate them into final state particle distributions. To exploit the resulting phenomenological opportunities, however, one needs a robust prescription for separating medium recoils from the initial thermal

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component of recoiling partons that is part of the soft background activity. For the event generator Jewel [5], such a tool was validated recently in Ref. [6]. It enables us in the present study to distinguish in fully dynamical jet quenching simulations between effects that are due to the splitting of jet constituents, and effects that arise from momentum transfers to recoiling medium scattering centers. We emphasize that while both effects are part of the same physical process, there is no model parameter that would allow one to vary their relative strength and trade one for the other.[1] Moreover, both effects manifest themselves differently in different kinematical regions. It is in this sense that we can separate here both effects operationally in a model-independent way.

Jewel is a microscopic model for jet evolution in a dense background based entirely on perturbative QCD. It implements the following set of assumptions: (i) hard partons in a jet interact with the background by resolving the partonic structure of the medium, (ii) an infra-red continued version of pQCD matrix elements can be used to describe these jet-medium interactions, (iii) the interplay between different sources of radiation is governed by formation times, and (iv) the LPM effect as calculated in the eikonal limit extends to general kinematics. Jewel describes with $2 \to 2$ matrix elements the scatterings of partons belonging to a jet with partons resolved in the medium. The radiation associated to these $2 \to 2$ scatterings is generated by a parton shower. In this way, momentum transfer and radiation are dynamically related, elastic and inelastic scatterings are generated with the correct relative rates and vacuum-like and medium-like radiation is treated in a common framework (in fact there is no distinction between the two in Jewel). According to the LPM algorithm derived in [7], multiple momentum transfers act coherently when they occur within the formation time of the emitted gluon. When the formation times of two gluon emissions overlap, only the one with the shorter formation time will be emitted. In this way, only scatterings that are hard enough to resolve a virtual parton can induce radiation. This shares similarities with the refined LPM calculations for color coherence in an antenna [8,9], but it neglects the radiation from the total charge in the unresolved case. Implementing these conceptual ideas, Jewel allows for modifications of the vacuum-like scale evolution of the jet by scattering in the medium, and the interplay between vacuum-like and medium-like emissions becomes fully dynamic. More details about the modified jet evolution in Jewel and other aspects of the event generator can be found in [10].

Jewel has been tested against a large class of jet quenching measurements, including traditional jet observables built from the jet $p_\perp$ and axis (such as jet R_{AA}, dijet asymmetry A_J) [10,11], as well as jet shape observables that are more sensitive to medium effects [6]. The simulations shown in this work are based on dijet events generated in the standard setup [5] at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. No attempt was made to improve comparison to data by retuning model parameters. While the following discussion focuses on the physics of two particular jet substructure observables, we emphasize that Jewel with the model parameter settings used here is documented to provide a correct qualitative and good quantitative description of jet quenching in general.

The Soft Drop algorithm [12,13] reconstructs jets with the anti-$k_\perp$ algorithm [14] and reclusters them with a prescription entirely based on angles (Cambridge/Aachen). The last step of this reclustering is then undone to give the two prongs with the largest angular separation. If the $p_\perp$-sharing between the two prongs satisfies

$$z_g \equiv \frac{\min\left(p_{\perp,1}, p_{\perp,2}\right)}{p_{\perp,1} + p_{\perp,2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}, \tag{1}$$

then the prongs are accepted and the algorithm terminates. Otherwise, the softer of the prongs is rejected, the last reclustering step on the hard prong is undone, and the algorithm continues till condition (1) is satisfied. This is one of a variety of grooming techniques that can be used to systematically reject (or study) soft contributions associated to jets. In eq. (1), R denotes the jet radius. In the following, we work for $\beta = 0$, and we use the default $z_{\mathrm{cut}} = 0.1$. We also require that only configurations with $\Delta R_{12} > 0.1$ are included in the z_g-distribution. This condition was added by the CMS collaboration to the original Soft Drop proposal, and we adopt it to facilitate comparison to the preliminary data [15].

Here, we investigate the physical mechanisms underlying the softening of the groomed shared momentum fraction z_g in Jewel, including the possibility that recoil effects contribute. In general, the momentum of recoiling partons is composed of a thermal component that they carry before the jet-medium interaction, as well as the momentum transferred when interacting with jet constituents. Only the latter contributes to the medium response, the former is removed experimentally by background subtraction techniques. However, these techniques cannot be applied to Jewel as it does not generate full heavy ion events. Instead, consistent with experimental procedures, the (thermal) background contribution is subtracted from generated event samples with a so-called 4-momentum subtraction technique validated in [6].

