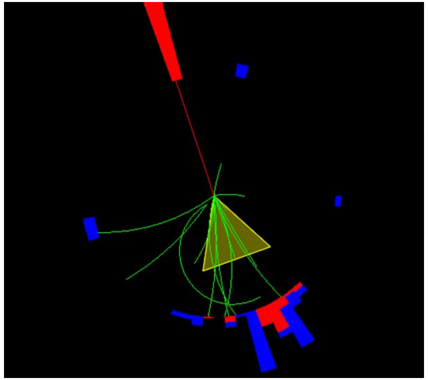
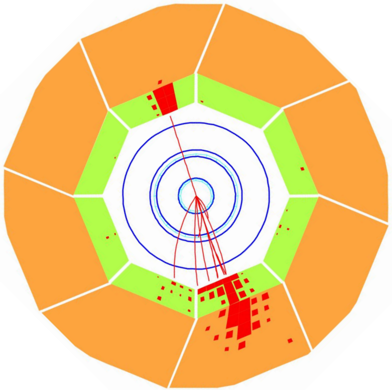
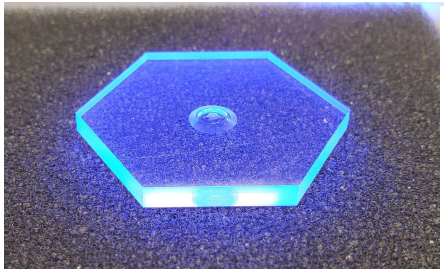
Jet Tomography of the Proton and Its Enabling Technologies

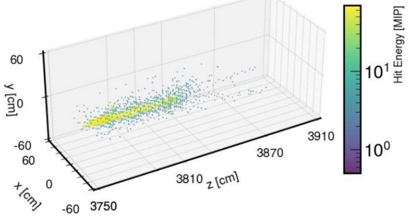




Miguel Arratia

UC RIVERSIDE





FPD Seminar, SLAC, October 3th 2023

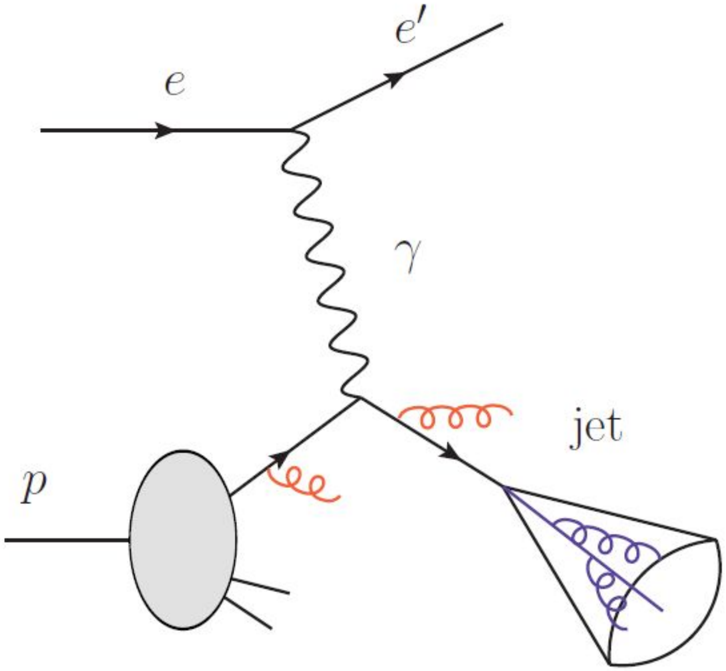
Outline

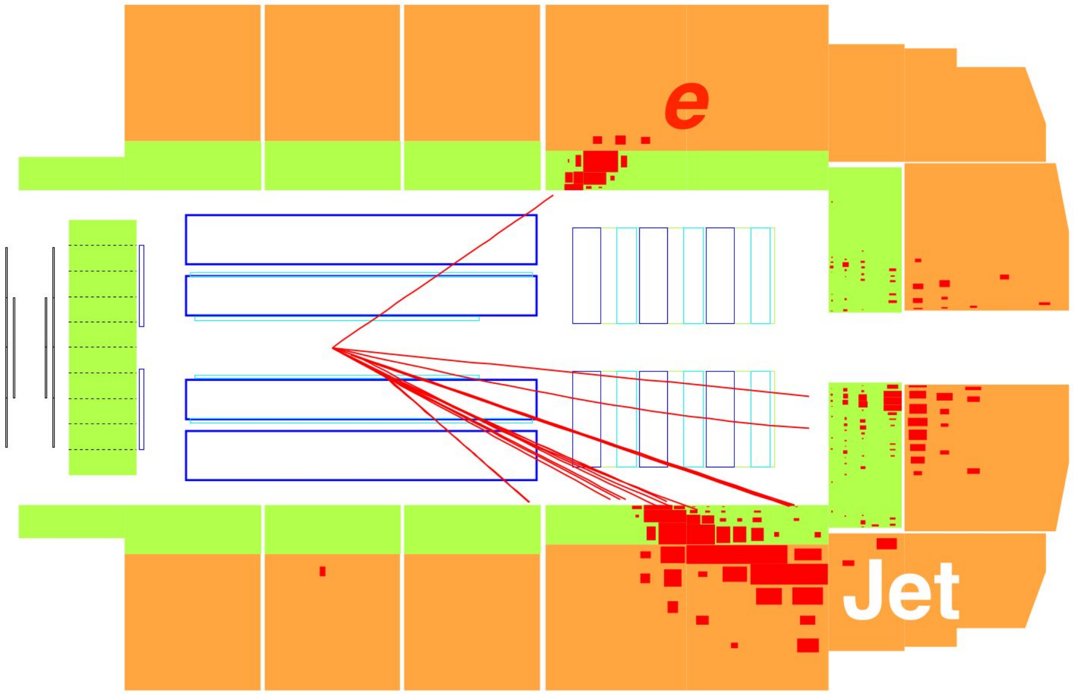
- Quantum tomography in QCD.
- Future prospects at the Electron-Ion Collider (EIC).
- An EIC pathfinder program with HERA data.
- Enabling technology (high-granularity calorimeters).

HERA: the first electron-proton collider

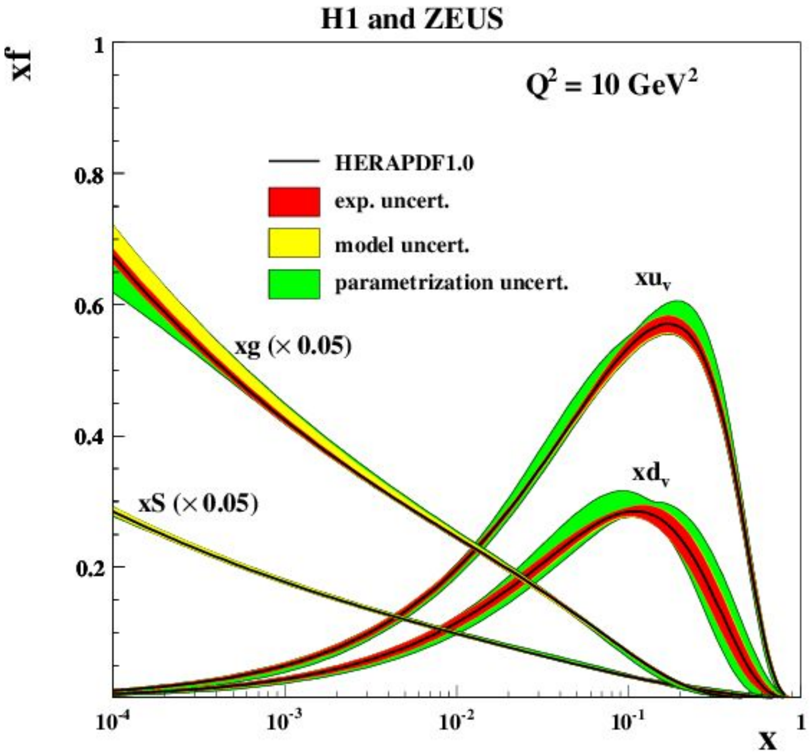
Operated at Hamburg, Germany from 92 to 2007

Deep-inelastic scattering





HERA Legacy: precision QCD

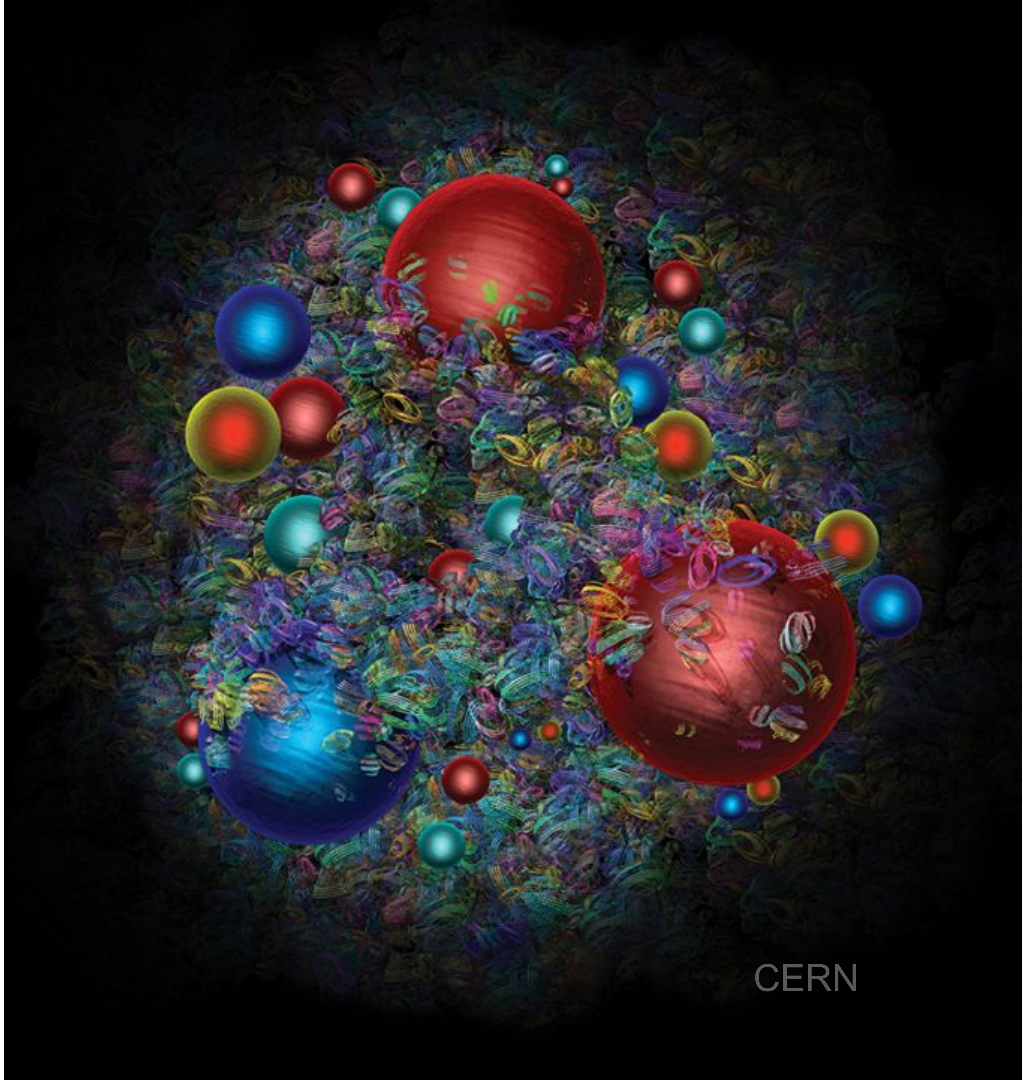


Momentum fraction carried by quark or gluon

Evolution Equations at the core or parton-distribution functions (PDF) extractions:

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

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


CERN

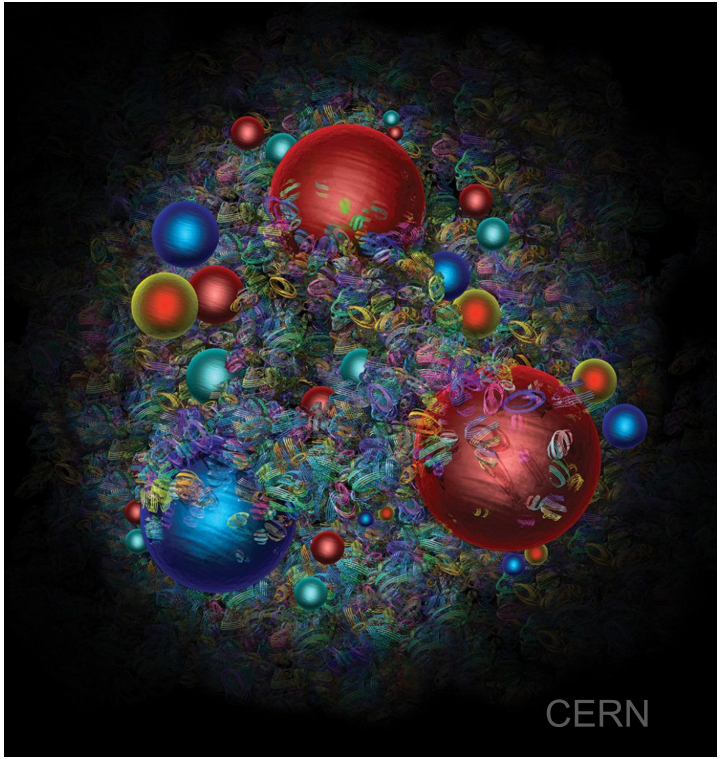
“Quantum tomography” of the proton involves measuring its Wigner function, which can be generalized from:

$$\mathcal{W}(x,k) = \int \frac{dx'}{2\pi} e^{ikx'} \psi^*\left(x + \frac{x'}{2}\right) \psi\left(x - \frac{x'}{2}\right)$$

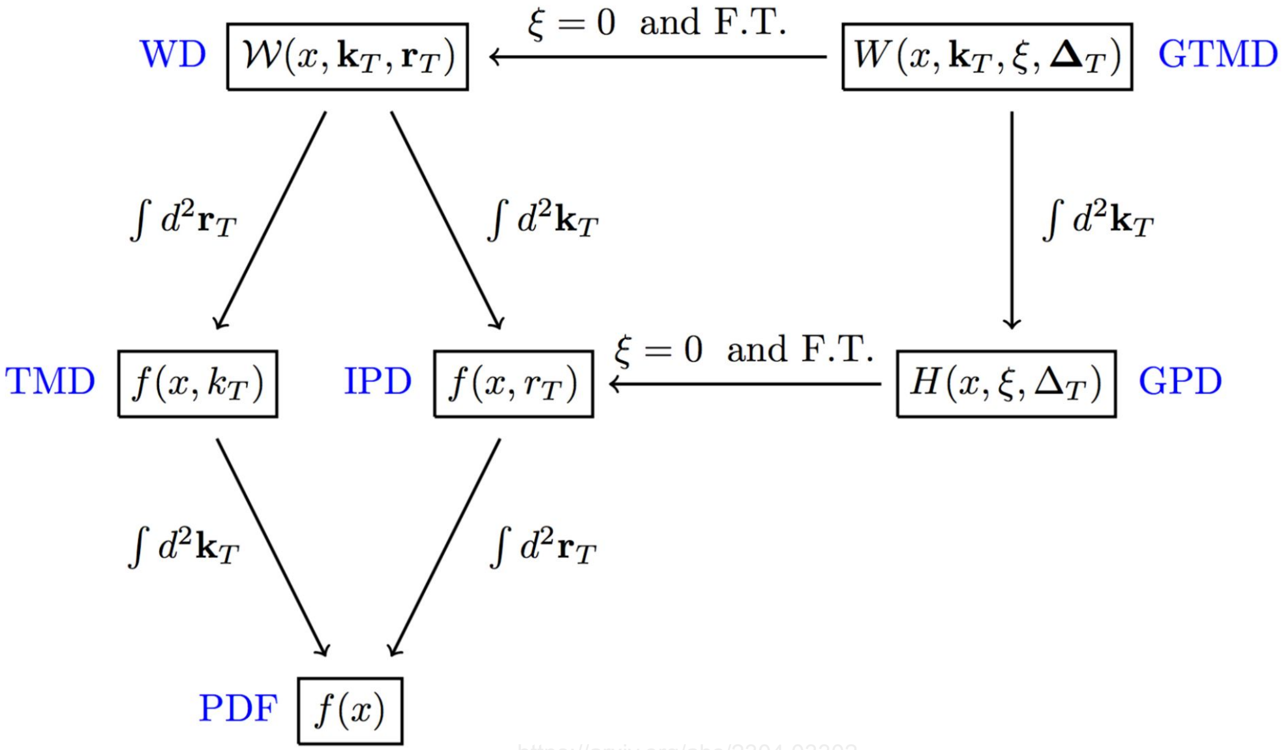
$$\langle O \rangle = \int dx\, dk\, O(x,k)\, \mathcal{W}(x,k)$$

