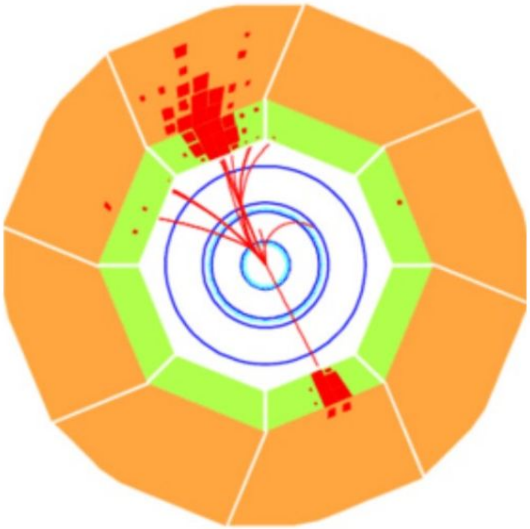
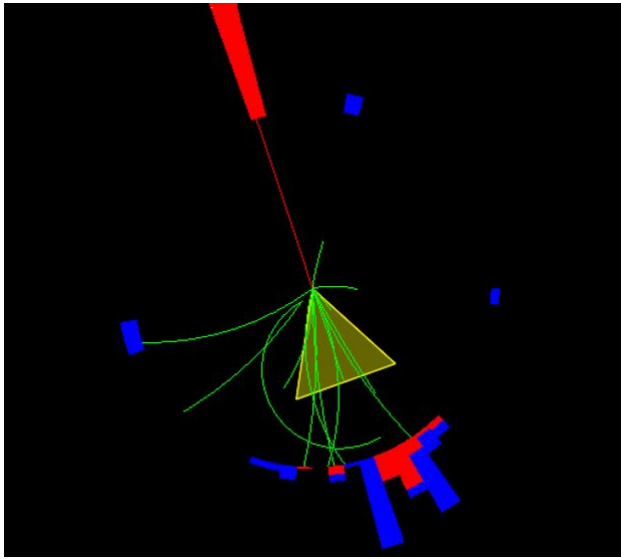
# Jet-based TMD measurements in DIS



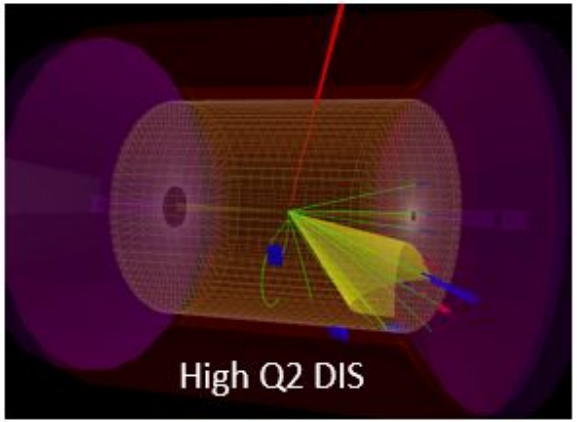
Miguel Arratia

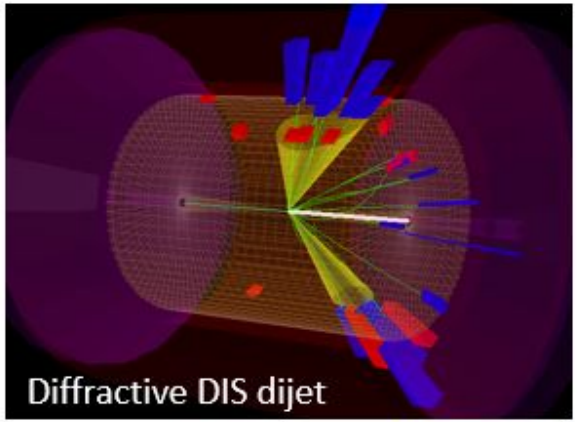
UC RIVERSIDE

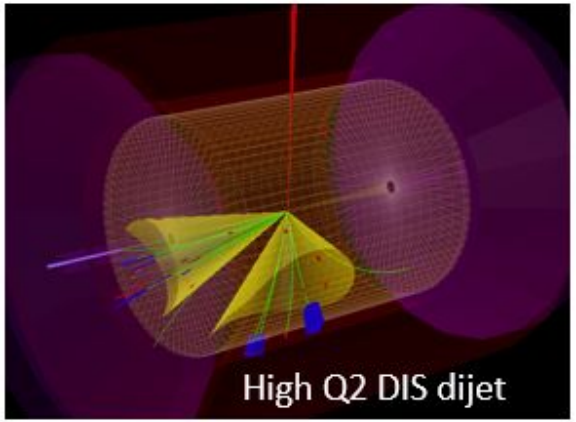
Jefferson Lab

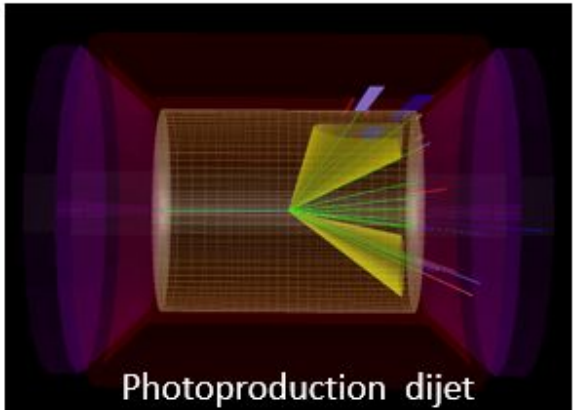


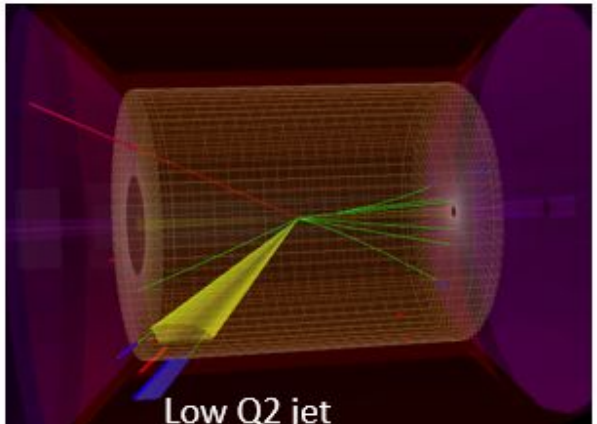
# The EIC, a jet factory, will make the first jets in nuclear DIS and proton-polarized DIS

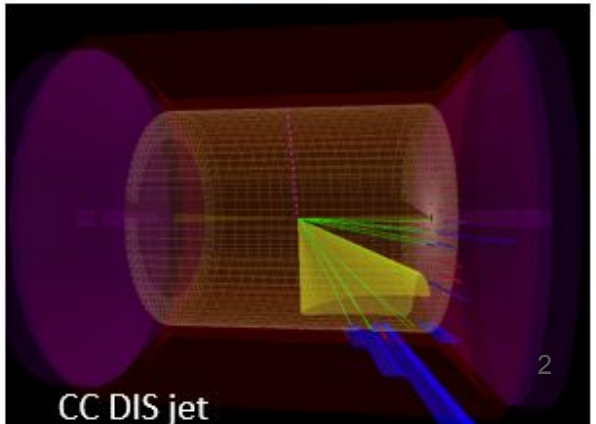


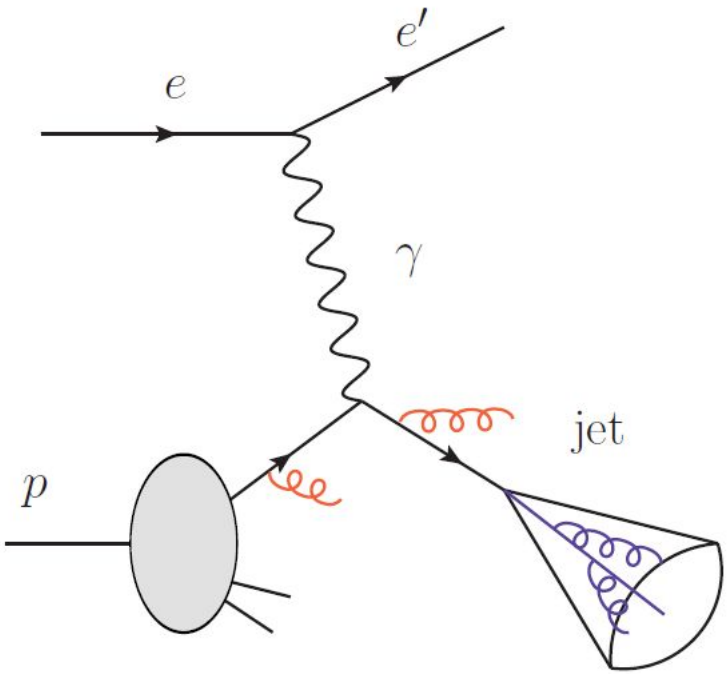



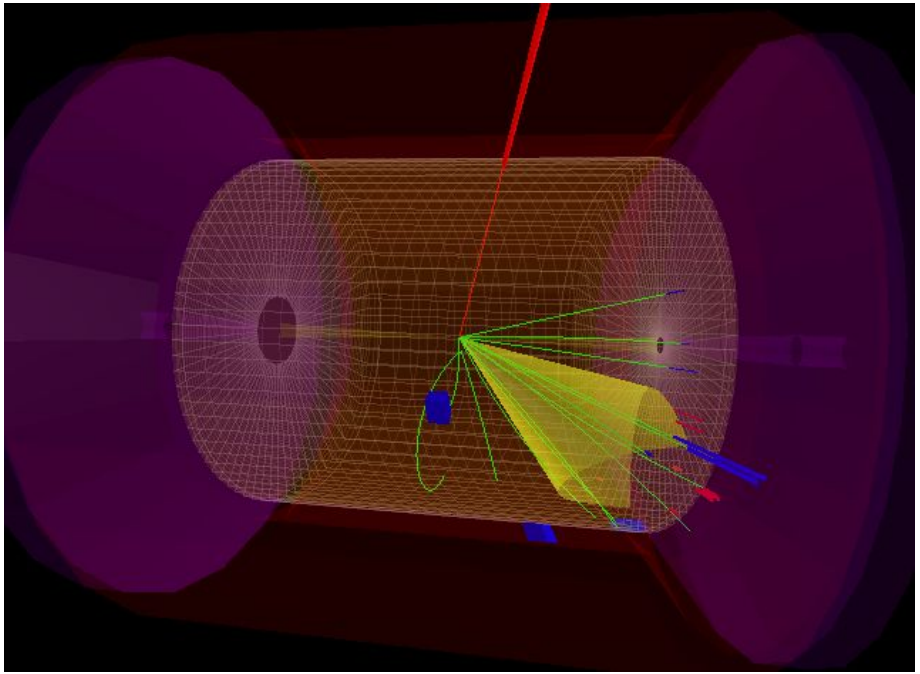



# Jets in neutral-current deep-inelastic scattering



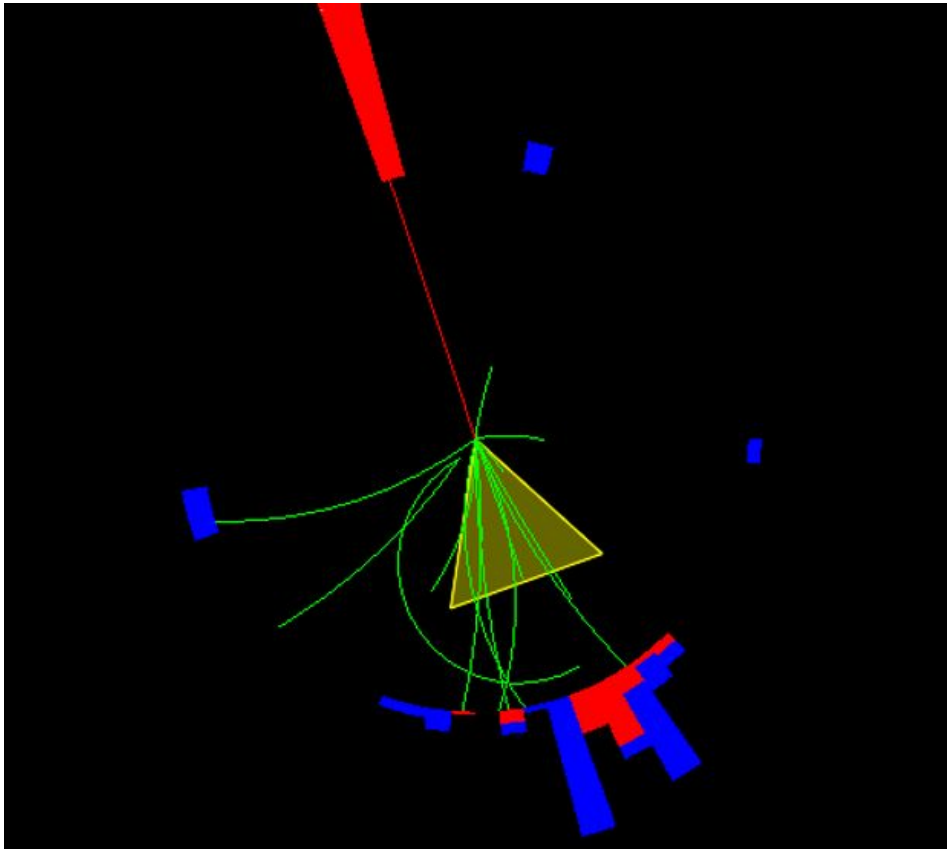

Theory



Experiment (simulated)

