

Simple Scaling Laws for Energy Correlators in Nuclear Matter

Carlota Andres¹, Fabio Dominguez², Jack Holguin³, Cyrille Marquet⁴, and Ian Moul⁵

¹*Center for Theoretical Physics—a Leinweber Institute, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

²*Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela 15782, Spain*

³*Department of Physics and Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom*

⁴*CPHT, CNRS, École polytechnique, Institut Polytechnique de Paris, 91120 Palaiseau, France*

⁵*Department of Physics, Yale University, New Haven, Connecticut 06511, USA*

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Collider experiments involving nuclei provide a direct means of studying exotic states of nuclear matter. Recent measurements of energy correlators in both proton-nucleus (p-A) and nucleus-nucleus (A-A) collisions reveal sizable modifications, attributable to nuclear effects, compared to proton-proton (p-p) collisions. Energy correlators, and their associated light-ray operator product expansion (OPE), allow scaling behaviors of the measured spectrum to be directly mapped to properties of the underlying quantum field theory. Here, we demonstrate for the first time how this mapping occurs in nuclear collisions, and highlight how the light-ray OPE characterizes leading nuclear effects. We show that the leading modification to the energy correlator distribution is characterized by an enhancement of the expectation value of twist-4 light-ray operators, resulting in a scaling for the ratio of the two-point correlator in nuclear matter to that in vacuum of $\sim 1 + a\theta^2$ up to quantum corrections. We verify that this leading twist-4 correction accurately describes recent A-A and p-A data, and is thus sufficient to capture the scaling behavior within the angular range measured for jet radii used in nuclear experiments. Our light-ray OPE based approach lays the groundwork for a rigorous characterization of nuclear modification to energy correlator observables.

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Introduction—Collider experiments involving large nuclei, such as electron-ion (e-A), proton-ion (p-A), and heavy-ion (A-A) collisions, provide valuable insights into the properties of nuclear matter by examining the propagation of energetic partons produced in the underlying hard scattering process [1–12]. Among these hard probes, single-inclusive hadron production is the most theoretically well understood. In e-A collisions, it is rigorously described by factorization theorems [13,14], with nuclear modifications encoded in higher-twist operators [15–22] whose matrix elements are enhanced by the size of the nucleus, $A^{1/3}$ [23–30]. Under certain assumptions, this framework extends to p-A and A-A collisions [31–34], where the production of high- p_T hadrons has been extensively studied experimentally [35–49]. Despite their theoretical simplicity, the phenomenological understanding of these processes remains challenging due to their reliance on

nonperturbative fragmentation functions, and the interplay between initial and final state effects.

Over the past decade, high-energy jets and their substructure have become powerful tools to probe nuclear modifications [4–7,50–52]. Jet substructure offers several phenomenological advantages, particularly due to its multi-scale nature, which provides richer information than single-hadron measurements. A prominent example is energy correlators [53–56], a class of jet substructure observables defined as correlation functions of the average null energy (ANE) operator $\mathcal{E}(n)$ [57–64]. The one-point correlator measures the energy distribution as a function of direction, simply corresponding to (moments of) inclusive single hadron production. Higher-point correlators provide access to transverse scales. The simplest of these, the two-point correlator (EEC), defines the scale, $p_T\theta$ with θ the angle between the two detectors and p_T the initial hard scale, allowing to isolate dynamics at specific physical scales, including the confinement [65–68], saturation [69], and heavy-quark scales [70–72]. Such sensitivity offers a much more detailed view into the interactions between energetic partons in hot and cold nuclear matter [71–84]. Energy correlators have recently been measured across various collider systems [65–68,85–88], revealing clear nuclear

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modifications in p-A and A-A collisions relative to proton-proton (p-p) collisions [66,85–87].