From it one can derive:

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



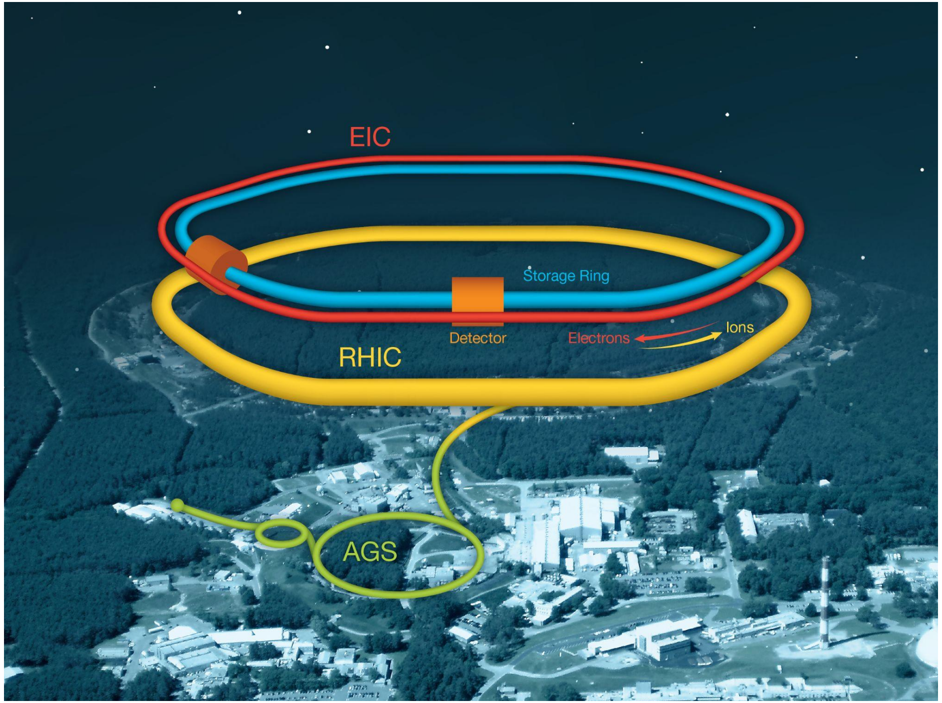
Goal: measure "projections" of the quantum-phase density in either position or momentum space ("GPDs" or "TMDs")



These functions follow a more complex set QCD of evolution equations

https://arxiv.org/abs/2304.03302

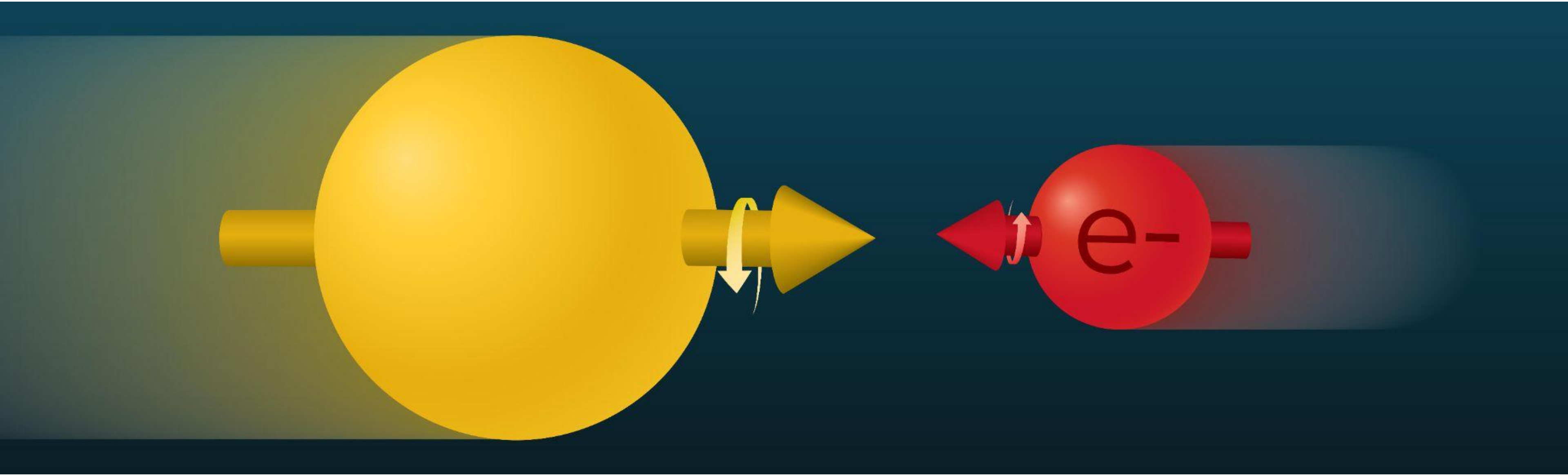
The Electron-Ion Collider



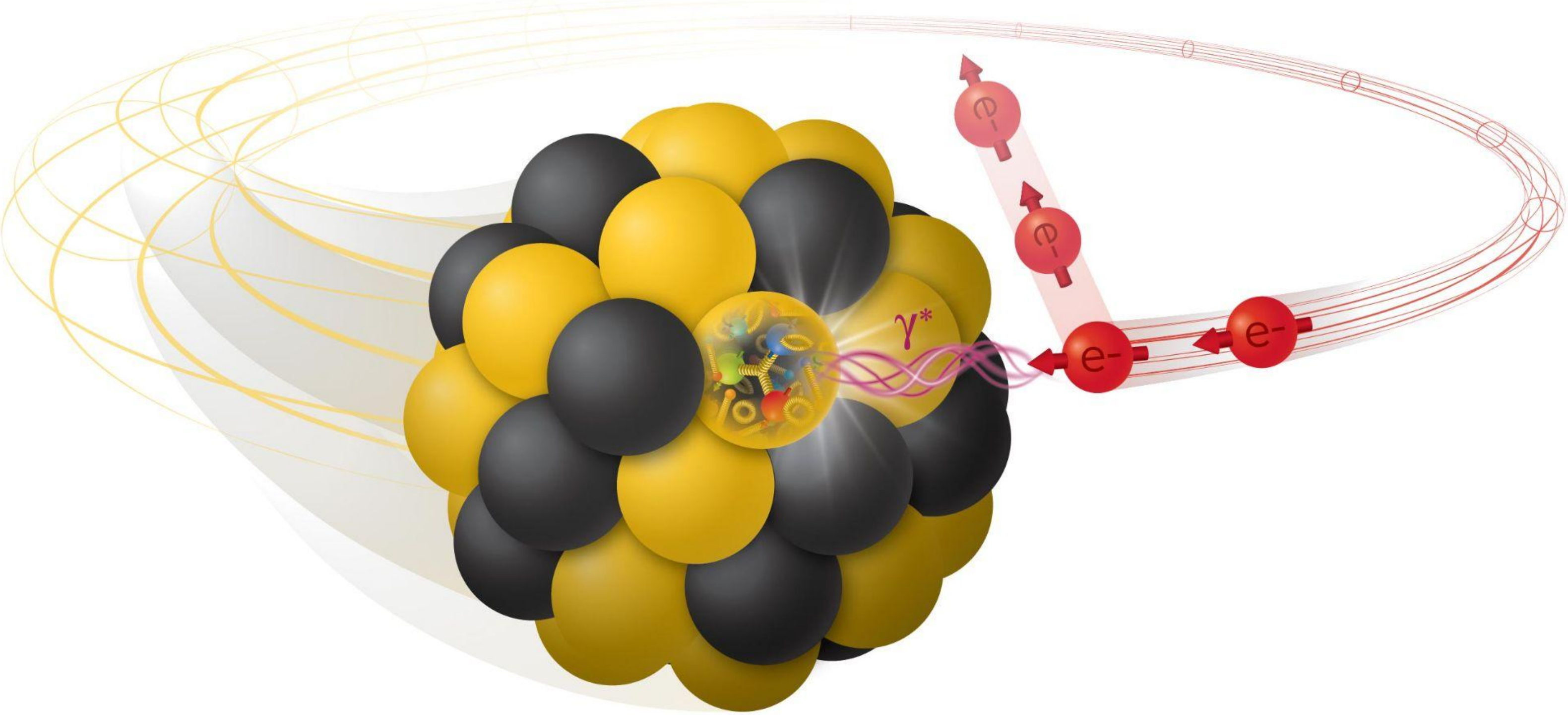
- high luminosity
- high beam polarization (electron, protons, and light ions)
- Wide range of nuclear beams
- Variable center of mass up to 140 GeV

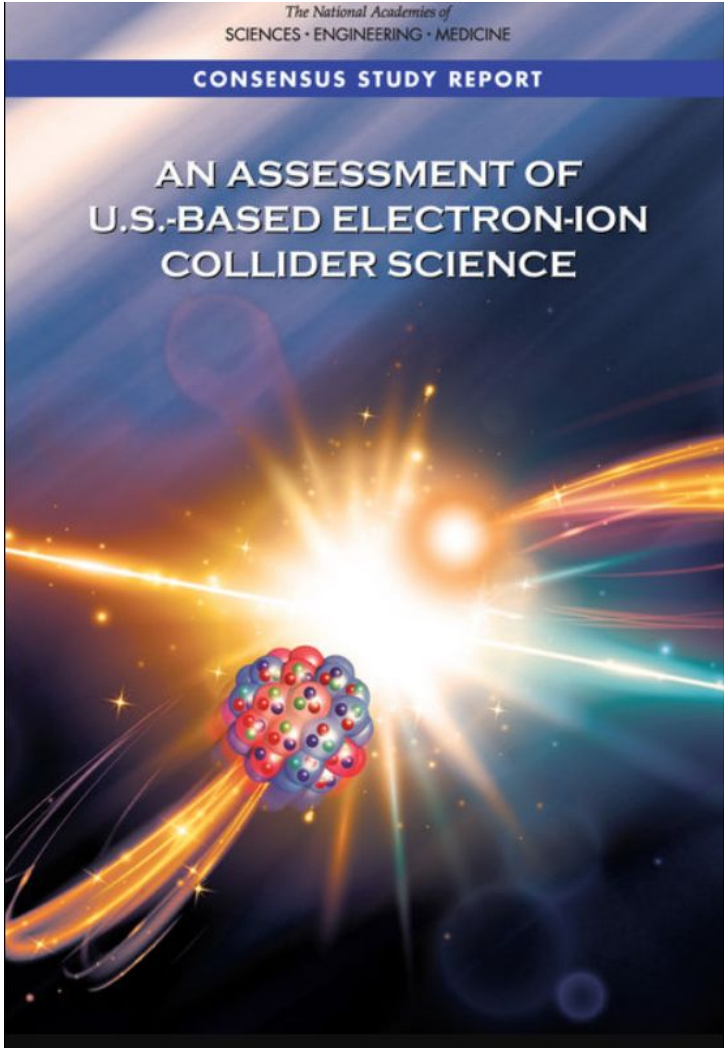
Brookhaven National Laboratory

EIC: the first polarized ep collider



EIC: the first eA collider

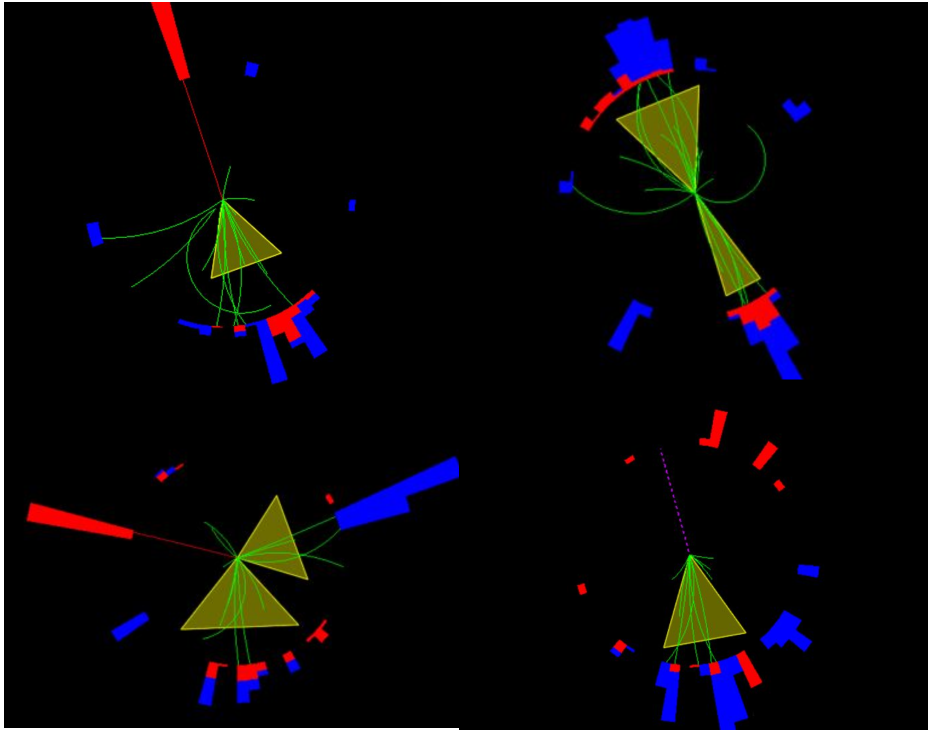




The EIC seeks to answer:

- How does the spin of the proton arise?
- How does the mass of the proton arise?
- What are the emerging properties of dense system of gluons?

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

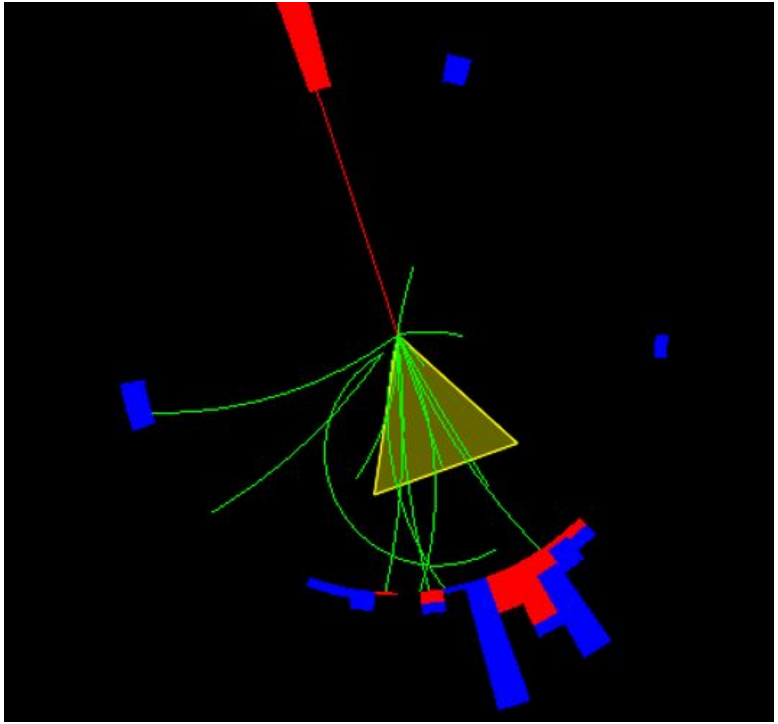


What is a jet?

