Summary of Jet Studies at the EIC

Brian Page

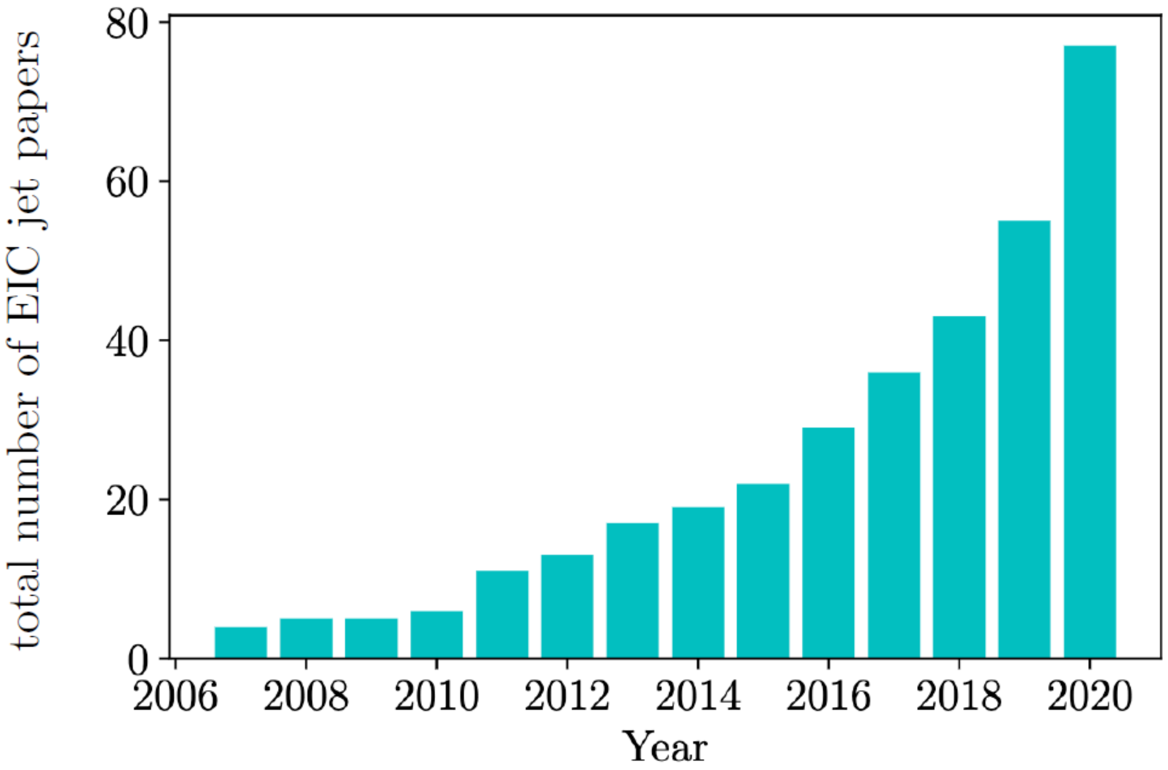
Jets for 3D Imaging at the EIC

November 23rd, 2020

Outline

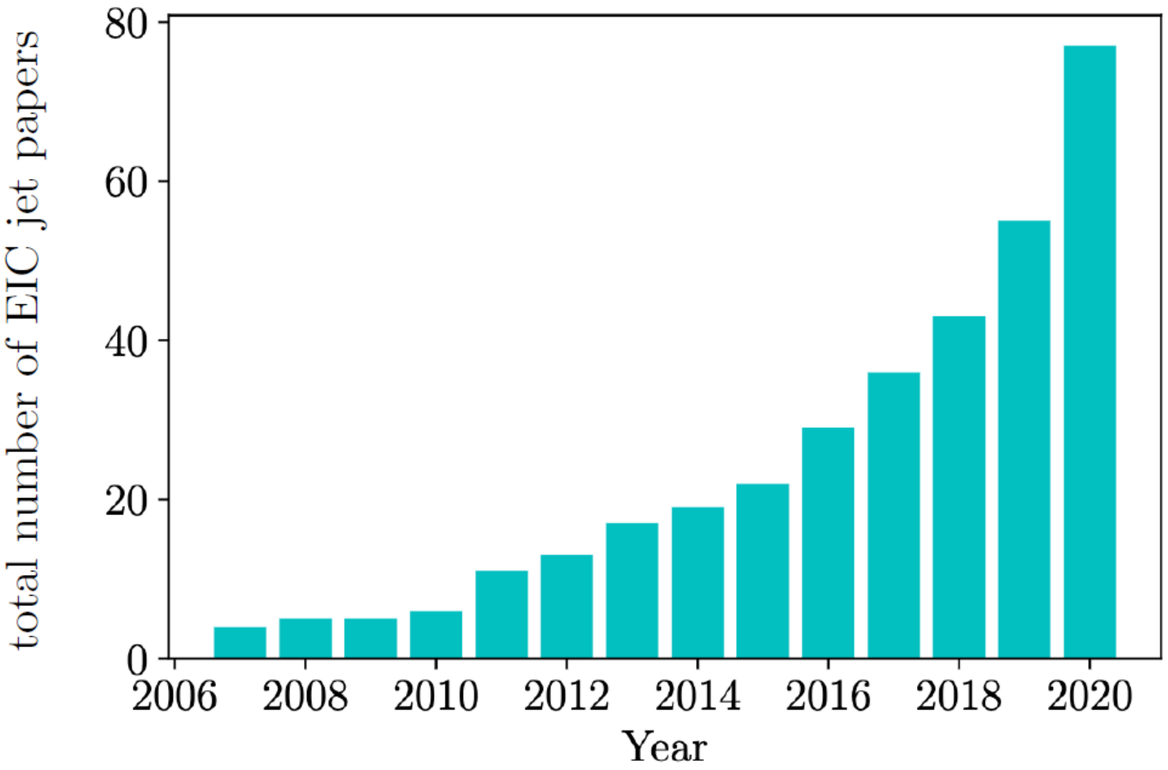
- Introduction
- Select Measurements
- Detector Requirements
- Conclusions

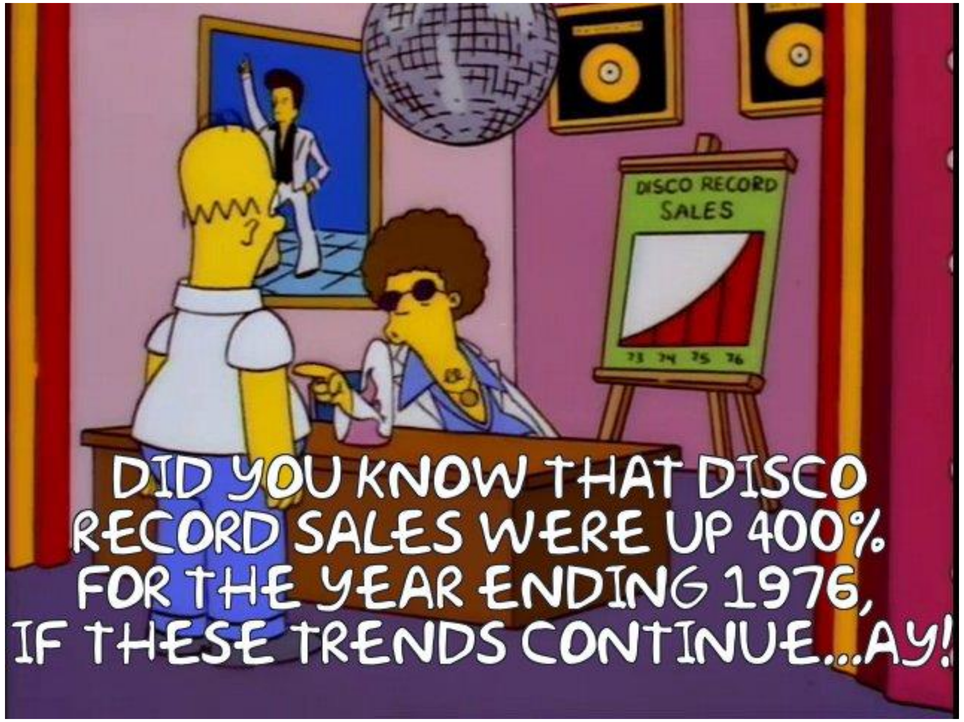
Introduction



- Clearly rising interest in jets at the EIC – past the point where an overview talk can cover all that is being done (apologies)
- Not bad for a topic which was not even mentioned in the EIC whitepaper

Introduction





- Clearly rising interest in jets at the EIC – past the point where an overview talk can cover all that is being done (apologies)

- Not bad for a topic which was not even mentioned in the EIC whitepaper

- Unlike disco, I think there is a bright future ahead for jets at the EIC!