We emphasize that for hadronization, Jewel converts all recoiling partons into gluons that are inserted into the strings that connect the partons forming the jets. It is therefore not meaningful to label hadrons in the event record as belonging to the jet or to the medium response. However, one can hadronize events in Jewel with or without the recoiling partons. Fig. 1 shows the corresponding z_g-distributions. Since recoiling partons do not rescatter in Jewel, and since rescattering induces thermalization processes, generated events with recoiling partons may overestimate the physically expected medium response. The truth is therefore expected to lie in between the green (without recoil) and blue (with recoil) curves in Fig. 1, and the difference between both curves should be regarded as an upper bound for the expected medium-response.

Even without including recoiling partons, the simulated z_g-distribution in Fig. 1 shows a mild tilt towards smaller z_g in comparison to the proton–proton baseline. Without additional information, the interpretation of this tilt remains ambiguous. The reason is that the z_g-distribution is a self-normalizing curve. A tilt of the type shown in Fig. 1 can therefore arise either (i) from an enhanced contribution at small z_g (that reduces the bin entries at large z_g due to normalization), or (ii) from a depletion of jets with large z_g (that would enhance bin entries at small z_g by normalization). The first of these two possibilities has been argued [17,18] to be the dominant one, based on the following two observations: first, to lowest perturbative order in QCD (and without medium-effects), the z_g-distribution $p(z_g)$ for $\beta = 0$ is given by the LO QCD splitting functions $P(z)$ [16]

$$p(z_g) = \frac{P\left(z_g\right) + P\left(1 - z_g\right)}{\int_{z_{\mathrm{cut}}}^{1/2} \mathrm{d}z \left[P\left(z_g\right) + P\left(1 - z_g\right)\right]}, \tag{2}$$

and second, medium-induced gluon radiation is expected to soften the perturbative splitting functions. Therefore, if one neglects re-

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[1] More precisely, it is possible within Jewel to trade a lower infra-red cut-off of the parton shower for a lower α_s within the tight experimental constraints set by LEP data. This provides some freedom for varying the amount of radiation versus scattering and therefore recoil. However, this effect has not been explored systematically, it is expected to be small and we do not discuss it further in the present paper as it will not affect our main conclusions.

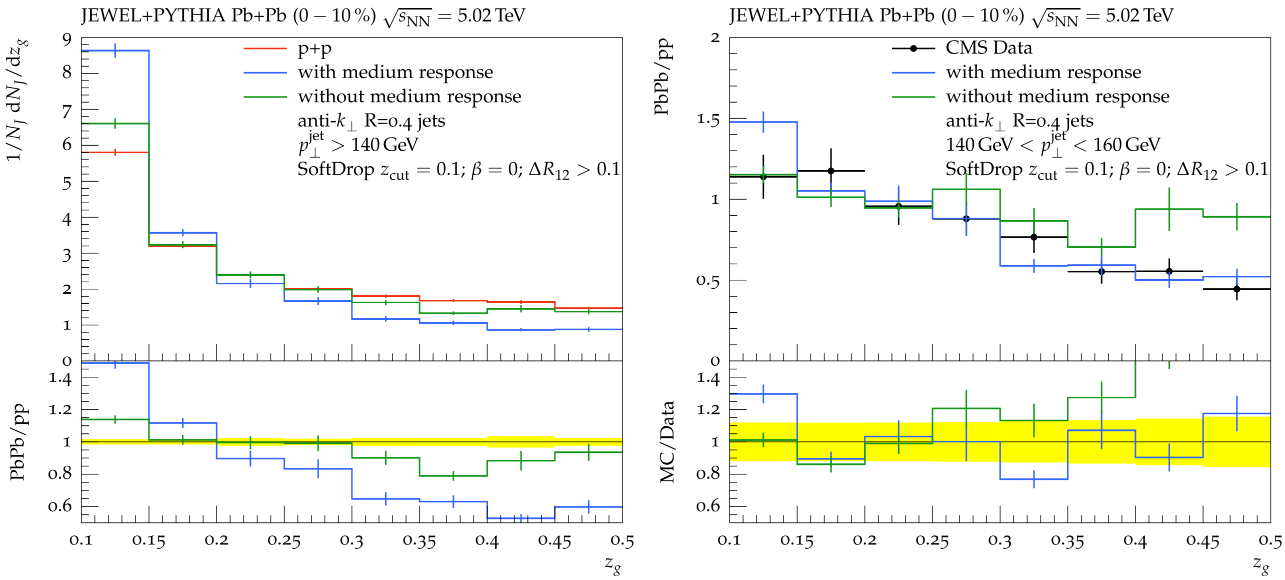

Fig. 1. (l.h.s.) Jewel+Pythia result for the groomed shared momentum fraction z_g in central PbPb events analyzed with (blue curve) and without (green curve) keeping track of medium response and compared to simulated pp events (red curve). (r.h.s.) The ratio of the z_g-distributions in PbPb and pp events, compared to CMS data for jet $p_\perp$ between 140 GeV and 160 GeV. All results are for $\sqrt{s_{NN}} = 5.02$ TeV and are shown background subtracted (4-momentum subtraction method) and on hadron level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

