An Overview of Jet Measurements at the EIC

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Physics Opportunities at an Electron-Ion Collider XI

February 24 – 28, 2025

Outline

- ❑ Introduction to Jets in DIS
- ❑ Specific Jet Measurements
- ❑ Jet Finding at ePIC

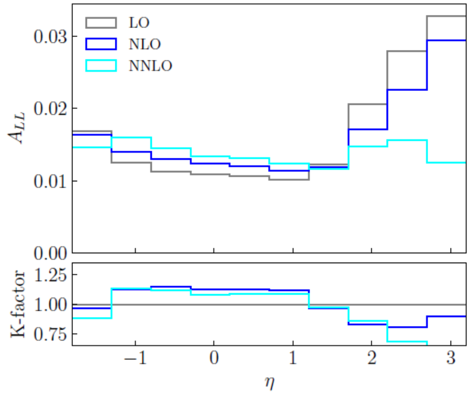
Jet Physics at the EIC

The importance of jet probes was reflected in the EIC Yellow Report where they touched on nearly every major physics topic (Nucl. Phys. A, Vol 1026, 122447)

Jets have several properties which will make them important tools for realizing the EIC physics program

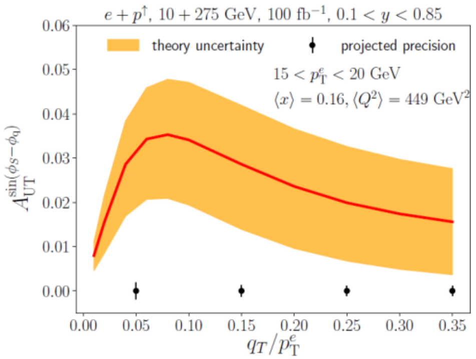
- Well understood theoretically and experimentally
- Excellent proxies for the underlying parton kinematics
- Showers probe QCD from hard interaction to hadronization scale within the same event – can explore dynamics at different time (angular) scales
- Precision tools exist to probe these shower properties - substructure

Global properties and parton structure of hadrons



Borsa, de Florian, Pedron `20

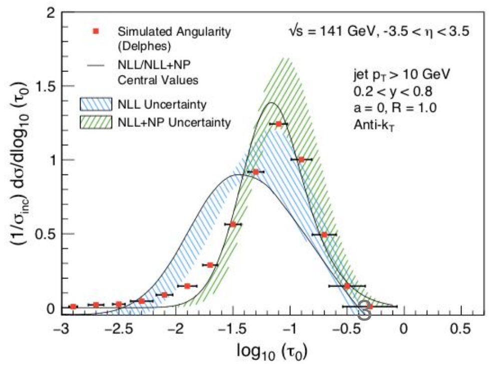
Multi-dimensional imaging of nucleons, nuclei and mesons



Arratia, Kang, Prokudin, Ringer `20

The nucleus: a laboratory for QCD

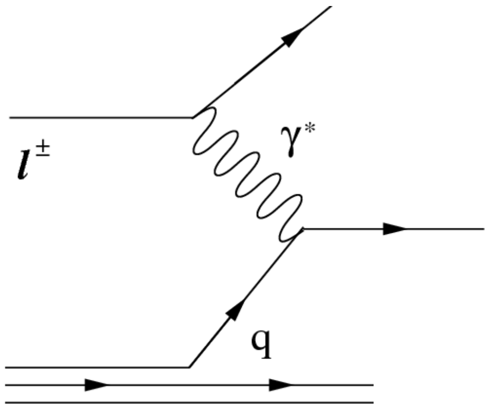
Understanding hadronization



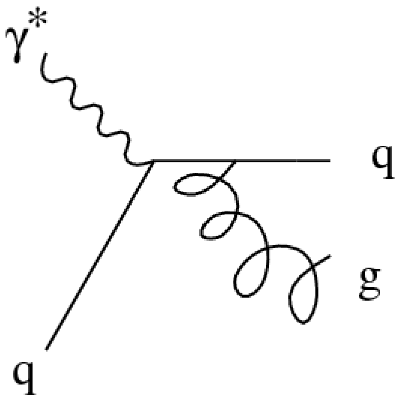
J. Adam et al 2022 *JINST* 17 P10019

Relevant Subprocesses

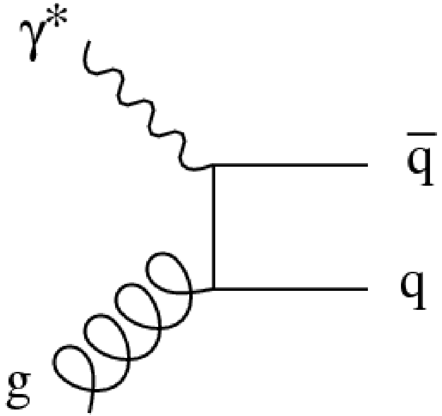
DIS



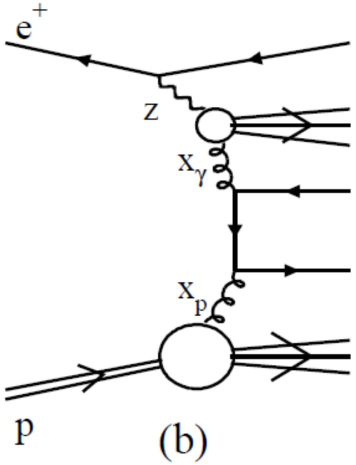
QCD-Compton (QCDC)



Photon-Gluon Fusion (PGF)



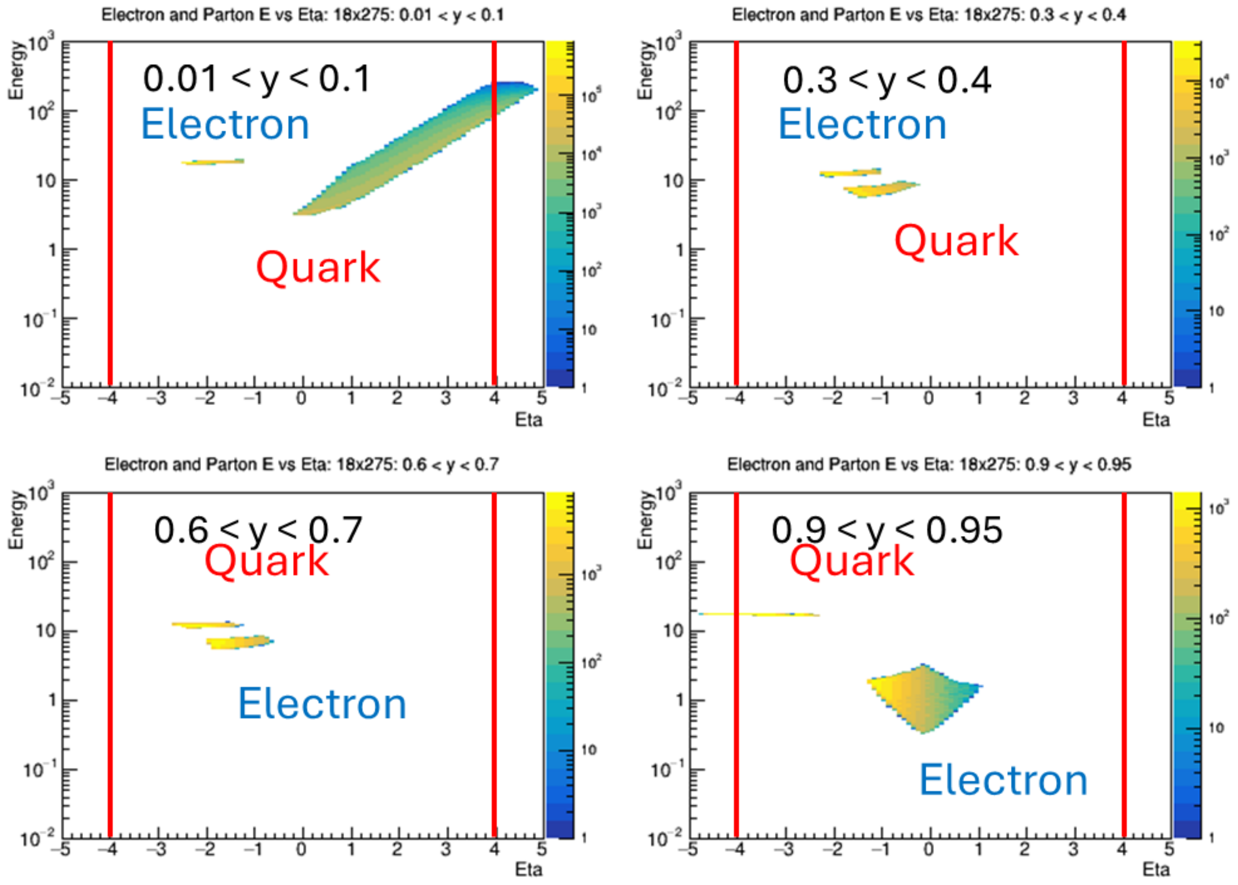
Resolved



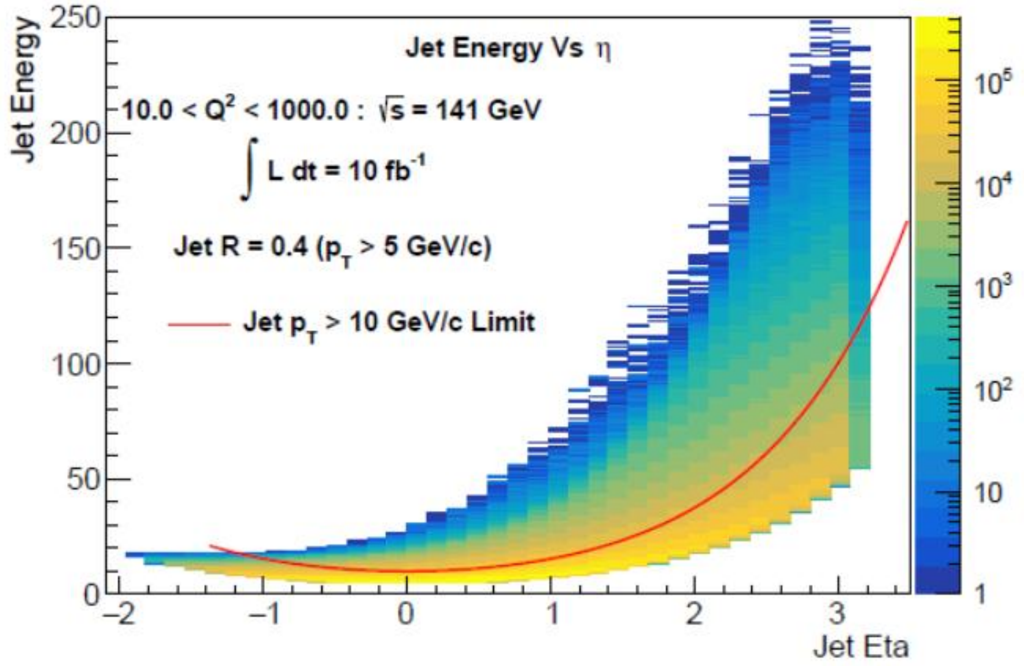
- ❑ Leading order process gives rise to a single jet (not counting target remnant) whose kinematics are largely determined by the underlying event kinematics
- ❑ Higher-order corrections to this process can give rise to back-to-back jet configurations (dijets) which break the dependencies on event kinematics
- ❑ At low Q2, the hadronic (resolved) nature of the virtual photon becomes important and parton – parton (2 -> 2) scattering can give rise to dijet states
- ❑ Jets can also arise from diffractive events for example

Lepton – Parton – Jet Kinematics

$10 < Q^2 < 100$



- As y -> 0, the struck quark can take the full ion beam energy
- As y -> 1, the struck quark takes the full electron beam energy
- Different detector considerations in forward and backward regions



Jet Algorithms

Anti_k$_T$

$$d_{ij} = \min[p_{ti}^{-2}, p_{tj}^{-2}]\Delta R_{ij}/R$$

EE_kT (Spherically Invariant)

$$d_{ij} = 2 * \min[E_i^2, E_j^2](1 - \cos\Delta_{ij})$$

Centauro

$$d_{ij} = \left[(\Delta f_{ij})^2 + 2 f_i f_j (1 - \cos\Delta\phi_{ij})\right]/R^2$$

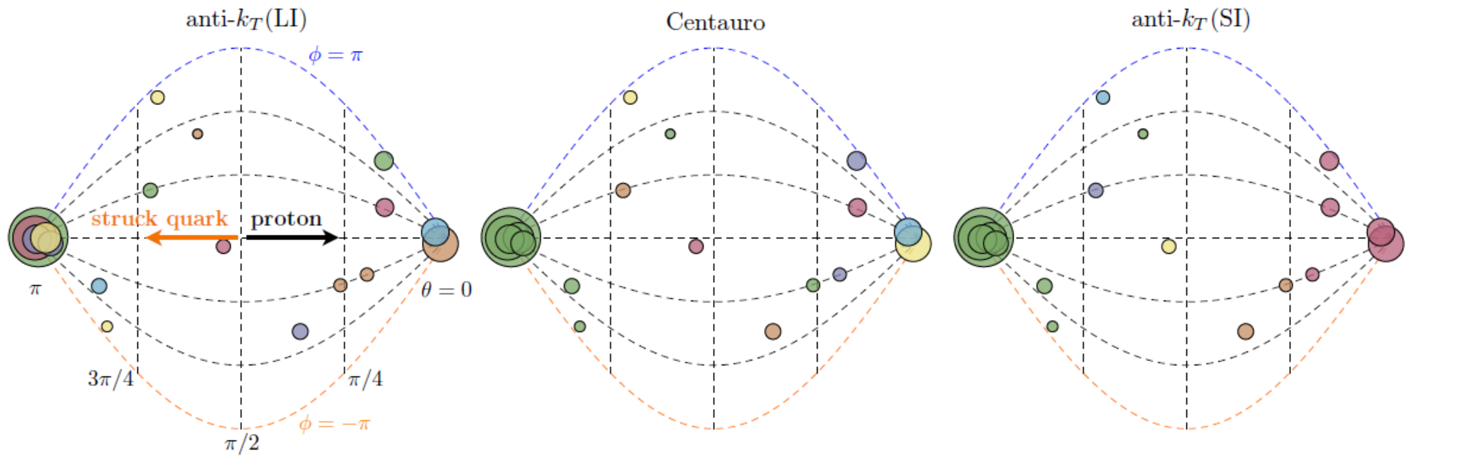
Asymmetric measure is necessary

$$f(x) = x + \mathcal{O}(x^2)$$

$$\bar{\eta}_i = -\frac{2Q}{\bar{n}\cdot q}\frac{p_i^\perp}{n \cdot p_i}$$

$$\bar{\eta}_i(\mathrm{BF}) = 2p_i^\perp/p_i^+$$

- ❑ Sequential recombination algorithms, especially Anti_k$_T$, have been the "industry standard" at hadron colliders for a number of years
- ❑ Is this appropriate for very forward jets or Born-level jets in the Breit frame where transverse momenta are by definition small?
- ❑ Look at alternative distance measures such as spherically invariant and symmetric EE_k$_T$ or longitudinally invariant and anti-symmetric centauro algorithms



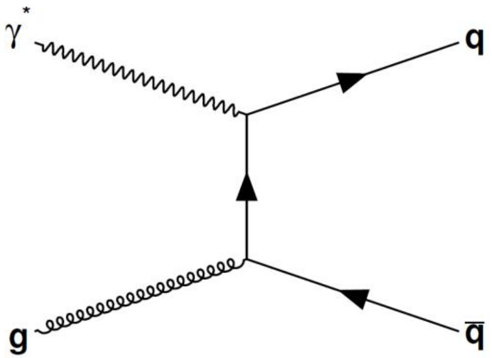
Longitudinally invariant Symmetric

Longitudinally invariant Asymmetric

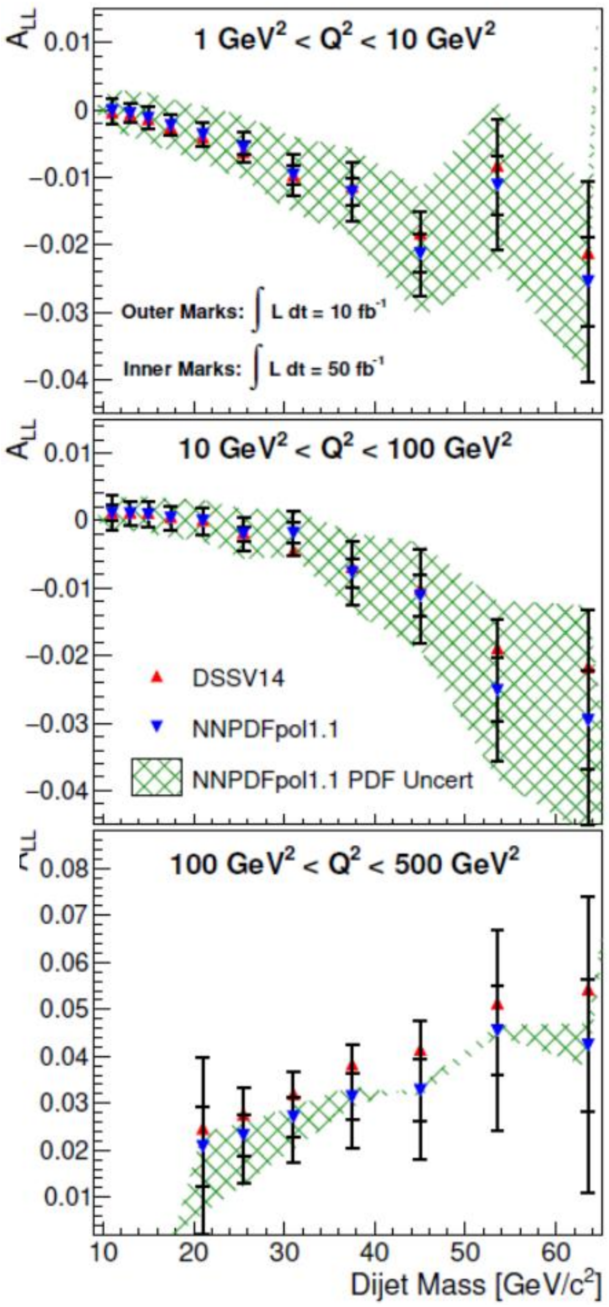
Spherically invariant Symmetric

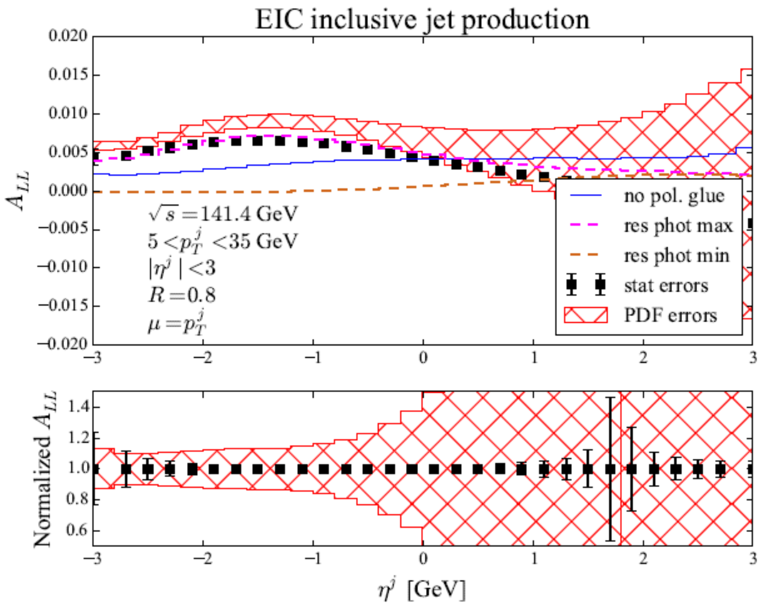
Longitudinal Spin Structure

- Recent results on inclusive and dijet A_{LL} at NLO and NNLO both with and without tagged lepton
- Complimentary to inclusive – access Q^2 and flavor dependance, gamma/Z, charged current
- Feasibility study for dijet A_{LL} in the Breit frame also performed – access to gluon via PGF process