Community Activities

EIC Yellow Report Initiative

- Year-long effort by the EICUG community to advance the EIC physics case and better define necessary detector performance: http://www.eicug.org/web/content/yellow-report-initiative
- Dedicated Jet and Heavy Flavor group with over 90 Members giving nearly 40 presentations on a number of jet topics
- Final report expected at the end of February

SnowMass2021

- US particle physics community planning exercise – gather input for the P5 process
- EF06 & EF07 (Hadronic structure & Heavy Ion) groups are leading EIC engagement with sessions on heavy flavor, saturation, TMDs, jets, and PDFs
- Recent meeting dedicated to jets at the EIC: https://indico.fnal.gov/event/46427/
- LOI with ~80 signatures has been drafted and submitted

Jets in the Yellow Report

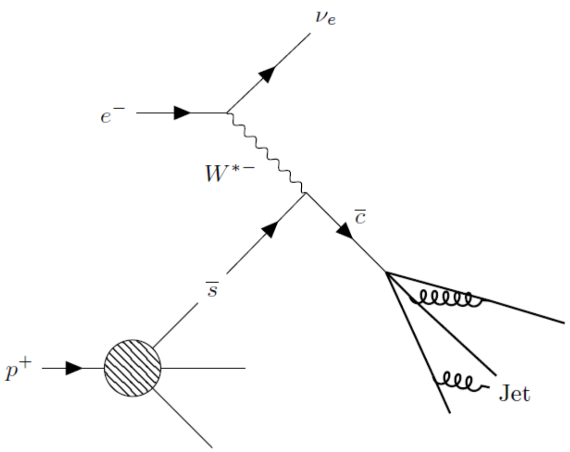
The EIC Measurements and Studies

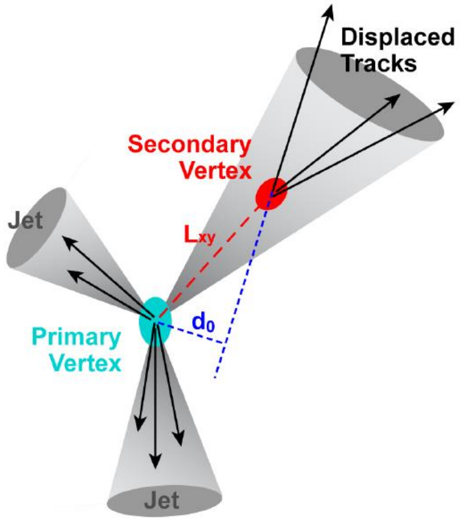
- Global properties and parton structure of hadrons
  - Unpolarized parton structure of the proton and neutron
  - Spin structure of the proton and neutron
  - Inclusive and hard diffraction
  - Global event shapes and the strong coupling constant
- Multi-dimensional imaging of nucleons, nuclei and mesons
  - 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

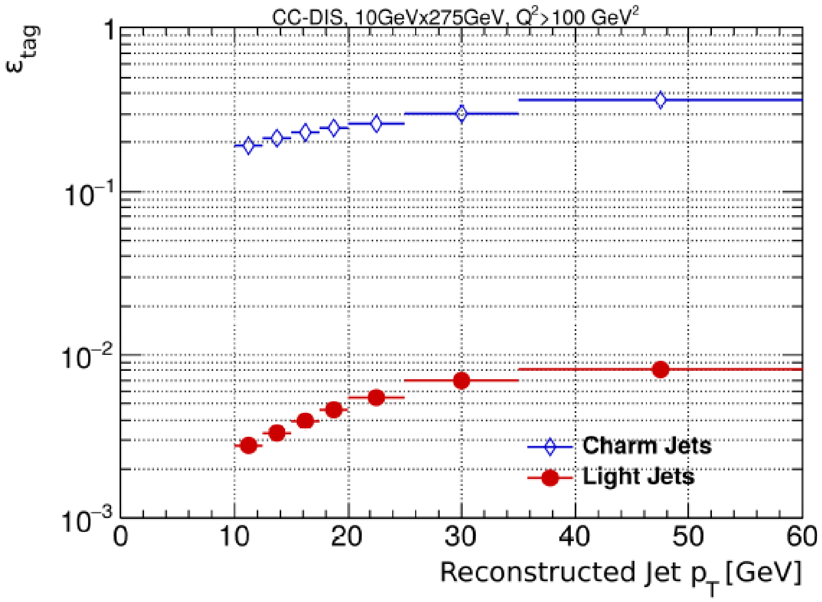
Detector Requirements

- Simulation and detector modeling
- Kinematics summary
- Tracking
  - Momentum resolution
  - Vertex resolution
  - Additional considerations
- PID
- Calorimetry
  - Electromagnetic calorimetry
  - Hadron calorimetry
  - Coverage continuity

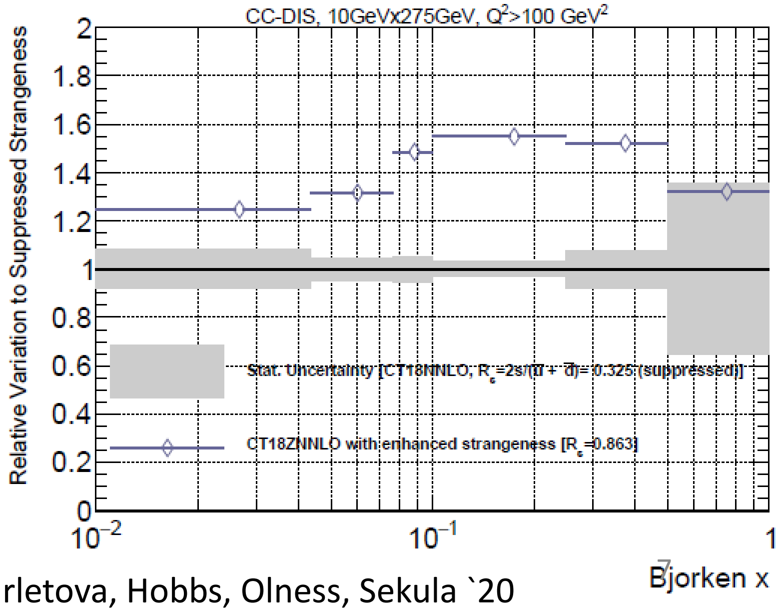
Charm Jet Tagging for Strangeness







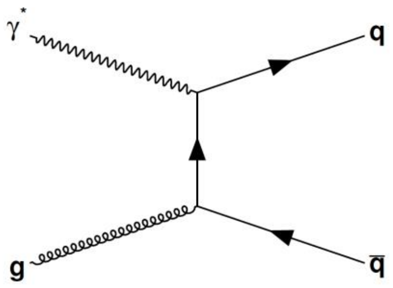
- Tension exists between neutrino DIS and SIDIS measurements of strange content and LHC extractions
- EIC is sensitive to strange content via charm production in charged-current DIS
- Charm is tagged within a jet via the presence of displaced tracks – good charm efficiency is seen, and methods are being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



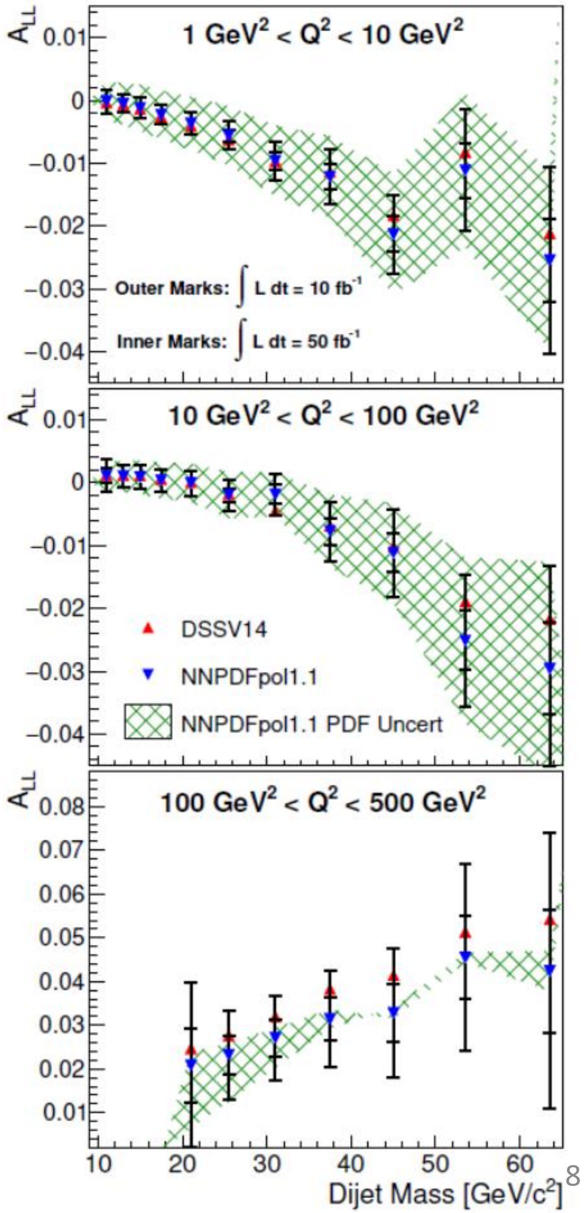
Arratia, Furletova, Hobbs, Olness, Sekula `20

