# Jets for 3D imaging

Miguel Arratia

UNIVERSITY OF CALIFORNIA
UC RIVERSIDE

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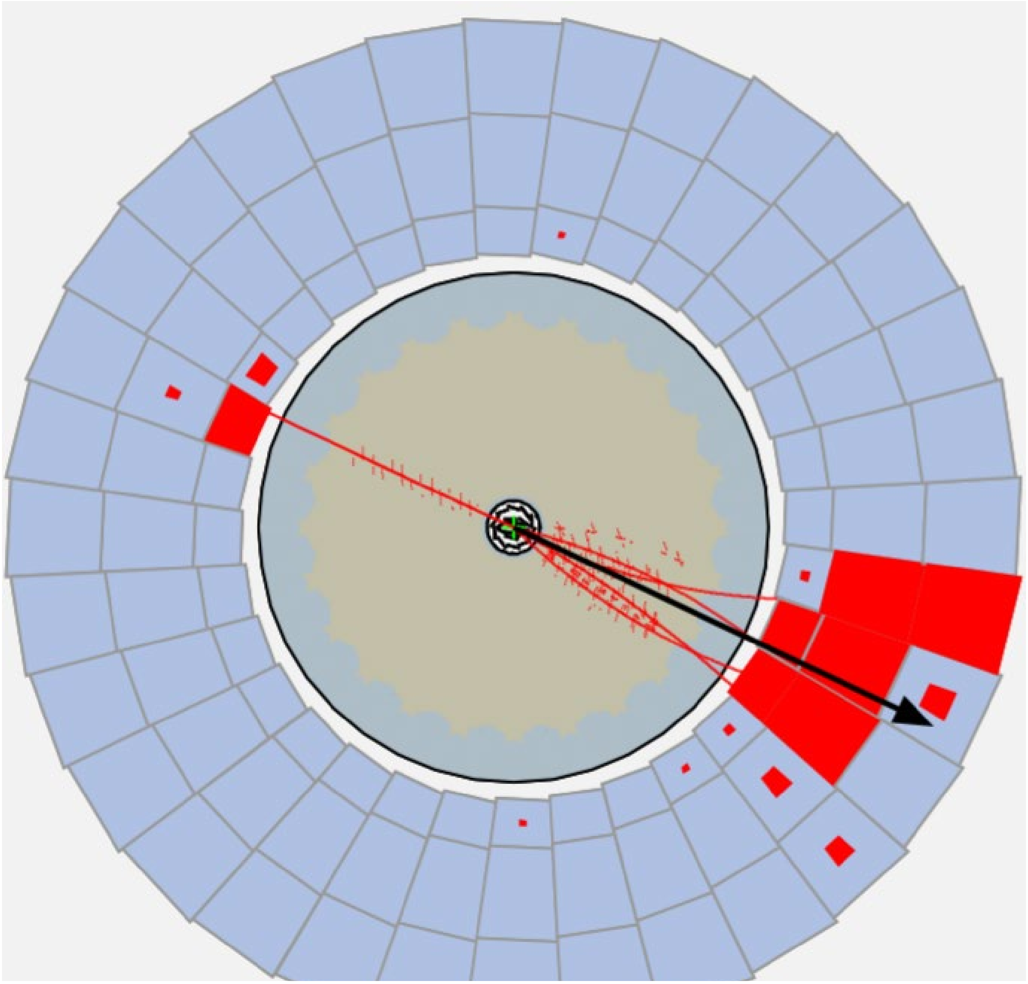
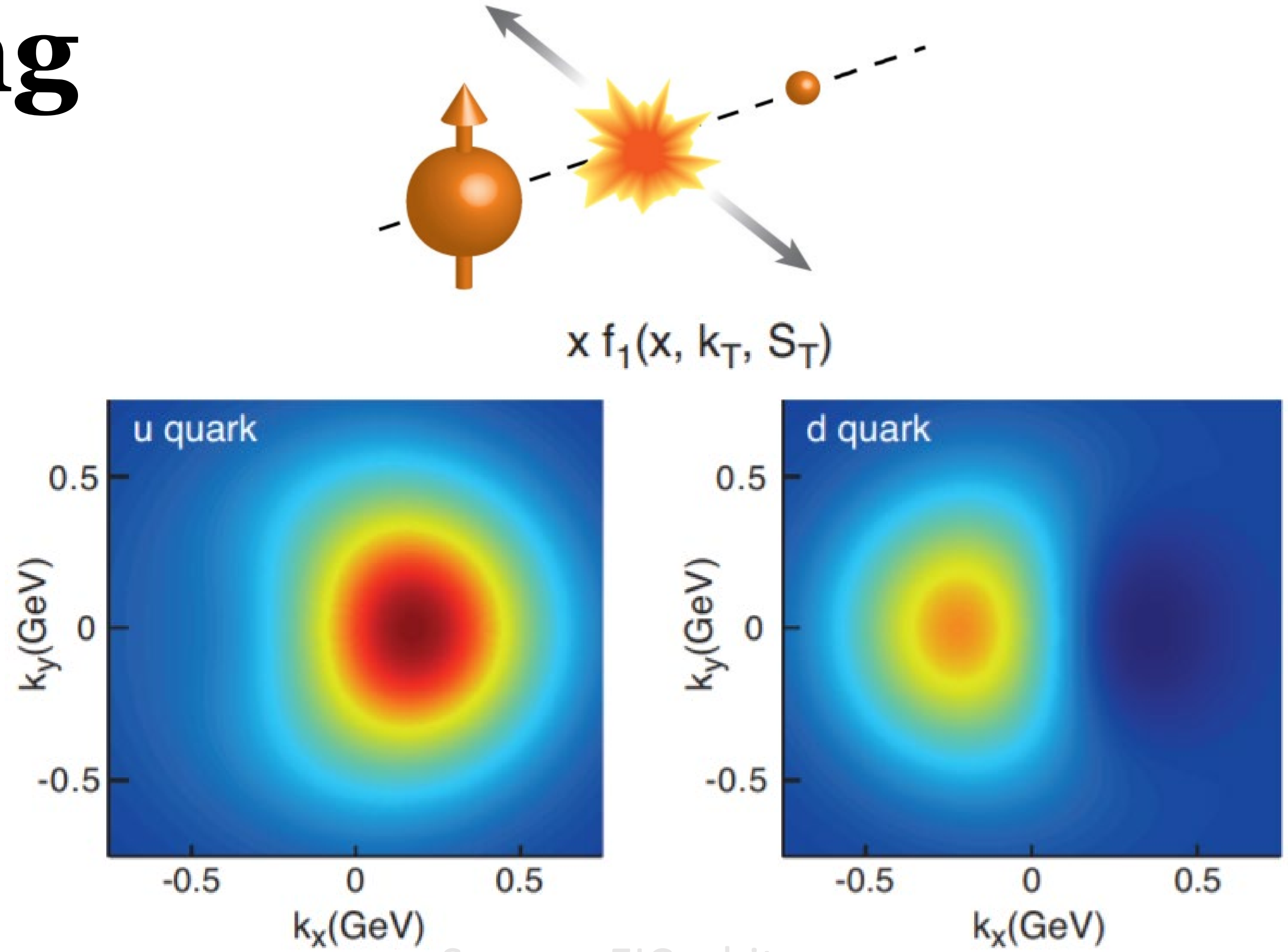


Rev. Mod. Phys. 86, 1037 (2014)

# Jet for 3D-imaging

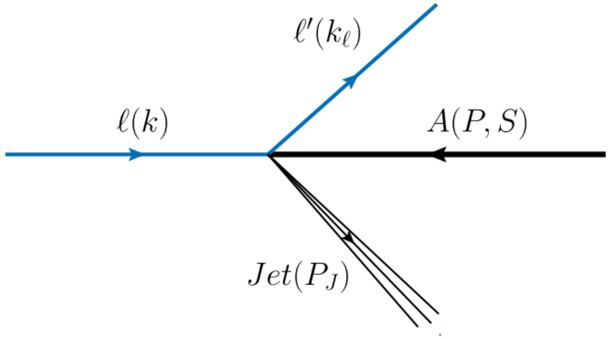
- DIS jets are a novel tool for 3D imaging.
- Complementary and more direct way for EIC flagship measurements.
- Potential for unique jet program, unlike any previous collider or fixed-target experiment.
- Could 3D imaging benefit from jet substructure technology?