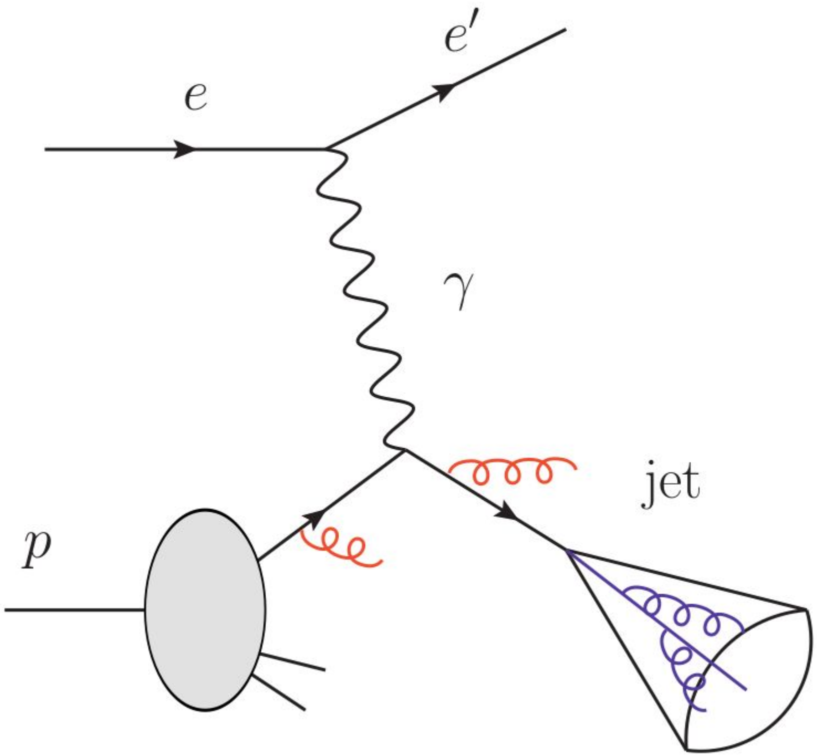
Output of a jet algorithm

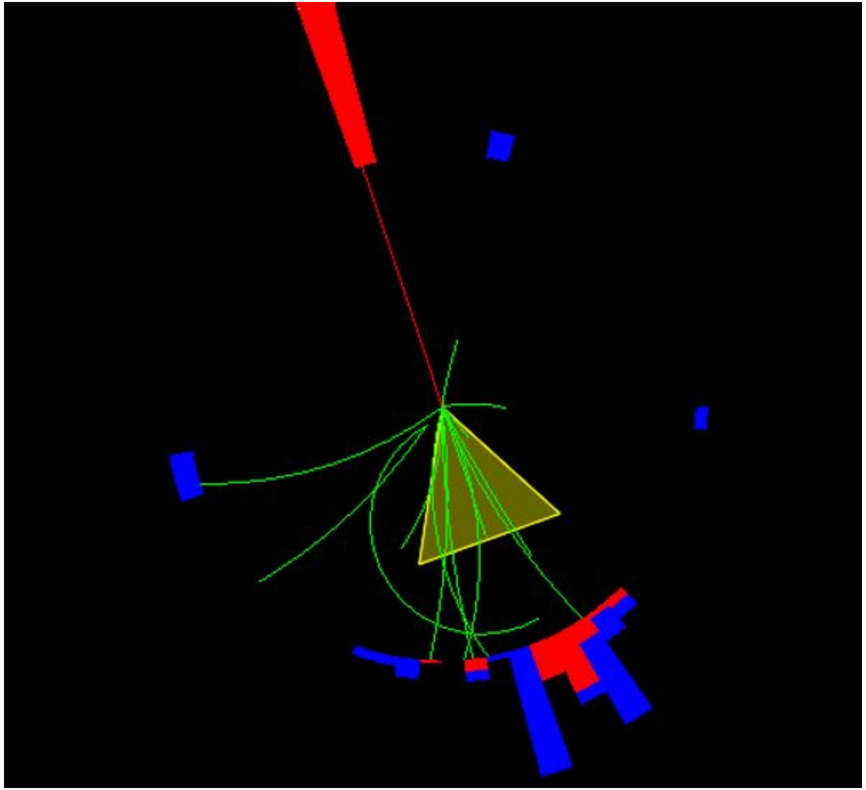
Why are jets useful?

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



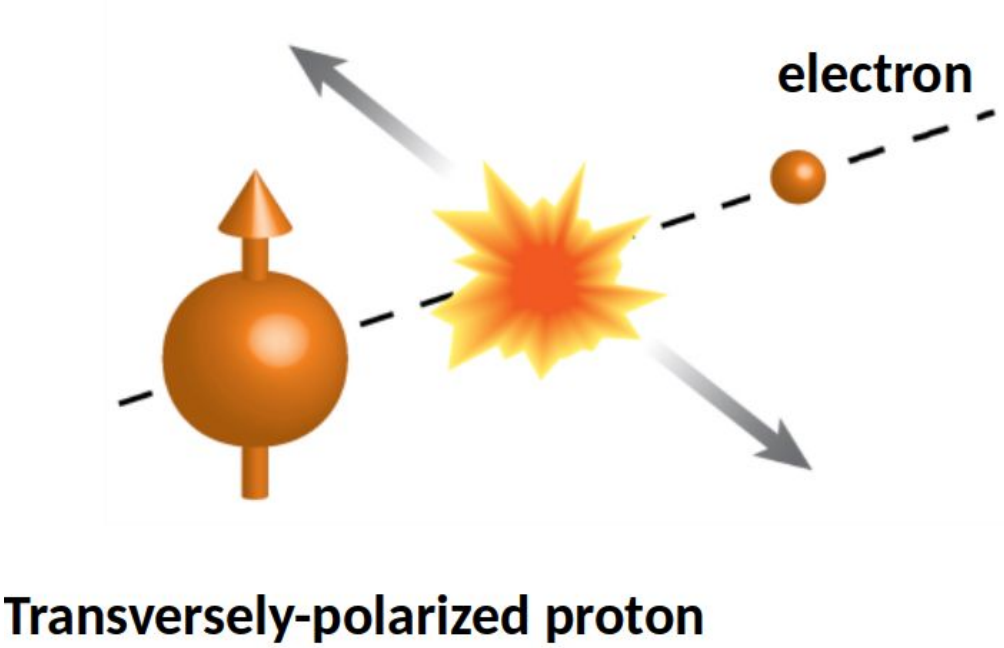
Back-to-back topology probes quark TMDs

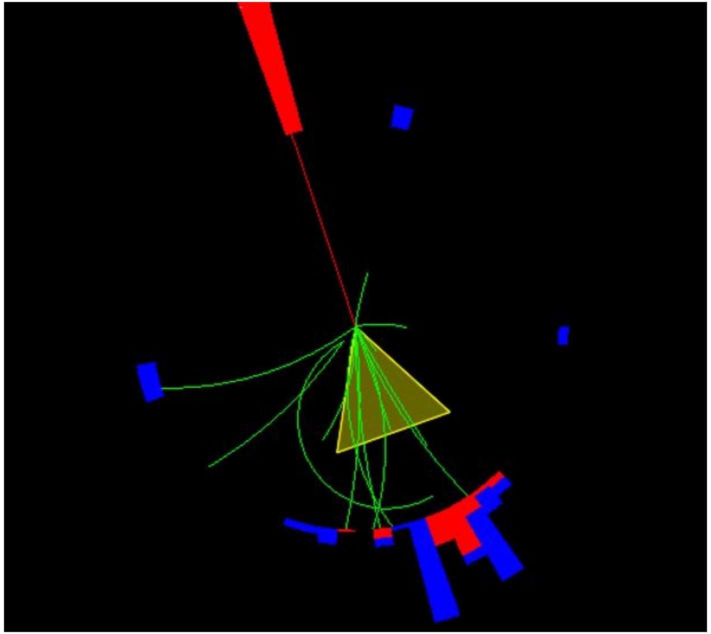




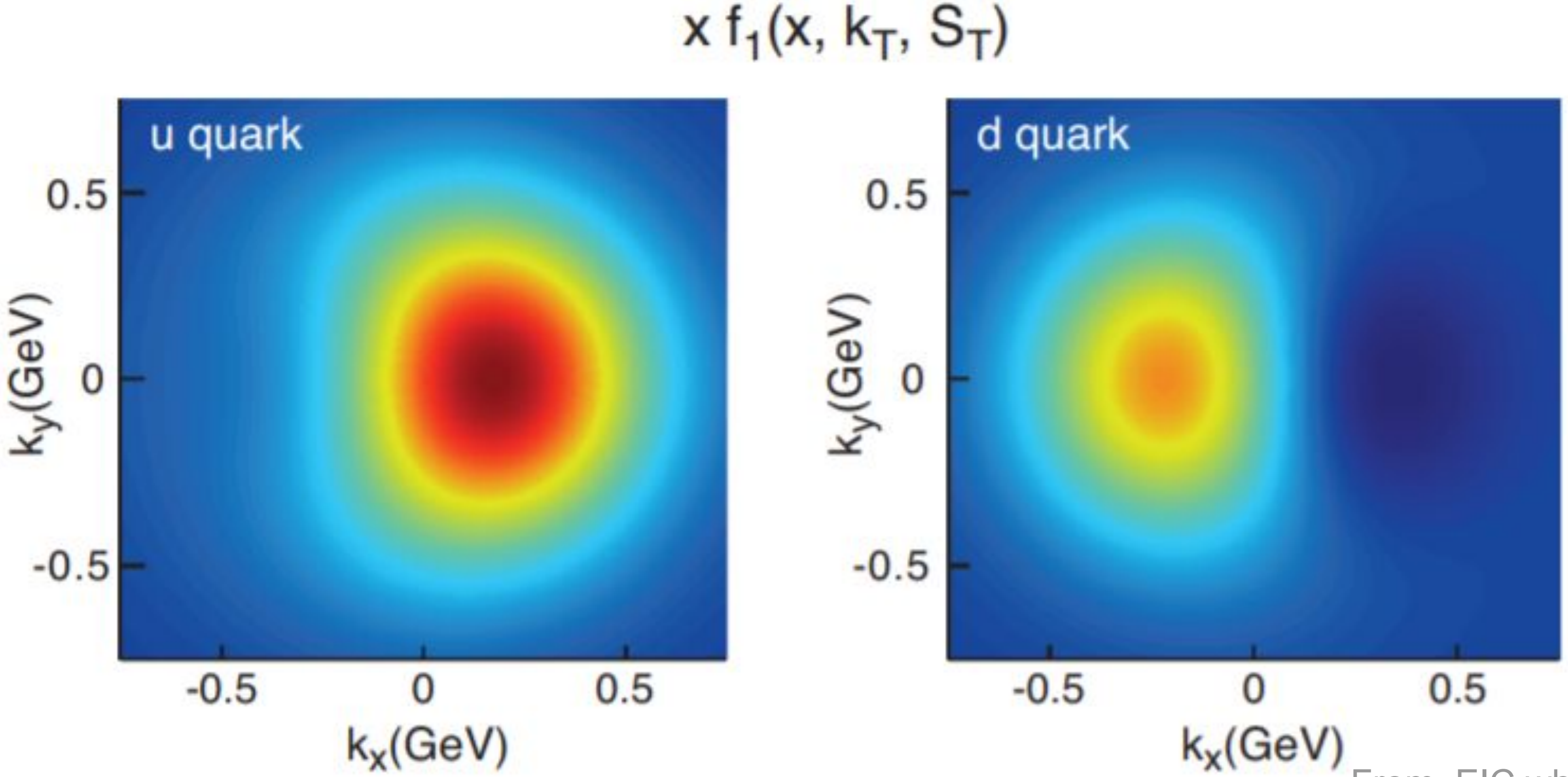
Liu et al. PRL. 122, 192003, Gutierrez et al. PRL. 121, 162001

Spin-orbit correlations lead to azimuthal asymmetries



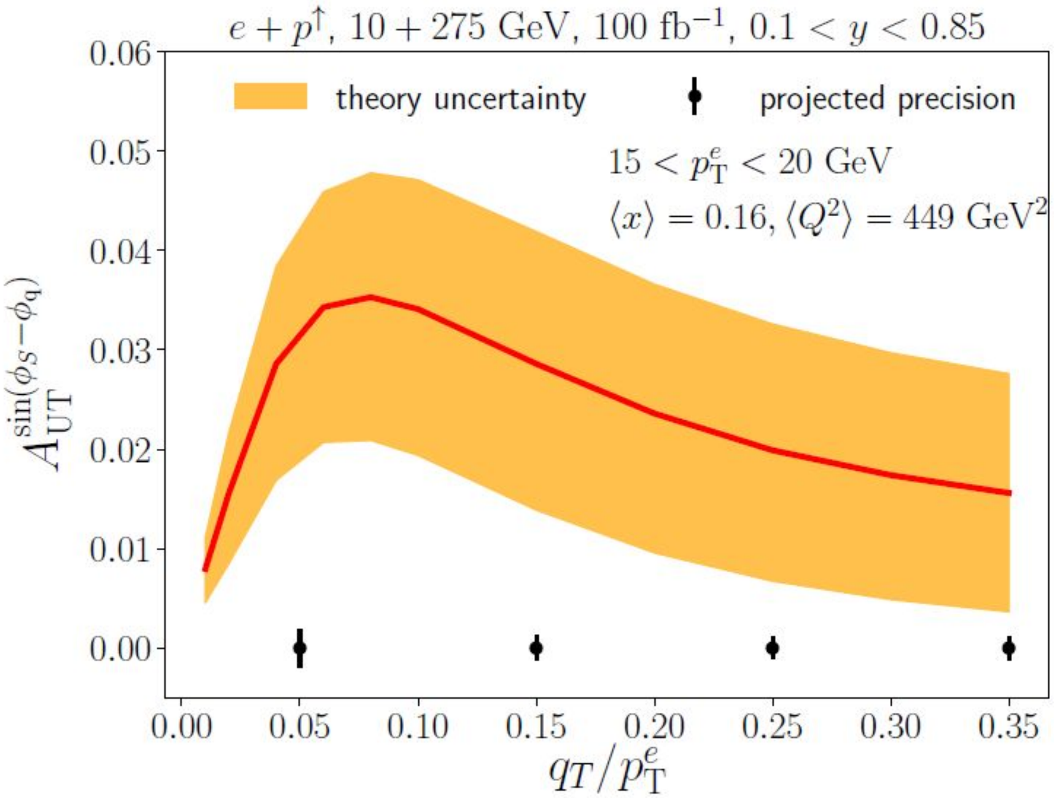


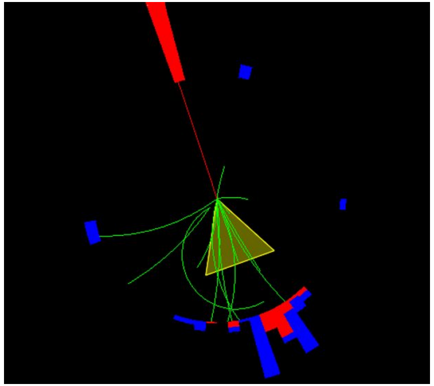
The asymmetry strength reflects a correlation between proton spin and quark momentum, “Sivers function”