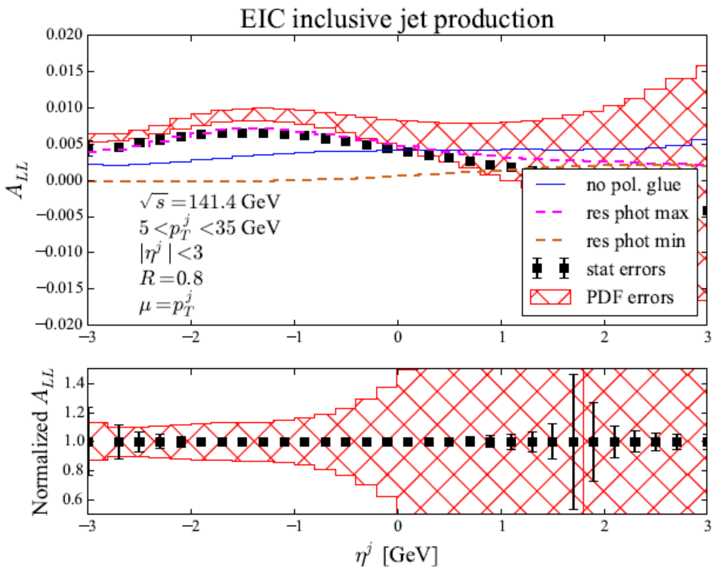
Longitudinal Spin Structure with Jets

- 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

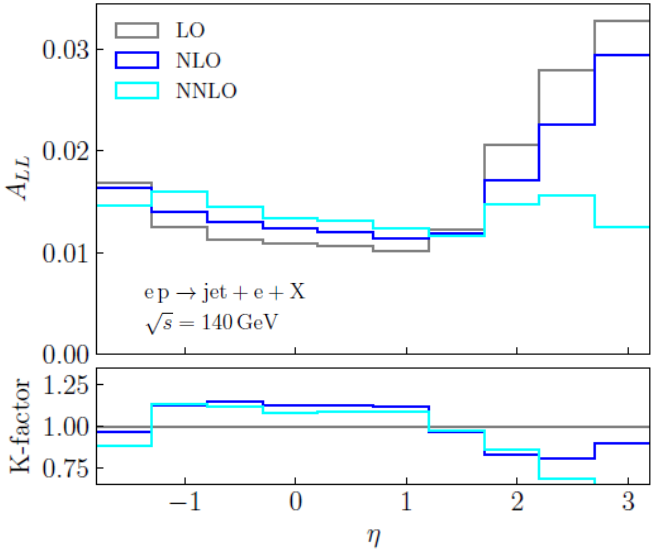


Page, Chu, Aschenauer `20





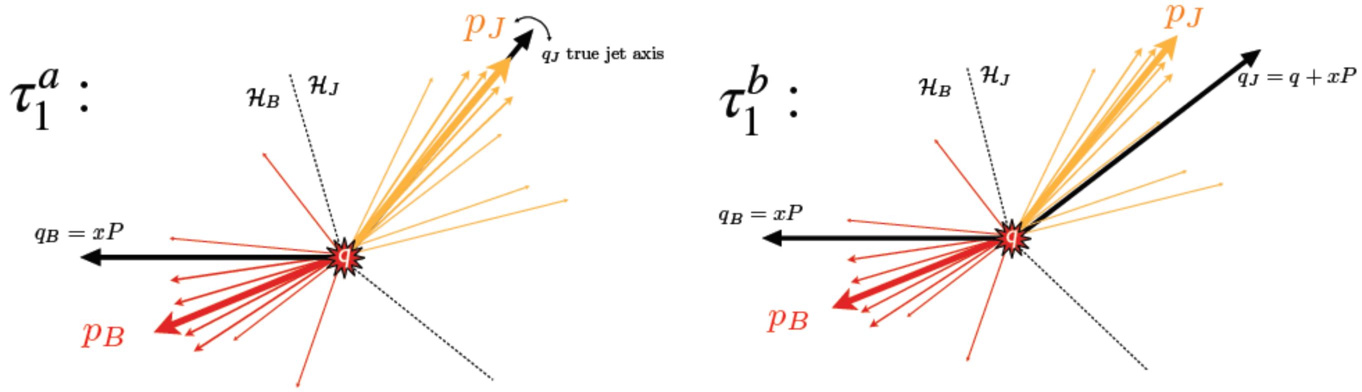
Boughezal, Petriello, Xing `18

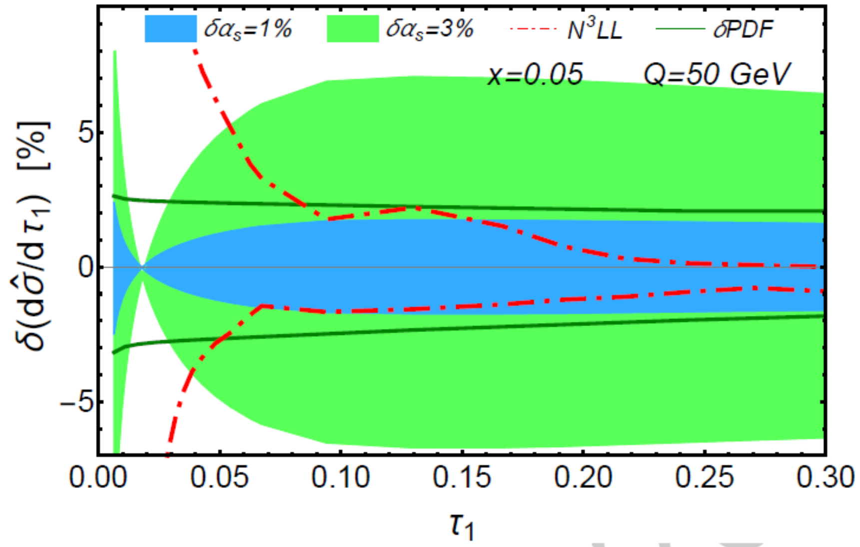


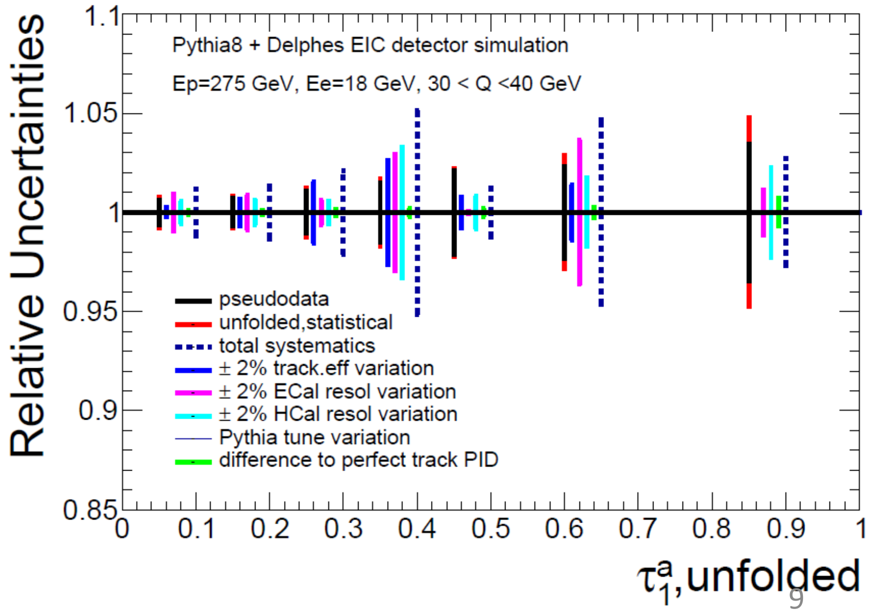
Borsa, de Florian, Pedron `20

Global Event Shapes

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

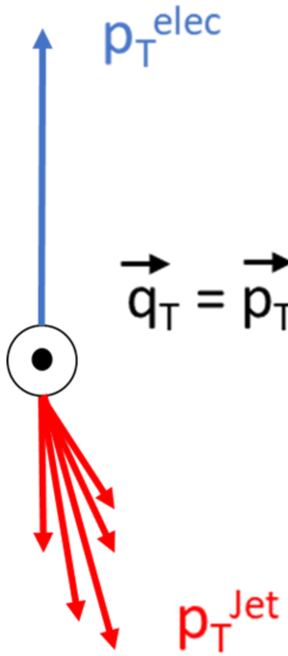






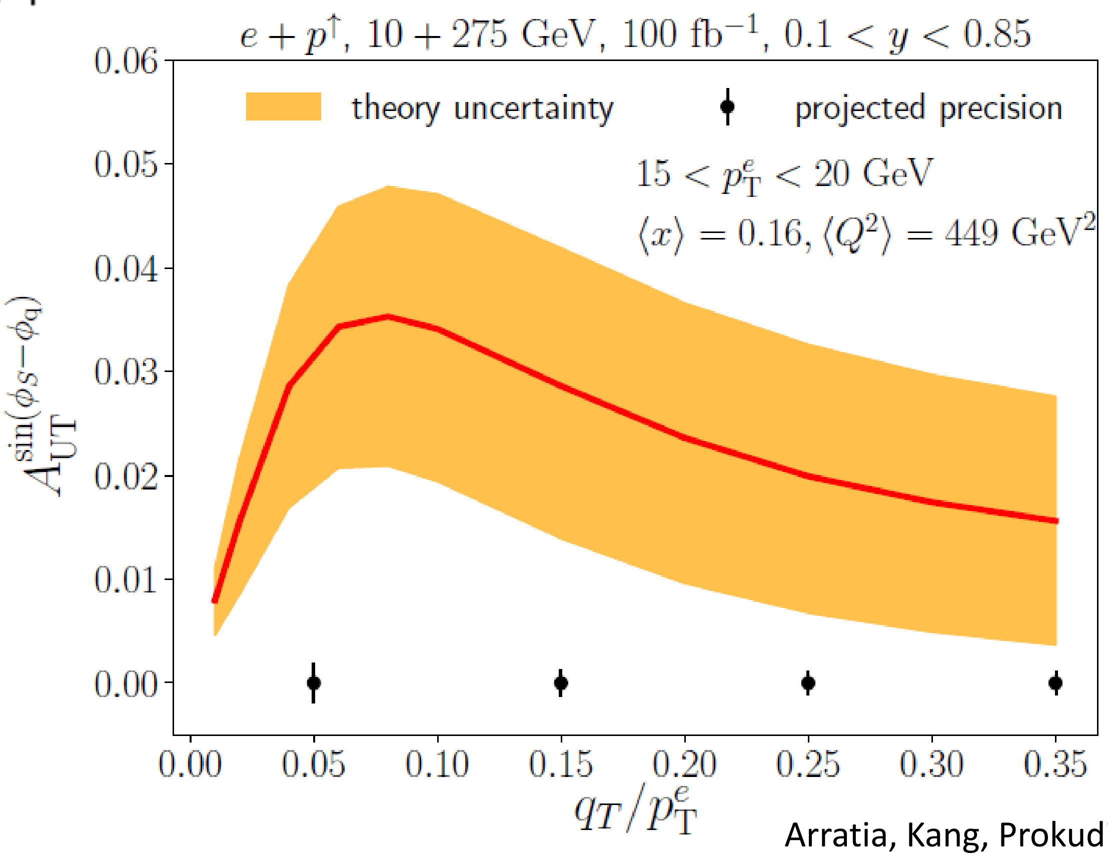
- Global event shapes offer possibility of very high precision measurements for extractions of non-perturbative parameters such as the strong coupling constant
