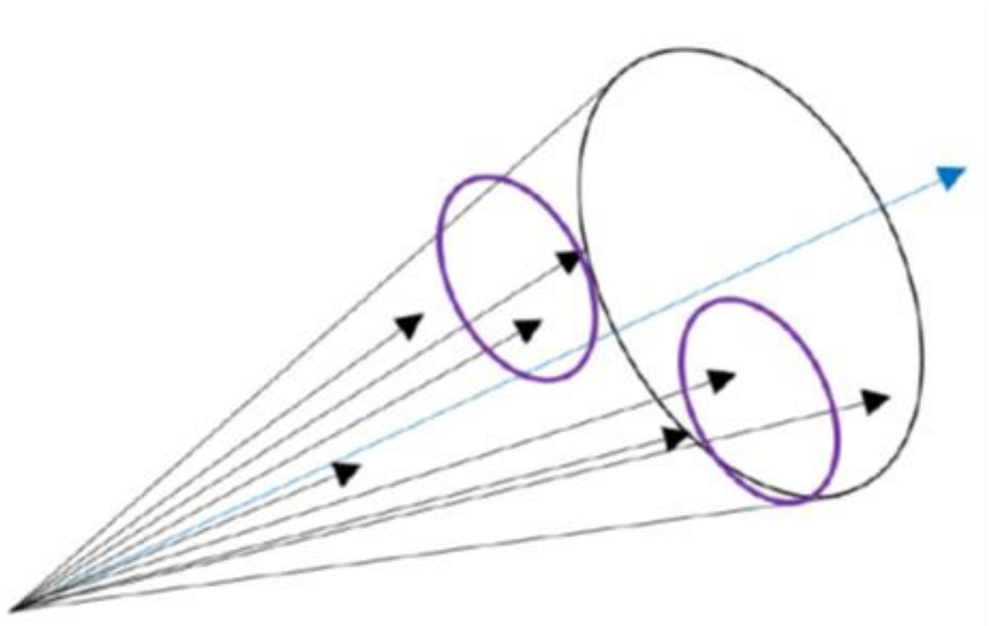
An Overview of Jets at the EIC

Brian Page

2nd Workshop on Non-perturbative QCD and Energy Flow

November 6th, 2023



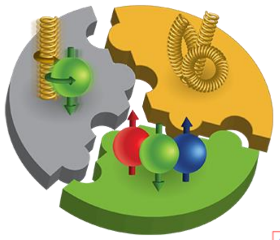
Outline

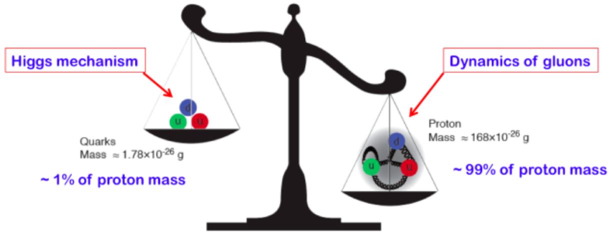
- ❑ Introduction
- ❑ Select Jet Measurements
- ❑ Practical Aspects of Jet Measurements at EIC
  - ➢ Partonic -> Particle -> Jet Kinematics
  - ➢ Detector Considerations
- ❑ Conclusions

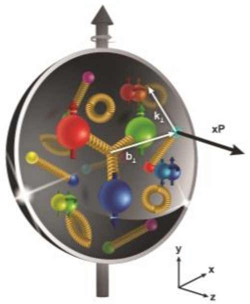
The EIC Physics Pillars

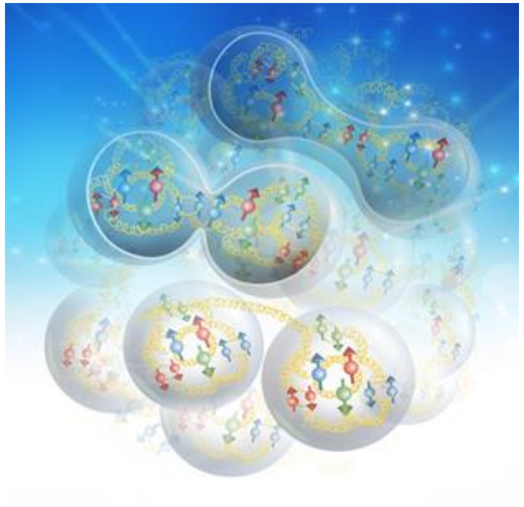
How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

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









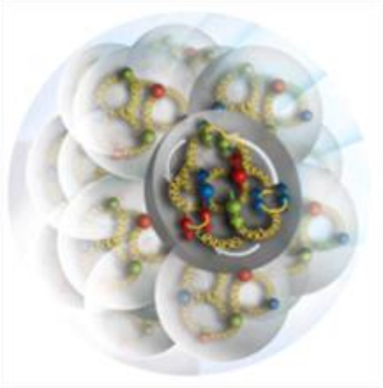
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

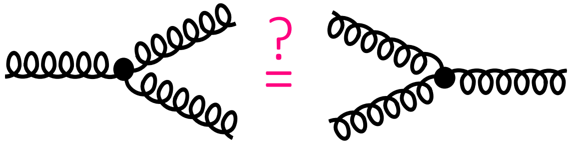
How do the confined hadronic states emerge from these quarks and gluons?

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?





Jet Physics at the EIC

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

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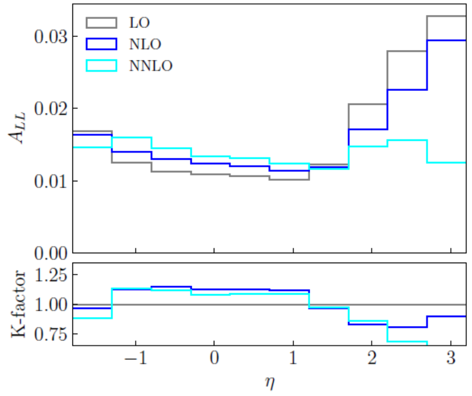
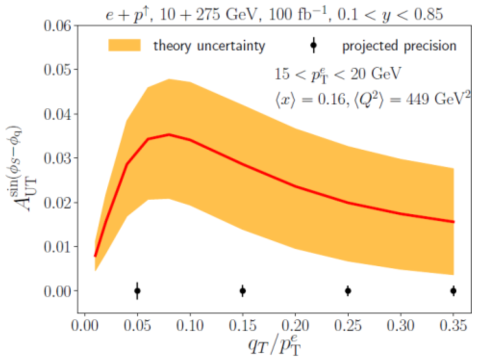
The importance of jet probes was reflected in the EIC Yellow Report where they touched on nearly every major physics topic (Nucl. Phys. A, Vol 1026, 122447)

Global properties and parton structure of hadrons



Borsa, de Florian, Pedron `20

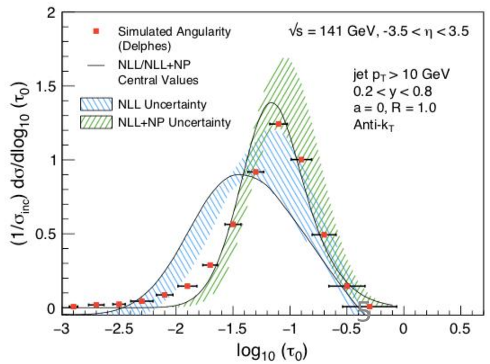
Multi-dimensional imaging of nucleons, nuclei and mesons



Arratia, Kang, Prokudin, Ringer `20

The nucleus: a laboratory for QCD

Understanding hadronization



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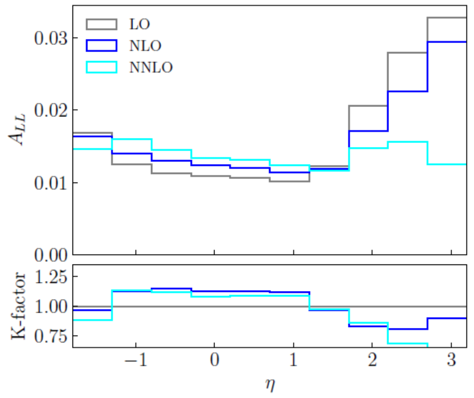

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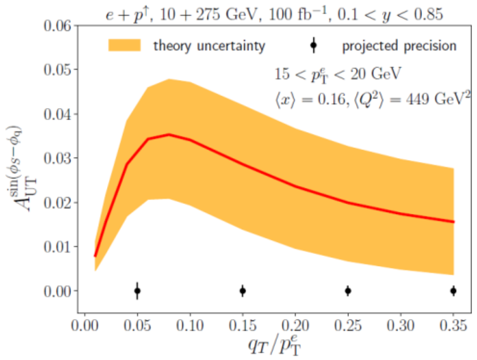

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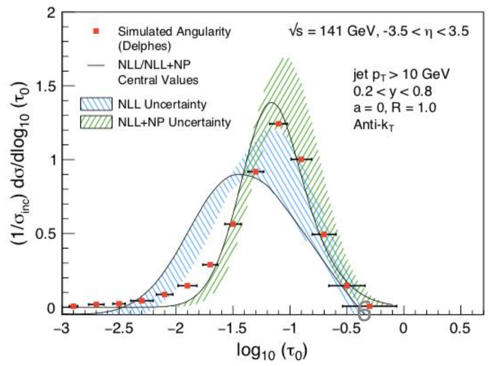

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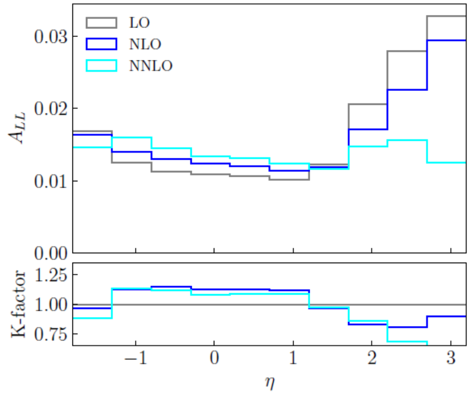

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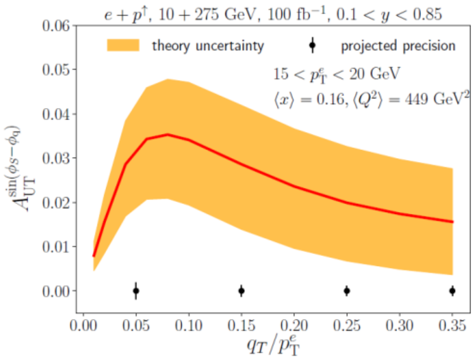

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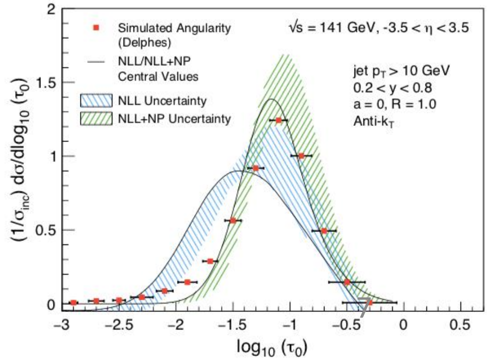

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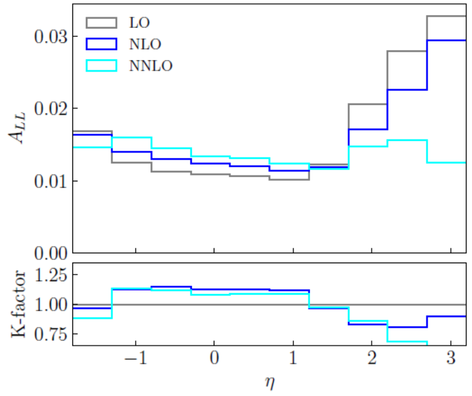

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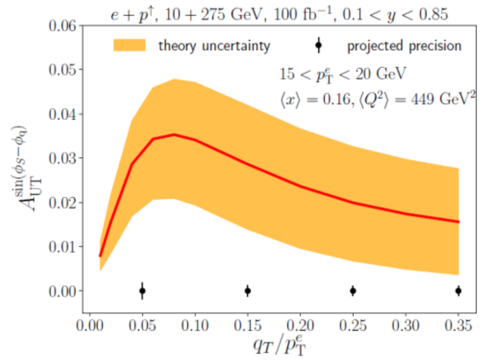

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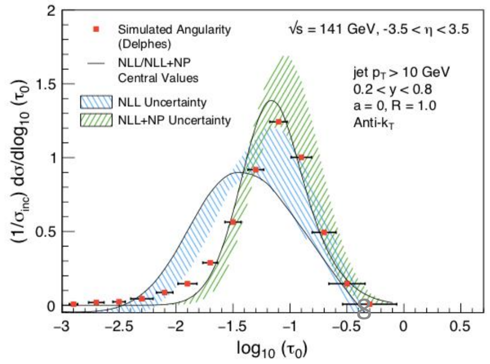

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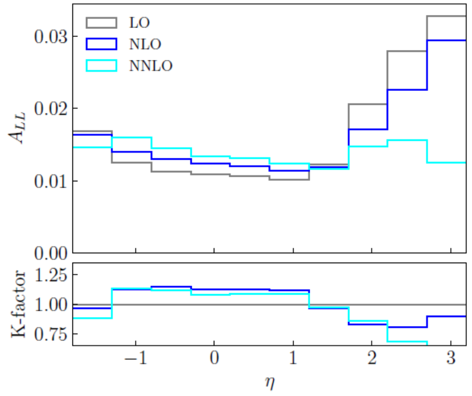

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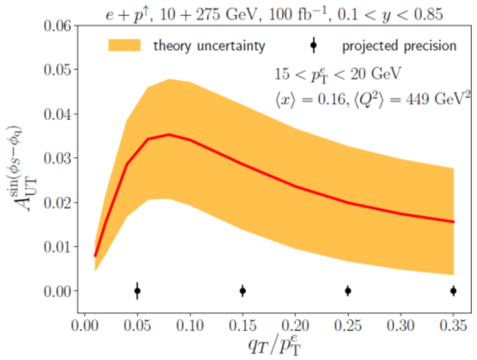

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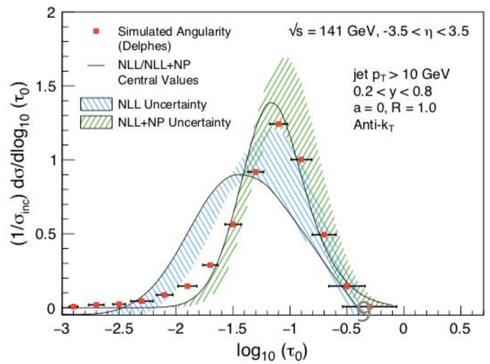

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Jets in the Yellow Report

Global properties and parton structure of hadrons

- Unpolarized parton structure of the proton and neutron
- Spin structure of the proton and neutron
- Inclusive and hard diffraction
- Global event shapes and the strong coupling constant

Multi-dimensional imaging of nucleons, nuclei and mesons

- Imaging of quarks and gluons in momentum space
- Wigner functions

The nucleus: a laboratory for QCD

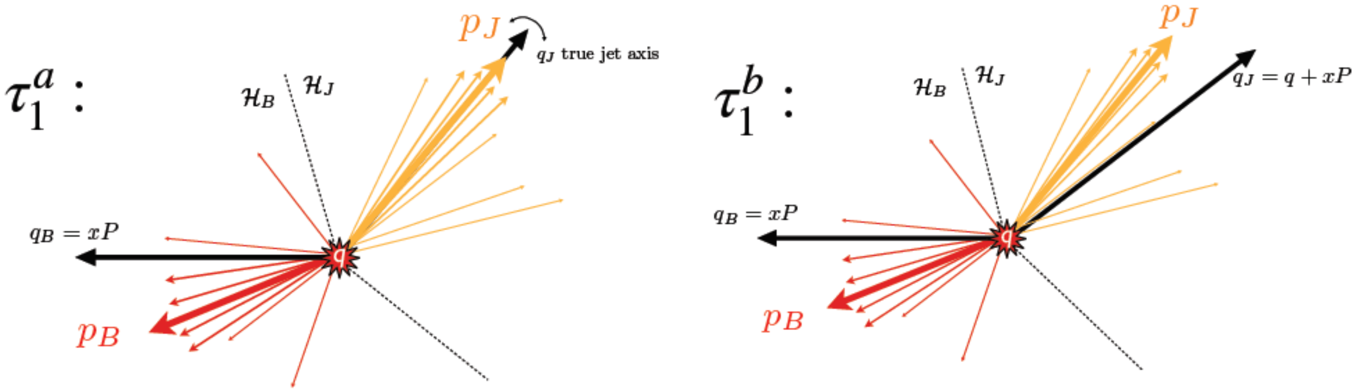
- High parton densities and saturation
- Particle propagation in matter and transport properties
- Special opportunities with jets and heavy quarks

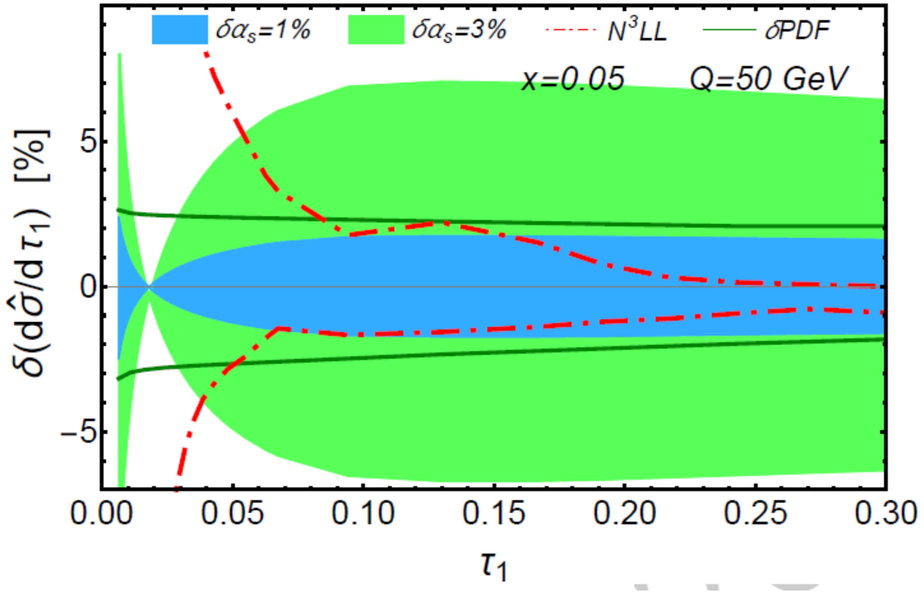
Understanding hadronization

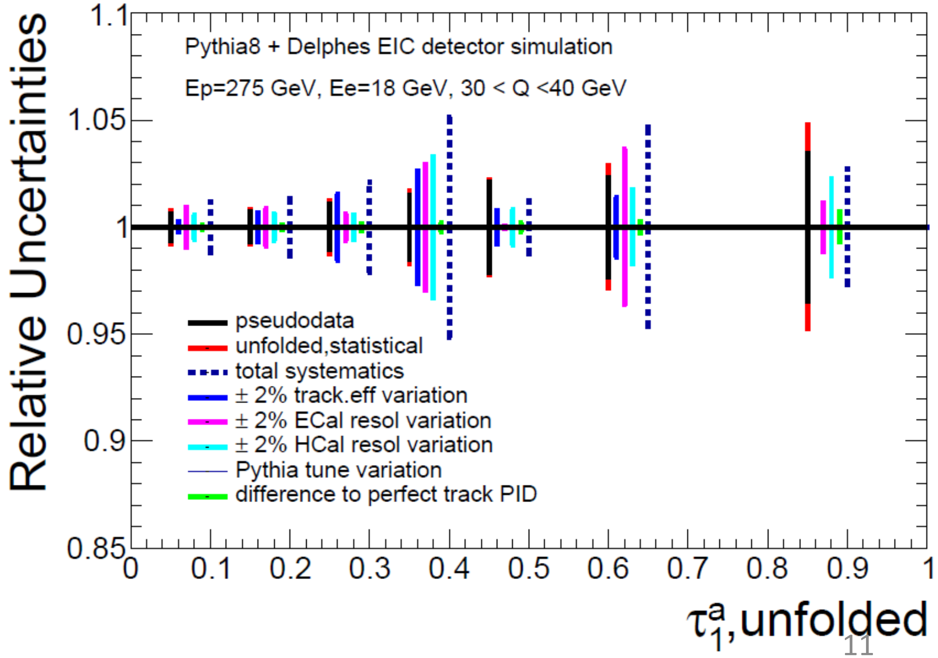
- Hadronization in the vacuum
- Hadronization in the nuclear environment

Global Event Shapes

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



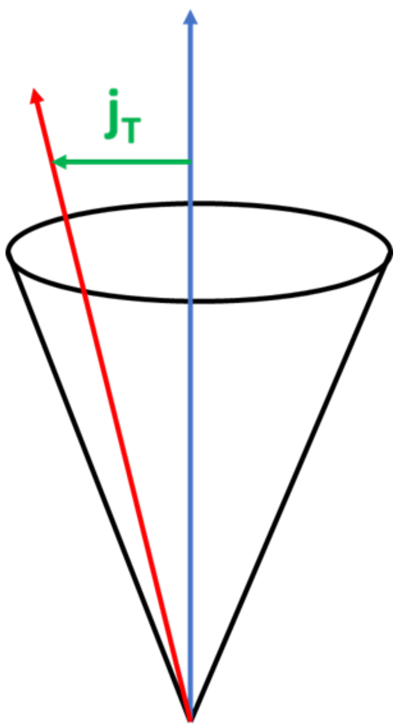




- Global event shapes offer possibility of very high precision measurements for extractions of non-perturbative parameters such as the strong coupling constant
- Detailed feasibility studies of 1-jettiness observable were carried out as part of the Yellow Report effort taking into account uncertainties on tracking efficiency and calorimeter resolution
- At N^3LL, roughly 1% precision is possible, challenging experimental problem, but recent studies show promise

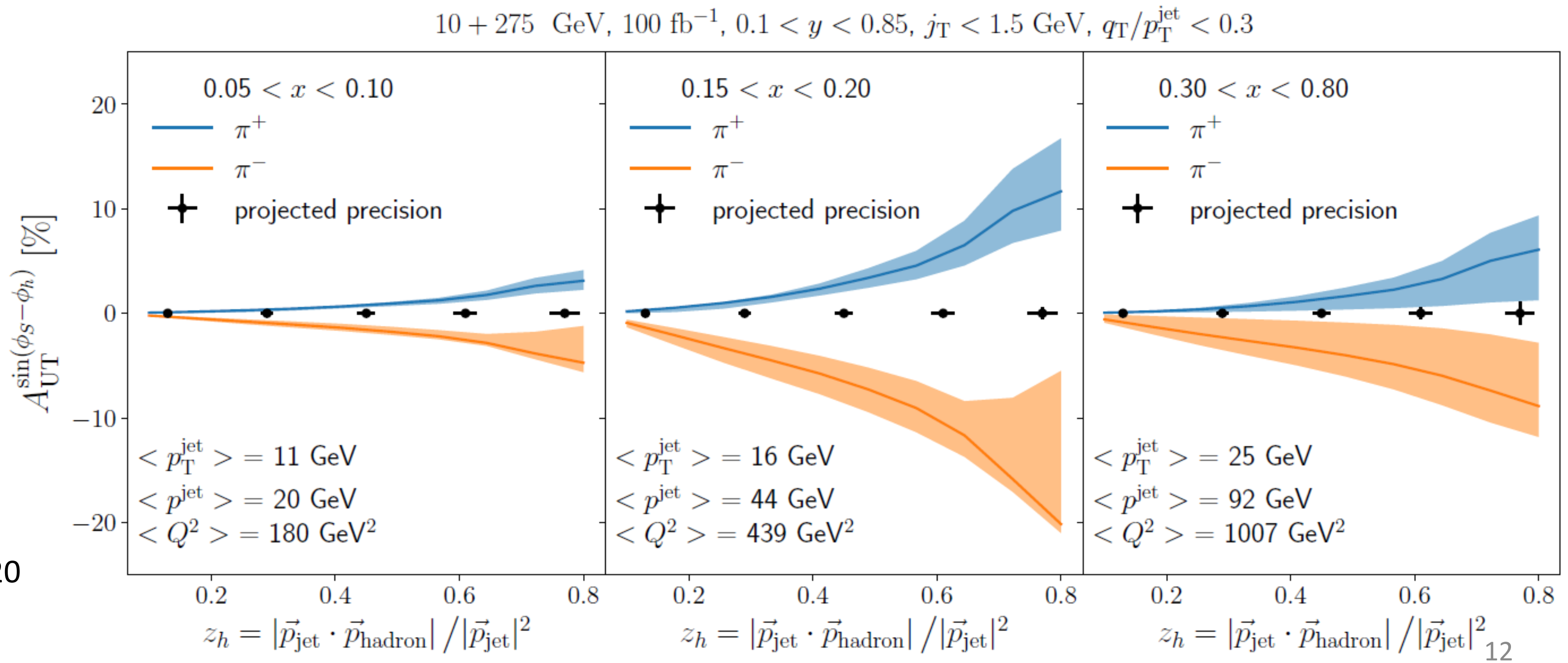
Hadron-in-Jet: Collins TMD

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



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

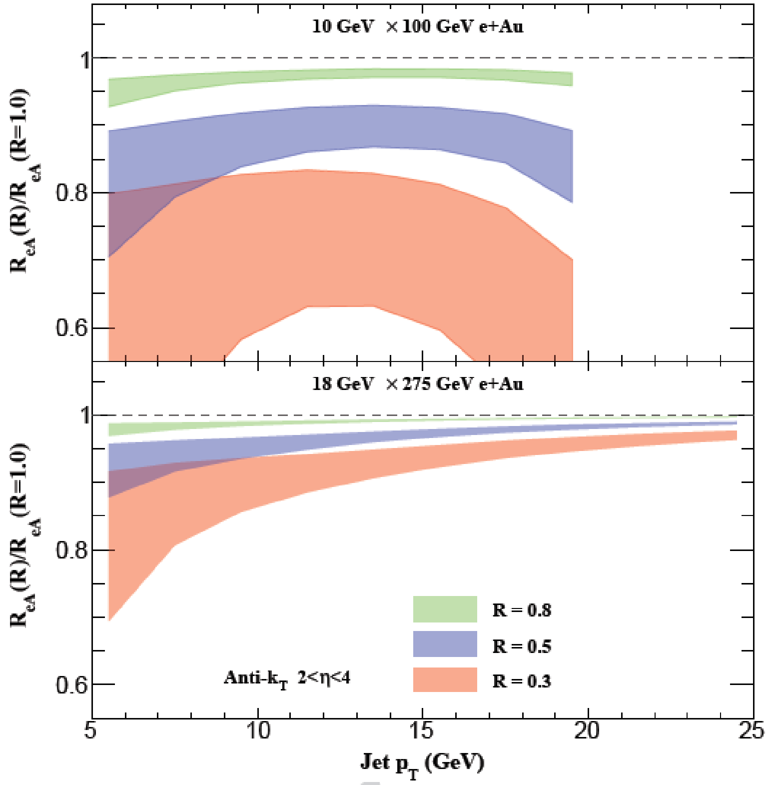


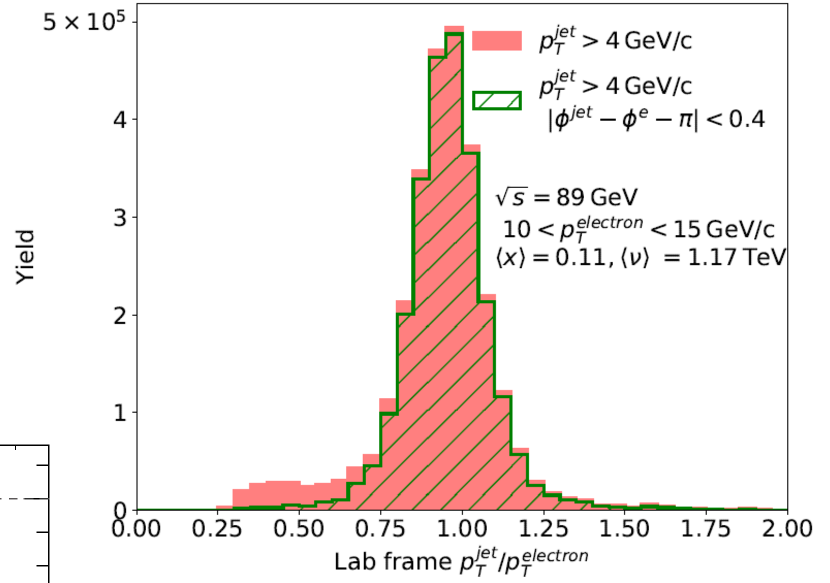
Jets in the Medium: CNM Properties

- 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-dijet 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





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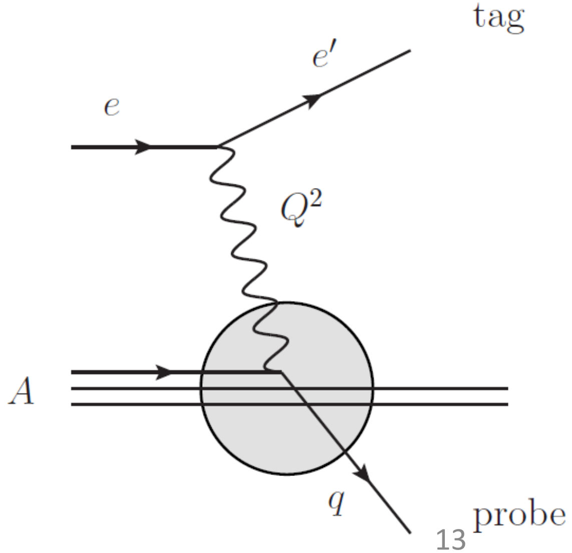
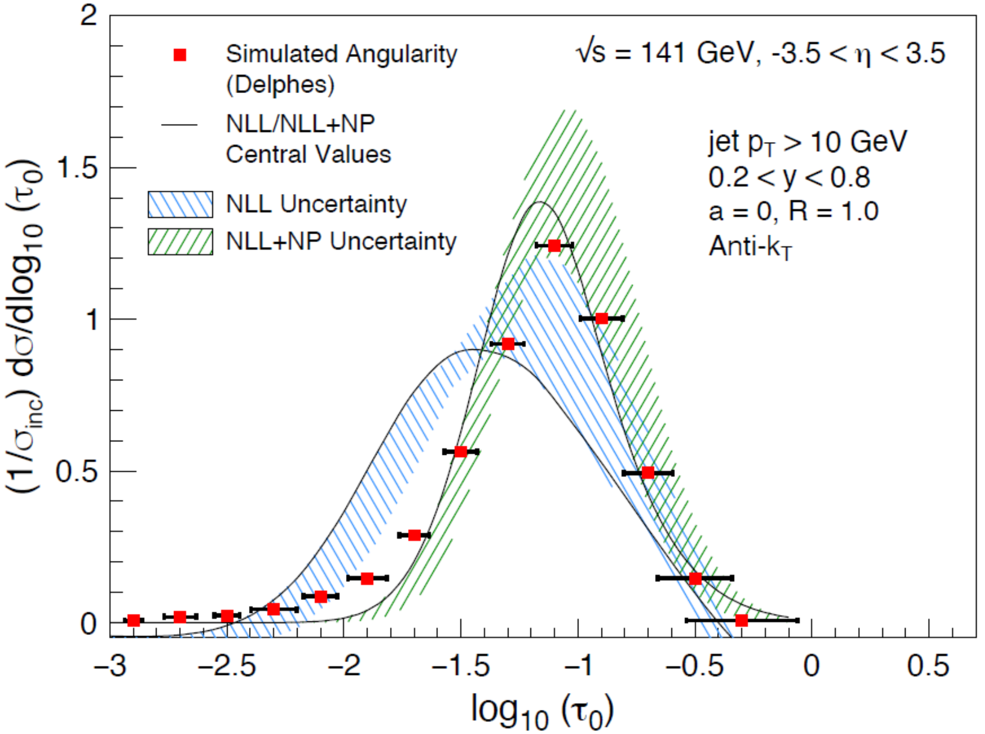


