Sensitivity of jet substructure to jet-induced medium response

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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 subjects 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 $\Delta R_{12}$ a characteristic increase with $\Delta R_{12}$, and they introduce a characteristic enhancement of the girth of the subleading subject 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 $p_T$-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 $p_T$ and jet axis (such as the jet nuclear modification factor) are dominated by hadron 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 $\hat{g}$ and $\hat{\epsilon}$) 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 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 [7]. 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 has been tested against a large class of jet quenching measurements, including traditional jet observables built from the jet $p_T$ axis (such as jet $R_{AA}$, dijet asymmetry $A_{jj}$) [8,9], as well as jet shape observables that are more sensitive to medium effects [6]. The simulations shown in this work are based on di-jet events generated in the standard setup [5] at $\sqrt{s_{NN}} = 5.02$ 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 [10, 11] reconstructs jets with the anti-\(k_{t}\) algorithm [12] 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 \(p_{l1}\)-sharing between the two prongs satisfies

\[
\begin{align*}
\zg & \equiv \min \left( \frac{\min (p_{l1,1}, p_{l2,1})}{p_{l1,1} + p_{l2,1}} \right) > z_{\text{cut}} \left( \frac{\Delta R_{12}}{R} \right)^\beta, \\
\end{align*}
\]

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 \(z_{\text{cut}} = 0.1\). We also require that only configurations with \(\Delta R_{12} > 0.1\) are included in the \(\zg\)-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 [13].

Here, we investigate the physical mechanisms underlying the softening of the groomed shared momentum fraction \(\zg\) 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 \(\zg\)-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 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 \(\zg\)-distribution in Fig. 1 shows a mild tilt towards smaller \(\zg\) in comparison to the proton-proton baseline. Without additional information, the interpretation of this tilt remains ambiguous. The reason is that the \(\zg\)-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 \(\zg\) (that reduces the bin entries at large \(\zg\) due to normalization), or (ii) from a depletion of jets with large \(\zg\) (that would enhance bin entries at small \(\zg\) by normalization). The first of

FIG. 1. (top) JEWEL+PYTHIA result for the groomed shared momentum fraction \(\zg\) 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). (bottom) The ratio of the \(\zg\)-distributions in PbPb and pp events, compared to CMS data for jet \(p_{l}\) 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.
these two possibilities has been argued [15, 16] 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 $P(z)$ [14]

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

and second, medium-induced gluon radiation is expected to soften the perturbative splitting functions. Therefore, if one neglects recoiling partons, the medium-induced enhancement of gluon splittees in the parton shower provides a candidate mechanism for enhancing the fraction of subleading subjects 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 $O(E_{jet} z_g)$ to make it above the cut [1], and hadronization reduces this contribution further. Also, in simulations without recoiling parton, the likelihood of medium-induced splittees to cluster with other jet fragments to subjects 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 parton 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 [8, 17, 18]. 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 subjects 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.

To this end, we study first for the jet sample that contributes to the $z_g$-distribution the relative separation $\Delta R_{12}$ 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 $\Delta R_{12}$ that pass the analysis cut is strongly reduced. If medium response is included in the analysis, the $\Delta R_{12}$-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 $\Delta R_{12}$ is larger. As a consequence, the $\Delta R_{12}$-distribution increases with increasing $\Delta R_{12}$ up to a separation scale that is set by the jet radius. Therefore, the $\Delta R_{12}$-distribution (blue curve) peaks at a value $\Delta R_{12}$ somewhat smaller than $R$. We conclude that the increase of the $\Delta R_{12}$-distribution with increasing $\Delta R_{12}$ 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 [6, 18, 19]. 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 [6, 18]. However, the kinematical distribution of recoil is generally different from

![FIG. 2. Distribution in the relative separation $\Delta R_{12}$ of the two subjets for jets that pass the Soft Drop condition [1], supplemented by the $\Delta R_{12} > 0.1$ requirement (grey band).](image-url)
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

$$\Delta R_{k,J}$$ from the jet axis,

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

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 $z_g \approx 0.1$ than for $z_g \approx 0.5$. 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.

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
interpretation implies characteristic features in the ∆R recoil interpretation, we have argued that the same in-
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[7] More precisely, it is possible within JEWEL to trade a lower infra-red cut-off of the parton shower for a lower αs within the tight experimental constraints set by LEP data. This provides some freedom for varying the amount of radiation versus scattering and therefore recoil. How-
ever, 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.
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