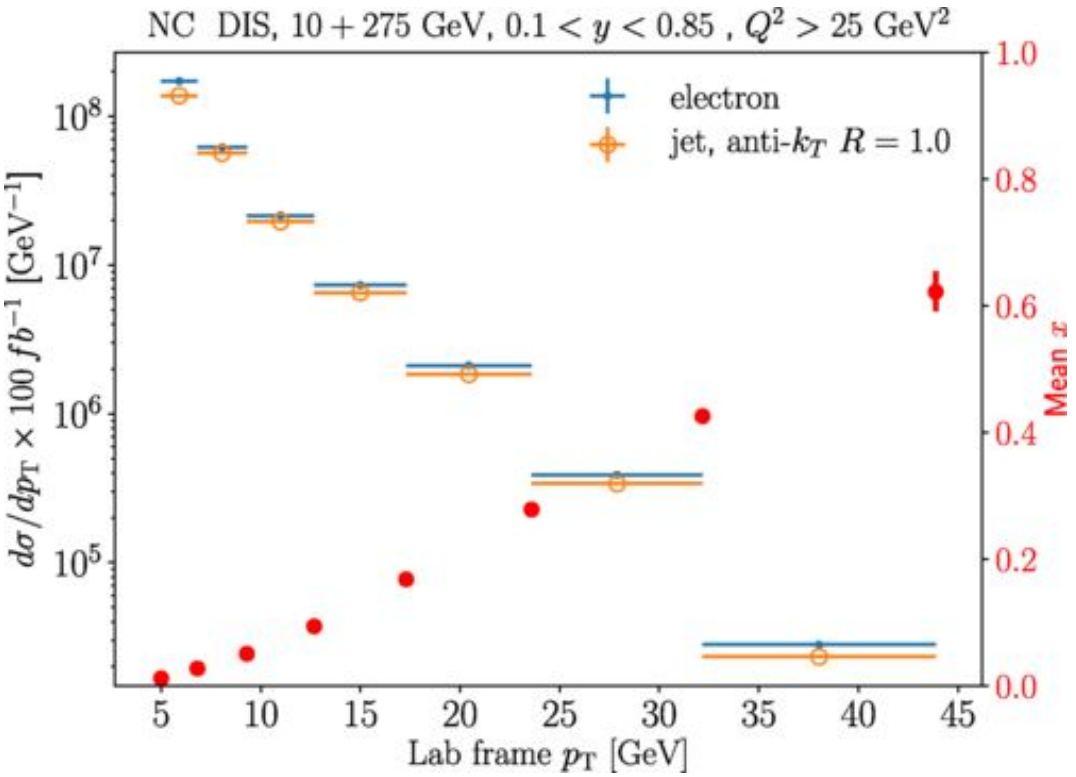
# A new channel to probe for quark TMDs and evolution

Liu et al. PRL. 122, 192003,  Gutierrez et al. PRL. 121, 162001



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

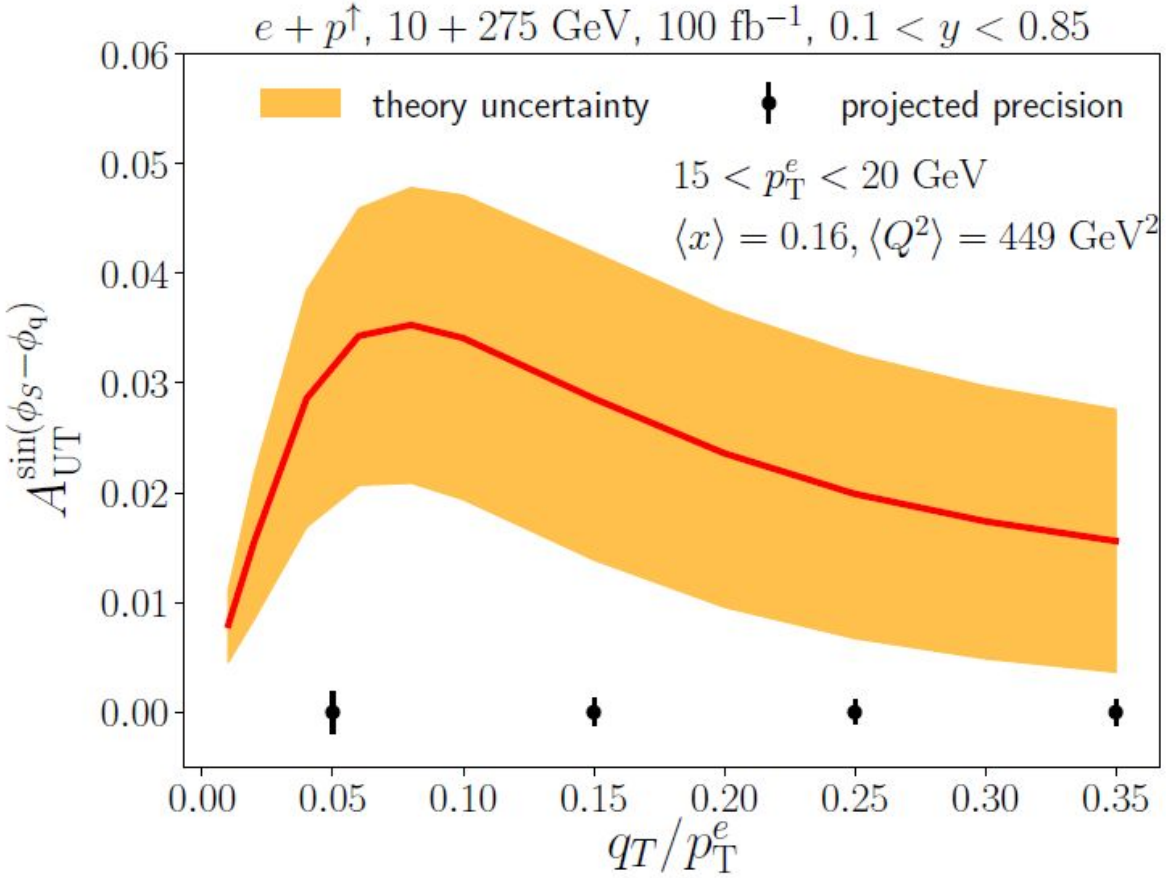
# Expected rate, x coverage (@100 GeV)



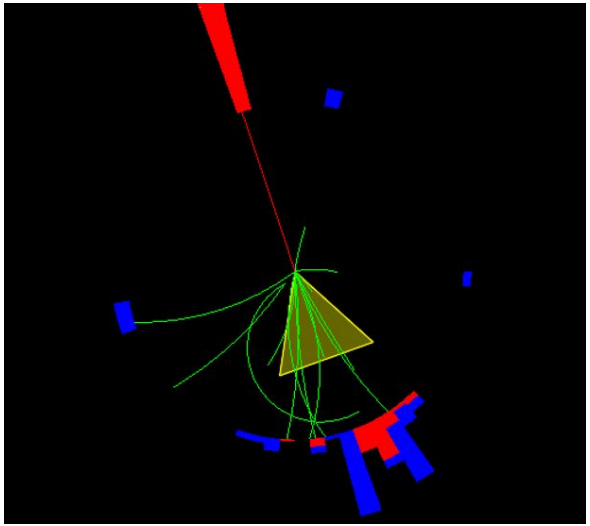

Unique opportunity to measure high-x at high Q2 (complementing fixed-target experiments)

**-> Nail down TMD evolution**

# Projection for Lepton-jet Sivers asymmetry

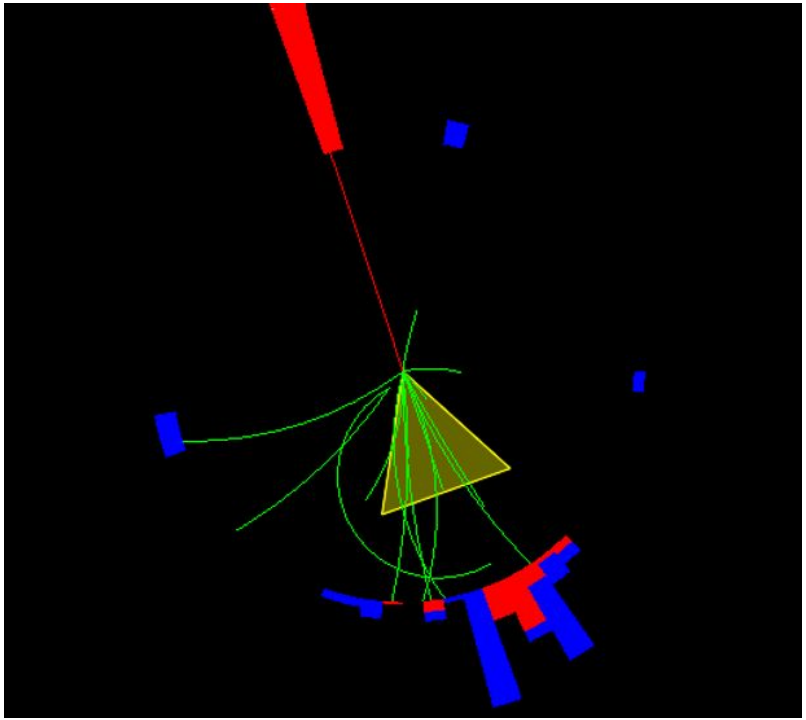


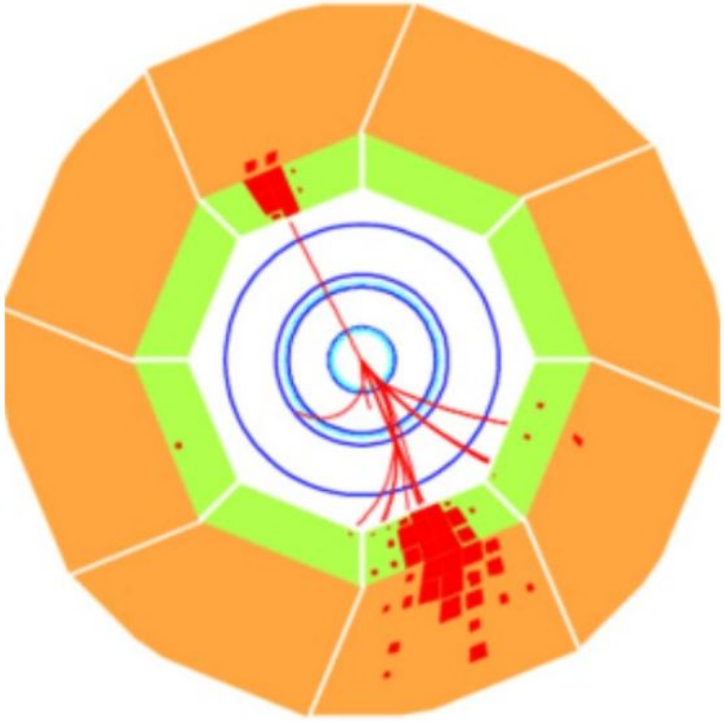

$$q_T = |\vec{p}_T^{\,e} + \vec{p}_T^{\,\mathrm{jet}}|$$



Prediction & projection in
Arratia et al. PRD 102, 074015 (2020
Based on formalism in
Liu et al. PRL. 122, 192003