Jet Substructure: Angularity

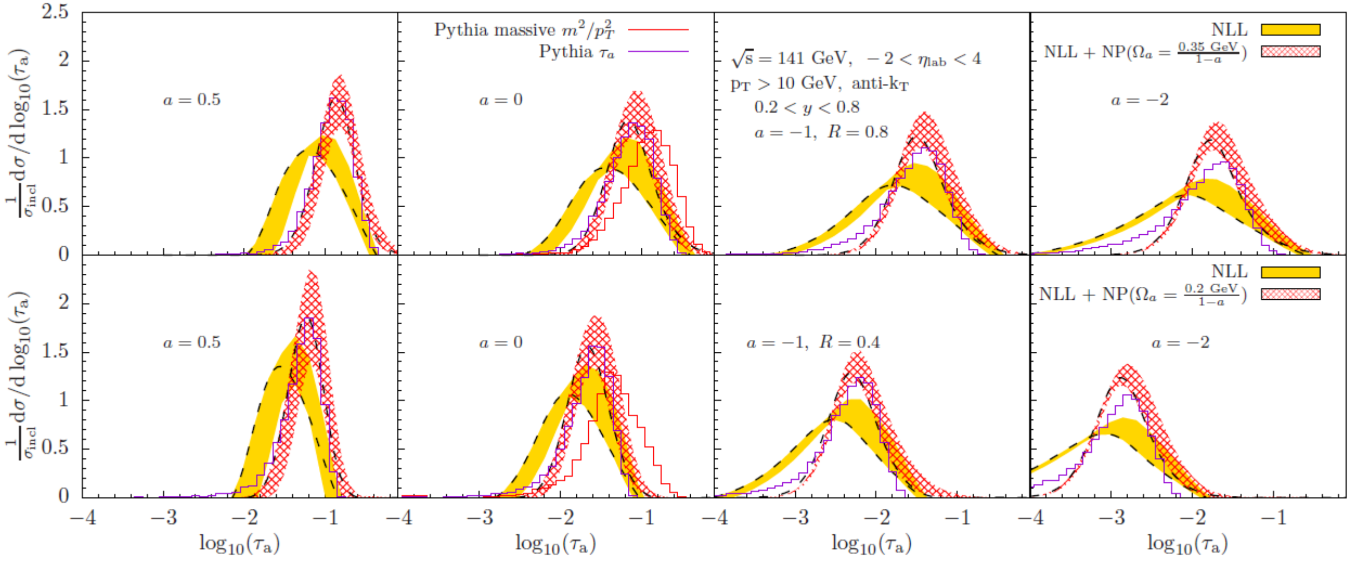
$$\tau_a \equiv \frac{1}{p_T} \sum_{i \in J} p_T^i \left(\Delta R_{iJ}\right)^{2-a}$$



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

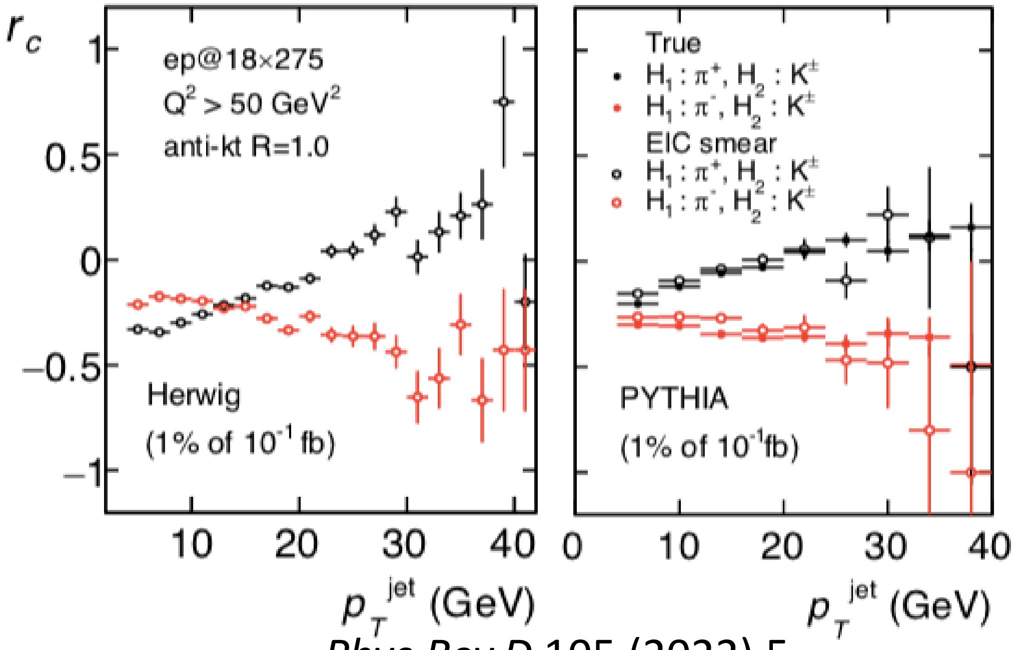


Leading Di-hadron Correlations

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

- 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
- See differences in how charge and flavor are distributed vs jet p_T and formation time between different hadronization models

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



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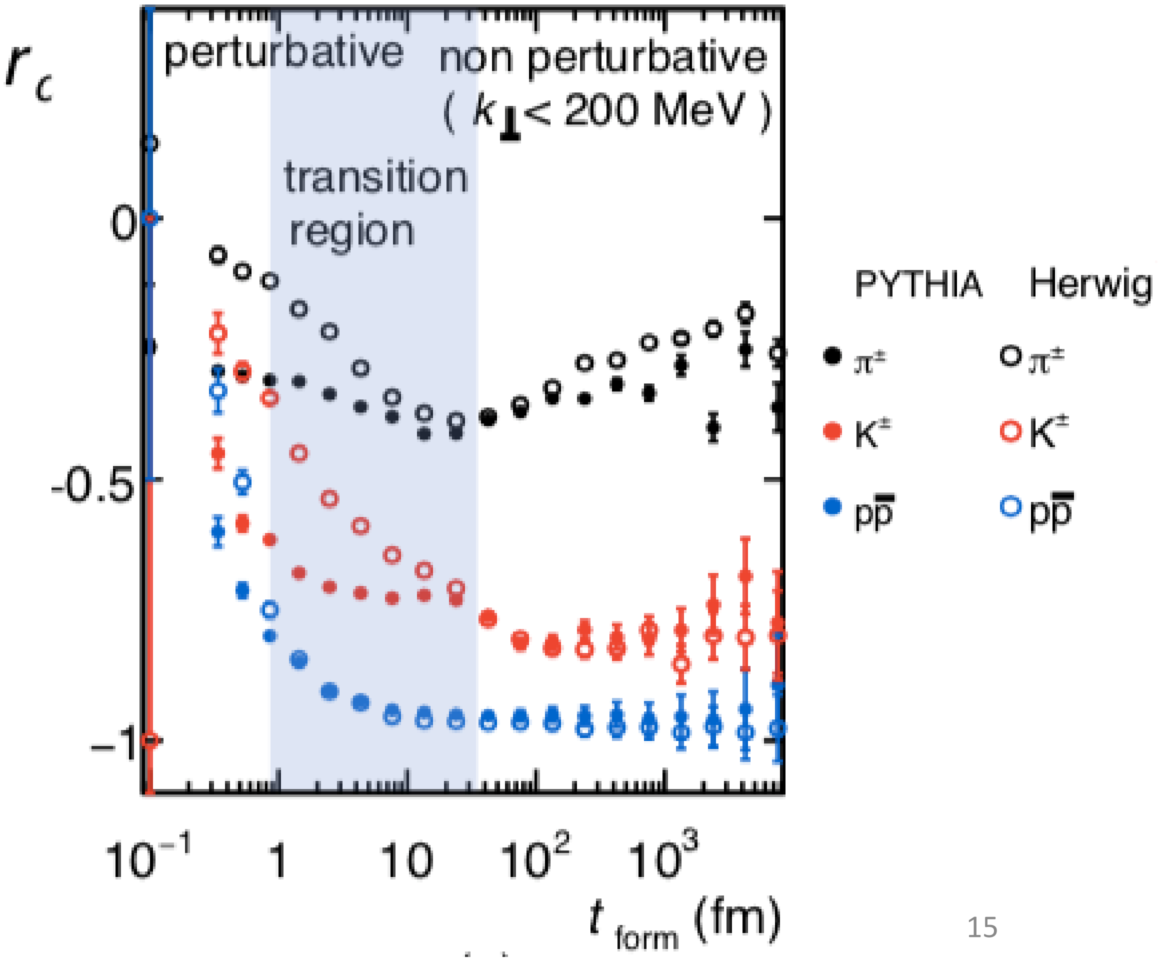
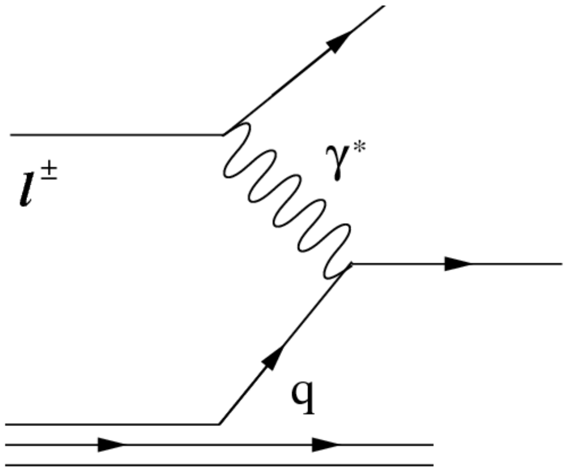
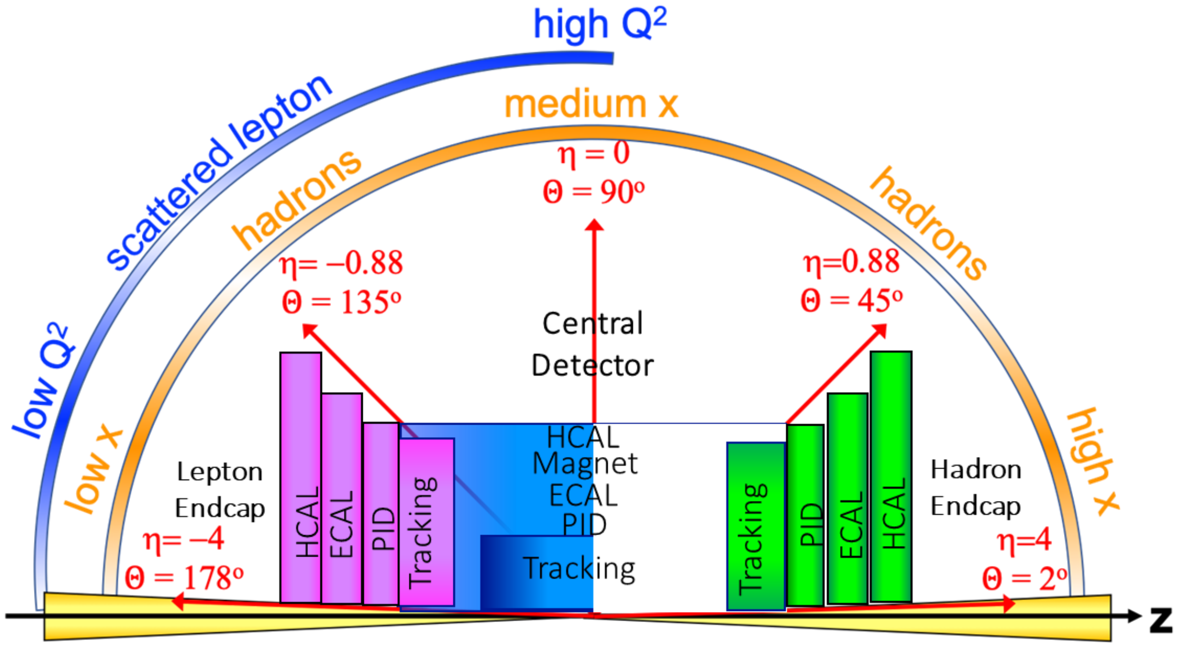
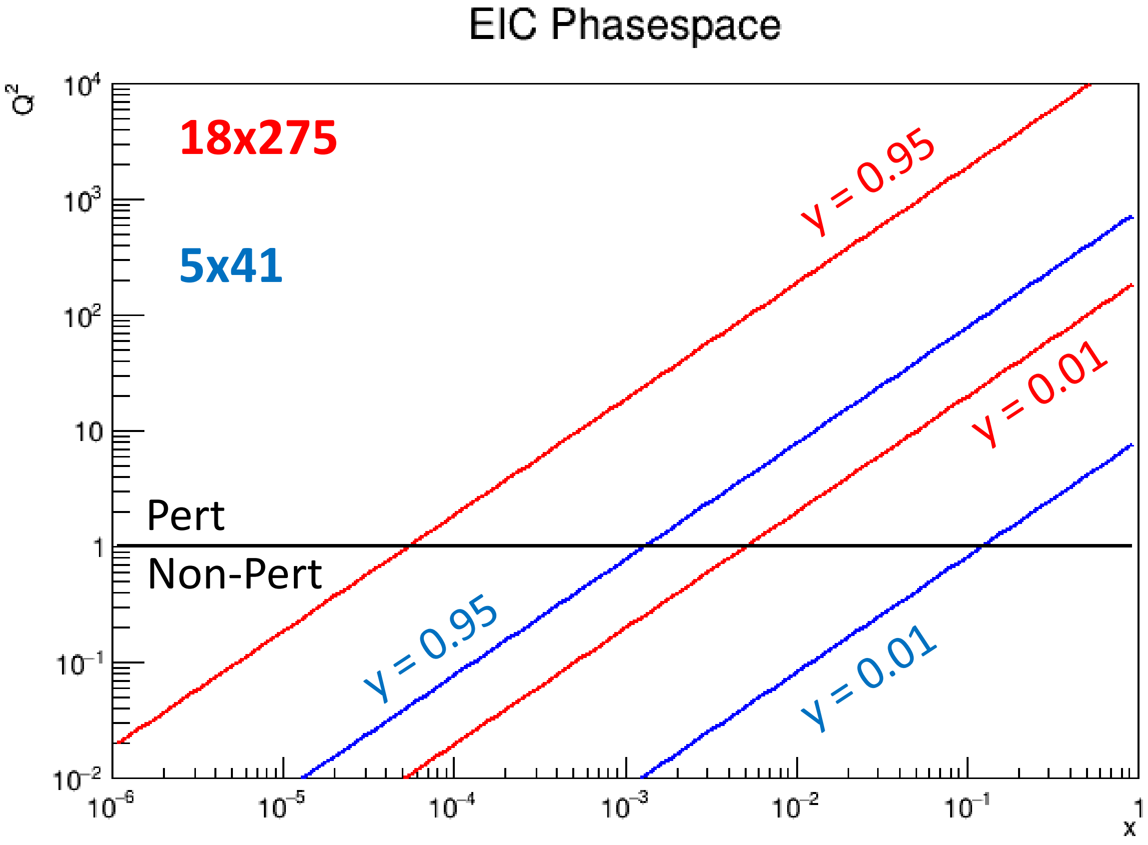


DIS Event Kinematics



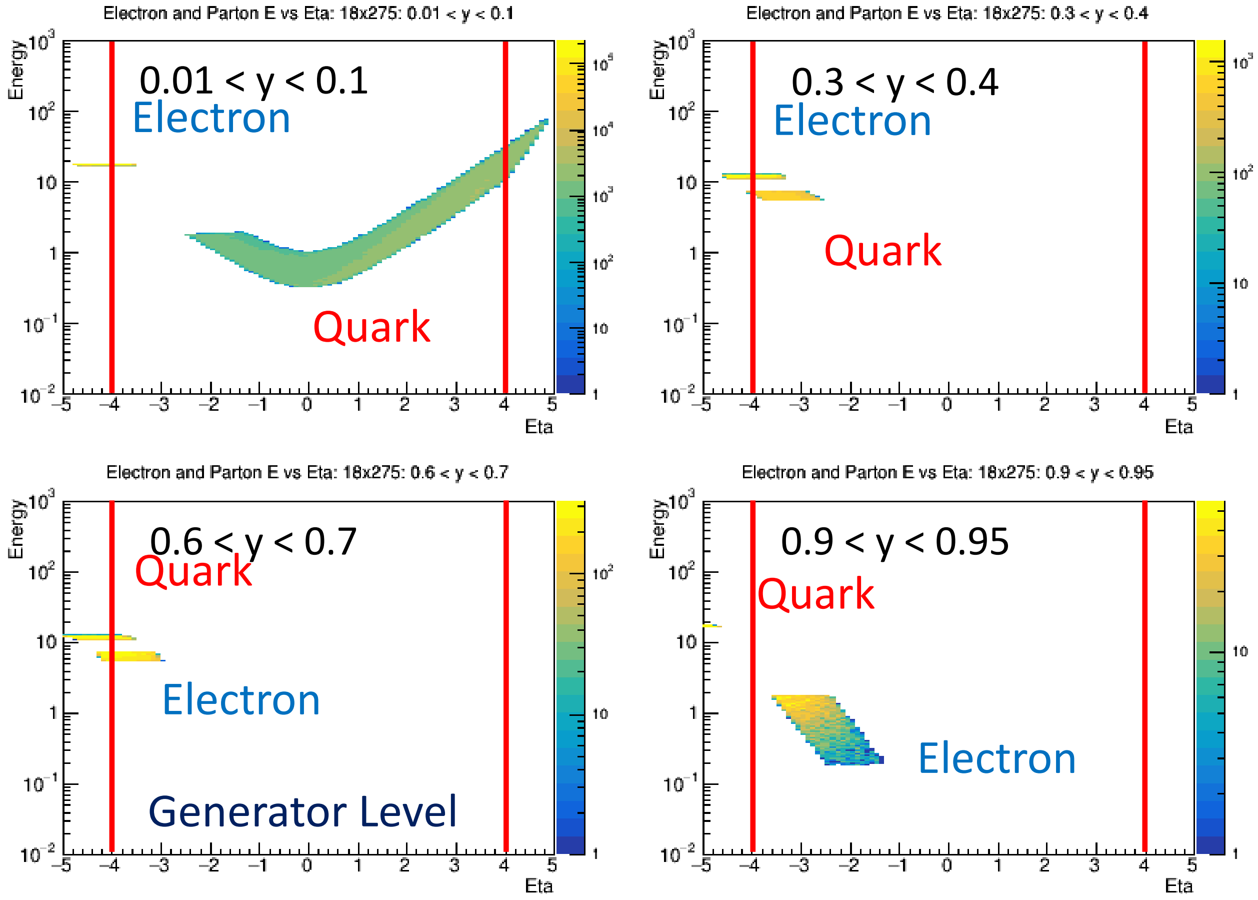




- ❑ For the leading order process, jet location and energy are dictated by the event kinematics (x, Q^2, y)
- ❑ For a given Q^2, inelasticity determines x value probed and pseudorapidity of the jet
  - ➢ Low y -> high x, jet at positive pseudorapidity
  - ➢ High y -> low x, jet at negative pseudorapidity

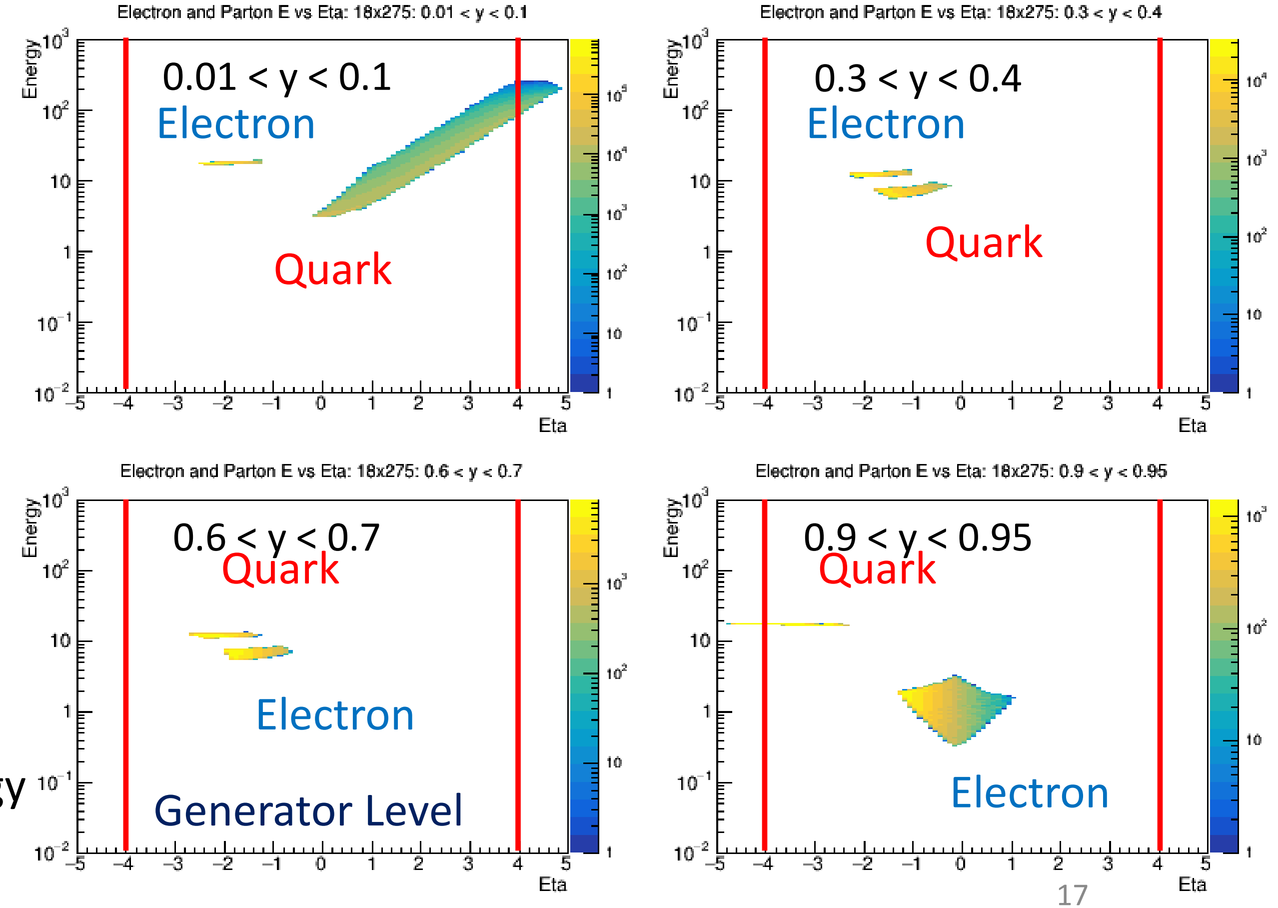
Electron and Struck Quark (18x275)

- 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



$0.1 < Q^2 < 1.0$

$10 < Q^2 < 100$

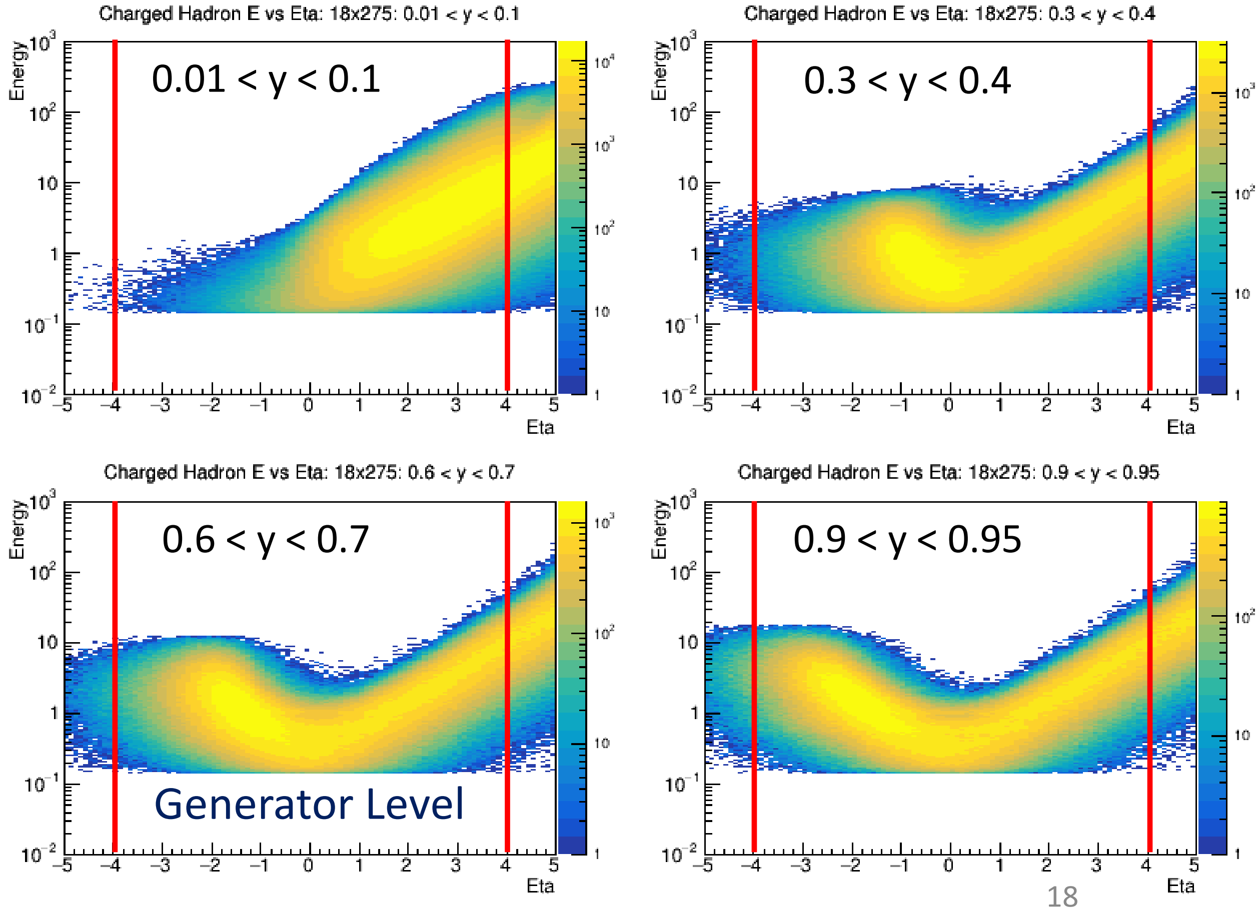


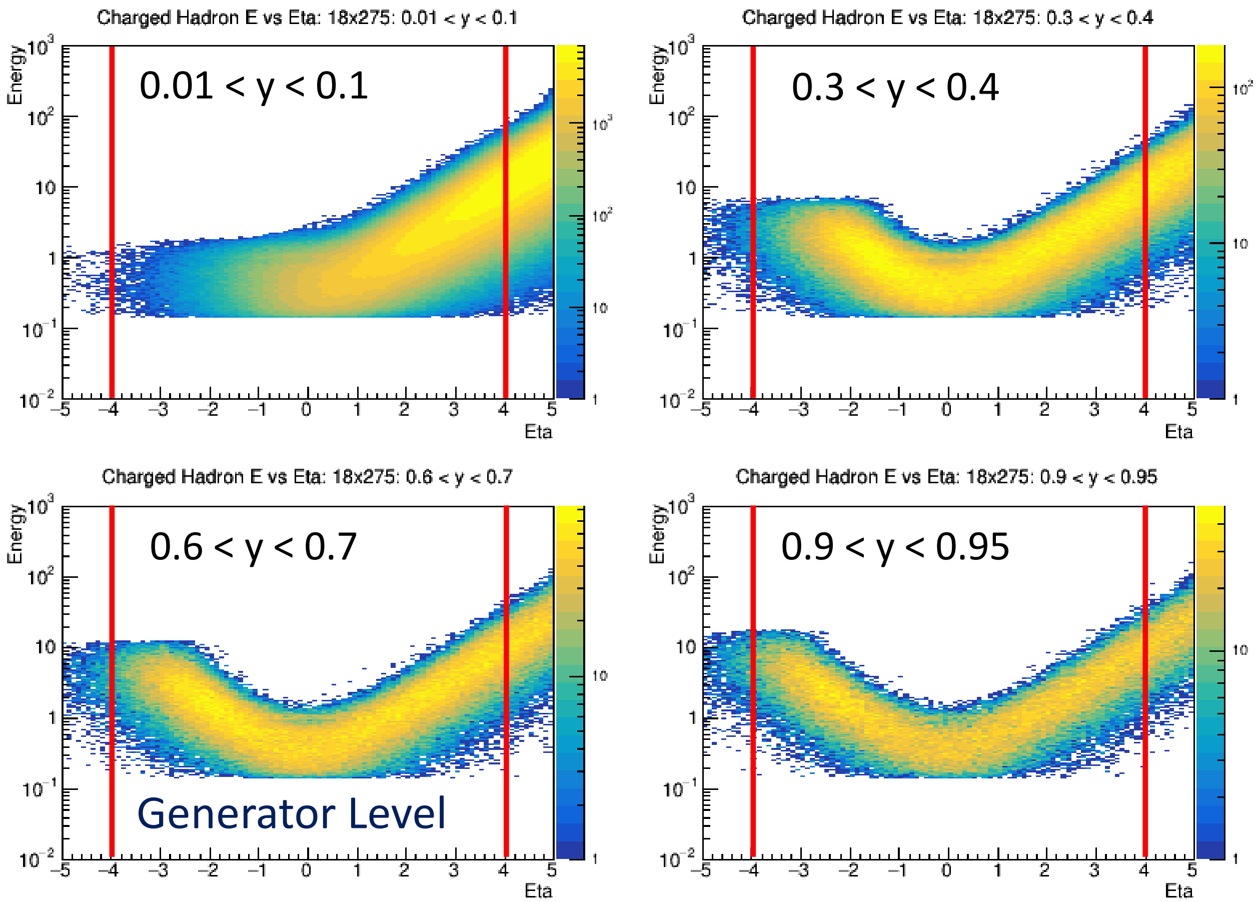
- As y -> 0, the struck quark can take the full ion beam energy
- As y -> 1, the struck quark takes the full electron beam energy
- Different detector considerations in forward and backward regions

