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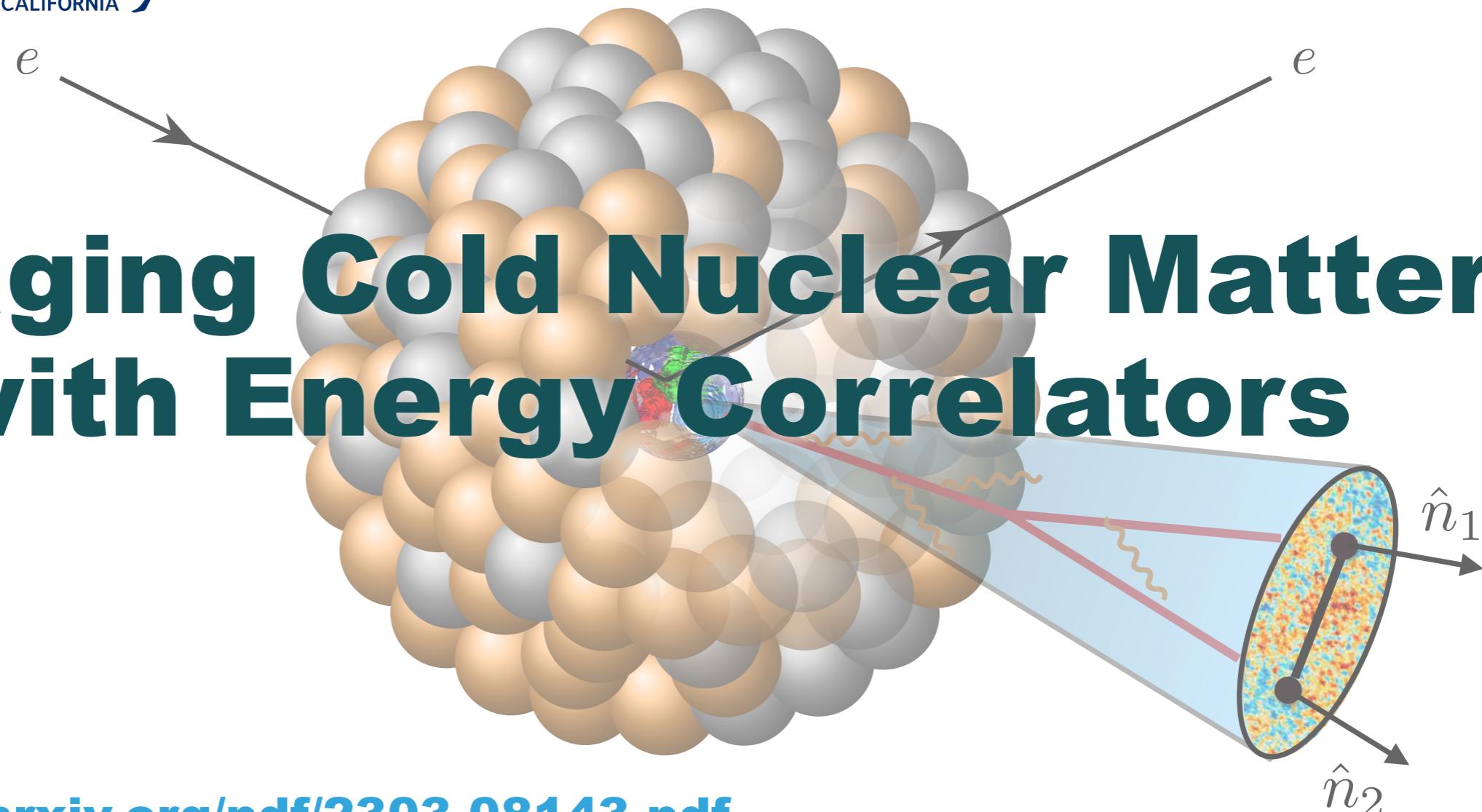
DIS23
MICHIGAN STATE
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Imaging Cold Nuclear Matter with Energy Correlators

<https://arxiv.org/pdf/2303.08143.pdf>

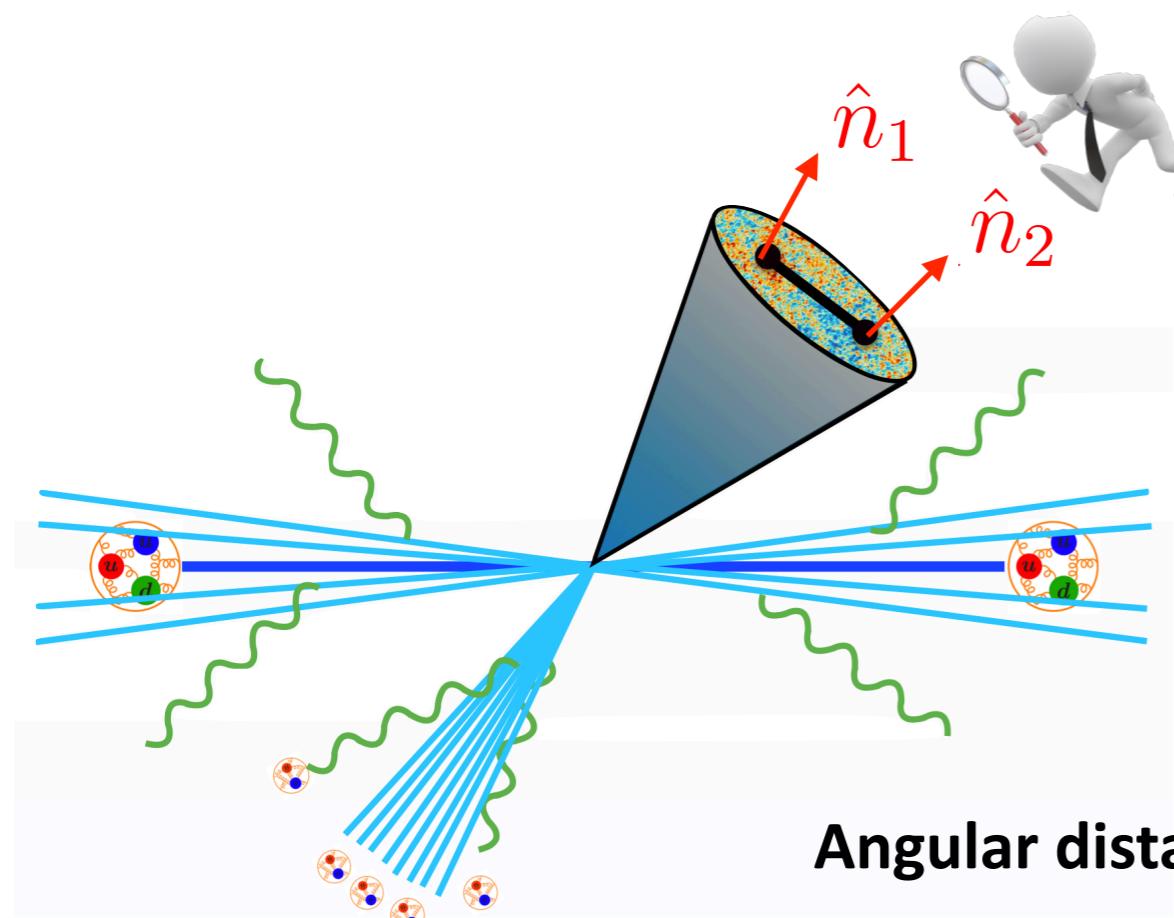
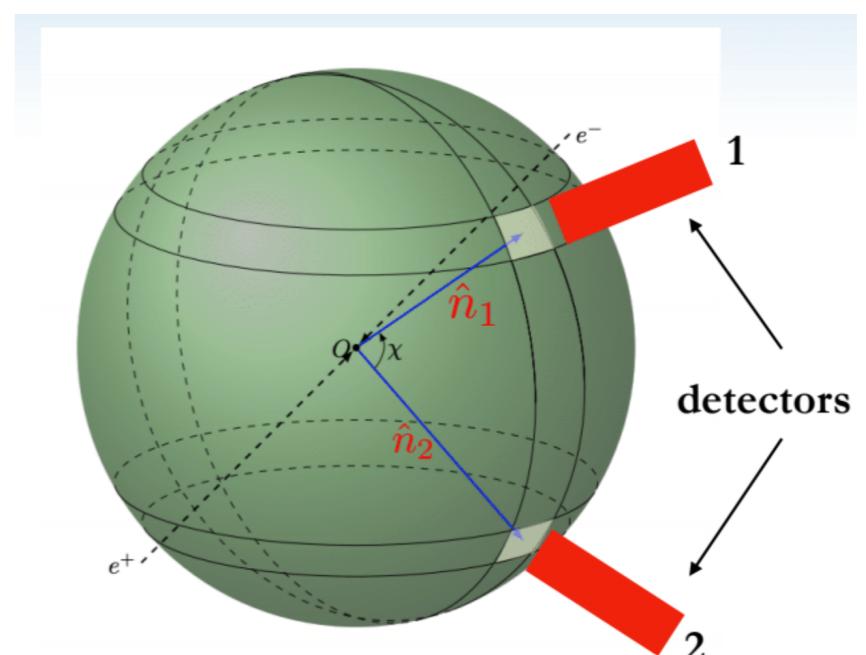
Kyle Devereaux, Wenqing Fan, Weiyao Ke, Kyle Lee and Ian Moult

DIS 2023, 03/30/2023



Energy correlators in e^+e^- and $p+p$ collisions

- ▶ IRC safe, energy weighted cross section
 - ❖ Has been predicted and measured in e^+e^- collider
 - ❖ Used to constrain α_s
- ▶ In the collinear limit, they are jet substructure observables
 - ❖ Perturbative calculation in QCD available
 - ❖ Probing fixed scale with fixed angular distance of the pairs: θ (also denoted as R_L)



Two point energy correlator (EEC)

Step 1. Jet clustering

Step 2. Count number of weighted track pairs with angular distance θ or R_L

weight power

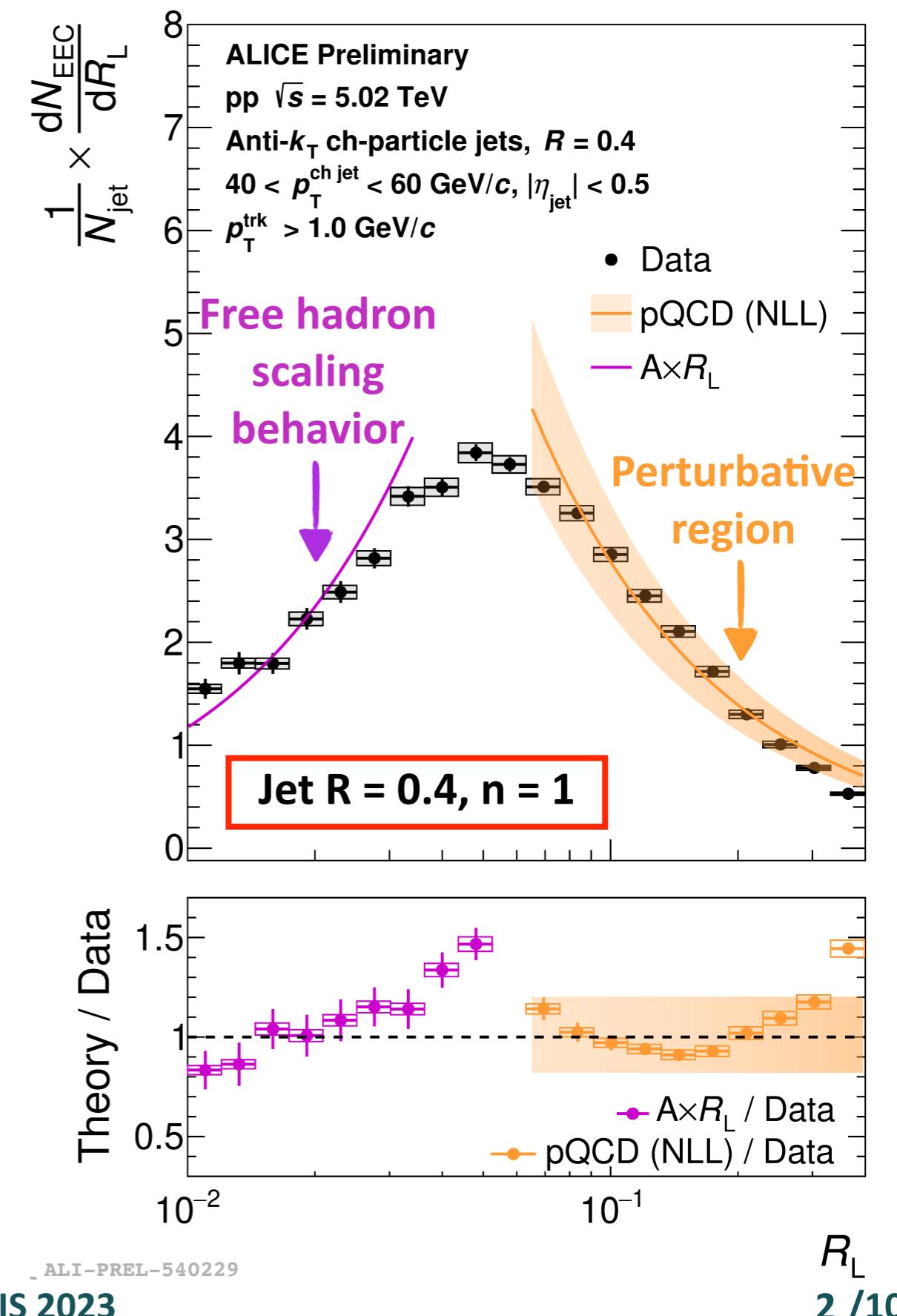
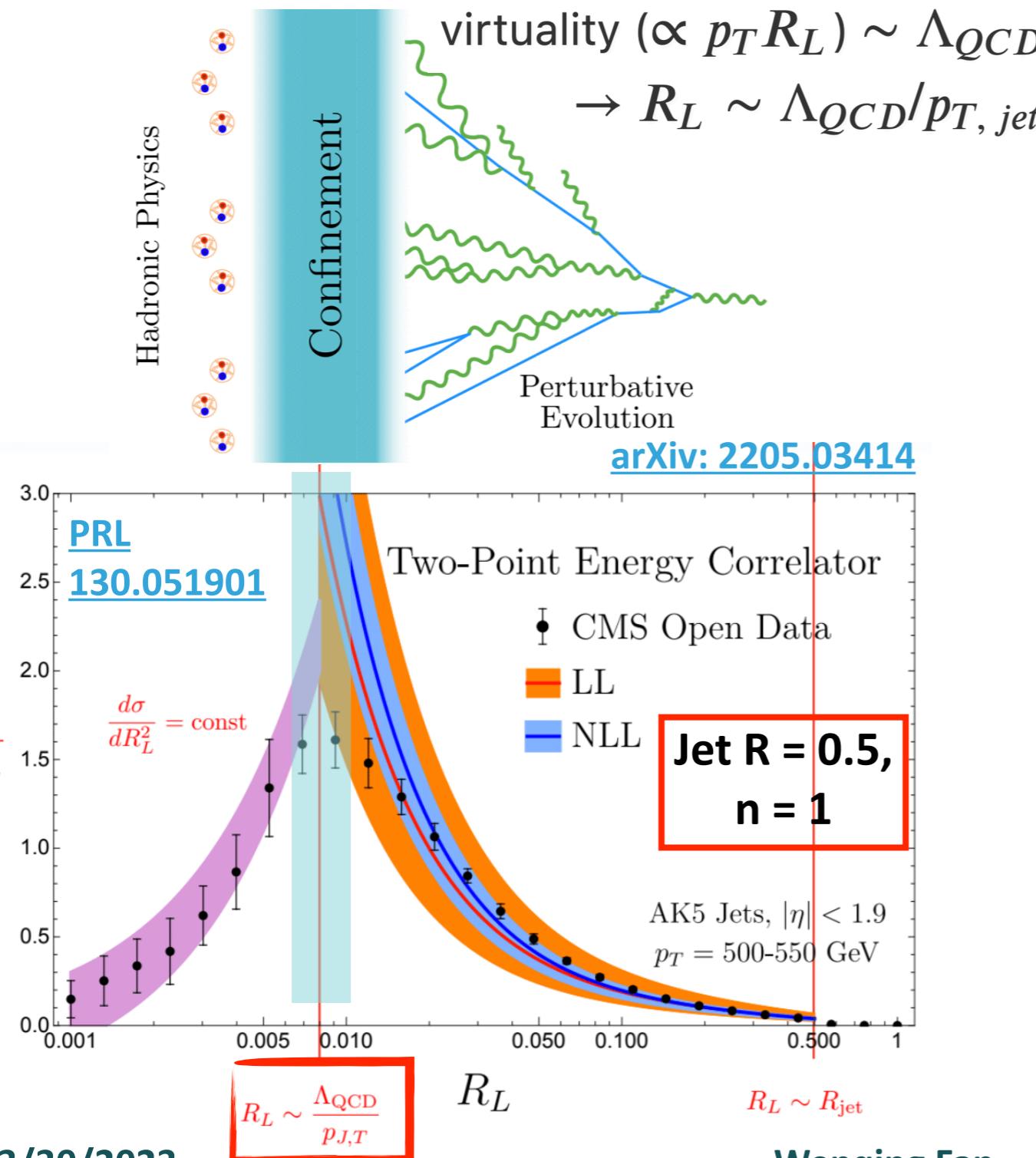
$$\frac{d\sigma_{EEC}}{d\theta} = \sum_{i,j} \int d\sigma(\theta') \frac{p_{T,i}^n p_{T,j}^n}{p_{T,jet}^{2n}} \delta(\theta' - \theta_{ij})$$

$$\text{Angular distance } \theta = \sqrt{\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2}$$