**We can actually explore feasibility of these measurements and test the TMD calculations with the unpolarized data taken at HERA**





# Constraining TMD evolution with HERA data

Bridging DIS from fixed-target exp. and high Q2 Drell-Yan at colliders.
Fixing open issues of TMD factorization & universality

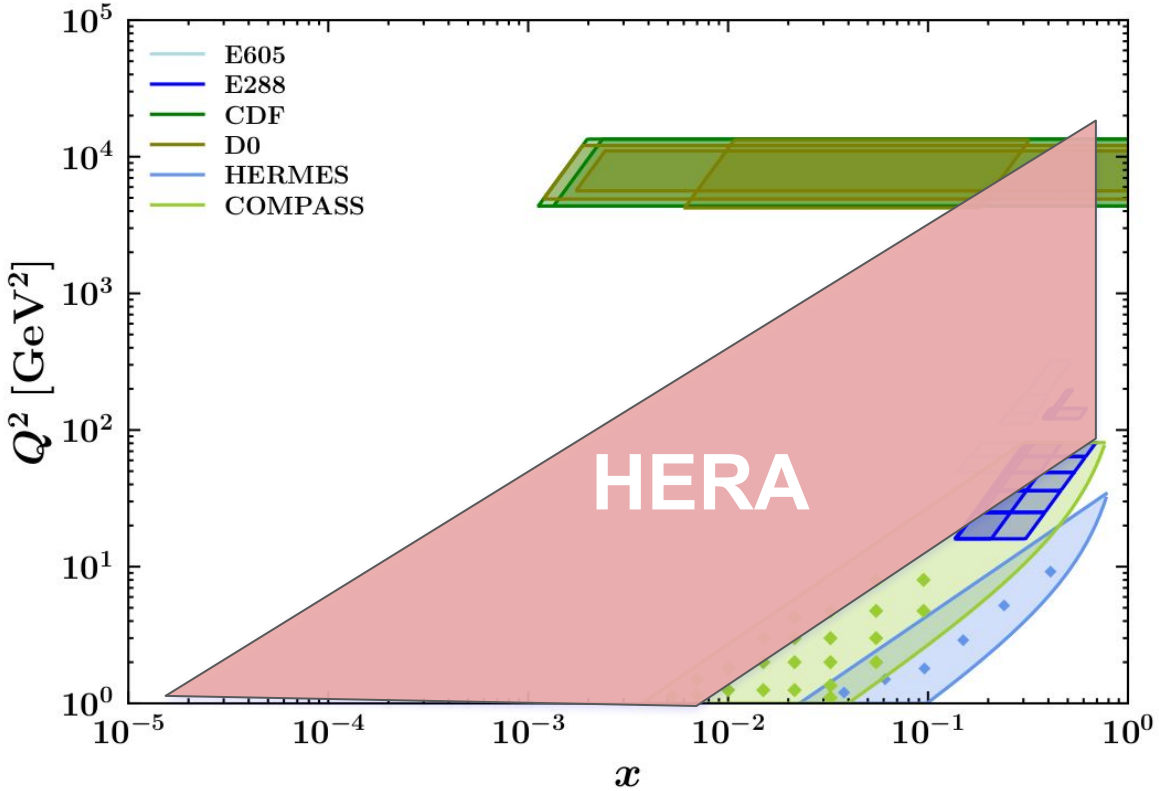
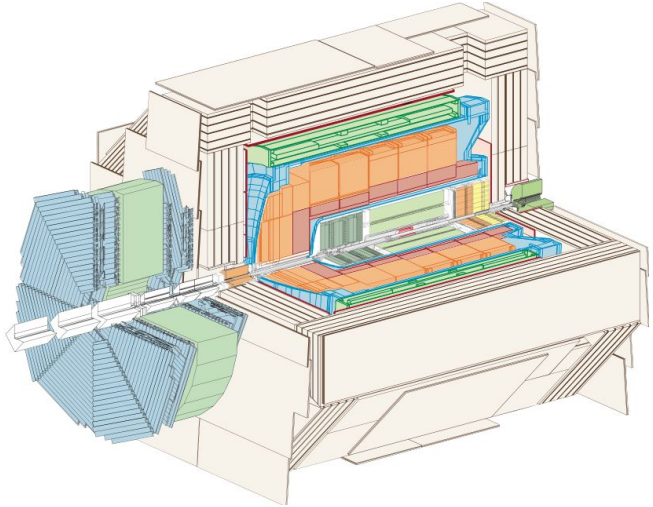
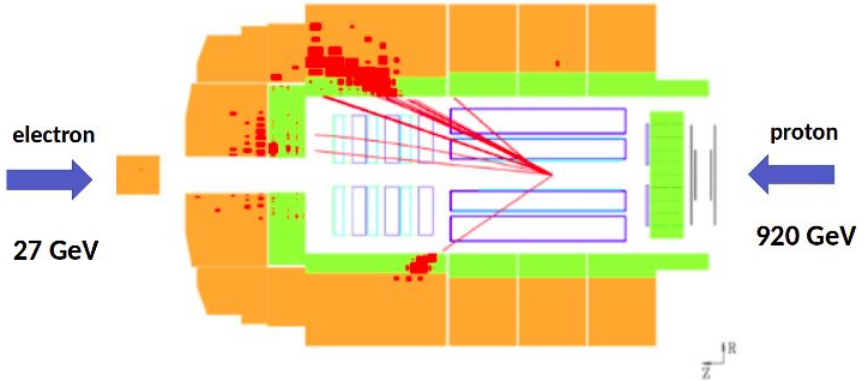



Fig adapted from rom Alessandro's slides

# New, preliminary H1 results






https://www-h1.desy.de/h1/www/publications/htmlsplit/H1prelim-21-031.long.html

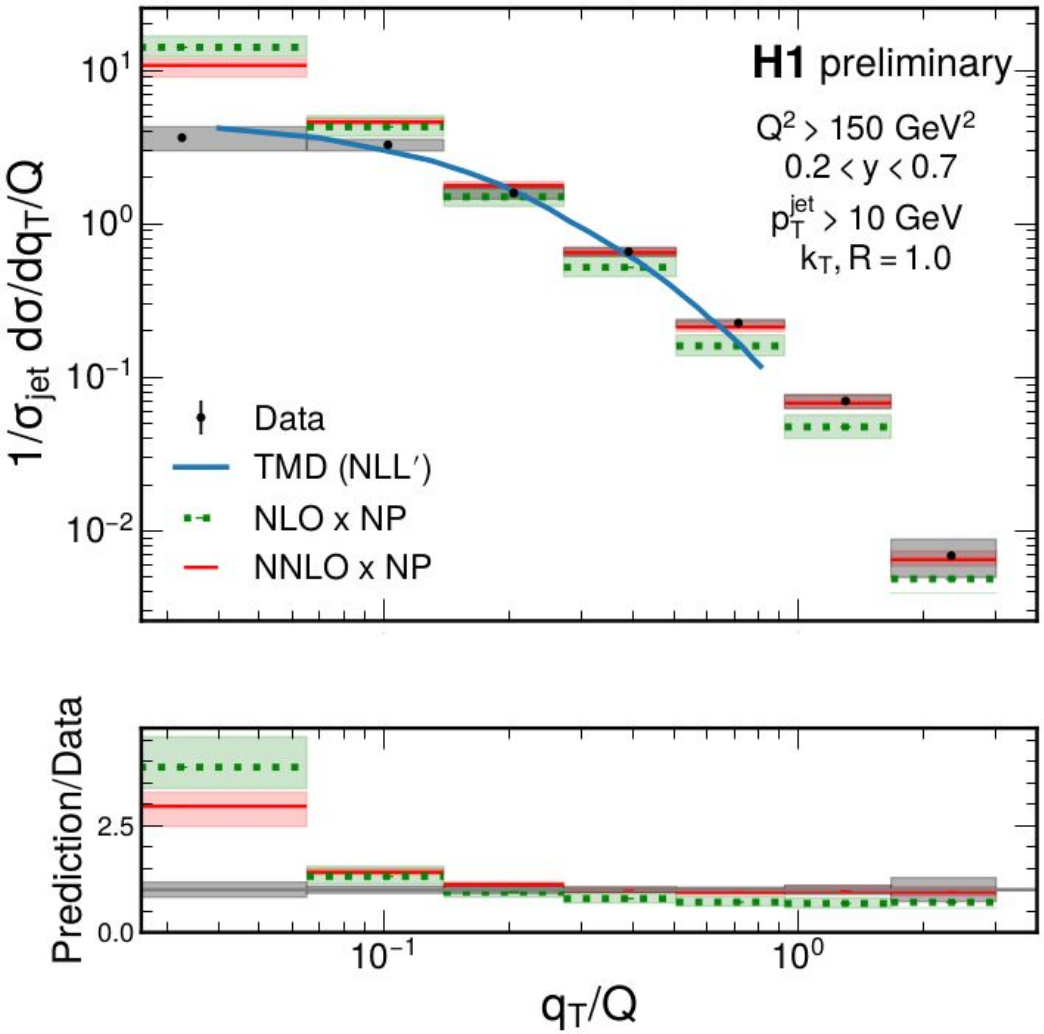
H1prelim-21-031
April 5, 2021

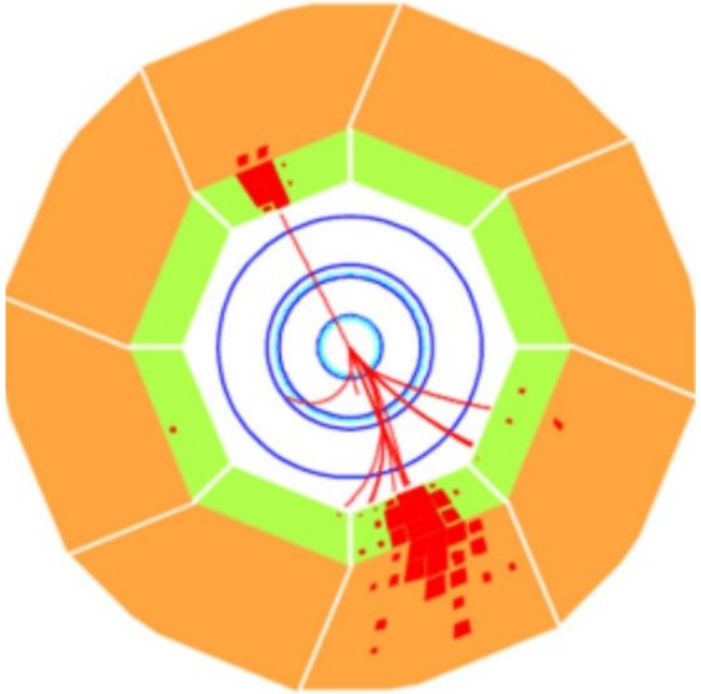
**Measurement of lepton-jet correlations in high $Q^2$ neutral-current DIS with the H1 detector at HERA**

The H1 Collaboration

**Abstract**

A measurement of jet production in high $Q^2$ neutral-current DIS events close to the Born-level configuration $\gamma^* q \to q$ (Born kinematics) is presented. This cross section is measured deferentially as



