

Particle Correlations in Jets

Wenbin Zhao^{1,2,3,*}, Volker Koch^{2,†} and Feng Yuan^{2,‡}

¹*Institute of Particle Physics and Key Laboratory of Quark and Lepton Physics (MOE),
Central China Normal University, Wuhan, 430079, Hubei, China*

²*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

³*Physics Department, University of California, Berkeley, California 94720, USA*



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We study particle correlations in high energy jets by comparing the measured energy-energy correlator with that constructed from two individual energy flows with respect to the jet axis. This comparison demonstrates that the genuine correlations are stronger at moderate or large angles across all jet energies, indicating that they are coming from correlated splitting. Meanwhile, at small angles, they increase with jet energy, exhibiting a peculiar pattern that can be used to explore jet energy loss in heavy-ion collisions. This method will provide a unique tool to disentangle different physics by comparing the genuine correlations in jet energy-energy correlators between heavy-ion collisions and proton-proton collisions.

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Introduction—Energy-energy correlators (EECs) in e^+e^- annihilation were introduced to test the asymptotic freedom of quantum chromodynamics (QCD) more than three decades ago [1–3]. Theoretical developments have advanced its applications to extract various physics and study precision strong interaction physics [4–15]. In recent years, a renaissance of interest in EECs has spanned different fields [16–55]; see a recent review [56]. In particular, EECs have been extensively applied to systematic measurements of jet substructure in proton-proton collisions and heavy-ion collisions at the Large Hadron Collider (LHC) and the Relativistic Heavy Ion Collider (RHIC) [57–62]. In the following, we study this physics from a different perspective, focusing on the correlation between particles inside the high energy jets. The goal is to help us to understand the underlying physics and to reveal hadronization effects in these correlation measurements.

The EEC inside the jet is defined as

$$\frac{d\langle \text{EEC}(\theta) \rangle_{\text{full}}}{d^2\theta} = \frac{1}{N_{\text{jet}}} \sum_{\text{jets } J} \sum_{i \neq j \in J} \frac{E_i E_j}{E_J^2} \delta^{(2)}[\vec{\theta} - (\vec{\theta}_i - \vec{\theta}_j)], \quad (1)$$

*Contact author: WenbinZhao@lbl.gov

†Contact author: vkoch@lbl.gov

‡Contact author: fyuan@lbl.gov

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where N_{jet} represents number of jets. The sum is over all particles (i, j) in the jet so that $\text{EEC}(\theta)$ corresponds to the energy weighted sum (distribution) of all pairs with relative angle θ , and jet energy $E_J = \sum_i E_i$. At colliders, the definition of the angle includes the rapidity difference between the two particles, e.g., $R_L = \sqrt{\delta\eta^2 + \delta\phi^2}$ is used in pp collisions where $\delta\eta$ represents the rapidity difference and $\delta\phi$ for the azimuthal angle difference. However for small angle $R_L = \theta$ to very good approximation. In the transverse plane perpendicular to the jet axis, each angle represents the distance between the particle and the jet axis. Because they are all within the jet with a small jet size, the angular distribution from the above will peak at small angle and the dominant contributions from perturbative QCD come from collinear radiation. The soft gluon radiation is suppressed due to the energy weight. Therefore, a perturbative QCD prediction can be applied to the EEC observables [1].

In the perturbative collinear region ($\theta > 0.1$), additional gluon radiations to all orders can be resummed through a factorization approach [13] with logarithmic corrections. With additional contributions from renormalons [15] and power corrections [34,35], these precision improvements play an important role in describing the experimental data from EECs in e^+e^- annihilation. Toward the other end in the angular distribution ($\theta \sim 0$), additional physics has to be taken into account such as the assumption of a “free hadron” phase [22]. Recently, a nonperturbative transverse momentum dependent (TMD) fragmentation mechanism has been proposed to describe the distribution in this region [41,44] and further theoretical developments along this direction have been reported [50–55].

While the EEC, Eq. (1), is commonly called a “correlator,” it is actually an energy weighted pair distribution,

and thus will not vanish even in the absence of any particle correlations in the jets. To extract the true, genuine correlations one typically subtracts the product of the single particle distributions, which removes all uncorrelated pairs. Alternatively one uses mixed events to determine the uncorrelated pair distribution. In the context of hadronic physics this is, for example, done for particle interferometry measurements to determine the size of the particle emitting source [63]. In this Letter, we will take exactly this approach in order to extract and identify the true two-particle correlations.

