# Simulations of nuclear modification effects using energy correlators in jets for the EIC

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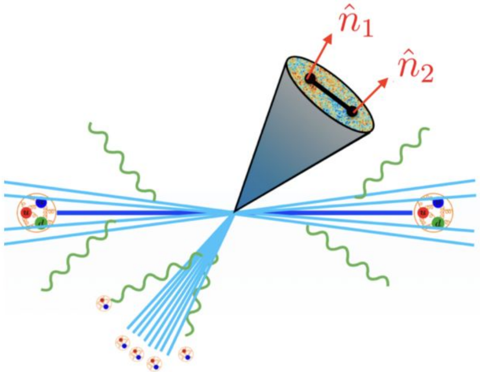
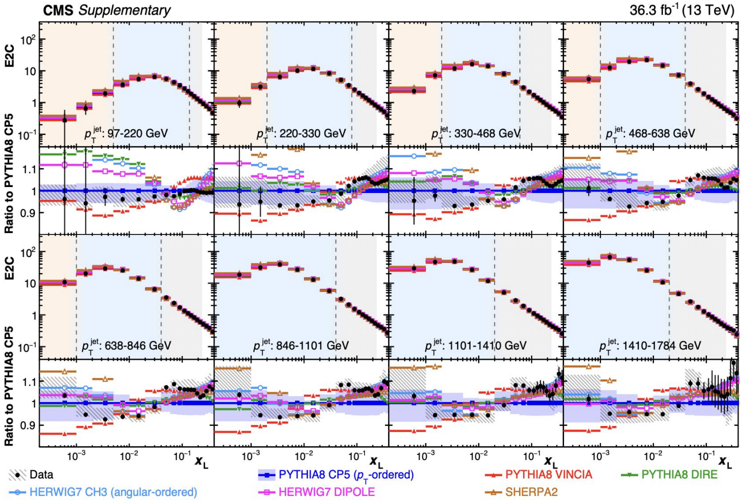
# Energy-energy correlators (E2C)




- E2Cs probe the correlation between energy fluxes at different angles.
- Mathematically, E2C is an energy weighted two point correlator, expressed as a function of angular distance between the two points

$$\mathrm{E2C}(\theta) \equiv \frac{d\sigma^{[2]}}{d\theta} = \sum_{i,j} \int d\sigma \left(\frac{E_i E_j}{E^2}\right)^n \delta(\theta - \theta_{ij})$$

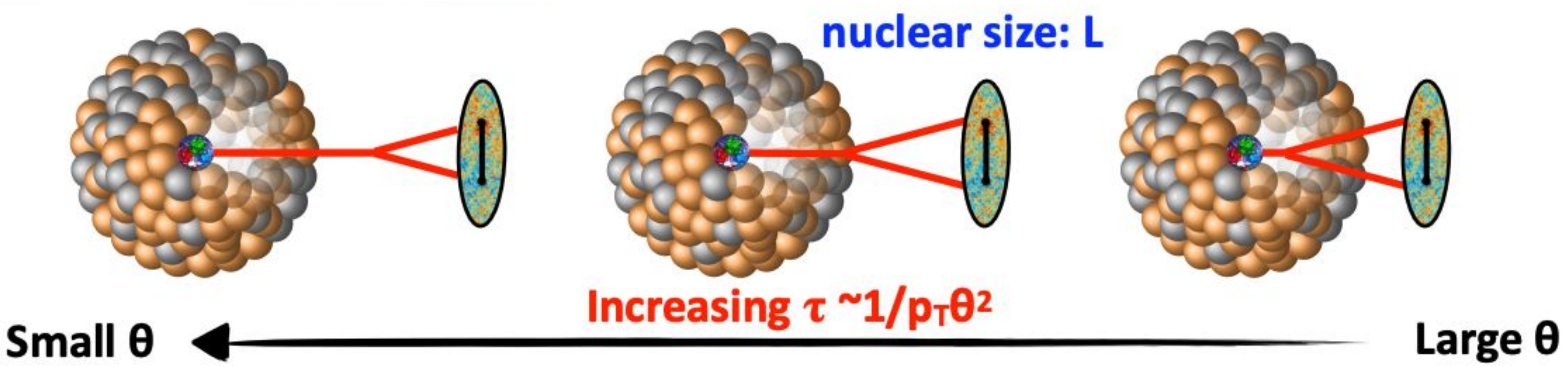
*Placeholder variable




E2C using pp collision data at LHC. [4]

# E2C is sensitive to the timescales of hadronization

- E2C can show the parton splitting timescale–how early does parton splitting happen in the patron shower
  - Larger angle, earlier splitting

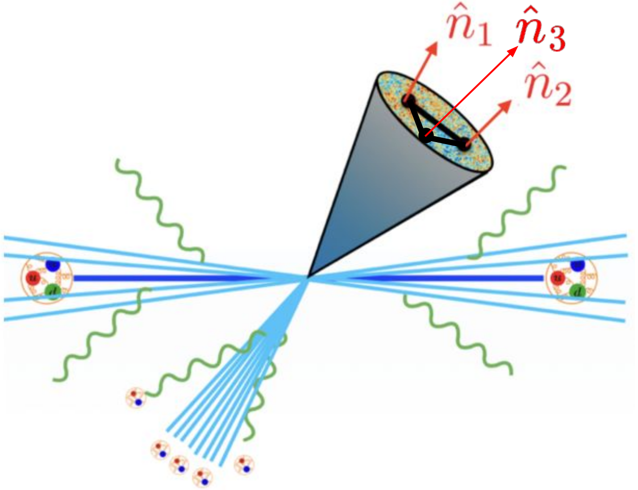



Parton splitting timescale scaling with hadron opening angle [5]

# E3C

- Like how E2C are two-point energy correlators, E3C are three-point energy correlators
- Higher-point correlator can serve as probe for nuclear shape and nuclear medium, as it is sensitive to multi-parton correlations, and higher-order parton splitting in parton shower

$$\mathrm{E3C}(\theta) = \frac{d\sigma^{[3]}}{d\theta} = \sum_{i,j,k} \int d\sigma \left( \frac{E_i E_j E_k}{E^3} \right)^n \delta(\theta - \max(\theta_{ij}, \theta_{jk}, \theta_{ki}))$$



