

Tracing the evolution of nuclear excitation at the future Electron-Ion Collider

Niseem Magdy ^{*}*Department of Physics, Texas Southern University, Houston, Texas 77004, USA
and Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA*

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The evolution of nuclear excitation in electron-gold ($e + \text{Au}$) collisions at the forthcoming Electron-Ion Collider (EIC) is investigated using the BEAGLE event generator. The EIC's collider kinematics and detector-motivated rapidity selections enable a clear separation, in the laboratory frame, of the dominant reaction stages: hard scattering, intranuclear cascade (INC), and nuclear deexcitation. A systematic study of the event-by-event mean transverse momentum fluctuation observable κ reveals strong sensitivity to the intranuclear-cascade formation time and to nuclear geometry, with only weak dependence on the electron-beam energy. These findings indicate that κ can serve as an exploratory diagnostic for disentangling the cascade and deexcitation stages of nuclear excitation at the EIC. The pronounced sensitivity observed within the BEAGLE framework underscores the model dependence of the present results while at the same time motivating systematic cross-model investigations to establish the broader applicability of κ . The results yield stage-resolved, testable predictions for early EIC measurements.

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Understanding the evolution of nuclear excitation, specifically, how energy is deposited, redistributed, and ultimately dissipated following high-energy lepton-ion interactions, remains an active area of research [1–5]. Despite decades of investigation, several aspects of these processes are still not fully understood. Nuclear excitation mechanisms govern a wide range of phenomena, including particle emission, fission, fragmentation, and γ -ray deexcitation [3,6–9]. A central challenge is the clear separation of the various dynamical stages that contribute to nuclear excitation and subsequent decay [10]. In lepton- or photon-nucleus collisions, the reaction typically proceeds through three distinct stages in the nuclear rest frame, as illustrated in Fig. 1: (i) an instantaneous hard scattering [11,12], (ii) a rapid intranuclear cascade occurring within approximately 10^{-22} s [13], and (iii) a longer-timescale deexcitation process lasting up to 10^{-16} s [8,9,14]. The duration and characteristics of each stage are expected to depend on both the properties of the target nucleus and the specific collision kinematics [15,16]. Advancing the understanding of nuclear excitation, therefore, depends critically on the ability to distinguish between the different reaction stages and to clarify how each stage influences the others. In particular, the interplay between the intranuclear cascade phase and the thermalized compound nucleus deexcitation remains a key

open question in the field [10,17]. Addressing this issue has been challenging, in large part due to limitations in experimental methods; most studies to date have been restricted to fixed-target configurations [18–20]. These limitations are exemplified in Fig. 2(a), which shows the rapidity dependence of particle multiplicity ($dN/d\eta$) for $e + \text{Au}$ collisions at 18×0 GeV, with substantial overlap among the hard scattering, intranuclear cascade, and nuclear deexcitation processes that complicates efforts to clearly distinguish their contributions.

Beyond the constraints of fixed-target experiments, a significant challenge lies in the absence of robust experimental constraints on how the intranuclear cascade process modulates the breakup of excited nuclei. This modulation generally depends on the intranuclear cascade formation time (τ_f), defined as the interval between the production of a secondary hadron and the onset of its ability to interact further within the nuclear medium [17,21]. For very short τ_f , secondary hadrons interact almost immediately after their production, resulting in a dense intranuclear cascade and high excitation energies; for very long τ_f (i.e., $\tau_f \gtrsim R_A/c$), hadrons can escape the nucleus before reinteracting, thereby suppressing the cascade and resulting in minimal nuclear excitation. Meeting these challenges requires (i) identifying experimental-kinematic regions that can isolate different reaction stages and (ii) establishing observables that can constrain τ_f [5].

