Towards a Quantum Imaging of Nuclei

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UC RIVERSIDE

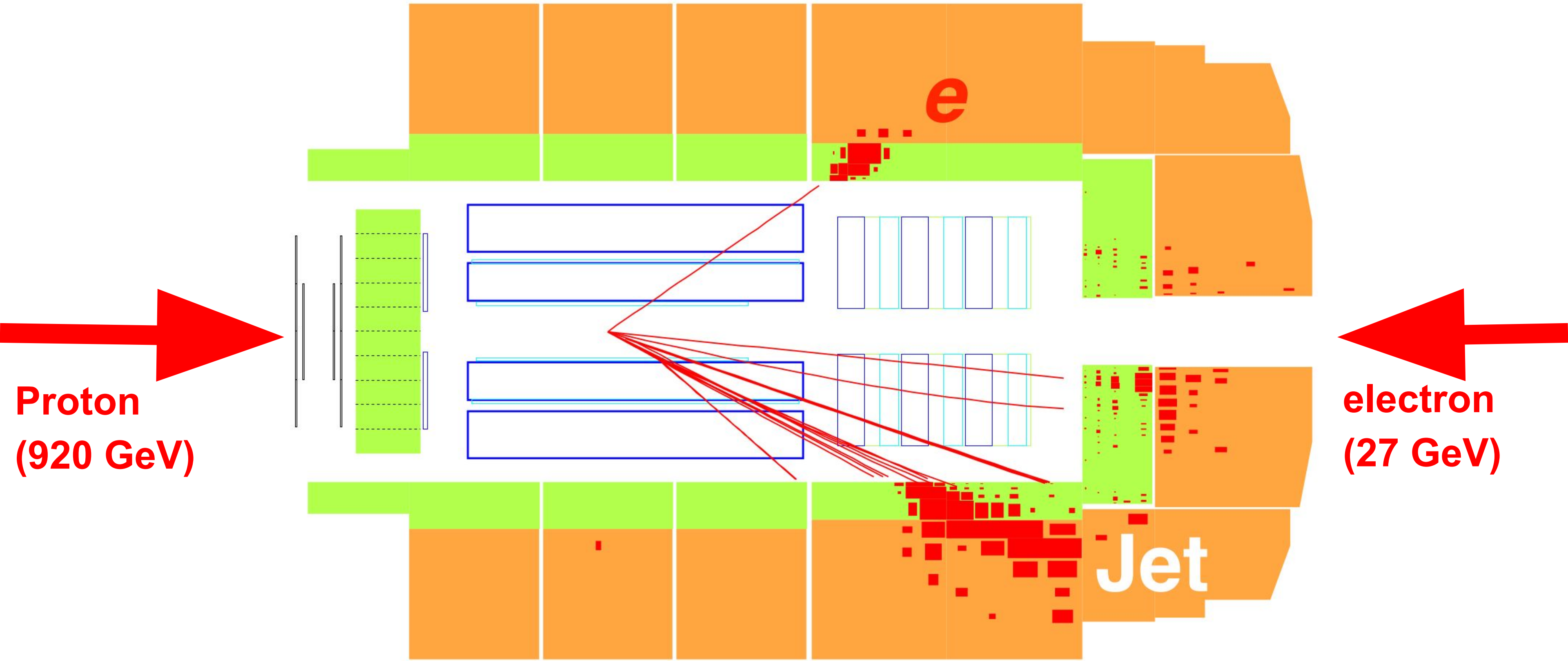
Institute of Nuclear and Particle Physics seminar, April 11th 2023, Ohio University

Outline

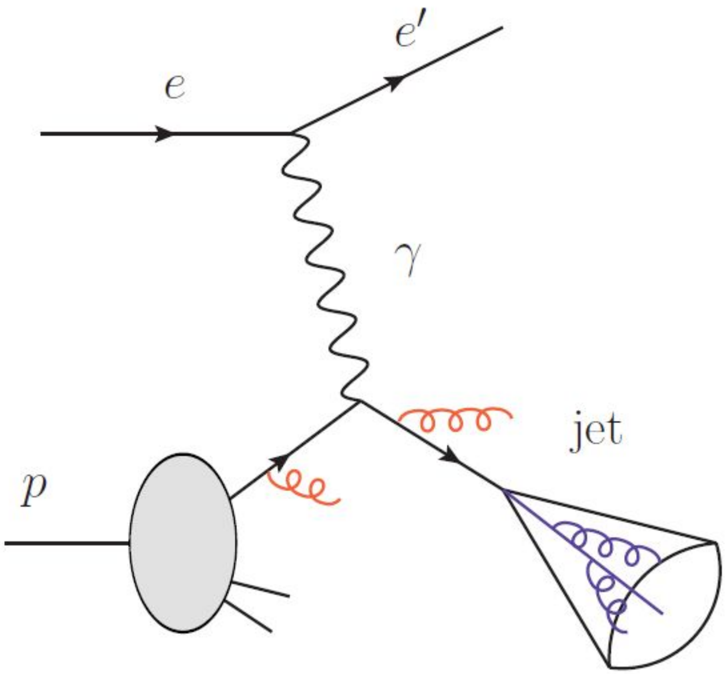
- Quantum tomography in QCD.
  Origins, current, and future trends
- Experimental efforts at JLab
- Future prospects at the Electron-Ion Collider

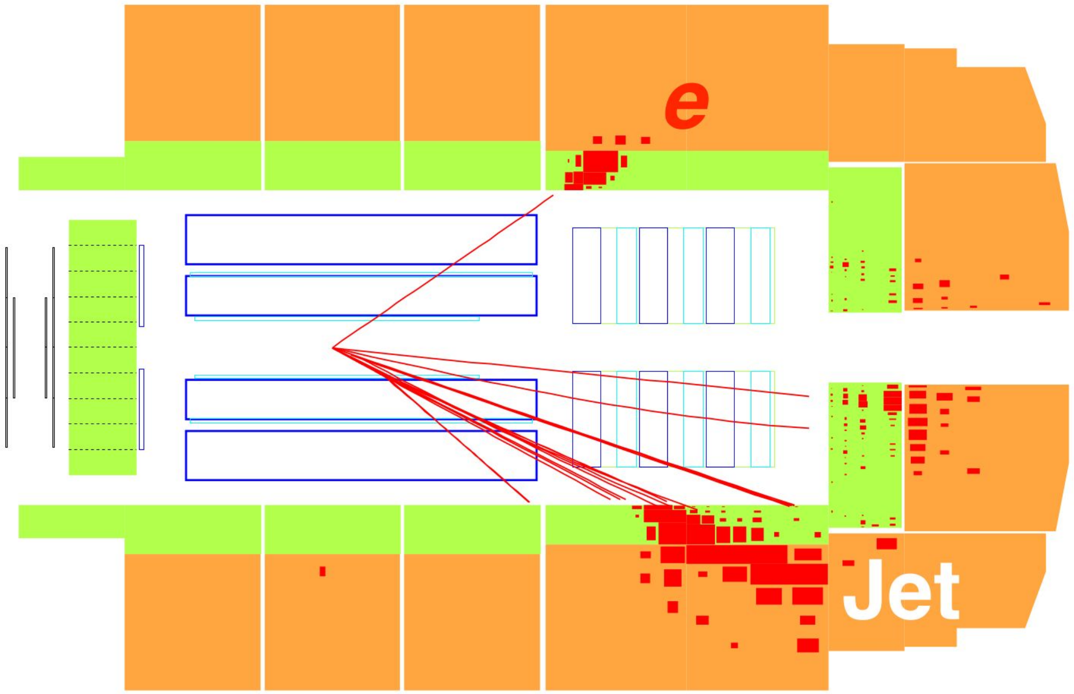
HERA: the first electron-proton collider

Operated at Hamburg, Germany from 92 to 2007

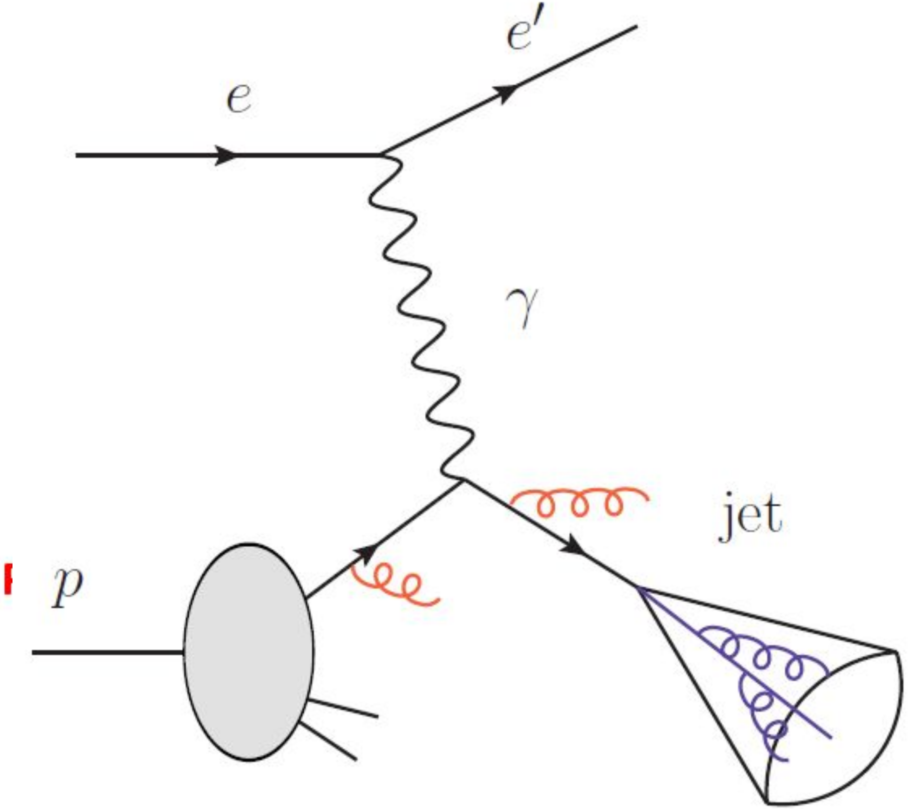

e
Jet
Proton
(920 GeV)
electron
(27 GeV)

Deep-inelastic scattering





Deep-inelastic scattering

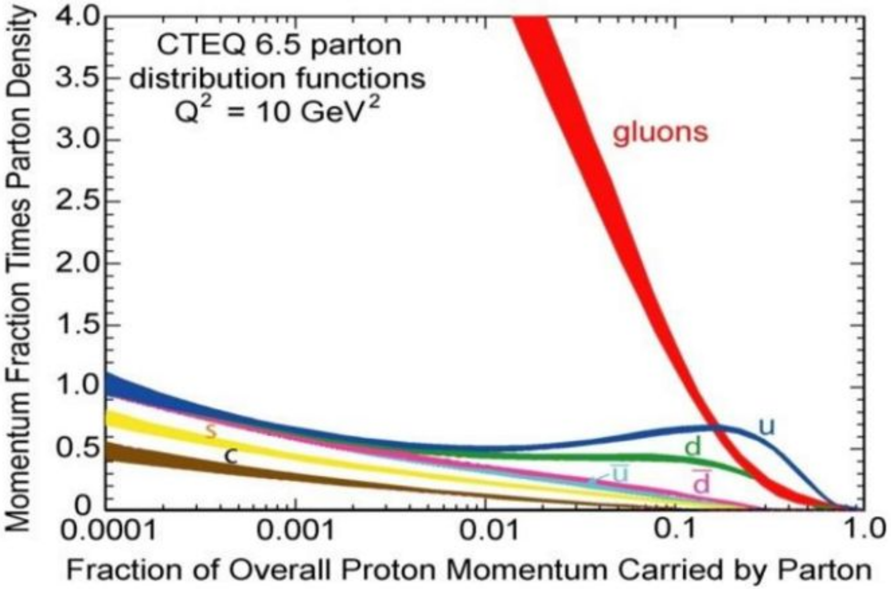


By measuring electron angle and energy, one can know:

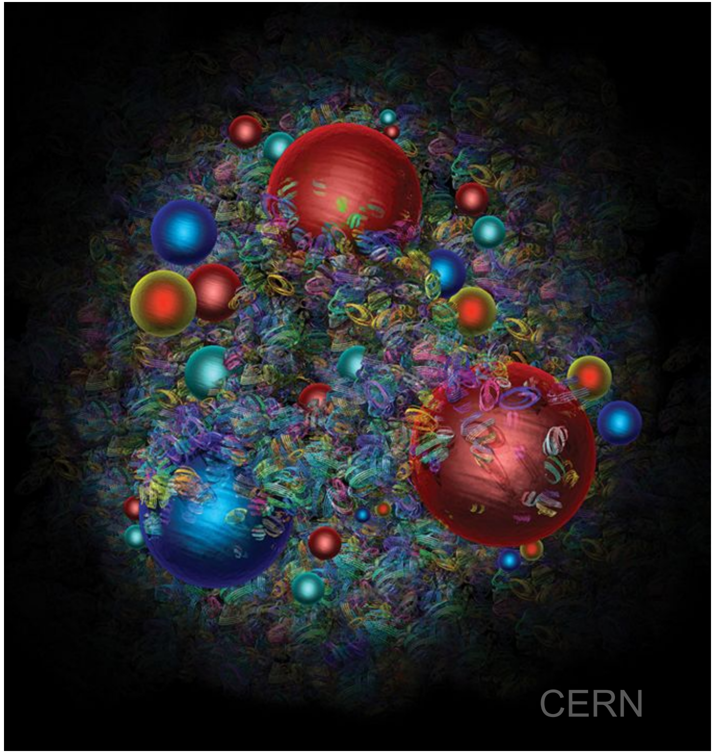
Q^2 Momentum transfer (resolution power)

X Fraction of momentum carried by quark

HERA discovered that the density of gluons in proton is very large at high energies (low-x)



X



The scale dependence of quark and gluon densities follow a beautiful set of equations:

$$\frac{d}{dt} q_i(x,t) = \frac{\alpha_s(Q)}{2\pi} [q_i \otimes P_{qq}] + \frac{\alpha_s(Q)}{2\pi} [g \otimes P_{qg}]$$

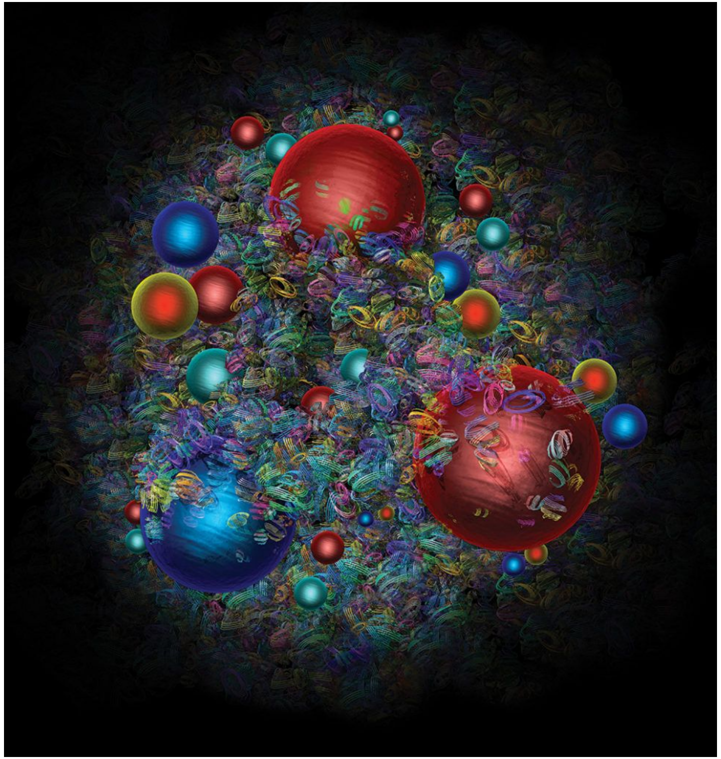
$$\frac{d}{dt} g(x,t) = \frac{\alpha_s(Q)}{2\pi} [\sum_i (q_i + \bar{q}_i) \otimes P_{gq}] + \frac{\alpha_s(Q)}{2\pi} [g \otimes P_{gg}]$$

G. Altarelli, G. Parisi
Nucl.Phys.B126 (1977) 298-318

Nice, but that is only a 1D picture of the proton!