From EIC white paper

Projection for Lepton-jet Sivers asymmetry

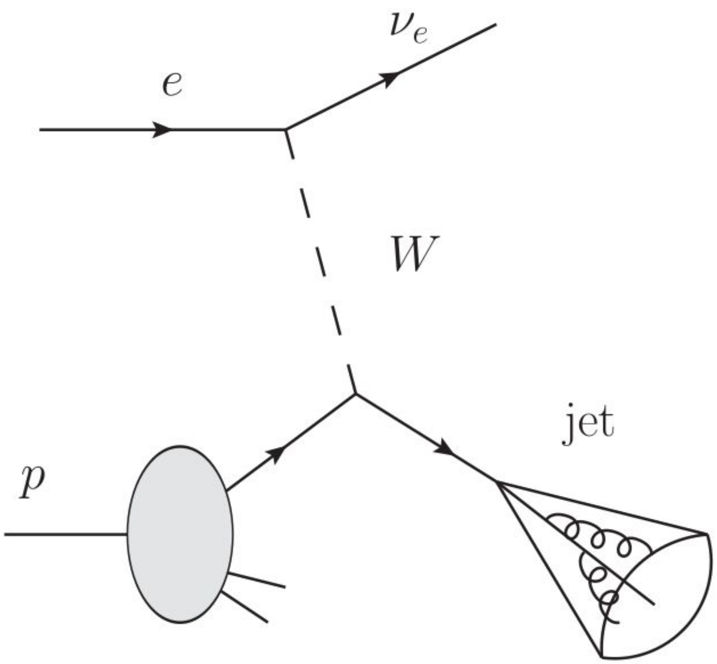


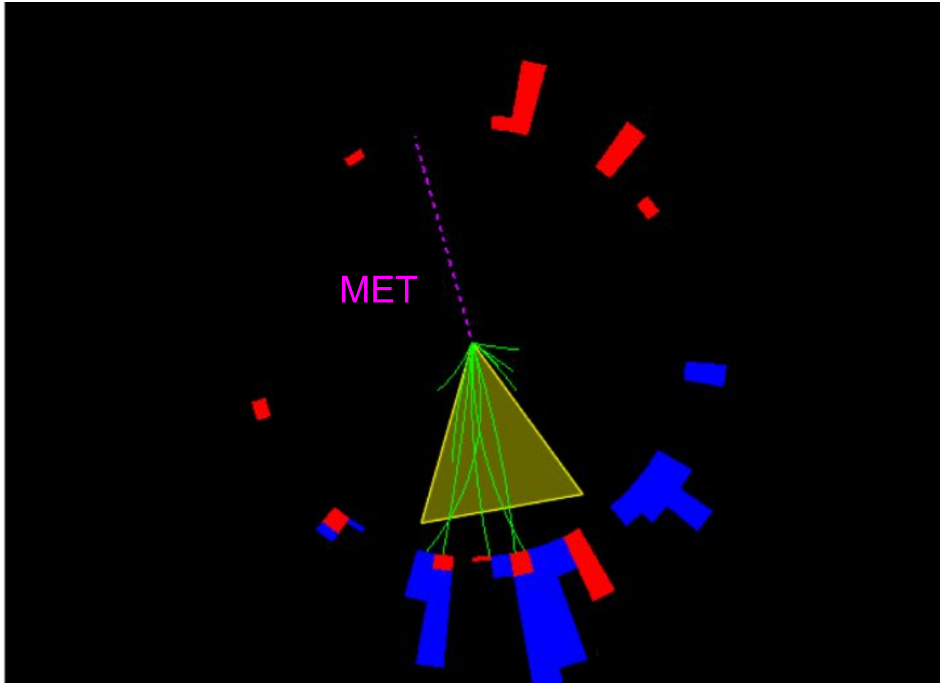


$$q_T = |\vec{p}_T^{\,e} + \vec{p}_T^{\,\mathrm{jet}}|$$

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

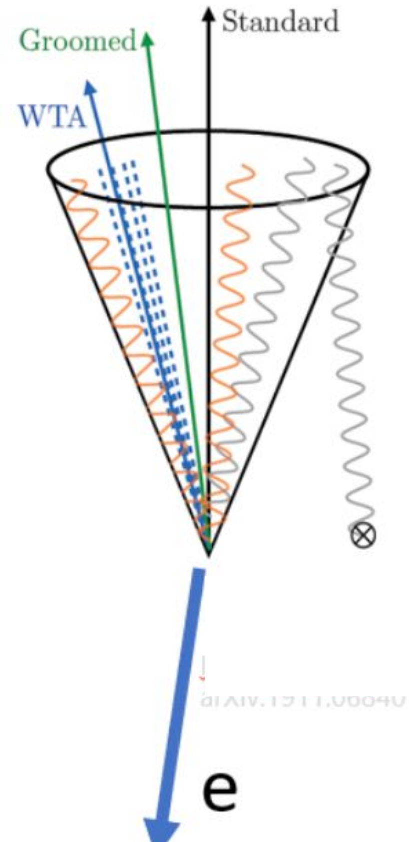
Jets in charged-current DIS offer complementarity in flavour sensitivity and chiral structure

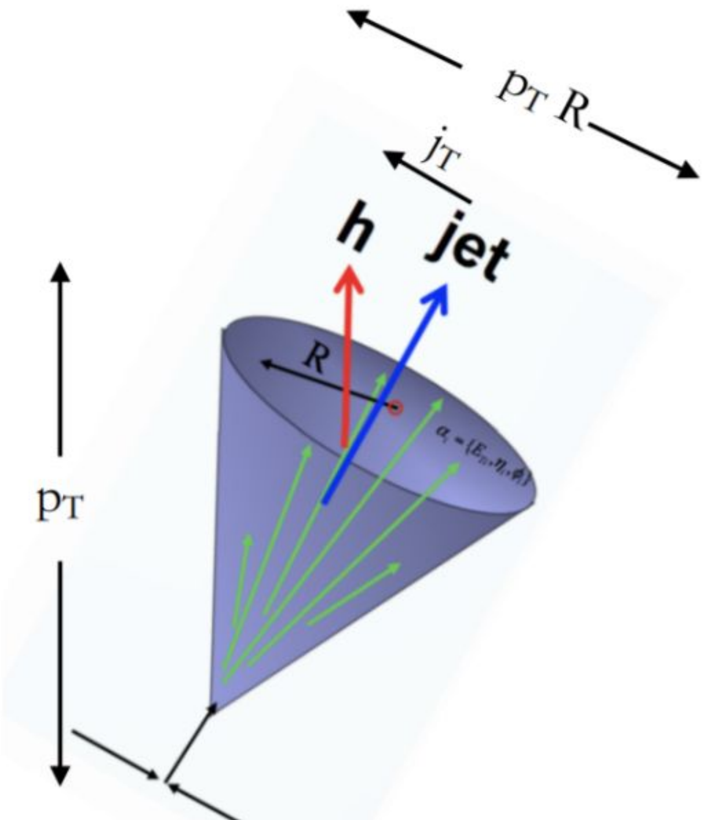


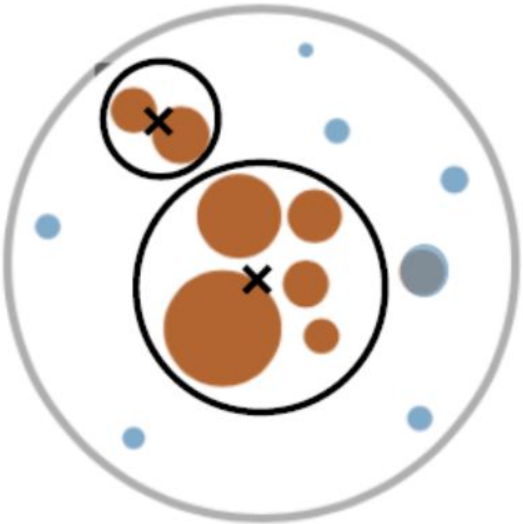


"Neutrino-tagged jets at the EIC", M. Arratia et al. PRD 107 (2023) 9, 094036
"Charm jets as a probe for strangeness at the future EIC", M. Arratia et al. PRD 103 (2021) 7, 074023

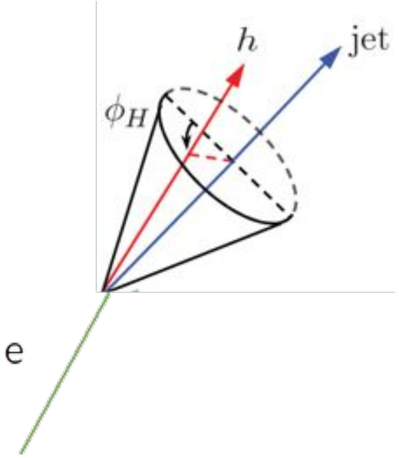
Jets have rich substructure, which encodes rich TMD info such fragmentation, TMD evolution, and access to TMDs



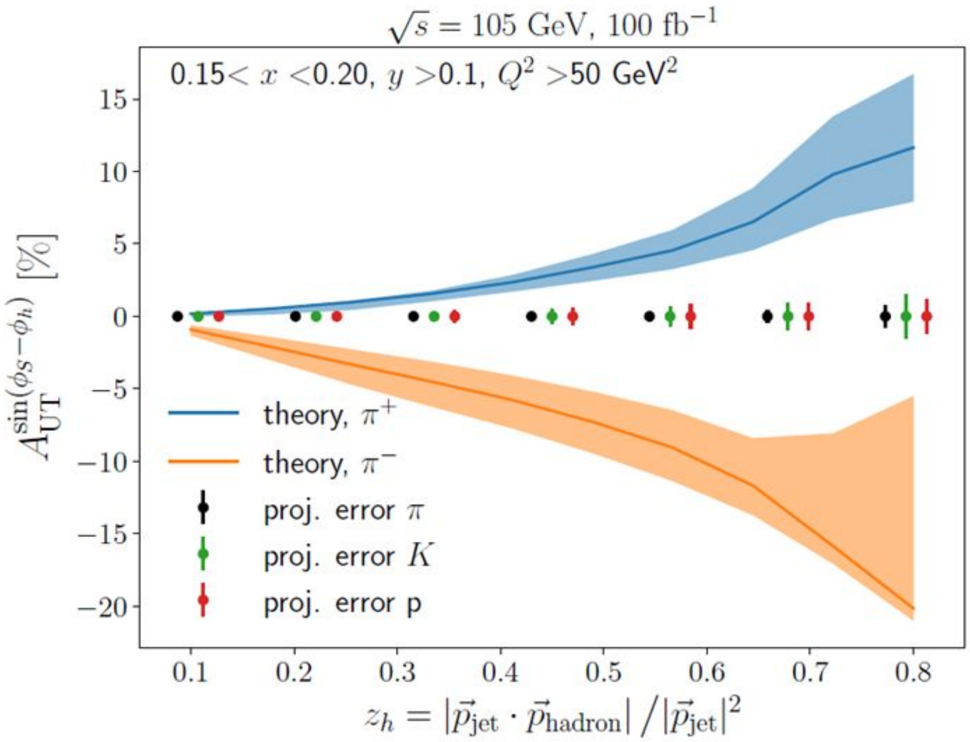




“Hadron-in-jet asymmetries” will yield a wealth of information

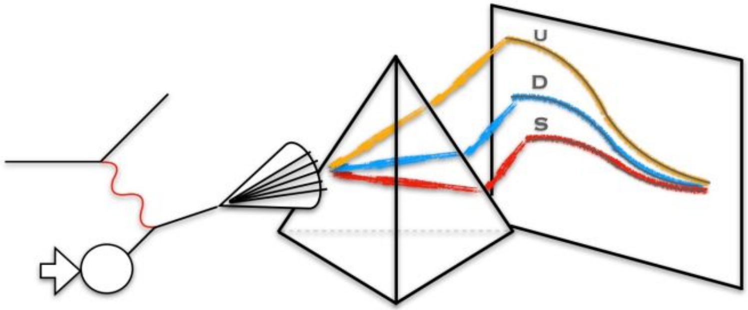


Simultaneous measurement of electron, hadron and jet provides powerful tool to unravel TMD effects

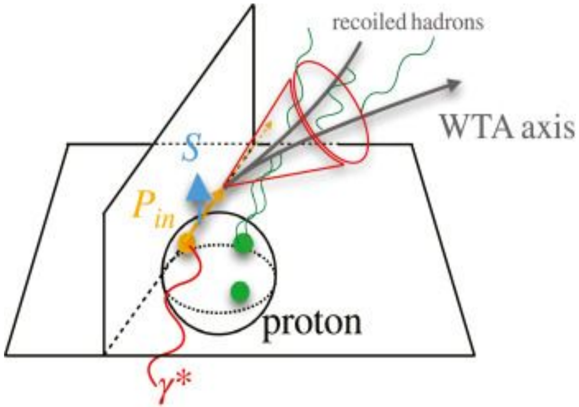


Arratia et al. PRD 102 (2020) 7, 074015

Some examples of jet substructure for TMDs

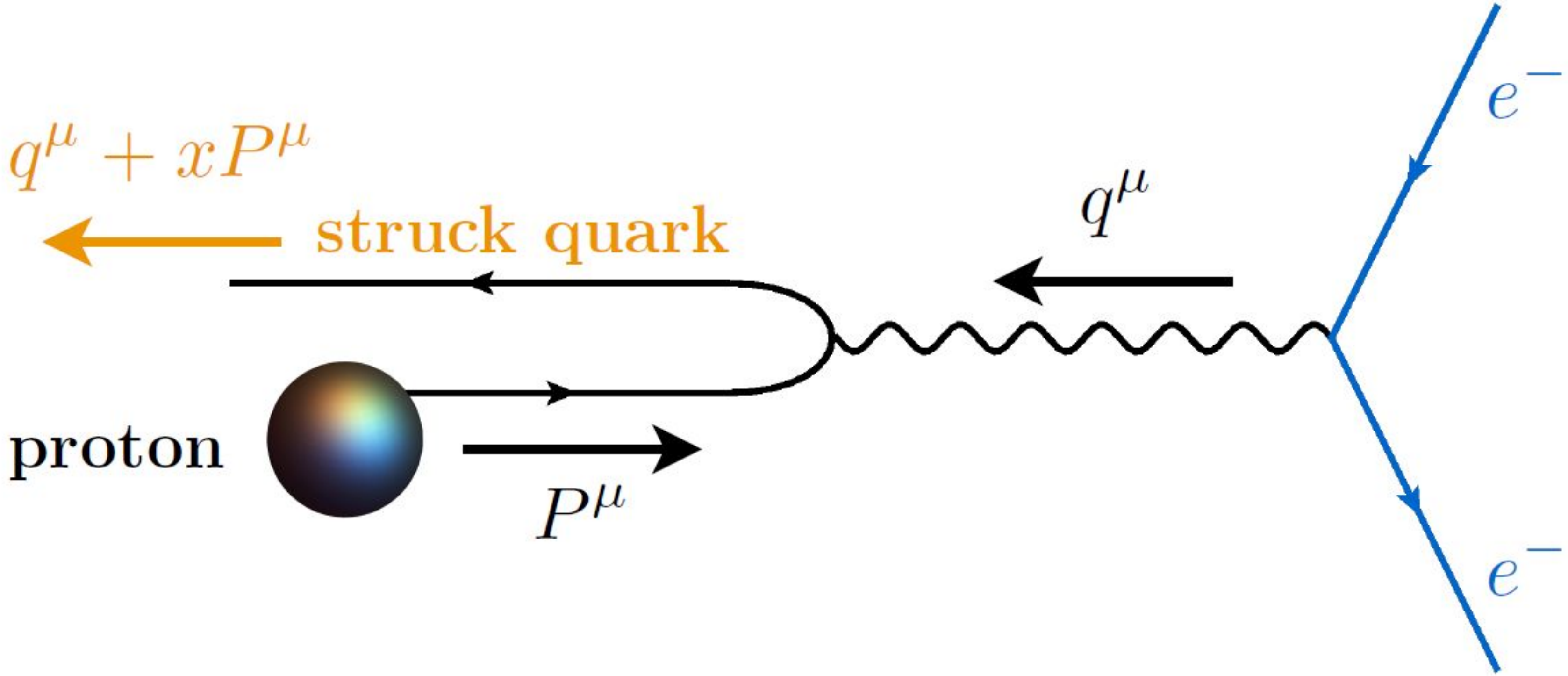


"Jet Charge: A Flavor Prism for Spin Asymmetries at the EIC",
Z. Kang PRL 125, 242003 (2020)



Unveiling Nucleon 3D Chiral-Odd Structure with
Jet Axes, Lai et al. arXiv:2205.04570