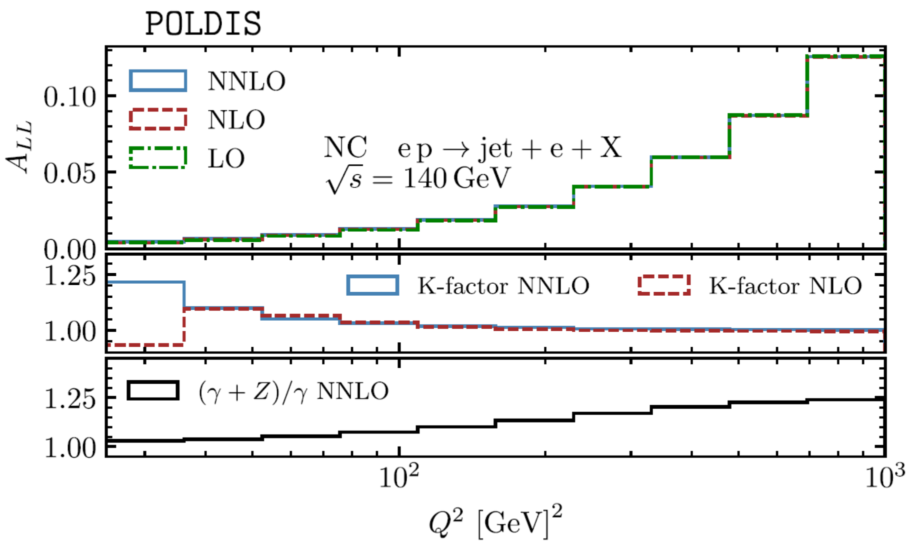


Page, Chu, Aschenauer `20





Boughezal, Petriello, Xing `18



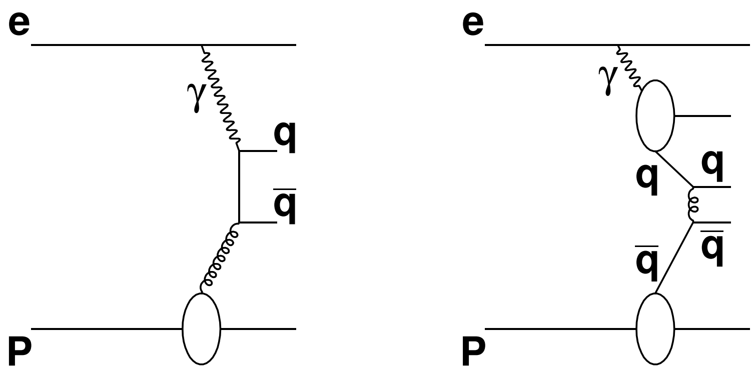
Borsa, de Florian, Pedron `23

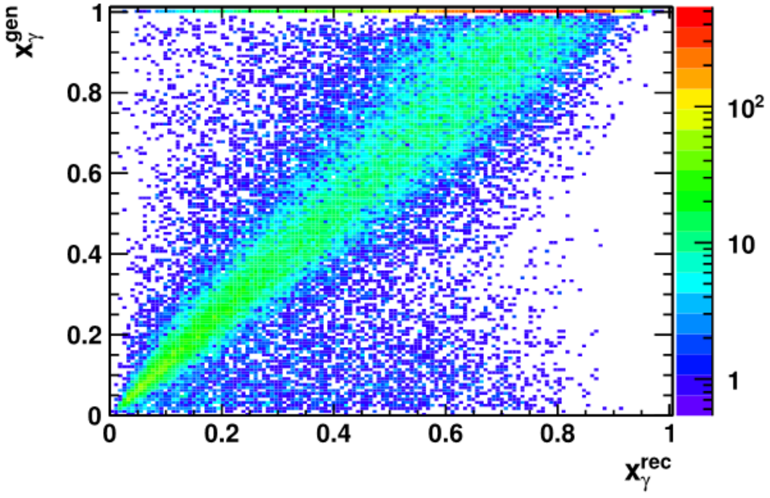
(Polarized) Photon Structure

- At low Q2, virtual photon can behave hadronically and initiate 2->2 type scattering events

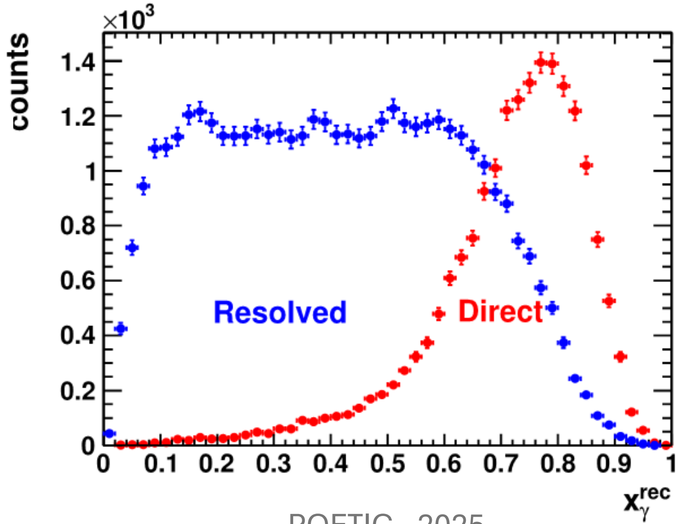
- Results in a quark/anti-quark final state with high transverse momentum

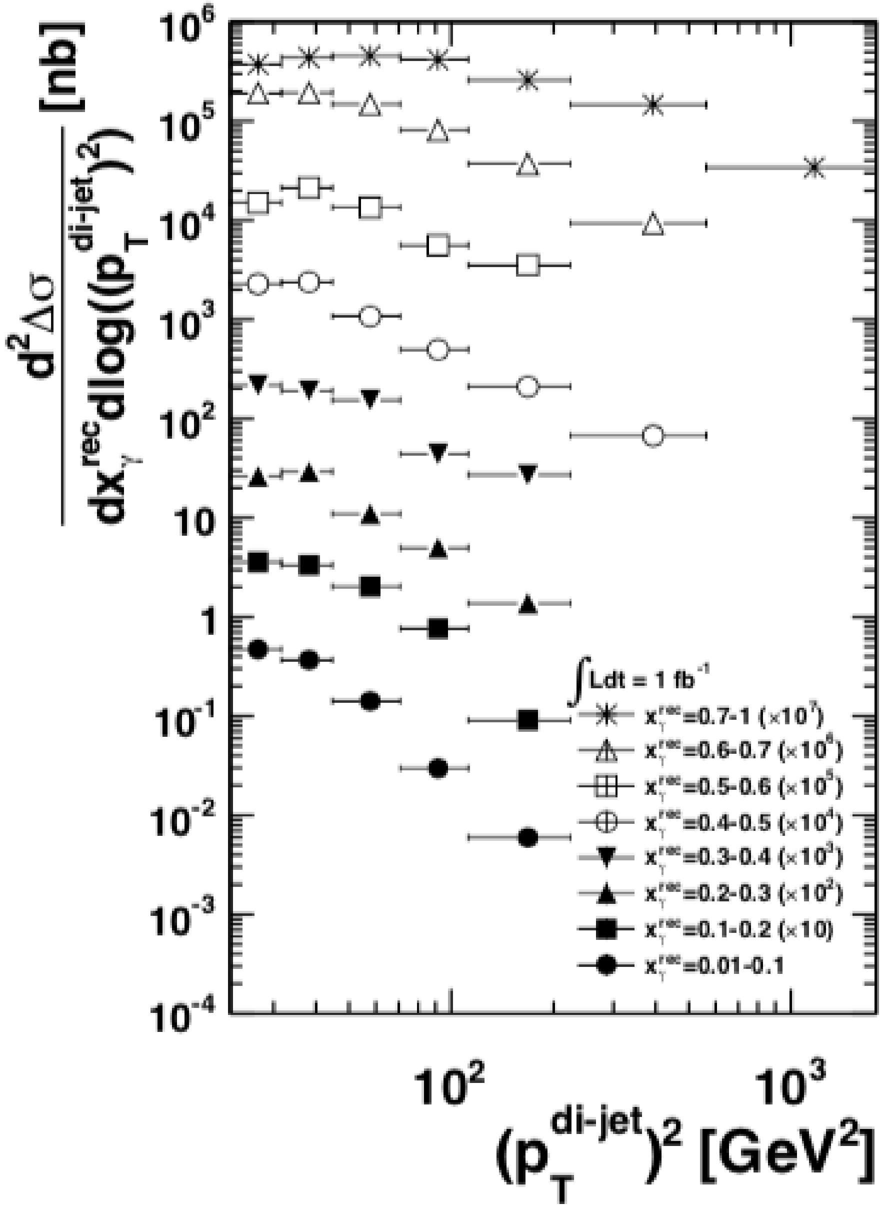
- Dijet allows to reconstruct event characteristics to separate signal and background and characterize the structure of the photon





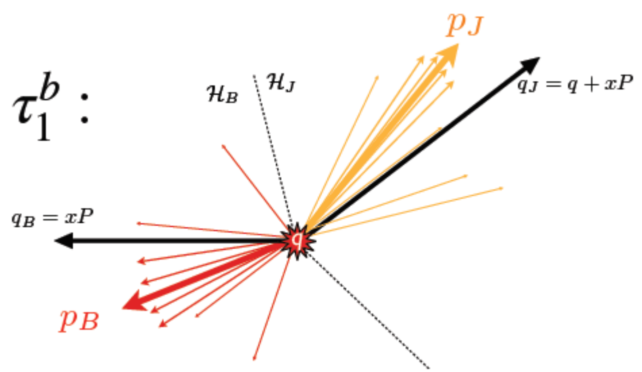
$$x_\gamma^{rec} = \frac{1}{2E_e y}\left(p_{T1}e^{-\eta_1} + p_{T2}e^{-\eta_2}\right)$$

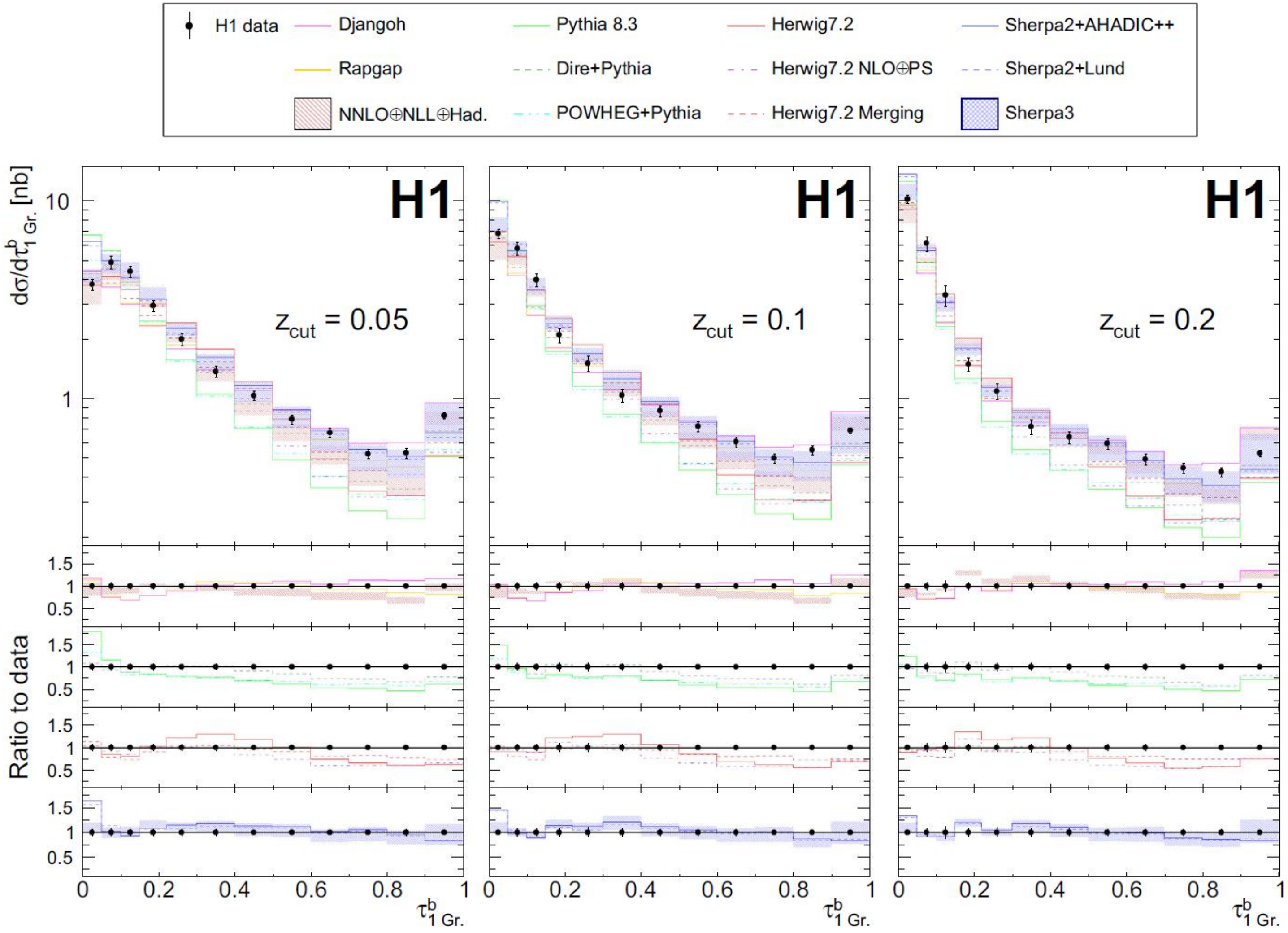




Global Event Shapes

$$\tau_1 = \frac{2}{Q^2}\sum_{i\in X}\min\{q_B\cdot p_i, q_J\cdot p_i\}$$

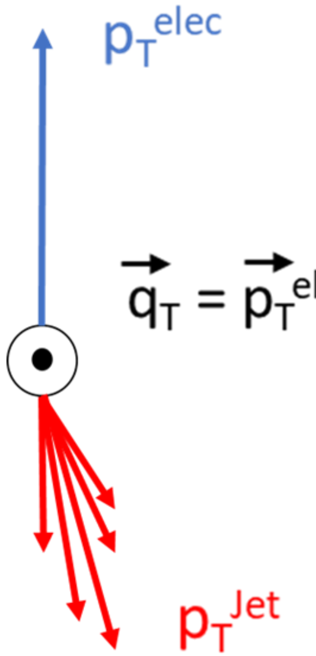




EPJC Vol 84, 718 (2024)

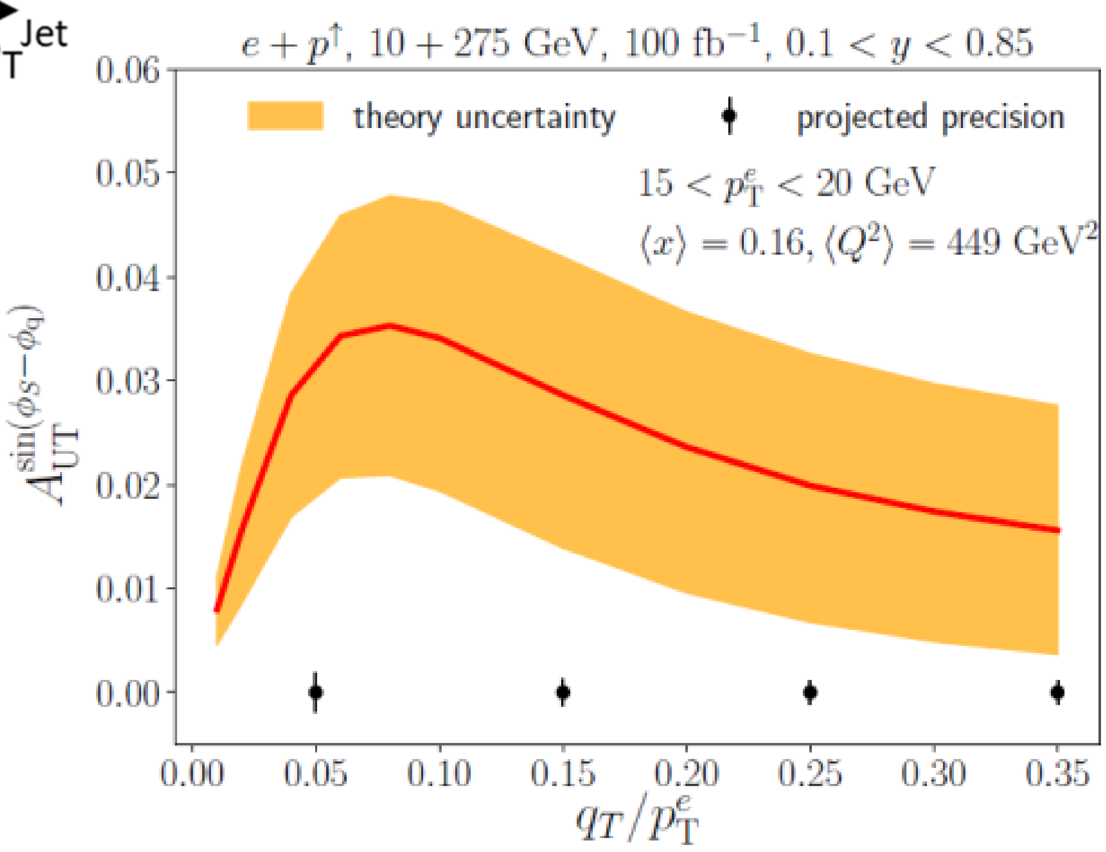
- Global event shapes offer possibility of very high precision measurements for extractions of non-perturbative parameters such as the strong coupling constant and MC tuning
- Introduce grooming to remove soft and wide angle radiation in a controlled way – improve experimental and theoretical precision
- Recent work at H1 involves clustering entire event using Centauro algorithm and declustering with modified mass drop type condition
- Results provide significant new tests of (non) perturbative aspects of theory and MC

Lepton-Jet Correlations: Sivers TMD



$\vec{q}_T = \vec{p}_T^{\,elec} + \vec{p}_T^{\,Jet}$

$$e + p(\vec{s}_T) \rightarrow e + (\mathrm{jet}(\vec{q}_T))h(z_h, \vec{j}_T)) + X$$

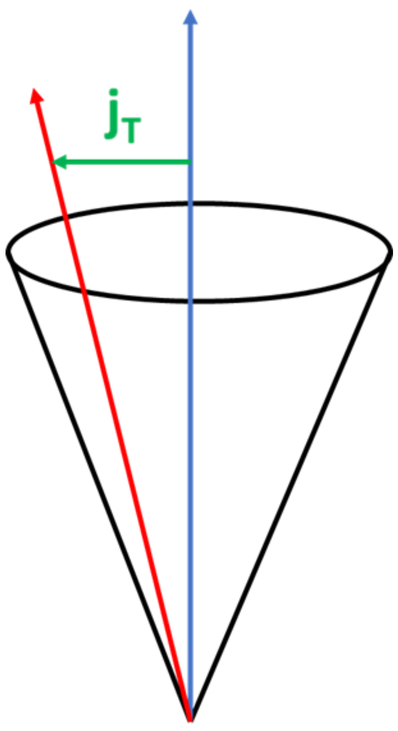


Arratia, Kang, Prokudin, Ringer `20

- ❑ Jet measurements for 3D imaging of nucleons at the EIC is emerging as a fruitful field
- ❑ Jets are complementary to standard SIDIS extractions of TMDs and provide better surrogates for parton kinematics while allowing cleaner separation of target and current fragmentation regions
- ❑ Jet measurements allow independent constraints on TMD PDFs and FFs from a single measurement
- ❑ Azimuthal correlation between jet and lepton sensitive to TMD PDFs (Sivers)

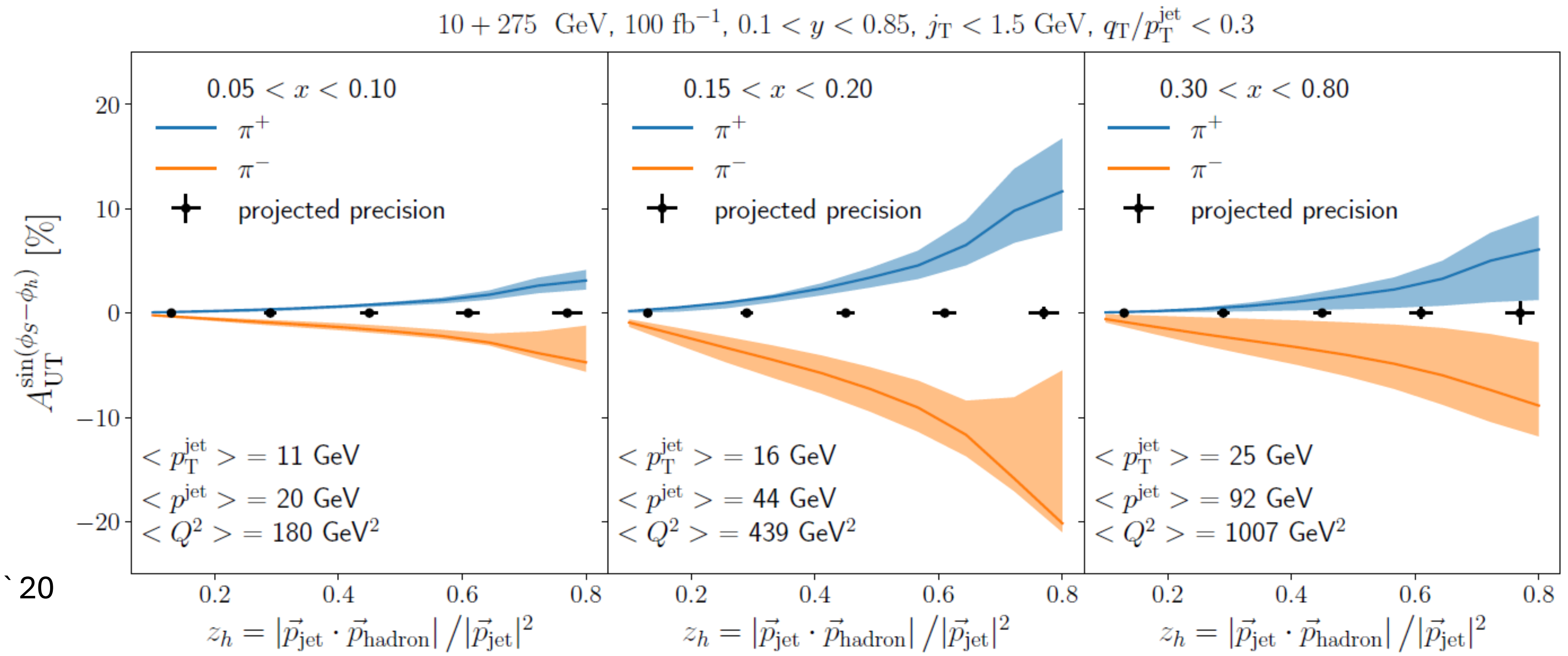
Hadron-in-Jet: Collins TMD

$$e + p(\vec{s}_T) \to e + (\text{jet}(\vec{q}_T)\, h(z_h, \vec{j}_T)) + X$$



Arratia, Kang, Prokudin, Ringer `20

- ❑ Measurement of hadrons within jet give access to TMD FFs
- ❑ Relevant variables are j_T – transverse momentum of the hadron with respect to the jet and z – fraction of jet momentum carried by hadron
- ❑ Collins asymmetry correlates proton spin vector with j_T
- ❑ Identified hadrons allow for flavor separation of Collins FF

