# Jets for 3D imaging

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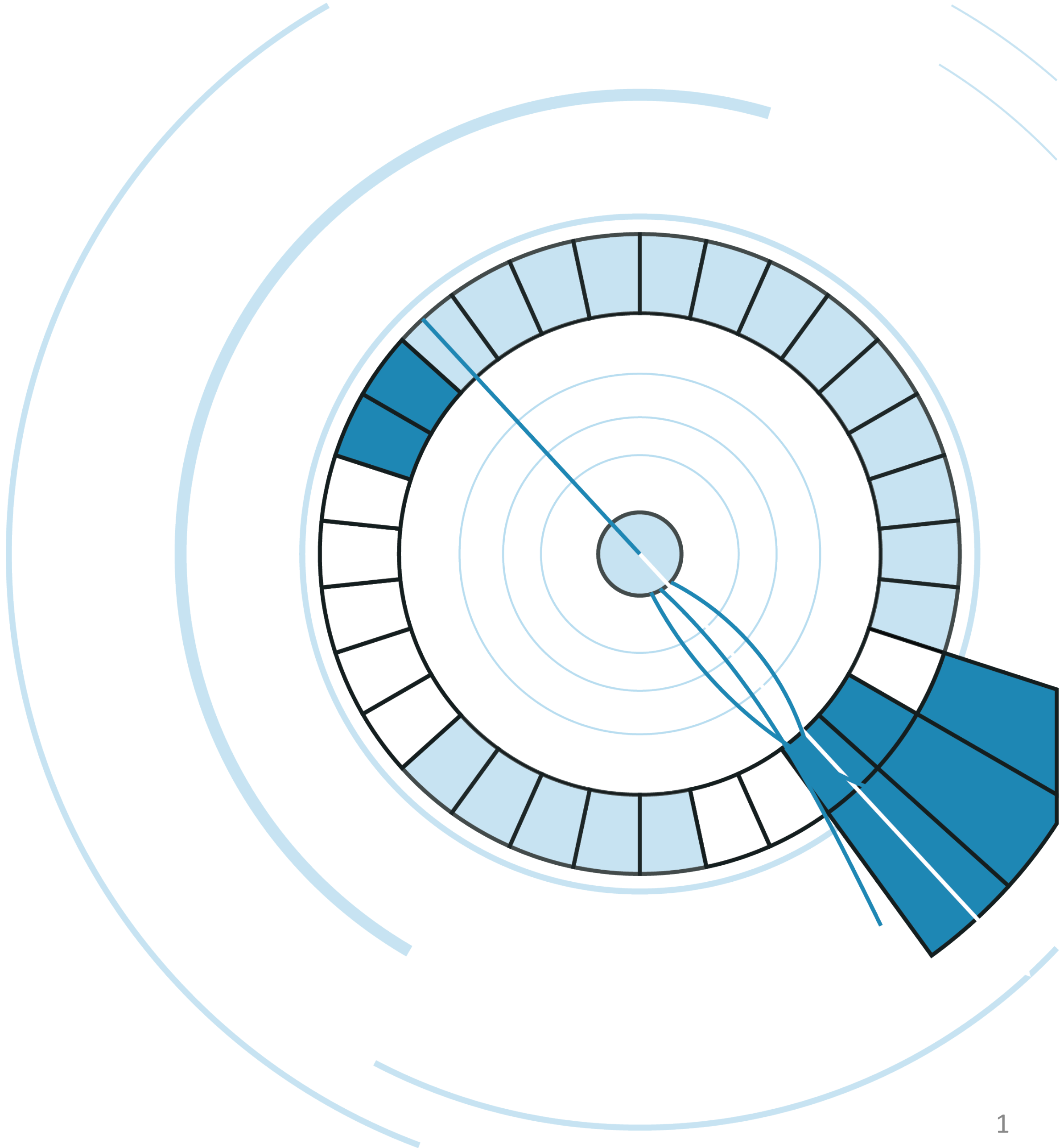
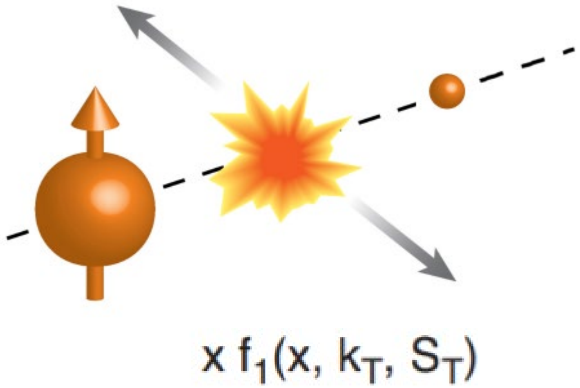
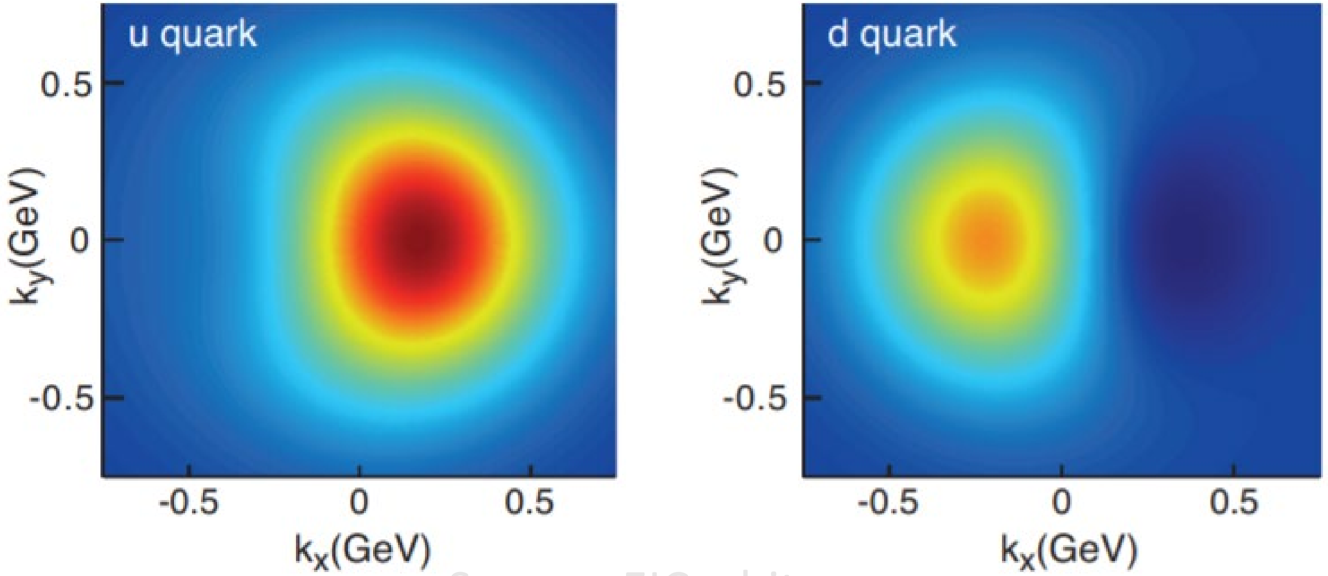


# Jet for 3D-imaging



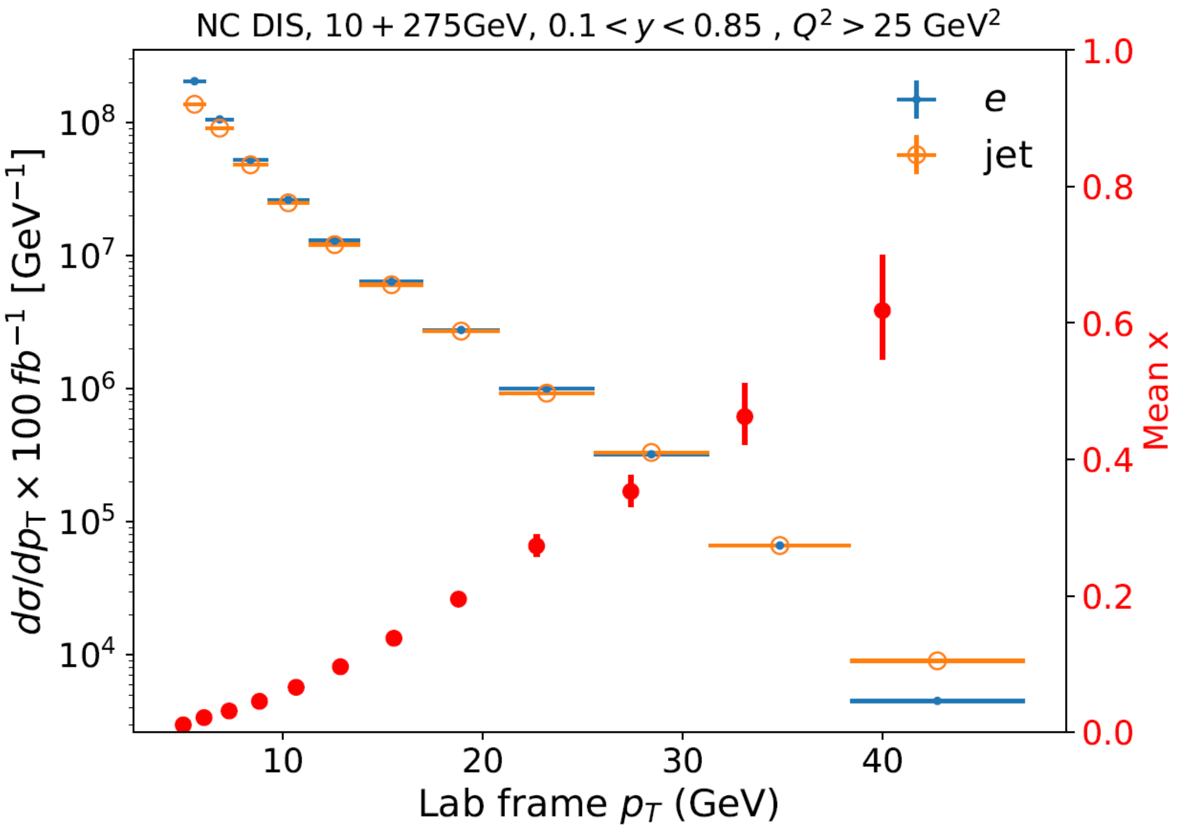

- DIS jets are a novel tool for 3D imaging
- Complementary and more direct way for EIC flagship measurements
- Potential for unique jet program, unlike any previous collider or fixed-target experiment



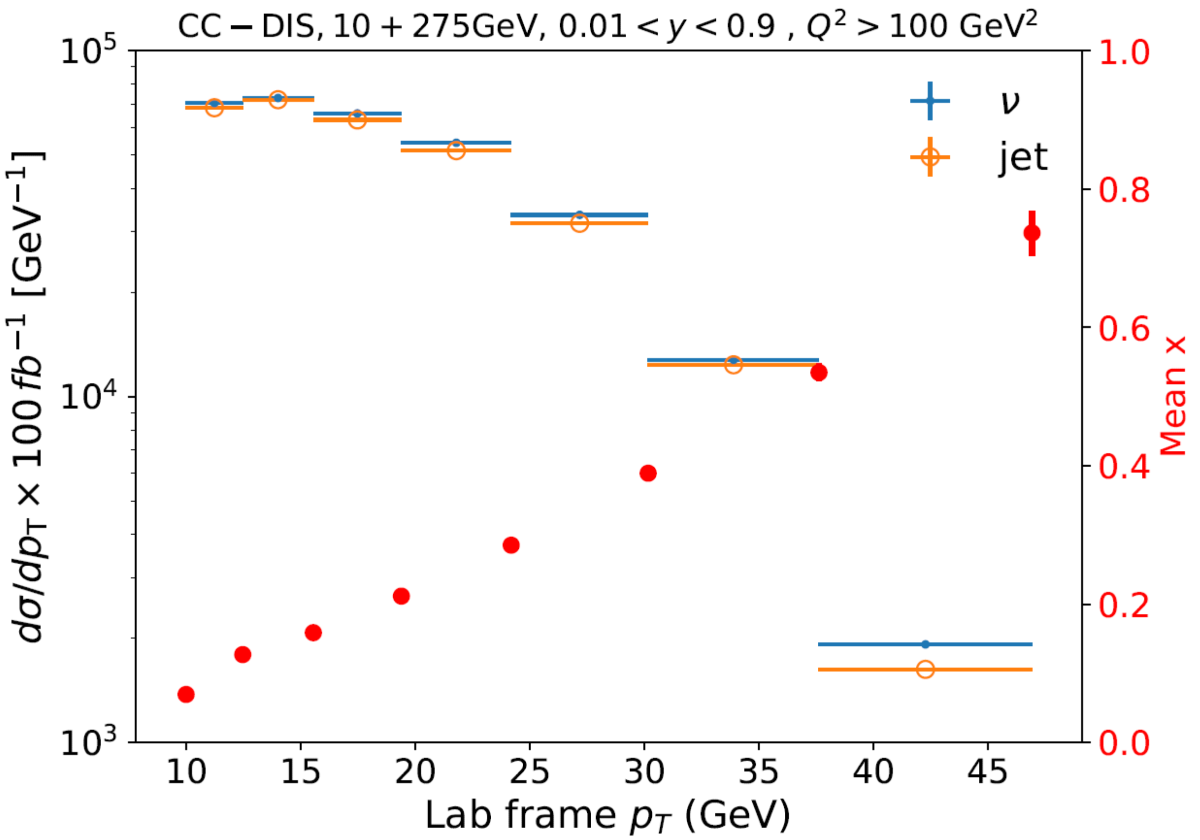

Source: EIC white paper

# Jet cross-section (anti-kT, R=1.0)

**Neutral-current events**



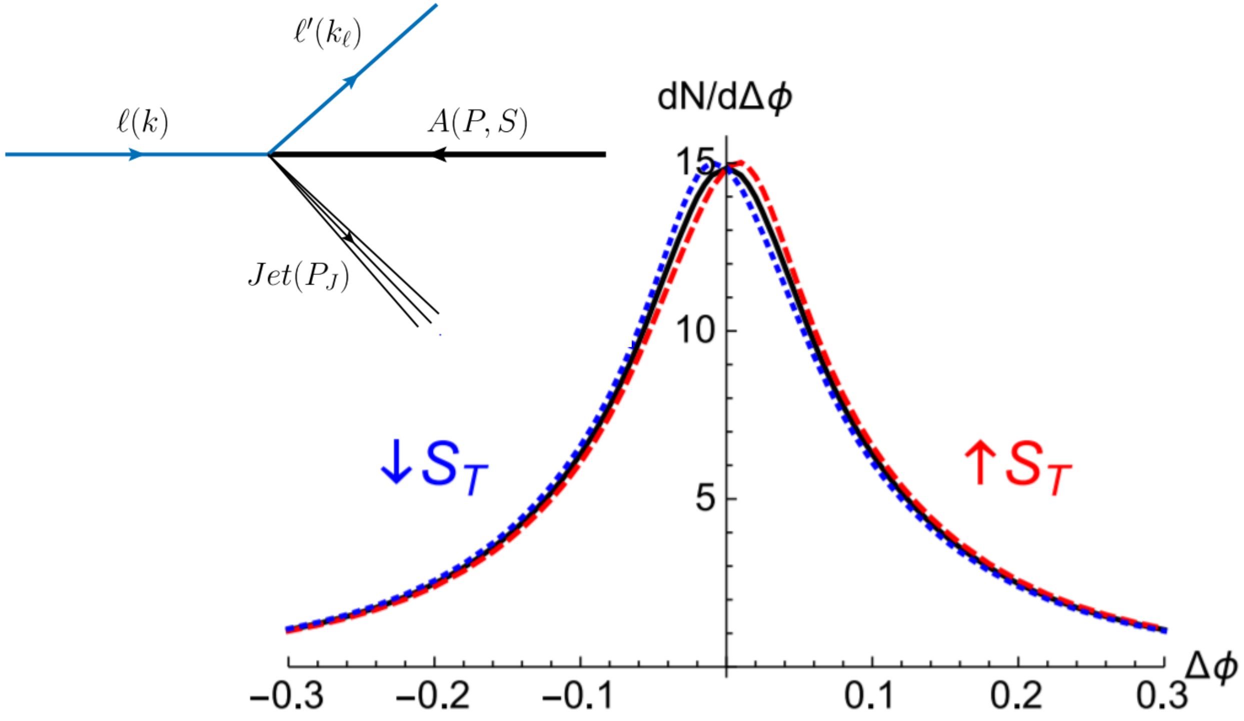

**Charged-current events**




- **Contributions beyond LO are very small (<10%), so Pythia8 (LO) provides an excellent approximation for both NC and CC DIS**