- Feasibility of 1-jettiness observable is underway – for each particle, minimize the distance between a beam axis or jet axis
- At N^3LL, roughly 1% precision is possible, challenging experimental problem, but recent studies show promise

TMDs with Jets



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

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

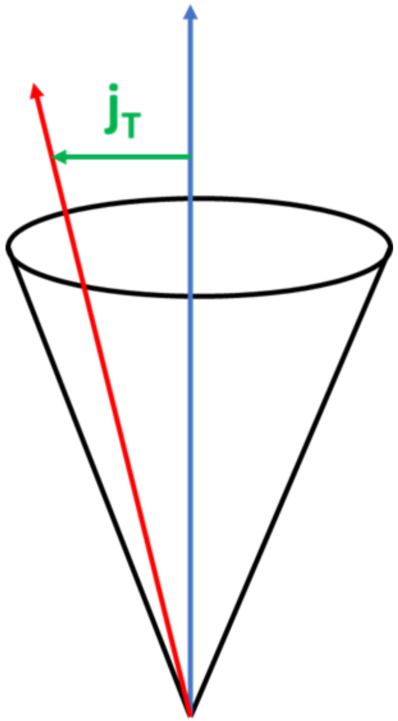


Arratia, Kang, Prokudin, Ringer `20

- Jet measurements for 3D imaging of nucleons at the EIC is emerging as a fruitful field (its why we are all here!)
- 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)