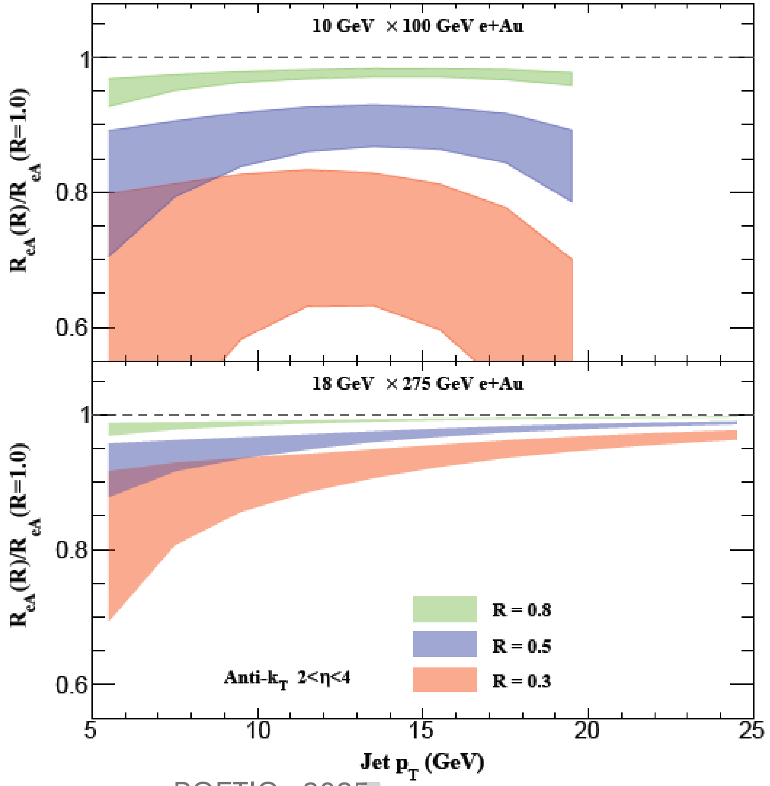


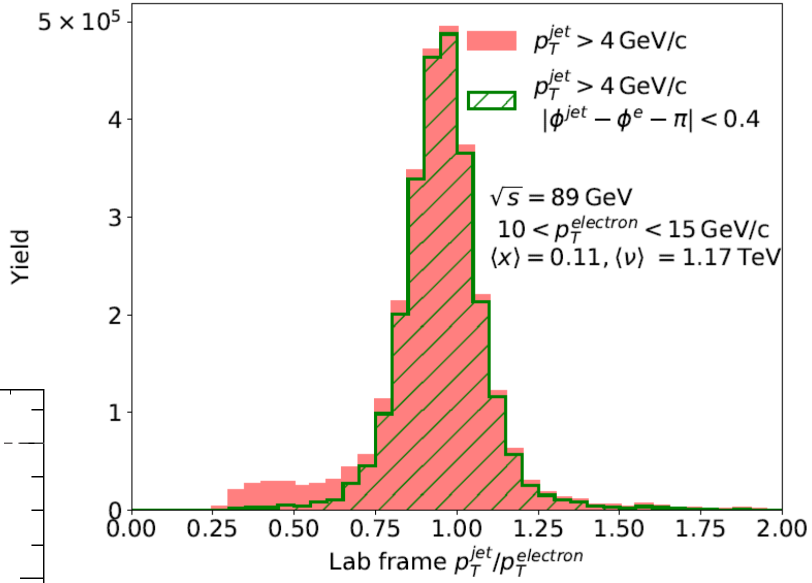
Jets in the Medium: CNM Properties

- Many opportunities to study the properties of cold nuclear matter with jets
- Simple comparisons of jet yields in ep vs eA will be informative – double ratio $R_{eA}(R)/R_{eA}(R = 1.0)$ will reduce impact from nPDFs and enhance final state effects
- Lepton – Jet correlations in Born level DIS can be thought of as analogous to boson – Jet measurements with the lepton as the tag and the jet as the probe of the medium
- Dijets and gamma-jet correlations also expected to be powerful probes of saturation / small-x dynamics

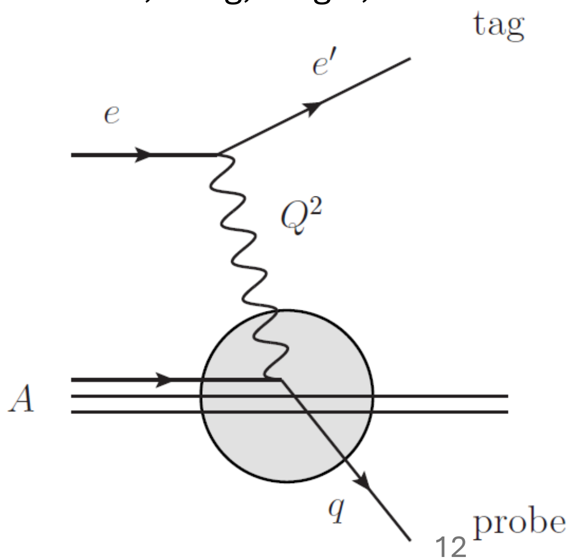
$$R_{eA}(R) = \frac{1}{A}\frac{\int_{\eta 1}^{\eta 2} d\sigma/d\eta dp_T|_{e+A}}{\int_{\eta 1}^{\eta 2} d\sigma/d\eta dp_T|_{e+p}}$$

Li & Vitev '20



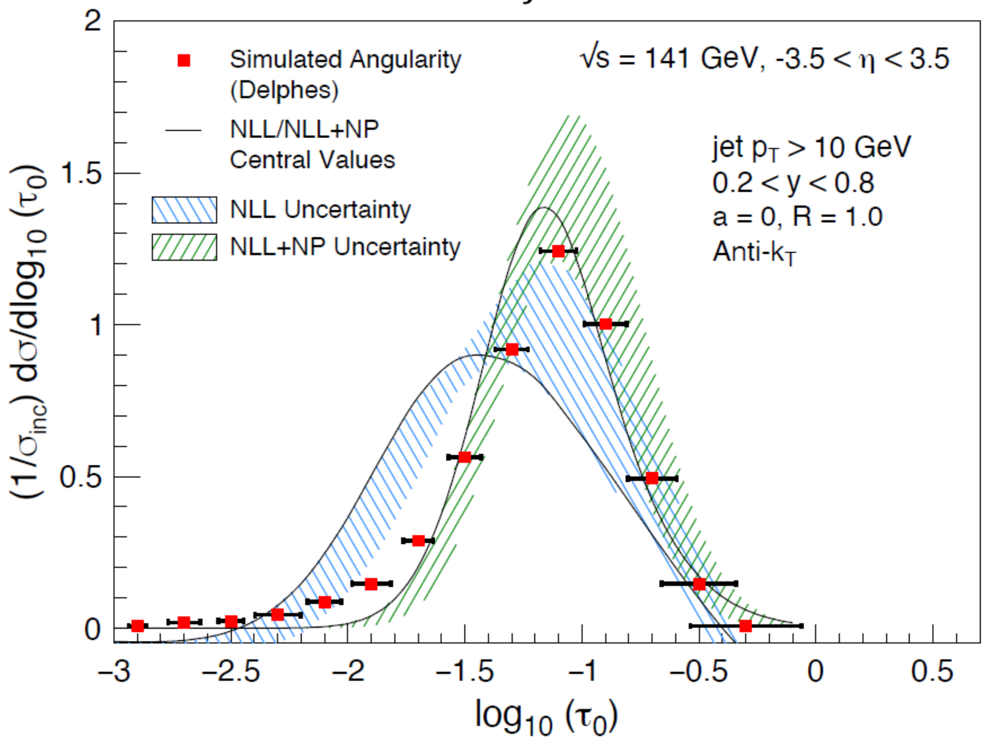


Arratia, Song, Ringer, Jacak '20



Jet Substructure: Angularity

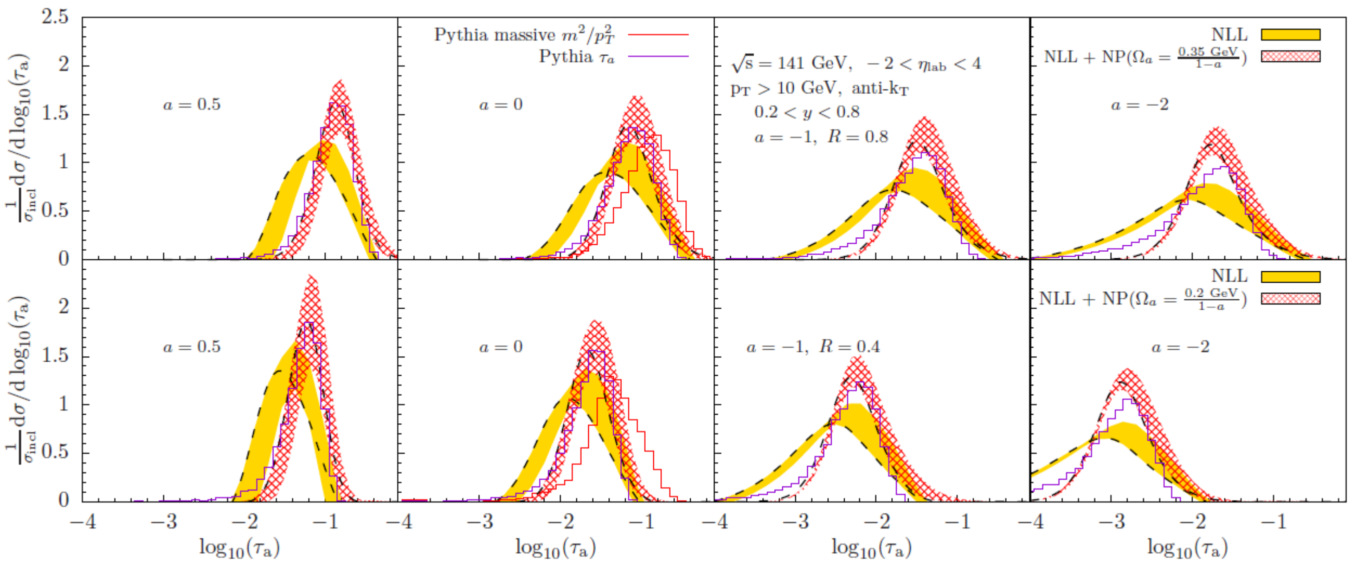
$$\tau_a \equiv \frac{1}{p_T} \sum_{i \in J} p_T^i \left(\Delta R_{iJ}\right)^{2-a}$$



Aschenauer, Lee, Page, Ringer `20 & ATHENA Proposal

$$F_\kappa(k) = \left(\frac{4k}{\Omega_\kappa^2}\right) \exp\left(-\frac{2k}{\Omega_\kappa}\right)$$ NP Effects

- Jet angularity are a family of one-parameter substructure observables correlating momentum and radial distance of particles in a jet
- Different choices of ‘a’ parameter interpolate between familiar substructure observables such as mass and broadening
- Sensitive to hadronization effects via convolution with the non-perturbative shape function Ω_1

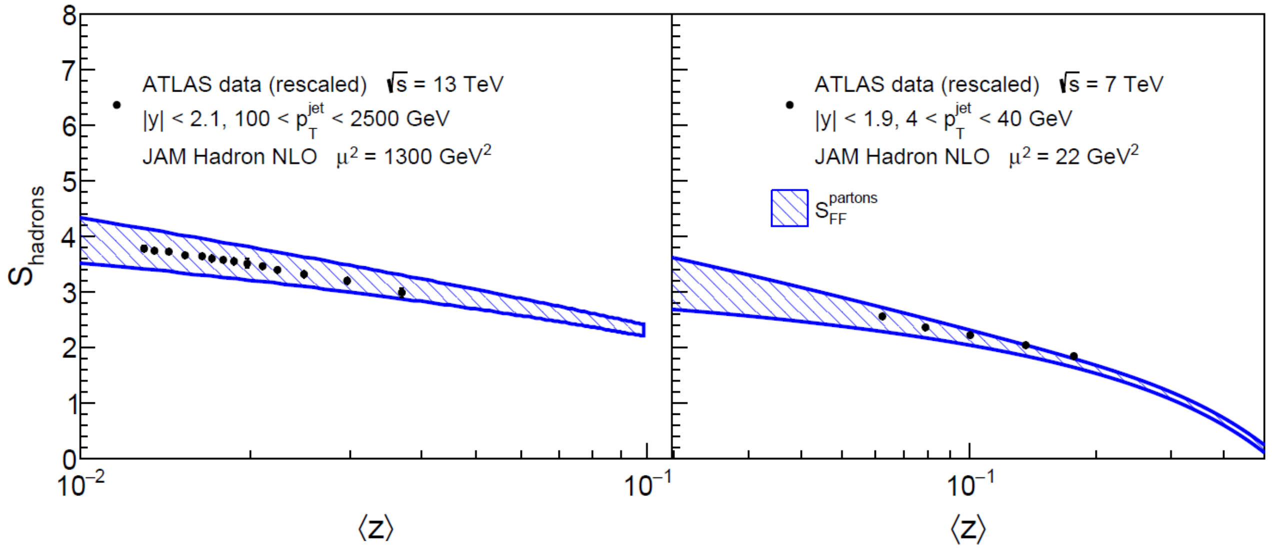


Jets as a Probe of Hadonization

$$r_c(X) = \frac{d\sigma_{h_1 h_2}/dX - d\sigma_{h_1 \overline{h_2}}/dX}{d\sigma_{h_1 h_2}/dX + d\sigma_{h_1 \overline{h_2}}/dX}$$

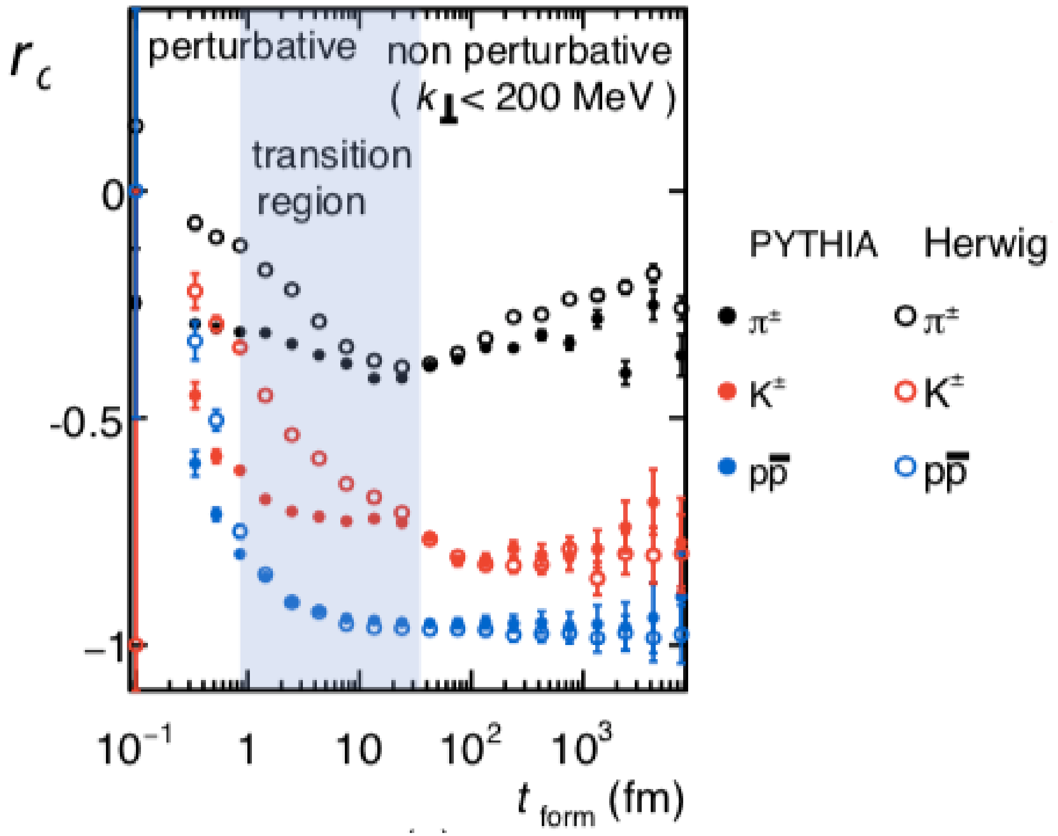
$t_{form} = \frac{z(1-z)p}{k_\perp^2}; p = p_1 + p_2; z = \frac{p_2}{p}$; $k_\perp$= rel trans mom

- Quantify distributions of charge, flavor, spin, etc within a jet -> study hadronization process
- Define the ratio r_c to explore the charge and flavor correlations between leading hadrons within a jet. Can also apply grooming to enhance areas where we expect had effects to be greater (PRD 111, 034008 (2025))
- Exciting new relations between fragmentation and entanglement entropy in jets point at a new way of exploring hadronization



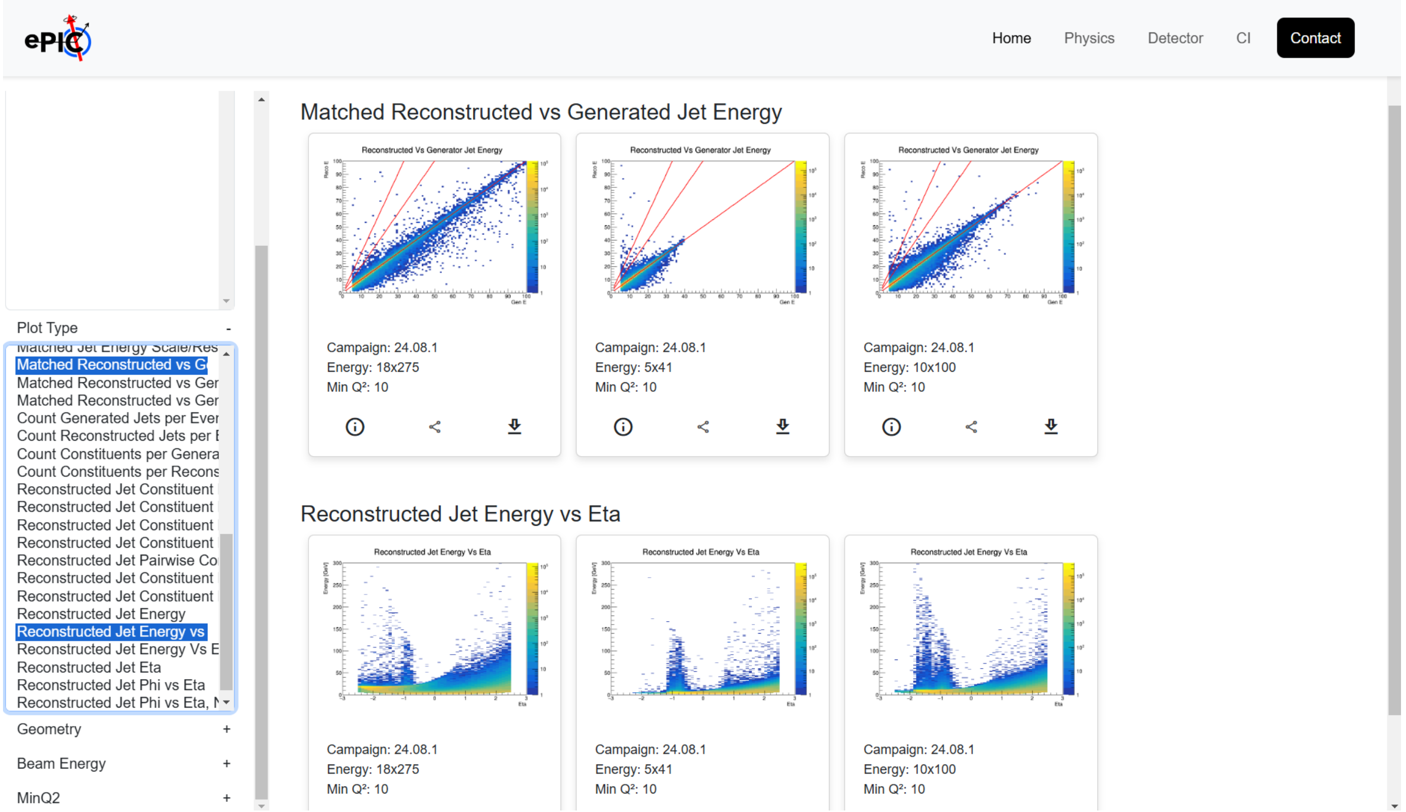
$$S_{FF}^{q/g} = S_{q/g} + \ln\left[\int_{z_{\min}(p_\perp^{\rm jet})}^{1} dz\, D_{q/g}^{\rm h}\left(z, p_\perp^{\rm jet}\right)\right]$$

$$S_{\rm hadrons} = -\sum P_n \ln(P_n)$$



Phys.Rev.D 105 (2022) 5

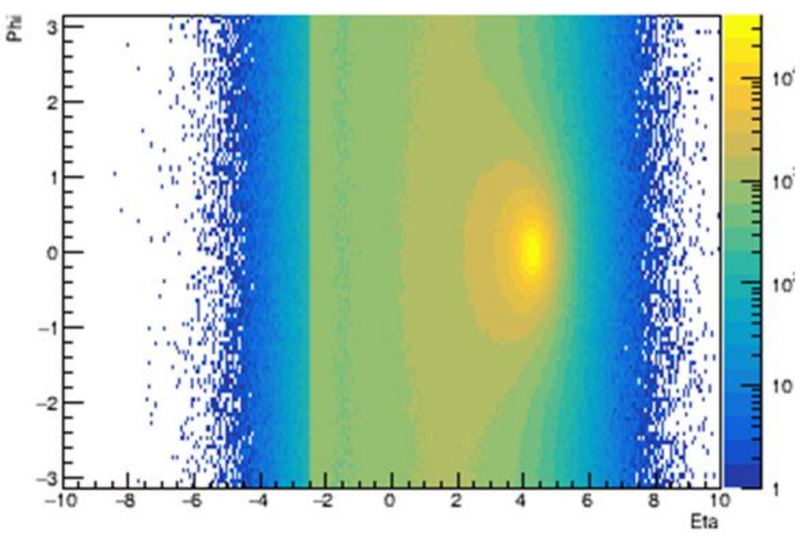
Jet Reconstruction at ePIC: Infrastructure