coiling partons, the medium-induced enhancement of gluon splittees in the parton shower provides a candidate mechanism for enhancing the fraction of subleading subjets with small groomed momentum fraction z_g. However, for this mechanism to be efficient, medium-induced gluon radiation must be sufficiently hard to pass the cut (1). Inspection of generated events reveals that this condition is rarely satisfied in Jewel. Indeed, while medium-induced parton splitting underlies the simulation of jet quenching in Jewel, partonic splittees induced by jet-medium interactions carry rarely a sufficient energy $O\left(E_{\text{jet}}\, z_g\right)$ to make it above the cut (1), and hadronization reduces this contribution further. Also, in simulations without recoiling partons, the likelihood of medium-induced splittees to cluster with other jet fragments to subjets that pass the cut (1) is small. Rather the dominant contribution to the small tilt of $(1/N_J)dN_J/dz_g$ in simulations without recoiling partons comes from the fact that all partons in the shower undergo parton energy loss and that this suppresses in particular the yield of events with large z_g. As jets with a large z_g will show a softer fragmentation, this is consistent with earlier observations that such broader jets are more susceptible to energy loss and thus more likely to fail analysis cuts [11,19,20]. We have checked this statement for the present analysis (data not shown).

Once recoiling partons are included in the analysis, the tilt in the z_g-distribution increases significantly and the shape is in quantitative agreement with experimental data (see r.h.s. of Fig. 1). In contrast to the case without recoil, the dominant contribution to the tilt comes now from an enhancement of jets with soft subleading subjets that pass the grooming cut (1). The reason is that soft large-angle recoil contributions get clustered into (sub)jets and can thus promote candidate prongs of low z to above the Soft Drop condition (1). Our simulations thus suggest that the long-sought medium response that provides a negligible or difficult to discriminate contribution in many other jet quenching observables may dominate the z_g distribution. We next ask to what extent this interpretation can be corroborated by complementary measurements.

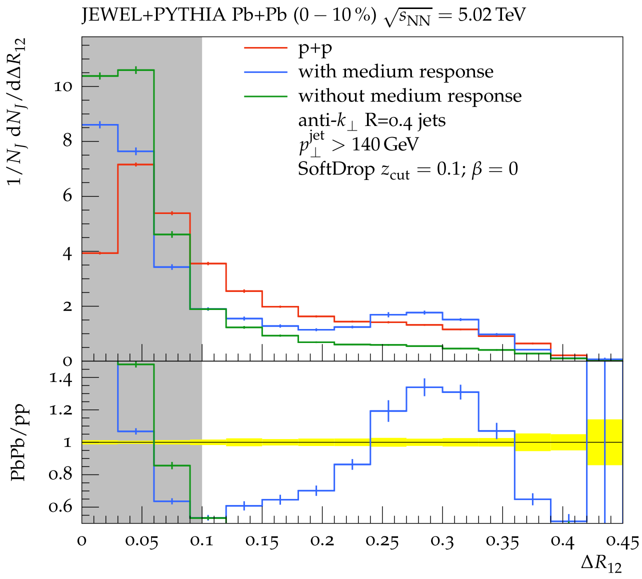

Fig. 2. Distribution in the relative separation ΔR_{12} of the two subjets for jets that pass the Soft Drop condition (1), supplemented by the $\Delta R_{12} > 0.1$ requirement (gray band). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

To this end, we study first for the jet sample that contributes to the z_g-distribution the relative separation ΔR_{12} in the $\Delta\eta \times \Delta\phi$-plane between the leading and subleading prongs. As described above, jets with broader fragmentation patterns are expected to fail analysis cuts such as (1) more easily. Consistent with this picture, in the absence of recoil effects (see green curve on the r.h.s. of Fig. 2) the fraction of jets with large ΔR_{12} that pass the analysis cut is strongly reduced. If medium response is included in the analysis, the ΔR_{12}-distribution changes qualitatively in a very characteristic way. The reason is that if a subleading candidate prong is further separated from the leading prong, then there is a larger area in the $\Delta\eta \times \Delta\phi$-plane from which soft recoil contributions can be clustered together with this soft prong. This makes it more likely to promote soft prongs above the Soft Drop condition (1) if ΔR_{12} is larger. As a consequence, the ΔR_{12}-distribution increases with increasing ΔR_{12} up to a separation scale that is set by the jet radius. Therefore, the ΔR_{12}-distribution (blue curve)