# E2C- $\theta_{ij}$ vs $\Delta R_{ij}$

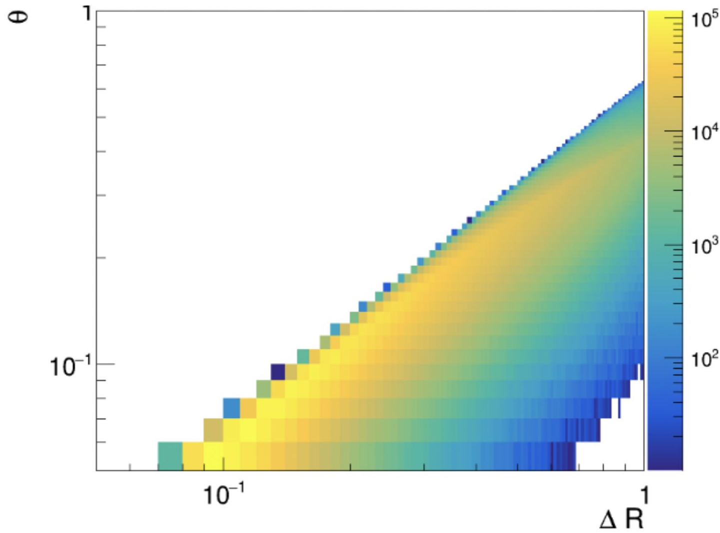
- Different conventions for angles between hadrons
  - EIC related papers use $\theta_{ij}$, physical angular separation in Breit Frame, which directly connects to parton splitting angles
  - CMS and ALICE paper use $\Delta R_{ij}$, which is boost-invariant, and matches jet algorithms

$$\Delta R_{ij} = \sqrt{(\Delta\eta_{ij})^2 + (\Delta\phi_{ij})^2}$$

$$\mathrm{E2C}(\theta) \equiv \frac{d\sigma^{[2]}}{d\theta} = \sum_{i,j} \int d\sigma \left(\frac{E_i E_j}{E^2}\right)^n \delta(\theta - \theta_{ij})$$

$$\mathrm{E2C}(x_L) = \frac{d\sigma^{[2]}}{dx_L} = \sum_{i,j} \int d\sigma \left(\frac{E_i E_j}{E^2}\right)^n \delta(x_L - \Delta R_{ij})$$

*Placeholder variables



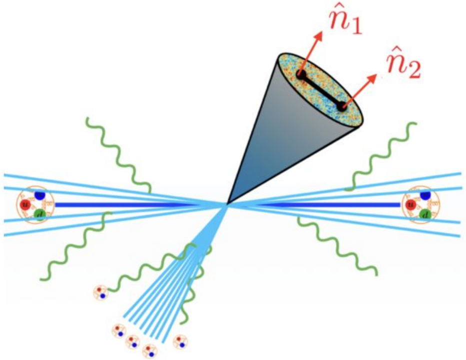

At small theta, although most of the ΔR are also small, there are still some high ΔR contributions, which could wash out traces of modifications

# Parameters

- Event generation
  - ep and eAu events generated using BeAGLE, a Monte Carlo event generator tuned to EIC collision geometry and detector acceptances
  - Beam energy 18x110 GeV
  - For eAu events at 18x110 GeV, the luminosity is $0.52 \times 10^{33}$ $cm^{-2}$ $s^{-1}$. Running for 30 weeks of operation, this corresponds to an integrated luminosity of $10 fb^{-1}$, roughly $4 \times 10^{8}$events [6]
  - Four-momentum transfer squared, $Q^2$: 700-10000 $GeV^2$
  - No shadowing (no data in shadowing region $x_B<0.1$), Genshd=1 (BeAGLE parameter)
- Smearing
  - Truth-level information is what we see if we have a perfect detector with 100% efficiency and resolution
  - Smearing is performed with the official EIC-smear package, which passes the truth-level particle information through a detector matrix from the Yellow Report Detector Working Group, which includes different momentum and energy resolution at different detectors
  - Only charged particles get smeared

# Parameters

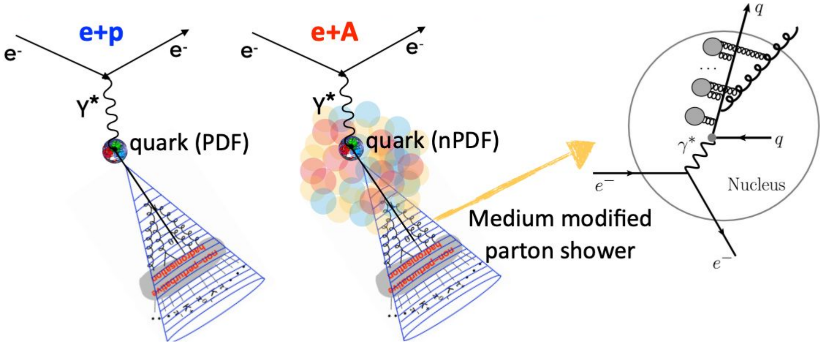
- Jet parameters and selections
  - Jets are clustered using anti-$k_t$ algorithm[8] in the FastJet package [9].
  - Final-state particles only (hadrons, leptons, photons)
  - $1<\eta<3.5$
  - Jet radius R=1.0
- E2C parameter
  - n=0.5
  - Higher n suppress soft particles strongly, smaller n more sensitive
  - Pair only hadrons into E2C
    - Charged hadrons+neutral hadrons (although smeared only have charged hadrons)
  - Normalized by jet count (hadron-only jets)



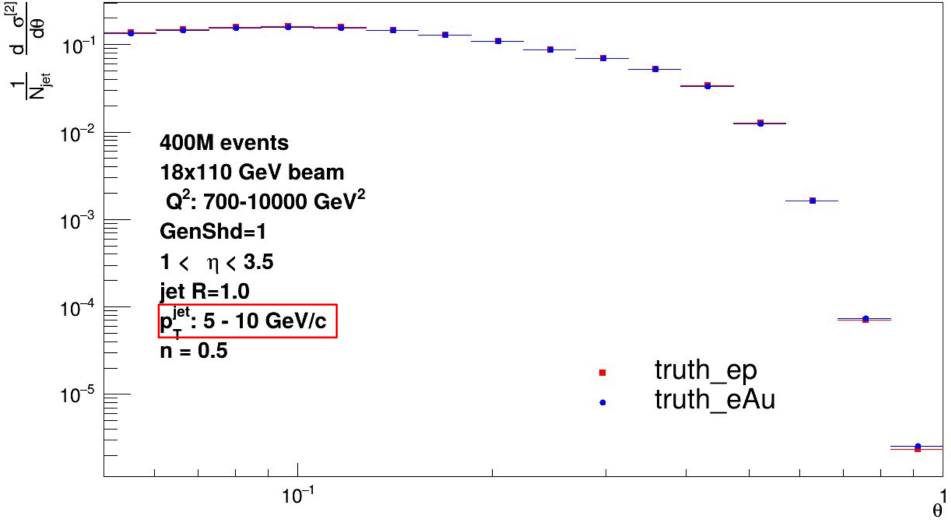

$$\mathrm{E2C}(\theta) \equiv \frac{d\sigma^{[2]}}{d\theta} = \sum_{i,j} \int d\sigma \left(\frac{E_i E_j}{E^2}\right)^{n} \delta(\theta - \theta_{ij})$$