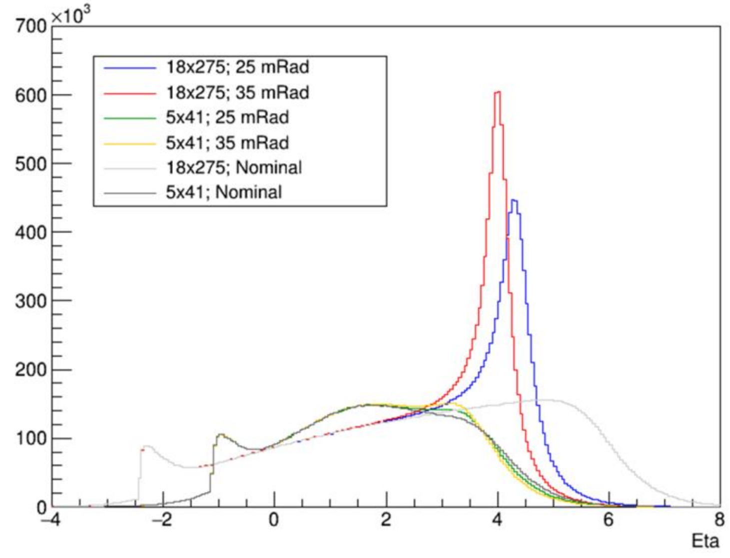
- Algorithmic and more general software infrastructure needed for jet analyses at ePIC currently under development
- Jets are track-based now but particle-flow techniques to consistently include calorimeter information are under development
- Jets (Centauro and Anti-kT) are automatically reconstructed with each simulation run and stored in standard output trees
- Benchmark plots which track many jet properties are automatically generated with each simulation production and displayed via a webpage -> track jet reconstruction as software/geometry change

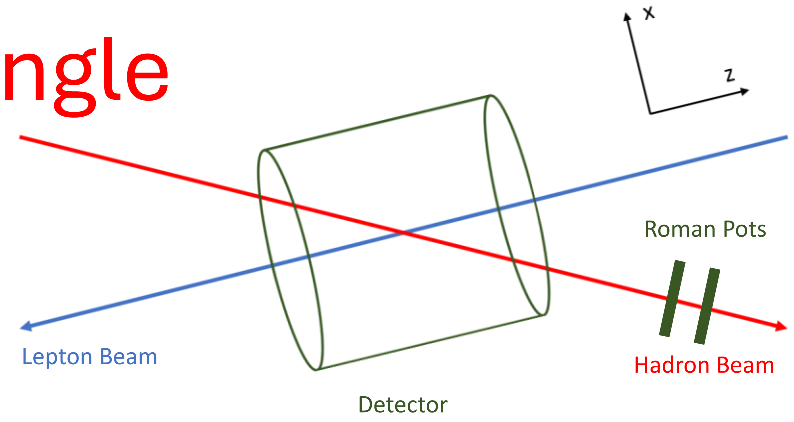
Jet Reconstruction at ePIC: Crossing Angle

Final State Particle Phi Vs Eta: 18x275 25mRad

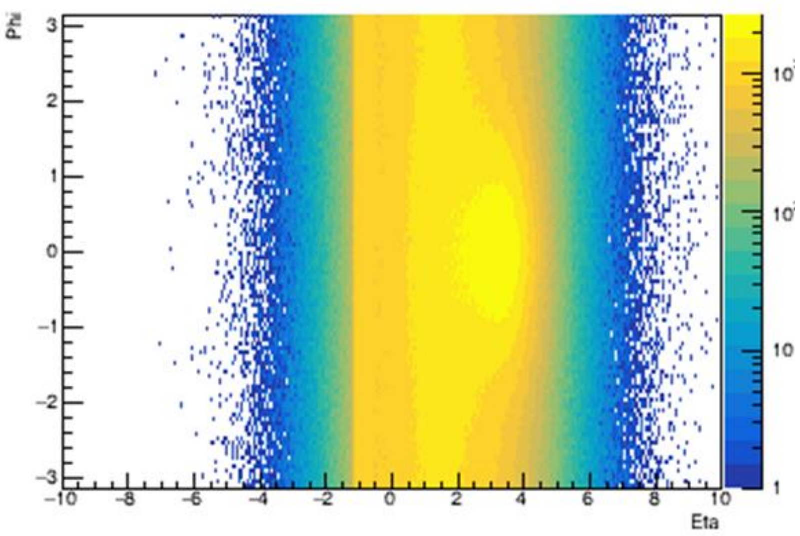


Final State Particle Eta

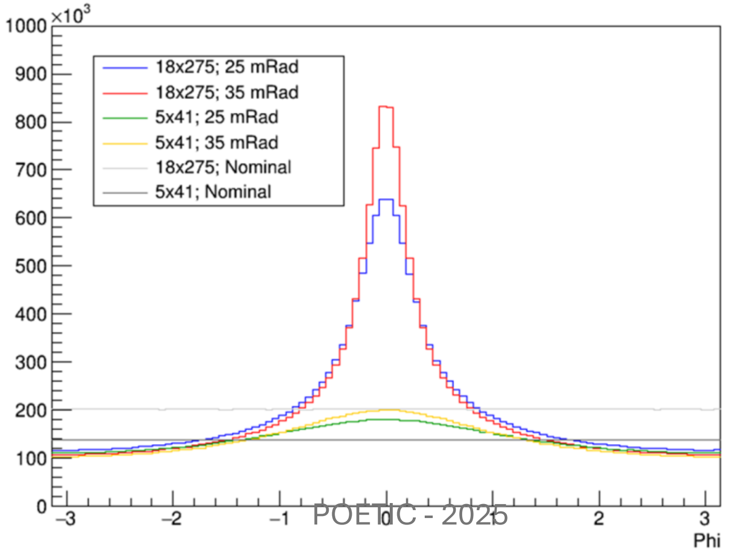




Final State Particle Phi Vs Eta: 5x41 25mRad

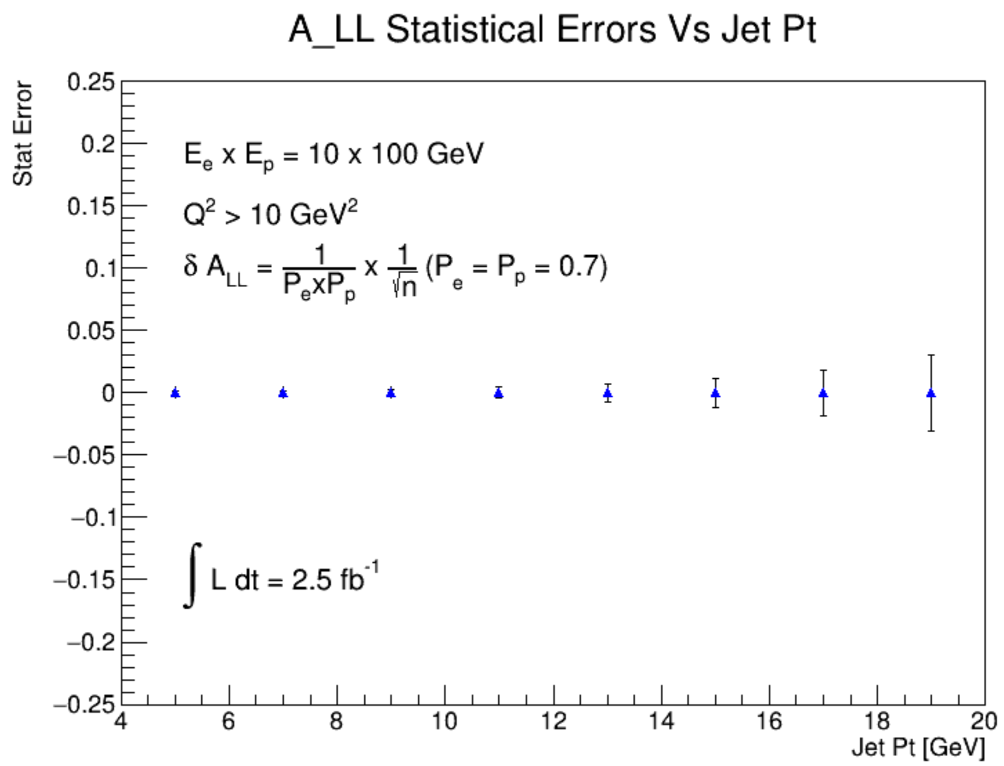


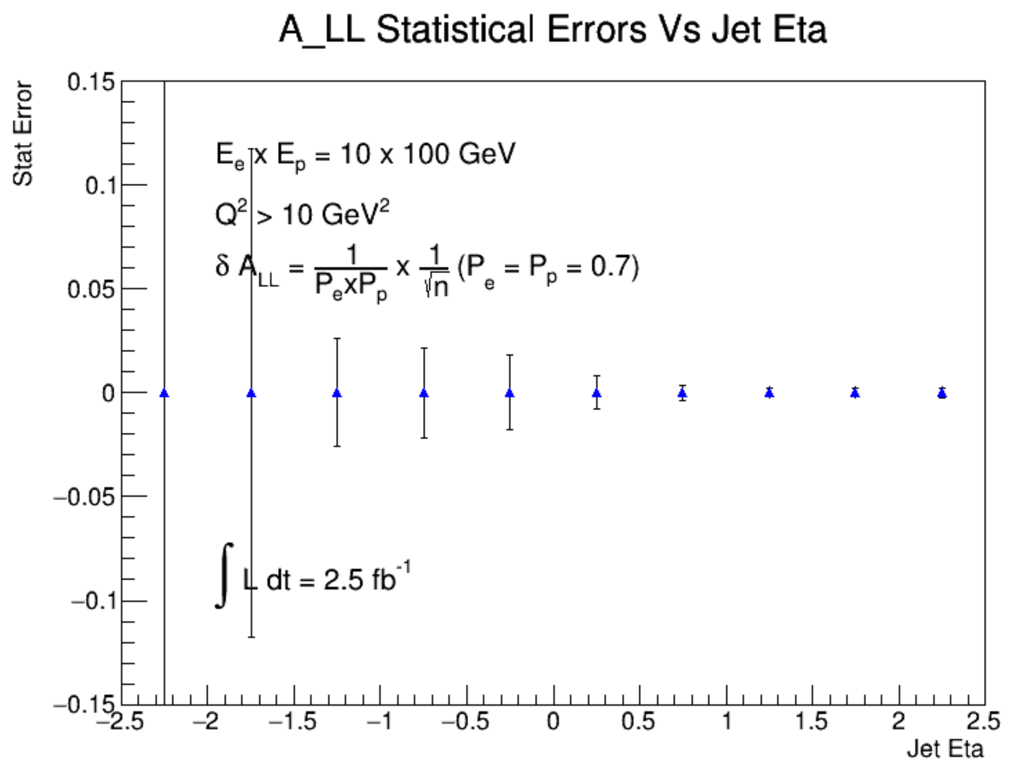
Final State Particle Phi



- Detector solenoid must align with electron beam to minimize synchrotron radiation: “lab frame” -> electron beam = z-axis
- When measuring in lab frame coordinates – see a hot spot in eta/phi corresponding to the beam direction
- More pronounced for more relativistic beams
- How do we mitigate these features?

Jet Reconstruction at ePIC: Projections

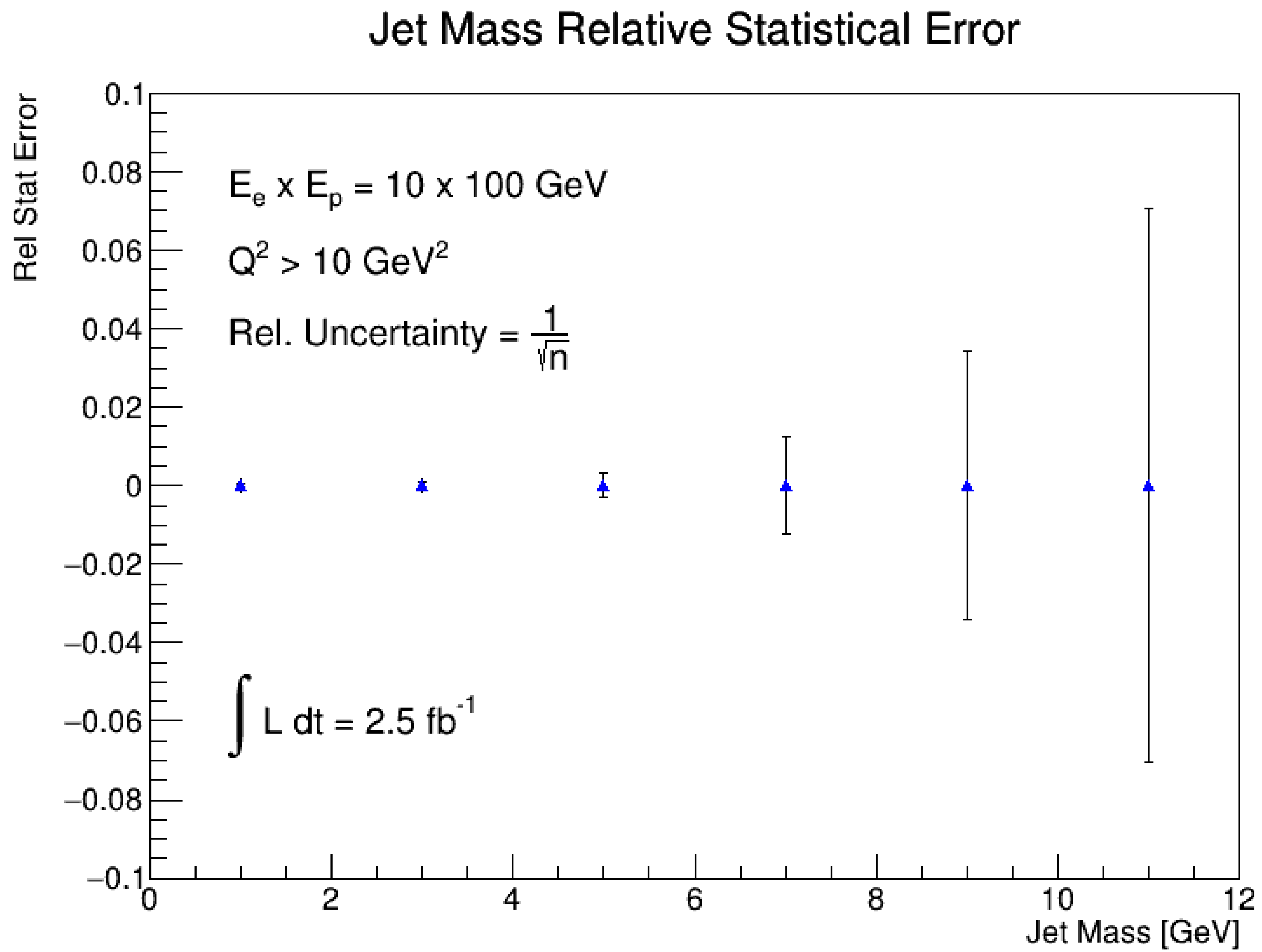




- Efforts ongoing to define science goals in early running
- Trade-off between physics requirements and necessary ramp-up of machine capabilities and performance

- Example: look at projections for inclusive jet A_{LL} in first year with longitudinal hadron polarization
- Beam energies will be near 10x100 and an integrated luminosity of around 2.5 fb^{-1} is expected

Jet Reconstruction at ePIC: Projections



- ❑ Unpolarized measurements will be important too – more statistics as polarization is ramped up
- ❑ Example substructure measurement: jet mass
- ❑ Low hadron beam energy and integrated luminosity limit reach of precision measurements
- ❑ Other substructure observables need to be evaluated

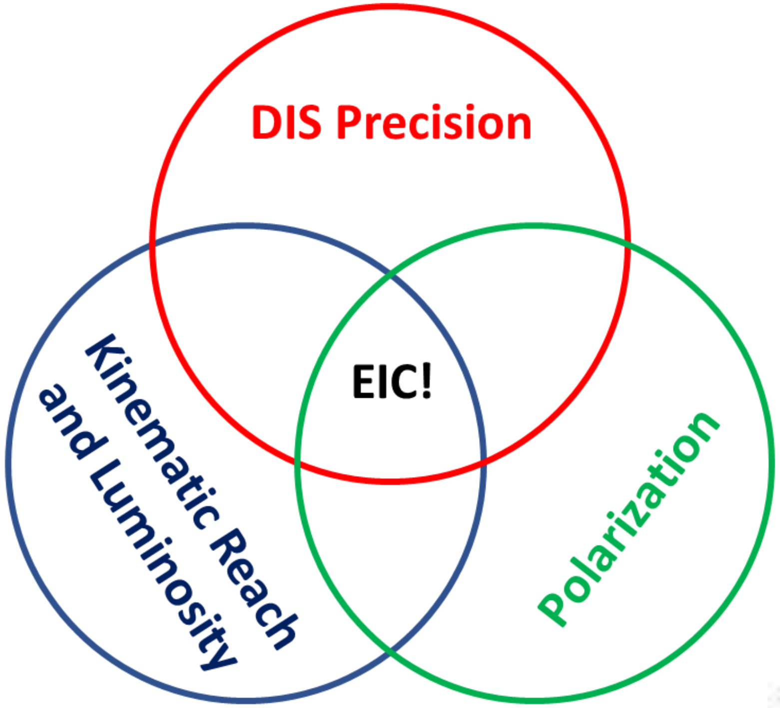
Summary

- Jet production in DIS will probe a number of interesting subprocesses and reconstruction in different detector regions and with different jet algorithms will emphasize different physics
- Jet observables will contribute to nearly every area of the EIC science program, both complementing more traditional inclusive and semi-inclusive measurements and providing unique capabilities of their own
- The ePIC Collaboration has developed a number of tools to analyze jets and is working on particle flow techniques to fully exploit the hadronic final state
- The process of defining the physics program in the early years of EIC running is beginning and impacts of jet measurements are being explored

Back-up

The Ultimate QCD Microscope

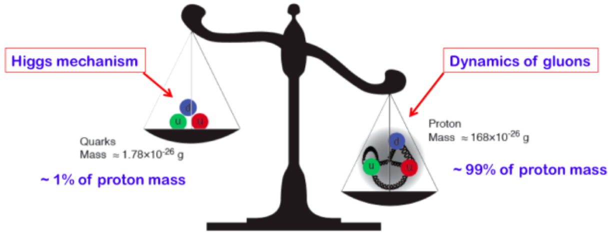
- Understanding internal dynamics of QCD bound states will require precision measurements over a wide kinematic regime – the EIC fits the bill
- Equally important will be high resolution, hermetic detectors with good PID and far-forward detection capabilities to fully characterize the final states of collisions
- Finally, need observables which are well understood theoretically, and which connect to the properties we want to explore
- This talk will focus on the unique capabilities jet observables will bring to the EIC science program

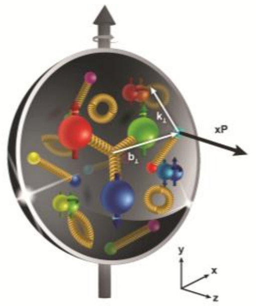


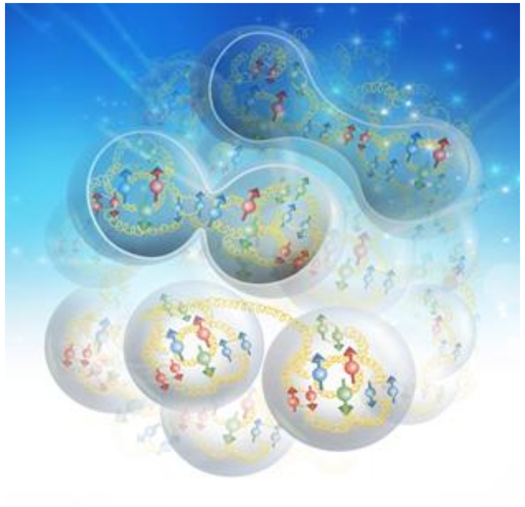
The EIC Physics Pillars

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

How do the nucleon properties emerge from them and their interactions?