# Quark Sivers effect with Jets

*Liu, Ringer, Vogelsang, Yuan, PRL 122 192003 (2019)*



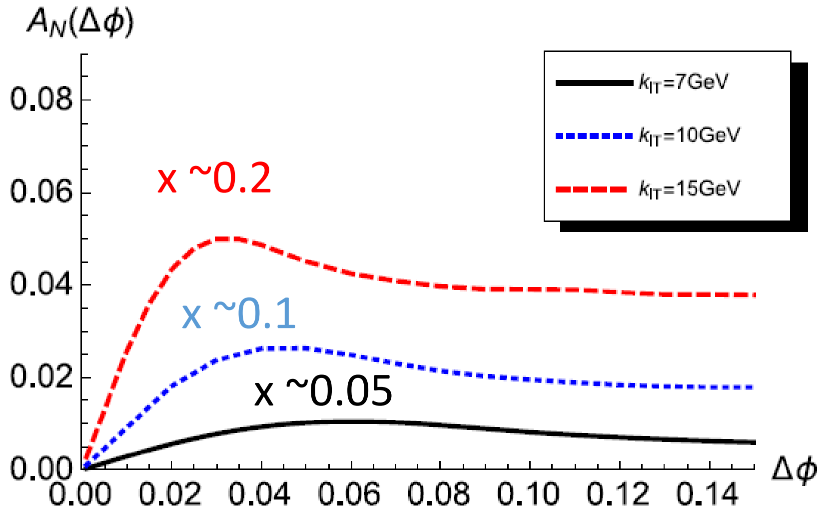
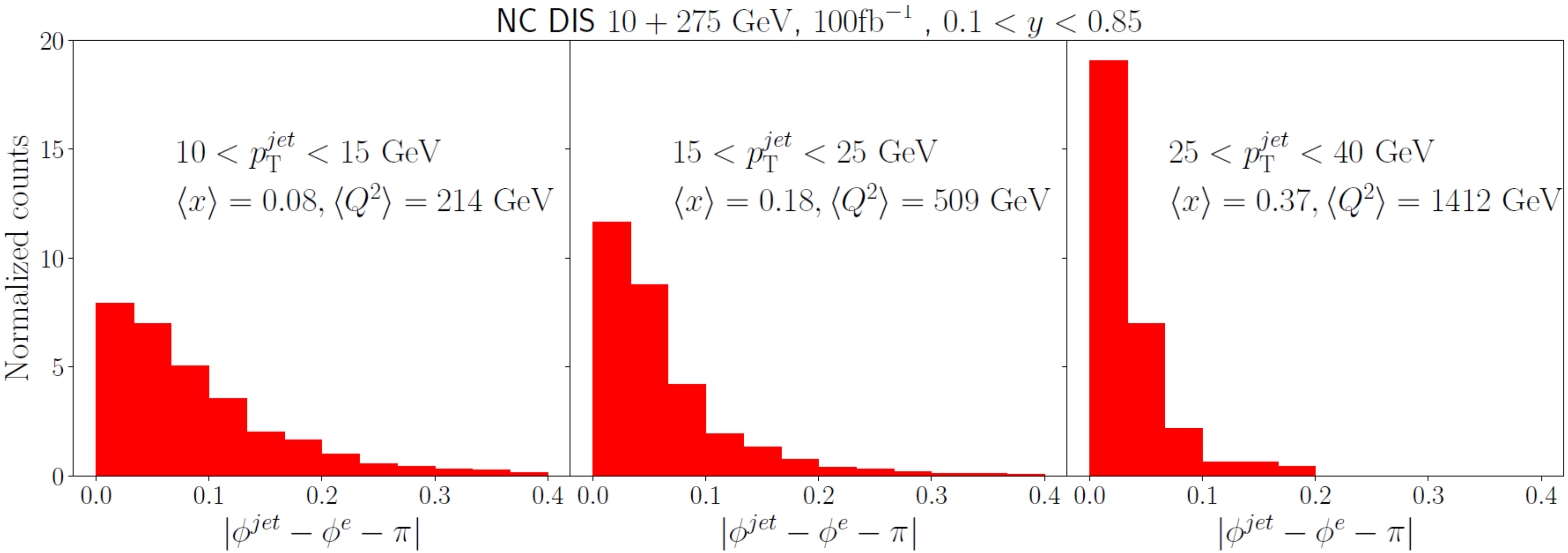




FIG. 3. The single transverse spin asymmetry as a function of $\Delta\phi = \phi_J - \phi_\ell - \pi$ for different lepton transverse momenta $k_{\ell\perp} = 7$, 10, and 15 GeV, respectively, which illustrates the transverse momentum dependence of the quark Sivers function.

*"The advantage of the lepton-jet correlation as compared to the standard SIDIS processes is that it does not involve TMD fragmentation functions."*

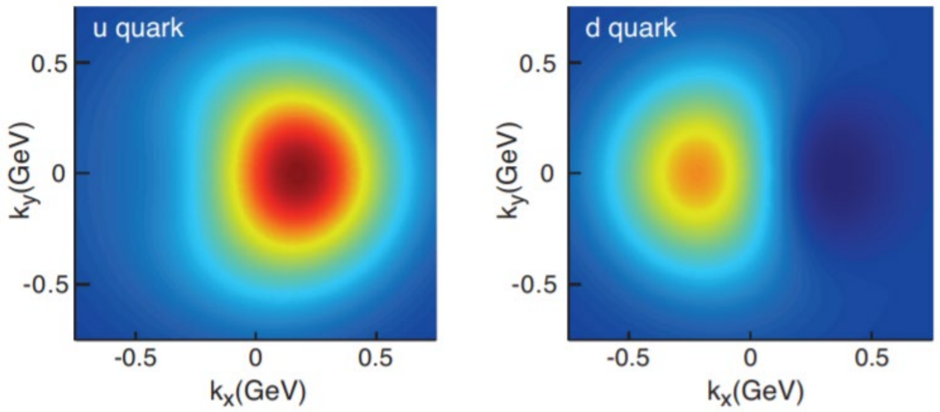
$$\frac{d^5\sigma(\ell p \to \ell' J)}{dy_\ell d^2k_{\ell\perp} d^2q_\perp} = \sigma_0 \int d^2k_\perp d^2\lambda_\perp x f_q(x, k_\perp, \zeta_c, \mu_F) \times H_{\mathrm{TMD}}(Q, \mu_F) S_J(\lambda_\perp, \mu_F)\, \delta^{(2)}(q_\perp - k_\perp - \lambda_\perp)\ .$$

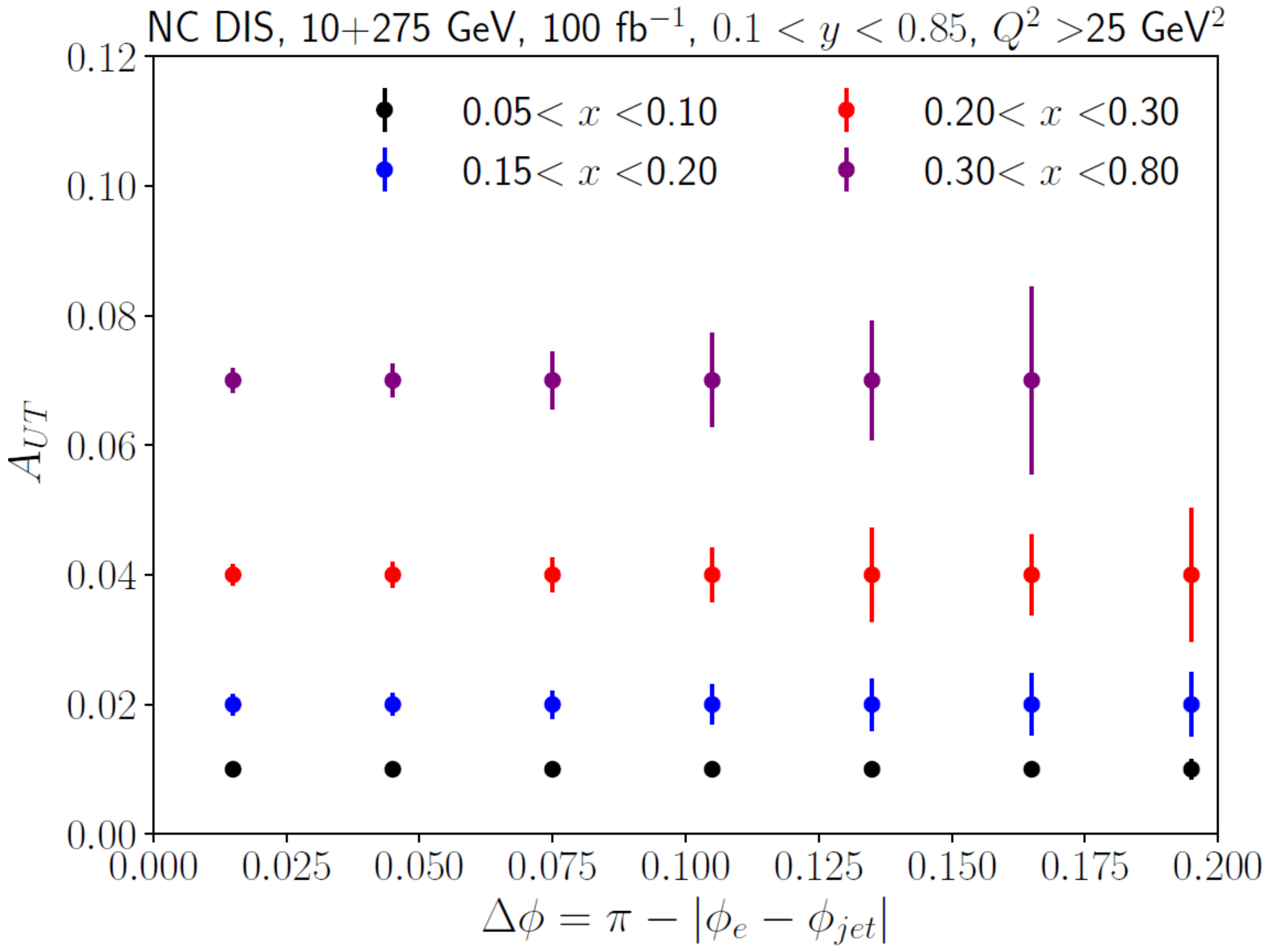
# Lepton-jet correlation




- Strong kinematic dependence on the width, but in general widths <0.1 rads.
- This observable probes TMD PDFs. It has never been measured before (not done at HERA)

# kT-dependence of Quark Sivers function

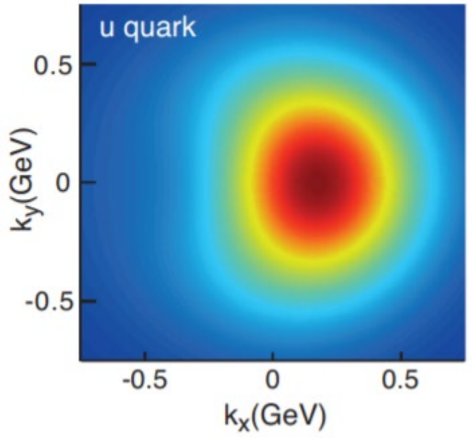


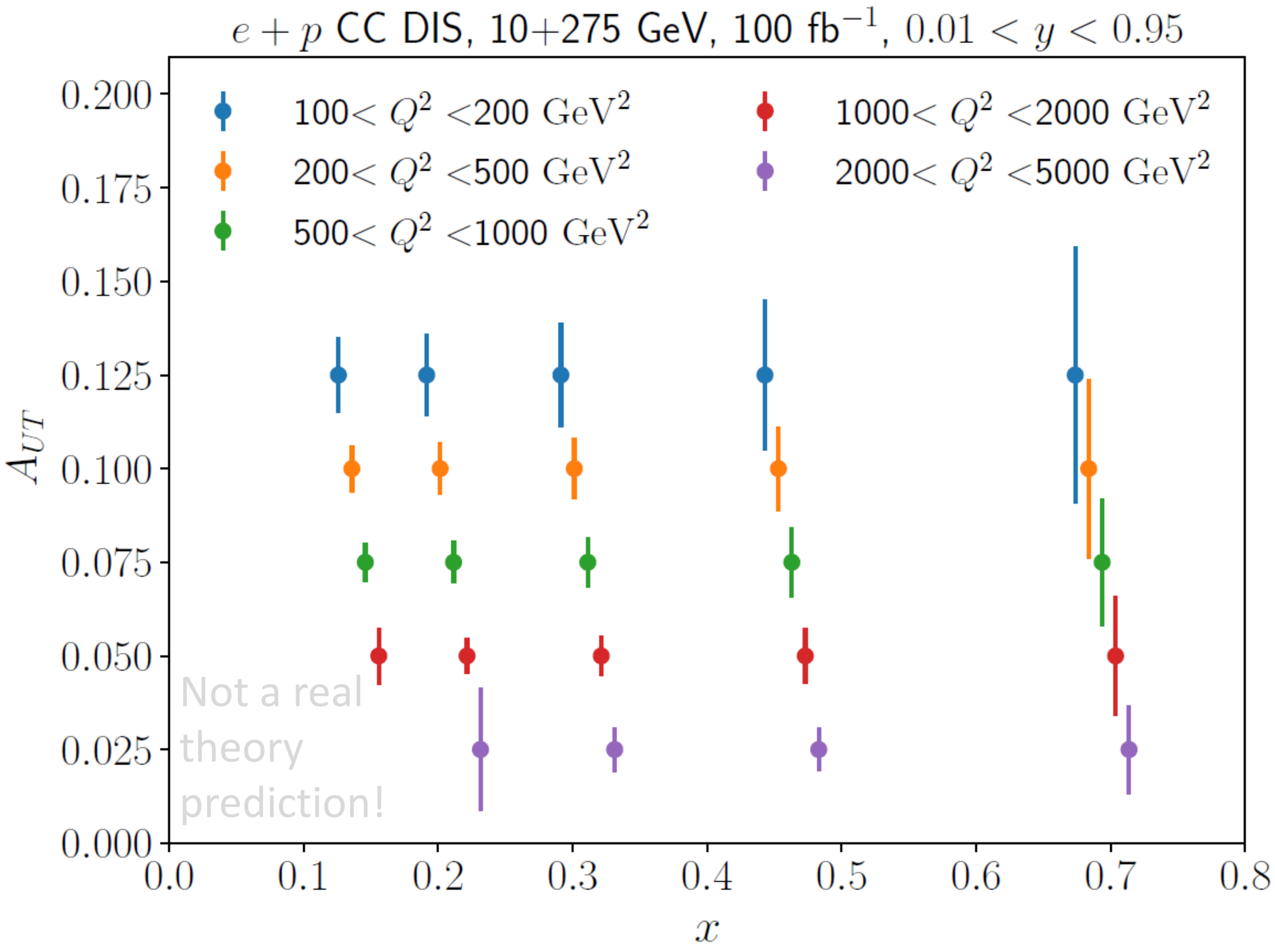




$$\delta A_N = \frac{1}{P_e P_I P_N f_D} \cdot \frac{1}{\sqrt{N_{raw}}} \cdot \sqrt{1 - A^2}$$
$$\approx \frac{1}{P_e P_I P_N f_D} \cdot \frac{1}{\sqrt{N_{raw}}}$$

- Statistical projections assume 100 fb-1, 70% polarization, 50% overall efficiency.
- Most systematic cancels in the ratio.
- Need enough resolution to bin in azimuthal angle (kT dependence), and coverage to fit R=1.0 radius.

# u-quark Sivers with neutrino-jet correlations

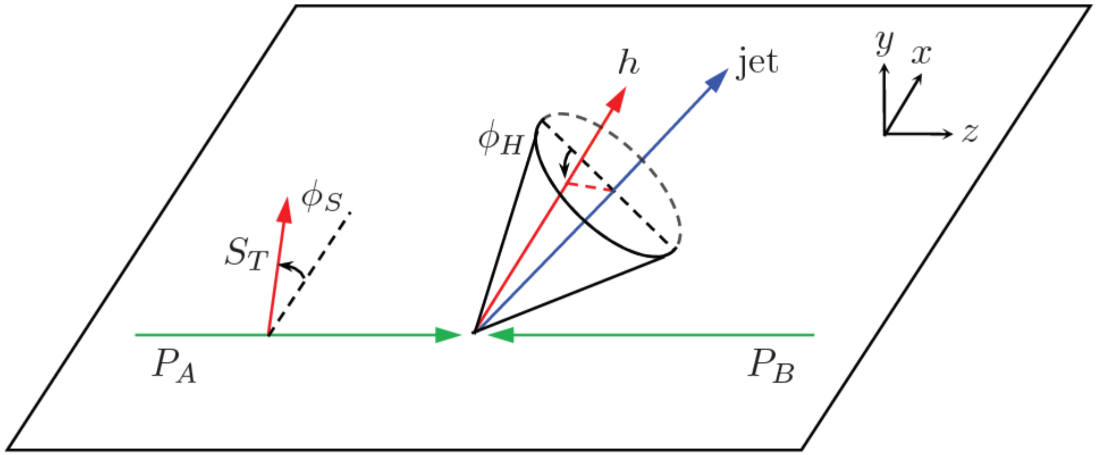



- Statistical projections assume 100 fb-1, 70% polarization, 50% overall efficiency.
- Most systematic cancels in the ratio.
- Needs measurement of neutrino, i.e. missing energy, azimuthal angle.
  [This requirement is intrinsic to CC DIS, and for Jacquet-Blondet method for NC DIS]
- Binning inspired in PRD 88, 114025 (2013)

