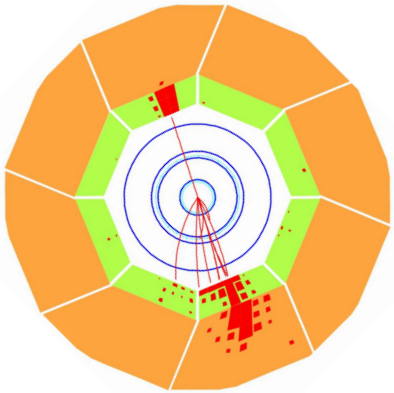
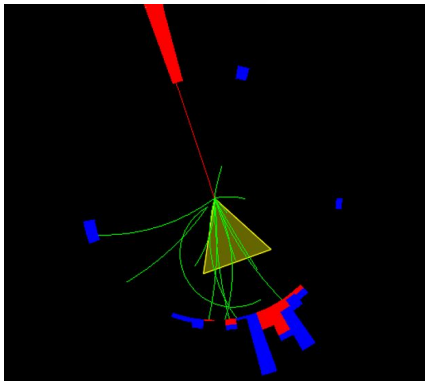
Jet in DIS as as a tool for Quantum tomography of the Proton



Miguel Arratia

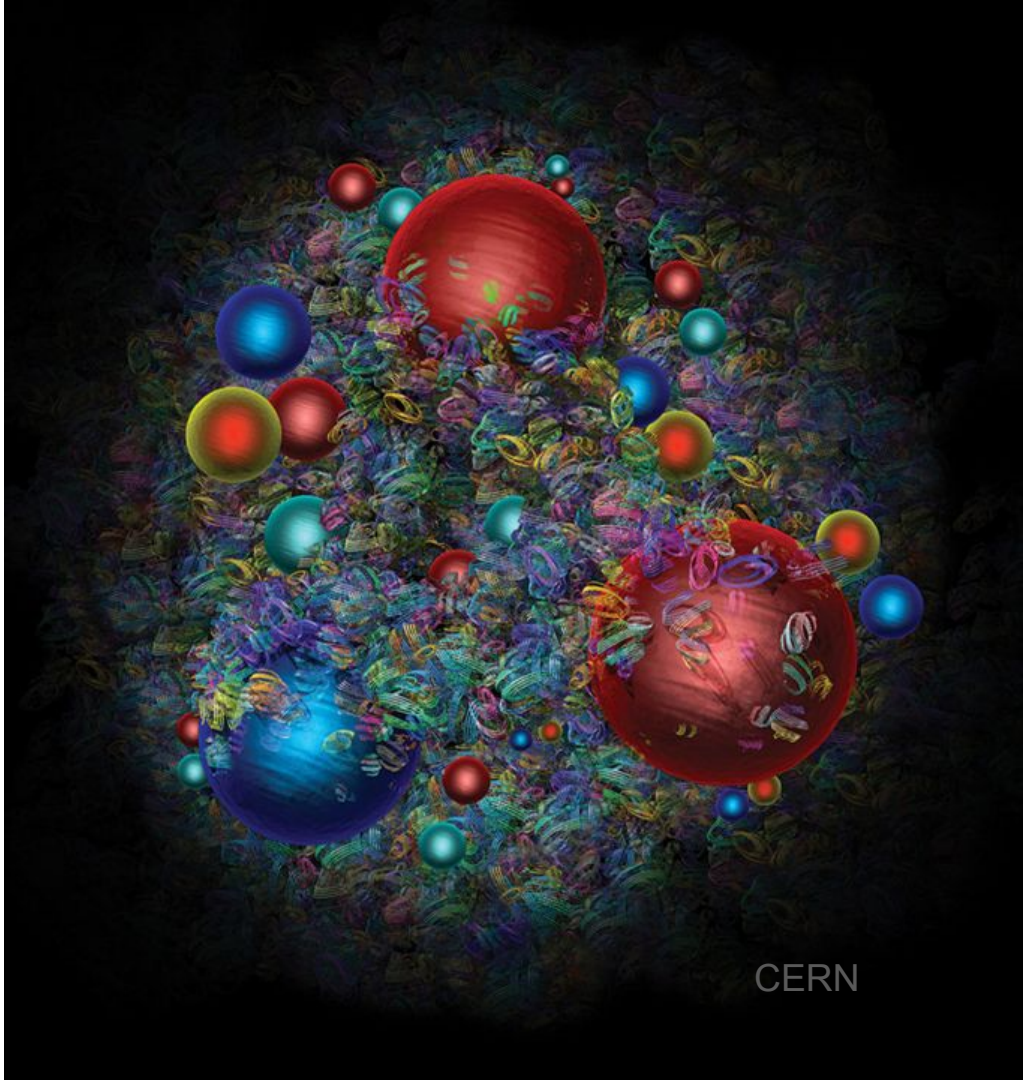
UC RIVERSIDE



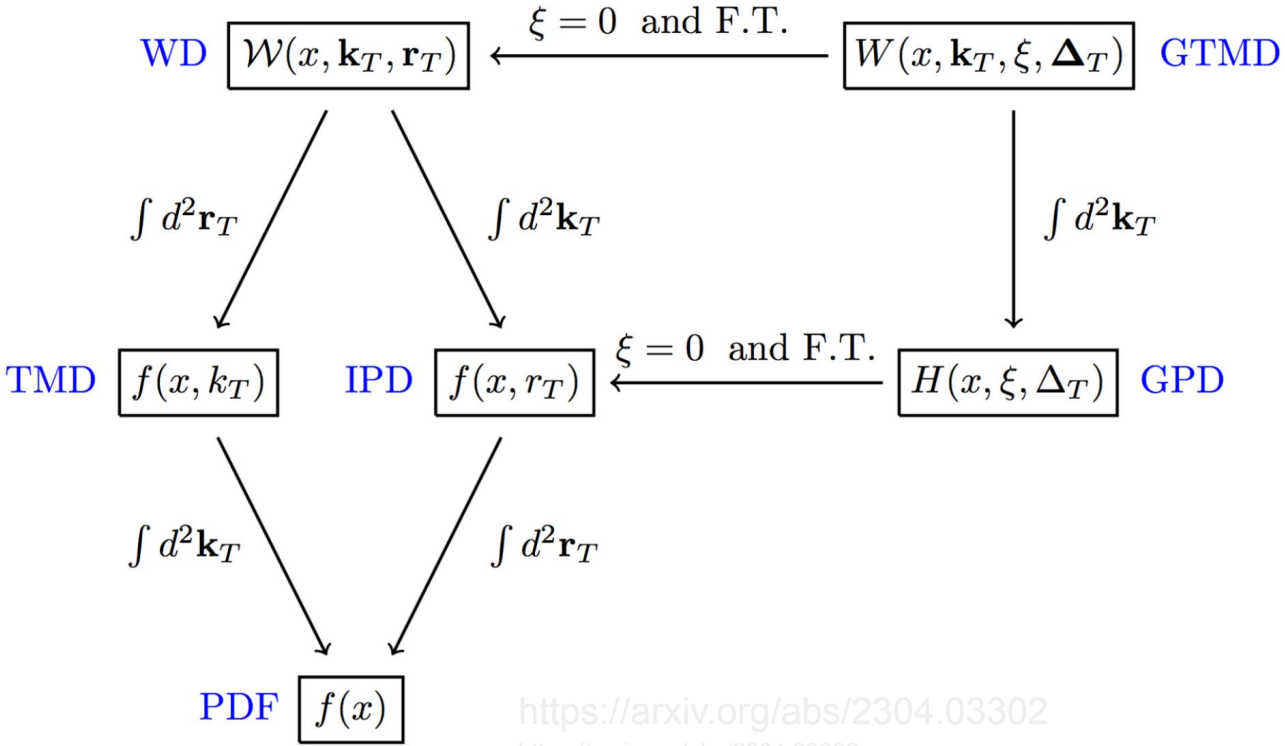
CTEQ Fall meeting, Nov 9th 2023

Outline

- Jets in DIS as tool for Quantum tomography in QCD.
- Future prospects at the Electron-Ion Collider (EIC).
- An EIC pathfinder program with HERA data.


CERN

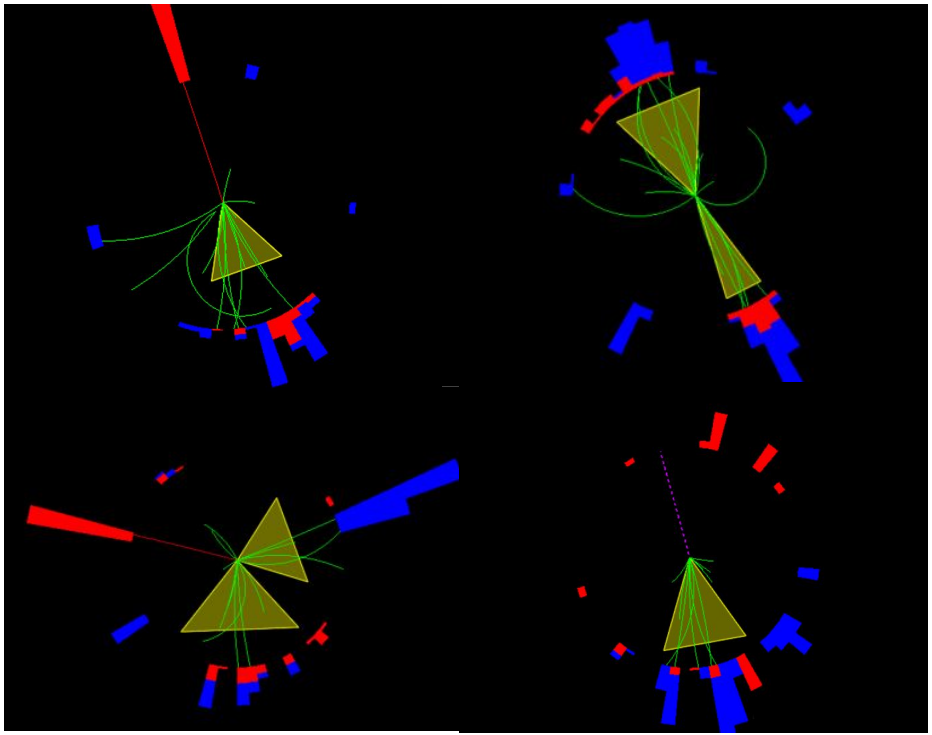
Goal: measure “projections” of the quantum-phase density in either position or momentum space (“GPDs” or “TMDs”)