Despite their significant phenomenological advantages, jet substructure observables are theoretically complicated by the presence of transverse scales, in contrast to single-inclusive observables, which depend on longitudinal variables and can be expressed in terms of light-ray operators. Remarkably, energy correlators bridge this gap by giving access to transverse scales, such as θ , while being formulated in terms of the ANE operator. This allows their transverse structure to be expanded using the light-ray OPE [61], reducing them to a series in θ , with coefficients given by matrix elements of light-ray operators. Hence, this expansion establishes a precise correspondence between distinct scalings in θ and matrix elements of the underlying field theory. In p-p collisions, the light-ray OPE successfully maps the small-angle scaling in the perturbative regime of the energy correlators ($\Lambda_{\text{QCD}}/p_T < \theta < 1$) to the anomalous dimensions of twist-2 light-ray operators, enabling precision calculations [89–91], and the most precise extraction of α_s from jet substructure measurements [65]. Motivated by this success, we now apply the light-ray OPE to the more complex case of nuclear collisions.

In this Letter, we take the first step in this direction by showing that the leading nuclear modification of the EEC in the perturbative regime is encoded in the light-ray OPE as enhanced matrix elements of twist-4 light-ray operators. This predicts the ratio of the EEC in nuclear media (p-A or A-A) to vacuum to behave as $\sim 1 + a\theta^2$ in the classical limit, where a encodes properties of the nuclear medium. For typical experimental jet radii R , this leading correction is sufficient to describe the data in the range $\Lambda_{\text{QCD}}/p_T < \theta \lesssim R$, as verified using CMS data from Pb-Pb collisions [86] and ALICE data from p-Pb collisions [87]. Our results highlight the potential of the light-ray OPE as a rigorous framework for understanding nuclear modifications of jet substructure observables in nuclear collisions.

The light-ray OPE—The light-ray OPE, introduced in [61] and developed in conformal field theories (CFTs) in [92,93], has also been explored in QCD [94–97]. Much like how the local OPE provides an expansion in the separation of local operators, the light-ray OPE provides an expansion in the angular separation θ of light-ray operators. This expansion is ideally suited for jet substructure, where measurements are performed at small angles within the jet radius.

To use the light-ray OPE to understand nuclear collisions in real-world QCD, it is essential to highlight key differences compared to its formulation in CFTs. Specifically, we must distinguish between differences in the structure of the OPE itself and modifications to the observable arising from performing the measurement in a hot or cold nuclear state. The light-ray OPE, as an operator statement, is a property of the theory rather than the state. The dependence on the state resides in the expectation values of the light-ray

operators appearing in the OPE. In CFTs, the light-ray OPE for two ANE operators takes the schematic form of an expansion [61,92]

$$\mathcal{E}(n_1)\mathcal{E}(n_2) = \sum_i \theta^{\tau_i-4} \mathcal{C}_i \mathbb{O}_i^{[3]}, \quad (1)$$

with a scaling dictated by their twist τ_i . The spin J of the operator, fixed at $J = 3$, is denoted in the superscript [61]. The OPE coefficients $\mathcal{C}_i$ include kinematic twist effects, which are resummed into celestial blocks [92,95,98]. In weakly coupled gauge theories, the leading operators contributing to the angular scaling have classical twist 2 plus a quantum correction given by their anomalous dimension [61]. While we do not focus here on the explicit structure of the light-ray operators, recent progress in understanding their form, particularly beyond leading twist, is noteworthy [99,100].

In QCD, this OPE is modified by the presence of the confinement scale Λ_{QCD} and the nonvanishing β function, both of which lead to violations of the $J = 3$ selection rule [89,97,101]. Corrections of $\mathcal{O}(\Lambda_{\text{QCD}})$ can be suppressed at high energies, while β -function corrections can be incorporated perturbatively. These effects are intrinsic to the quantum field theory itself. To distinguish these intrinsic modifications from changes in the expectation values of the light-ray operators, which reflect state-specific properties relevant in nuclear collisions, we use the light-ray OPE in its form (1). Modifications from hadronization and the running coupling can be included as needed but are omitted in this Letter for clarity.