“Quantum tomography” of the proton involves measuring a multi-dimensional phase-space density:

$$W(x,p) = \int \psi^*(x-\eta/2)\psi(x+\eta/2)e^{ip\eta}d\eta \ ,$$



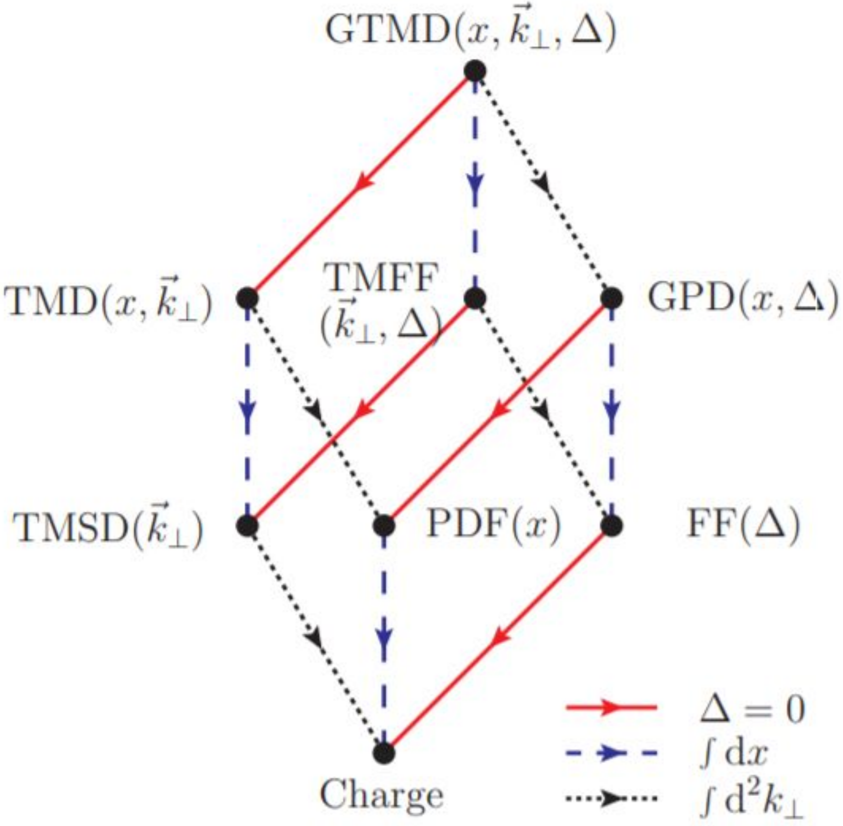
Belitsky et al. Phys.Rev.D69:074014, 2004

$$W(x,p) = \int \psi^*(x - \eta/2)\psi(x + \eta/2)e^{ip\eta}d\eta \ ,$$

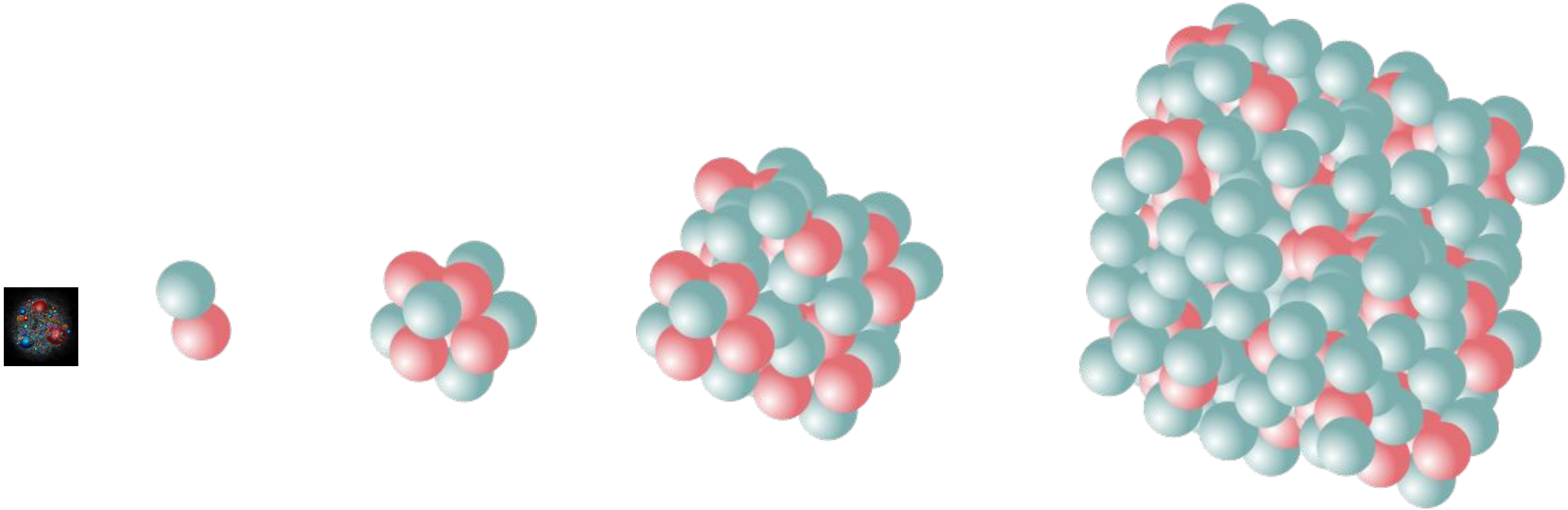
Measure quantum phase density to get:

- Orbital angular momentum of quarks, gluons
- Spin-orbit and spin-spin correlations, etc
- Input to calculate Energy Momentum Tensor

Difficult, so attempt to measure “projections” of the quantum-phase density in either position or momentum space

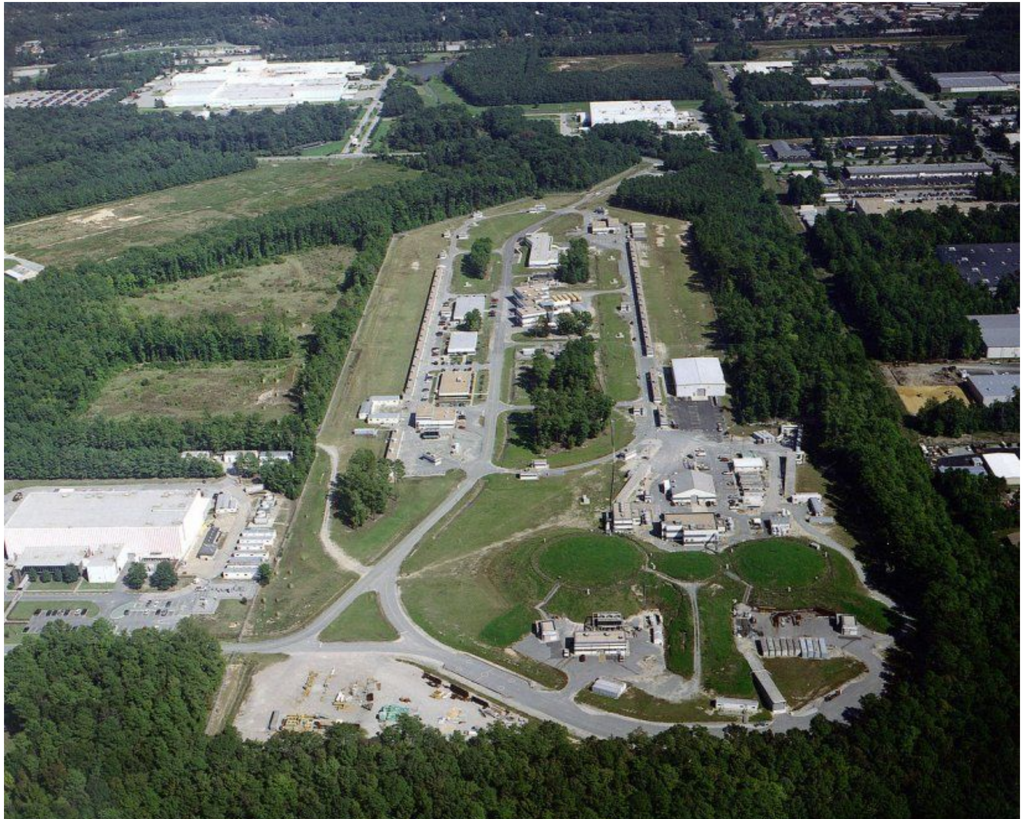


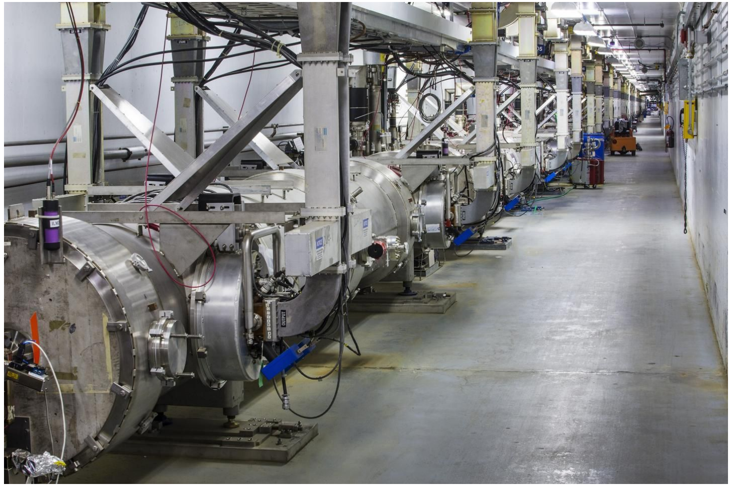
Quantum tomography of unbound nucleons



We know since a while that nuclear binding changes quark structure of nuclei!

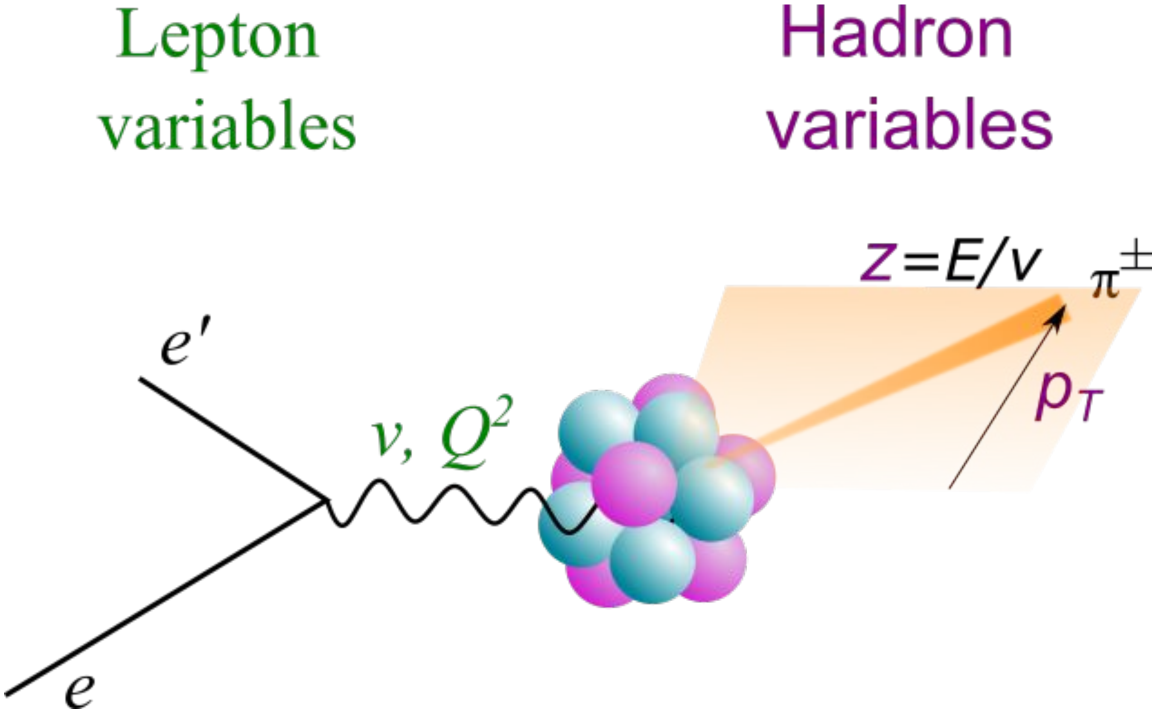
Thomas Jefferson National Laboratory
CEBAF upgrade: 2017-





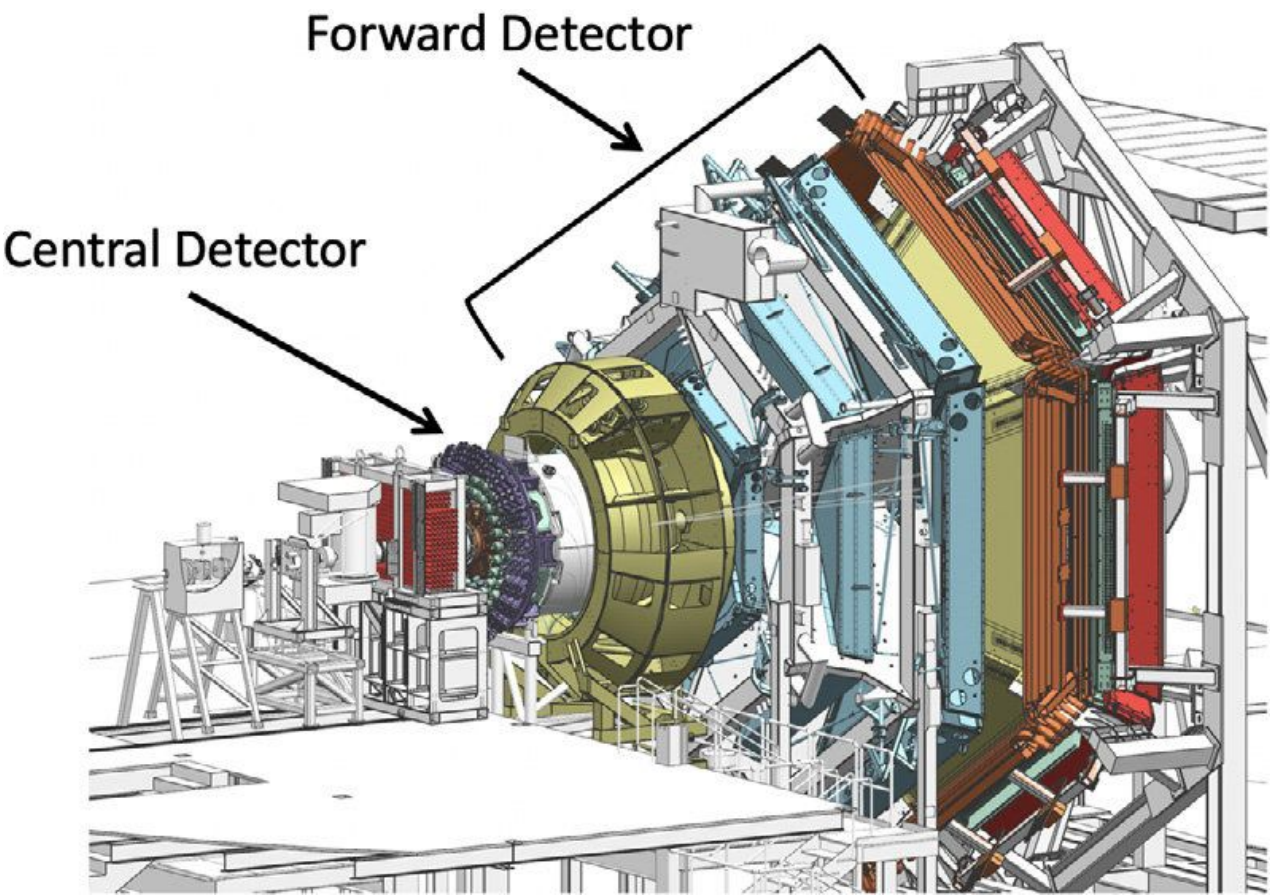
High energy, high intensity, high polarization electron beam

Semi-inclusive DIS



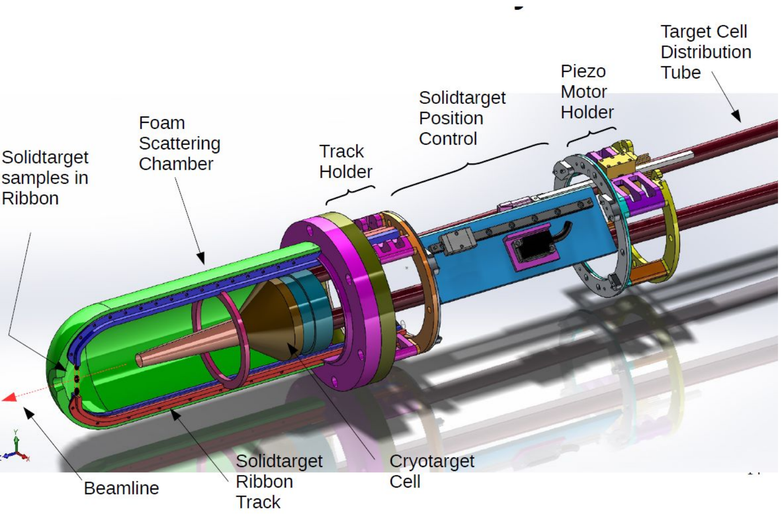
Cross-section probes quark densities in 3D momentum space*

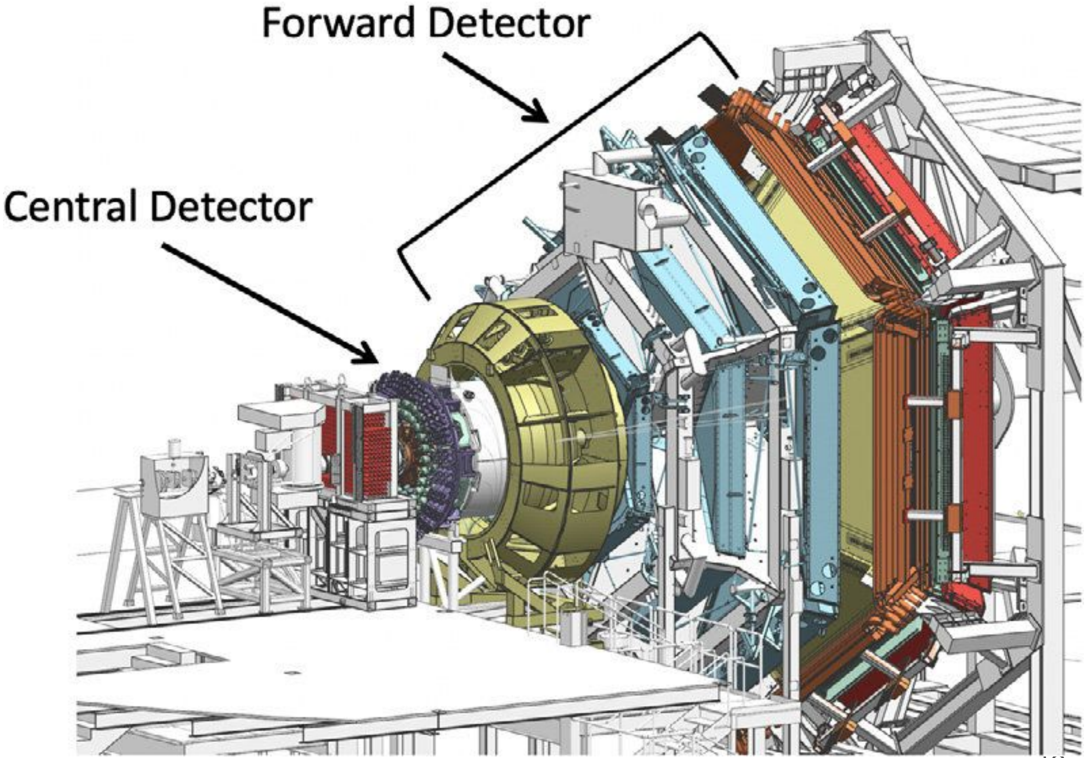
CLAS12 detector at JLab Hall-B



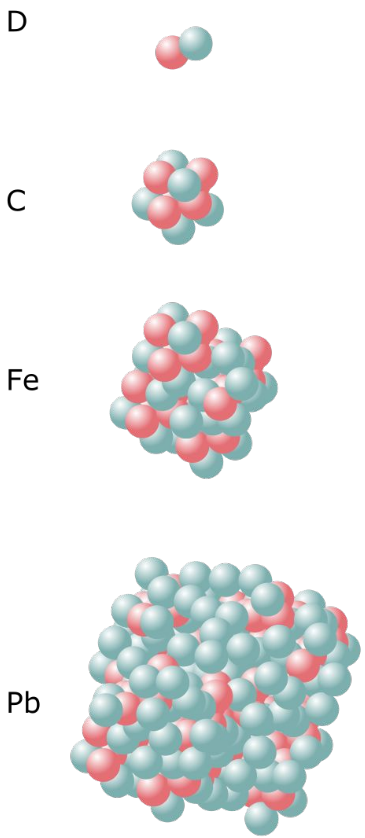
DO NOT ENTER
U.S. GENERAL
MAYVILLE 2033

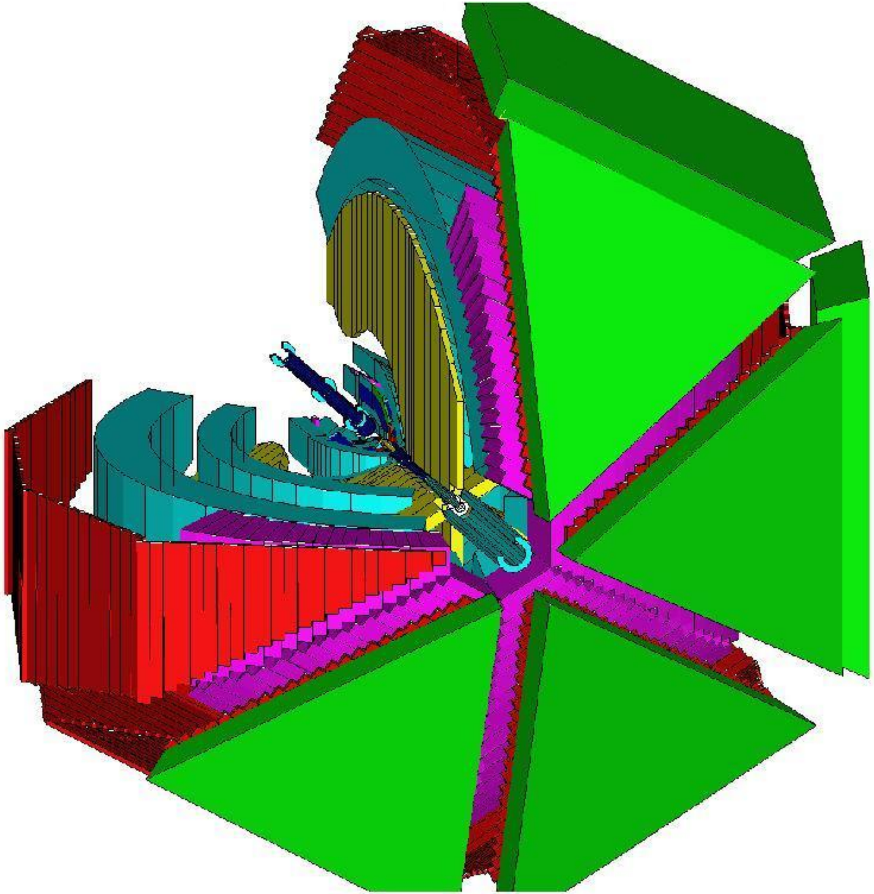
First 11 GeV experiments with nuclear targets are yet to run…