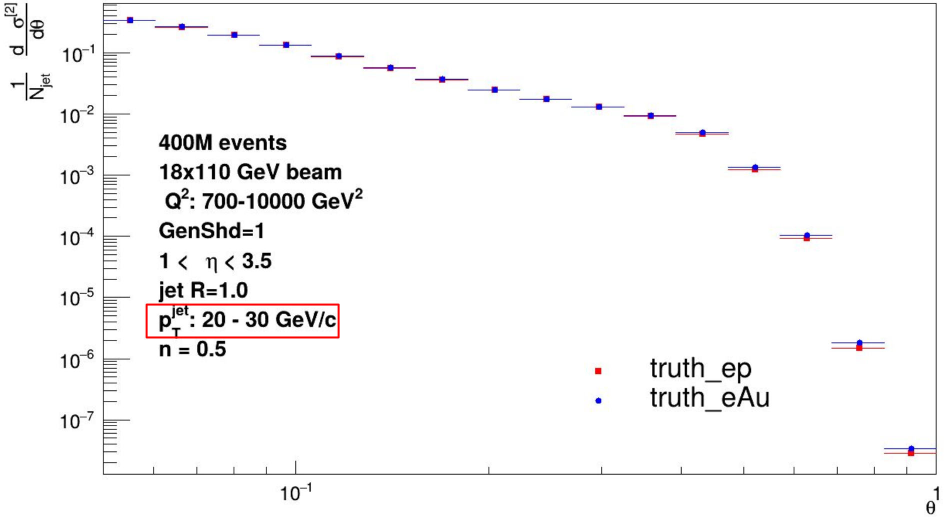
# What are nuclear modifications?

- In an ep collision, after a quark is struck out of the proton, it propagates in vacuum while undergoing through parton showering and eventually forming a jet.
- In eA collisions, the struck-out quark travels in the presence of other nucleons (a medium) in the nucleus. The parton shower is modified by the medium in two ways:
    - Energetic quark traveling through medium loses energy by soft gluon radiation from multiple scattering in medium
        - Dominant in high-$p_T$ jets, due to Landau-Pomeranchuk-Migdal effect
    - Collisional broadening of $p_T$ with angular spread $\sqrt{\langle \delta\theta^2 \rangle} \sim \sqrt{\hat{q}_g L / p_T}$, due to random elastic collisions with the medium
        - Prominent in low-$p_T$ jets and large nucleus
        - Dominant in backward regions, where there's little contribution from radiation



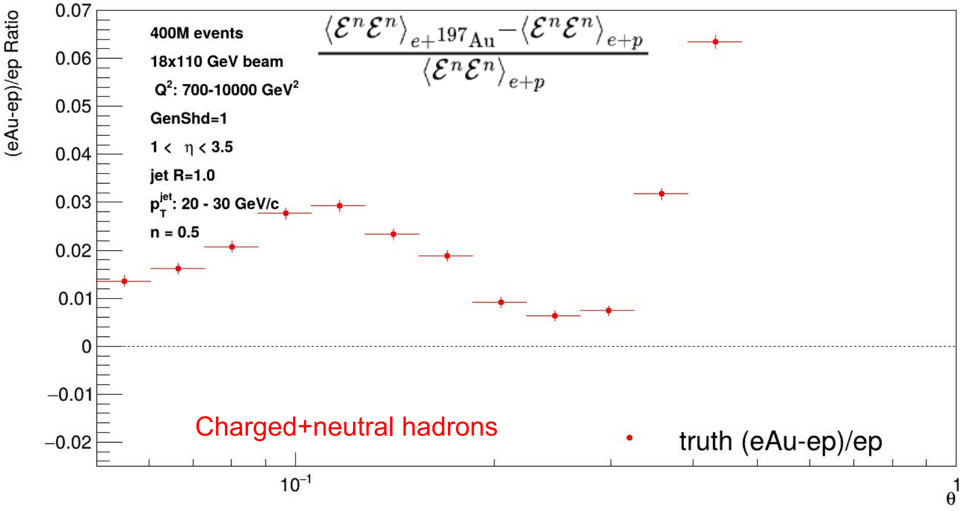
# E2C truth



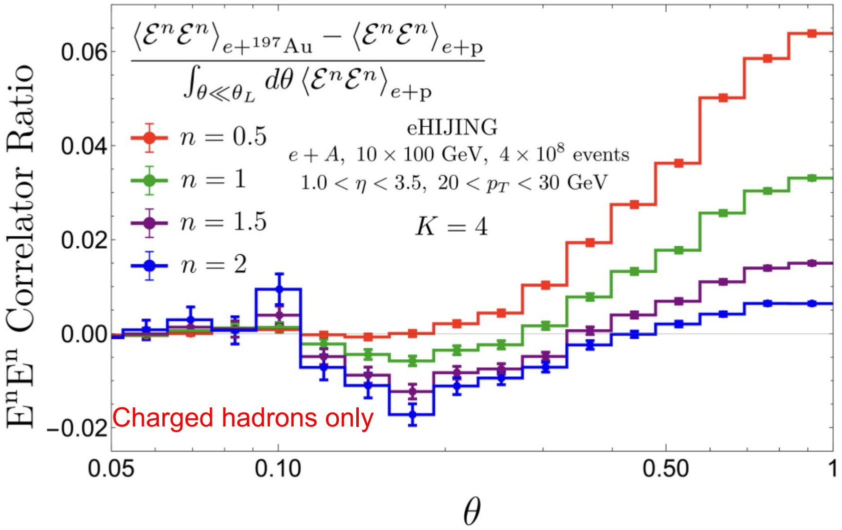




At small angles, the E2C from ep and eAu events are nearly identical, but modifications start to show up at larger angles, where it reflects parton splitting structures

# Nuclear modification ratio with E2C



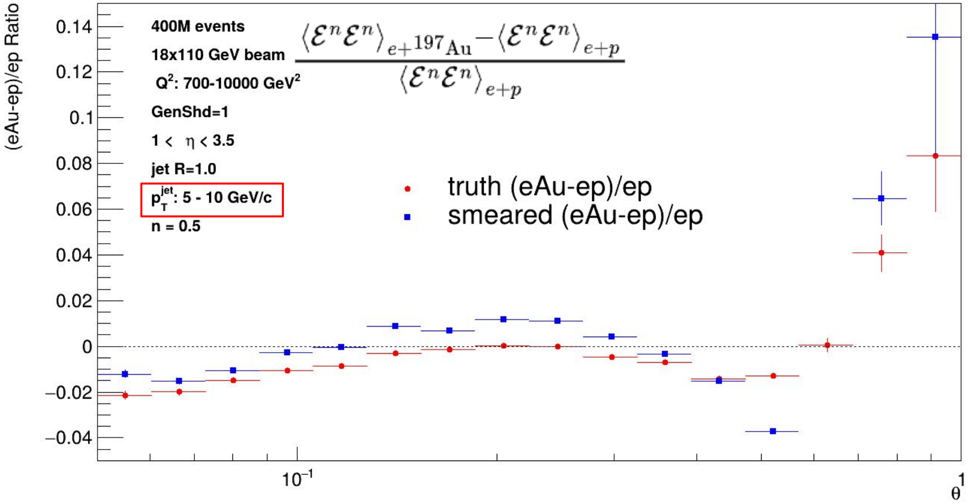

Nuclear modification using ratio of E2C for ep and eAu, using BeAGLE to generate events.