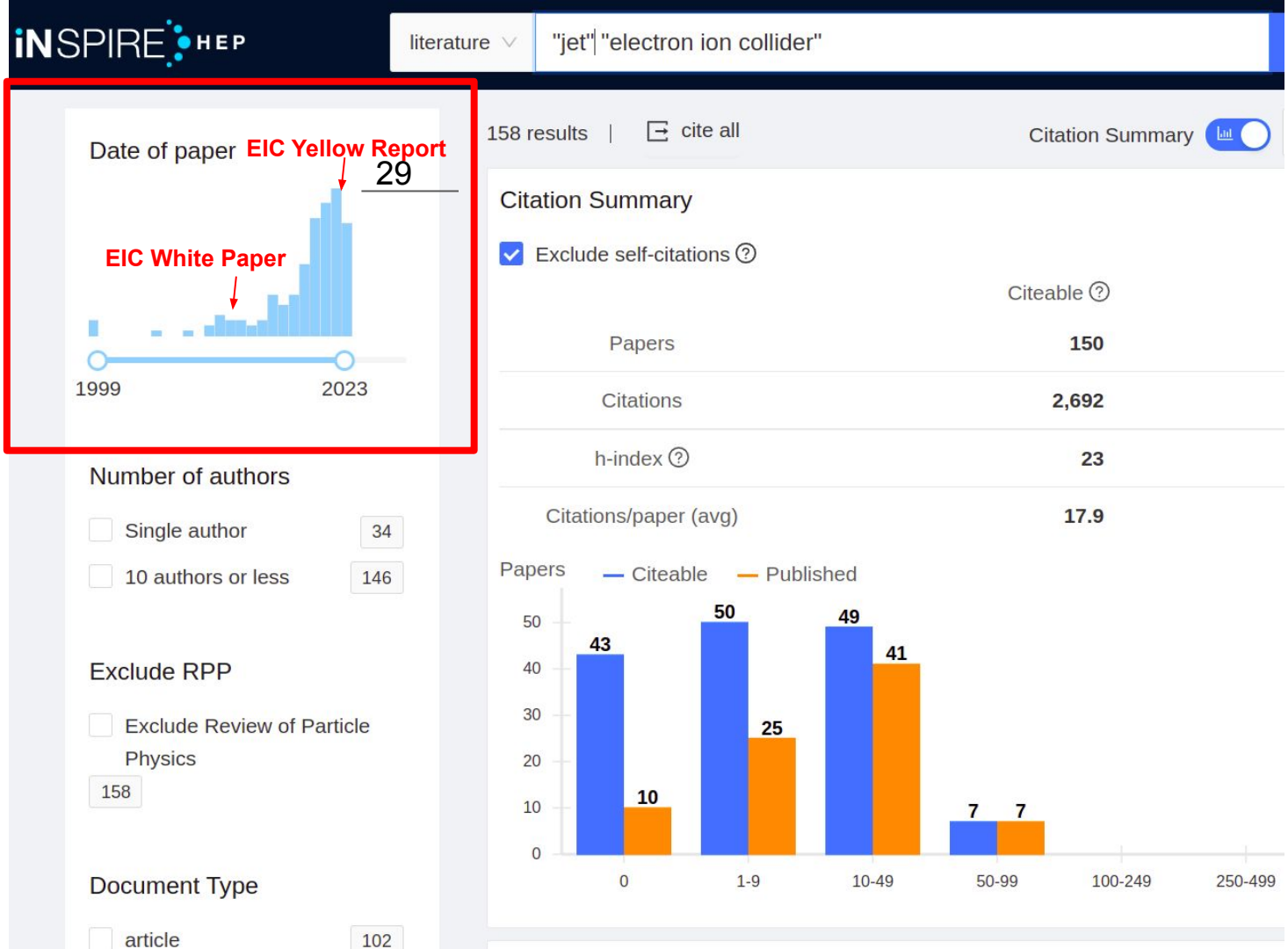


These functions follow a more complex set QCD of evolution equations

https://arxiv.org/abs/2304.03302
https://arxiv.org/abs/2304.03302

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




iNSPIRE HEP
literature
"jet" "electron ion collider"
Date of paper
EIC Yellow Report
29
EIC White Paper
1999
2023
Number of authors
Single author 34
10 authors or less 146
Exclude RPP
Exclude Review of Particle Physics
158
Document Type
article 102
158 results
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Citations 2,692
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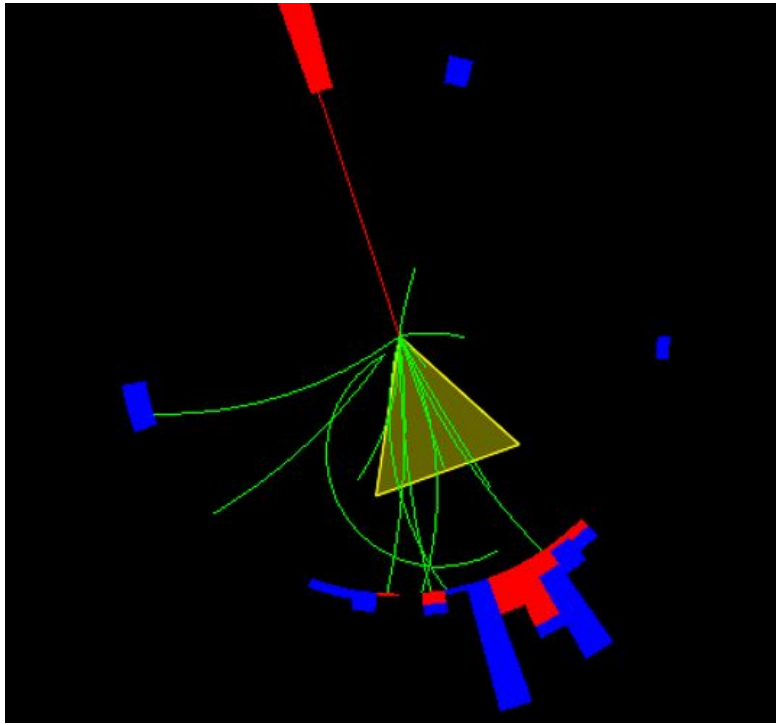
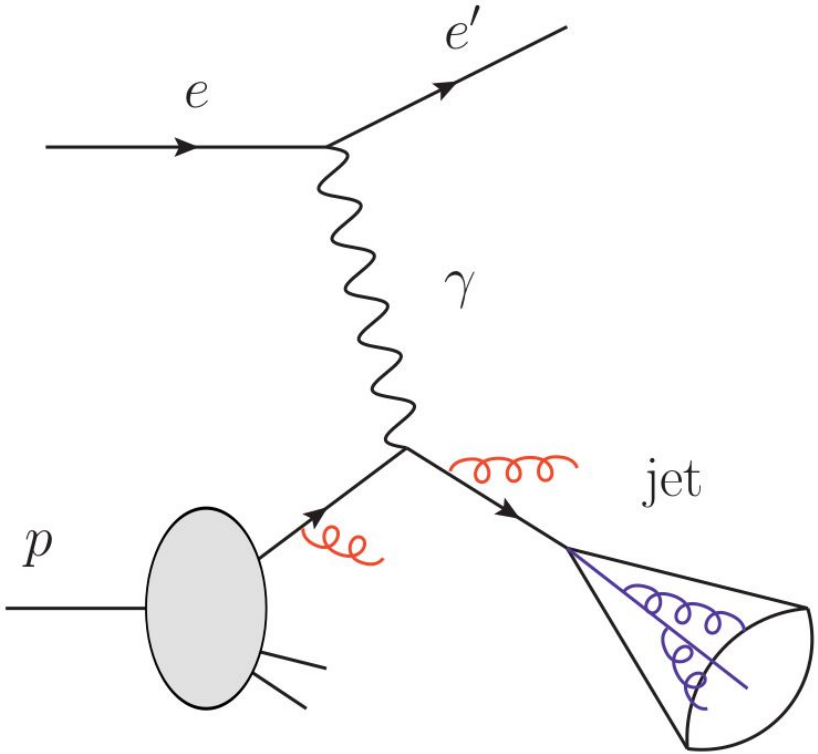
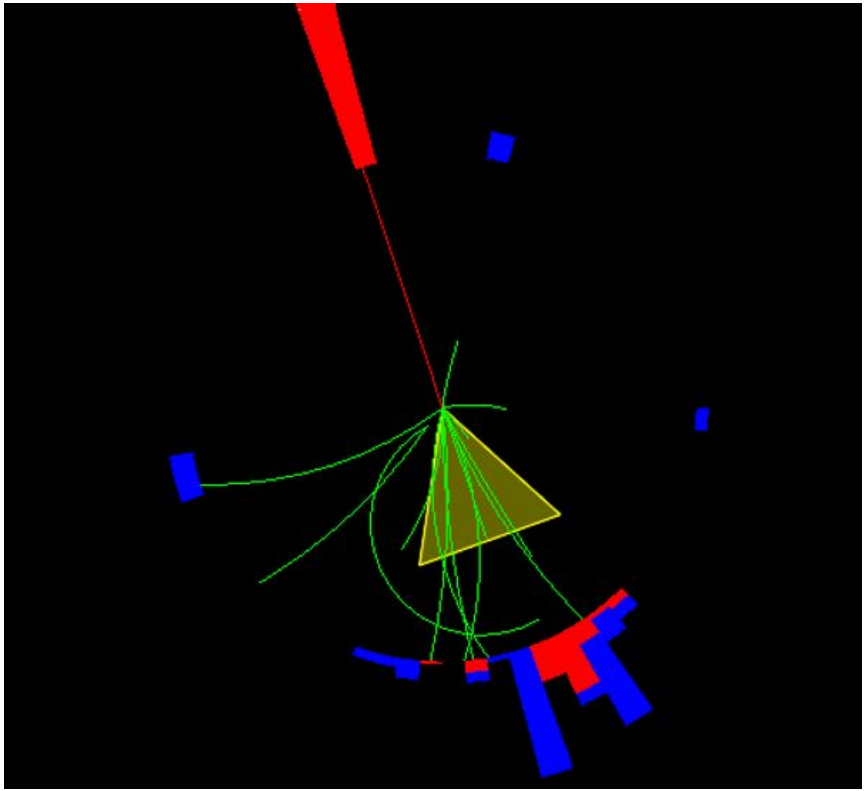
Why are jets useful?

- Proxies to quark and gluons
- their substructure encodes rich & useful info



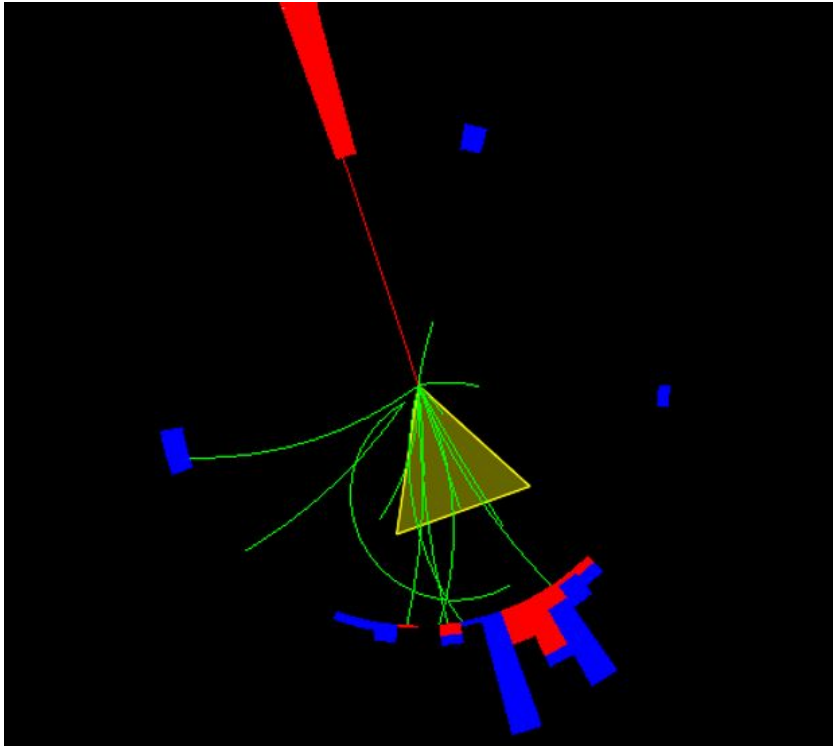
Back-to-back topology in DIS





Electron-jet correlation: A new channel to probe for quark transverse-momentum distributions (TMDs) and evolution

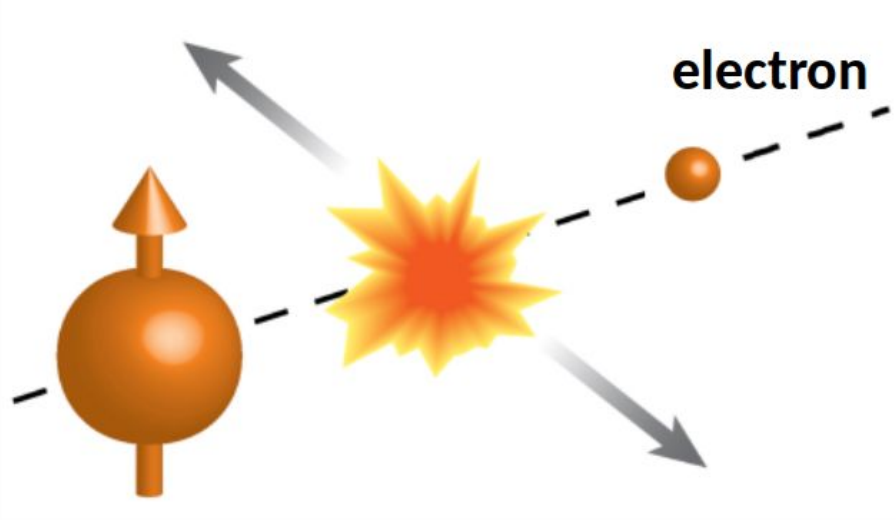
Liu et al. PRL. 122, 192003, Gutierrez et al. PRL. 121, 162001