Performing such an analysis will enable us to highlight the physics behind the three different regions in the EEC in jet. In particular, we find that the correlation is significant in both small and moderate θ regions. Although their physics are totally different—nonperturbative TMD fragmentation dominates small θ while collinear splitting dominates the moderate $\theta > 0.1$ —they both come from correlations, i.e., two particles originating from one source. In this Letter, we employ the PYTHIA 8.306 event generator [64] to demonstrate our proposed approach. We further perform a proof-of-principle analysis using the CMS 2011 Open Data [65] and show qualitative agreement with our PYTHIA 8 simulation baseline.

Disconnected two-particle distributions from single-particle distributions—The disconnected two-particle distributions based on the single-particle distributions need to be carefully defined. For this purpose, the jet axis can be used as an appropriate reference. In the experimental measurements, the energy correlations are counted against the particles inside a jet. Therefore, a jet axis can be identified. Because of the rotation symmetry around the jet axis, the above angular correlation is a two-dimensional distribution,

$$\vec{\theta} = \vec{\theta}_i - \vec{\theta}_j, \quad (2)$$

where $\vec{\theta}_i = \vec{P}_{i\perp}^h / (z_i E_J)$ represents the angle of hadron i with respect to the jet axis, and z_i is its momentum fraction of the jet energy. We consider a jet radius of $R \ll 1$. Therefore, $|\vec{P}_{i\perp}^h| \ll E_i = z_i E_J$, i.e., the transverse momentum of the hadron $|\vec{P}_{i\perp}^h|$ is much smaller than its longitudinal momentum E_i .

With the jet axis well defined, one can also define the correlator depending on two angles,

$$\frac{d\langle \text{EEC}(\theta_1, \theta_2) \rangle}{d^2\theta_1 d^2\theta_2} = \frac{1}{N_{\text{jet}}} \sum_{\text{jets } J} \sum_{i \neq j \in J} \frac{E_i E_j}{E_J^2} \times \delta^{(2)}(\theta_1 - \theta_i) \delta^{(2)}(\theta_2 - \theta_j), \quad (3)$$

from which we can derive the angular distribution of EEC of Eq. (1) [3],

$$\begin{aligned} & \frac{d\langle \text{EEC}(\theta) \rangle}{d^2\theta} \\ &= \int d^2\theta_1 d^2\theta_2 \frac{d\langle \text{EEC}(\theta_1, \theta_2) \rangle}{d^2\theta_1 d^2\theta_2} \delta^{(2)}[\vec{\theta} - (\vec{\theta}_1 - \vec{\theta}_2)]. \end{aligned} \quad (4)$$

However, Eq. (3) contains disconnected uncorrelated contribution from two energy flows through a construction,

$$\left. \frac{d\langle \text{EEC}(\theta_1, \theta_2) \rangle}{d^2\theta_1 d^2\theta_2} \right|_{\text{Disc}} \propto \frac{d\langle E(\theta_1) \rangle}{d^2\theta_1} \times \frac{d\langle E(\theta_2) \rangle}{d^2\theta_2}, \quad (5)$$

where the single energy distribution is defined as

$$\frac{d\langle E(\theta) \rangle}{d^2\theta} = \frac{1}{N_{\text{jet}}} \sum_{\text{jets } J} \sum_{i \in J} \frac{E_i}{E_J} \delta^{(2)}(\vec{\theta} - \vec{\theta}_i). \quad (6)$$

The above equations will be used to construct the subtraction term for the genuine correlations.

To construct the disconnected correlator, one has to properly take into account the energy weighting and, related to that, the normalization of the angular integral of Eq. (1). Clearly, the latter is not normalized to 1. To account for this difference, we introduce a normalization factor N_{Disc} for the disconnected correlation

$$\begin{aligned} \frac{d}{d^2\theta} \langle \text{EEC}(\theta) \rangle_{\text{Disc}} &= N_{\text{Disc}} \int d^2\theta_1 d^2\theta_2 \\ &\times \frac{d\langle E(\theta_1) \rangle}{d^2\theta_1} \frac{d\langle E(\theta_2) \rangle}{d^2\theta_2} \delta^{(2)}[\vec{\theta} - (\vec{\theta}_1 - \vec{\theta}_2)]. \end{aligned} \quad (7)$$

Without N_{Disc} , the right-hand side of the above equation will be normalized to 1 by definition. For the typical jet energy at the LHC, we find that $N_{\text{Disc}} \approx 0.85$, which is equal to the integral of Eq. (1) over θ for a particular jet energy range and also related to the integrated dihadron fragmentation functions; see Ref. [51].

