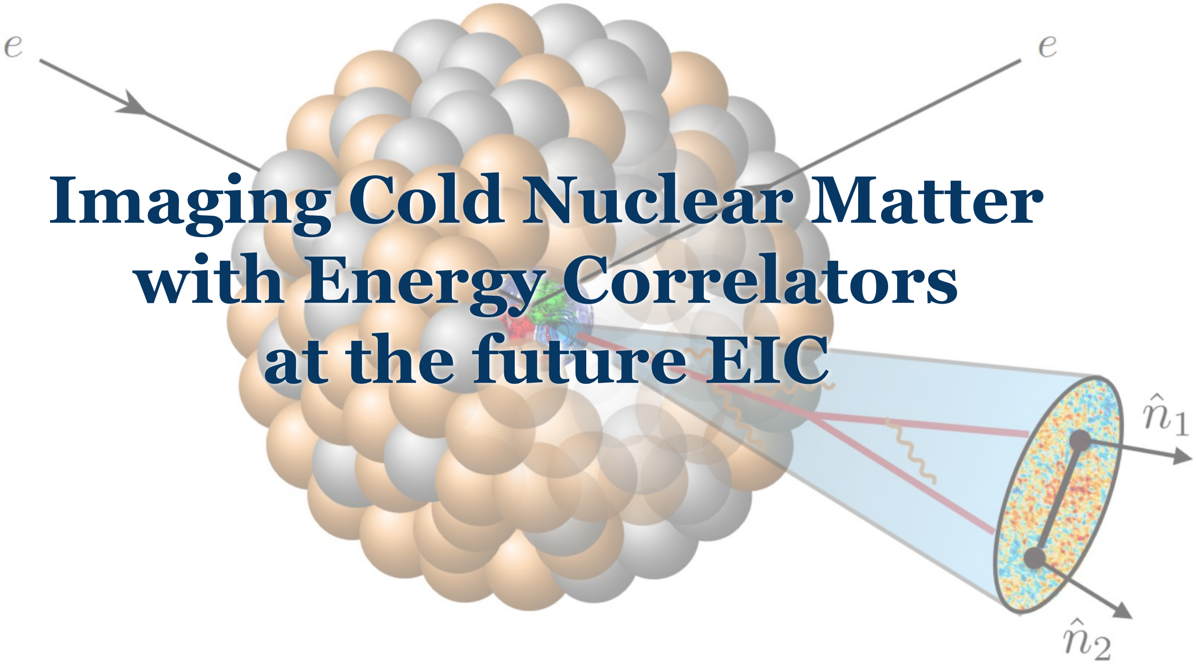
Imaging Cold Nuclear Matter with Energy Correlators at the future EIC



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BERKELEY LAB

Two-point energy correlator

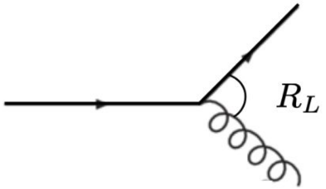
- IRC safe, energy weighted cross section
- A jet substructure observable, in the collinear limit

$$\langle \mathcal{E}^n \mathcal{E}^n \rangle = \sum_{ij} \int dR'_L \left(\frac{p_{T,i}\, p_{T,j}}{p^2_{T,\mathrm{jet}}} \right)^n \delta(R'_L - R_L)$$

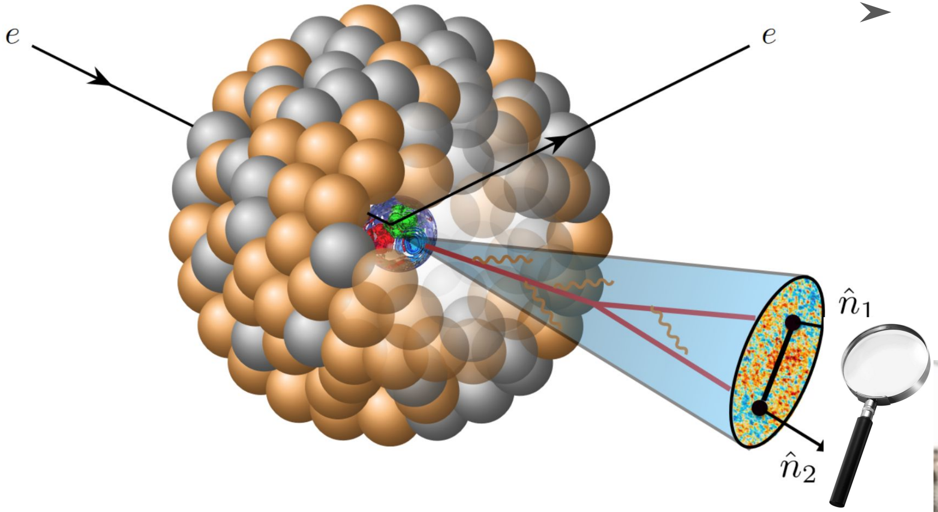
weight power

energy weight

angular distance



$$R_L = \sqrt{(\eta_j - \eta_i)^2 + (\phi_j - \phi_i)^2}$$

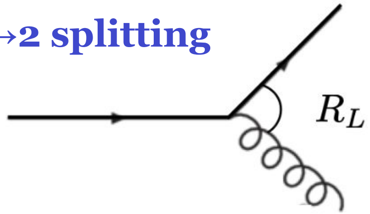


- Measured so far in
  - $e^+ e^-$ experiments, measurement of α_s
    [OPAL Coll., Phys. Lett. B 276, 547–564]
  - CMS open data, no detector effects
    [P. Komiske, I. Moult, J. Thaler, H-X. Zhu]
  - ALICE and STAR p+p
    [HARD PROBES 2023]
  - Many ongoing studies

EEC in ALICE p+p collisions

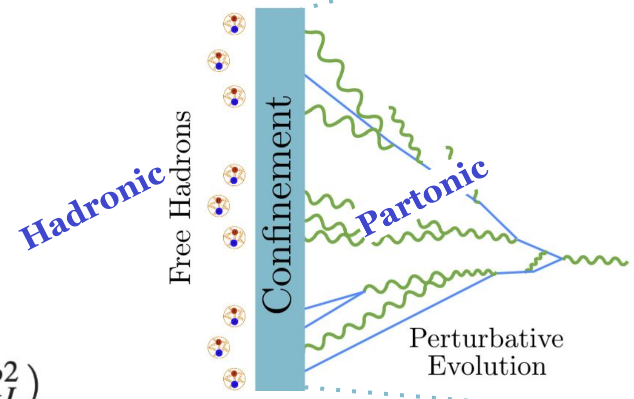
- Clear separation between hadronic and partonic regions
  - Hadronic: uniformly distributed hadron scaling behavior
  - Partonic: pQCD calculation
- Transition region corresponds to confinement region
  - Onset occurs when $\text{virtuality} \sim p_T R_L \sim \mathcal{O}(\Lambda_{\mathrm{QCD}})$
  - Scales with jet pT