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

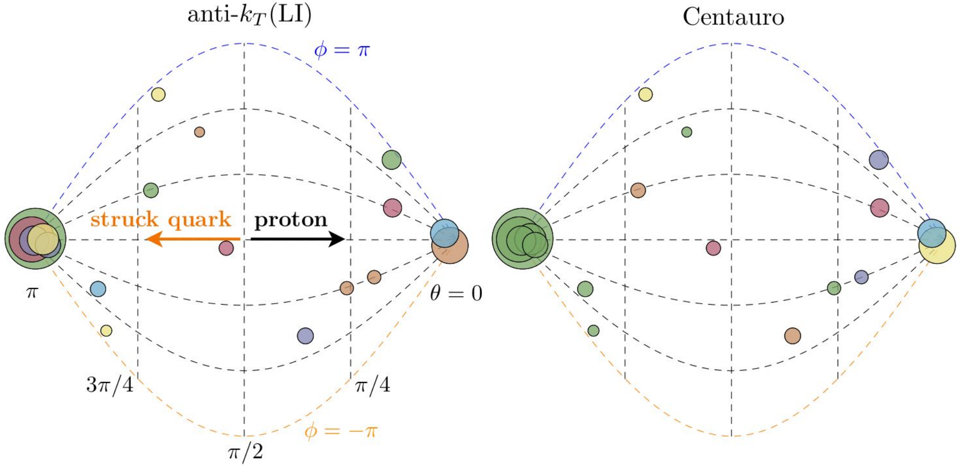


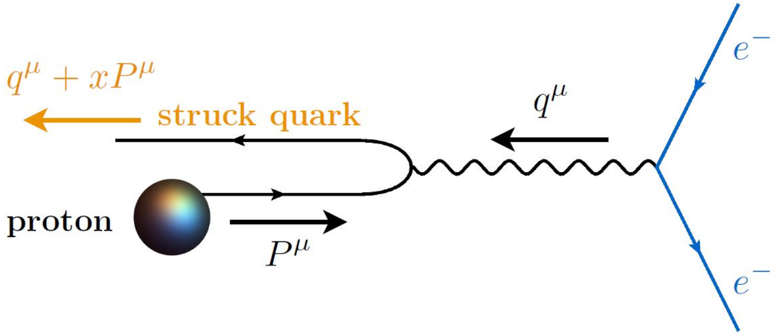
Centauro Jet Algorithm

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

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

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

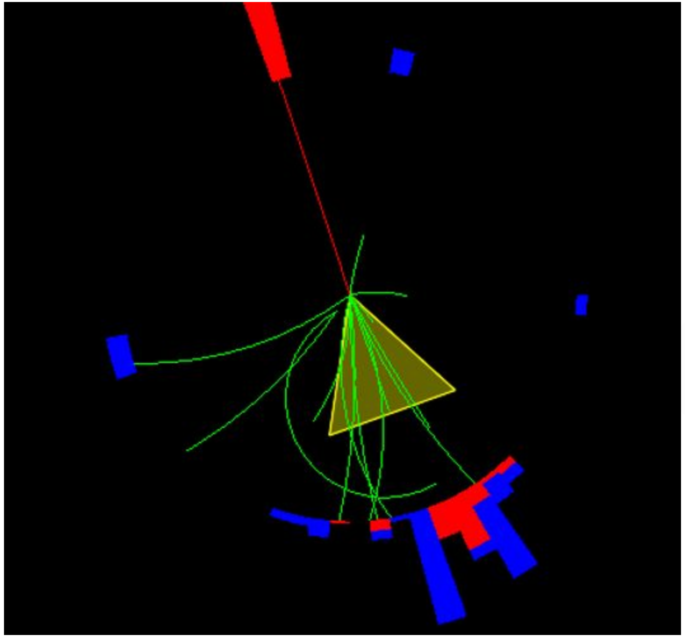




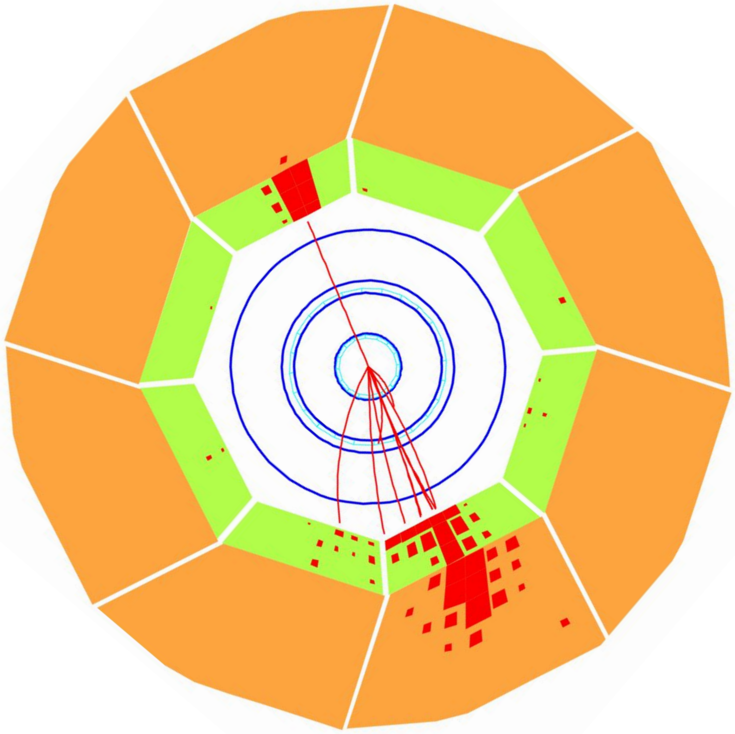
M. Arratia et al. PRD 104, 034005 (2021)

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

EIC

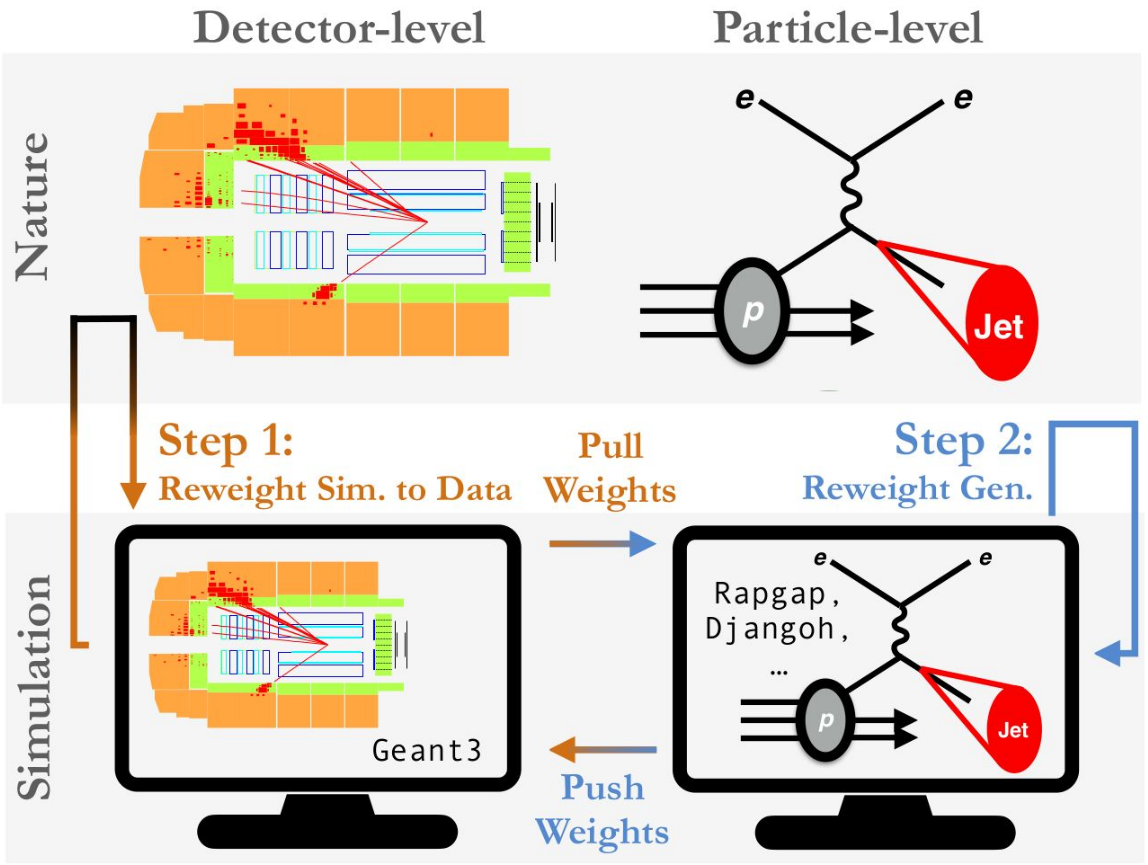


H1@HERA



Unfolding with Omnifold (via machine-learning).

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

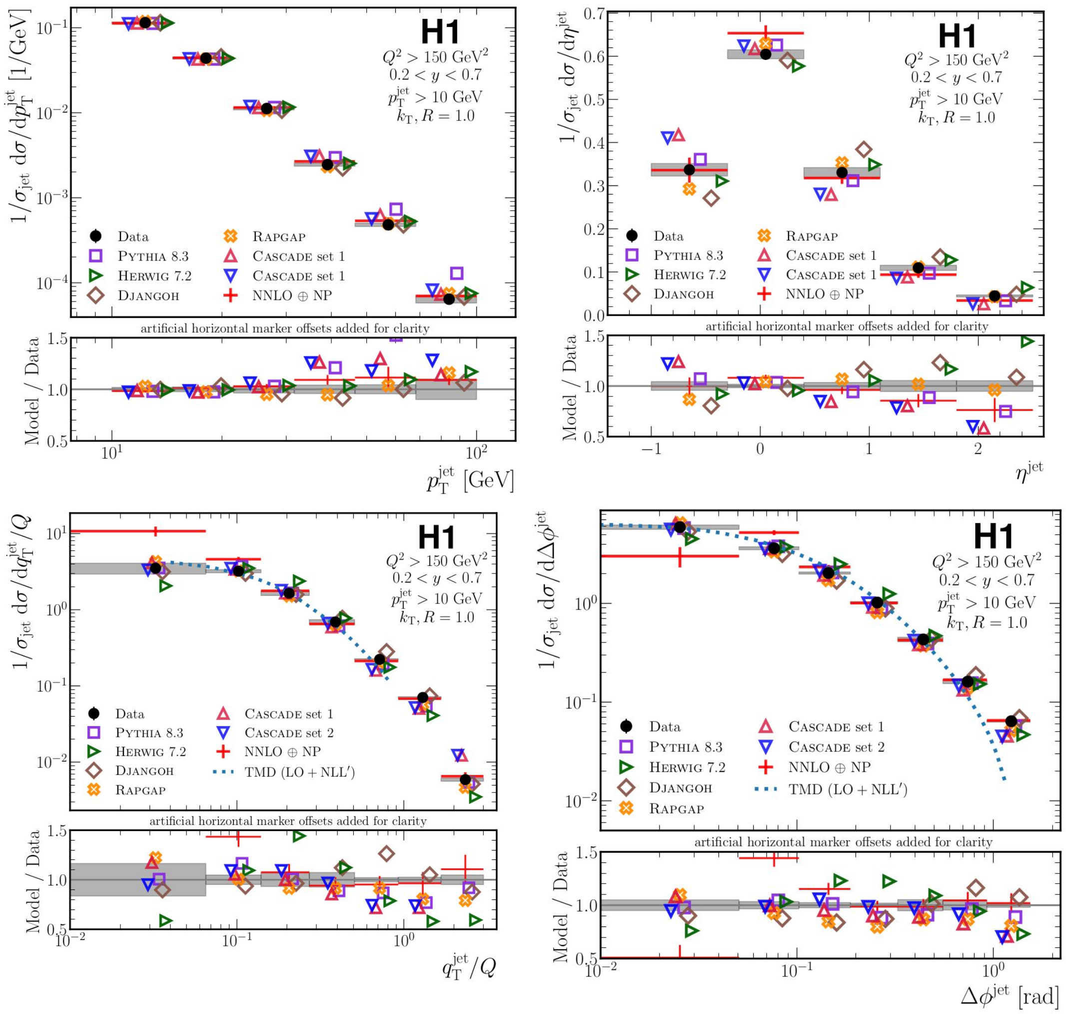


Unbinned
high-dimensional

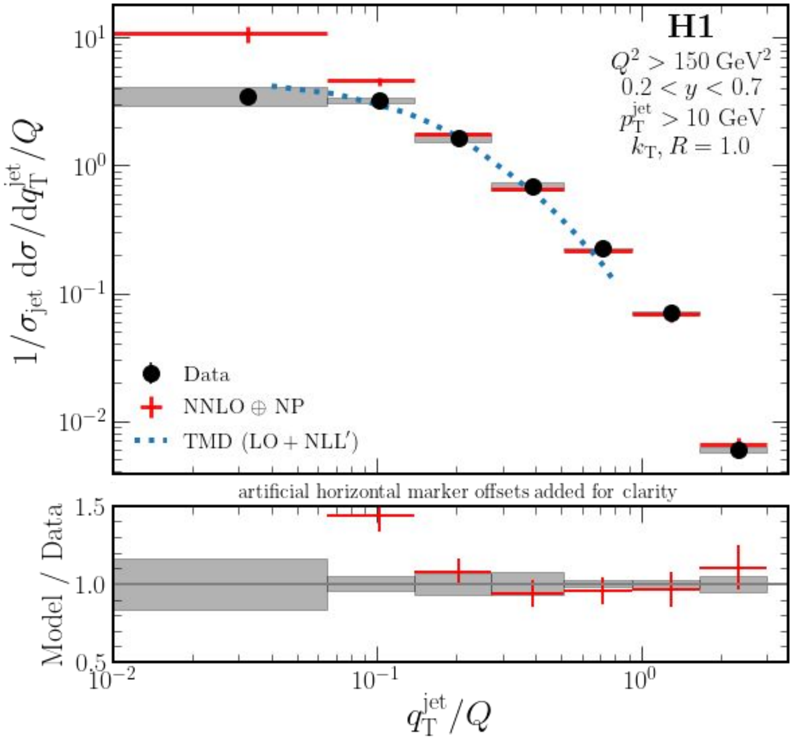
Omnifold allowed us to do a simultaneous, unbinned unfolding
in 8D (probably a record)

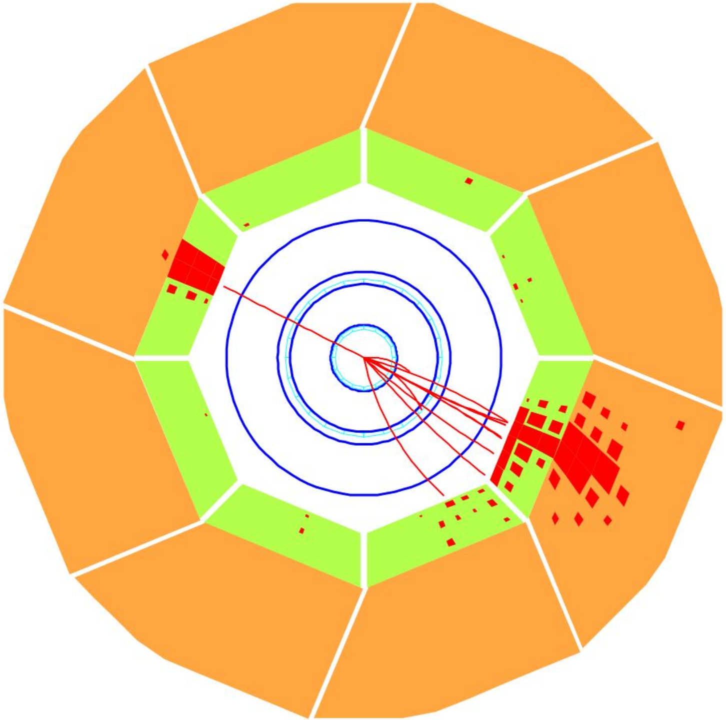
"This measurement also represents a milestone in the use of ML techniques…"