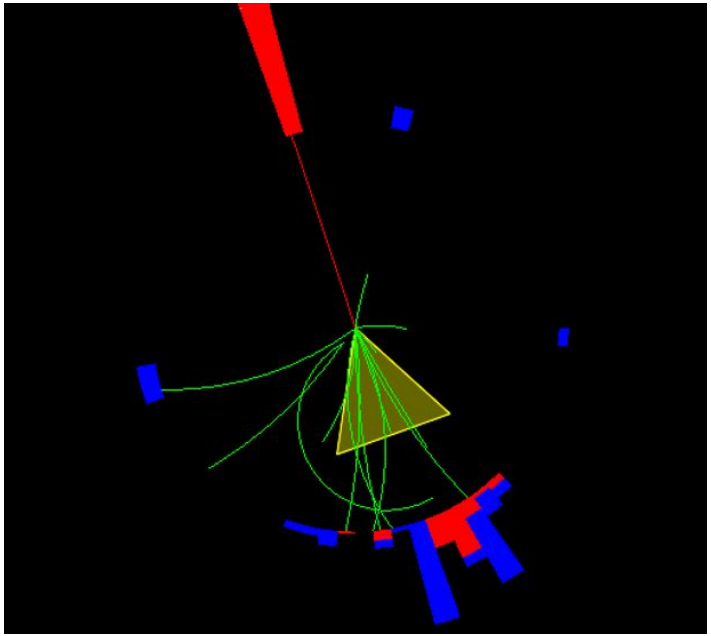


"The advantage of the lepton-jet correlation as compared to the standard SIDIS processes is that it ***does not involve TMD fragmentation functions."***

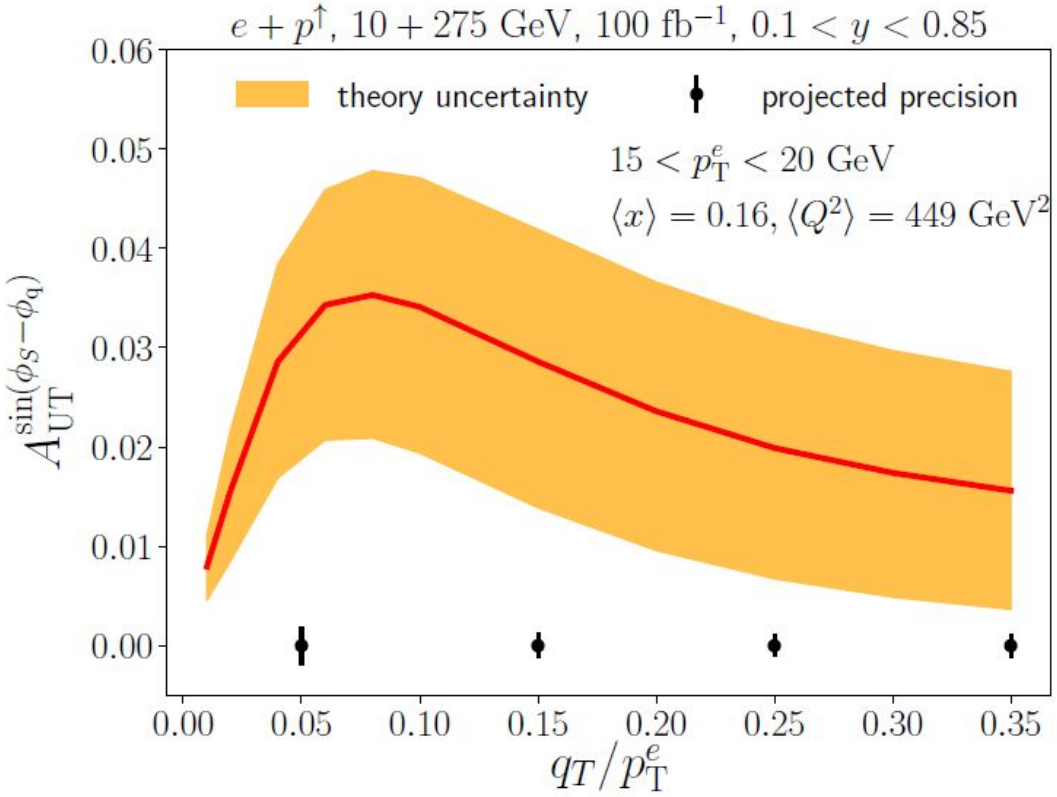
$$\frac{d^5\sigma(\ell p \to \ell' J)}{dy_\ell d^2k_{\ell\perp} d^2q_\perp} = \sigma_0 \int d^2k_\perp d^2\lambda_\perp x f_q(x, k_\perp, \zeta_c, \mu_F) \times H_{\mathrm{TMD}}(Q, \mu_F) S_J(\lambda_\perp, \mu_F) \times \delta^{(2)}(q_\perp - k_\perp - \lambda_\perp).$$

Spin-orbit correlations lead to azimuthal asymmetries

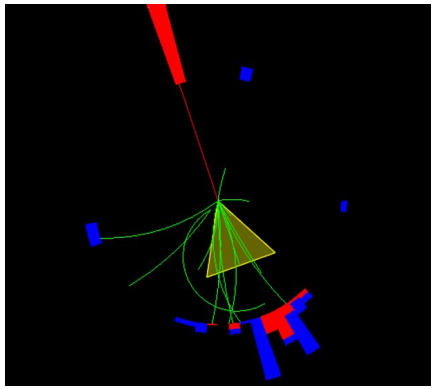




Projection for Lepton-jet Sivers asymmetry



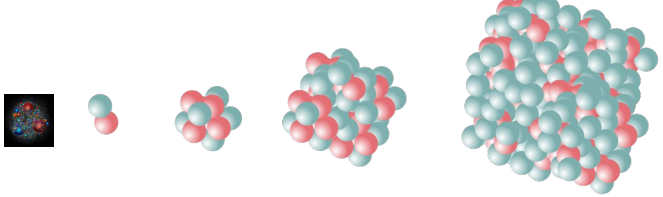
Arratia et al. PRD 102 (2020) 7, 074015



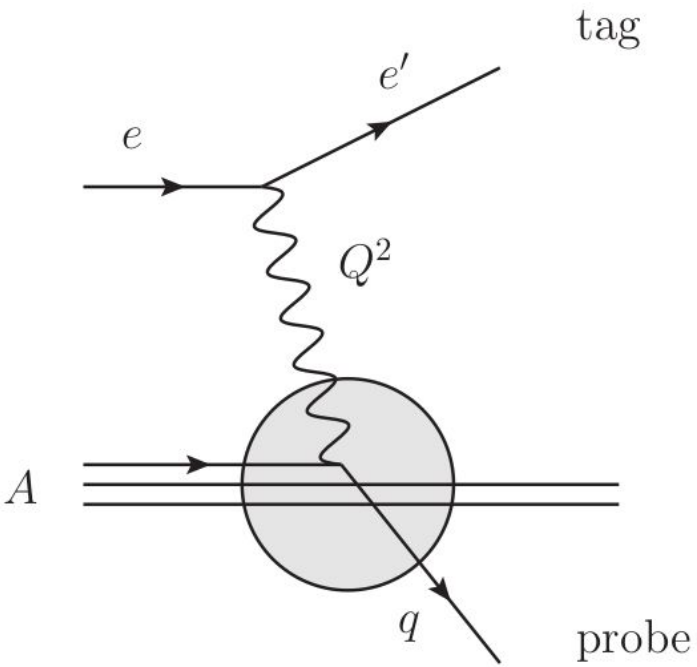
$$q_T = |\vec{p}_T^{\,e} + \vec{p}_T^{\,\mathrm{jet}}|$$

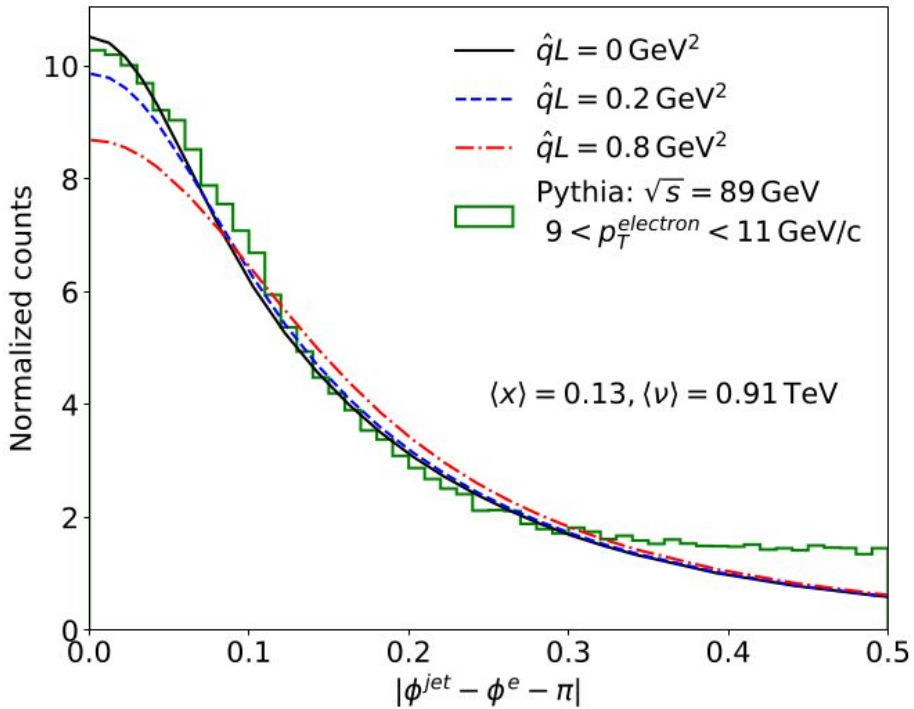
We estimated it to be feasible

Jets as precision probes in eA



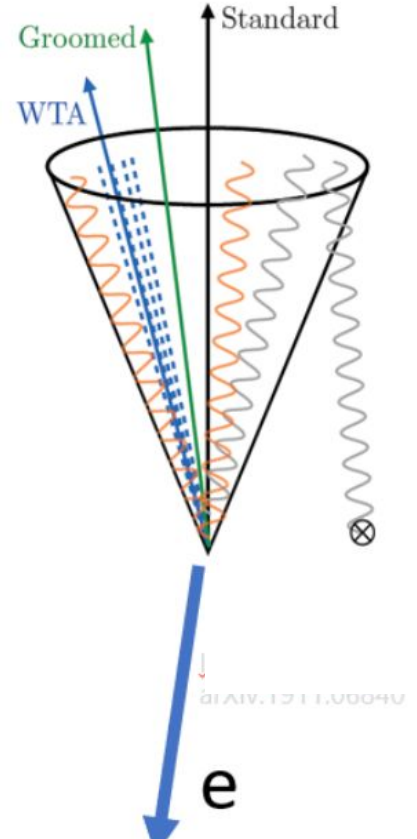
M. Arratia et al. PRC 101 (2020) 6, 065204