$n \geq 1$ suppress soft background

Clear separation of parton region and hadron region

When the virtuality approaches $\mathcal{O}(\Lambda_{QCD})$, EEC undergo transition into confinement region

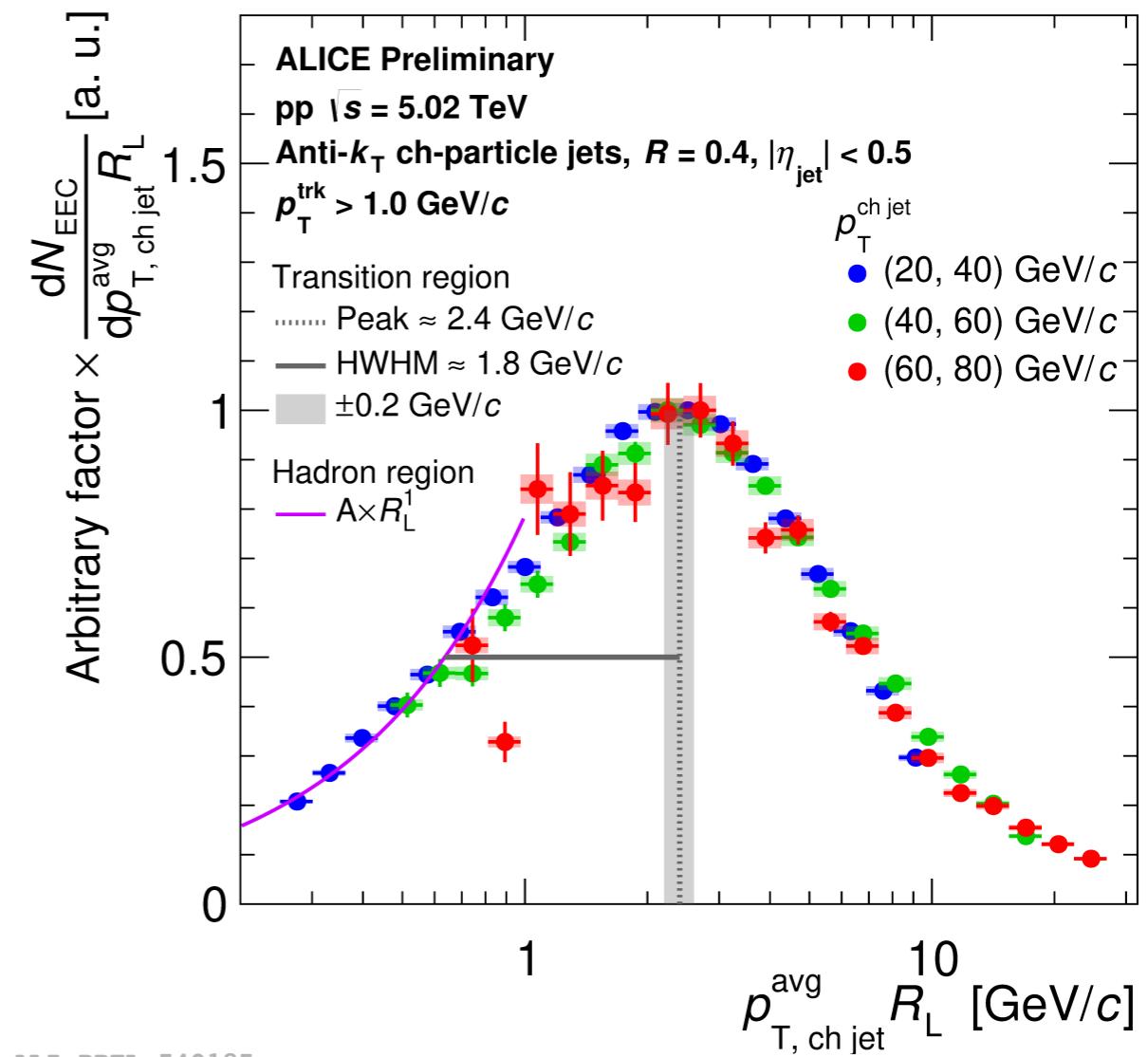
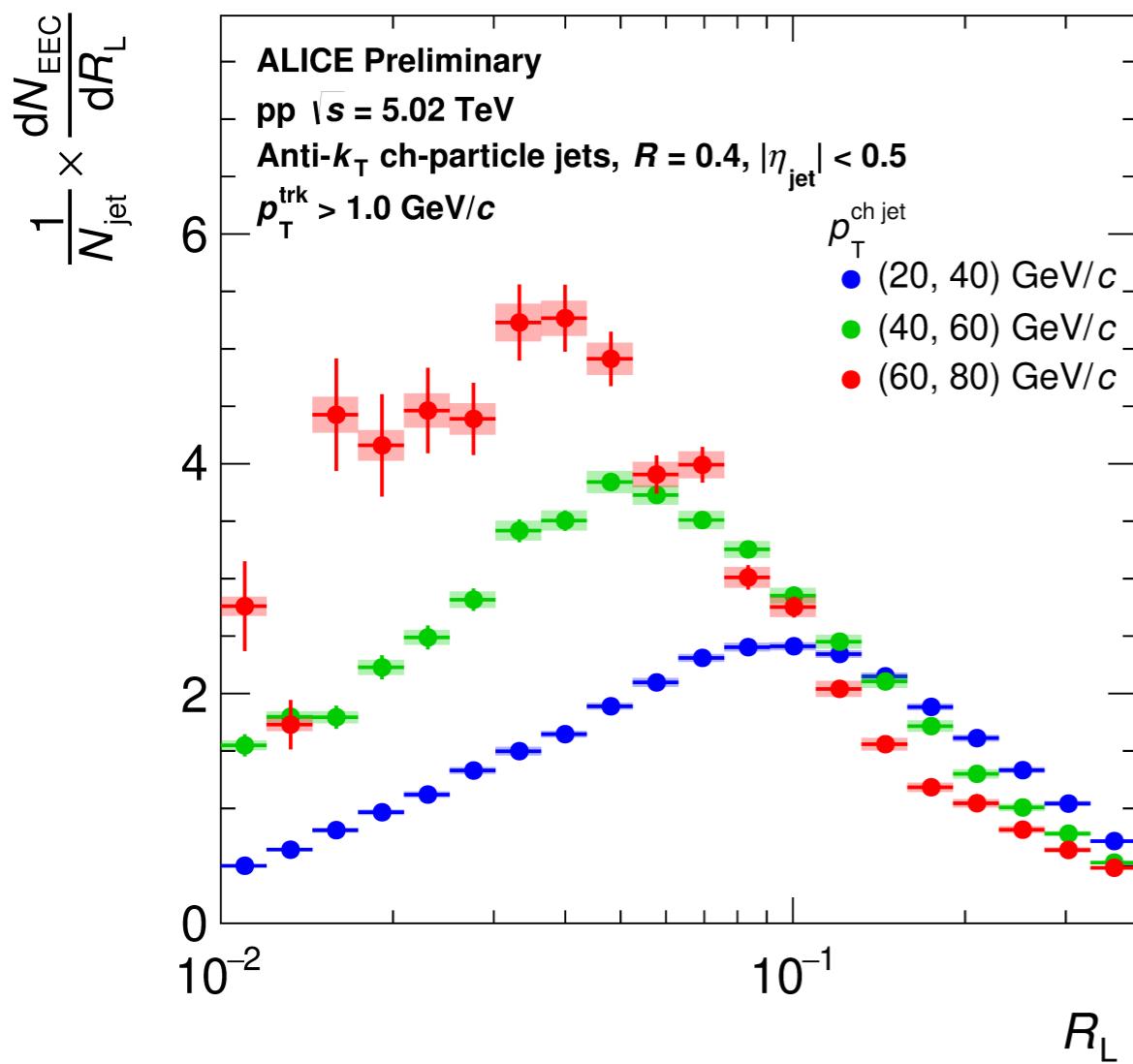
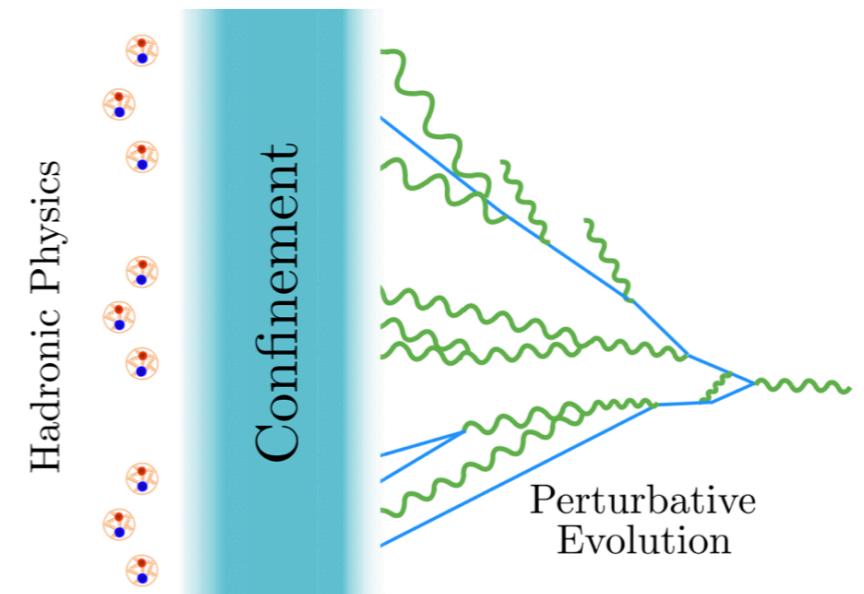


Universal behavior of the transition region

virtuality $\sim p_T R_L$

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

Scaling angle R_L
by jet p_T and
normalize y scale

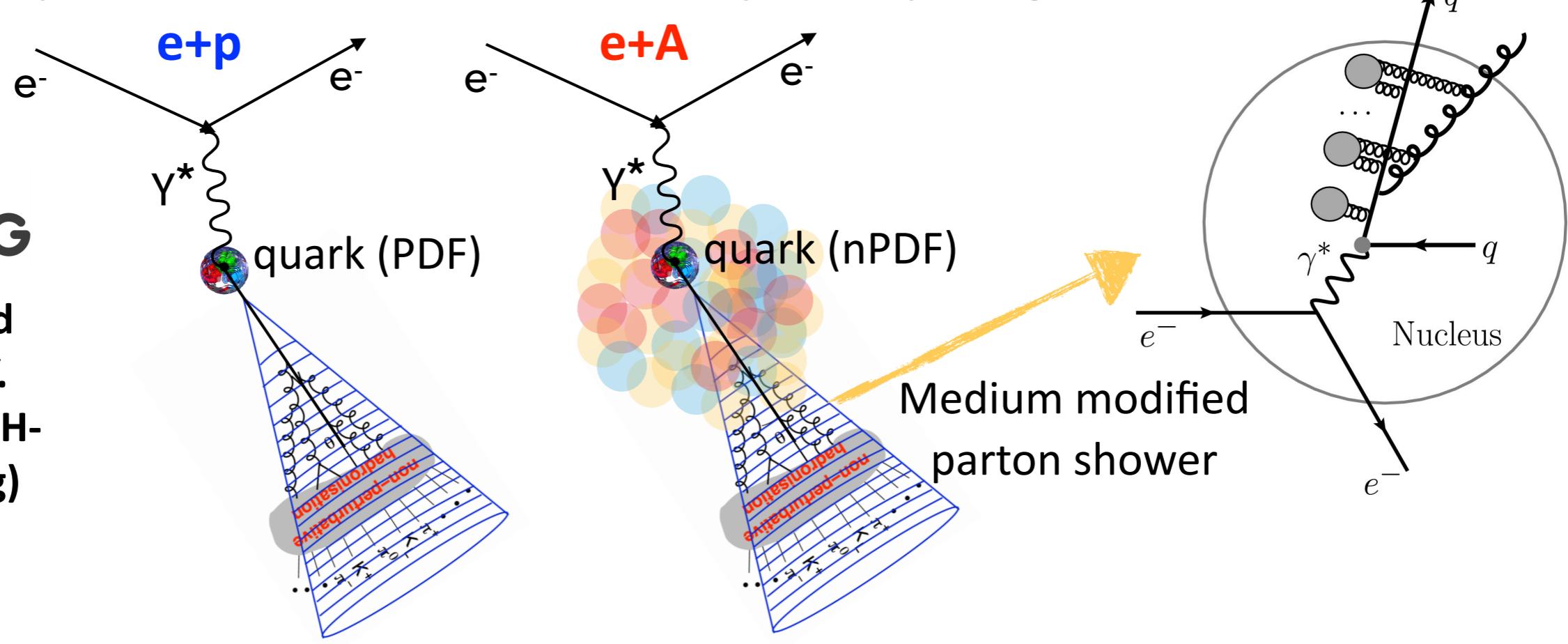


Study e+p and e+A collisions with eHIJING event generator

- ▶ What can we learn from e+p/A collisions?
 - ❖ Will we see the scale of hadronization in e+p?
 - ❖ How will the interaction between jets and the nuclear medium modify the energy correlator distributions? Will we observe the scale of nuclear size?
- ▶ eHIJING: developed to study nuclear-modified jet evolution in DIS events
 - ❖ e+p: equivalent to Pythia 8
 - ❖ e+A: initial DIS process via Pythia 8 + medium modified parton shower (p_T broadening via multiple collisions and medium induced parton splitting)



