Jets for 3D imaging

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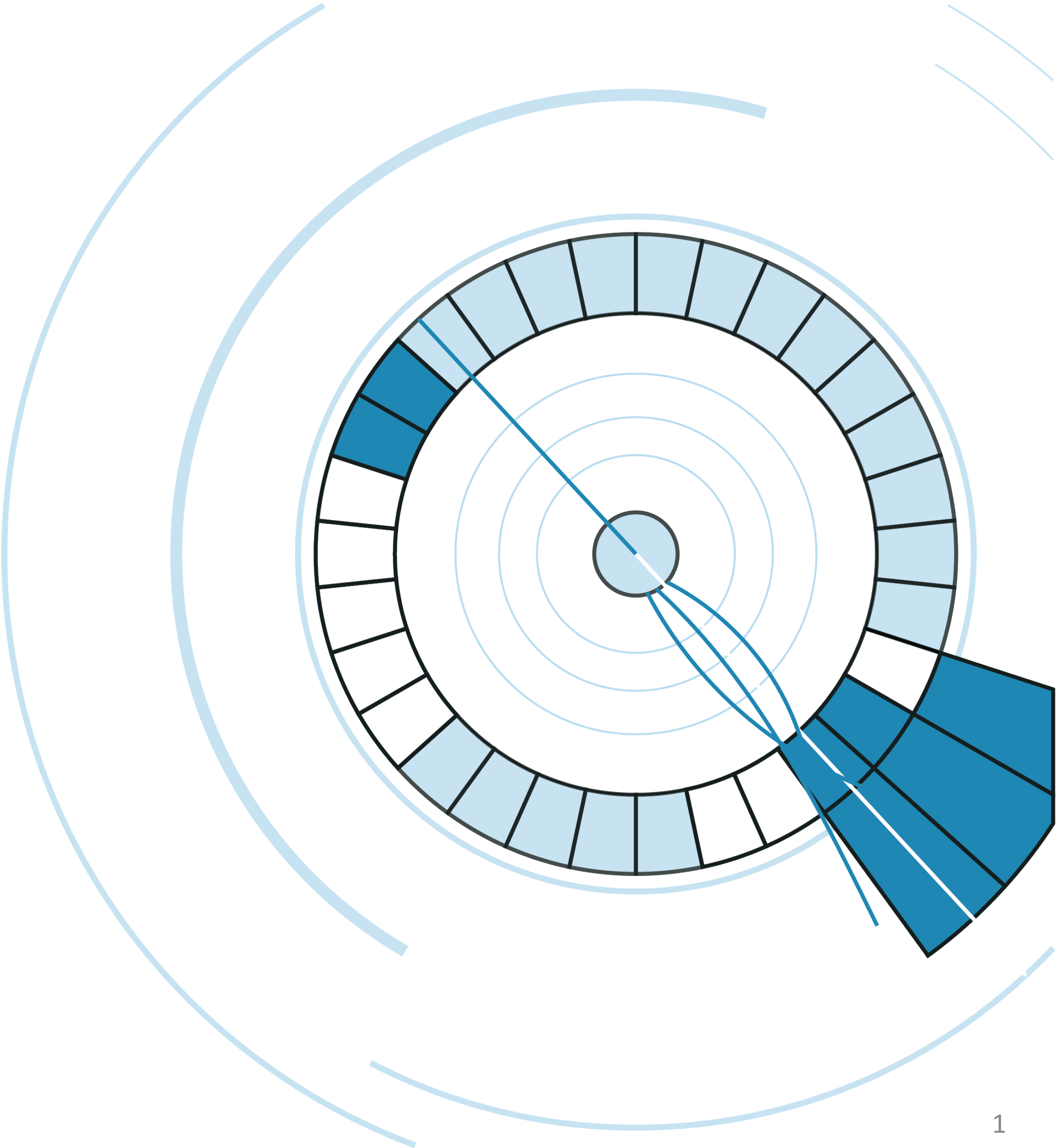


Why bother with jets?

- 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.

Simulation parameters

- Pythia8, unpolarized 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, 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

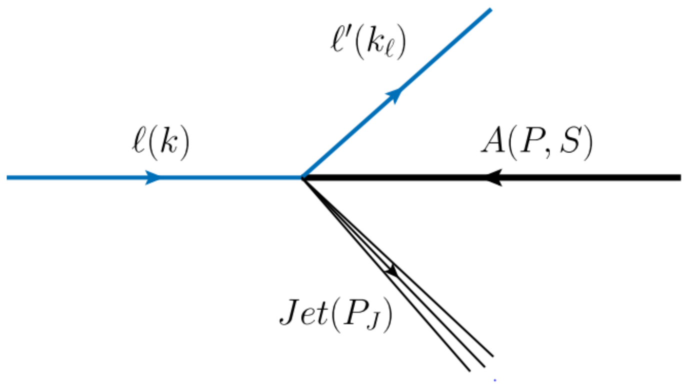


FIG. 1. Lepton-jet correlation for the tomography of the nucleon or nucleus at the EIC. *Liu et al. PRL 122 192003*

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

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

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,

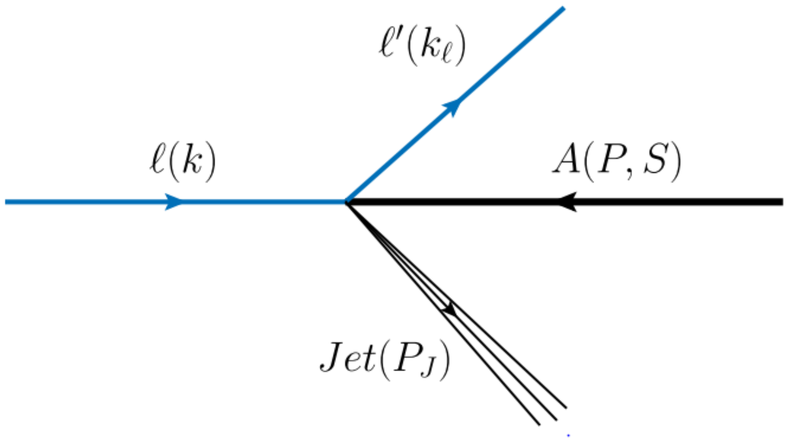
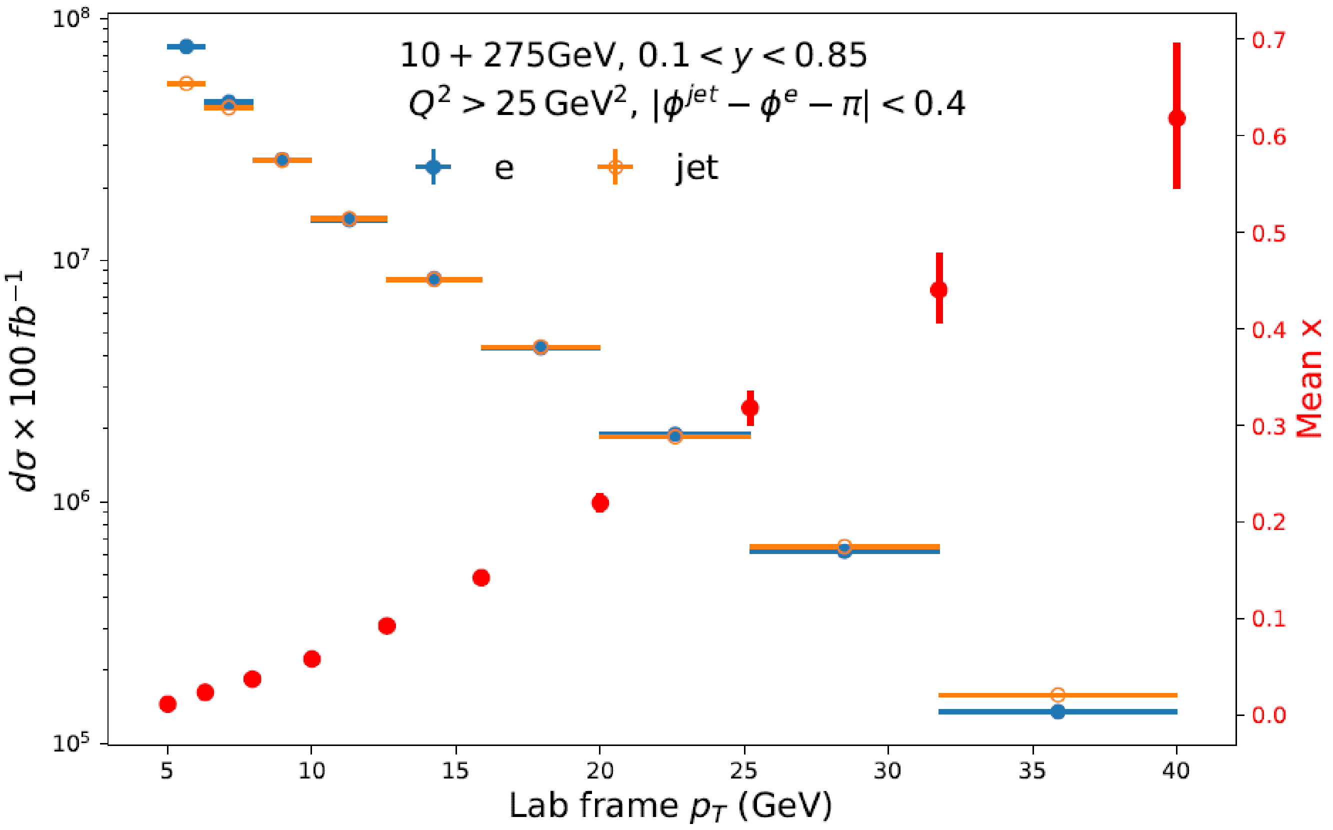


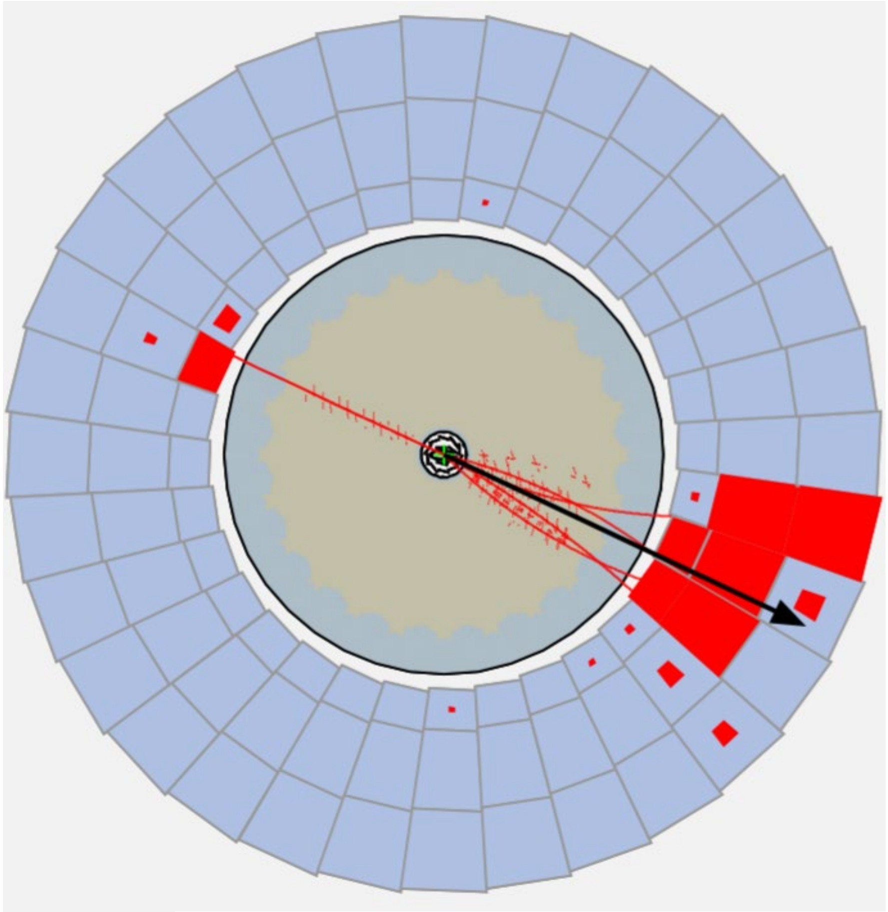
FIG. 1. Lepton-jet correlation for the tomography of the nucleon or nucleus at the EIC.

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

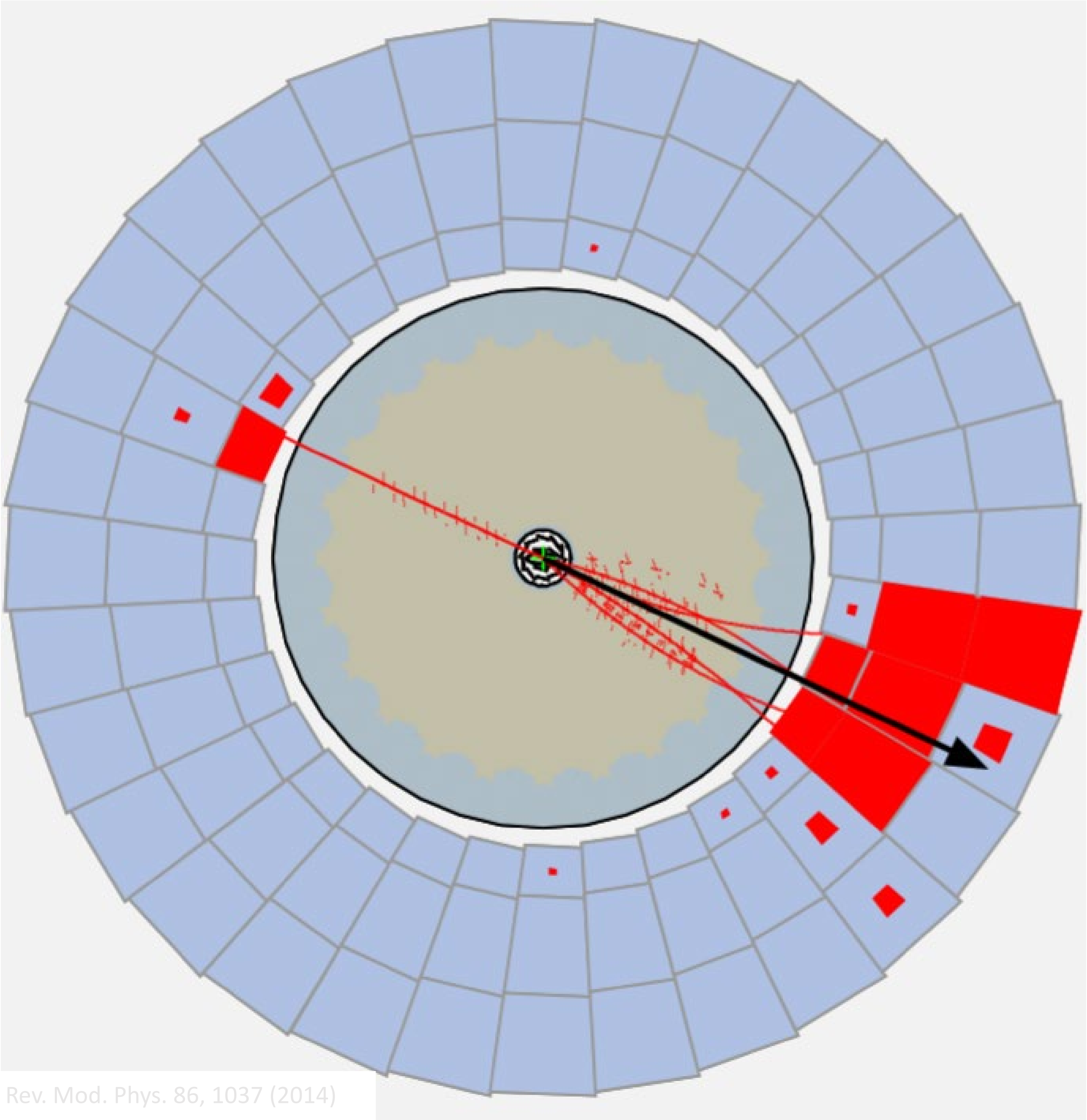
Kinematics



This provides sensitivity to parton transverse momentum…



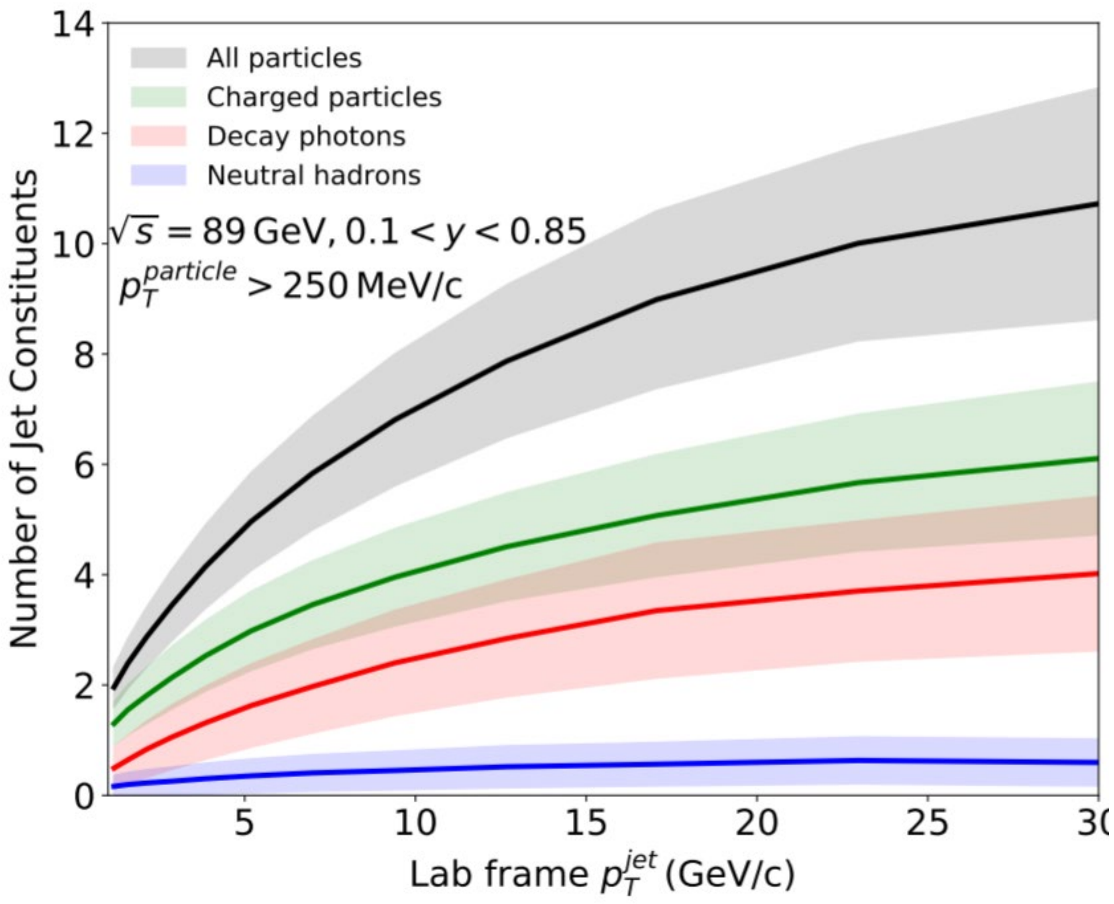
Rev. Mod. Phys. 86, 1037 (2014)