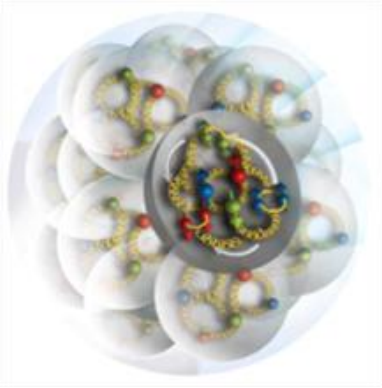
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

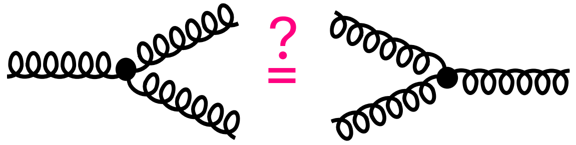
How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

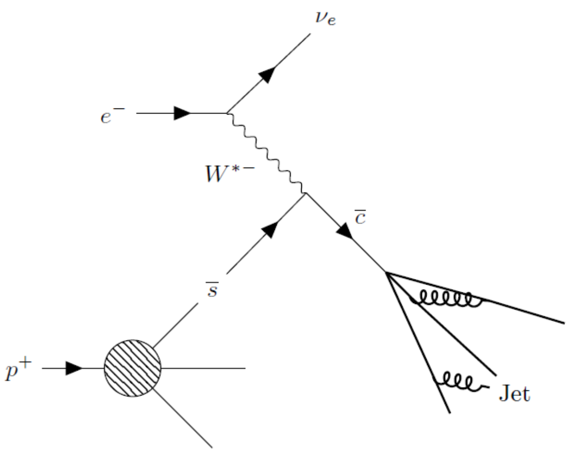
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

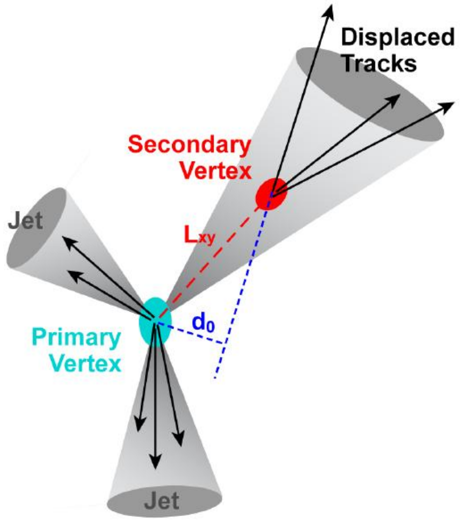


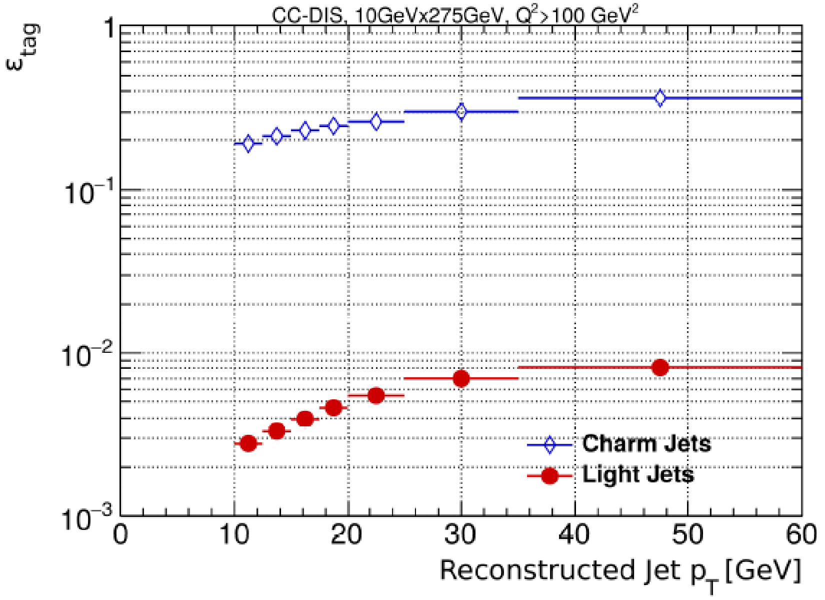


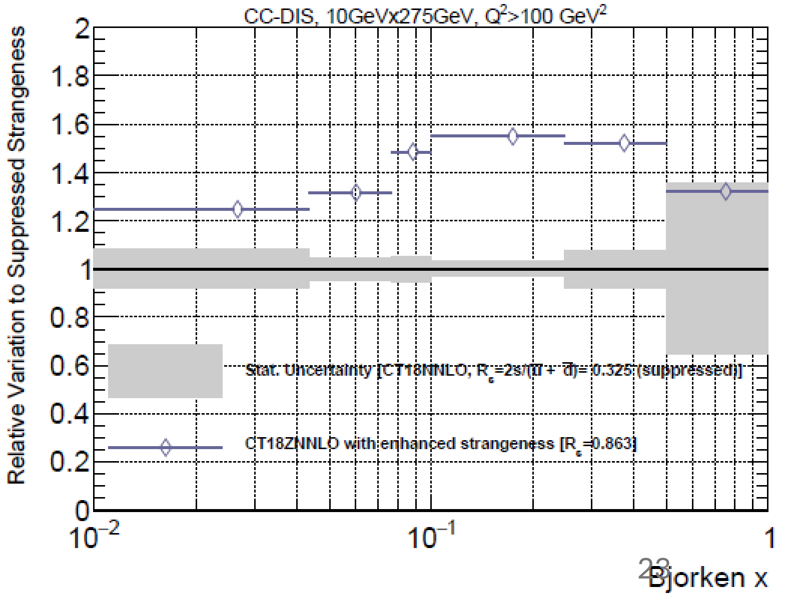
Strangeness PDF: Charm Jets

Arratia, Furletova, Hobbs, Olness, Sekula `20



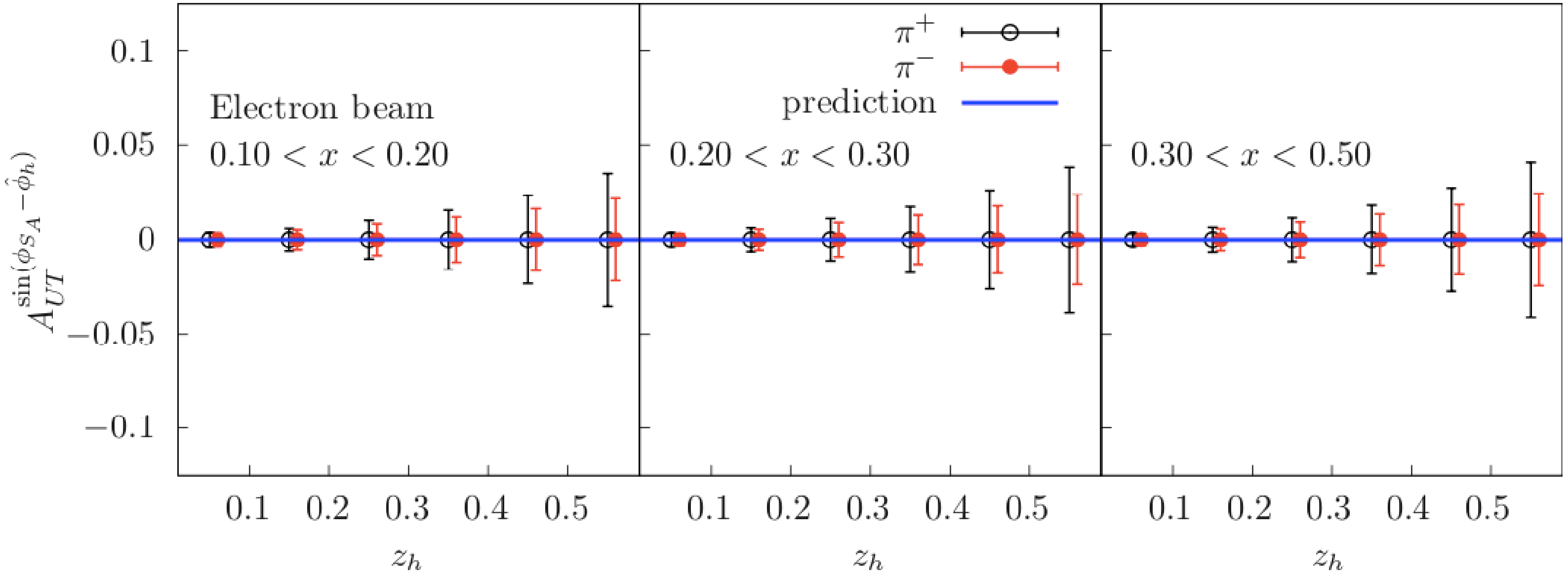


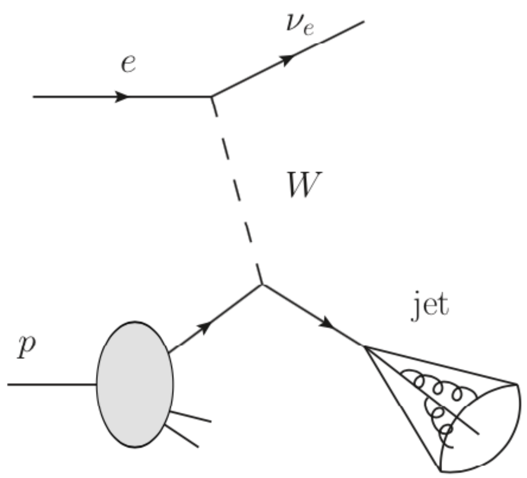


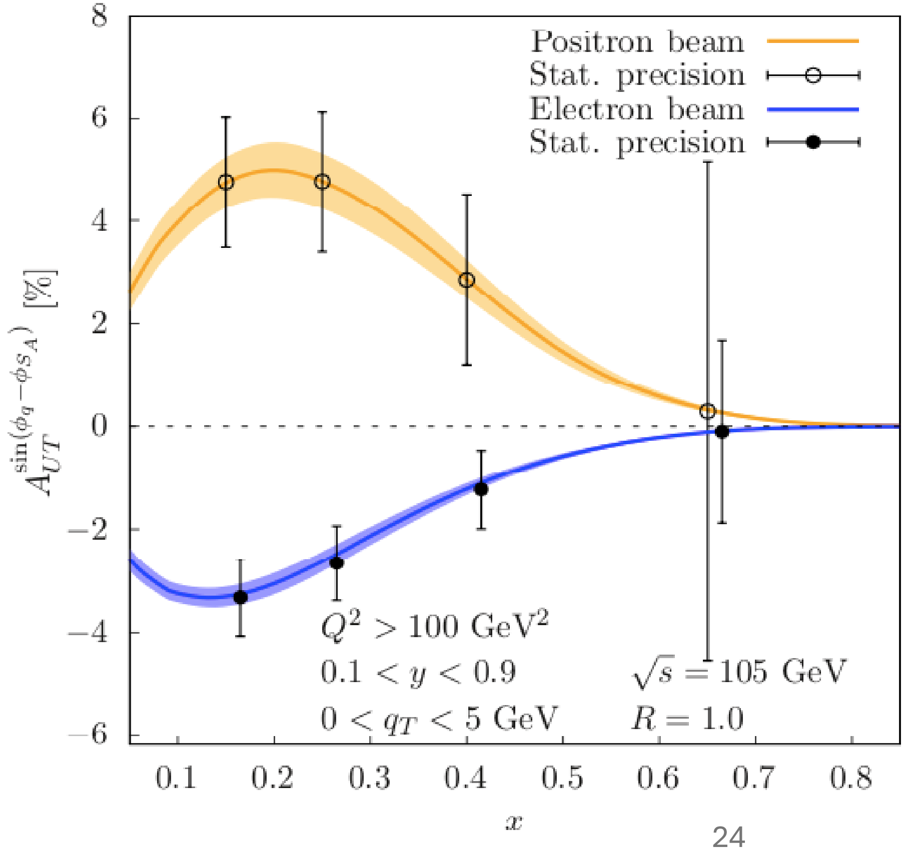


- Tension exists between neutrino DIS and SIDIS measurements of strange content and LHC extractions
- EIC is sensitive to strange content via charm production in charged-current DIS
- Charm is tagged within a jet via the presence of displaced tracks – good charm efficiency is seen, and methods are being refined
- Charm jet measurements at EIC should be able to discriminate between low and high strangeness scenarios

Charged Current Lepton-Jet Correlations

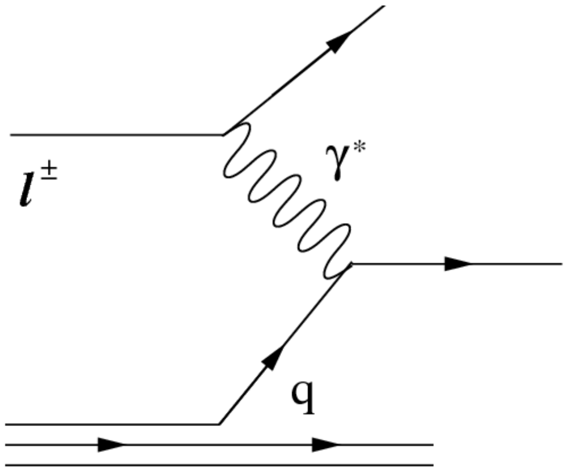


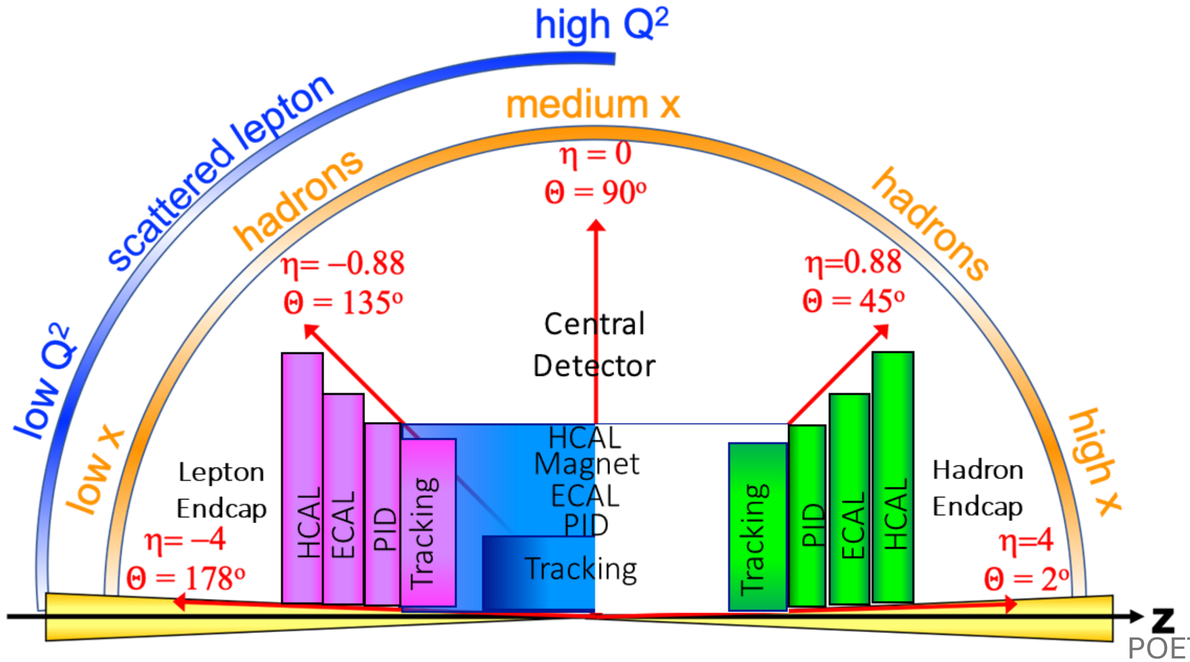


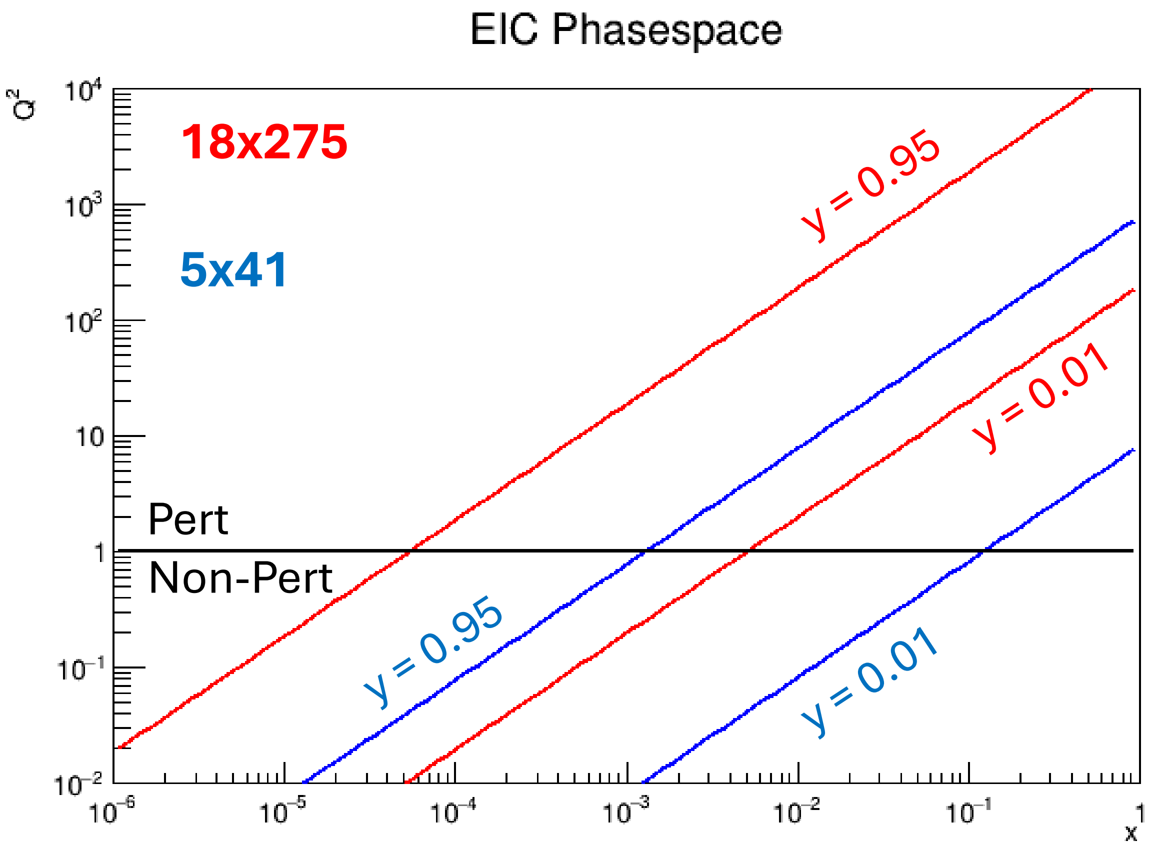


- ❑ Previous lepton-jet and hadron-in-jet measurements can also be carried out in charged current DIS where the outgoing neutrino is deduced via missing transverse energy
- ❑ Charge conservation leads to flavor separation
- ❑ Chiral odd nature of interaction means Collins asymmetries vanish at leading order