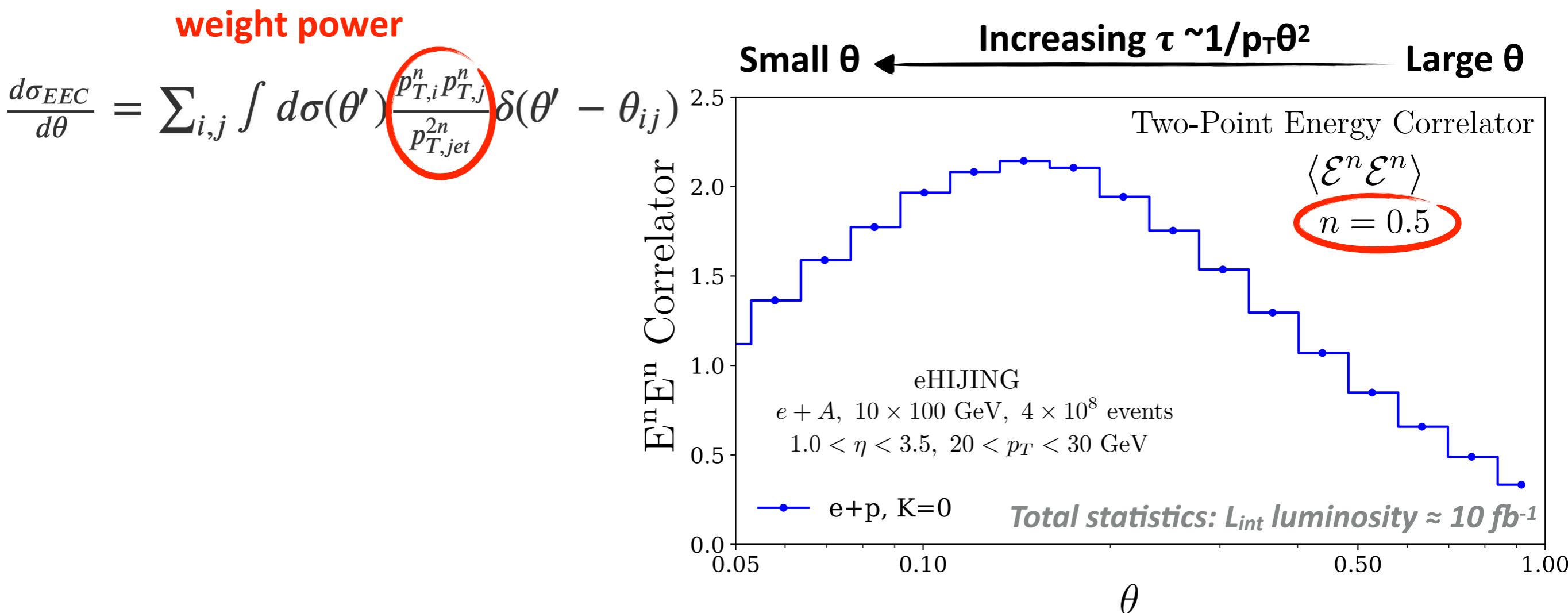
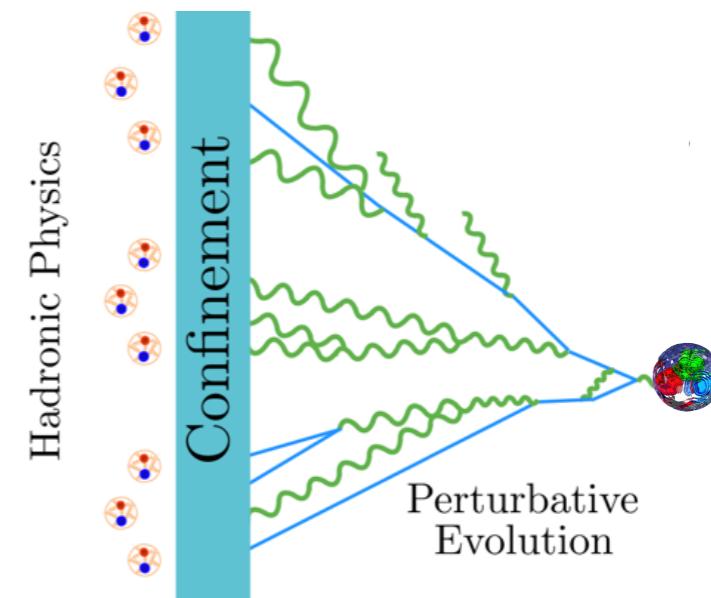
To be published
soon! (W. Ke, Y.
He, X-N Wang, H-
X Xing, Y Zhang)



e+p baseline: clear separation of parton and hadron region

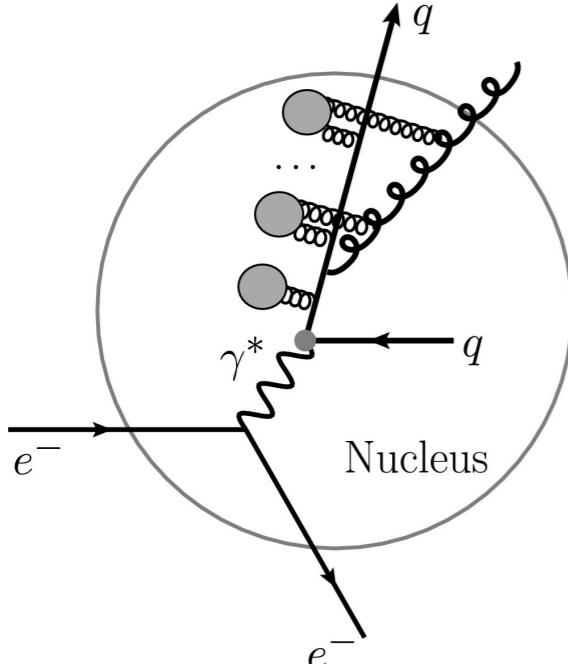
- Cleaner environment in e+p/A collisions and wide detector acceptance

- ❖ Less background compared to p+p (pileup, MPI)
- ❖ Use larger jet radius $R = 1.0$
- ❖ Use smaller energy weight power $n = 0.5$

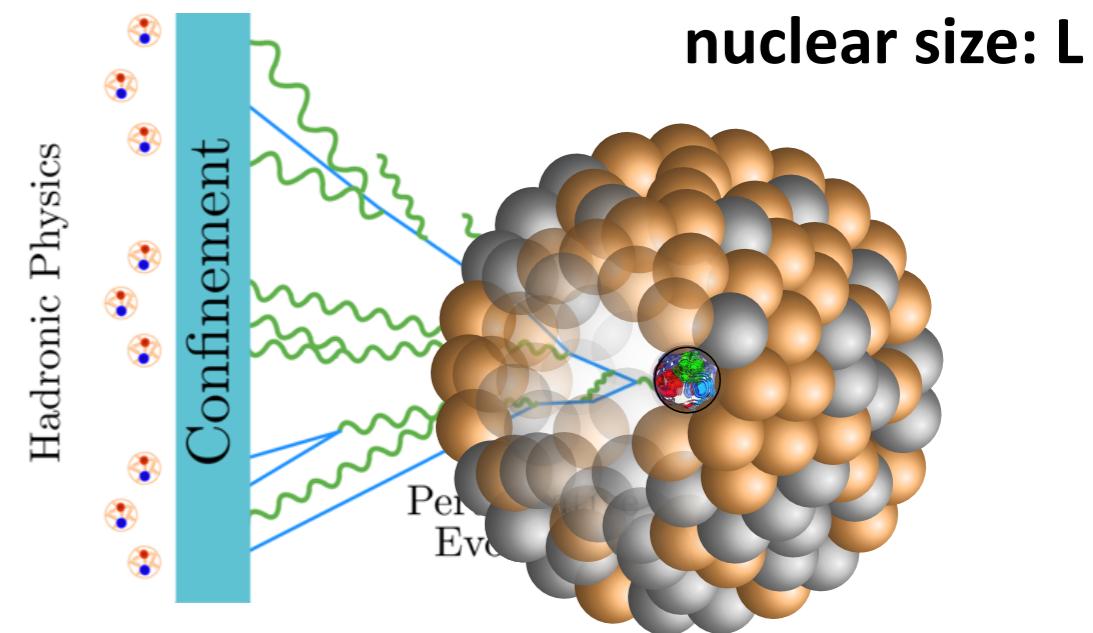


e+A: modification at large angle region

Figure from PLB.2021.136261



Induced parton splitting + collisional broadening of the pair angle

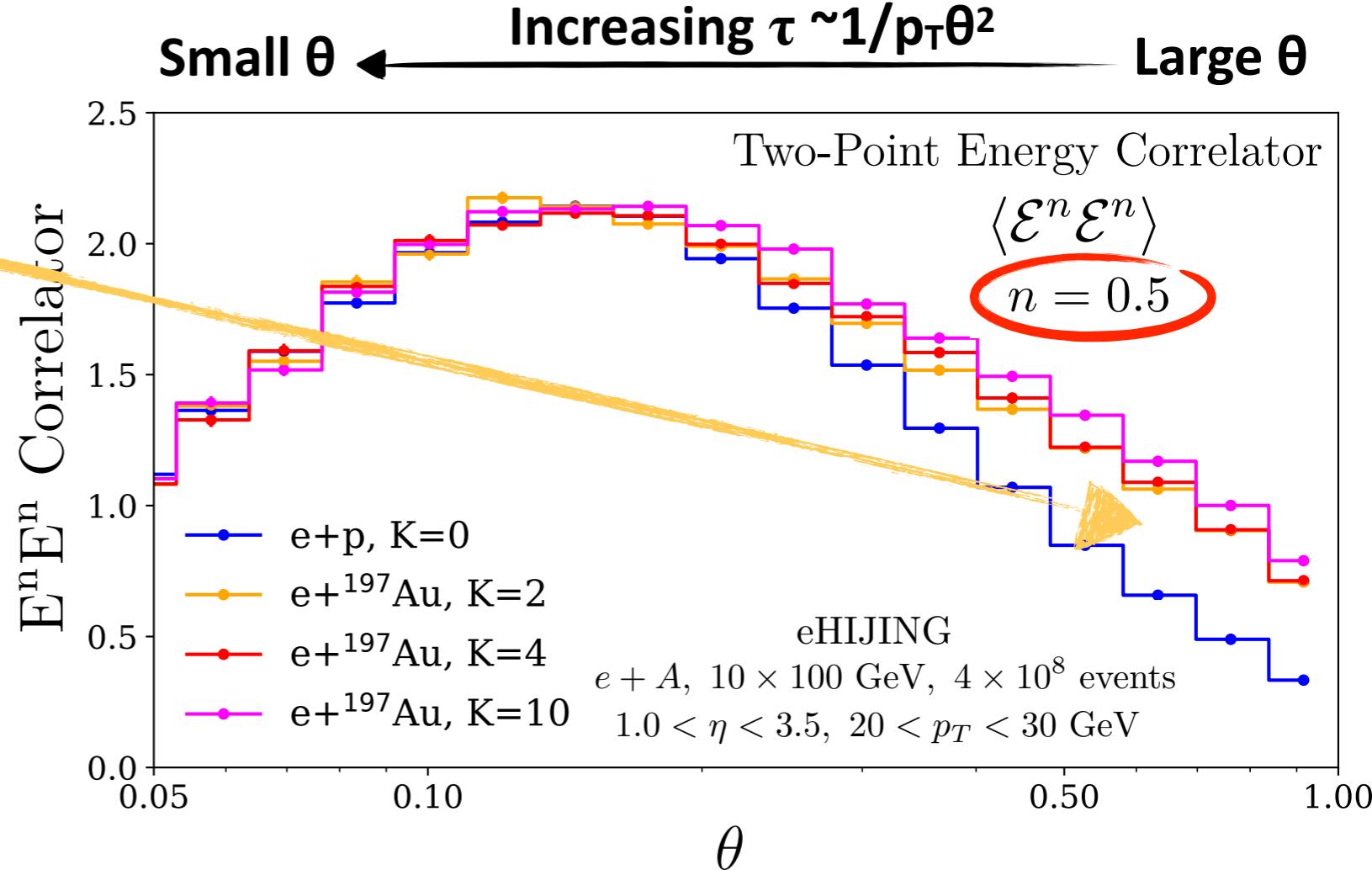


Modification at large θ region

→ Early splitting inside the nucleus modified by the nuclear medium

More enhancement with larger qhat

$K = 2$ to $10 \rightarrow q\hat{=} = 0.063$ to $0.172 \text{ GeV}^2/\text{fm}$ at $x_B = 0.1$ and $Q^2 = 1 \text{ GeV}^2$ (default tuning $K=4$ benches mark to HERMES data)

