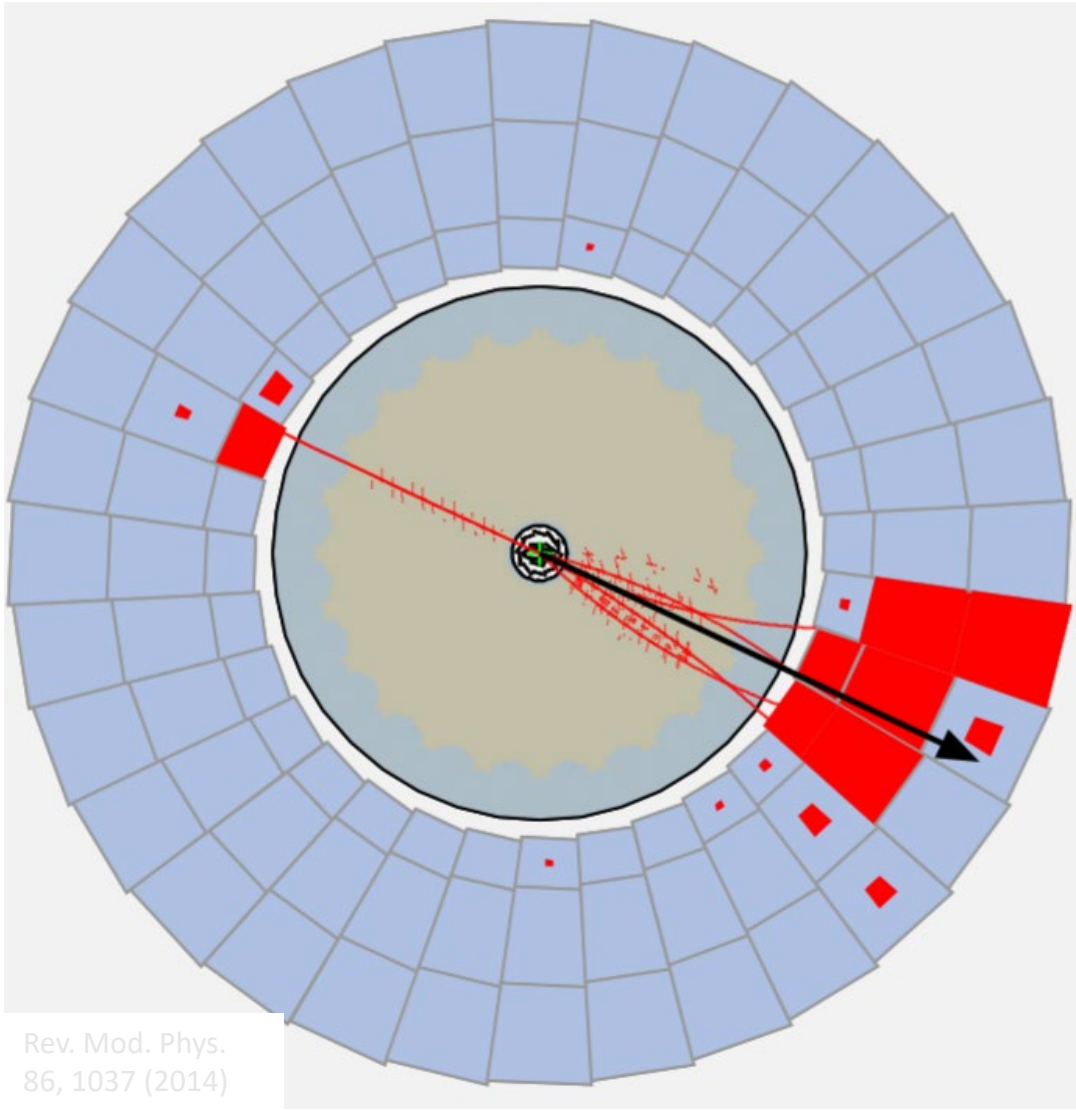
Jets for TMD physics

Miguel Arratia
University of California, Riverside



Rev. Mod. Phys. 86, 1037 (2014)

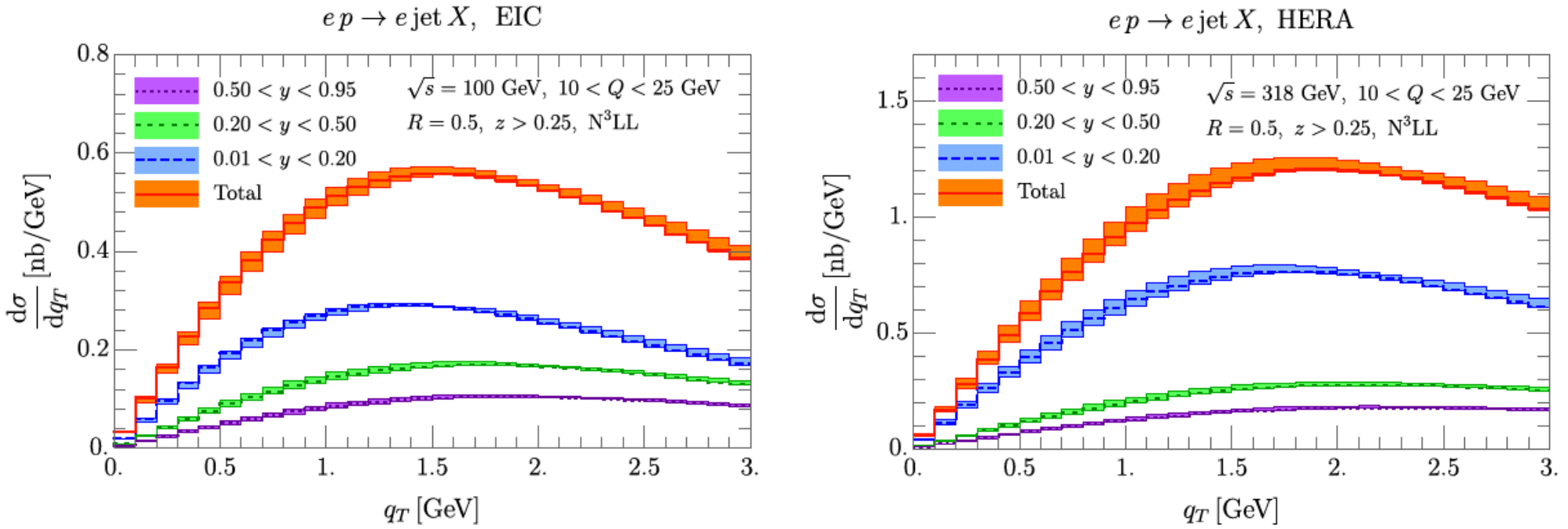
Outline:

- Motivation for jet measurements
- Pythia8 simulations
- Plans

Why jets?

- Complements SIDIS with hadrons and di-hadrons.
- Access to TMD PDFs without convolution with FFs.
  Better proxies for parton kinematics.
- Allows us to test Universality.
- Allows us to reach scales beyond those of single-hadrons (i.e. higher pT)
- Unlike hadrons, jets have substructure.
- The EIC will copiously produce jets

"Transverse momentum dependent distributions with jets"
PRL 121, 162001 (2018). Gutierrez-Reyes et al.
"Transverse-momentum dependent distributions in e+e- and semi-inclusive deep-inelastic scattering using jets" *JHEP 10 (2019) 031* Gutierrez-Reyes et al.



"The study of the TMD distribution of the proton can benefit from using jets (instead of hadrons) as final state. A clear advantage is that the jet momentum can be calculated in perturbation theory, while the fragmentation of hadrons is an intrinsically non-perturbative process. "

HERA experiments did require high p_T in the Breit Frame We need an orthogonal approach for TMDs studies at EIC

~ 0 p_T in Breit frame
Background

High p_T in Breit frame
Signal.

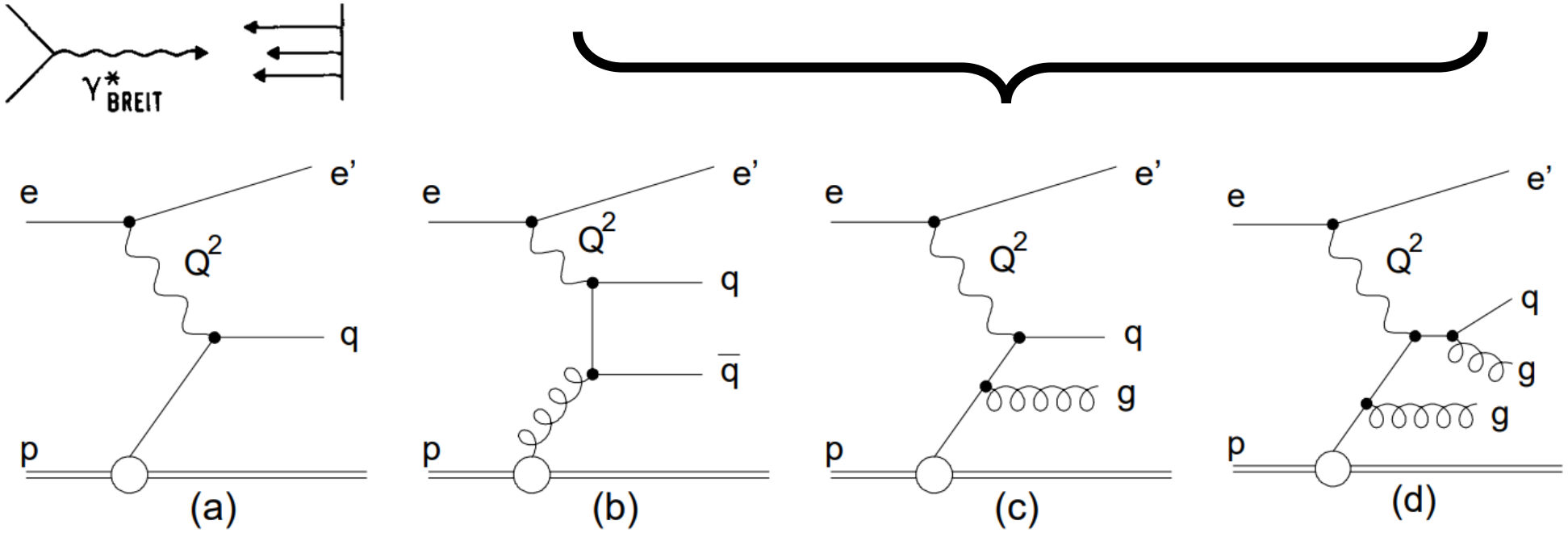
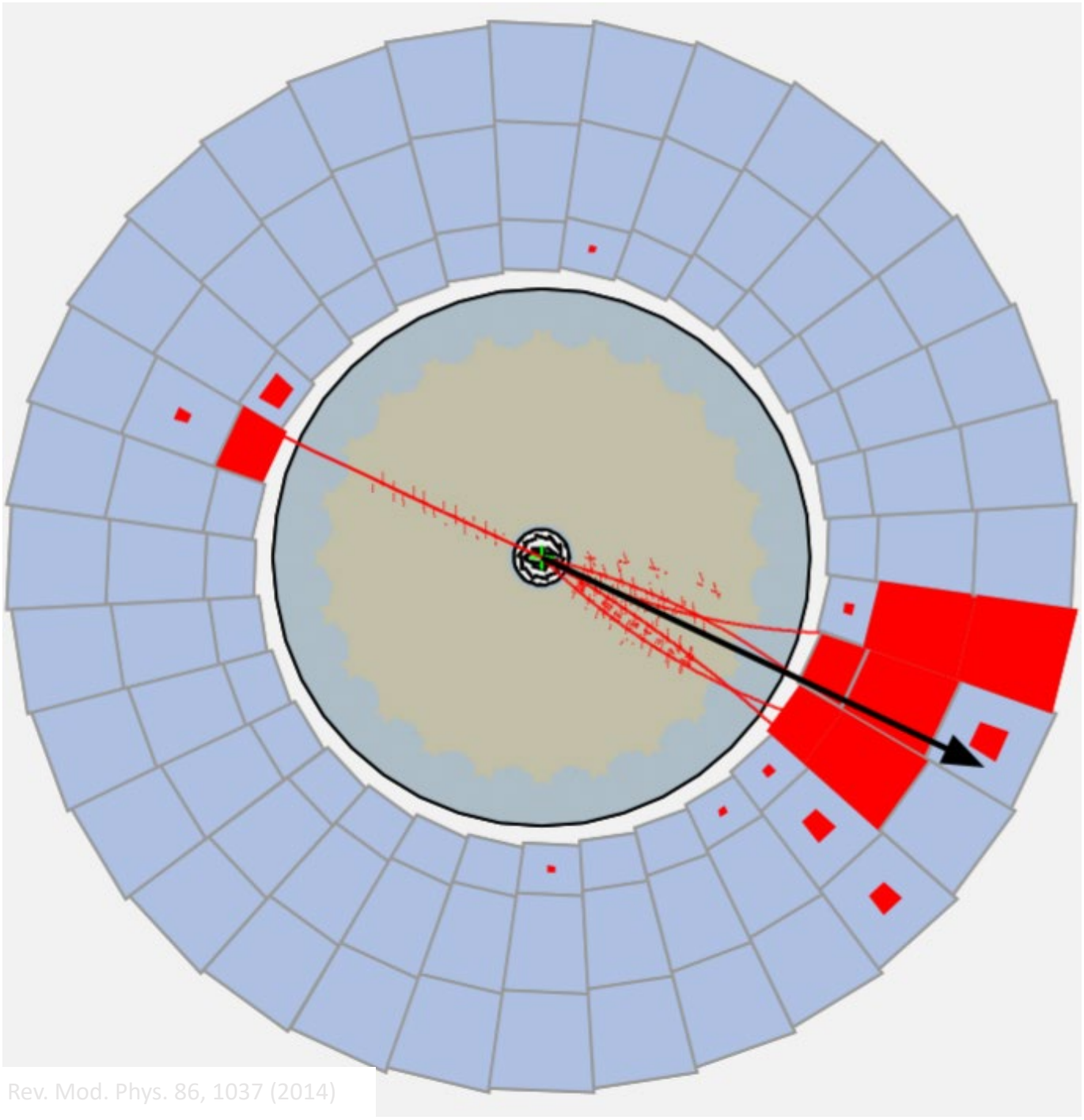