DIS Event Kinematics

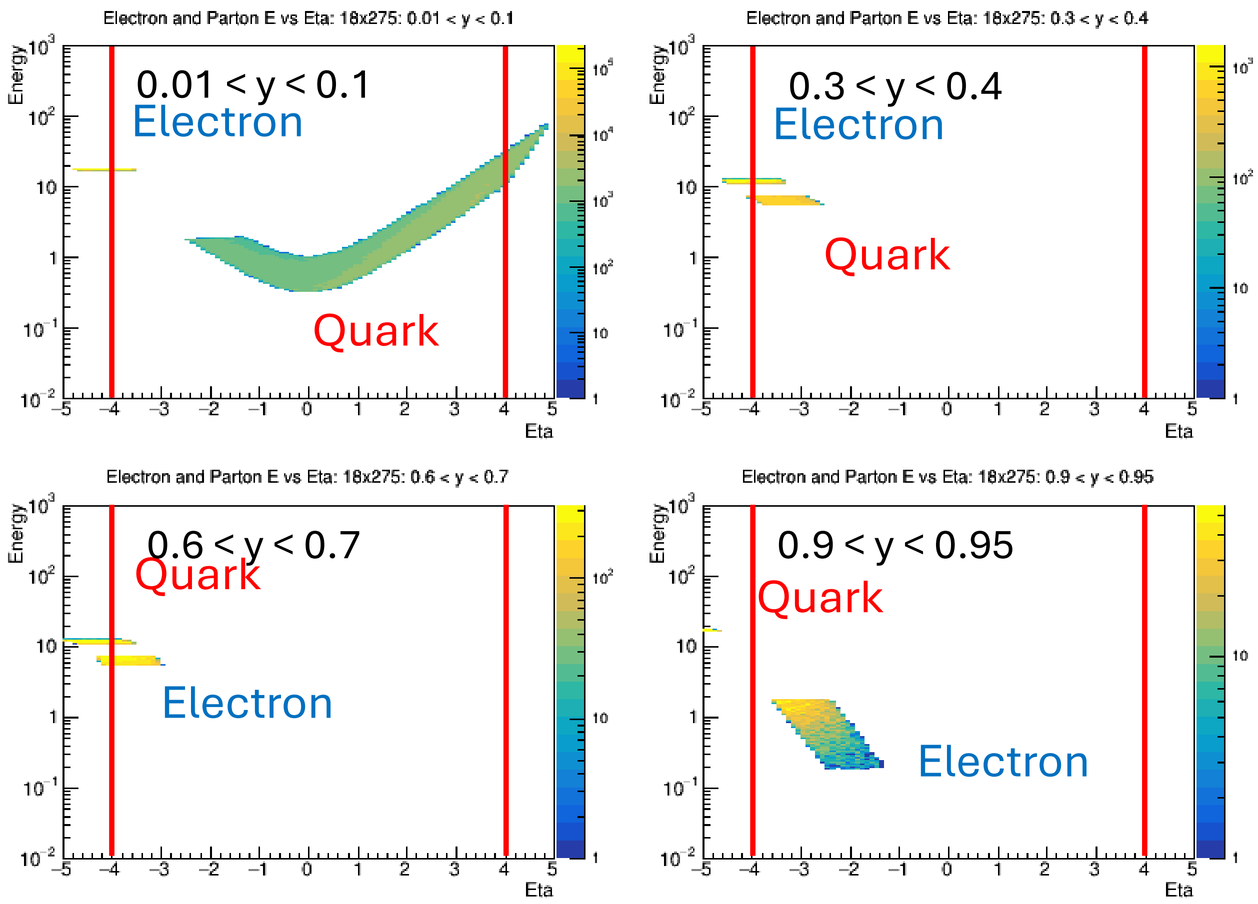






- ❑ For the leading order process, jet location and energy are dictated by the event kinematics (x, Q^2, y)
- ❑ For a given Q^2, inelasticity determines x value probed and pseudorapidity of the jet
  - ➢ Low y -> high x, jet at positive pseudorapidity
  - ➢ High y -> low x, jet at negative pseudorapidity

Electron and Struck Quark (18x275)

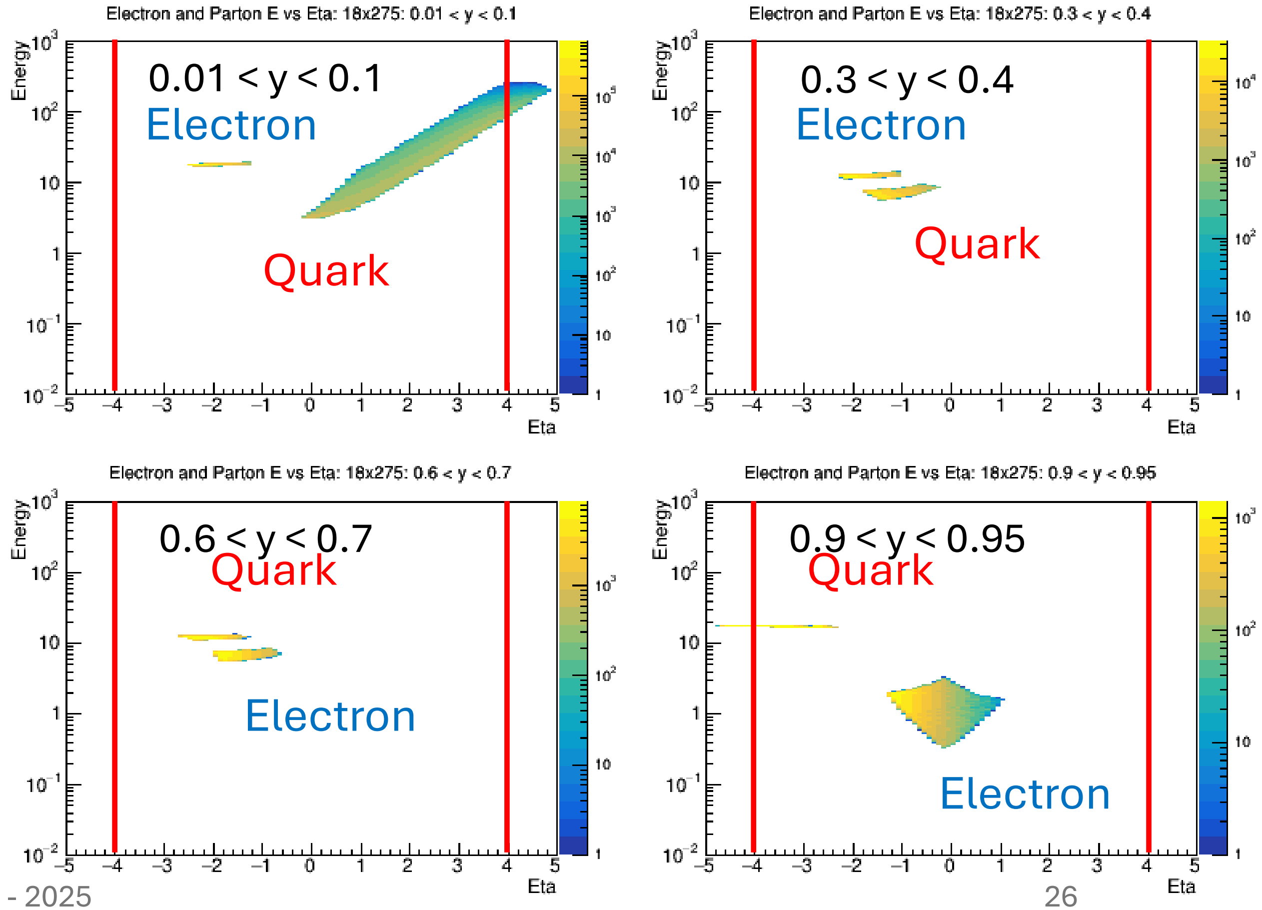


$0.1 < Q^2 < 1.0$

- ❑ As y -> 0, the struck quark can take the full ion beam energy
- ❑ As y -> 1, the struck quark takes the full electron beam energy

- ❑ At fixed Q^2 and y, larger beam energies push the electron and parton to lower pseudorapidity values

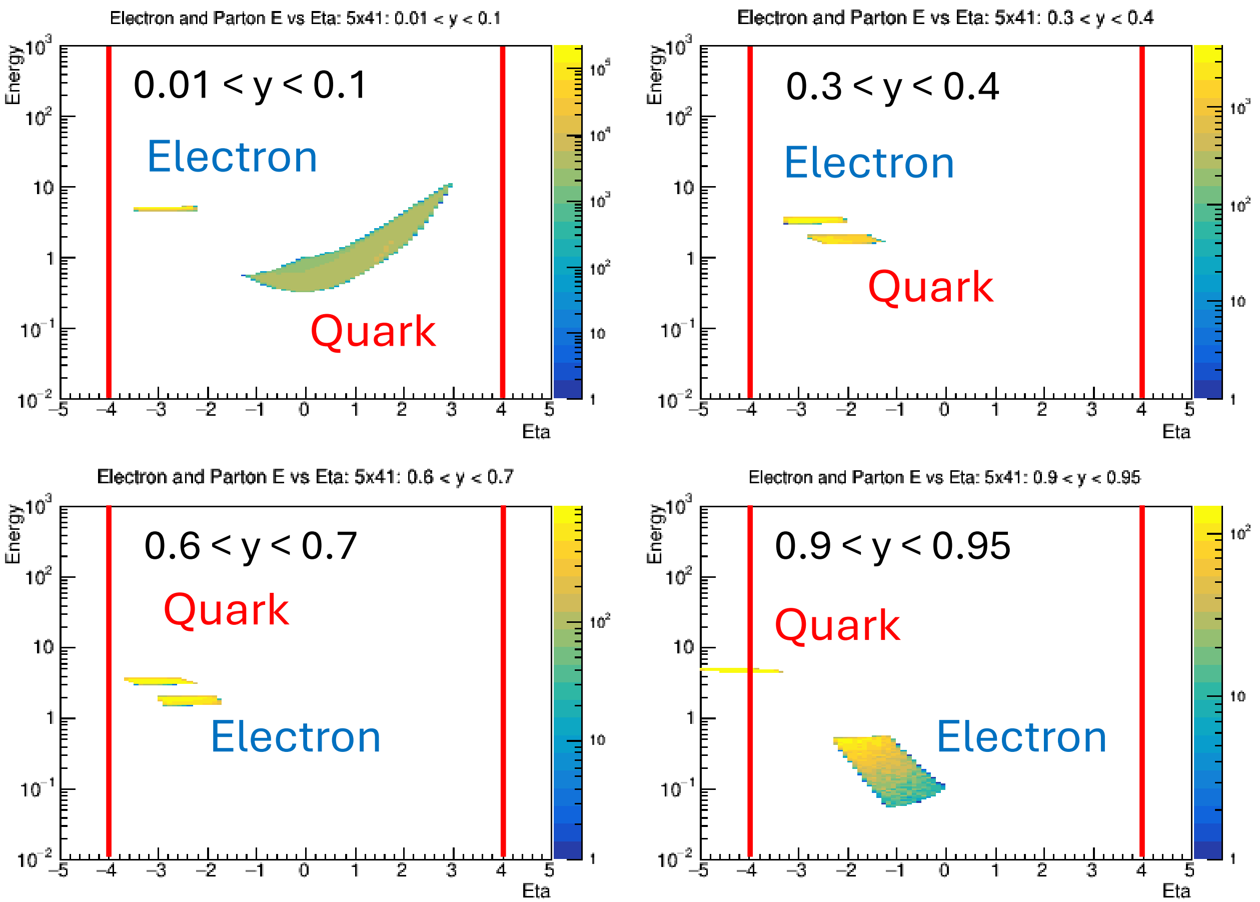
$10 < Q^2 < 100$



Electron and Struck Quark (5x41)

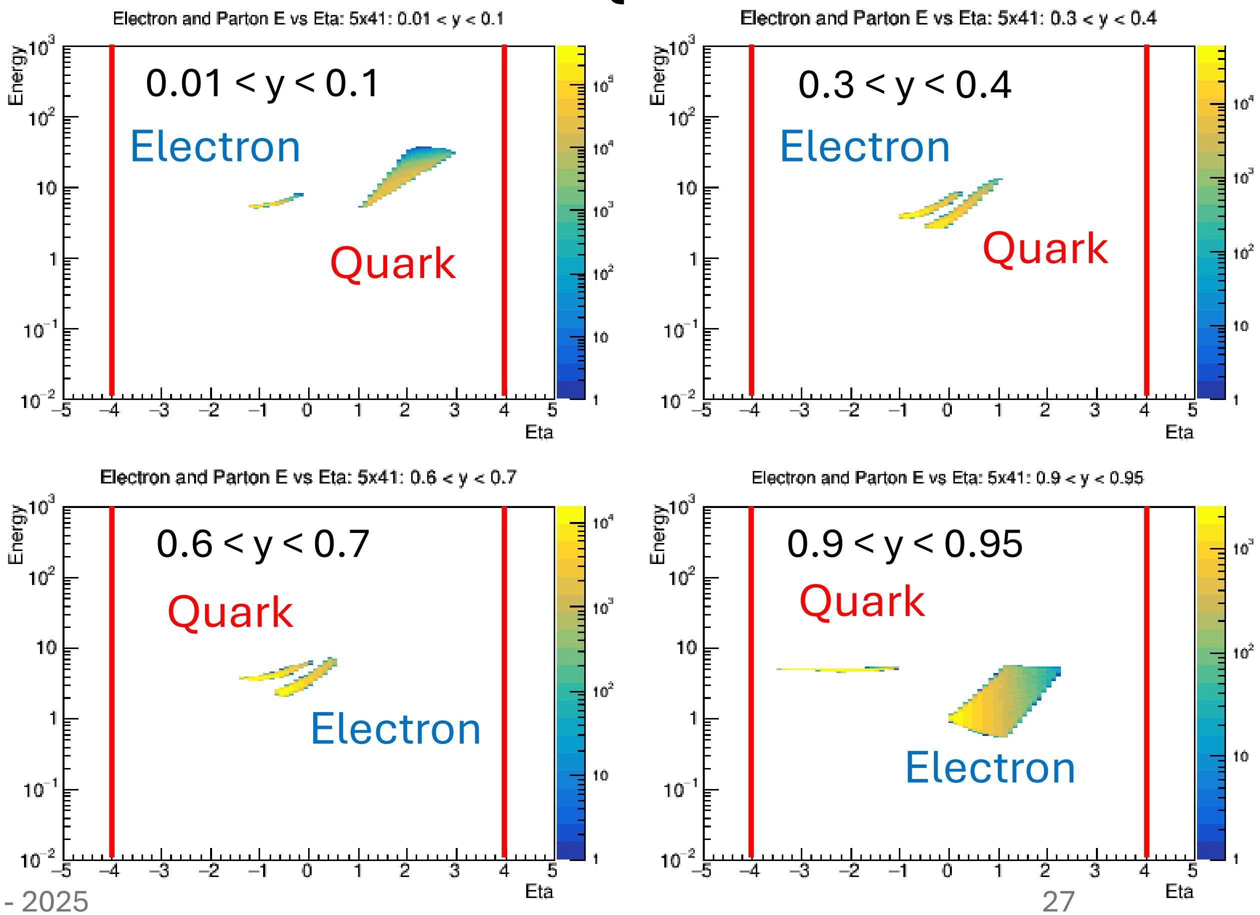
- ❑ Look at energy vs pseudorapidity of the scattered electron and struck quark as a function of y and Q^2

- ❑ For fixed Q^2, as y increases, electron eta increases while parton eta decreases



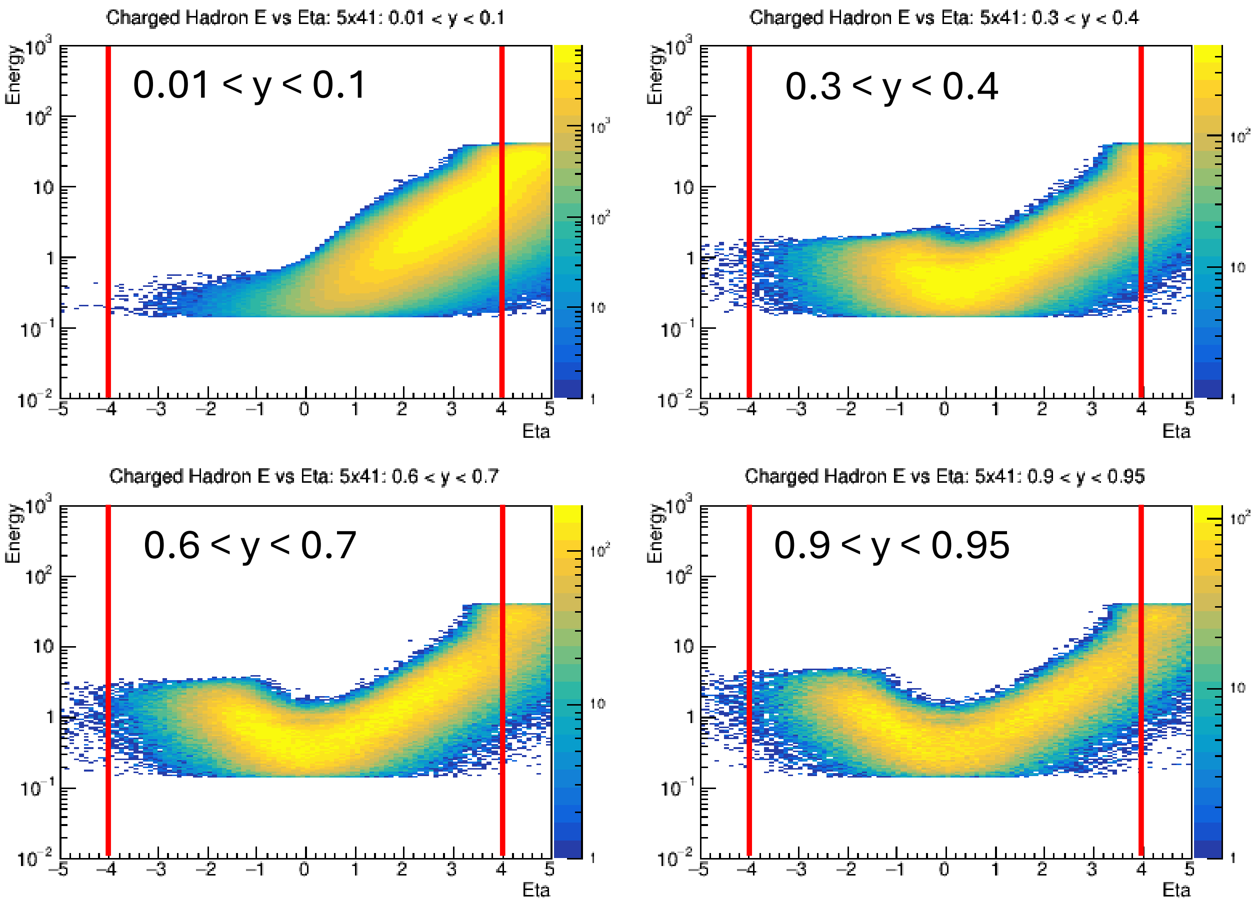
$0.1 < Q^2 < 1.0$

$10 < Q^2 < 100$



- ❑ As Q^2 increases, both the scattered electron and struck quark move to larger eta for all values of y

(Charged) Particle Distributions (5x41)