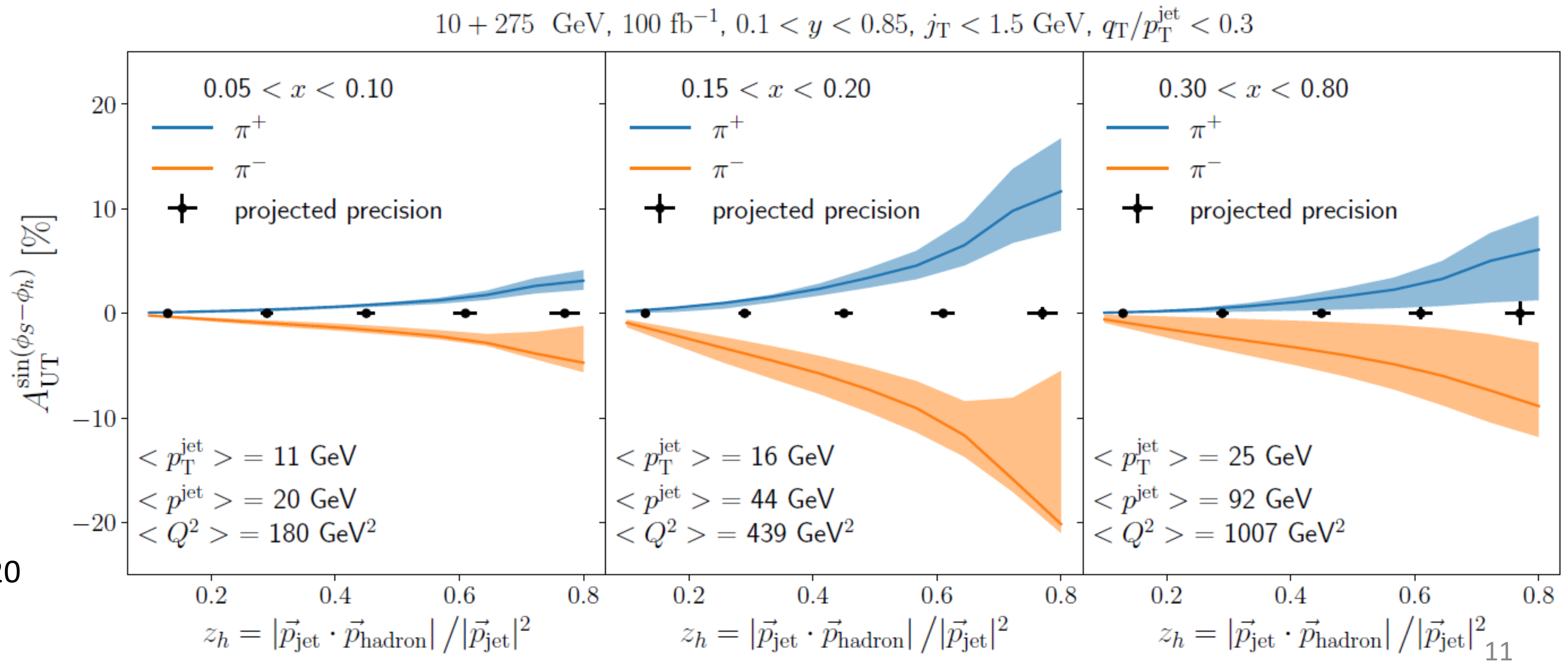
TMDs with Jets

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



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

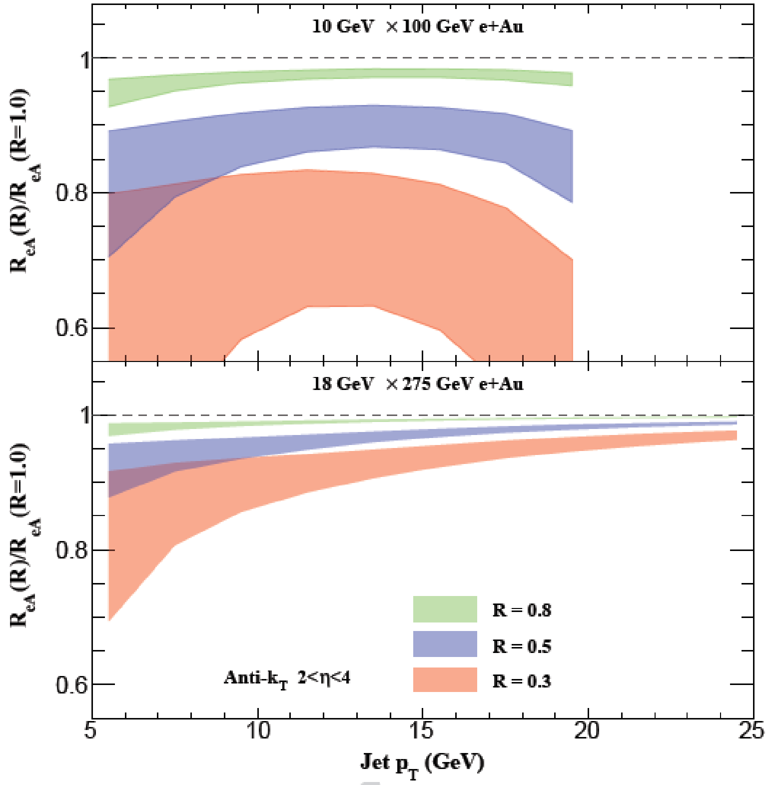


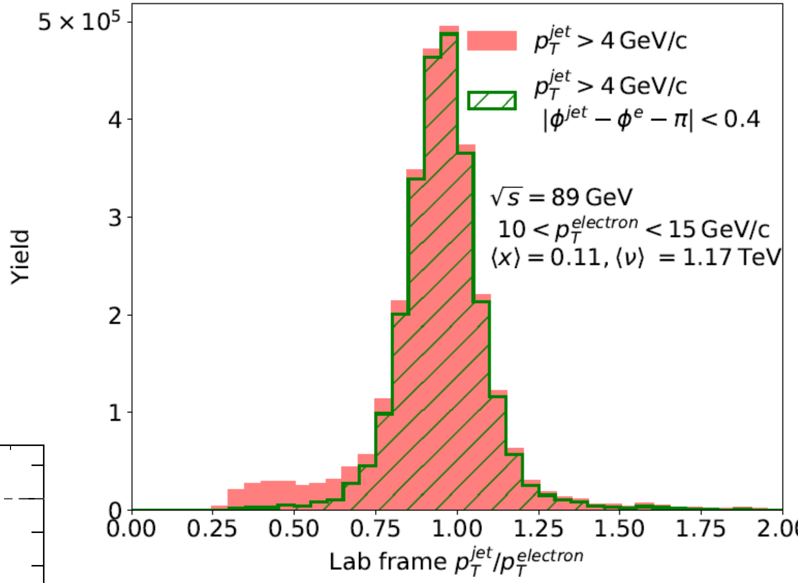
Jets in the Medium

- 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

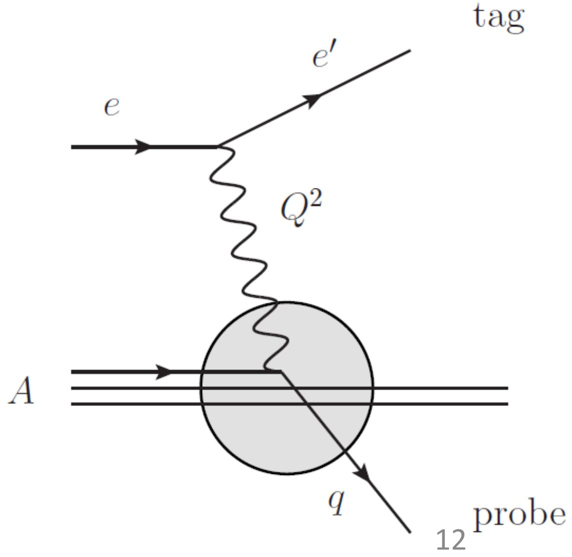
$$R_{\rm eA}(R) = \frac{1}{A}\frac{\int_{\eta 1}^{\eta 2} d\sigma/d\eta dp_T\big|_{e+A}}{\int_{\eta 1}^{\eta 2} d\sigma/d\eta dp_T\big|_{e+p}}$$

Li & Vitev '20





Arratia, Song, Ringer, Jacak '20



Angularity

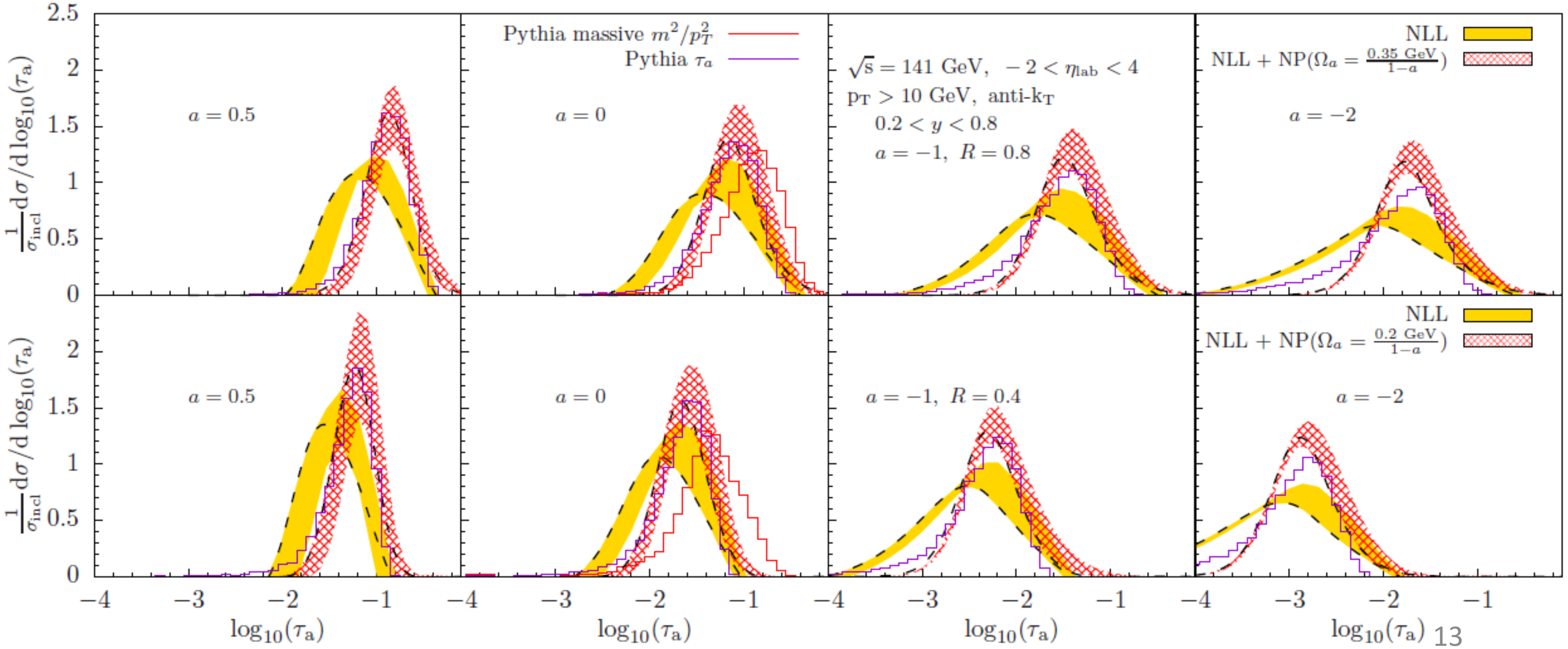
$$\tau_a \equiv \frac{1}{p_T} \sum_{i \in J} p_T^i \left(\Delta R_{iJ}\right)^{2-a}$$

- 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
- Comparison with alternative definition allows quantification of significance of sub-leading power corrections