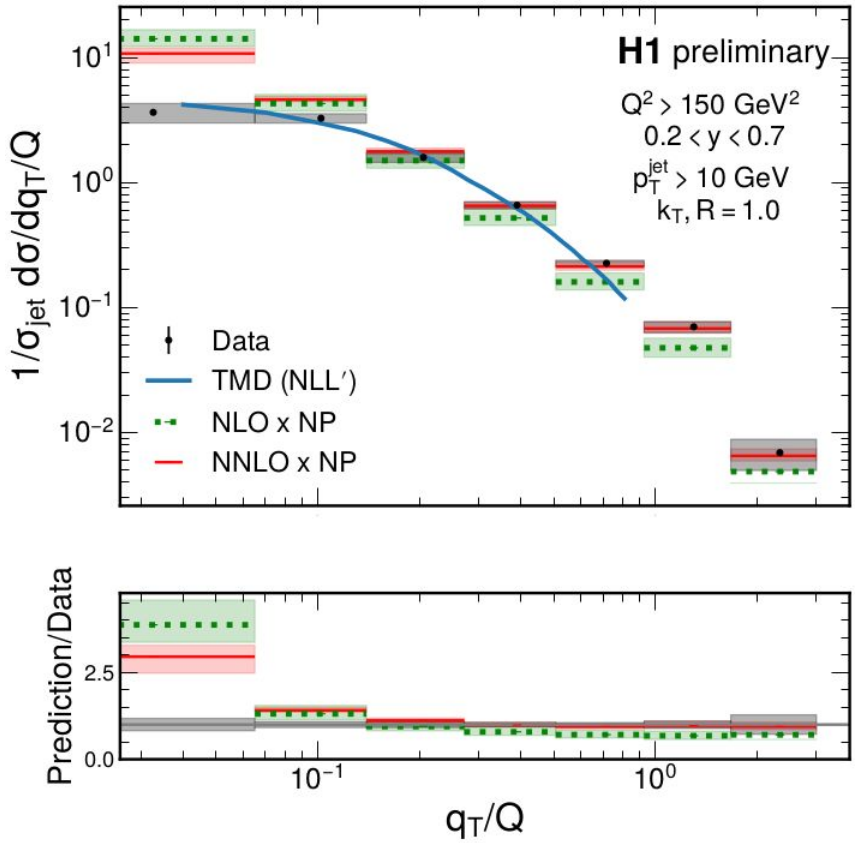



$$q_T = |\vec{p}_T^{\,e} + \vec{p}_T^{\,\mathrm{jet}}|$$

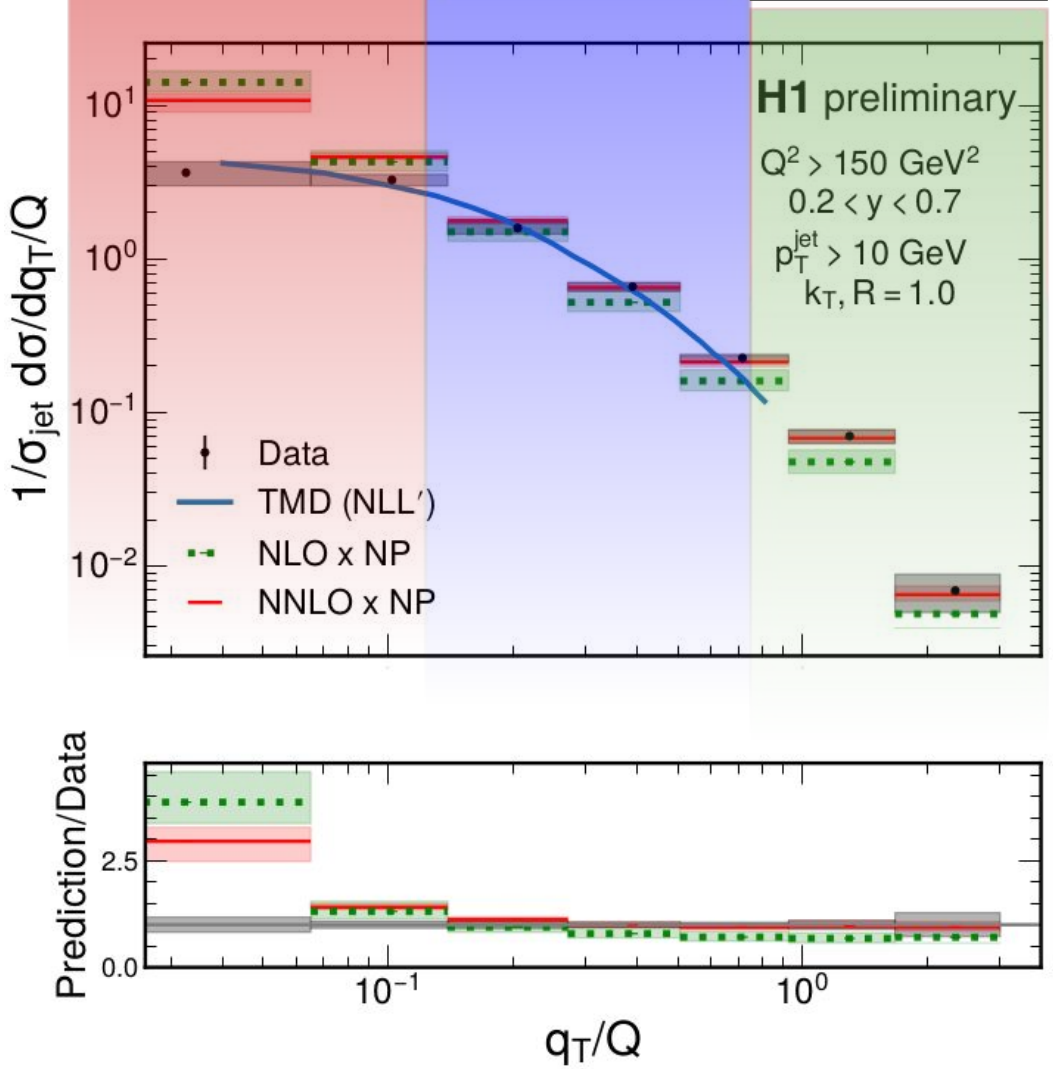
Caltulations: Kang, Yuan, de Florian et al.

# TMD calculation, without free parameters, describes data over wide kinematic range

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



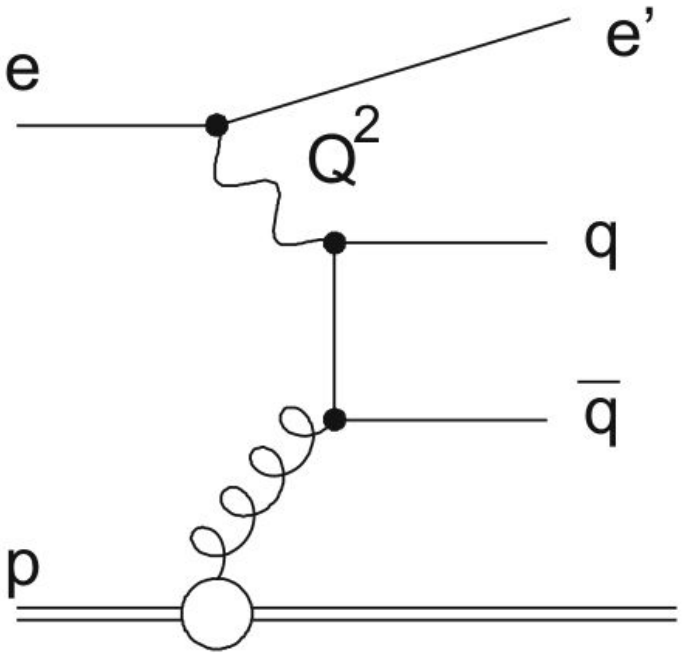

- TMD PDFs and soft factors extracted from low Q2 DIS and DY data. Sun et al. arXiv:1406.3073
- Recently tested in Echeverria et al. JHEP 01 (2021) 126
- pQCD calculations from Borsa et al. PRL. 125, 082001 (2020)

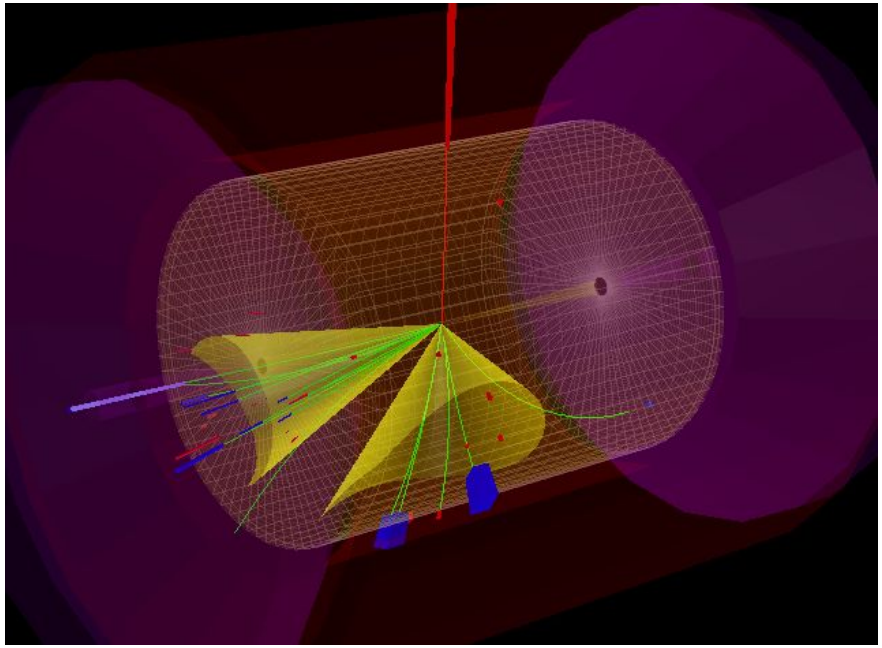



**Textbook example of matching?**

**First time seen in DIS?**

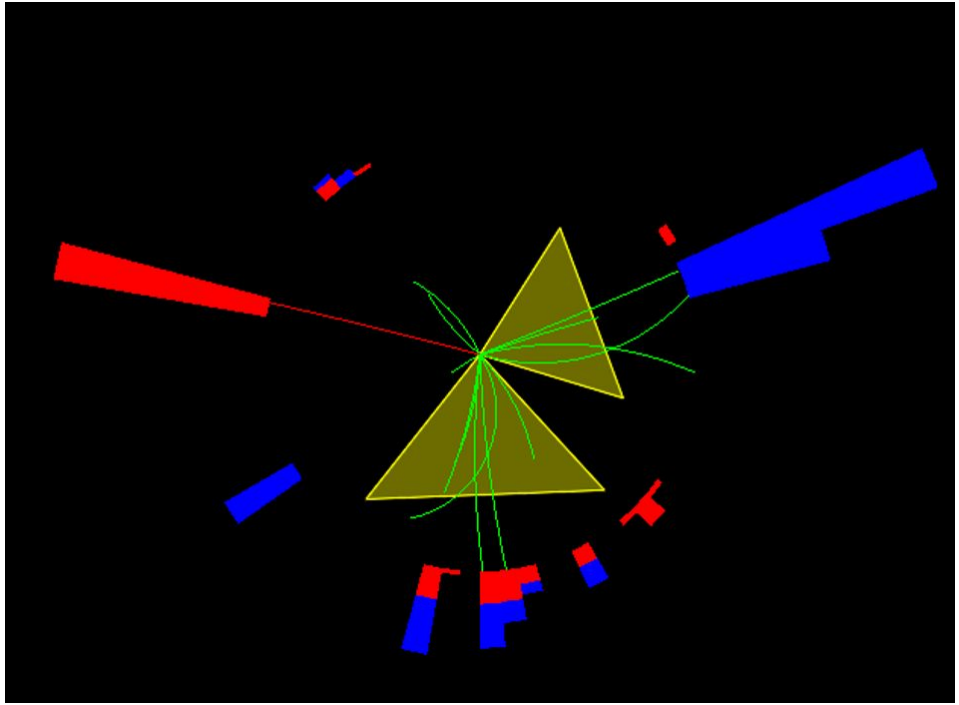
# Dijet events probe the gluon TMD distributions