The upcoming Electron-Ion Collider (EIC) [22,23] presents a unique opportunity to investigate the evolution of nuclear excitation with collider kinematics in $e + A$ interactions. The EIC's kinematics offer a key advantage over fixed-target setups. The ion beam's large Lorentz boost converts the temporal ordering of reaction stages into a spread of rapidities in the laboratory frame. Consequently, in collider-based $e + A$ interactions, the three reaction stages illustrated

^{*}Contact author: niseem.abdelrahman@tsu.edu

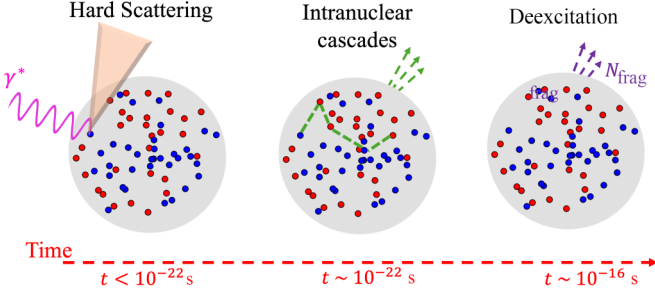


FIG. 1. Cartoon illustrating the reaction stages expected in lepton-nucleus collisions.

in Fig. 1 are expected to be well separated in the laboratory frame, as shown in Fig. 2. The illustration given in Fig. 2(b) demonstrates that it is possible to isolate kinematic regions dominated by each reaction stage [16,24]. In Fig. 2(b), the regions labeled ePIC-I, ePIC-II, and ePIC-III correspond to the acceptance ranges of the three primary subsystems anticipated for the ePIC detector [25], which are the focus of this study. Beyond these intrinsic capabilities of the EIC, I propose utilizing event-by-event fluctuations in the mean transverse momentum $[M(p_T)]$ as a measurement to constrain the τ_f effect in $e + A$ collisions [26–28]. Specifically, $M(p_T)$ fluctuations encode information about the origin of emitted particles: the deexcitation stage tends to yield more thermallike, isotropic, and statistically narrow momentum distributions, whereas the intranuclear cascade phase leads to broader and more irregular distributions due to the stochastic and non-thermal character of secondary particle interactions. Thus, $M(p_T)$ fluctuations are expected to serve as a sensitive probe of the underlying particle production mechanism, which is anticipated to depend on τ_f . Consequently, conducting such studies at the EIC will be essential for refining nuclear excitation models and for achieving deeper insight into the structure and dynamics of the target nucleus [15,16,22,23].

This study employs version 1.03 of the Benchmark eA Generator for Leptonproduction (BEAGLE) [24] Monte Carlo simulation code. BEAGLE is a hybrid event generator that integrates several well-established codes, including DPMJET [29], PYTHIA6 [30], PYQM [31], FLUKA [32–34], and LHAPDF5 [35], to comprehensively describe high-energy lepton-nucleus scattering processes. In this modular workflow (PYTHIA6 $\rightarrow$ PYQM $\rightarrow$ DPMJET $\rightarrow$ FLUKA), PYTHIA6 simulates the hard partonic interaction and vacuumlike fragmentation; the PYQM module implements Salgado-Wiedemann quenching weights to describe medium-induced partonic energy loss; hadron formation and intranuclear rescattering are handled by DPMJET; and the excited remnant is deexcited in FLUKA [24]. In all simulations presented, I used the standard parameter set provided by the default version of BEAGLE [24], with no additional tuning. Moreover, BEAGLE provides explicit particle-level flags that enable identification of the production stage (hard scattering, intranuclear cascade, or nuclear deexcitation).

The present analysis establishes a baseline within the BEAGLE framework, where the sensitivity of κ reflects the specific physics content of the DPMJET and FLUKA implementations. This well-defined reference point demonstrates the