H1 Collaboration, PRL 128 (2022) 13, 132002



Lepton-jet correlation





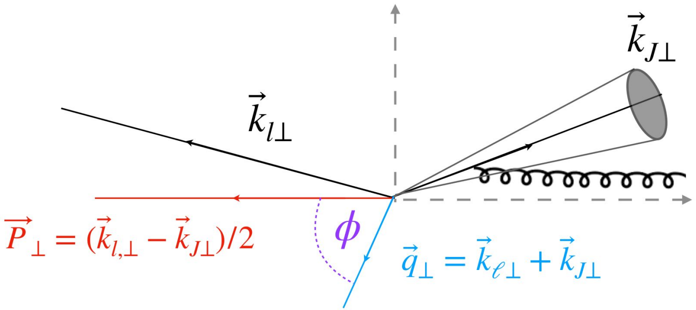
H1 Collaboration, PRL 128 (2022) 13, 132002

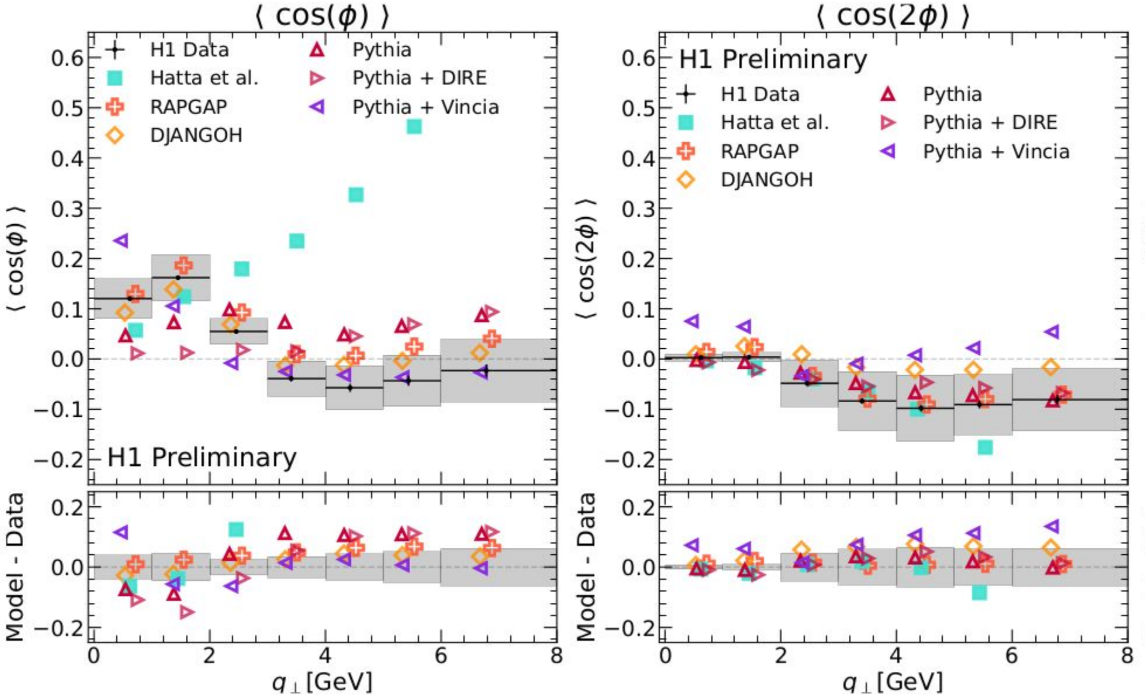
Textbook example of “matching” between collinear and TMD frameworks

First time seen in DIS!

Follow up analysis: lepton-jet azimuthal modulations

Same data, same unfolding as first lepton-jet paper



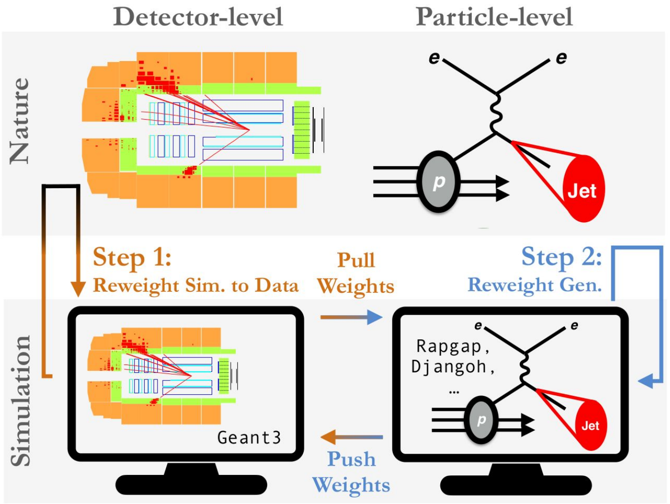


Novel observable
Promising for TMD studies
But sensitive to gluon radiation as well

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

Credit to Fernando Torales-Acosta (LBNL)

H1 Collaboration PRL 128, 132002
was the first baby step towards unbinned cross-sections…



First-ever real measurement using **unbinned** unfolding, **unbinned** acceptance & efficiency corr.

But we reported **Binned** cross-sections…

Next step is **unbinned** all the way, see community paper: JINST 17 (2022) 01, P01024

Idealized EIC central detector

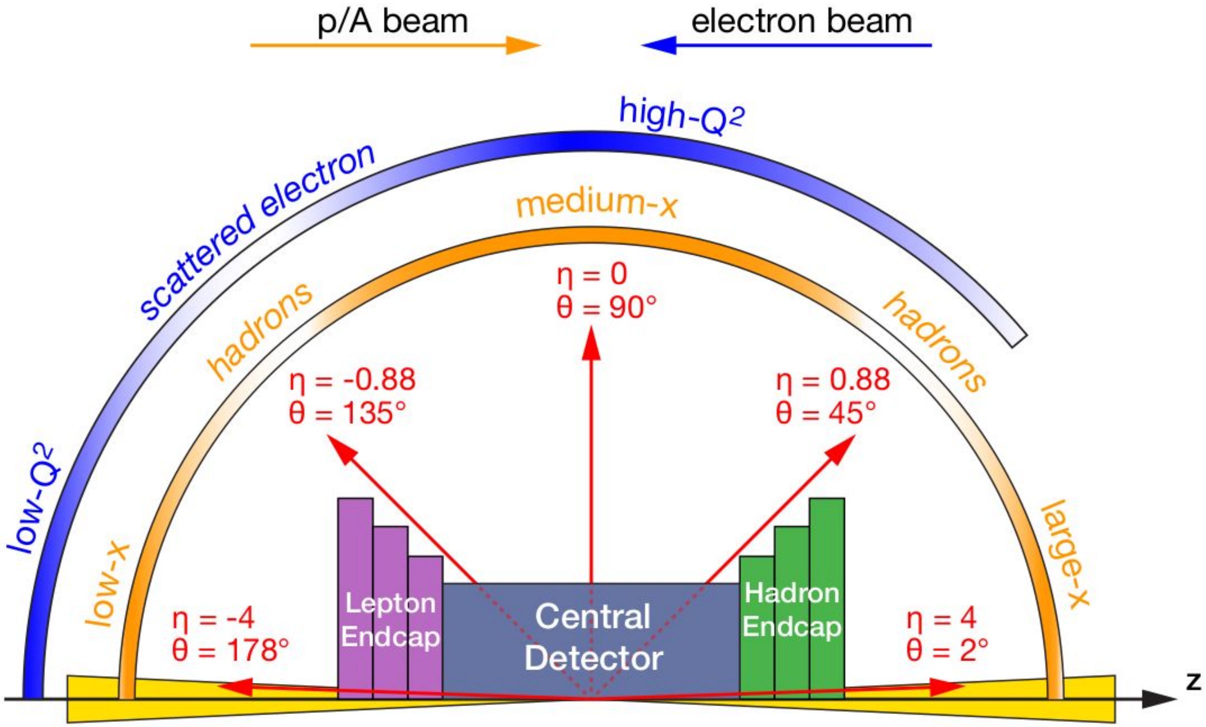
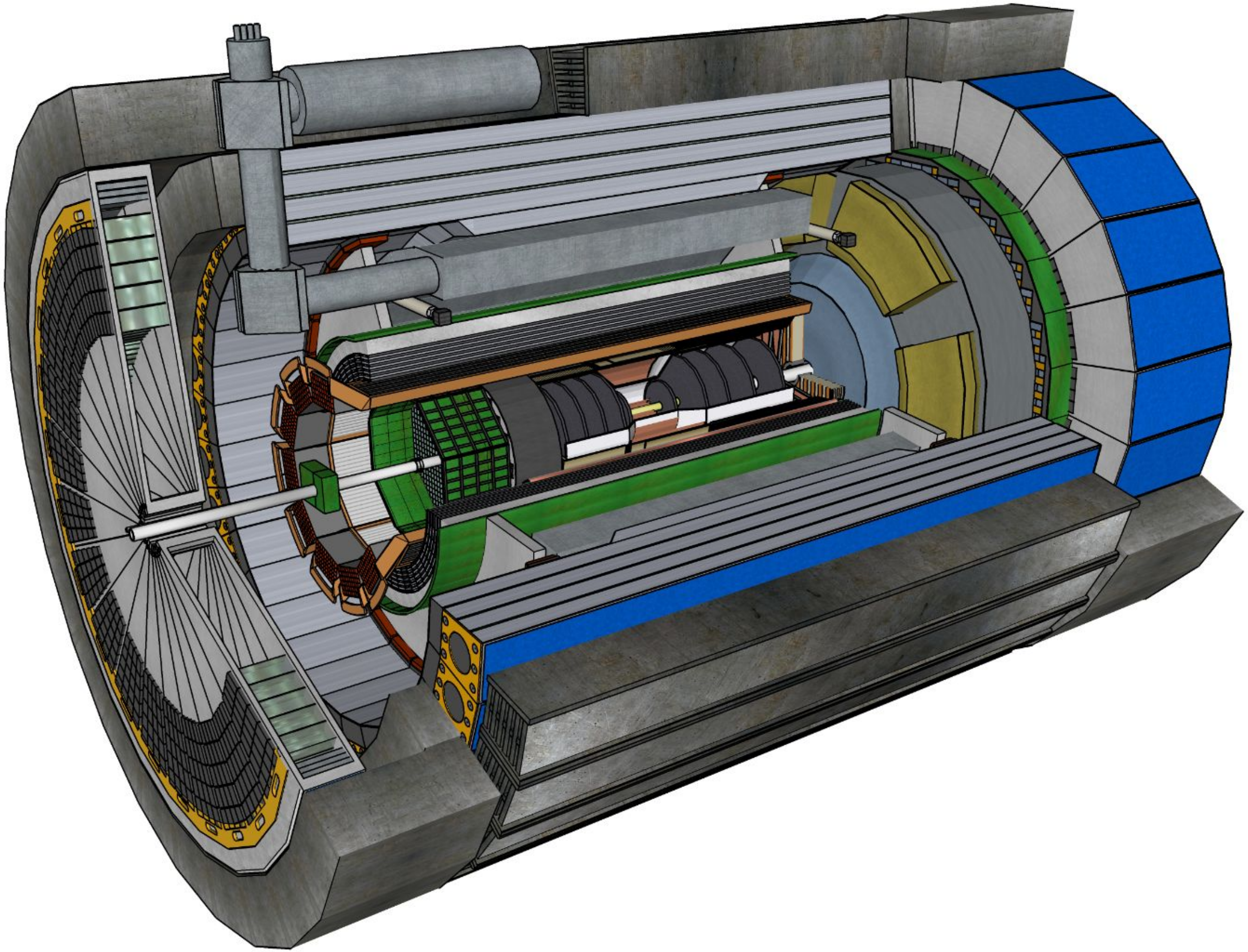


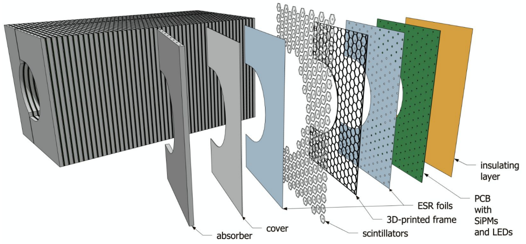
Figure source: EIC YR

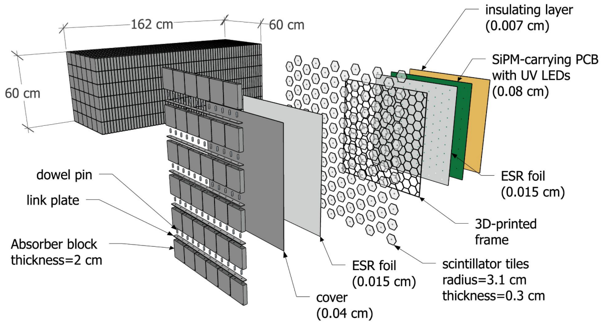
A key requirement is to have **"as large coverage as technically possible"**, up to $|\eta|=4.0$

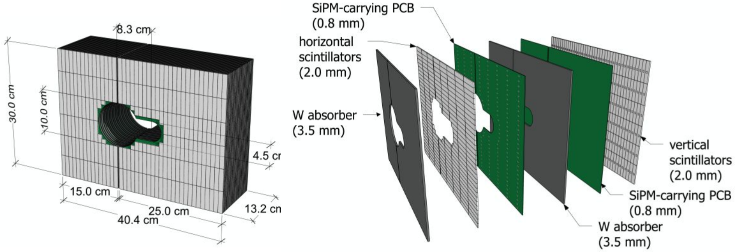
“ePIC” central detector



I will describe 3 sub-detectors that my group has conceived





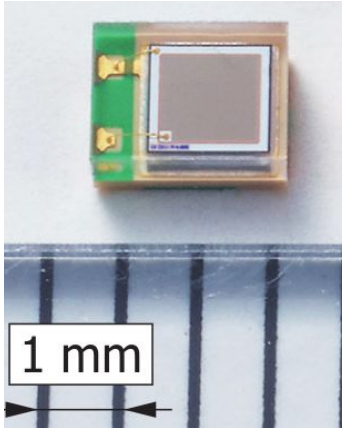


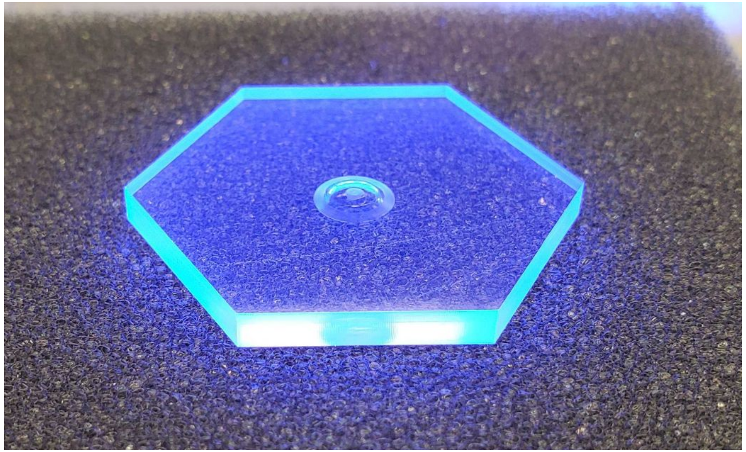
- Forward HCAL "insert", $3<\eta<4$
  NIMA 1047 (2023) 167866 (design)
  JINST 18 (2023) 05, P05045 (benchtop R&D)
  arXiv:2309.00818 (test beam)

- Zero Degree Calorimeter (ZDC) $\eta>6$
  arXiv:2308.06939 (design & algorithm)
  arXiv:2310XXXX (TBD) (design)

- Few degree Calorimeter (FDC) $-4.6<\eta<-3.6$
  arXiv:2307.12531 (design)