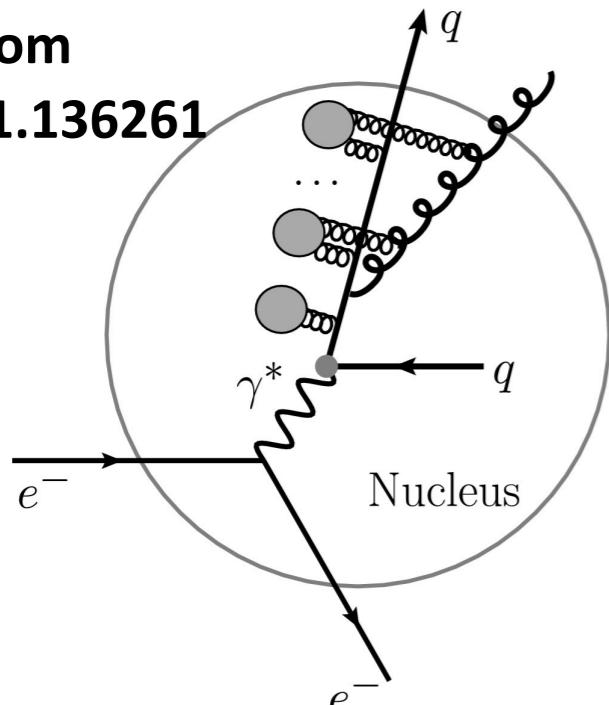


Larger modification with smaller energy weight

$n < 1$ enhance medium induced soft radiation

Figure from

PLB.2021.136261



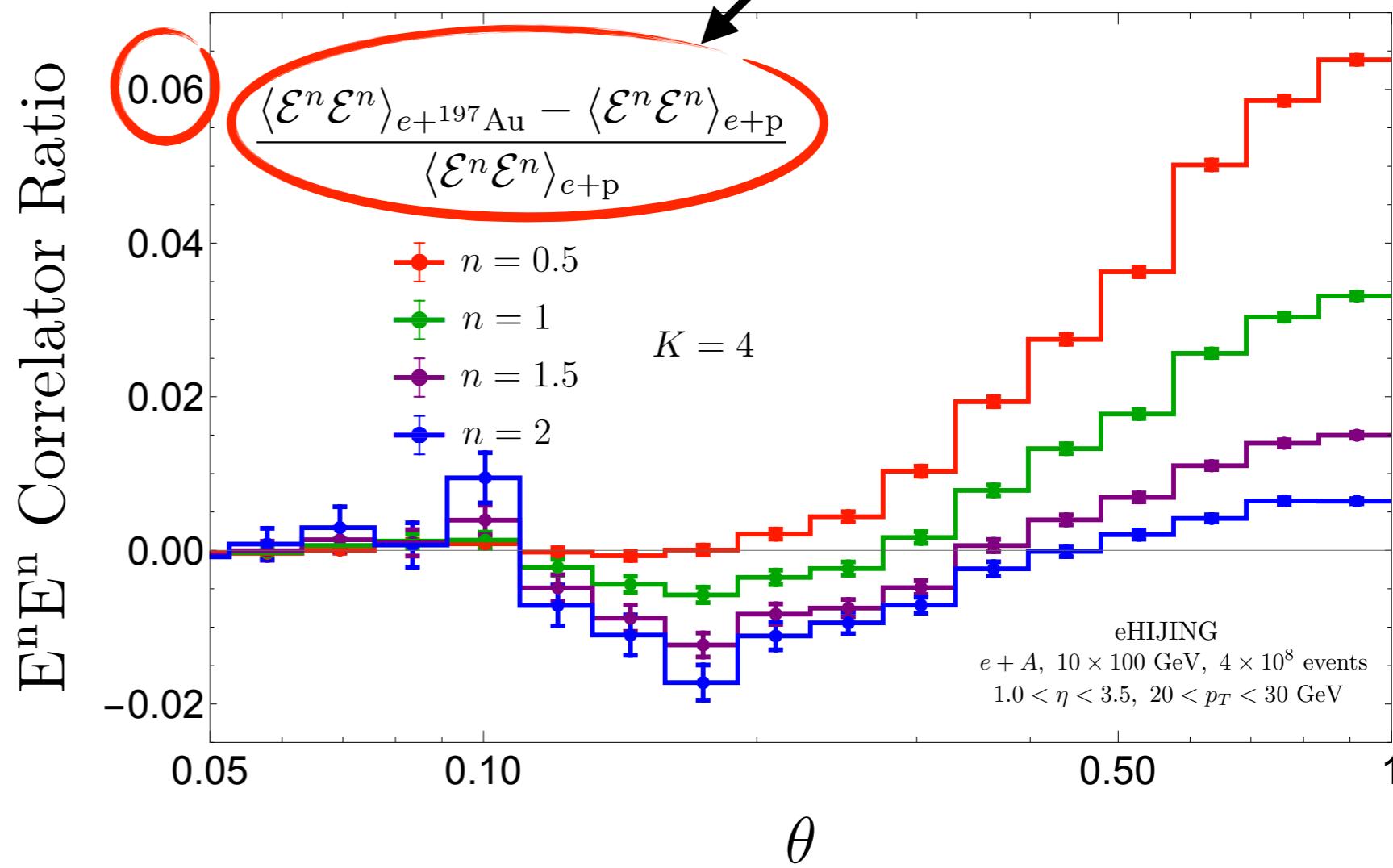
Most significant enhancement at very large angle ($0.5 \sim 1$)

Energy weight dependence should be sensitive to the shape of the in-medium splitting

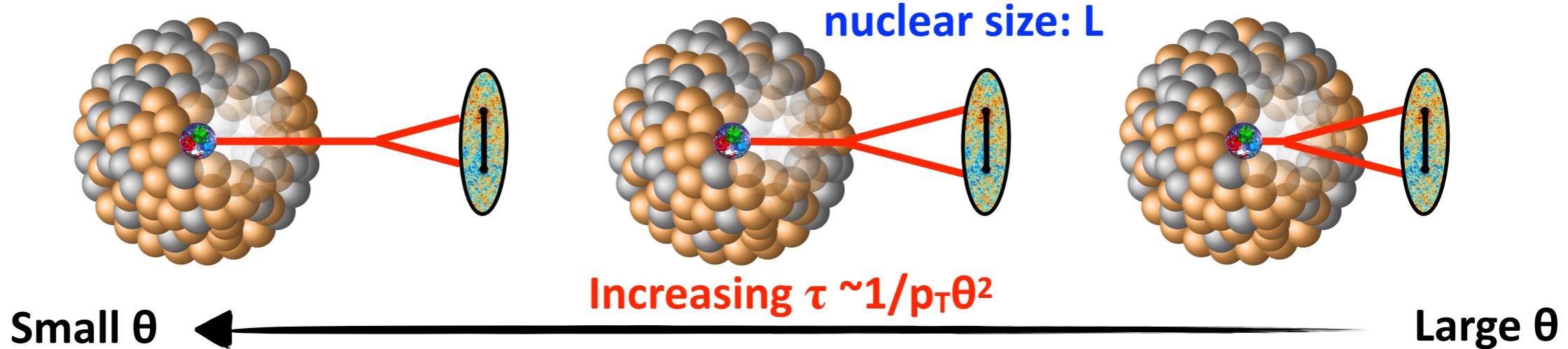
energy weight power

$$\frac{d\sigma_{EEC}}{d\theta} = \sum_{i,j} \int d\sigma(\theta') \frac{p_{T,i}^n p_{T,j}^n}{p_{T,jet}^{2n}} \delta(\theta' - \theta_{ij})$$

Focusing on modification: $(e + Au - e + p) / e + p$



Scaling behavior of onset angle θ_L with jet p_T



Onset of modification

expected at $\tau \sim L \rightarrow$

$$\theta_L \sim (p_T L)^{-1/2}$$

Similar onset position

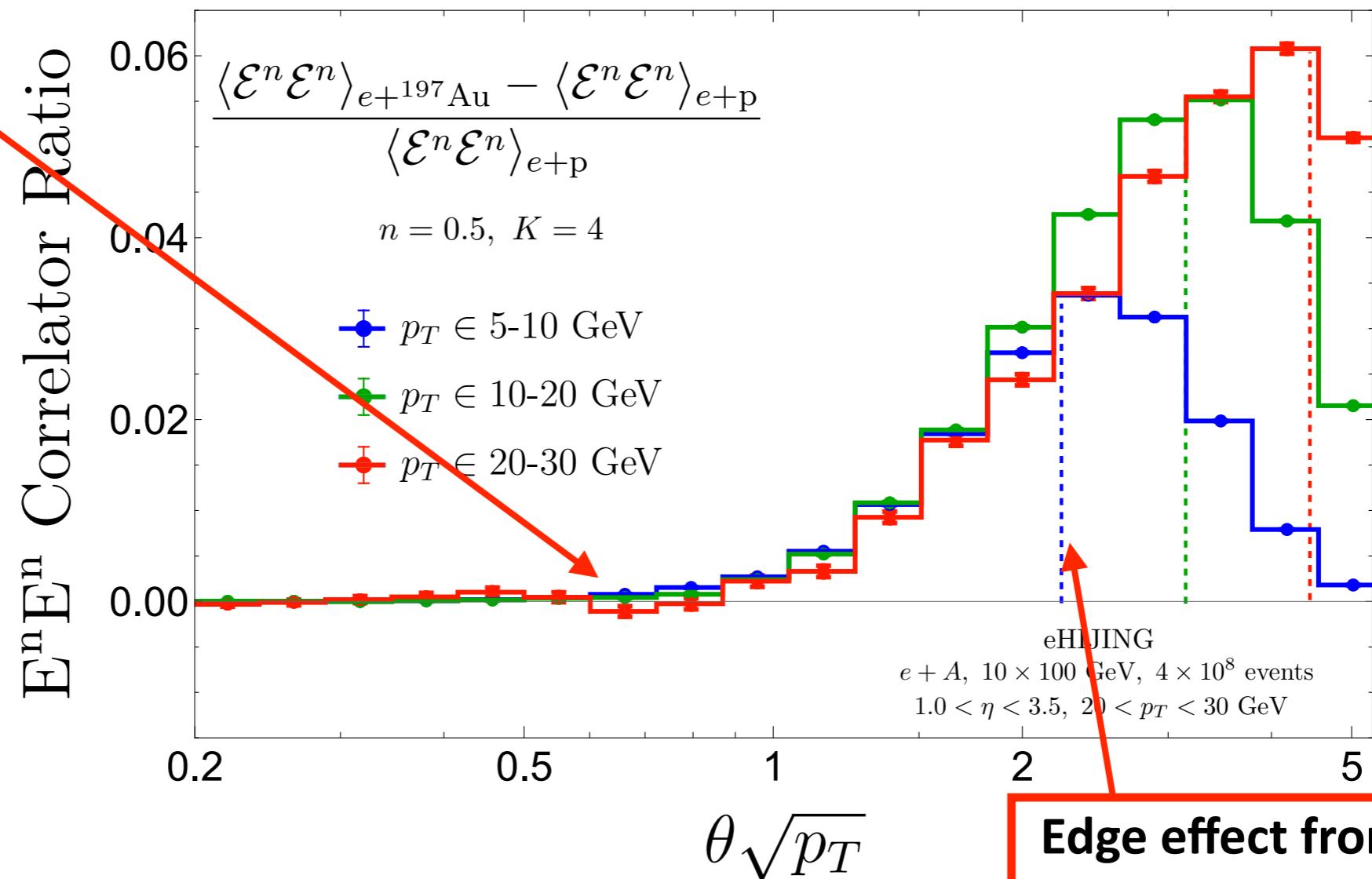
for different jet p_T

after scaling θ by $p_T^{1/2}$

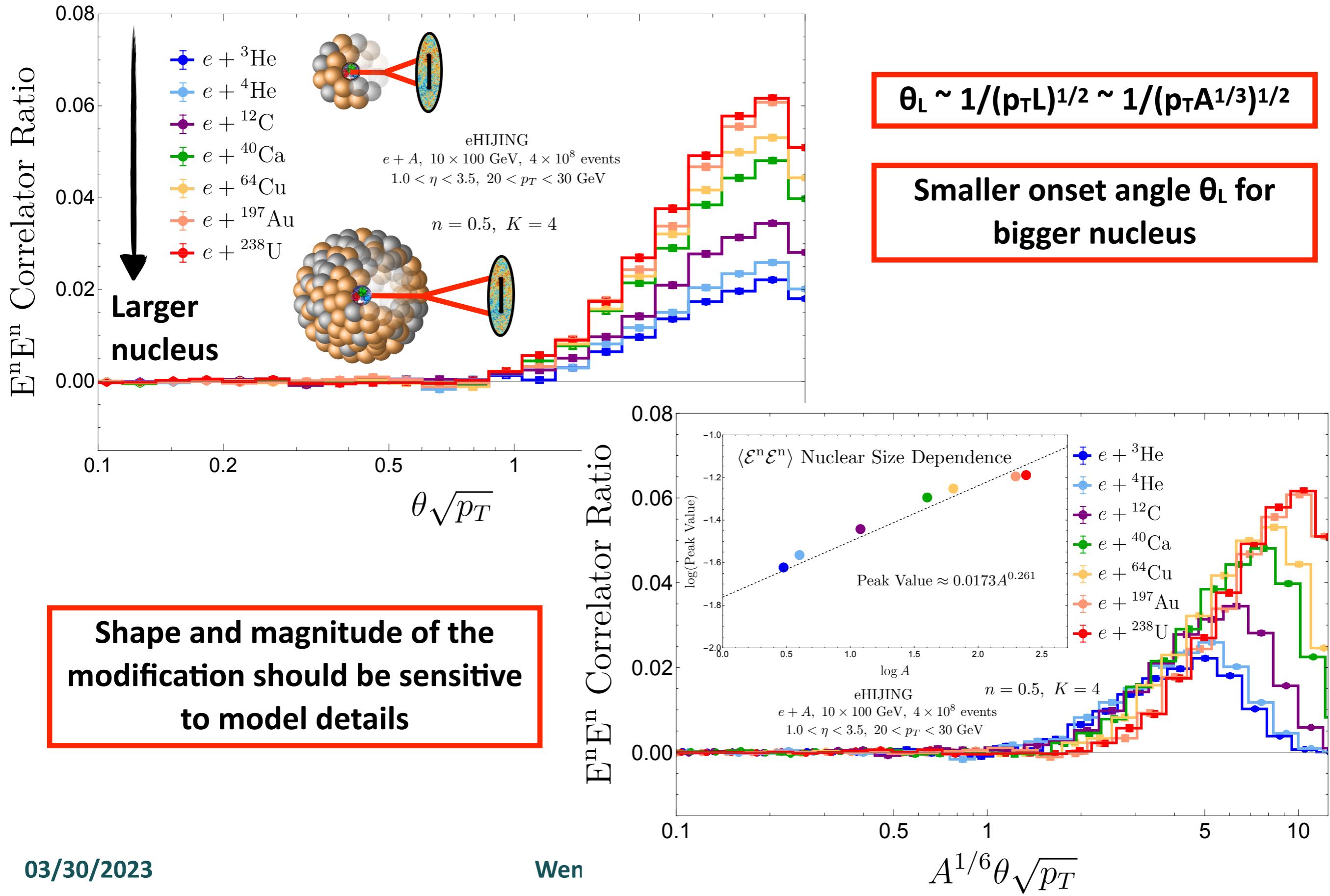
Peak width further

broadened by

collisional effect



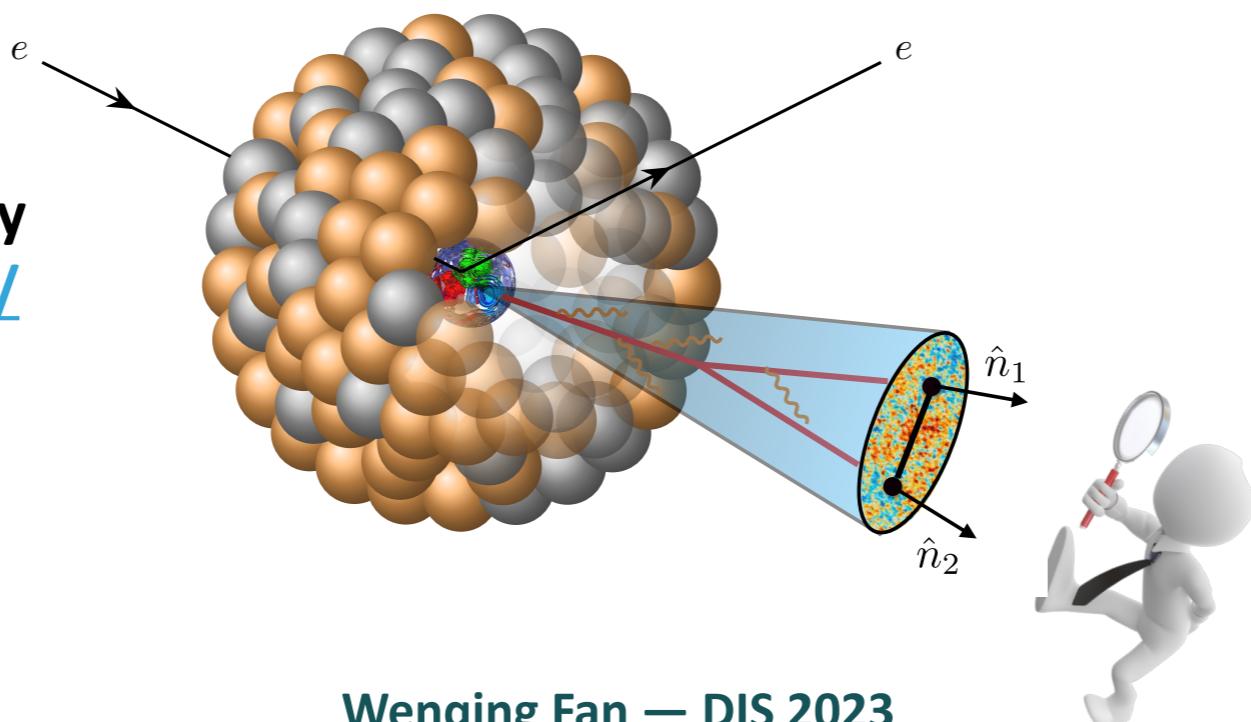
Scaling behavior of onset angle θ_L with nucleus size



Summary

- ▶ Energy correlators can probe the dynamics of jet at varying scales
 - ❖ Clear separation between hadronic, partonic, and transition (hadronization) regions observed in both p+p data and e+p simulation
- ▶ New scales of nuclear size appears in e+A collisions: $\theta_L \sim 1/(p_T L)^{1/2} \sim 1/(\sqrt{s} p_T A^{1/6})$
 - ❖ Similar observation (scale of the QGP medium) in heavy ion collision calculation (arXiv: 2209.11236)
 - ❖ Observe medium modification at large angle region due to medium modified parton shower → size and shape of the modification can be sensitive to model details
 - ❖ At EIC, we can study the jet-medium interaction as function of nuclear size
 - ❖ Can also be used to study if hadronization is modified inside cold nuclear matter

More details of this study
in: <https://arxiv.org/pdf/2303.08143.pdf>



Stay tuned for more interesting studies with energy correlators in e+p, e+A, p+p, p+A and A+A collisions!