(Charged) Particle Distributions (18x275)

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

10 < Q^2 < 100





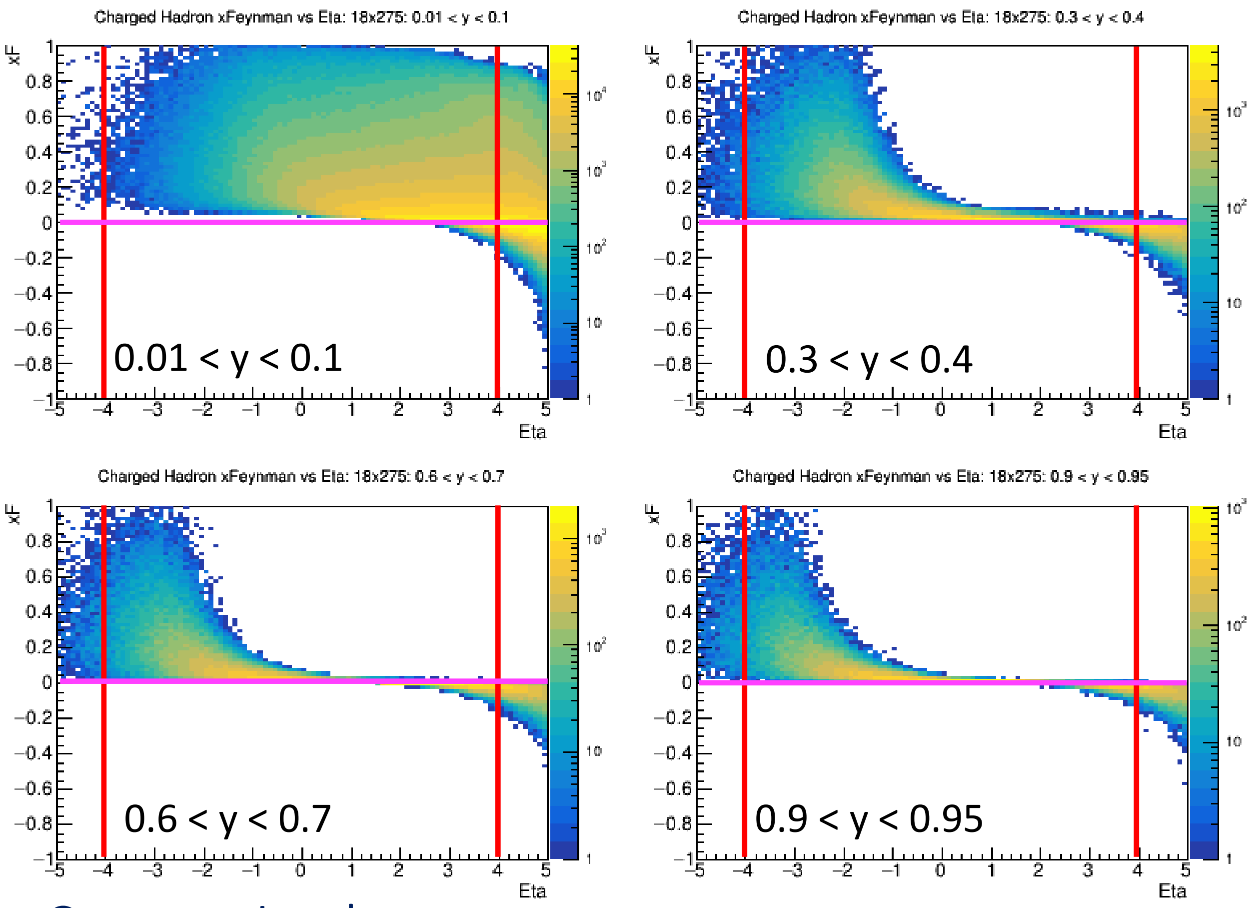
0.1 < Q^2 < 1.0

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

(Charged) Particle x-Feynman (18x275)

- ❑ Define xF as 2*particle_pZ/W in the hadron-boson center of mass frame

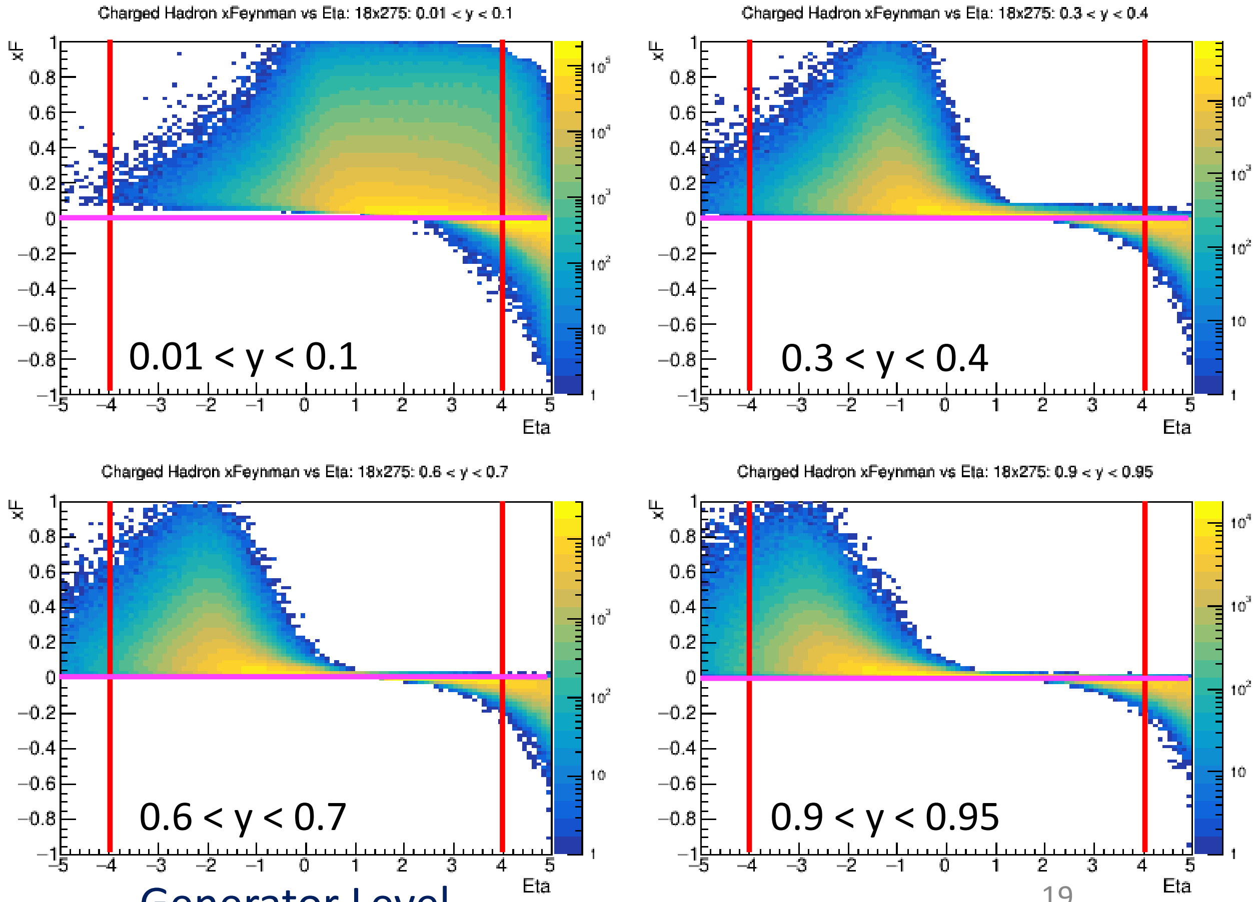
- ❑ Z-axis defined w.r.t. the virtual photon



Generator Level

$0.1 < Q^2 < 1.0$

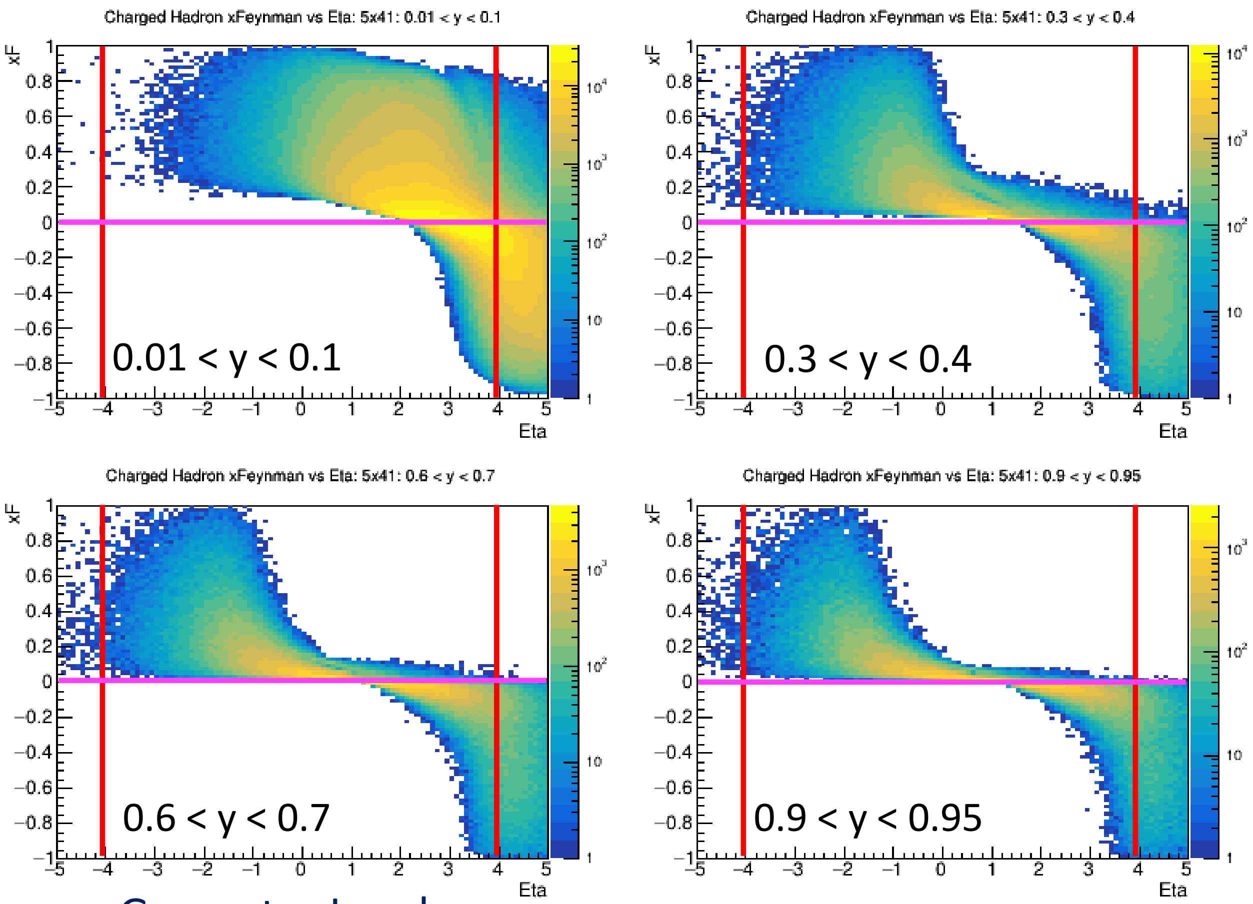
$10 < Q^2 < 100$



Generator Level

- ❑ Positive xF indicates particles more associated with the struck quark

(Charged) Particle x-Feynman (5x41)

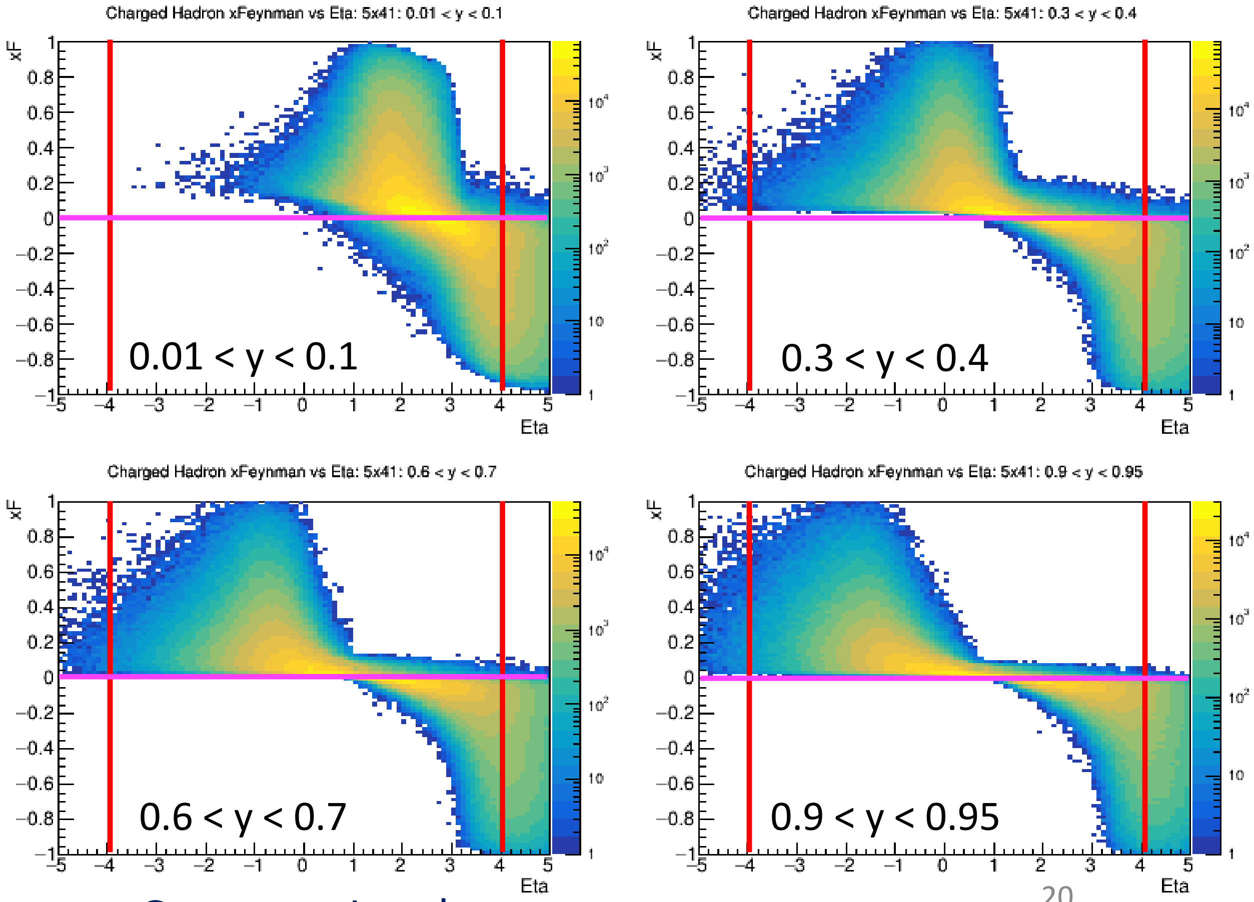


Generator Level

$0.1 < Q^2 < 1.0$

- ❑ Larger negative xF particles come into the detector acceptance for lower beam energies

$10 < Q^2 < 100$



Generator Level

- ❑ Study differences in fragmentation in these regions
- ❑ Look at correlations between these 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

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

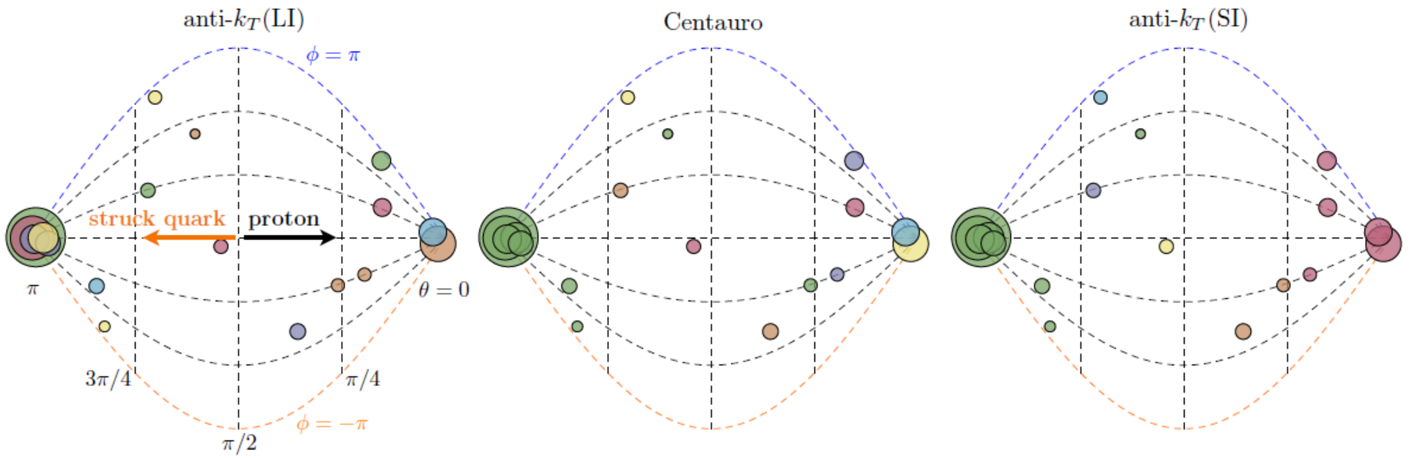
Asymmetric measure is necessary

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

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

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

- 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



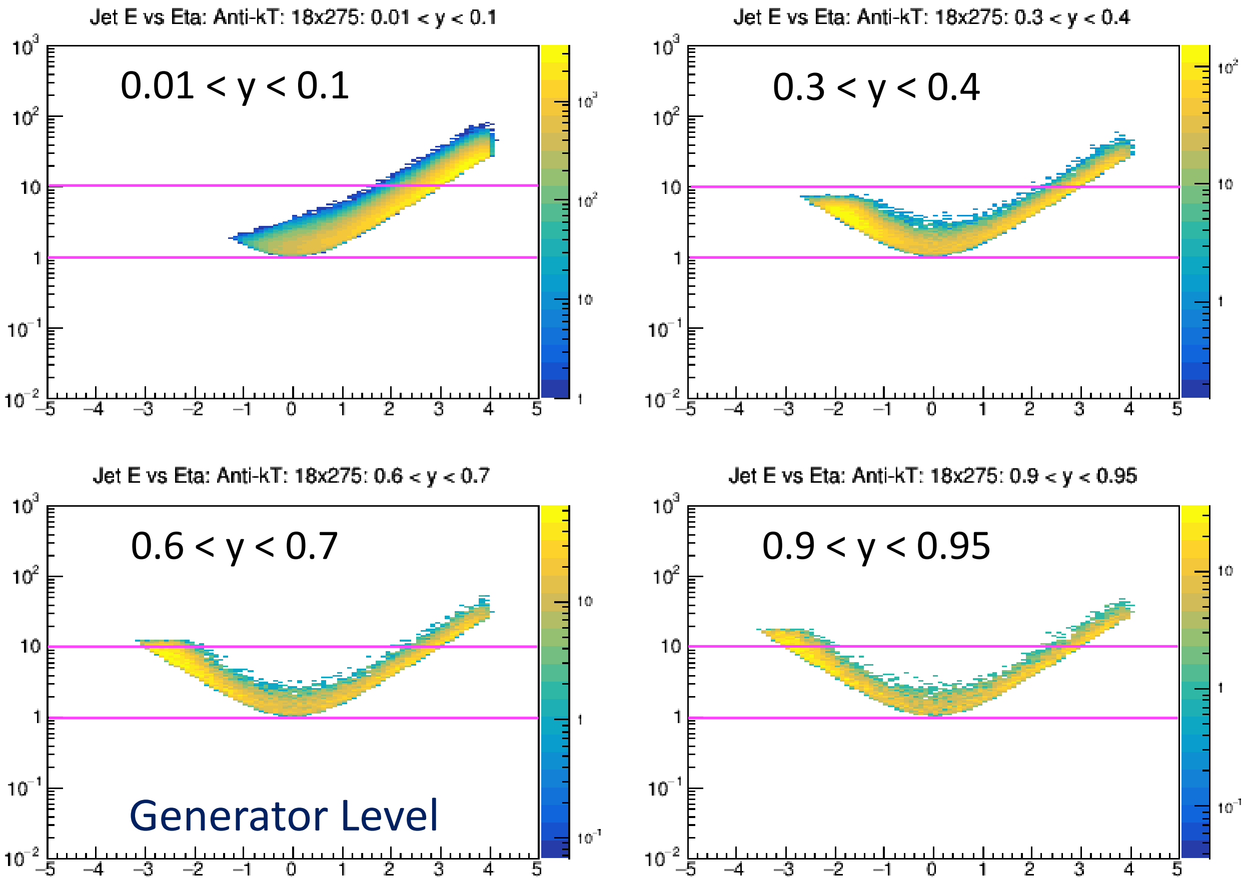
Longitudinally invariant Symmetric

Longitudinally invariant Asymmetric

Spherically invariant Symmetric

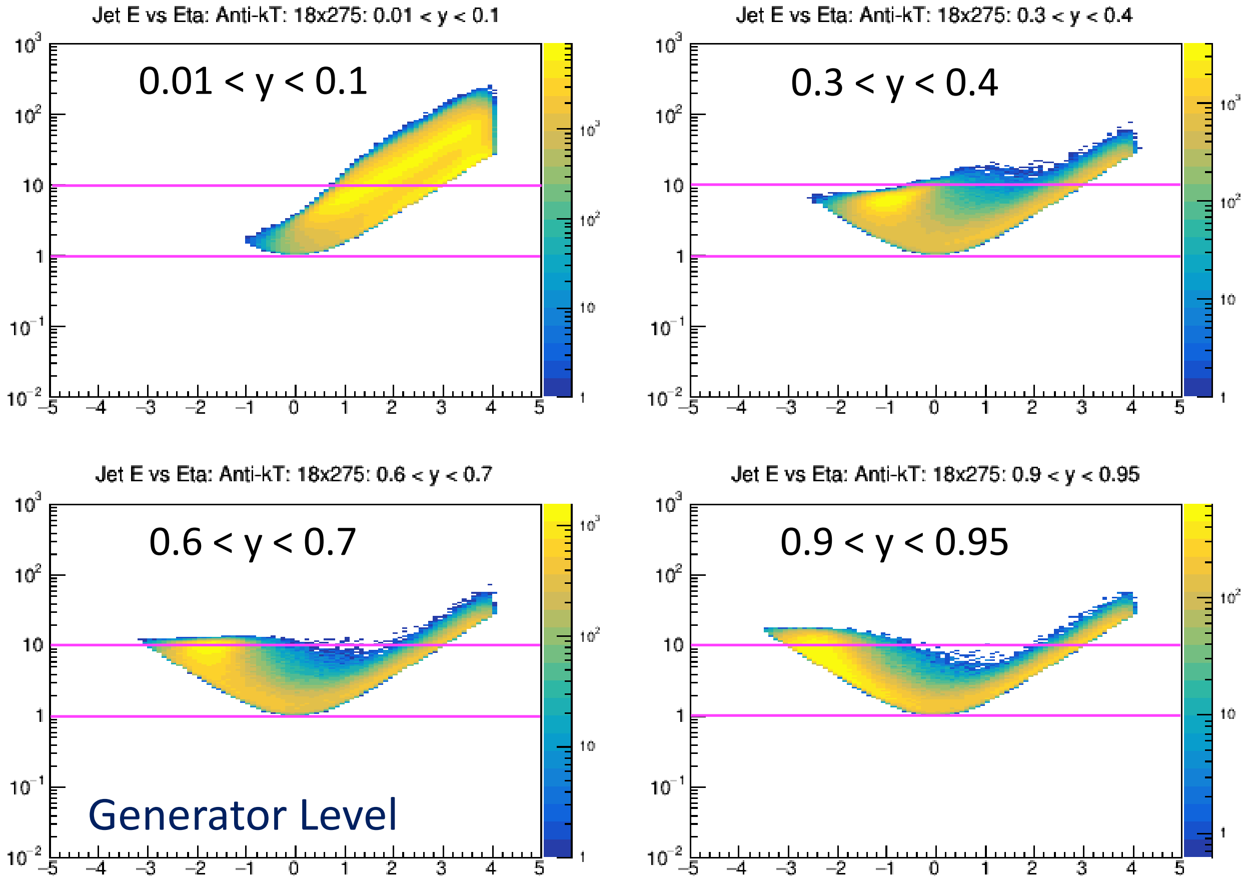
Jet Distributions: Anti_k_T (18x275)

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

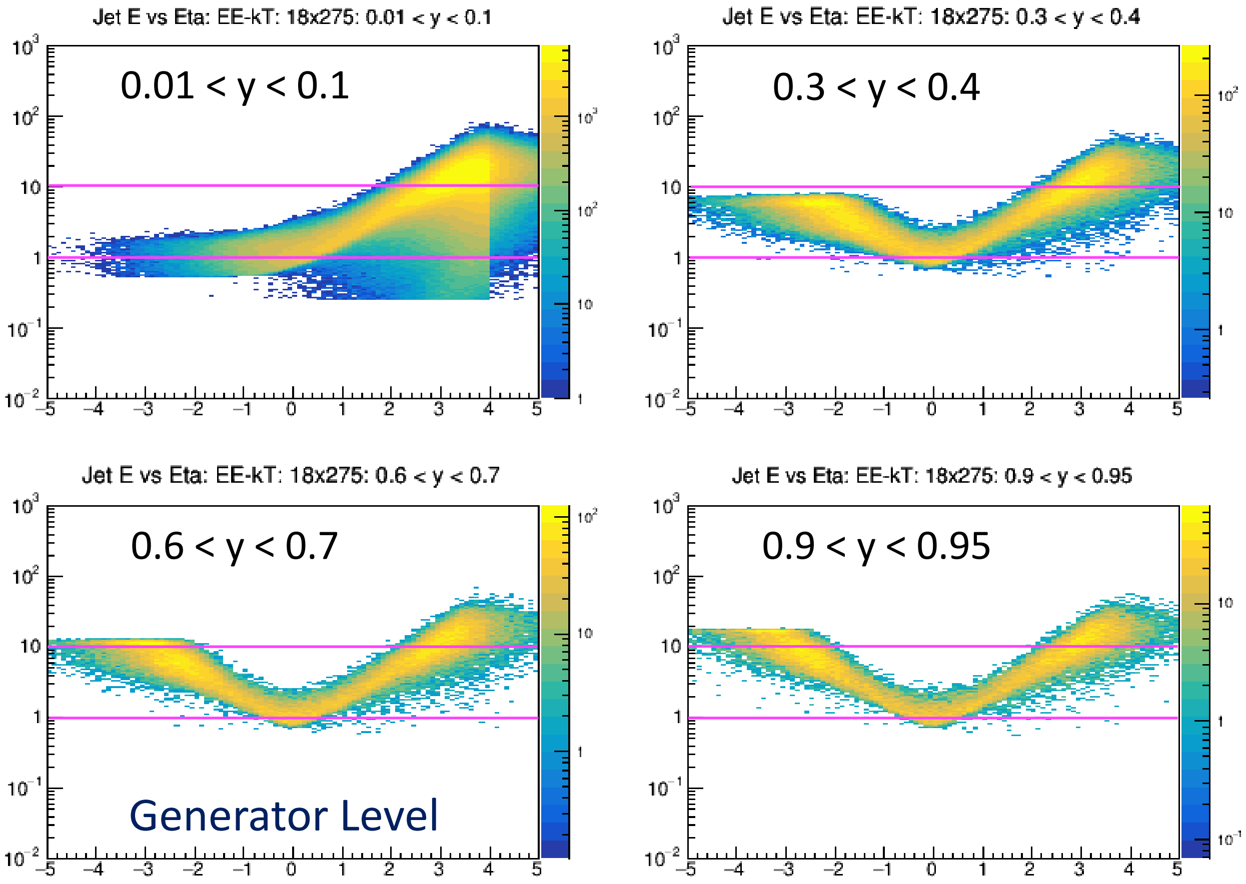


$0.1 < Q^2 < 1.0$

$10 < Q^2 < 100$



Jet Distributions: EE_k_T (18x275)