Figure 1: Deep-inelastic ep scattering at different orders in α_s: (a) Born contribution to inclusive NC DIS ($O(\alpha_{em}^2)$), (b) photon-gluon fusion ($O(\alpha_{em}^2\alpha_s)$), (c) QCD Compton scattering ($O(\alpha_{em}^2\alpha_s)$) and (d) a trijet process $O(\alpha_{em}^2\alpha_s^2)$.



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Their Calibration, Our Signal

Lepton-Jet Correlations in Deep Inelastic Scattering at the Electron-Ion Collider

Xiaohui Liu, Felix Ringer, Werner Vogelsang, and Feng Yuan
Phys. Rev. Lett. **122**, 192003 – Published 15 May 2019

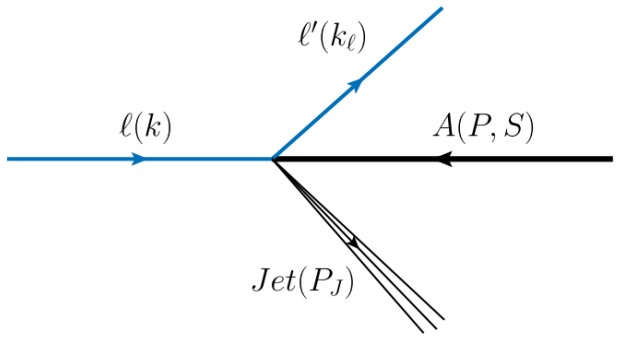


FIG. 1. Lepton-jet correlation for the tomography of the nucleon or nucleus at the EIC.

$$\frac{d^5\sigma(\ell p \to \ell' J)}{dy_\ell d^2k_{\ell\perp} d^2q_\perp} = \sigma_0 \int d^2k_\perp d^2\lambda_\perp x f_q(x, k_\perp, \zeta_c, \mu_F)$$
$$\times H_{\rm TMD}(Q, \mu_F) S_J(\lambda_\perp, \mu_F)\, \delta^{(2)}(q_\perp - k_\perp - \lambda_\perp)\ .$$

"The advantage of the lepton-jet correlation as compared to the standard SIDIS processes is that it does not involve TMD fragmentation functions. Extensions to other observ-ables that are sensitive to the various TMD quark distributions at leading order shall follow".

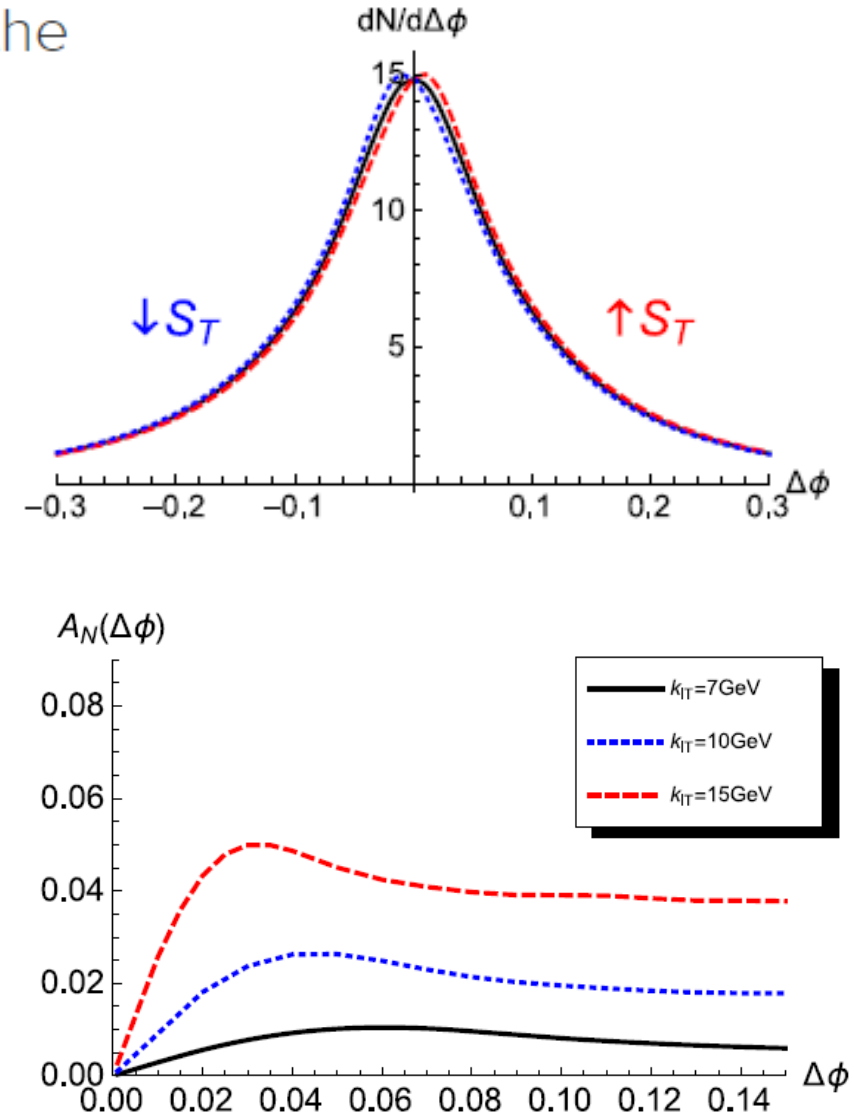
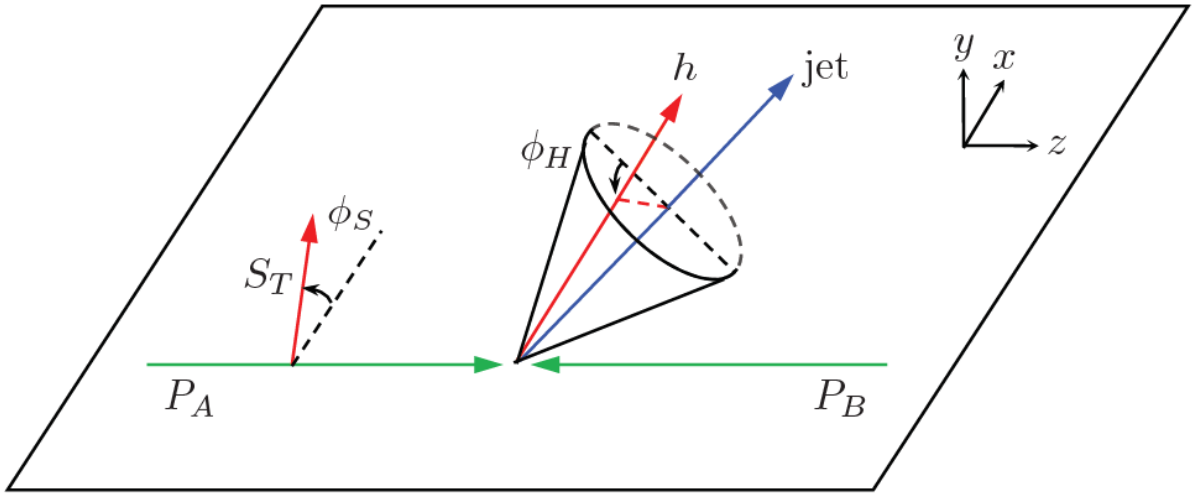


FIG. 3. The single transverse spin asymmetry as a function of $\Delta\phi = \phi_J - \phi_\ell - \pi$ for different lepton transverse momenta $k_{\ell\perp} = 7$, 10, and 15 GeV, respectively, which illustrates the transverse momentum dependence of the quark Sivers function.

Of course, jets can also be used to study fragmentation, e.g this work applies to SIDIS as well:

Collins azimuthal asymmetries of hadron production inside jets

Zhong-Bo Kang[a,b,c], Alexei Prokudin[d,e], Felix Ringer[f], Feng Yuan[f]



Simulation parameters

- Pythia8 e-p DIS, DIRE parton shower (angular ordered)
- 45 GeV cm energy, E^{proton} = 50 GeV, $E^{electron}$ = 10 GeV
- Event cuts: 0.1 < y < 0.85, Q^2 > 1 GeV^2
- Jets are reconstructed with the anti-k_T algorithm with R = 1.0 using FastJet
- Particle cuts: $|\eta^{part}|$ < 4.5, p_T^{part} > 0.25 GeV
- No radiative corrections yet.
- No detector response yet.