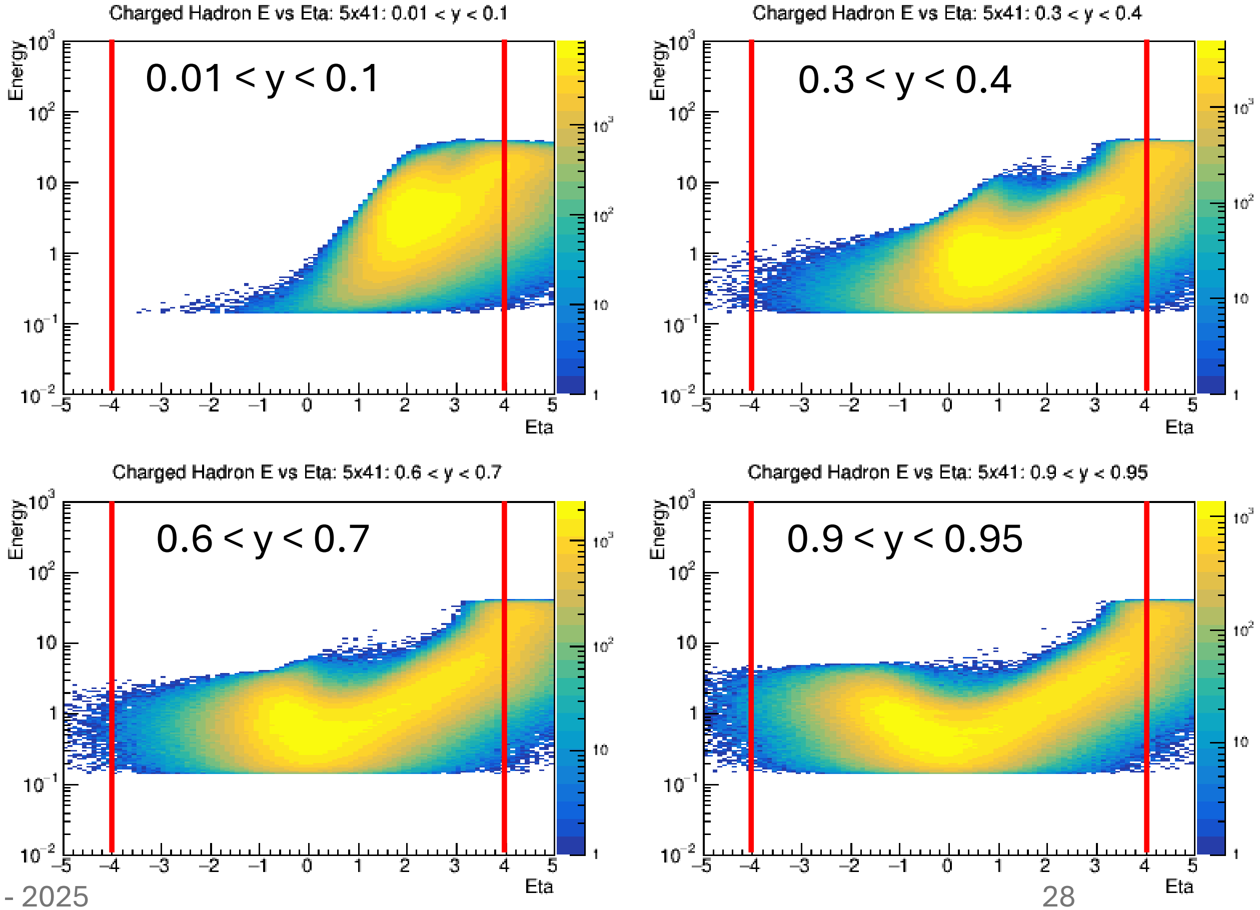


$0.1 < Q^2 < 1.0$

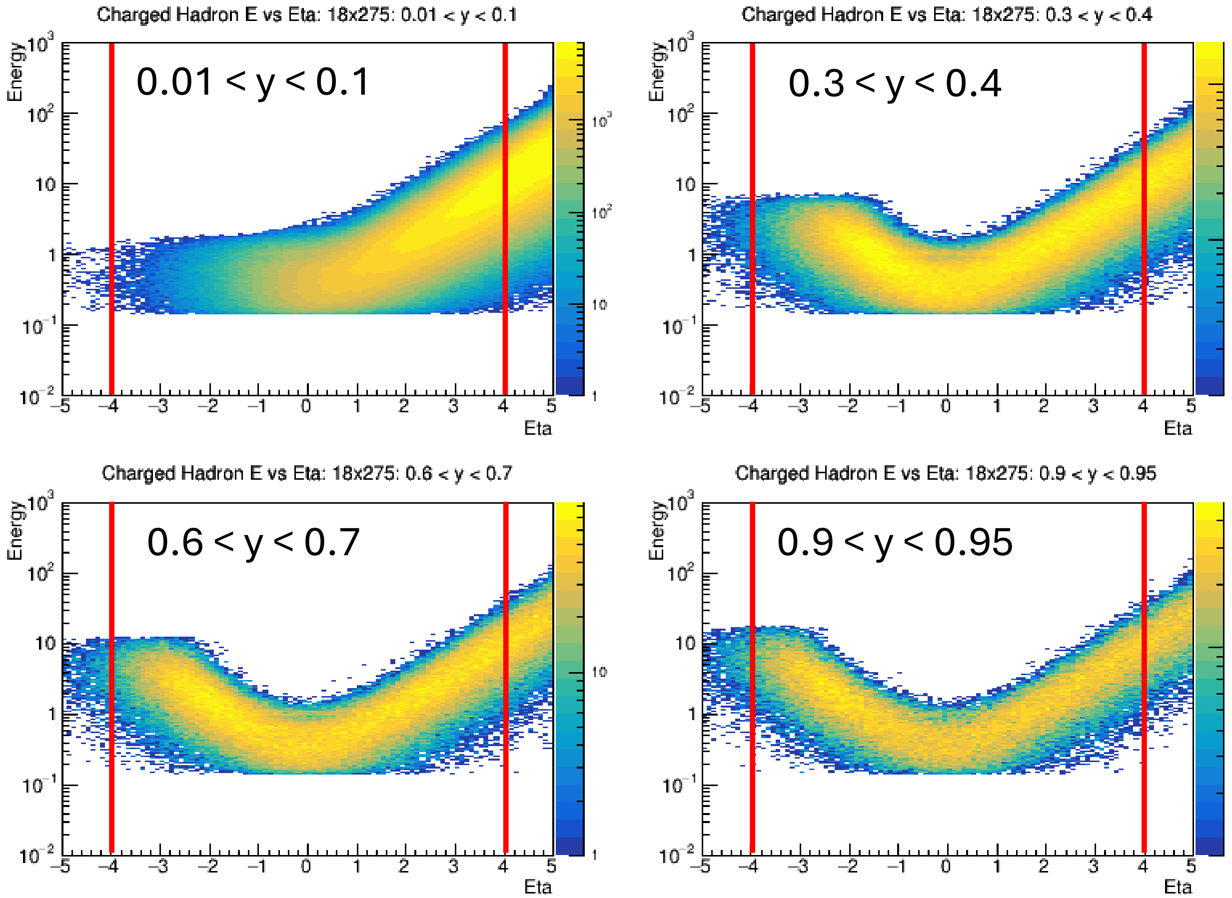
- ❑ Particle production not associated only with struck parton
- ❑ Gammas and neutrals follow same pattern

- ❑ Of course, it is final state hadrons which are measured
- ❑ Differences with y and Q2 are now somewhat less pronounced

$10 < Q^2 < 100$



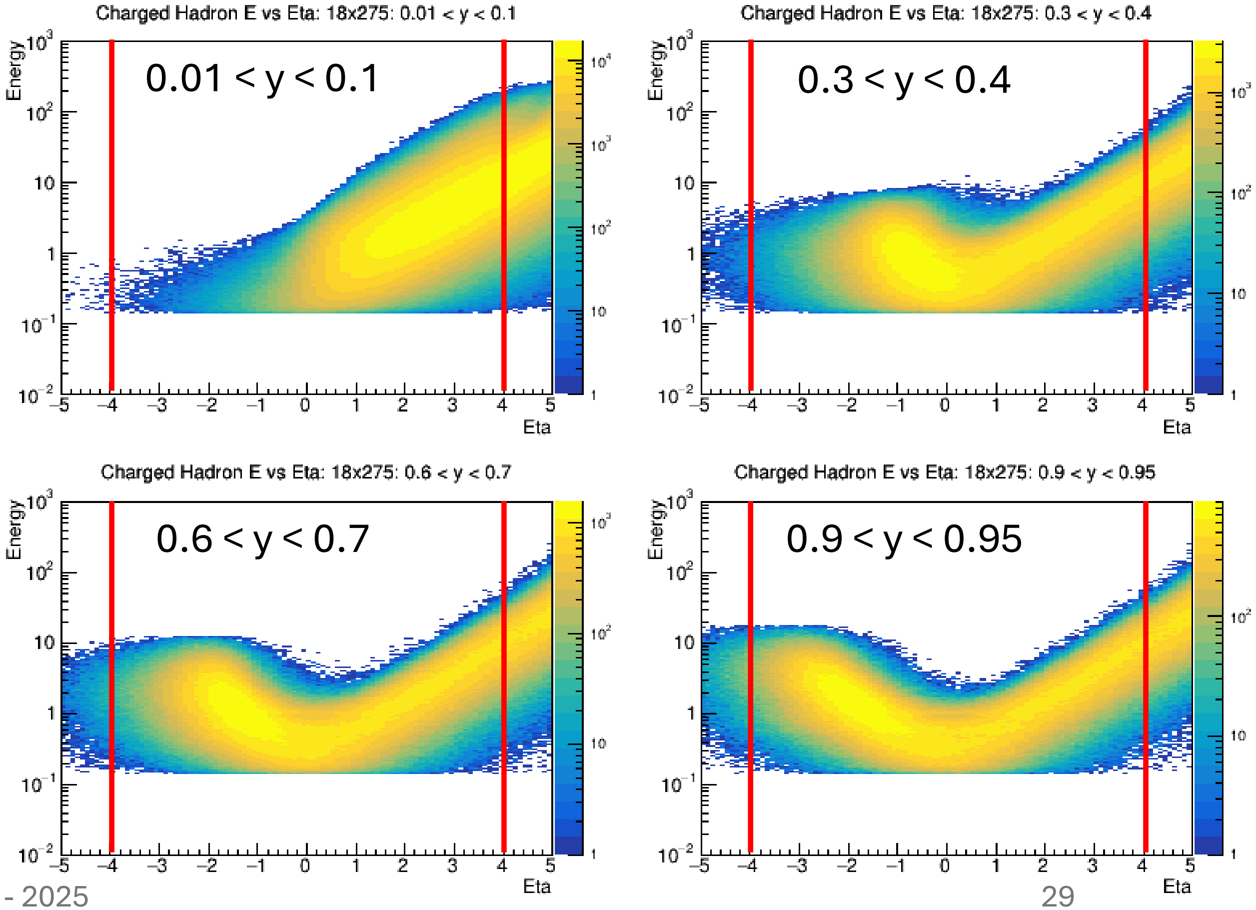
(Charged) Particle Distributions (18x275)



$0.1 < Q^2 < 1.0$

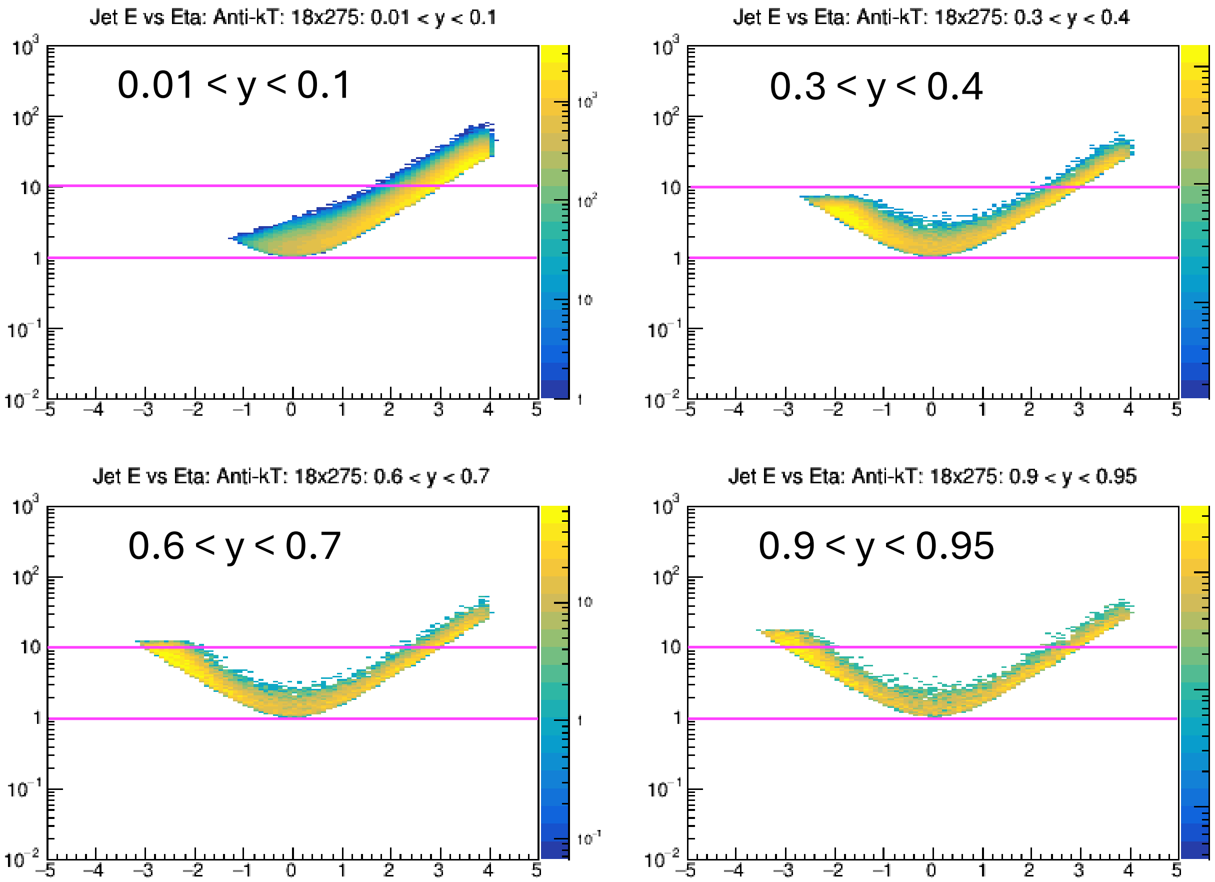
- ❑ Higher energy extends energy range somewhat, but basic distributions are similar

$10 < Q^2 < 100$



- ❑ How well can we reconstruct the parton kinematics from these particles?
- ❑ Can we form jets away from the struck parton?

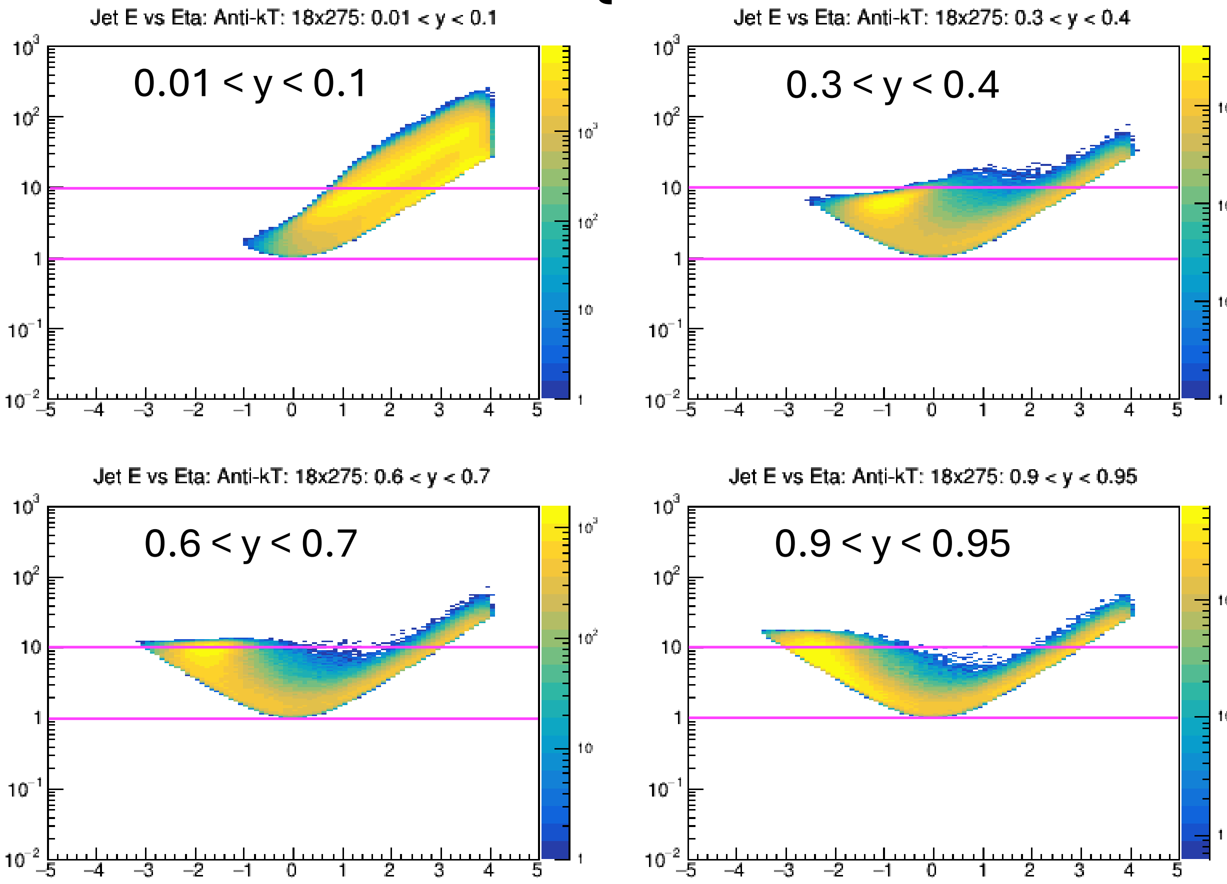
Jet Distributions: Anti_k_T (18x275)



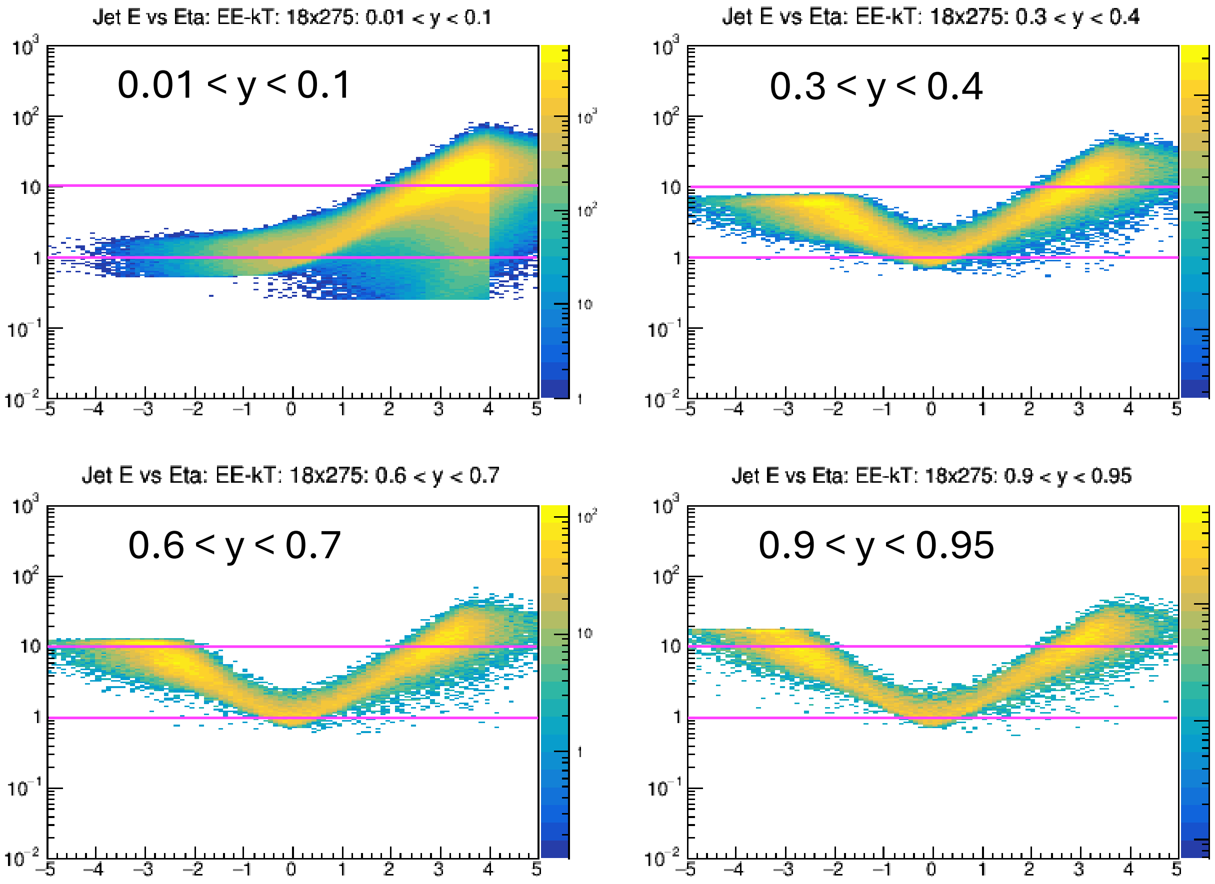
$0.1 < Q^2 < 1.0$

- Run inclusive Anti_k_T on all stable particles (|eta| < 4) with 1 GeV minimum p_T cut
- Jets roughly follow particle distributions

$10 < Q^2 < 100$



Jet Distributions: EE_k_T (18x275)

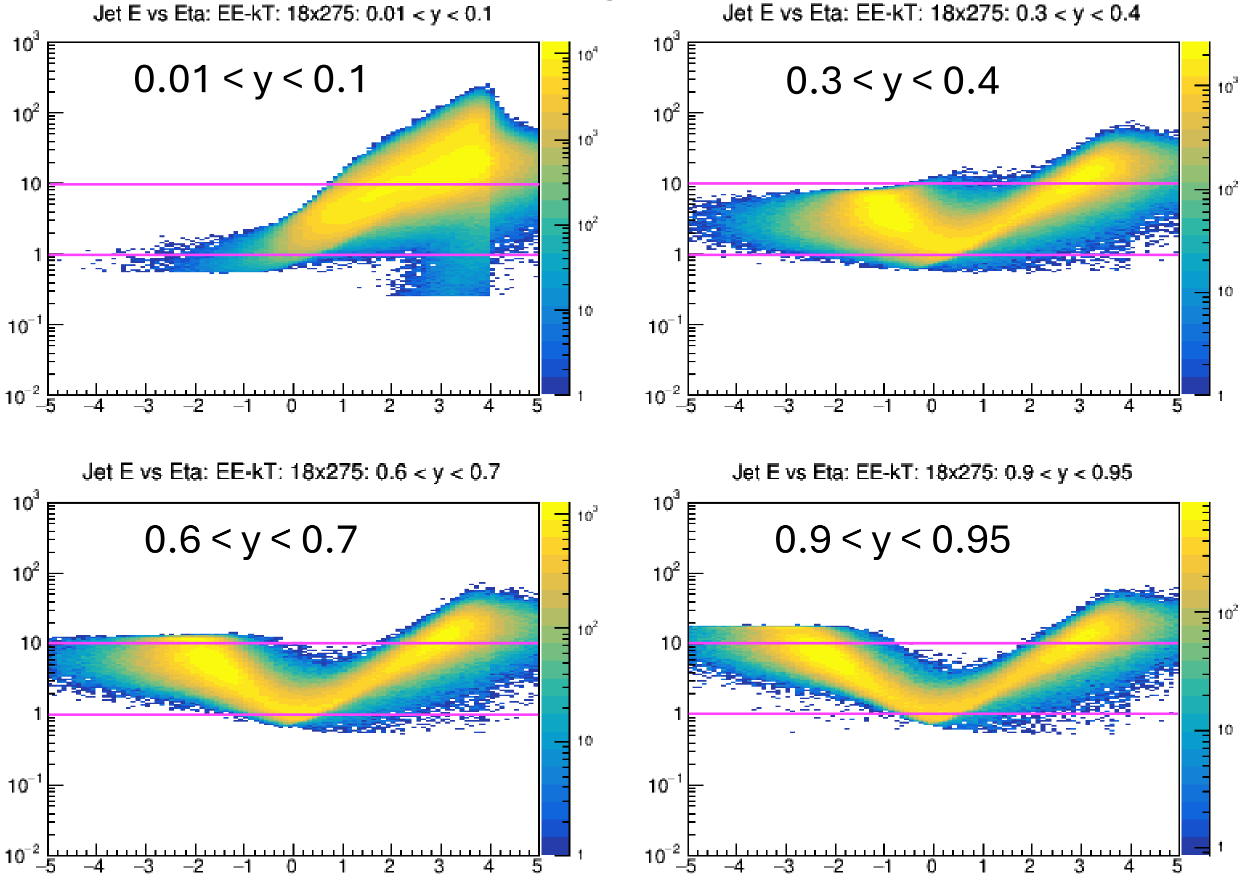


$0.1 < Q^2 < 1.0$

- ❑ Need to understand the artifact around eta = 4, must be related to particle eta cut