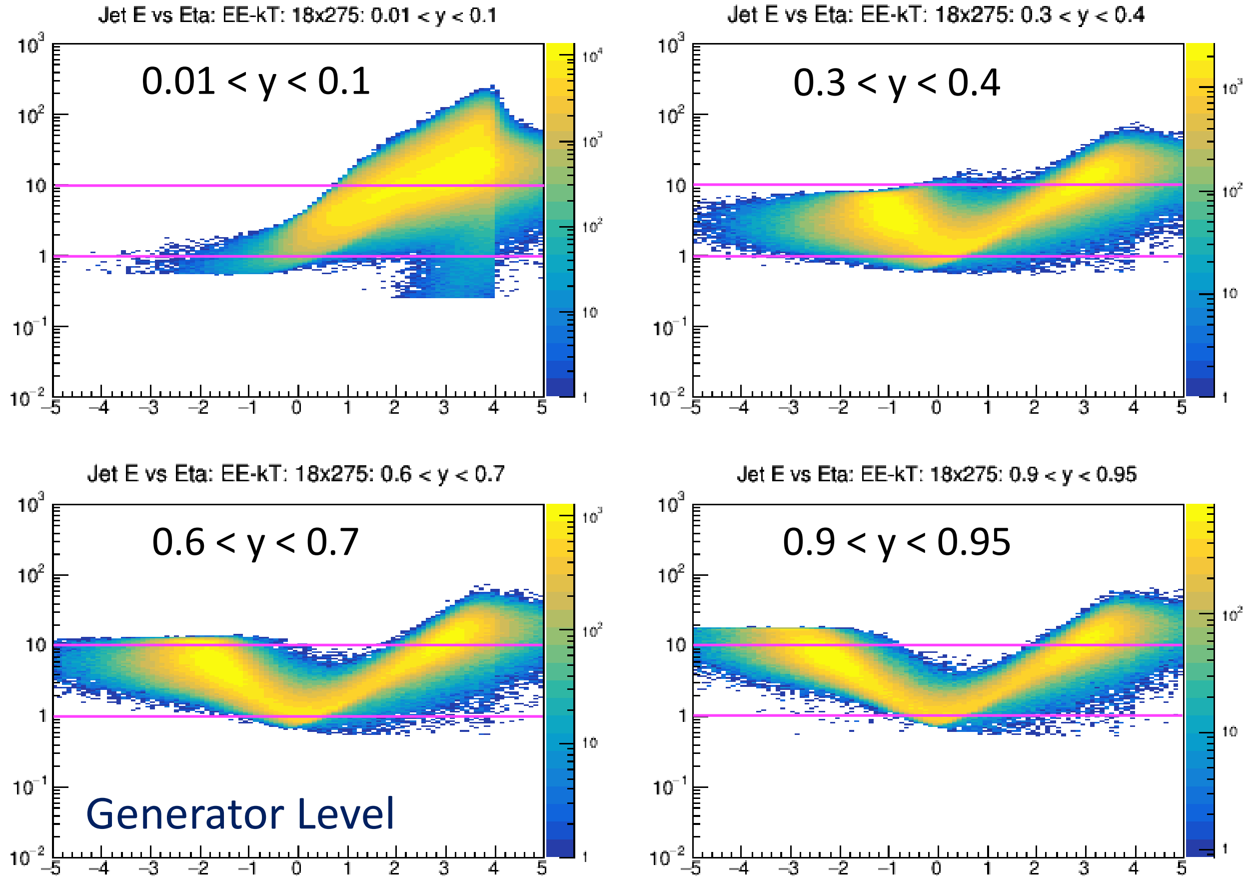
$0.1 < Q^2 < 1.0$

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

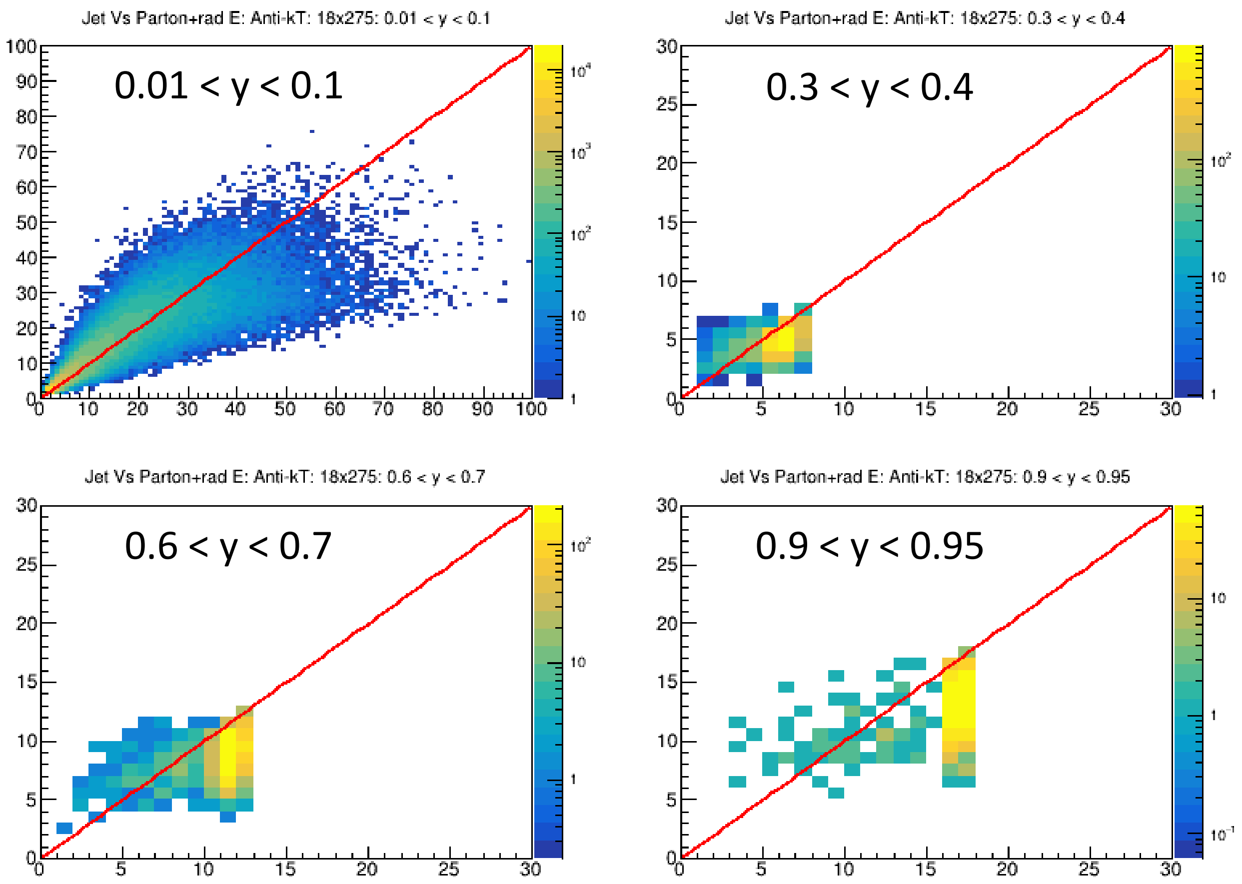
- ❑ Overall distributions are similar for EE_k_T algorithm

- ❑ In general, see larger number of jets, more jets at higher eta, and more jets away from struck quark

$10 < Q^2 < 100$



Jet – Parton Energy Comparison: Anti_k_T (18x275)



Generator Level

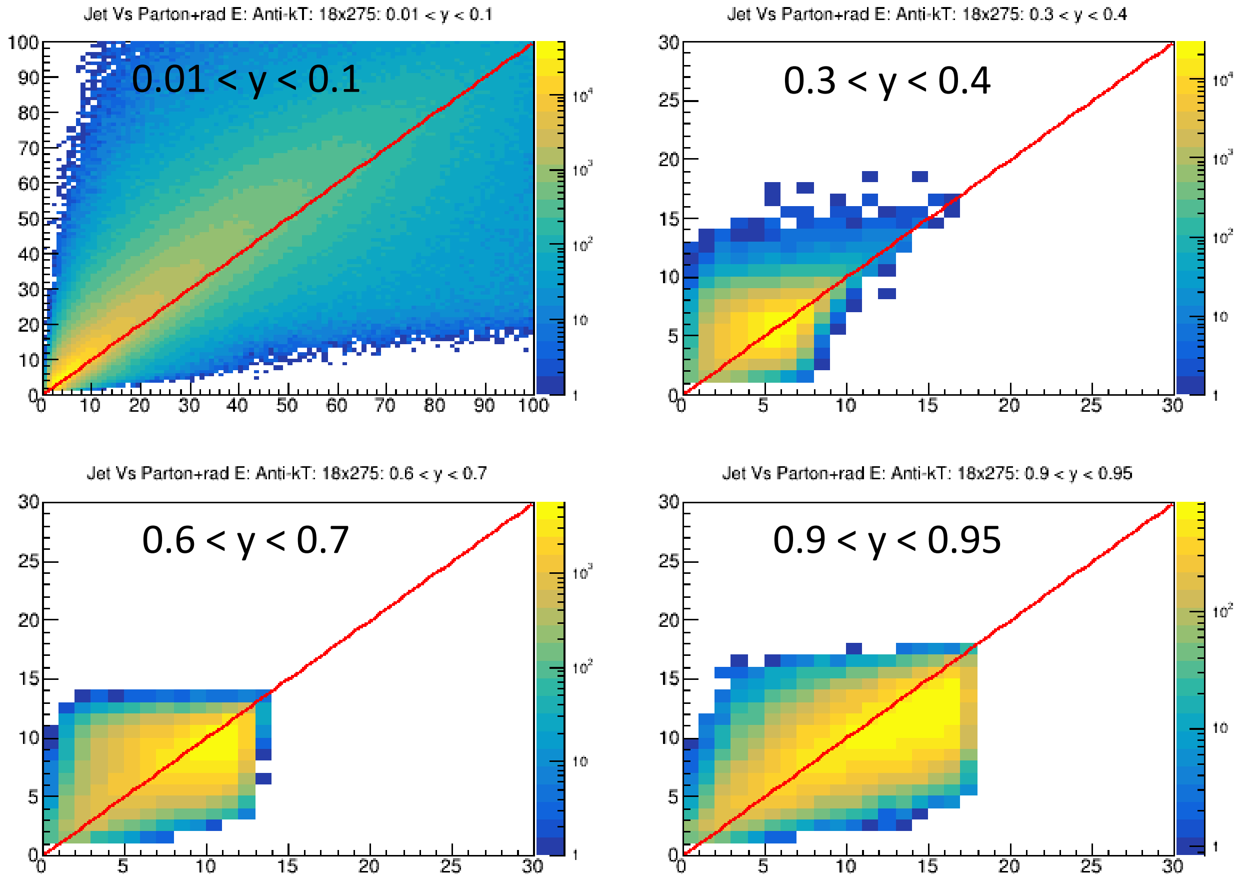
0.1 < Q^2 < 1.0

- ❑ Performance degrades somewhat at larger y (backward jets)

- ❑ How well do jets represent the parton?

- ❑ Plot jet energy vs parton+FSR energy for different Q^2 and inelasticity

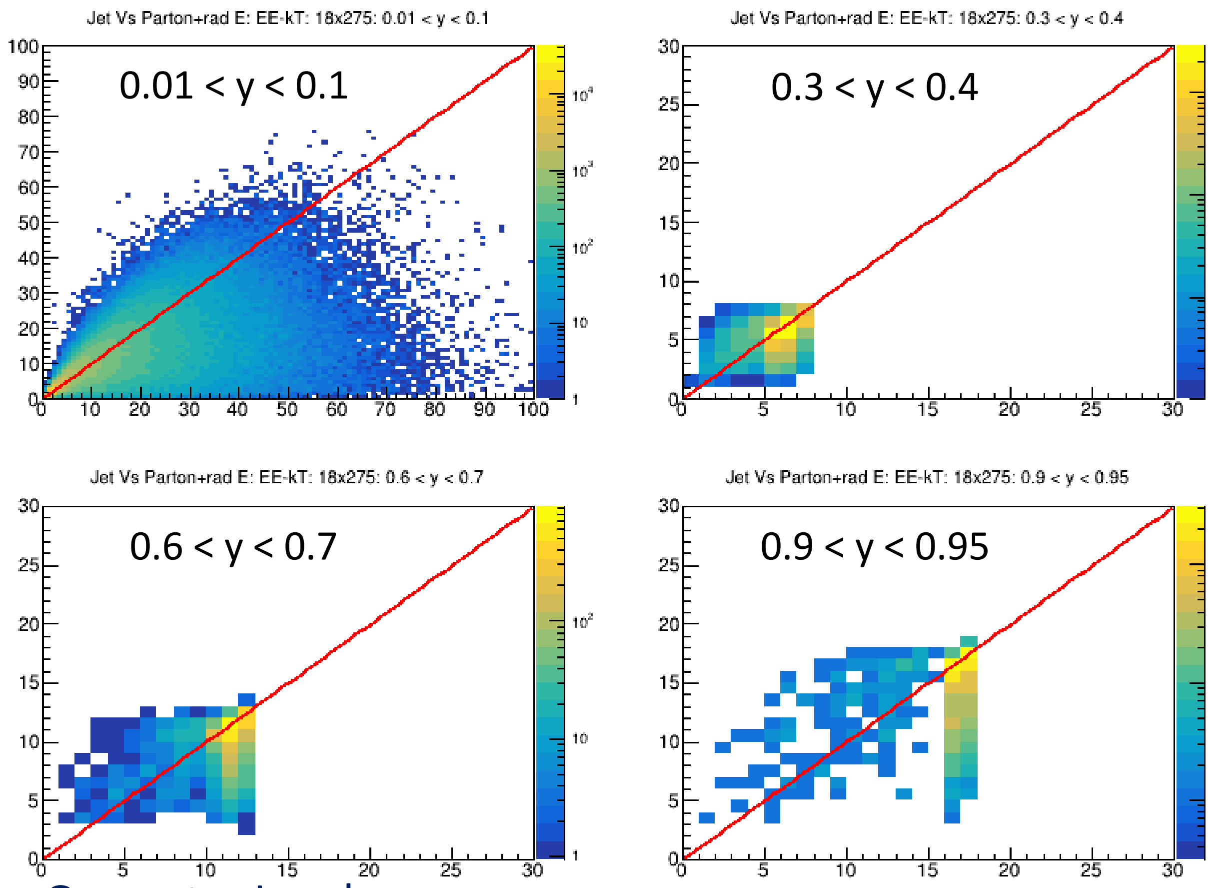
10 < Q^2 < 100



Generator Level

Jet – Parton Energy Comparison: EE_k_T (18x275)

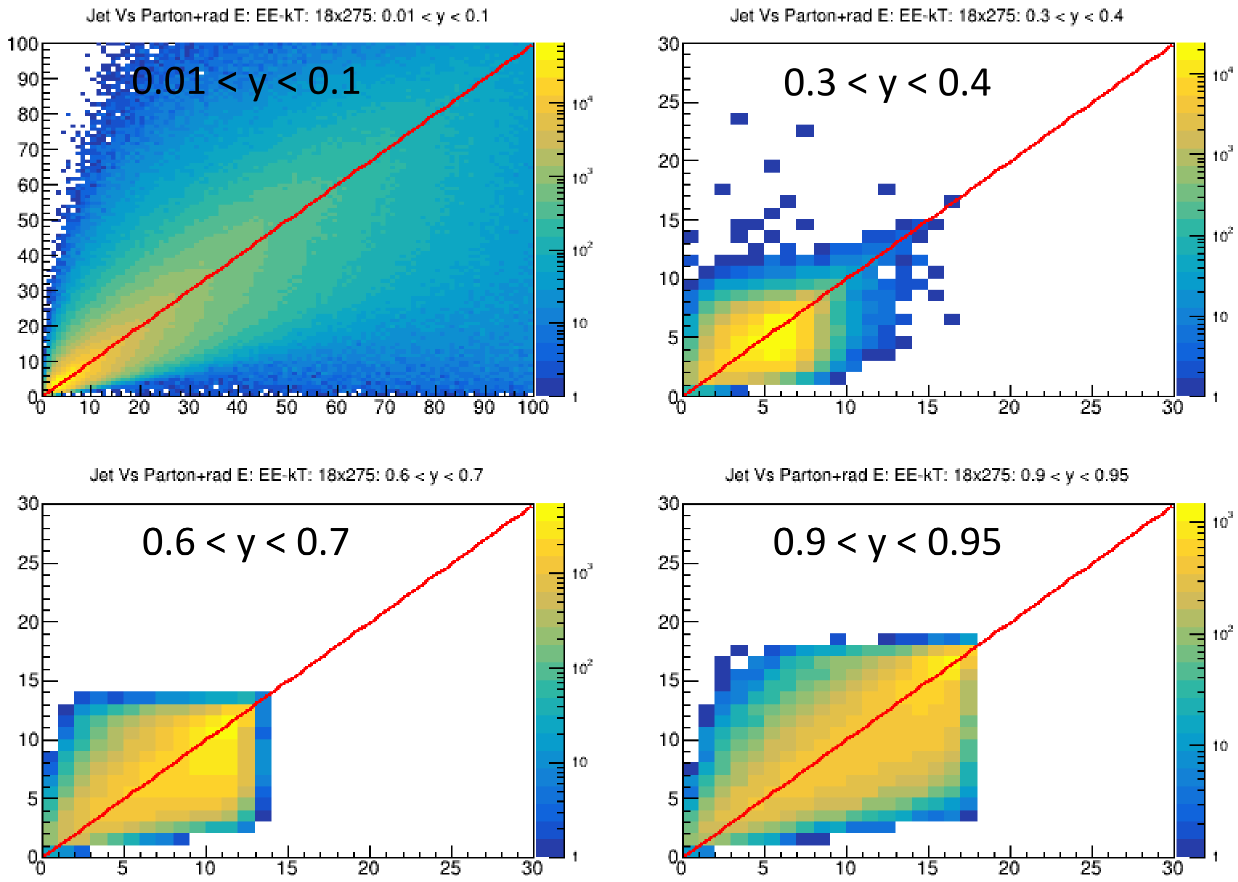
- ❑ Better agreement between parton and jet seen with EE_kT algorithm, especially at high y



Generator Level

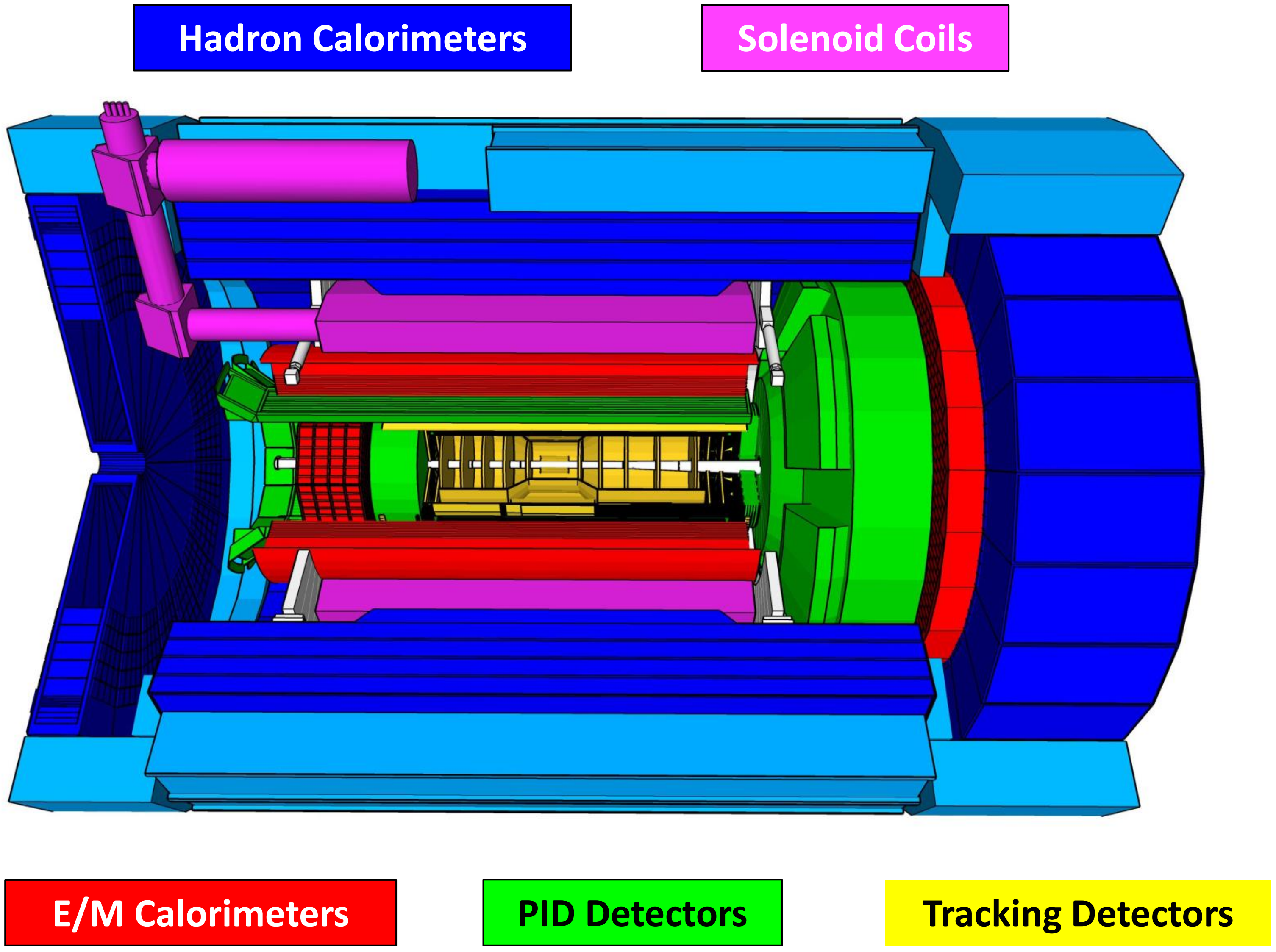
0.1 < Q^2 < 1.0

10 < Q^2 < 100



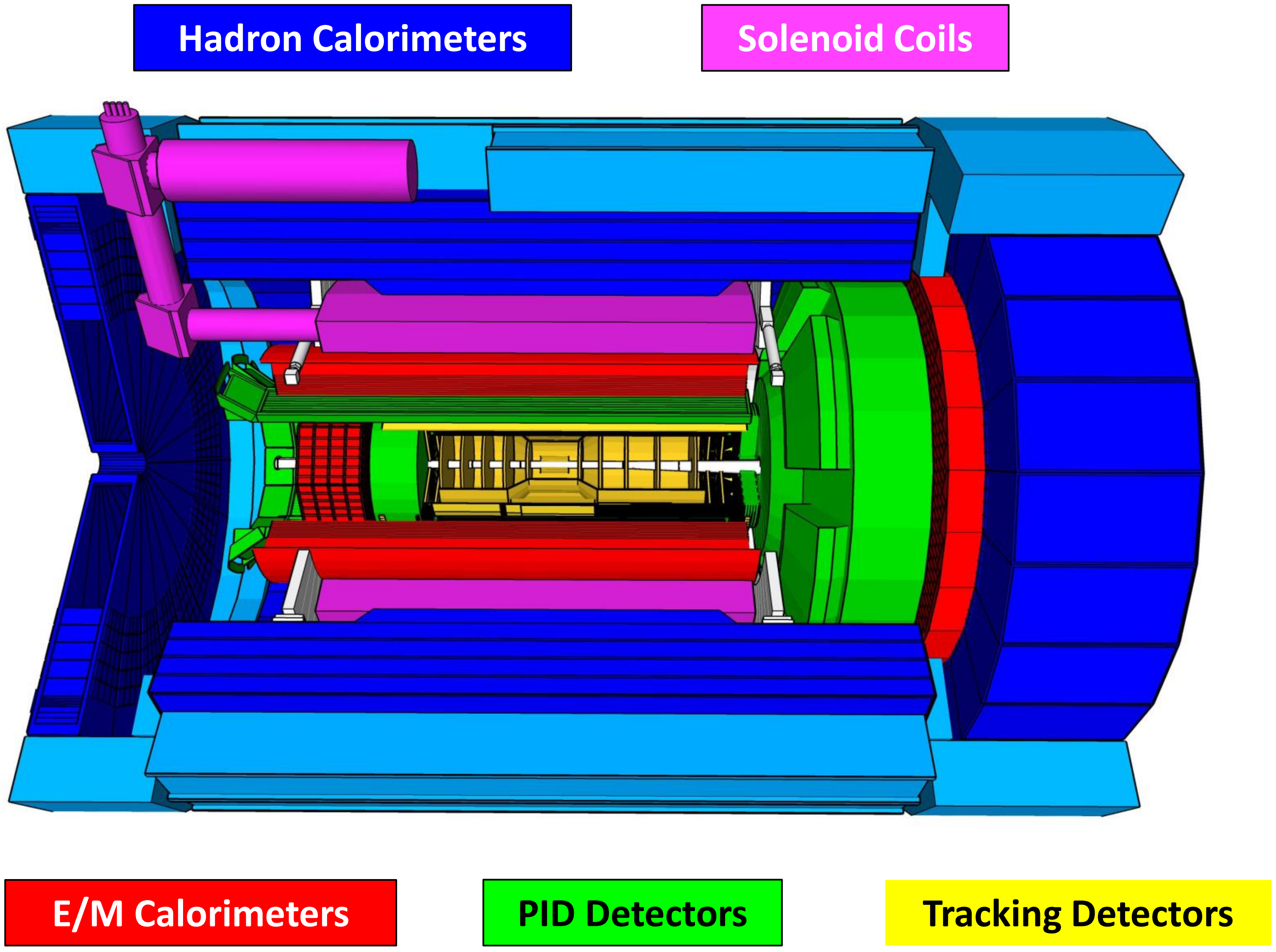
Generator Level

ePIC Detector Configuration



- ❑ Tracking
  - ➢ New 1.7 T solenoid
  - ➢ Si MAPS Tracker
  - ➢ MPGDs (uRWELL/uMegas)
- ❑ PID
  - ➢ hpDIRC
  - ➢ pfRICH
  - ➢ dRICH
  - ➢ AC-LGAD (~30 ps TOF)
- ❑ Calorimetry
  - ➢ Imaging Barrel EMCal
  - ➢ PbW04 EMCal (backward)
  - ➢ Finely segmented EMCal+Hcal (forward)
  - ➢ Outer Barrel Hcal (sPHENIX)
  - ➢ Backward Hcal (tail-catcher)

ePIC Detector Configuration



Energy Flow Wishlist

- ✓ Large acceptance / hermetic
- ✓ Large coverage high-resolution tracking
- ✓ High-resolution granular calorimetry (some variation in calorimeter functionality, especially for HCals)
- ✓ Good PID coverage (don't forget about flavor)

Summary

- ❑ 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 ability to accurately measure jets from low to high energy over the full detector span will be critical to probing both high and low-x physics and exploring interesting correlations between jets

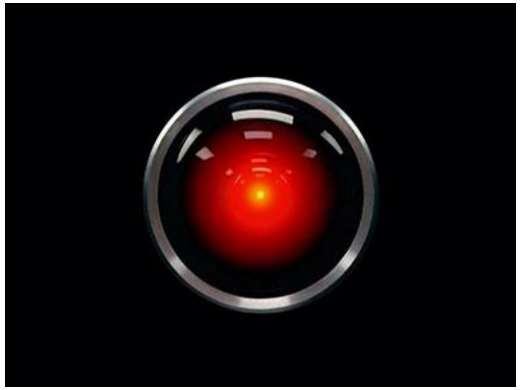
- ❑ ePIC detector will enable high-precision jet measurements and will be amenable to energy-flow observables

- ❑ Further development of jet clustering and substructure techniques, AI/ML applications, extensions to wider event classifications, etc will surely lead to new applications for jets in the future – data-taking is 10 years from now, the most exciting jet measurements may be something we have not even thought of yet!