We emphasize that the state-independence of the OPE makes it a powerful tool for systematically understanding the EEC in complex states, such as those produced in p-A and A-A collisions. By removing the transverse structure, the light-ray OPE maps contributions from specific light-ray operators to different power-law scalings. When energy correlators are measured in a specific state $|\Psi\rangle$, the coefficients of these scalings in θ are determined by expectation values of the light-ray operators in that state:

$$\langle \Psi | \mathcal{E}(n_1)\mathcal{E}(n_2) | \Psi \rangle = \sum_i \theta^{\tau_i-4} \mathcal{C}_i \langle \Psi | \mathbb{O}_i^{[3]} | \Psi \rangle. \quad (2)$$

This links the power-law behavior of the observable to well-defined matrix elements of light-ray operators, which can be computed to the desired order in the OPE expansion instead of computing the full observable directly.

Enhanced higher twist effects in nuclear collisions—We now apply the light-ray OPE to characterize the leading modifications of the EEC in nuclear collisions relative to its vacuum scaling. As the OPE of the EEC is fixed in (1) and (2) shows that the nuclear modification is encoded in the relative size of the expectation values of light-ray operators with different twists. A useful analog in $\mathcal{N} = 4$ super-Yang-Mills guides our intuition. In [102], the EEC was

computed at weak coupling in heavy states created by the $1/2$ BPS operator $O_H(x) = \text{tr}[\phi^K(x)]$ with dimension $\Delta_H = K$. In the OPE limit, they found that

$$\langle \mathcal{E}(n_1)\mathcal{E}(n_2) \rangle \sim \frac{\langle \mathcal{O}_i^{[3]} \rangle_H}{\theta^{2-\gamma(3)}} + 1, \quad (3)$$

with $\langle \mathcal{O}_i^{[3]} \rangle_H \lesssim 1/\Delta_H$ for large K . This reveals the critical angle $\theta_*^{2-\gamma(3)} \sim 1/\Delta_H$, determining the radius of convergence of the light-ray OPE. For $\theta < \theta_*$ the twist-2 scaling dominates, while for $\theta > \theta_*$, the uniform twist-4 scaling takes over. Thus, the leading dependence on the state arises from the ratio between the twist-2 and twist-4 OPE coefficients. This calculation can be viewed as perturbatively building a jet in a many-particle background, suggesting its analogy with asymptotically free jets modified by a nuclear state.

Applying this intuition to energy correlators in nuclear collisions, we note that unlike the case of heavy operators in $\mathcal{N} = 4$ nuclear states involve multiple dimensional parameters, including transport coefficients $\hat{q}$, temperature T , and nucleus (QGP) size A (L). Nevertheless, a critical angle must exist below which the OPE converges, with leading nuclear effects encoded in the ratio of expectation values of the twist-2 and twist-4 operators. Multiple characteristic angles, such as $\theta_L \sim 1/\sqrt{p_T L}$ and $\theta_c \sim 1/\sqrt{\hat{q} L^3}$, have appeared in EEC calculations [71,73,74,76,103–108], and the light-ray OPE is expected to converge for θ small enough so the medium scales do not dominate the EEC entirely. Nuclear effects are well known to enhance higher-twist contributions in inclusive hadron production [23,27,30], with terms in the twist expansion enhanced by powers of $A^{1/3}$ in cold nuclear matter, closely aligning with our intuition from $\mathcal{N} = 4$.

To characterize the leading nuclear effects in the EEC, we first make the approximation, well justified from analytic calculations and data [65–67,90,91], that the small-angle perturbative ($\Lambda_{\text{QCD}}/p_T < \theta < 1$) scaling of the EEC in vacuum is governed by leading twist operators

$$\langle \Psi | \mathcal{E}(n_1)\mathcal{E}(n_2) | \Psi \rangle \sim \frac{1}{\theta^2} \langle \Psi | \vec{\mathcal{C}}_2 \cdot \vec{\mathcal{O}}_{\tau=2}^{[3]} | \Psi \rangle. \quad (4)$$