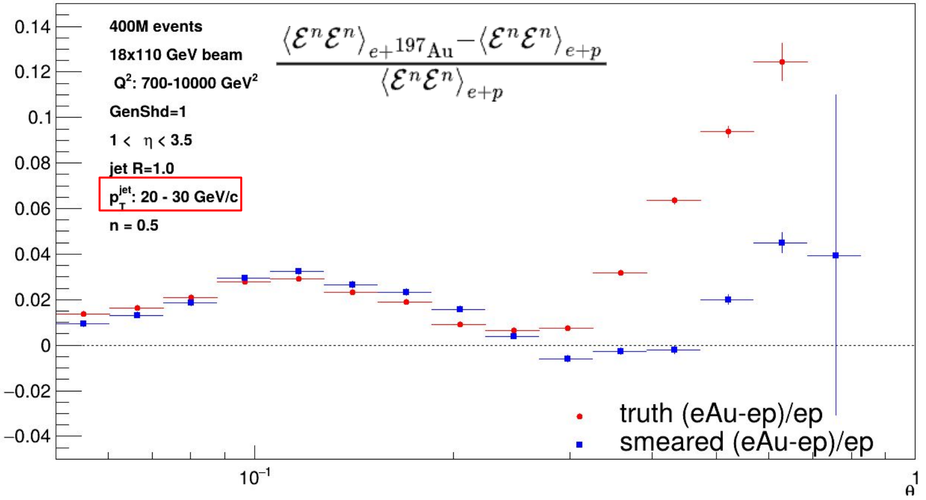



Nuclear modification using ratio of E2C for ep and eAu. This paper uses eHIJING to generate events [6]

- Larger nuclear modification in my study using BeAGLE than a previous study by others using events from eHIJING. Still performing cross checks.

# Feasibility of measuring modification with E2C

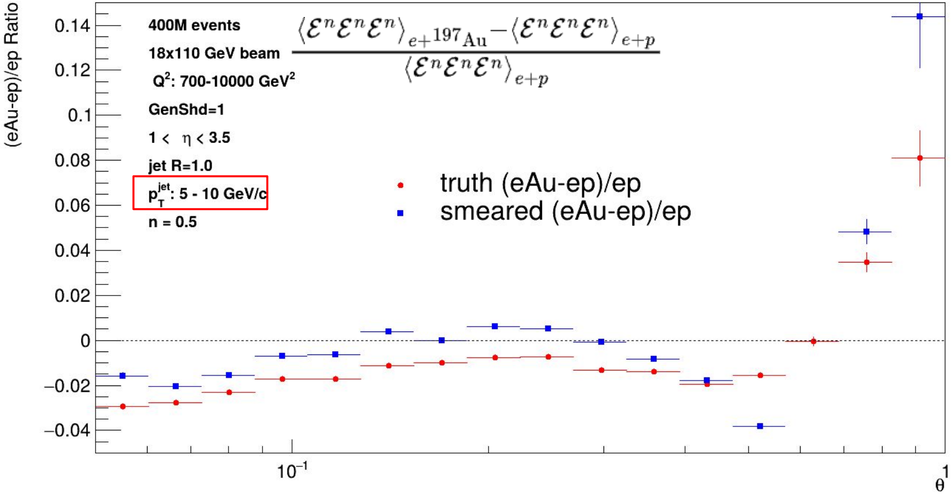


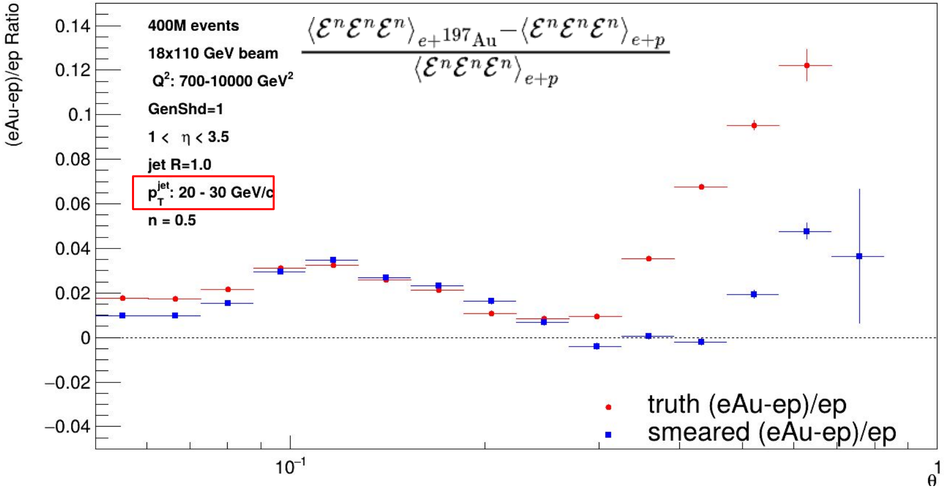




Modification is still measurable at EIC even after fast smearing. Larger differences between smeared and truth likely come from truth including neutral hadrons and charged hadrons, but smeared only having charged hadrons.

The lack of sufficient data at large angular region due to jet radius made precise measurements difficult.

# Feasibility of measuring modification with E3C

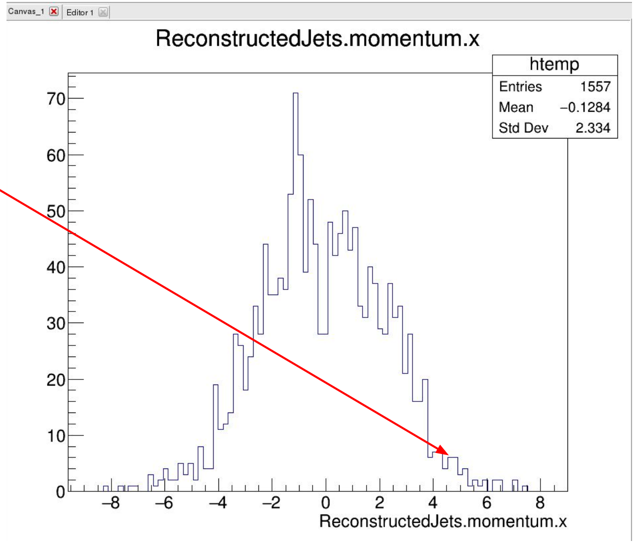



Since E3C are built on the same data as E2C, the magnitude of modification is very similar. However, due to more combinations (triples rather than pairs), the standard deviation in the modification is smaller.