[Bianka Mecaj's talk](#)
[Fanyi Zhao's talk](#)

Backup



Electron-Ion Collider: a precision laboratory for QCD

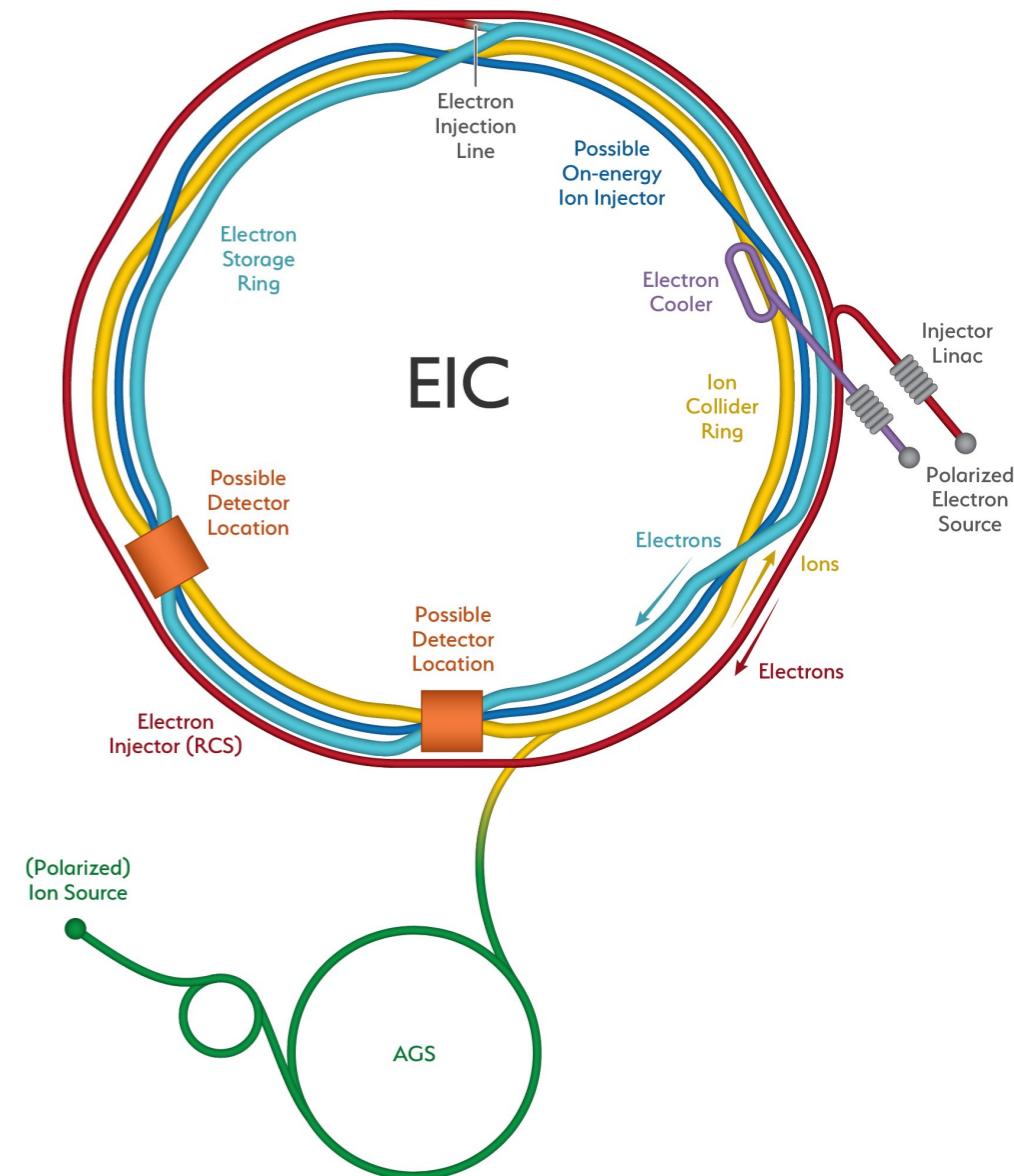
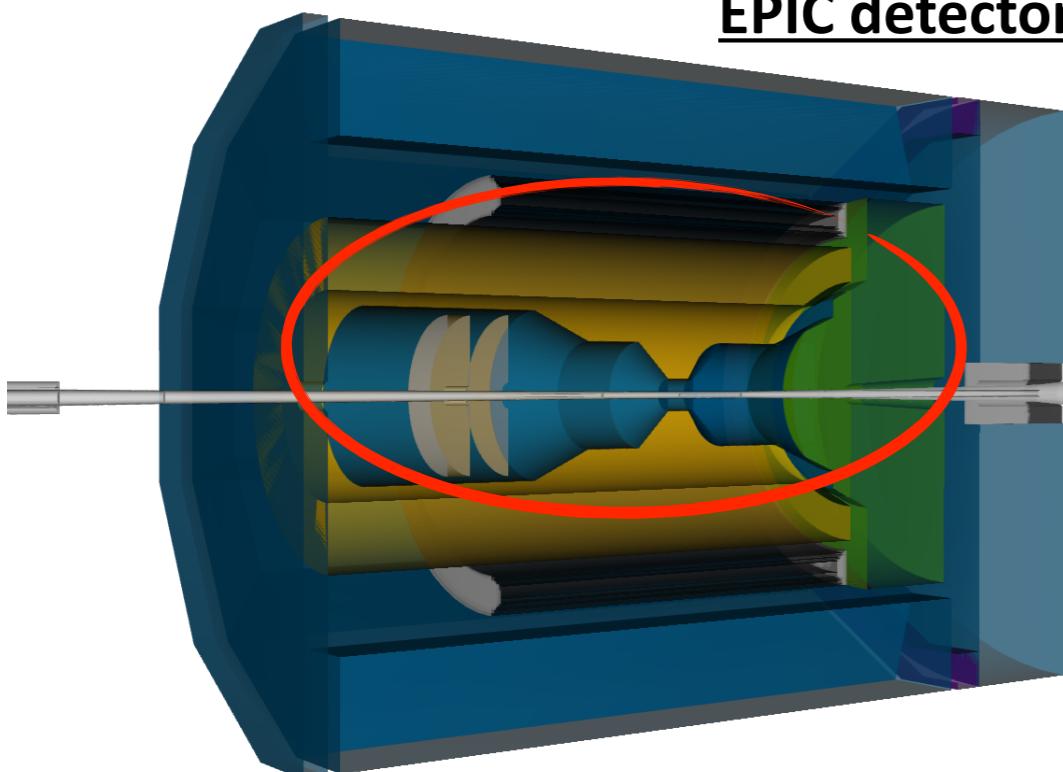
► Versatile and high-luminosity

- ❖ \sqrt{s} : 20 – 140 GeV
- ❖ Wide kinematic coverage
- ❖ Ion beam: Proton to Uranium
- ❖ $L_{max} = 10^{34} \text{ cm}^{-2} \text{s}^{-1}$

EIC Yellow Report

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

EPIC detector



- Hermetic detector with wide coverage of
 - ❖ High precision tracking/vertexing system
 - ❖ Particle identification, Electromagnetic calorimeter, Hadronic calorimeter

[Overview talk by Richard Milner \(WG6 Tuesday 9 am\)](#)

Energy-energy correlator (EEC) at e^+e^- collider

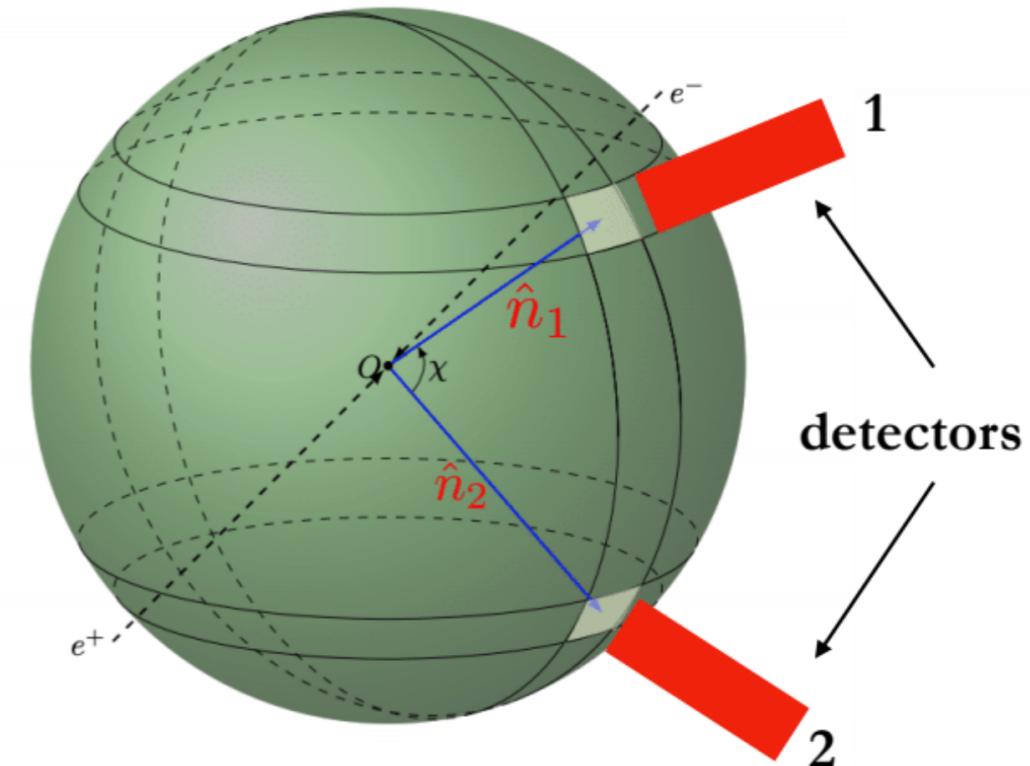
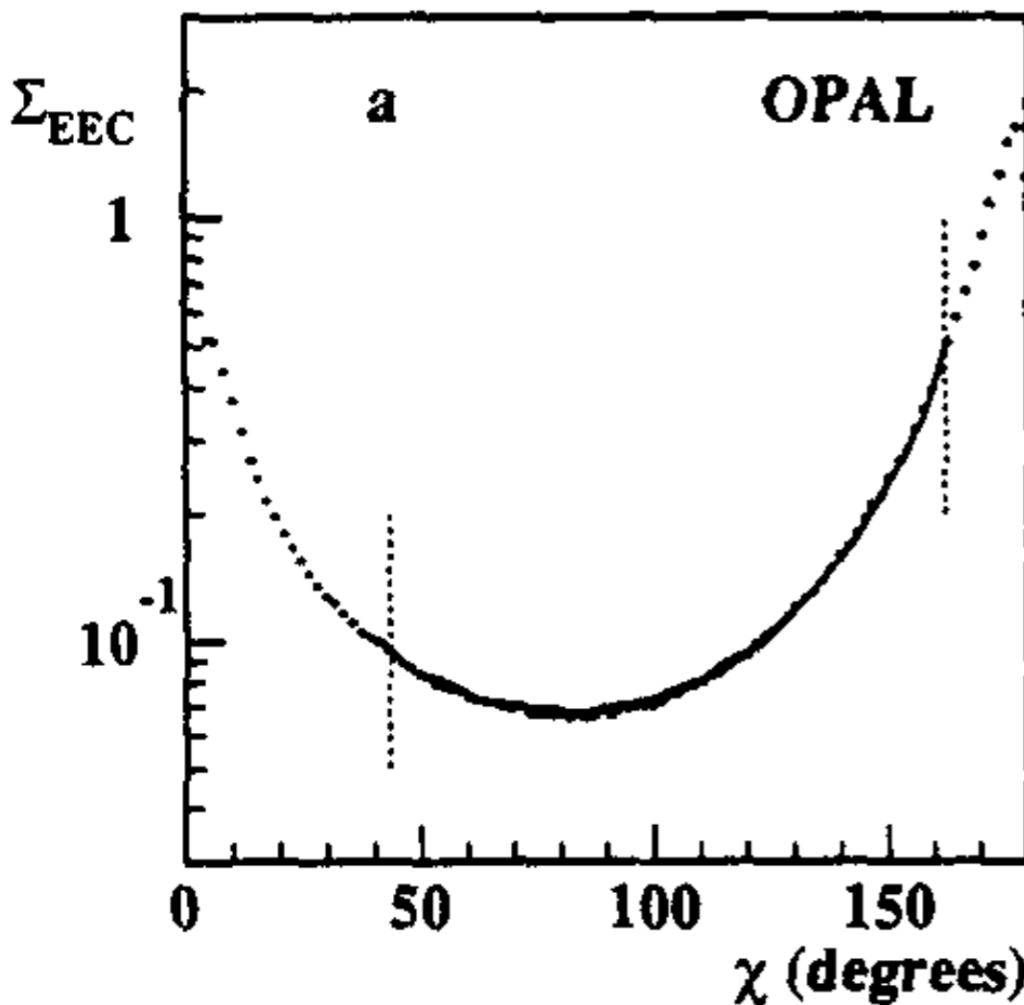
► IRC safe, energy weighted cross section