Backup

Future Directions

- AI and Machine Learning are quickly becoming common tools in many areas of physics – what about EIC jets?
  - AI/ML assist for design / calibration / reconstruction for relevant detector components
  - 'Physics Aware' AI which can extract underlying physics directly from event / jet observables
  - See arXiv:2012.06582; https://iris-hep.org/projects/ml4jets.html; YR Sec 11.12

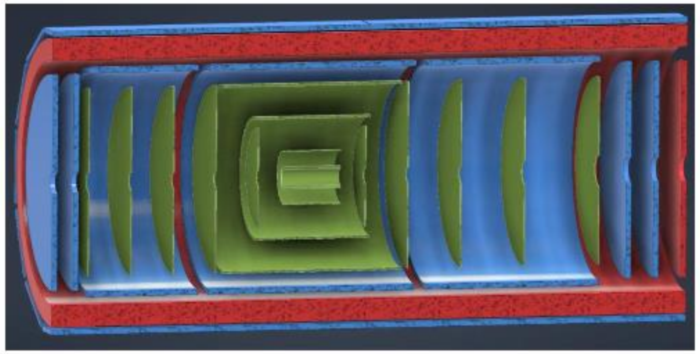


- Events at EIC will be relatively sparse – can we adapt tools & techniques developed for jets to characterize the full event?
  - See for example arXiv:2101.02708 for event level grooming

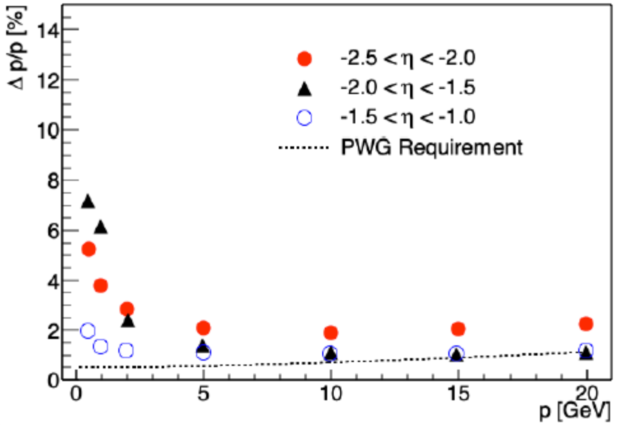
- Major aspect of EIC physics program will be exploration of low-x / saturation phenomena
  - Implies low energy / p_T jets – develop tools needed to understand these jets theoretically and experimentally

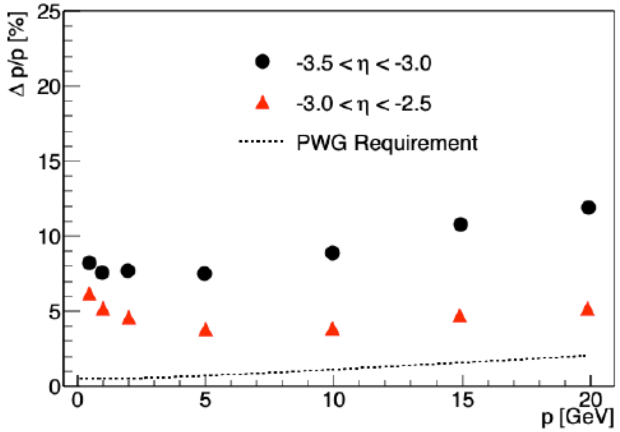
- Expand use of jets to understand non-perturbative aspects of QCD

Tracker Performance

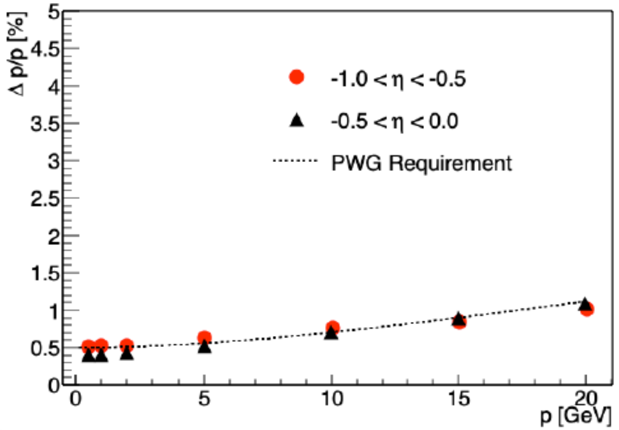


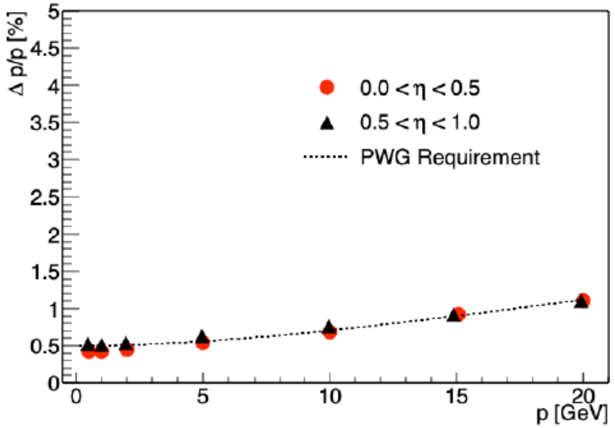
Backward



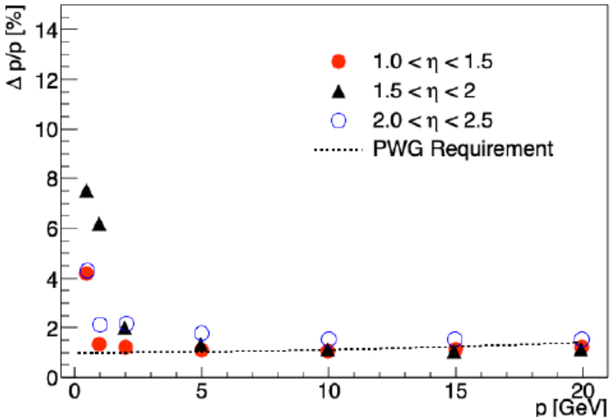


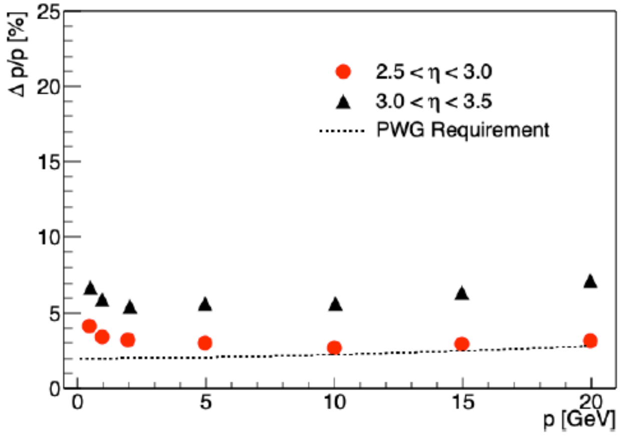
Central



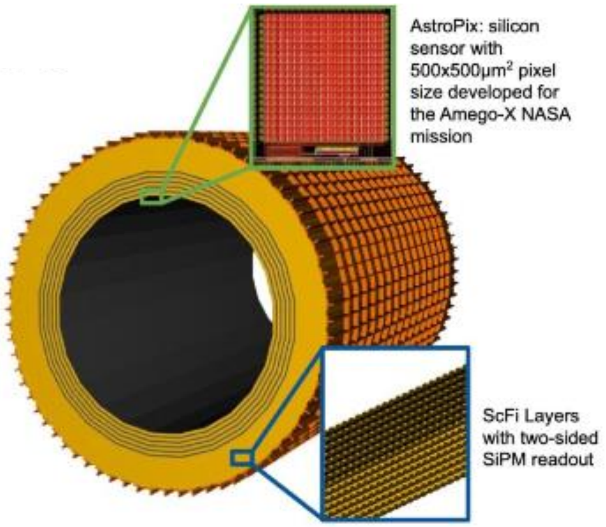


Forward

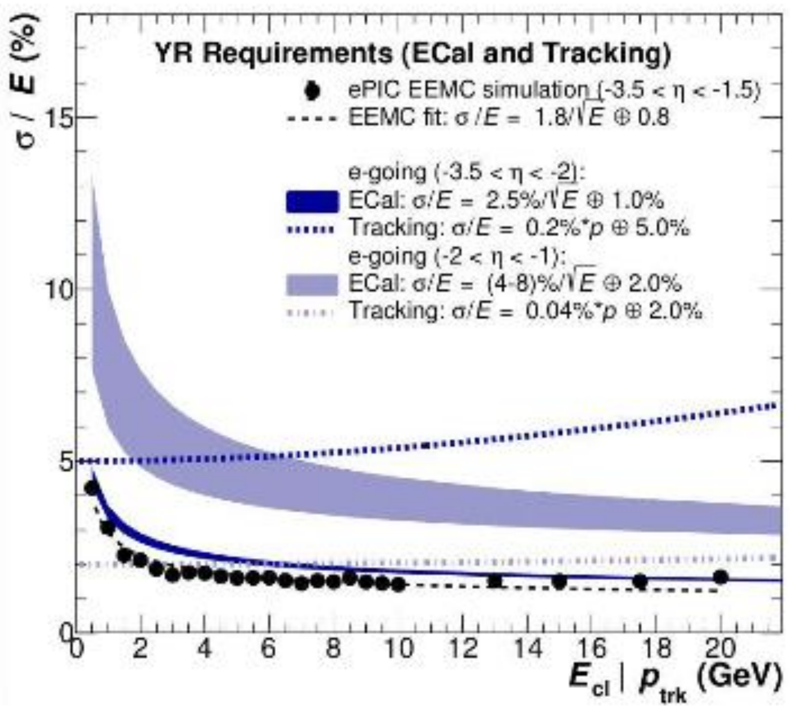




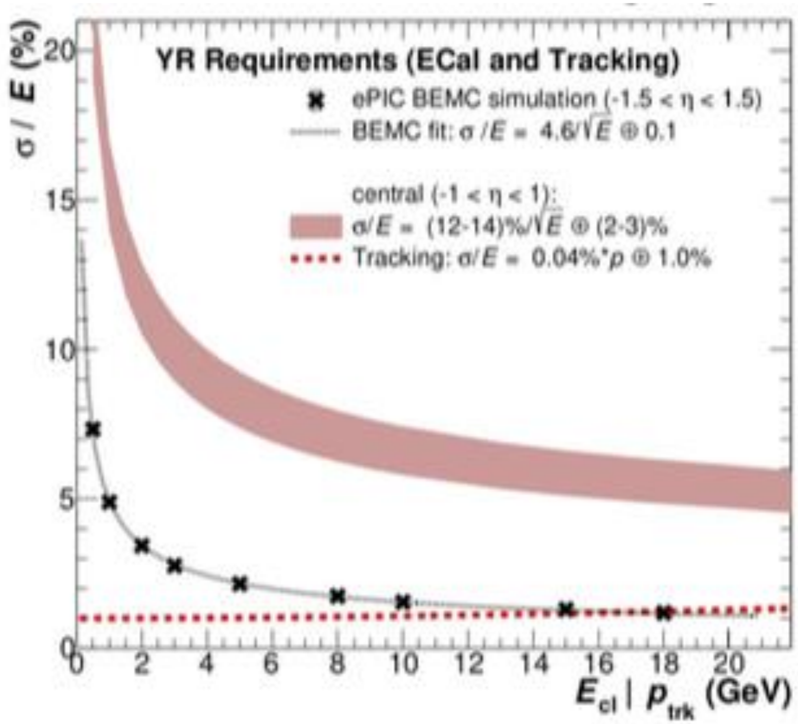
E/M Calorimeter Performance



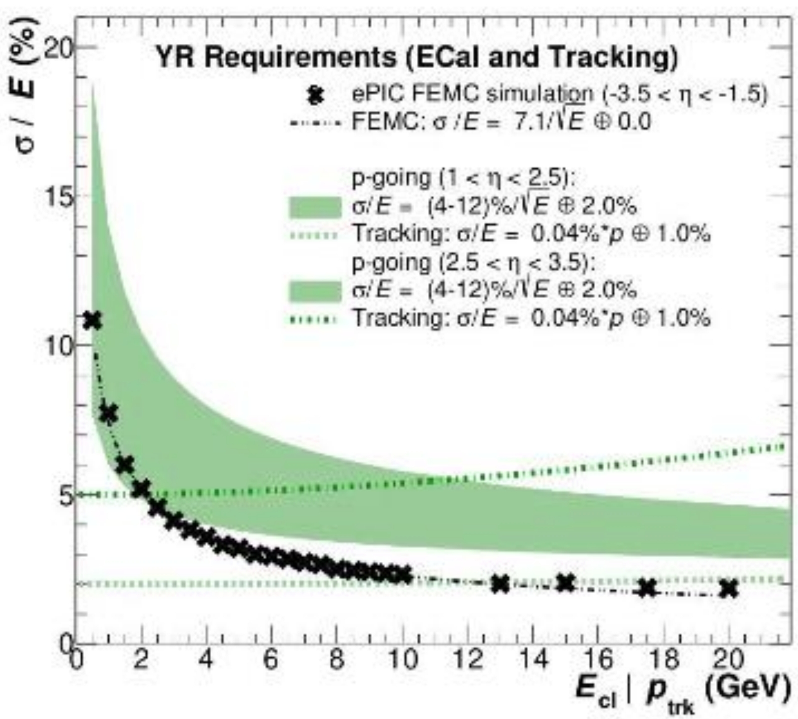
Electron Endcap



Barrel



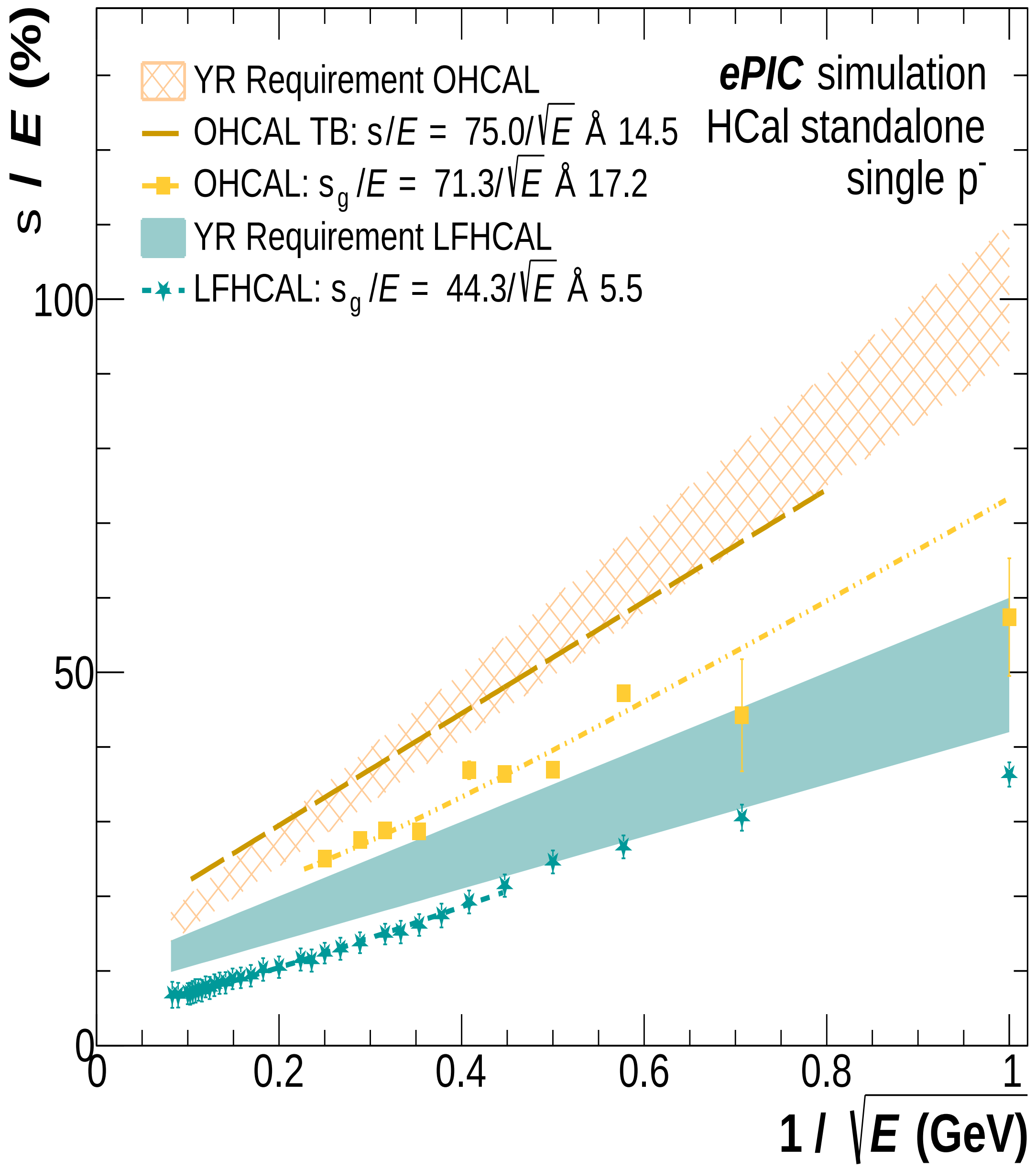
Hadron Endcap



Hadron Calorimetry at ePIC

- Forward Calorimetry System
  - W/Scint & Fe/Scint sampling calorimeter
  - Tungsten layers on front face as collimator
  - Multiple towers per module to increase granularity and reduce dead area
  - Longitudinal segmentation -> particle flow

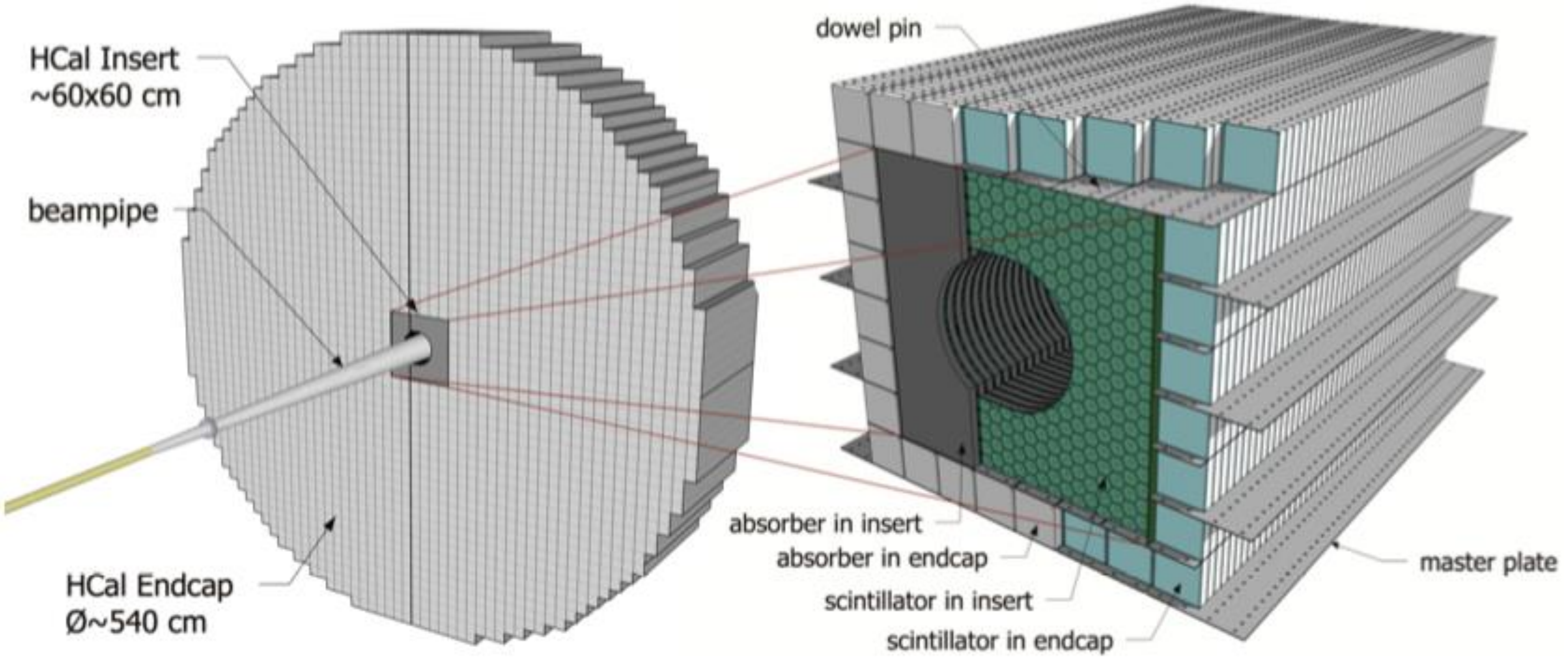
- Barrel HCal System
  - Fe/Scint sampling calorimeter
  - Partial reuse of sPHENIX calorimeter
  - Also serves as magnet flux return

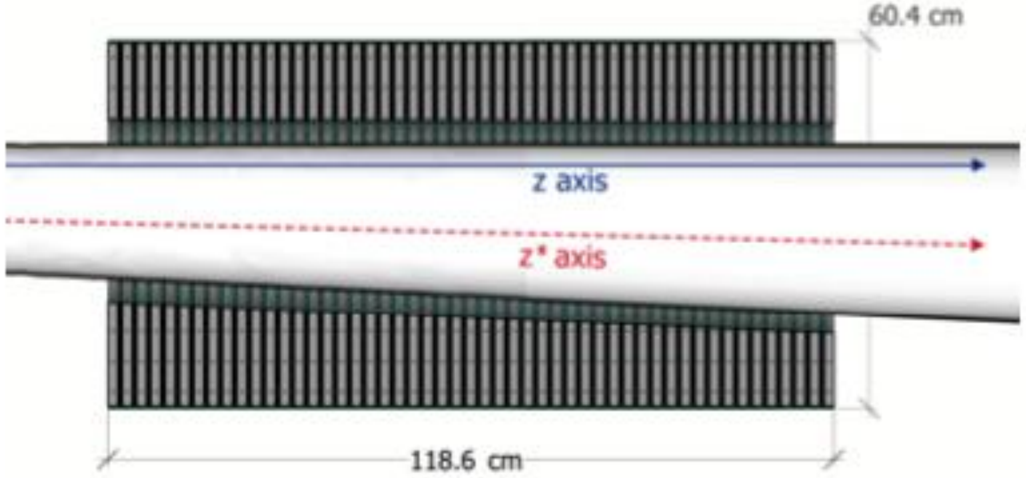


Detector Considerations: Calorimeter Insert

arXiv:2208.05472

- Precision calorimetry in the most forward regions of the central detector (3 < η < 4) will be important as tracking performance degrades rapidly while particle energy is the largest
- Coverage in this region important for classification of the hadronic-final-state, detection of highest energy jets, and tagging beam-induced backgrounds
- Propose a steel/tungsten – scintillator sampling calorimeter insert in this region
- Cutouts in each layer will vary along z to follow the shape of the beampipe and maximize coverage

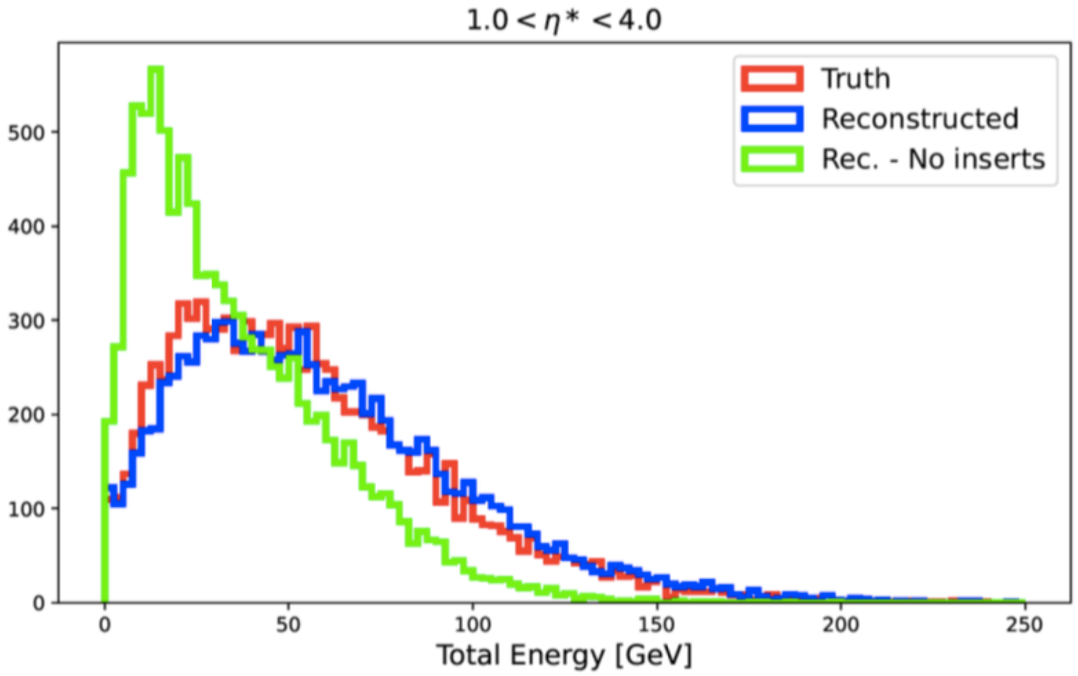




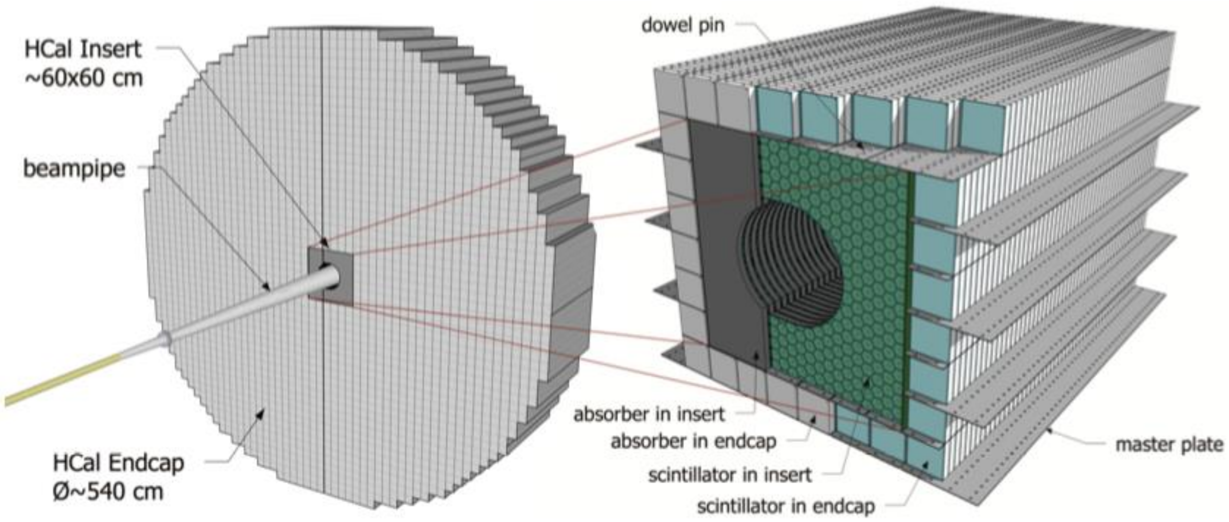
Forward Acceptance: Calorimeter Insert

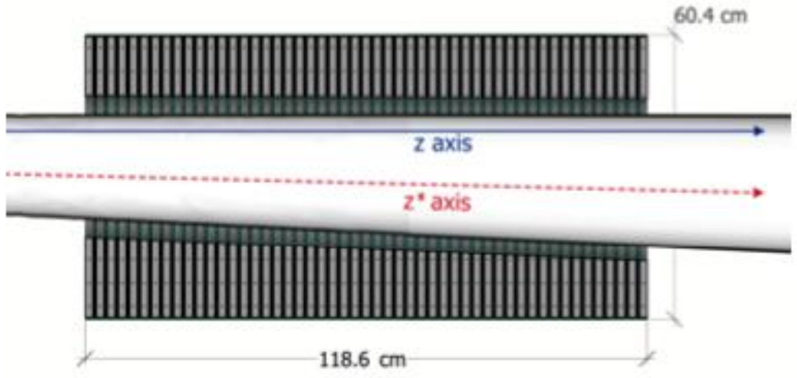
- Calorimeter should sit as close as possible to the beam to maximize acceptance
  - Reduce phi-dependent acceptance effects as discussed above
  - Improve reconstruction of the total energy in event -> kinematic reconstruction

- Proposal in ePIC for a high-granularity insert whose geometry changes in z to follow the beam pipe



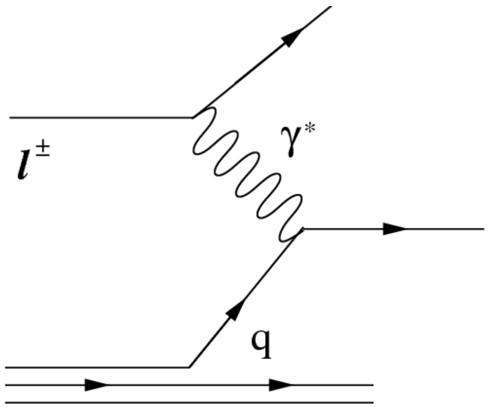
arXiv:2208.05472



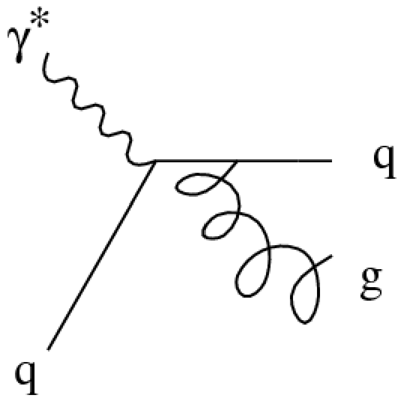


Relevant Subprocesses

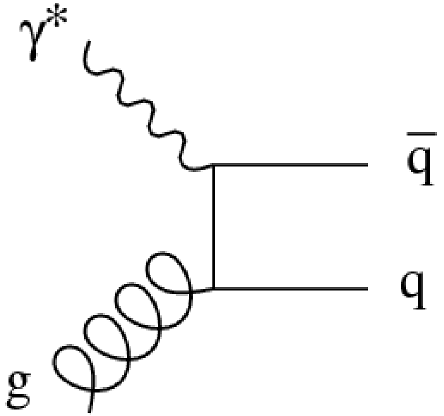
DIS



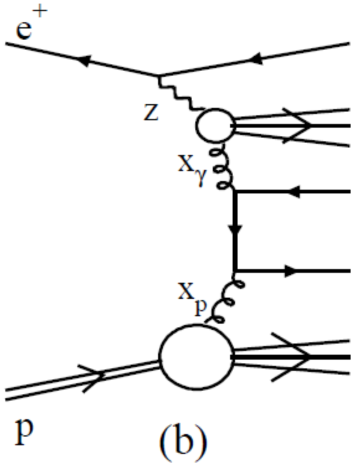
QCD-Compton (QCDC)



Photon-Gluon Fusion (PGF)

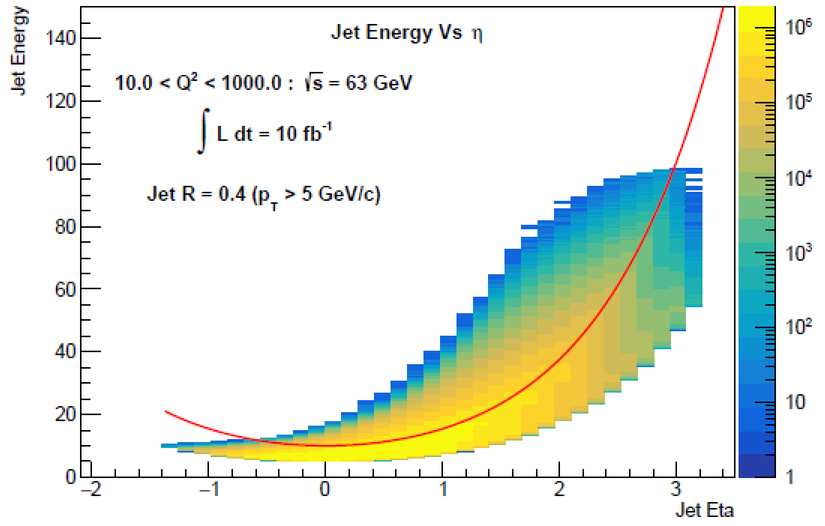


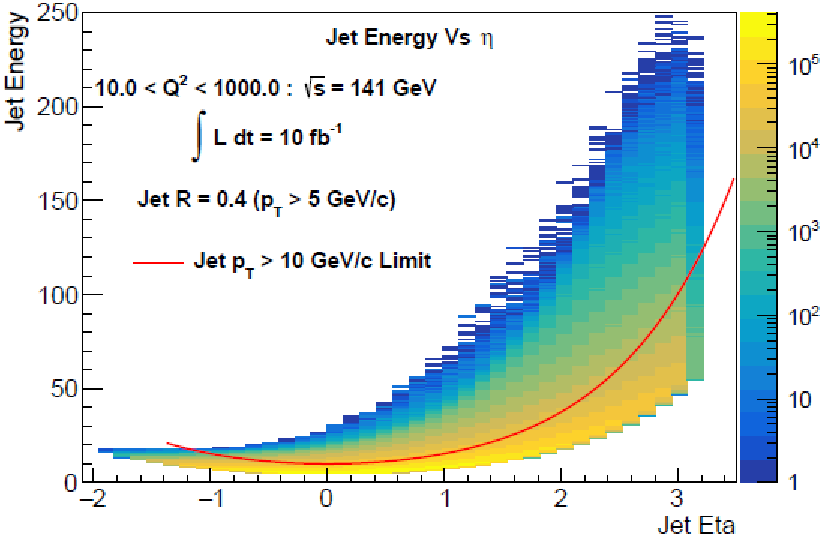
Resolved

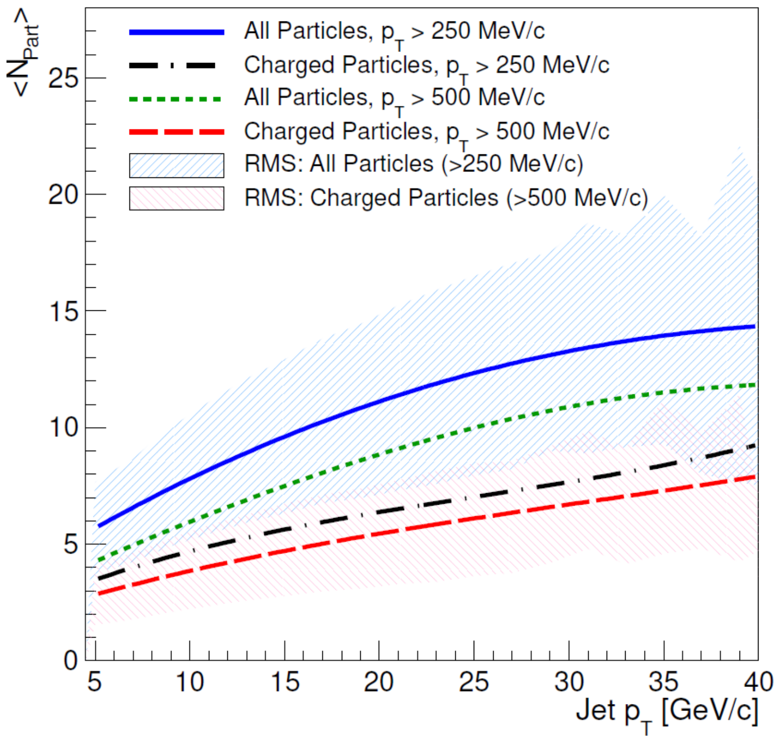


- ❑ Leading order process gives rise to a single jet (not counting target remnant) whose kinematics are largely determined by the underlying event kinematics
- ❑ Higher-order corrections to this process can give rise to back-to-back jet configurations (dijets) which break the dependencies on event kinematics
- ❑ 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