In experiment, one can also construct the above disconnected correlation by means of mixing event or rather jet mixing. As detailed in Supplemental Material [66], one generates “mixed” jets by picking particles from random jets. For example, given a *true* jet with n particles the corresponding *mixed* jet is made with n particles with one each from n randomly selected true jets. Given the mixed jets, the disconnected, uncorrelated EEC is then obtained from Eq. (1), where the true jets are replaced by the mixed jets with an additional normalization factor,

$$\begin{aligned} \frac{d\langle \text{EEC}(\theta) \rangle_{\text{mix}}}{d^2\theta} &= C_{\text{mix}} \frac{1}{N_{\text{jet mixed jets } J}} \sum \\ &\times \sum_{i \neq j \in J} \frac{E_i}{E_{J,i}} \times \frac{E_j}{E_{J,j}} \delta^{(2)}[\vec{\theta} - (\vec{\theta}_i - \vec{\theta}_j)]. \end{aligned} \quad (8)$$

To account for the proper summation of mixed jets at different rapidities, here we keep the original energy fraction for each particle, e.g., $E_i/E_{J,i}$ for particle i from Jet_i .

In the above equation, we introduce a normalization factor $\mathcal{C}_{\text{mix}}$ to account for the differences between the mixing jet events and the true jet events. The reason behind this is that the above sum favors particles with larger momentum fractions in the mixed jet, although the angular distribution remains. We have verified that the above two Eqs. (7) and (8) lead to the same shape of the angular distribution of the disconnected EEC for the jet production at the LHC (see Fig. S3 in Supplemental Material [66]). Of course, the application of the mixed-event method to real data must consider detector inefficiencies, limited acceptance, and other systematic effects that could obscure small correlation signals. Although our Letter focuses on the theoretical framework under idealized conditions, the agreement between the disconnected two-particle correlations obtained from both the mixed-event and single-particle approaches provides a valuable cross-check. This comparison can help experimental groups isolate the genuine physics signals once the detector-related systematics are properly addressed.

Similarly we can evaluate the single energy flow result from Eq. (6) by using mixed jets. As we show in Supplemental Material [66], they agree with those obtained from the true jets, as they should.

Meanwhile, it has been shown in the literature that the particle distributions inside a jet can be described by the parton fragmentation functions in both the collinear case [67–69] and the TMD case [70–72]. In particular, a recent paper [73] has shown that the TMD fragmentation functions can be applied to the angular distribution of Eq. (6) with a typical parametrization [74]; see also Ref. [75]. In Supplemental Material [66], we show that these TMD fragmentation functions can also give a reasonable description of the disconnected EEC at small angle.

Two-particle correlations in a jet—With these results, we now compare the correlations between Eqs. (1) and (7). As we see from Fig. 1, they have a similar shape, peaked at small angles, but there are obvious differences that are due to the actual true correlations.

These genuine correlations can be extracted by the difference between the two correlators,

$$\langle \text{EEC}(\theta) \rangle_C = \frac{d\langle \text{EEC}(\theta) \rangle_{\text{full}}}{d^2\theta} - \frac{d\langle \text{EEC}(\theta) \rangle_{\text{Disc}}}{d^2\theta}. \quad (9)$$

Again, the second term in the right-hand side of the above equation can be obtained by the integral form of Eq. (7) or via mixed jets cf. Eq. (8). The angular integral of the above correlation vanishes by construction. In Fig. 2 (upper plot), we show the above correlations, Eq. (9), as functions of $R_L = \theta$ for the typical jet energies at the LHC. The graph

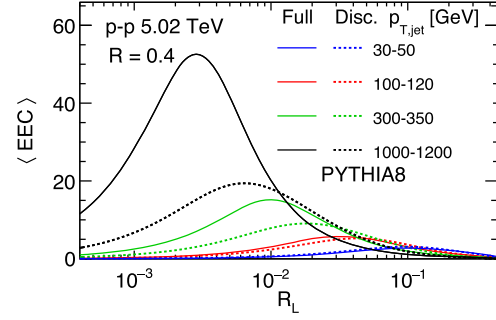


FIG. 1. The PYTHIA simulations of angular distributions for the EECs in jet for different jet energies at the LHC. Here, we compare the full correlation, $\langle \text{EEC} \rangle_{\text{full}}$, corresponding to the experiment measurements of Eq. (1) and the disconnected correlation, $\langle \text{EEC} \rangle_{\text{Disc}}$, constructed from two separate energy flows of Eq. (7). Here, $R_L = \theta$ in these equations.