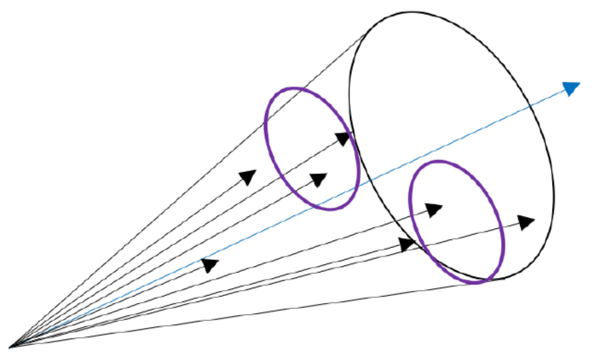
- Angularity is sensitive to hadronization effects via a convolution with the non-perturbative shape function Ω1
- Values are seen to be much less than at LHC
- Look at changes between ep and eA

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

Aschenauer, Lee, Page, Ringer `20



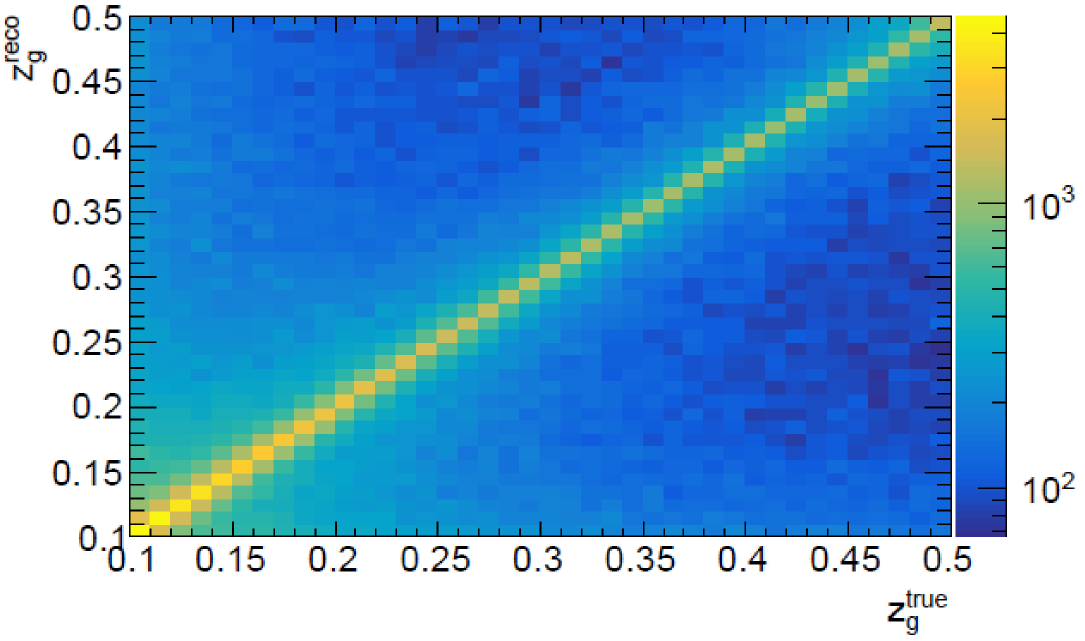
Soft Drop (Heavy) Jet Substructure

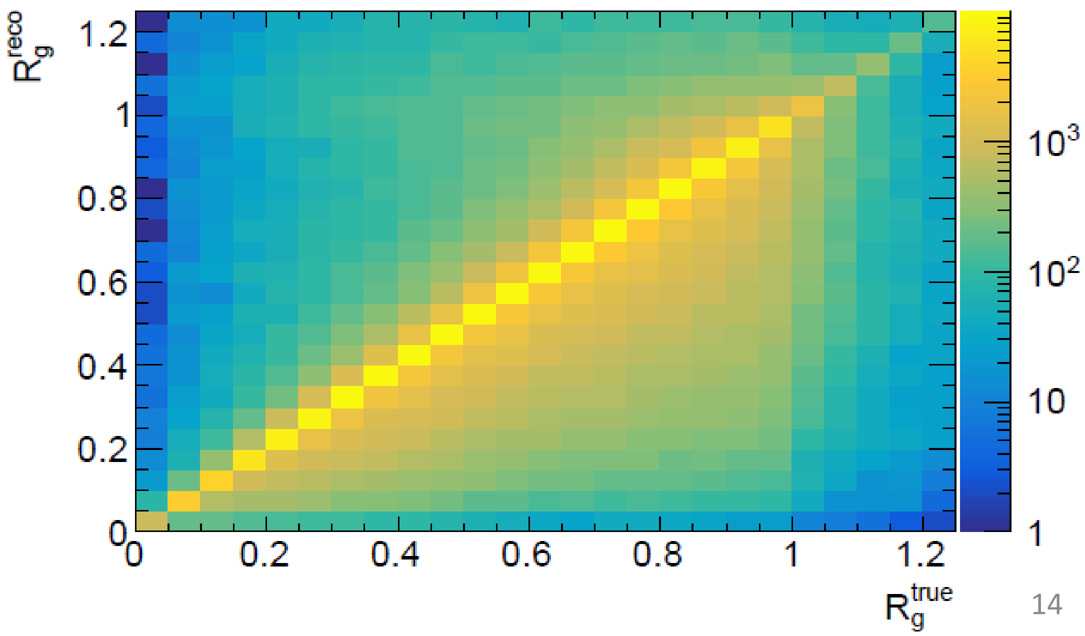


$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

$$R_g = \Delta R(p_{T,1}, p_{T,2})$$

- Techniques such as soft drop declustering / grooming will allow us to trace the ‘history’ of parton fragmentation
- Comparing ep and eA will tease out differences in fragmentation and hadronization in vacuum vs the nuclear medium – groomed heavy quark jets for mass dependence
- Given low number of particles in jets at the EIC, no guarantee grooming will work – initial studies are promising





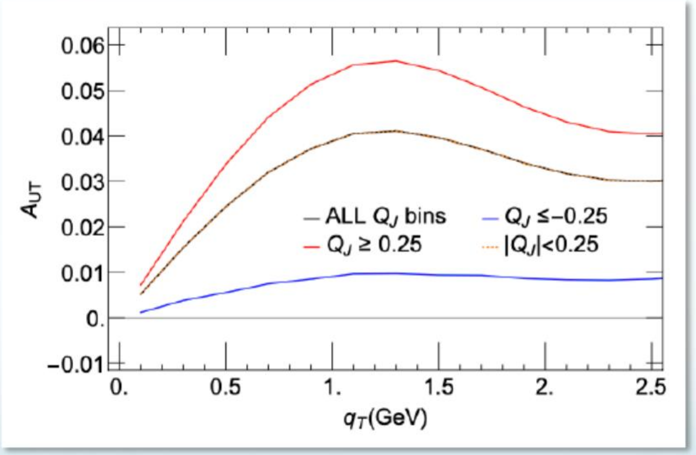
New (and Not-so-New) Tools

- Renewed interest in jet charge as a method for disentangling light quark flavors in a number of settings
- New longitudinally invariant asymmetric clustering algorithm for jet finding in the Breit frame

Kang, Liu, Mantry, Shao `20

$$Q_\kappa = \sum_h Q_\kappa^h \equiv \sum_{h \in \text{jet}} z_h^\kappa Q_h$$

$$A_{UT}(Q^N_{\kappa,\text{bin}}) = \frac{d\sigma(S^\uparrow) - d\sigma(S^\downarrow)}{d\sigma(S^\uparrow) + d\sigma(S^\downarrow)} = \frac{d\sigma_{UT}(Q^N_{\kappa,\text{bin}})}{d\sigma_{UU}(Q^N_{\kappa,\text{bin}})}$$