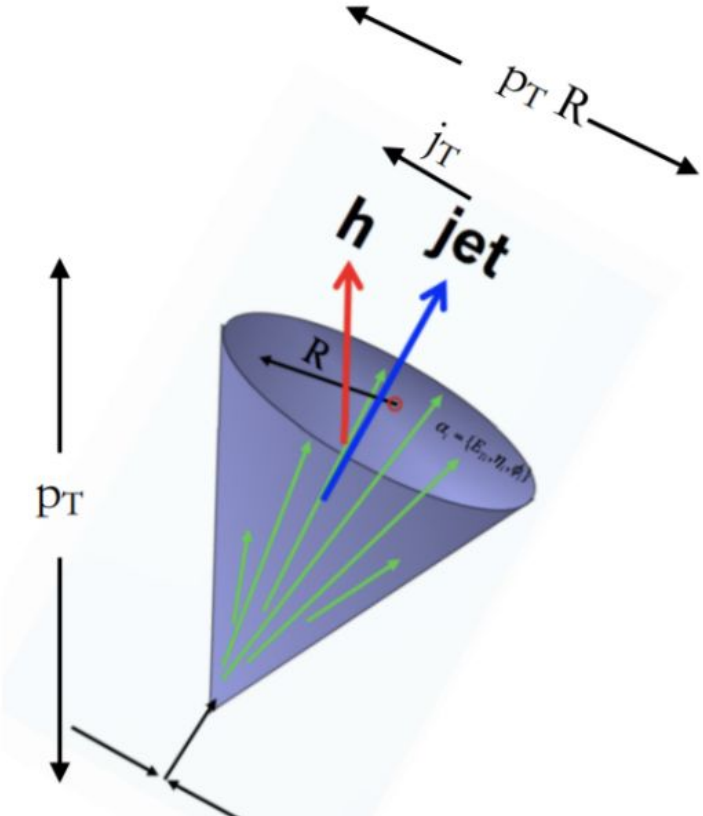


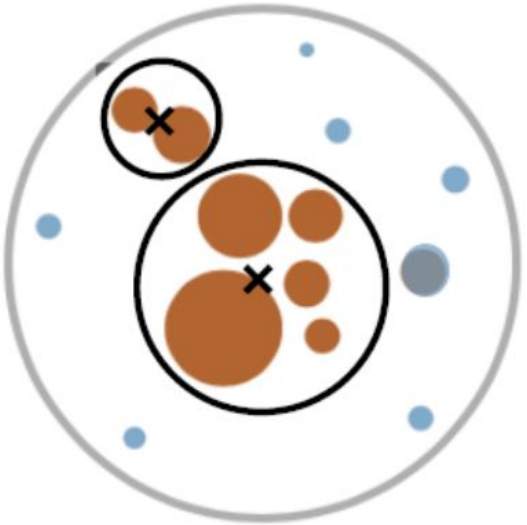


$\hat{q}$ **is proportional to gluon TMD in nuclei**

Jets have rich substructure, which encodes rich TMD info such fragmentation, TMD evolution, and access to TMDs

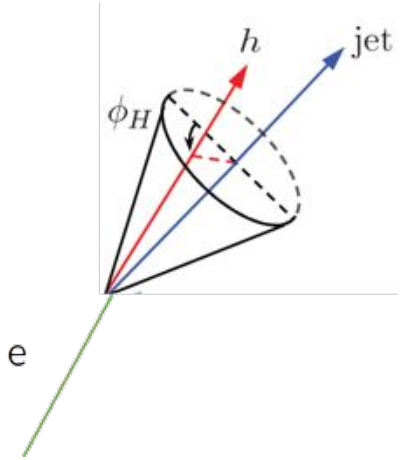




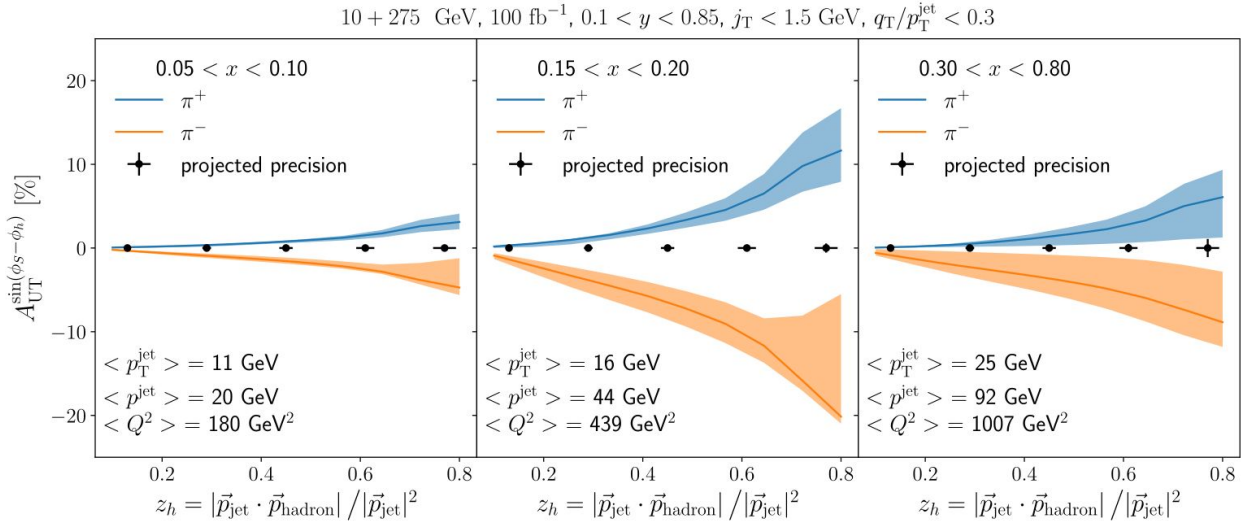


“Hadron-in-jet asymmetries” will yield a wealth of information

$$e + p(\vec{s}_T) \rightarrow e + (\mathrm{jet}(\vec{q}_T)h(z_h, \vec{j}_T)) + X.$$



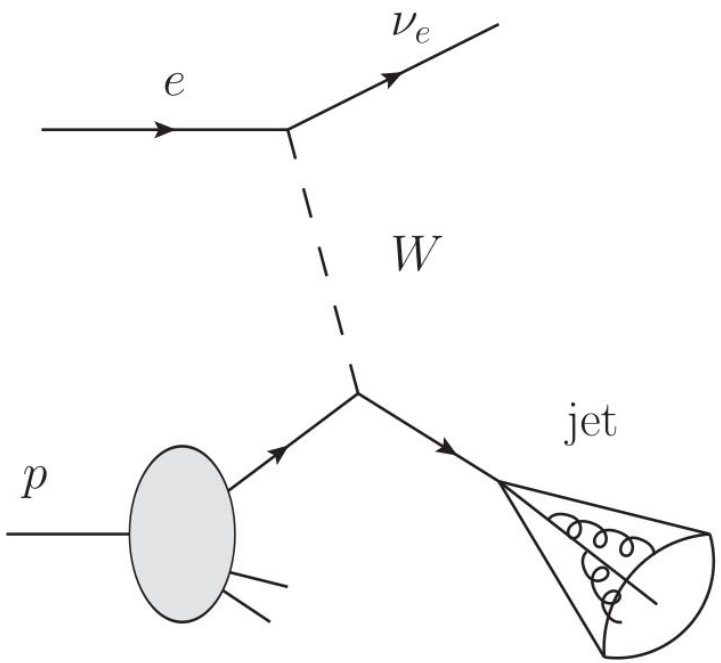
Arratia et al. PRD 102 (2020) 7, 074015

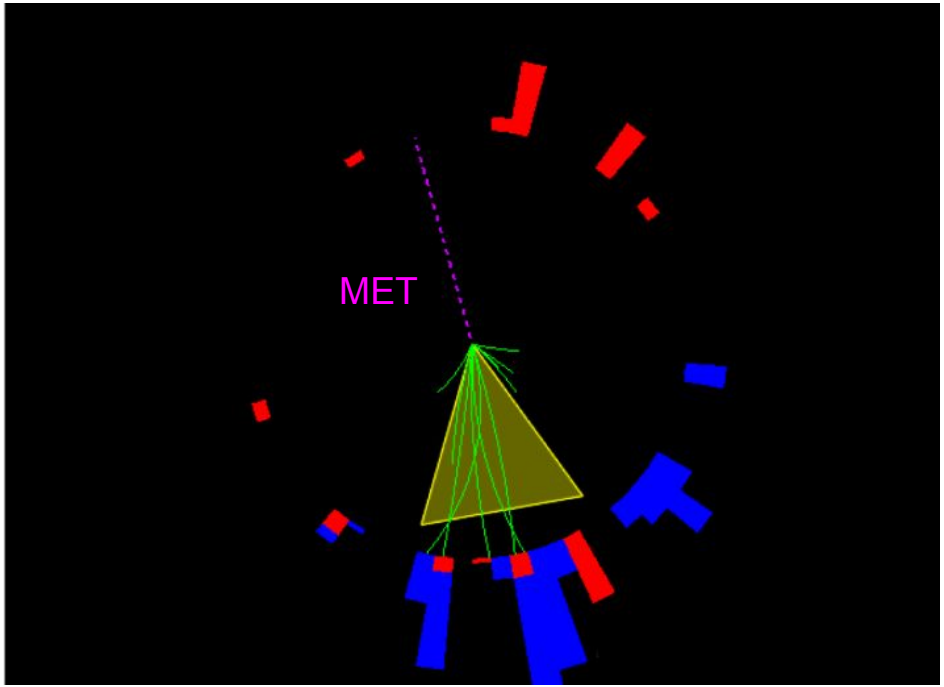


Simultaneous measurement of electron, hadron and jet provides powerful tool to unravel TMD effects

$$\frac{\mathrm{d}\sigma^h(\vec{s}_T)}{\mathrm{d}\mathcal{P}S\mathrm{d}z_h\mathrm{d}^2\vec{j}_T^h} = F_{UU}^h + \sin(\phi_s - \phi_h)F_{UT}^{\sin(\phi_s-\phi_h)},$$

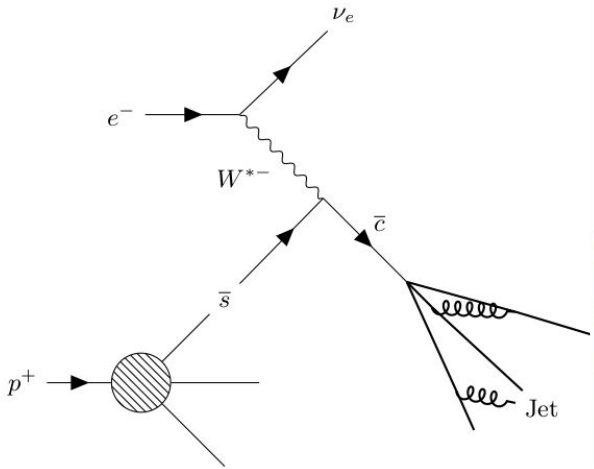
Jets in charged-current DIS offer complementarity in flavour sensitivity and chiral structure