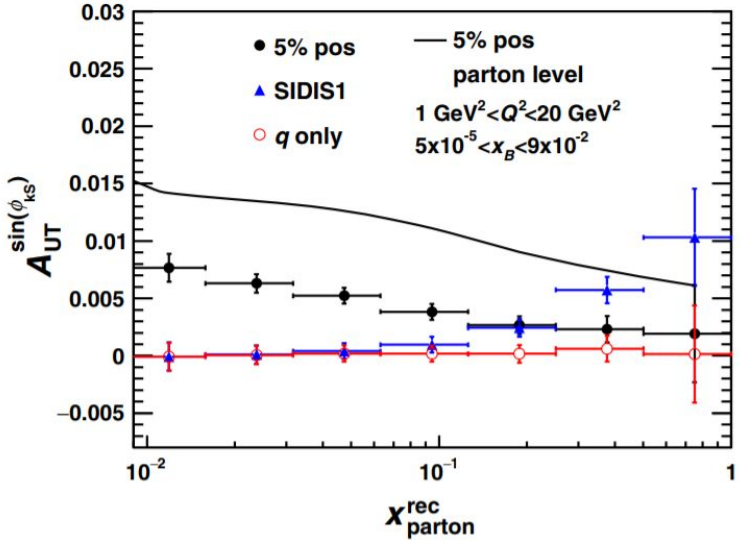


# “Di-jet channel is the most promising way to constrain the magnitude of the Gluon Sivers function”

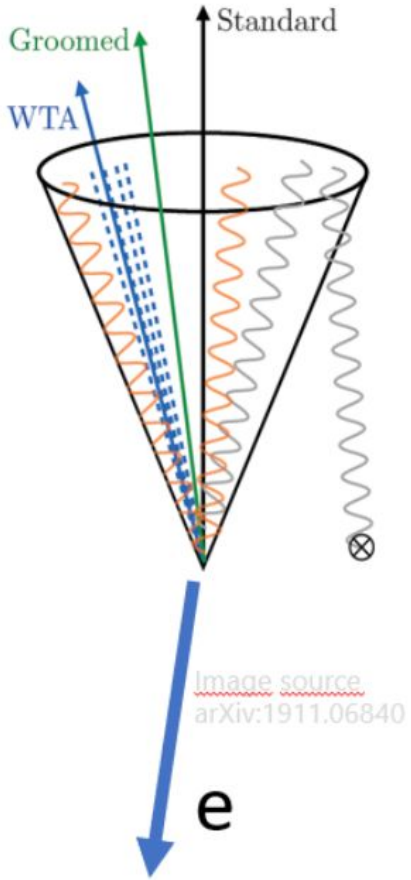
*L. Zheng et al. Phys. Rev. D 98, 034011 (2018)*

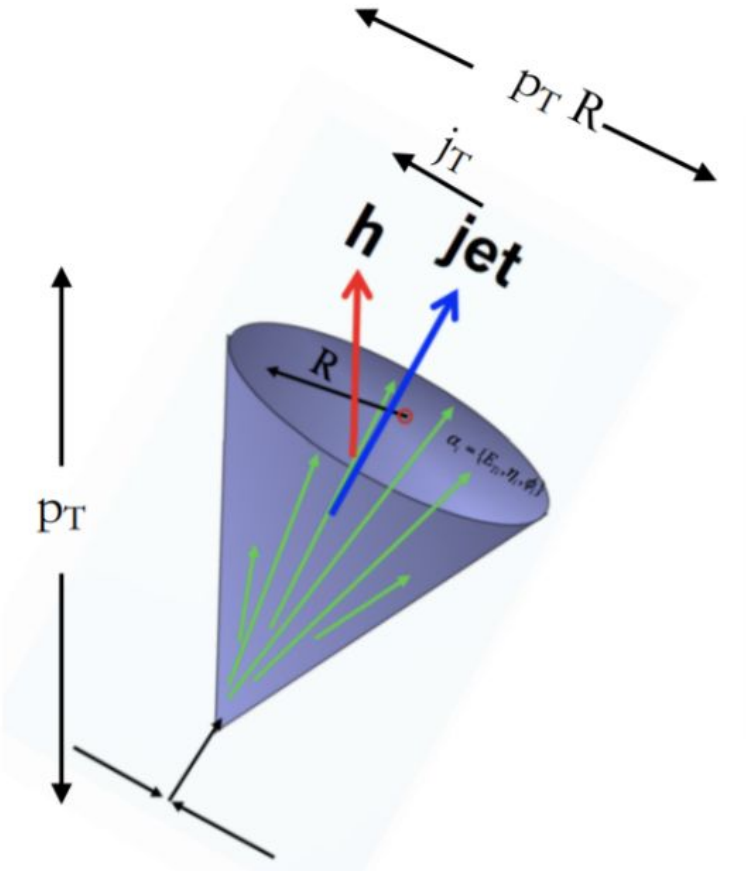


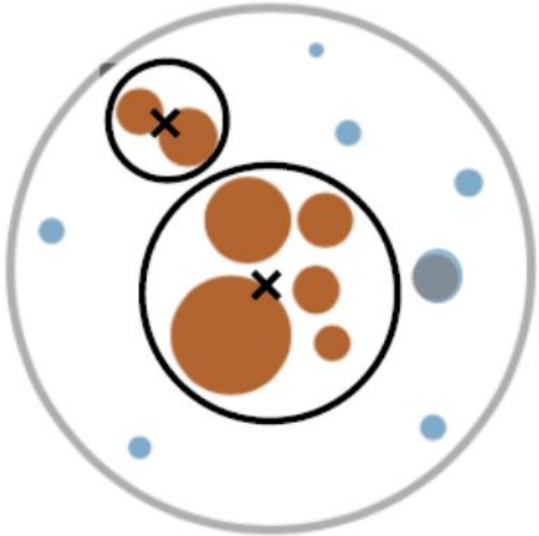



There is a ton of recent work on this topic...

# Jets have rich substructure, which encodes TMD effects



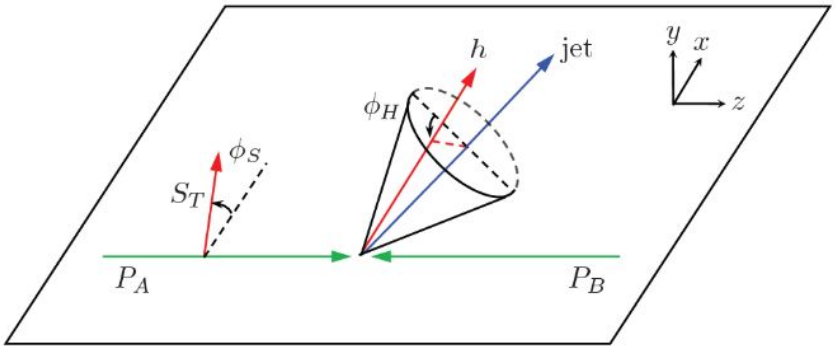



# Transversity with jets

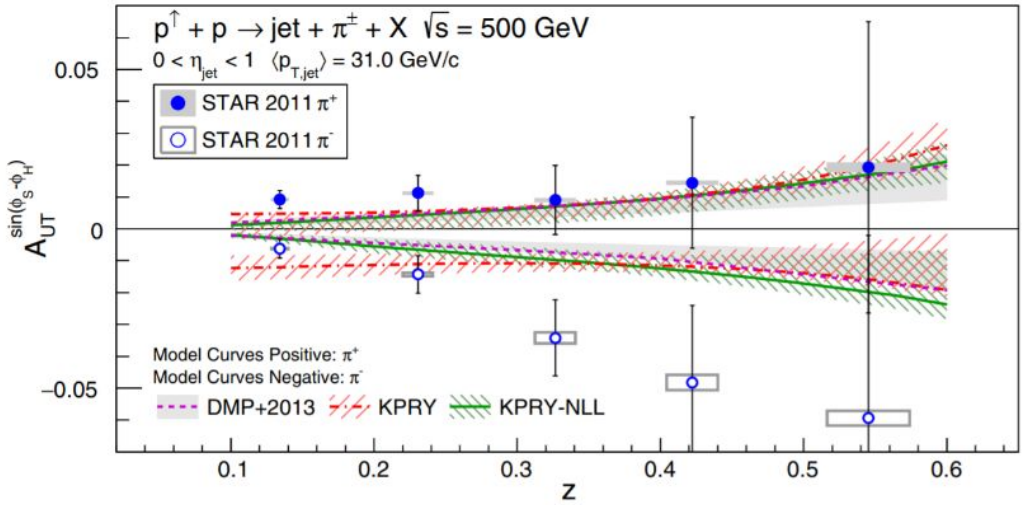
distribution of transversely polarized quarks inside a transversely polarized nucleon

This is measured with “Hadron-in-jet” azimuthal asymmetries:

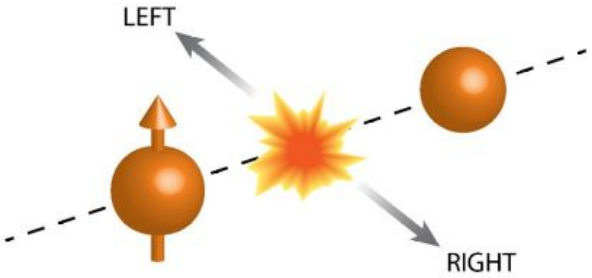



Phys. Lett. B 774, 635 (2017), Kang et al.
Phys.Rev.D77:074019 (2008) Yuan.

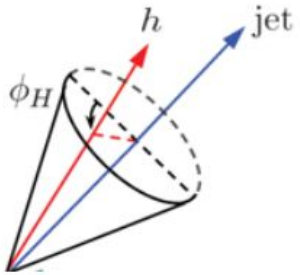
Measured at the RHIC proton-collider
STAR Collaboration, Phys. Rev. D 97, 032004 (2018)

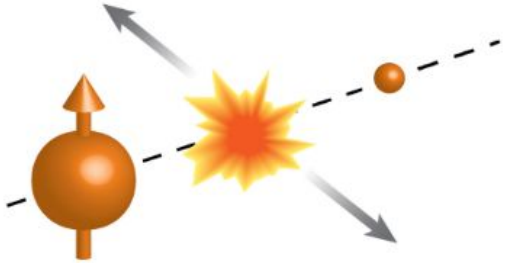


# Complementarity

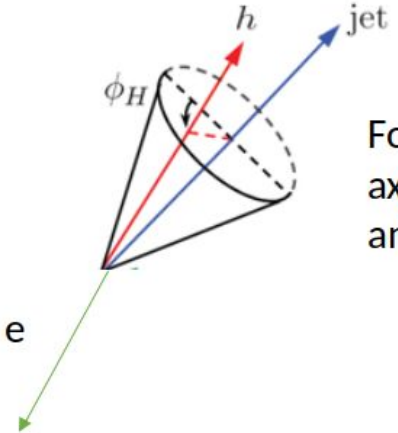



**pp at RHIC**

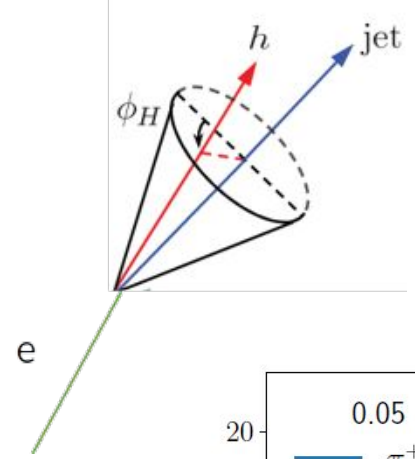


**ep at EIC**




For DIS we will have 2 axes (virtual photon and jet).