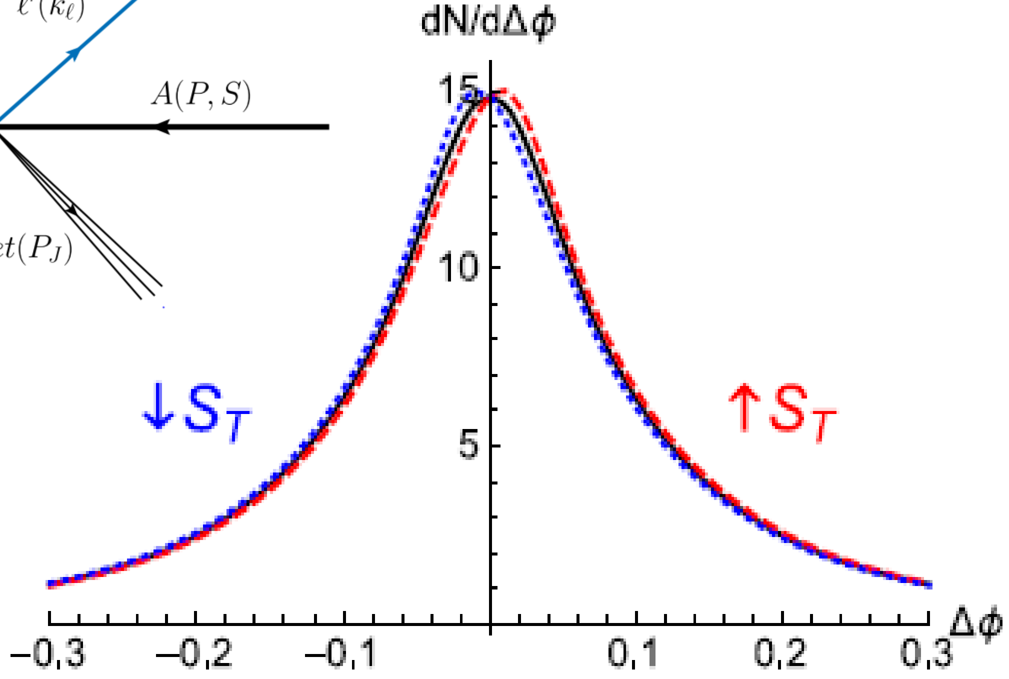



Source: EIC white paper

# Direct measurement of quark Sivers effect with jets

*Liu et al. PRL 122 192003 (2019)*



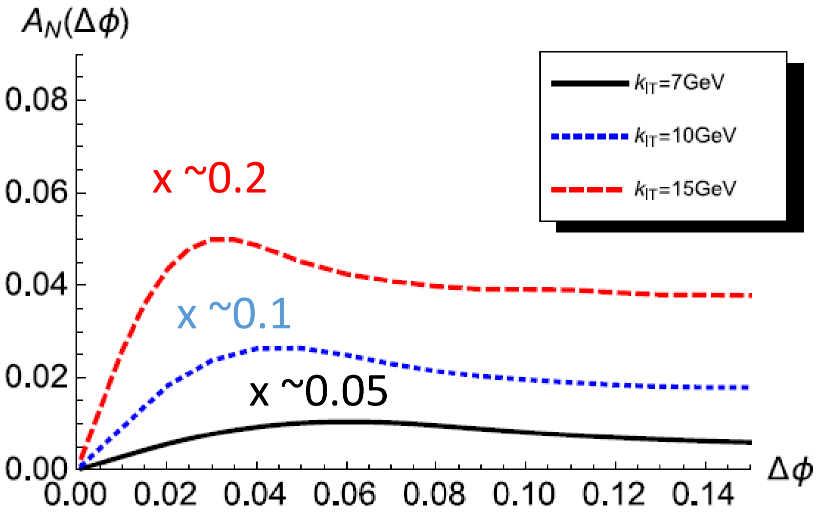
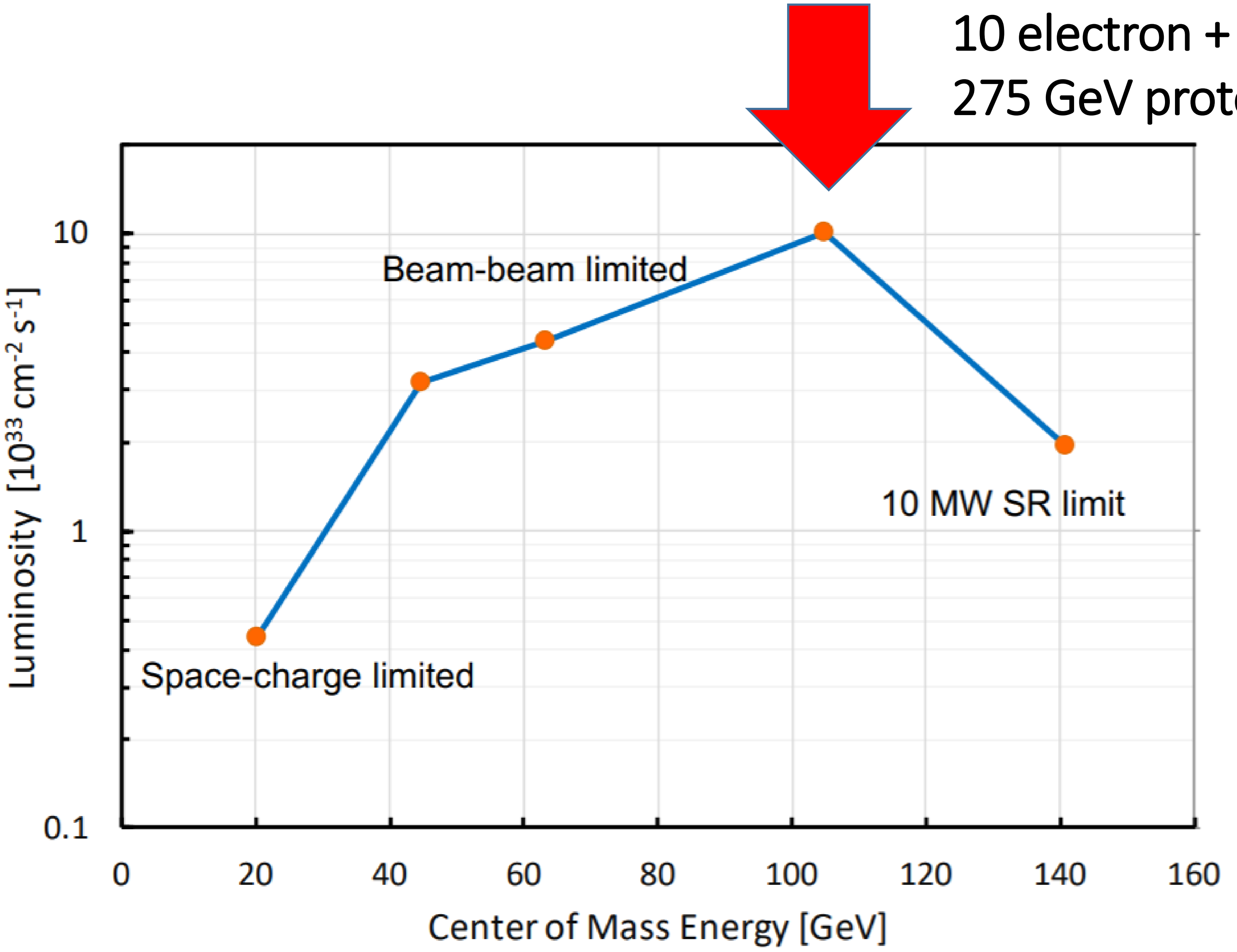




FIG. 3. The single transverse spin asymmetry as a function of $\Delta\phi = \phi_J - \phi_\ell - \pi$ for different lepton transverse momenta $k_{\ell\perp} = 7$, 10, and 15 GeV, respectively, which illustrates the transverse momentum dependence of the quark Sivers function.

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

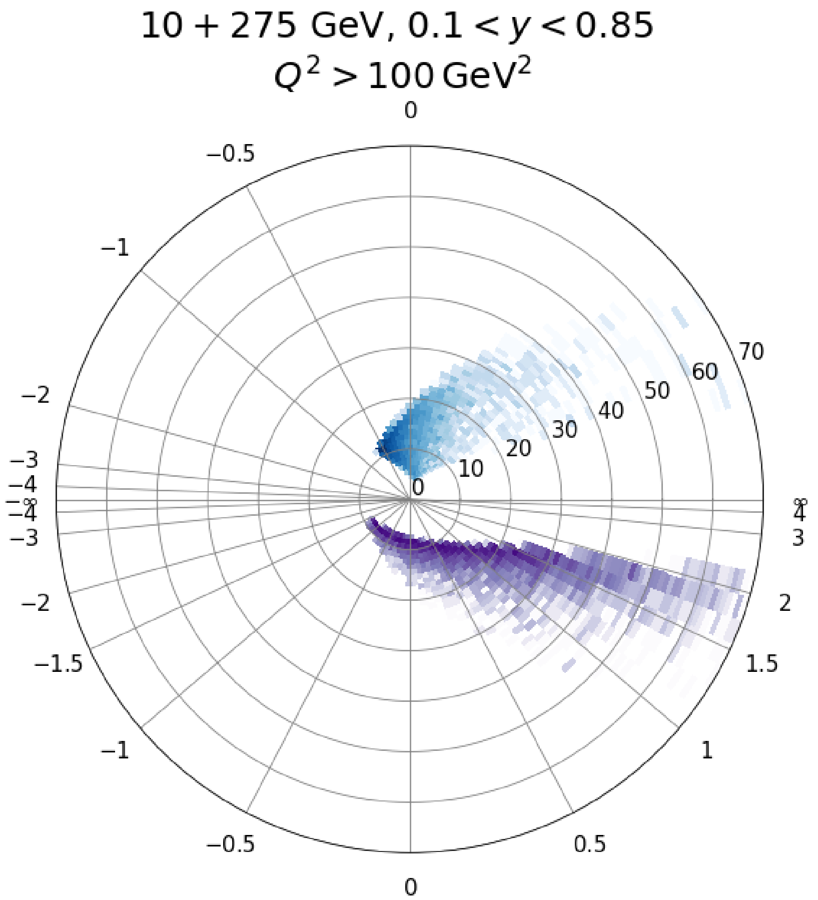
# Optimal operating point for 3D-imaging