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

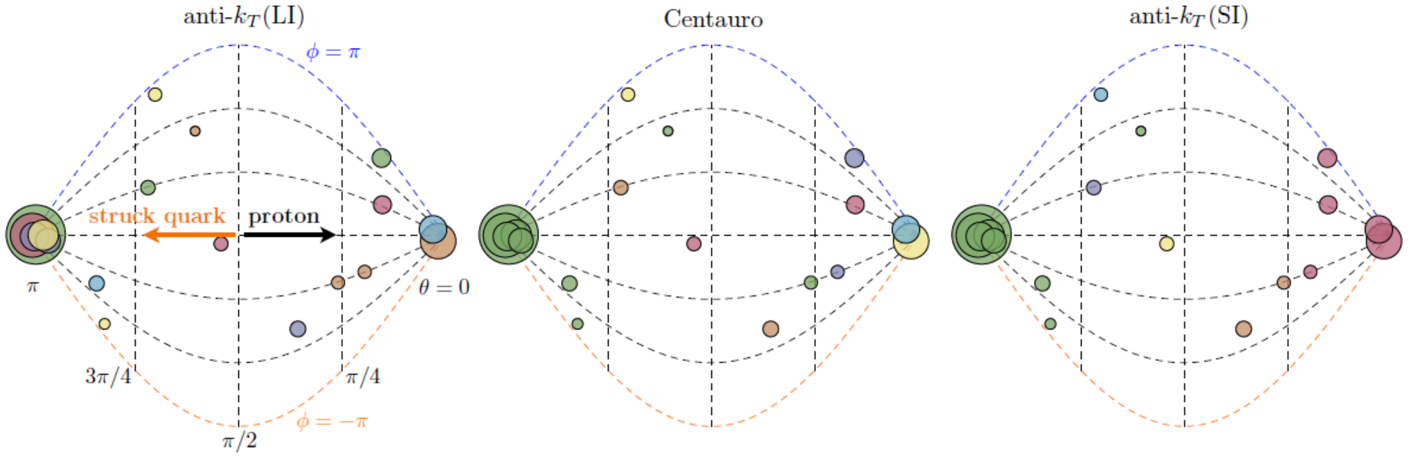
Asymmetric measure is necessary

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

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

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

Arratia, Makris, Neill, Ringer, Sato `20



Longitudinally invariant Symmetric

Longitudinally invariant Asymmetric

Spherically invariant Symmetric

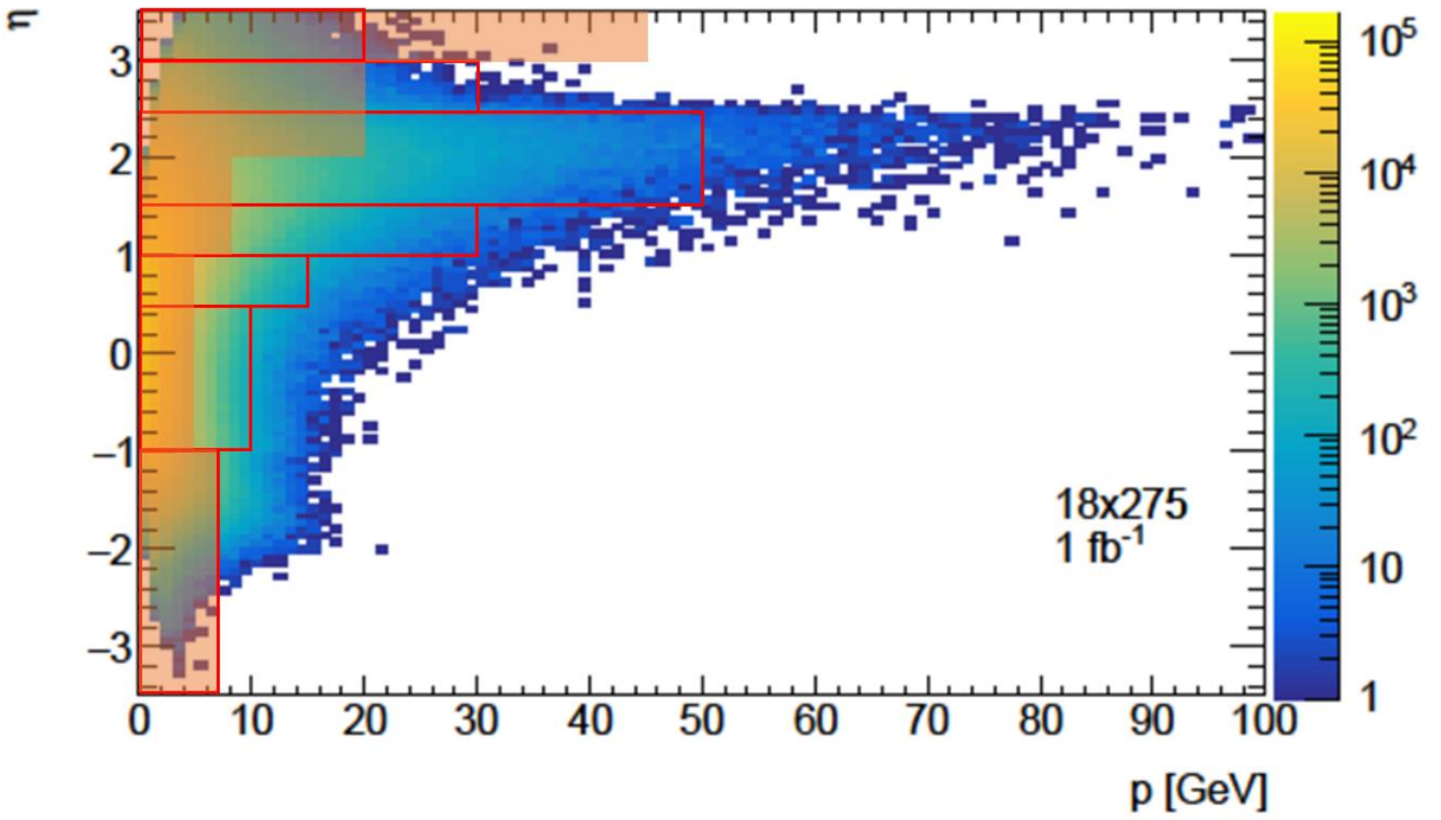
PID Requirements

PID Momentum Coverage

Eta Range	Default Momentum Coverage	Requested Momentum Coverage
-3.5 < η < -1.0	≤ 7 GeV	Same
-1.0 < η < 0.0	≤ 5 GeV	≤ 10 GeV
0.0 < η < 0.5		
0.5 < η < 1.0		≤ 15 GeV
1.0 < η < 1.5	≤ 8 GeV	≤ 30 GeV
1.5 < η < 2.0		≤ 50 GeV
2.0 < η < 2.5	≤ 20 GeV	
2.5 < η < 3.0		≤ 30 GeV
3.0 < η < 3.5	≤ 45 GeV	Can tolerate ≤ ~20 GeV

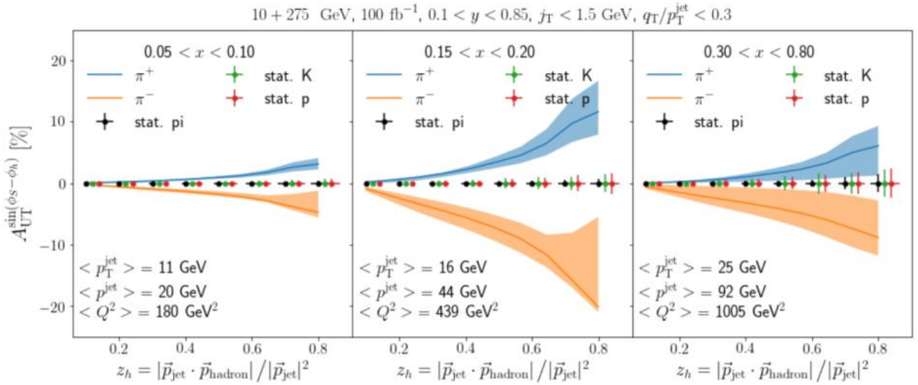
- Plot of pseudorapidity vs momentum of pions found within jets
- Default PID ranges leave significant gaps in coverage
- Reduction of particle momenta at highest (and lowest) eta are due to jet radius

18x275

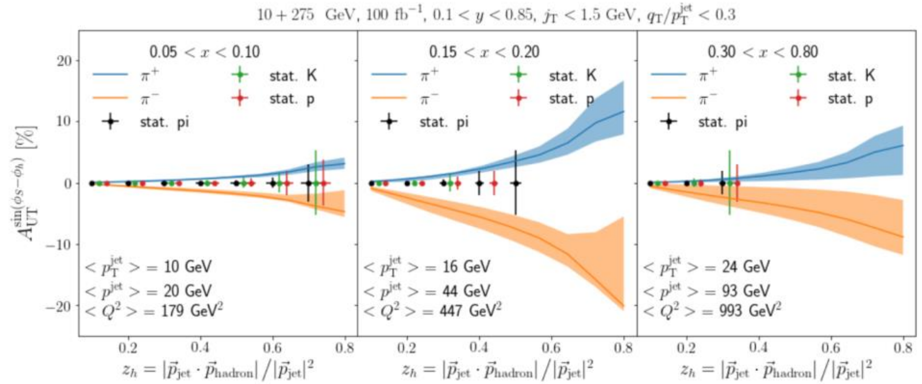


- Shaded boxes = default momentum coverage
- Red outlined boxes = requested momentum coverage