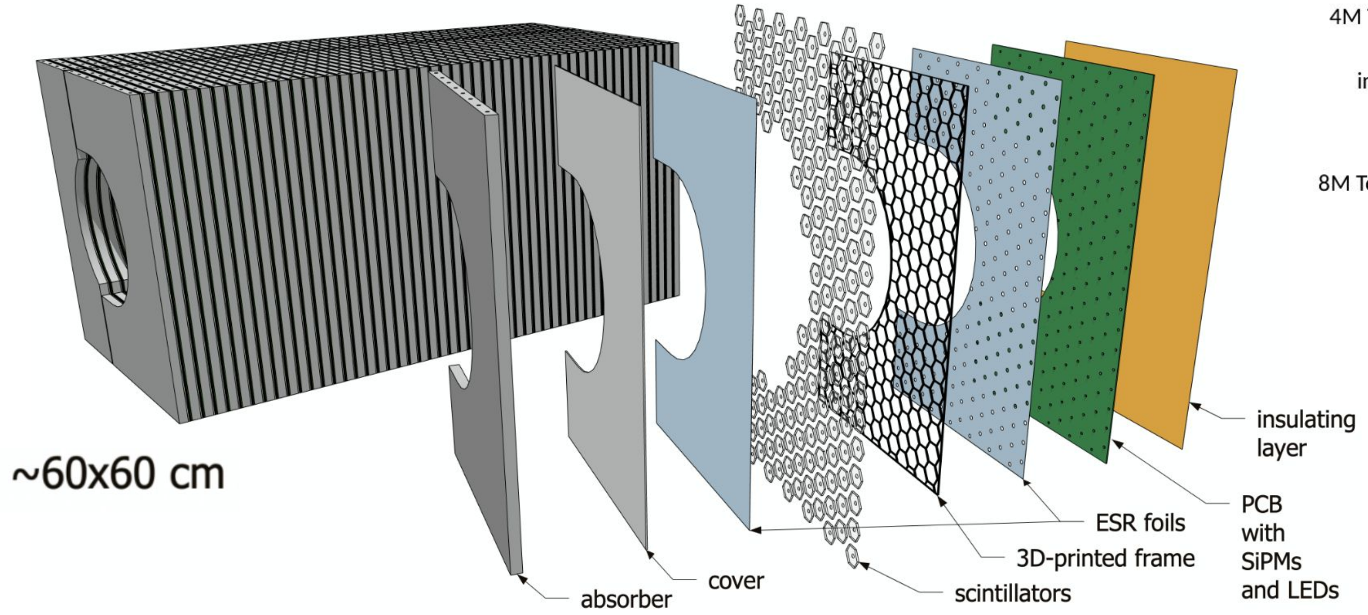
Enabling Technology: “SiPM-on-Tile”

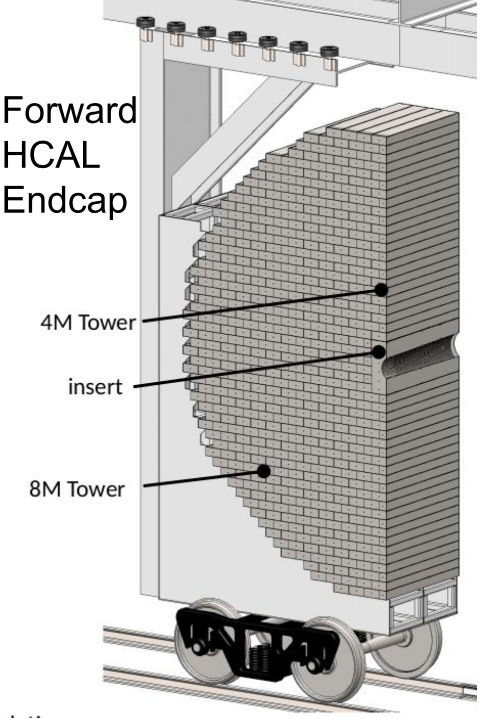




Developed for HEP (ILC, LHC), it offers flexibility, cost-effectiveness and high-performance and for EIC

The Calorimeter Insert (CALI)

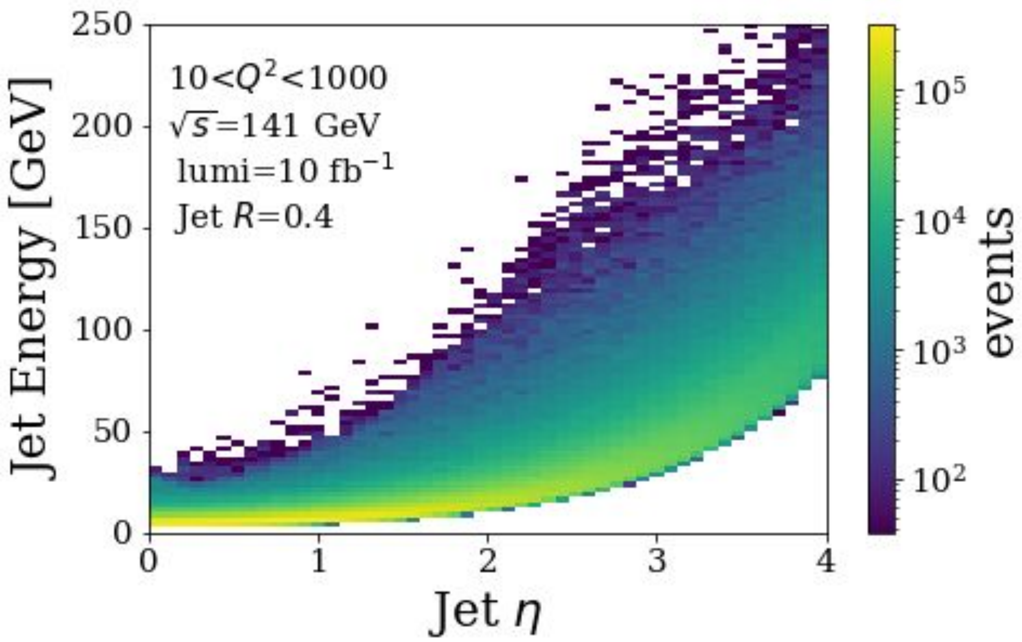


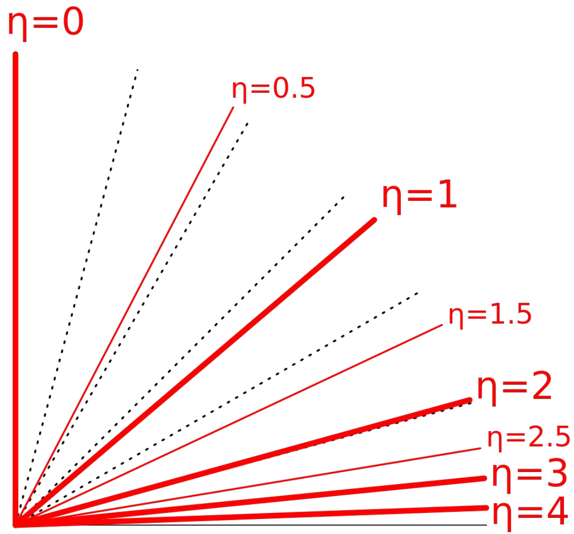


$3<\eta<4$

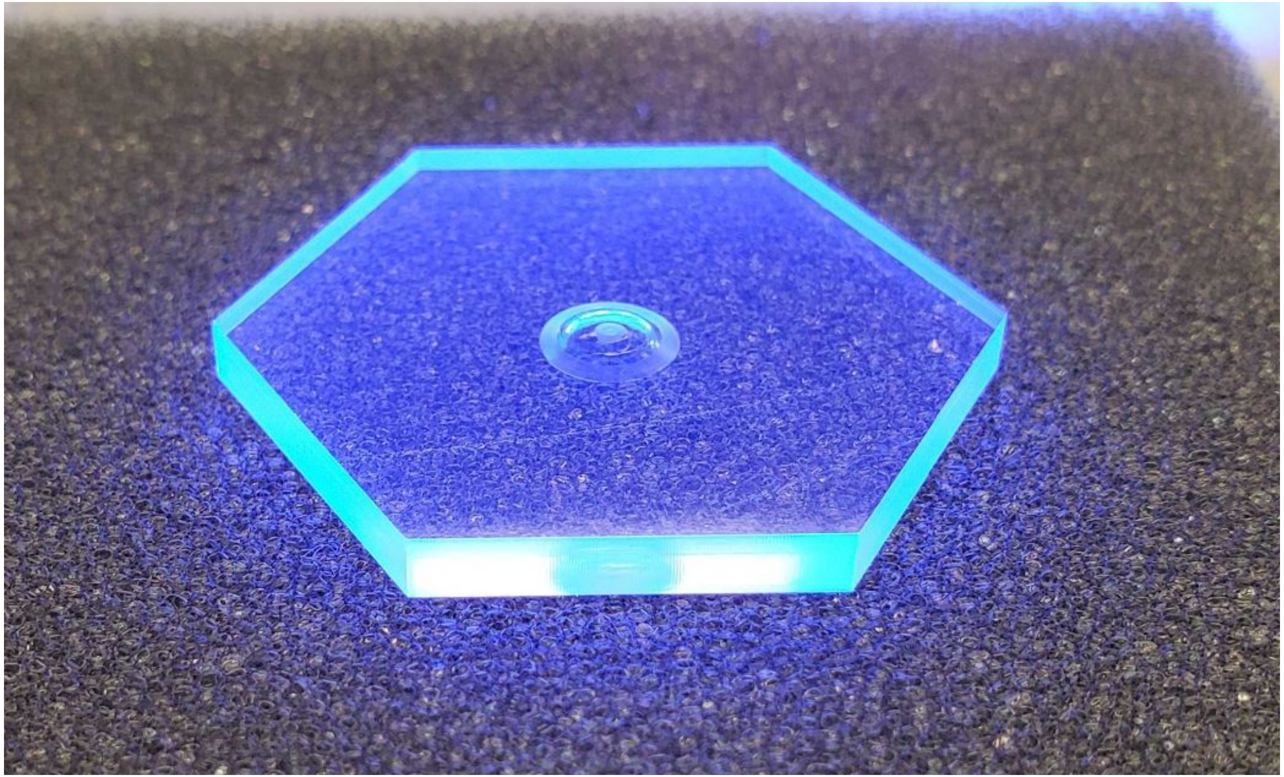
M. Arratia et al. NIMA 1047 (2023) 167866

Jet spectra in DIS at the EIC

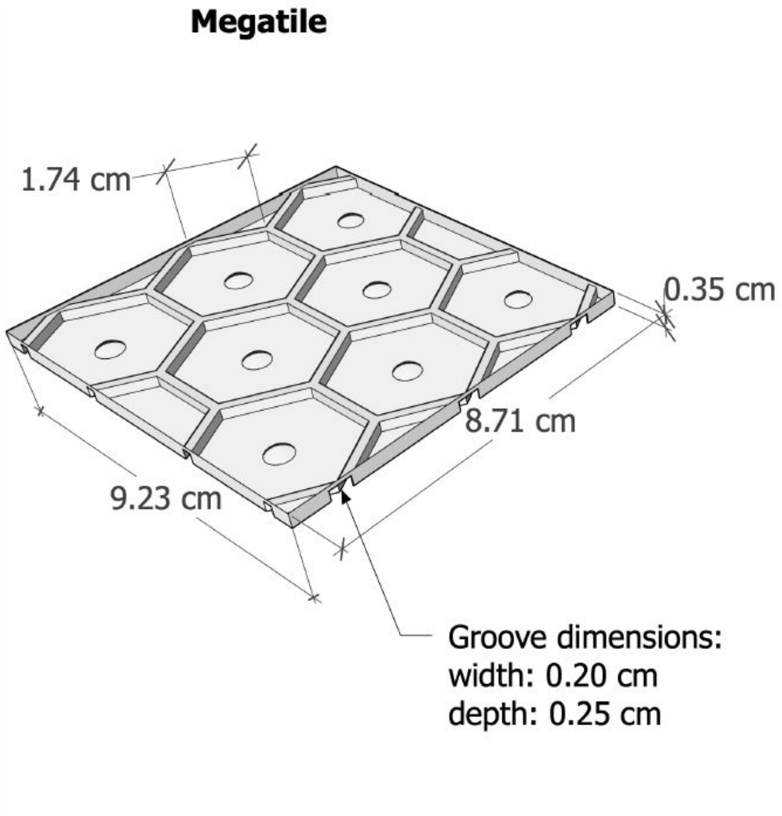


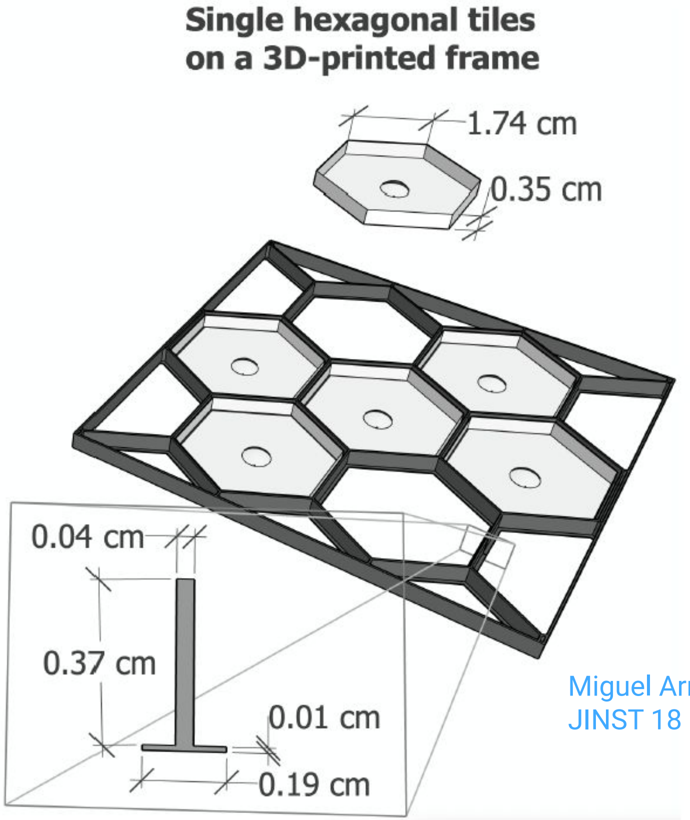


Ongoing and planned R&D



Options to concretize SiPM-on-tile Calorimeter Insert





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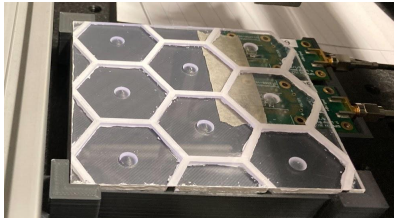
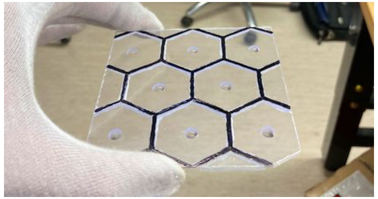
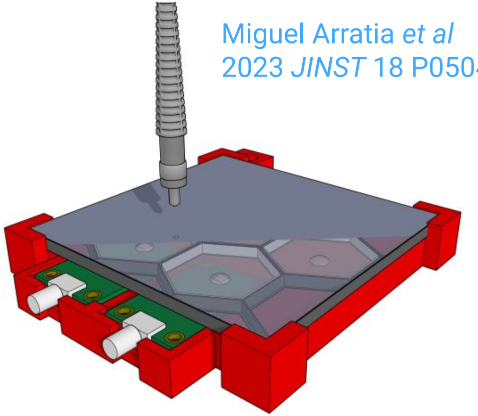
JINST 18 (2023) 05, P05045