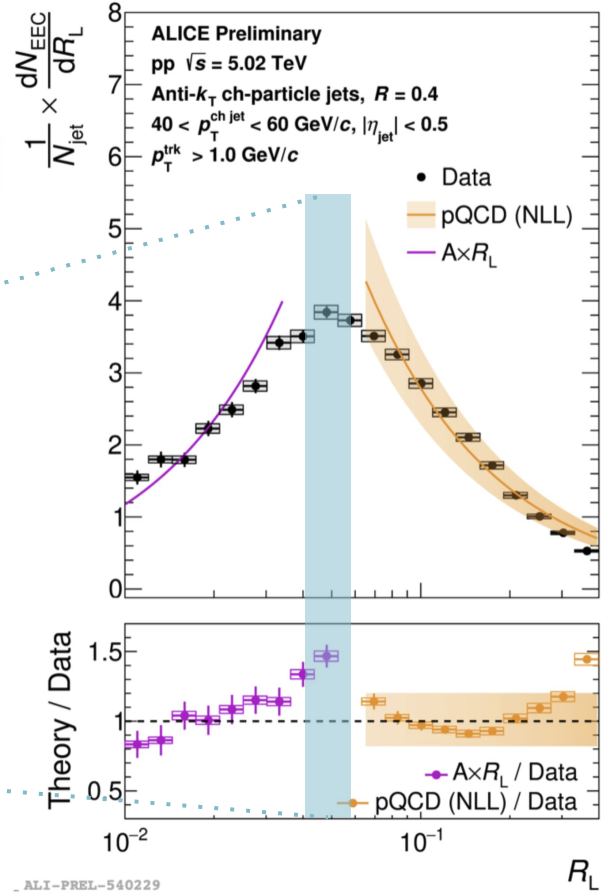
1→2 splitting



virtuality ~ $p_T R_L$

$\tau \simeq 1/(p_T R_L^2)$

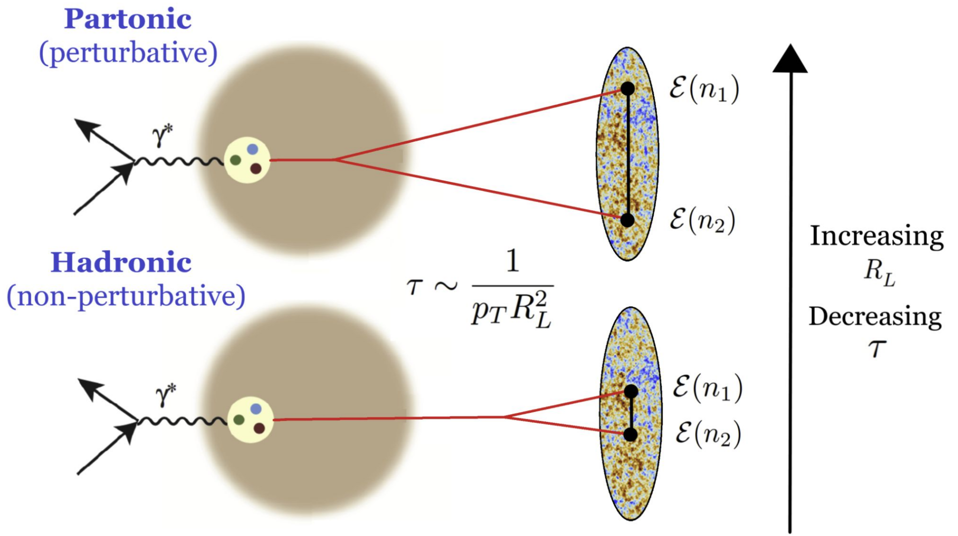


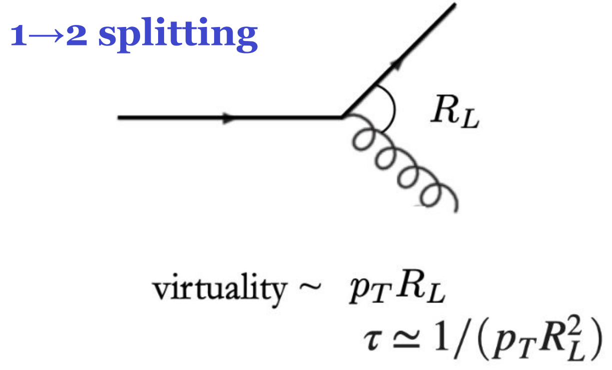


Two-point energy correlator

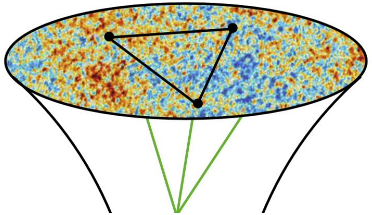
➤ Probes medium interactions as *a function of scale*

- Higher R_L ↔ earlier splitting
- Differentiates hadronic and partonic regions
- Sensitive to virtuality, formation time of parton shower, effective path length
- Onset of modification probes size of the medium

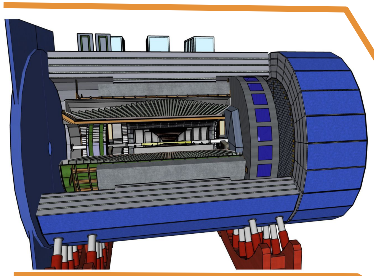




EECs with Cold Nuclear Matter



- ➤ Motivated by heavy ion QGP EEC study [C. Andres, F. Dominguez, R.K. Elayavalli, J. Holguin, C. Marquet, I. Moult]
- ➤ Now we want to study in cold nuclear matter how the EEC distribution is modified and whether system size is imprinted
- ➤ EEC provides "common language from hot to cold nuclear matter"