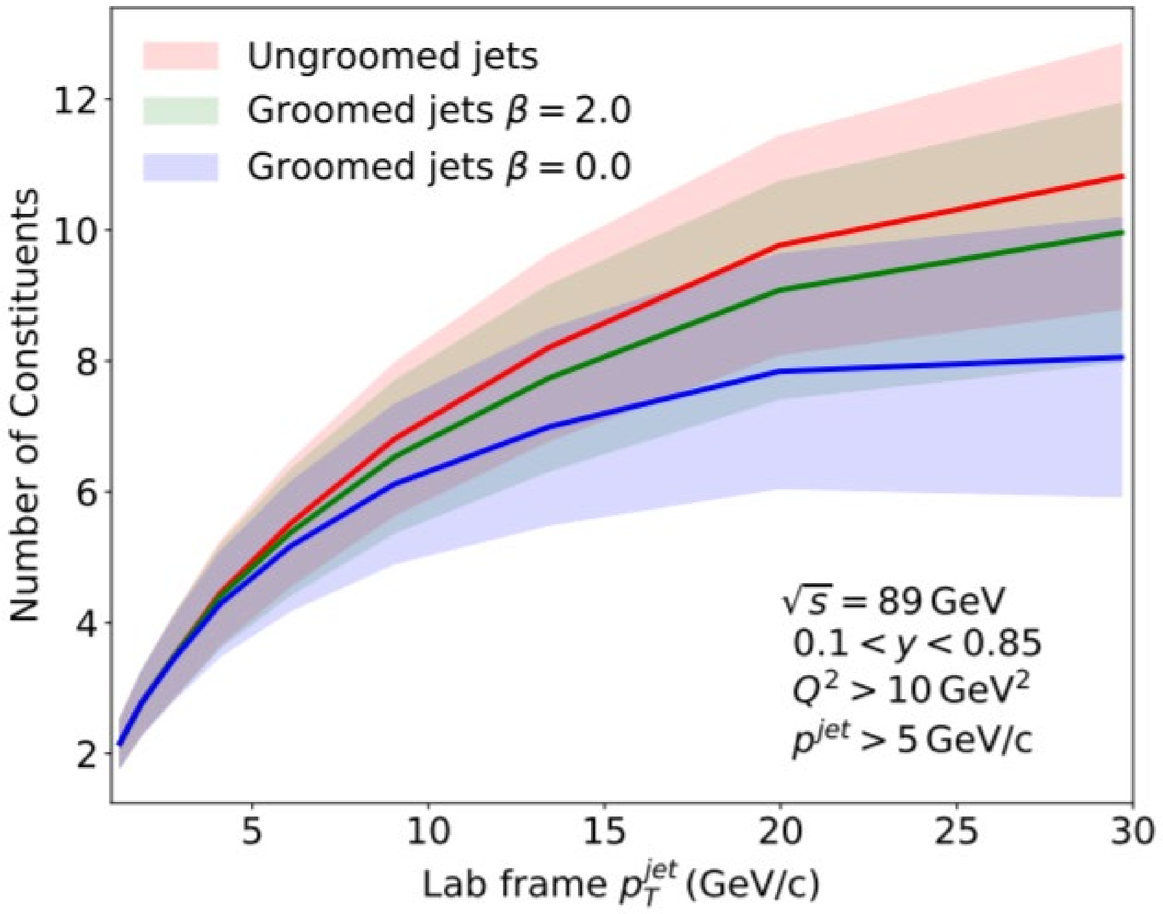


Rev. Mod. Phys. 86, 1037 (2014)

Their Calibration, Our Signal (for quark TMDs)

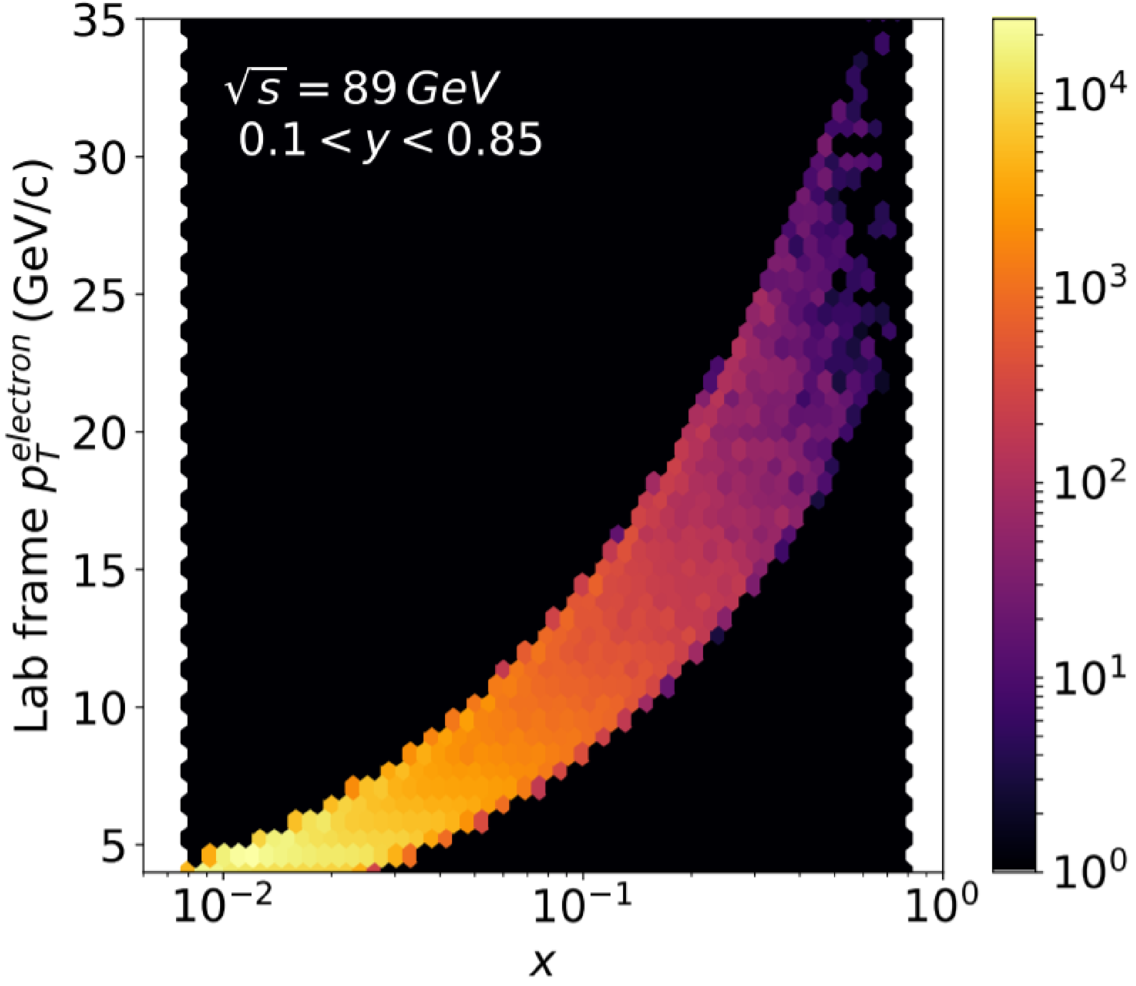
Number of constituents *Arratia et al. arXiv:1912.05931*