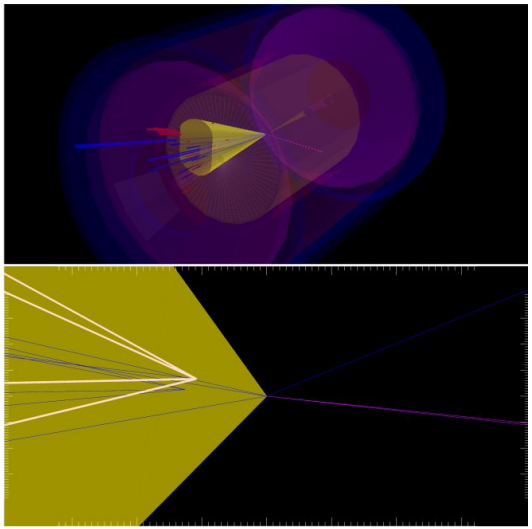


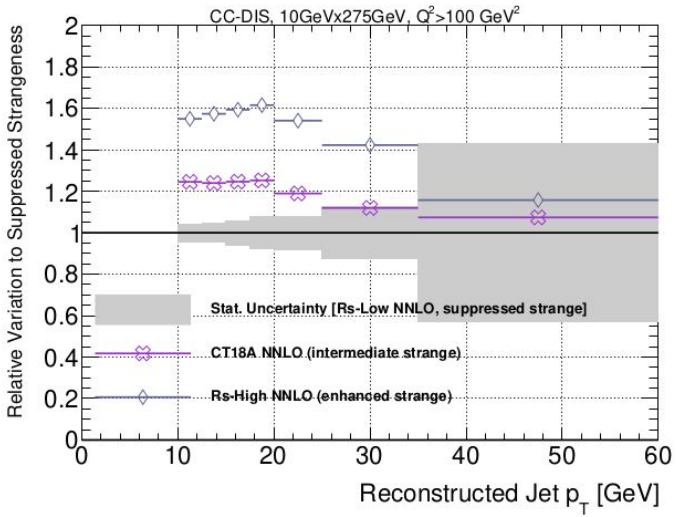


"Neutrino-tagged jets at the EIC", M. Arratia et al. PRD 107 (2023) 9, 094036
"Charm jets as a probe for strangeness at the future EIC", M. Arratia et al. PRD 103 (2021) 7, 074023

Charm jets as a probe for strangeness



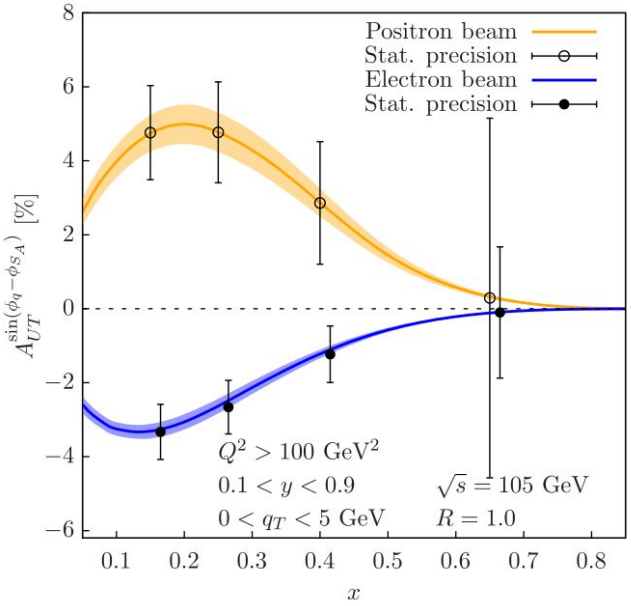




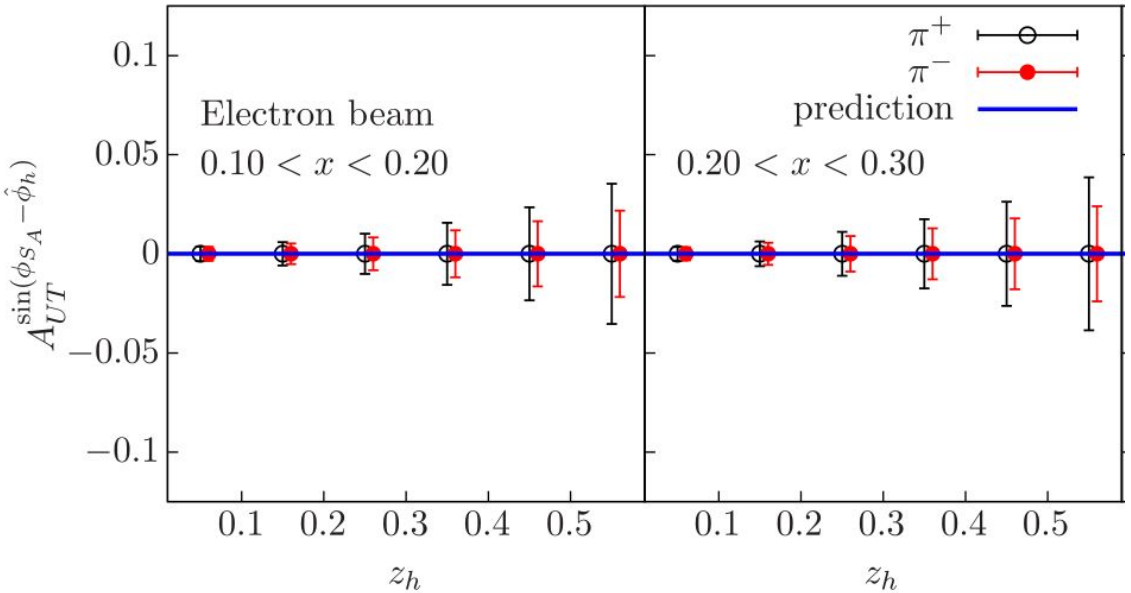
Our feasibility studies suggest that the prospects for constraining unpolarized nucleon strangeness are rather promising in this channel.

M. Arratia et al. PRD 103 (2021) 7, 074023

Neutrino-jet transverse-spin asymmetry (Sivers function)



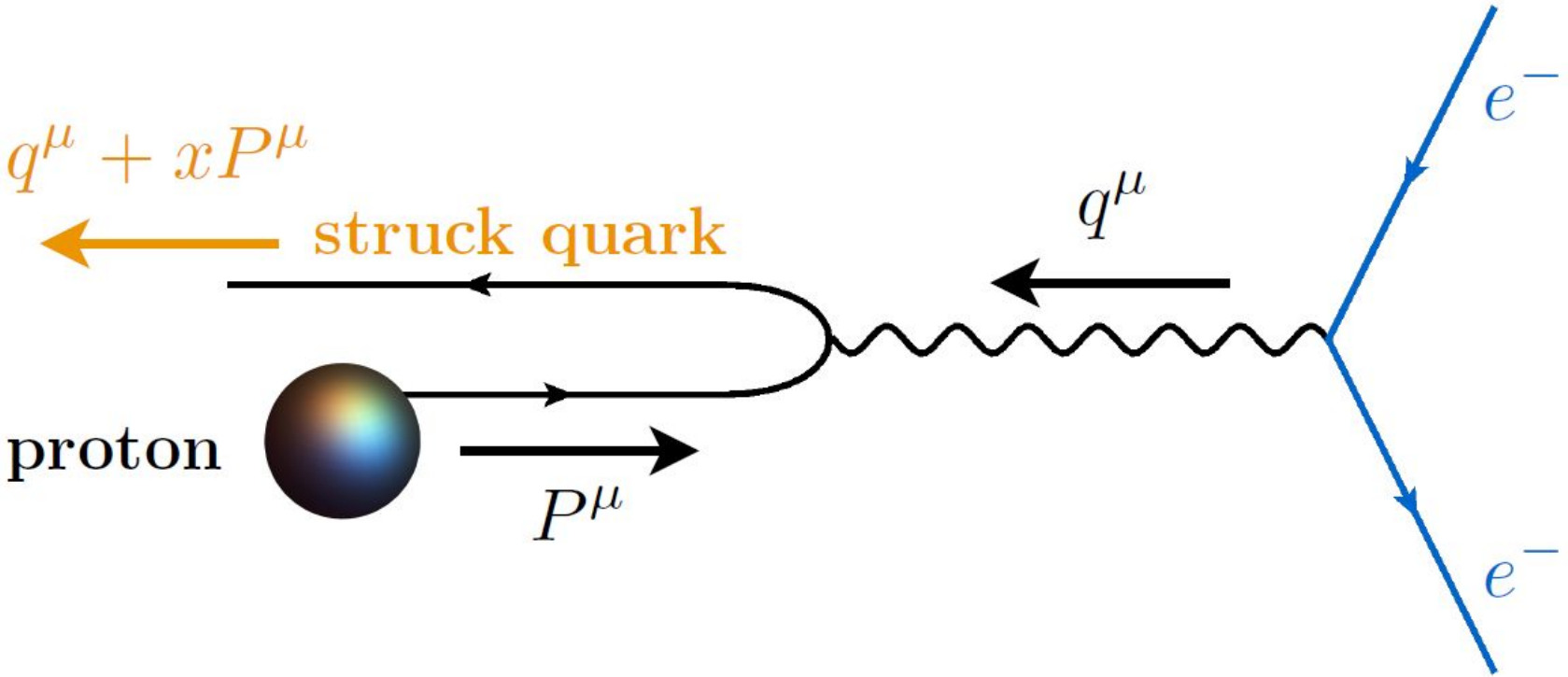
Hadron-in-jet with neutrino tagging (Collins effect = Zero exactly)



CC DIS offers complementary channel to NC DIS TMD studies

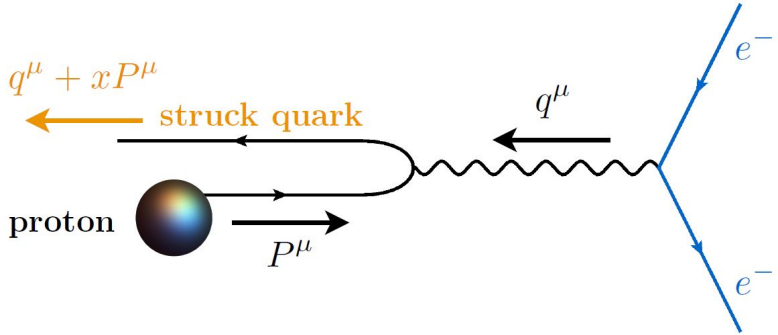
"Neutrino-tagged jets at the EIC", M. Arratia et al. PRD 107 (2023) 9, 094036

How to do jet clustering in the Breit Frame ("brick wall frame")?



Centauro Jet Algorithm

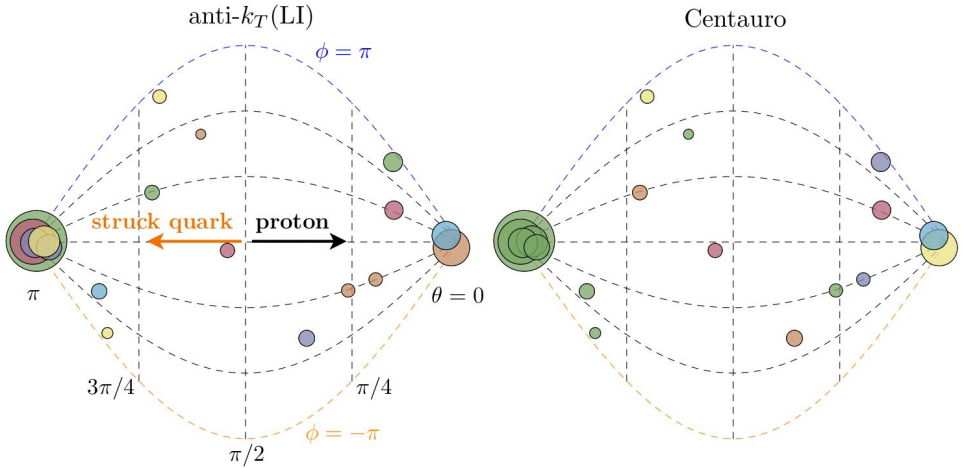
"Asymmetric jet clustering in deep-inelastic scattering", M. Arratia et al. PRD 104, 034005 (2021)

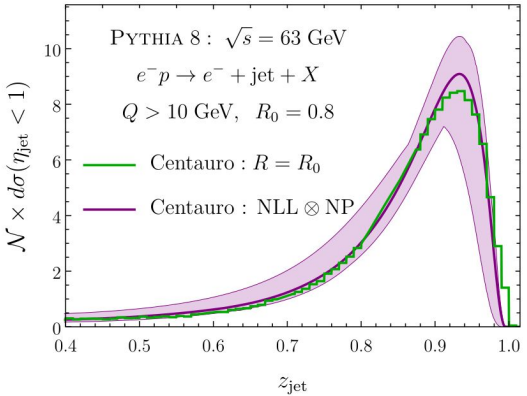


$$d_{ij} = (\bar{\eta}_i - \bar{\eta}_j)^2 + 2\bar{\eta}_i\bar{\eta}_j(1 - \cos(\phi_i - \phi_j))$$