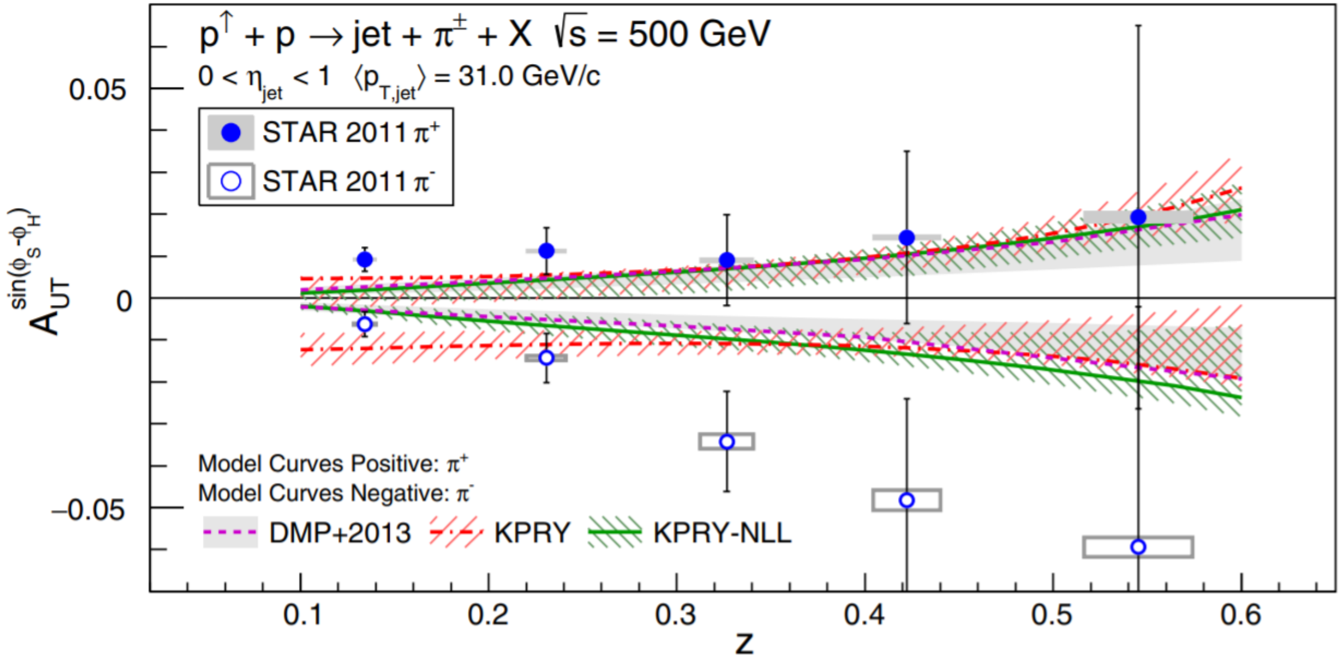
# Transversity, Collins, with hadron-in-jet

distribution of transversely polarized quarks inside a transversely polarized nucleon



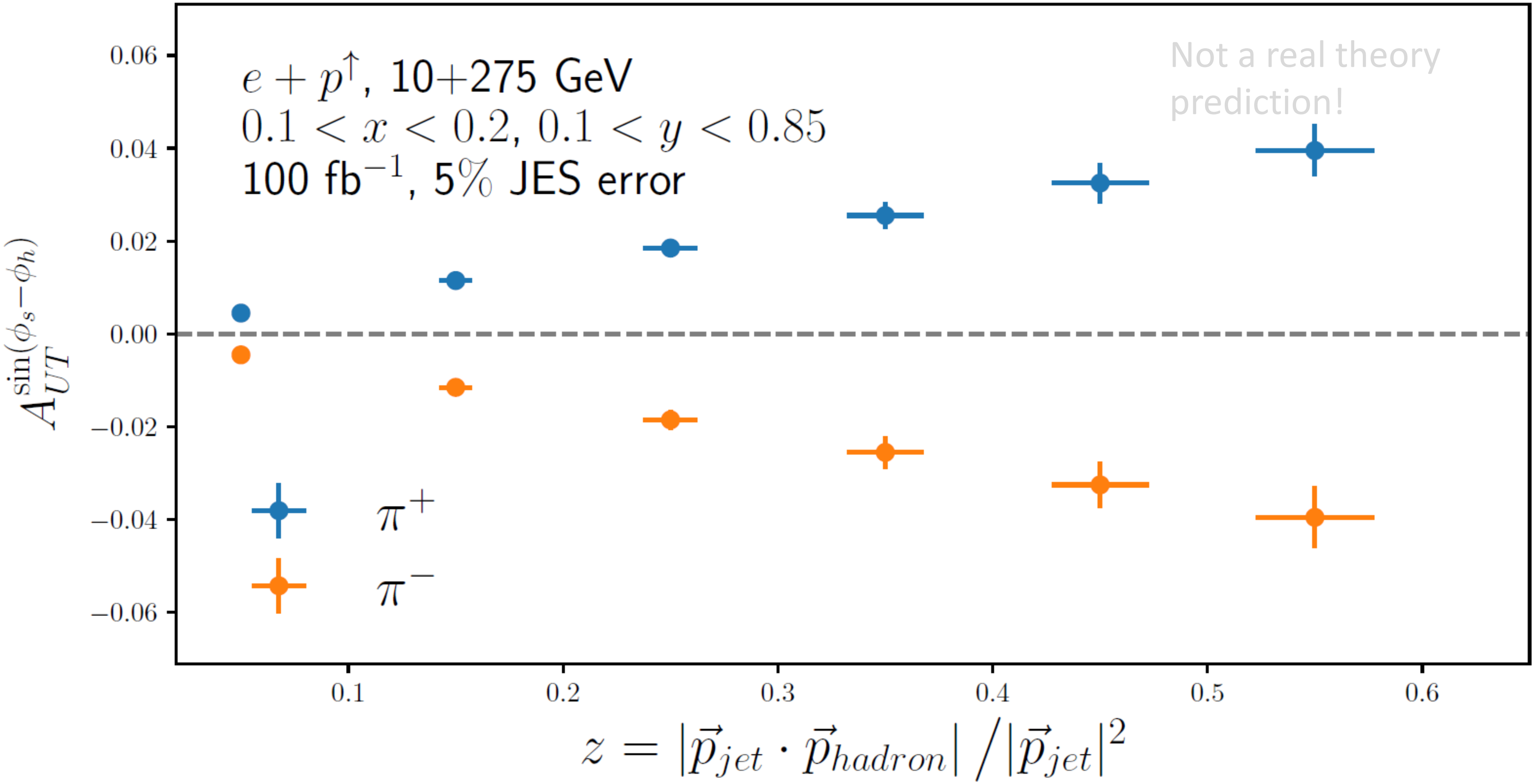

"Collins azimuthal asymmetries of hadron production inside jets
Phys. Lett. B 774, 635 (2017), Kang et al.
"The transverse momentum distribution of hadrons within jets"
JHEP 1711 (2017) 068, Kang et al.

**STAR Collaboration**, Phys. Rev. D 97, 032004 (2018)



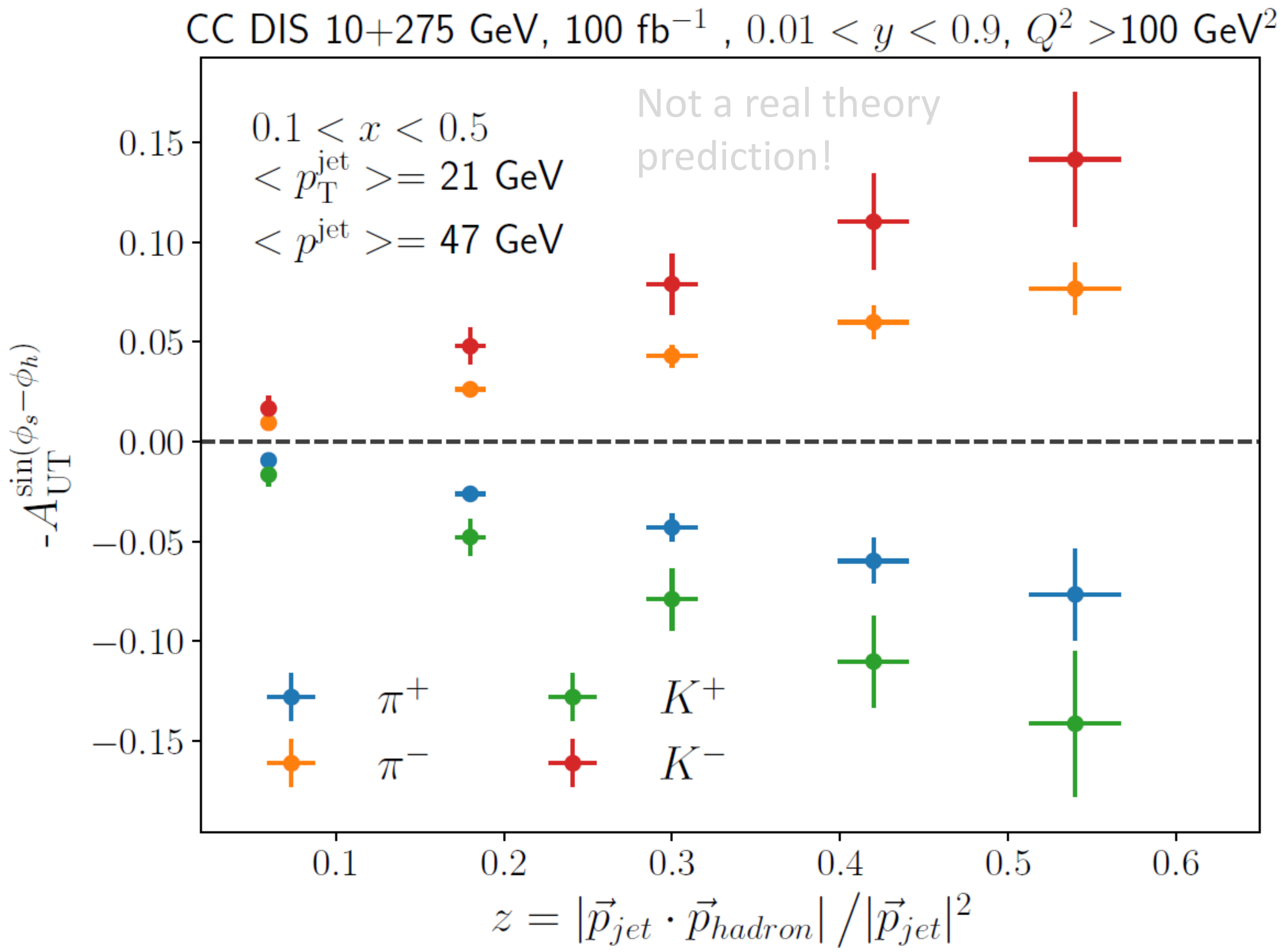

- Jet measurement crucial to factorize initial and final state TMD effects.
- At EIC, we could explore this observable with much higher precision, kinematic control. Tests of TMD evolution & universality; complements di-hadron measurements.

# Hadron-in-jet statistical projection



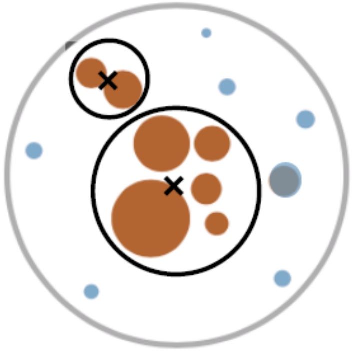

- Projections assume 100 fb-1, 70% polarization, 50% overall efficiency, sqrt(2) for statistical extraction of modulation

# u-quark Transversity in charged-current DIS




- Decent statistics, specially for pions.
- Flavor specific (u-quark for electrons; d-quark for positrons)
- Non-cancellation of u/d transversity will lead to larger asymmetries.

# Jet substructure, the key to novel TMD studies?



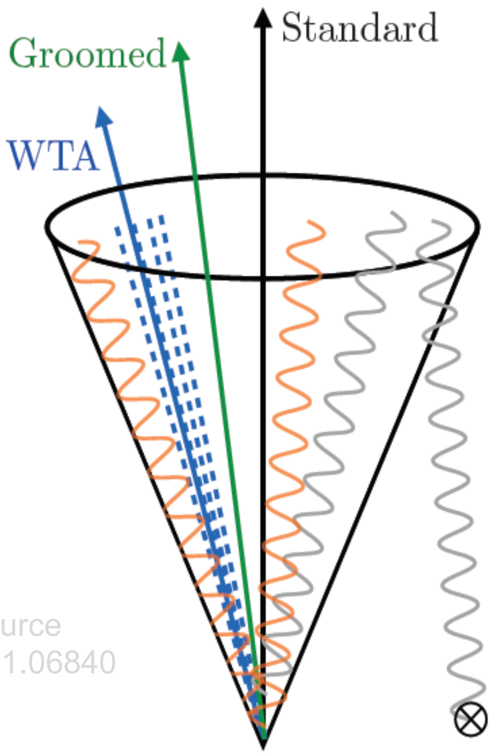
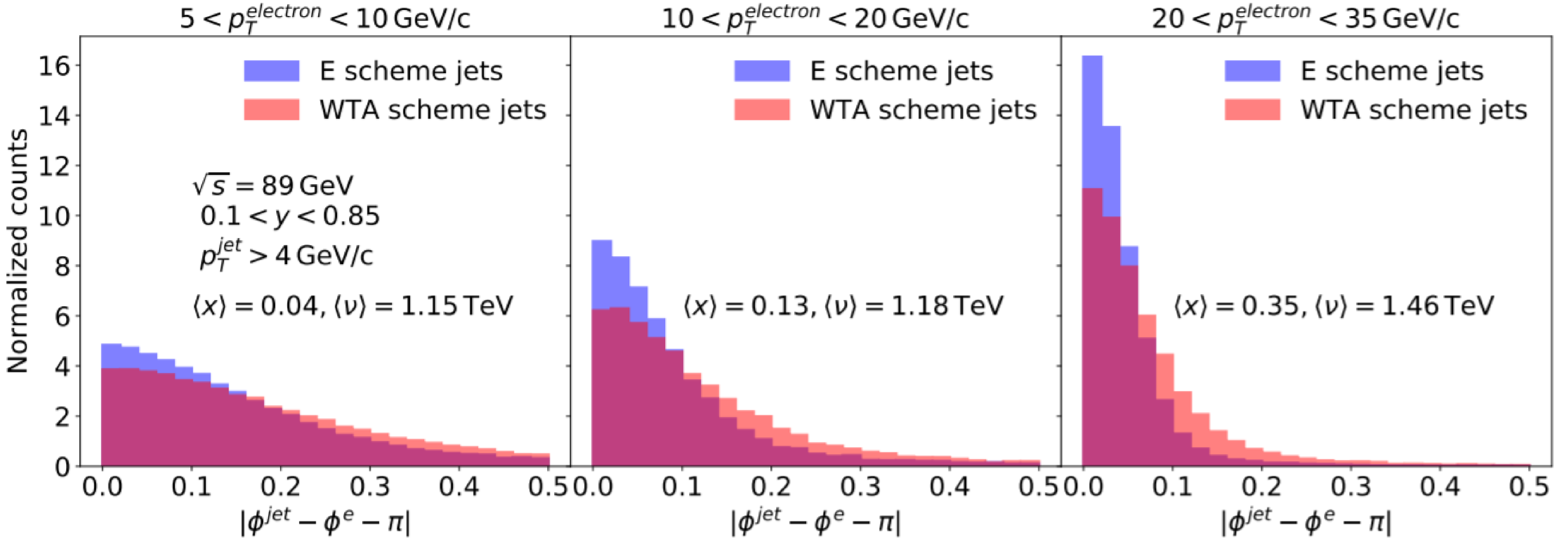



Image source
arXiv:1911.06840

- Grooming: new tool to control hadronization for better access to TMD PDFs:
  *Gutierrez-Reyes et al. JHEP 08 (2019) 161 . Yiannis Makris et al. JHEP 07 (2018) 167 .*
- “Jet axes” studies from LHC research will likely flourish at EIC to study TMD fragmentation and TMD evolution e.g. *Cal et al. arXiv:1911.06840 , Niell et al. 10.1007/JHEP04(2017)020*

# Jet axes at the EIC
## (winner-take-all vs standard)

*Arratia et al. arXiv:1912.05931*




*"The significant difference between the standard and winner-take-tall axis observed here motivates further theoretical efforts in this direction"*

# How does the topic fit in the Yellow report?

- Lepton-jet correlations, hadron-in-jet measurements, and jet substructure are new tools to extend the 3D imaging program and meet key EIC goals (including but not limited to Sivers, Transversity)
- Shared goals and complementarity with the SIDIS group.

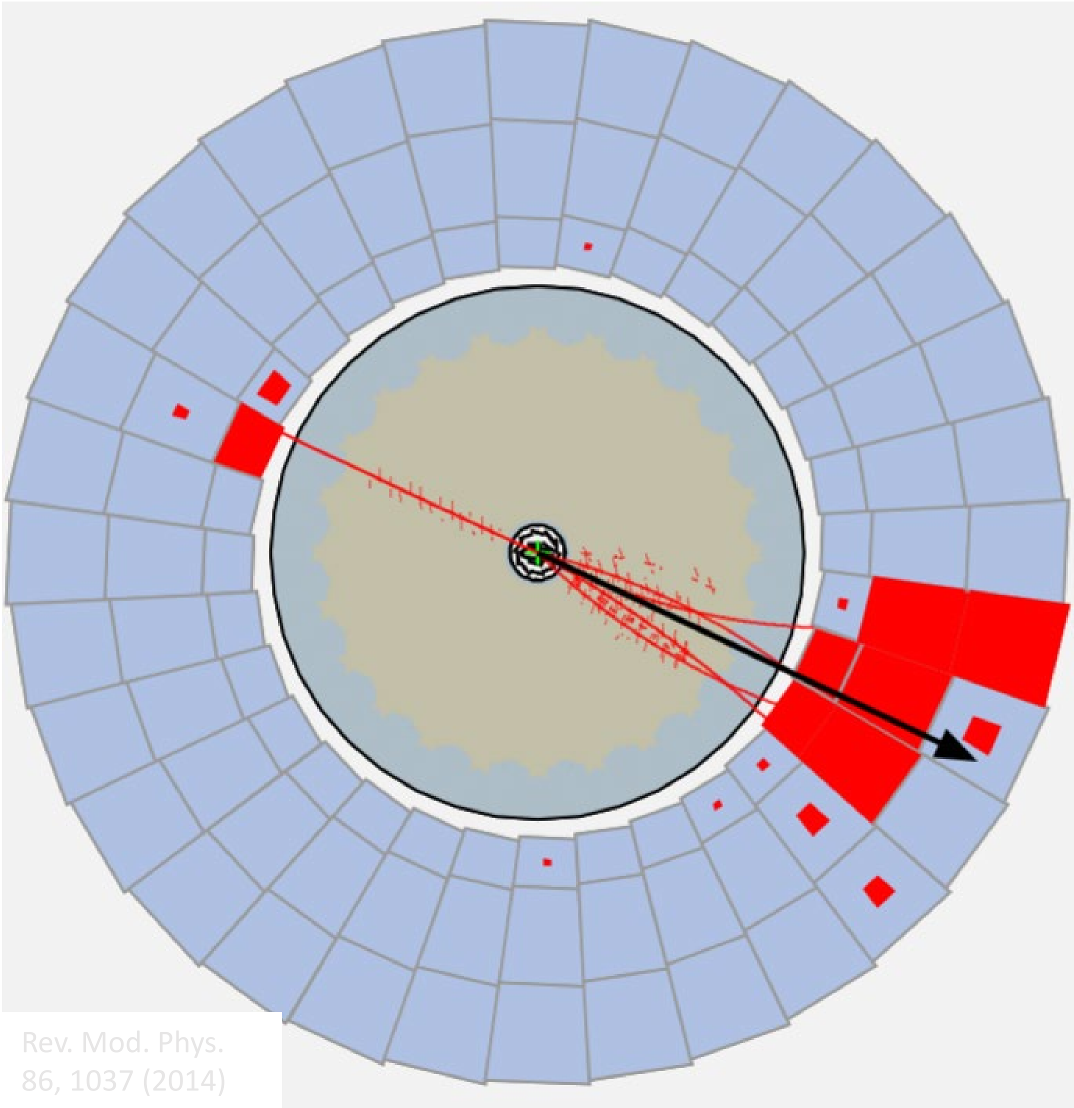
# Plans:

Now that we have identified the key channels that we want to focus on, and after having projected statistical uncertainties and kinematic reach, we plan to move on to full detector sims and focus on:

- Jet/ETmiss performance for azimuthal correlations.
- PID requirements for hadron-in-jet (common with SIDIS).
- Studying jet potential of lower center-of-mass energies

# Summary

- Studies with jets at EIC will be unlike any previous collider (even HERA!).
  Key measurements include:
  - lepton-jet correlations
    (**quark Sivers, quark g1T** et al.),
  - jet fragmentation
    (**quark Transversity, Collins** et al.)
  - jet substructure (**new!**)
- Jets for 3D imaging is an excellent opportunity for the convergence of the collider and fixed-target community at the EIC.