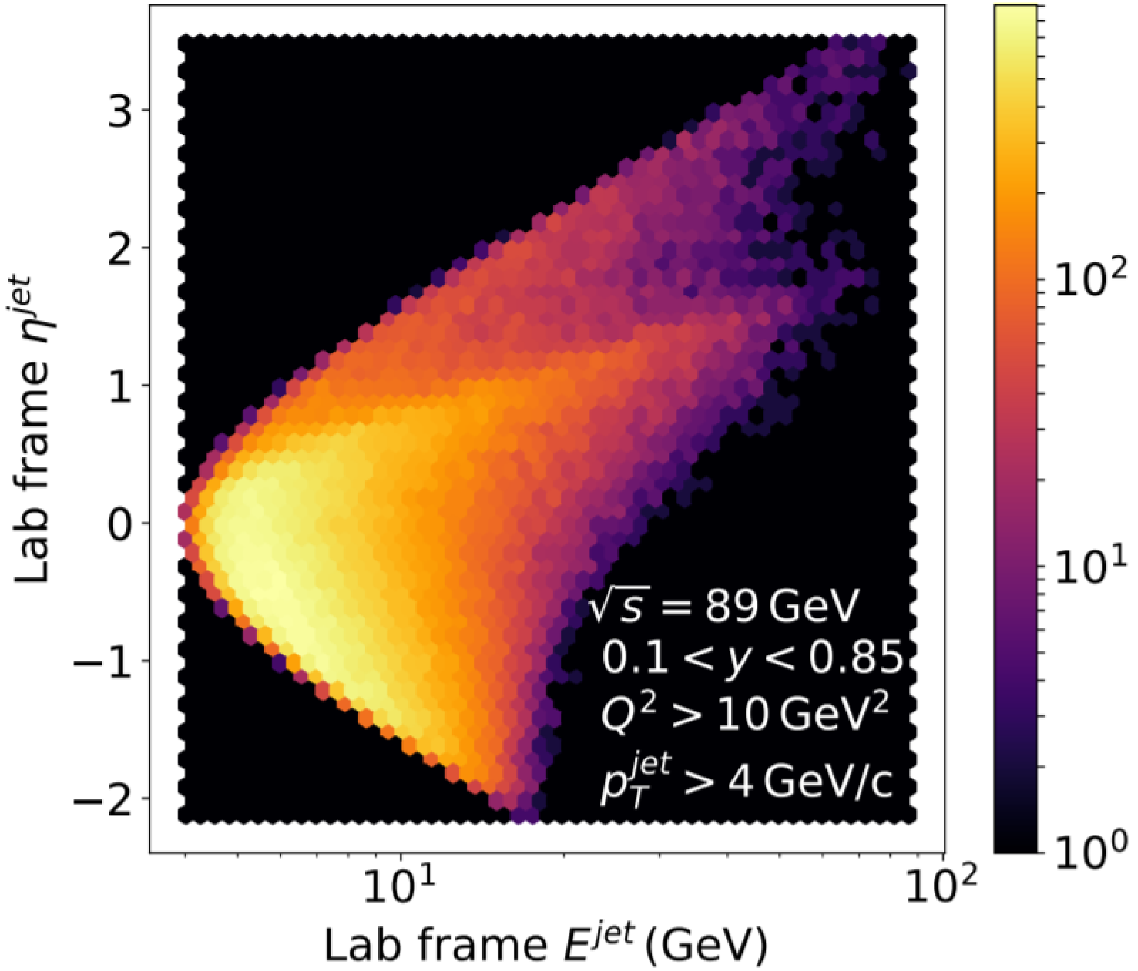




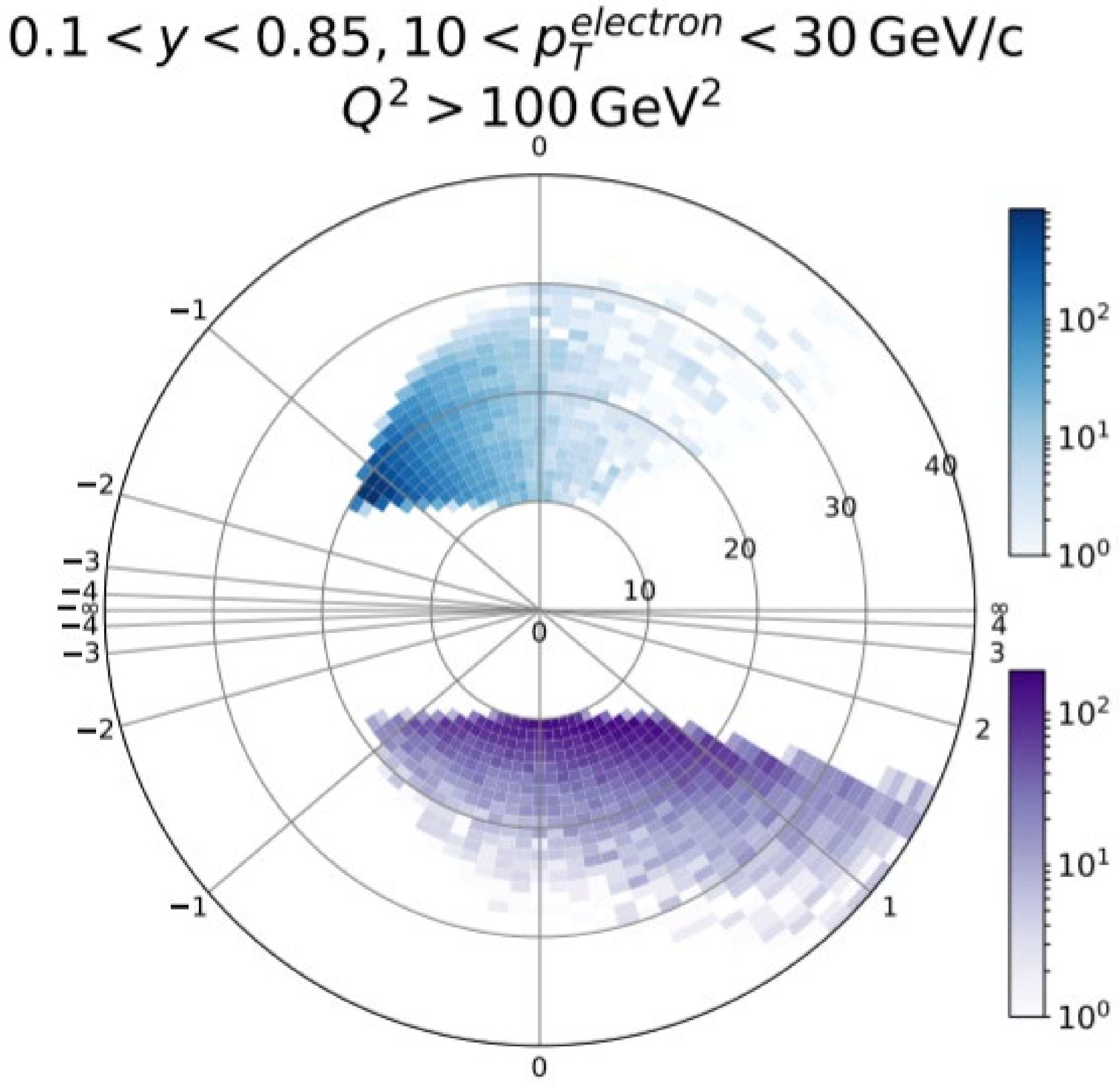
Kinematics

Arratia et al. arXiv:1912.05931





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

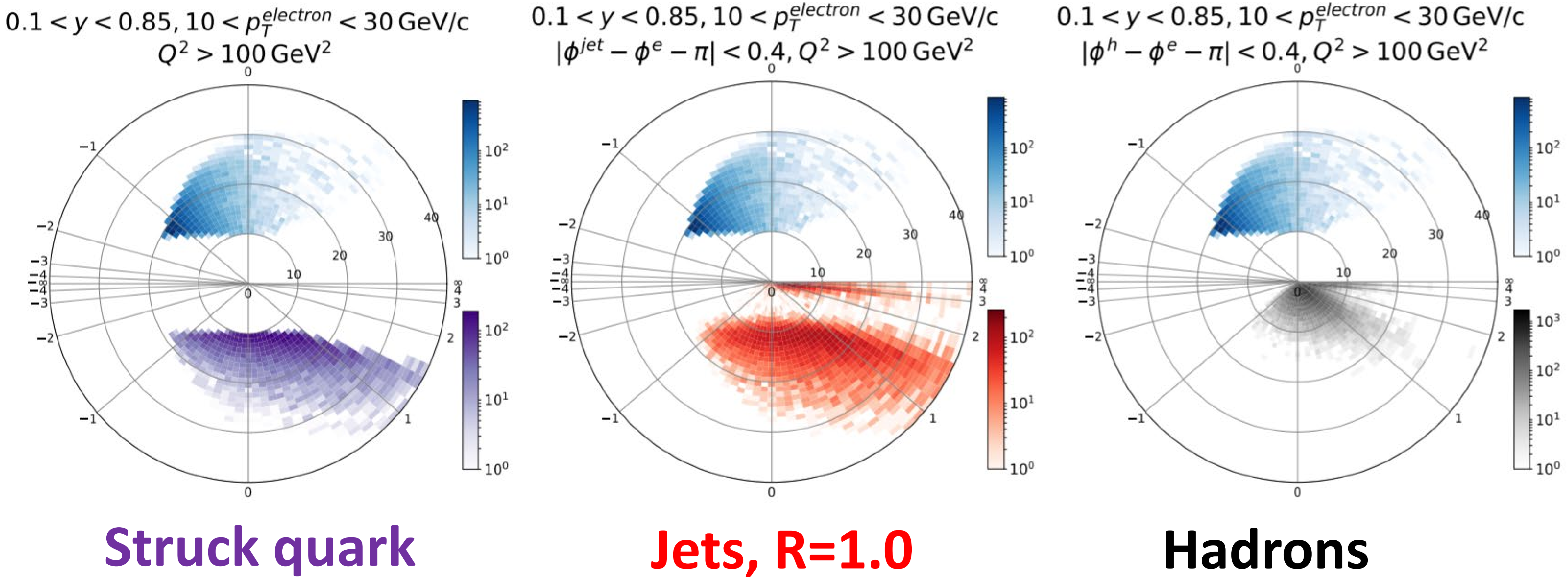


Electron

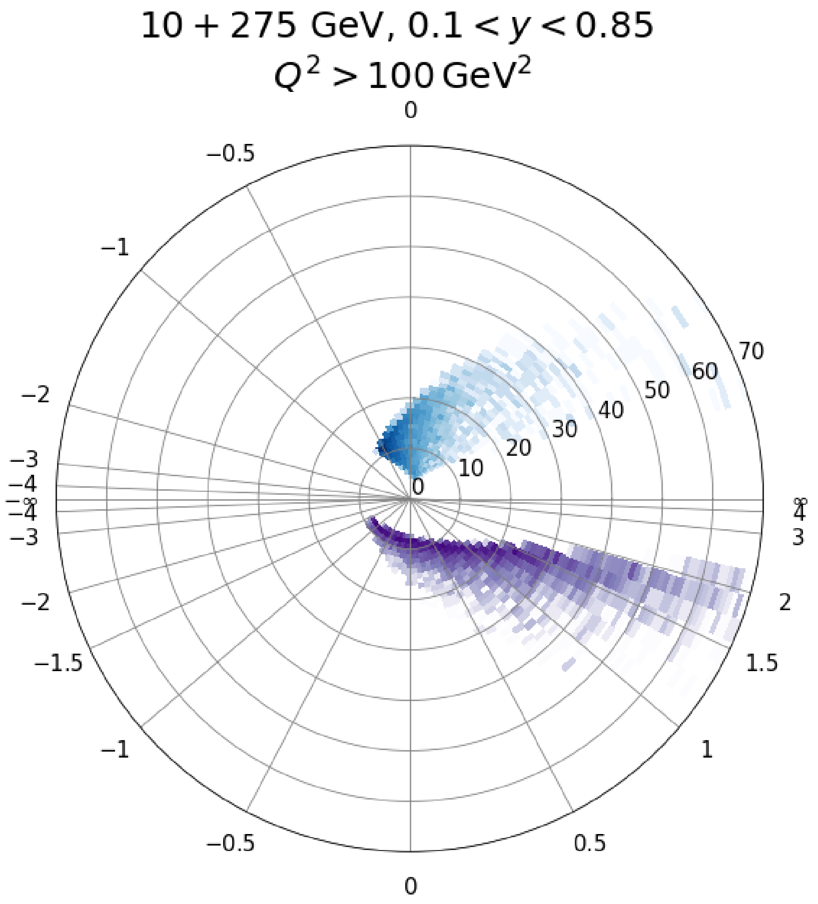
Struck quark

Jets are excellent proxies for quark kinematics

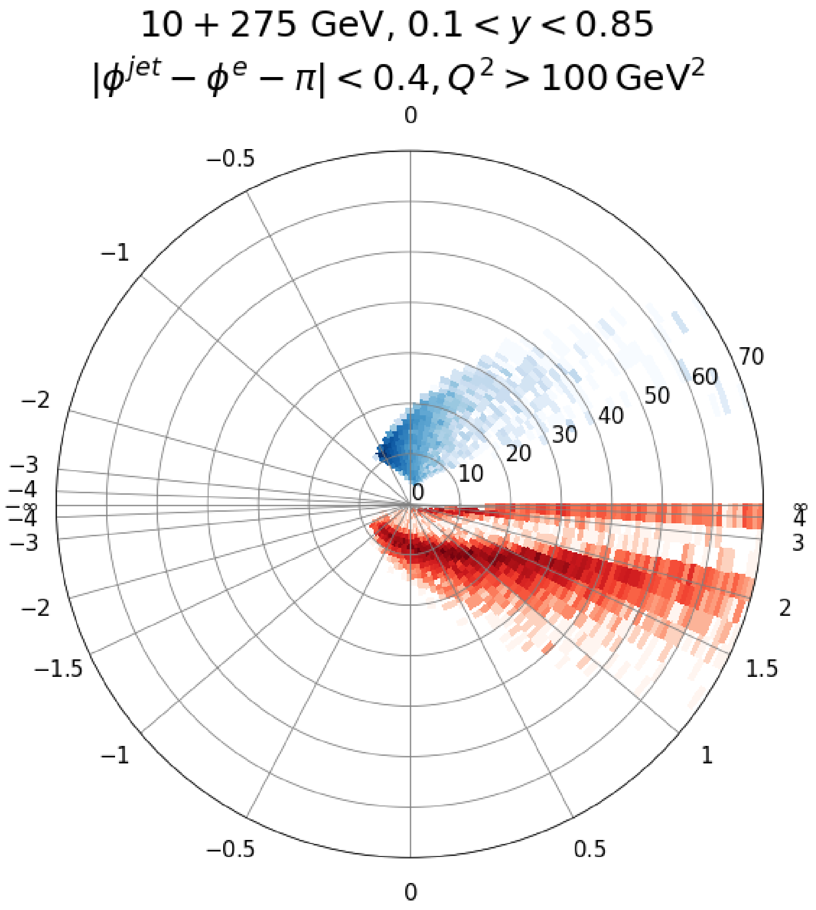
Arratia et al. arXiv:1912.05931



Optimal configuration for luminosity:

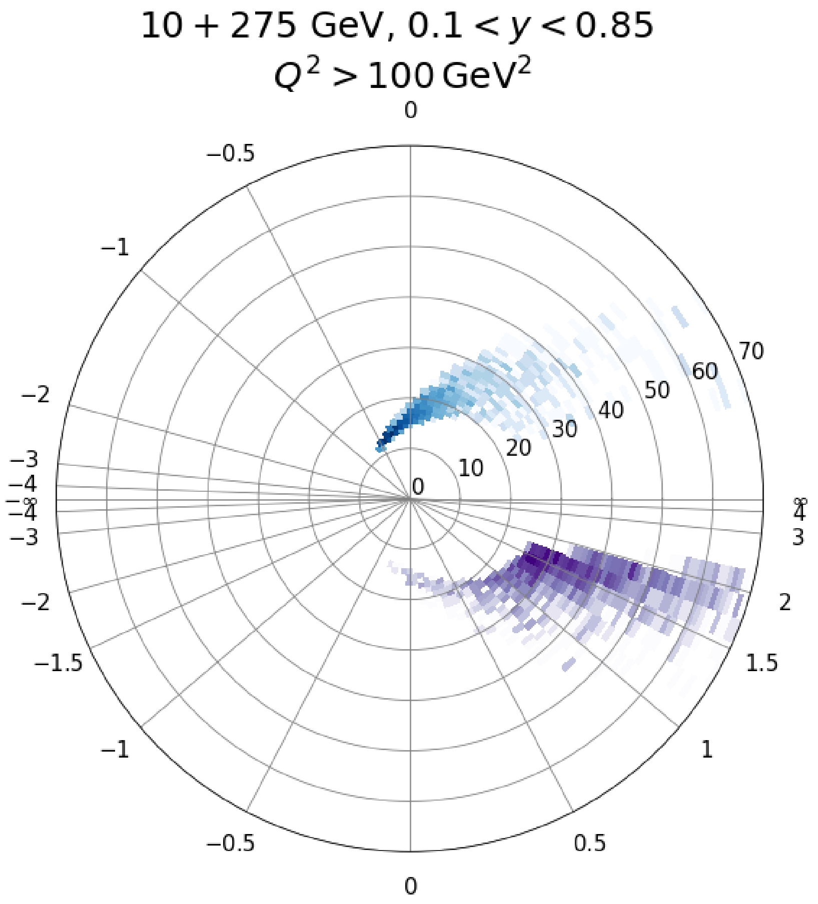


Struck quark

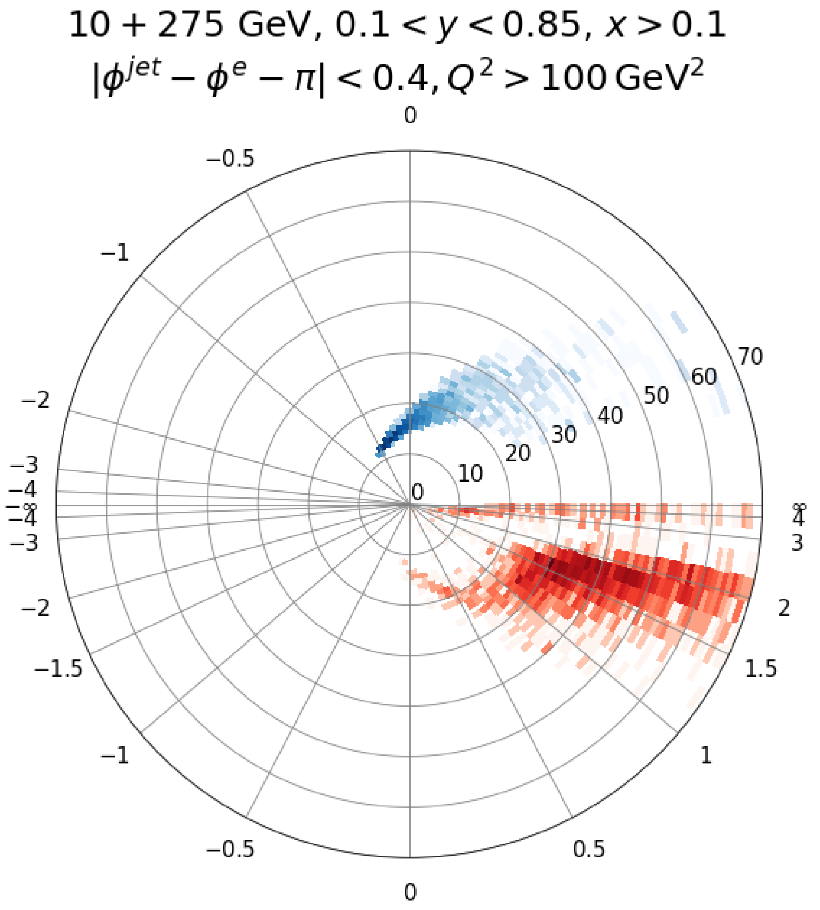


Jets, R=1.0

Focus on the large x



Struck quark

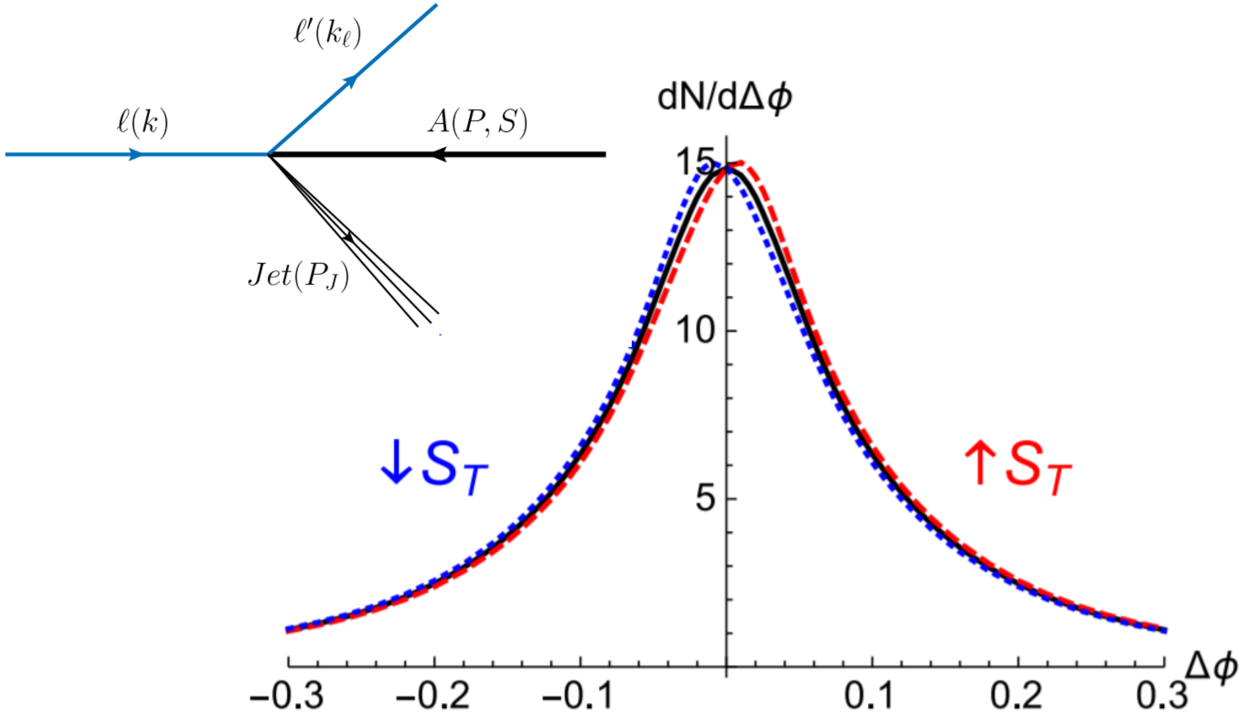


Jets, R=1.0

What can we learn from jets measurements?

Direct measurement of quark Sivers effect with jets

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



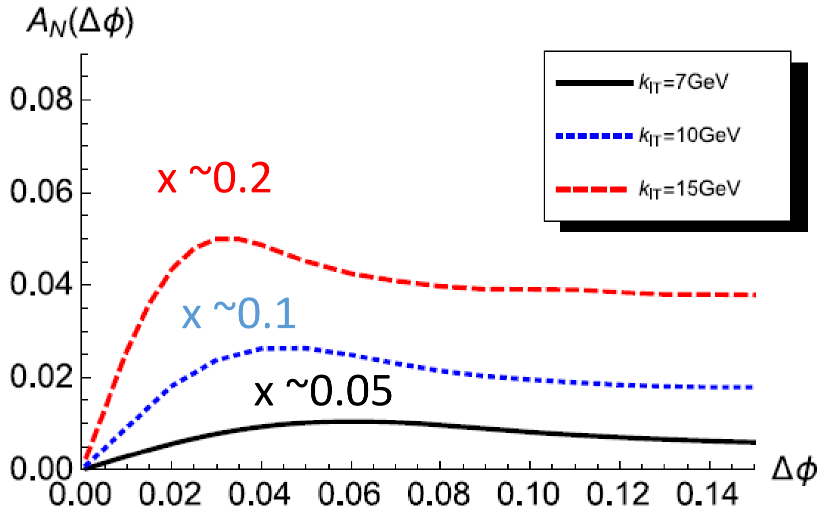
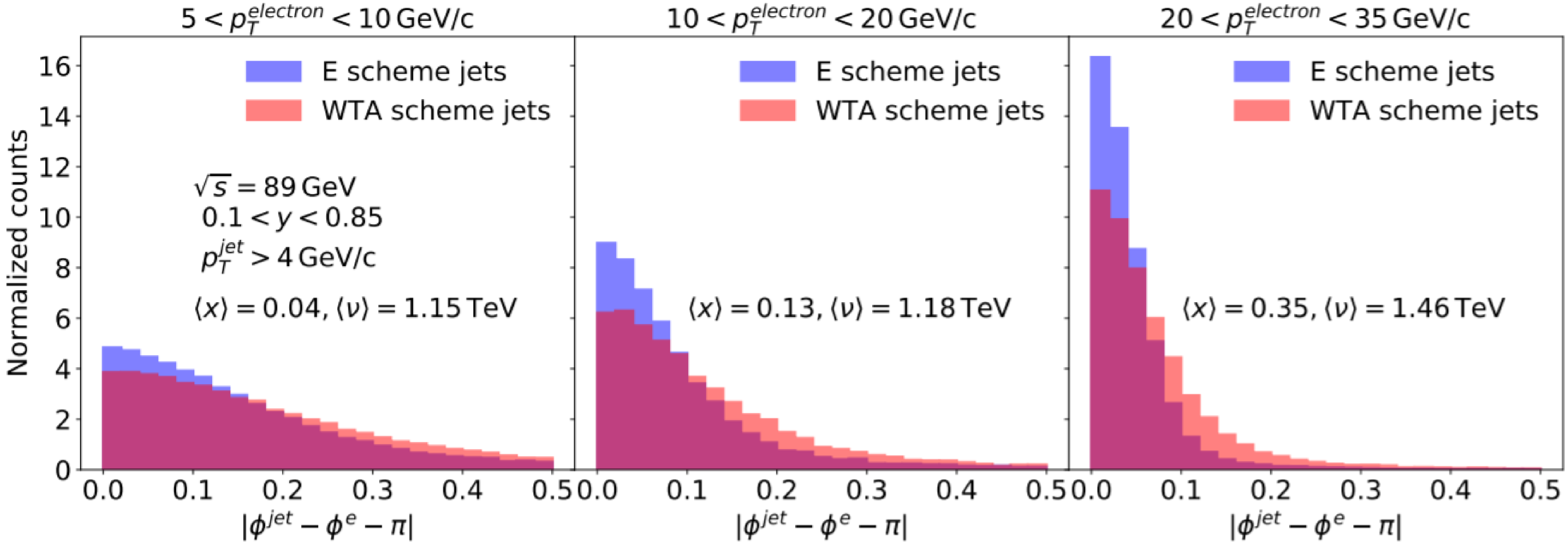


FIG. 3. The single transverse spin asymmetry as a function of $\Delta\phi = \phi_J - \phi_\ell - \pi$ for different lepton transverse momenta $k_{\ell\perp} = 7$, 10, and 15 GeV, respectively, which illustrates the transverse momentum dependence of the quark Sivers function.