Jet Kinematics



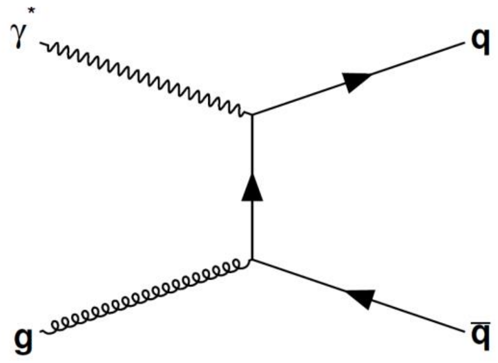




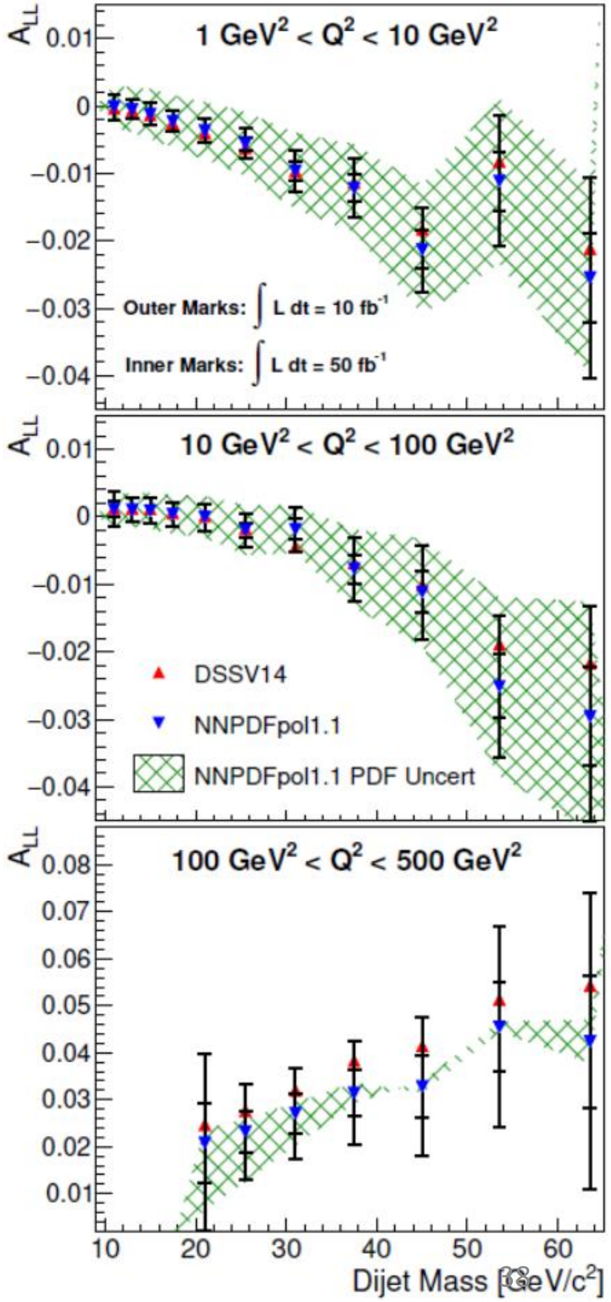
- Bulk of jets produced at the EIC will be low energy / low pT
- Pushing to analyze the lowest energy jets will provide access to the lowest x values, which will be important for spin structure and saturation studies
- In addition to being relatively low energy, jets will be quite broad and have few particles
- Must ensure theory and MC can make robust predictions for low energy jets and hadronization models can handle low multiplicity jets

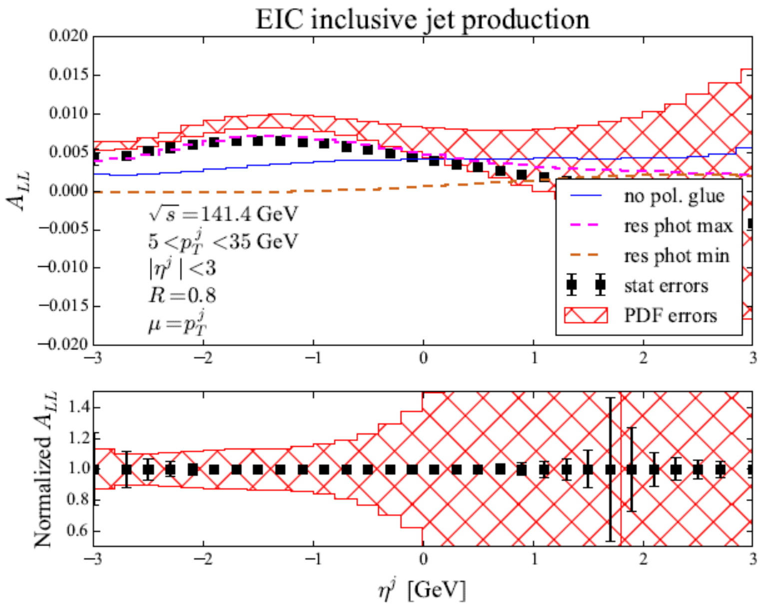
Longitudinal Spin Structure

- Recent results on inclusive jet A_{LL} at NLO and NNLO both with and without tagged lepton
- Will place strong constraints on helicity distributions
- Feasibility study for dijet A_{LL} in the Breit frame also performed – access to gluon via PGF process

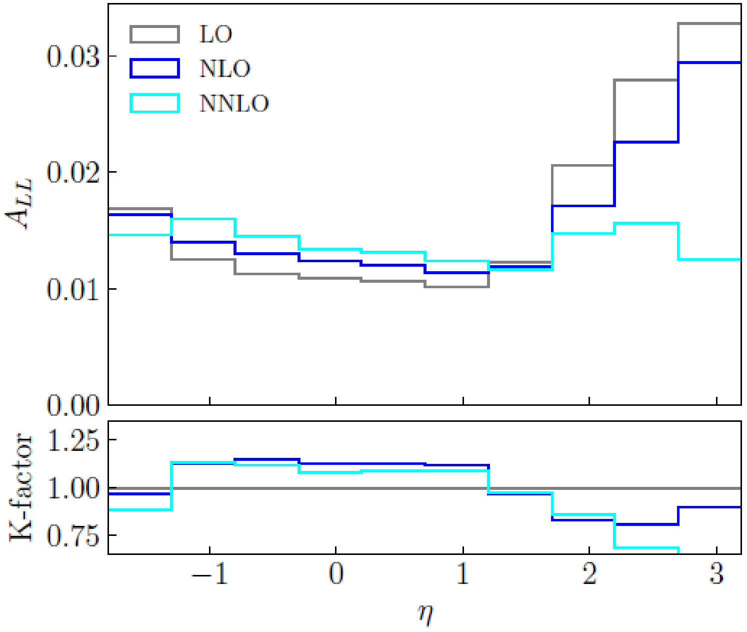


Page, Chu, Aschenauer `20





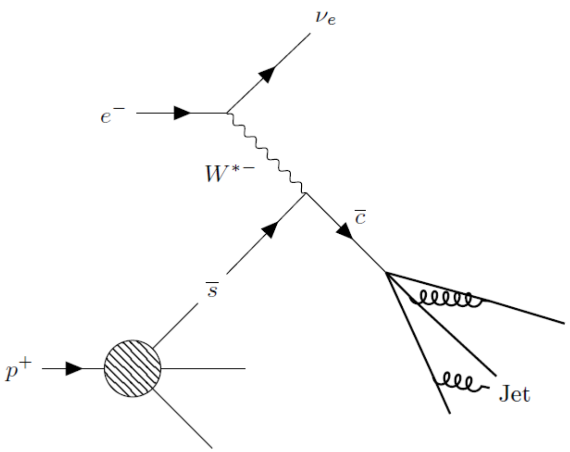
Boughezal, Petriello, Xing `18

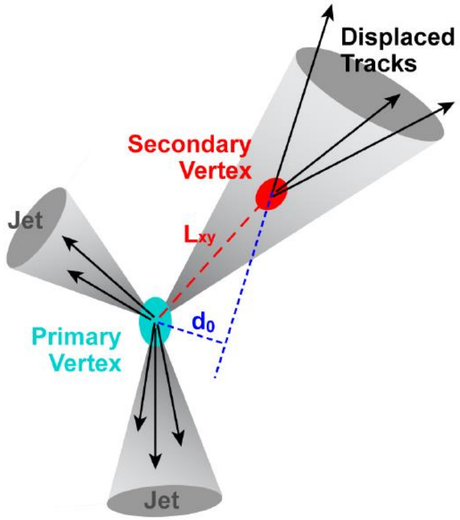


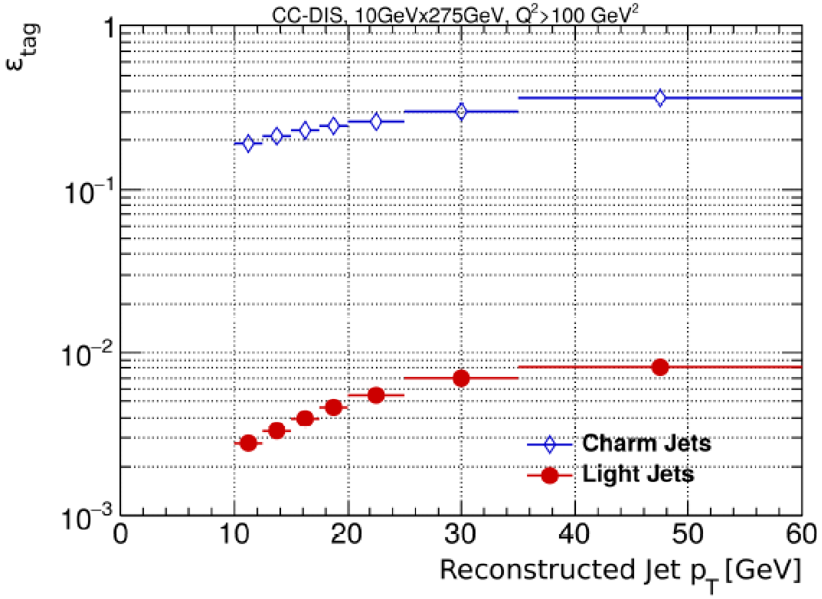
Borsa, de Florian, Pedron `20

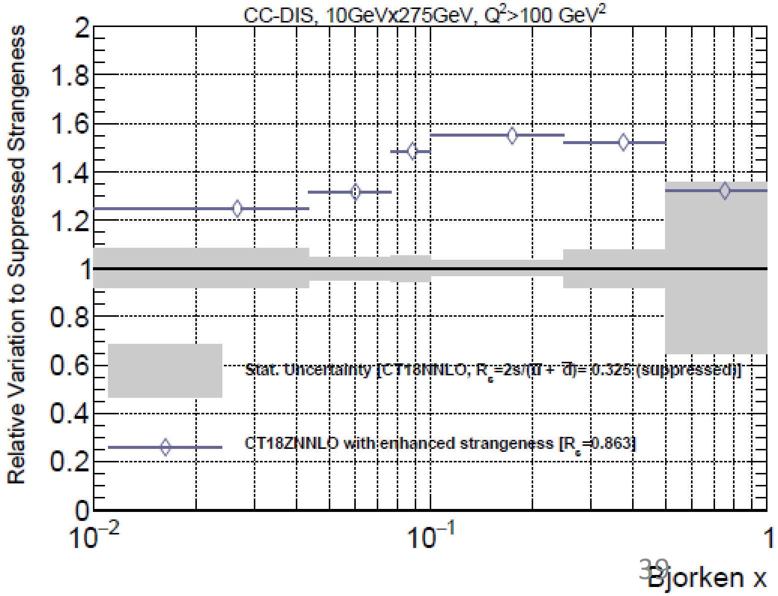
Strangeness PDF: Charm Jets

Arratia, Furletova, Hobbs, Olness, Sekula `20





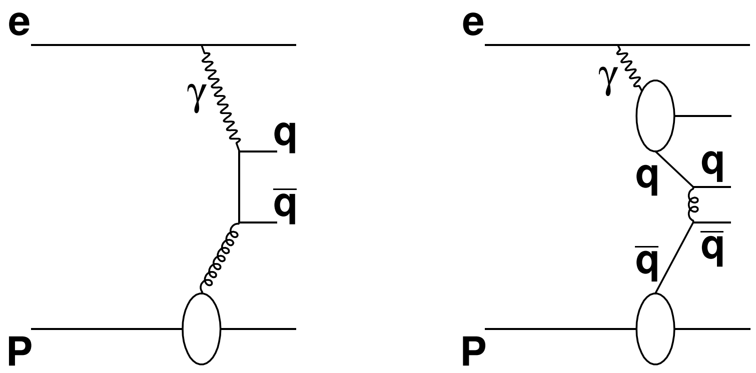


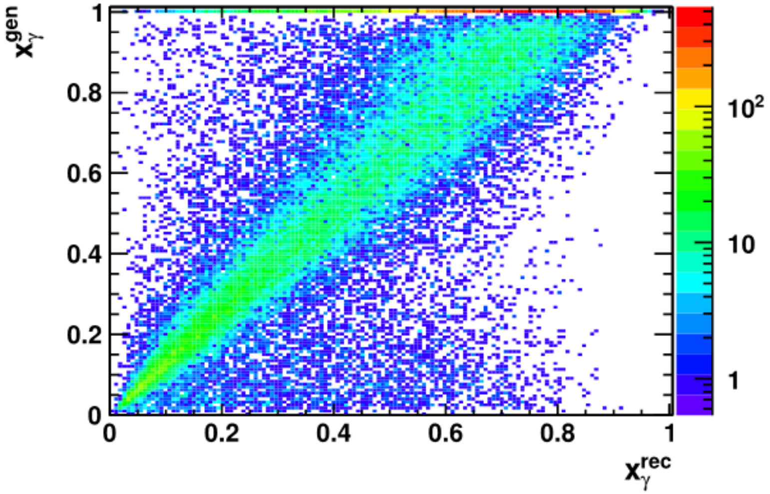


- Tension exists between neutrino DIS and SIDIS measurements of strange content and LHC extractions
- EIC is sensitive to strange content via charm production in charged-current DIS
- Charm is tagged within a jet via the presence of displaced tracks – good charm efficiency is seen, and methods are being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

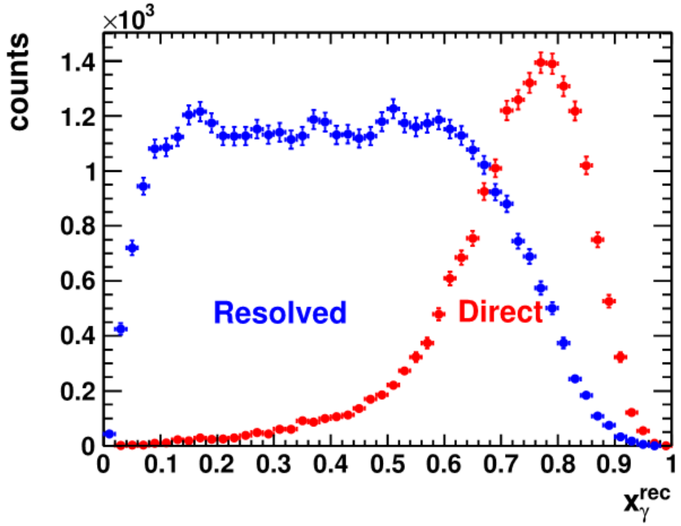
(Polarized) Photon Structure

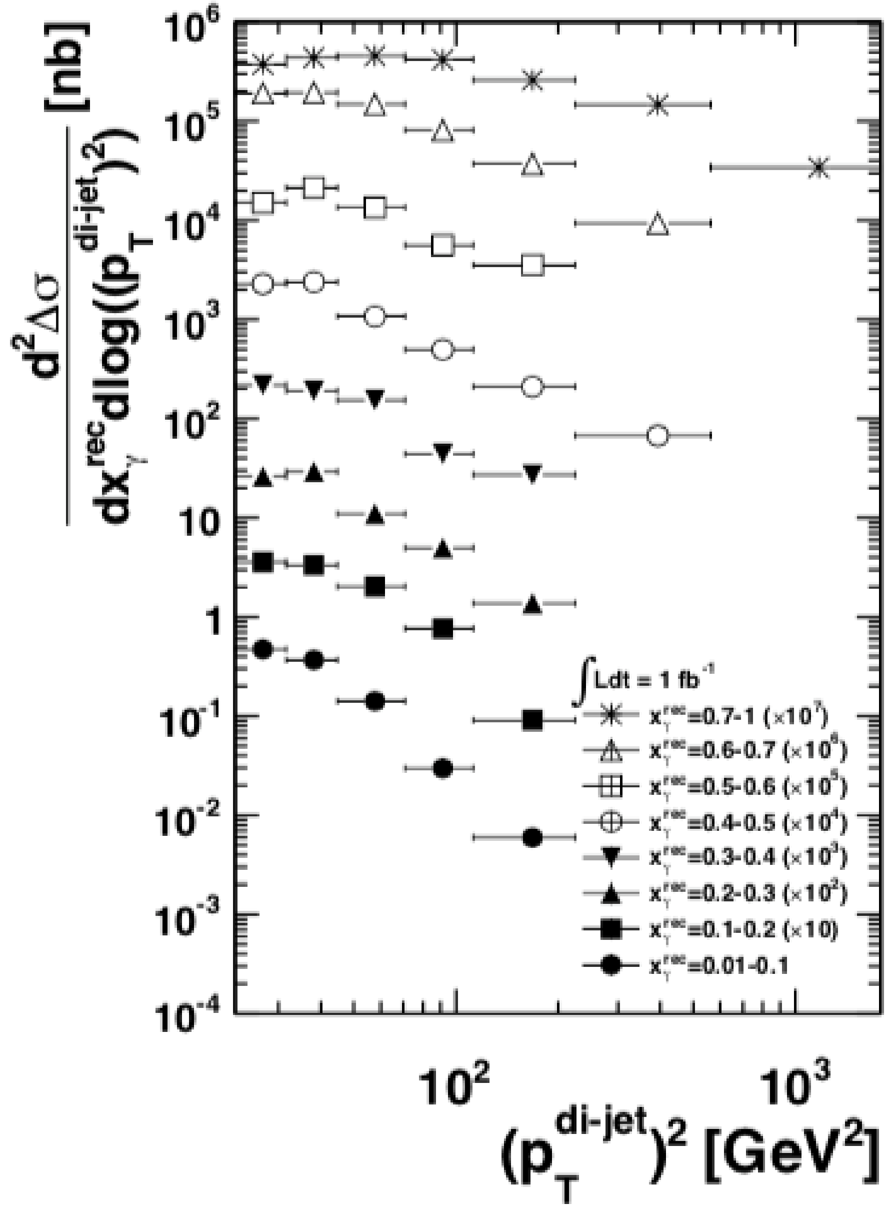
- At low Q2, virtual photon can behave hadronically and initiate 2->2 type scattering events
- Results in a quark/anti-quark final state with high transverse momentum
- Dijet allows to reconstruct event characteristics to separate signal and background and characterize the structure of the photon



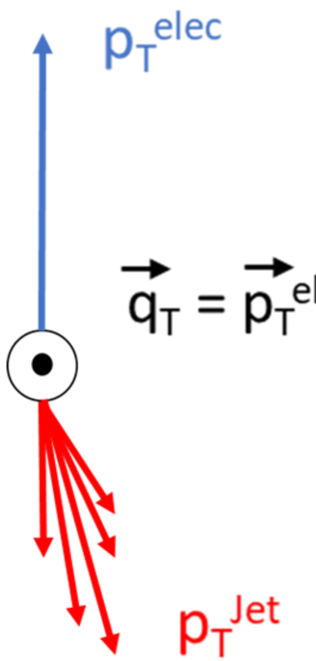


$$x_\gamma^{rec} = \frac{1}{2E_e y}\left(p_{T1}e^{-\eta_1} + p_{T2}e^{-\eta_2}\right)$$



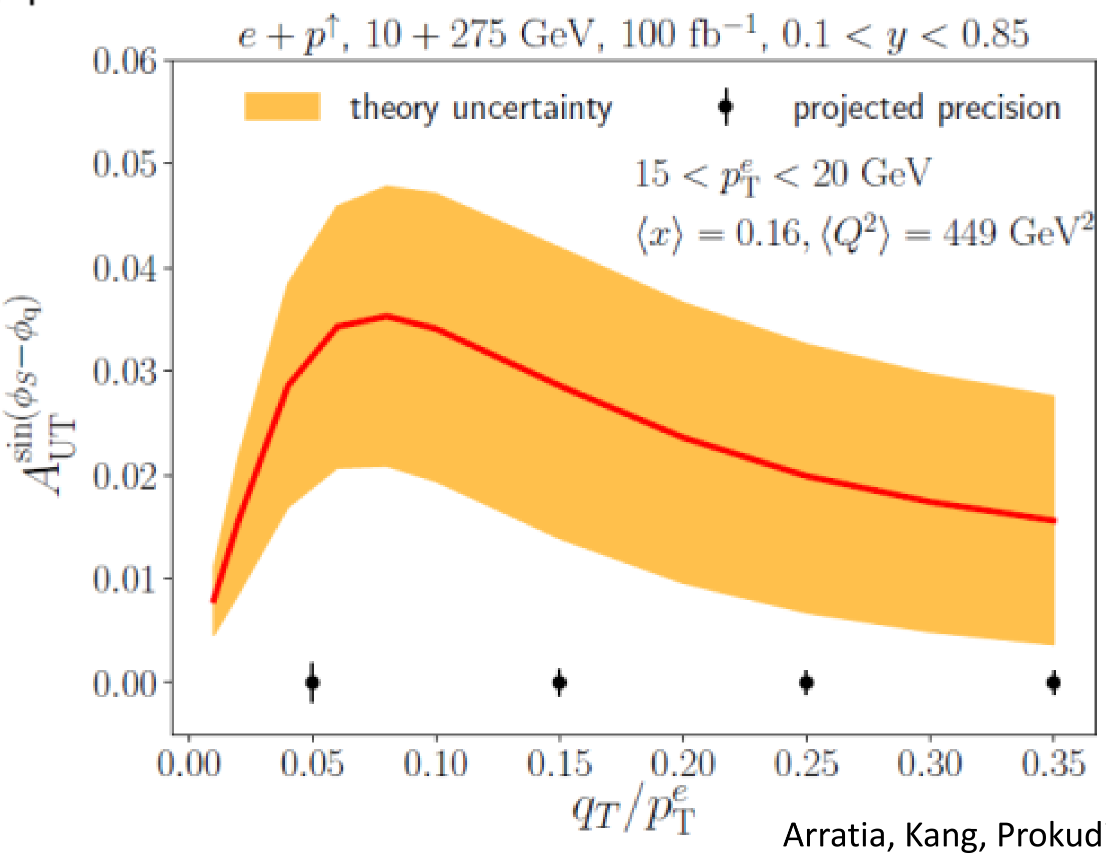


Lepton-Jet Correlations: Sivers TMD



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

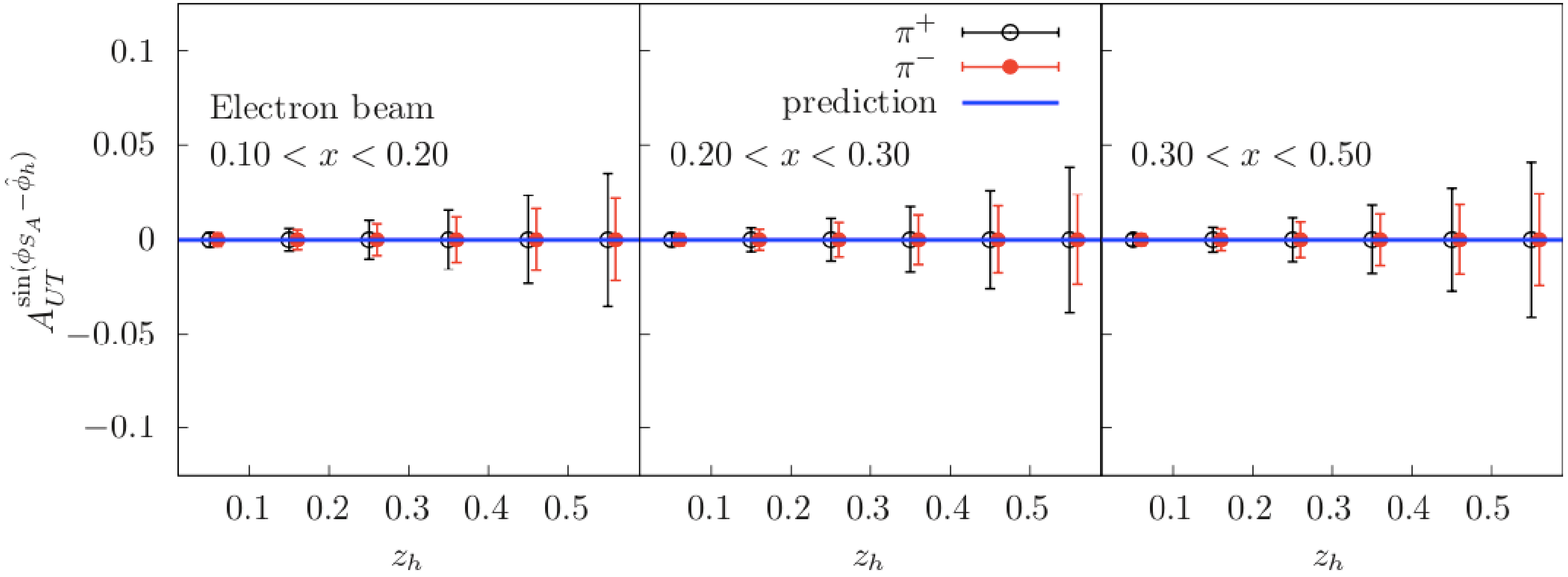
$$e + p(\vec{s}_T) \to e + (\text{jet}(\vec{q}_T)\, h(z_h, \vec{j}_T)) + X$$

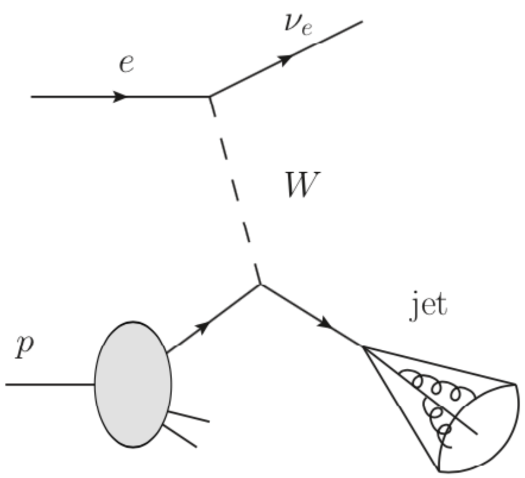


Arratia, Kang, Prokudin, Ringer `20

- ❑ 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)

Charged Current Lepton-Jet Correlations

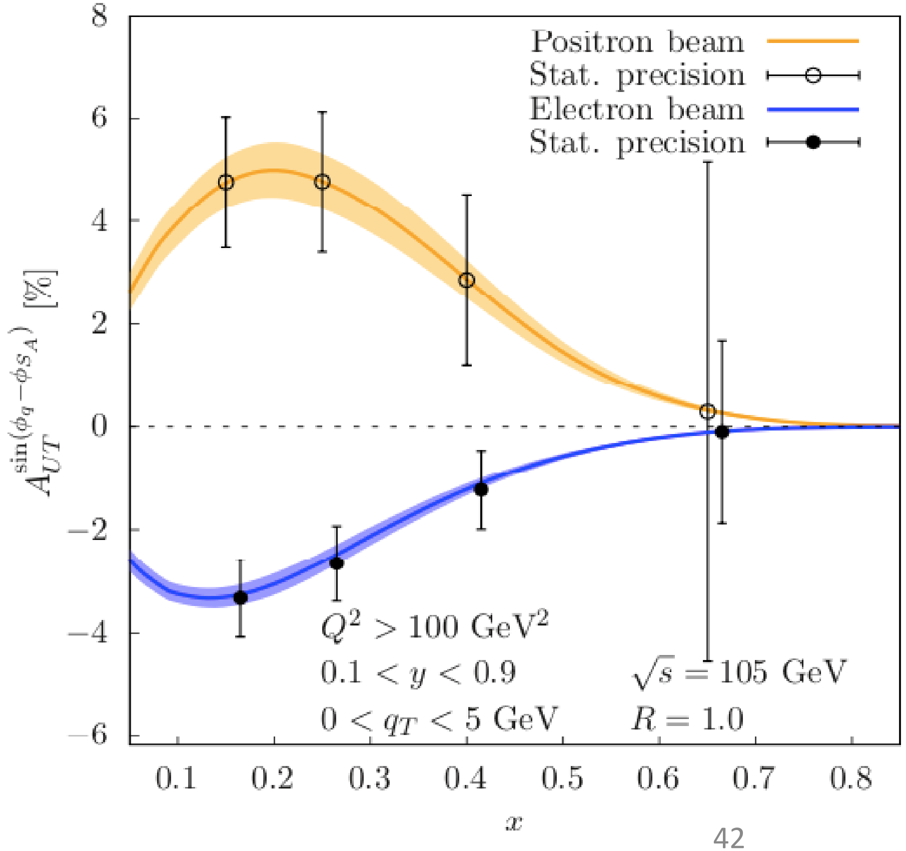




- Previous lepton-jet and hadron-in-jet measurements can also be carried out in charged current DIS where the outgoing neutrino is deduced via missing transverse energy