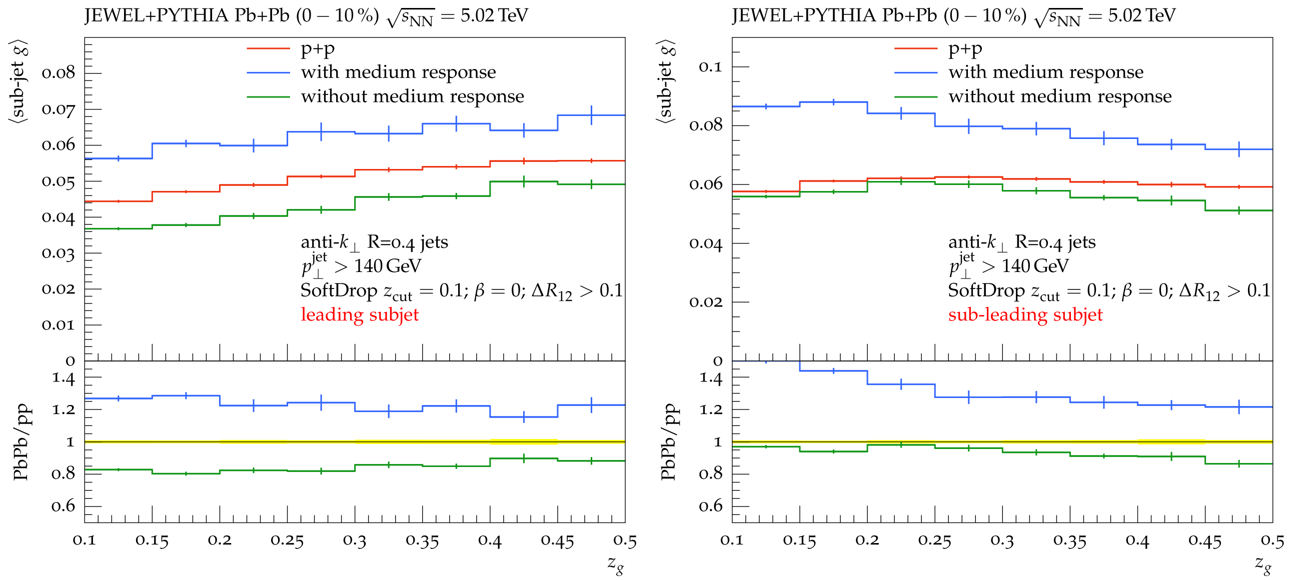

Fig. 3. JEWEL+PYTHIA results for the first radial moment (3) (girth g) of the leading (l.h.s.) and subleading (r.h.s.) subjet in jets reconstructed with the anti-$k_\perp$ algorithm for $R = 0.4$ and that pass the Soft Drop condition (1). Results are for jets simulated on hadron level in $\sqrt{s_{\rm NN}} = 5.02$ TeV PbPb collisions with (blue curve) and without (green curve) recoil effects, as well as for proton–proton reference data (red curve). The 4-momentum subtraction method is used to provide background subtracted data consistent with experimental procedures. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

peaks at a value ΔR_{12} somewhat smaller than R. We conclude that the increase of the ΔR_{12}-distribution with increasing ΔR_{12} would be a characteristic telltale sign for the dominance of recoil effects in medium-modifications of the groomed shared momentum fraction z_g.

By now, several independent model studies support the at least partial cancellation of two qualitatively different effects in many jet quenching observables [20,21,6]. On the one hand, parton energy loss effectively peels off soft components from the jet, thereby narrowing the jet core. On the other hand, medium response can counteract this tendency as recoil effects contribute to jet broadening. The interplay of both effects has been observed to be at work also in some jet shape observables, including jet mass and girth [20,6]. However, the kinematical distribution of recoil is generally different from that of medium-induced radiation, and despite partial cancellation of both effects, differential distributions in other jet substructure observables may thus be expected to maintain some characteristic sensitivity to medium response. Here, we discuss this possibility for girth g, which is defined by summing over the momenta $p_\perp^{(k)}$ of all constituents of the jet with a weight given by the distance ΔR_{kJ} from the jet axis,

$$g = \frac{1}{p_\perp^{\rm jet}} \sum_{k\in J} p_\perp^{(k)} \, \Delta R_{kJ} \, . \tag{3}$$

In general, this radial moment of the jet profile is expected to increase with recoil effects that broaden the jet, and it is expected to decrease if radiation narrows the jet core by peeling off preferentially soft large angle components. Both mechanisms are clearly seen at work for the girth of the leading subjet, where the girth in PbPb events reconstructed without recoil effects is seen to be reduced compared to the pp baseline, while the girth is increased in events including recoil effects (top panel, Fig. 3). Both effects cancel partially, consistent with earlier observations. For the leading subjet, the net effect is a shift of the magnitude of girth that is approximately independent of z_g.