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

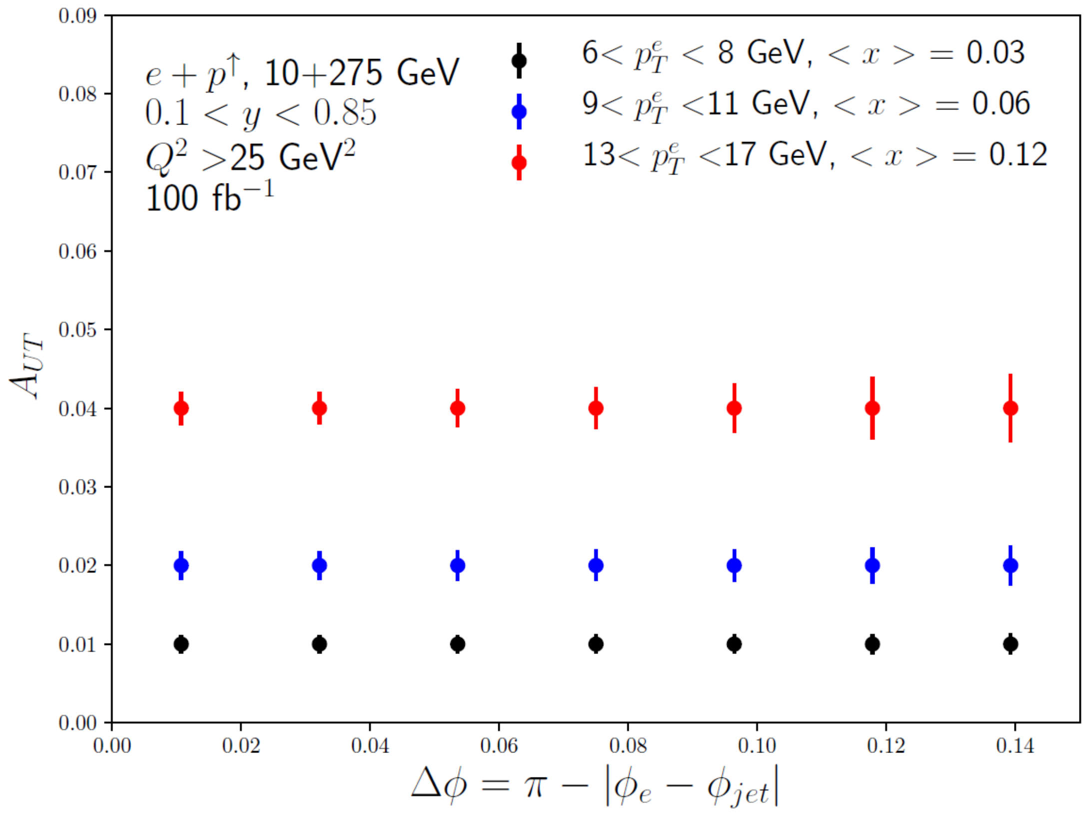
Electron-jet azimuthal correlations

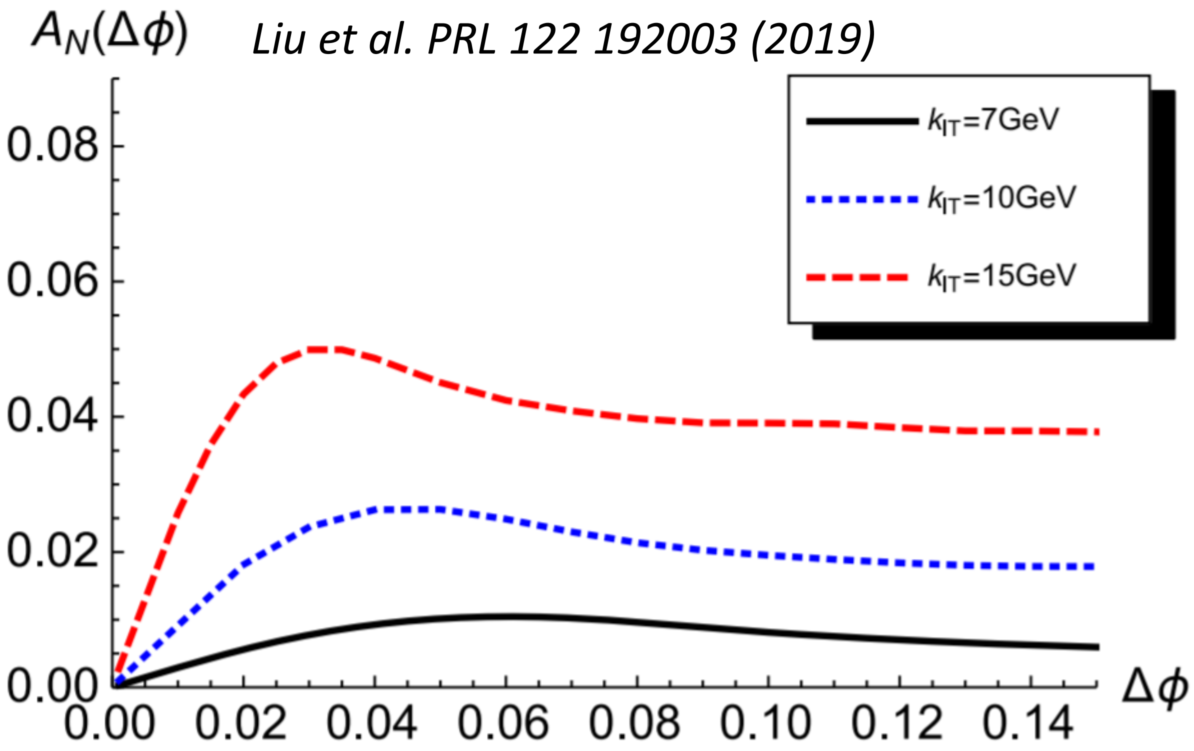
Arratia et al. arXiv:1912.05931



- The larger the electron transverse momentum, the narrower the peak. (difference between blue and red it not relevant for this discussion)

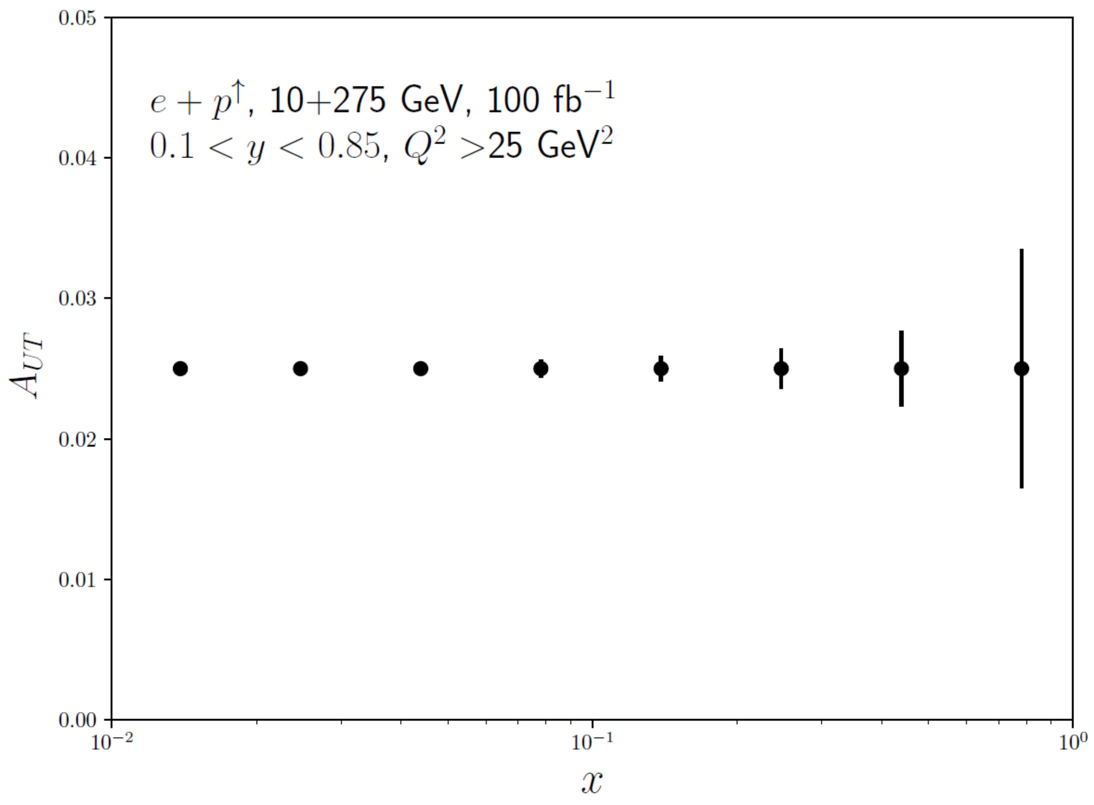
Statistical projection for Sivers effect with electron-jet correlations

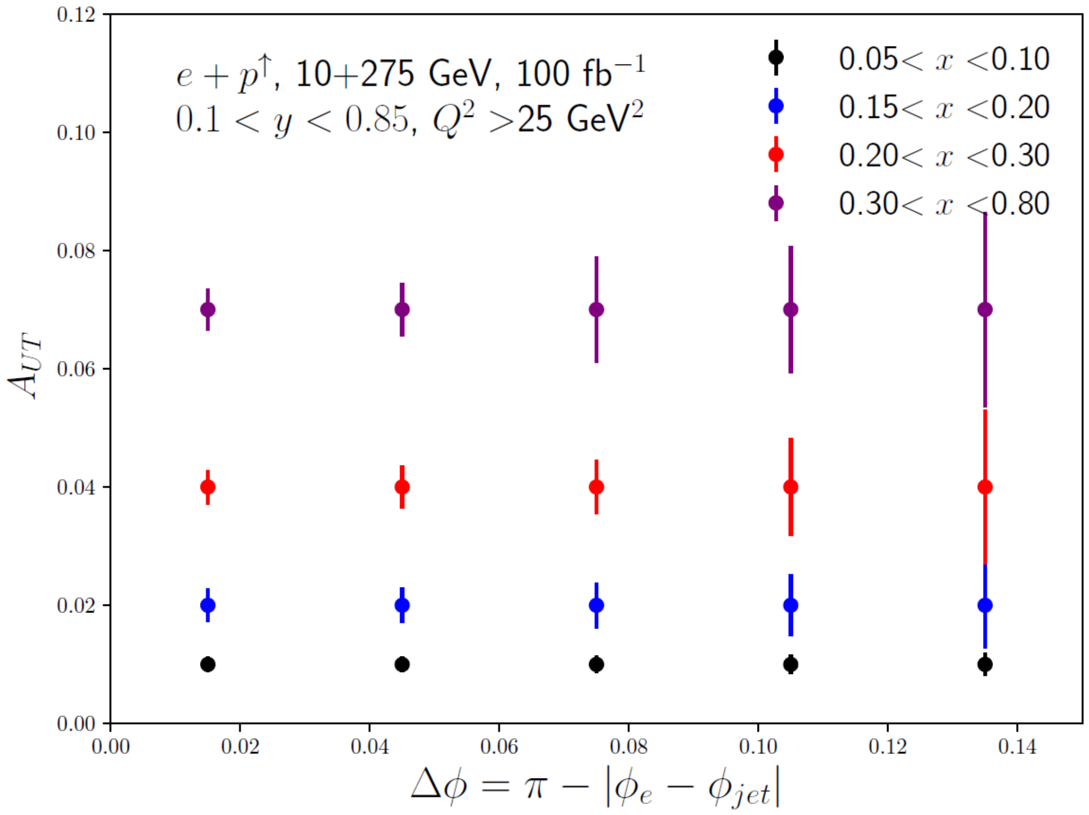




- Projections assume 100 fb-1, 70% polarization, 50% overall efficiency
- Excellent prospects for "direct" measurement of Sivers effect, most systematics cancel completely in the ratio

x-dependence of quark Sivers

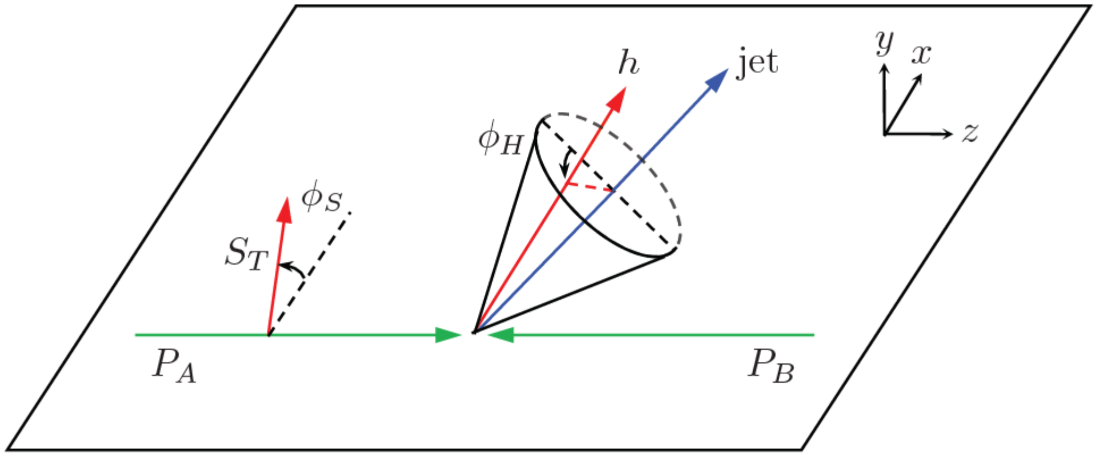




- Excellent kinematic coverage, precise data

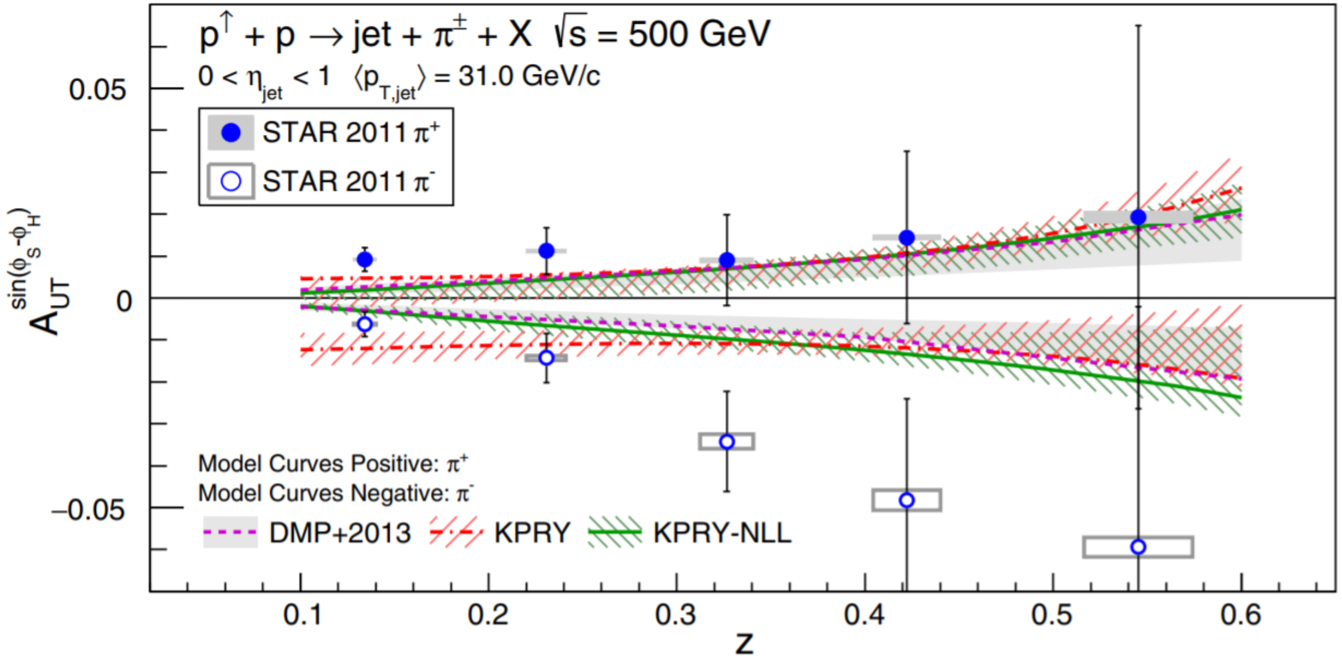
Transversity, h(x), with jets

distribution of transversely polarized quarks inside a transversely polarized nucleon



"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.