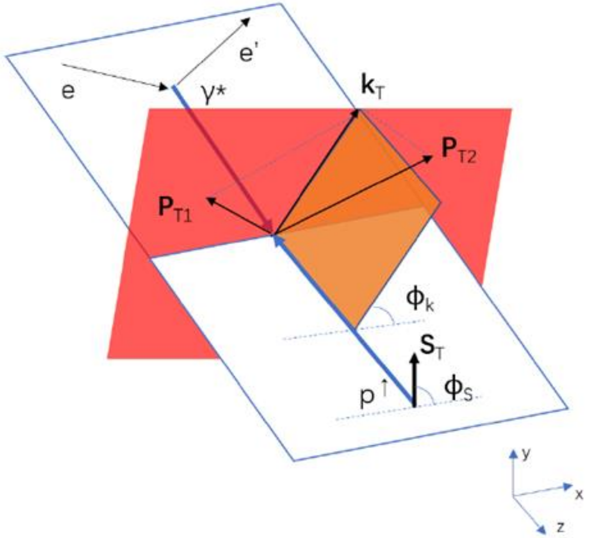
- Charge conservation leads to flavor separation

- Chiral odd nature of interaction means Collins asymmetries vanish at leading order



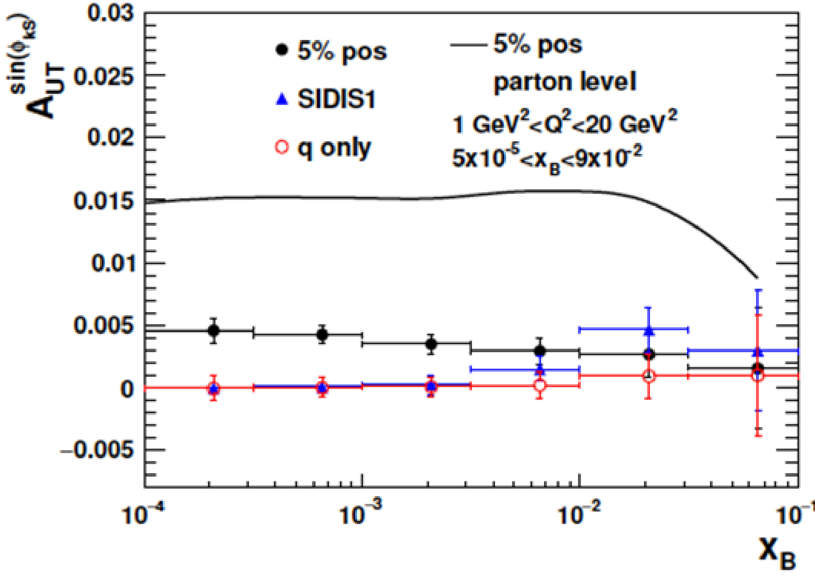
Dijet Correlations: Gluon Sivers TMD

Phys. Rev. D 98, 034011 (2018)

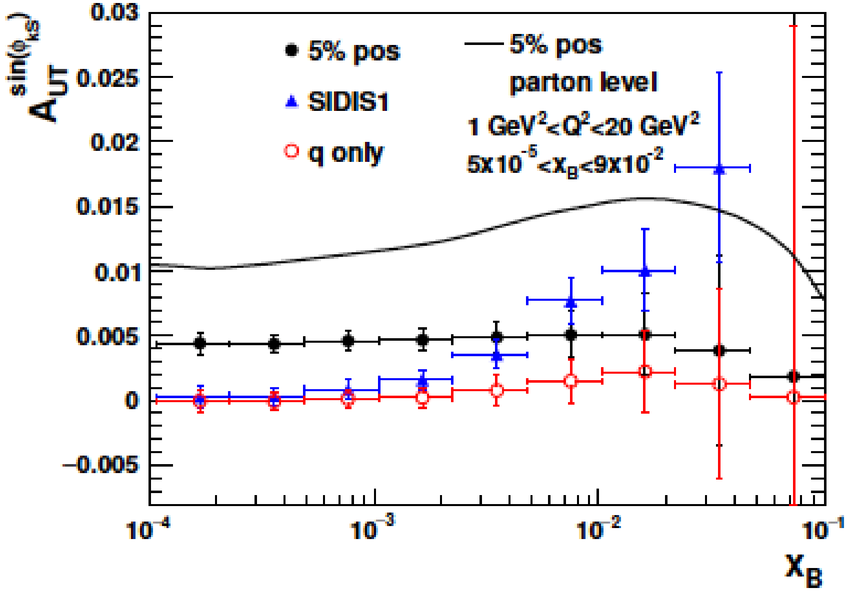


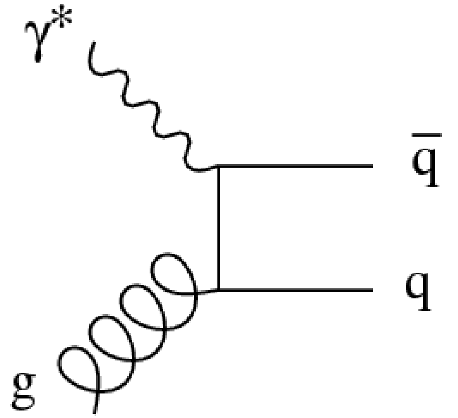
- Modulations of the angle between the proton spin vector and the sum of the di-parton system provide access to gluon sivers function
- Use of dijets has several advantages over di-hadrons including lower dilution of asymmetry and better separation between models of gluon sivers effect
- Jets don't suffer from uncertainties arising due to fragmentation (although hadronization still a concern)

Di-Hadrons



Dijets

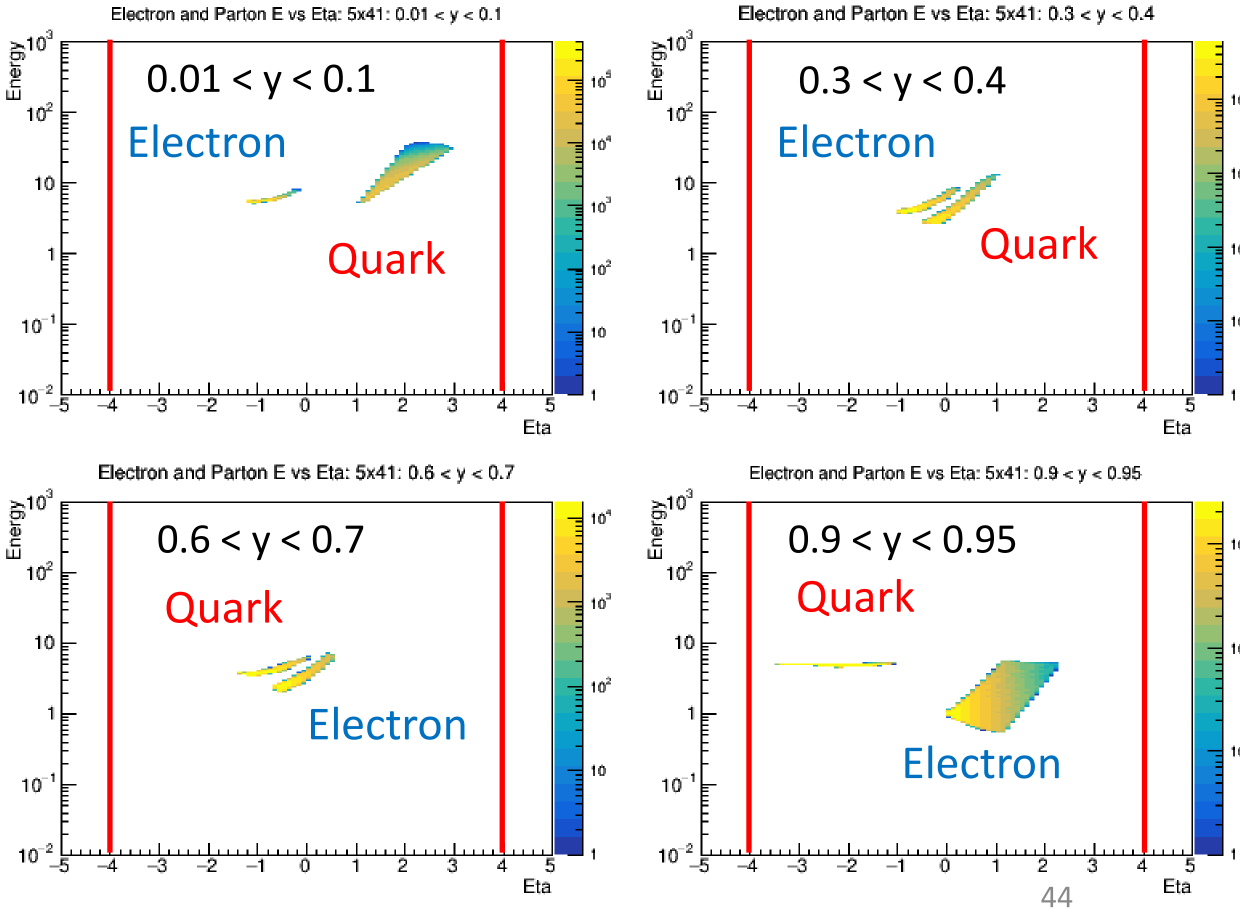


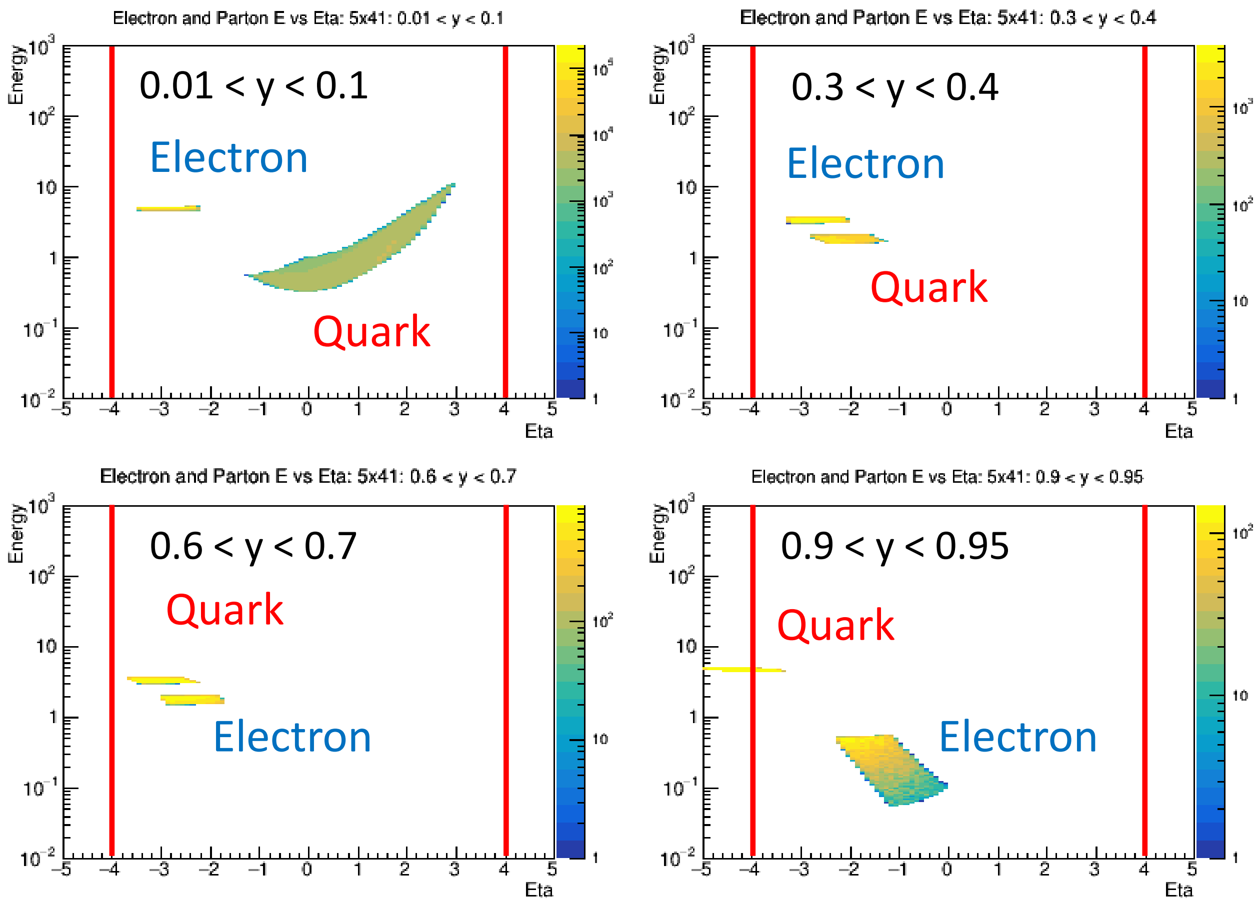


Electron and Struck Quark (5x41)

- 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

$10 < Q^2 < 100$



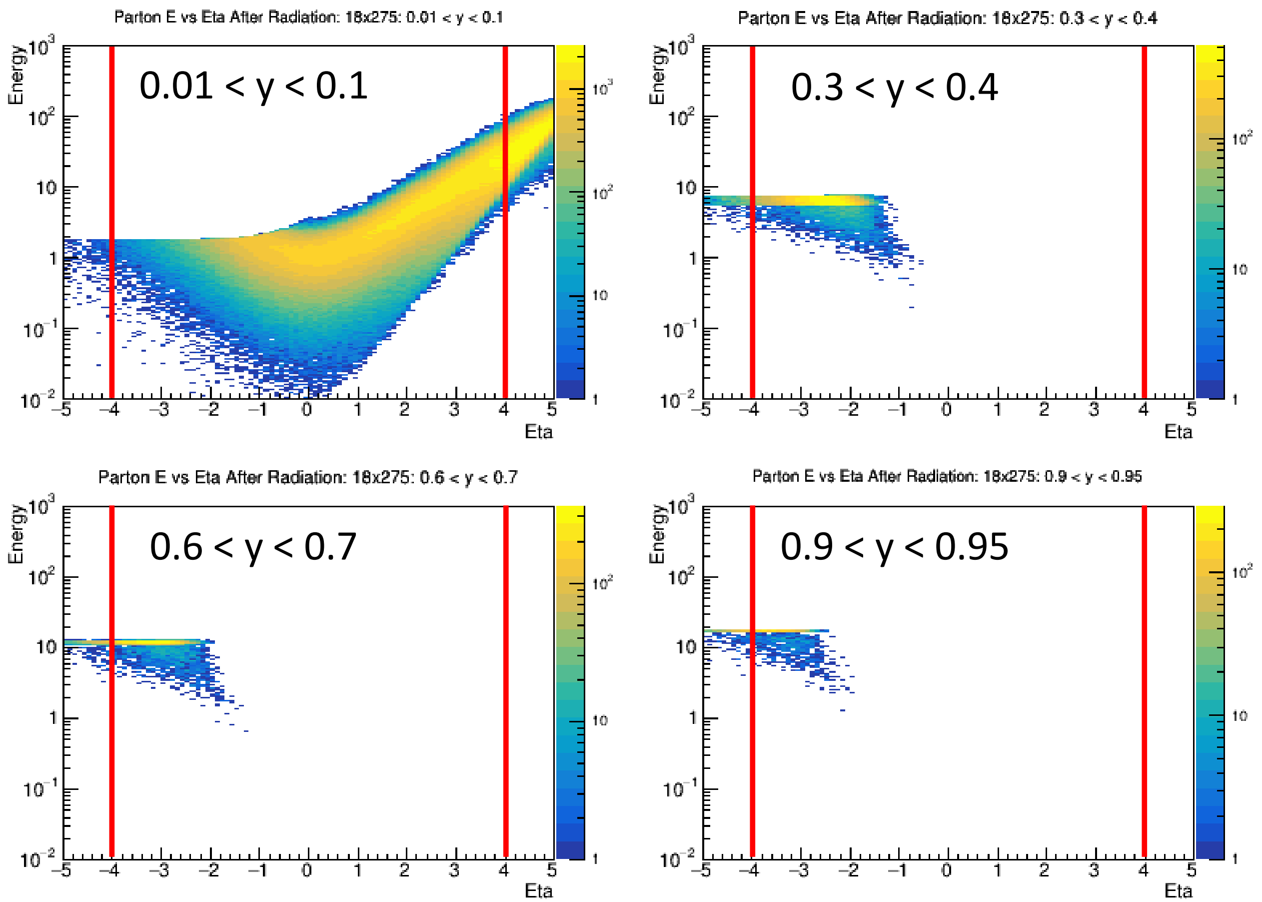


$0.1 < Q^2 < 1.0$

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

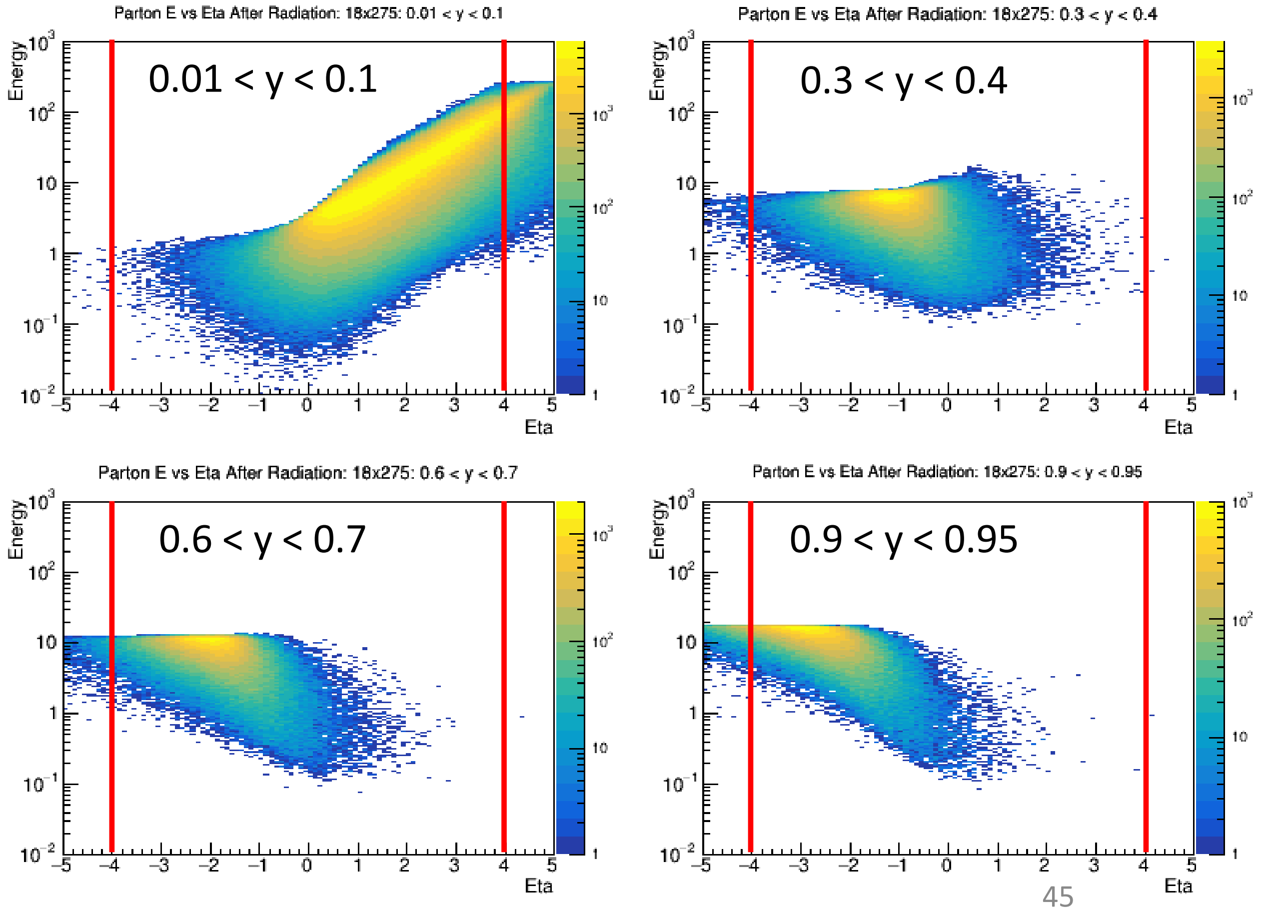
Struck Quark + FSR (18x275)

- For Born-level process, struck quark kinematics are correlated with event kinematics
- Final state radiation can alter quark kinematics significantly



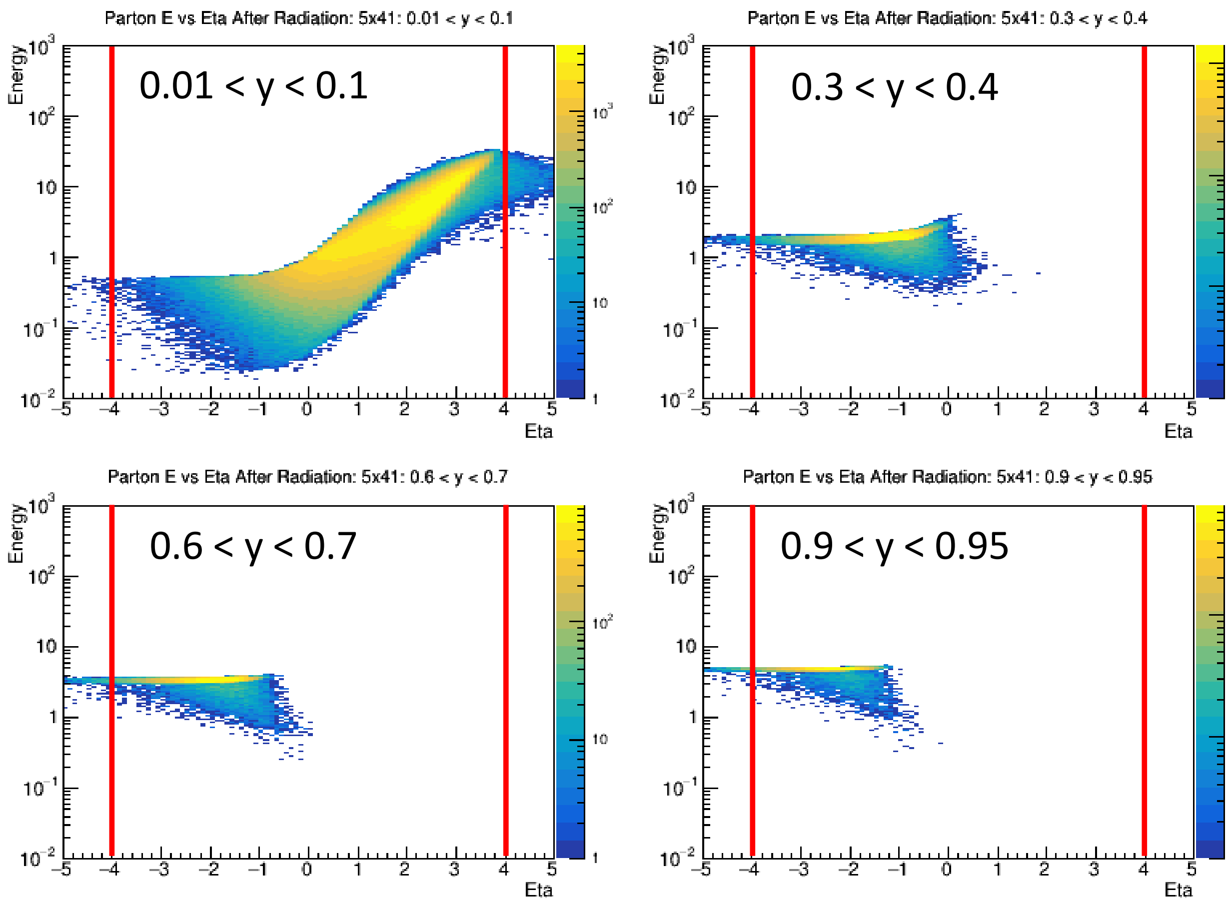
$0.1 < Q^2 < 1.0$

$10 < Q^2 < 100$



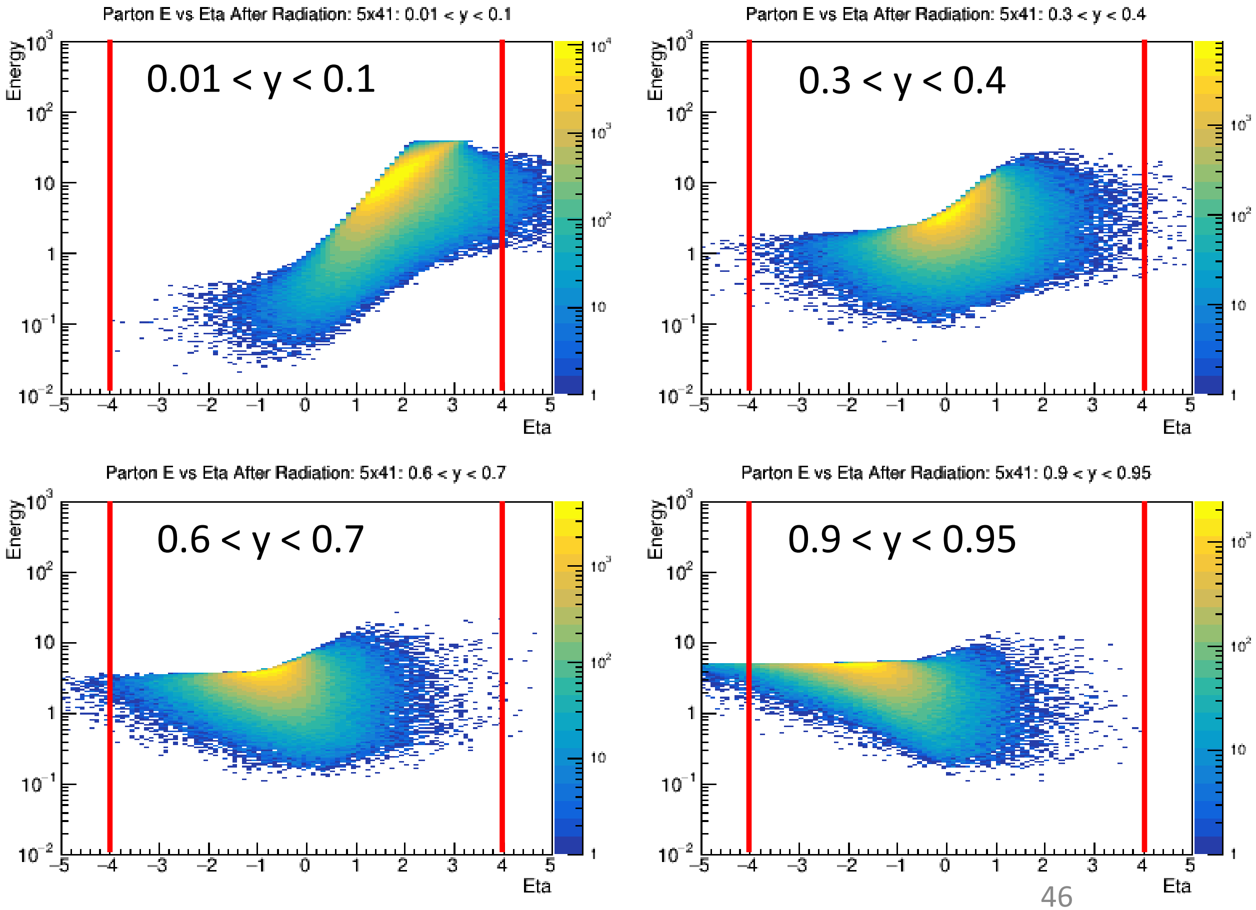
Struck Quark + FSR (5x41)