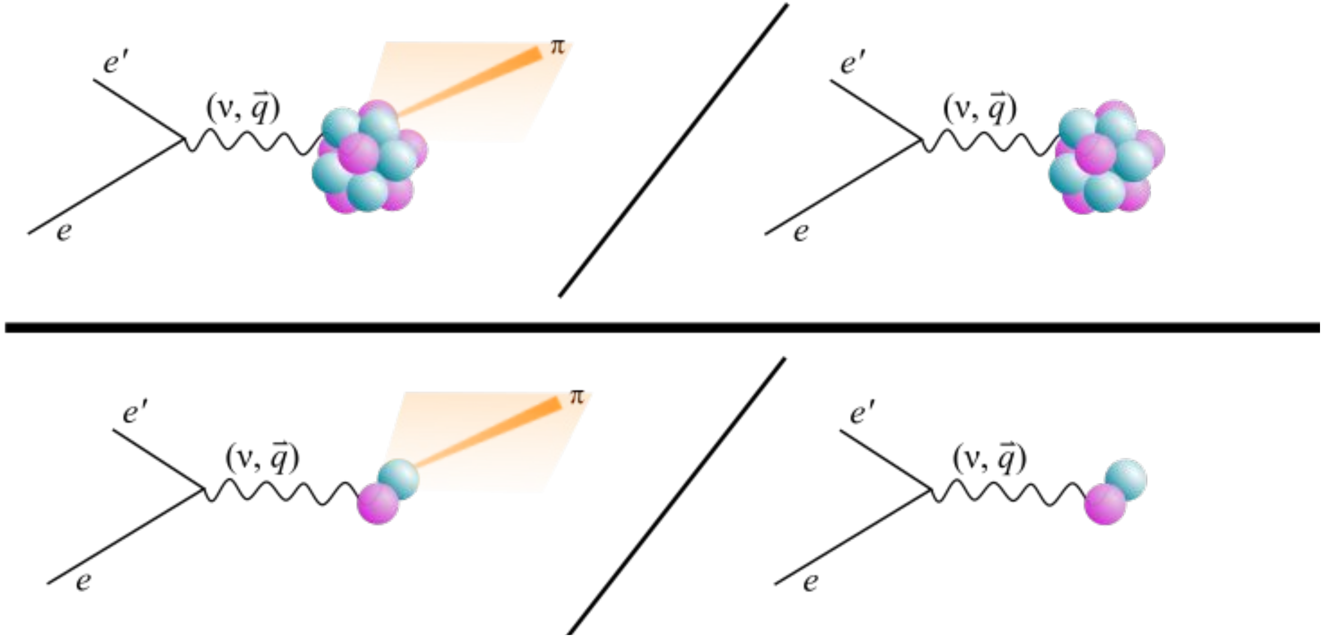


Old CLAS data: 5 GeV electron beam on nuclear targets





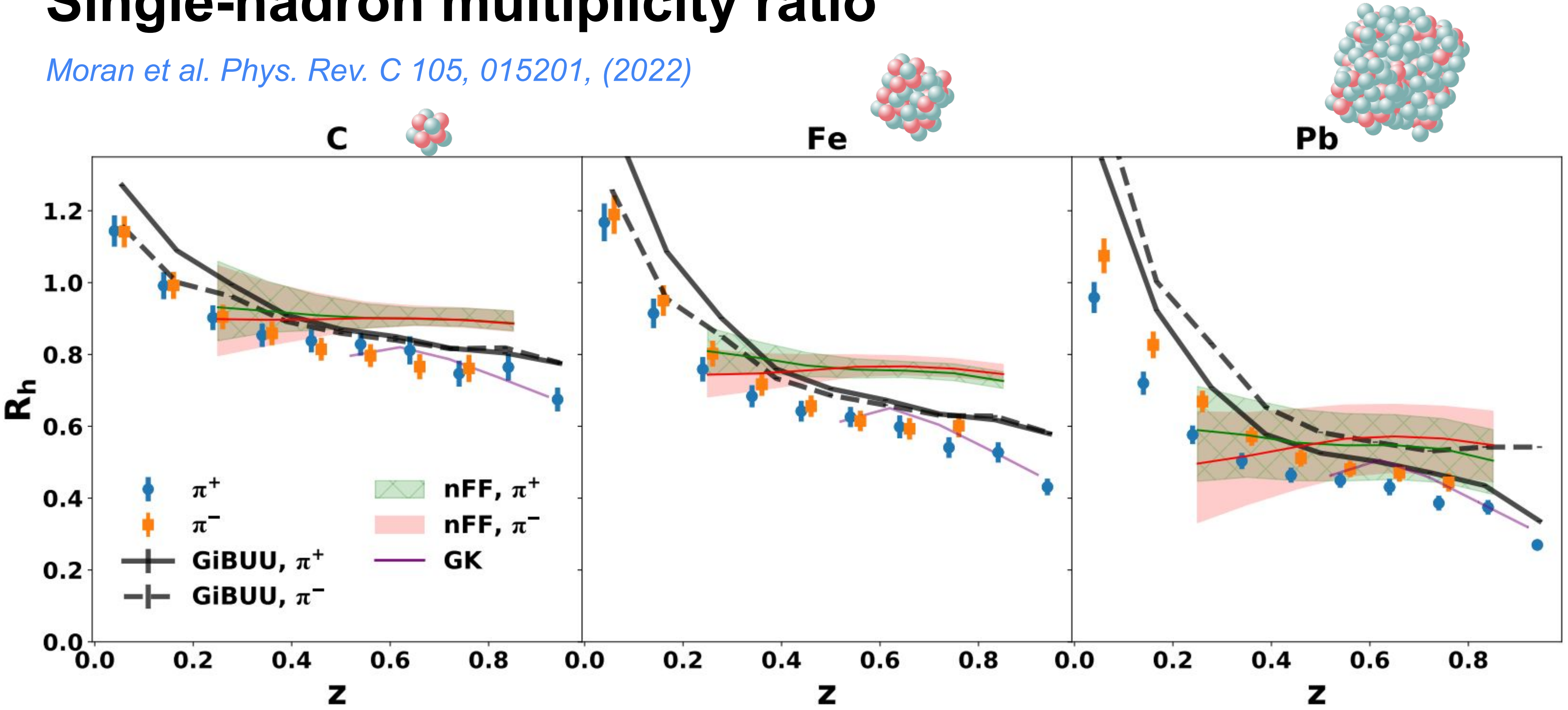
Single hadron production ratio:



$$R_h(\nu, Q^2, z, p_T^2) = \frac{N_h^A(\nu, Q^2, z, p_T^2)/N_e^A(\nu, Q^2)}{N_h^D(\nu, Q^2, z, p_T^2)/N_e^D(\nu, Q^2)}.$$

Single-hadron multiplicity ratio

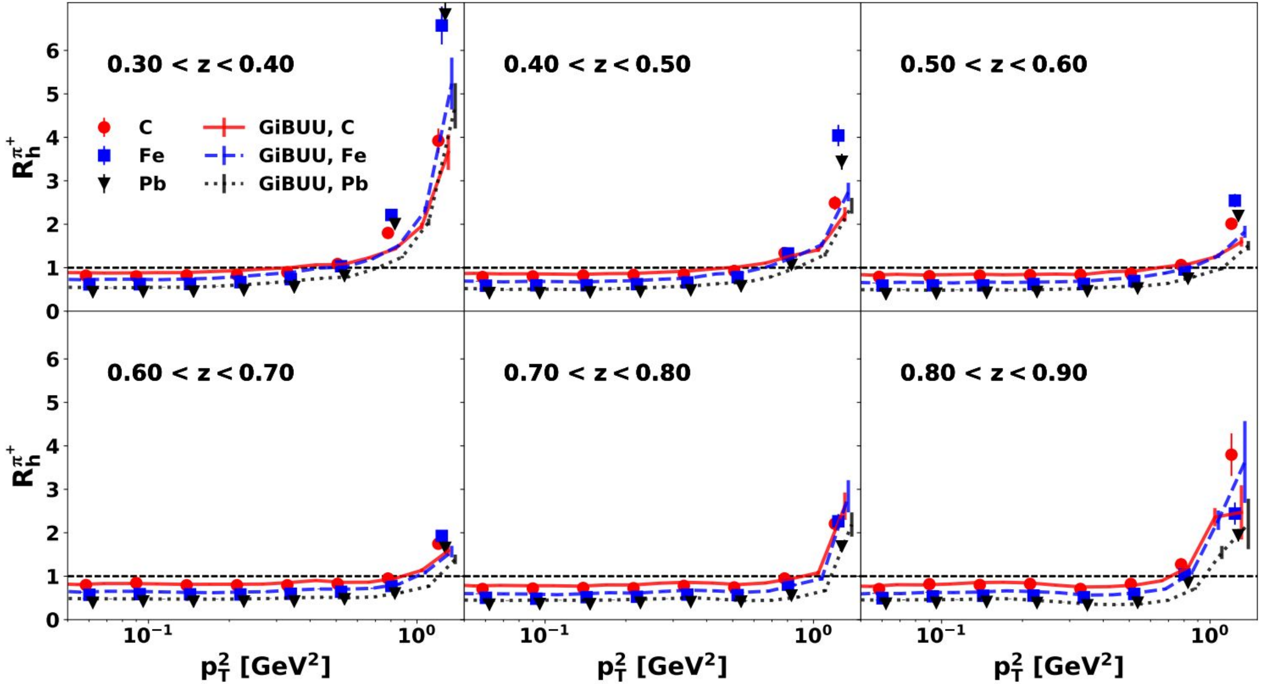
Moran et al. Phys. Rev. C 105, 015201, (2022)

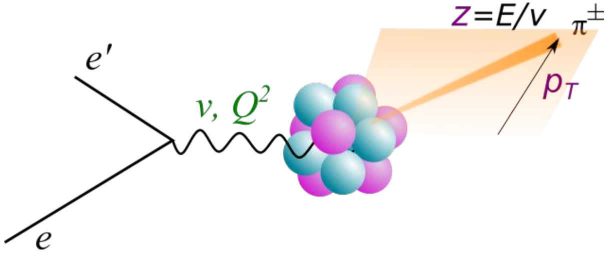


Energy spectra of hadrons (fragmentation function) is strongly modified

Modification ratio differential in transverse momentum

Moran et al. Phys. Rev. C 105, 015201, (2022)



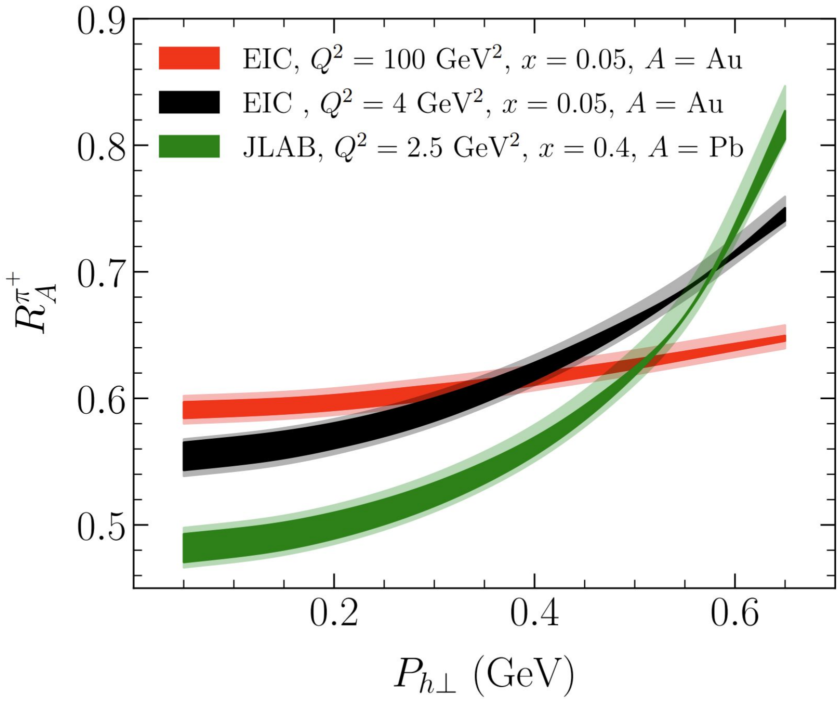


Excess of high transverse-momentum hadrons with non-monotonic dependence

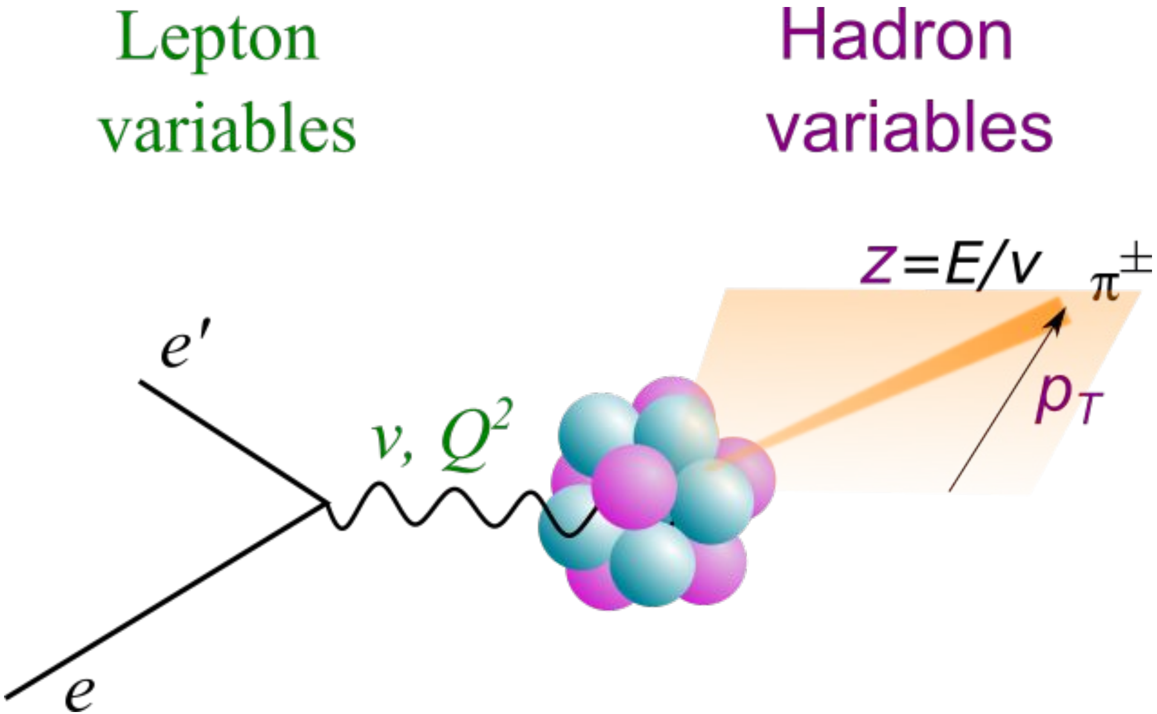
Towards Quantum Imaging of Nuclei (Emerging Theory)

“Quarks in nuclei are more broadly distributed in transverse momentum than in a proton”