Modifications of the EEC scaling behavior in p-A and A-A collisions must then arise from enhanced contributions from higher-twist operators. In the perturbative regime, twist-3 corrections are absent [89,95,109], so the leading corrections appear at twist-4:

$$\langle \Psi_N | \mathcal{E}(n_1)\mathcal{E}(n_2) | \Psi_N \rangle \sim \langle \Psi_N | \frac{\vec{\mathcal{C}}_2 \cdot \vec{\mathcal{O}}_{\tau=2}^{[3]}}{\theta^2} + \vec{\mathcal{C}}_4 \cdot \vec{\mathcal{O}}_{\tau=4}^{[3]} | \Psi_N \rangle. \quad (5)$$

Here, Ψ_N denotes a state produced in a nuclear collision. In general, there are multiple twist-4 operators. Since we do

not study their renormalization in this Letter, they are all degenerate, and we can view this as their total matrix element. Taking the ratio of the EEC in the nuclear medium (5) to that in vacuum (4) yields a simple prediction for the leading deviations due to nuclear effects

$$\frac{\langle \Psi_N | \mathcal{E}(n_1)\mathcal{E}(n_2) | \Psi_N \rangle}{\langle \Psi | \mathcal{E}(n_1)\mathcal{E}(n_2) | \Psi \rangle} \sim \frac{\langle \Psi_N | \vec{\mathcal{C}}_2 \cdot \vec{\mathcal{O}}_{\tau=2}^{[3]} | \Psi_N \rangle}{\langle \Psi | \vec{\mathcal{C}}_2 \cdot \vec{\mathcal{O}}_{\tau=2}^{[3]} | \Psi \rangle} + \theta^2 \frac{\langle \Psi_N | \vec{\mathcal{C}}_4 \cdot \vec{\mathcal{O}}_{\tau=4}^{[3]} | \Psi_N \rangle}{\langle \Psi | \vec{\mathcal{C}}_2 \cdot \vec{\mathcal{O}}_{\tau=2}^{[3]} | \Psi \rangle}, \quad (6)$$

which, as we will show, provides an excellent description of the data for the jet radii used in experiments.

The remarkable aspect of the light-ray OPE is its prediction of the functional form of the leading nuclear modifications. In the classical limit, the matrix elements in (6) are independent of θ , making the ratio effectively behave as $1 + a\theta^2$, with the coefficient given in terms of the expectation value of a twist-4 operator in the nuclear state. This matrix element can be computed analytically or fitted to data, enabling the determination of its dependence on the state's properties. When quantum corrections are included, a mild θ dependence arises in the matrix elements in (6) through anomalous dimensions [89].

Direct applications to measurements: A-A—We now apply the light-ray OPE to understand the θ dependence of the recent EEC measurement in Pb-Pb collisions [85,110], which reveals a clear nuclear enhancement. This demonstrates the OPE's power: even in complex nuclear collisions, nuclear modifications follow the scaling in (6).

Our analysis examines the modifications of the EEC in Pb-Pb relative to p-p using the OPE for each individual spectrum, a method that significantly reduces experimental systematics. For this approach to be valid, both expansions must share the same domain of convergence. However, experimental selection-bias shifts the nonperturbative transition in the Pb-Pb EEC, misaligning the lower bound of the perturbative window in θ between the two samples. To maximize the extent of the perturbative window in the Pb-Pb/p-p ratio, minimizing the effects of selection bias is thus essential. Following [79,80], we correct the Pb-Pb EEC spectrum with the factor C_2 , which is classically one in the small-angle perturbative regime. Should higher p_T measurements become available, where the misalignment diminishes, the need for this correction will decrease.

Since the expectation values of the twist-4 operators $\langle \Psi_N | \mathcal{O}_{\tau=4}^{[3]} | \Psi_N \rangle$ in different states are unknown, we treat them as parameters to be fitted to the data in the lowest jet p_T bin. A common feature of twist expansions is that matrix elements are accompanied by factors of $p_T^{-\tau}$ in the large- p_T limit, fixed classically by dimensional analysis [23–30]. We thus determine the twist-4 matrix elements in higher p_T bins by scaling the fitted result from the lowest