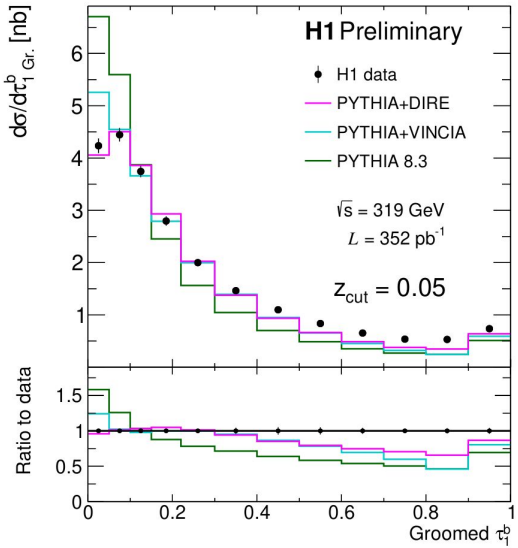
$$\bar{\eta}_i \equiv -\frac{2Q}{\bar{n}\cdot q}\frac{p_i^\perp}{n\cdot p_i}$$

- Longitudinally invariant like kT but it can cluster struck-quark jet.
- First asymmetric clustering metric ever





Event shapes with Centauro metric



1-jettiness with jet axis at O(α s) in deep inelastic scattering

1-jettiness with jet axis at O(α s) in deep inelastic scattering

Chut et al. JHEP 06 (2022) 111

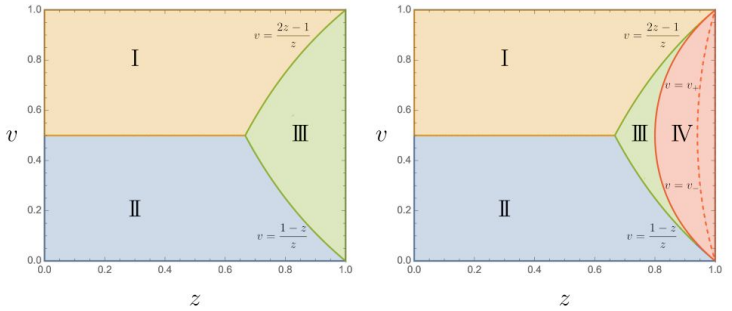
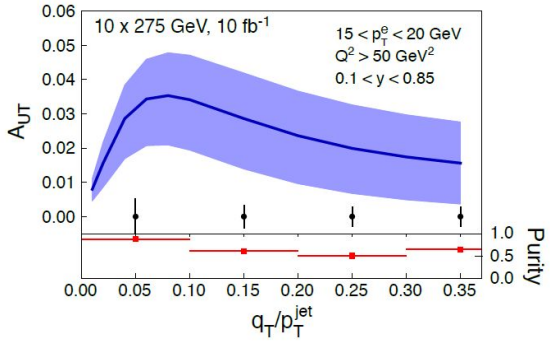
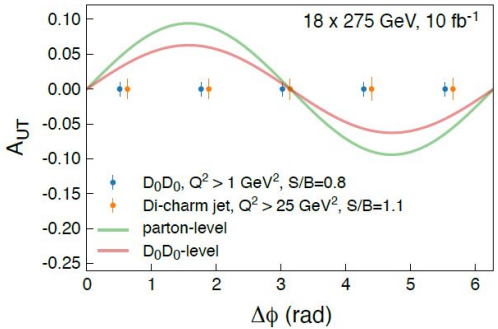


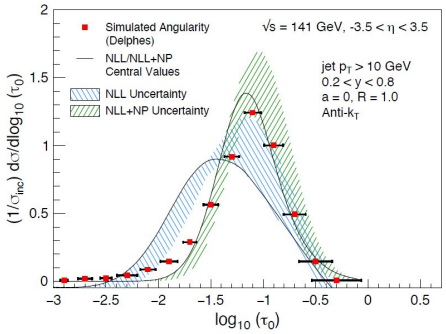
Figure 1. Two-body phase space for 1-jettiness, $\tau^{\mathrm{jt,kt}}$ with jettiness/anti-k_T axis (left) and τ^{ct} with Centauro axis (right). 1-jettiness takes the same expression in first three regions while the

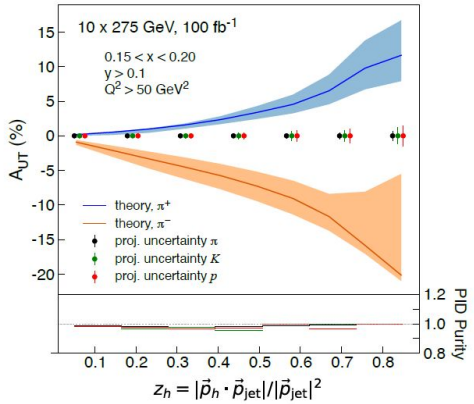
Jets were featured extensively in EIC detector proposals

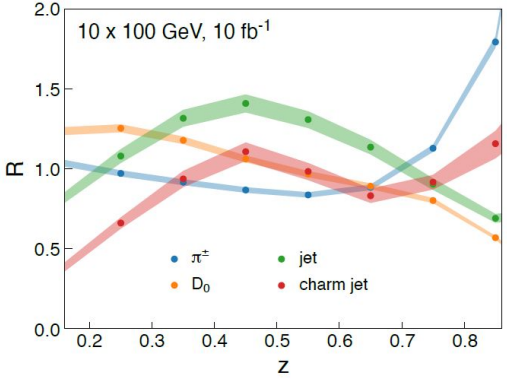
ATHENA Collaboration J. Adam *et al* 2022 *JINST* 17 P10019

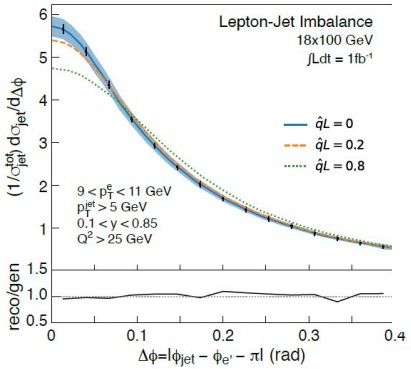


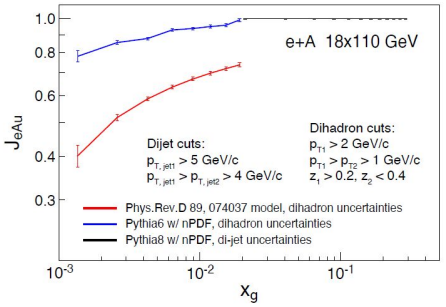






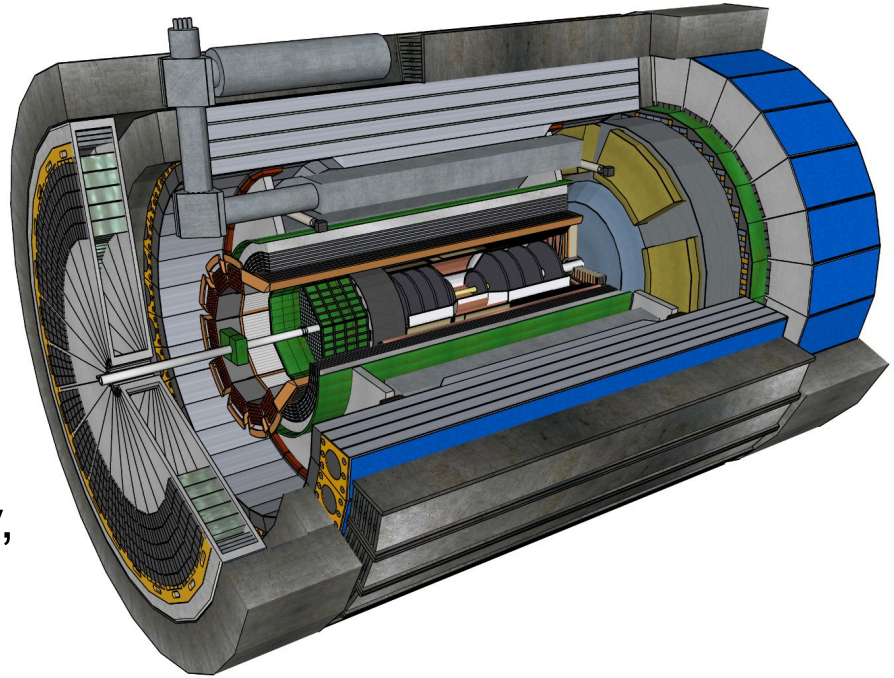


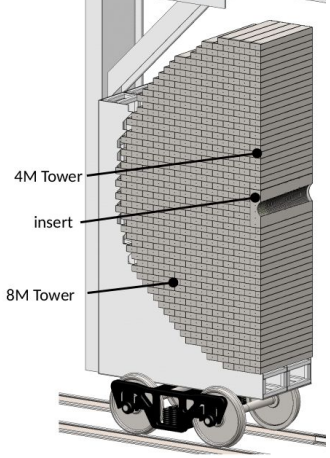


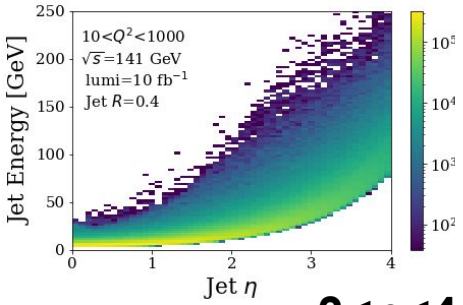


ePIC

a great jet detector with large-coverage Full calorimetry, PID and and tracking







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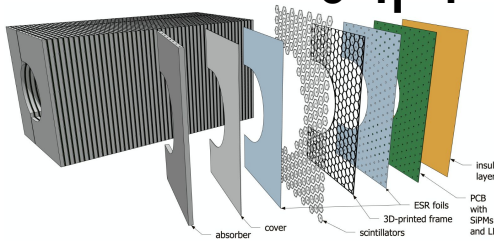
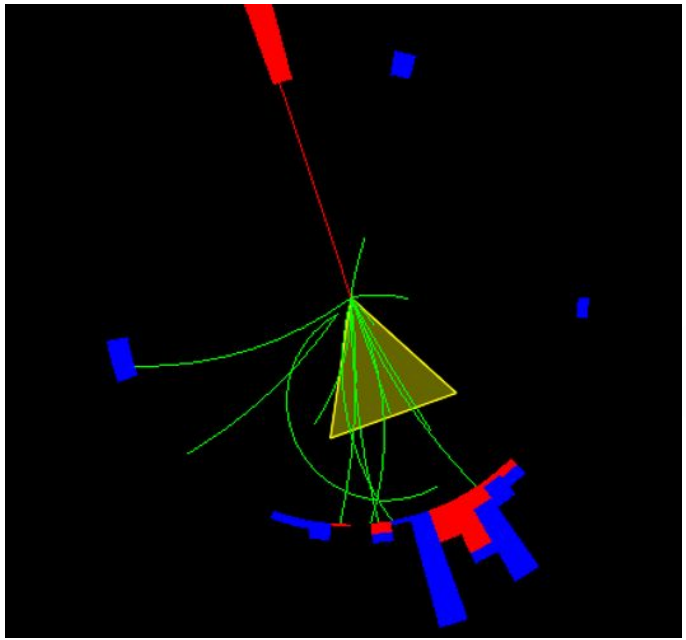


Dedicated detectors for forward jets:

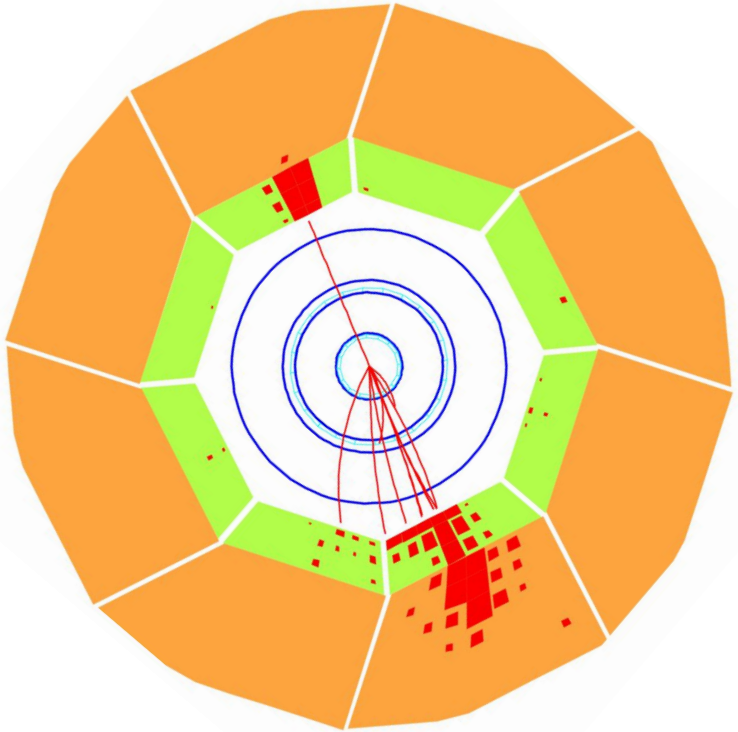
M. Arratia et al. *NIMA 1047 (2023) 167866*

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

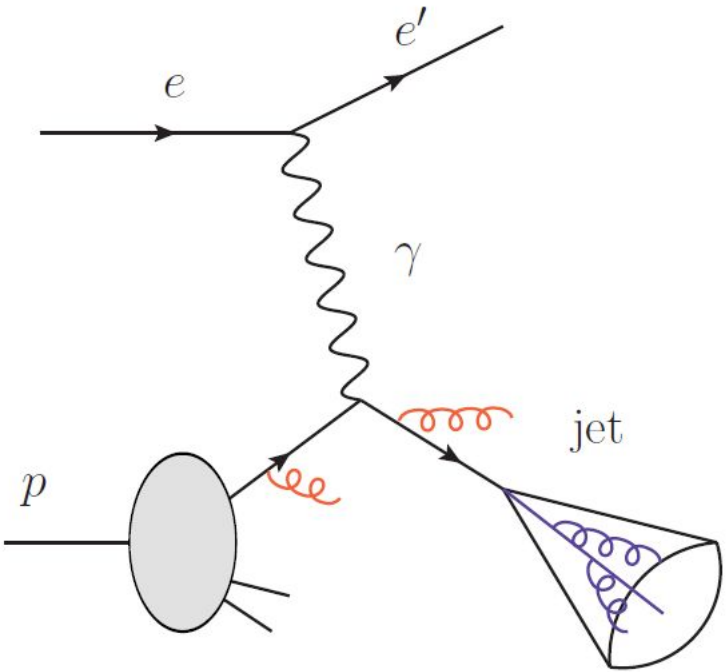
EIC



H1@HERA



BACK
TO THE FUTURE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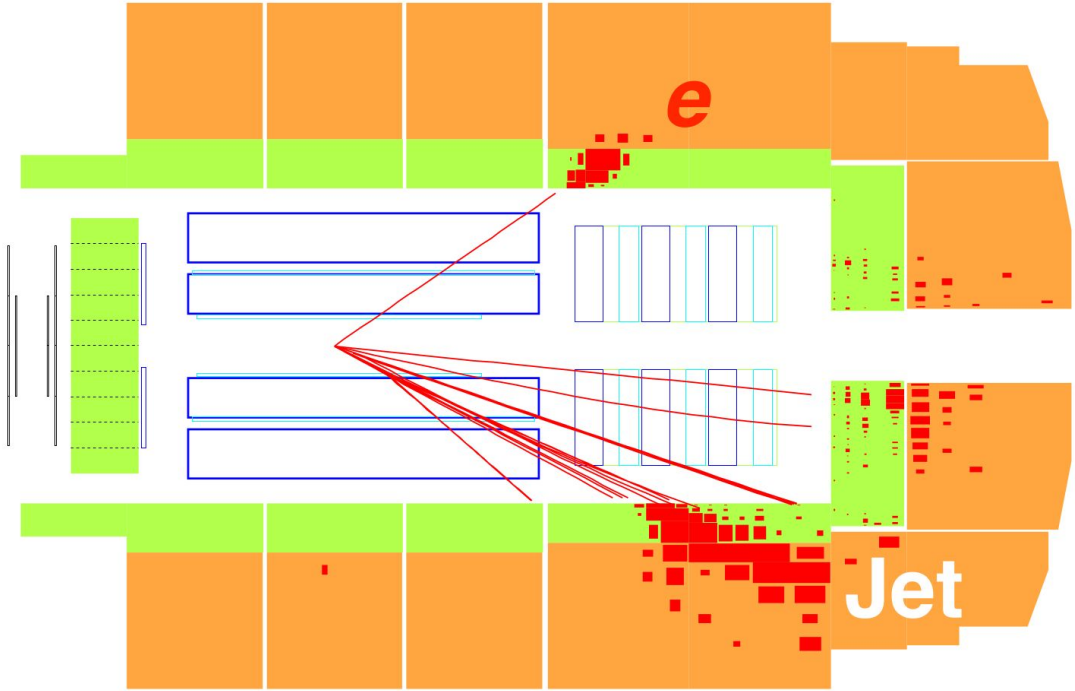
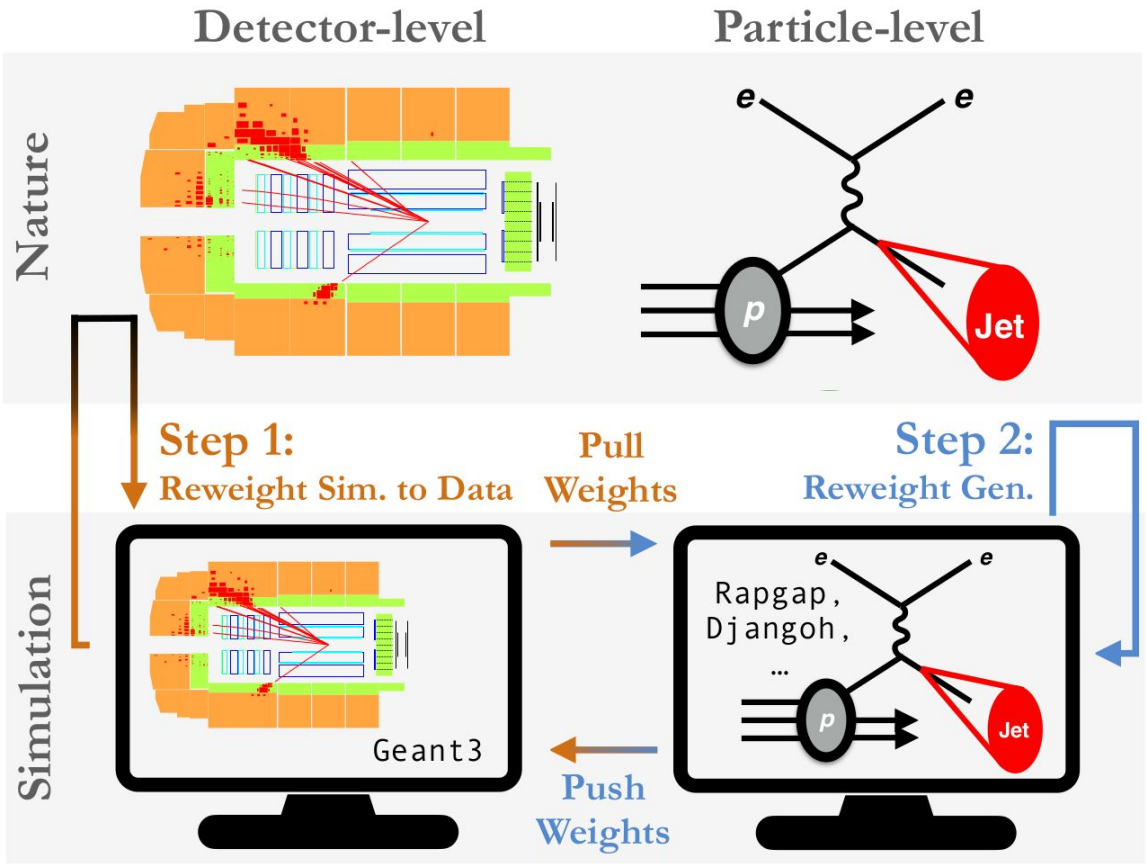

e
Jet

Unfolding with Omnifold (via machine-learning).

Andreassen et al. PRL **124**, 182001 (2020)