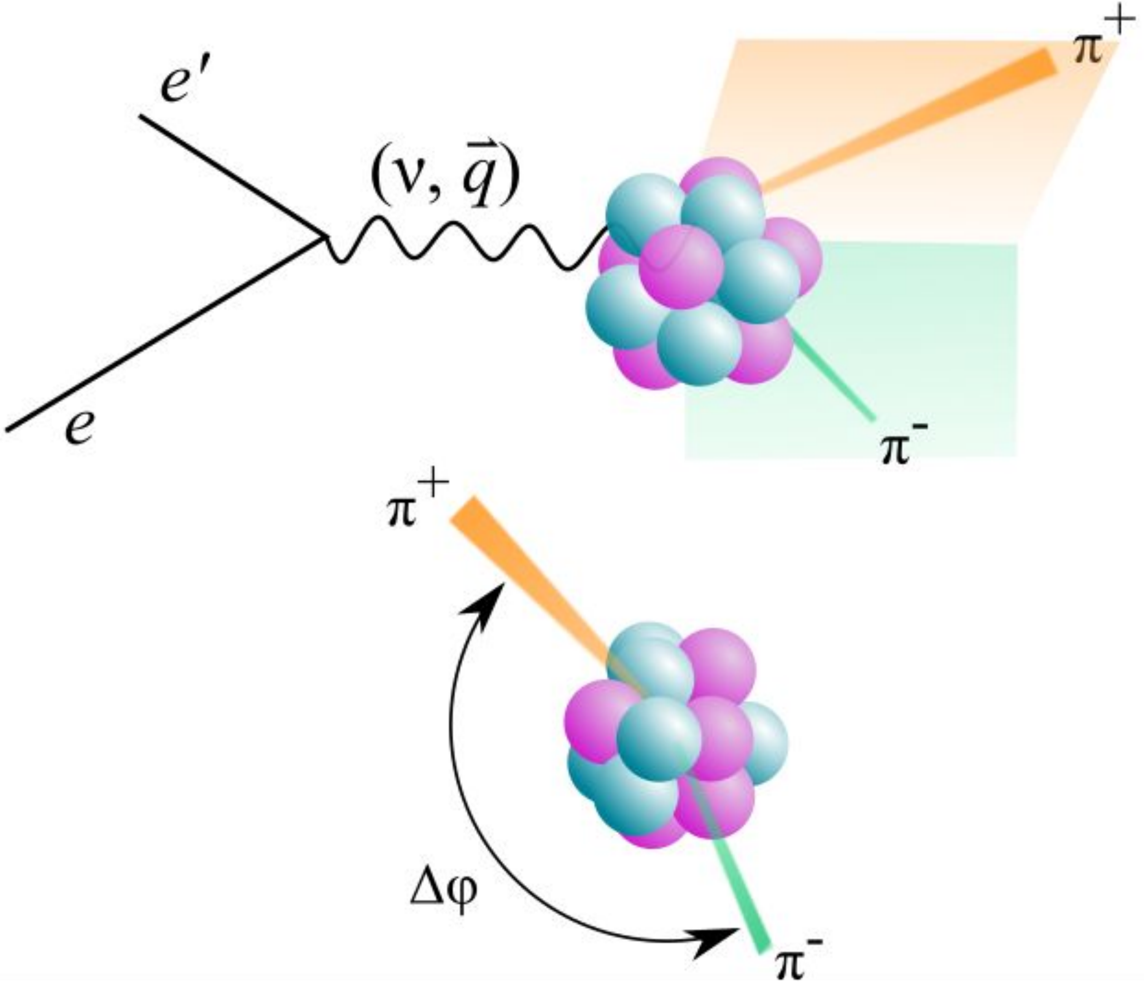
Nuclear Modification of Transverse Momentum Dependent Parton Distribution Functions by a Global QCD Analysis”,
[*Alrashed et al. PRL 129 (2022) 24, 242001*]



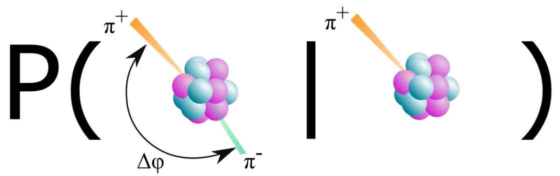
Can we measure more than this?

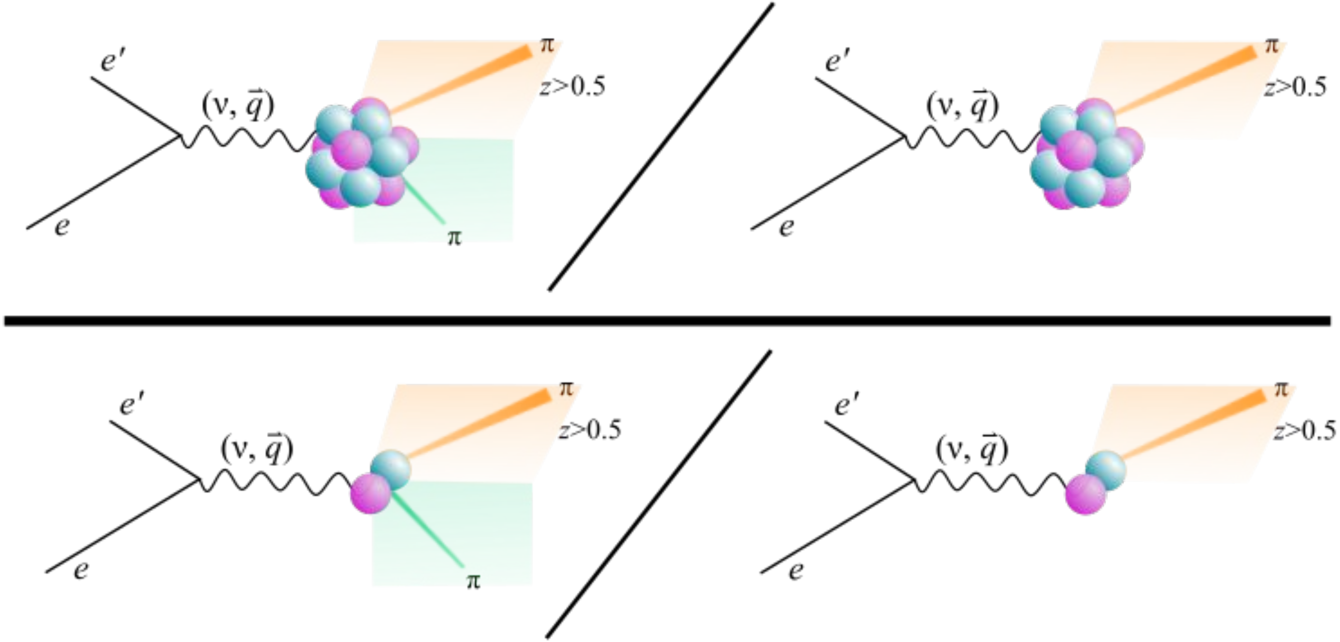


Double-hadron production



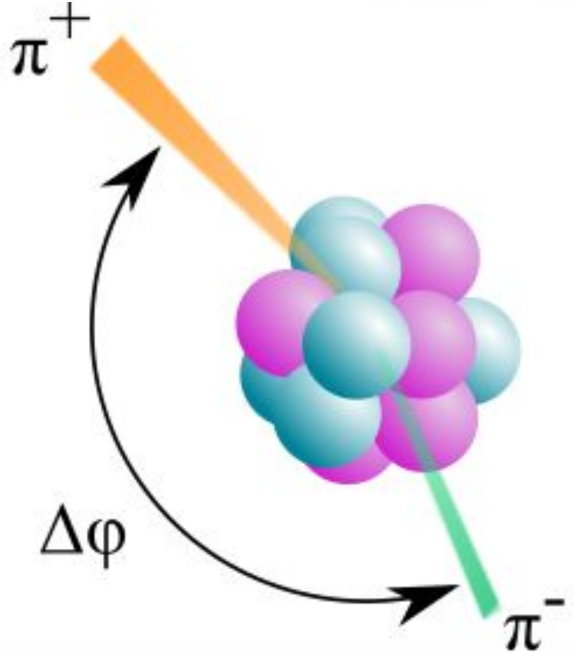
Double hadron production ratio

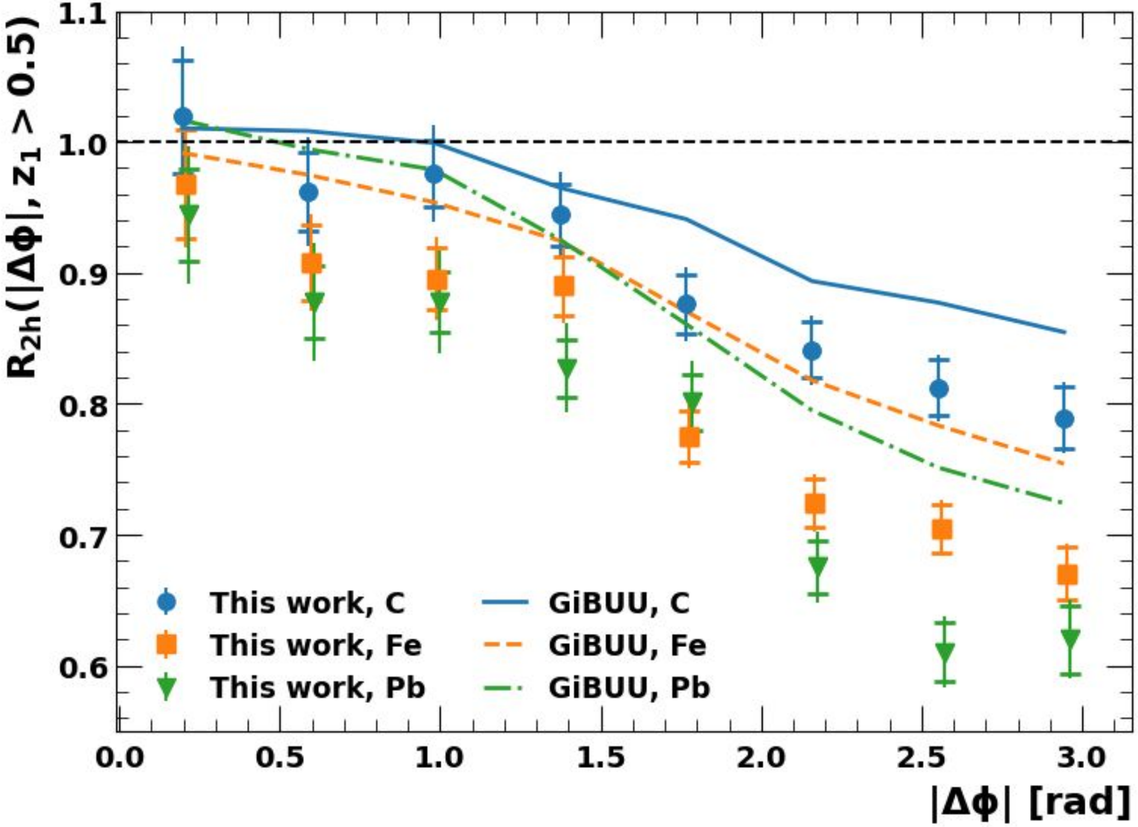




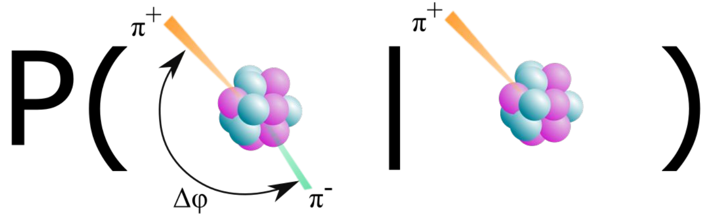
Back-to-back pion suppression

S. J Paul et al. Phys.Rev.Lett. 129 (2022) 18, 18



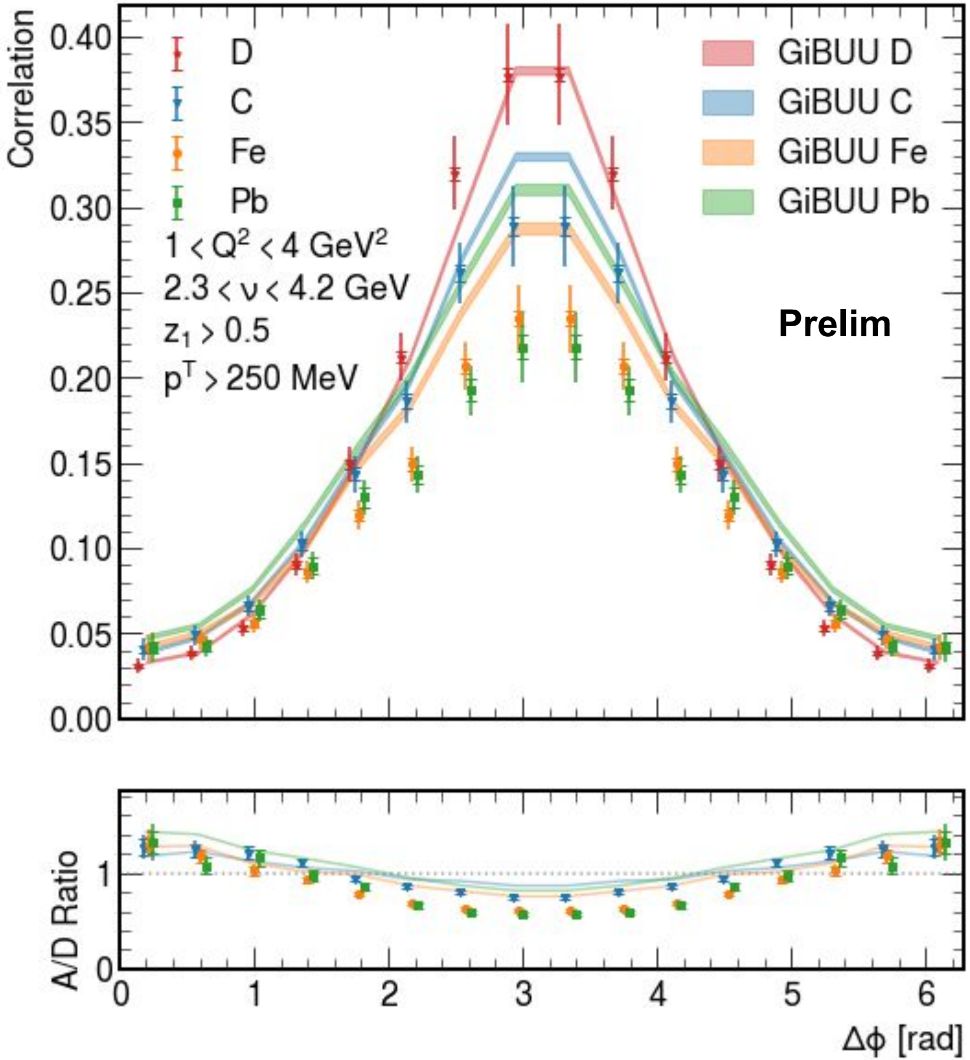


Two-point correlation functions



$$C = C_0 \frac{1}{N^h(z_1)} \frac{dN^{2h}(z_1, z_2, \Delta\phi, \Delta Y)}{d\Delta\phi\Delta Y}$$

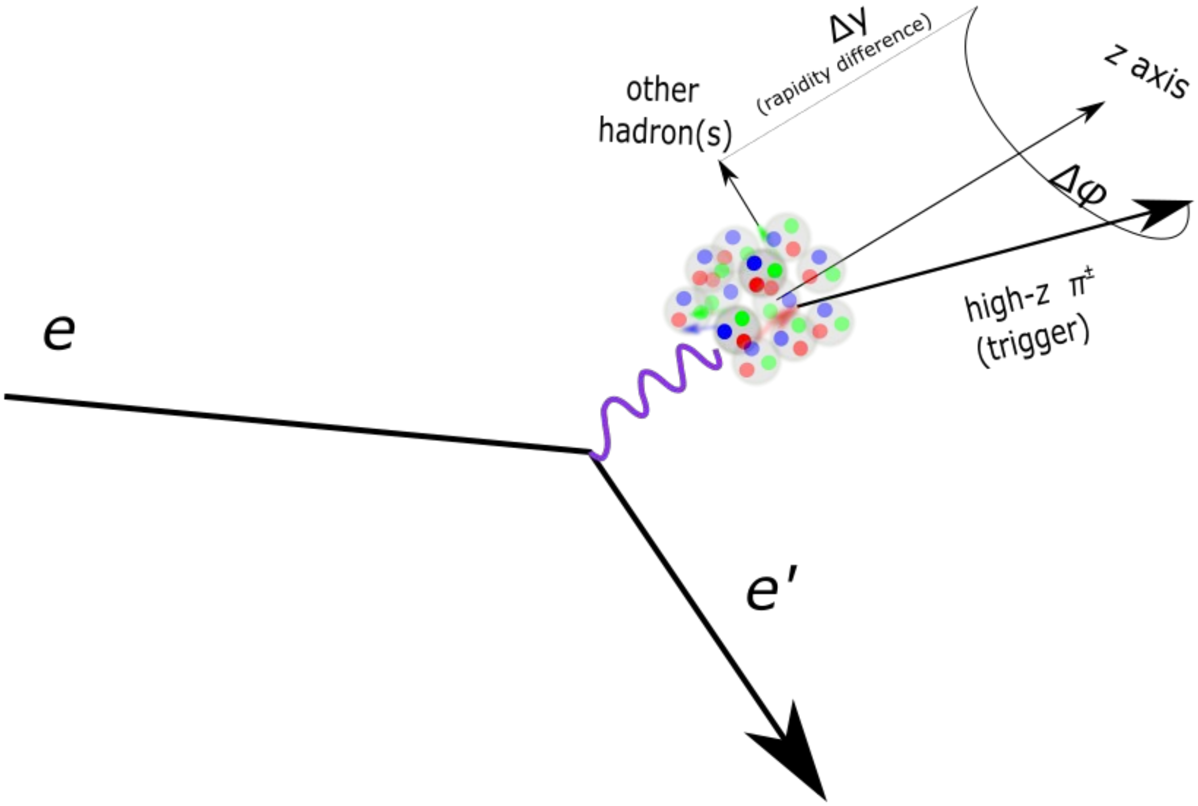
Nuclear broadening of correlations observed