# Hadron-in-jet Collins asymmetry at EIC

PRD 102, 074015 (2020)

# Jet substructure, the key to novel TMD studies

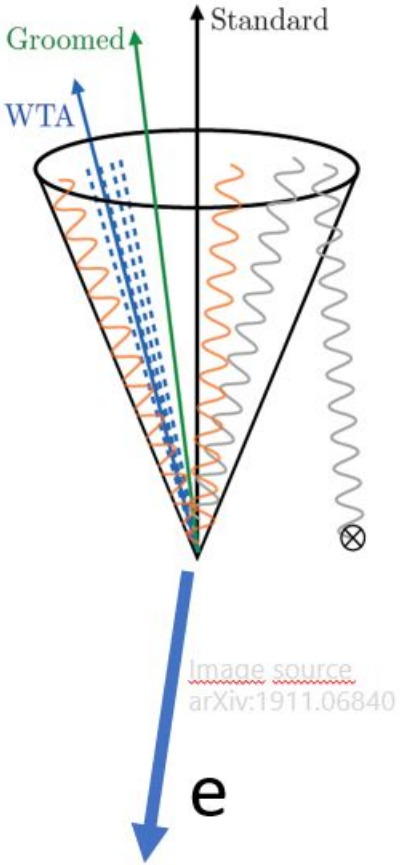



Image source
arXiv:1911.06840

Recent example:
“T-odd jets” (arXiv:2104.03328)

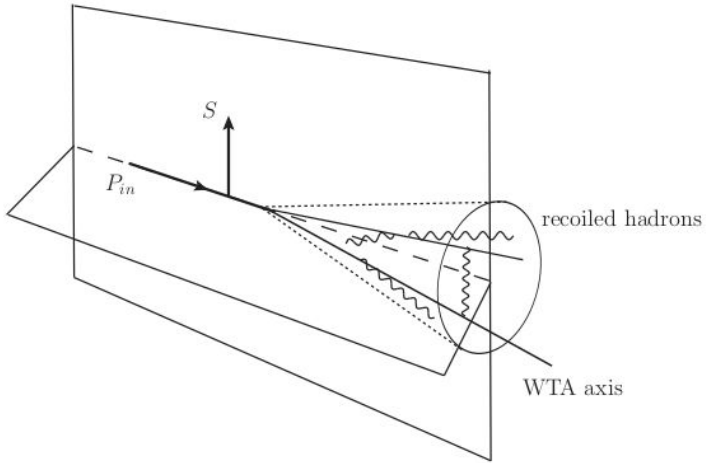



FIG. 1. Origin of the jet T-odd contributions. The WTA jet axis lies outside the plane by the spin $S$ and $P_{in}$, to allow for the asymmetry due to the quantum correlation between parton's spin and its hadronization about the plane.

- **Grooming**

  Gutierrez et al. JHEP 08 (2019) 161 . Makris et al. JHEP 07 (2018) 167
- **Jet axes**

  Cal et al. JHEP 04 (2020) 211, Niell et al. JHEP04 (2017 )020 Liu et al. arXiv: 2104.03328
- **Declustering?**

## 7) The EIC measurements at large *x*, including coverage, resolutions, large $Q_2$ behavior of SSAs, complementarity with JLab

- EIC can probe large-x “Can EIC reach x~0.5?”-> yes (at high Q2)

- EIC cannot reach high-x and low Q2, so JLab data is crucial and complementary to fully constrain TMD evolution.

- Jet-based TMDs measurements are feasible and can probe TMD region. We probed it with HERA data. Complements SIDIS and makes possible new class of studies (substructure)

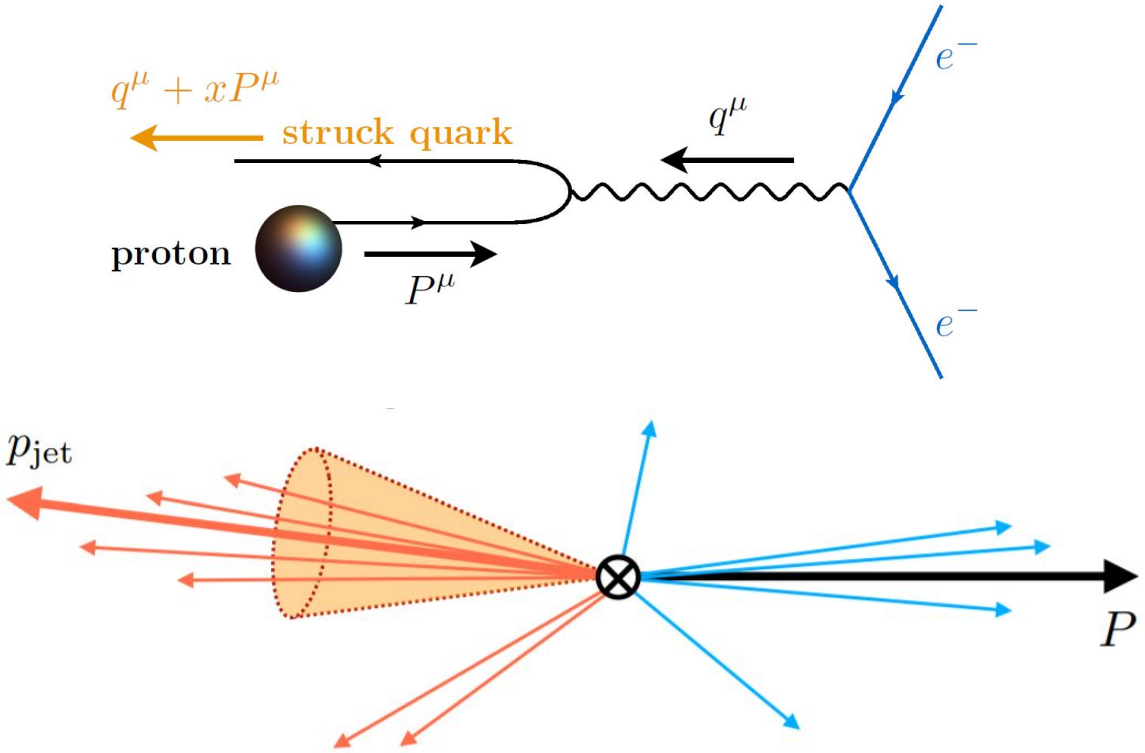
- We have predictions and projections for jet-based Sivers at high Q2. We have tested the TMD evolution used in that prediction with unpolarized HERA data. Works beautifully, and provides first DIS evidence of “matching” between TMD and fixed-order QCD.

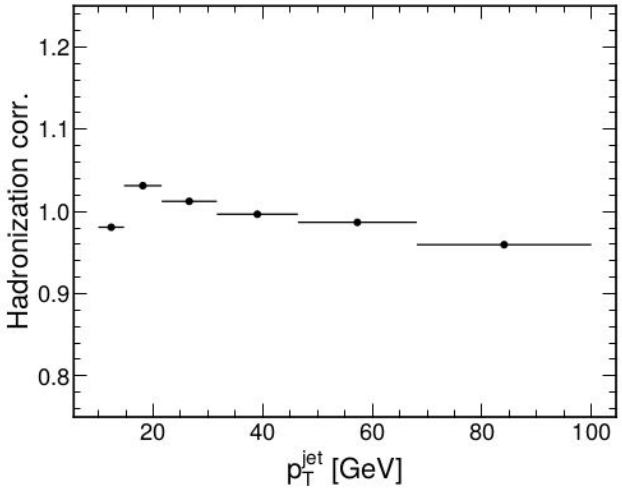
- The field of jets@EIC is growing exponentially, the best is yet to come. Stay tuned.

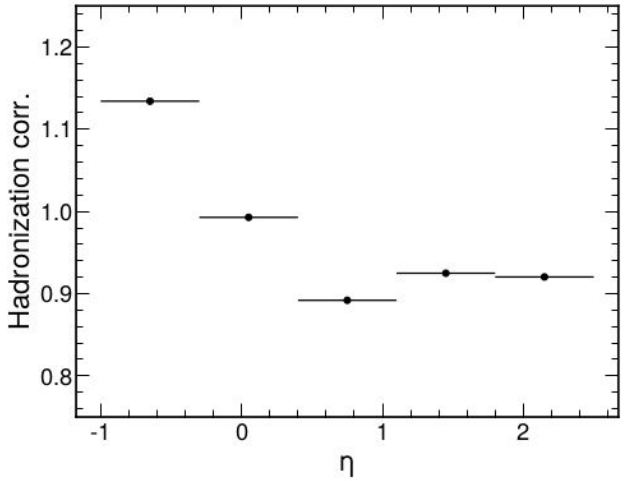
- HERA data can be used to create the ideal “EIC pathfinder program”

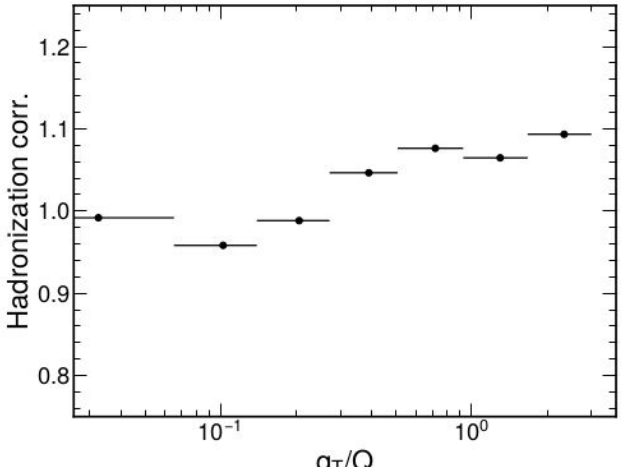
# Backup

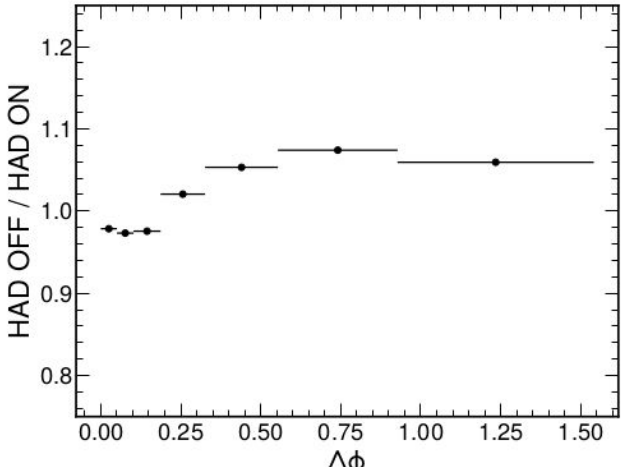
**These studies also possible in Breit frame (in complete analogy to SIDIS), but requires dedicated jet algorithms, like Centauro**



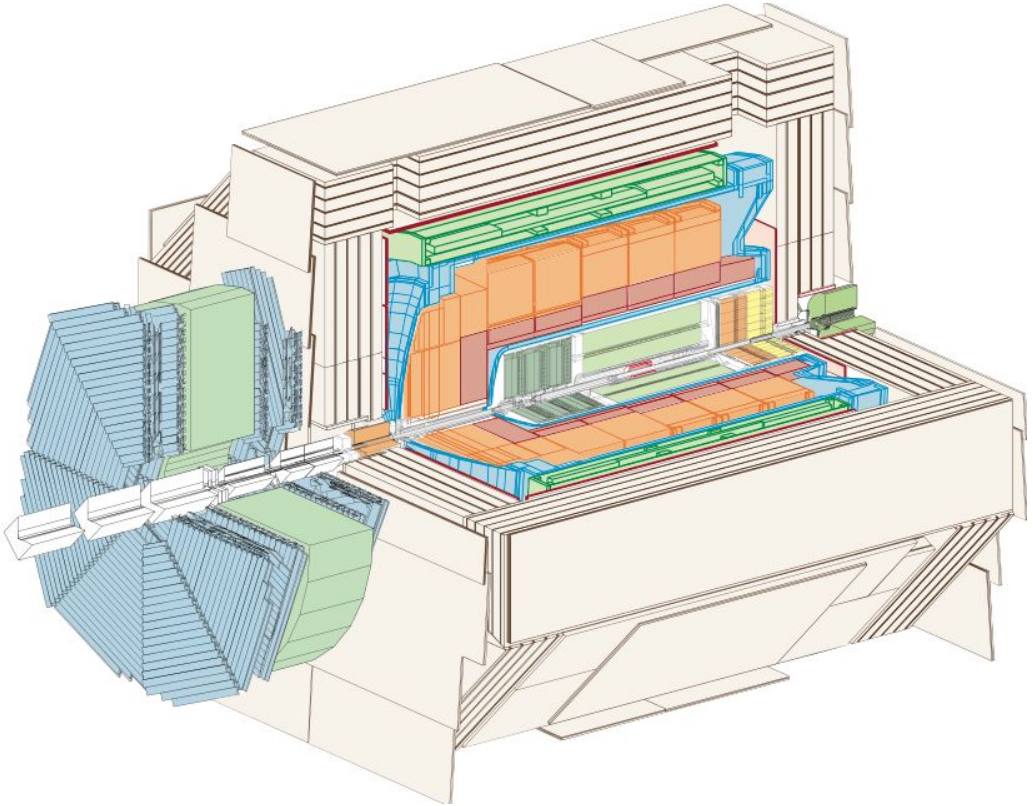

Hadronization corr.
1.2
1.1
1.0
0.9
0.8
20
40
60
80
100
$p_T^{jet}$ [GeV]