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


Just before the Berkeley YR meeting,

Topics:

- Jet observables, advantages, and opportunities for EIC
- Novel observables via jet substructure
- TMD and SCET formalism for jets and substructure.
- 3D and 5D imaging with exclusive jets (GPDs and Wigner functions)
- Connections to Lattice QCD
- Detector requirements for the EIC

- BACKUP

# Simulation parameters

- Pythia8, unpolarized e-p DIS,
  DIRE parton shower (angular ordered)
- $E^{proton} = 275$ GeV, $E^{electron} = 10$ GeV
- Event cuts:

For NC DIS: $0.1 < y < 0.85$, $Q^2 > 25$ GeV$^2$

For CC DIS: $0.01 < y < 0.90$, $Q^2 > 100$ 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, ctau> 10mm exclude neutrinos and scattered electron.
- **No radiative corrections yet.**
- **No detector response yet.**

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

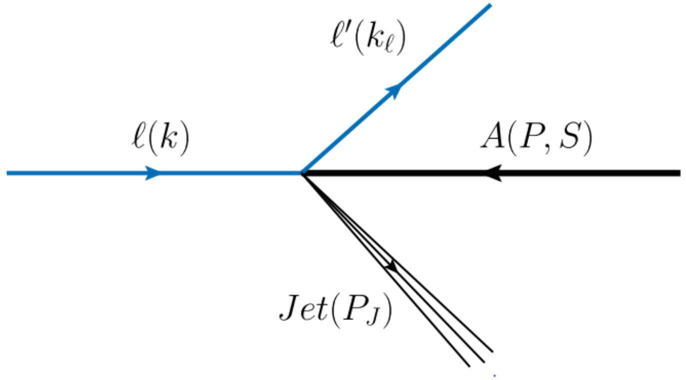



FIG. 1. Lepton-jet correlation for the tomography of the nucleon or nucleus at the EIC. *Liu et al. PRL 122 192003*

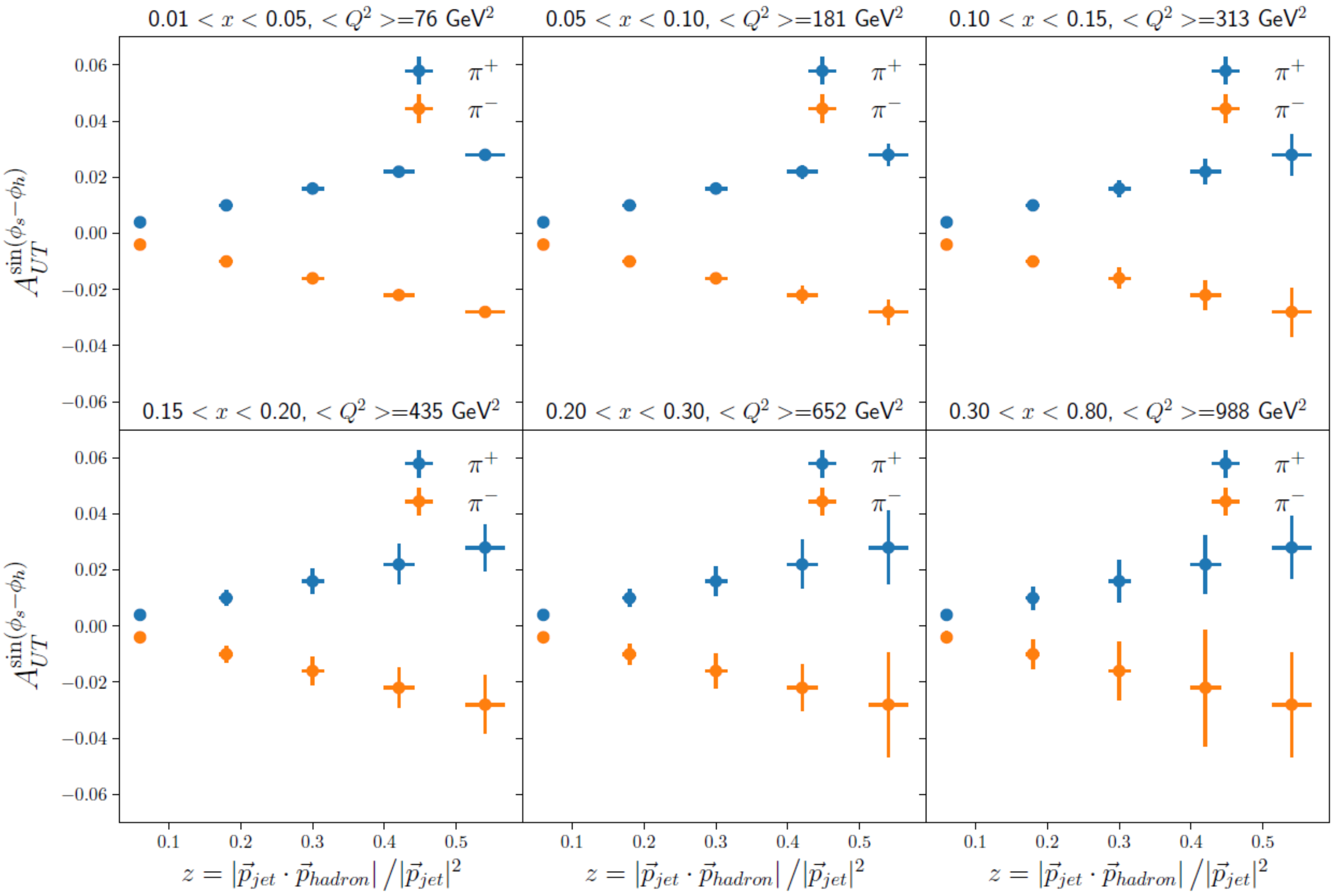
$$Q^2 = -\hat{t} = \sqrt{s}\, p_T^e\, e^{-y_e}$$

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

# Why bother with jets?

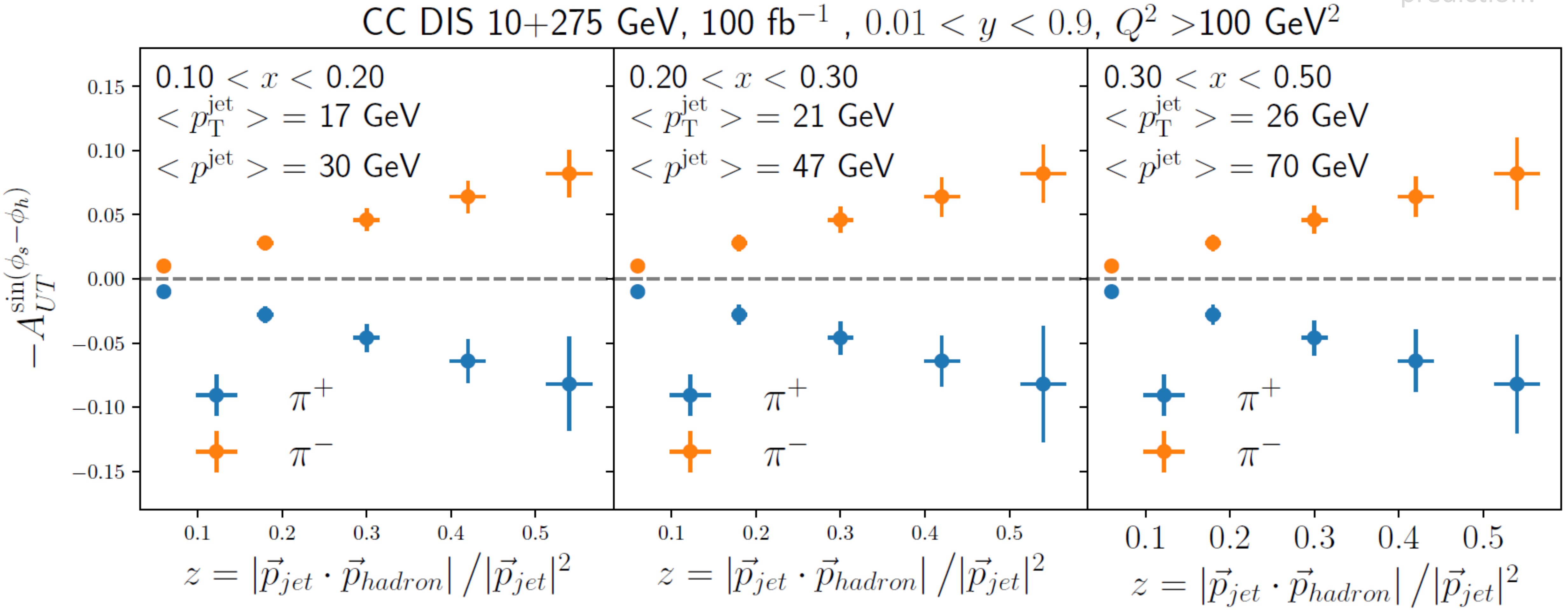
- Complements traditional SIDIS with hadrons and di-hadrons.
- Allows us to test TMD universality and factorization.
- Access to TMD PDFs without convolution with FFs, and viceversa.
- Better proxies for parton kinematics than single-hadrons,
  which suppress “dilution effect” of asymmetries due to hadronization.
- Allows us to reach scales beyond those of single-hadrons (i.e. higher pT, x)
- Jet substructure encodes rich QCD dynamics.
  This will be a new tool for TMD studies.
- Because jets are a qualitatively new tool that the collider era will bring us.

# Covering the entire x-range relevant for transversity

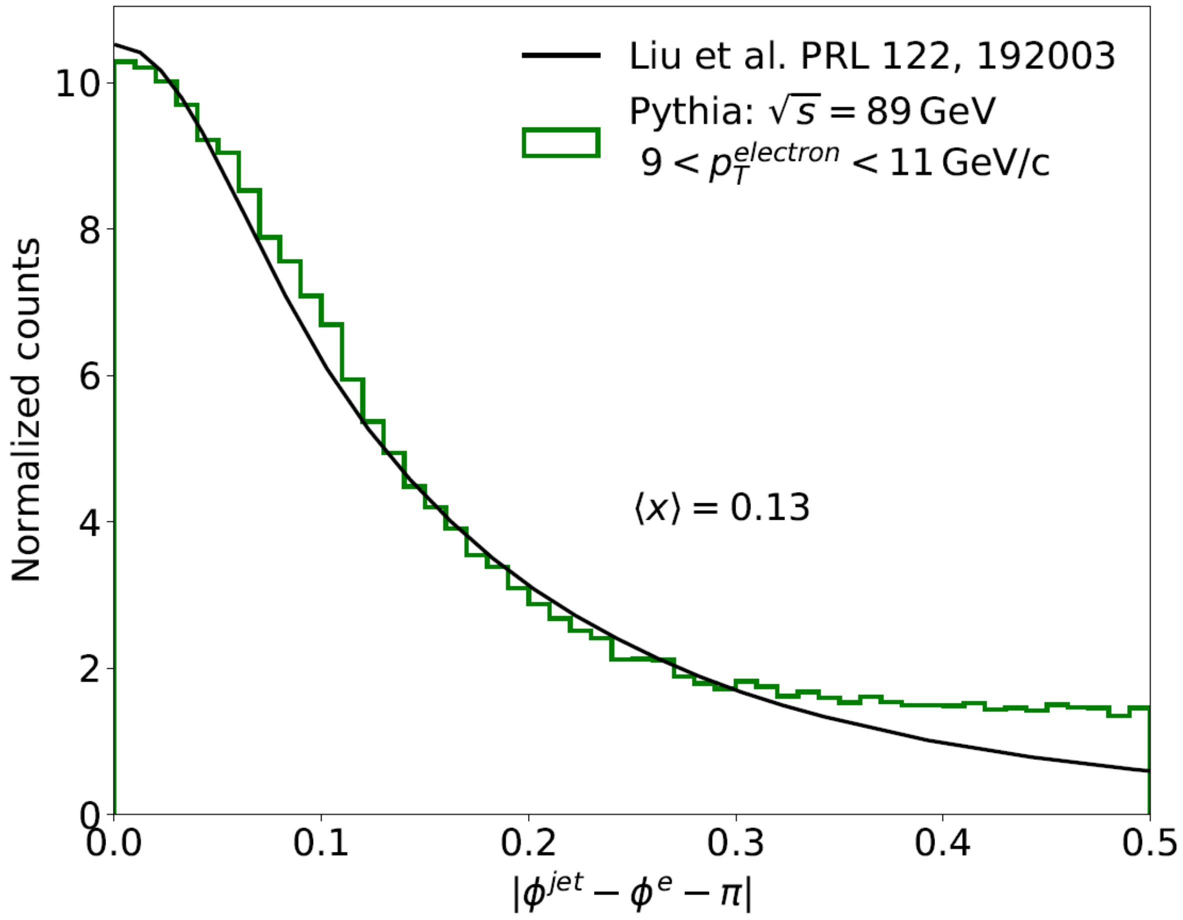


# u-quark Transversity

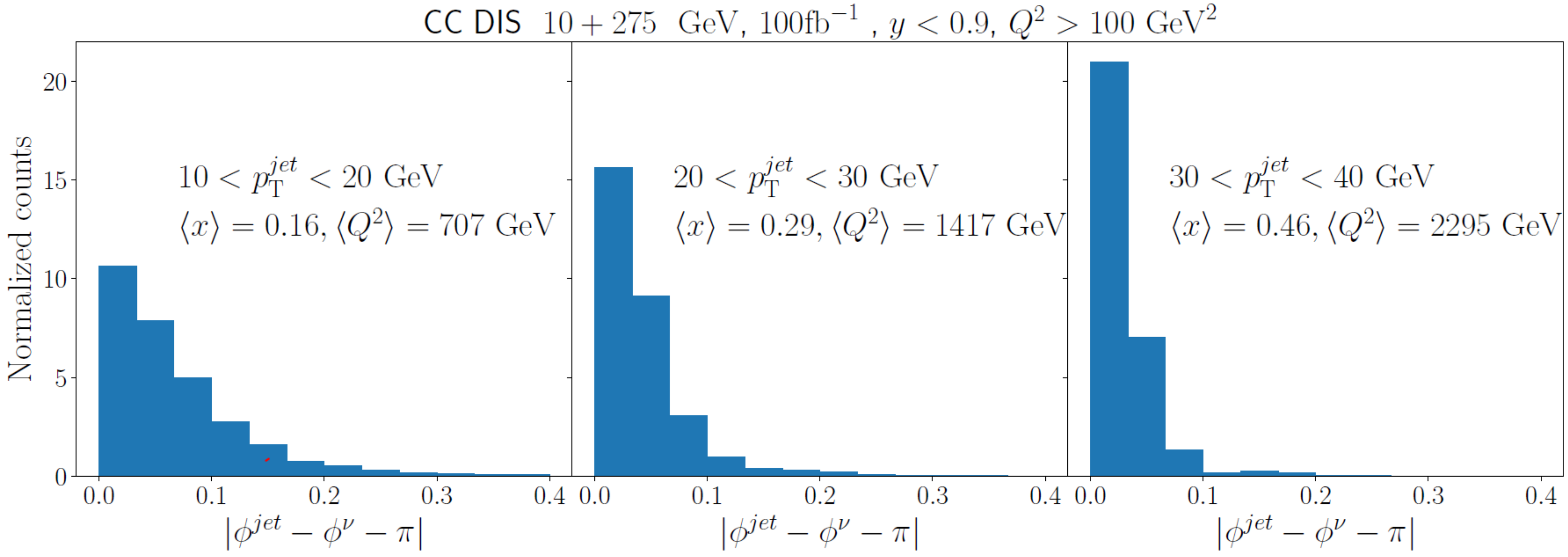
Not a real theory prediction!