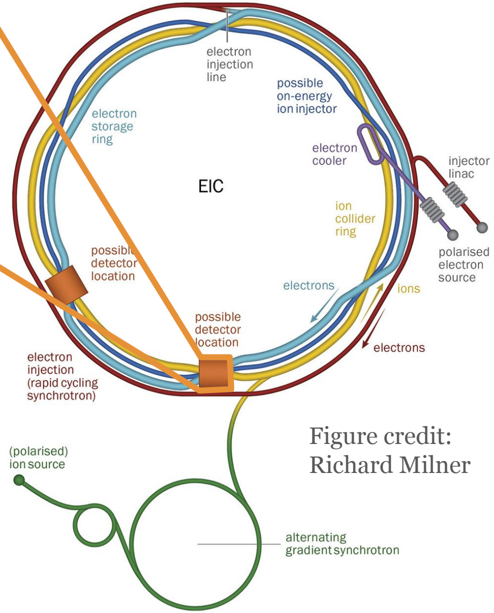


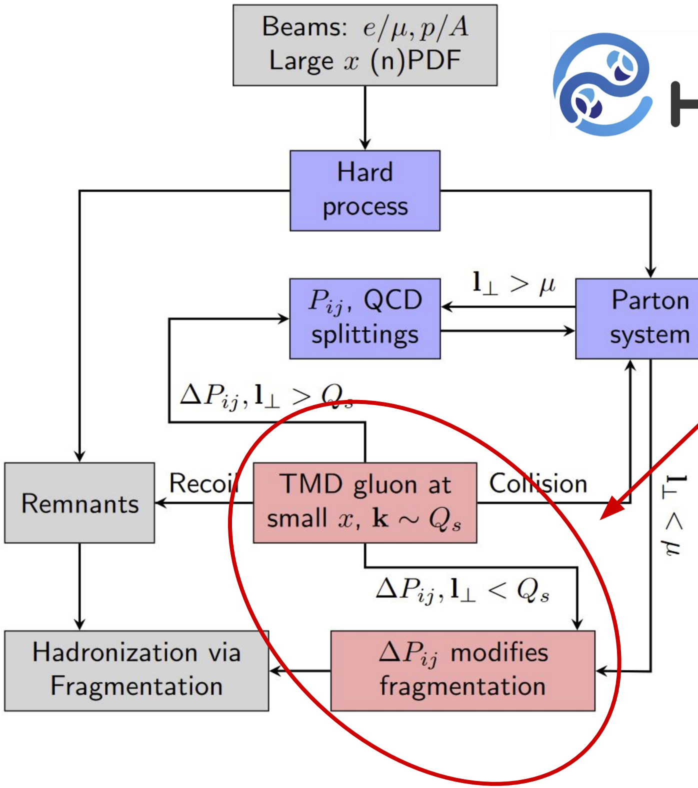
Figure credit: Richard Milner

- ➤ EIC well-suited to study cold nuclear matter
  - New and clean environment to apply EEC techniques
  - First high-energy e+A collisions an a variety of nuclei A
  - Wide acceptance and high luminosity
  - Larger jet radii possible

[EIC Yellow Report]

Collision Species and Energies Supported by the EIC				
Nuclei species A	e+A Beam Energies (GeV)			
proton	18 on 275	10 on 100	5 on 100	5 on 41
deuterium / ^{3}He / ^{4}He	18 on 110	10 on 110		5 on 41
C / ^{40}Ca / Cu	18 on 110	10 on 110		5 on 41
Au	18 on 110	10 on 110		5 on 41

Simulating EIC with eHIJING



HIJING

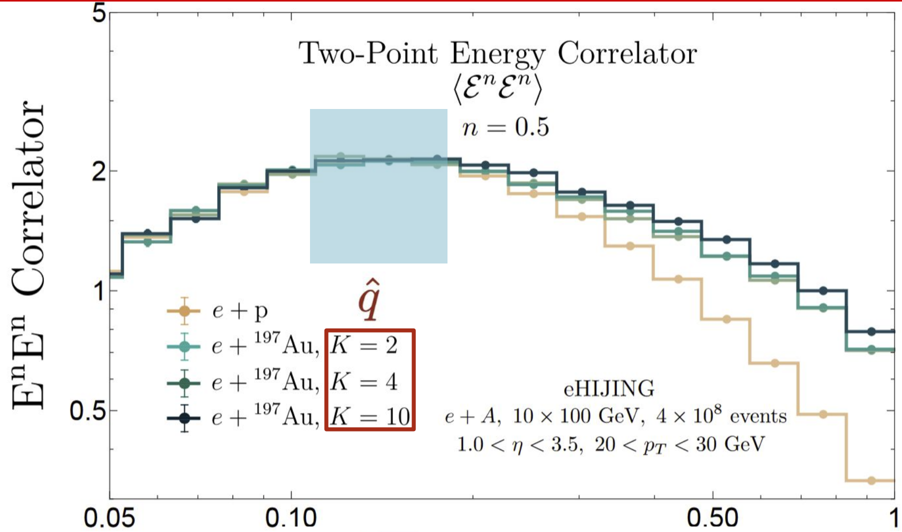
- eHIJING simulates nuclear-modified jet evolution in DIS events
  - PYTHIA8 for initial interaction
  - $\boxed{\text{Medium modifications}}$ for shower:
    - p_T broadening via multiple collisions
    - Medium-induced parton splitting
  - Benchmarked against HERMES fixed-target

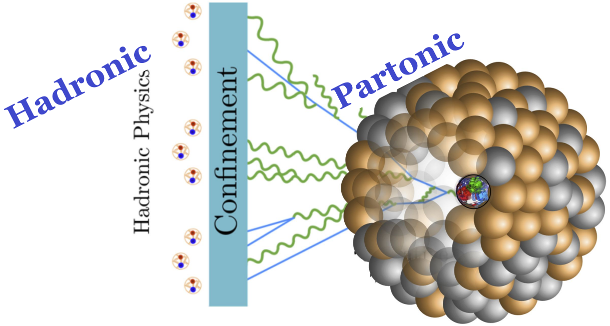
[W. Ke, Y. He, X-N. Wang, H-X. Xing, Y. Zhang arXiv:2304.10779]

- EIC settings
  - 10 GeV electron beam, 100 GeV hadron beam
  - 4E8 events, ~1 year (10^{-1} fb) luminosity
  - e+p baseline
  - Jet reco: anti-kT, R=1