We are using the lab frame, which is trivially related to the lepton-nucleon frame

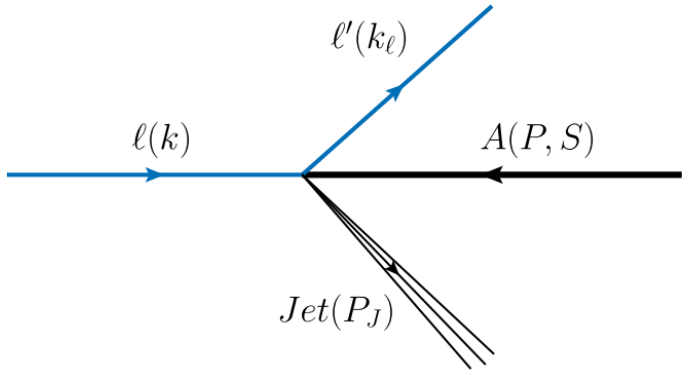
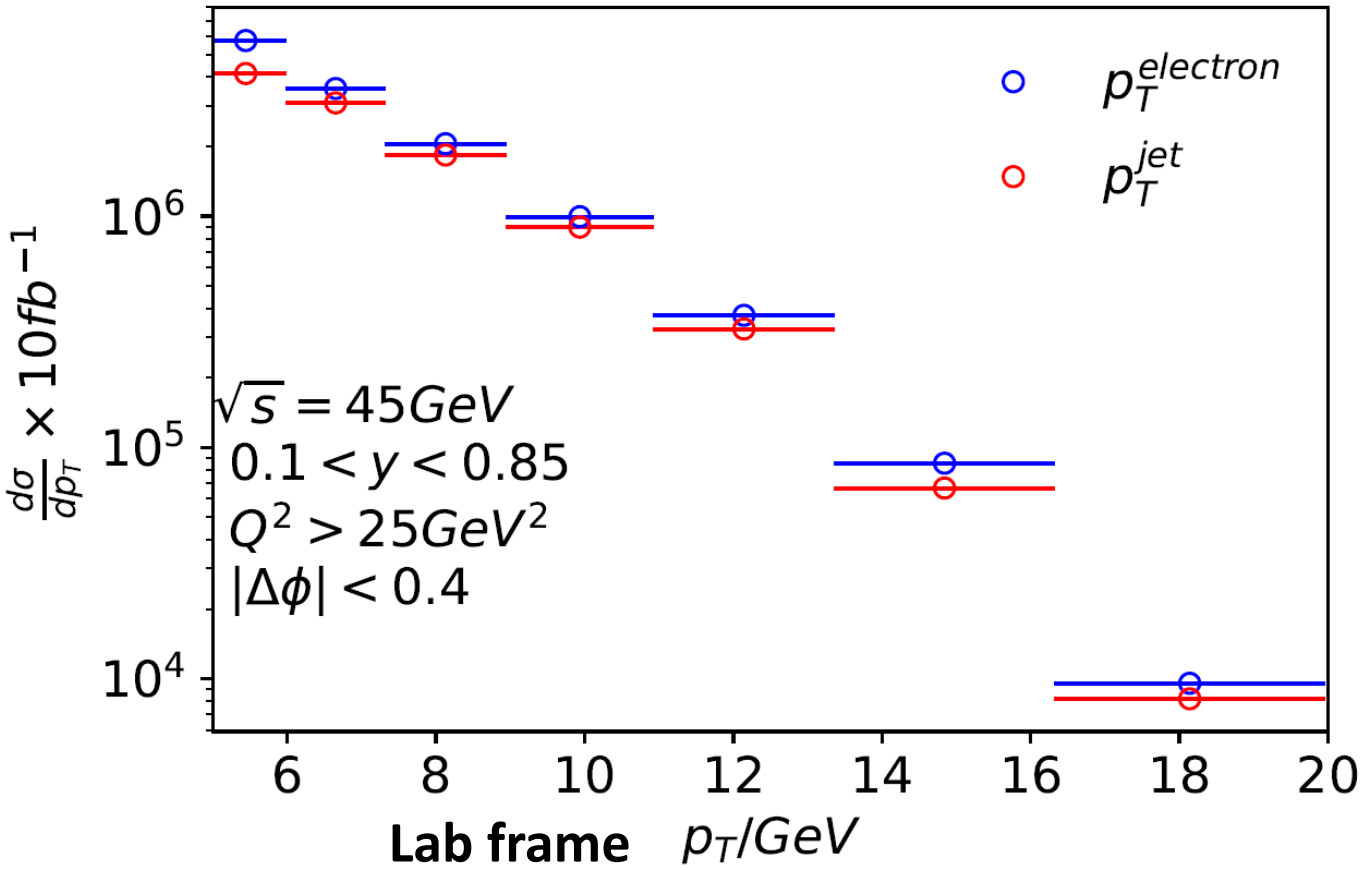


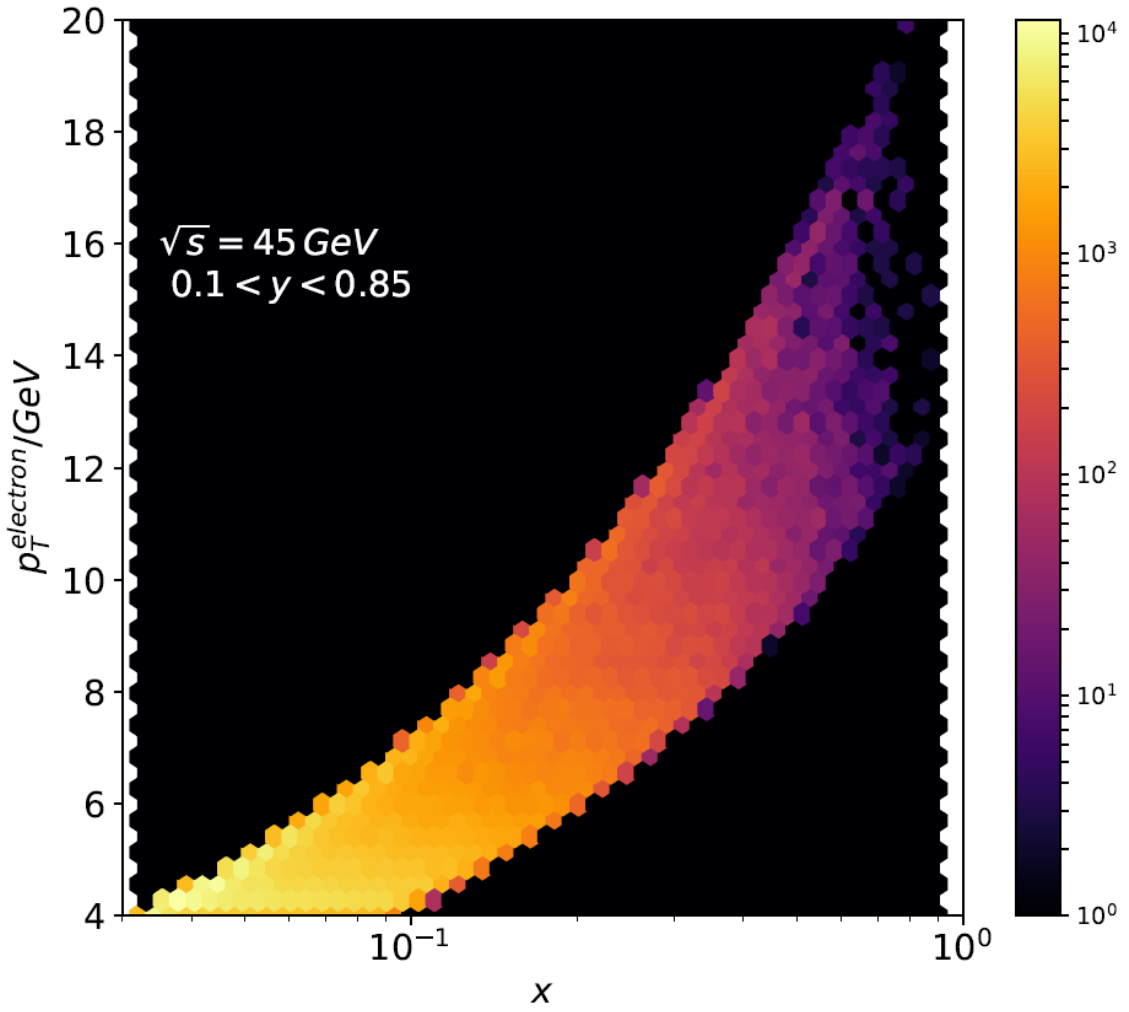
FIG. 1. Lepton-jet correlation for the tomography of the nucleon or nucleus at the EIC. *Liu et al. PRL 122 192003*