- ❖ Has been predicted and measured in e^+e^- collider
- ❖ Used to constrain α_s

$$\frac{d\sigma_{EEC}}{dz} = \sum_{i,j} \int d\sigma(z) \frac{E_i E_j}{Q^2} \delta(z - \frac{1-\cos\chi_{ij}}{2})$$

where $z = (1 - \cos\chi)/2$

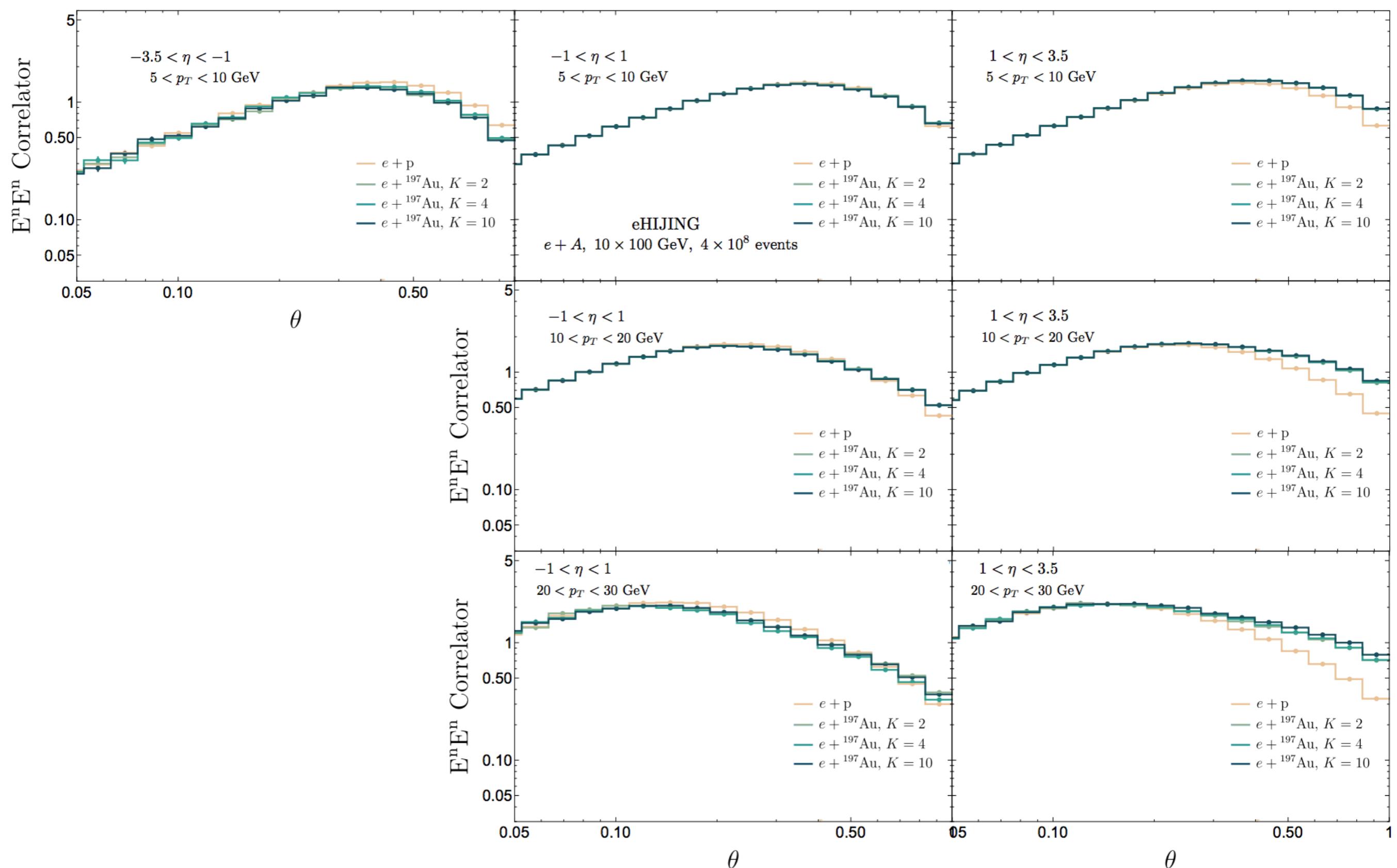
[Phys. Lett. B 276, 547–564](#)



$$\Sigma_{EEC}(\chi) = \frac{1}{\Delta\chi \cdot N} \sum_N \int_{\chi - \frac{1}{2}\Delta\chi}^{\chi + \frac{1}{2}\Delta\chi} \sum_{i,j} \frac{E_i E_j}{E_{vis}^2} \cdot \delta(\chi' - \chi_{ij}) d\chi', \quad (4)$$

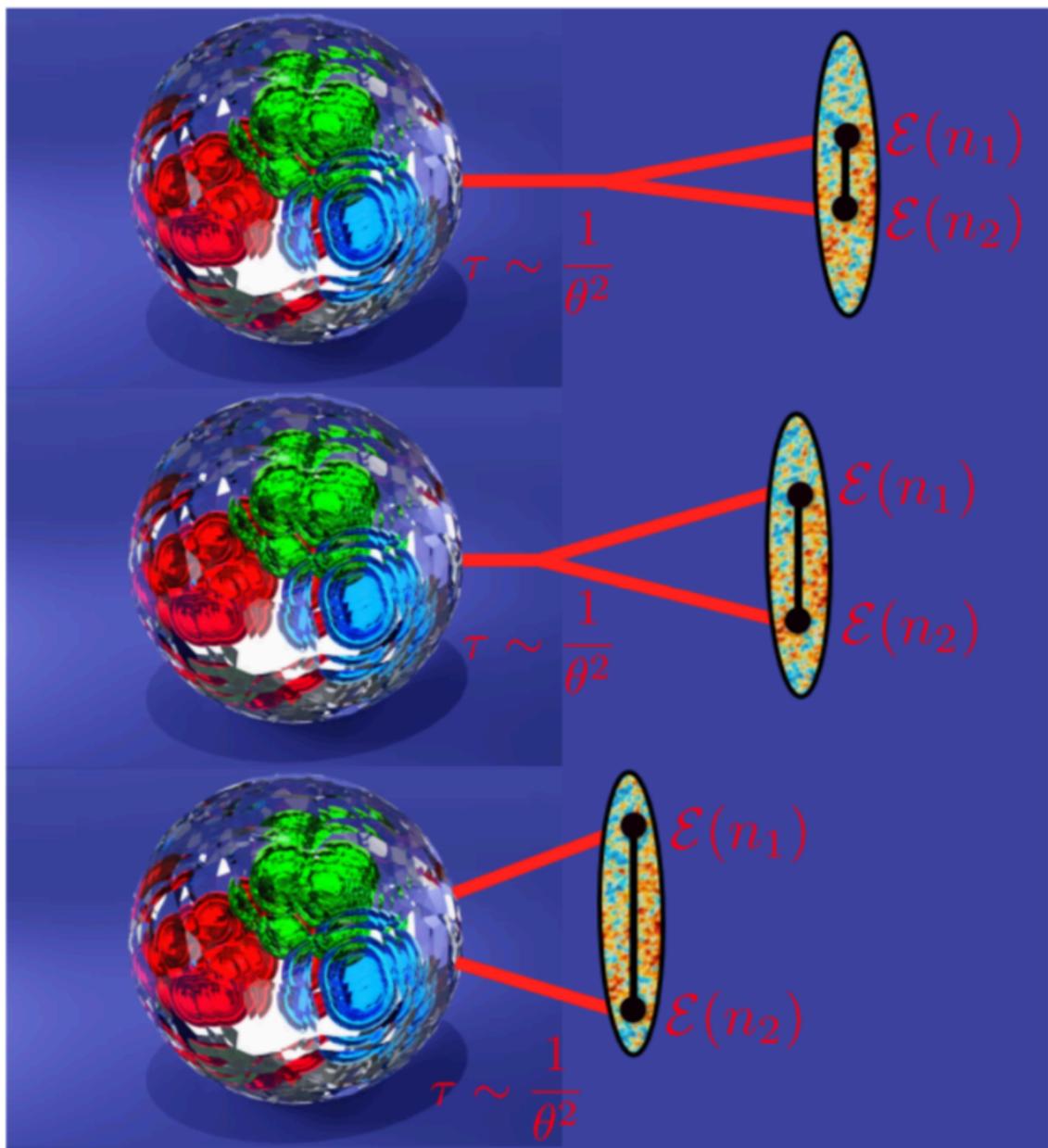
where E_i and E_j are the energies of particles i and j , E_{vis} is the sum over the energies of all particles in the event, $\Delta\chi$ is the angular bin width and N is the total number of events. The normalization ensures that the integral of $\Sigma_{EEC}(\chi)$ from $\chi = 0^\circ$ to 180° is unity.

Jet p_T and η dependence

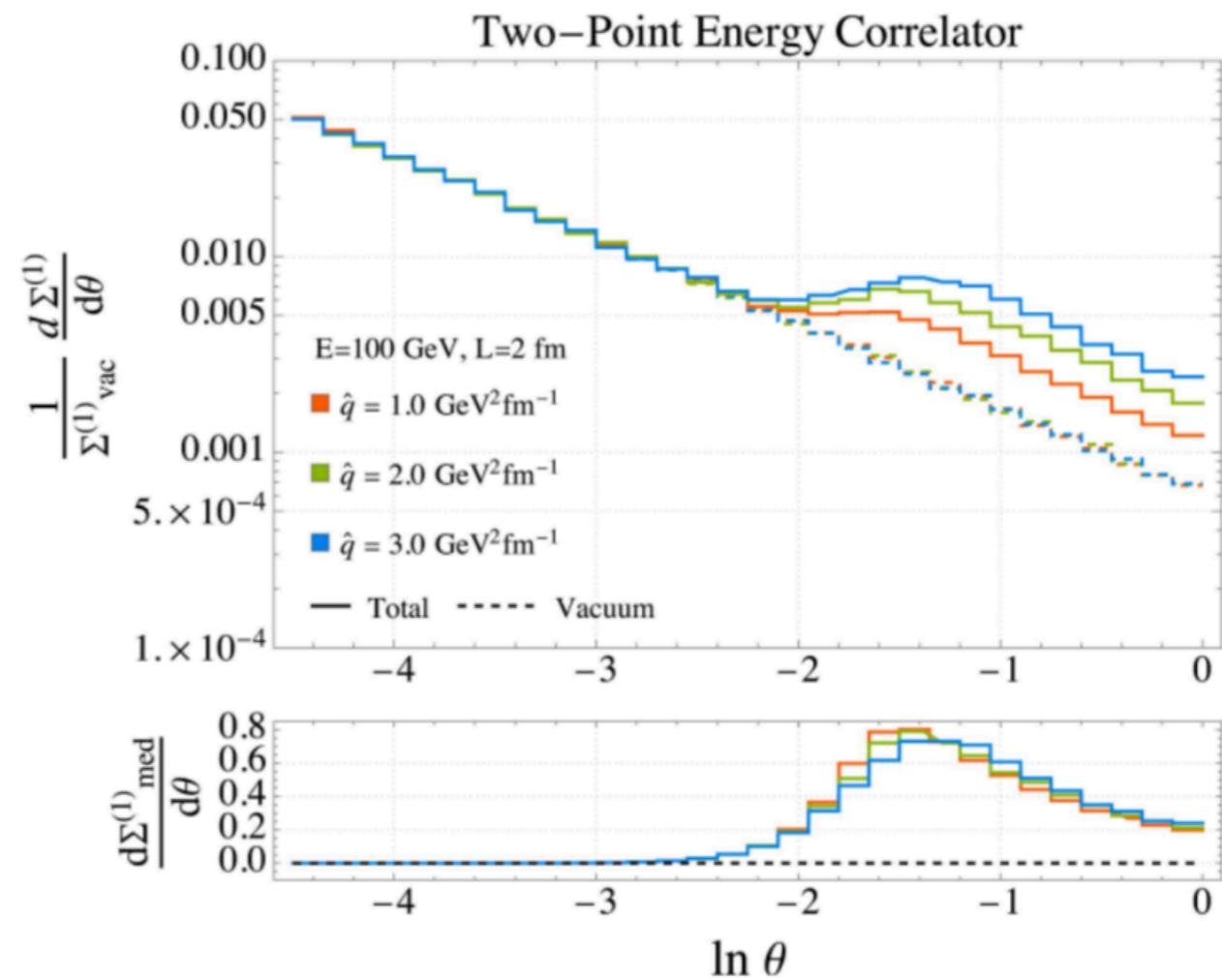


Using EEC to probe QGP

arXiv: 2209.11236



Increasing θ

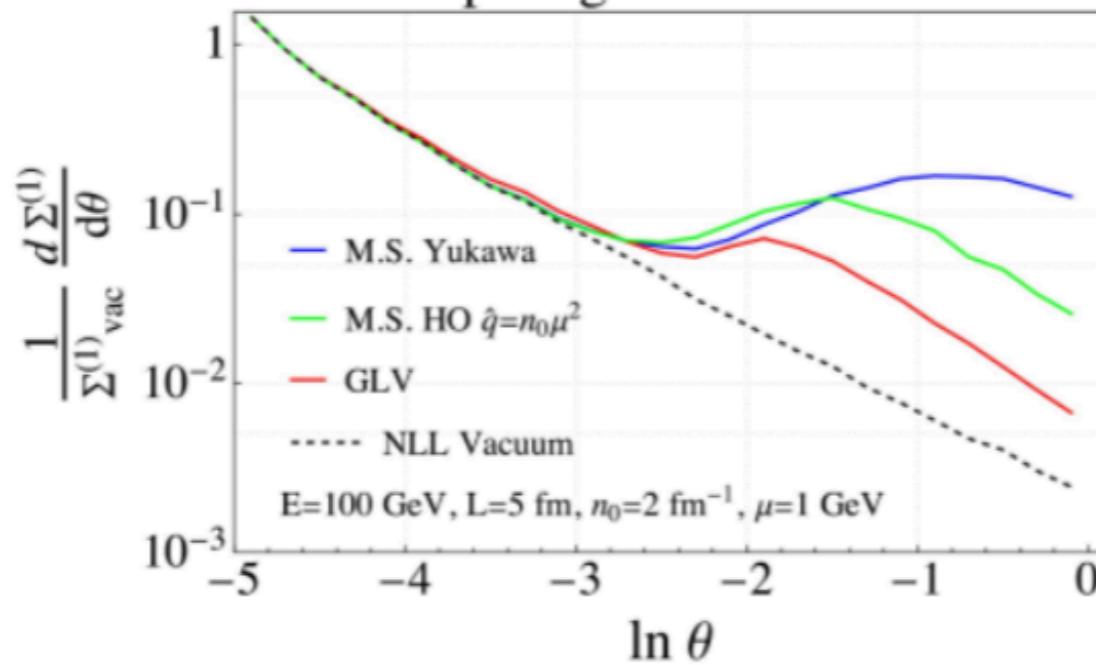


Increasing θ

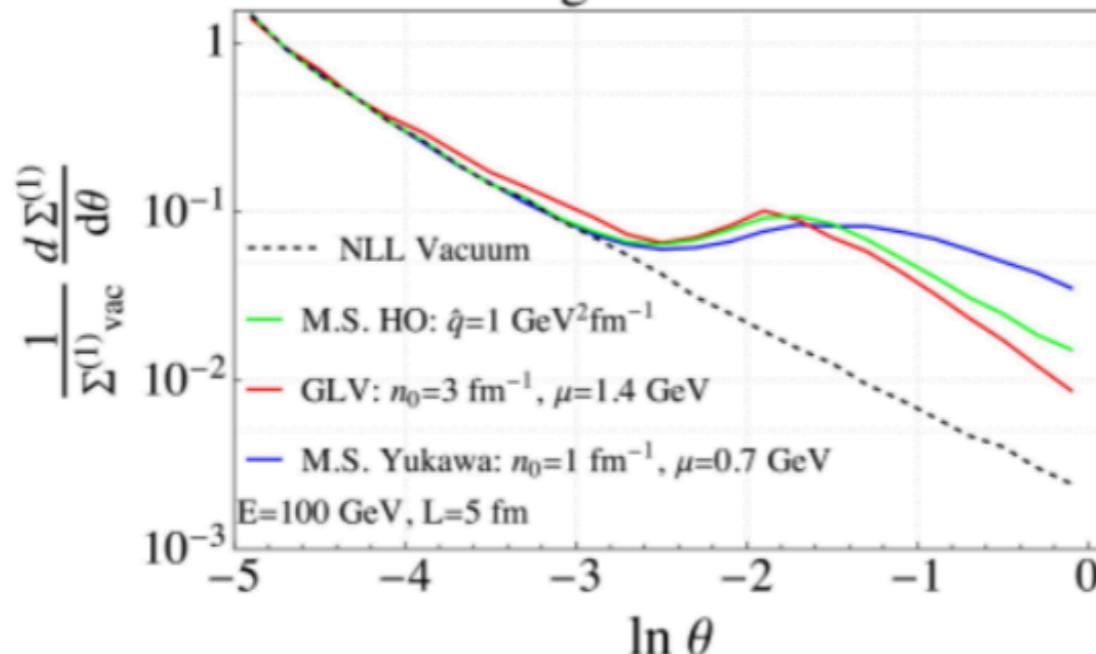
Using EEC to probe QGP

[arXiv: 2303.03413](https://arxiv.org/abs/2303.03413)