Azimuthal and Rapidity correlations

$$Y = \frac{1}{2} \ln \frac{E_h + p_{z,h}}{E_h - p_{z,h}}$$

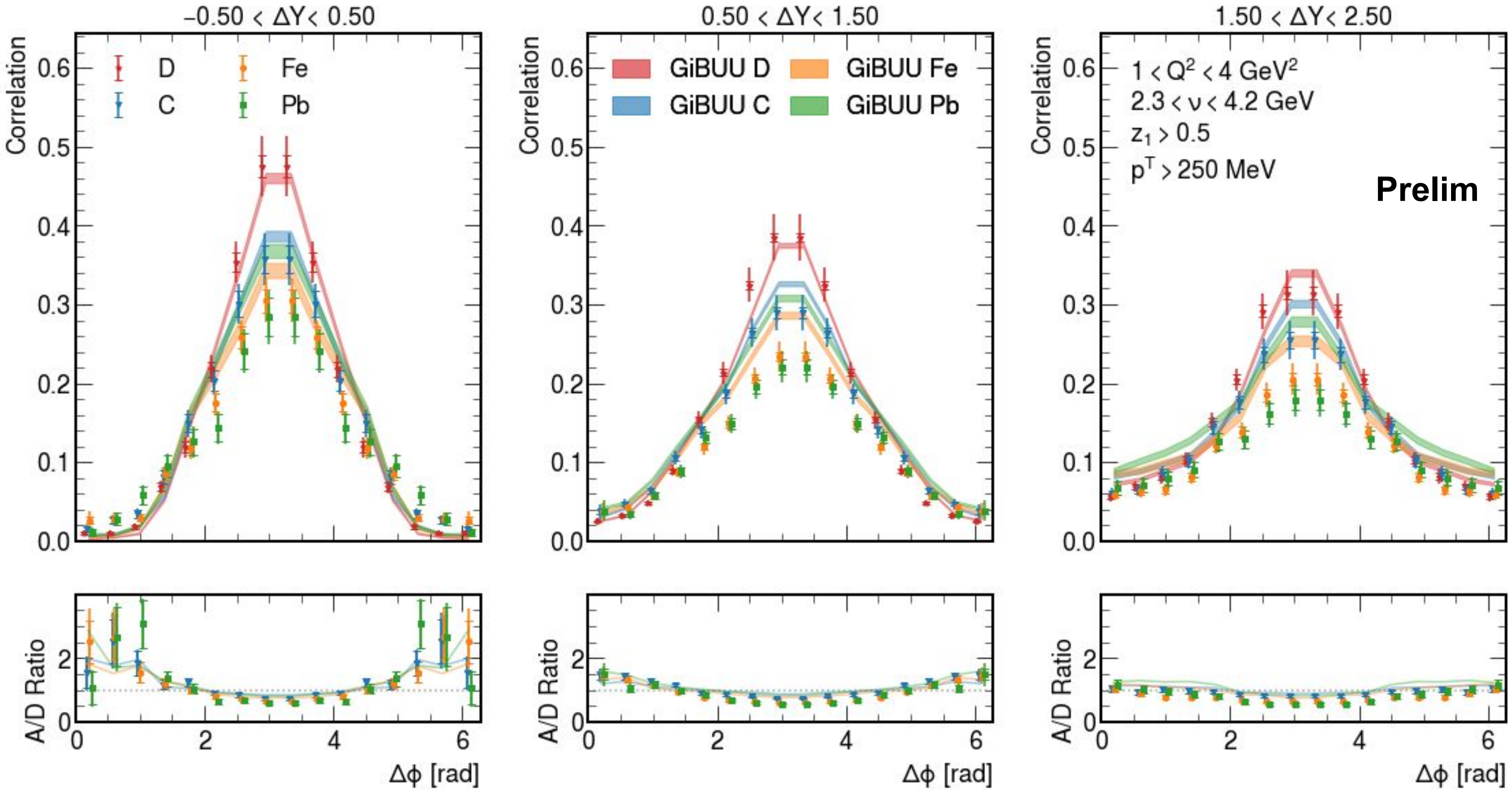
$\Delta Y = Y_1 - Y_2$



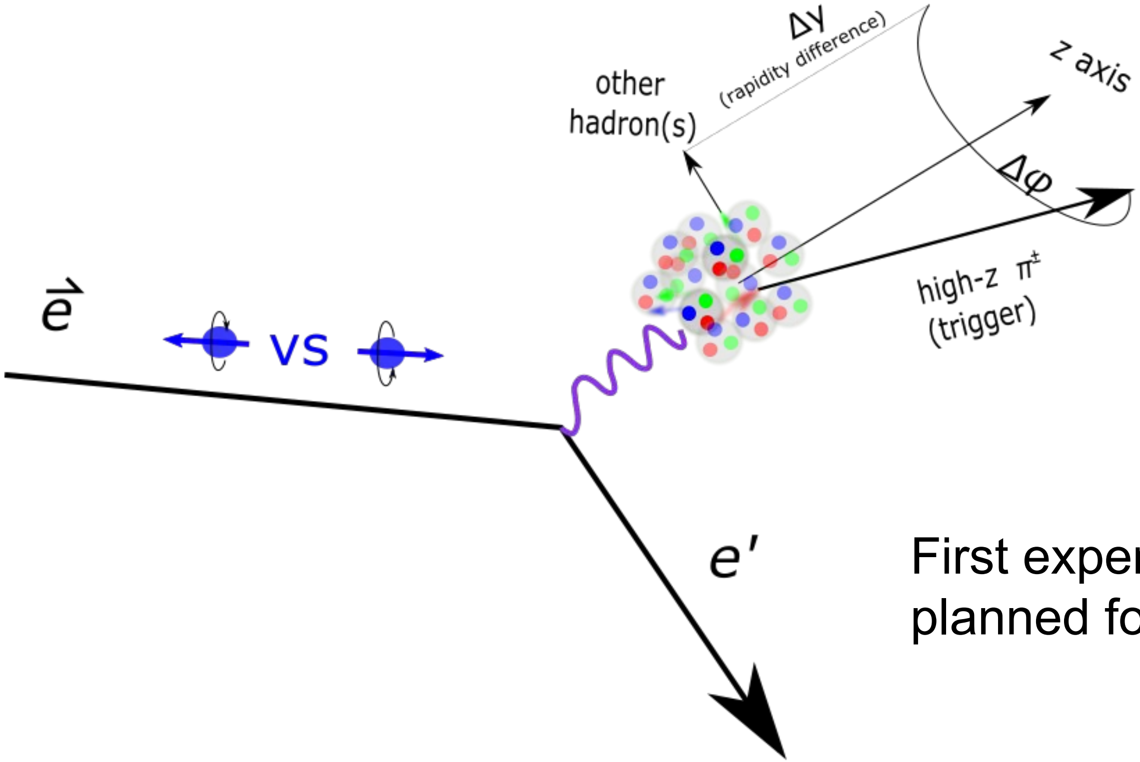
Rapidity dependence of C(ΔΦ)

$\Delta Y = Y_1 - Y_2$

$$Y = \frac{1}{2}\ln\frac{E_h + p_{z,h}}{E_h - p_{z,h}}$$



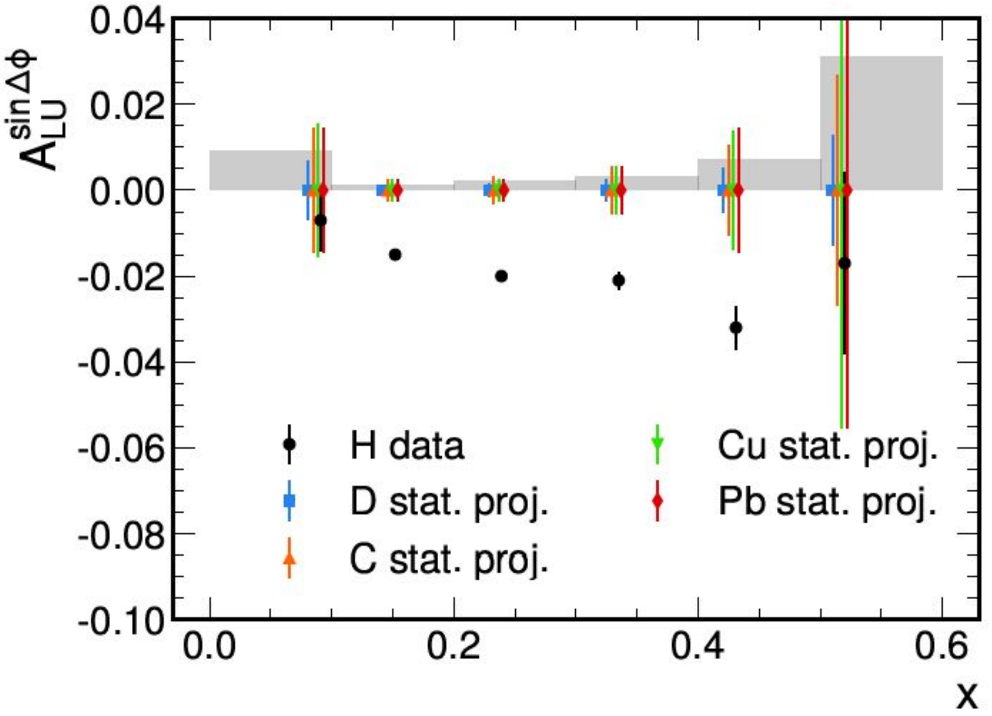
Enter Spin

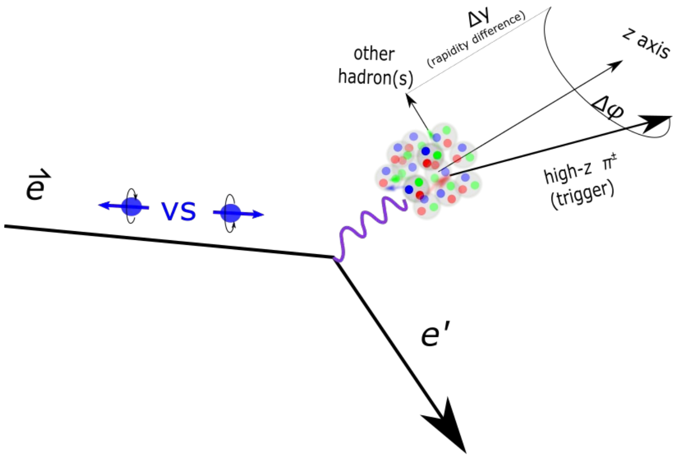


First experiment is planned for January 2024

Beam-spin asymmetry (projected statistical error)

$$A_{LU} = \frac{1}{P}\frac{N^+(\Delta\phi) - N^-(\Delta\phi)}{N^+(\Delta\phi) + N^-(\Delta\phi)} \approx A_{LU}^{\sin(\Delta\phi)} \sin(\Delta\phi)$$

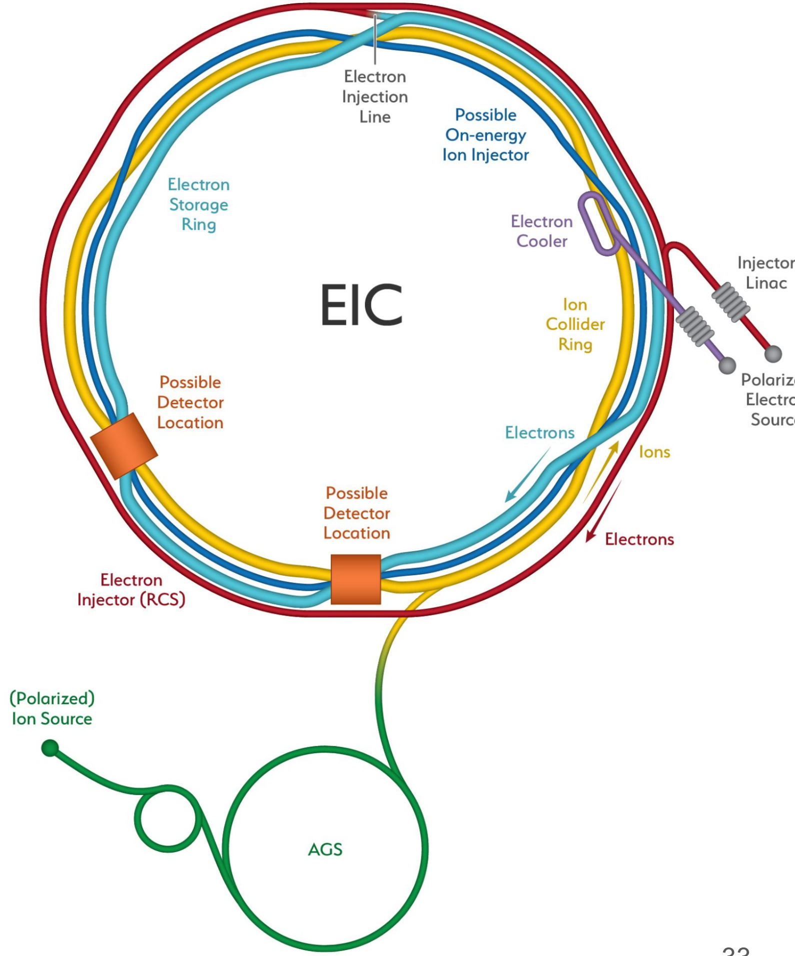




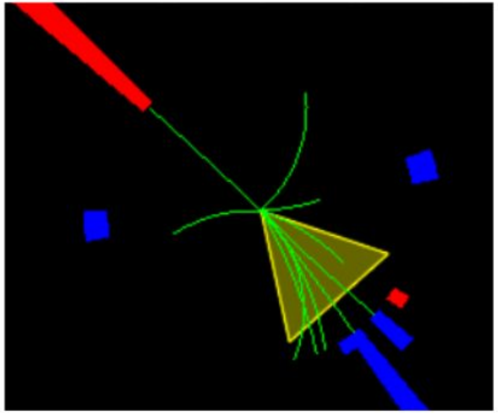
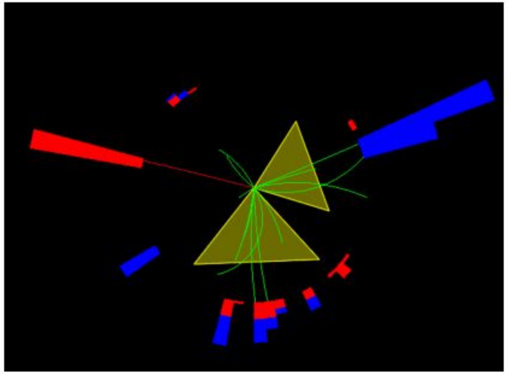
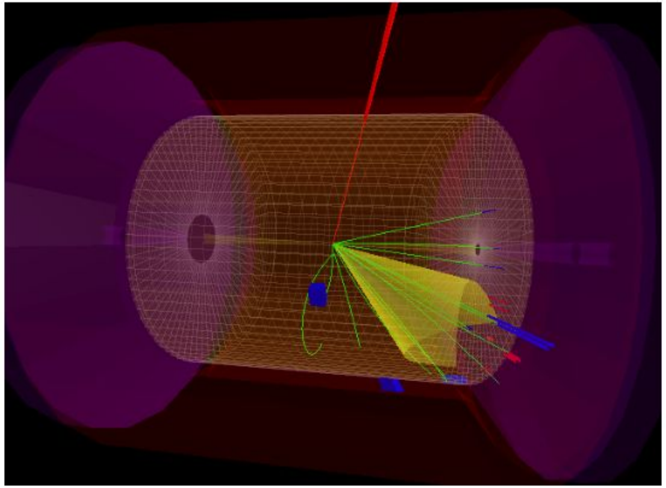
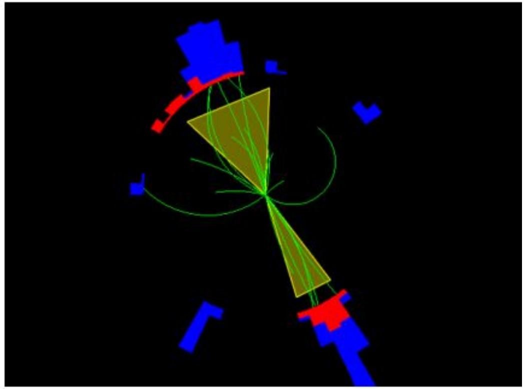
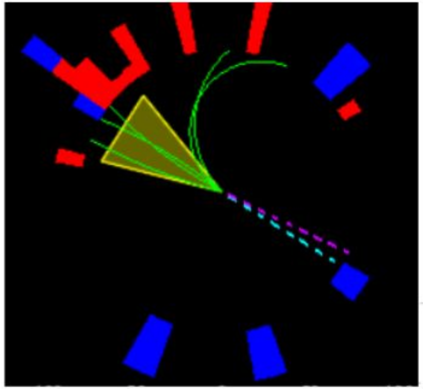
Will search for evidence for entanglement between scattered quarks and the nuclear remnants.

The quantum tomography of the proton requires a new tool

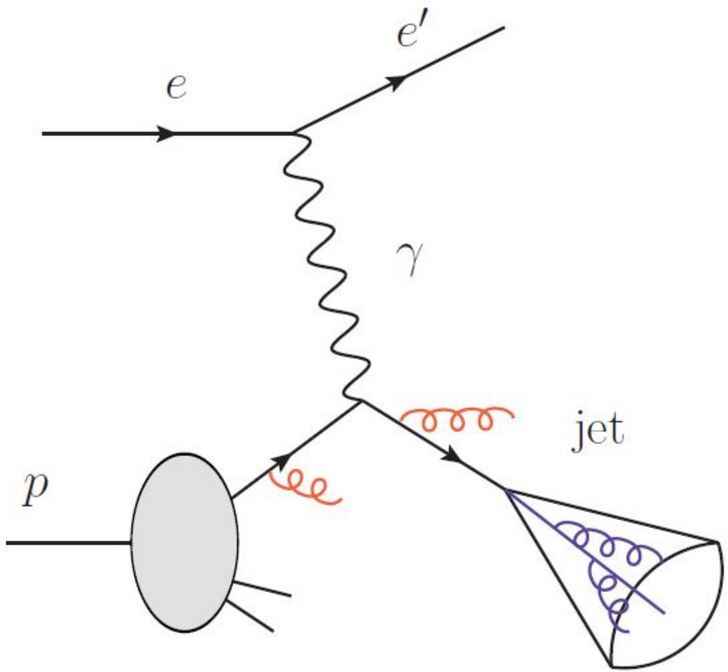
- high luminosity
- high beam polarization (electron, protons, and light ions)



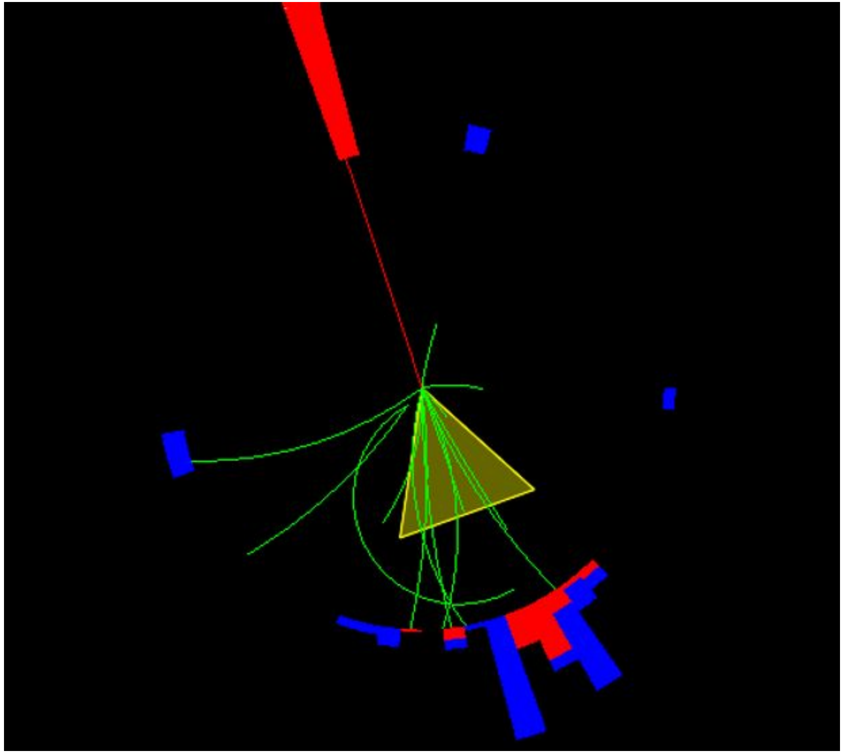
The EIC, a jet factory, will make the first jets in nuclear DIS and proton-polarized DIS