10 electron +
275 GeV proton

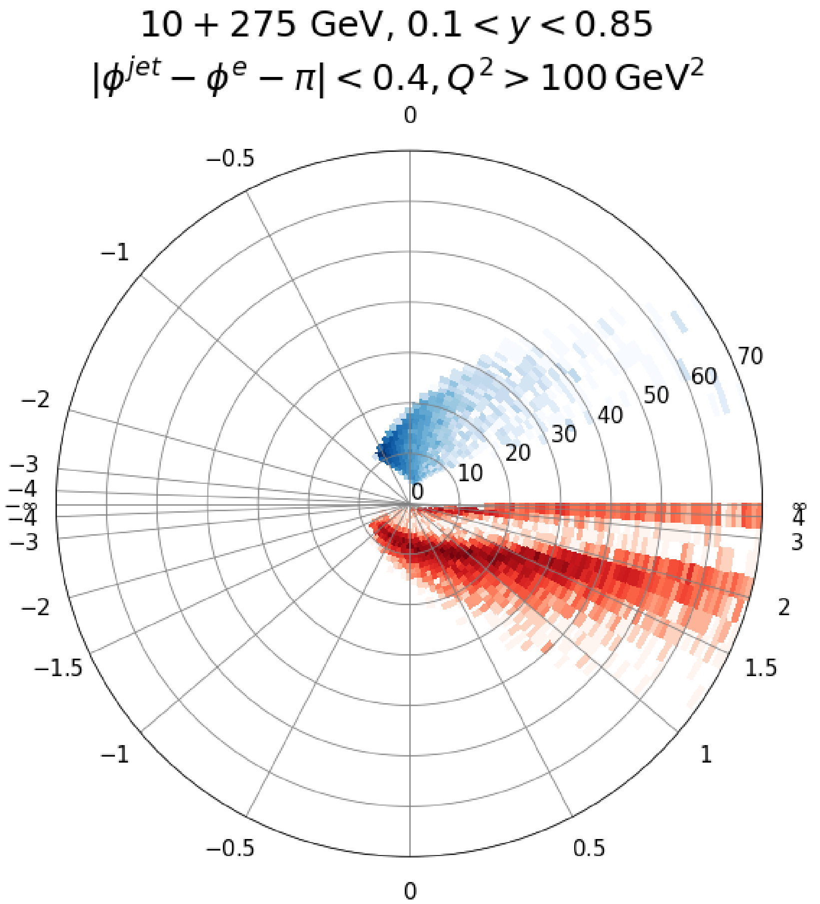



Source: eRHIC design study

# Optimal configuration for luminosity:

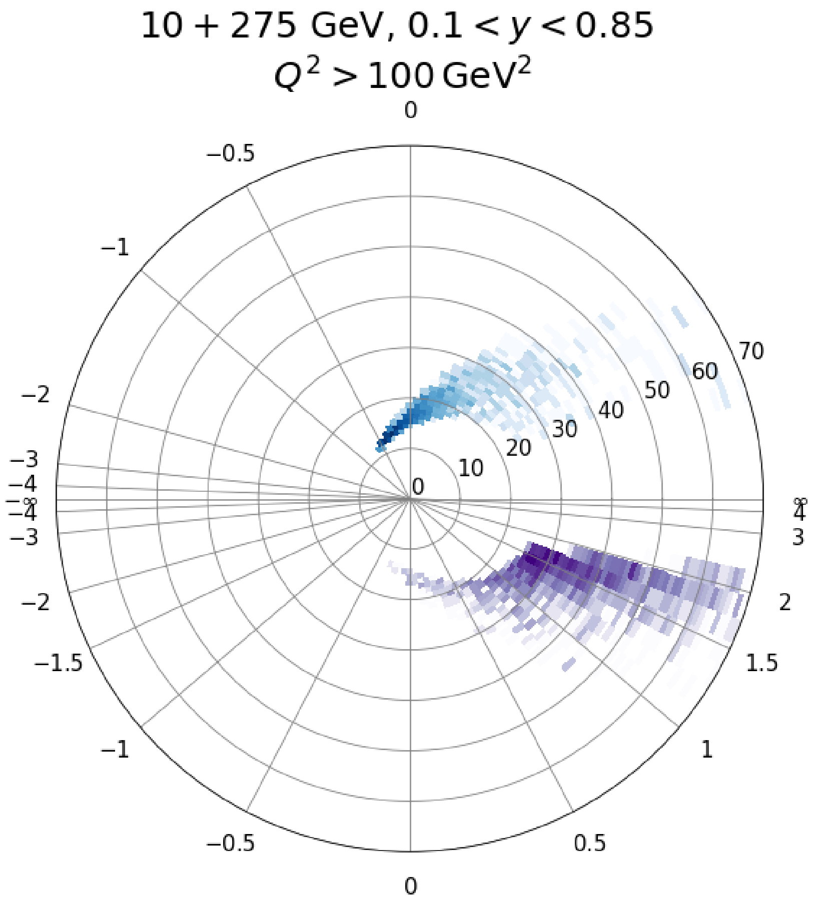


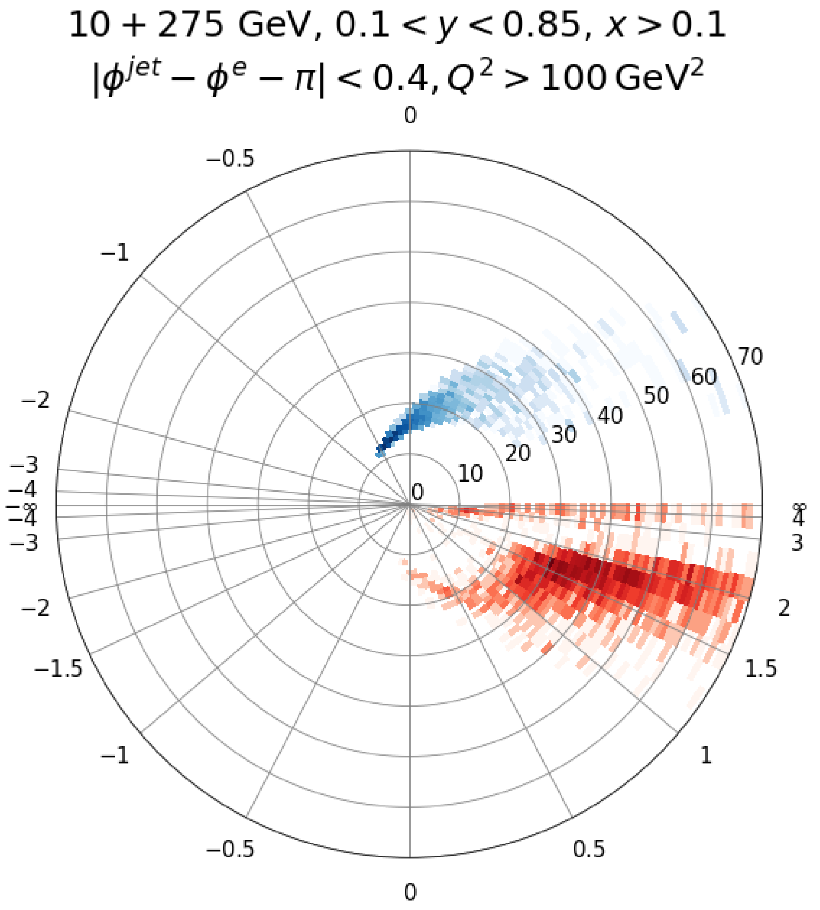

Struck quark



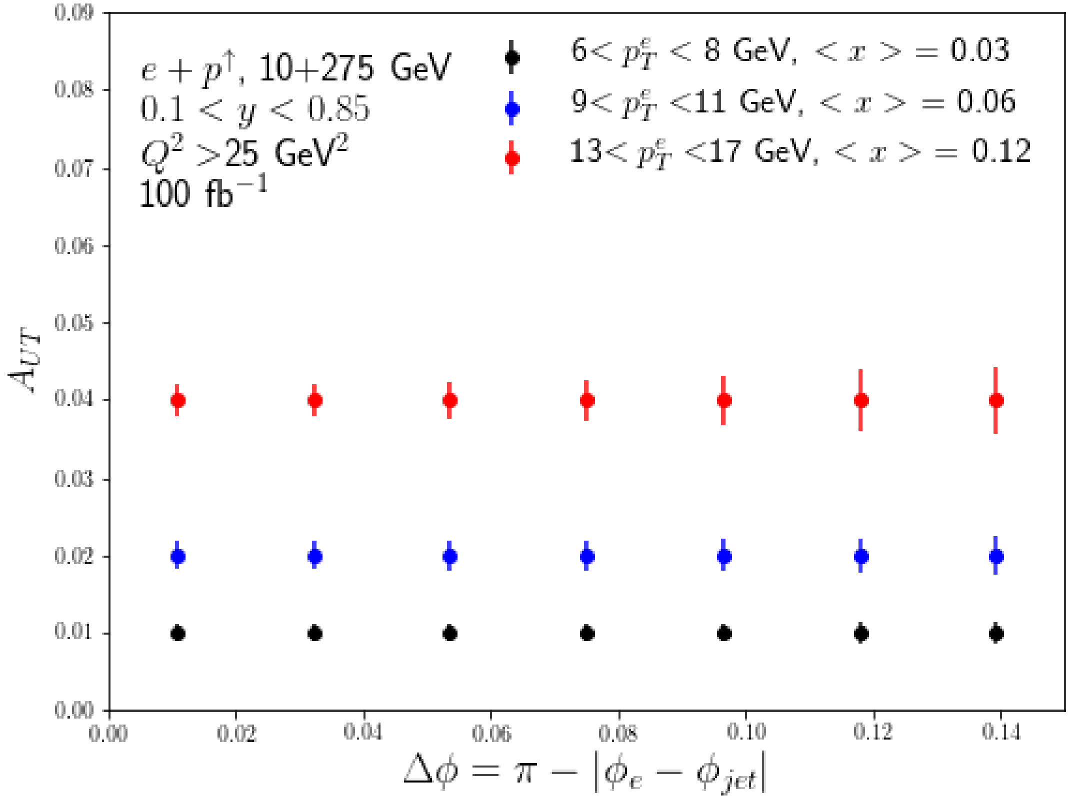

Jets, R=1.0

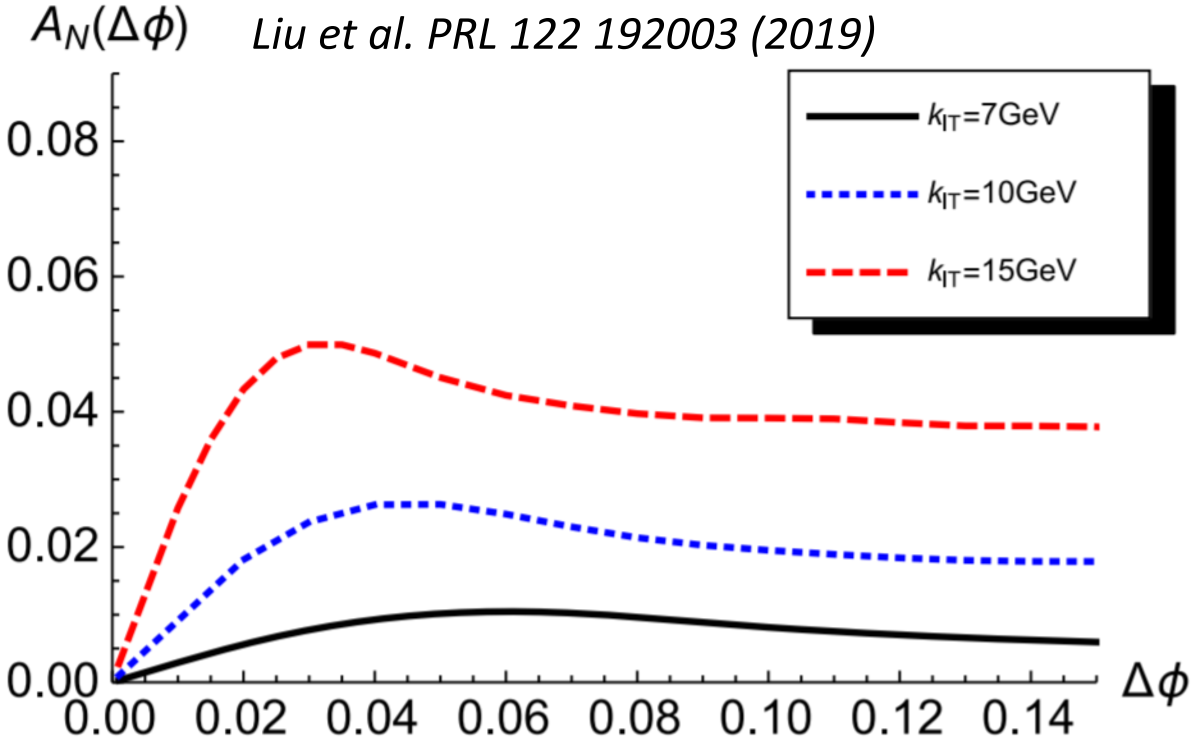
# Focus on the large x



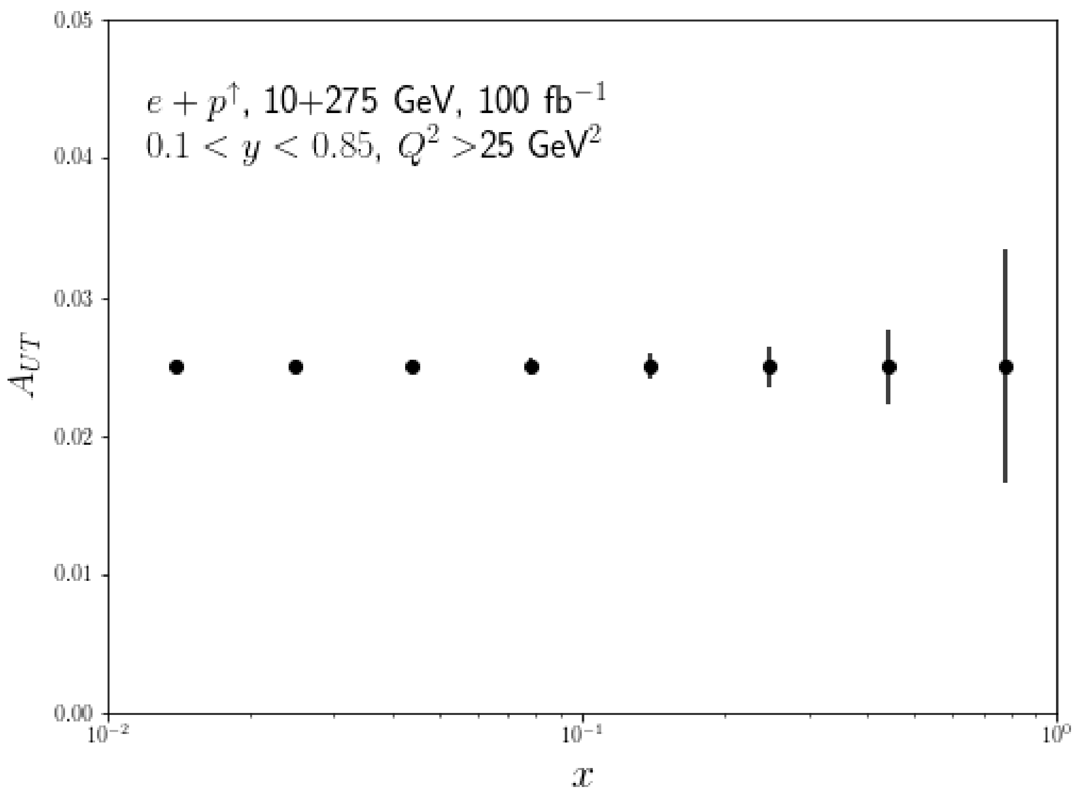
# Statistical projection for Sivers effect with electron-jet correlations

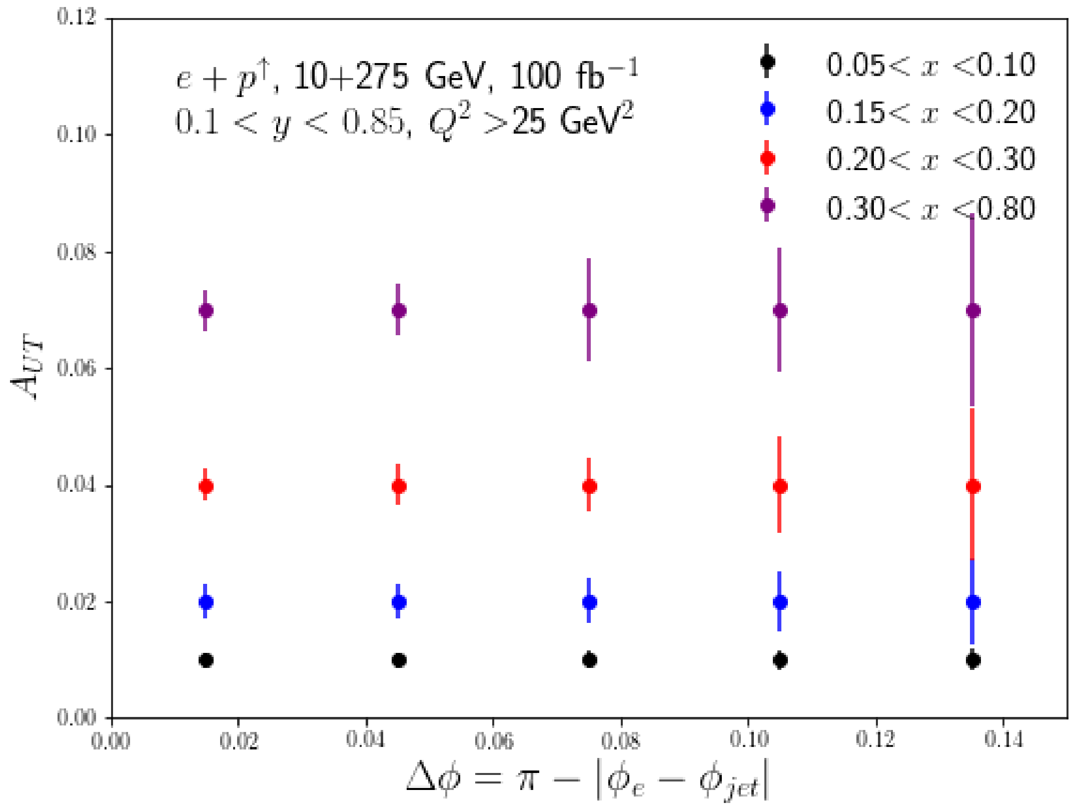



- Projections assume 100 fb-1, 70% polarization, 50% efficiency, sqrt(2) penalty factor due to statistical extraction.
- Excellent prospects for "direct" measurement of Sivers effect, most systematics cancel completely in the ratio