EEC @ EIC

➤ e+Au and e+p EEC, for several $\hat{q}$ settings (controlled by K parameter)





probability of medium induced emissions

$$\sim \hat{q}L^2 \sim \hat{q} \cdot (r_0 A^{1/3})^2$$

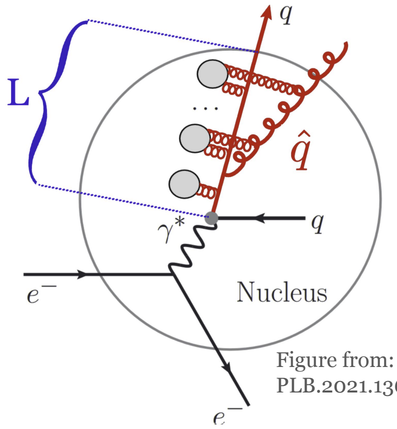


Figure from: PLB.2021.136261

- Hadronic and partonic regions cleanly separated
- Modification enhanced at high R_L (early splitting → inside the nucleus)
- Greater enhancement with larger $\hat{q}$

K = 2 to 10 ➜ qhat = 0.063 to 0.172 GeV2/fm
at xB = 0.1 and Q2 =1GeV2
(default tuning K=4 benched mark to HERMES data)

Jet p_T dependence

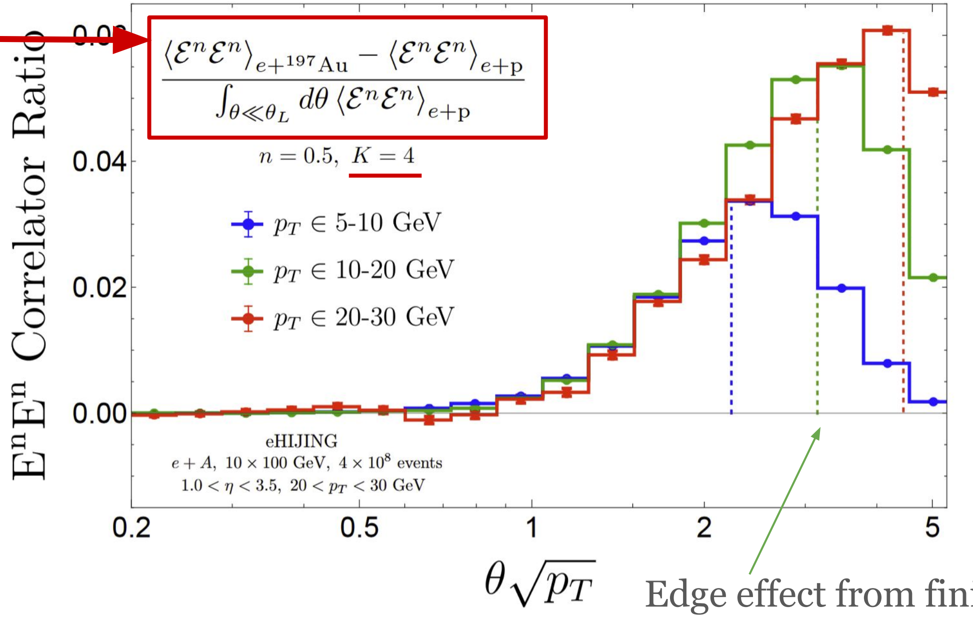
➤ Relative Difference of e+Au and e+p EEC

- Onset happens at a characteristic length scale

  ~ the formation time of the shower

$$\boxed{\tau \sim \frac{1}{p_T R_L^2}}$$

- Scaling the x-axis by $\sqrt{p_T}$ causes the onsets to coincide



Edge effect from finite jet radius

➤ Effective path length determined by

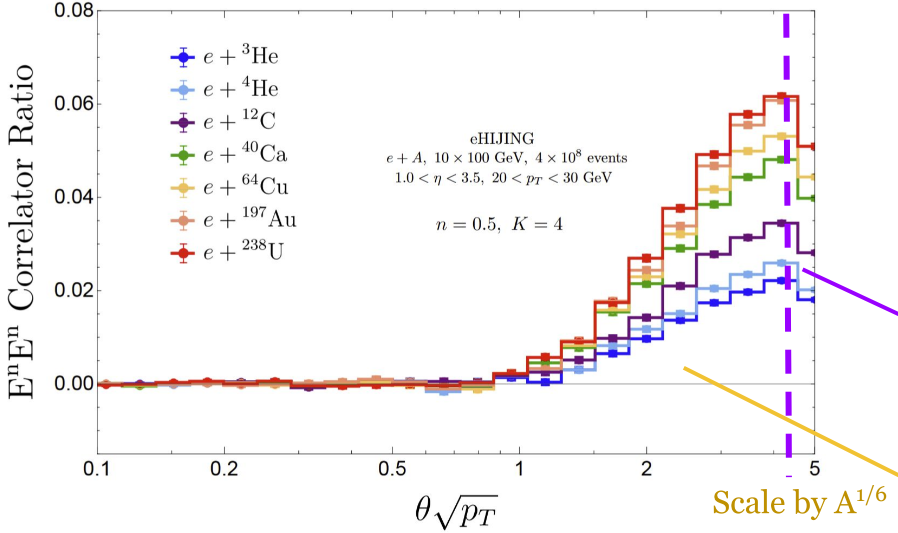
1) Formation time of splitting
2) Nucleus size ...