# Conclusions & future work

- Measuring nuclear modification with E2C at EIC is certainly possible, but a bit difficult at large angle region, where modification is most prominent.
- Future: Use official ePIC simulation data
  - Fully reconstructed jets, using official pipeline
  - Challenges:
    - low $Q^2$ range (10-100 $GeV^2$)=few high-$p_T$ jets
    - small number of events (~5M)
    - fewer workable jets per event than my simulations
    - hard to see the small 6% modification
- Event-based rather than jet-based E2C can provide information on angular distribution of energy in full events, without the limitations of jet radius
- Studying E2C for heavy flavor quarks (charm) can provide insight into quark mass effects in hadronization



# Acknowledgement

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# references


[1]. Image credit: Bigeng Wang

[2]. Image credit: BNL

[3]. K. Lee, B. Mecaj, I. Moult, Phys. Rev. D. 111, L011502 (2025)

[4]. CMS collaboration A. Hayrapetyan et al., Phys. Rev. Lett. 133 (2024) 071903, 2402.13864.

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[6]. K. Devereaux, W. Fan, W. Ke, K. Lee, I. Moult., Phys. Rev. C. 112, 035202 (2025).

[7]. EMC, Aubert, J.J. et al. Phys. Lett. B123, 275 (1983)

[8]. Cacciari, G. Salam, G. Soyez, JEP 0804:063 (2008)

[9]. Cacciari, G. Salam, G. Soyez, arXiv:1111.6097 (2011)

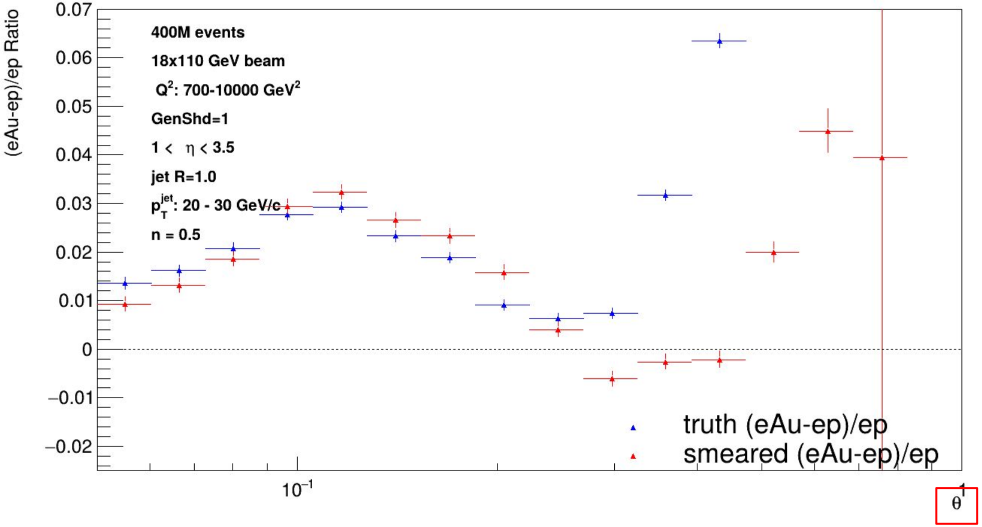
PHYSICS

# Back up

# Smearing-detector matrix

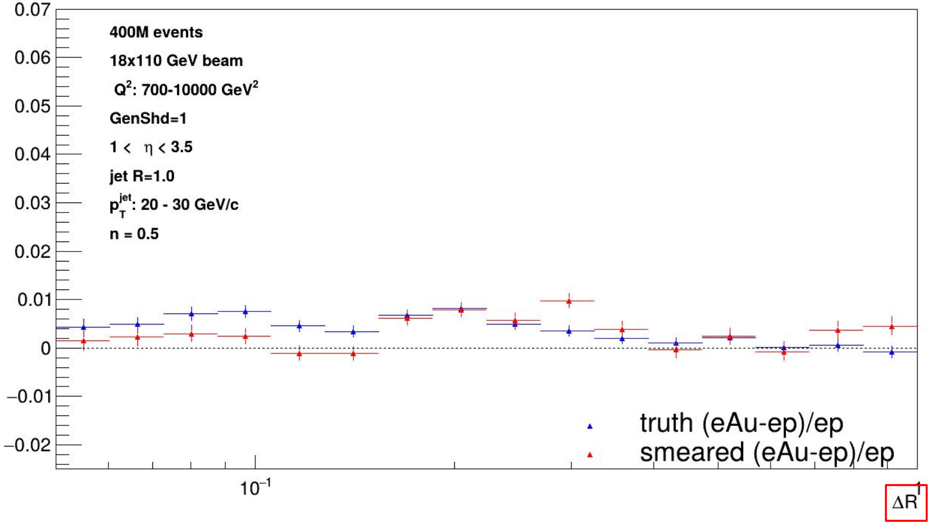
| η | θ | Nomenclature | | | Tracking | | | | | | Electrons and Photons | | | π/K/p | | HCAL | | Muons |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Resolution | Relative Momentum | Allowed $X/X_0$ | Minimum-pT | Transverse Pointing Res. | Longitudinal Pointing Res. | Resolution $\sigma_E/E$ | PID | Min E Photon | p-Range (GeV/c) | Separation | Resolution $\sigma_E/E$ | Energy | |
| < -4.6 | | ↓ p/A | Far Backward Detectors | low-Q2 tagger | | | | | | | | | | | | | | |
| -4.6 to -4.0 | | | | | Not Accessible | | | | | | | | | | | | | |
| -4.0 to -3.5 | | | | | | Reduced Performance | | | | | | | | | | | | |
| -3.5 to -3.0 | | | Central Detector | Backward Detector | | $\sigma_p/p$ ~0.2%×p⊕5% | ~5% or less X | 70-150 MeV/c (B=1.5 T) | | | 1%/E ⊕ 2.5%/√E ⊕ 1% | π suppression up to 1:1E-4 | 20 MeV | ≤ 10 GeV/c | ≥ 3 σ | 50%/√E⊕10% | ~500MeV | Muons useful for bkg, improve resolution |
| -3.0 to -2.5 | | | | | | | | | | | | | | | | | | |
| -2.5 to -2.0 | | | | | | $\sigma_p/p$~0.04%×p⊕2% | | | | | | | | | | | | |
| -2.0 to -1.5 | | | | | | | | | dca(xy) ~ 40/pT μm ⊕ 10 μm | dca(z) ~ 100/pT μm ⊕ 20 μm | 2%/E ⊕(4-8)%/√E ⊕ 2% | π suppression up to 1:(1E-3 - 1E-2) | 50 MeV | | | | | |
| -1.5 to -1.0 | | | | | | | | | | | | | | | | | | |
| -1.0 to -0.5 | | | | Barrel | | $\sigma_p/p$ ~0.04%×p⊕1% | | 200 MeV/c | dca(xy) ~ 30/pT μm ⊕ 5 μm | dca(z) ~ 30/pT μm ⊕ 5 μm | 2%/E ⊕(12-14)%/√E ⊕ (2-3)% | π suppression up to 1:1E-2 | 100 MeV | ≤ 6 GeV/c | | 100%/√E+10% | | |
| -0.5 to 0.0 | | | | | | | | | | | | | | | | | | |
| 0.0 to 0.5 | | | | | | | | | | | | | | | | | | |
| 0.5 to 1.0 | | | | | | | | | | | | | | | | | | |
| 1.0 to 1.5 | | | | Forward Detectors | | $\sigma_p/p$ ~0.04%×p⊕2% | | 70 - 150 MeV/c (B = 1.5 T) | dca(xy) ~ 40/pT μm ⊕ 10 μm | dca(z) ~ 100/pT μm ⊕ 20 μm | 2%/E ⊕ (4*-12)%/√E ⊕ 2% | 3σ e/π up to 15 GeV/c | 50 MeV | ≤ 50 GeV/c | | 50%/√E+10% | | |
| 1.5 to 2.0 | | | | | | | | | | | | | | | | | | |
| 2.0 to 2.5 | | | | | | | | | | | | | | | | | | |
| 2.5 to 3.0 | | | | | | $\sigma_p/p$ ~0.2%×p⊕5% | | | | | | | | | | | | |
| 3.0 to 3.5 | | | | | | | | | | | | | | | | | | |
| 3.5 to 4.0 | | ↑ e | | Instrumentation to separate charged particles from photons | | Reduced Performance | | | | | | | | | | | | |
| 4.0 to 4.5 | | | | | Not Accessible | | | | | | | | | | | | | |
| > 4.6 | | | Far Forward Detectors | Proton Spectrometer<br>Zero Degree Neutral Detection | | | | | | | | | | | | | | |