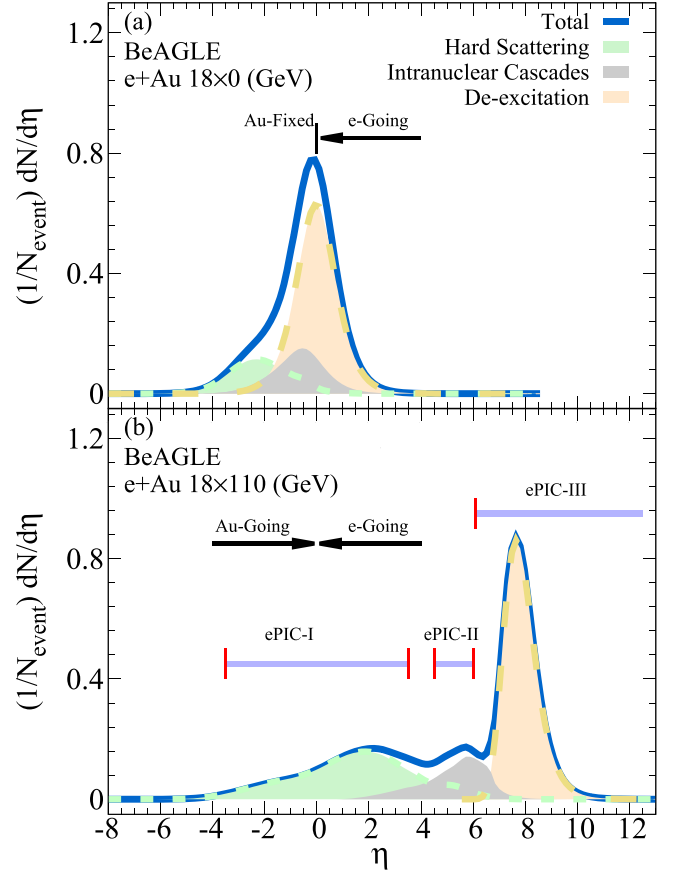


FIG. 2. The $dN/d\eta$ of the $e + A$ collisions at (a) 18×0 (GeV) and (b) 18×110 (GeV) from the BEAGLE model. The shaded areas represent the different contributions, and the horizontal lines represent the η acceptance given by the ePIC experiment at the EIC [22,25].

discriminatory power of κ and provides guidance for systematic future comparisons across alternative transport and deexcitation models.

The present analysis specifically examines the interplay between intranuclear cascades and nuclear thermal deexcitation processes achieved by varying the formation-time parameter τ_f . In DPMJET, the intranuclear cascade (INC) follows a formation-zone prescription in which each produced hadron is assigned a laboratory-frame formation time sampled from an exponential with mean:

$$\tau = \tau_f \frac{E}{m} \frac{m^2}{m^2 + p_{\perp}^2}, \quad (1)$$

where E , m , and $p_{\perp}$ are the hadron energy, mass, and transverse momentum, respectively [24]. Within this framework, the parameter τ_f functions as an effective control on the temporal window for secondary hadronic rescattering inside the nucleus. A shorter τ_f enhances rescattering, leading to greater energy deposition in the residual nucleus and broader momentum distributions, which in turn amplify the fluctuation measure κ . In contrast, a longer τ_f suppresses rescattering, reduces excitation energy, and narrows the fluctuations. This qualitative dependence is consistent with expectations

from transport-theory studies of intranuclear cascades and fluctuation observables, where the variance of collective quantities grows with the degree of rescattering and energy deposition. Although model dependent, this treatment demonstrates how variation of τ_f within BEAGLE modulates the balance between intranuclear cascades and deexcitation, providing an exploratory probe of late-stage dynamics. In this modular setup, τ_f should be interpreted strictly as an effective control parameter for the onset of hadronic rescattering in DPMJET, whereas medium-induced partonic energy loss is handled separately in the PYQM module. This distinction makes explicit the respective roles of partonic and hadronic dynamics in the BEAGLE framework.

Because PYQM precedes the INC stage, partonic energy loss can further modulate these dynamics by softening the hadron kinematics at the INC entry and, in options that deposit soft-gluon energy in the nucleus, by mildly raising the remnant excitation. However, dedicated BEAGLE studies find that forward-region yields are only modestly affected by PYQM variations, whereas backward “gray-track” production remains dominated by hadronic rescattering [36]. These cascades set the initial conditions for the subsequent compound-nucleus evolution modeled in FLUKA [32,34]. The values of τ_f explored in this study (5–20 fm/c) bracket the limiting cases from early reinteraction to near escape, with the upper bound comparable to R_A/c for heavy nuclei. This interval provides a physically motivated window that exposes contrasting behaviors of κ across cascade- and deexcitation-dominated regions.