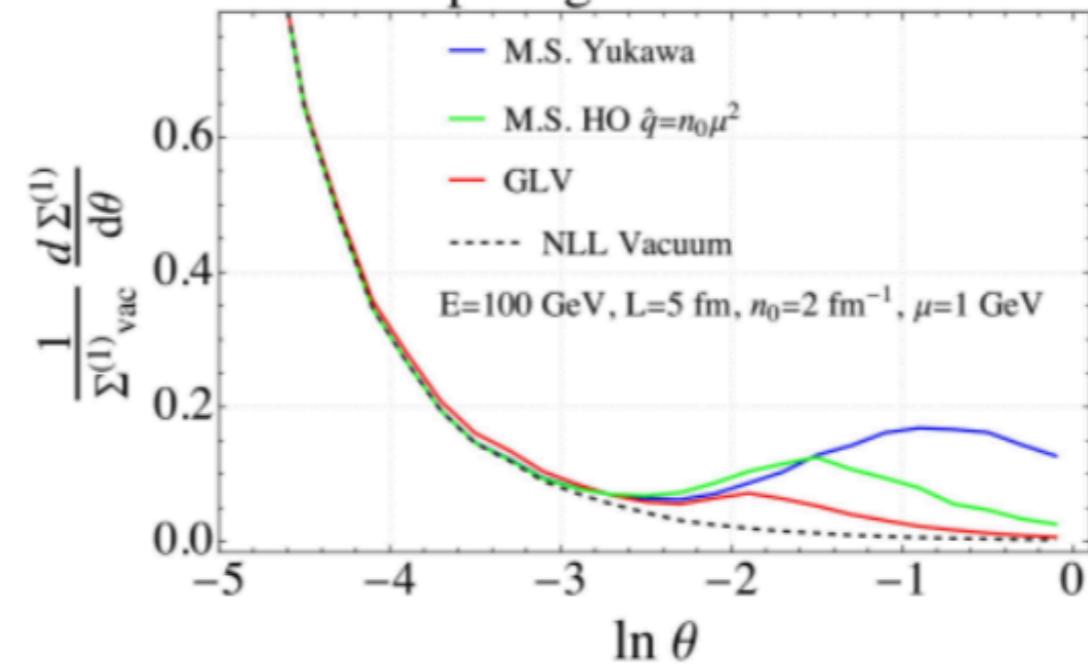
Two-Point Energy Correlator
Comparing Medium Models



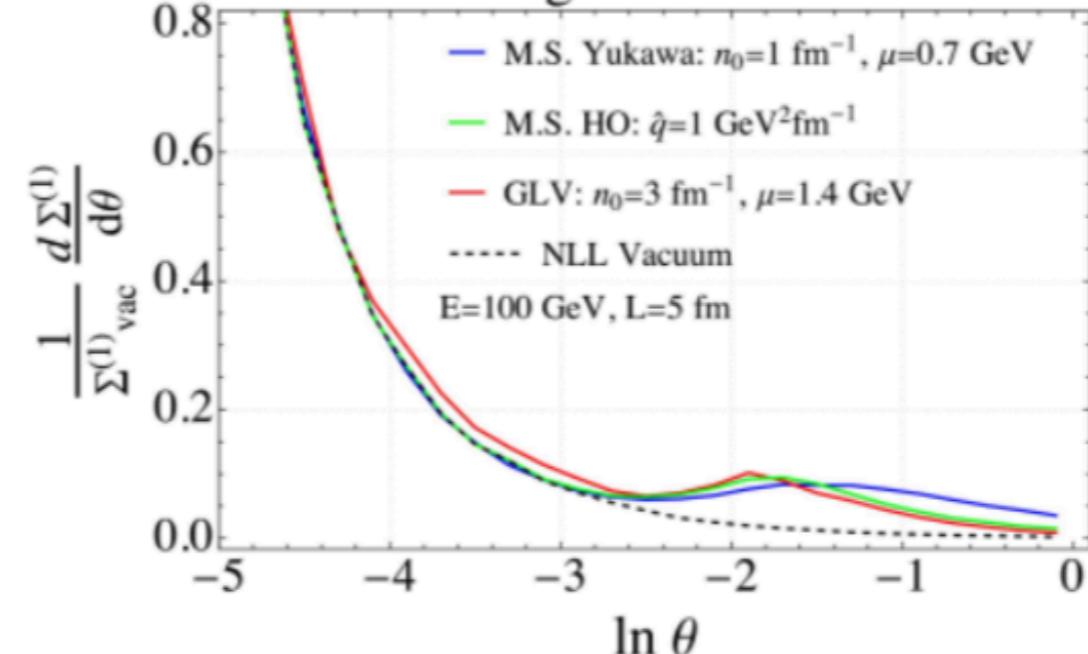
Two-Point Energy Correlator
Matching Medium Models



Two-Point Energy Correlator
Comparing Medium Models



Two-Point Energy Correlator
Matching Medium Models

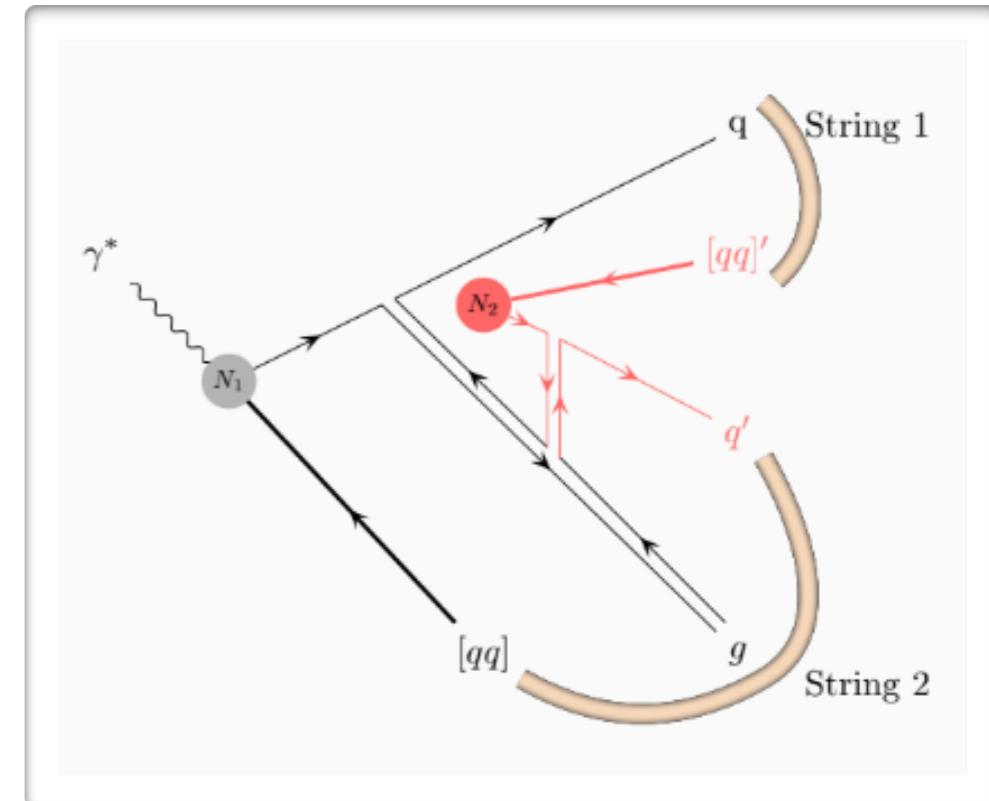


e+A events with eHIJING

- ▶ eHIJING (electron-Heavy-Ion Jet Interaction Generator): developed to study nuclear-modified jet evolution in DIS events

Figure credit: Weiyao Ke

- ❖ Initial hard DIS process via Pythia 8
- ❖ EPPS16 nPDF input: isospin, EMC, (anti-)shadowing effects
- ❖ Multiple qA, gA collisions + nucleus geometry (round with size $\sim r_0 A^{1/3}$)
- ❖ Medium modified parton shower: p_T broadening via multiple collisions with small x gluons and medium induced parton splitting
- ❖ Medium modified hadronization

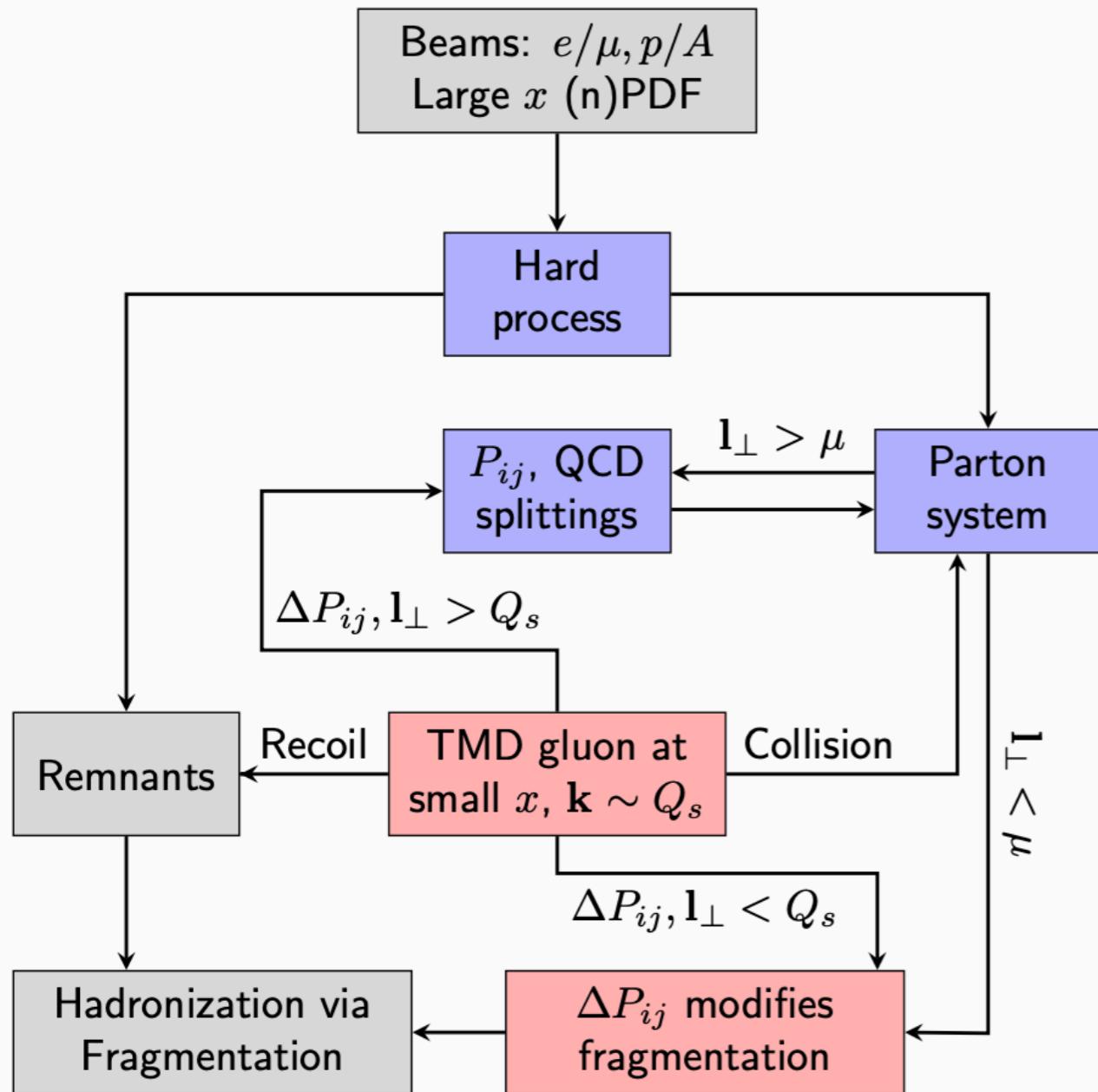


- ▶ \hat{q} controlled by a input K factor, and envolves with (x_B, Q^2)
- ❖ Default tuning (K=4) benched mark to HERMES data
- ❖ $K = 2 \text{ to } 10 \rightarrow \hat{q} = 0.063 \text{ to } 0.172 \text{ GeV}^2/\text{fm}$ at $x_B = 0.1$ and $Q^2 = 1 \text{ GeV}^2$

eHIJING (electron-Heavy-Ion-Jet-INteraction-Generator)



HIJING To be published soon! (W. Ke, Y. He, X-N Wang, H-X Xing, Y Zhang)



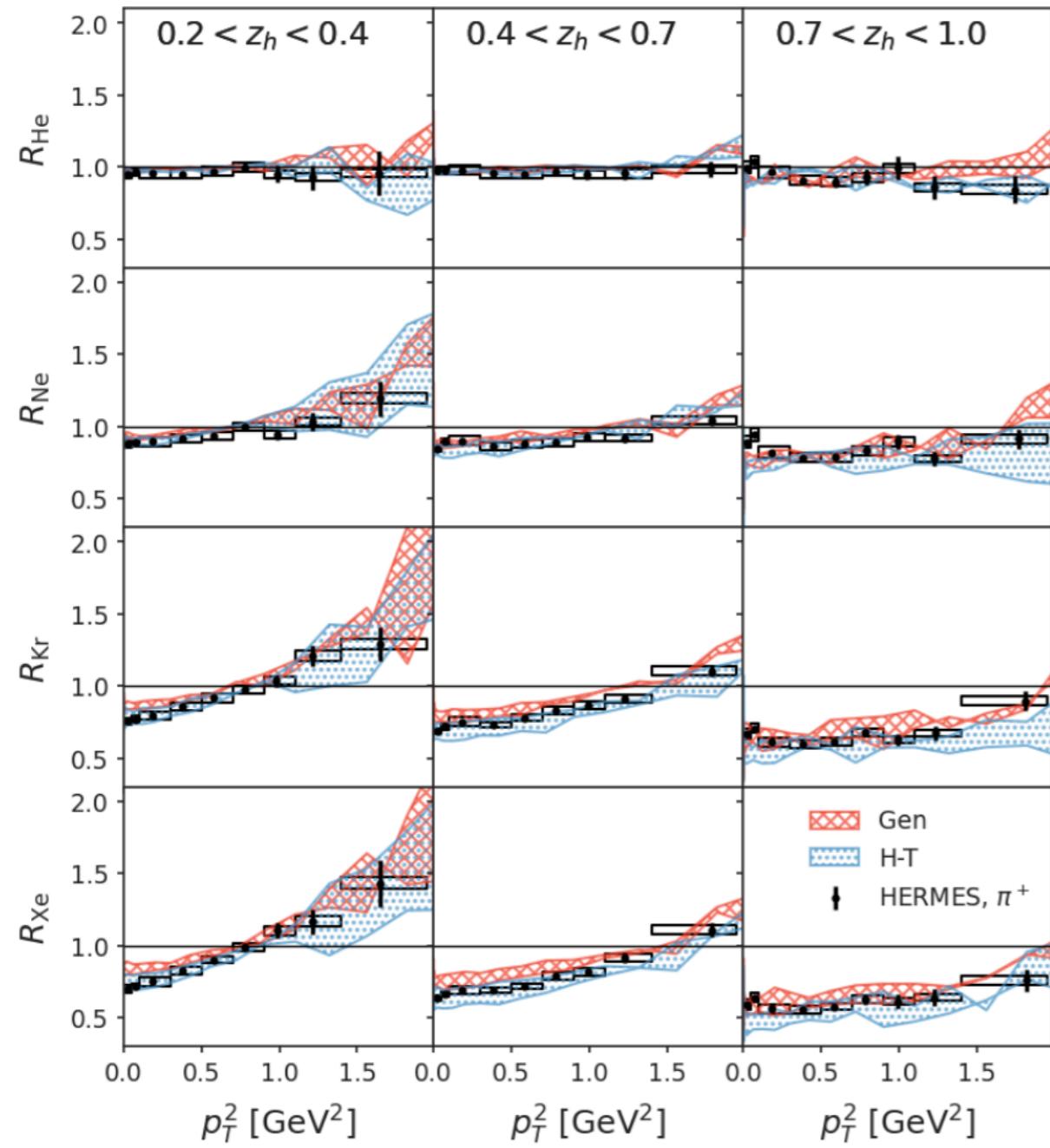
A Monte Carlo model for jet shower modifications in $e-A$:

- $e-p$ event generation from Pythia8.
- $e-A$ (c++17, including modifications to Pythia8):
 - 1) multiple Glauber scatterings
 - 2) modified splitting functions
 - 3) in-medium parton shower
 - 4) hadronization

eHIJING (electron-Heavy-Ion-Jet-INteraction-Generator)



HIJING To be published soon! (W. Ke, Y. He, X-N Wang, H-X Xing, Y Zhang)



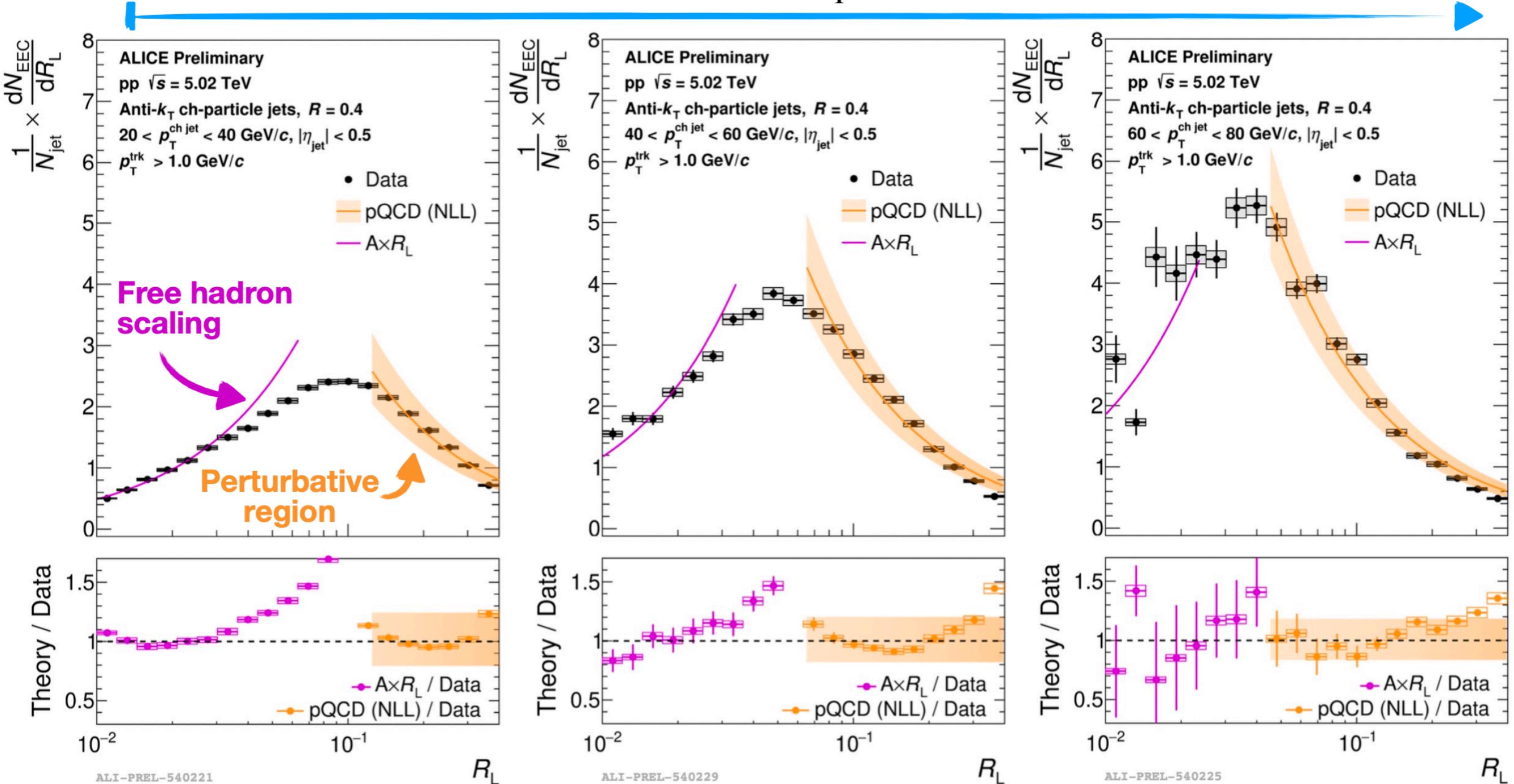
$$R_A = \frac{(N_h(\nu, Q^2; z_h, p_t)/N_\gamma)_{eA}}{(N_h(\nu, Q^2; z_h, p_t)/N_\gamma)_{ed}}$$

- Large z : suppression due to parton energy loss of leading particles.
- Small z : interplay of k_T broadening and the parton shower evolution.

[HERMES, Nuclear Physics B 780, 24 (2007)]

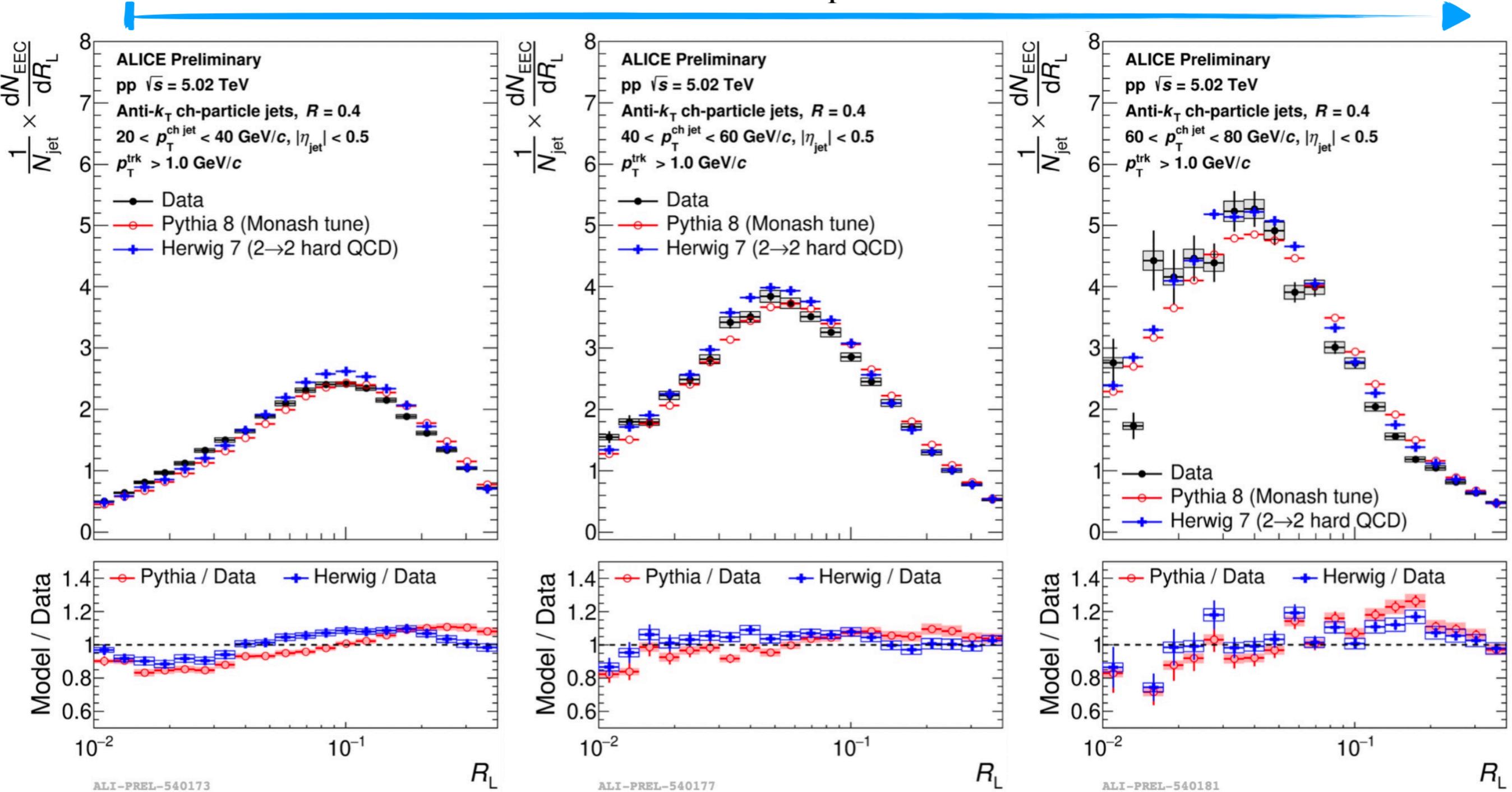
Comparison with pQCD

Higher $p_T^{\text{ch jet}}$

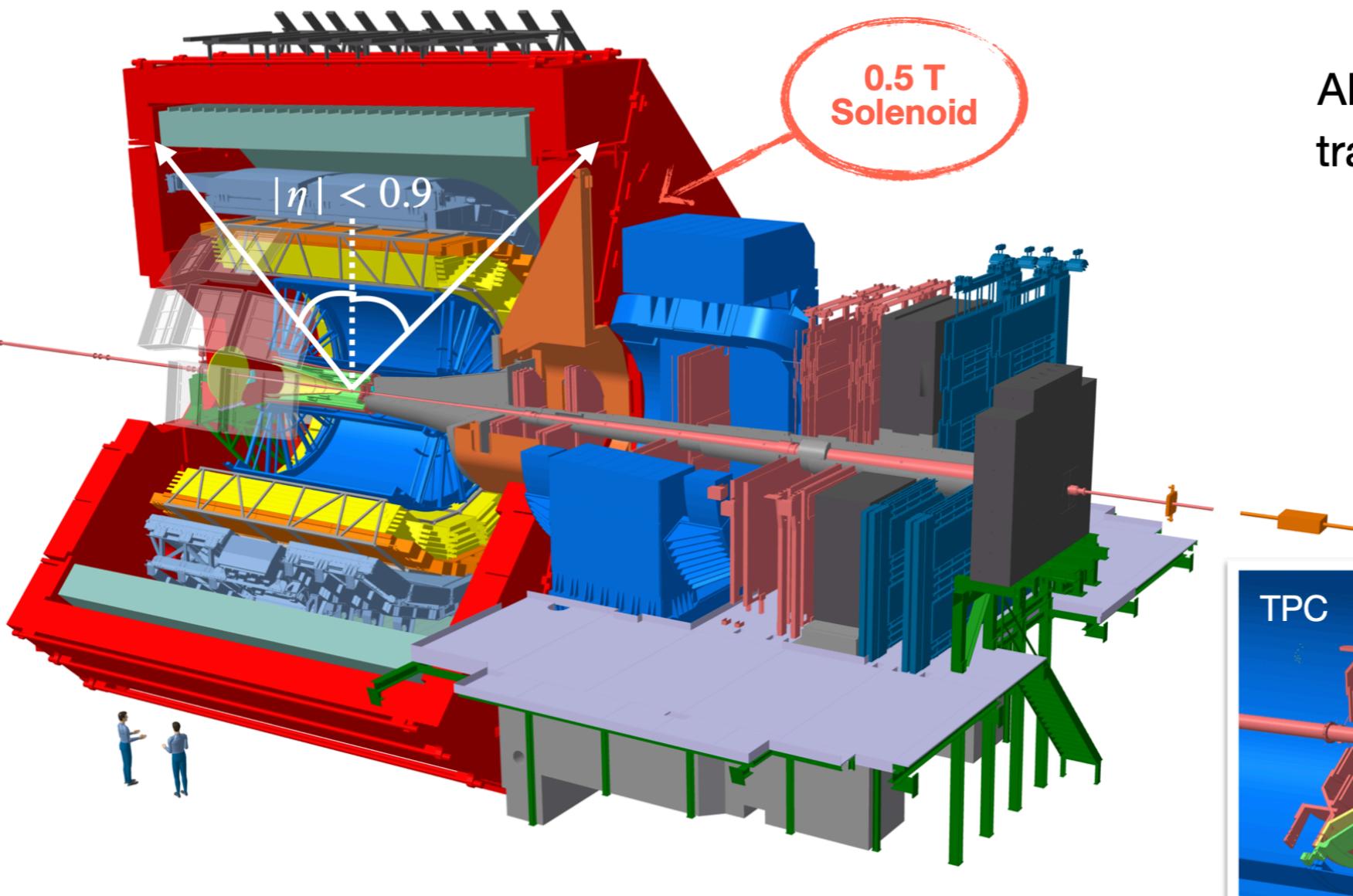


Comparison with models

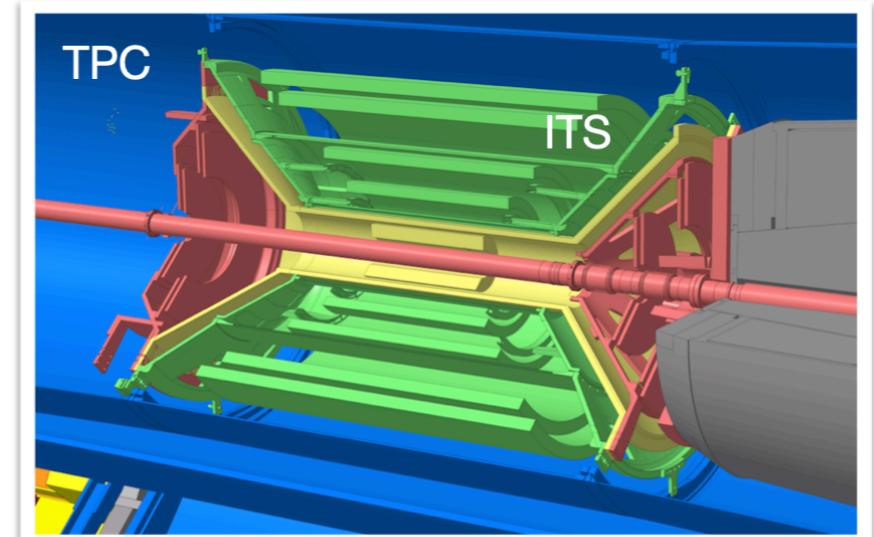
Higher $p_T^{\text{ch jet}}$



ALICE detector



ALICE high-resolution
tracking (ITS+TPC) →
high-precision
measurement



Separation of parton and hadron region in e+p