- Behavior as a function of Q^2, y, and beam energy is still seen



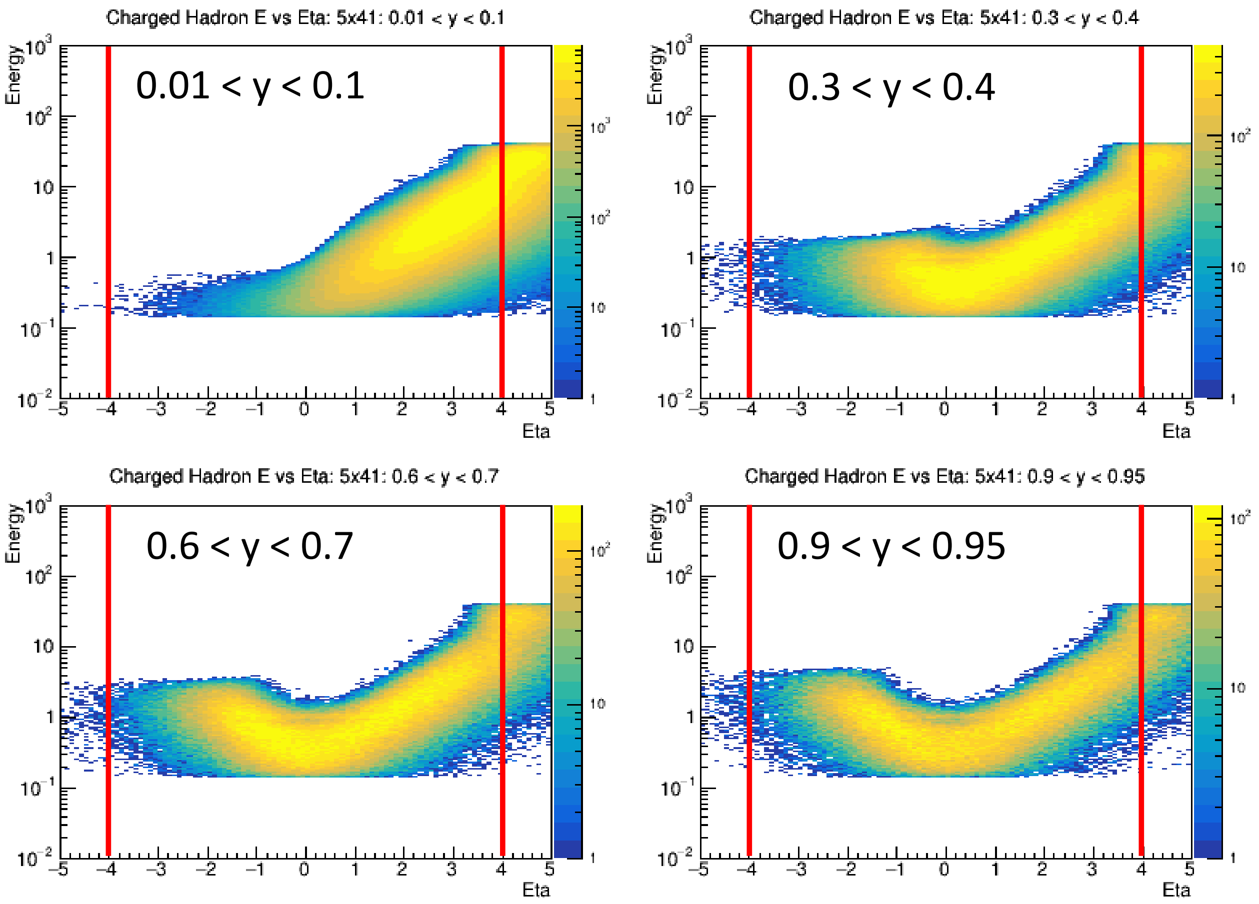
$0.1 < Q^2 < 1.0$

$10 < Q^2 < 100$



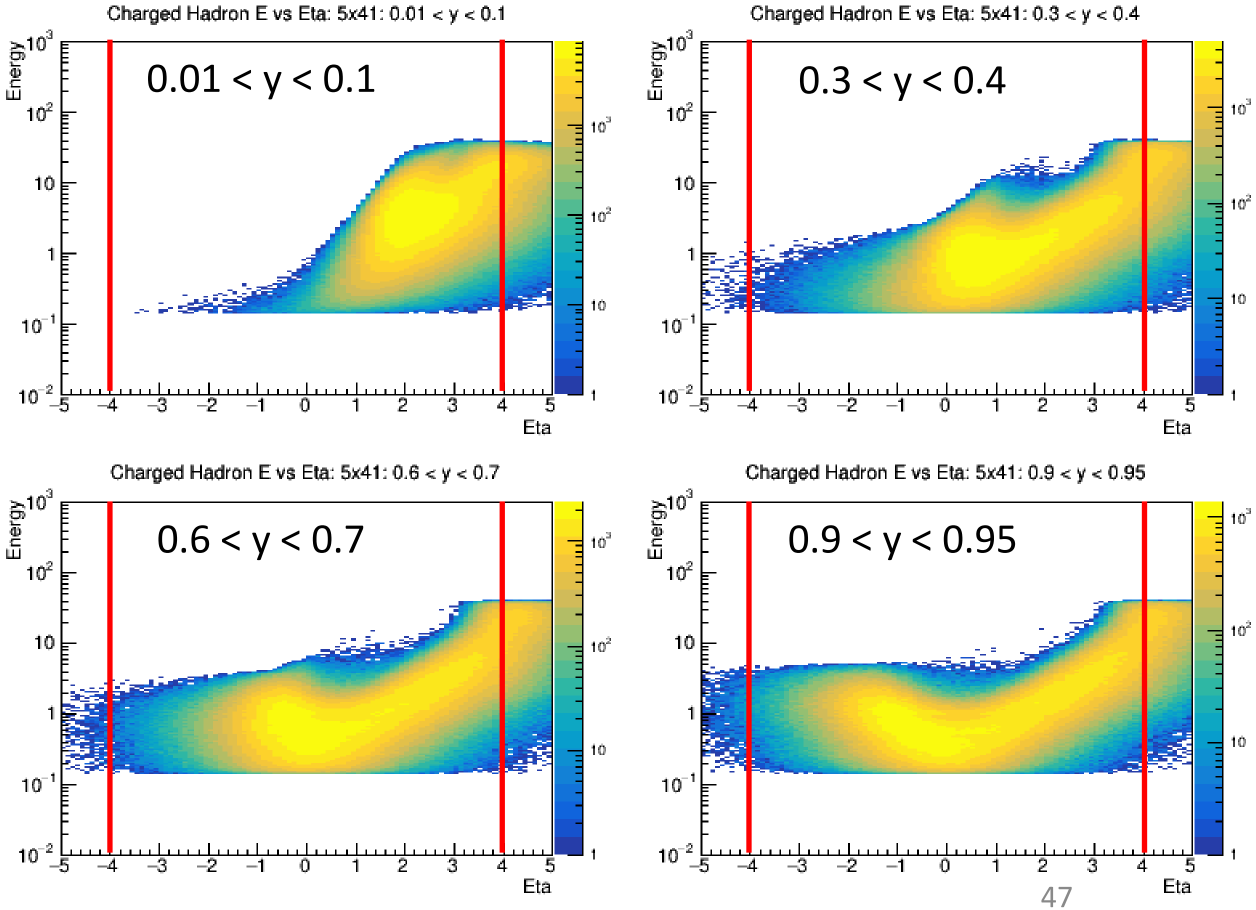
(Charged) Particle Distributions (5x41)

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



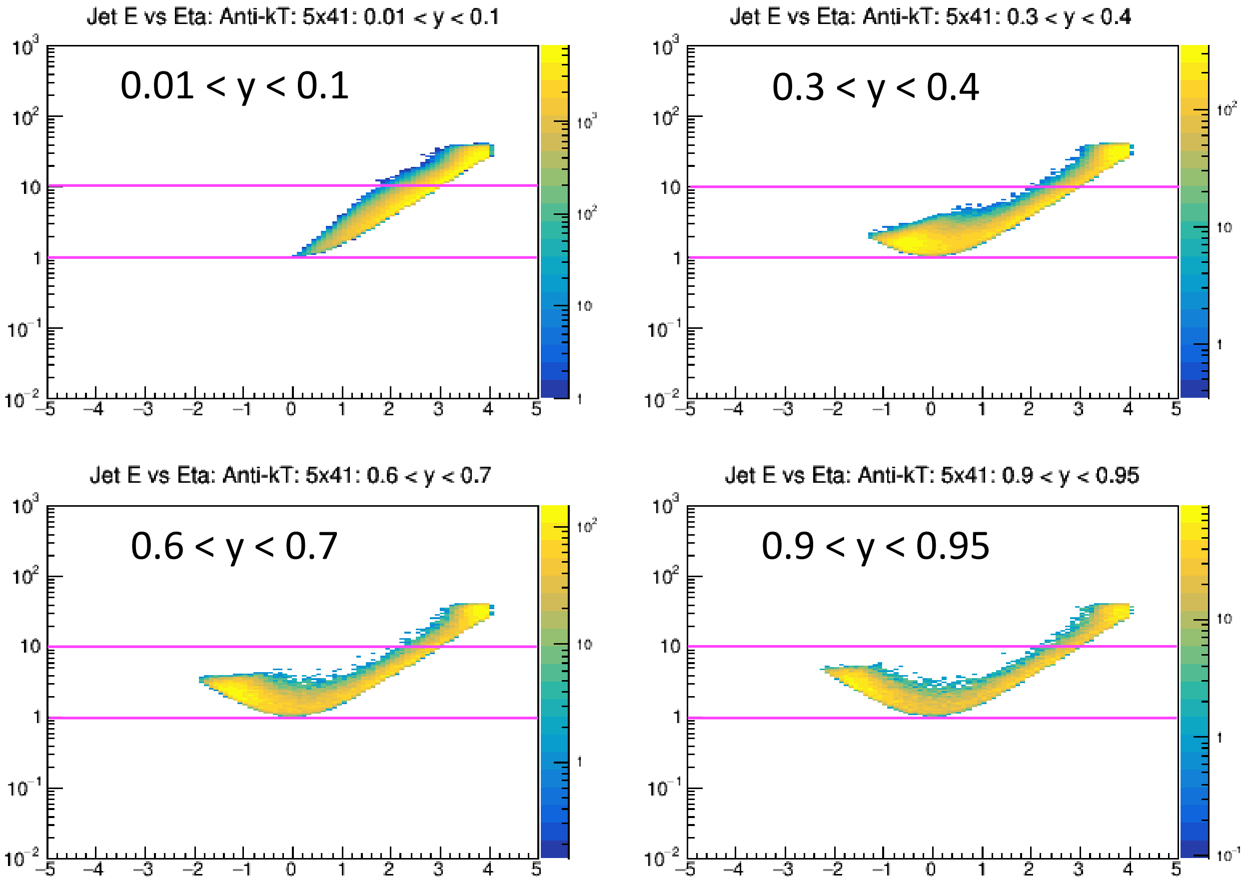
0.1 < Q² < 1.0

10 < Q² < 100



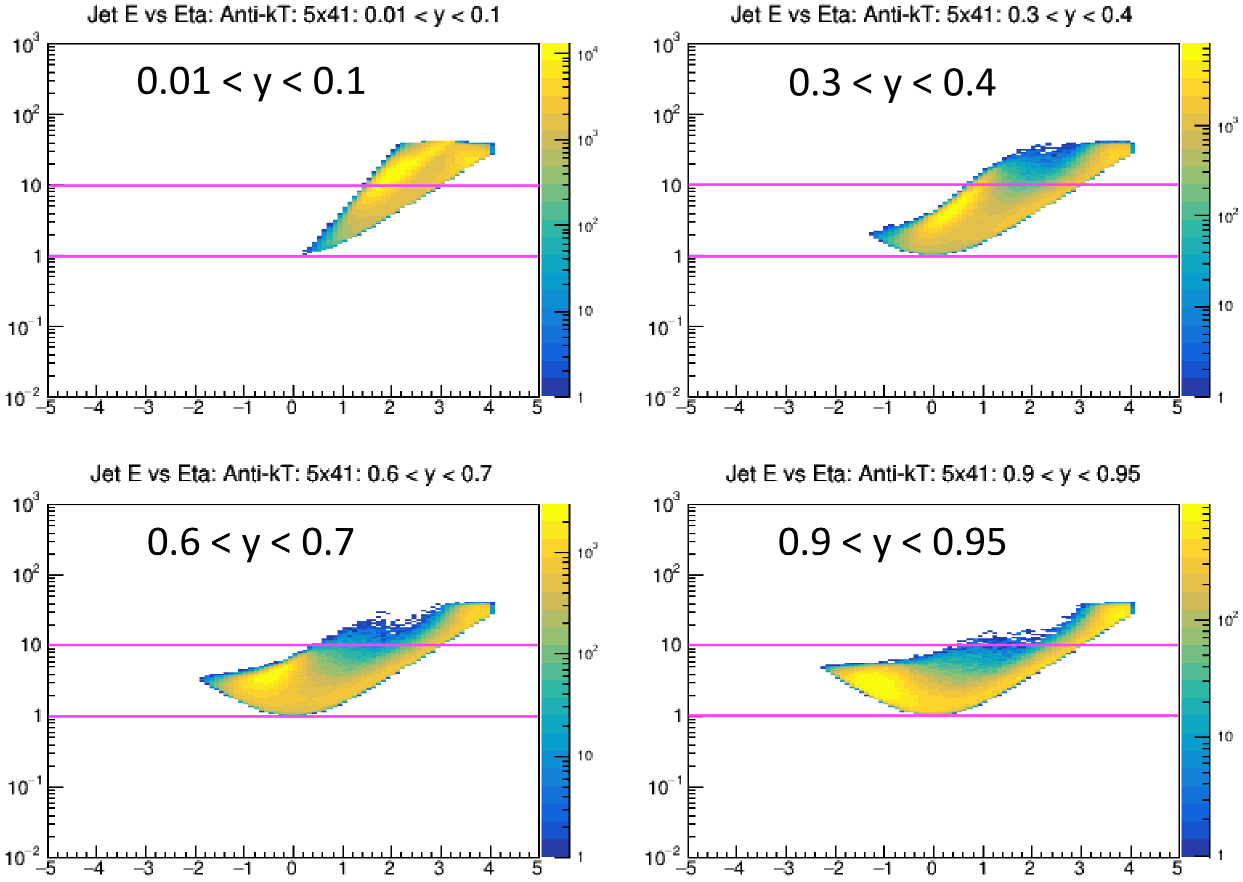
- Particle production not associated only with struck parton
- Gammas and neutrals follow same pattern

Jet Distributions: Anti_kT (5x41)

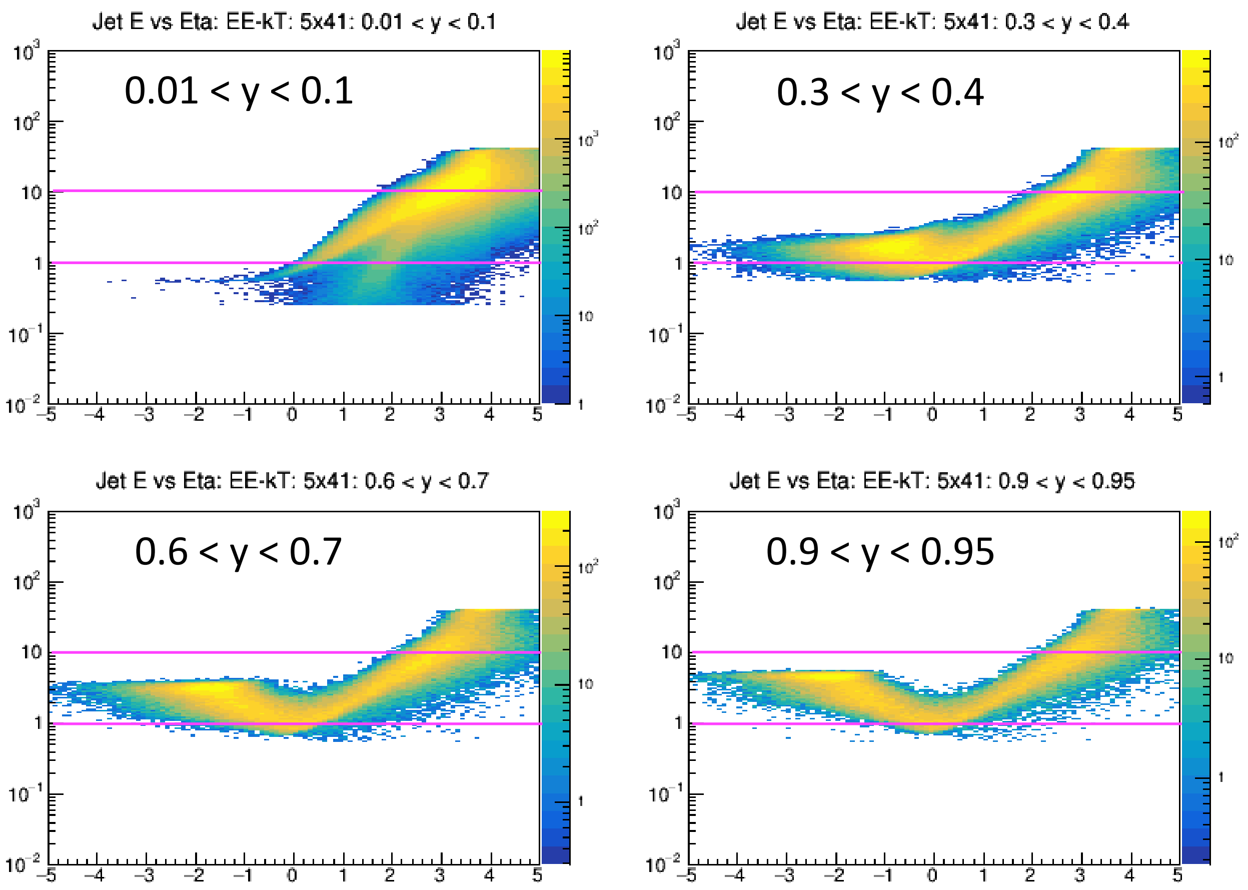


$0.1 < Q^2 < 1.0$

$10 < Q^2 < 100$

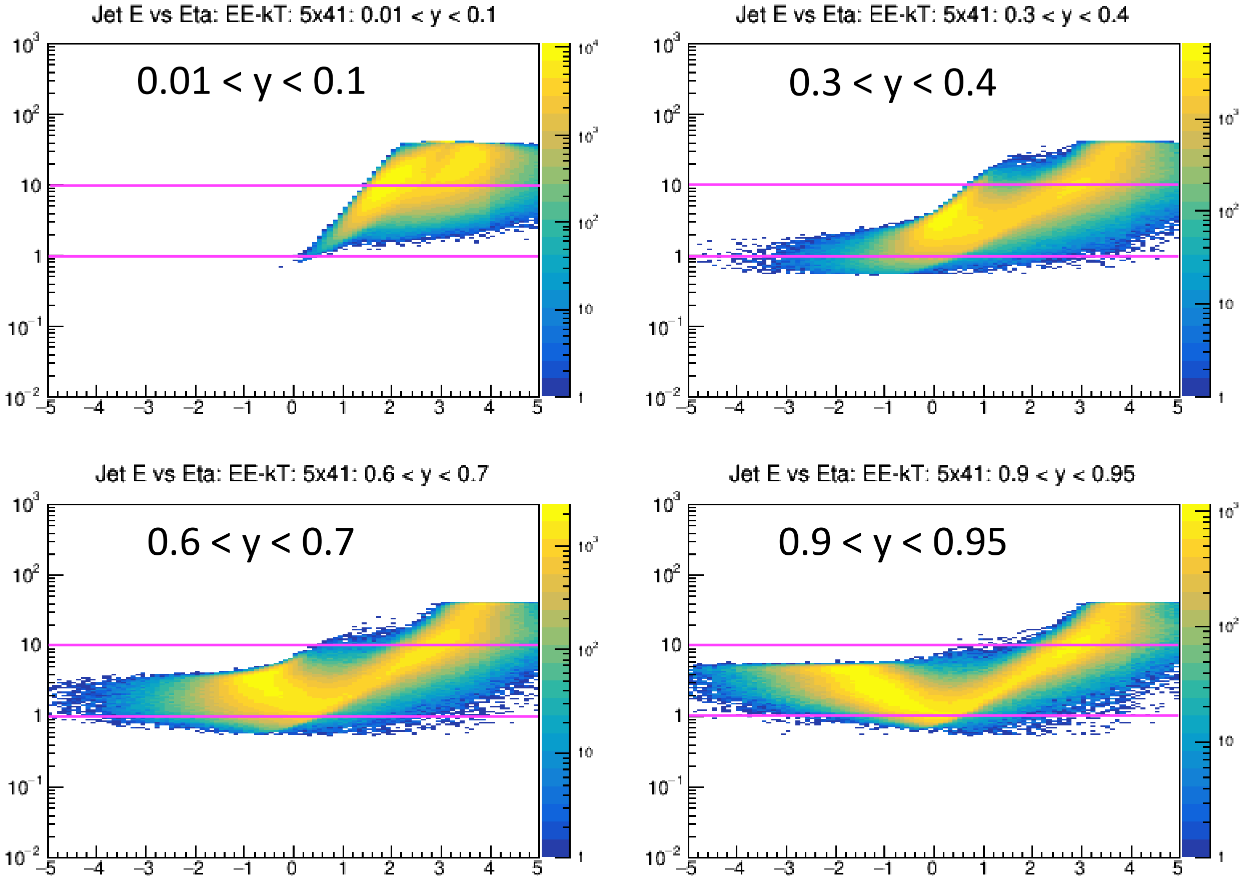


Jet Distributions: EE_kT (5x41)

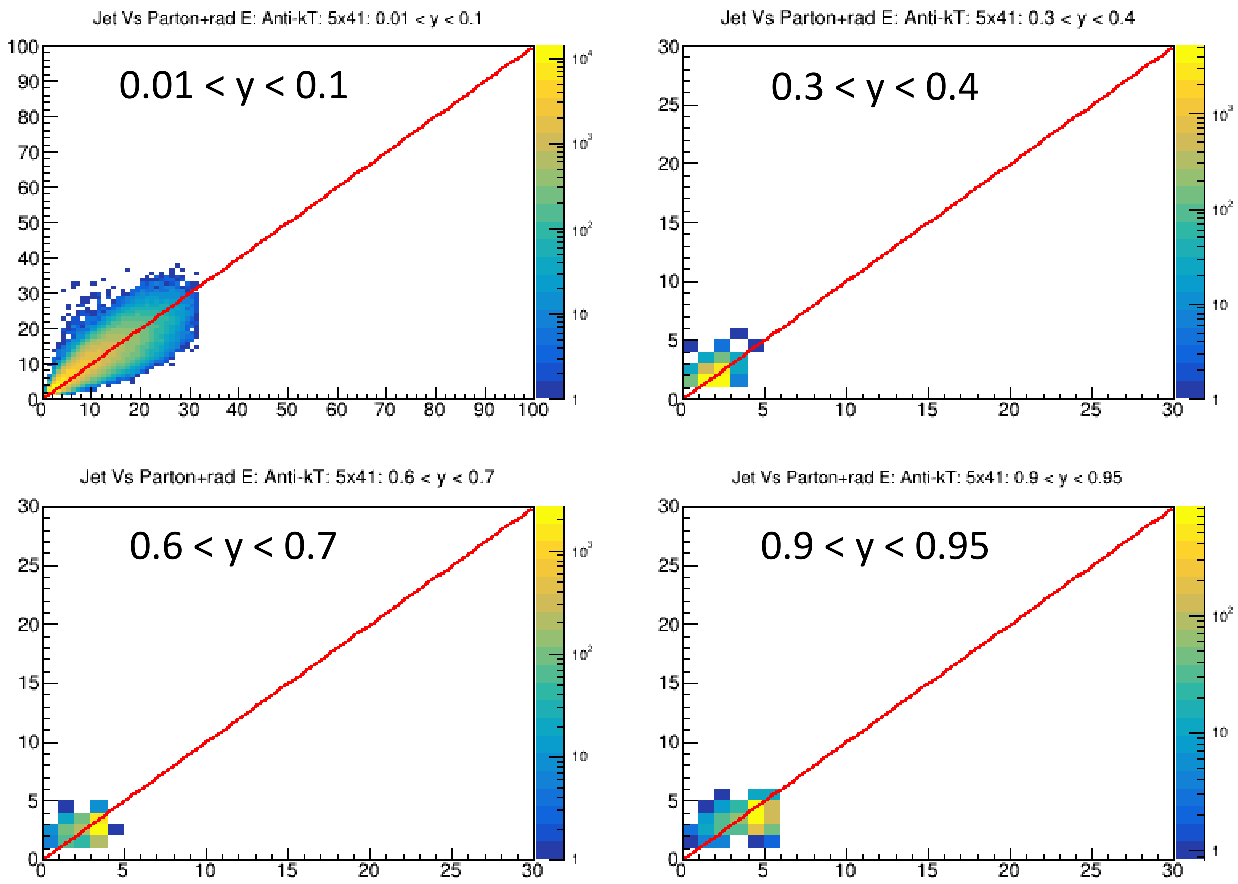


$0.1 < Q^2 < 1.0$

$10 < Q^2 < 100$

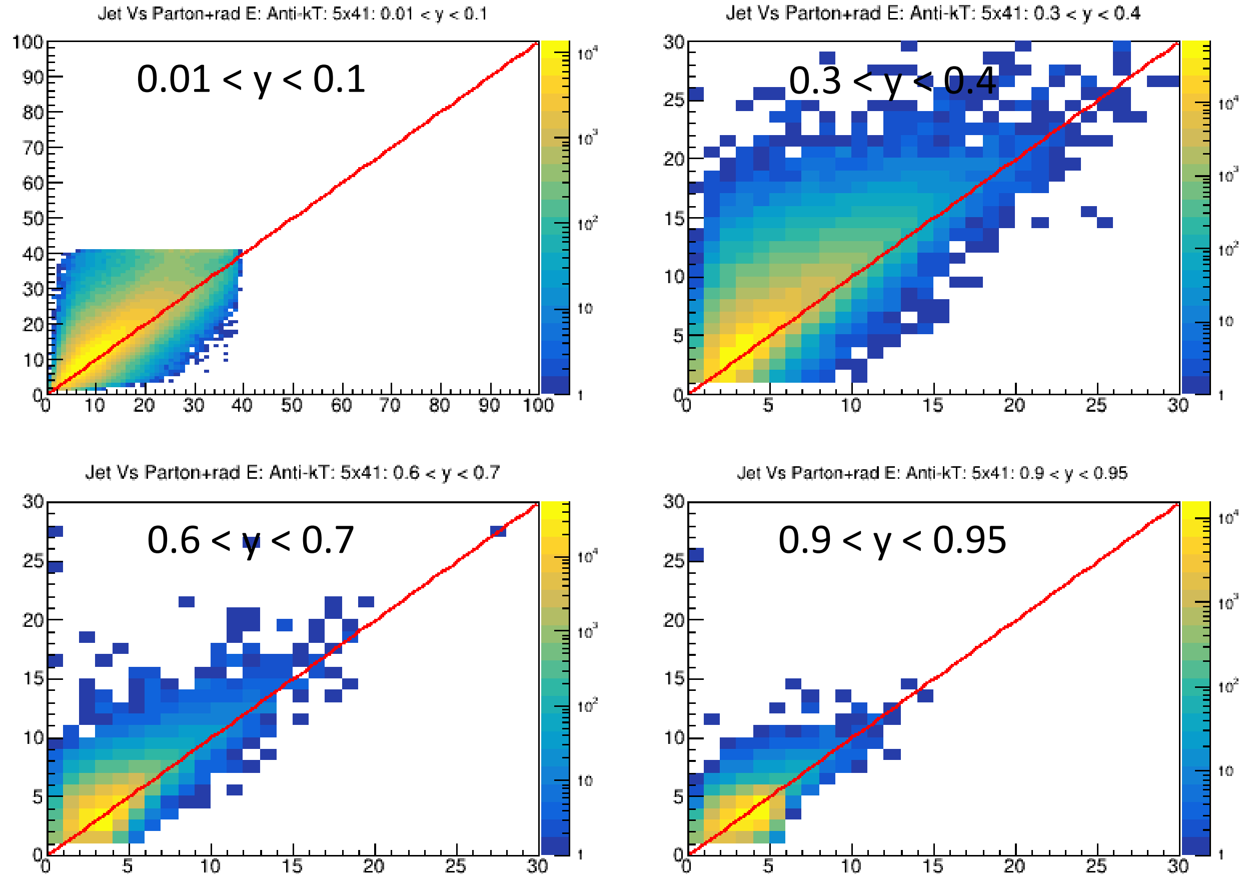


Jet – Parton Energy Comparison: Anti_kT (5x41)

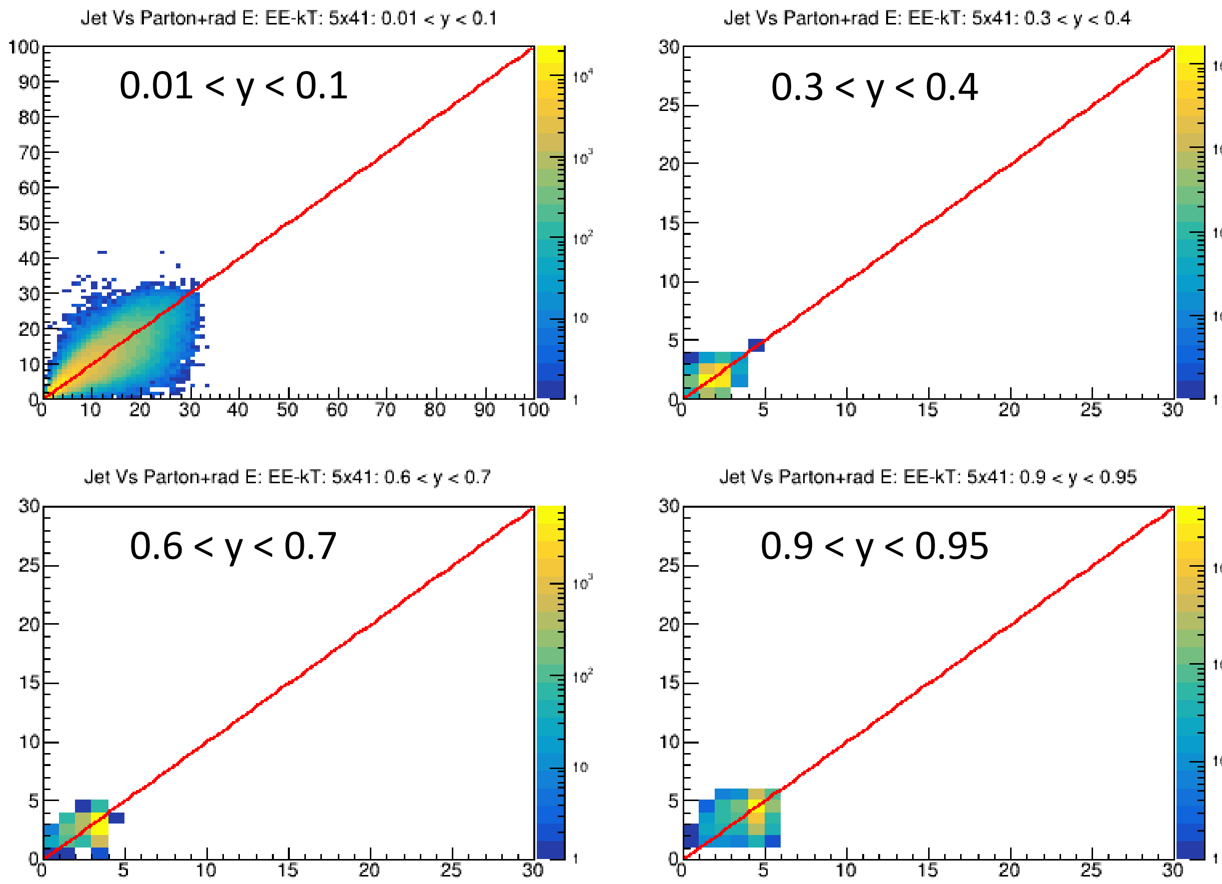


$0.1 < Q^2 < 1.0$

$10 < Q^2 < 100$



Jet – Parton Energy Comparison: EE_kT (5x41)



$0.1 < Q^2 < 1.0$

$10 < Q^2 < 100$