$$Q^2 = -\hat{t} = \sqrt{s}\, p_T^e\, e^{-y_e}$$

$$\hat{u} = \sqrt{s}\, x\, p_T^e\, e^{y_e}$$

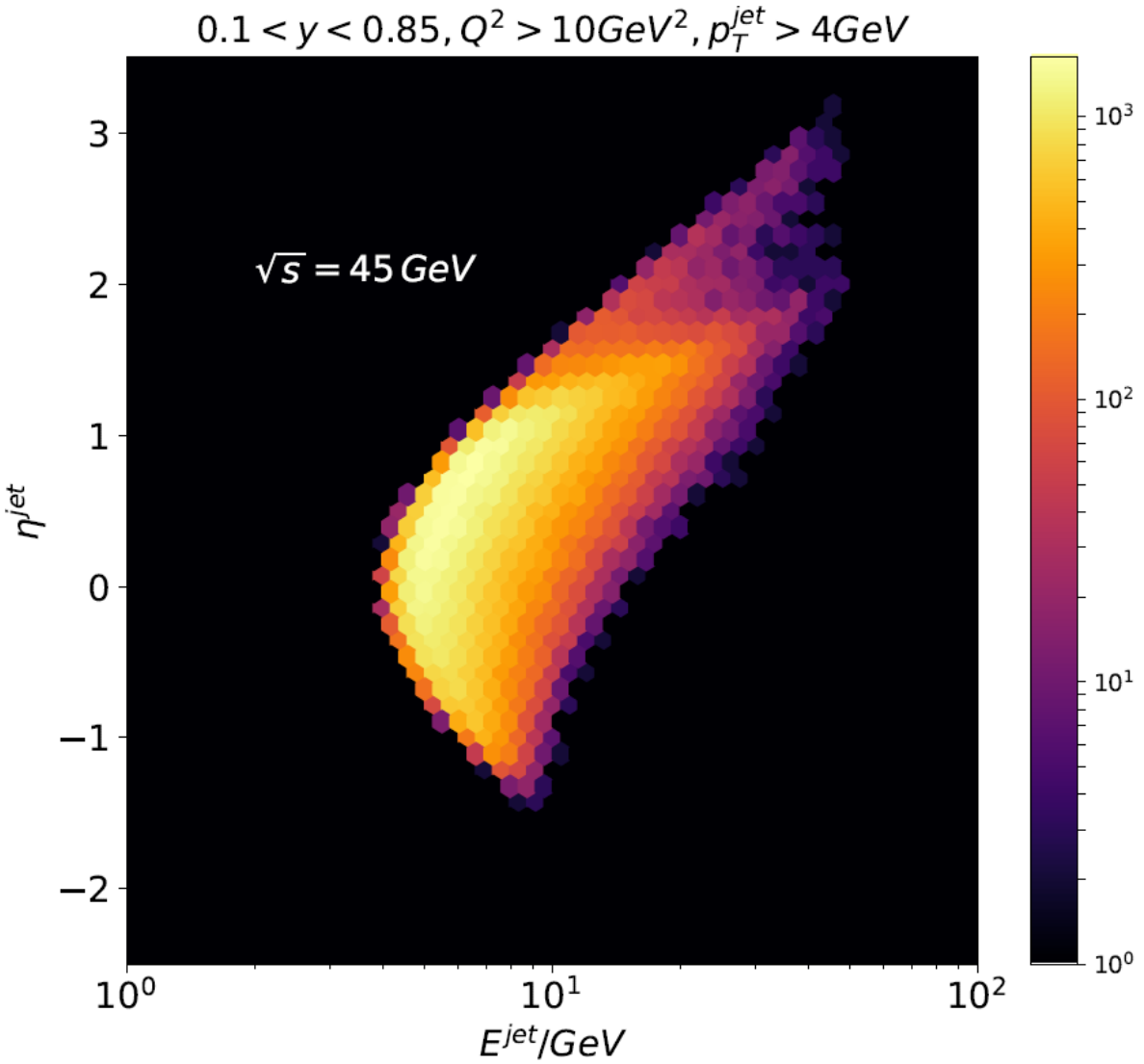
Kinematics and projected statistics

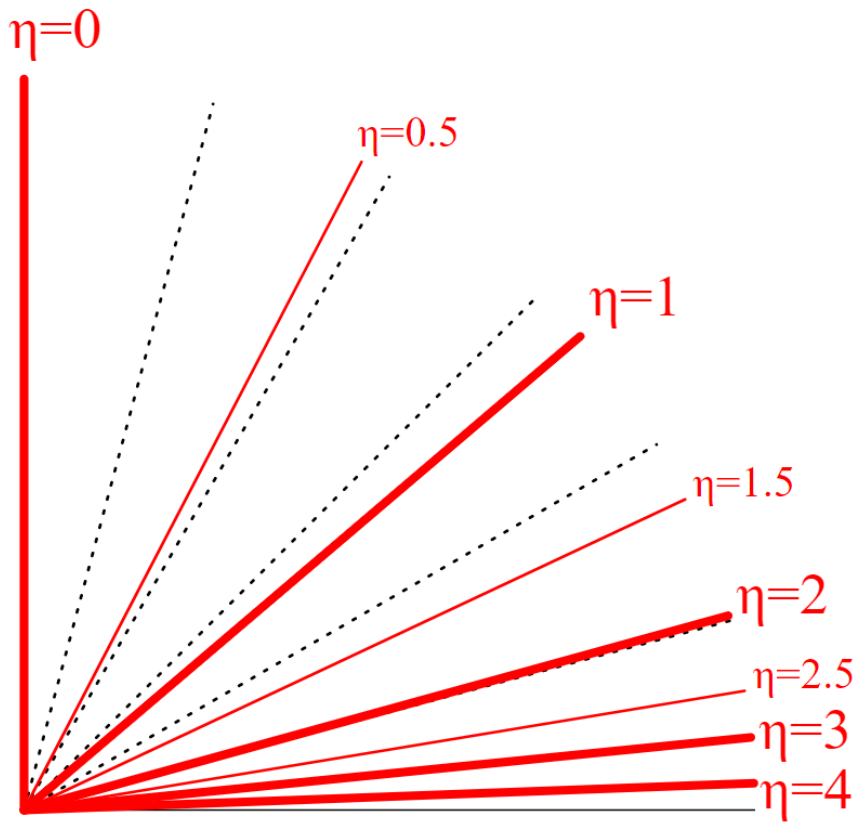




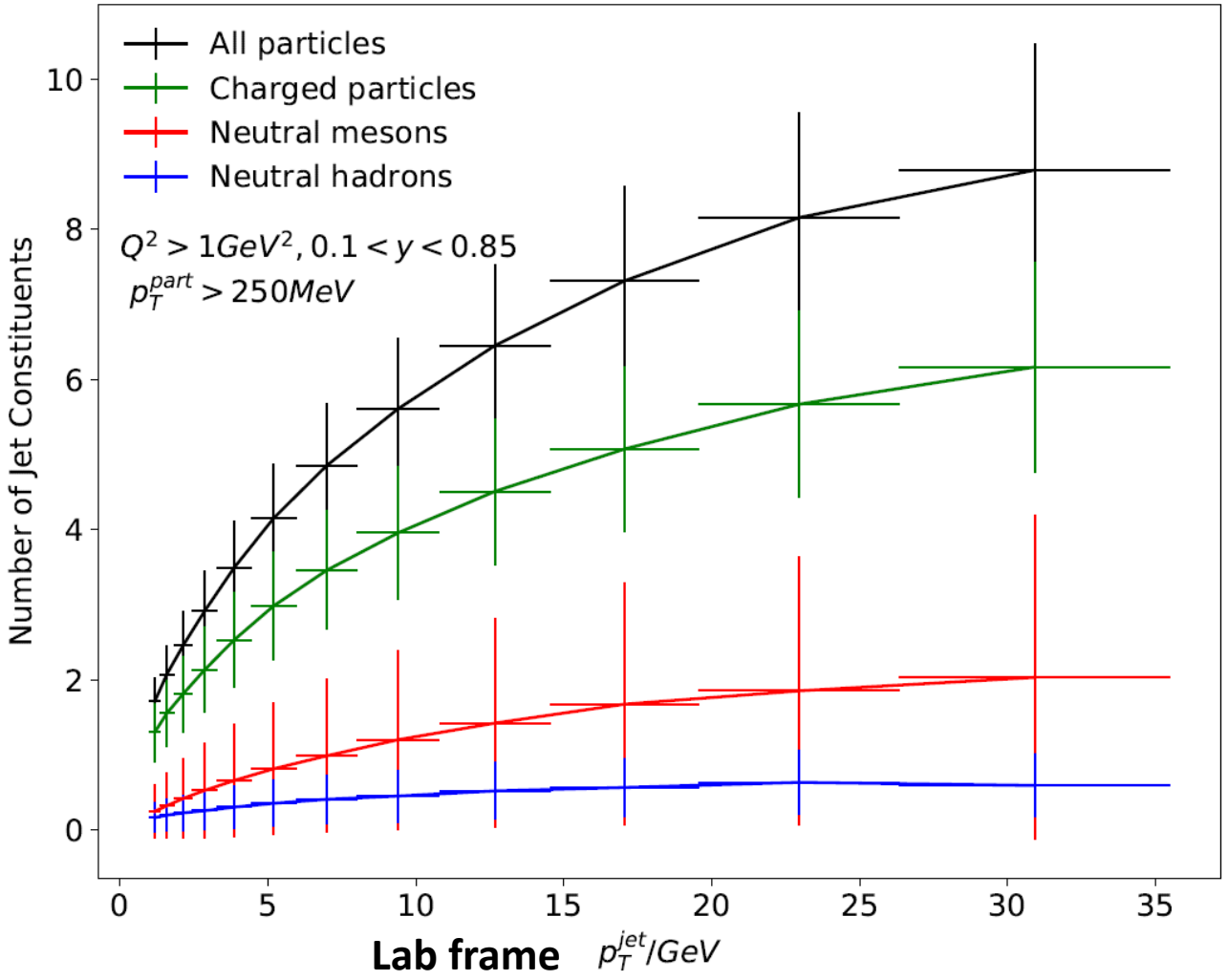
- Lepton-jet measurements with negligible stat. errors up to ~20 GeV
- Can cover sea-quark dominated region and valence region at high-Q2.

Jet energy vs pseudorapidity (in lab frame)