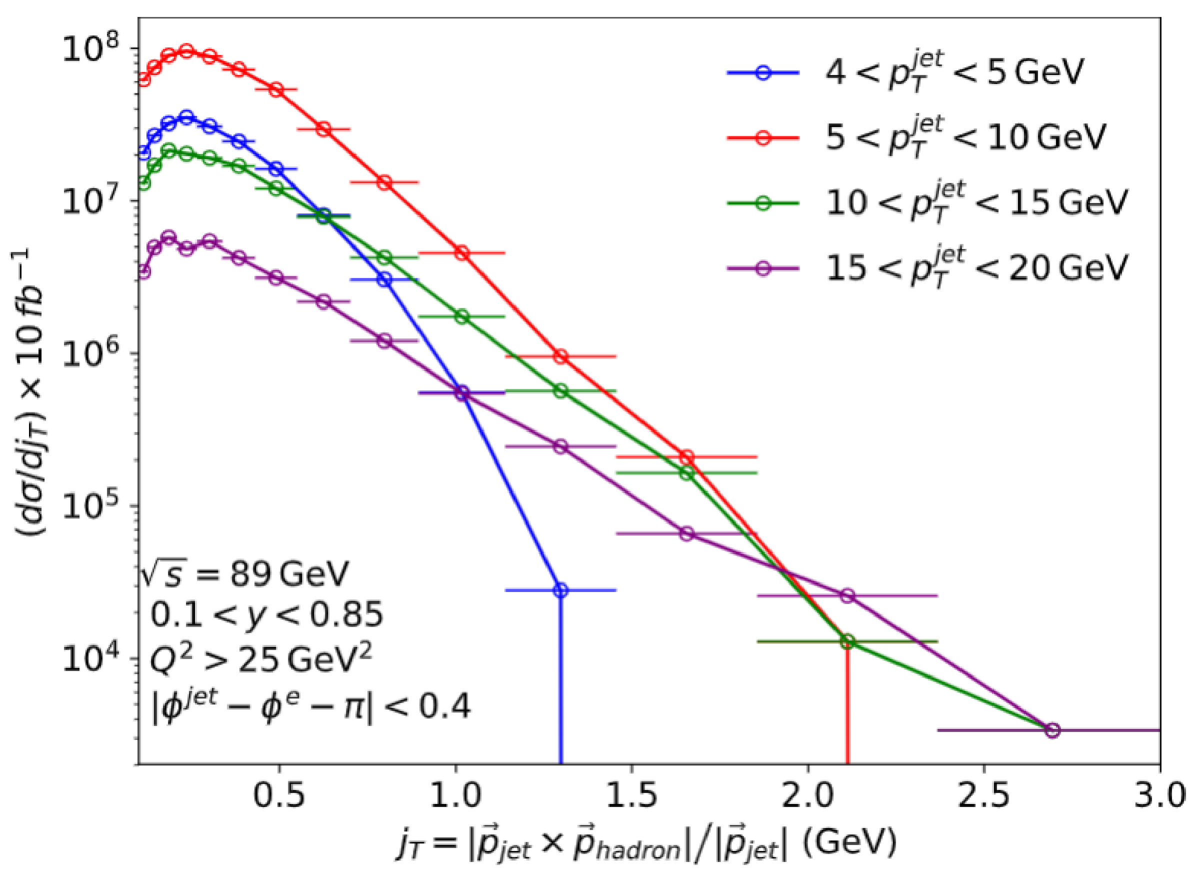
STAR Collaboration, Phys. Rev. D 97, 032004 (2018)

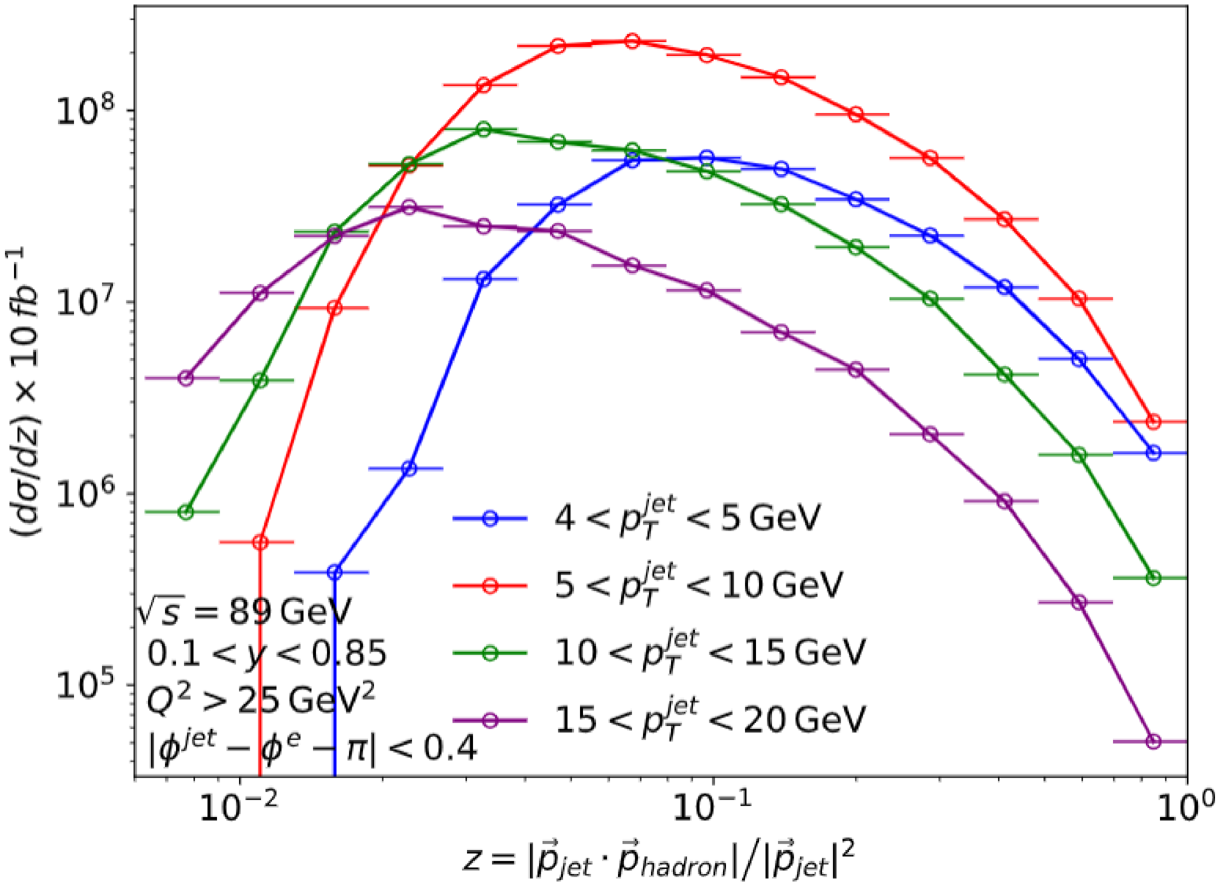


- Jet measurement crucial to factorize initial and final state TMD effects.
- At EIC, we could explore this observable with much higher precision, kinematic control. Tests of TMD evolution & universality; complements di-hadron measurements.

Hadrons-in jet @ EIC

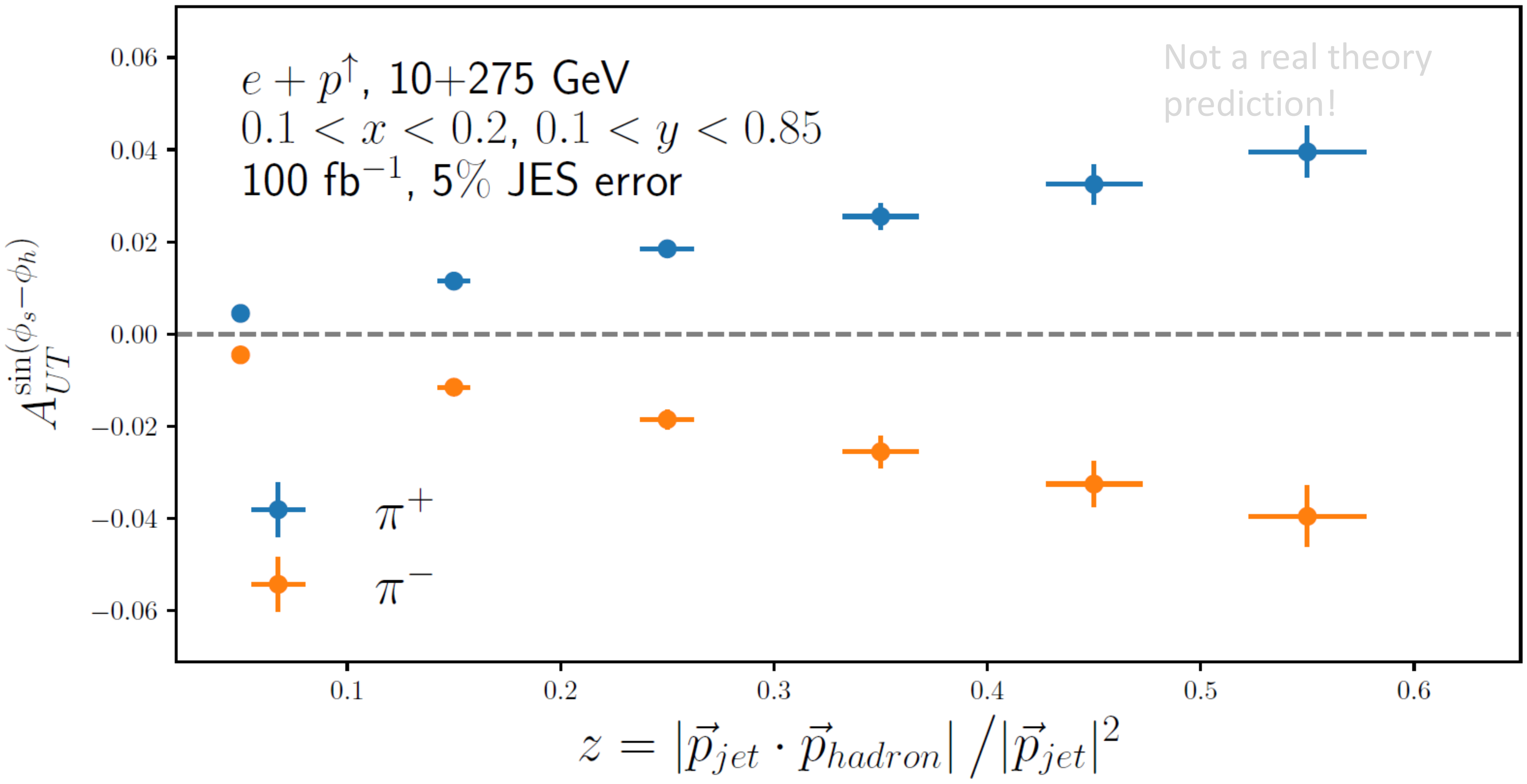
Plot by Youqi Song



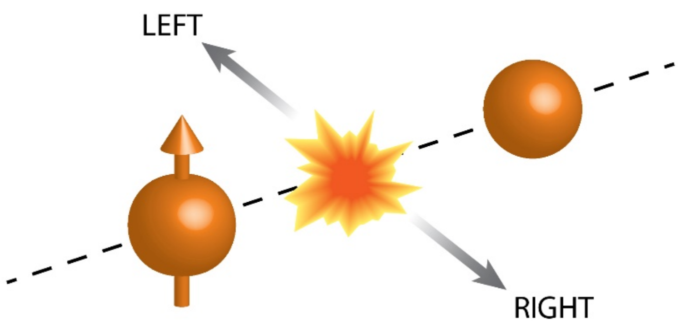


- Plenty of statistics!

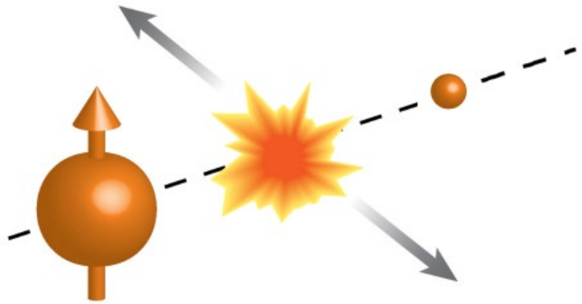
Hadron-in-jet statistical projection



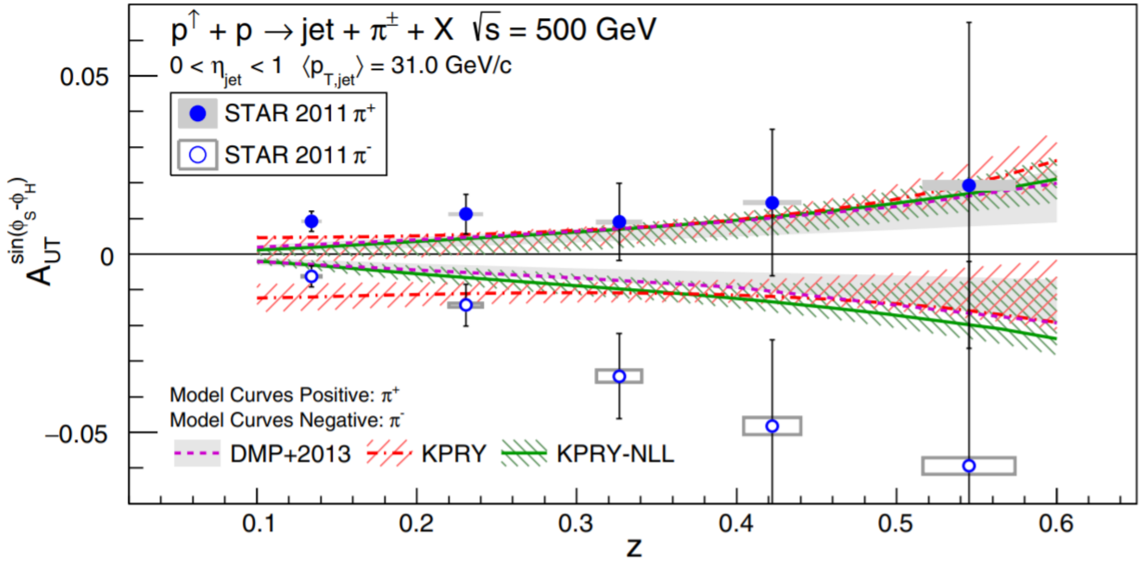
- Projections assume 100 fb-1, 70% polarization, 50% overall efficiency, sqrt(2) for statistical extraction of modulation



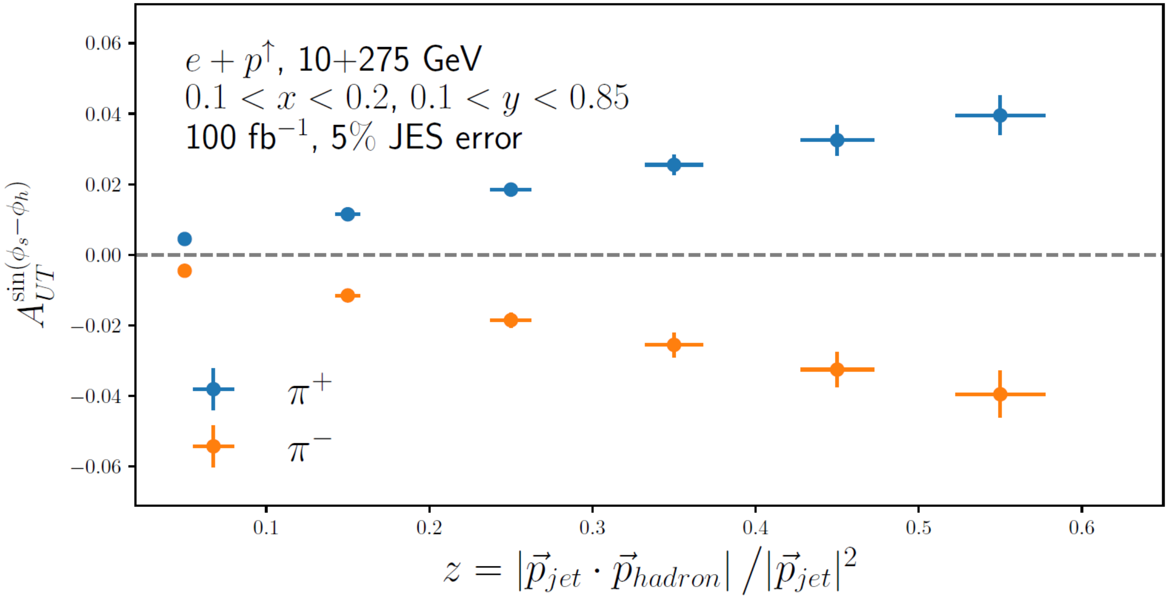
pp at RHIC



ep at EIC

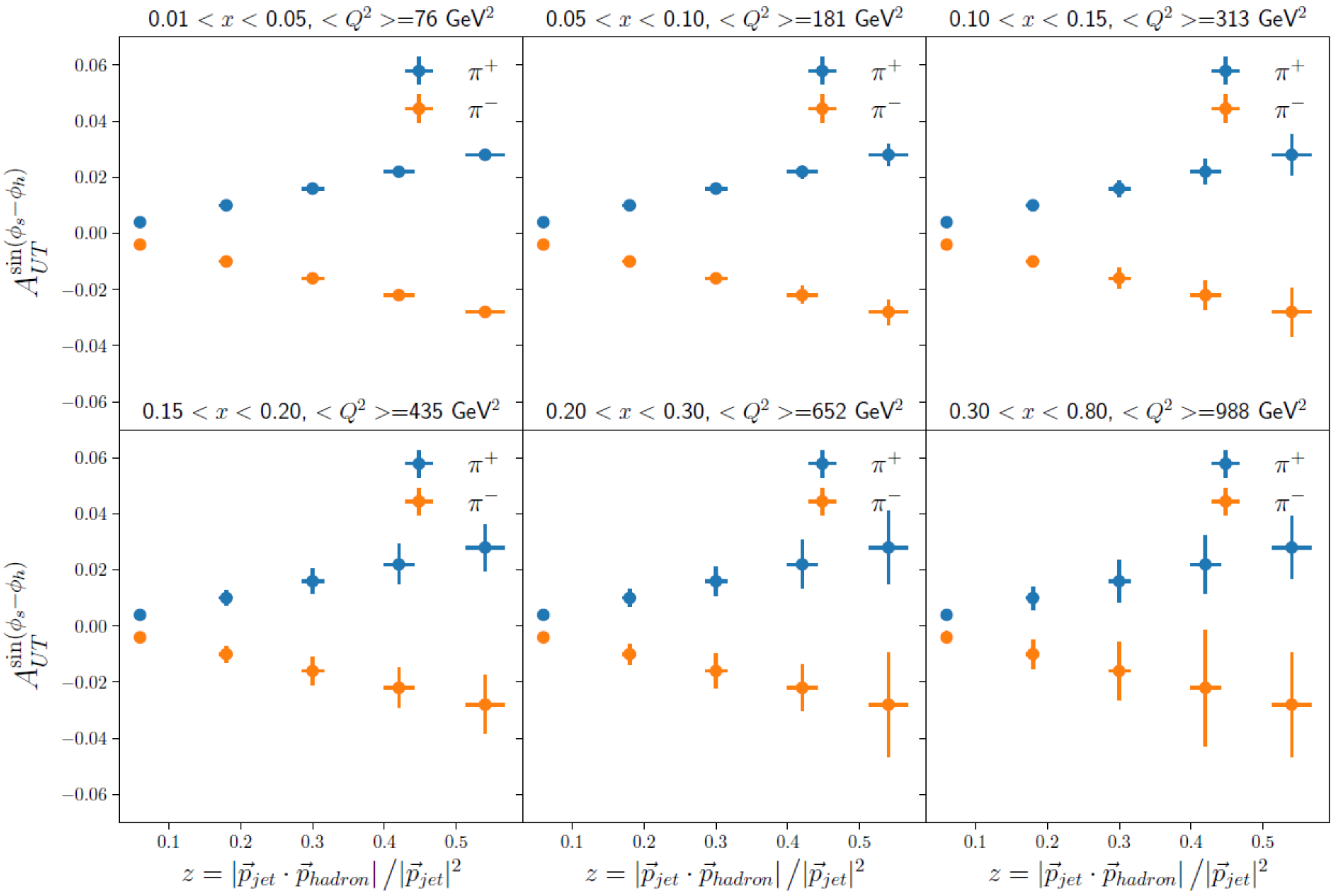


Phys. Lett. B 774, 635 (2017), Kang et al.