# x-dependence of quark Sivers



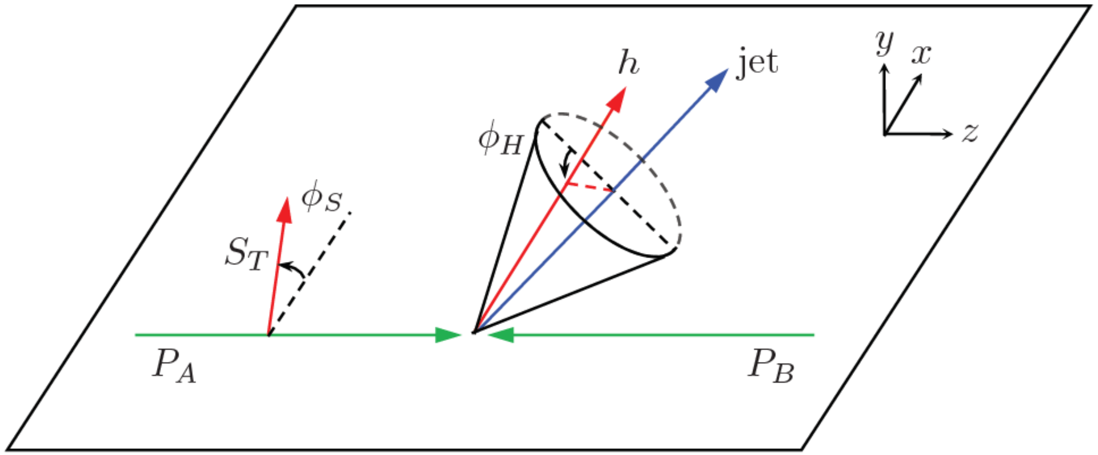



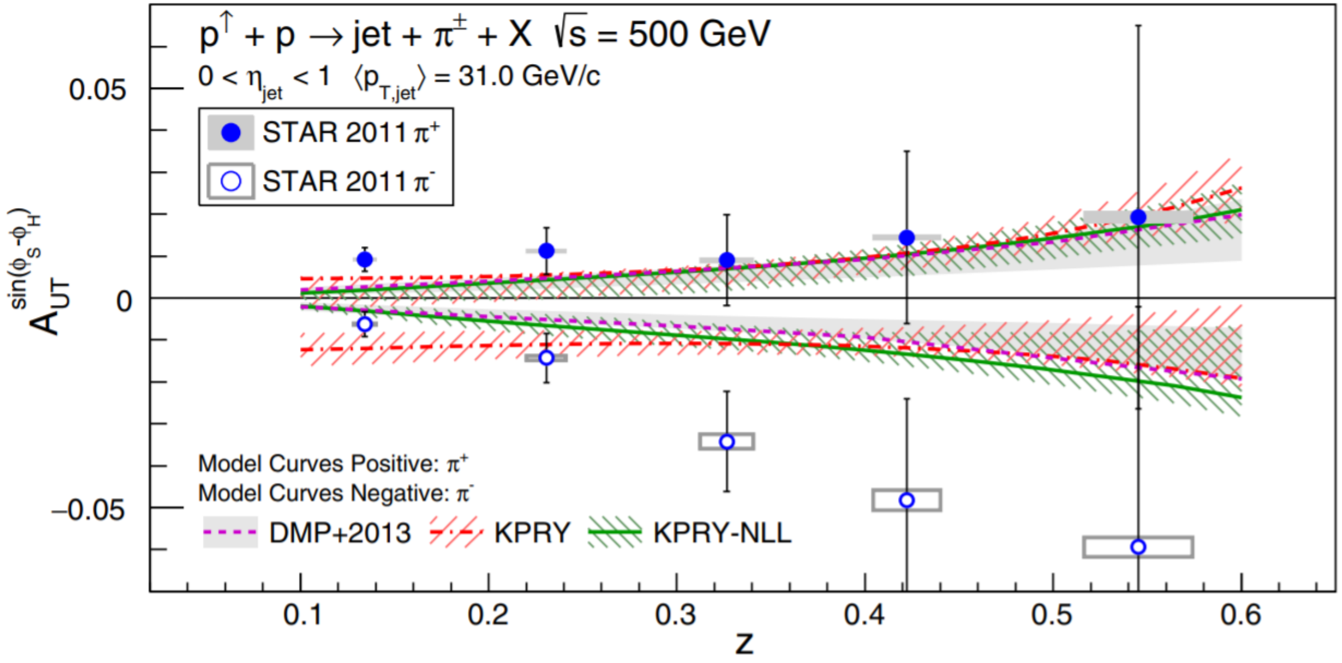

- Excellent kinematic coverage, precise data

# Transversity, h(x), with jets

distribution of transversely polarized quarks inside a transversely polarized nucleon

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



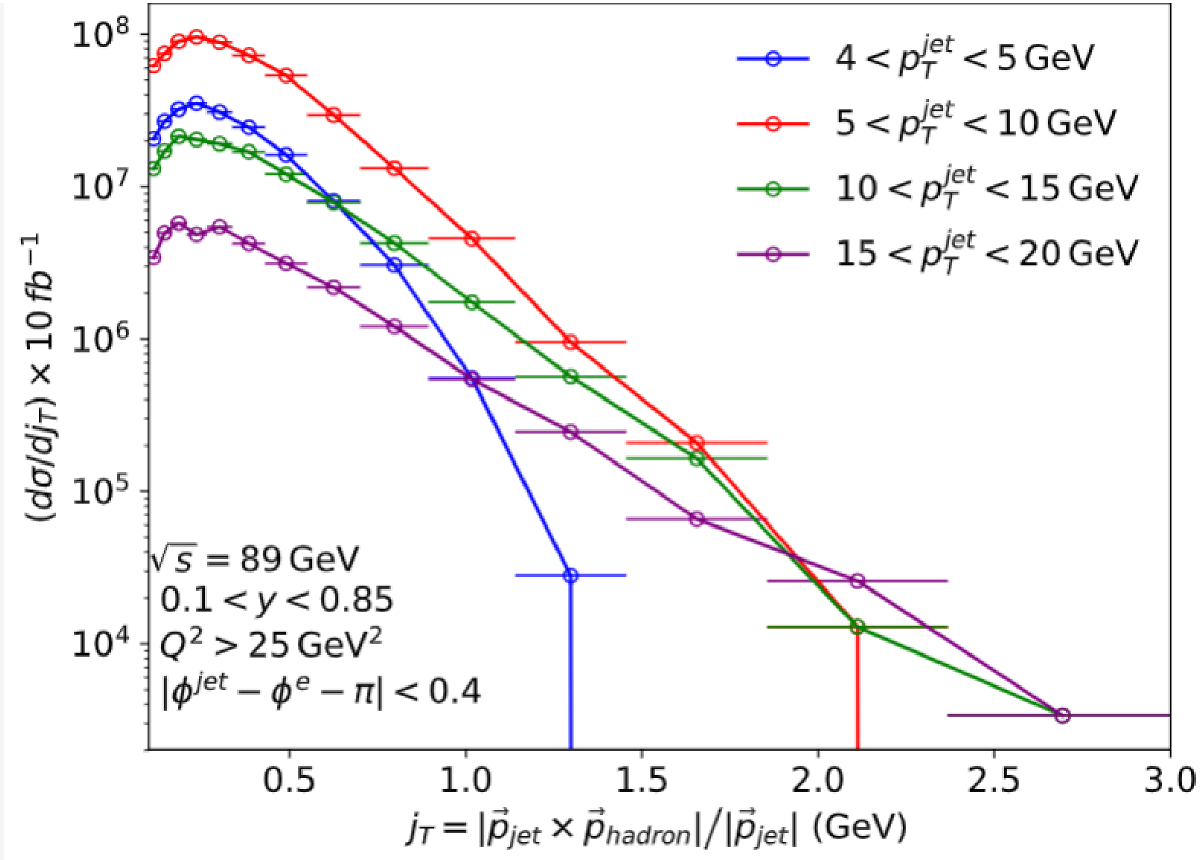



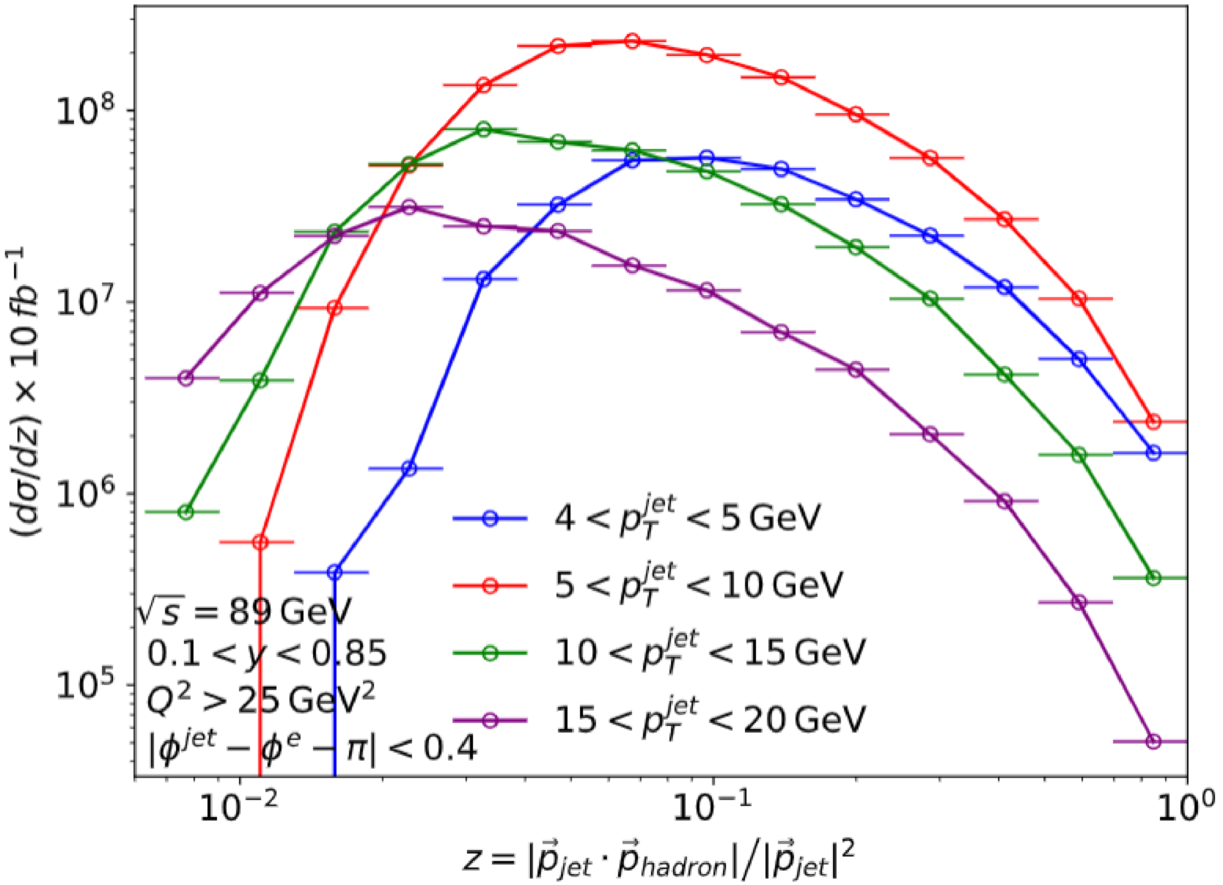

"Collins azimuthal asymmetries of hadron production inside jets
Phys. Lett. B 774, 635 (2017), Kang et al.
"The transverse momentum distribution of hadrons within jets"
JHEP 1711 (2017) 068, Kang et al.