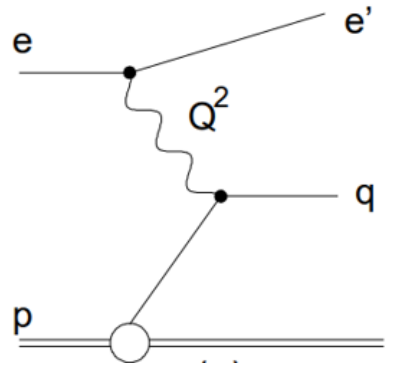


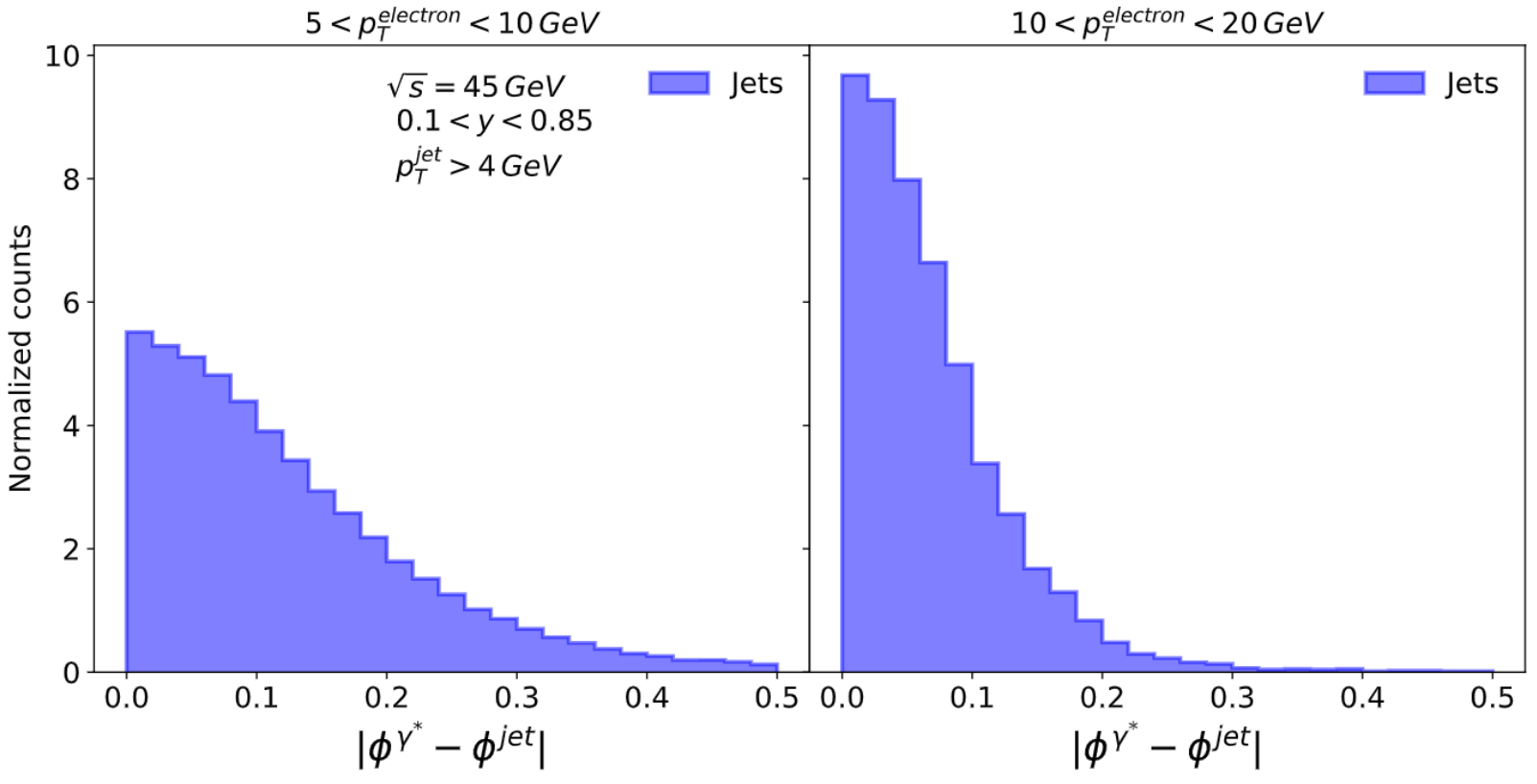
Number of particles in jet



- Dependent only on transverse momentum, not eta (energy)
- Much lower energy than @LHC; much cleaner environment than at RHIC.
- 5-8 particles leads to rich information encoded event-by-event. Think of jets as a n-th particle correlation measurement

Lepton-jet azimuthal correlation

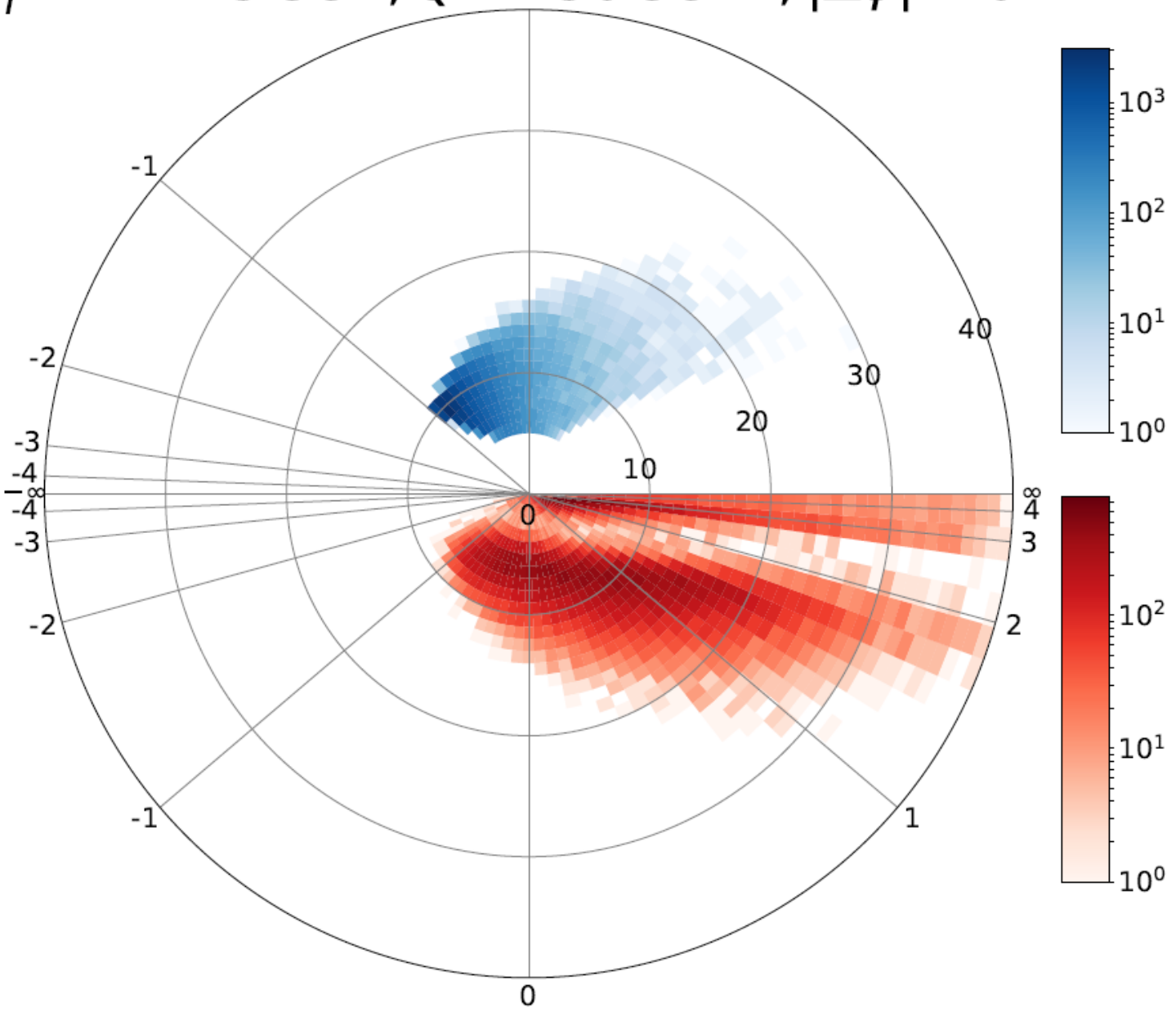




- in e-p, clean channel for quark TMD PDF, quark Sivers function *Liu et al. PRL 122 192003*
- in e-A, clean channel for energy loss, nuclear TMDs
- Large jet pT dependence. This demands good jet energy scale calibration.

$\sqrt{s} = 45\,GeV, 0.1 < y < 0.85$

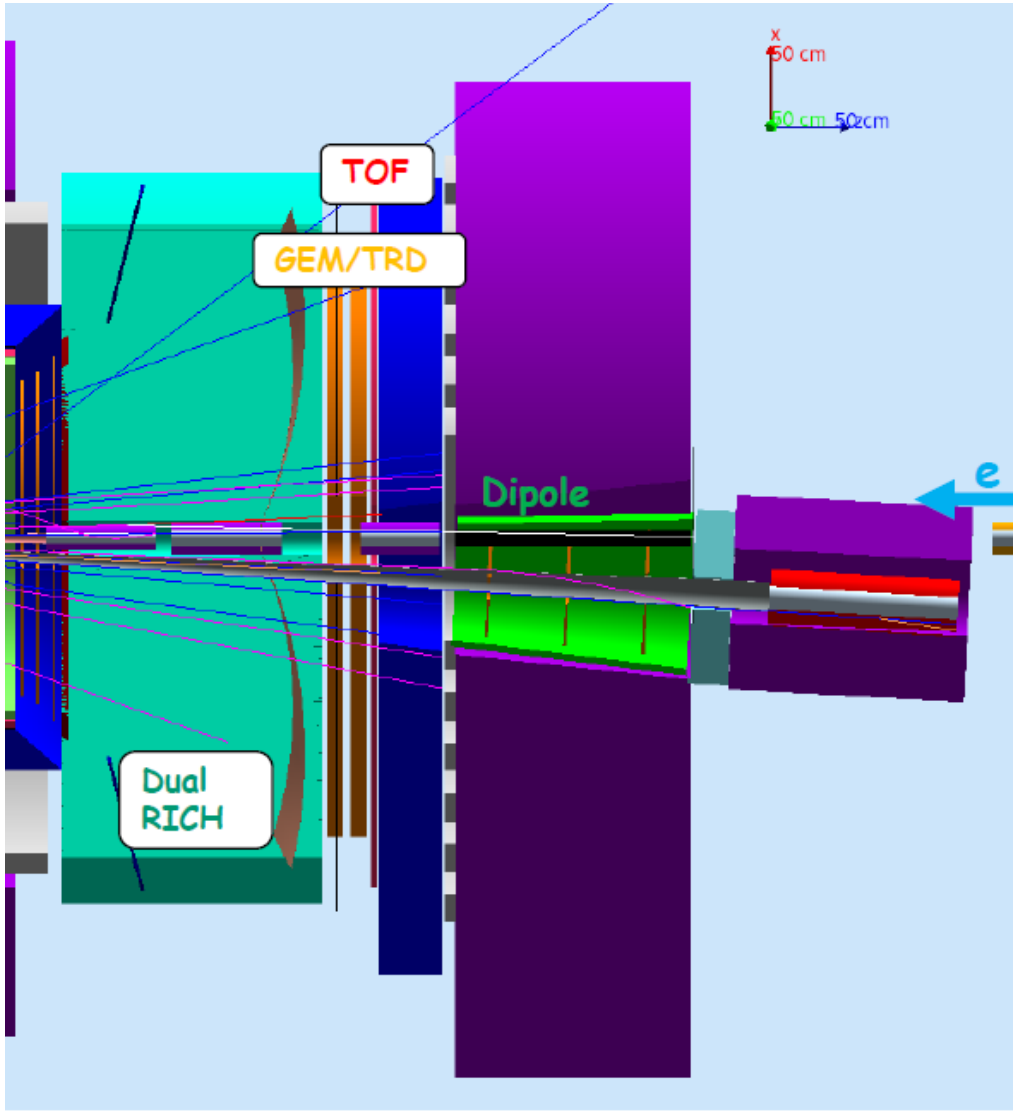
$p_T^{electron} > 5\,GeV, Q^2 > 50\,GeV^2, |\Delta\phi| < 0.4$



Electron

Jets

This will be a first in the history of colliders



My group will explore how to exploit the unique capabilities in JLEIC-concept for jet measurements:

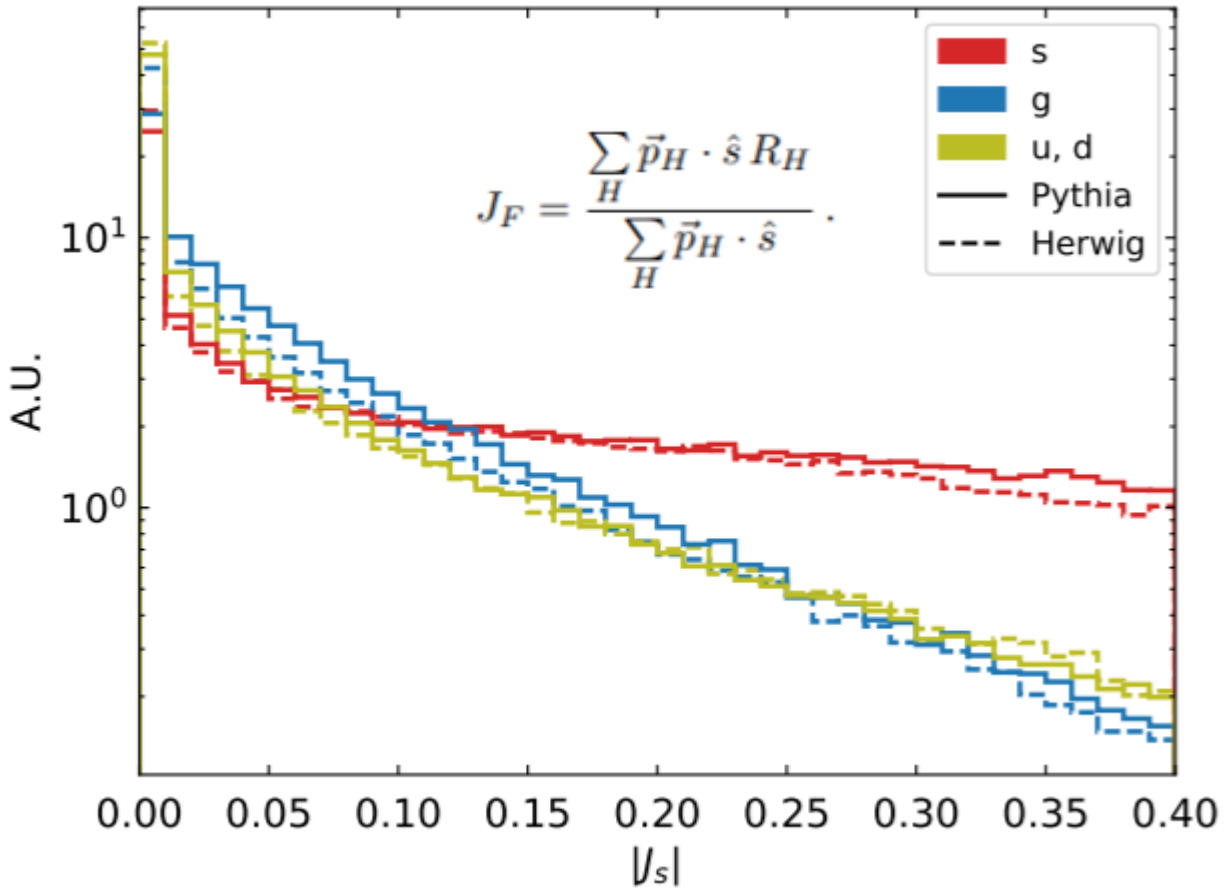
- Improvement of HCAL jet response with leading-hadron PID info.
- PID for jet substructure and jet tagging (strange jets)
- Measurements of “beam-remnant jet” with forward HCAL, correlations.

Strange jets?

The only flavor missing: b-jet, c-jet, q/g and u/d separation are considered a solved problem

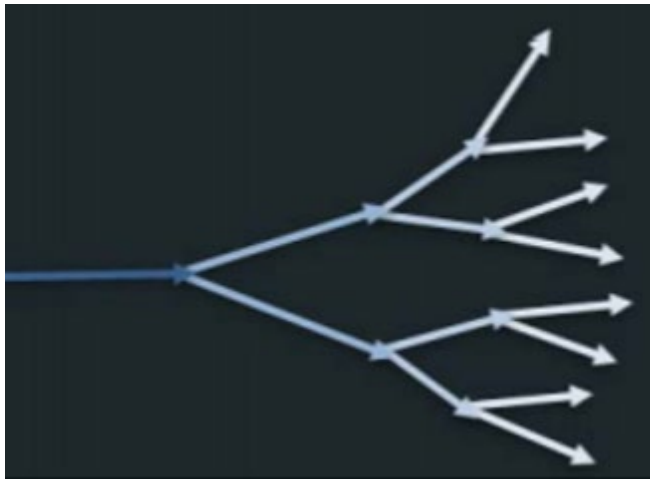
Scarce literature, not possible until now because of lack of PID in colliders:

- *"Probing the strange Higgs coupling at lepton colliders using light-jet flavor tagging"* arXiv:1811.09636v1
- *"A tagger for strange jets based on tracking information using long short-term memory"* arXiv:1907.07505
- *"Deep Learning Strange Jets", Y. Nakai, Machine Learning for Jet Physics, November 2018*

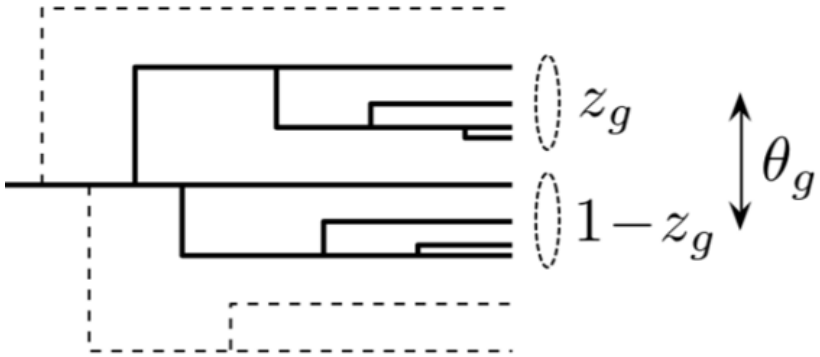


Jets have rich substructure…

- Jets are not just 4-vectors
- Jet substructure field as old as jet themselves, but now field booming due to LHC
- How could EIC physics benefit from those developments?



A. Larkoski et al., Phys. Rev. Lett. 119, 132003 (2017)



e.g. Jets with soft-drop grooming,

(an algorithm which recursively removes soft wide-angle radiation from a jet)

"Probing Transverse-Momentum Distributions With Groomed Jets"
JHEP 08 (2019) 161 , Gutierrez-Reyes et al.
"Probing Transverse-momentum dependent evolution with Groomed jets"
JHEP 07 (2018) 167 , Yiannis Makris et al.

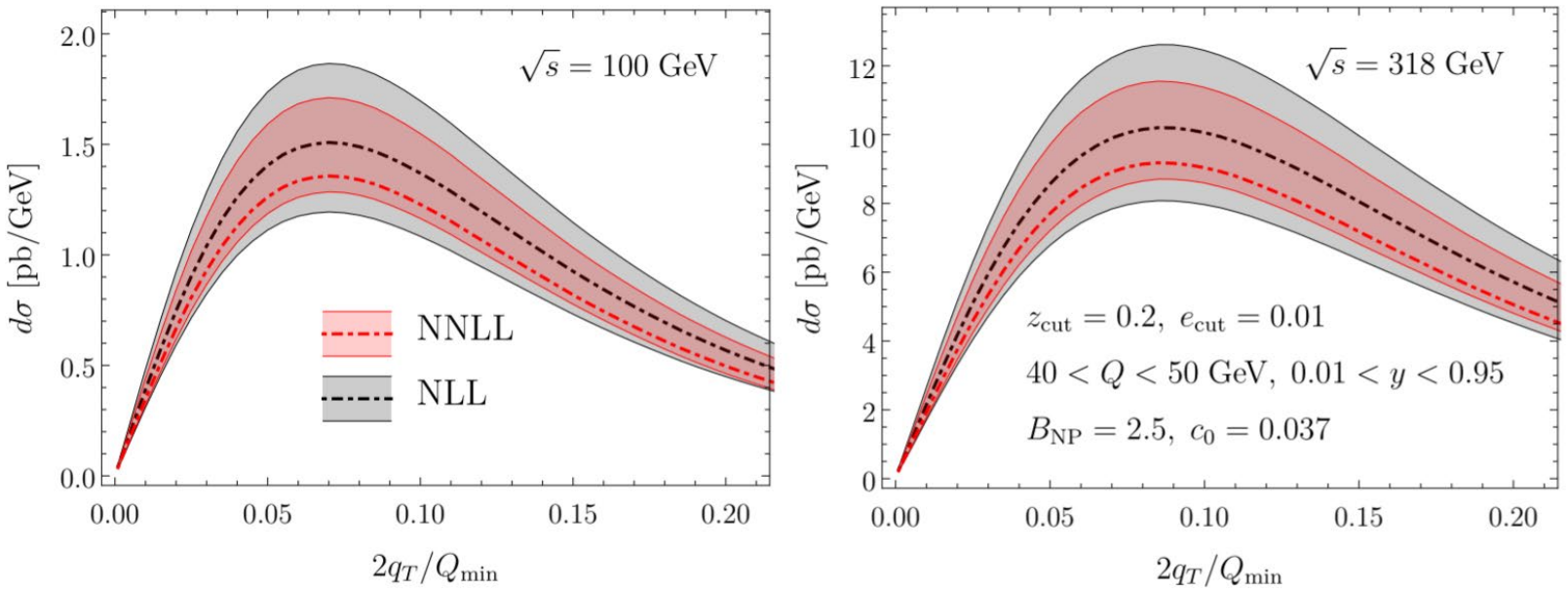
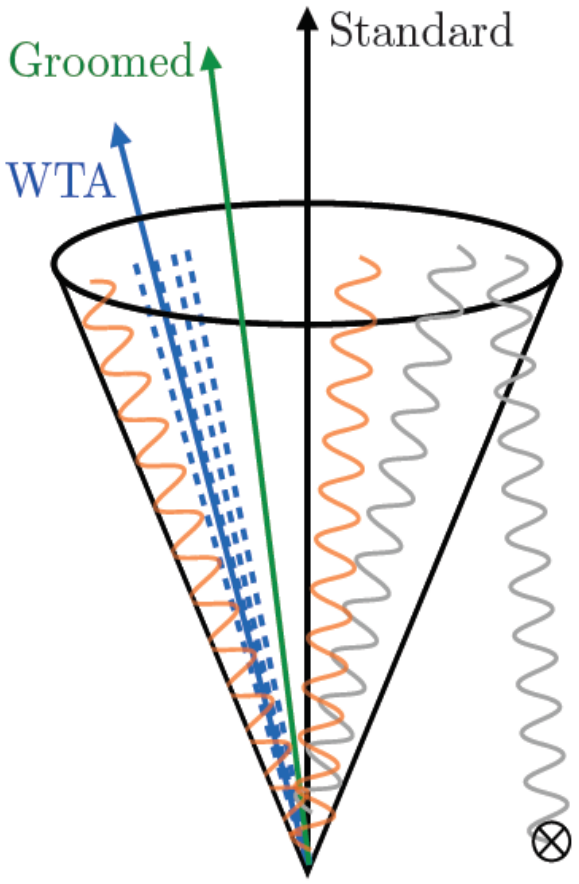
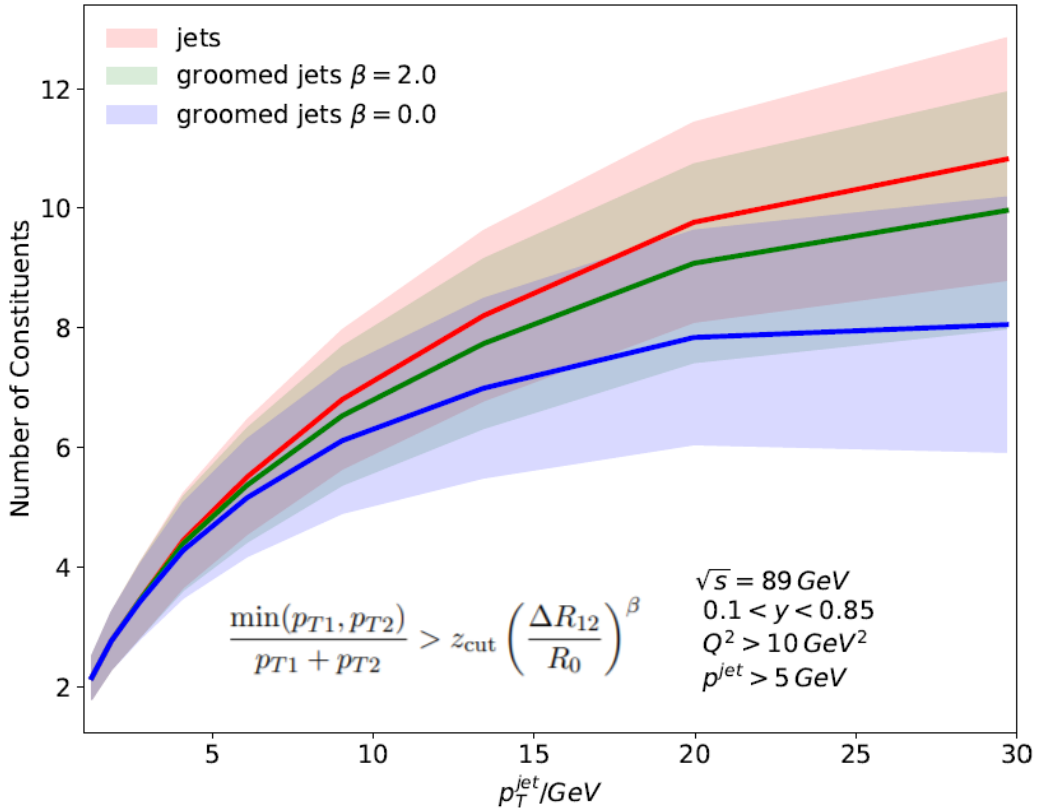