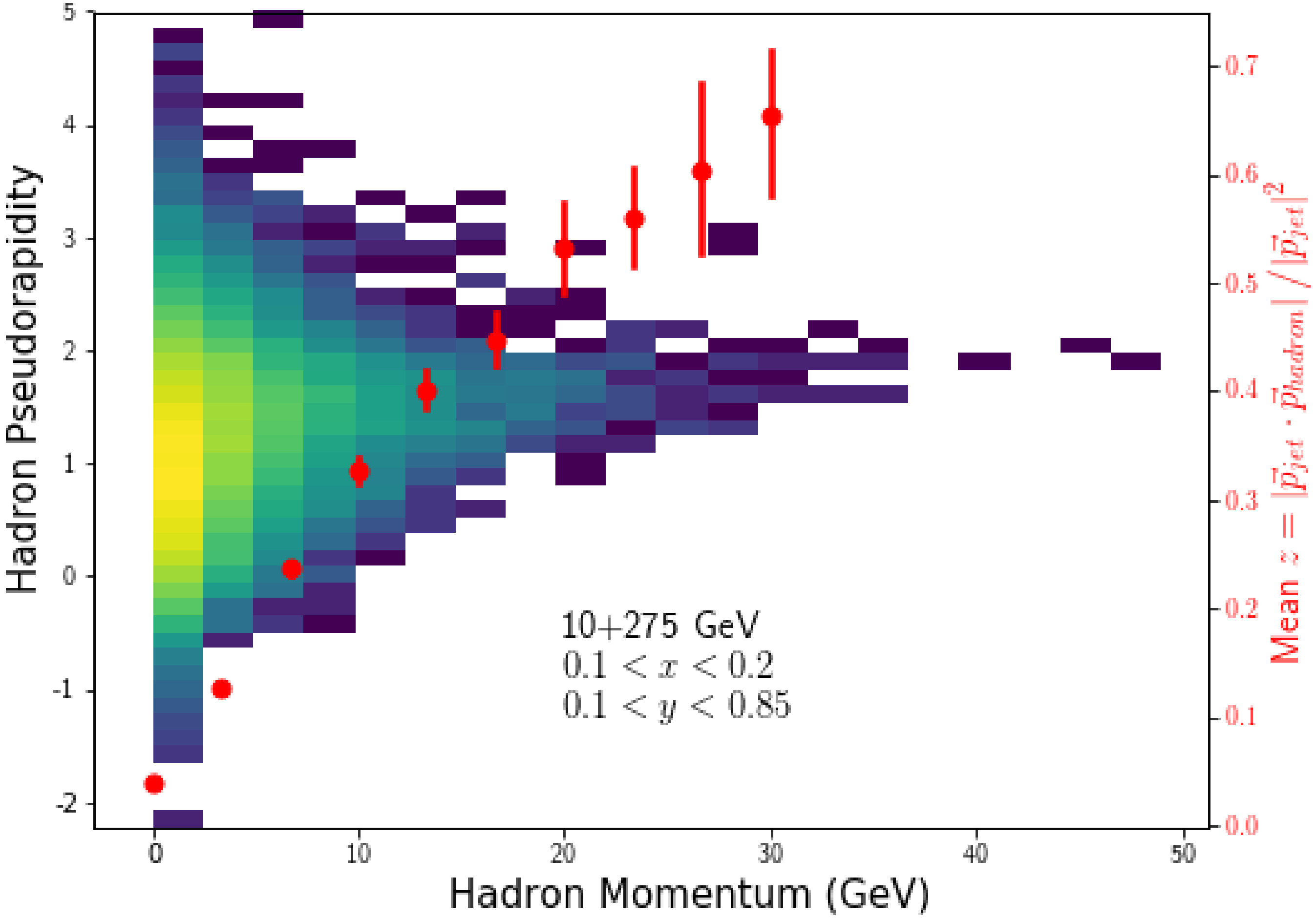


- **Most systematics cancel in the ratio…**

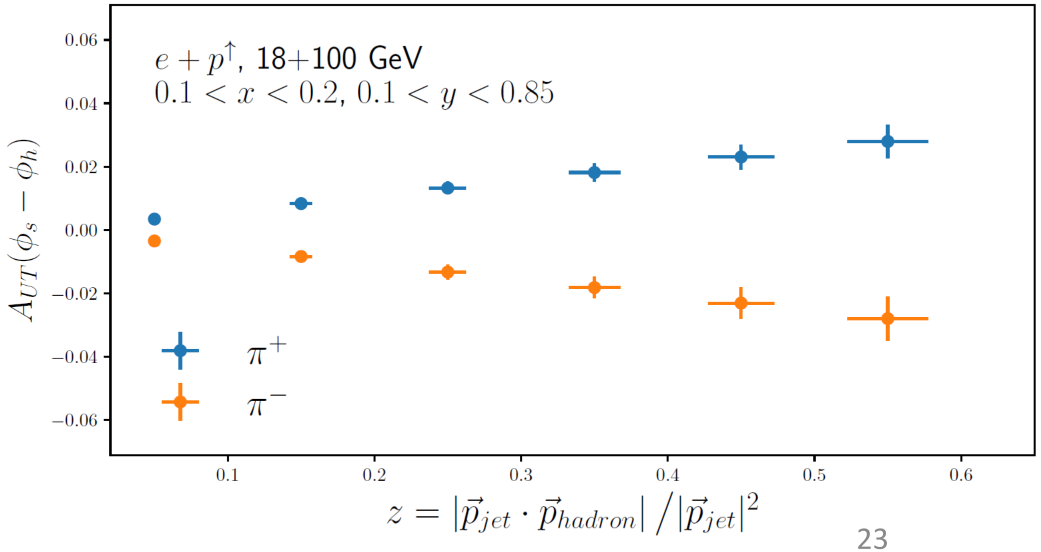
Covering the entire x-range relevant for transversity



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

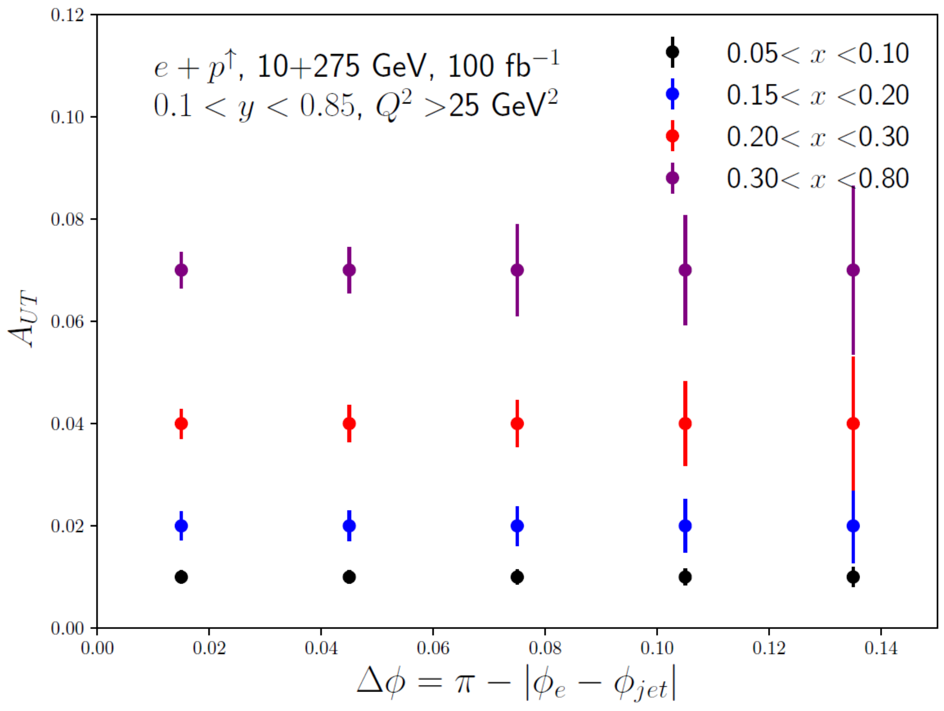


- <u>Mandatory</u> for this measurement. "Charged hadron" would not work.
- Charged pions separation from Kaons and protons up to ~30 GeV
- EMCAL granularity for pi0.

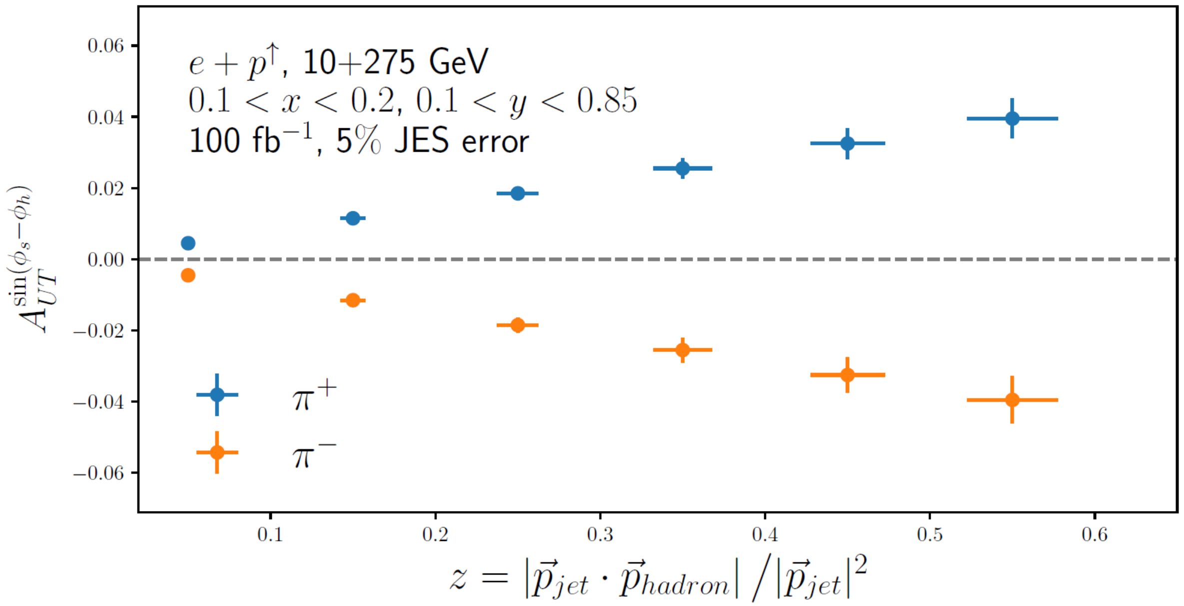


Proposed "money plots"

Quark Sivers



Quark Transversity



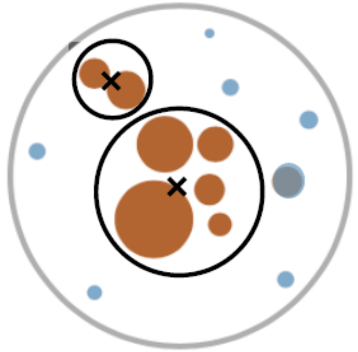
What else can we learn from jets measurements?

Dijets also yield sensitivity to gluon Sivers

gluon Sivers effects is limited. An alternative method using inclusive D mesons provides sensitivity to a gluon Sivers function with a magnitude of 10% of the positivity bound for a nominal integrated luminosity of $\mathcal{L}_{\text{int}} = 10\ \text{fb}^{-1}$. But the smearing between the parton-level and measured asymmetries is significantly increased. The high-p_T charged dihadron channel is statistically more favorable and can resolve a magnitude of the gluon Sivers function down to 5% of the positivity bound. The most precise analyzer for the gluon Sivers effects at an EIC is the dijet channel; due to its statistical advantage it provides the best sensitivity even for the small Sivers effects and can span the largest Q^2 range to study TMD evolution effects. Due to its tight correlation between parton and jet kinematics, it has the smallest dilution between the parton-level and measured asymmetries. Overall it is thus the most promising experimental channel to determine and study all features of the gluon Sivers effect at the future EIC.

Zheng, Zhong, Aschenauer, Lee, Xiao, Yin
Phys.Rev. D98 (2018) no.3, 034011

Jet substructure, the key to novel TMD studies?



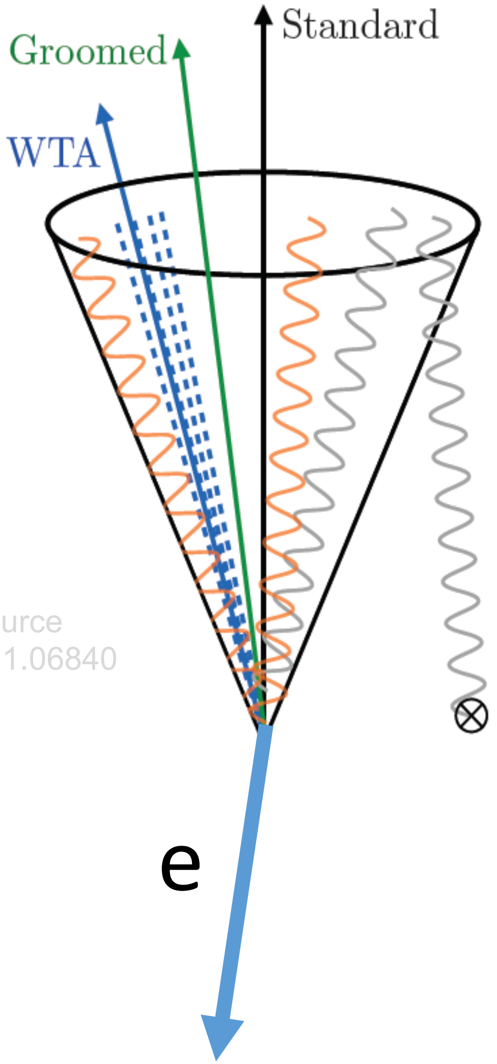


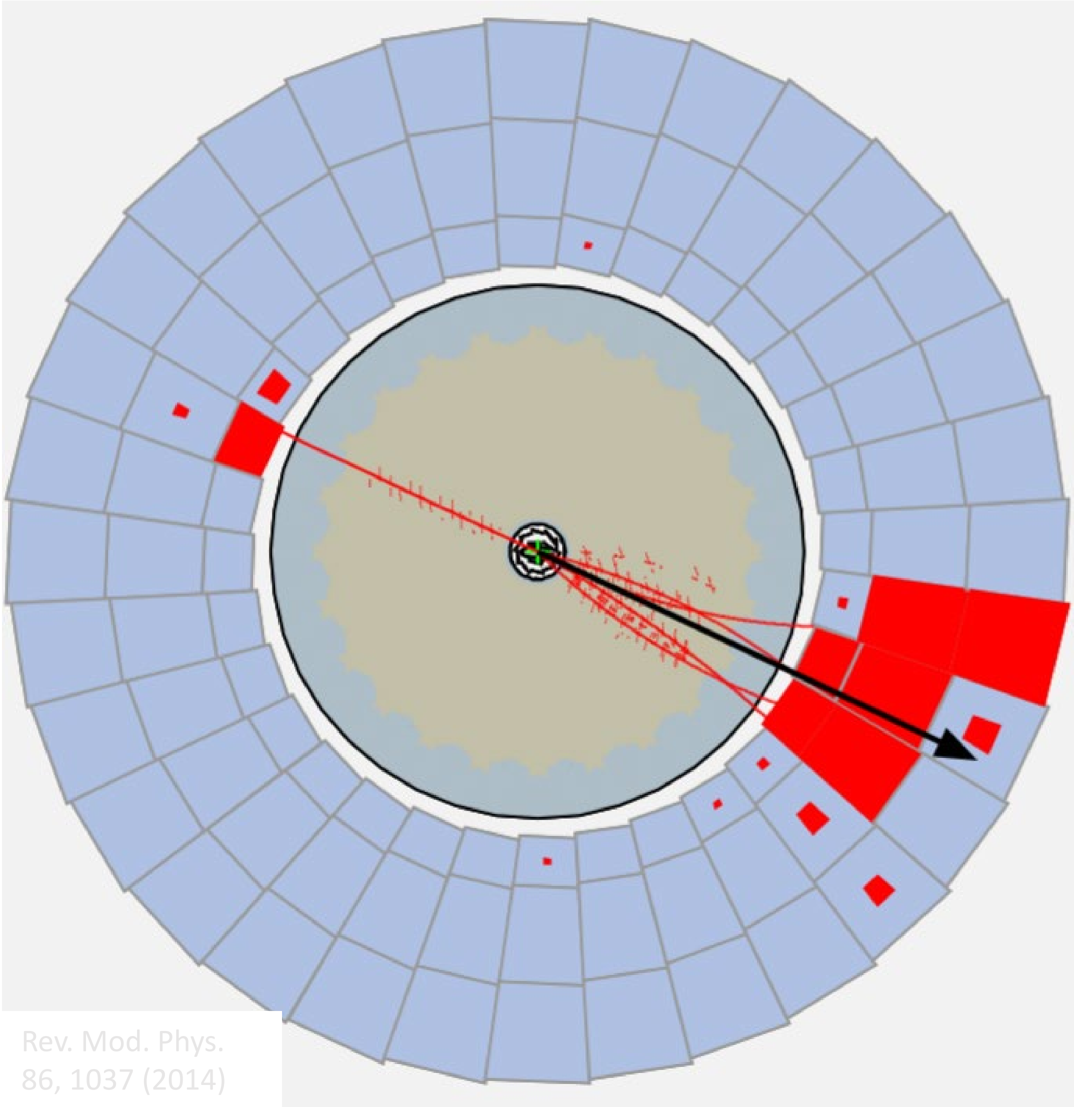
Image source arXiv:1911.06840

- "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 .