# θ vs ΔR



(eAu-ep)/ep Ratio
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
−0.01
−0.02
400M events
18x110 GeV beam
Q²: 700-10000 GeV²
GenShd=1
1 < η < 3.5
jet R=1.0
p_T^jet: 20 - 30 GeV/c
n = 0.5
truth (eAu-ep)/ep
smeared (eAu-ep)/ep
10⁻¹
1
θ

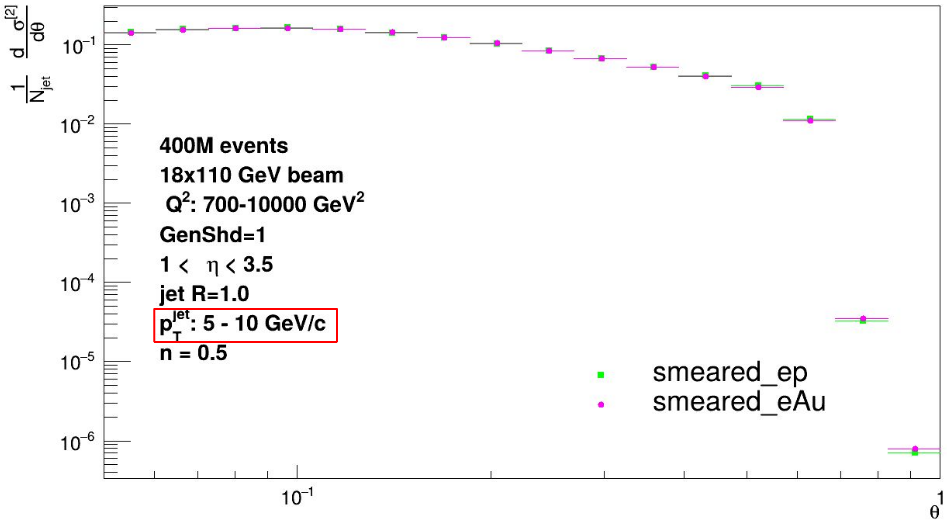

θ



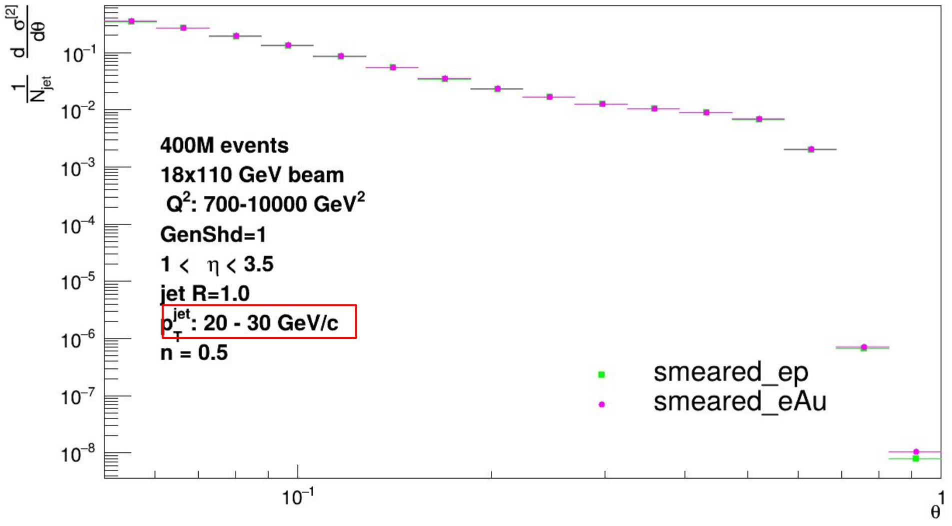
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
−0.01
−0.02
400M events
18x110 GeV beam
Q²: 700-10000 GeV²
GenShd=1
1 < η < 3.5
jet R=1.0
p_T^jet: 20 - 30 GeV/c
n = 0.5
truth (eAu-ep)/ep
smeared (eAu-ep)/ep
10⁻¹
1
ΔR


ΔR

# E2C smeared



400M events
18x110 GeV beam
$Q^2$: 700-10000 $GeV^2$
GenShd=1
1 < η < 3.5
jet R=1.0
$p_T^{jet}$: 5 - 10 GeV/c
n = 0.5
smeared_ep
smeared_eAu
$\frac{1}{N_{jet}} \frac{d\sigma^{[2]}}{d\theta}$
θ

400M events
18x110 GeV beam
$Q^2$: 700-10000 $GeV^2$
GenShd=1
1 < η < 3.5
jet R=1.0
$p_T^{jet}$: 20 - 30 GeV/c
n = 0.5
smeared_ep
smeared_eAu
$\frac{1}{N_{jet}} \frac{d\sigma^{[2]}}{d\theta}$
θ