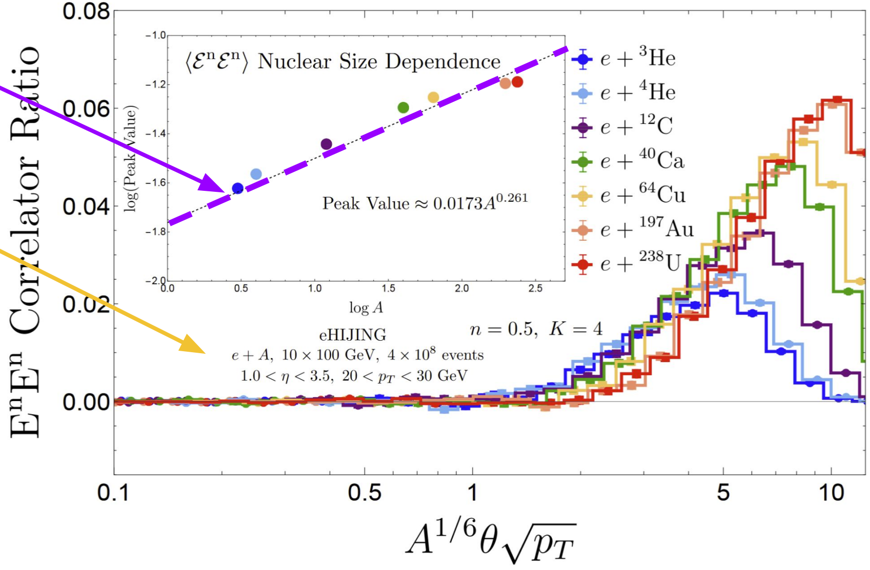
Nuclear size dependence

➤ e+A compared wrt e+p for many target species

$$\theta_R \sim \frac{1}{\sqrt{EL}} \sim \frac{1}{\sqrt{p_T A^{1/3}}} \sim \frac{1}{A^{1/6}\sqrt{p_T}}$$

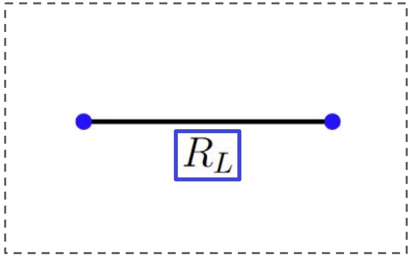
- Longer effective path length for larger nuclei $L \sim r_0 A^{1/3}$
- Scaling the x-axis by $A^{1/6}$ causes the onsets to coincide



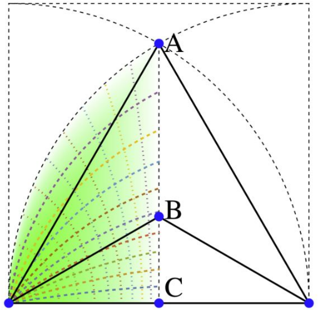


- Nuclear size dependence cleanly imprinted on EEC, femtometer resolution
- Shape and magnitude of modification sensitive to model details

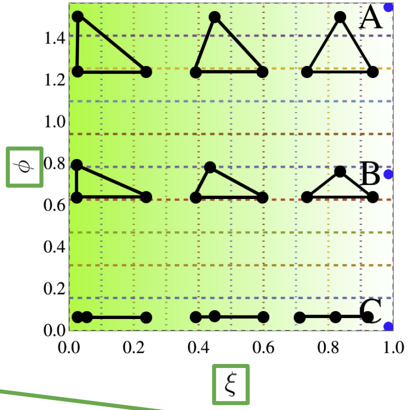
Three-point energy correlator



EEC: a function of *scale*



E3C: a function of *shape*



$$\langle \mathcal{E}^n \mathcal{E}^n \mathcal{E}^n \rangle = \sum_{i,j,k} \int dR'_L\, d\xi'\, d\phi' \left(\underbrace{\frac{p_{T,i}\, p_{T,j}\, p_{T,k}}{p^3_{T,\mathrm{jet}}}}_{\text{energy weight}} \right)^{\overset{\text{weight power}}{n}} \cdot \delta(R'_L - \underbrace{R_L}_{\text{triangle scale}})\delta(\xi' - \xi)\delta(\phi' - \phi)$$

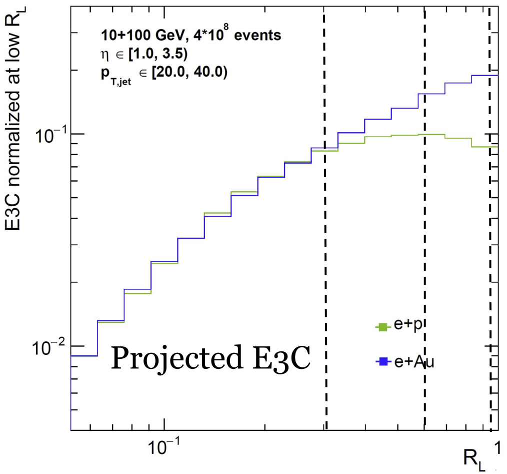
triangle shape

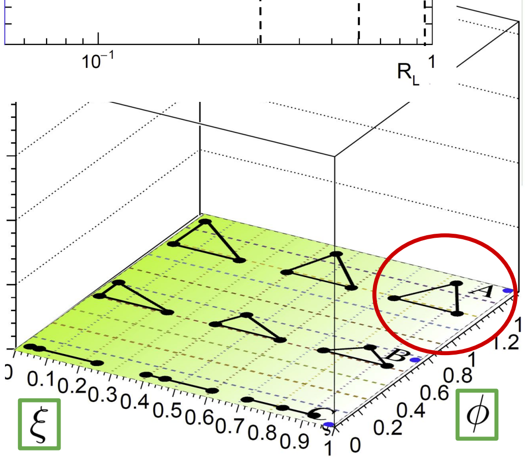
EEC used to find interesting scales R_L, *then* E3C used to study shape dependence (ξ, ϕ)