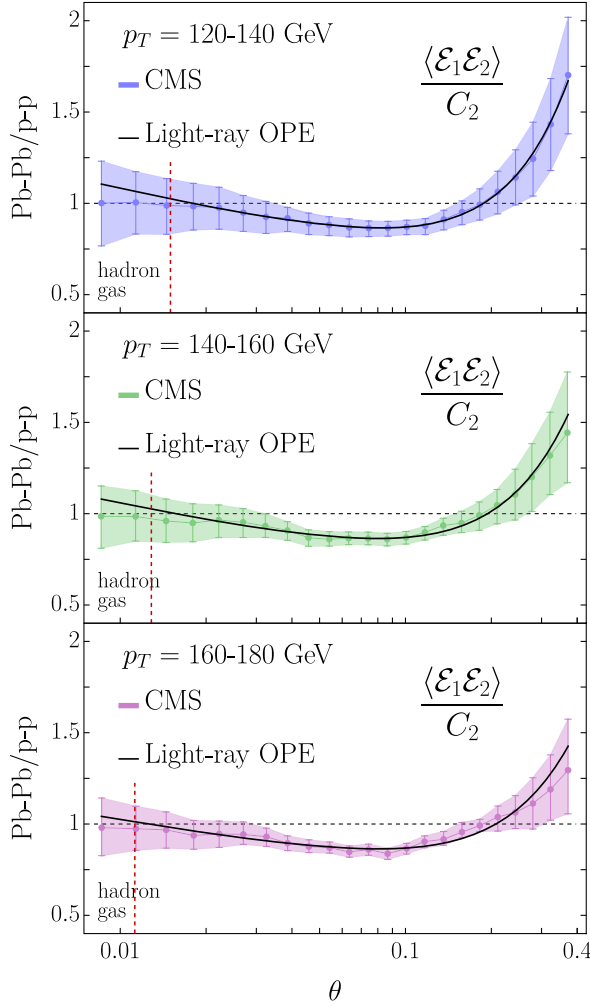


FIG. 1. Top: ratio of the EEC/ C_2 for inclusive jets with reconstructed p_T in the range $120 < p_T < 140$ GeV within the 0–10% centrality class in $\sqrt{s_{NN}} = 5.02$ TeV Pb-Pb collisions over that of p-p jets (colored band) compared to the OPE fit (7) (black). The EEC/ C_2 distribution is obtained from the CMS EEC measurement [85,86] using the unbiasing procedure from [79,80]. Middle (bottom): same as top for $140 < p_T < 160$ GeV ($160 < p_T < 180$ GeV).

bin according to this power law. To describe the data, we must also incorporate the anomalous dimensions of the twist-2 operators arising from their renormalization [89]. Twist-4 operators are treated classically, as their anomalous dimensions are currently unknown; incorporating them is an important direction for future work, motivating further exploration of their structure [99,100,111–117].

In Fig. 1, we present the Pb-Pb/p-p EEC ratio, corrected by the *unbiasing* function C_2 [79,80], compared to an OPE fit of the form

$$N/pp = \frac{\mathcal{M}_2 \theta^{\gamma_N} + \left(\frac{p_{T,0}}{p_T}\right)^2 \mathcal{M}_4(p_{T,0}) \theta^2}{\theta^{\gamma}}, \quad (7)$$

which makes explicit the p_T scaling of the twist-4 contribution and includes the twist-2 anomalous dimensions ($|\gamma|, |\gamma_N| \ll 1$), rendering the OPE fit sensitive to quark and gluon jet fractions. The matrix elements appearing in Eq. (6) are absorbed into the constants $\mathcal{M}_{2,4}$. Further details of the fit, as well as results for other p_T and centrality bins, are provided in Supplemental Material [118]. We find that the combination of the two leading terms in the OPE (black curve) describes the data remarkably well. At small angles, a negative slope arises from differences in quark/gluon fractions between Pb-Pb and p-p collisions (i.e., $\gamma_N \neq \gamma$), while the enhancement at large angles is driven by the twist-4 contribution [119]. Notably, the OPE correctly captures the large-angle behavior in the middle and bottom panels with no free parameters, since $p_{T,0}$ is chosen as the lowest- p_T bin.