# Pythia8 agrees with analytic calculation



# Neutrino-jet correlation

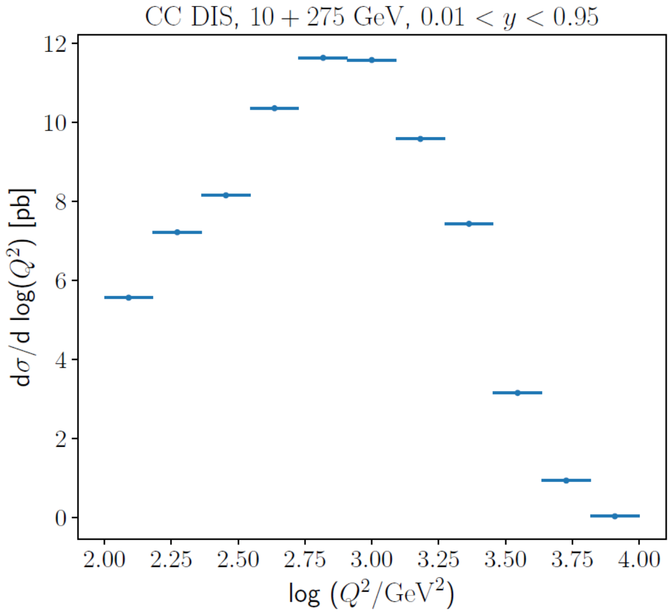


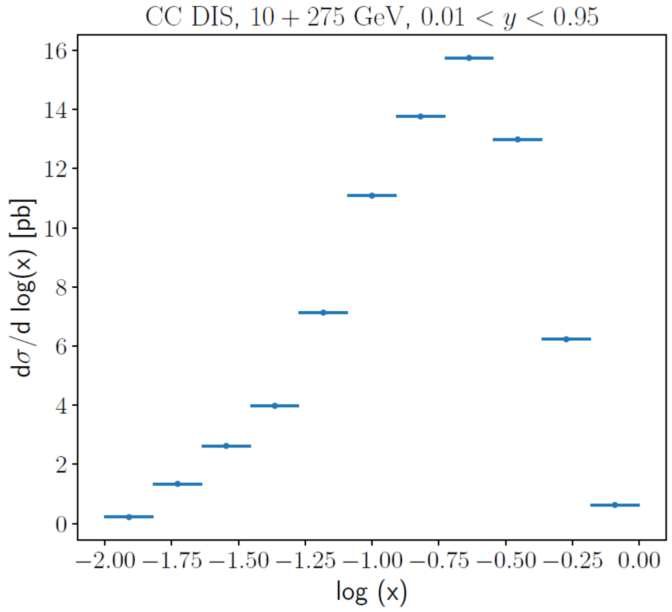
# Missing energy resolution and absolute scale are also relevant for measuring kinematics:

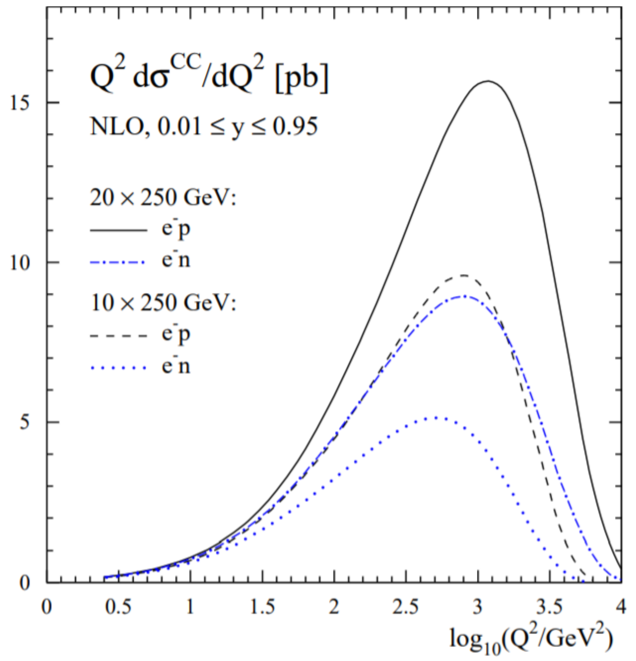
publication [8]. The kinematic variables $Q^2$, the inelasticity, $y$, and $x$ were estimated using the method of Jacquet-Blondel [23], which uses the information from the hadronic energy flow of the event, and corrected for detector effects as described elsewhere [9, 24]. These estimators were reconstructed as:

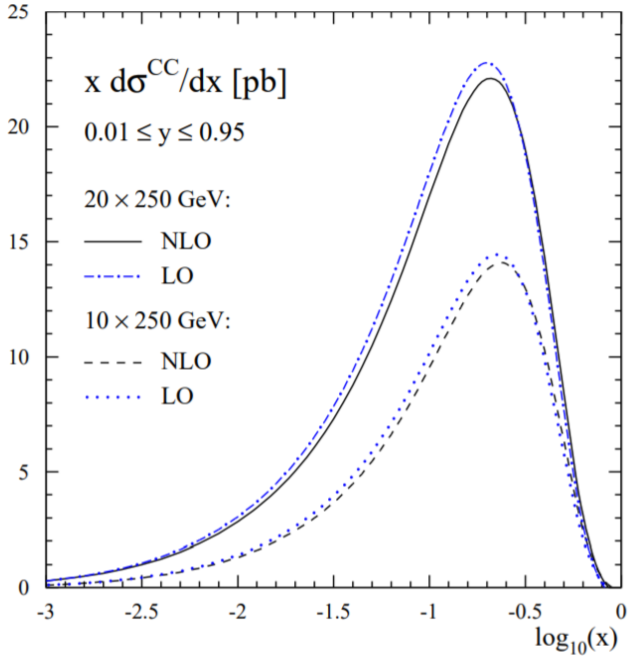
$$y_{\mathrm{JB}} = \frac{\sum_i (E_i - p_{Z,i})}{2\ E_e}, \qquad Q^2_{\mathrm{JB}} = \frac{(p_T^{\mathrm{miss}})^2}{1 - y_{\mathrm{JB}}} \qquad \text{and} \qquad x_{\mathrm{JB}} = \frac{Q^2_{\mathrm{JB}}}{s\ y_{\mathrm{JB}}},$$

- Neutrino energy (missing energy) reconstruction is crucial for Jacquet-Blondel method, which is crucial for inclusive DIS.
- Missing energy performance ~ jet performance in hermetic detector.
- Neutrino-jet azimuthal correlation “like dijet correlation”



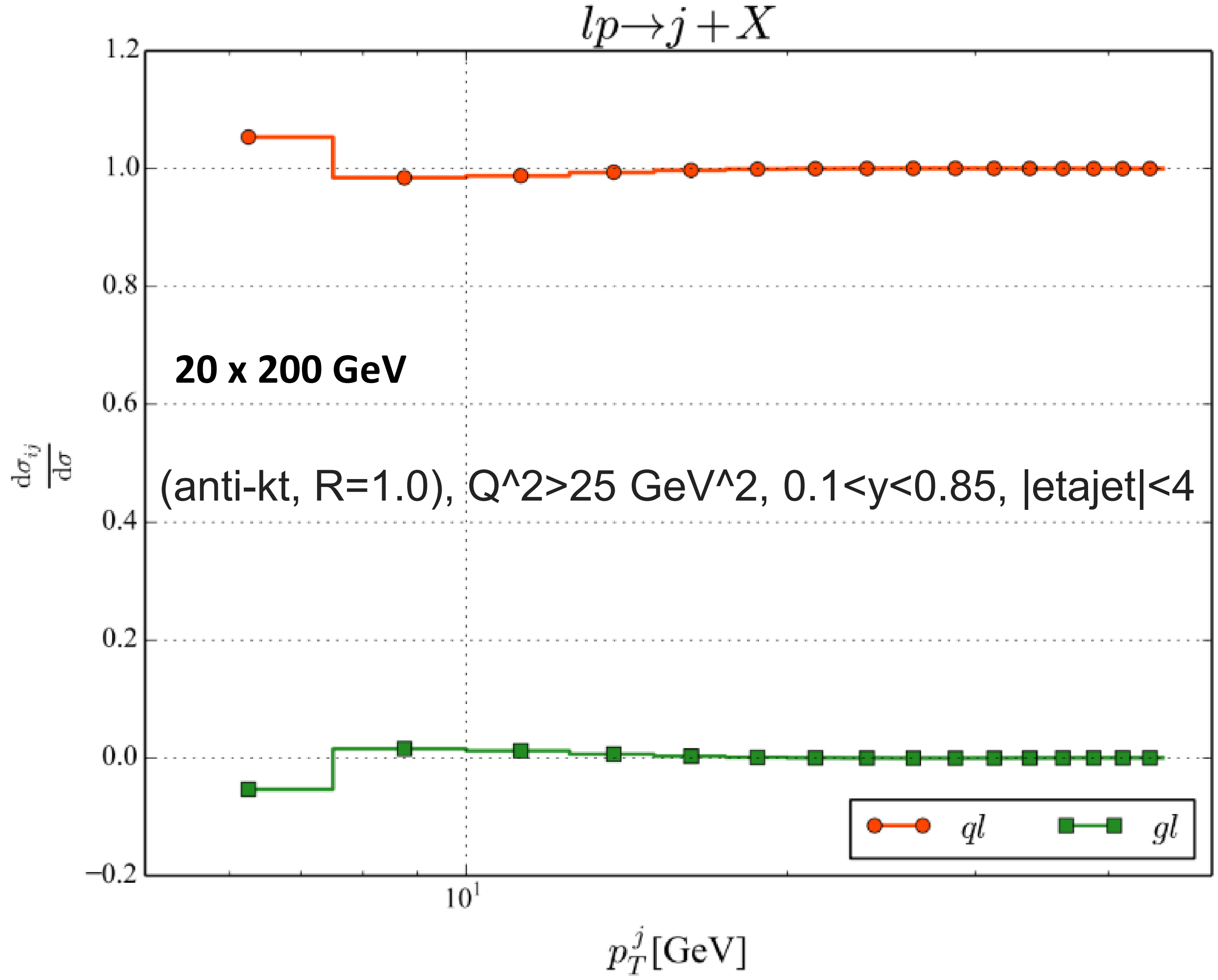



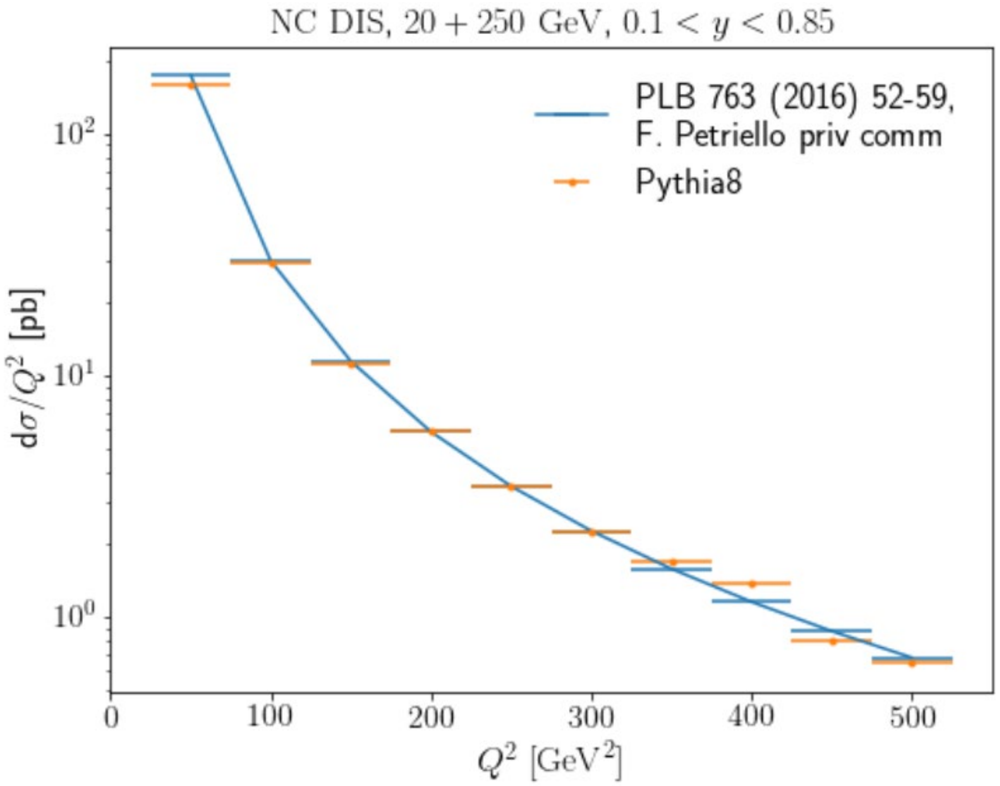




- Pythia (LO) very similar to calculations
- NLO effects are pretty small.
- Inclusive cross-section for Q2>100 GeV2 is 14.4 pb, or 1.4 M events in 100 fb-1.

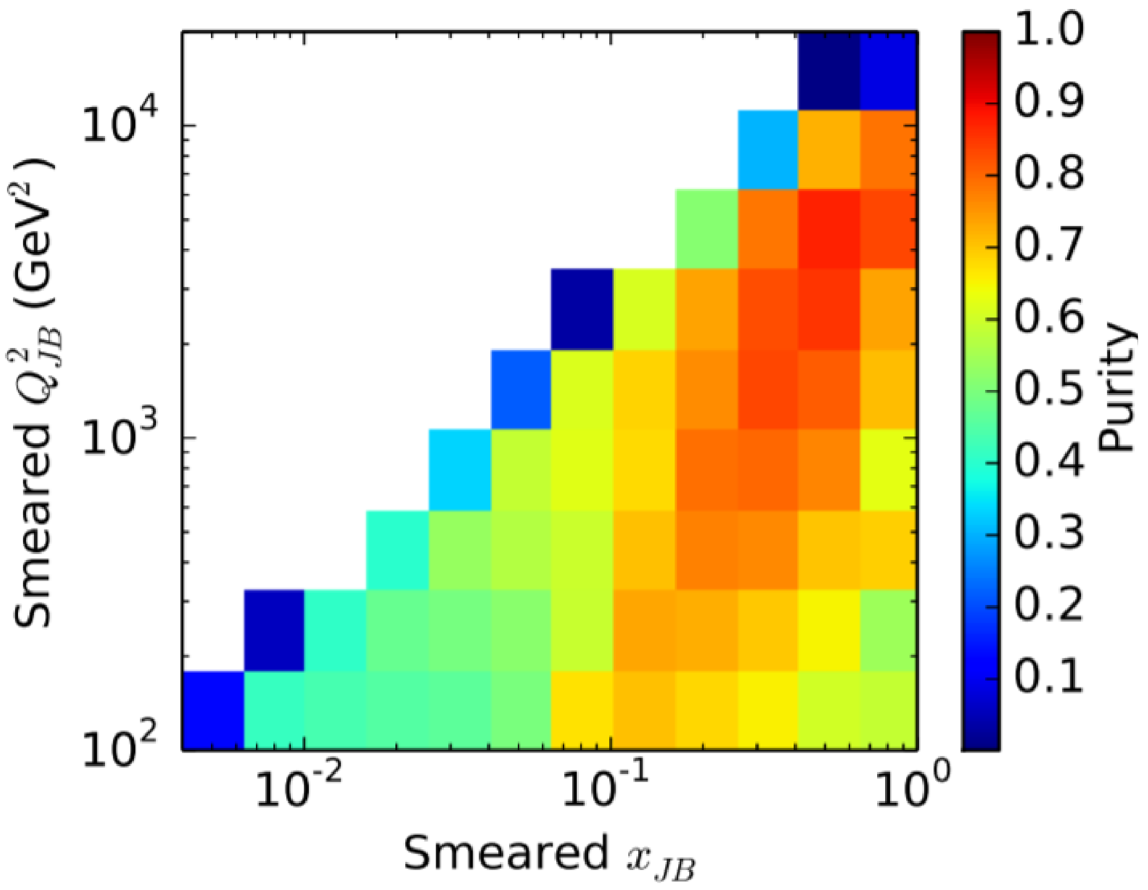
# Partonic channel, (NNLO calculation by F. Petriello)