Jets in neutral-current deep-inelastic scattering



Theory



Experiment (simulated)

Motivation

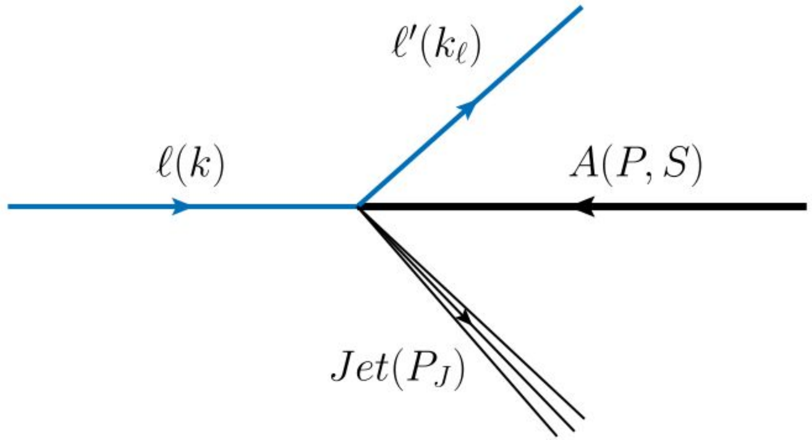
Lepton-jet imbalance $q_T = |\vec{k}_{l\perp} + \vec{p}^{\,j}_{\perp}|$

In Born-level configuration

Probes quark TMD PDFs

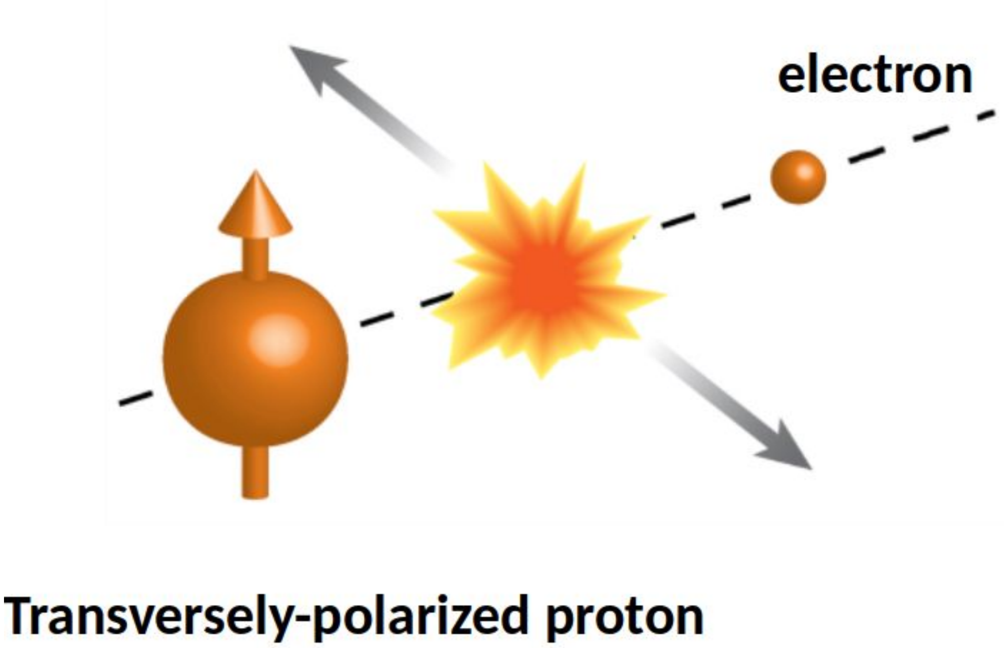
Liu et al. PRL. 122, 192003 (2019)

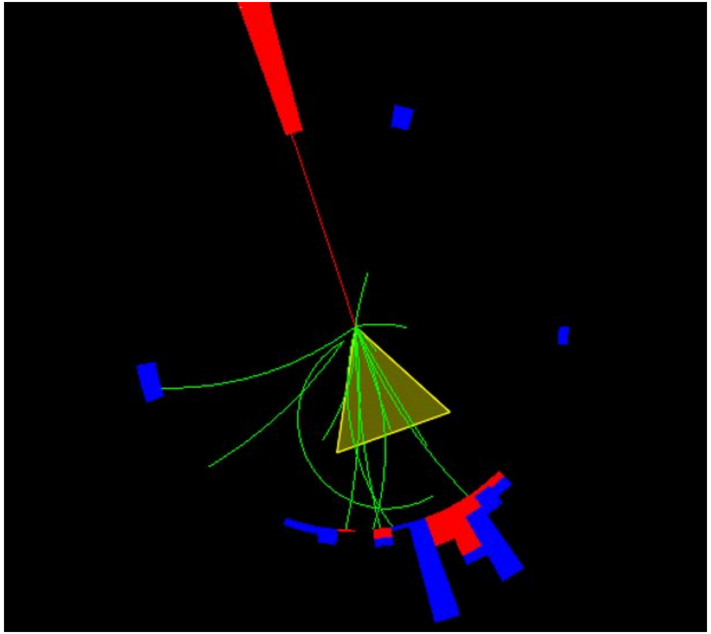
Gutierrez et al. PRL. 121, 162001 (2019)



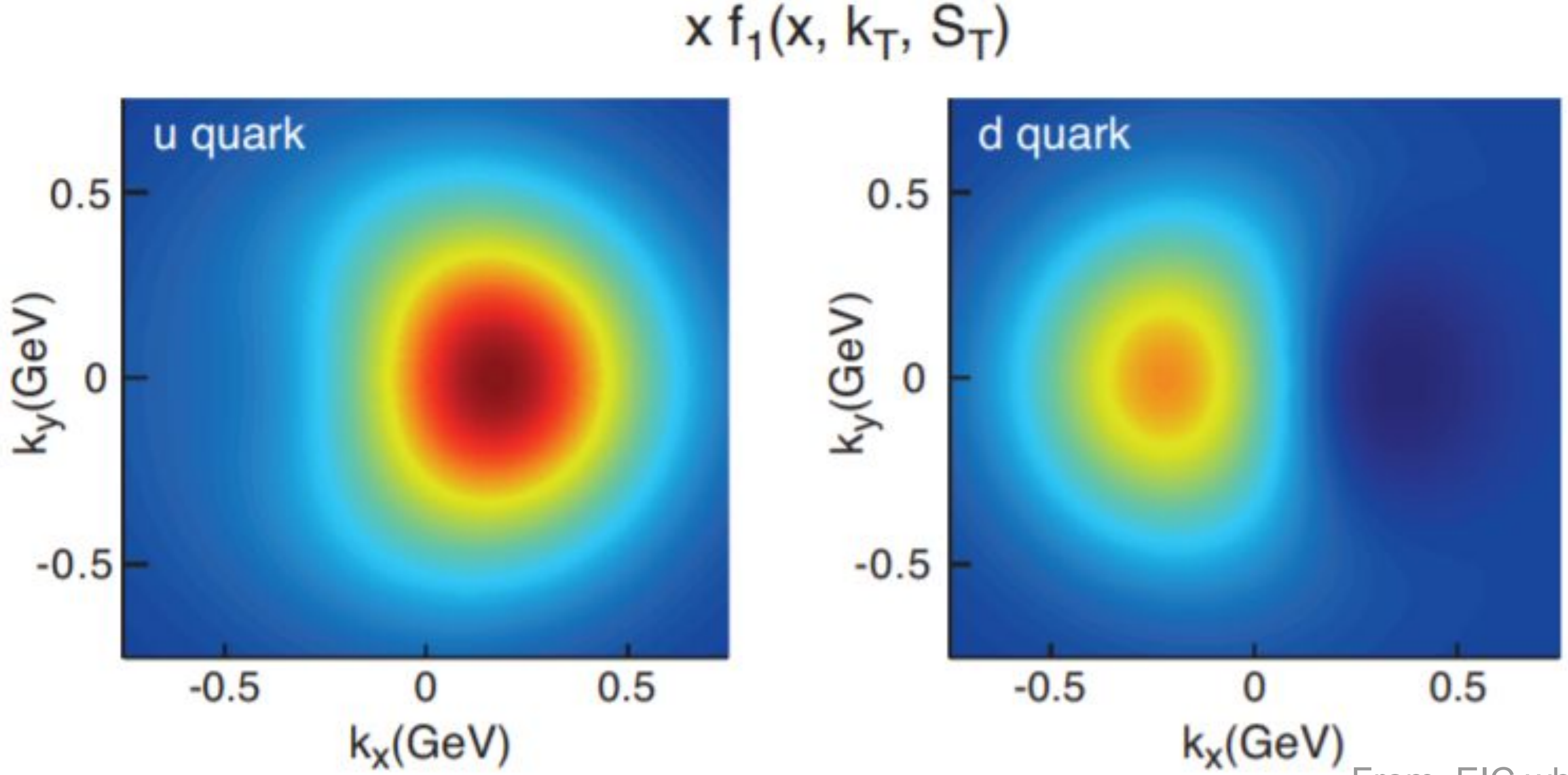
$$\frac{d^5\sigma(\ell p \to \ell' J)}{dy_\ell d^2k_{\ell\perp} d^2q_\perp} = \sigma_0 \int d^2k_\perp d^2\lambda_\perp x f_q(x, k_\perp, \zeta_c, \mu_F) \times H_{\mathrm{TMD}}(Q, \mu_F) S_J(\lambda_\perp, \mu_F) \times \delta^{(2)}(q_\perp - k_\perp - \lambda_\perp).$$

Spin-orbit correlations lead to azimuthal asymmetries



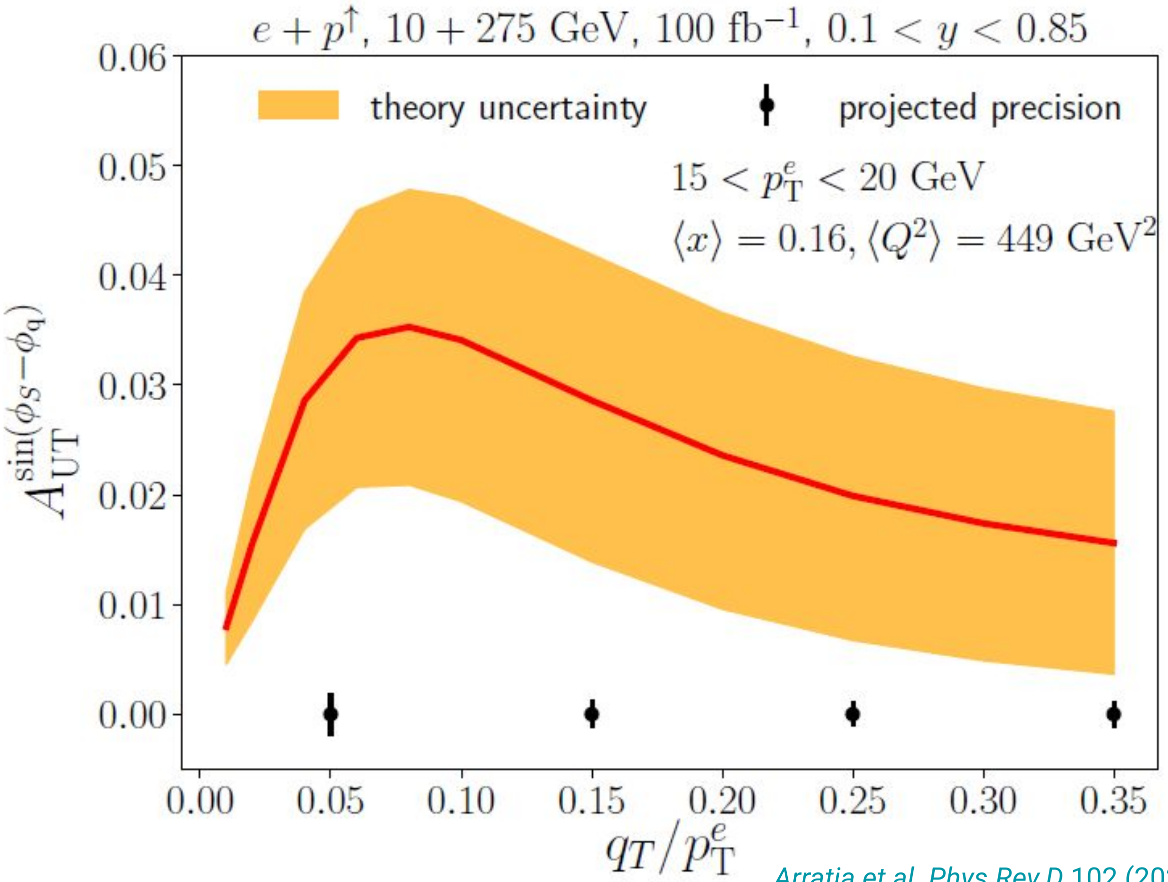


The asymmetry strength reflects a correlation between proton spin and quark momentum, “Sivers function”

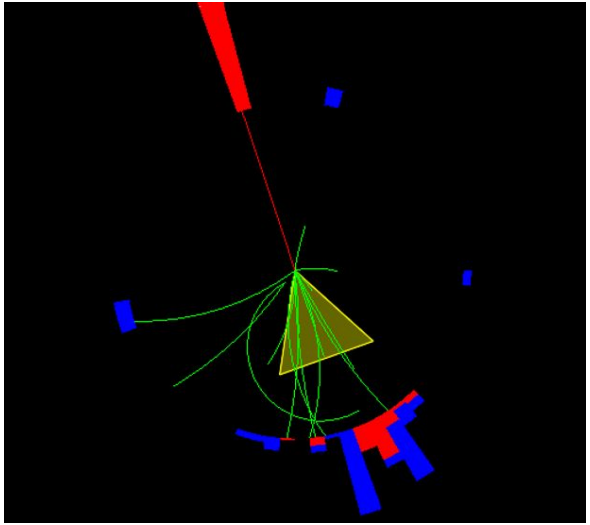


From EIC white paper

Projection for a key "asymmetry" lepton-jet Sivers



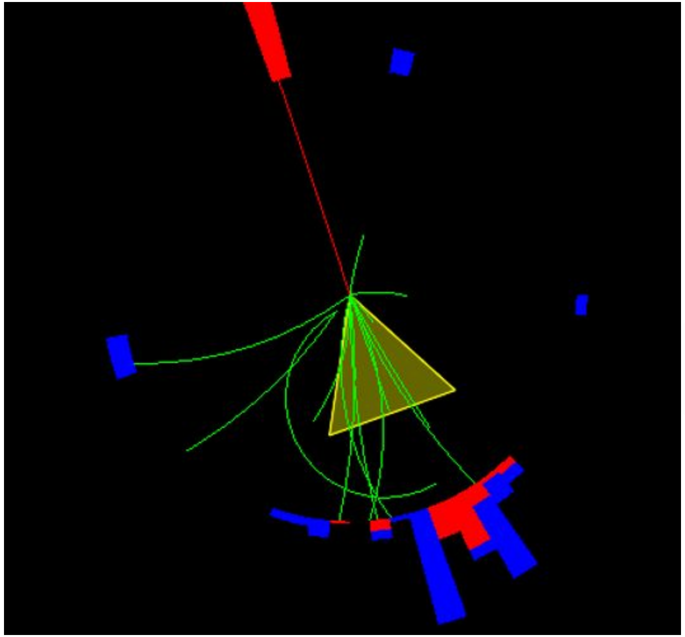
$$q_T = |\vec{p}_T^{\,e} + \vec{p}_T^{\,\text{jet}}|$$



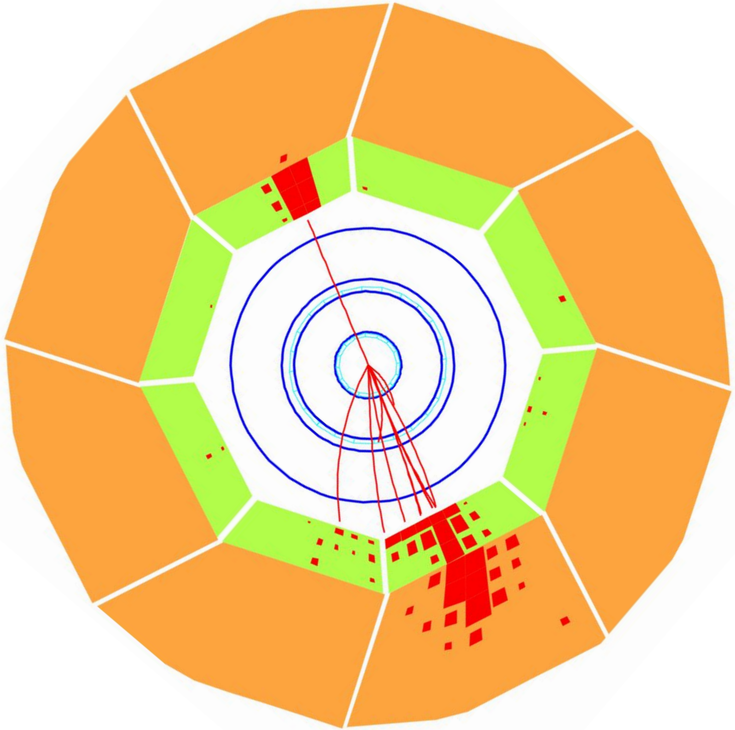
[Arratia et al. Phys.Rev.D 102 (2020) 7, 074015](#)