# E3C truth

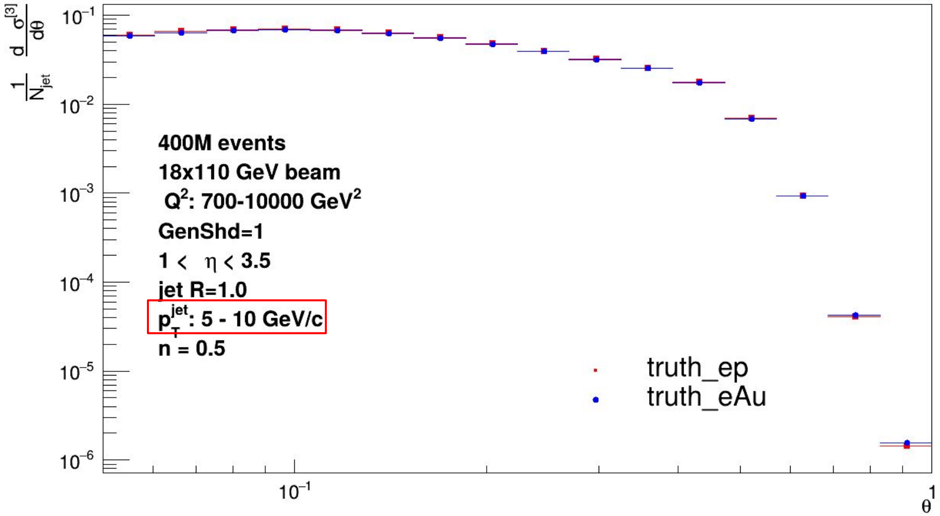



Figure 10.

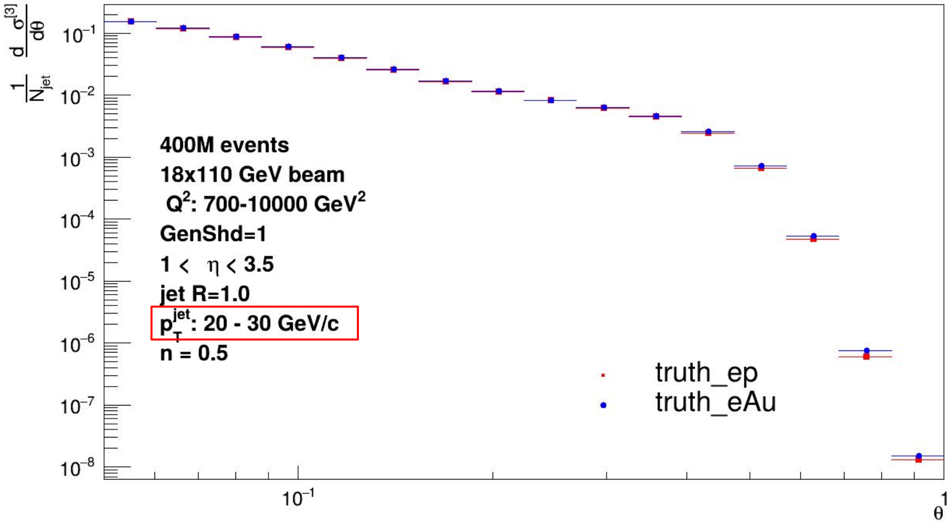



Figure 11.

# E3C smeared

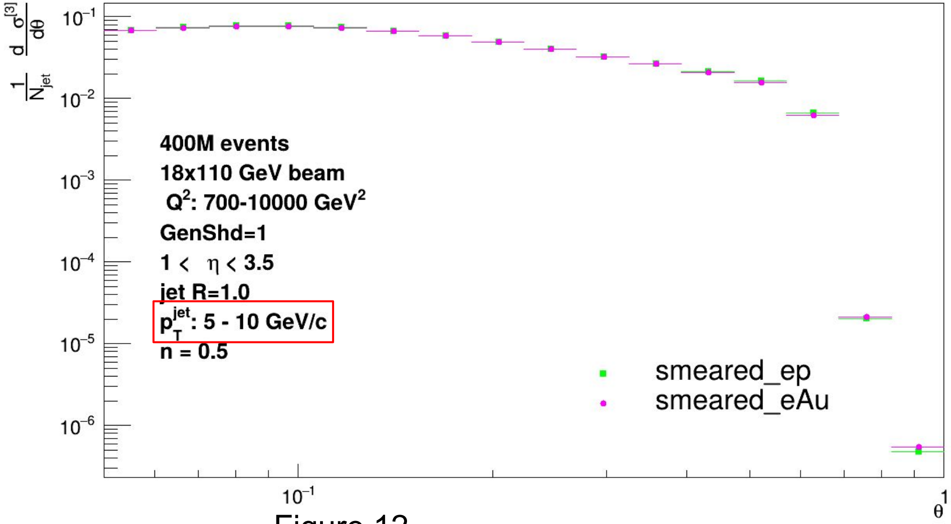



Figure 12.