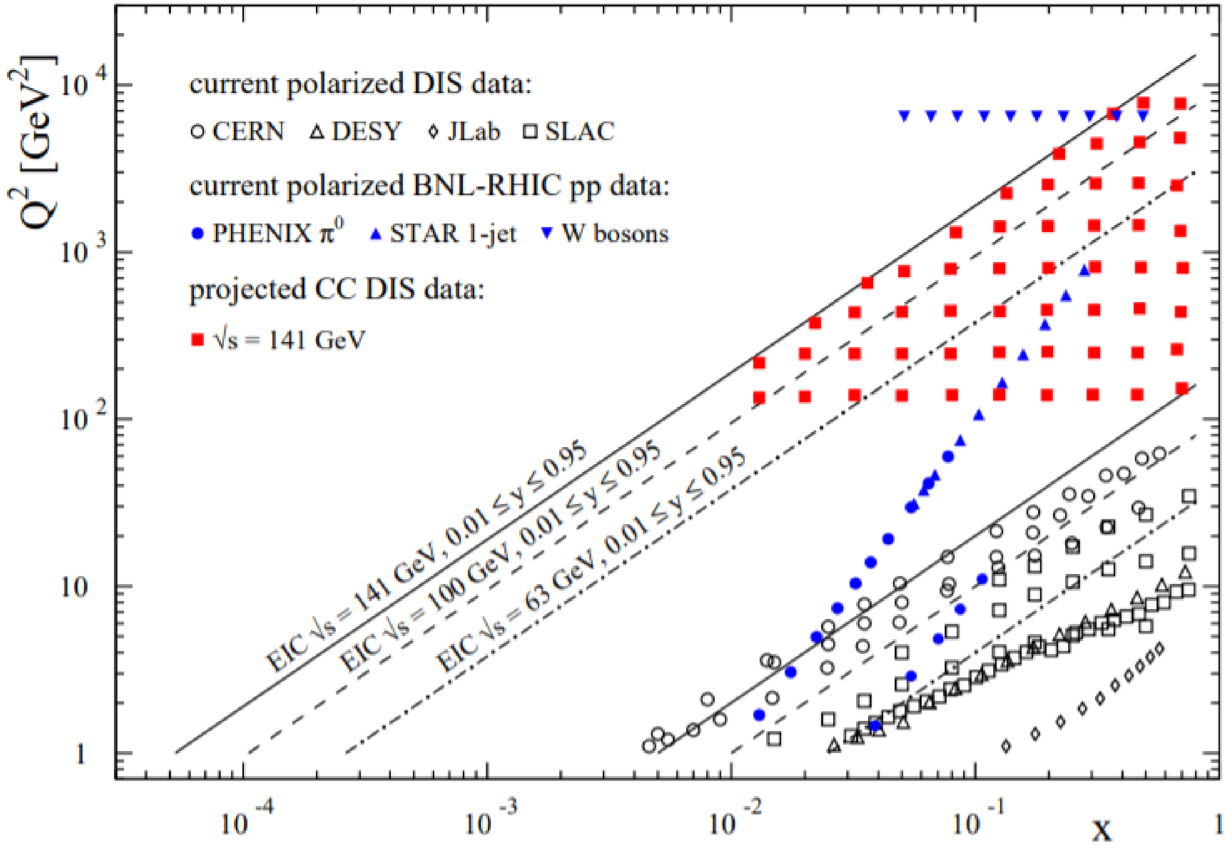


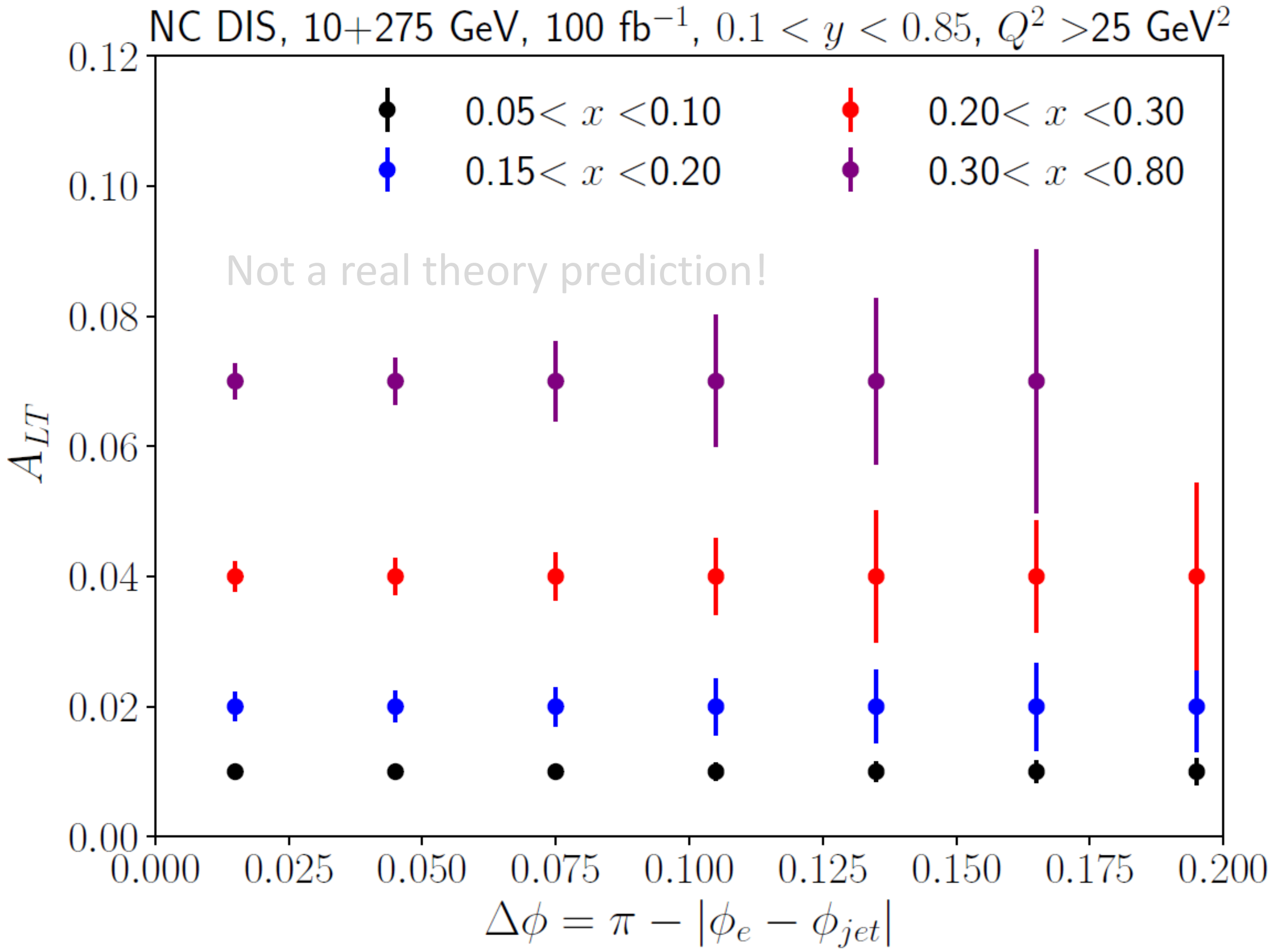
# Study of performance of Jacquet Blondet method to constrain kinematics: Aschenauer et al. Phys. Rev. D 88, 114025 (2013)

$$y_{\mathrm{JB}} = \frac{\sum_i (E_i - p_{Z,i})}{2\ E_e}, \qquad Q^2_{\mathrm{JB}} = \frac{(p_T^{\mathrm{miss}})^2}{1 - y_{\mathrm{JB}}} \qquad \text{and} \qquad x_{\mathrm{JB}} = \frac{Q^2_{\mathrm{JB}}}{s\ y_{\mathrm{JB}}},$$



# With longitudinal electron polarization, access to the “worm gear” **g1T**




- Statistical projections assume
  100 fb-1,
  70% polarization for both beams,
  50% overall efficiency.
- Most systematic cancels in the ratio.
- Need enough resolution to bin in azimuthal angle (kT dependence)
- Asymmetries expected to be larger, due to less cancelation of u and d distributions

# HERA experiments did require high $p_T$ in the Breit Frame
# We need an orthogonal approach at EIC

**~ 0 $p_T$ in Breit frame**
**Background**


**High $p_T$ in Breit frame**
**Signal.**

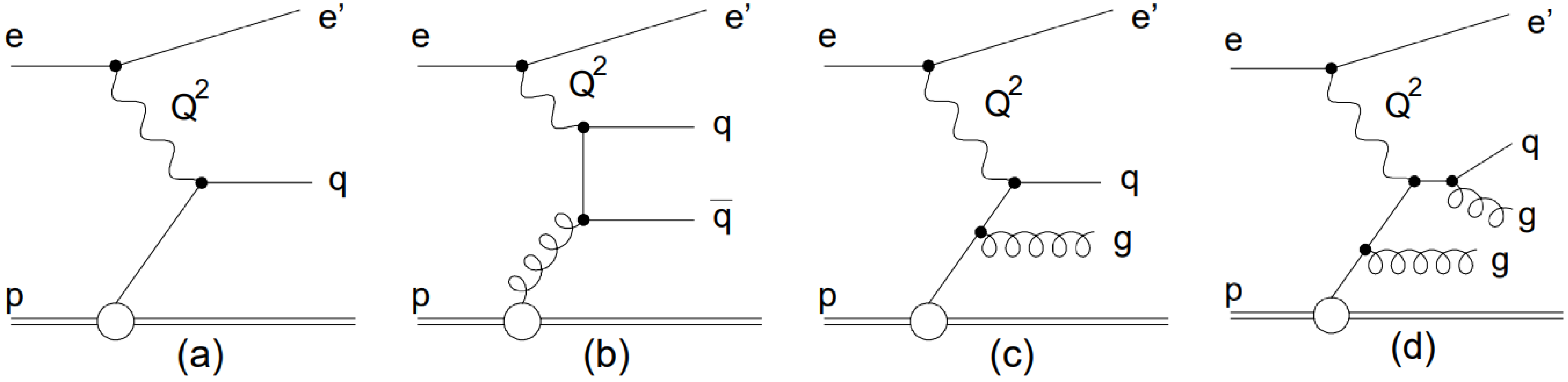
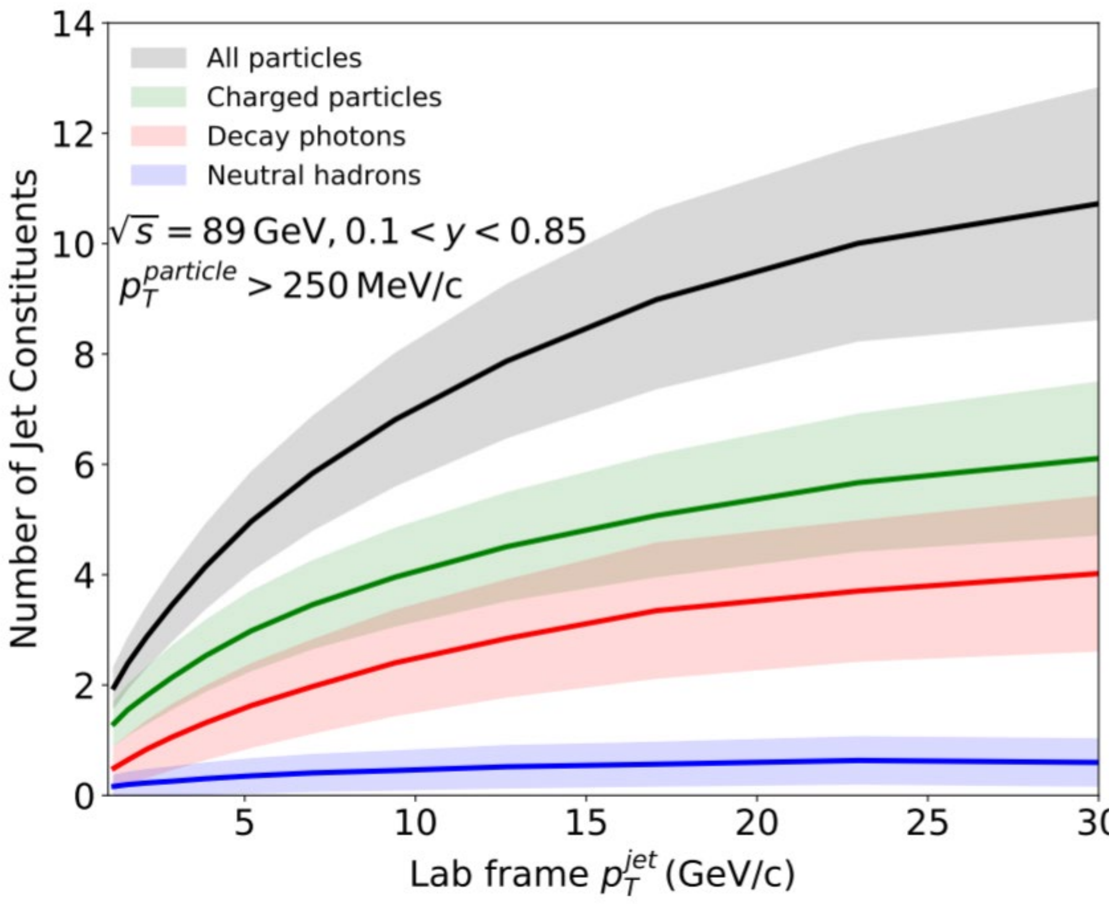
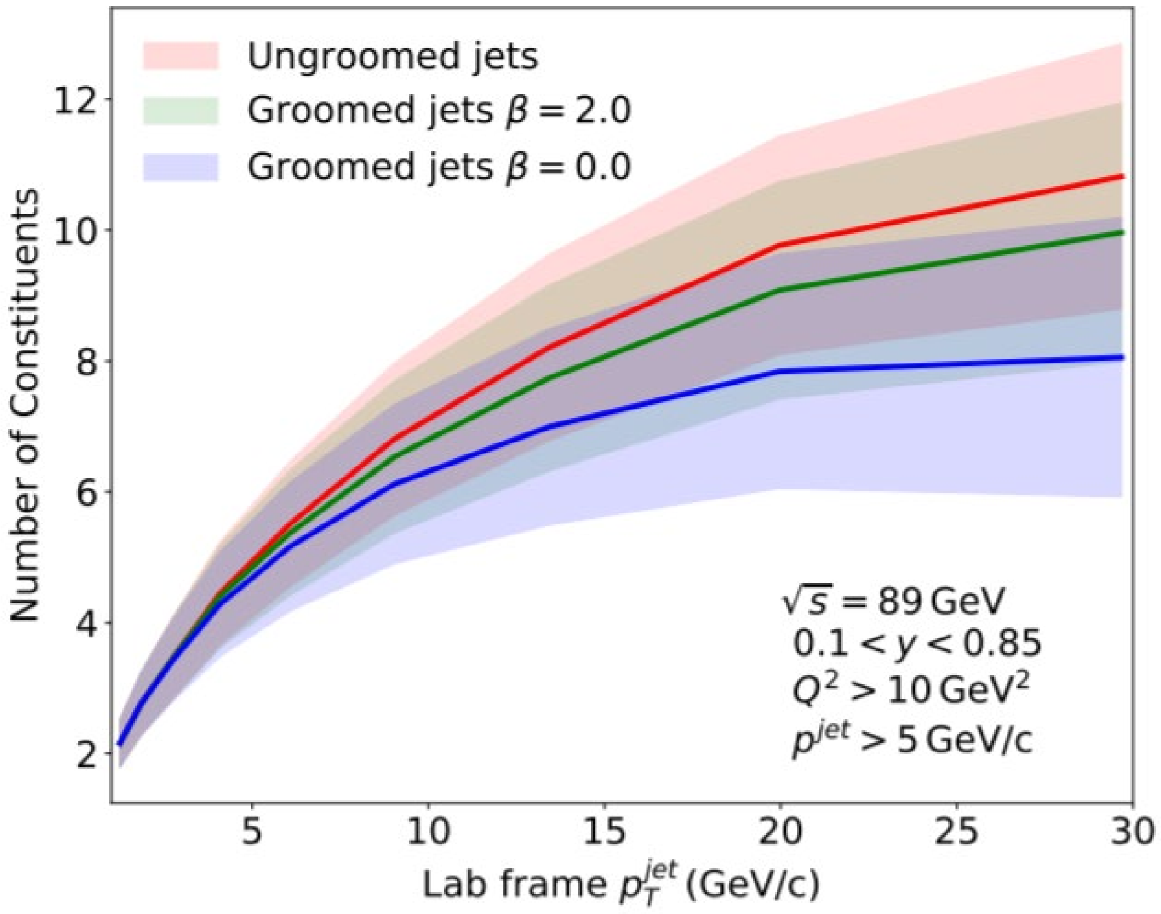



Figure 1: Deep-inelastic *ep* scattering at different orders in $\alpha_s$: (a) Born contribution to inclusive NC DIS ($\mathcal{O}(\alpha_{em}^2)$), (b) photon-gluon fusion ($\mathcal{O}(\alpha_{em}^2\alpha_s)$), (c) QCD Compton scattering ($\mathcal{O}(\alpha_{em}^2\alpha_s)$) and (d) a trijet process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

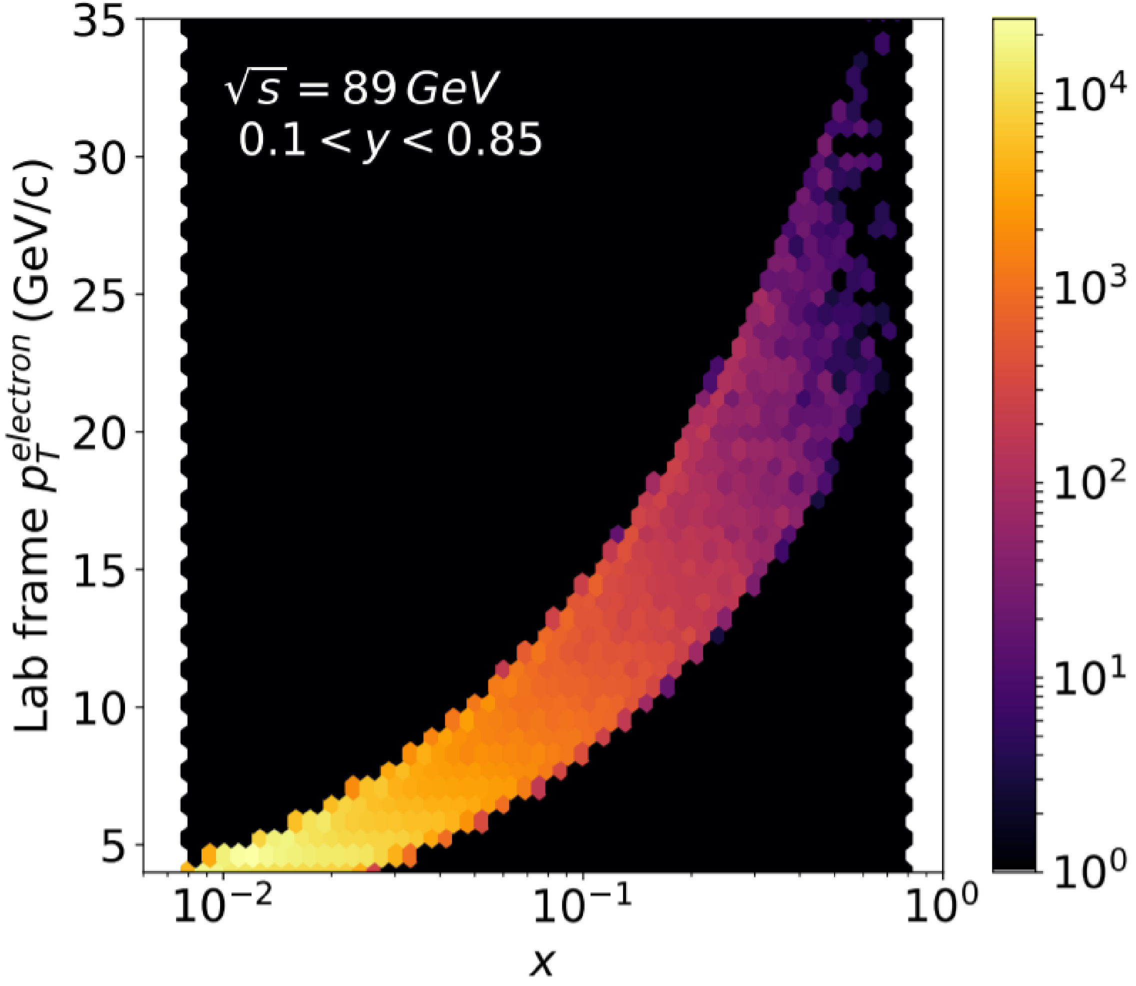
# Number of constituents *Arratia et al. arXiv:1912.05931*