Can jet technology do for 3D imaging what it did to heavy ions in the past decade?

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.



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

bnl.gov/jetobs20/index.php

Motivation

As the realization of an Electron Ion Collider moves forward, efforts from the nuclear physics community continue to grow. In addition to the ongoing detector R&D efforts, plans for novel analysis topics must be demonstrated to aid in the detector designs, so that we can maximize the physics output of the EIC. This relies on input from both the experimental and theory communities. The aim of this workshop is to gather experts as well as those with a developing interest in the EIC so that theorists and experimentalists with experience measuring jets in a variety of hadronic collision systems can discuss the possible advantages and challenges of making measurements of jets in e+p and e+A collisions at the EIC.

In recent years, measurements at RHIC and LHC have demonstrated that reconstructed jets are a robust probe of QCD physics. Meanwhile, much progress has been made in understanding the usefulness of measuring jets at an EIC since the EIC white paper was written in 2011. However, one limiting factor in furthering these studies is

- This will have a very significant TMD/spin section.
- We might make it online due to COVID19, in which case you are all welcomed to join.

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 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.

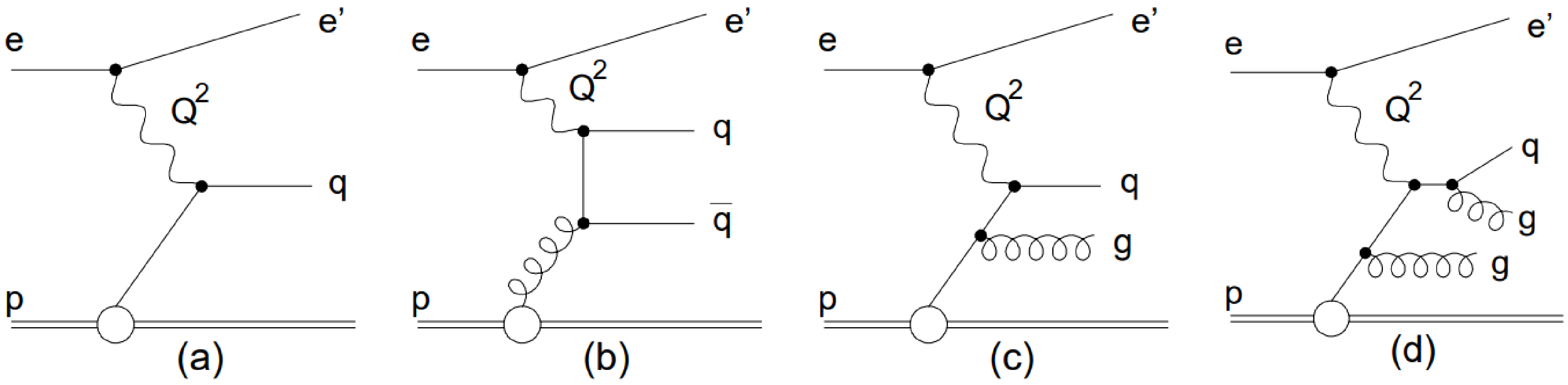
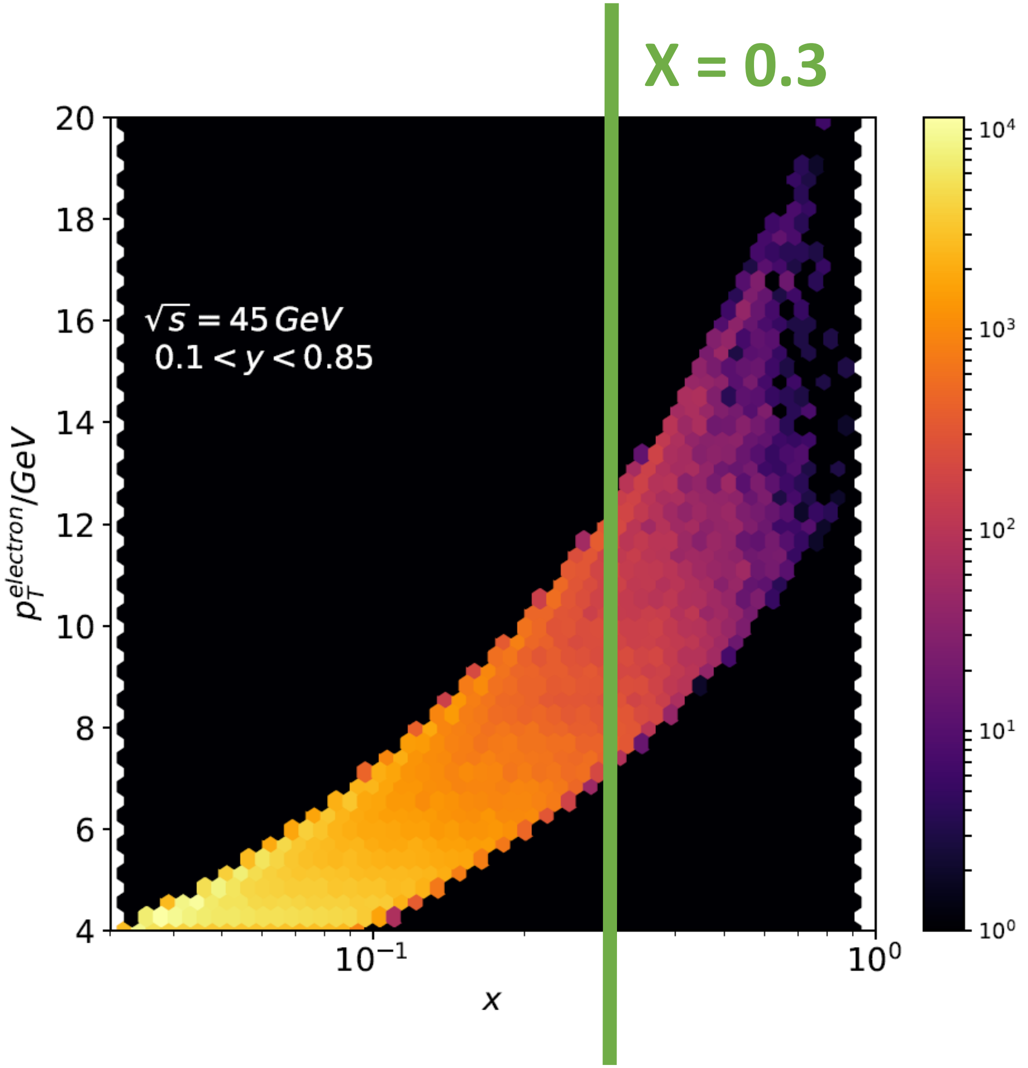
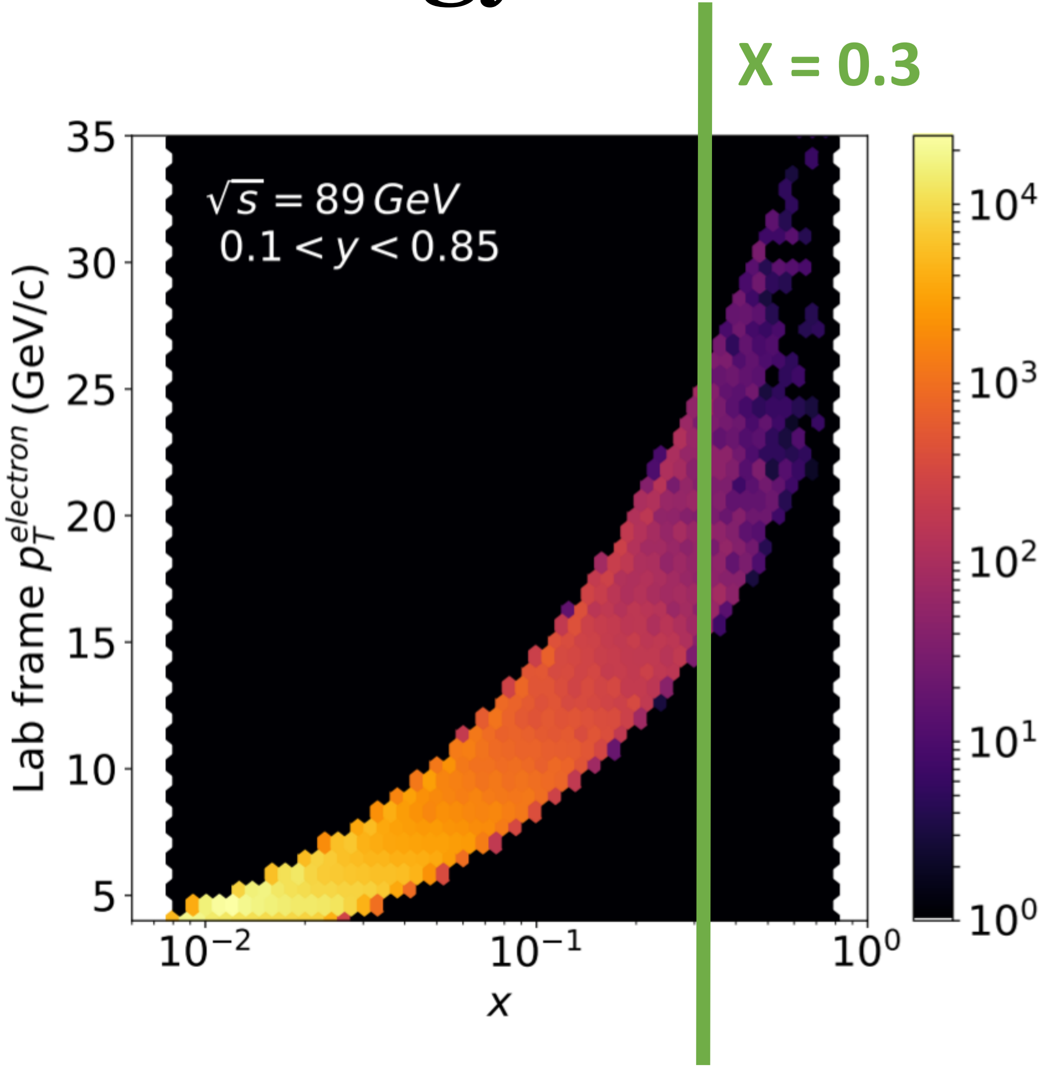


Figure 1: Deep-inelastic *ep* scattering at different orders in α_s: (a) Born contribution to inclusive NC DIS ($\mathcal{O}(\alpha_{\rm em}^2)$), (b) photon-gluon fusion ($\mathcal{O}(\alpha_{\rm em}^2\alpha_s)$), (c) QCD Compton scattering ($\mathcal{O}(\alpha_{\rm em}^2\alpha_s)$) and (d) a trijet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

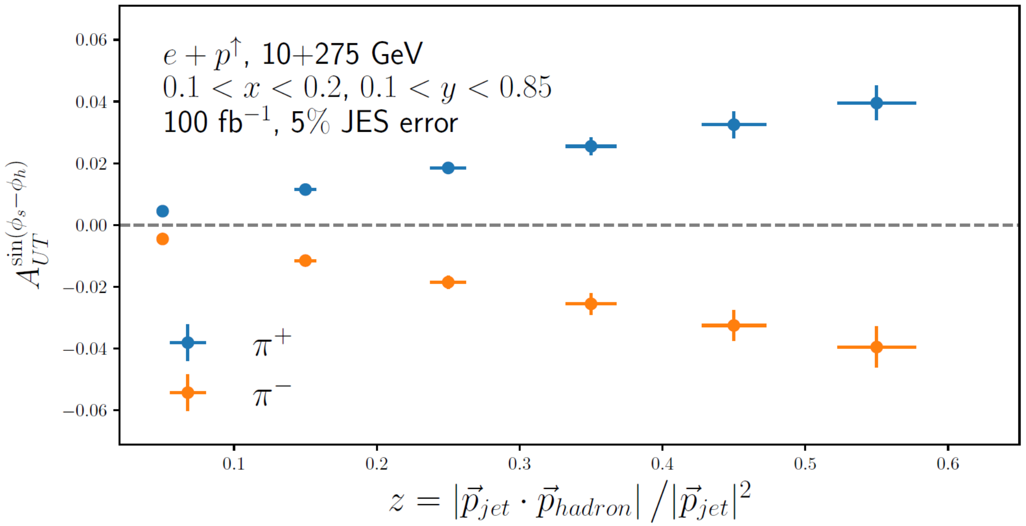
Spanning center-of-mass energy is crucial

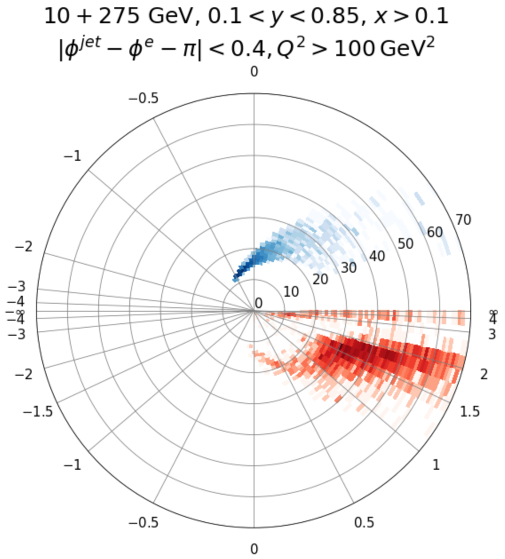




Jet uncertainties

- 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.





Transverse-Momentum-Dependent Distributions with Jets

Daniel Gutierrez-Reyes,[1] Ignazio Scimemi,[1] Wouter J. Waalewijn,[2,3] and Lorenzo Zoppi[2,3]

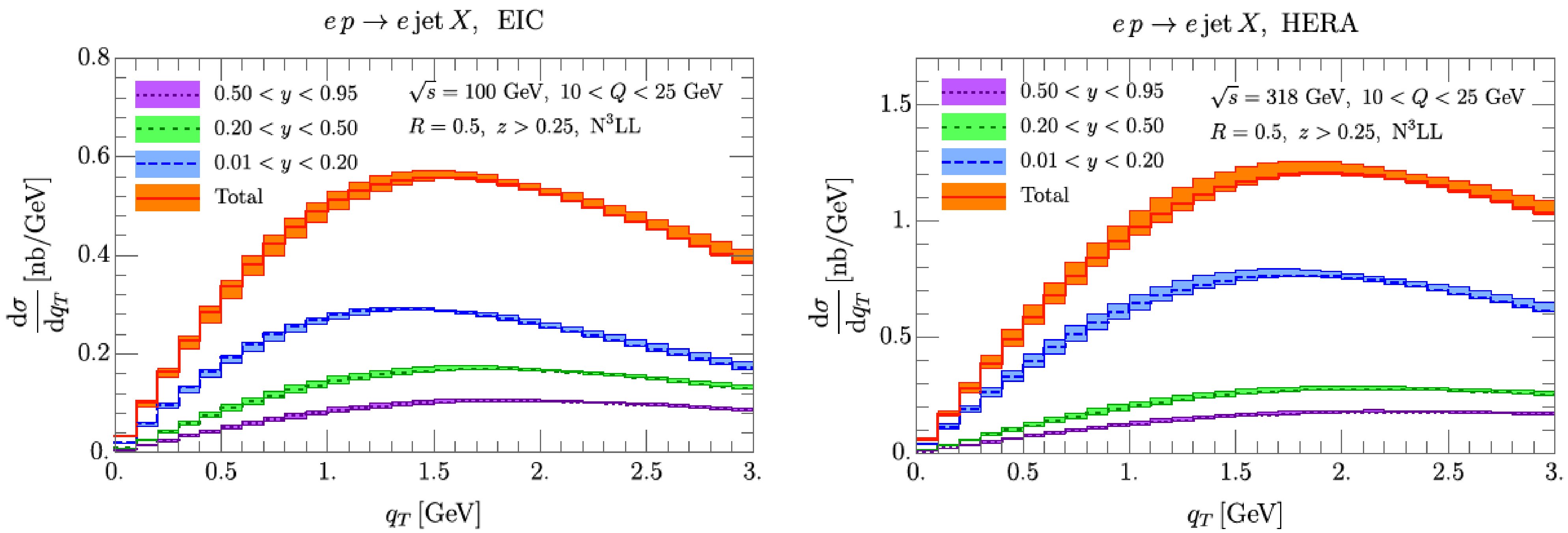
available. Our approach also applies to semi-inclusive deep inelastic scattering, where a jet instead of a hadron is measured in the final state, and we find a clean method to probe the intrinsic transverse momentum of quarks and gluons in the proton that is less sensitive to final-state nonperturbative effects.

evolution as TMD fragmentation functions. A particularly promising application is represented by SIDIS experiments, for which the factorization theorem is

$$\frac{d\sigma_{(eN\to eJX)}}{dQ^2 dx dz d\boldsymbol{q}} = \sum_a \mathcal{H}_a(Q^2,\mu) \int \frac{d\boldsymbol{b}}{(2\pi)^2} e^{-i\boldsymbol{b}\cdot\boldsymbol{q}} \times f_{a/N}(x,\boldsymbol{b},\mu,\zeta) J_q^{\text{axis}}(z,\boldsymbol{b},QR,\mu,\zeta), \quad (16)$$

enabling a clean extraction of the nonperturbative TMD parton distributions from this process. This factorization only holds for all R when the WTA axis is used.