shows a characteristic behavior in different angular regions. In particular, in the large θ region toward the jet boundary, the correlation $\langle \text{EEC}(\theta) \rangle_C$ decreases with θ . This is because both terms in Eq. (9) vanish and their difference vanishes, too. To expose a possibly interesting correlation signal in this region, it is advantageous to look at the ratio of the two distributions,

$$\mathcal{R}_{\text{EEC}}(\theta) = \frac{d\langle \text{EEC}(\theta) \rangle_{\text{full}}}{d^2\theta} / \frac{d\langle \text{EEC}(\theta) \rangle_{\text{Disc}}}{d^2\theta}, \quad (10)$$

where the numerator and denominator come from Eqs. (1) and (7), respectively. As shown in Fig. 2 (lower plot), this

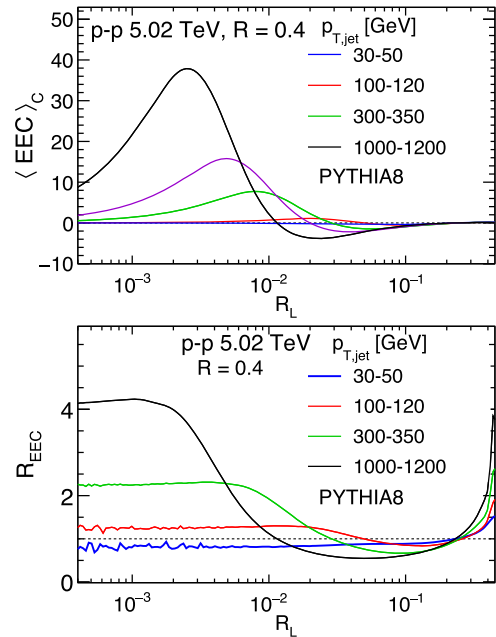


FIG. 2. The two-particle genuine correlations in jets as functions of the angle between them for different jet energies at the LHC: (upper) defined as difference, Eq. (9), and (lower) defined as ratio, Eq. (10). Here, as above, $R_L = \theta$.

ratio demonstrates the strength of the correlation at both small and large angle of θ .

Experimentally, all of the quantities that define the correlations in Eqs. (9) and (10) can be measured. Therefore, these correlations can be systematically studied in experiments at the LHC and RHIC. There are a number of interesting observations from Fig. 2. First, stronger correlations at moderate angles for all jet energies can be seen from the ratio curves and higher jet energies tend to have larger ratios as well. Meanwhile, the genuine correlation increases with jet energy at small angles. This can be seen from both $\langle \text{EEC}(\theta) \rangle_C$ and $\mathcal{R}_{\text{EEC}}(\theta)$ curves in the figure. Second, between these two regions, the lower the jet energies, the ratios are closer to 1. This means that the experiment measured EECs of Eq. (1) are close to the disconnected EECs constructed from the individual energy flows [Eq. (7)]. Third, three characteristic regions in these plots are very similar to those classified in Ref. [22], especially for high energy jets: at small angles (the “Free Hadrons Region”), R_{EEC} is essentially flat, indicating unmodified hadron emissions with negligible collinear effects; at moderate angles (the “Transition Region”), R_{EEC} decreases, signaling the onset of collinear dynamics and hadronization processes that suppress two-particle correlations; and at large angles (the “Collinear Region”), R_{EEC} rises again, driven by perturbative-QCD collinear splittings that enhance correlations. This demonstrates that the above ratio provides an alternative method to study the associated physics.

The ratio clearly highlights different physics in different kinematic regions. Experimental measurements of these genuine correlations will provide crucial information on the QCD dynamics involved in the particle correlations in high energy jets and help to investigate hadronization effects at collider energies. Especially, when the two hadrons are close to each other, they tend to be produced from a single nonperturbative fragmentation as suggested in Refs. [41,44,50–52]. The results shown in Fig. 2 expose these effects very clearly. The same discussion applies to low p_T jets at RHIC energies.

We further analyze the CMS 2011 Open Data sample [65] and compute the same EEC-based quantities defined in Eqs. (9) and (10).