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

EIC

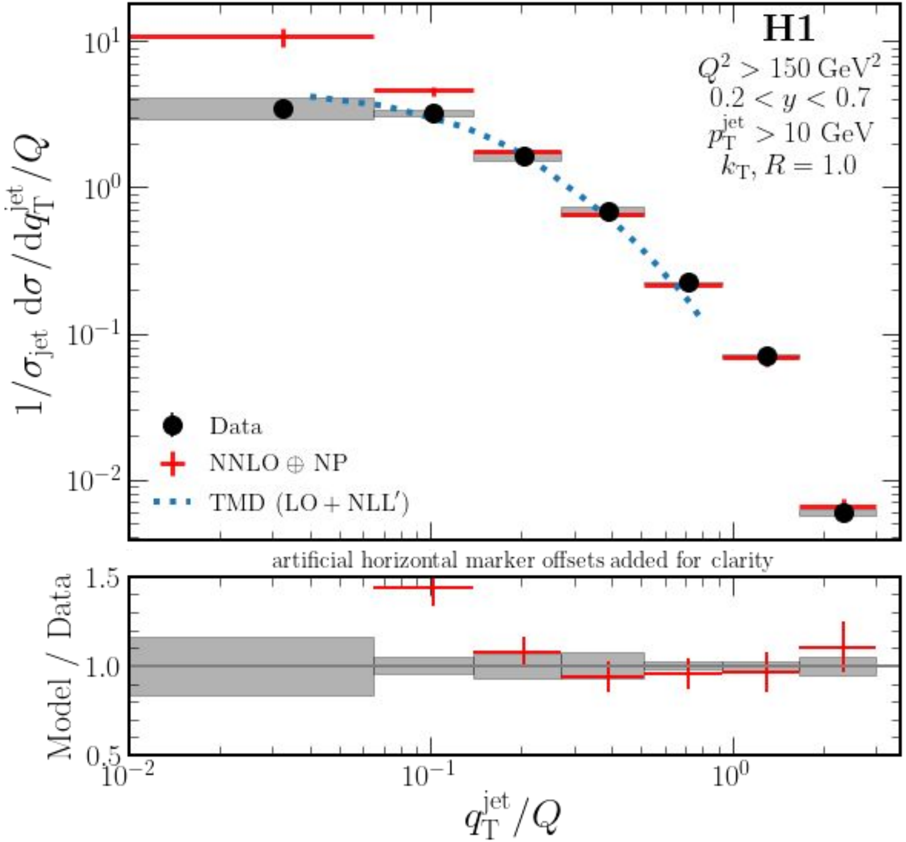


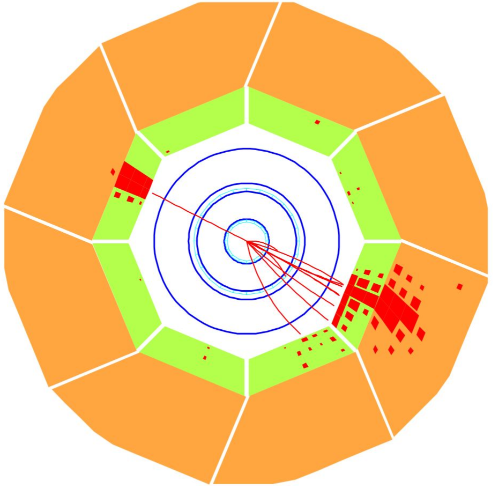
H1@HERA



Lepton-jet momentum imbalance

Phys.Rev.Lett. 128 (2022) 13, 132002



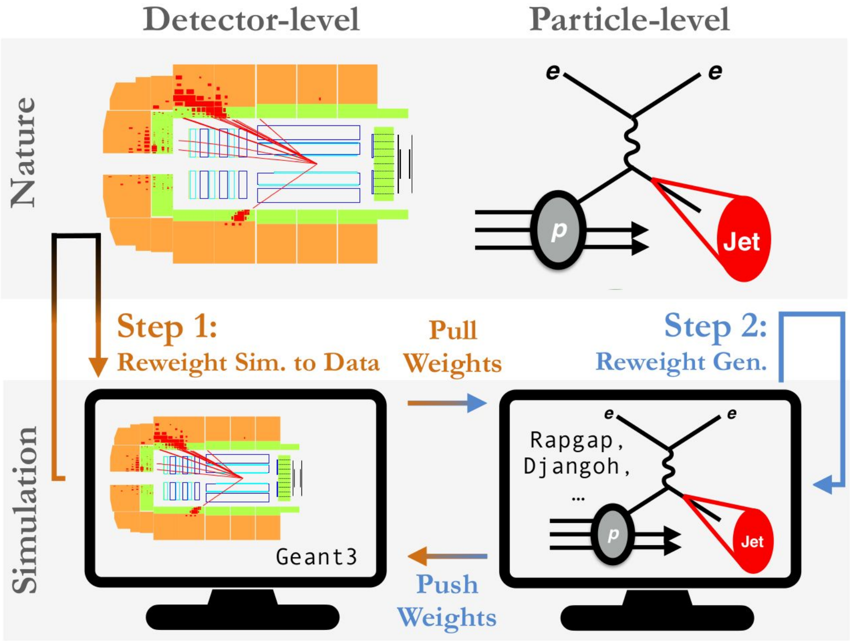


Textbook example of “matching” between collinear and TMD frameworks

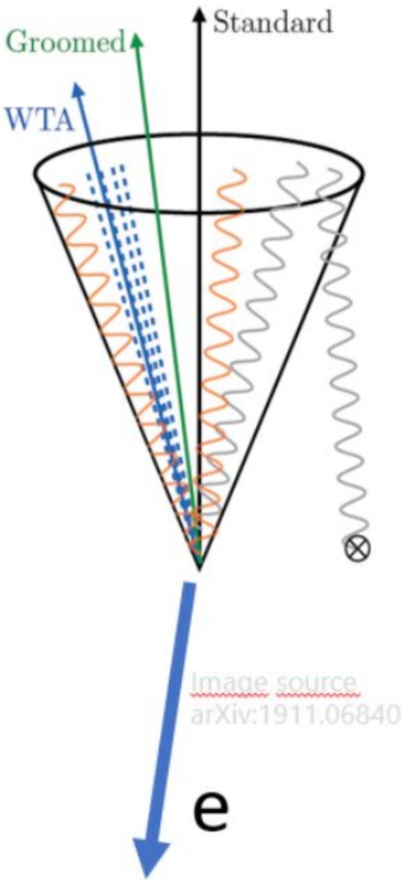
First time seen in DIS!
(not seen in fixed-target DIS)

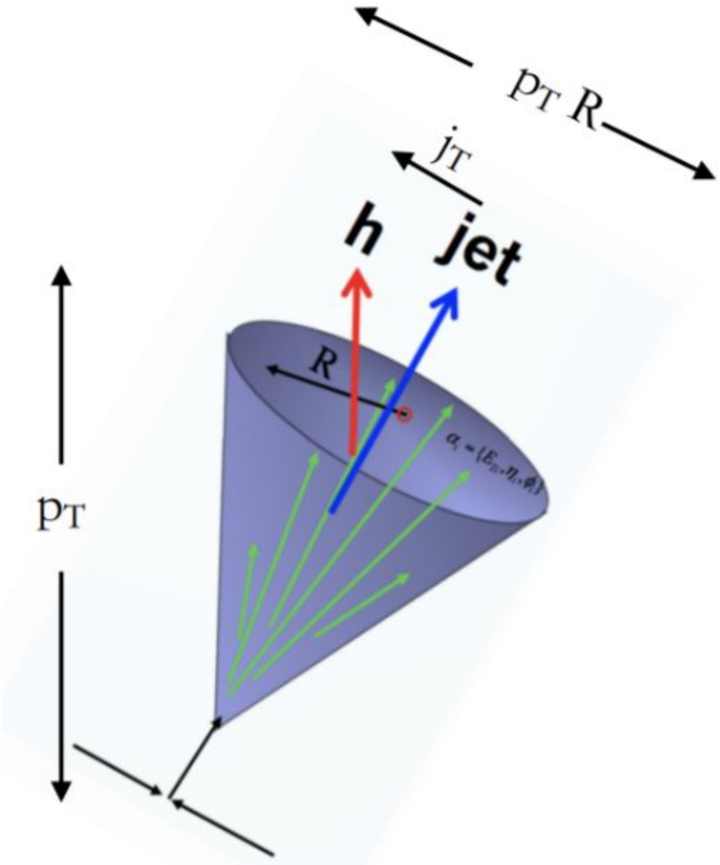
“This measurement also represents a ***milestone in the use of ML techniques for experimental physics,*** *as it provides the first example of ML-assisted unfolding,.... This opens up the possibility for high dimensional explorations of nucleon structure with H1 data and beyond”*

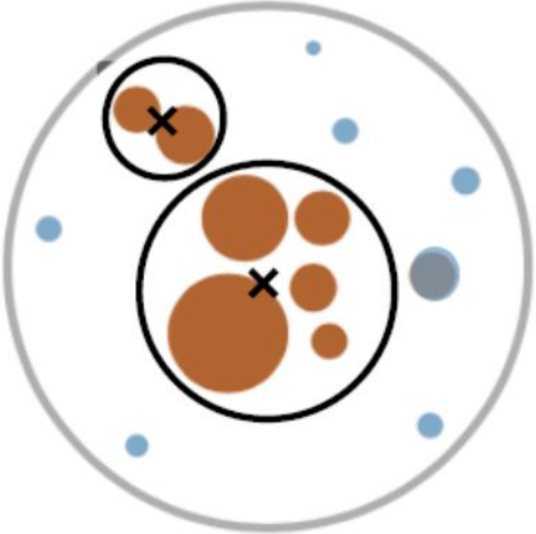
H1 Collaboration, Phys.Rev.Lett. 128 (2022) 13, 132002



Jets have rich substructure, which encodes rich dynamics



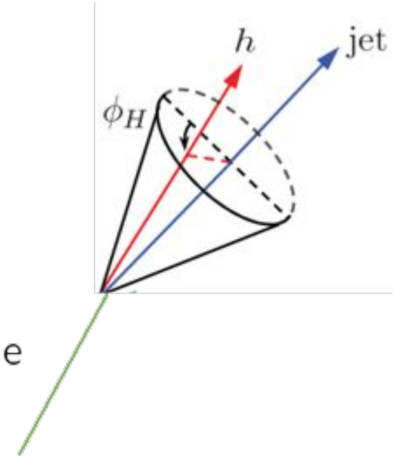


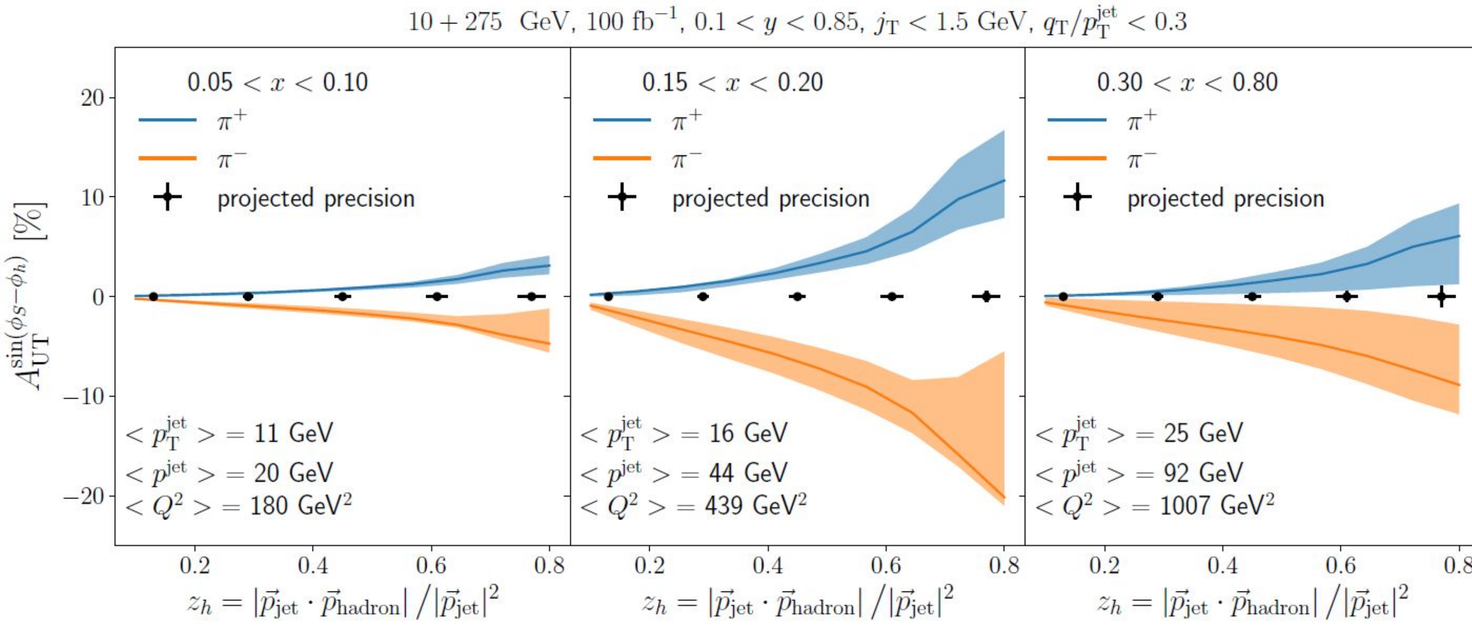


“Hadron-in-jet asymmetries” for proton tomography

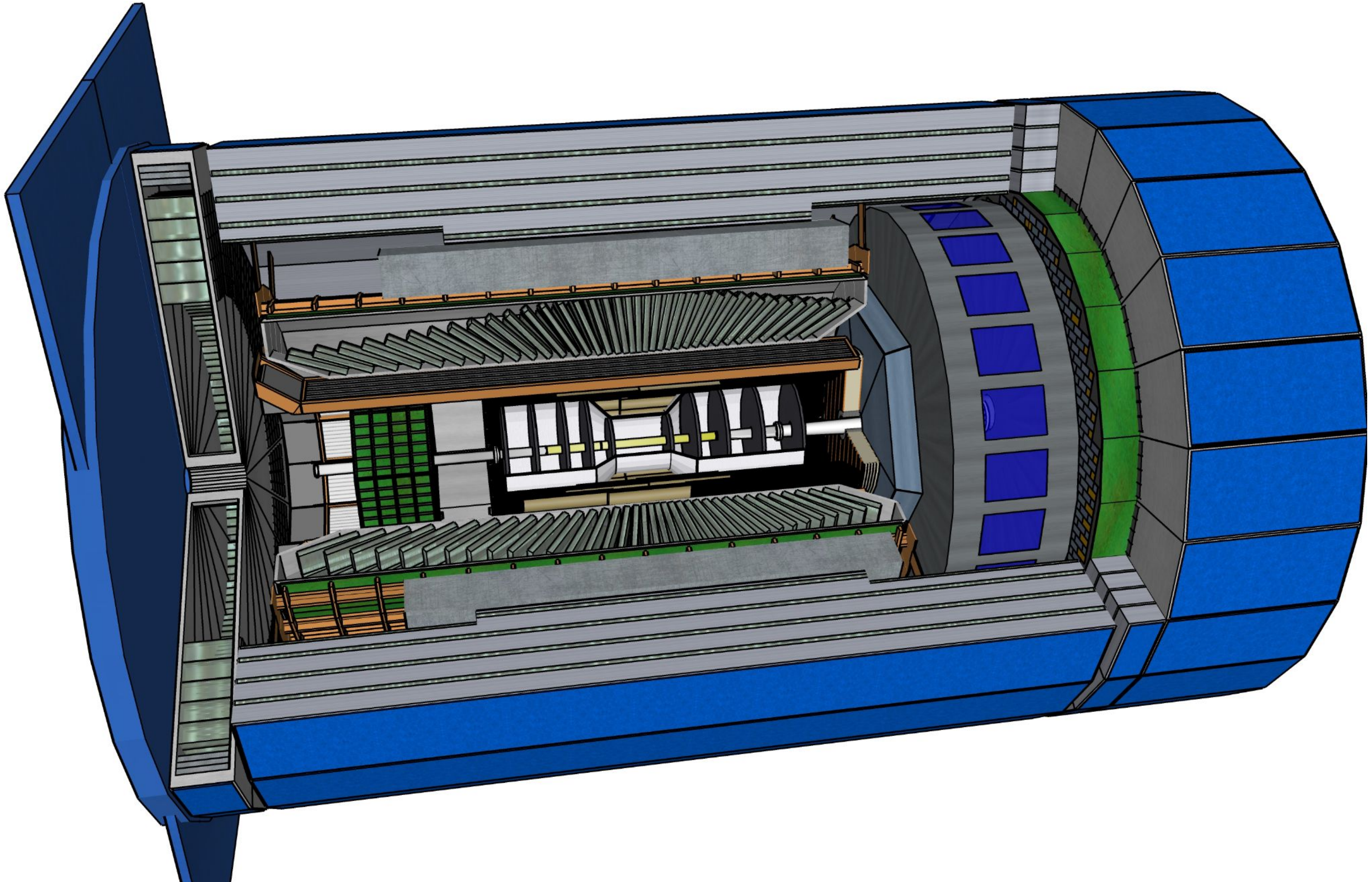
[Arratia et al. Phys.Rev.D 102 (2020) 7, 074015]

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

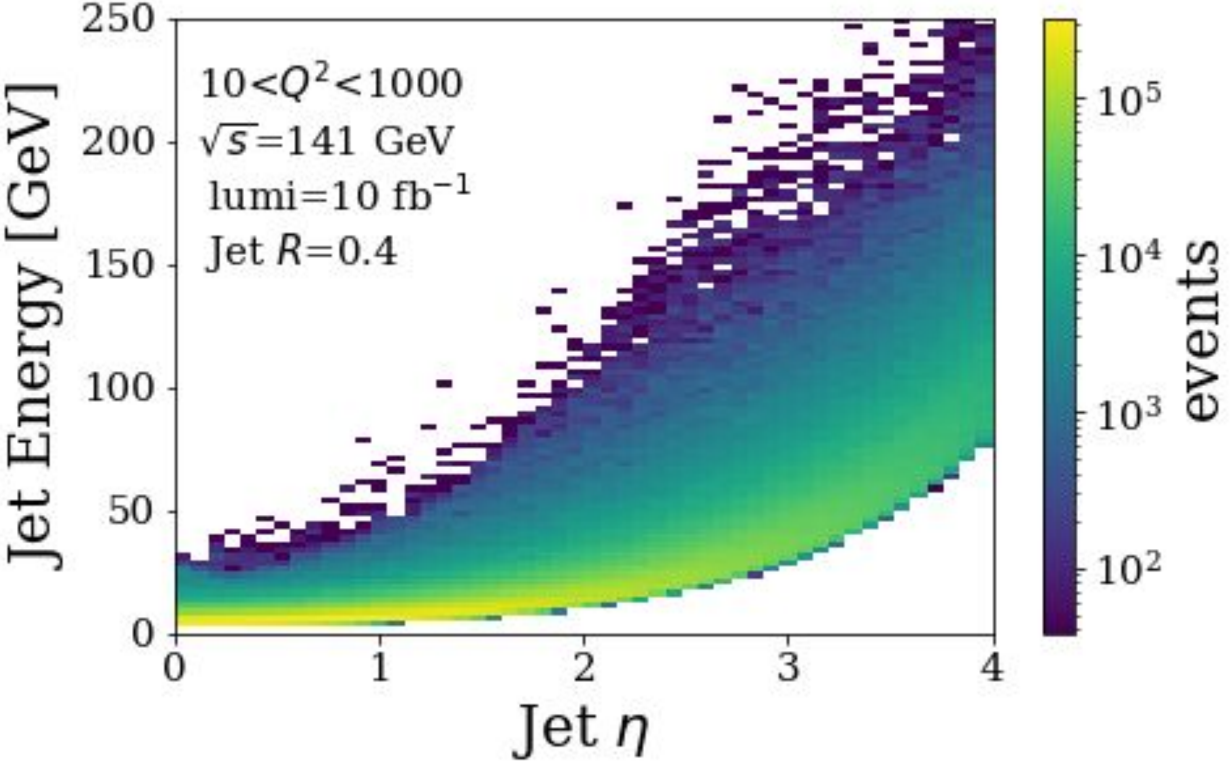


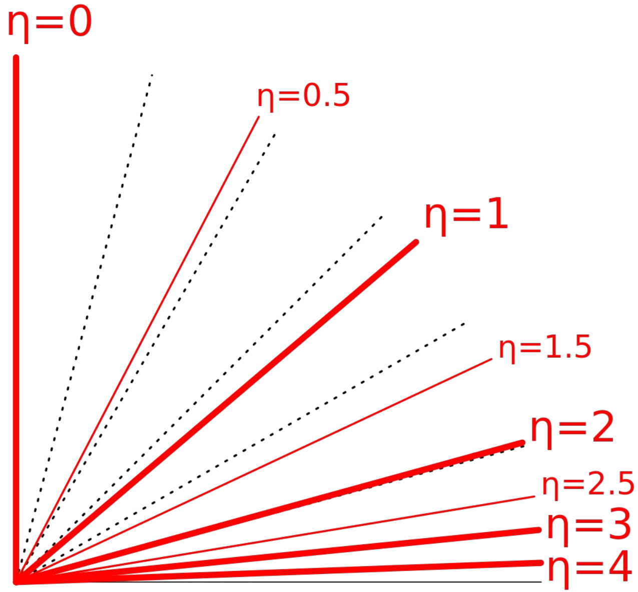


ePIC detector
(a general purpose hermetic detector at EIC)