“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__. “

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.

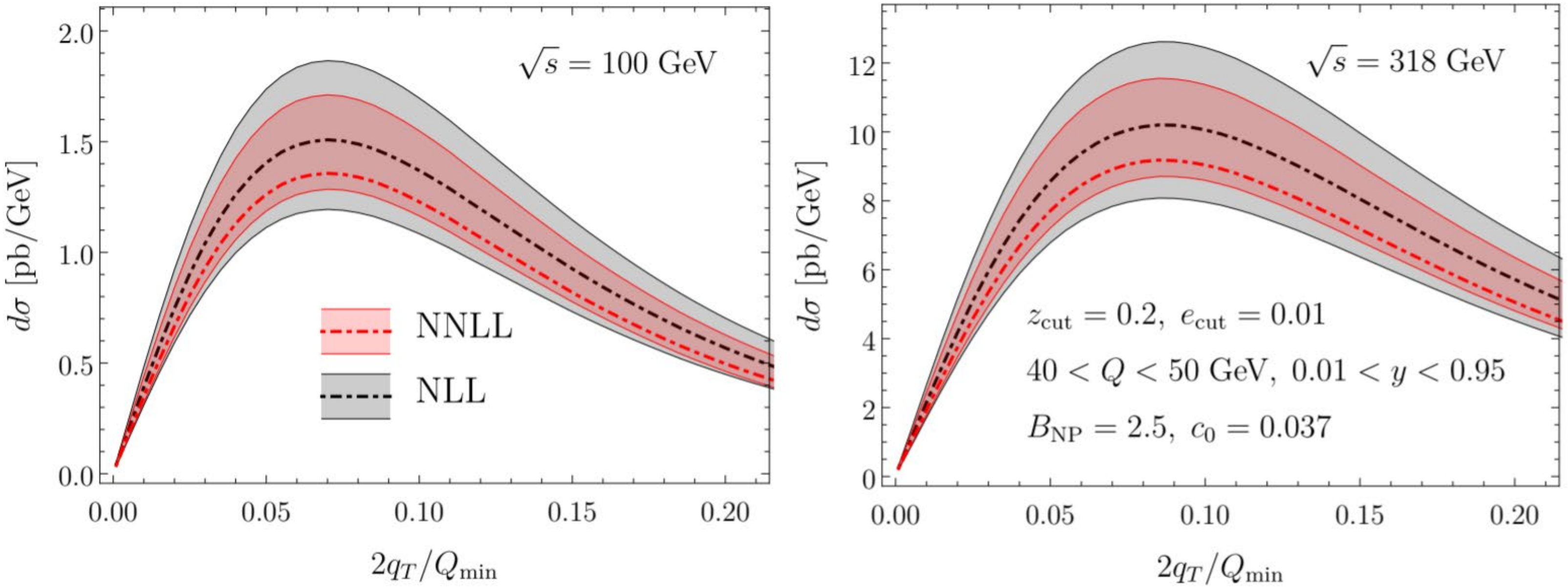
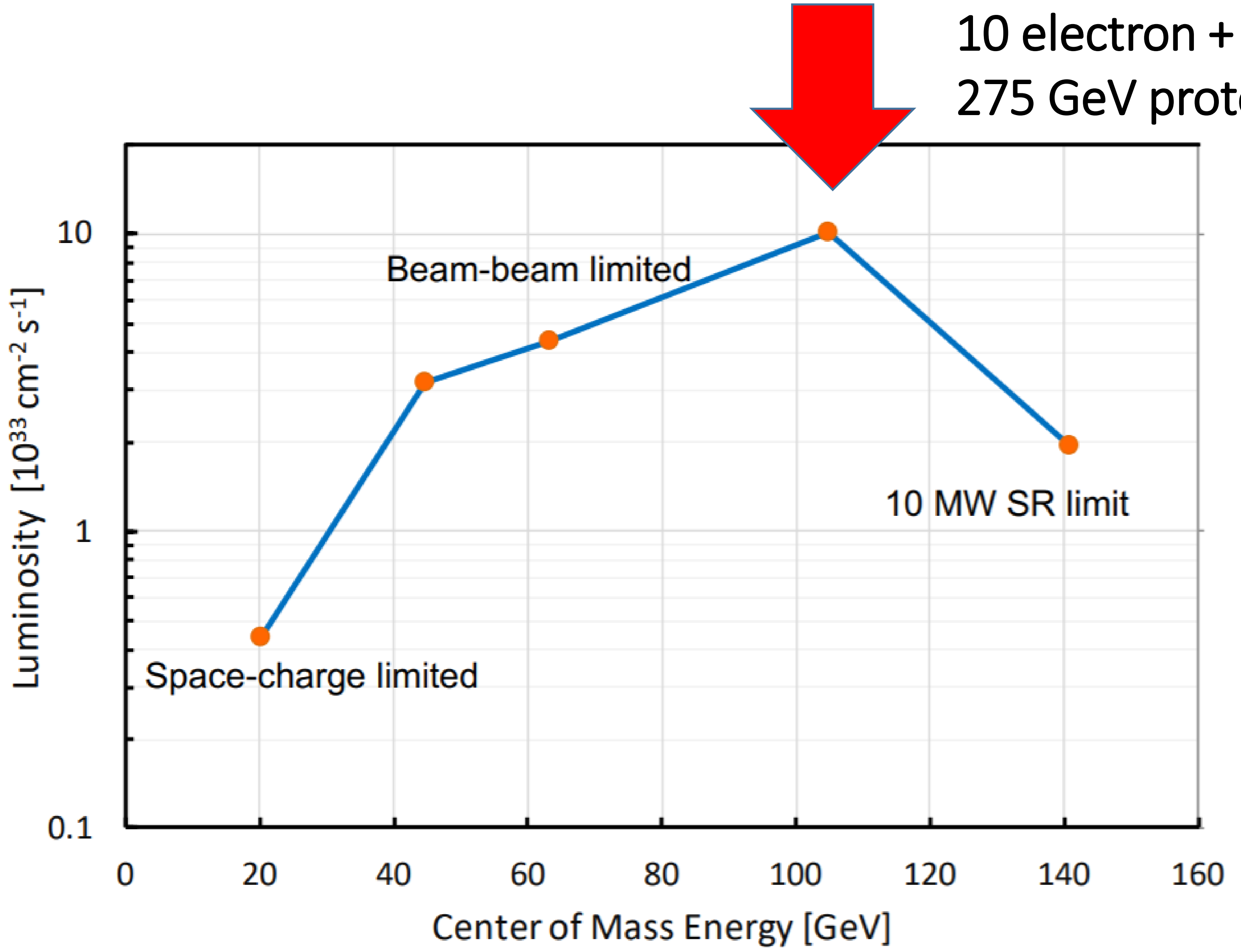


Figure 7. The NLL and NNLL TMD spectra for groomed jets in DIS for EIC (left: $\sqrt{100}$ GeV) and HERA (right: $\sqrt{s} = 318$ GeV) kinematics. The cross section are integrated in $y = Q^2/(xs)$ and

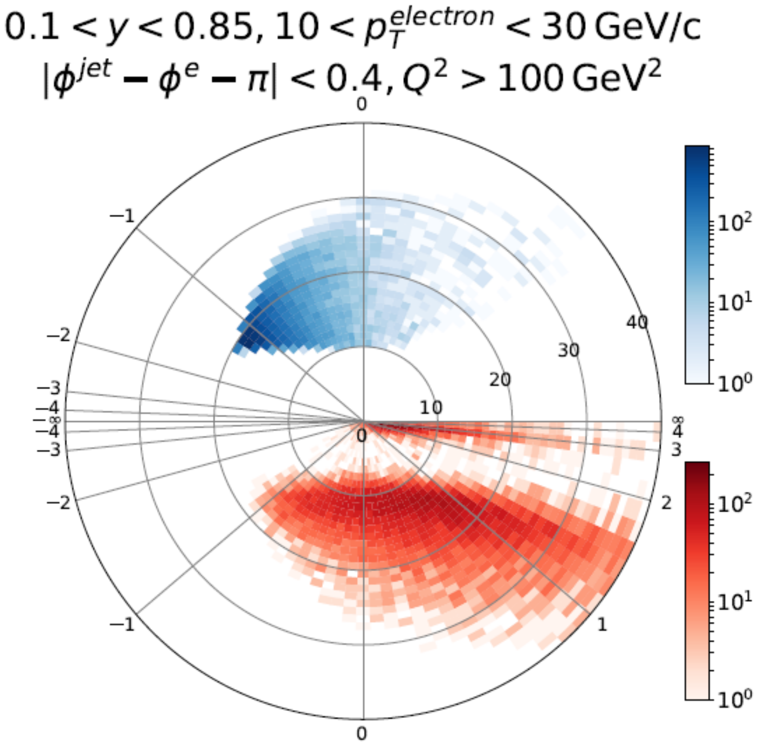
Optimal operating point for 3D-imaging

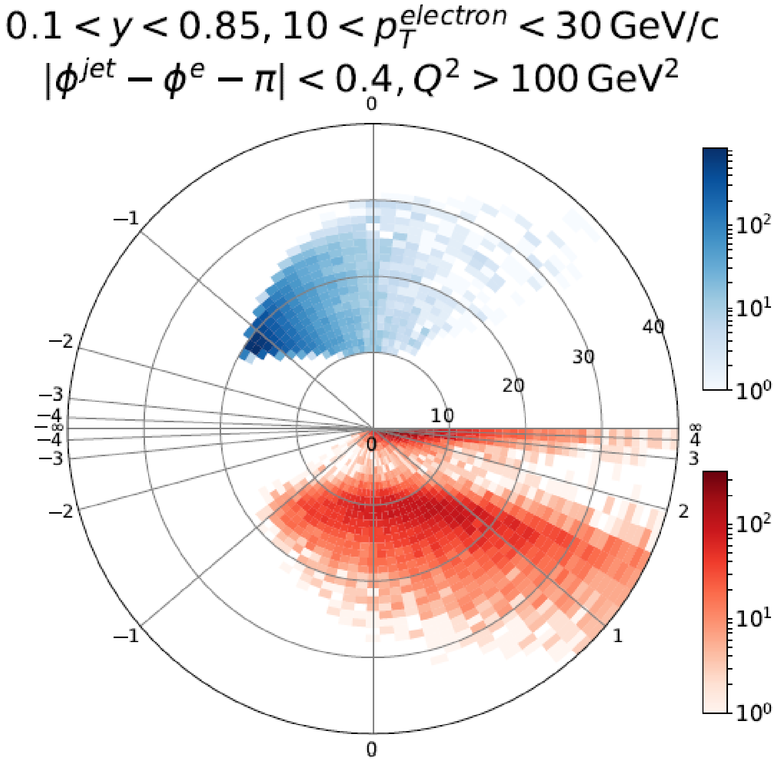
10 electron +
275 GeV proton

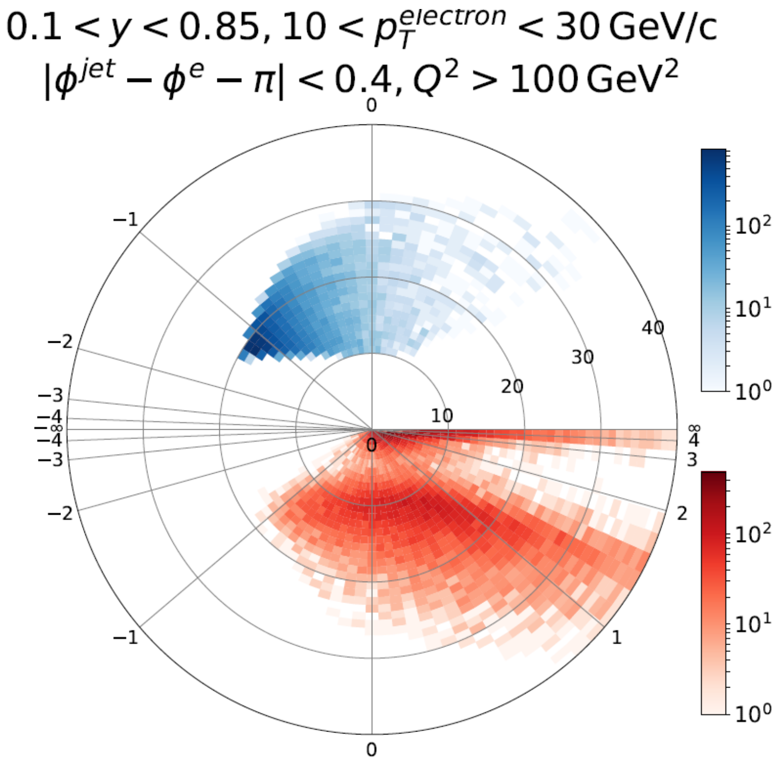


Source: eRHIC design study

R=1.0 R=0.7 R=0.5

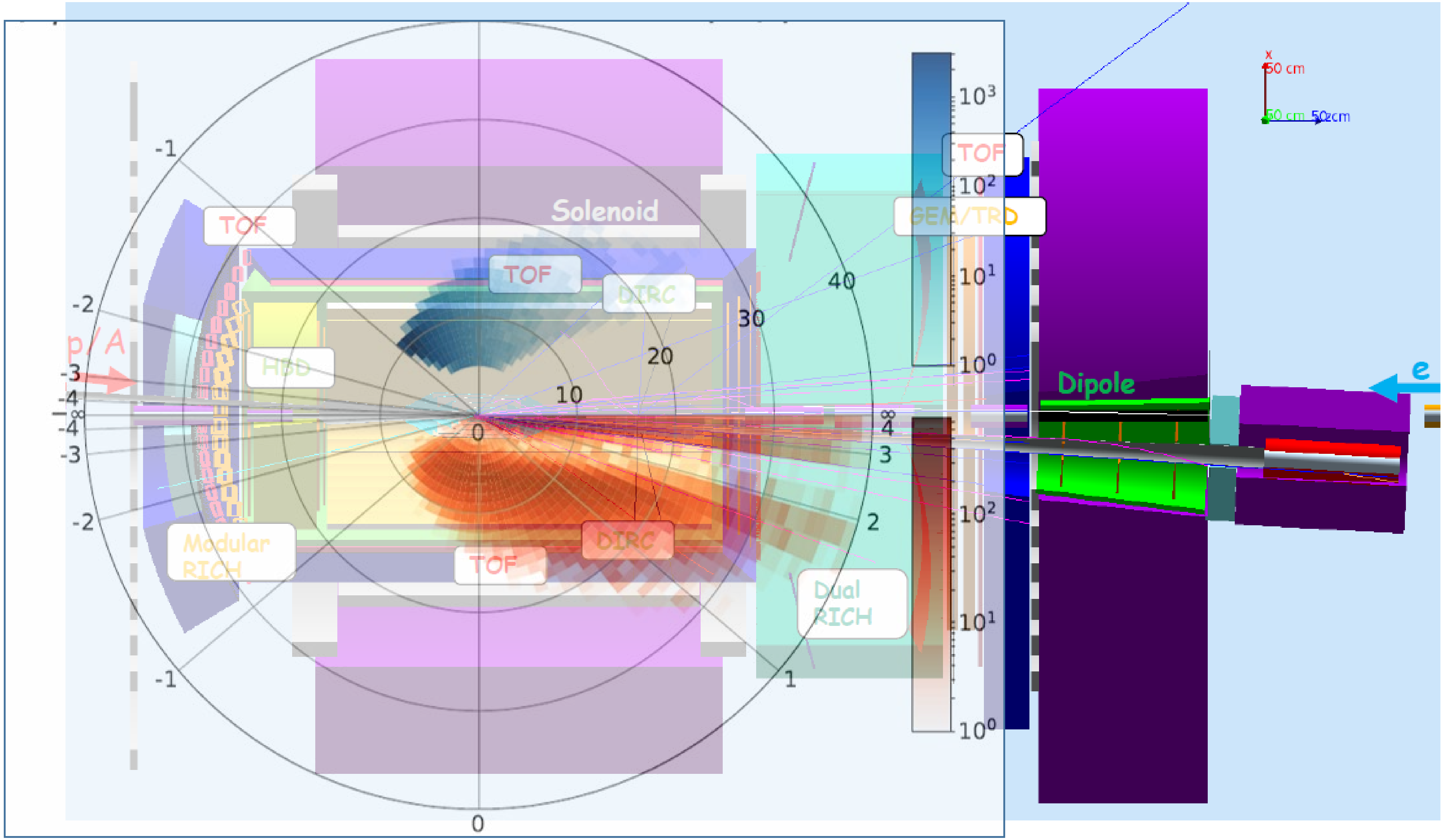






- Smaller R leads to larger ambiguity.
- Note that at HERA the use of R=1.0 lead to percent-level “hadronization correction”

Gaps in calorimeter coverage could limit large-R jets…



Partonic channel, (NNLO calculation by F. Petriello)