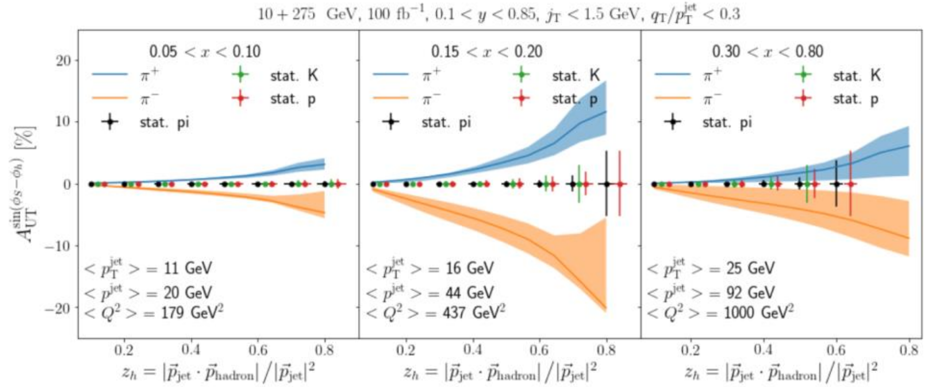
PID Requirements



Perfect

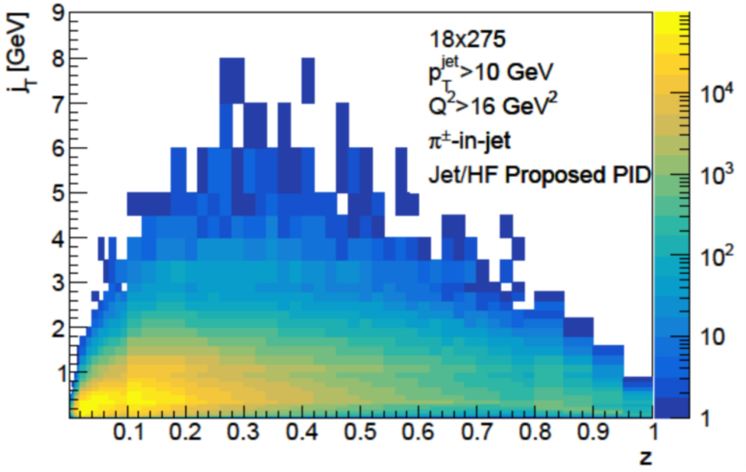


Default

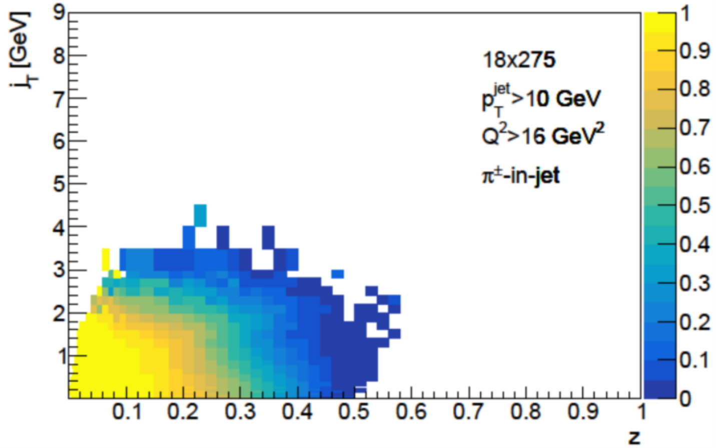


Requested

Requested Coverage: j_T Vs z



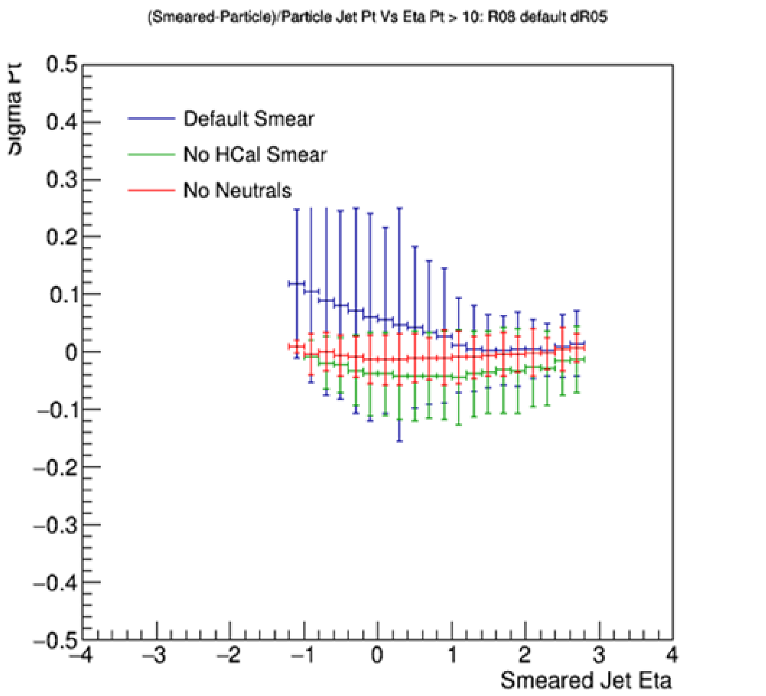
Default / Requested Ratio



Hadron Calorimeter Considerations

HCal Energy Resolution

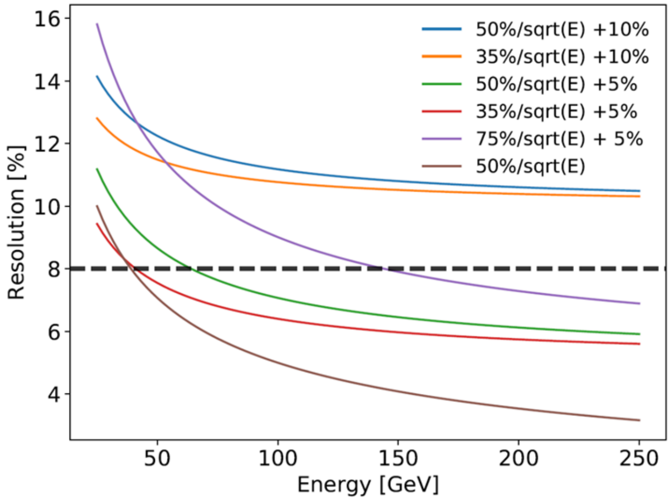
Eta Range	Default Resolution (σE/E)	Requested (σE/E)
-3.5 < η < -1.0	50%/√E	Same (~10% constant term is acceptable)
-1.0 < η < 1.0	N/A	85%/√E + 10%
1.0 < η < 3.0	50%/√E	50%/√E + 10%
3.0 < η < 3.5		50%/√E + 5%
3.5 < η < 4.0	N/A	

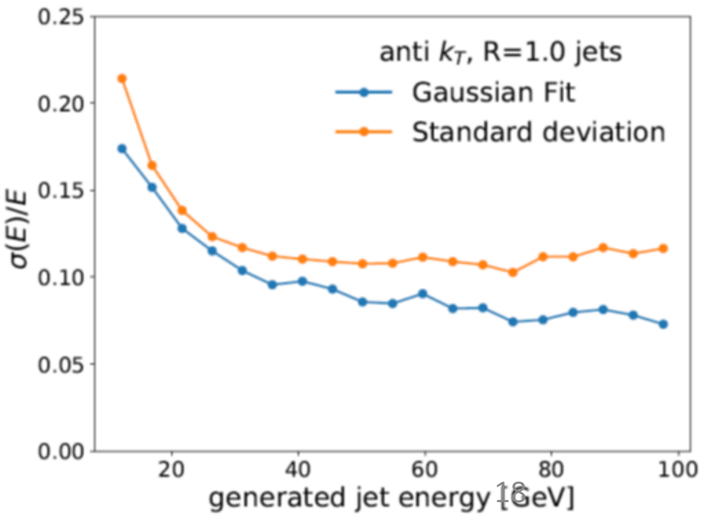


- Because of low particle energy and poor HCal resolution, the tracker will be primary detector for jets at all but the highest rapidities – HCal needed for neutral hadrons

- At mid-rapidity, HCal is needed to avoid large fluctuations due to missing neutral energy – in absence of good resolution, ability to isolate neutral deposits will be important as distortions from low energy neutral hadrons becomes significant

- In forward region, particle/jet energies are large, and resolution is driven by constant term – very difficult to achieve sub 10% given space considerations





Summary

- A unique, robust, and compelling jet program is taking shape, touching on all major aspects of EIC physics
- Yellow Report effort has brought into better focus what is needed from a detector standpoint for successful jet measurements
- An active and engaged community of people interested in jets at the EIC will be critical for moving the field forward – seeing this in meetings, the Yellow Report, and Snowmass efforts
- The future looks bright!