In this analysis, we use all particles inside the reconstructed jets, including photons, to ensure that the single-particle energy distribution defined in Eq. (6) is properly normalized (i.e., its integral is unity). The input particles are the particle-flow candidates provided in the CMS 2011 Open Data, which combine information from the tracker, calorimeters, and muon system to reconstruct individual charged and neutral particles. Jets are reconstructed from these candidates with the anti- k_T algorithm with radius parameter $R_{\text{jet}} = 0.5$. Jets are required to satisfy $|\eta_{\text{jet}}| < 1.9$, and $400 < p_{T,\text{jet}} < 600$ GeV, a window chosen to ensure sufficient statistics while restricting to a regime where the observable is theoretically well controlled. The energy

correlator is computed from the particle-flow candidates within each selected jet. The correlator is binned in $R_L \in [10^{-4}, 1.0]$ with 50 logarithmically spaced bins. The disconnected baseline and the genuine correlation are constructed from the same event sample, so that detector effects common to both enter consistently and cancel in their ratio. Figure 3 shows qualitative agreement between the data and our PYTHIA 8 simulations, demonstrating that the proposed measurement is feasible in a realistic hadron-collider environment. In particular, $\langle \text{EEC} \rangle_C$ is positive at small angles, becomes negative at intermediate angles, and approaches zero at large angles. The ratio R_{EEC} cleanly separates three regimes, characterized by $dR_{\text{EEC}}/dR_L \simeq 0$ (small angles), $dR_{\text{EEC}}/dR_L < 0$ (intermediate angles), and $dR_{\text{EEC}}/dR_L > 0$ (large angles), consistent with Ref. [22]. Comparing Figs. 2 and 3, we find that the transition values of R_L differ between the CMS Open Data and the PYTHIA simulations. We believe this is due to different methods in treating particle decays and the limitation of parton shower in describing small-angle intrajet correlator structure.

We also note that the Open Data sample contains only $\mathcal{O}(10^6)$ jets; modern LHC datasets enable substantially higher-precision and more differential measurements. We would like to emphasize that this is an analysis of the public CMS 2011 Open Data and is not an official CMS result. The data have not been corrected for detector effects, and accordingly we refer to this Letter as an “analysis” rather than a “measurement.” Our aim is to provide a proof of principle that the proposed observable is robustly extractable from real collider data. We note, moreover, that because our principal results are presented as ratios of

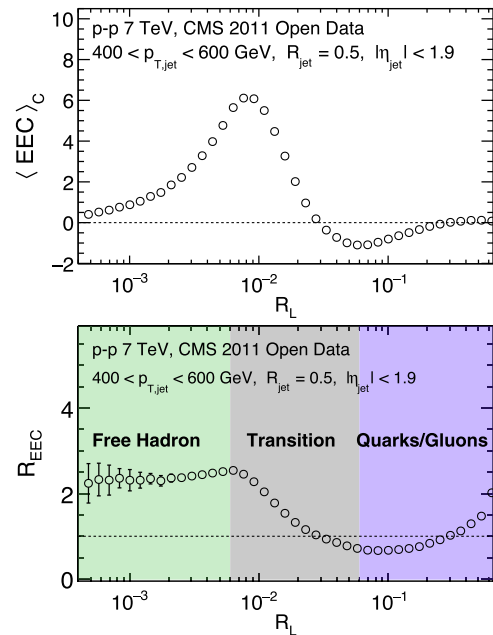


FIG. 3. Similar to Fig. 2, but analyzed using the CMS 2011 Open Data [65]. Only statistical uncertainties are shown.

self-normalized distributions, a substantial part of the detector-related effects largely cancel between numerator and denominator. This suppresses the sensitivity to detector systematics and supports the robustness of the qualitative features we report.

The correlation measurement proposed above will be very useful in deciphering the underlying mechanism for the nuclear modification of the EEC observables because it cancels out the single-particle nuclear effects inside the jet. For example, we can construct the difference or modification between the correlations of Eq. (9) for nucleus-nucleus (AA) and proton-proton (pp) collisions,

$$\Delta\langle\text{EEC}\rangle^{AA}(\theta) = \langle\text{EEC}(\theta)\rangle_C^{AA} - \langle\text{EEC}(\theta)\rangle_C^{pp}, \quad (11)$$

or a double ratio,

$$\mathcal{R}_{\text{EEC}}^{AA}(\theta) = \frac{\frac{d\langle\text{EEC}(\theta)\rangle_{\text{full}}^{AA}}{d^2\theta}}{\frac{d\langle\text{EEC}(\theta)\rangle_{\text{full}}^{pp}}{d^2\theta}} \bigg/ \frac{\frac{d\langle\text{EEC}(\theta)\rangle_{\text{Disc}}^{AA}}{d^2\theta}}{\frac{d\langle\text{EEC}(\theta)\rangle_{\text{Disc}}^{pp}}{d^2\theta}}. \quad (12)$$

We expect that the nuclear modification factors will be more evident in the regions of small and large θ where genuine correlations are expected to dominate.