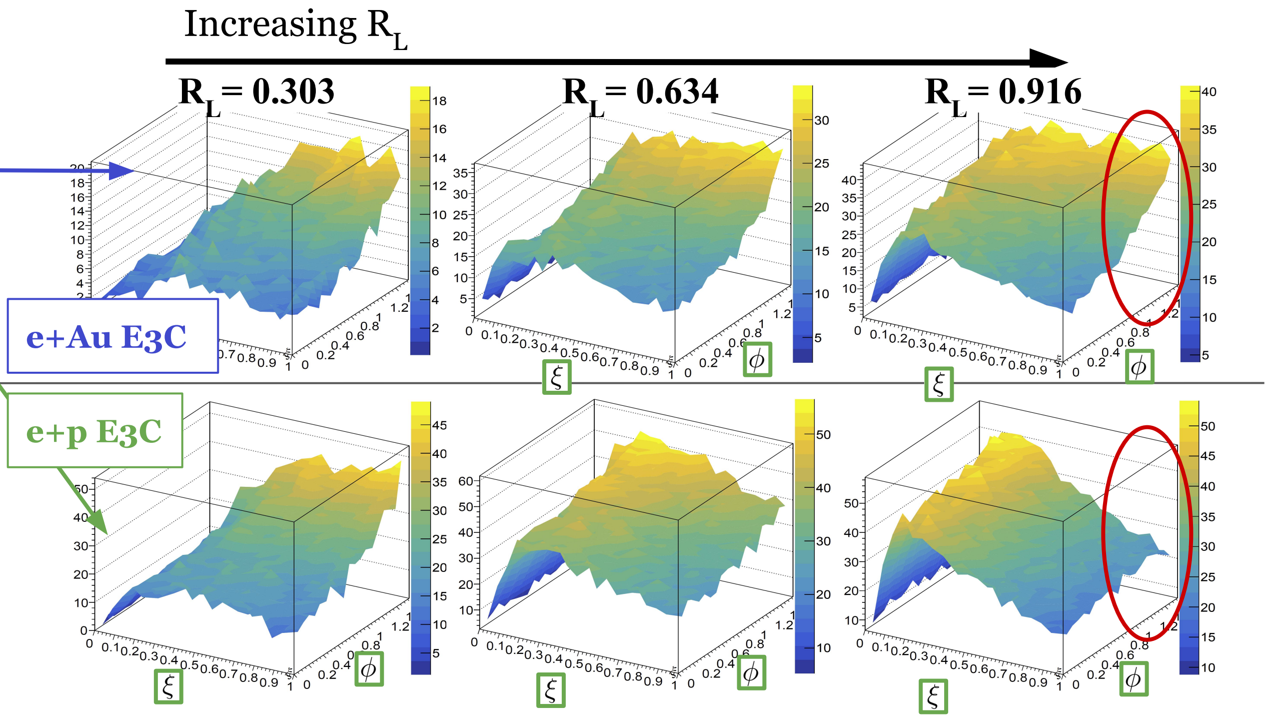
- Encodes 1→3 splitting function, “Non gaussianities” (not fully in eHIJING yet)
- Higher point correlators = higher moments of energy distribution
- Projected correlator done on CMS open data and is being analyzed in other LHC experiments

E3C @ EIC (preliminary)

➤ e+Au and e+p E3C







- Medium effects push radiation to higher angles
- Exact modification is model dependent
- Motivates higher point analytical investigations in cold matter and QGP

Equilateral shape filled in e+A

Summary

EEC & E3C together form cohesive imaging technique of energy flow within jets

- **EEC** measures modification as **function of scale** → **identify scales of interest**
- **E3C** measures modification as **function of shape** → **characterize fluctuations, interactions in jet**

EIC will be new, clean environment for energy correlator techniques

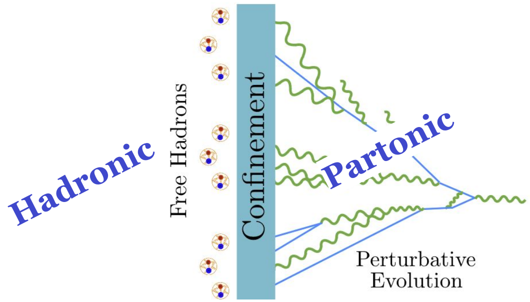
  - High precision, high luminosity, very low background
  - Variety of new nuclei collision species
  - Correlators sensitive the nuclear medium effects, nuclear size

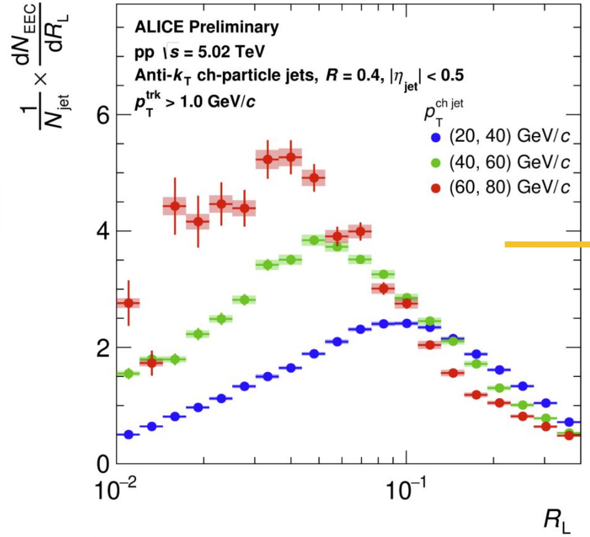
- Motivates study of higher point correlators in hot and cold nuclear matter

Backup

EEC in ALICE p+p collisions

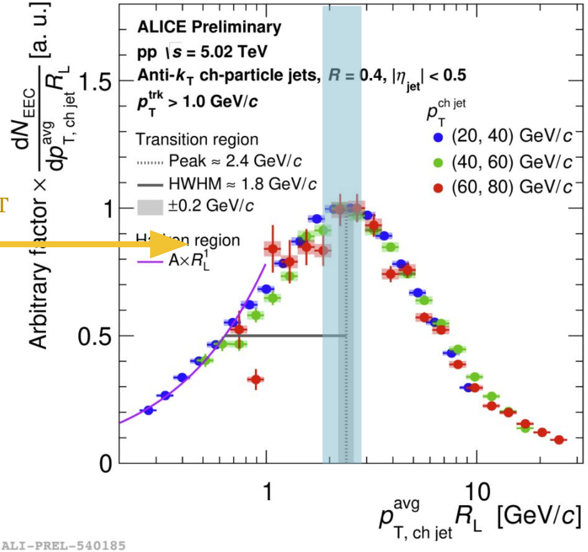
- Clear separation between hadronic and partonic regions
- Transition region corresponds to confinement region
  - Onset occurs when $\text{virtuality} \sim p_T R_L \sim \mathcal{O}(\Lambda_{\mathrm{QCD}})$
  - Scales with jet pT