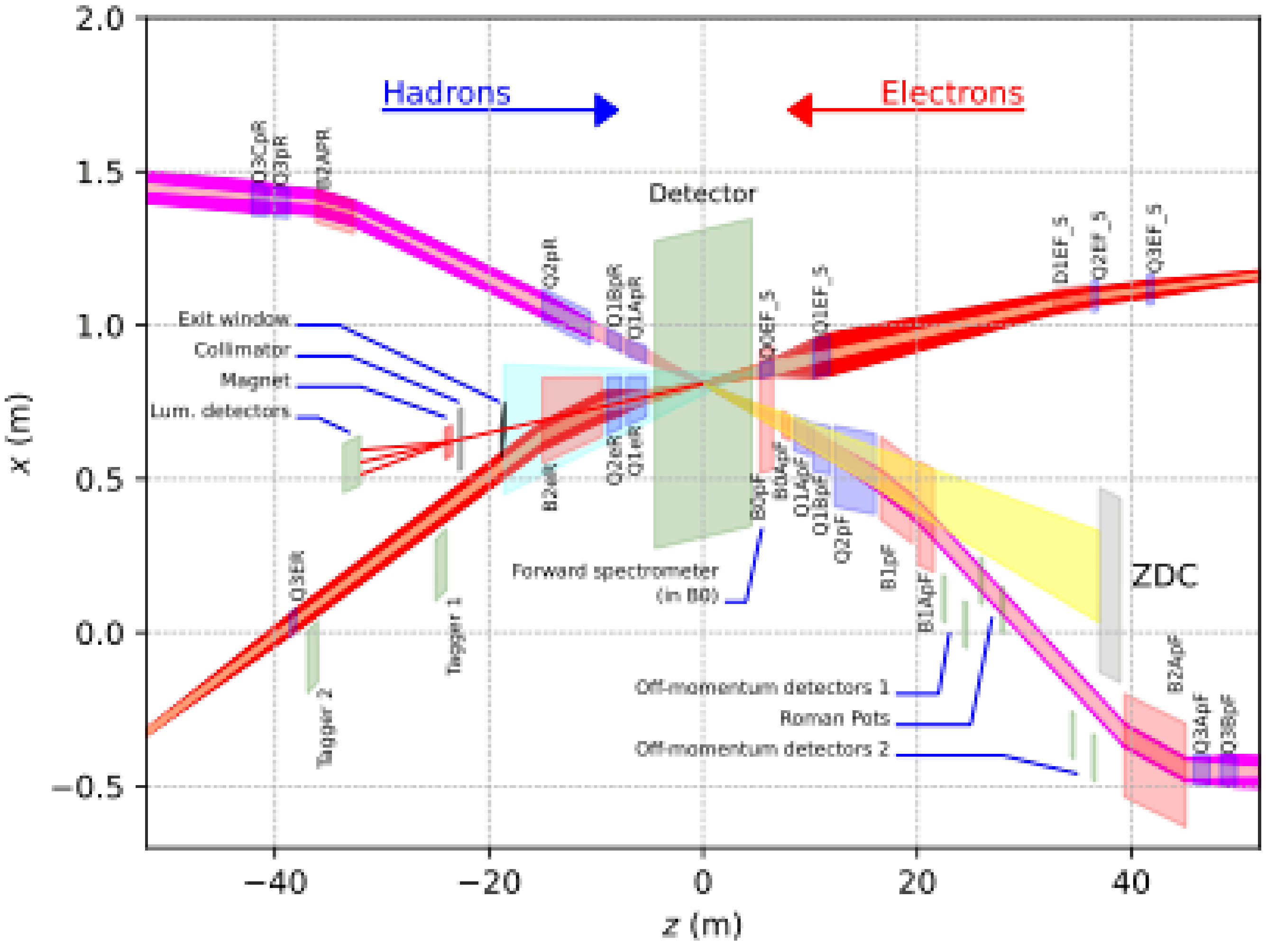
- ❑ Overall distributions are similar for EE_k_T algorithm
- ❑ In general, see larger number of jets, more jets at higher eta, and more jets away from struck quark

$10 < Q^2 < 100$



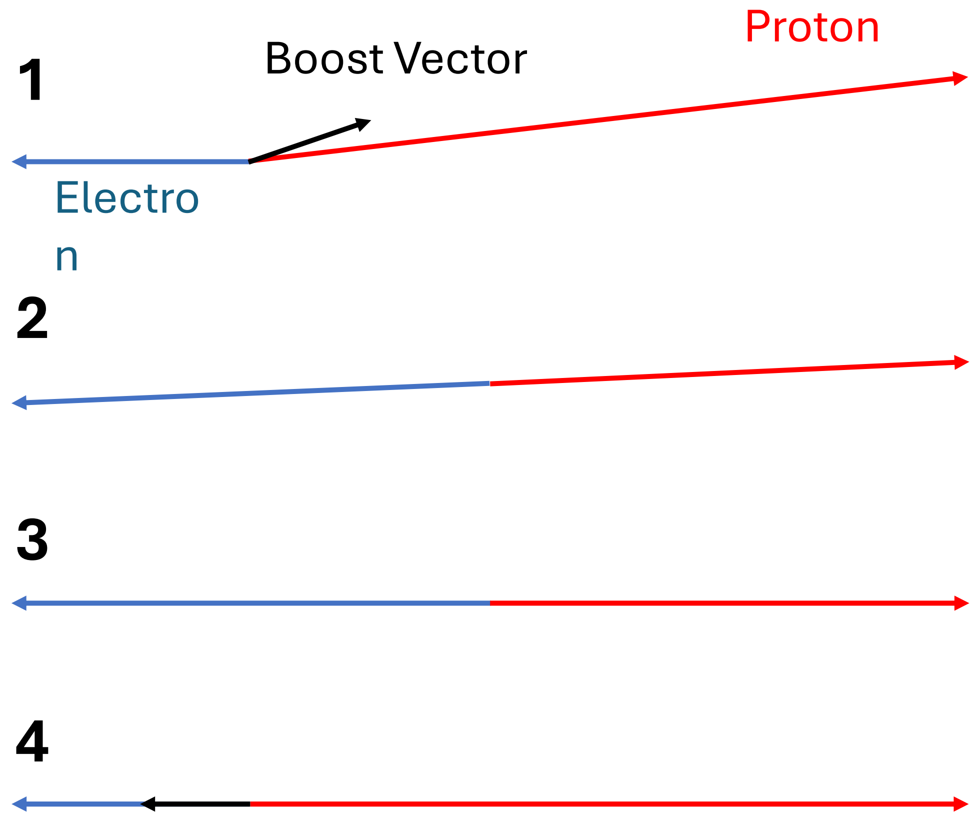
Beam Crossing Angle

- Both interaction regions at the EIC will feature significant beam crossing angles (25 mRad for IP6 and 35 mRad for IP8)
- Crossing angles needed to avoid parasitic collisions which would degrade beams
- Presence of crossing angle will affect acceptance and detector design in the proton-going endcap – a region of great importance for many jet measurements
- A summary of beam effects, including crossing angle, bunch crabbing, divergence, etc as well as methods for simulating these can be found in the technical note here: https://zenodo.org/record/6514605#.ZETiIOzMJAY



Head-On (Minimum Boost) Frame

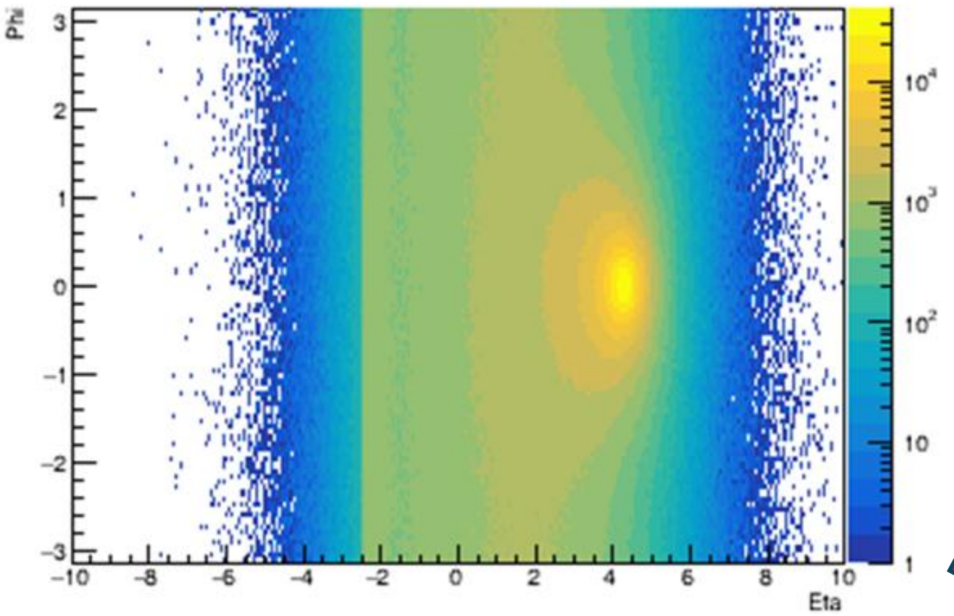
- ❑ Can boost and rotate into a frame in which the beams are collinear (no crossing angle) and energies are very close to the original (minimum boost)
- ❑ This should give an undistorted distribution of particles at high and low eta simultaneously



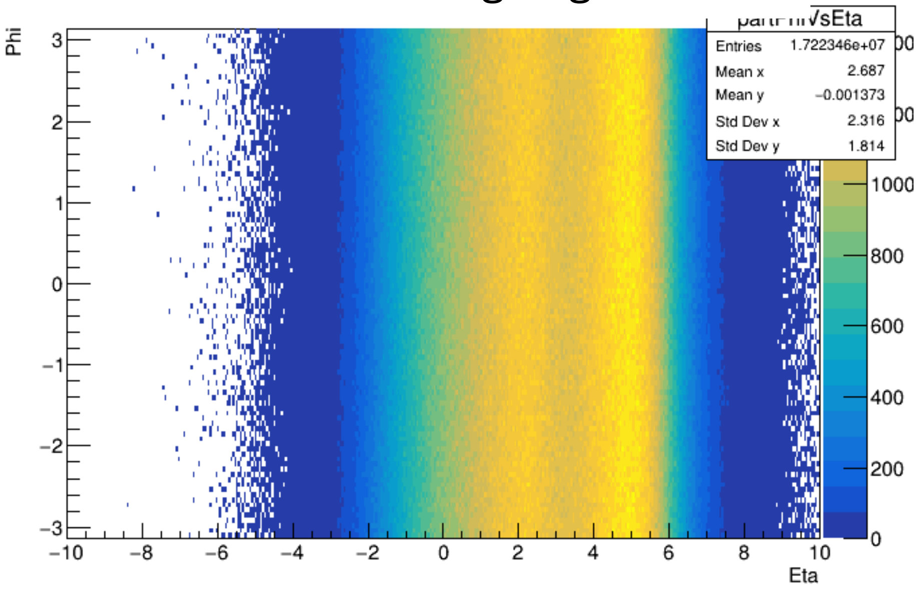
1. Initial Configuration in the Lab Frame includes a relative angle between the beams
2. Boost by sum of beam 4-momenta to get to CM Frame
3. Rotate about y-axis to eliminate x-component of momentum
4. Boost back along z to (nearly) restore original beam energies

Head-On Frame Particle Distributions

Lab Frame Distribution

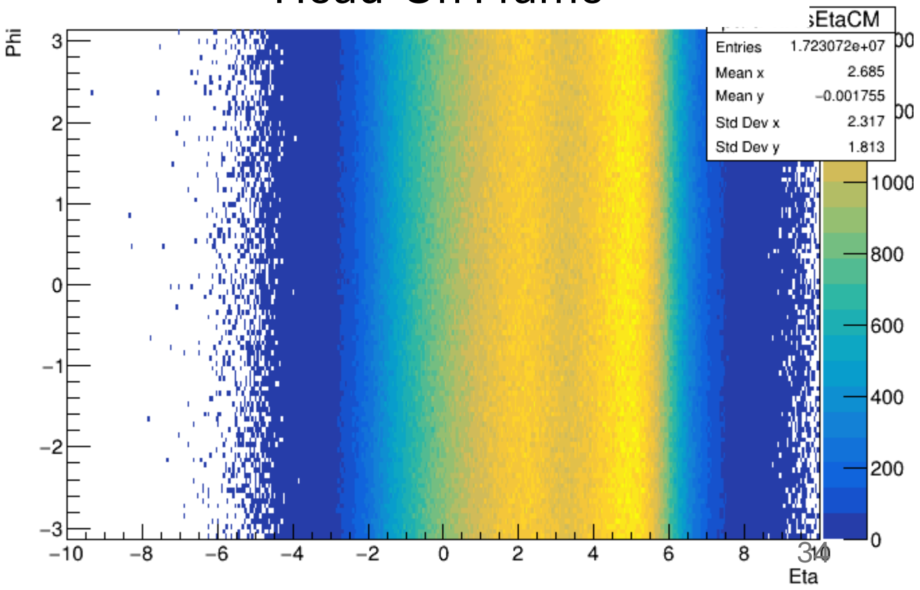


No Crossing Angle



Transform to Head-On

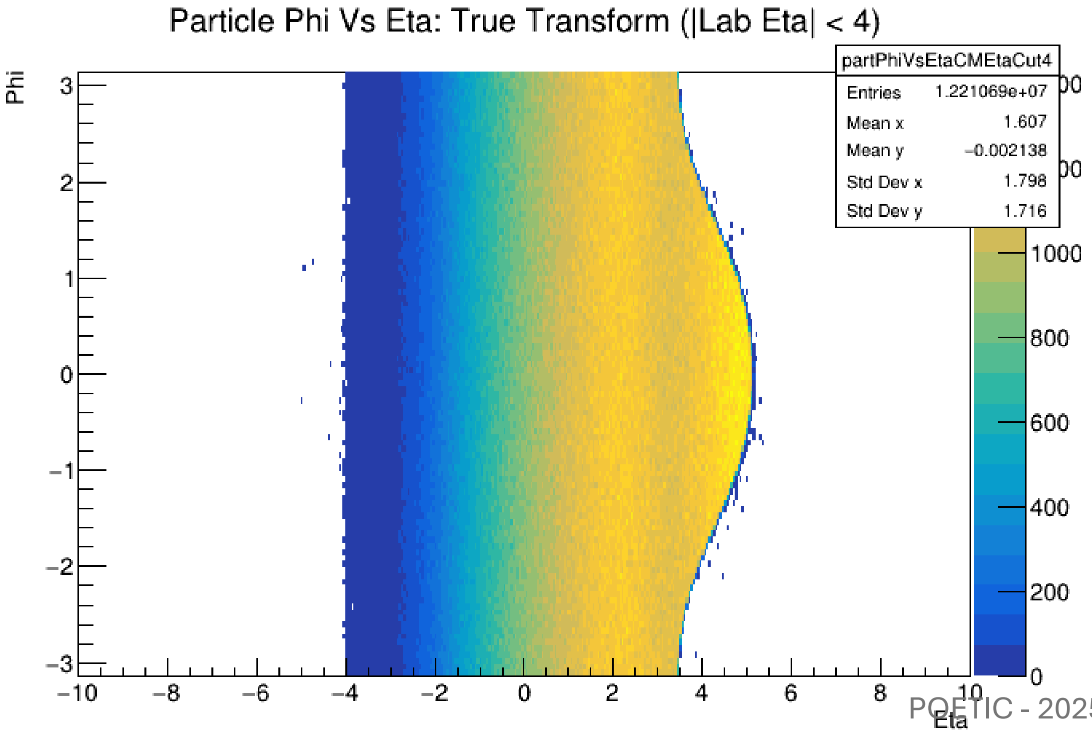
Head-On Frame



- Transformation to the head-on frame removes all features in the final state particle distribution for forward and backward regions simultaneously
- Resulting distribution matches that from default simulation with no crossing angle introduced

Detector Acceptance Consideratior

- The head-on frame distributions shown previously assumed infinite acceptance – what effect will finite detector acceptance have?
- Displacement between beams means that acceptance cuts in the lab frame (w.r.t. the electron beam) will introduce phi-dependent acceptance features in head-on frame
- Try defining acceptance cuts w.r.t. the hadron beam instead



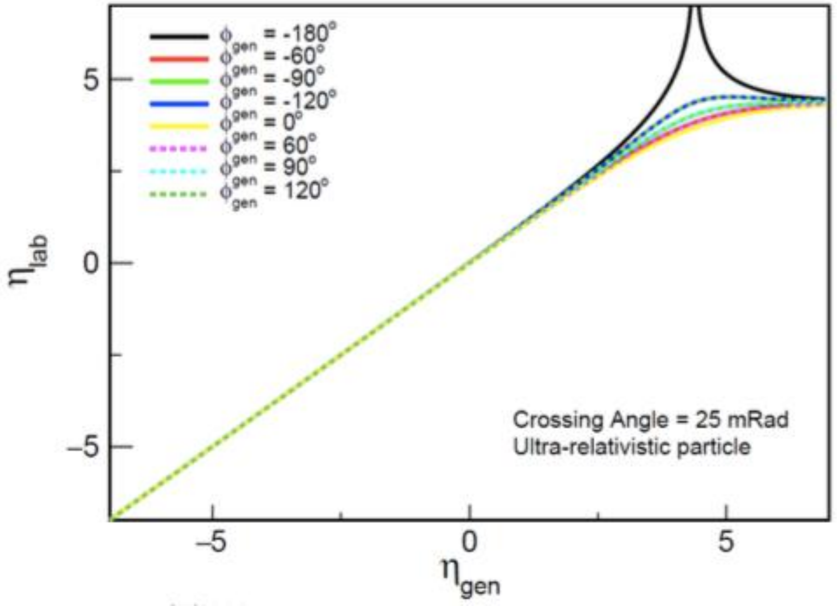
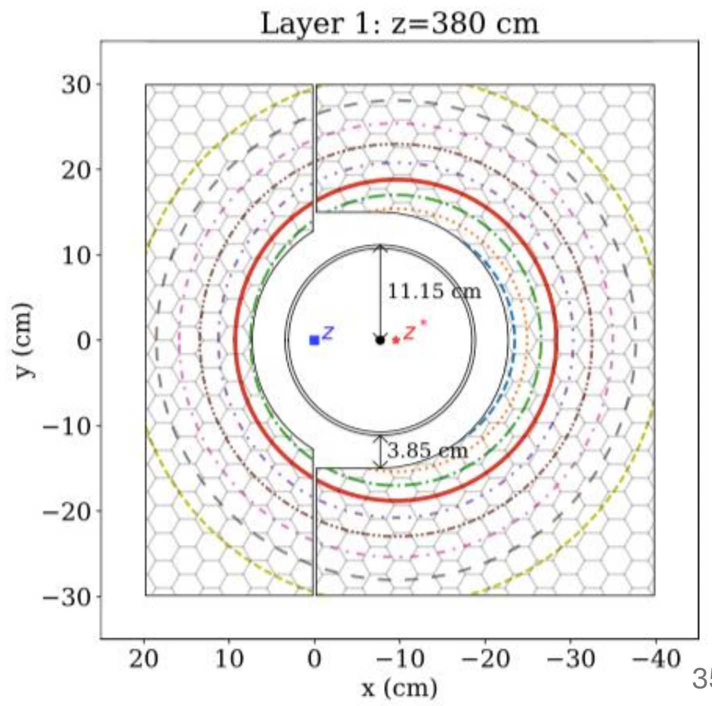


Figure by Barak Schmookler



arXiv:2208.05472

Defining Acceptance Cuts

- The beam line shape in the endcap region is complicated, but mostly follows the hadron beam direction

- The z-axis in the head-on frame corresponds to the direction of the lab frame proton beam -> defining detector acceptance w.r.t. the hadron beam should eliminate the phi-dependent artifact
- Both plots on the right show the phi vs eta distribution where these quantities are defined in the head-on frame
  - Top plot applies a cut for |eta| < 4 where eta is defined relative to the electron beam
  - Bottom plot applies a cut for |eta| < 4 where eta is defined relative to the hadron beam