For example, at very small angles, the dominant contribution comes from the jet energy loss. By studying the above double ratio, we may be able to directly extract the fraction of the jet energy loss in these measurements. This is because the correlation ratio is (almost) proportional to the jet energy (see bottom panel of Fig. 2). As a consequence, the ratio of Eq. (12) will be bigger than 1. The jet energy dependence of this double ratio shall provide crucial information on the jet energy loss as a function of the jet energy. Similarly, at large angle, we will be able to study the medium modification of the parton splitting. Again, the reason behind this is that in this region it is dominated by the splitting contributions. We have also verified this result using the state-of-the-art linear Boltzmann transport model [39]. Moreover, this method can be straightforwardly extended to small collision systems to search for potential in-medium effects, free from the systematic uncertainties associated with Glauber-model scaling. More detailed discussion about the results in heavy-ion collision and the small systems will be presented in the forthcoming follow-up paper.

In addition, it has been realized that the medium responses will modify the EEC of Eq. (1) in heavy-ion collisions [30,48], which might be misinterpreted as the medium modification of parton splitting in the medium. However, by measuring the genuine correlations, the contribution from the medium response will be canceled out in Eqs. (9) and (10) in AA collisions because the medium response has no particular angular dependence; see, for example, the discussions in Ref. [48]. That means there is no modification to Eqs. (11) and (12). This

demonstrates that we can disentangle different physics in the measurements of the EEC in heavy-ion collisions by focusing on the genuine correlations.

We note that the above discussion applies to the EEC measurements in proton-nucleus (pA) collisions as well, where we can define similar correlations. From that, we can study the difference (or ratio) between the correlations in pA collisions and those in pp collisions to investigate the underlying physics behind the nuclear modification observed in experiments [62].

Conclusion—In this Letter, we have proposed to study the particle correlations inside high energy jets by constructing a disconnected EEC through the two individual energy flows and comparing that with the measured EEC, as described by Eqs. (1) and (7). We have discussed the characteristic features of the ratios and differences defined from them as functions of angle between the two particles. The energy evolution of this ratio will help us to understand the underlying physics behind the energy-energy correlators and may reveal the hadronization effects in high energy jets at colliders.

While our baseline study uses PYTHIA 8 to establish qualitative expectations, the method is not intended as a generator-only proposal. As a proof of principle, we have also analyzed CMS 2011 Open Data and found that the main features of the observable are reproduced in real pp data within the available statistical precision. The robustness of the qualitative features is supported by their appearance in real data.

We further propose to measure the double ratios of Eq. (12) between heavy-ion collisions and proton-proton collisions as a crucial method to disentangle different contributions to the EEC observable. In particular, the small angle behavior of this double ratio will inform the jet energy loss fraction in heavy-ion collisions, and large angle double ratios will tell us about the medium modification of the parton splitting in the medium. On the other hand, we argue that the medium response will mostly be canceled out in these double ratios.

Our proposal could be straightforwardly extended to multipoint energy correlators. A comprehensive investigation of all of these correlators will deepen our understanding of the QCD dynamics involved in these measurements. Finally, a dedicated study in e^+e^- collisions, including comparisons across center-of-mass energies and to existing Large Electron-Positron Collider measurements, would provide a particularly clean benchmark of the method. In this Letter we have focused on pp , pA , and AA collisions, motivated by the immediate experimental accessibility at the LHC and RHIC and by the opportunity to quantify cold- and hot-nuclear-matter effects in nuclear collisions. Our Open Data analysis demonstrates that the proposed observable can be extracted from real pp data, supporting the feasibility of these dedicated measurements [66].

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Data availability—All the results presented in the manuscript can be reproduced using the publicly available PYTHIA 8.306 code cited in Ref. [64] and the CMS open source data in Ref. [65].

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