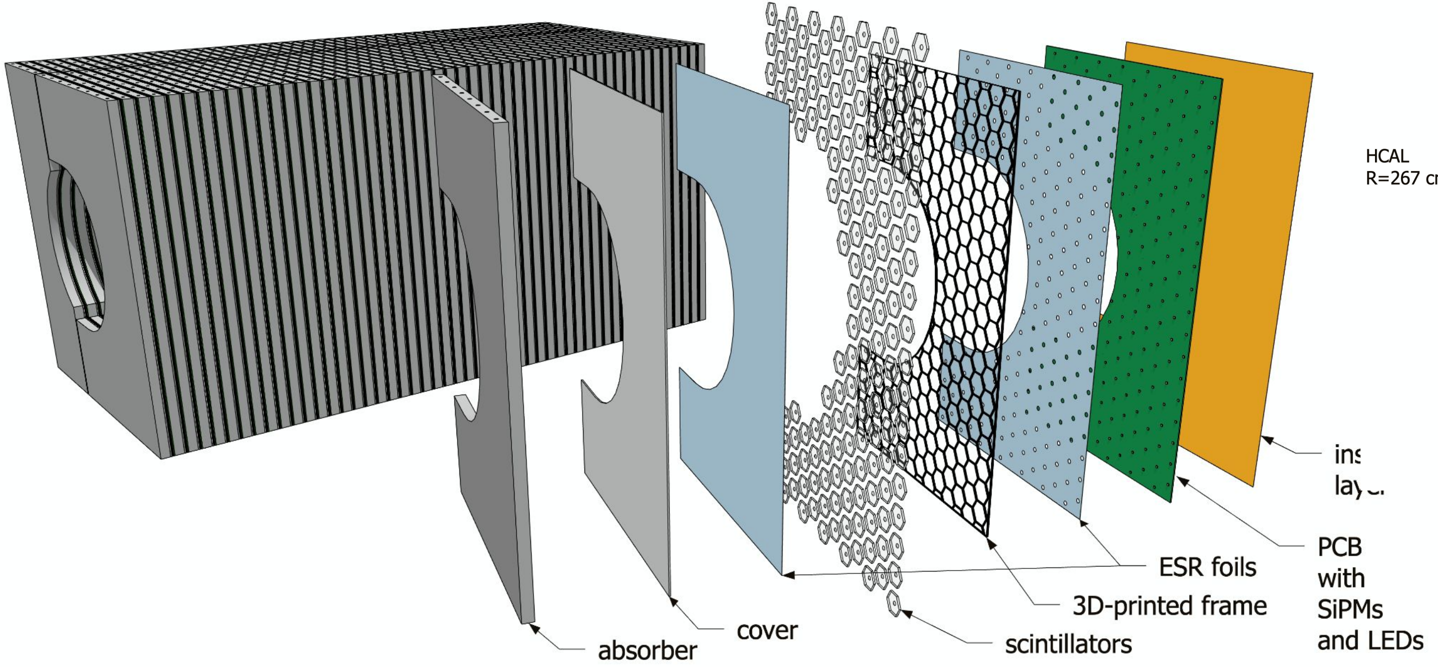
Jet spectra at the EIC

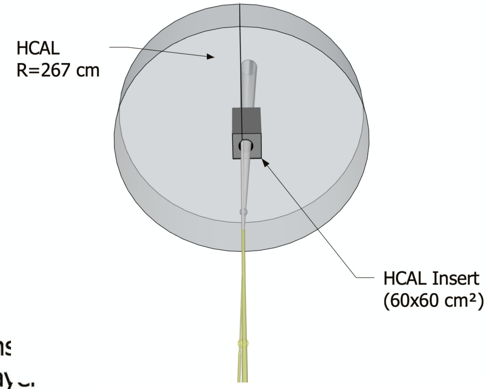




The Calorimeter Insert for ePIC

More details in:
https://arxiv.org/abs/2208.05472
https://arxiv.org/abs/2302.03646

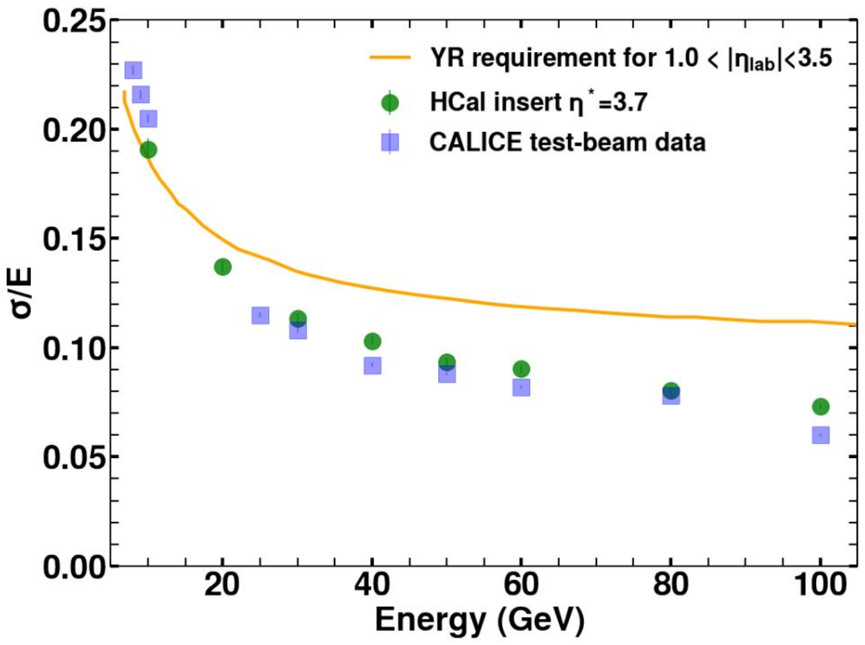


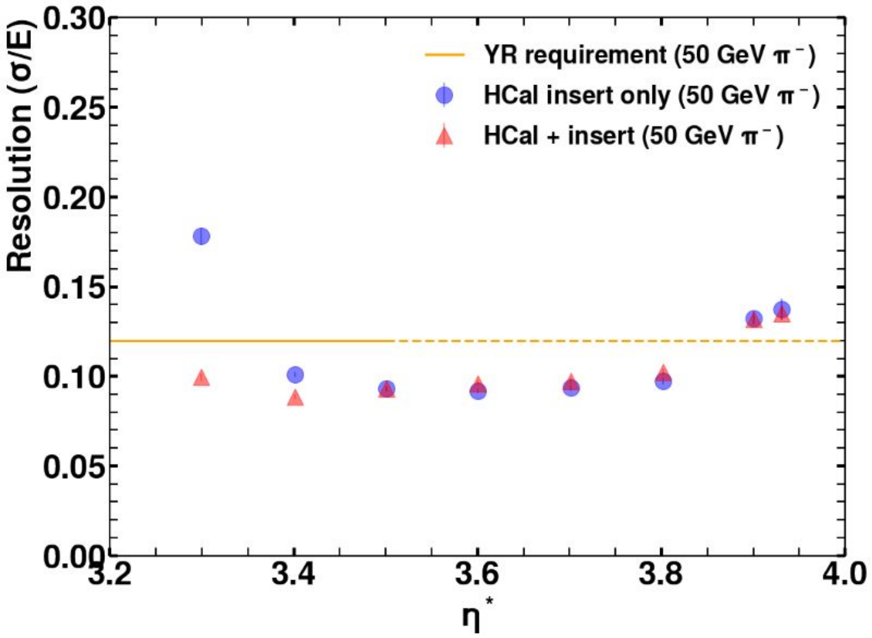


Optimal acceptance with high-granularity to cover $3<\eta<4$ range (poor tracking)
- To improve acceptance for jets and inclusive DIS reco via event transverse-momentum
- Tag beam-induced backgrounds with topology
- To ensure SiPMs and scintillator remain easily accessible for repair/maintenance & upgrades

Expected performance from simulation

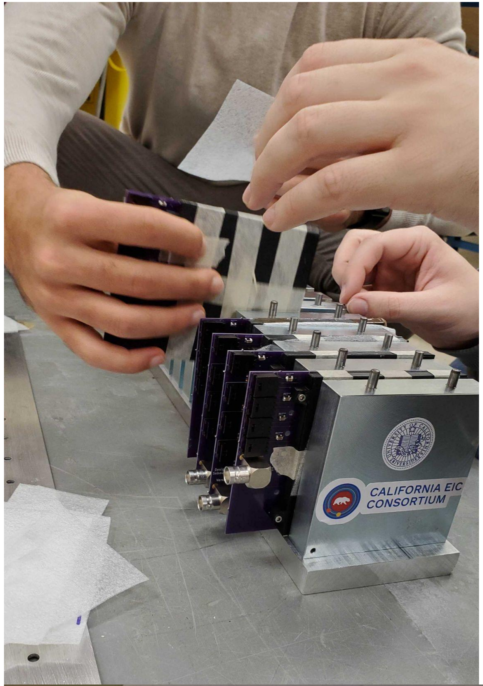
Arratia et al. Nucl.Instrum.Meth.A 1047 (2023) 167866

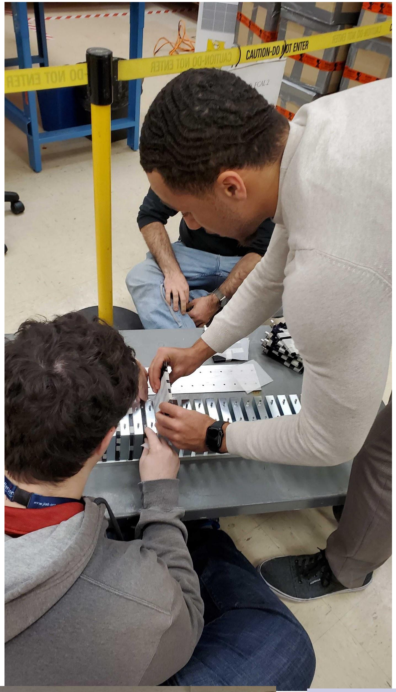


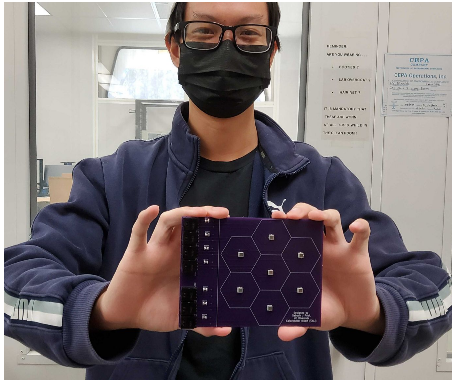


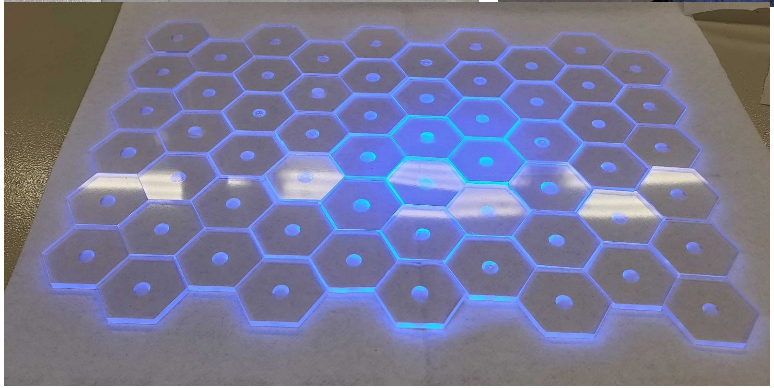
Excellent performance and acceptance pushed to the limit

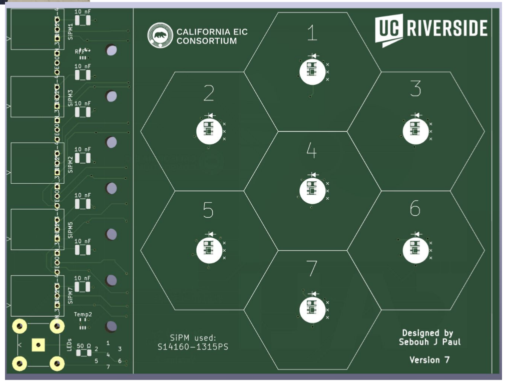
From Simulation to Reality

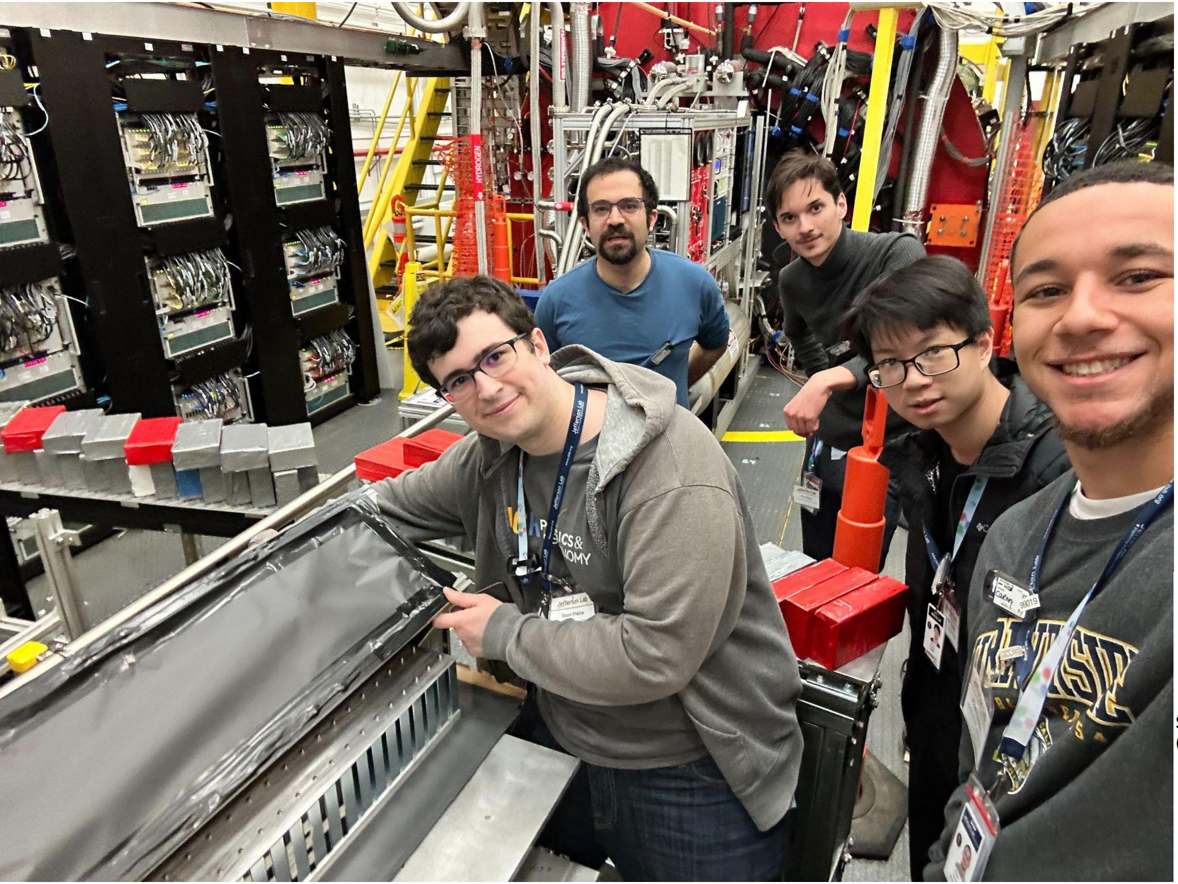




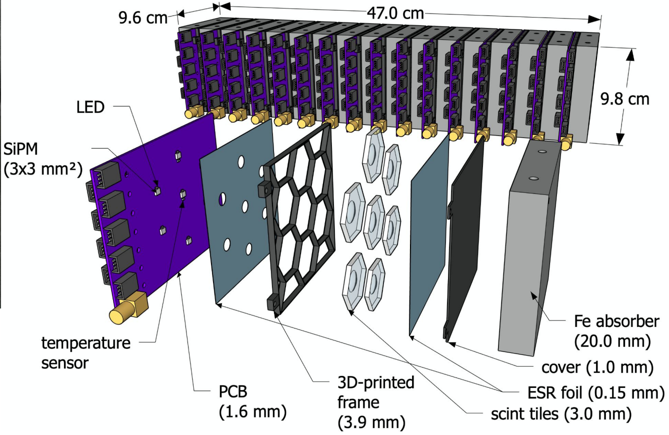









CALIFORNIA EIC
CONSORTIUM


9.6 cm
47.0 cm
9.8 cm
LED
SiPM
(3x3 mm²)
temperature
sensor
PCB
(1.6 mm)
3D-printed
frame
(3.9 mm)
Fe absorber
(20.0 mm)
cover (1.0 mm)
ESR foil (0.15 mm)
scint tiles (3.0 mm)

Summary

Upcoming experiments at JLab promise to establish first steps towards quantum tomography of nuclei.

Future experiments at EIC will provide promising new tool: jets