- 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.

# Hadrons-in jet @ EIC

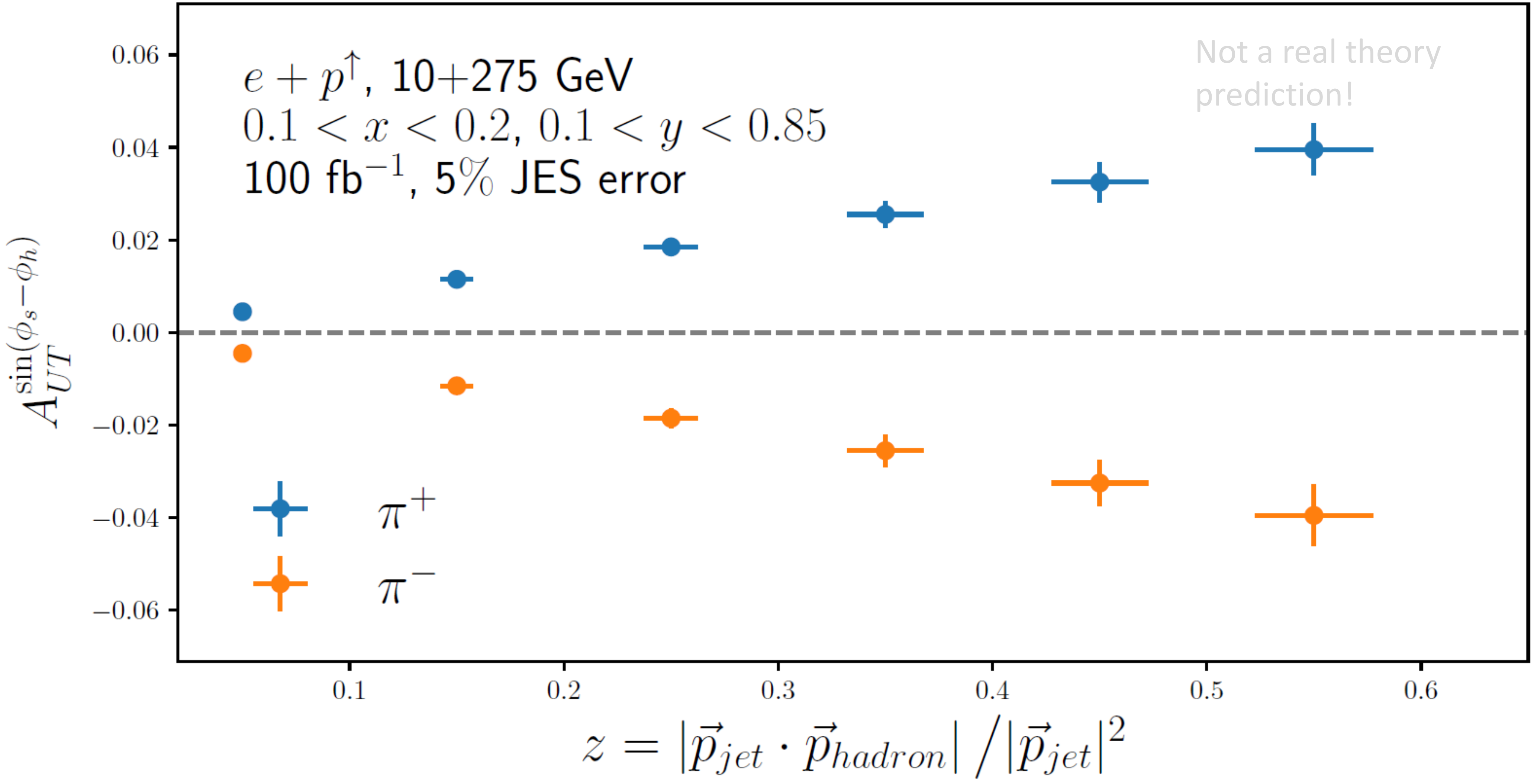
Plot by Youqi Song



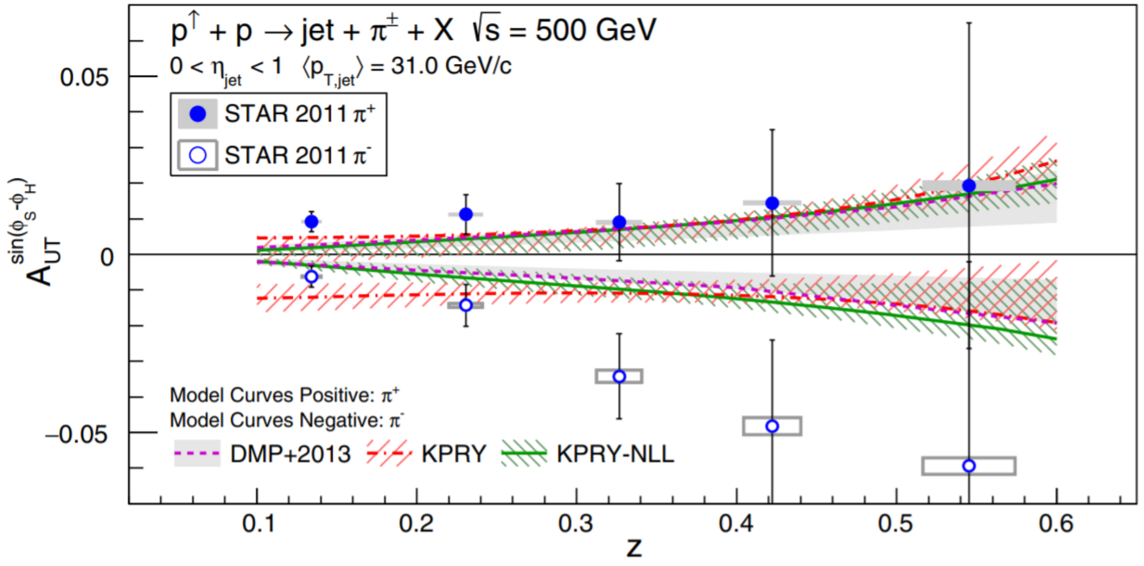

- Plenty of statistics!

# Hadron-in-jet statistical projection

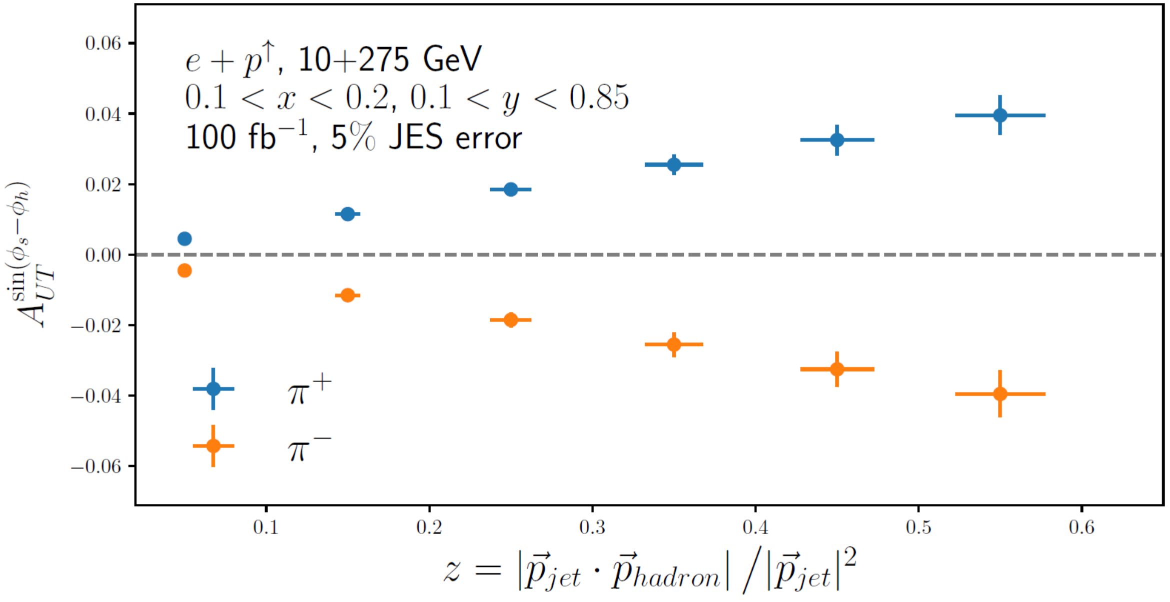


## pp at RHIC

## ep at EIC

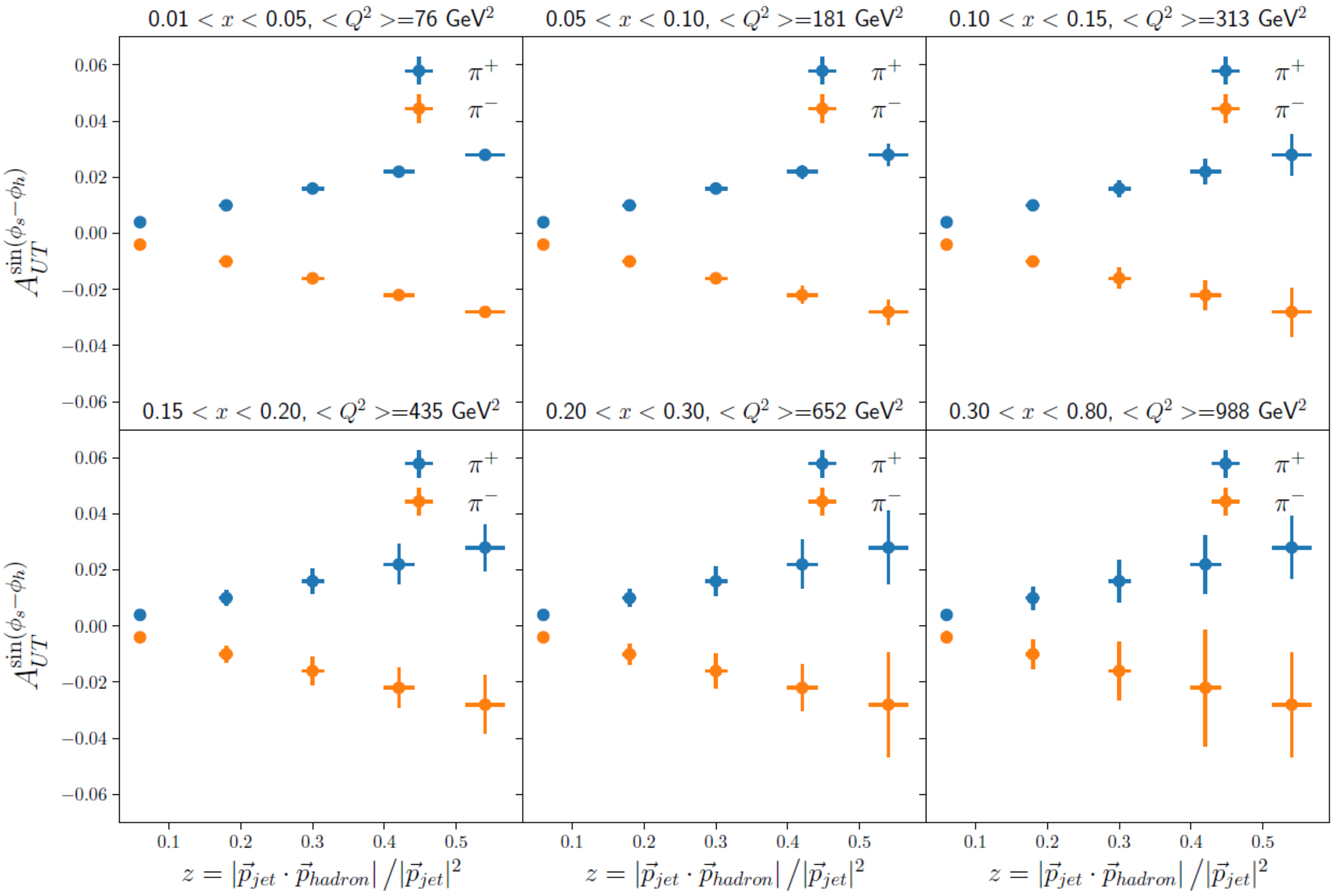



Phys. Lett. B 774, 635 (2017), Kang et al.