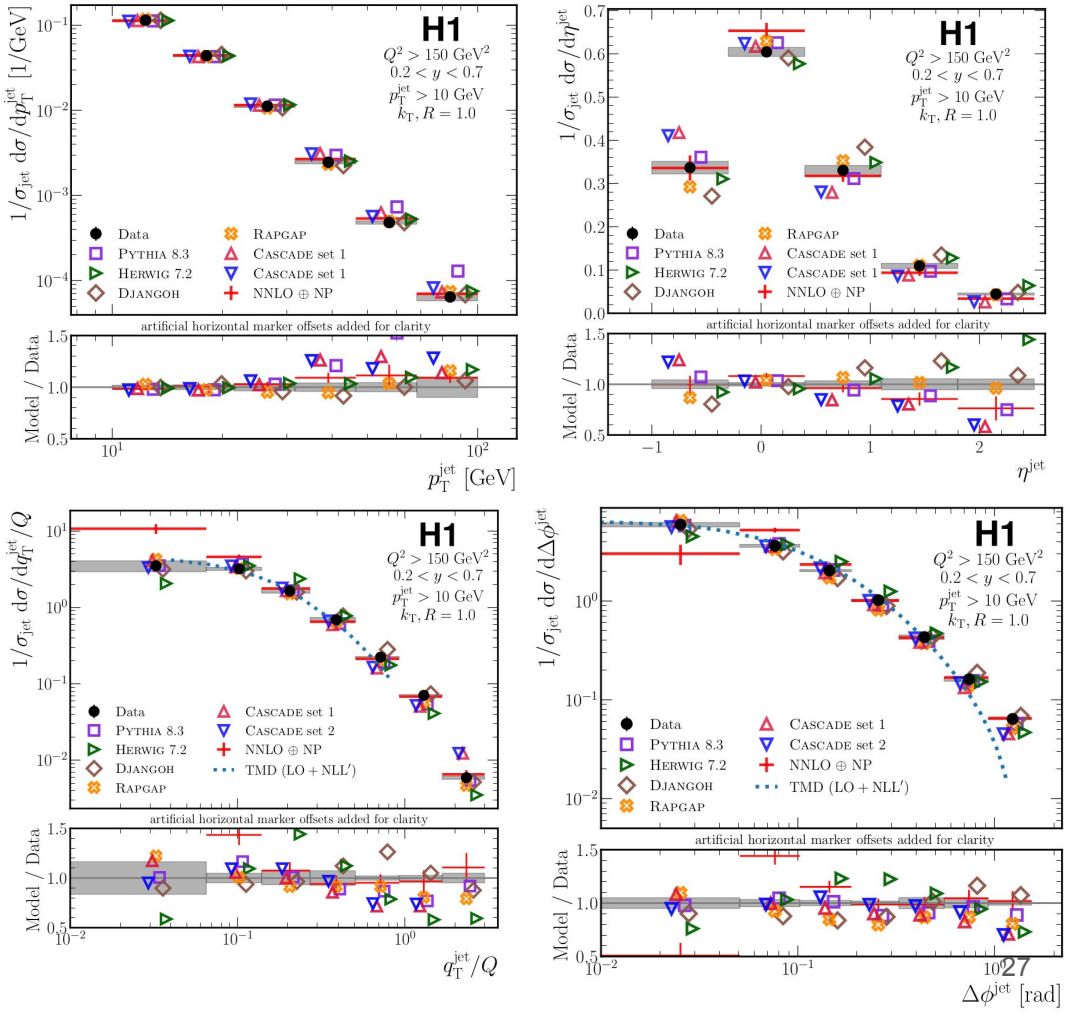
Unbinned

high-dimensional

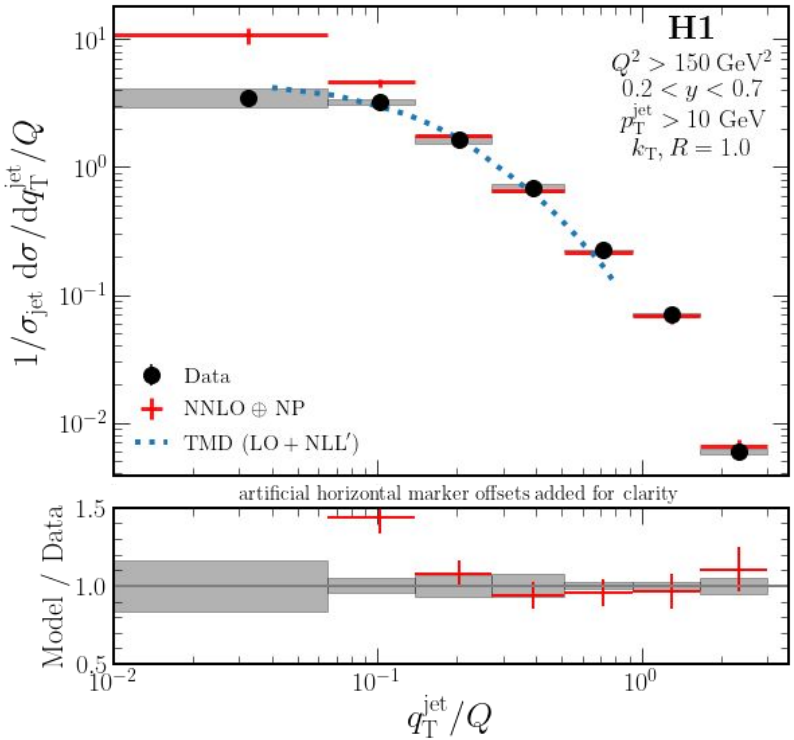
Omnifold allowed us to do a simultaneous, unbinned unfolding
in 8D (probably a record)

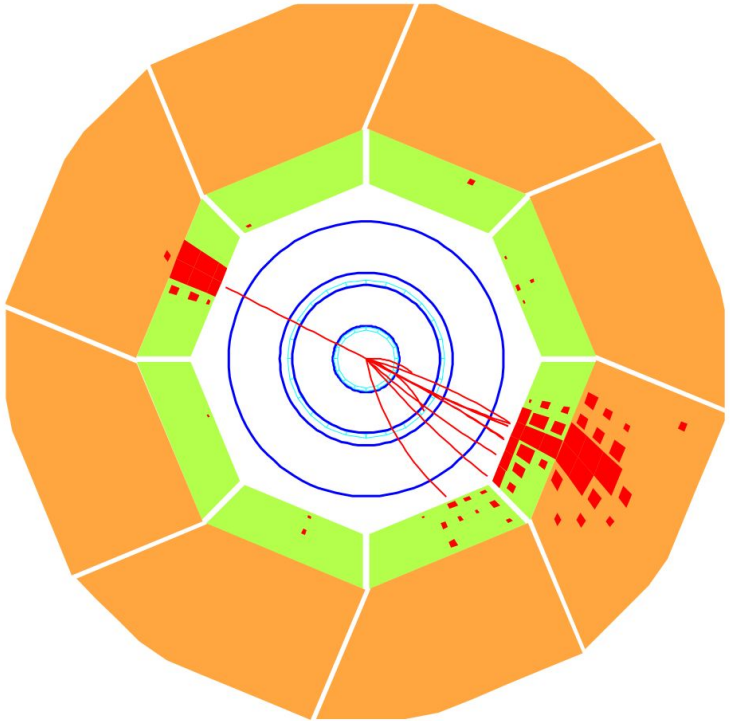
"This measurement also represents a milestone in the use of ML techniques…"

H1 Collaboration, PRL 128 (2022) 13, 132002



Lepton-jet correlation





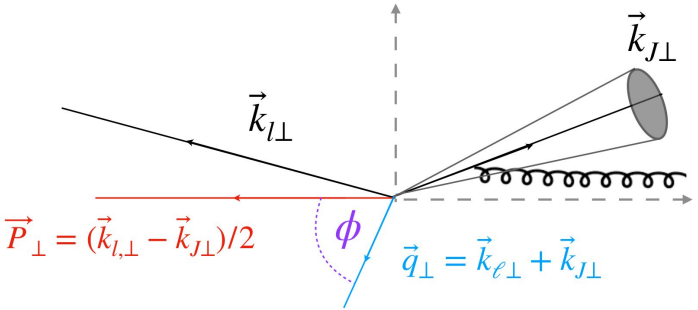
H1 Collaboration, PRL 128 (2022) 13, 132002

Textbook example of “matching” between collinear and TMD frameworks

First time seen in DIS!

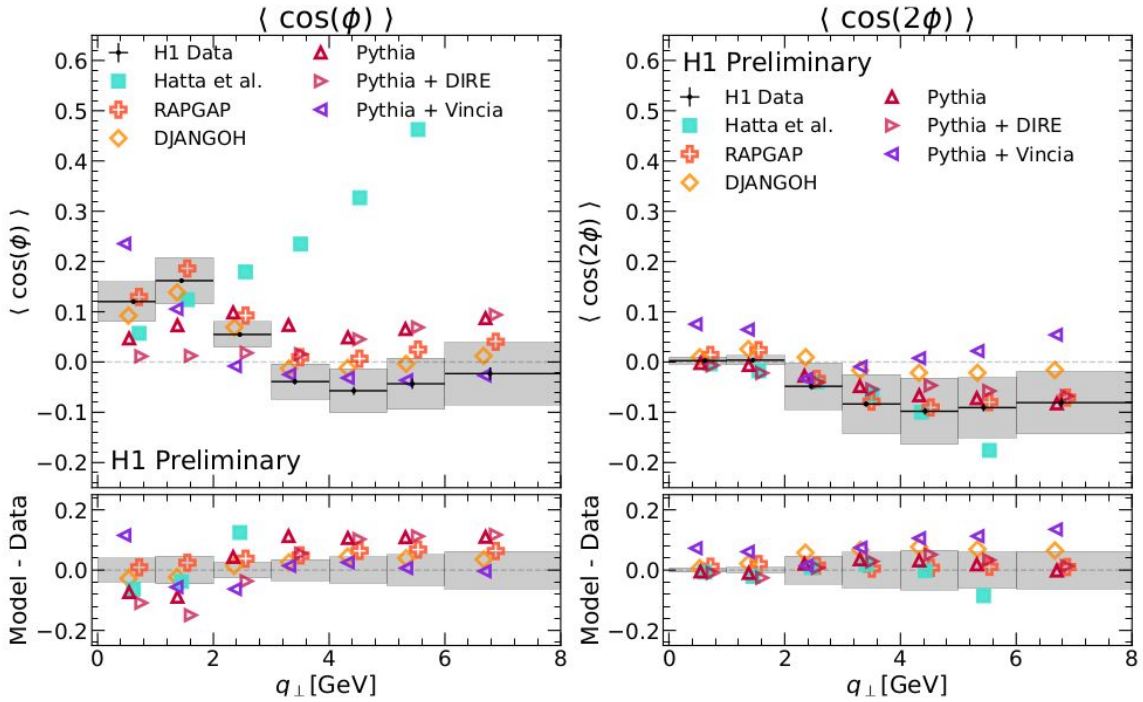
Follow up analysis: lepton-jet azimuthal modulations

Same data, same unfolding as first lepton-jet paper



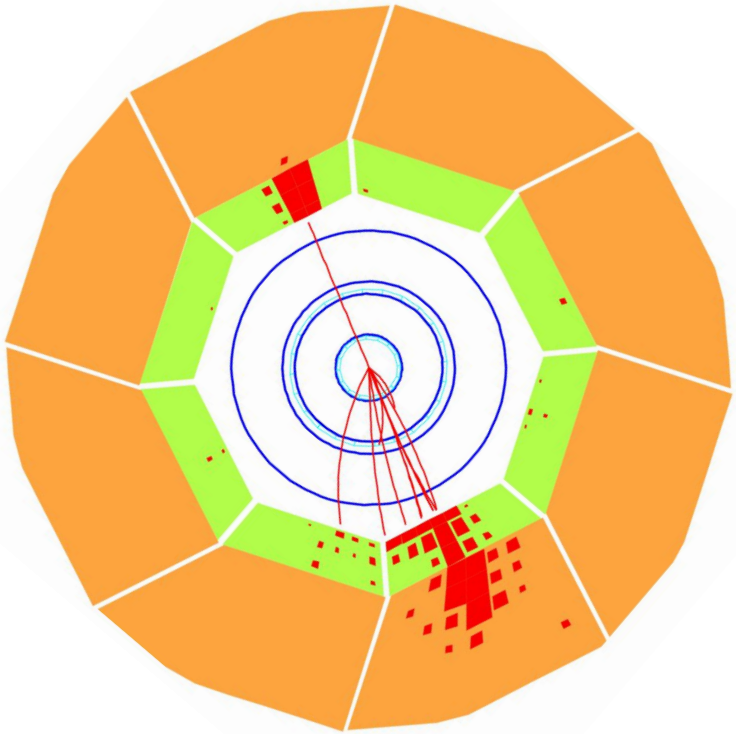
Novel observable
Promising for TMD studies
But sensitive to gluon radiation as well

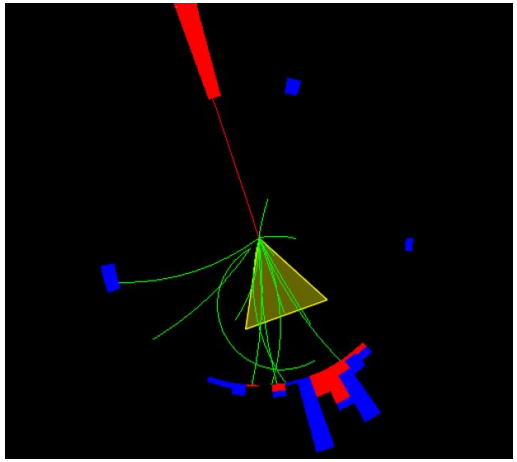
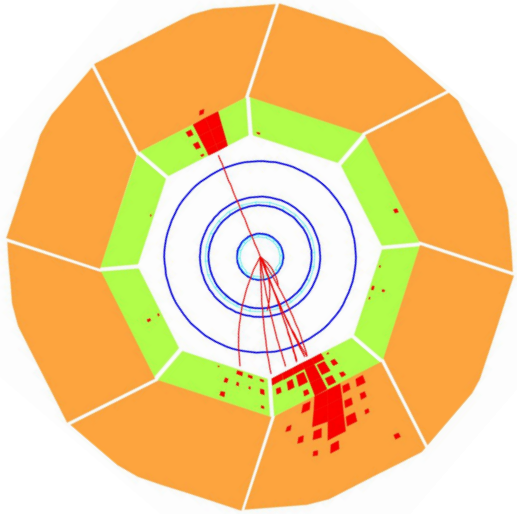
PRD 104 (2021) 5, 054037,
PRL. 126 (2021) 14, 142001



Credit to Fernando Torales-Acosta (LBNL)

The Damocles Sword



Summary

Jets will provide us with an exciting new tool for the quest of “Quantum Tomography” at the EIC. We can do a lot today at HERA