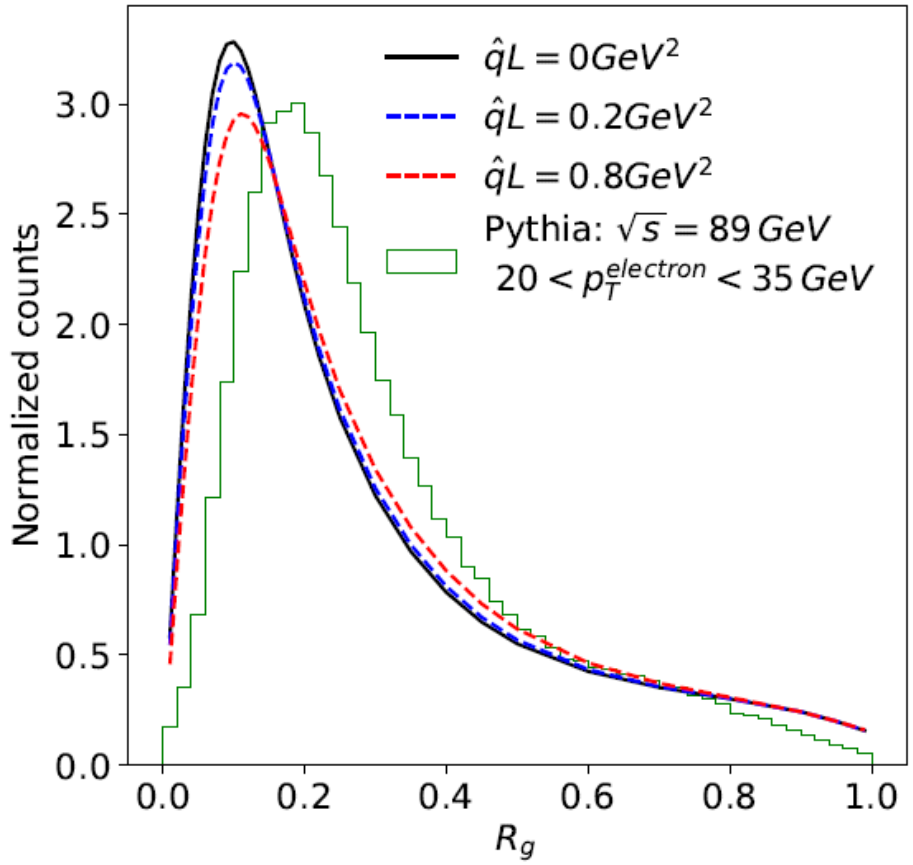
Figure 7. The NLL and NNLL TMD spectra for groomed jets in DIS for EIC (left: $\sqrt{100}$ GeV) and HERA (right: $\sqrt{s} = 318$ GeV) kinematics. The cross section are integrated in $y = Q^2/(xs)$ and



A novel way to better control hadronization effects.

Is jet substructure in general and jet grooming in particular feasible at the EIC?





Yes experimentally, Yes theoretically

"Jets as precision probes in e-A collisions at the EIC", Arratia, Ringer, Song, Jacak. (to appear in arXiv soon).

Needs:

- Simulations of e-p SIDIS (common to single-hadron and di-hadron studies). Realistic, full Geant-based JLEIC detector response.
  Different center-of-mass energies would be good: 45/60/100 GeV.
- Guidance on QED radiative corrections.
- Guidance on how to incorporate spin effects in simulation (i.e. Sivers effect)

Deliverables:

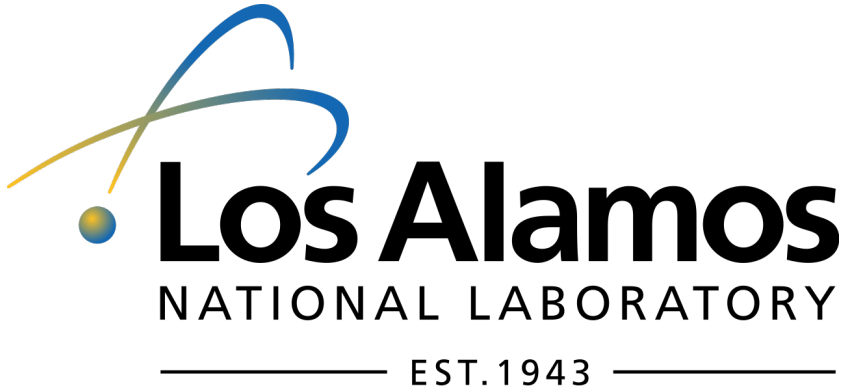
- Key performance plots (jet energy scale, jet energy resolution vs eta, pT).
- Projections for key observables (lepton-jet correlations).
- Feasibility studies for jet substructure measurements.

Who is doing it?

- My group at UC Riverside (1 postdoc, 1 graduate student + undergrads).
  We plan to spend a significant amount on time on EIC activities during next in the context of the Yellow Book report.

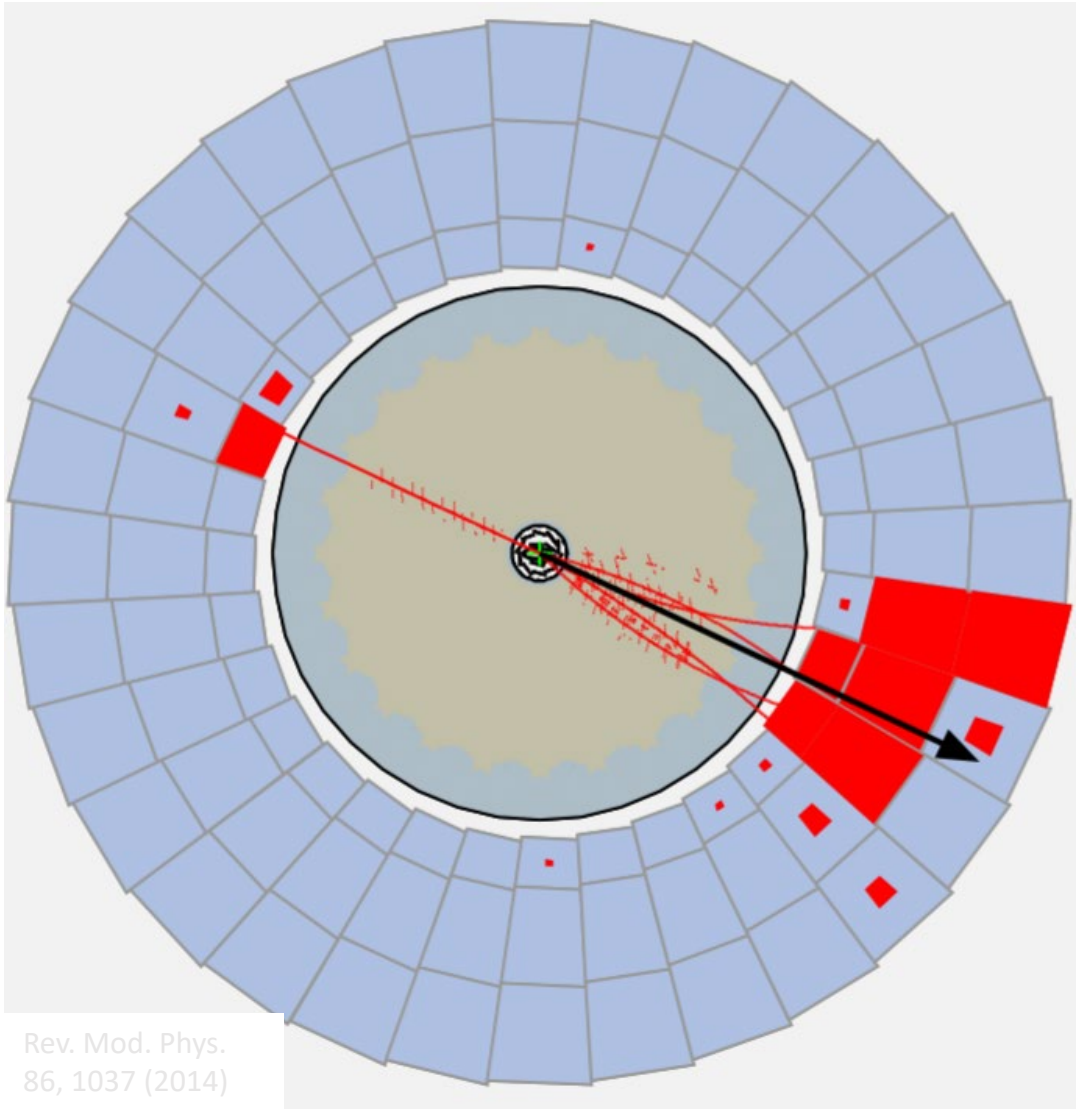
University of California EIC Consortium

4 UC campus (Berkeley, Riverside, Davis, Los Angeles)
3 National Labs (Berkeley, Los Alamos, Livermore)



Summary

- Studies with jets at EIC will be unlike any previous collider (even HERA!)
- Lepton-jet studies will likely play an important role for 3D tomography of nucleon and nucleus, spin, hadronization.
- I and my group will contribute to jet studies with JLEIC.
- We are open to collaborations.