It is striking that such a simple scaling emerges in these complex collisions, allowing the effective twist-4 matrix element, which is sensitive to the medium’s properties, to be measured and reducing the calculation of the EEC to the determination of this matrix element rather than a full function of θ .

p-A collisions—The first measurement of energy correlators in p-A has recently been reported [87], showing an unexpectedly large modification with respect to p-p in the lowest p_T bin. As in Pb-Pb, this measurement can also be understood using the light-ray OPE with the p_T dependence dictated by the twist of the light-ray operators.

To highlight the impact of the changes in the quark/gluon fractions in p-A relative to p-p, Fig. 2 compares the experimental p-Pb/p-p ratio [87] to both the full OPE fit in (7) (black), taking $p_{T,0}$ as the lowest p_T bin, and a fit to the twist-2 term only (dashed green). In the lowest p_T bin, the data can only be described by including both the anomalous dimensions and the twist-4 term in the fit. In the middle and bottom panels, the impact of the twist-4 matrix element is negligible. Using leading-log resummation [89], quark and gluon fractions can be extracted from the fitted γ and γ_N in (7). In Supplemental Material [118], we demonstrate that assuming an even q/g fraction in p-p, leads to an approximate p-A q/g fraction of 30/70 consistent with expectations from nuclear PDFs [120,121]. The importance of the anomalous dimensions highlights that a solid theoretical understanding will be crucial for properly interpreting energy-correlator measurements in p-A, as well as in other small systems. We believe that the p-A results deserve a more detailed study, beyond the scope of this Letter.

Factorizing the light-ray density matrix—Having shown how the light-ray OPE allows a systematic small-angle expansion, predicting definite scaling laws with coefficients given by expectation values of light-ray operators, we now connect the calculation of these matrix elements to higher twist inclusive hadron production. This link is key to relating energy correlators to the highly developed factorization theorems for inclusive hadron production, and

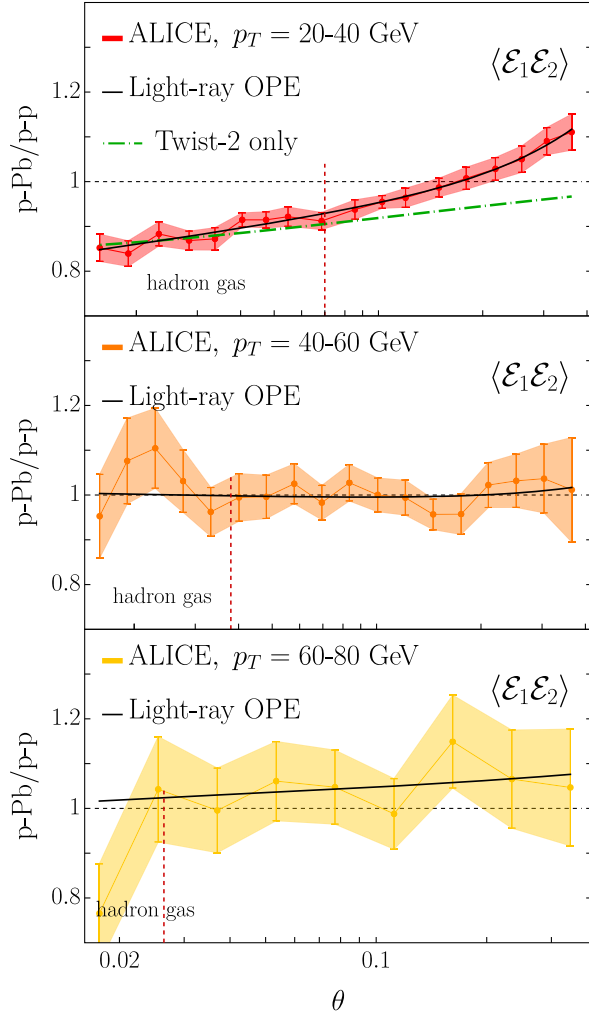


FIG. 2. Top: ratio of the EEC for inclusive jets with reconstructed p_T in the range $20 < p_T < 40$ GeV in $\sqrt{s_{NN}} = 5.02$ TeV p-Pb collisions over that of p-p jets (colored band) compared to the OPE (twist-2 + twist-4) fit (black solid) and to the twist-2 contribution only (green dot dashed). Middle (bottom): same as top for $40 < p_T < 60$ GeV ($60 < p_T < 80$ GeV).

facilitates computing these matrix elements within specific models.