This study utilizes the widely used variance of the event-by-event transverse momentum distribution, denoted by κ [37–39], which quantifies the strength of dynamical fluctuations relative to the inclusive mean transverse momentum, $M(p_T)$, for a selected class of particles. The quantity κ is formally defined as follows:

$$\kappa = \frac{C}{M(p_T)^2}, \quad (2)$$

where C is the second-order momentum correlation. Both, C and $M(p_T)$ are given as

$$C = \frac{1}{\sum_{k=1}^{n_e} N_k^{\text{pairs}}} \sum_{k=1}^{n_e} \sum_{i=1}^{n_p} \sum_{j=i+1}^{n_p} \times [p_{T_i} - M(p_T)][p_{T_j} - M(p_T)], \quad (3)$$

$$M(p_T) = \frac{1}{\sum_{k=1}^{n_e} N_k} \sum_{k=1}^{n_e} \sum_{i=1}^{n_p} p_{T_i}, \quad (4)$$

where N_k^{pairs} is the number of particle pairs in the k th event, n_p is the number of particles in that event, and n_e is the total number of events.

In this work, I analyze $e + {}^{197}\text{Au}$ at 5×110 GeV and $e + {}^{197}\text{Au}$, $e + {}^{96}\text{Ru}$, and $e + {}^{63}\text{Cu}$ at 18×110 GeV with the BEAGLE model, generating $\sim 5 \times 10^7$ events per collision system; given the EIC’s anticipated luminosity (order 4×10^{11} events), this provides ample statistical power. The ion beam energy is fixed to the initial EIC running value; varying it would mainly shift the rapidity regions of the stages

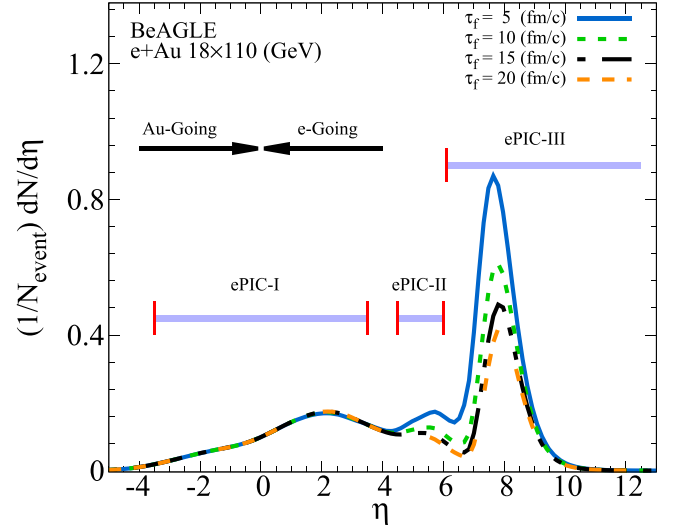


FIG. 3. Comparison of the $dN/d\eta$ in $e + \text{Au}$ collisions at 18×110 (GeV) from the BEAGLE model, shown for different formation times.

due to the nuclear boost, without changing their qualitative separation. Throughout, I use charged hadrons ($\pi^\pm$, $K^\pm$, p , $\bar{p}$) for the ePIC-I/II η acceptances and neutrons for ePIC-III. All presented results include statistical uncertainties; a detailed treatment of detector-efficiency effects and detector-specific systematics will be presented in future work.