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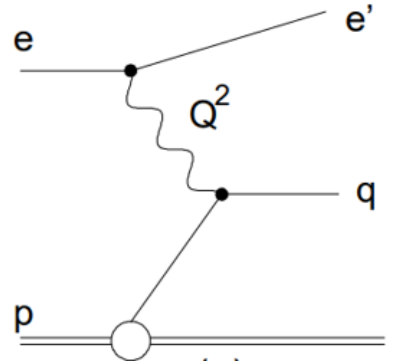
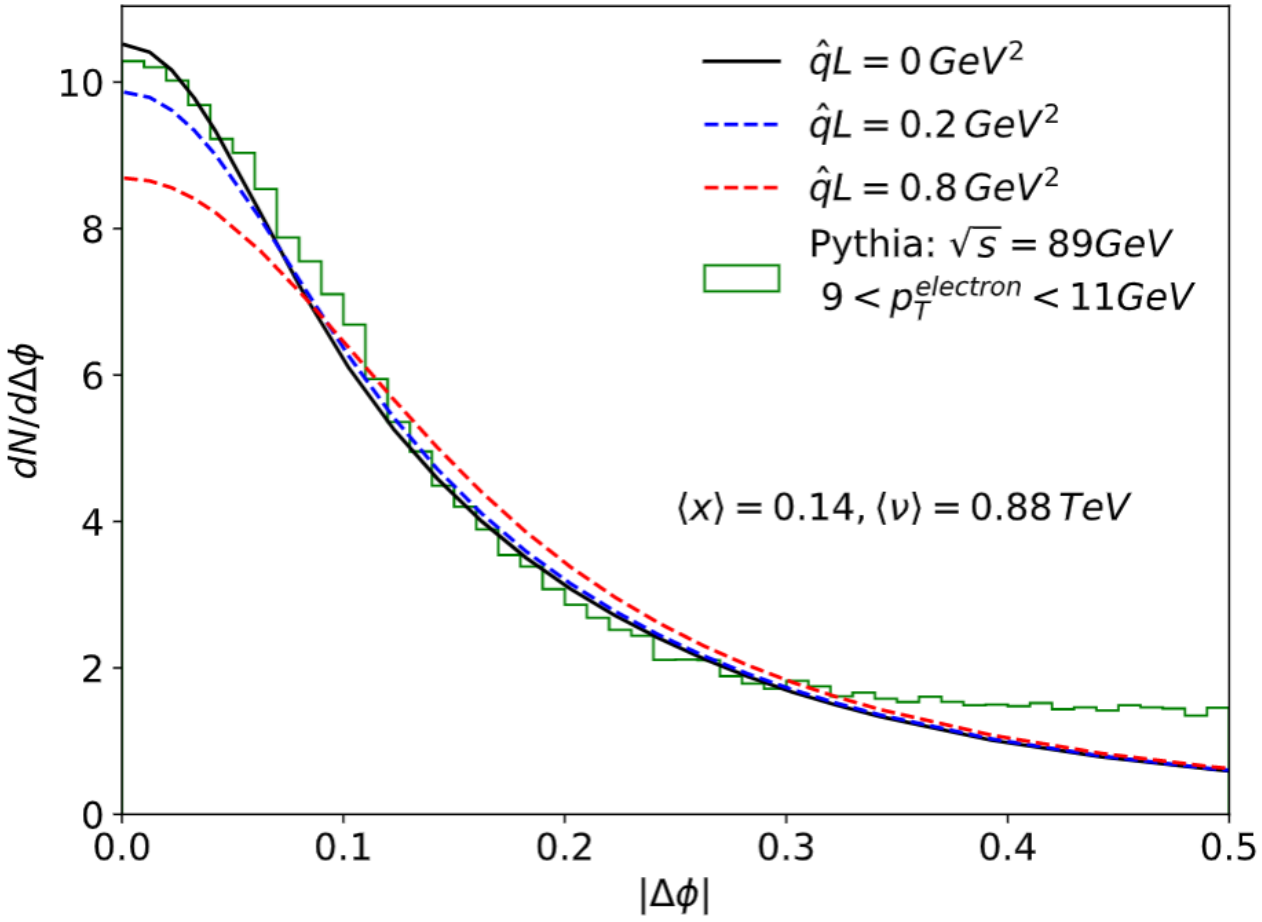
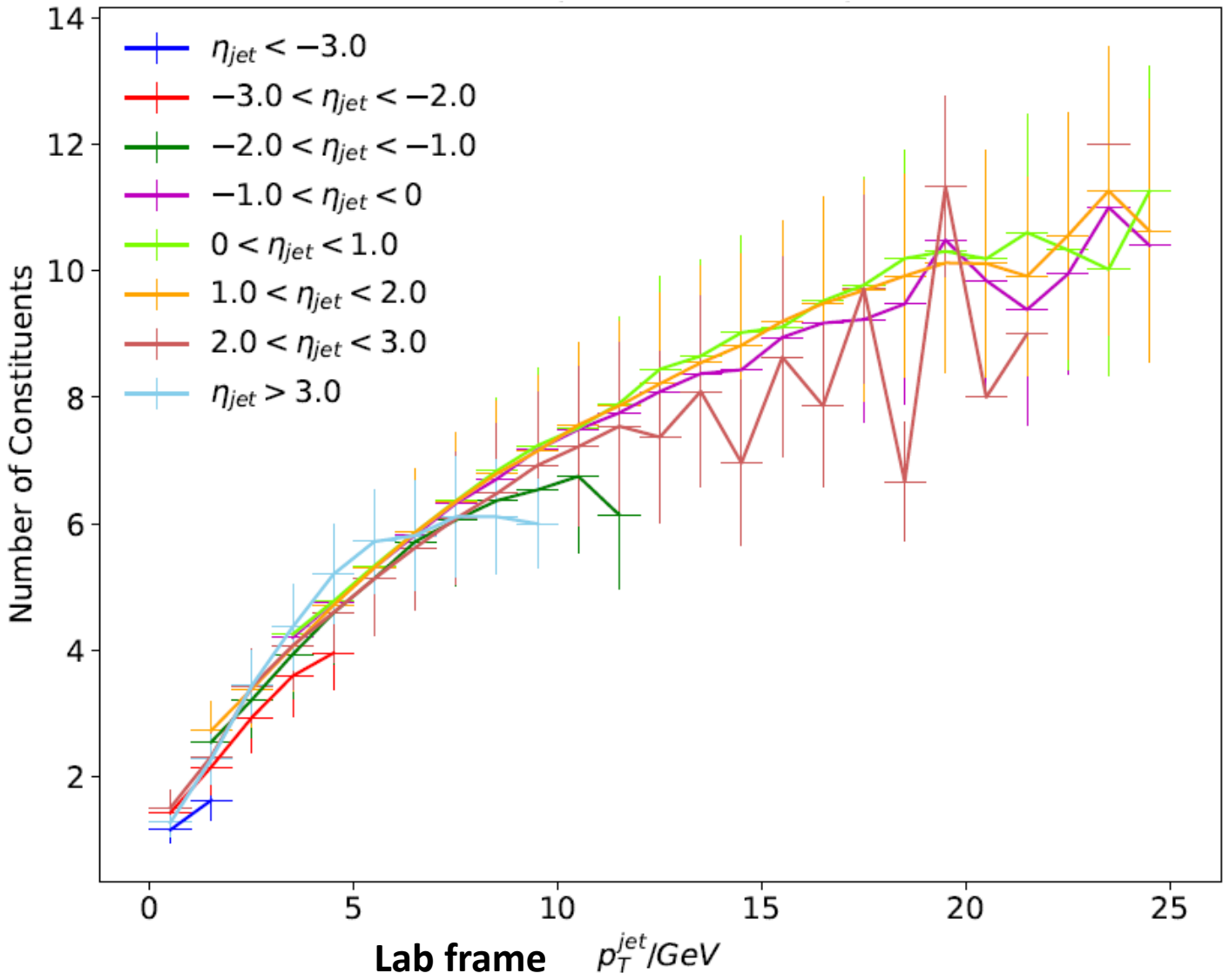
Backup

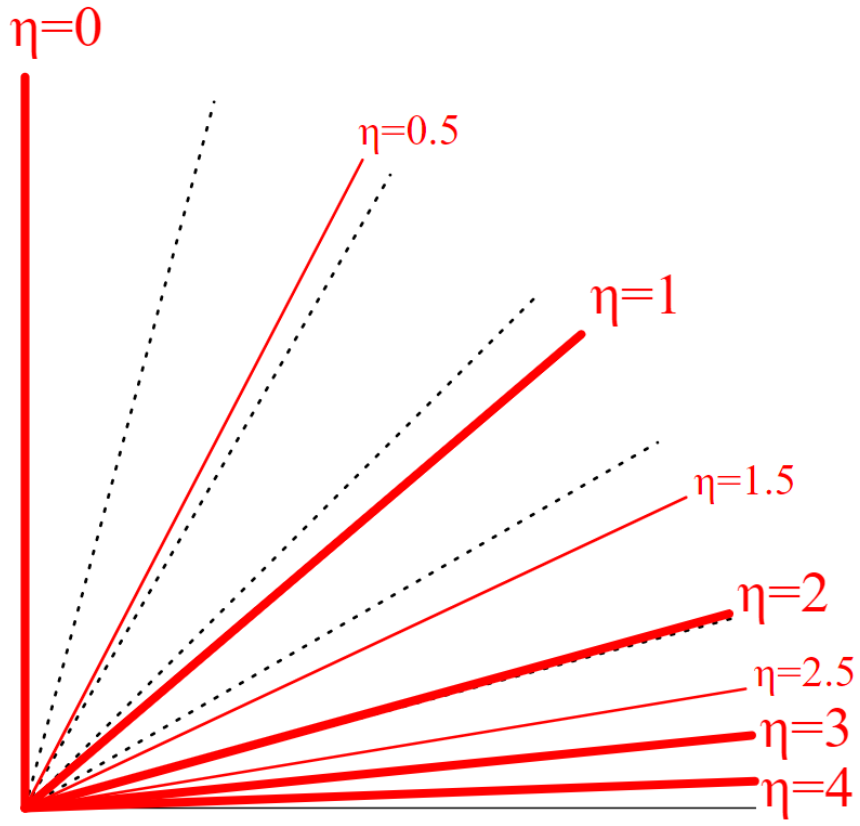
Lepton-jet azimuthal correlation





- Clean and unambiguous channel to measure jet transport parameter (nuclear quark TMD PDF); in e-p also quark TMD PDF, quark Sivers function *Liu et al. PRL 122 192003*
- Answer: *"How does the nucleus react to a fast color charge?"* (with precise probe, at the TeV scale!)





Dependent only on pT, not eta (not energy)

And jets at EIC seems to be getting a lot of attention recently, e.g:

PHYSICAL REVIEW D **100,** 094016 (2019)

Azimuthal asymmetries in semi-inclusive J/ψ + jet production at an EIC

Umberto D'Alesio,[1,2,*] Francesco Murgia,[2,†] Cristian Pisano,[1,2,‡] and Pieter Taels[2,§]

JHEP

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Phenomenology with a recoil-free jet axis: TMD fragmentation and the jet shape

Duff Neill,[a] Andreas Papaefstathiou,[b,c] Wouter J. Waalewijn[b,c] and Lorenzo Zoppi[b,c]