After applying the light-ray OPE, we must compute expectation values of specific light-ray operators in a given state, so far kept generic. The difficulty with nuclear collisions is that this state comes from colliding nuclei, instead of a local operator, and must therefore be computed using factorization theorems. For two nuclei A with momenta p_1, p_2 , we aim to compute the following expectation value:

$$\langle A(p_1)A(p_2) | \mathcal{O}_\tau^{[3]} | A(p_1)A(p_2) \rangle. \quad (8)$$

Here another simplification occurs because the light-ray operator has definite quantum numbers under the Lorentz group, specifically, spin J associated with longitudinal

boosts, and transverse spin j associated with transverse rotations. Since we consider only unpolarized measurements, we project onto $j = 0$ and omit this label. We can then insert a complete set of states $|\Psi_\tau^{[j]}\rangle$ dual to the light-ray operators, called light-ray densities [98], allowing us to only have to compute

$$|\langle A(p_1)A(p_2) | \Psi_\tau^{[3]} \rangle|^2, \quad (9)$$

which is simply a (higher-twist) inclusive hard function projected onto specific quantum numbers. At twist 2 the light-ray densities are single particle states, relating the calculation to leading twist inclusive hadron production [89,90]. At twist 4 they are up to two-particle states.

The light-ray OPE thus reduces the calculation of multi-point energy correlators at the LHC to computing the probability to produce specific multi-particle states $|\Psi_\tau^{[3]}\rangle$, which are under the best theoretical control. Particularly, in e-A and p-A they are described by higher-twist factorization theorems [15–22] with matrix elements enhanced by the nuclear size $A^{1/3}$ [23–30]. To date, these calculations use approximate hard functions that are derivatives of the four-parton hard function [24,27,28,122]; extending them to the full calculation will be interesting. Such calculations can also be performed within the color glass condensate framework [123–126]. Strictly, if the state is identified using a jet algorithm, factorization must be performed for hadron production inside an identified jet using the fragmenting jet formalism [127–133]. We find it particularly exciting that the light-ray OPE relates jet substructure to these well-understood objects, placing energy correlator calculations in nuclear collisions on firm theoretical footing.

Conclusions—Energy correlator observables offer immense potential for understanding the dynamics of nuclear collisions, as their dependence on θ allows to probe nuclear systems as a function of scale. Calculating their full θ dependence from first principles is challenging due to the complexity of nuclear collisions. Fortunately, unlike traditional jet substructure observables, energy correlators can be formulated directly in terms of light-ray operators. This enables a light-ray OPE, which we have shown organizes the modification of energy correlators in nuclear collisions through an expansion in θ , with coefficients given by matrix elements of light-ray operators. The leading nuclear modification arises from enhanced twist-4 light-ray operators, and incorporating just these operators allows us to predict the nuclear EEC p_T and θ dependence within the range of angles relevant in jet substructure, successfully describing both A-A and p-A experimental data.

From the theoretical perspective, our analysis motivates exploring the light-ray OPE in other states, such as thermal, large charge [134], or plasma ball states [135]. Experimentally, it motivates measuring higher point

correlators, both shape dependent and projected, in nuclear collisions. While previously studied in the hybrid model [78], the light-ray OPE allows now for analytic control. In particular, ratios of projected correlators [136] probe the anomalous dimensions of twist-4 light-ray operators, enabling these operators to be studied in data in the perturbative regime. It is interesting to study detectors involving higher energy weights or charges [137,138], for which the light-ray OPE approach introduced here provides a theoretical basis, which we hope will improve our understanding of exotic states of nuclear matter.

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Data availability—The data that support the findings of this article are openly available [85,87].

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