ALI-PREL-540213

Scale by p_T



ALI-PREL-540185

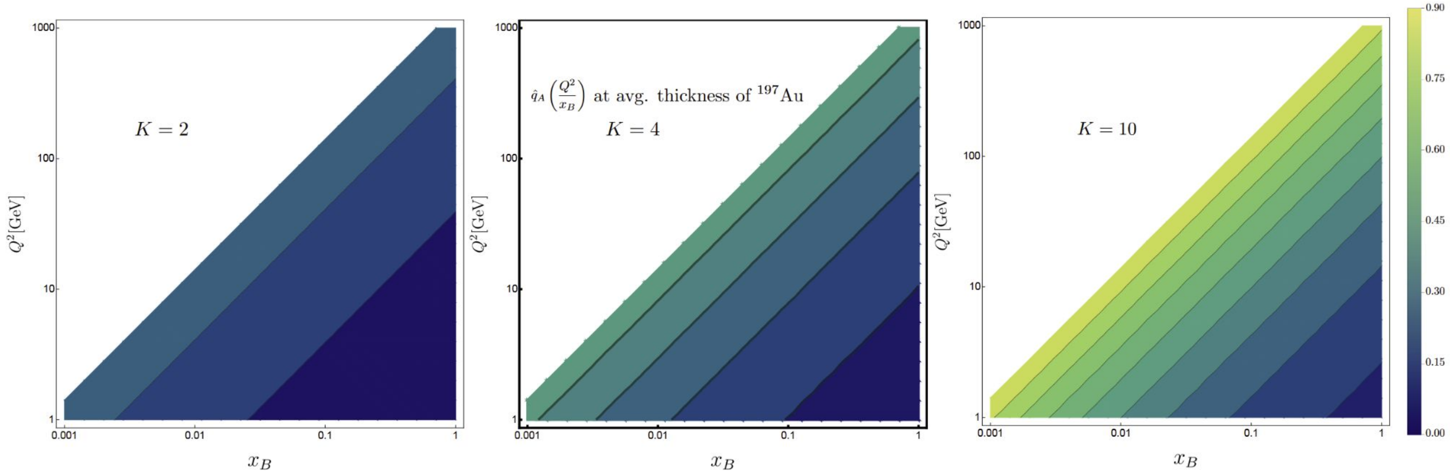
eHIJING

- eHIJING simulates jet evolution in DIS events from nuclear modification effects
  - Initial interaction modeled by PYTHIA8
  - EPPS16 nPDF input, isospin effects, EMC, (anti-)shadowing effects
  - Parton shower experiences medium modifications:
    - p_T broadening via multiple collisions with small x gluons
    - Parton splitting included
    - Hadronization

[W. Ke, Y. He, X-N. Wang, H-X. Xing, Y. Zhang]

qhat and K have relationship

- qhat is a nonlinear function of K, x_B, Q^2
- K = 2 to 10 ➜ qhat = 0.063 to 0.172 GeV2/fm, at xB = 0.1 and Q2 =1GeV2
- K=4 benchmarked by HERMES



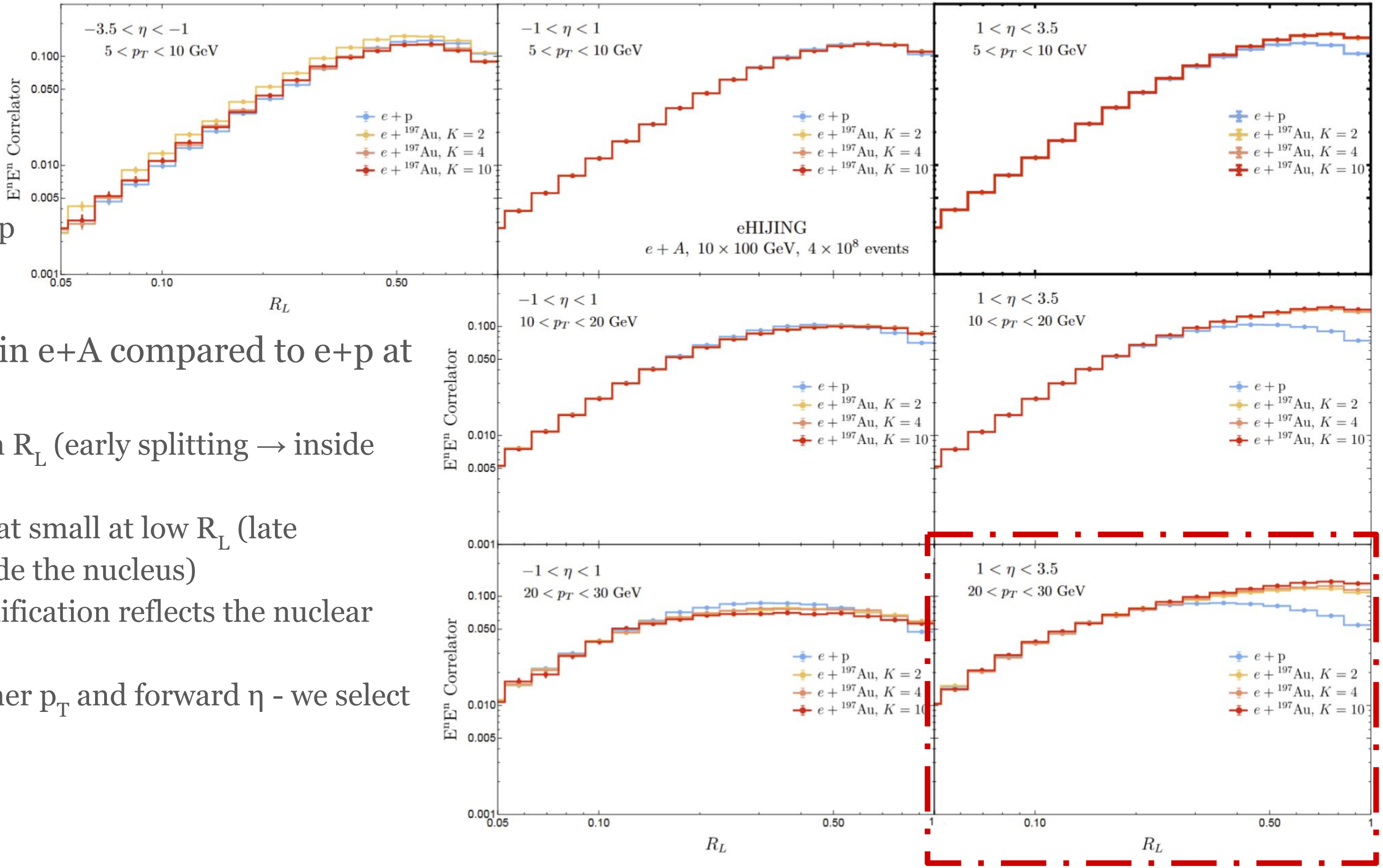
Modification observed in EEC

- Calculation

  $\alpha \cdot \langle \mathcal{E}^n \mathcal{E}^n \rangle$

  Relative normalization factor α forces e+A and e+p to match at low R_L

- Modification visible in e+A compared to e+p at default qhat
  - Enhanced at high R_L (early splitting → inside the nucleus)
  - No modification at small at low R_L (late splitting → outside the nucleus)
  - Onset of the modification reflects the nuclear size
  - Enhanced at higher p_T and forward η - we select this bin to study