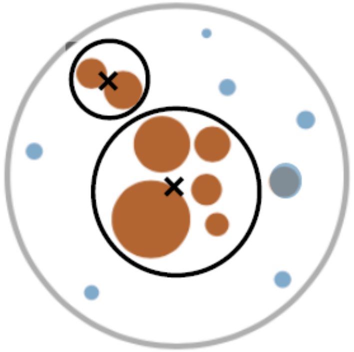



- **Most systematics cancel in the ratio….**
- **We will have sensitivity to TMD evolution effects.**

# Covering the entire x-range relevant for transversity



# Jet substructure, the key to novel TMD studies?



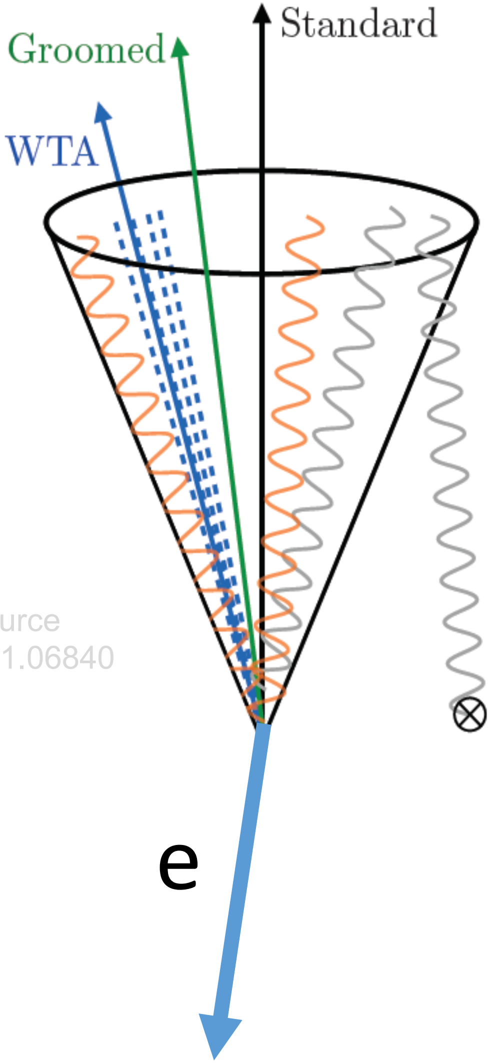


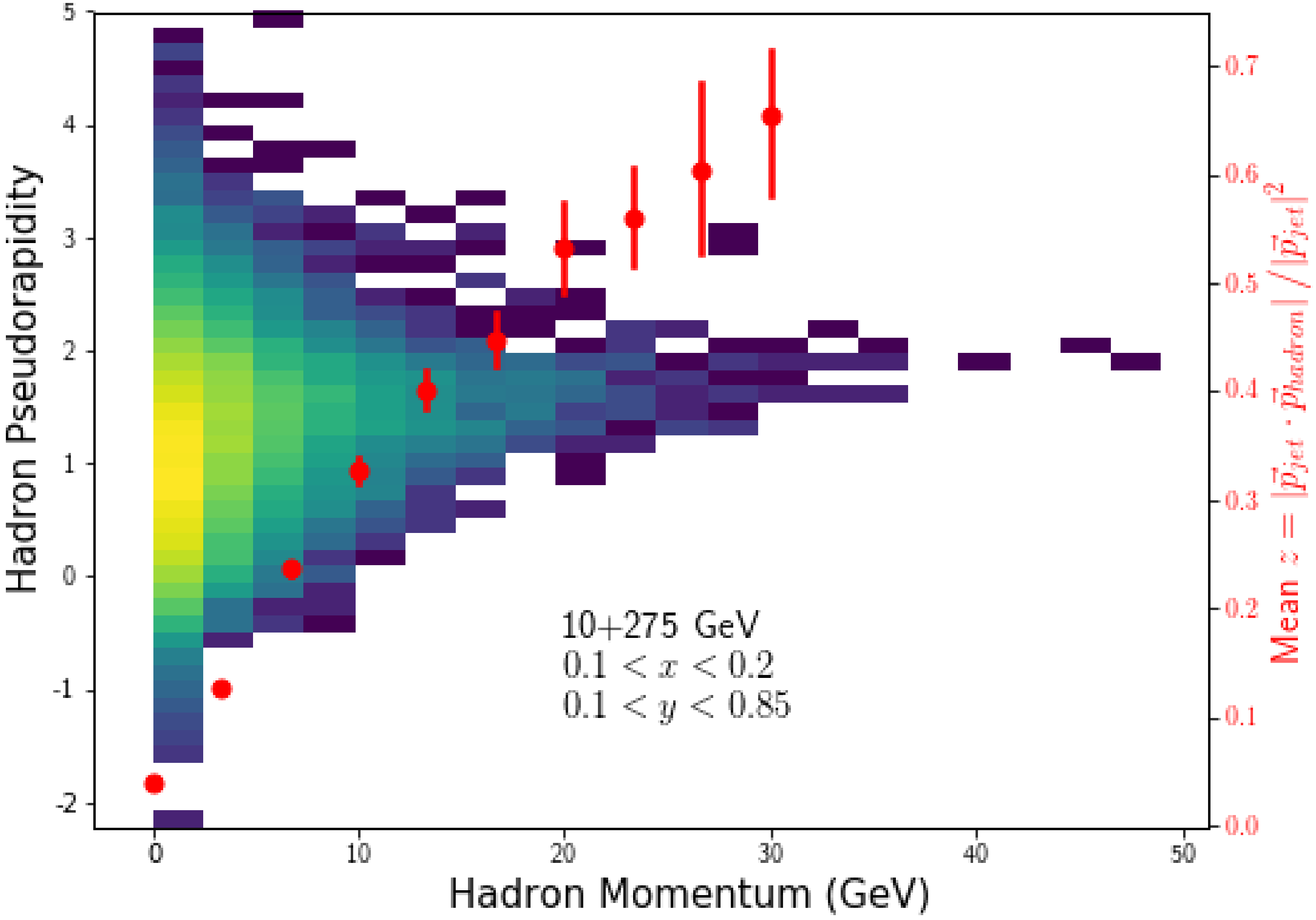

Image source arXiv:1911.06840

- "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
- 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 .
- Going from single-hadrons to jets studies might expand the field tremendously (sounds familiar?)

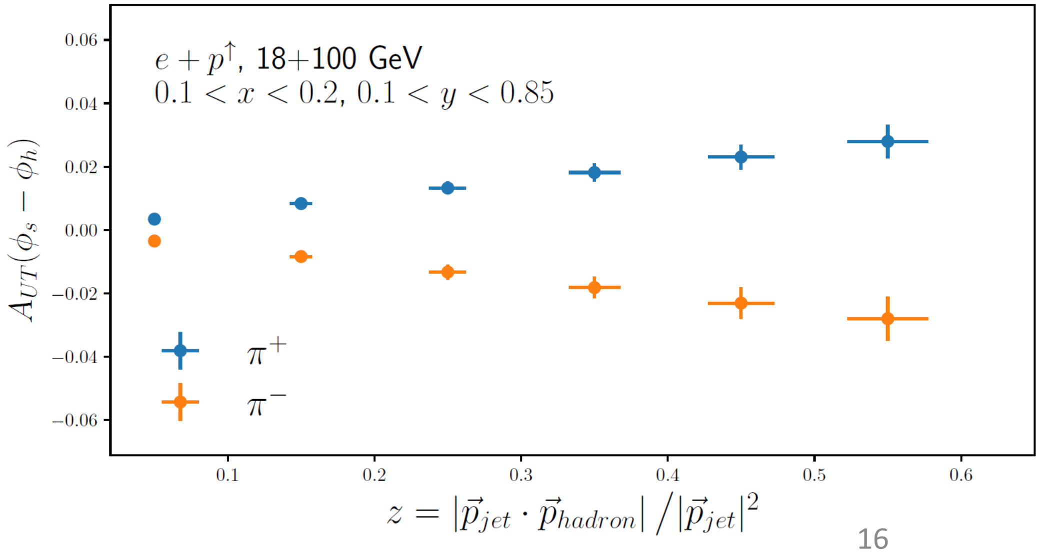
# Some thoughts on detector requirements

- PID & tracking
- Hermetic coverage
- Jet uncertainties

# PID requirements:

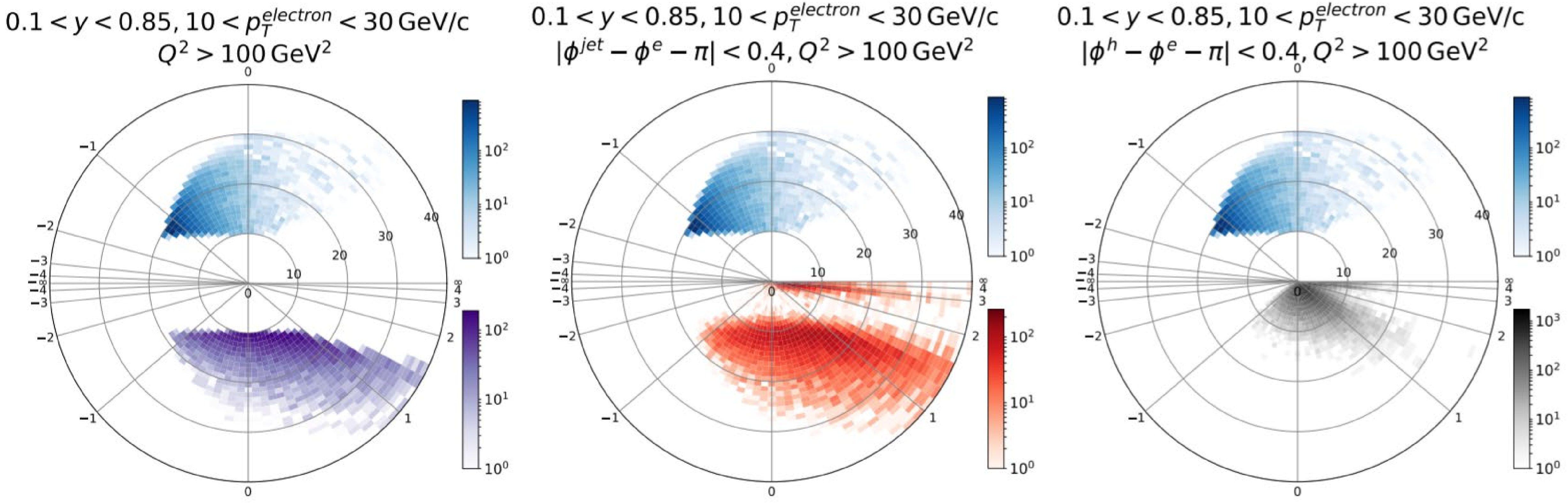



- **Mandatory** for this measurement. "Charged hadron" would not work.
- Charged pions separation from Kaons and protons up to ~30 GeV
- EMCAL granularity for pi0