Hadronization corr.
1.2
1.1
1.0
0.9
0.8
-1
0
1
2
η


Hadronization corr.
1.2
1.1
1.0
0.9
0.8
$10^{-1}$
$10^{0}$
$q_T/Q$


HAD OFF / HAD ON
1.2
1.1
1.0
0.9
0.8
0.00
0.25
0.50
0.75
1.00
1.25
1.50
Δφ

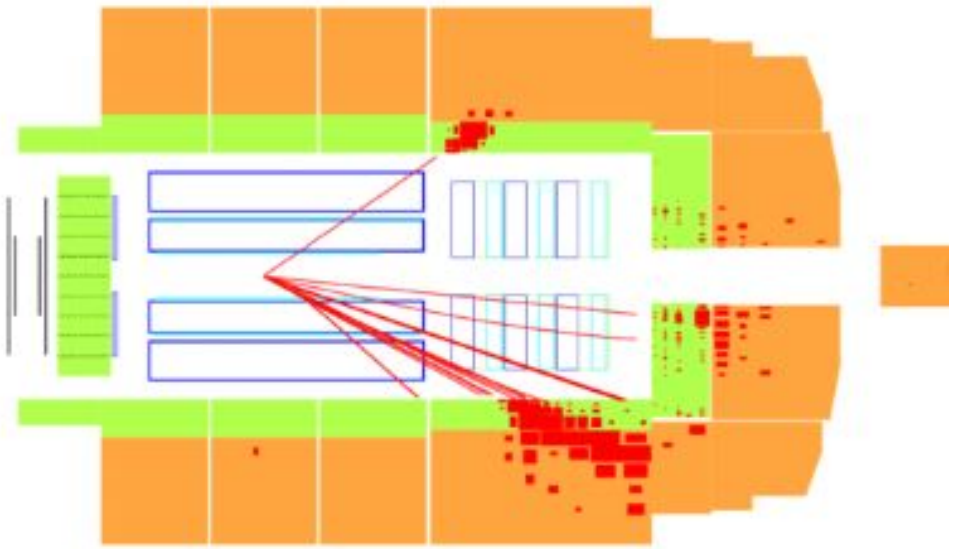
# The H1 experiment at HERA



- Tracking system
(silicon tracker, jet chambers,
proportional chambers)
- LAr calorimeter (em/had)
- Scintillating fiber
calorimeter

Both combined using
an energy flow algorithm

# Accurate and precise jet and lepton measurements

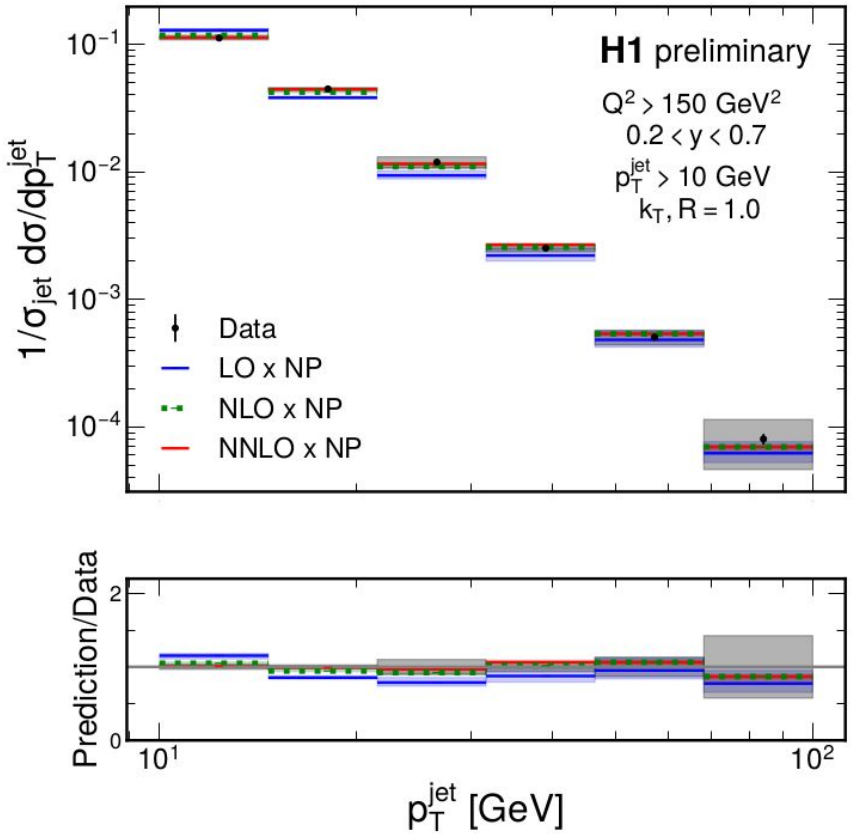


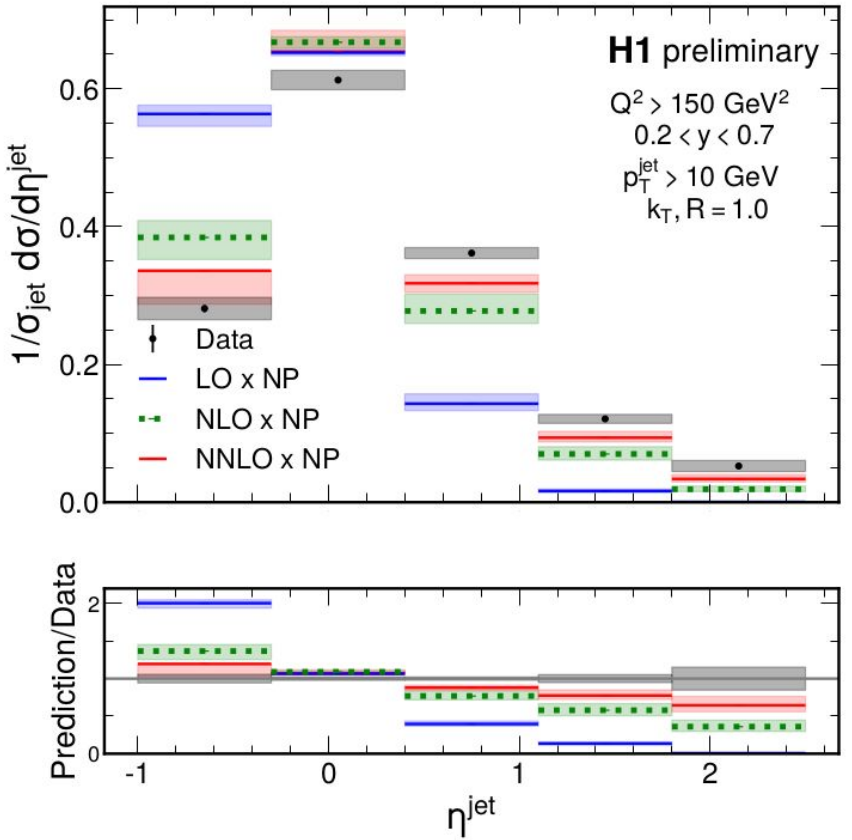
Neural-net based in-situ jet calibration for data and MC.

1% Jet energy scale

0.5-1% lepton energy scale

# Jet transverse momentum and pseudorapidity



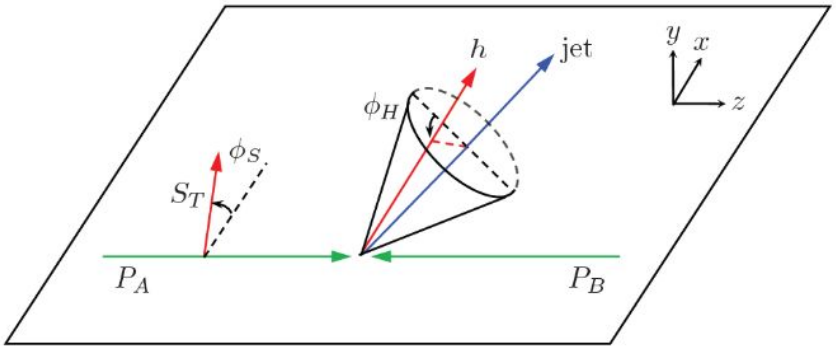




- Well described, quick convergence
- Hints at need of NNNLO

# Transversity with jets

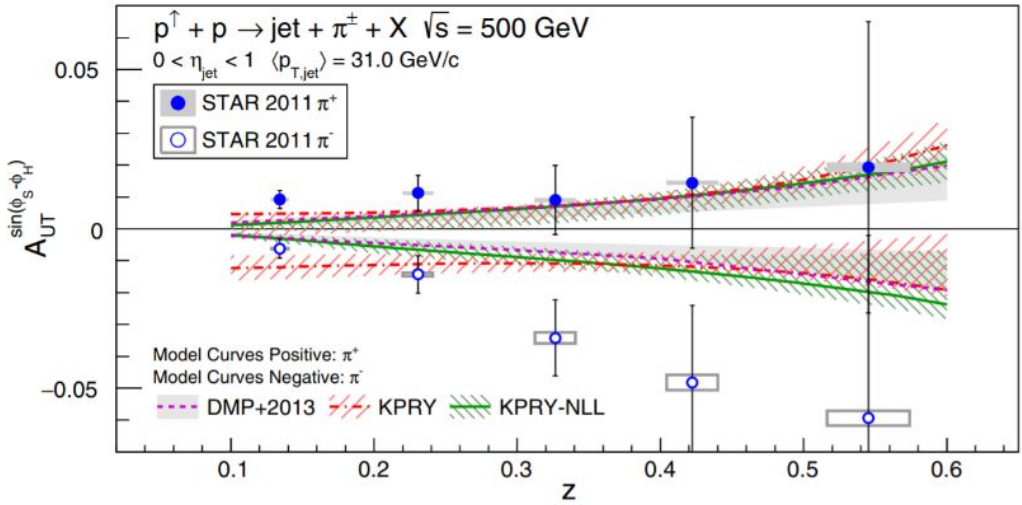
distribution of transversely polarized quarks inside a transversely polarized nucleon

This is measured with “Hadron-in-jet” azimuthal asymmetries:

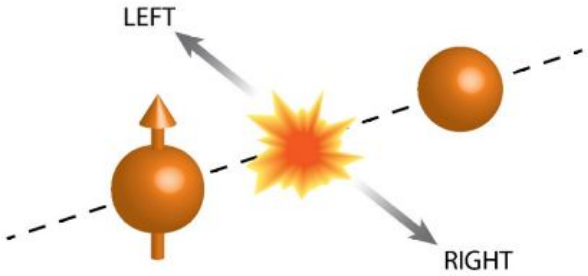



Phys. Lett. B 774, 635 (2017), Kang et al.
Phys.Rev.D77:074019 (2008) Yuan.