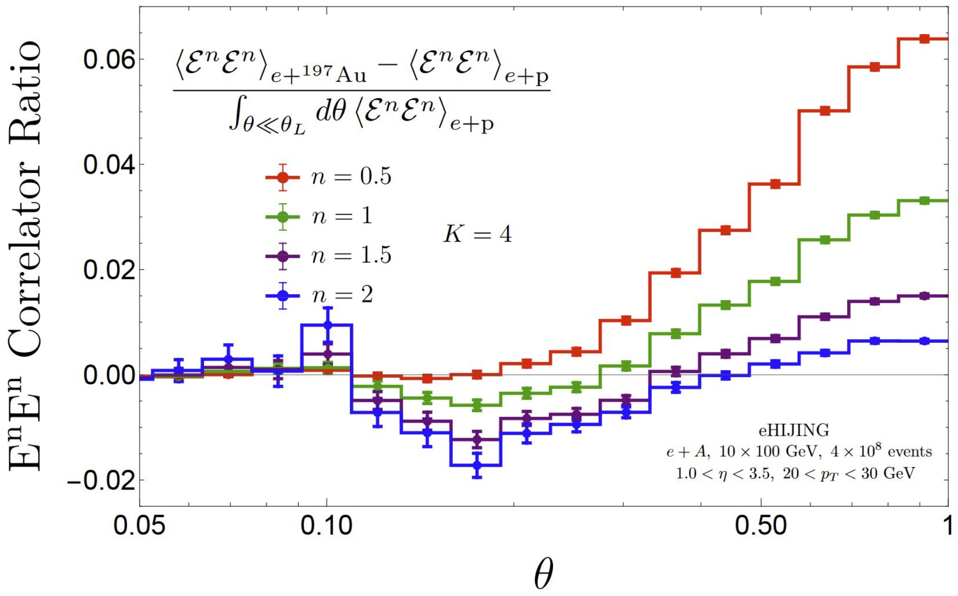


Weight power comparison

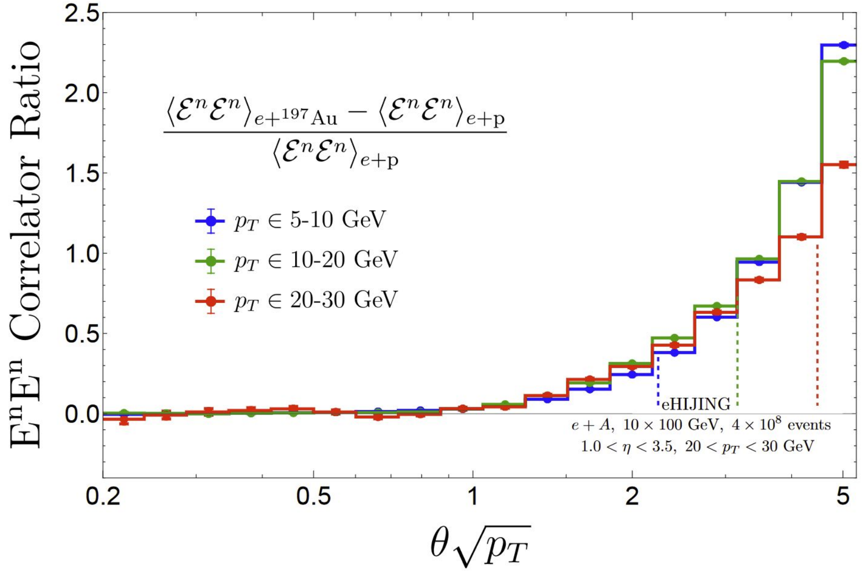
$$\langle \mathcal{E}^n \mathcal{E}^n \rangle = \sum_{ij} \int dR'_L \left(\frac{p_{T,i}\, p_{T,j}}{p^2_{T,\mathrm{jet}}} \right)^{n} \delta(R'_L - R_L)$$

weight power

- EEC with different weight powers n
- $n < 1$ enhances medium-induced soft radiation
- n=0.5 used since more clearly differentiates nuclei species and jet p_T



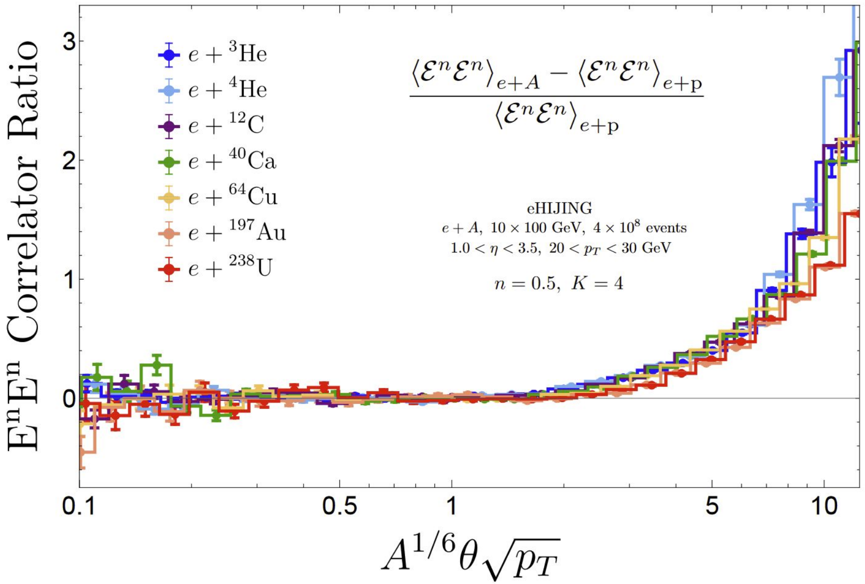
EEC @ EIC modification



➤ Onsets coincide when x-axis rescaled appropriately

➤ Modification ratio calculated for

- Jet pT dependance, e+p wrt e+Au modification
- Nucleus size dependence



EEC @ EIC modification

➤ E3C for e+p, e+C, e+Au for broad R_L range