The results in Fig. 2 confirm that, at the future EIC, the nuclear reaction stages can be separated using η -based selections. Motivated by this, I next examine how the formation time τ_f modulates the $dN/d\eta$ distribution. Figure 3 presents the $dN/d\eta$ distribution for $e + \text{Au}$ collisions at 18×110 GeV, as simulated with the BEAGLE model for different formation times. The results indicate no significant sensitivity to changes in formation time at midrapidity (ePIC-I range), where hard scattering processes dominate. In contrast, a clear increase in $dN/d\eta$ is observed with decreasing formation time at forward rapidity (ePIC-II range) and far-forward rapidity (ePIC-III range), where the intranuclear cascade and nuclear deexcitation processes, respectively, are dominant. However, because both ePIC-II and ePIC-III regions show increased particle production with decreasing formation time, it remains challenging to disentangle the effects arising from intranuclear cascades and those from deexcitation. This underscores the need for an additional observable capable of distinguishing between these two contributions.

This work proposes the widely used dimensionless ratio κ [Eq. (2)] as a tool to study nuclear excitation by varying the formation time in $e + A$ collisions. The observable κ is more informative than its constituents, $M(p_T)^2$ and C , considered separately. Its key advantages are (i) invariance under a global rescaling of transverse momenta, which removes trivial spectral hardening/softening that would otherwise move $M(p_T)$ and C in lockstep [40]; (ii) reduced, leading-order sensitivity to overall acceptance, efficiency, and volume effects [41,42]; and (iii) being dimensionless, it enables direct comparisons across systems and collision energies. Although this paper

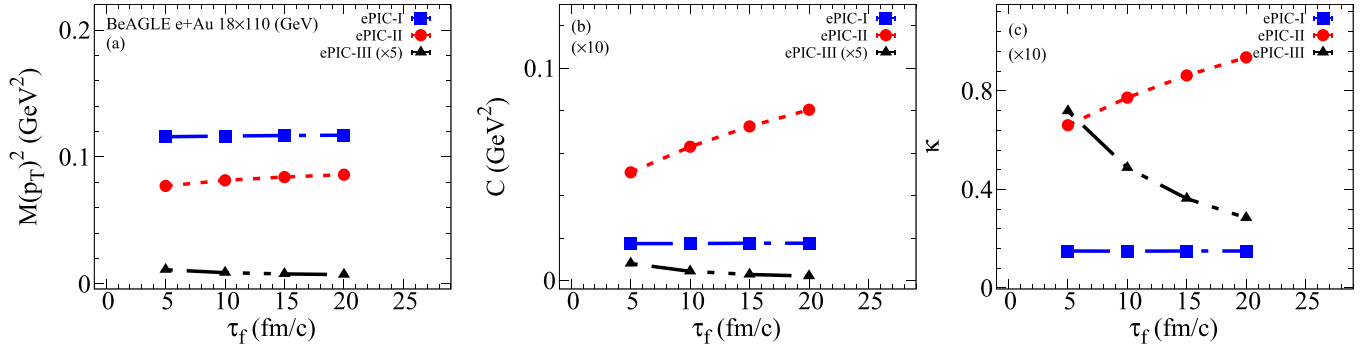


FIG. 4. Decomposition of the momentum-fluctuation observable κ in $e + \text{Au}$ collisions at 18×110 (GeV). Panel (a) shows the event mean transverse momentum $M(p_T)^2$. Panel (b) shows the two-particle transverse-momentum correlation C . Panel (c) shows κ . Results are presented for each ePIC rapidity selection (I–III) and for all τ_f settings studied.

focuses on the energy dependence and the system dependence of κ , I found it constructive to present the formation-time dependence of its components in $e + \text{Au}$ collisions at 18×110 (GeV) across the three rapidity selections, as shown in Fig. 4.

Figures 4(a)–4(c) shows that $M(p_T)^2$, C , and their ratio κ increase with τ_f in the acceptance region dominated by the INC. This observed increase of κ with τ_f in the ePIC-II region reflects the interplay between rescattering-induced source multiplicity and correlation dilution inside the nucleus. A short τ_f leads to multiple in-medium scatterings that produce a large number of quasi-independent emission centers. The hadrons emerging from these many sources reduce pairwise covariance because most particle pairs originate from unrelated emission sites. As τ_f increases, the number of intranuclear scatterings decreases, and particle emission becomes dominated by fewer, more coherent sources. Consequently, the hadrons share a stronger common ancestry and exhibit enhanced two-particle covariance C . Since $M(p_T)^2$ changes more modestly with τ_f than C , the resulting κ increases with τ_f .