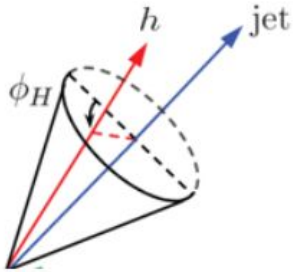
Measured at the RHIC proton-collider
STAR Collaboration, Phys. Rev. D 97, 032004 (2018)

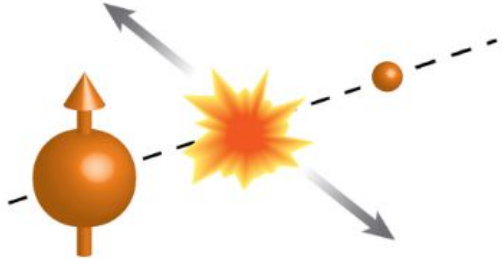


# Complementarity

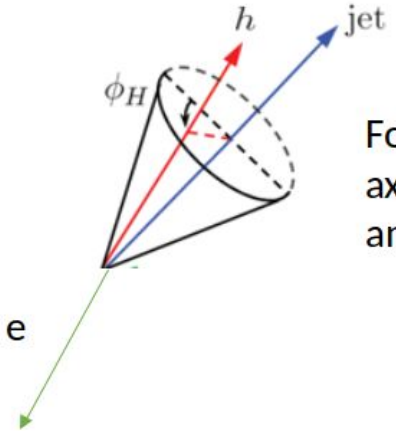



**pp at RHIC**



**ep at EIC**



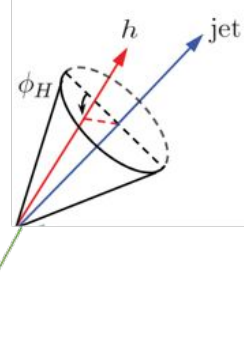

For DIS we will have 2 axes (virtual photon and jet).

## Extended to DIS:

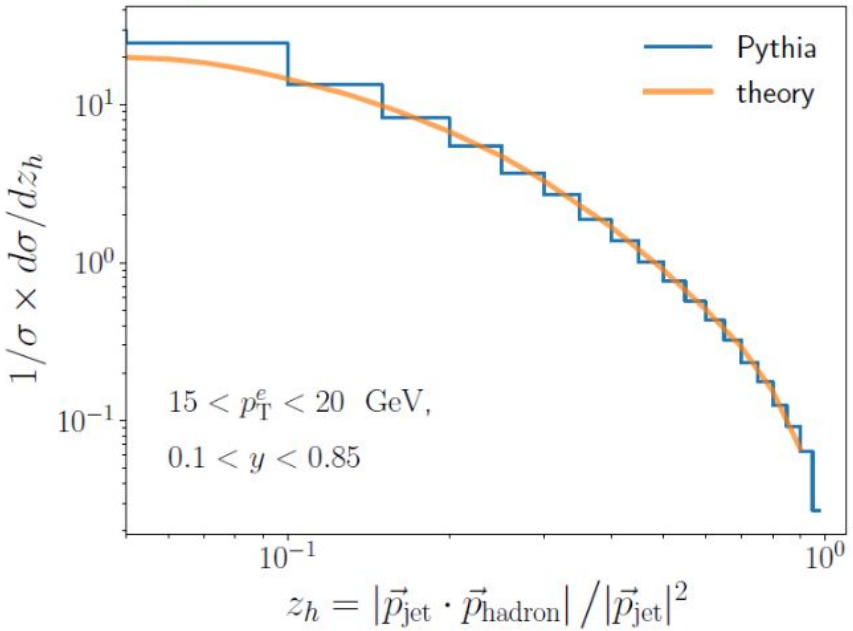
The unpolarized structure function $F_{UU}^h$ for hadron in-jet production is given by

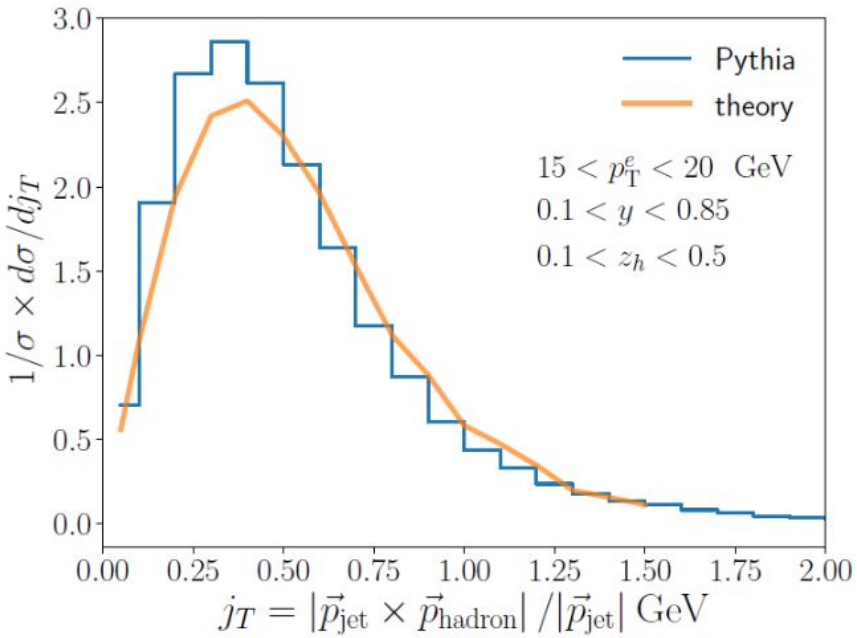
$$F_{UU}^h = \sigma_0 \, H_q(Q,\mu) \sum_q e_q^2 \, \mathcal{G}_q^h(z_h, \vec{j}_T, p_T^{\rm jet} R, \mu)$$

$$\times \int \frac{\mathrm{d}^2 \vec{b}_T}{(2\pi)^2} \, e^{i\vec{q}_T \cdot \vec{b}_T} \, f_q^{\rm TMD}(x, \vec{b}_T, \mu) \, S_q(\vec{b}_T, y_{\rm jet}, R, \mu) \, .$$

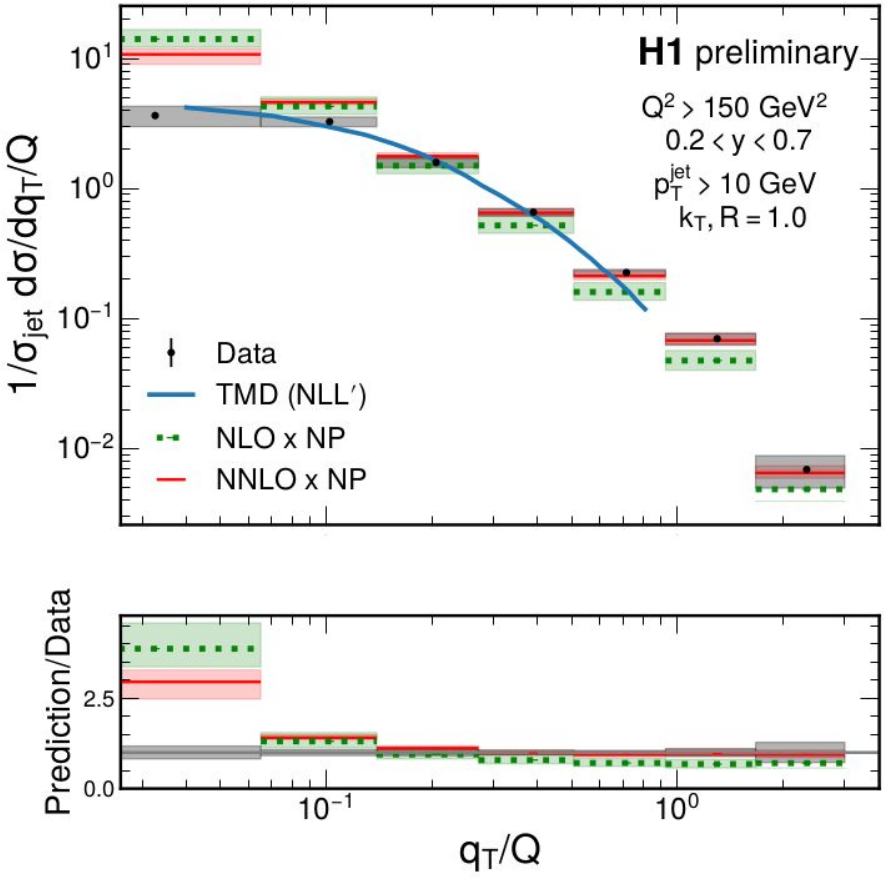


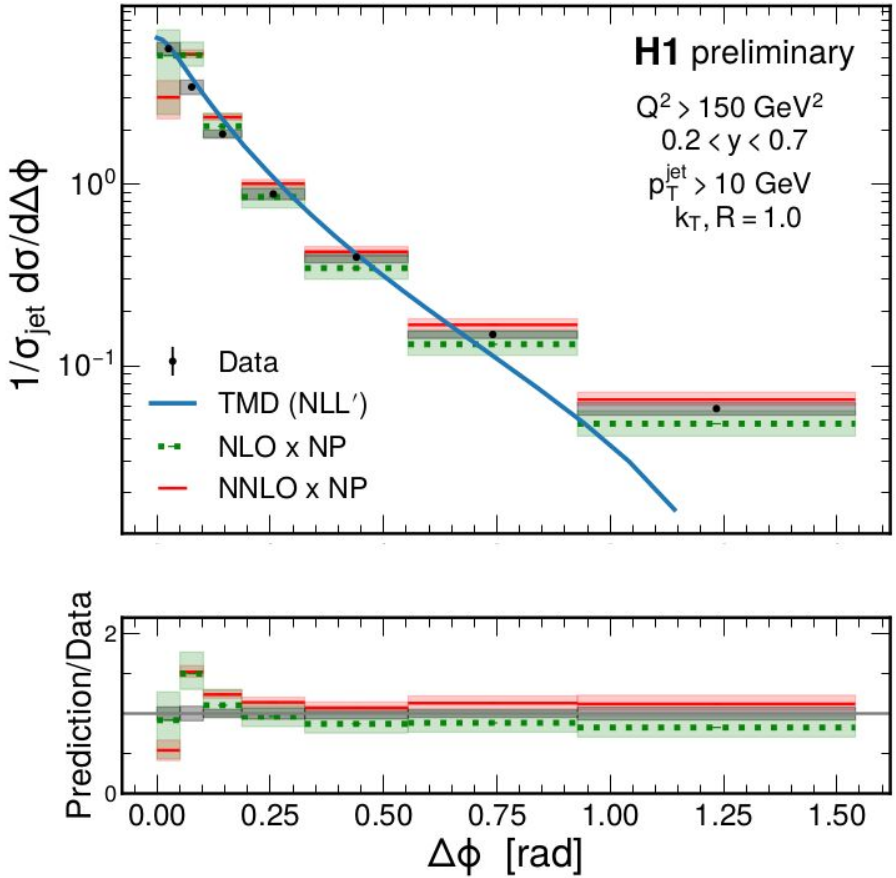

Arratia, Kang, Prokudin, Finger, Phys. Rev. D **102**, 074015



# Qualitatively the same results for azimuthal angle correlation



# Motivation

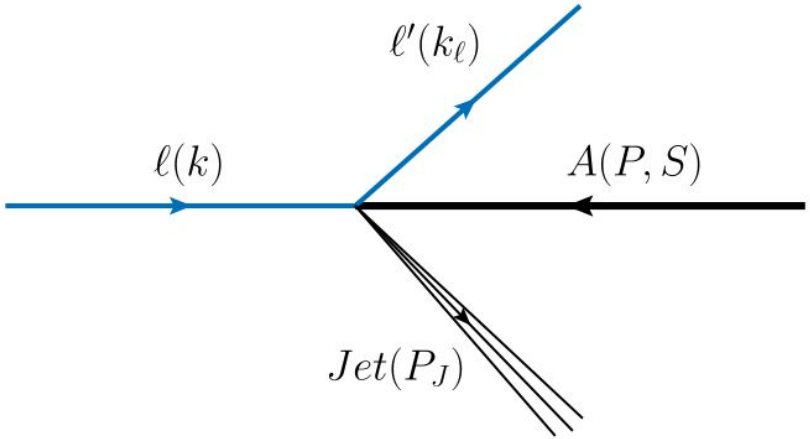
Lepton-jet imbalance $q_T = |\vec{k}_{l\perp} + \vec{p}^{\,j}_{\perp}|$

In Born-level configuration

Probes quark TMD PDFs

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

Gutierrez et al. PRL. 121, 162001 (2019)




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

# Dijets in photoproduction can probe the photon TMD structure