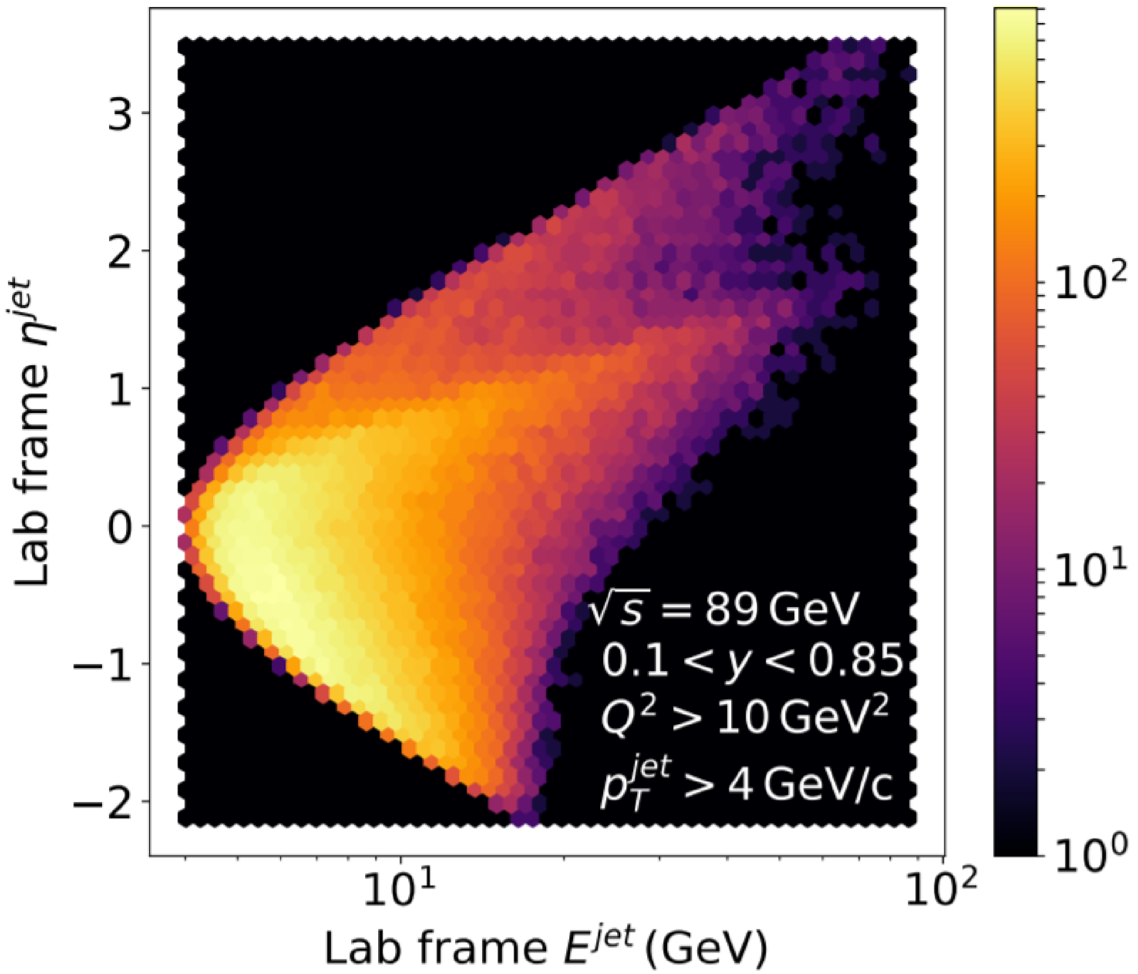


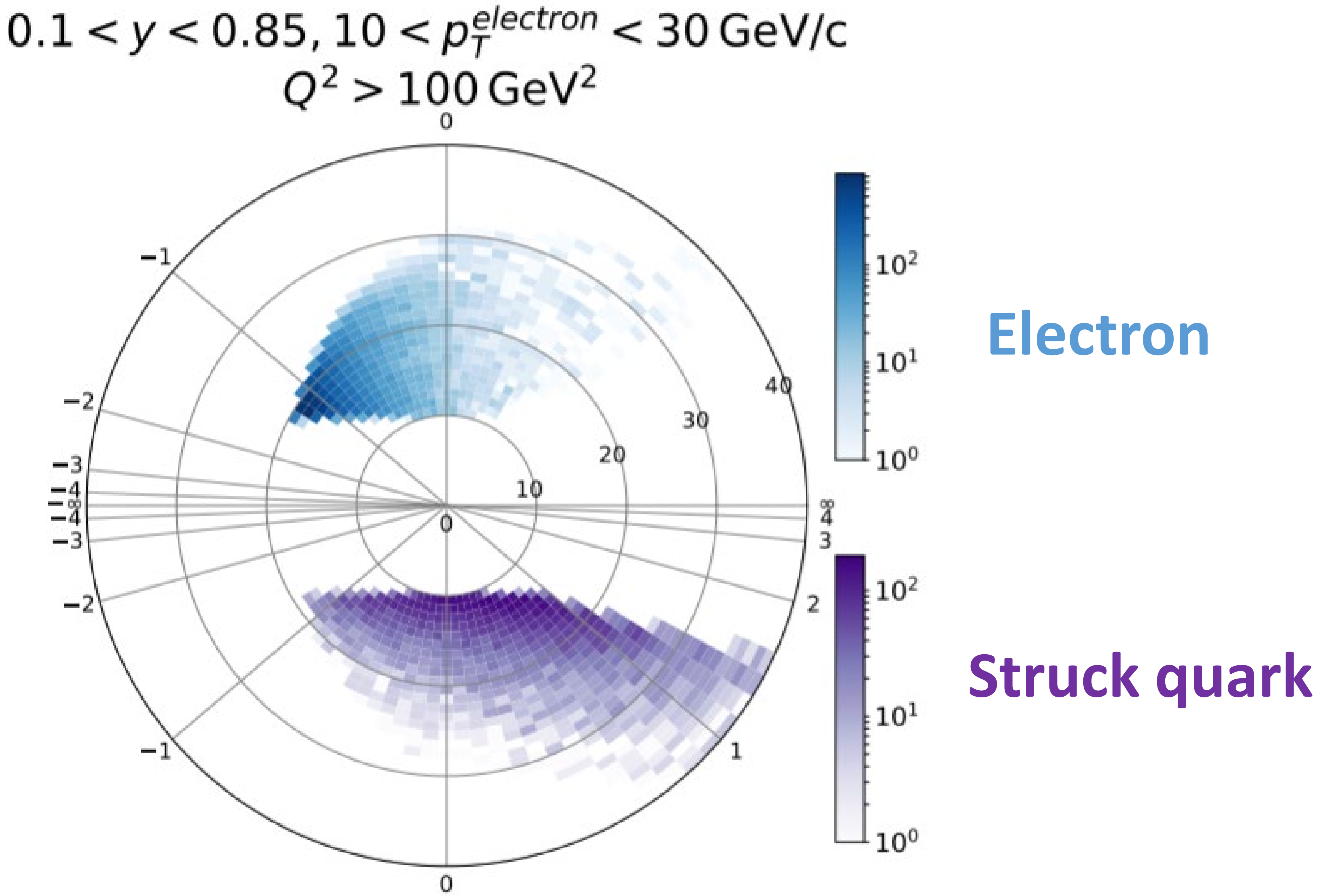
# Kinematics

*Arratia et al. arXiv:1912.05931*

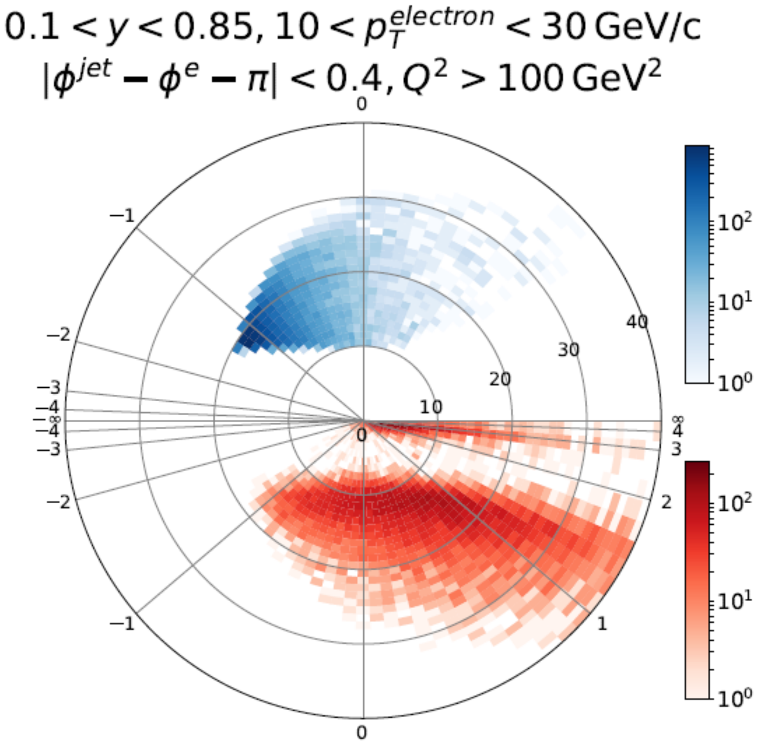


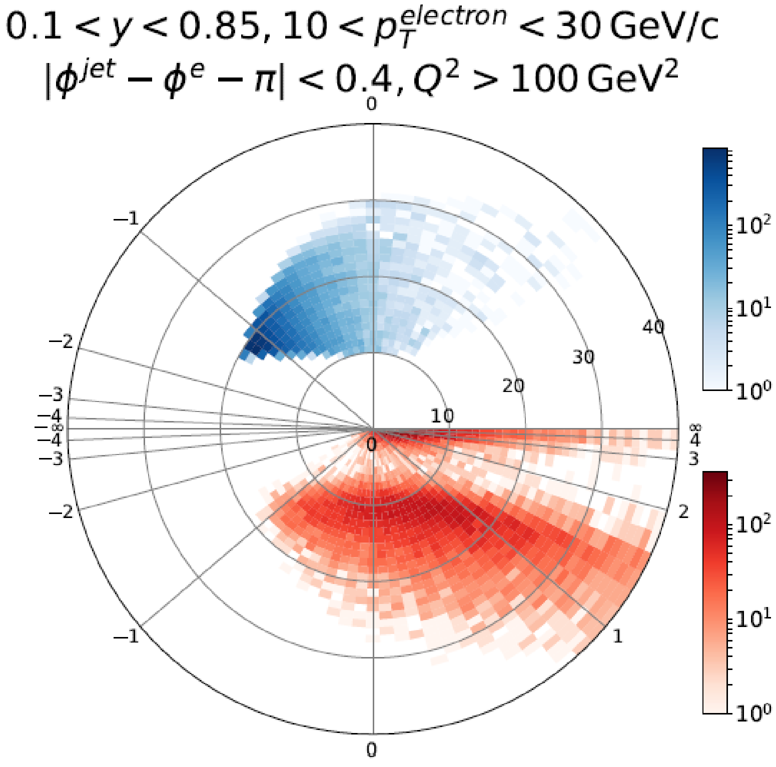
- Radial: momentum
- Angle: polar angle (eta)



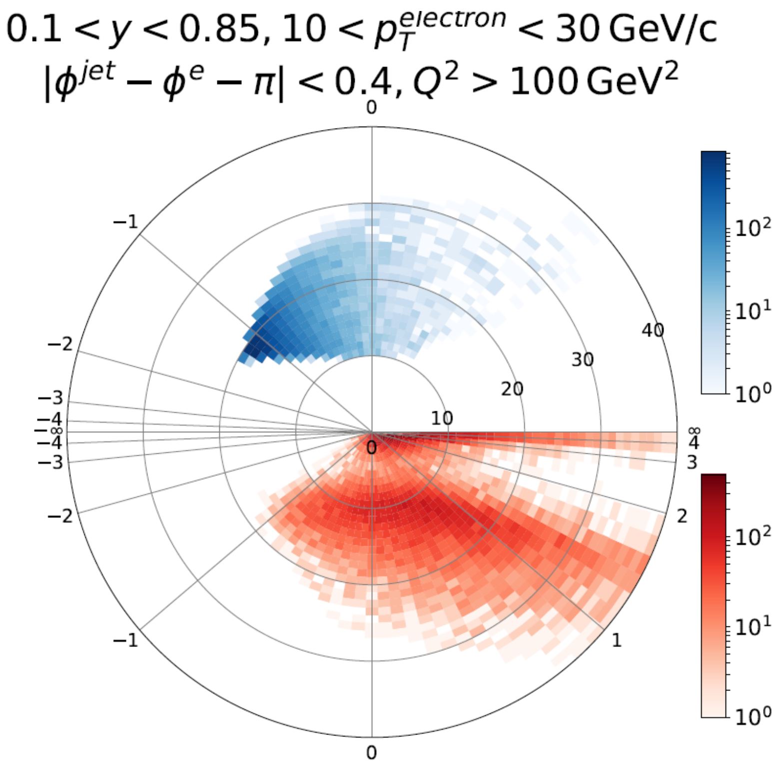
# R=1.0




# R=0.7

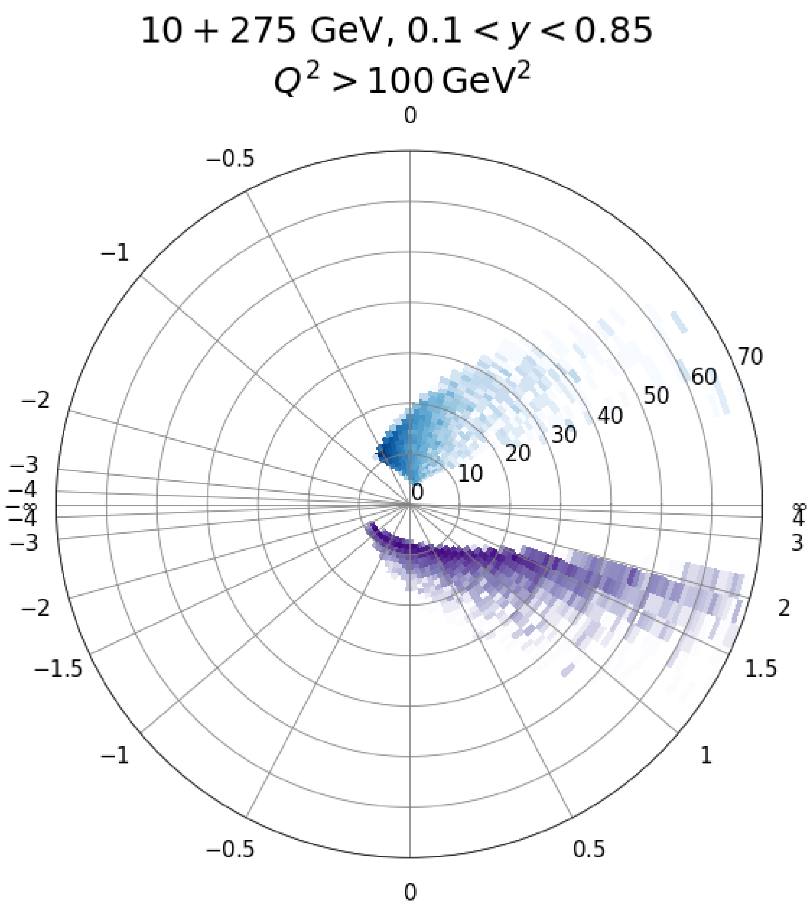



# R=0.5

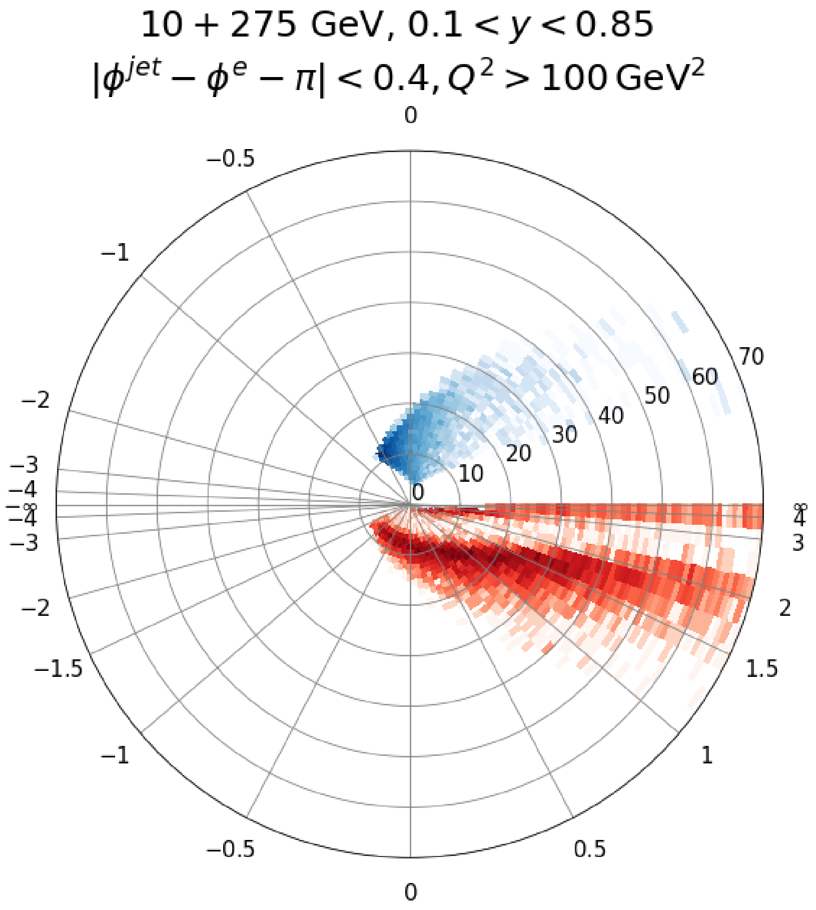



- Smaller R leads to larger ambiguity.
- Note that at HERA the use of R=1.0 lead to percent-level “hadronization correction”