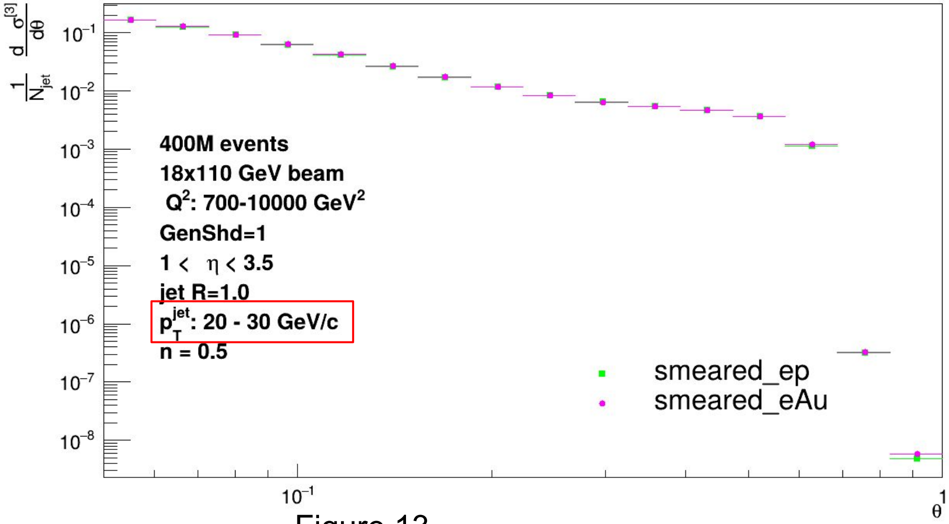
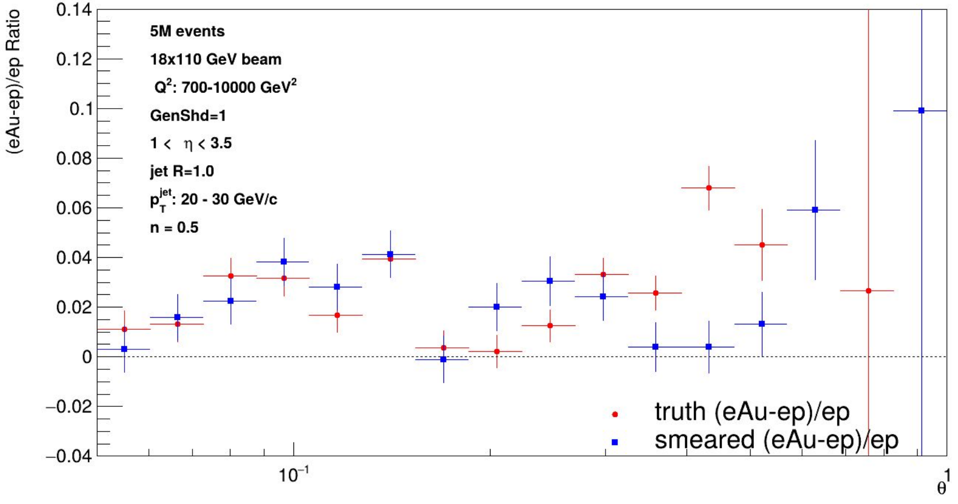
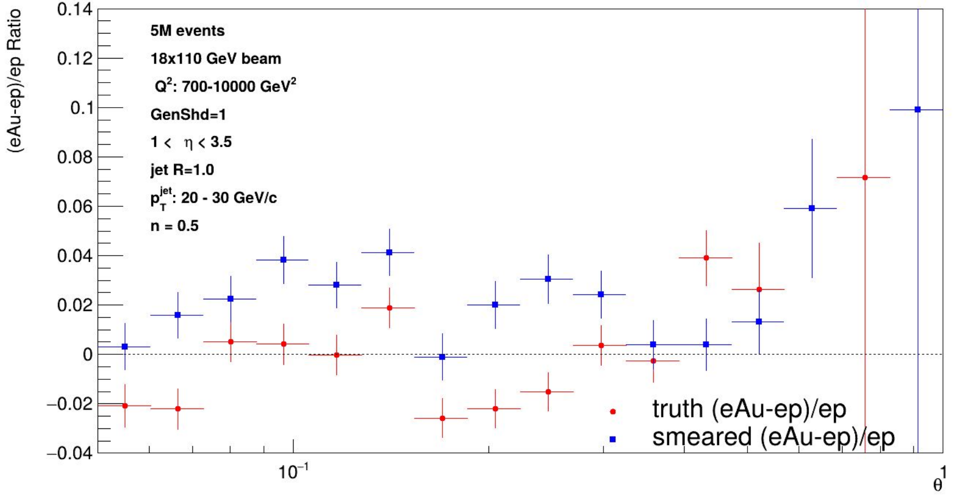



Figure 13.

# Modification ratio (5M events)

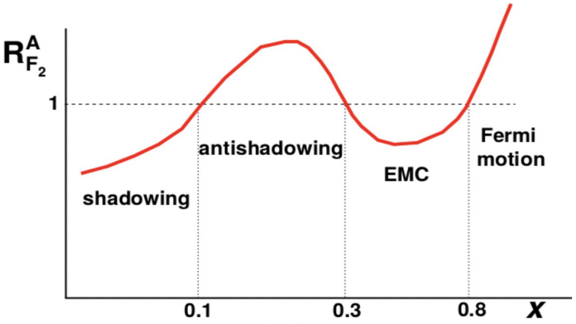



1<eta<3.5
nConstituents>=3
Jetcount: neutral+charged hadron, no lepton in jets
EEC: neutral hadron+charged hadron pair

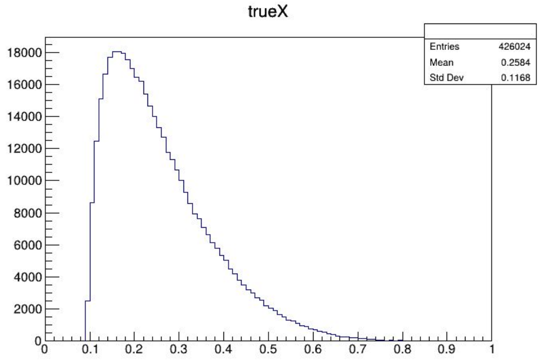


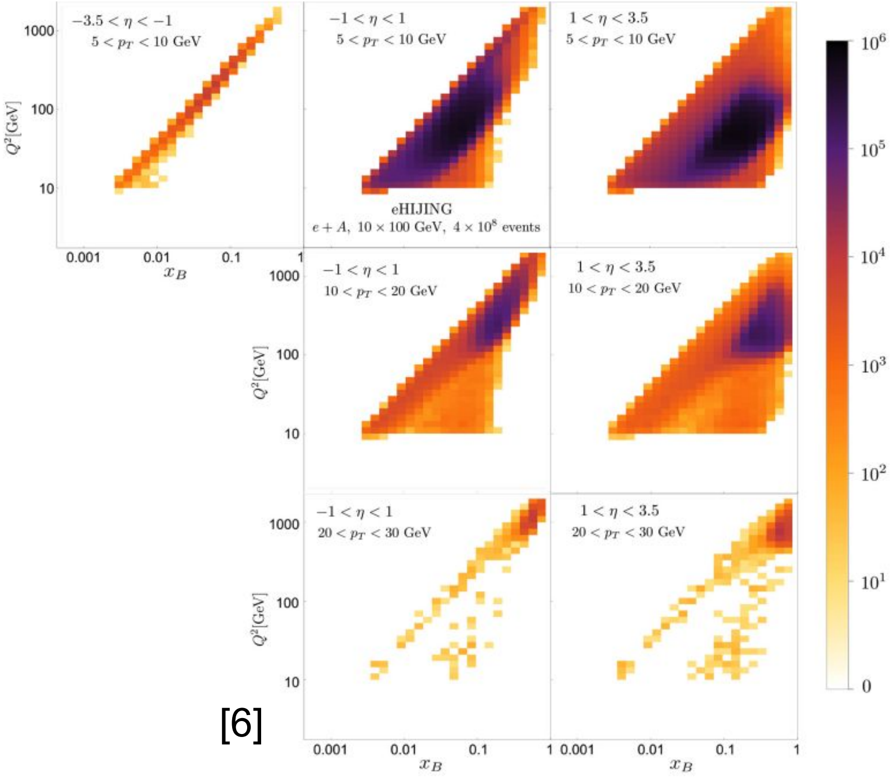

1<eta<3.5
nConstituents>=3
Jetcount: neutral+charged hadrons, hadron+lepton jets
EEC: pair using charged hadron only

# 1M eAu events $x_B$ distributions




[7]




[6]

Since our Q^2 setting is so high, no data are in the $x_B$<0.1 region, hence we turned off shadowing when generating events in BeAGLE