By contrast, Figs. 4(a)–4(c) shows that $M(p_T)^2$, C , and κ decrease with τ_f increase in the acceptance region dominated by nuclear deexcitation. Here, a short τ_f leads to intense in-medium interactions that deposit substantial energy into the nuclear remnant, producing a highly excited compound system with larger excitation energy E^* and temperature T . Its statistical deexcitation (evaporation/fission) yields more forward neutrons and fragments with a slightly harder spectrum, increasing $M(p_T)^2$ and, because emissions originate from a common excited source subject to global conservation laws, generating sizable eventwise correlation C . As τ_f increases, in-medium rescattering and energy deposition are reduced; the source is colder (smaller E^* and T), forward emission weakens and softens, and therefore $M(p_T)$ decreases and common-source correlations diminish (smaller C).

Finally, in the acceptance range dominated by hard scattering, I observe no significant dependence of $M(p_T)$, C , and κ on τ_f . This τ_f -flat behavior serves as a sanity check on the robustness of the proposed idea; the observables remain stable when stage-dependent nuclear dynamics are minimal, yet respond nontrivially in regions where cascade or deexcitation processes dominate.

Figure 5 displays κ as a function of formation time for various configurations. Figure 5(a) shows results for $e + \text{Au}$ collisions at 18×110 GeV and 5×110 GeV, while Fig. 5(b) presents results for $e + {}^{197}\text{Au}$, $e + {}^{96}\text{Ru}$, and $e + {}^{63}\text{Cu}$ at 18×110 GeV. The results are shown for the ePIC-II and ePIC-III rapidity selections, where the intranuclear cascade and nuclear deexcitation processes dominate, respectively. Similar to Fig. 4, results reveal that κ increases with τ_f in the intranuclear cascade-dominated region and decreases with τ_f in the deexcitation-dominated region for all presented energies and systems.

In Fig. 5(a), results indicate that for a fixed nuclear target, κ exhibits minimal dependence on the electron beam energy

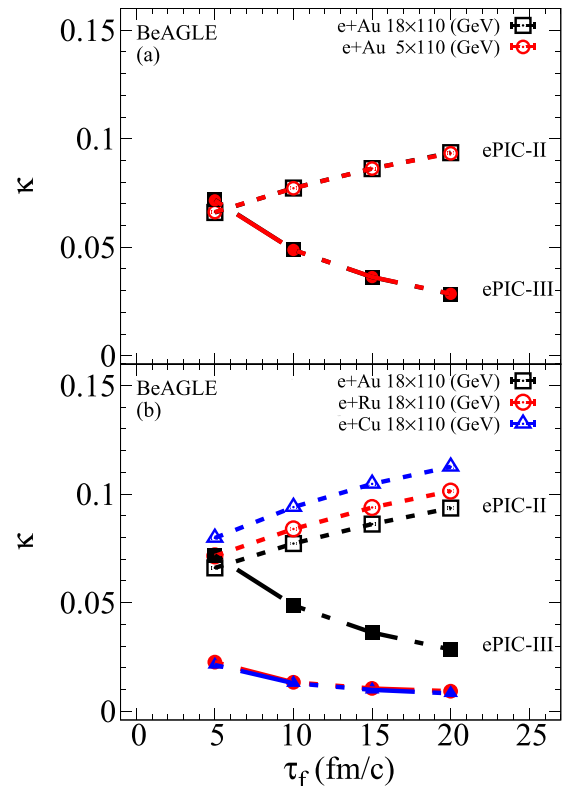


FIG. 5. The energy and system size dependence of κ as a function of formation time from the BEAGLE model.