# Struck-quark and jet kinematics

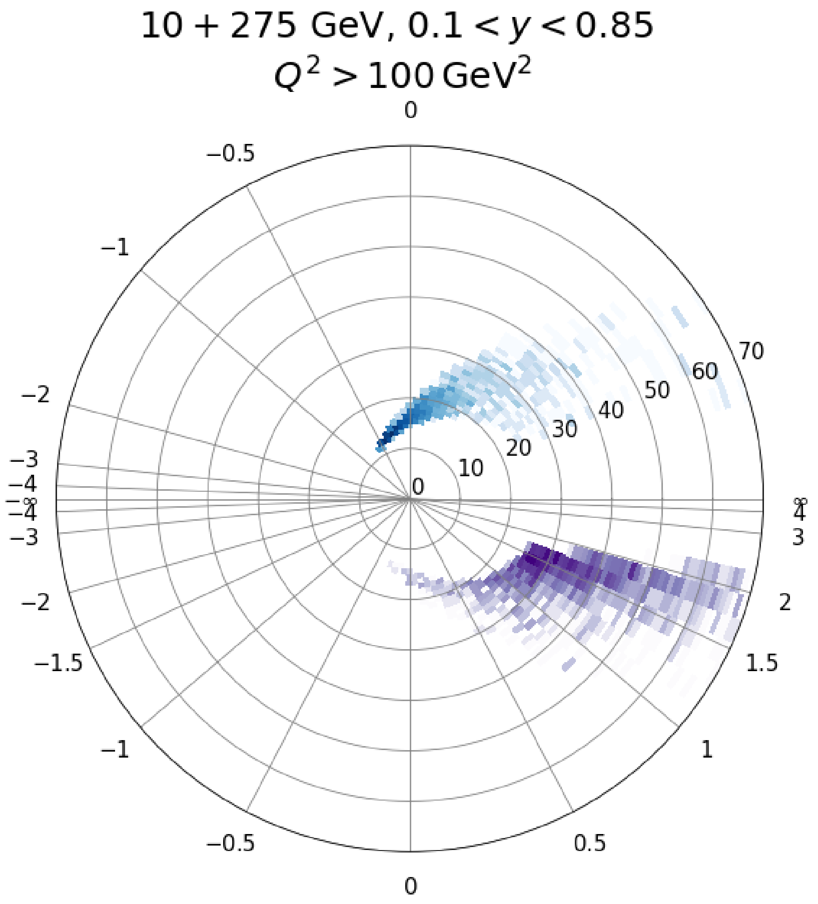


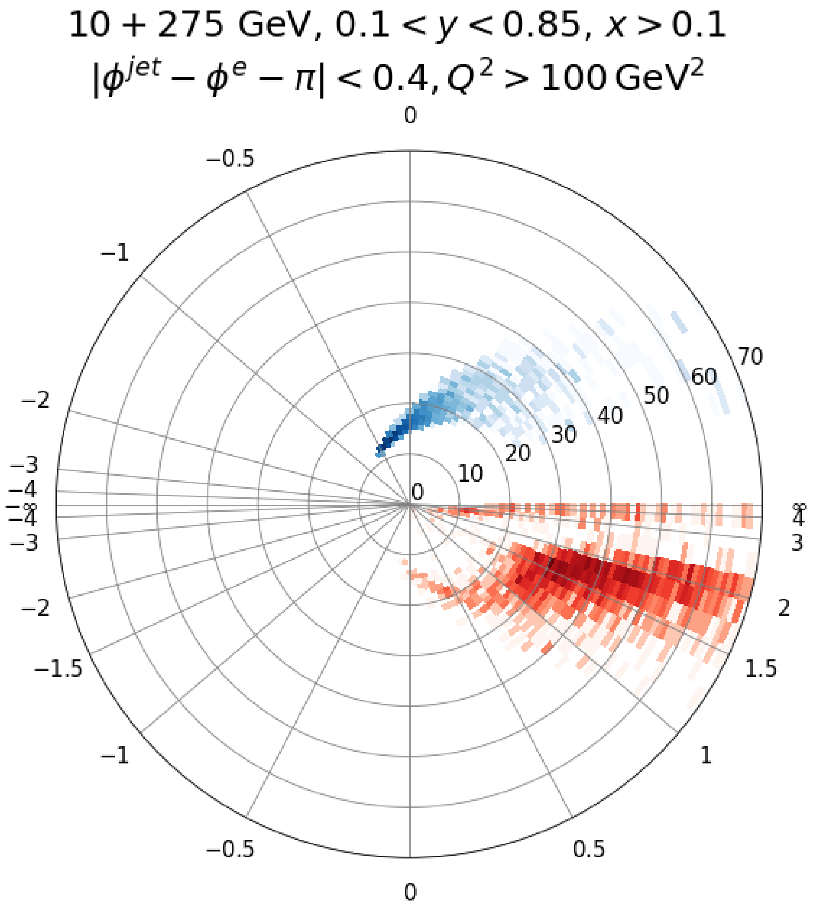

Struck quark




Jets, R=1.0

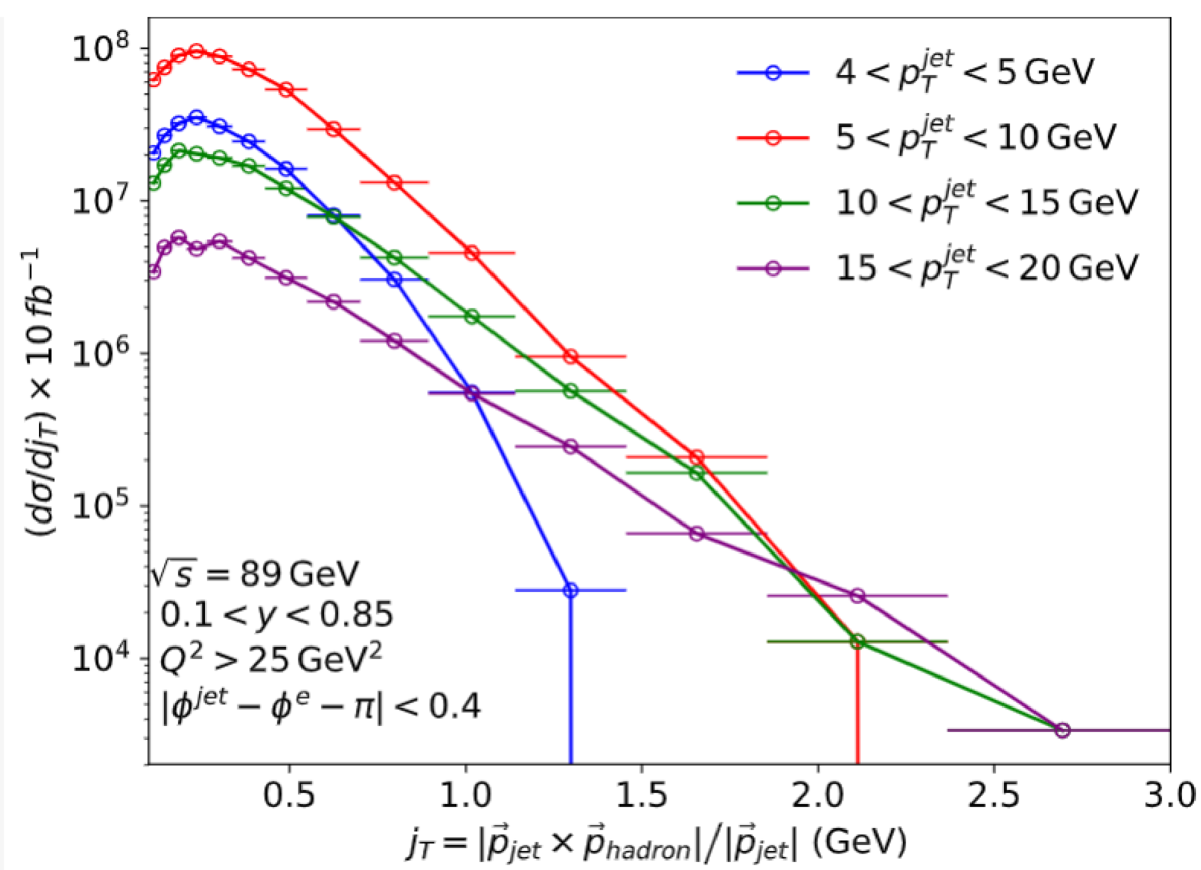
# Focus on the large x

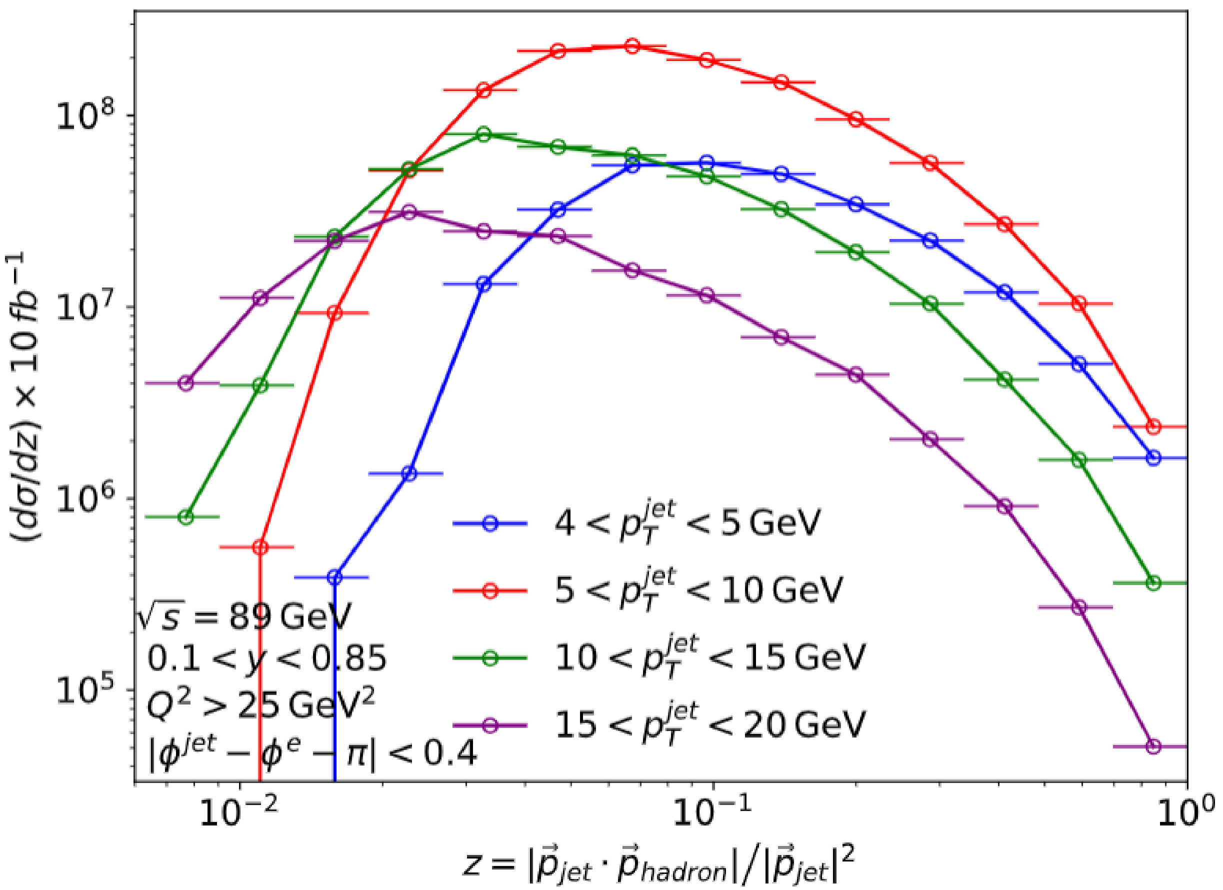


# Hadrons-in jet @ EIC

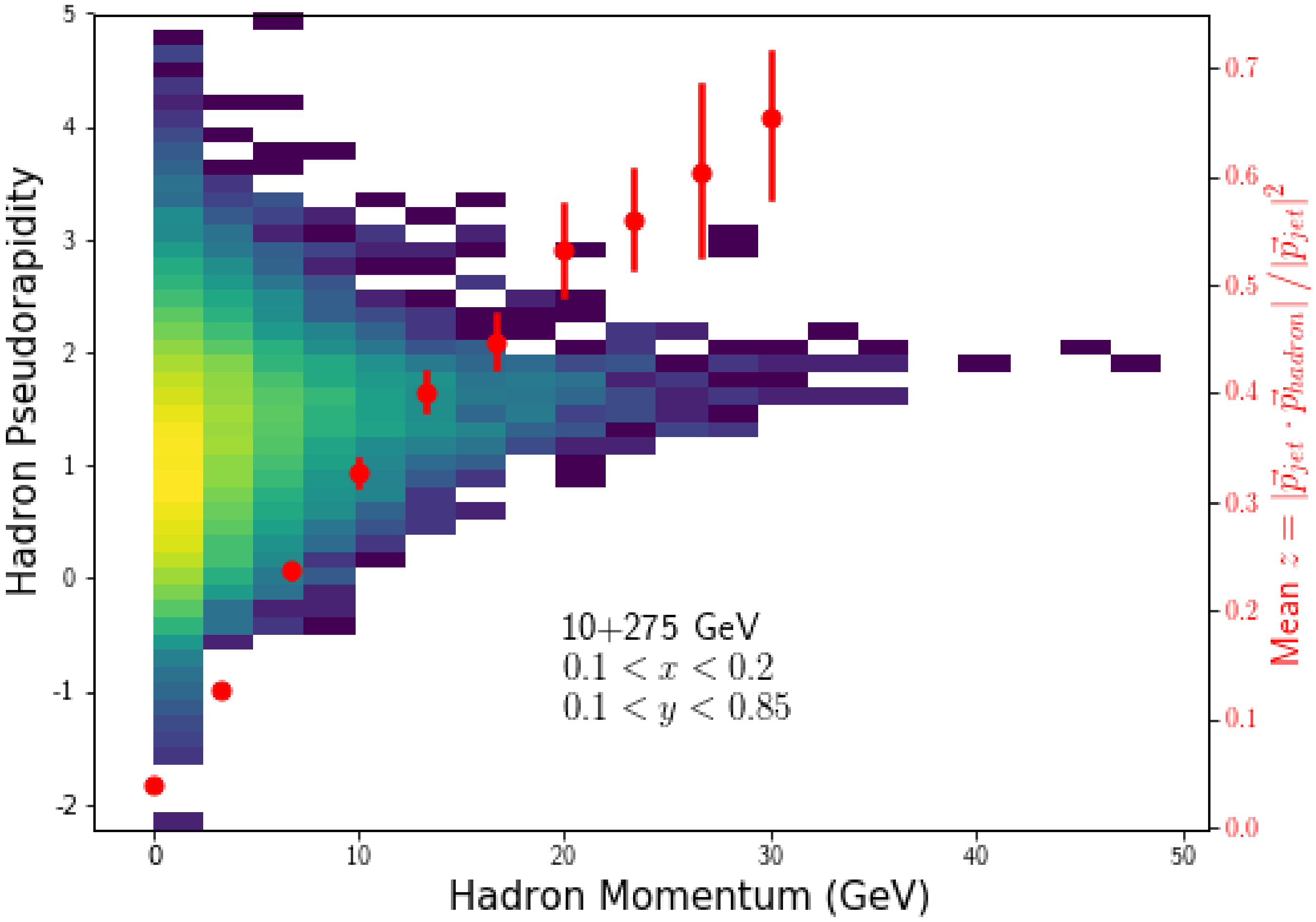
Plot by Youqi Song




- Plenty of statistics!

# PID requirements
## (very similar if not the same as for SIDIS)




- <u>Mandatory</u> for this measurement. "Charged hadron" would not work.
- Charged pions separation from Kaons and protons up to ~30 GeV
- EMCAL granularity for pi0.