The situation is somewhat different for the girth of the subleading subjet. First, in the absence of recoil effects, jet quenching leads to a much smaller reduction of girth. The reason is that the jet can only get narrower by losing energy, but subleading subjets cannot lose much energy without failing the Soft Drop condition (1). If the subleading subjet fraction z_g is larger, then this bias is less significant, and this explains the slight increase in the reduction of girth with increasing z_g. On the other hand, for the case in which recoil effects are included in the analysis, the girth of subleading subjets is approximately a factor 2 more strongly enhanced for small $z_g \simeq 0.1$ than for $z_g \simeq 0.5$. This is an independent test of the argument that the tilt of the z_g-distribution is mainly due to recoil effects that promote soft candidate prongs above the Soft Drop cut condition (1): if subleading subjets at low z_g have a pronounced recoil contribution, then they are expected to be particularly broad, and this is what is reflected in a more strongly enhanced girth at small z_g. The combined analysis of the girth of leading and subleading subjets provides thus independent sensitivity to recoil effects and can therefore help to disentangle effects from medium response in jet quenching models.

To what extent can this conclusion be expected to be independent of the model within which we have illustrated it here? JEWEL is based on the working hypothesis that jet medium interactions can be described with pQCD alone, an assumption justified for hard momentum transfers but questionable for the soft momentum transfers characteristic of recoil distributions. However, JEWEL provides phenomenologically successful descriptions for a broad range of jet quenching phenomena that involve momentum transfers comparable to those in the jet substructure observables discussed here. Therefore, we have no reason to expect that a fundamental breakdown of perturbative modeling would show up exclusively in jet substructure observables. The focus of JEWEL on pQCD implies also technical limitations. For instance, in the present version of JEWEL, recoil partons are not rescattered, and thus there is no mechanism that could potentially lead to isotropization or thermalization. Any such mechanism could move energy of recoil partons outside the jet cone and, if sufficiently efficient, could affect the relative weight of recoil and quenching effects inside the jet cone. The present study has not quantified such potential confounding effects. Instead, we have identified a qualitatively novel structure in the ΔR_{12}-distribution of subjets in Fig. 2 whose magnitude and shape is characteristic for perturbative recoil. Its observation would, to the best of our current understanding, provide a model-independent signal for the relative importance of recoil effects.

We finally dare to share our experience that physics conclusions about the presence of recoil effects can only be drawn from models of a certain technical maturity. For instance, hadronization effects are also known to contribute to the broadening of jets. In our simulations, the girth one extracts from generated data at (unobservable) parton level shows qualitatively similar but much stronger recoil effects than the data on hadron level discussed here. The use of an independently validated hadronization prescription is therefore important for arriving at realistic physics conclusions. An analogous remark applies to the use of background subtraction techniques.

The z_g-distribution and the girth of subjets are not the only jet measurements that are sensitive to recoil effects. Recent studies indicate that also the ratio of jet fragmentation functions, the jet mass and the radial jet profile show characteristic dependencies that are naturally accounted for by recoil effects [6,21]. Recoil effects have also been argued to affect γ-hadron azimuthal correlations [22] and single inclusive jet measurements [23]. We expect that a more complete analysis of medium response in jet quenching will profit from the totality of modern jet and in particular jet substructure measurements. In the present work, we have shown for the cases of z_g-distribution and girth that recoil effects found in a detailed simulation can be understood in terms of generic physical properties of recoil effects. Jet substructure measurements are sufficiently differential to test a recoil interpretation in multiple complementary ways. In particular, beyond demonstrating that the preliminary data for the tilt in the z_g-distributions are consistent with a recoil interpretation, we have argued that the same interpretation implies characteristic features in the ΔR_{12}-distribution (increase with increasing ΔR_{12}) and in the girth (increased enhancement of the girth of the subleading subjet at small z_g). These developments make us confident that 15 years after the first experimental indications for jet quenching, we are in a position to constrain the so far elusive but logically unavoidable counterpart of jet quenching: the jet-induced medium response.

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