# Jets are excellent proxies for quark kinematics

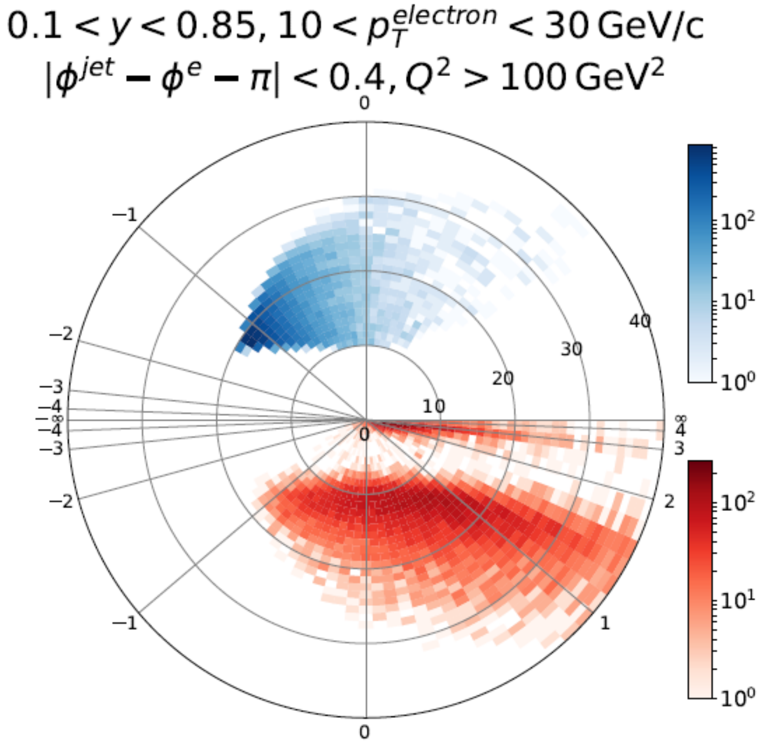
*Arratia et al. arXiv:1912.05931*



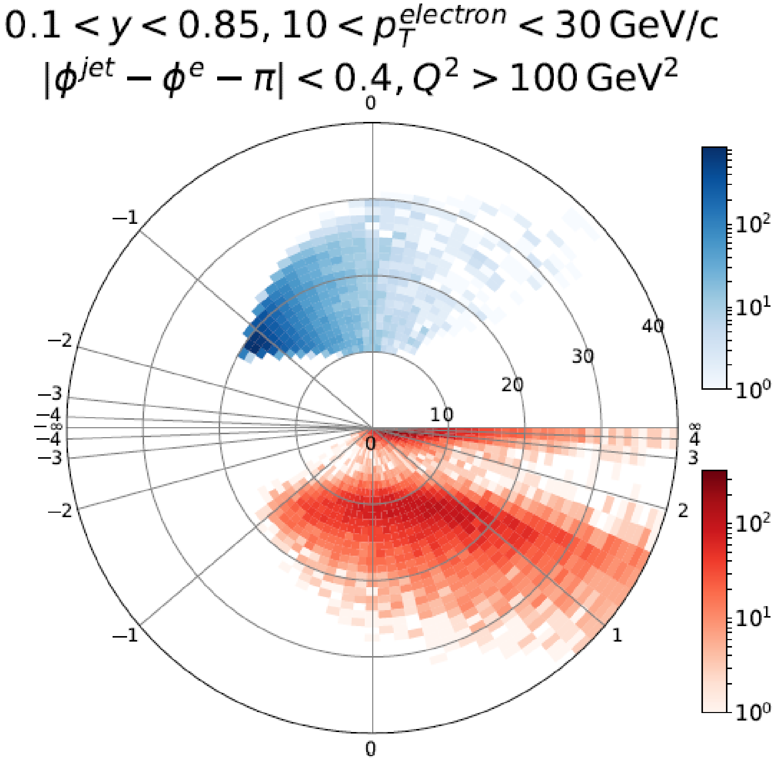

**Struck quark** **Jets, R=1.0** **Hadrons**

# Jets are excellent proxies for quark kinematics but…

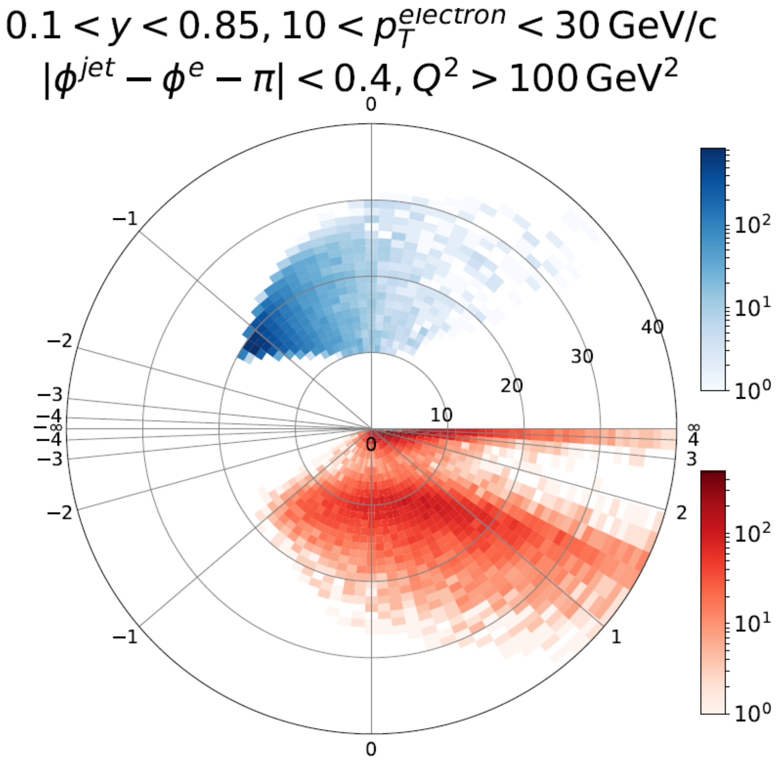
**R=1.0**




**R=0.7**



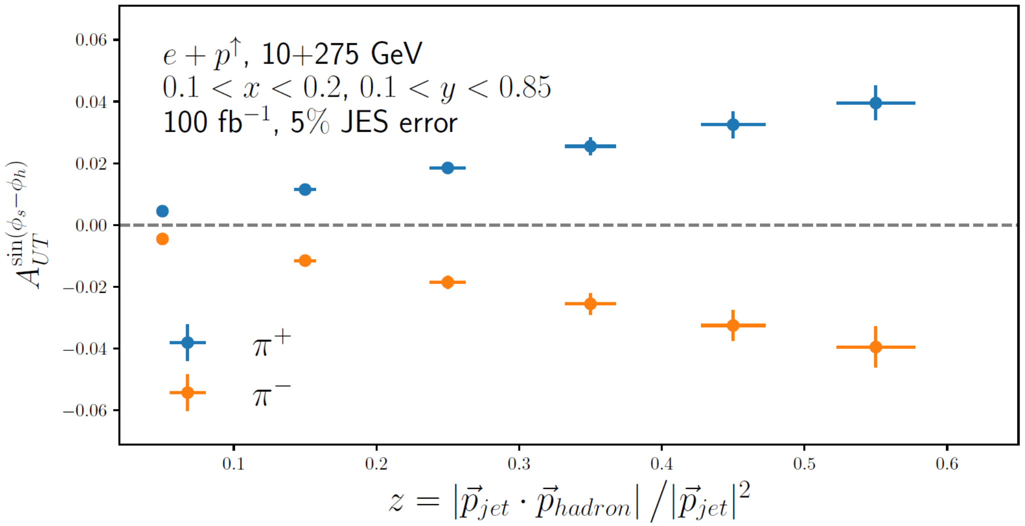

**R=0.5**

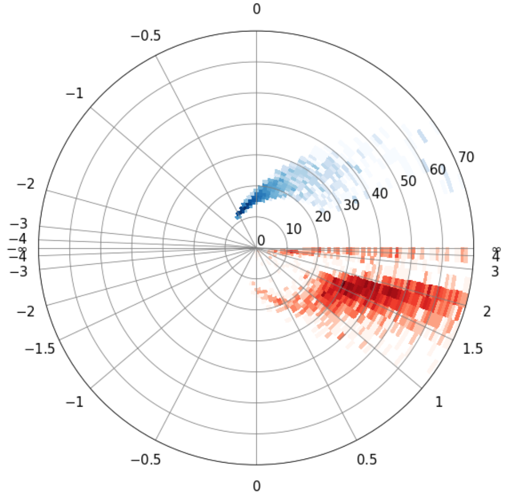



- Smaller R leads to larger ambiguity at low momentum. At HERA, the use of R=1.0 lead to percent-level “hadronization correction”
- Parton-to-jet matching is leading uncertainty at low pT in STAR hadron-in-jet measurement Phys. Rev. D 97, 032004 (2018)

# Jet uncertainties

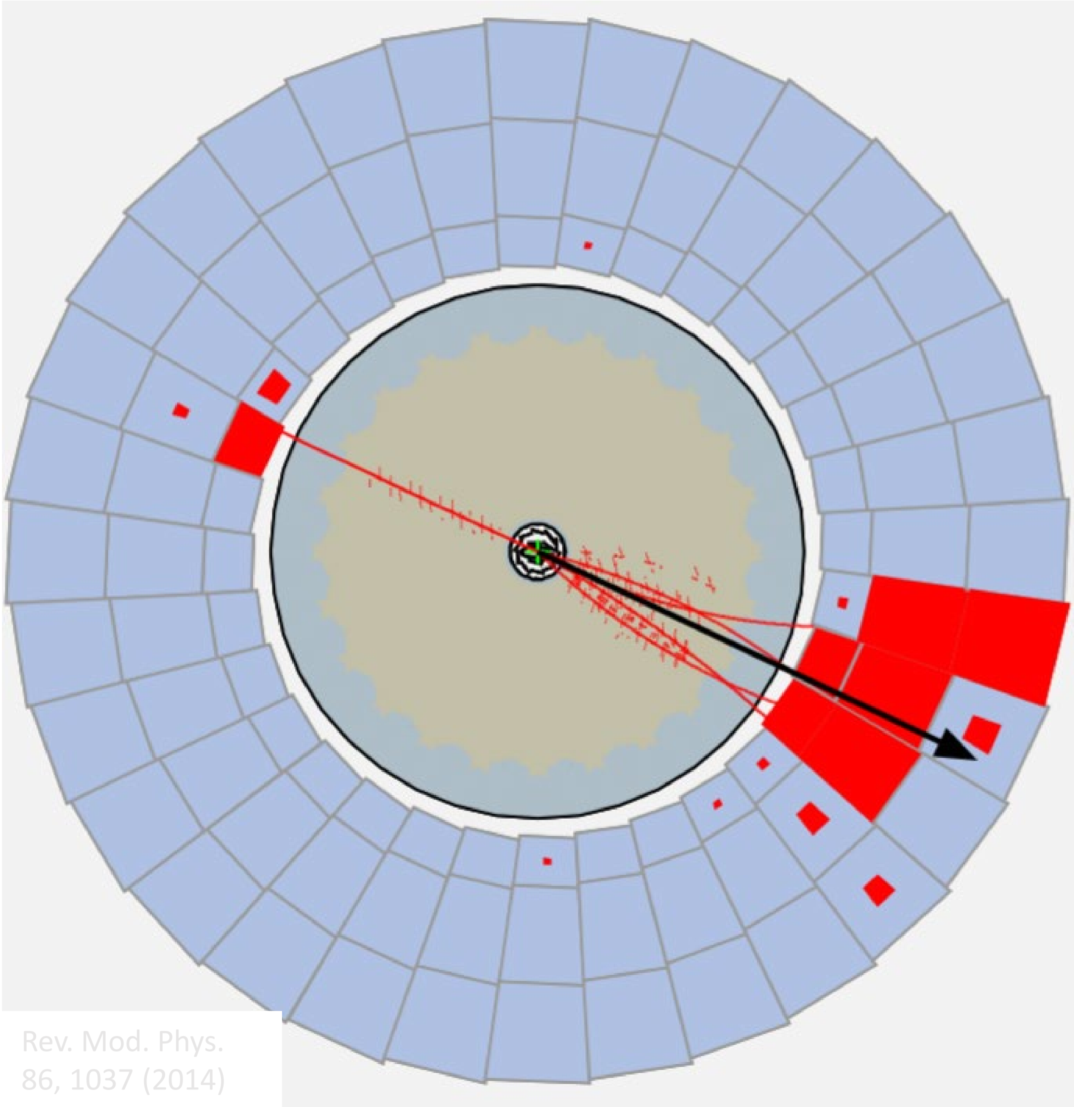
- JES uncertainty cancels completely in ratio, but appears in x-axis.
  JES uncertainty ~5-10% should be OK.
  (~1% was achieved at HERA).
- JER uncertainty cancels in the ratio.
  JER value likely dictated by tracking, which is needed for hadrons in range ~[-1.0, +3.5].
- Note that jet energy is at most ~60 GeV. Forward HCAL with 50%/sqrt(E) + 10% likely enough.
- Hermetic coverage might end up being more important to control systematics for asymmetry measurements.