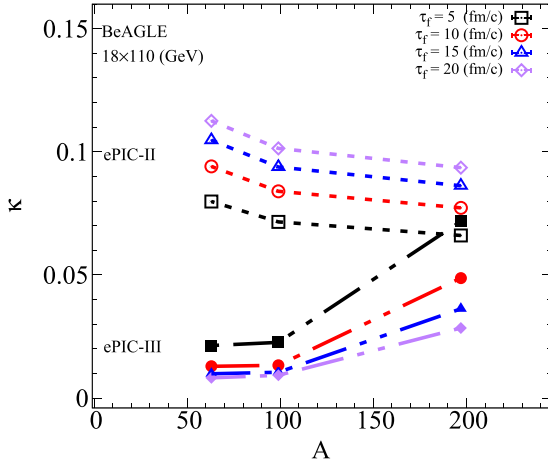


FIG. 6. The system size of κ as a function of the atomic mass number for several formation times from the BEAGLE model.

across both ePIC-II and ePIC-III rapidity regions. This energy independence suggests that the particle production dynamics encoded in the intranuclear cascade and nuclear deexcitation models within BEAGLE are relatively insensitive to the initial electron energy over the examined range. Specifically, varying the electron energy from 5 to 18 GeV has minimal impact on κ , indicating that the dominant source of fluctuations is governed by nuclear geometry and medium interactions rather than by the electron energy itself. In contrast, Fig. 5(b), demonstrates a pronounced sensitivity of κ to the size of the target nucleus. As the system size decreases from ^{197}Au to ^{96}Ru to ^{63}Cu , the magnitude and formation-time dependence of κ change significantly. This highlights the importance of geometric and nuclear density effects on the evolution of momentum fluctuations. Larger nuclei provide a more extended medium for secondary particle interactions, which can enhance or suppress fluctuations (ePIC-II or ePIC-III regions) depending on the process type and formation time. Thus, system size emerges as a critical factor in shaping the observed κ trends and offers an essential means for disentangling the contributions of intranuclear cascade and nuclear deexcitation mechanisms in future studies.

A direct measurement of the formation time remains inaccessible in experimental settings. To address this limitation, I present the calculations as a function of the atomic mass number A , which reflects the size and density profile of the target nucleus. This approach enables us to indirectly explore the effects of formation time by examining systematic trends in observables across nuclei of varying sizes. Figure 6 shows the behavior of κ for both the intranuclear cascade and deexcitation regions as a function of atomic mass

number. One finds that κ increases with decreasing atomic mass number for the ePIC-II selection (i.e., the intranuclear cascade-dominated region). In contrast, for the ePIC-III selection (i.e., the deexcitation-dominated region), κ decreases with A , with weaker system-size dependence for small nuclei. In addition, a clear formation time dependence was observed in both regions. Collectively, these results provide valuable benchmarks for future experimental studies and offer important constraints for the implementation of formation time in theoretical nuclear transport models. To assess robustness with respect to particle composition, κ was also computed using charged hadrons in all rapidity regions. In ePIC-III this sample is dominated by protons, yet the qualitative trends of κ remain unchanged. This confirms that the conclusions do not hinge on the specific particle species selected.

In summary, using the BEAGLE event generator, the analysis demonstrates that the Electron-Ion Collider will offer a *novel, uniquely kinematic handle* to separate contributions from distinct reaction mechanisms in $e + \text{Au}$ collisions. The collider kinematics, combined with the broad rapidity coverage and forward acceptance of the ePIC detector, enable selections that enhance the discrimination between intranuclear cascade and nuclear deexcitation, providing an exploratory path to investigate their interplay within the BEAGLE framework. Although the results are model dependent, the study offers a novel baseline framework that both demonstrates the sensitivity of κ and motivates future cross-model comparisons aimed at establishing its broader applicability.

Building on this separation strategy, and validating it in simulation, the event-by-event momentum fluctuation observable κ is examined to study the coupling between the cascade and the subsequent deexcitation of the residual nucleus. The results show that κ exhibits strong, monotonic sensitivity to the formation time τ_f and to the nuclear size A , while showing only mild dependence on the electron beam energy over the tested range. The contrasting system-size trends of κ in cascade-dominated versus deexcitation-dominated regions suggest a sensitive means to disentangle these stages at the EIC and to provide data-driven constraints on τ_f .

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Data availability. The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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