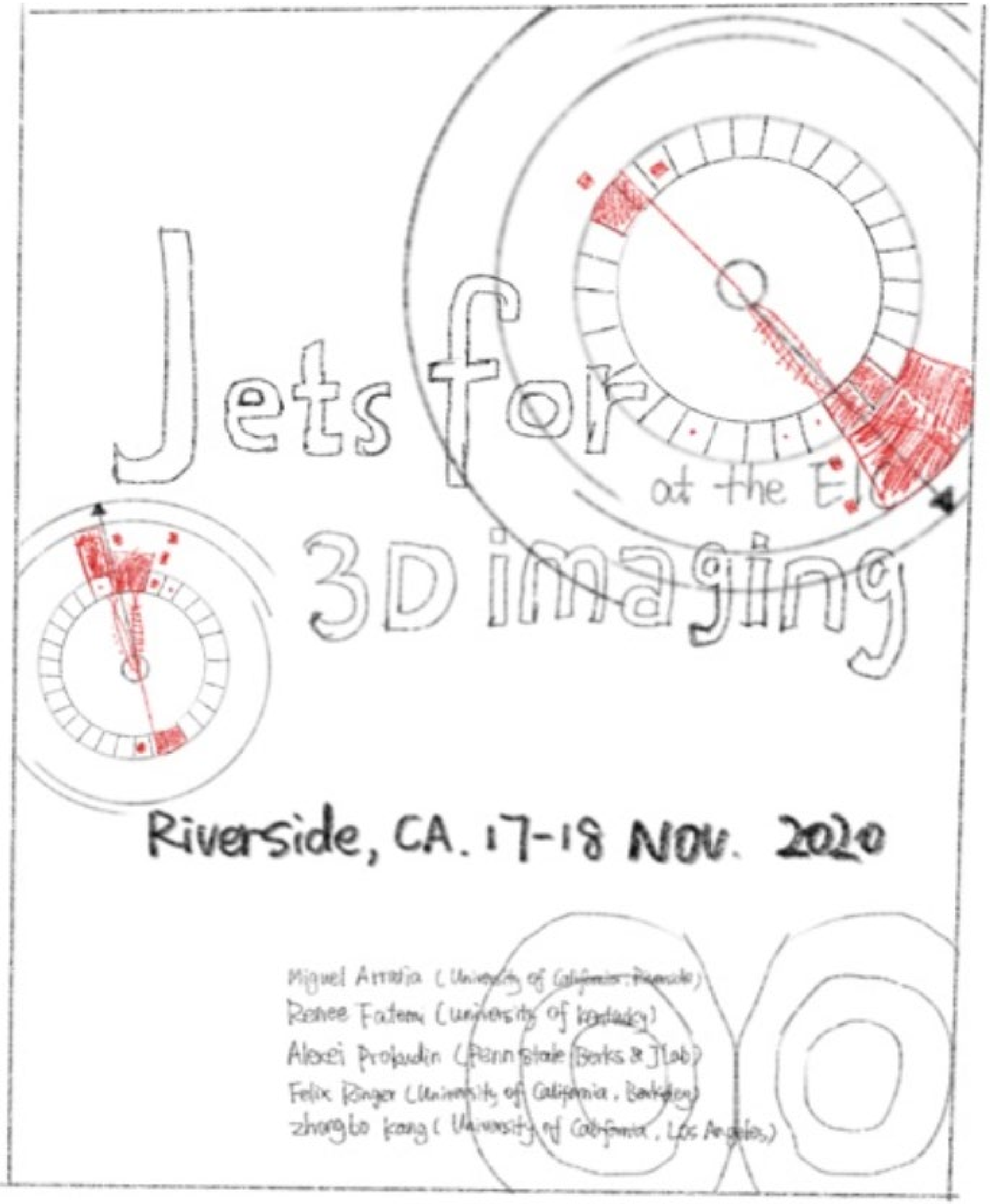



# Summary

- Studies with jets at EIC will be unlike any previous collider (even HERA!). Key studies include: electron-jet correlations (**Sivers**), jet fragmentation (**Transversity** et al.) and jet substructure (**new!**)
- Jets for 3D imaging is an excellent opportunity for the convergence of the collider and fixed-target community at the EIC.
- We have a lot of overlap and common goals with the SIDIS group.



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




- Just before the Berkeley YR meeting,
- We'll have more details soon.

# Backup slides

# 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.**

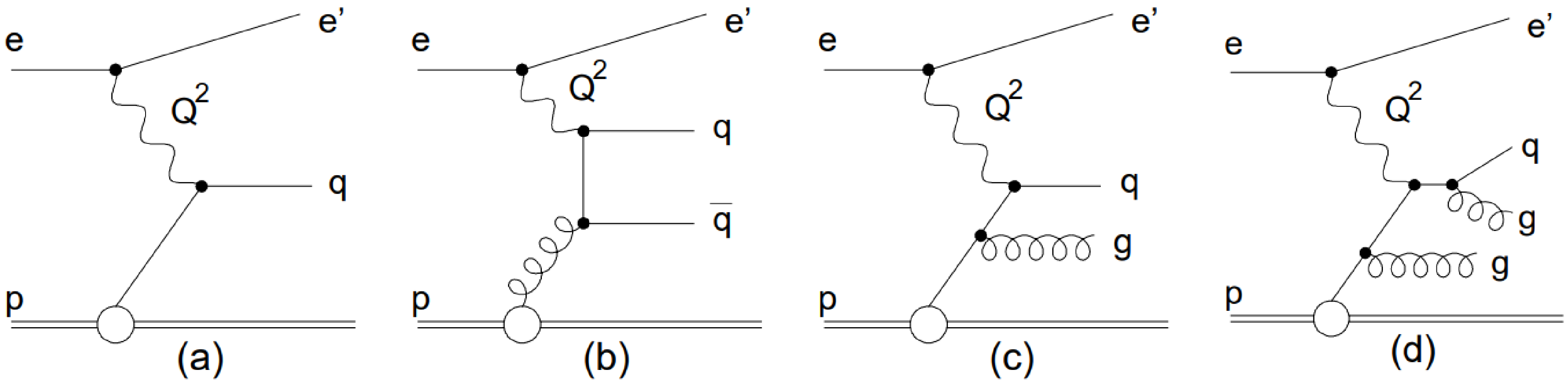



Figure 1: Deep-inelastic *ep* scattering at different orders in $\alpha_s$: (a) Born contribution to inclusive NC DIS ($\mathcal{O}(\alpha_{em}^2)$), (b) photon-gluon fusion ($\mathcal{O}(\alpha_{em}^2\alpha_s)$), (c) QCD Compton scattering ($\mathcal{O}(\alpha_{em}^2\alpha_s)$) and (d) a trijet process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

# Instead of Breit frame, we'll use lepton frame following:

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

We focus on large transverse momentum lepton-jet production in the center of mass (c.m.) frame of the incoming lepton and nucleon, see Fig. 1,

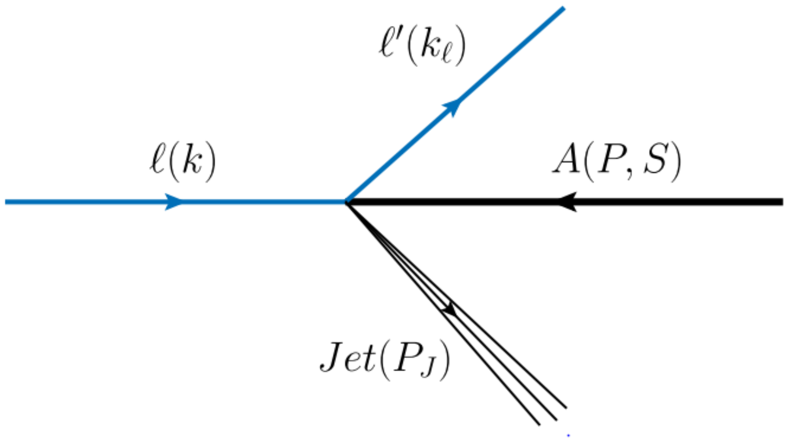



FIG. 1. Lepton-jet correlation for the tomography of the nucleon or nucleus at the EIC.

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

# Simulation parameters (for 3D imaging of proton)

- Pythia8 e-p DIS, DIRE parton shower (angular ordered)
- $E^{proton} = 275$ GeV, $E^{electron} = 10$ GeV
- Event cuts: $0.1 < y < 0.85$, $Q^2 > 25$ 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

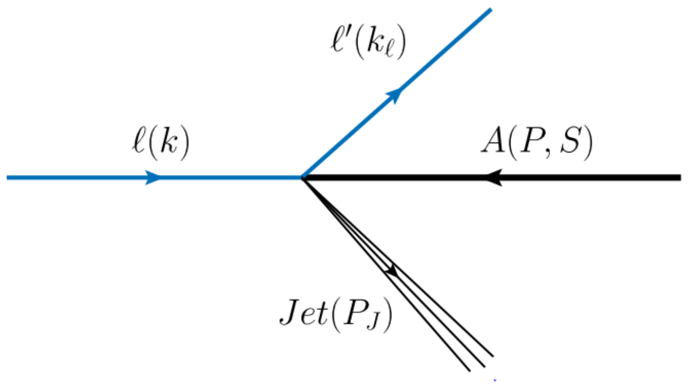



FIG. 1. Lepton-jet correlation for the tomography of the nucleon or nucleus at the EIC. *Liu et al. PRL 122 192003*

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

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

# e.g. Jets with soft-drop grooming,

*"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.*

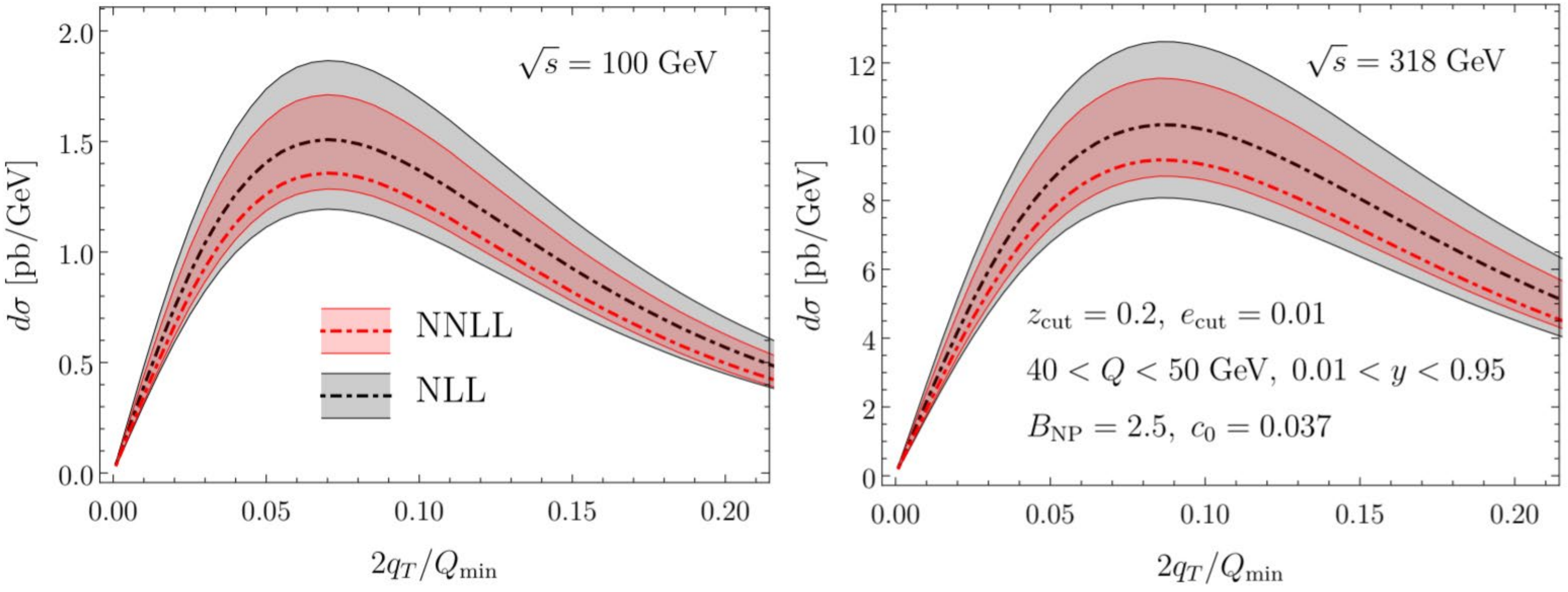



**Figure 7**. The NLL and NNLL TMD spectra for groomed jets in DIS for EIC (left: $\sqrt{100}$ GeV) and HERA (right: $\sqrt{s} = 318$ GeV) kinematics. The cross section are integrated in $y = Q^2/(xs)$ and