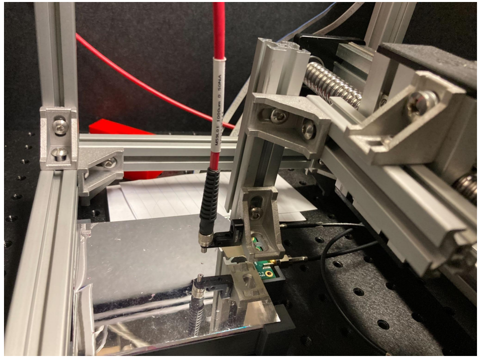
Optical Cross-talk

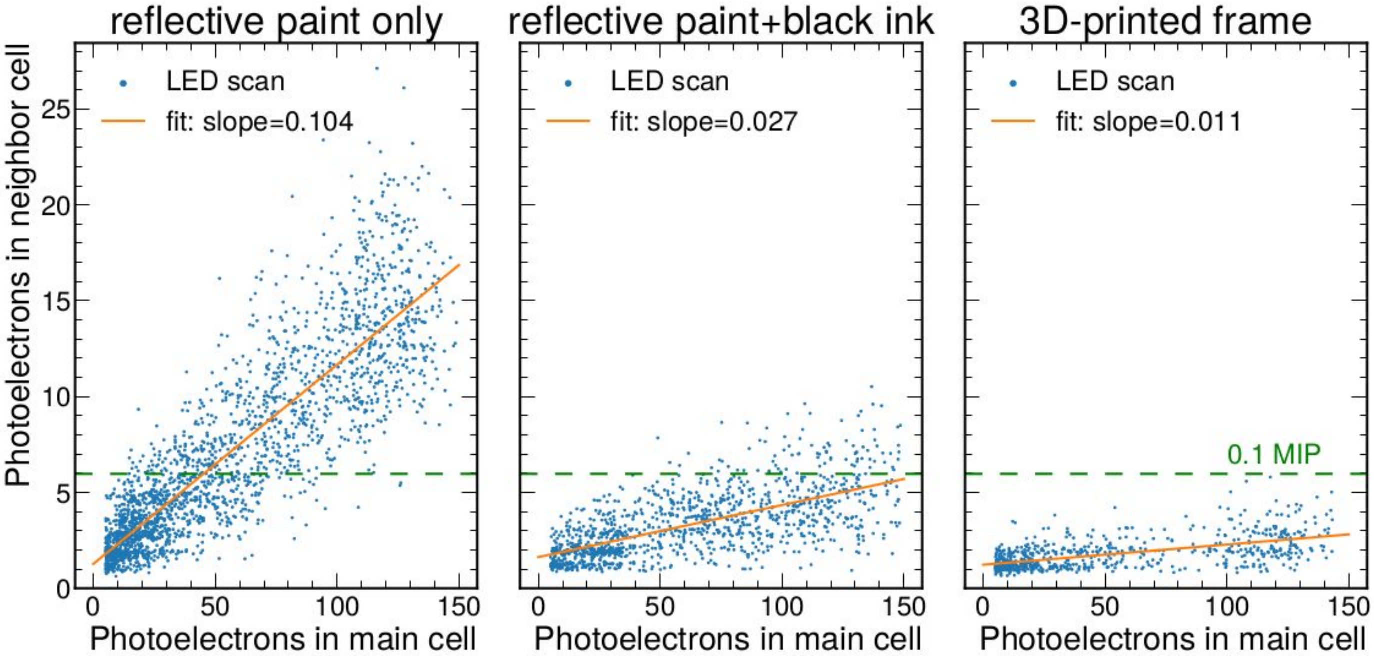
Miguel Arratia *et al*
2023 *JINST* 18 P05045

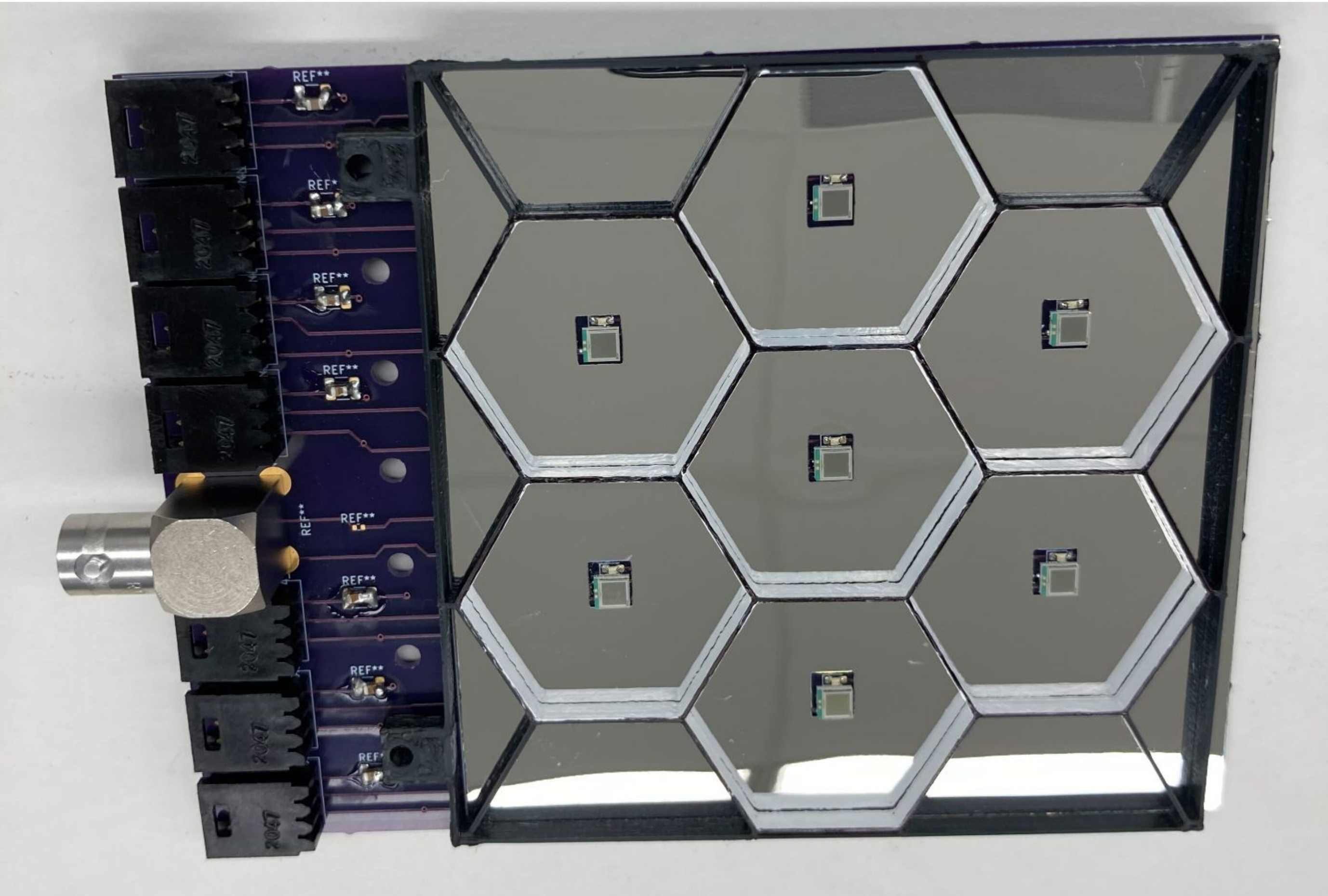






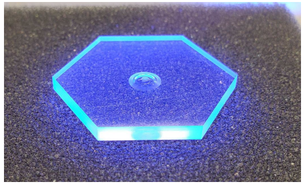






3D printed frames painted with reflective paint.

+



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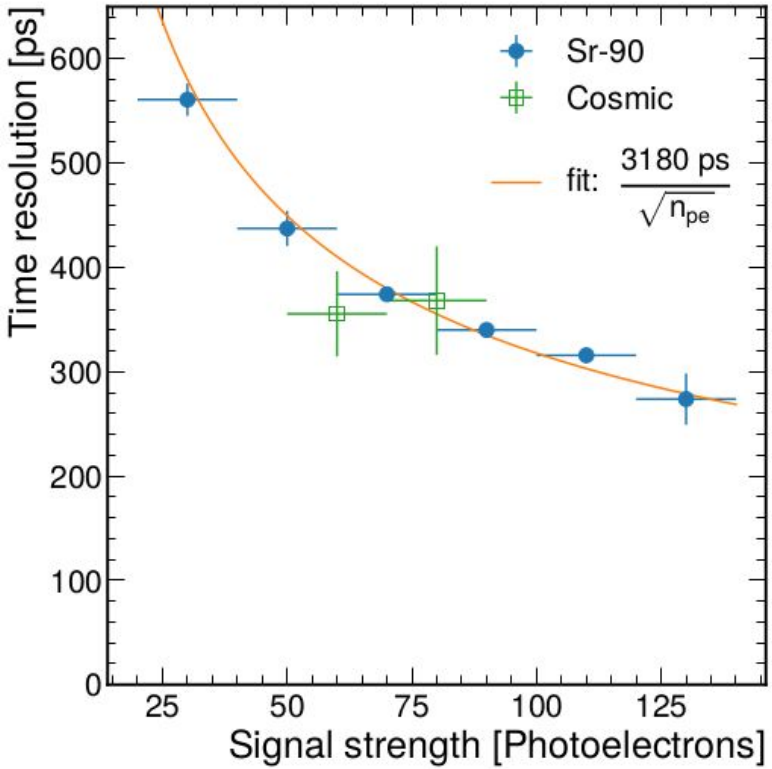
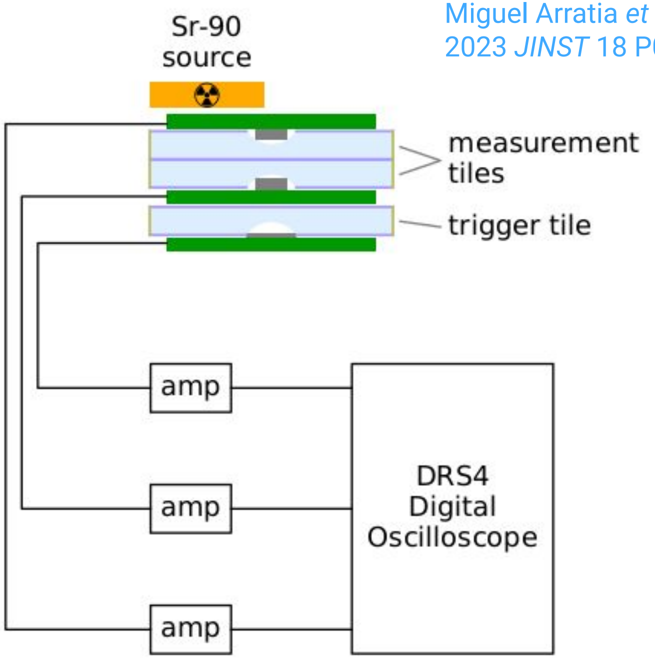
Sandwich of specular reflector foils

Time Resolution





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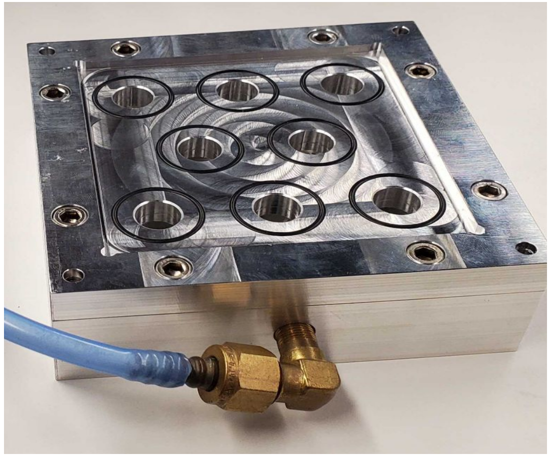
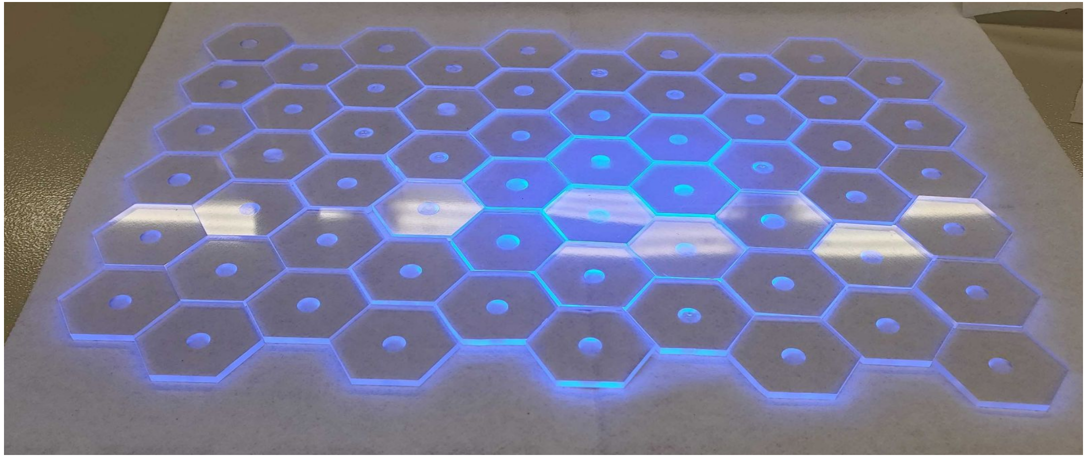
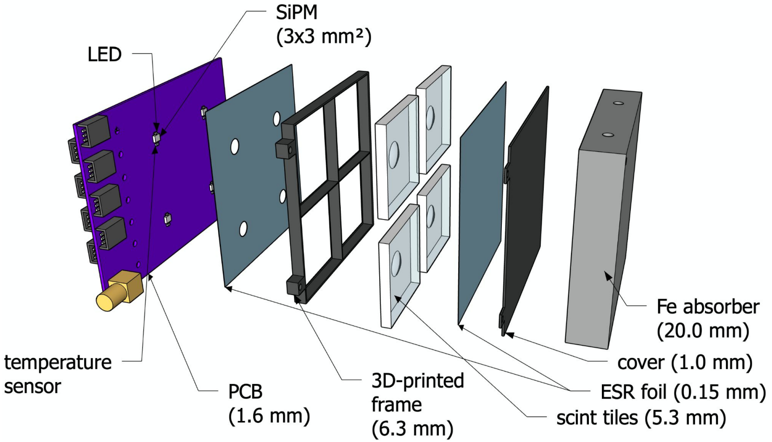
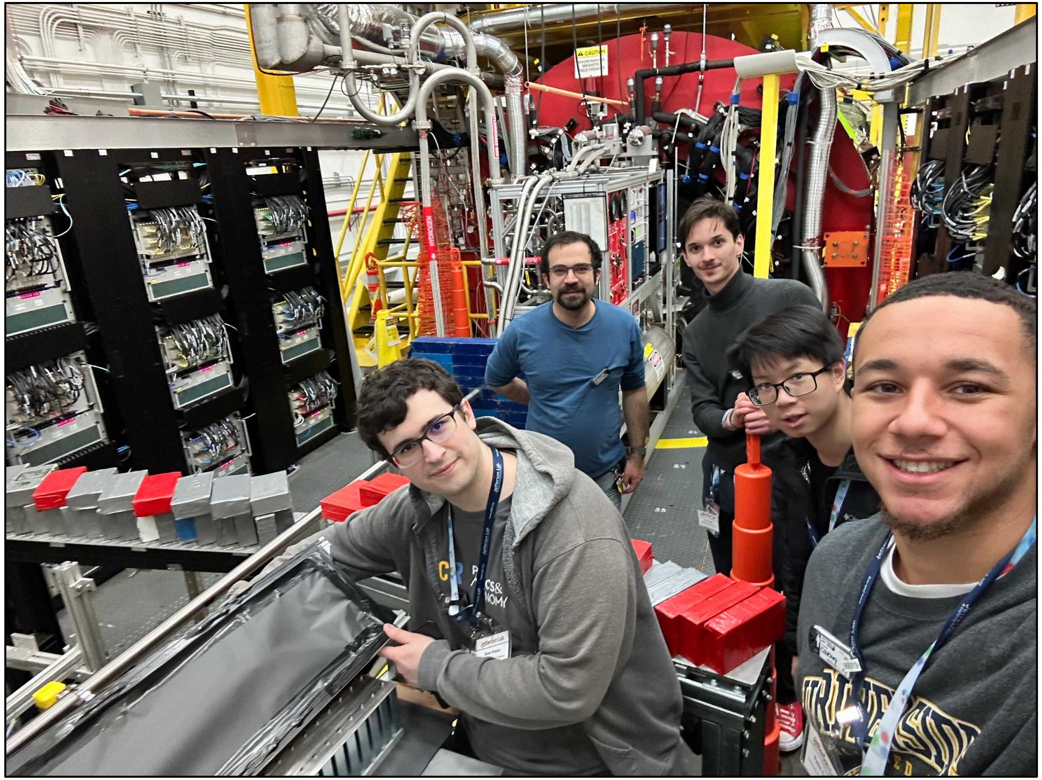
Machining Scintillator tiles



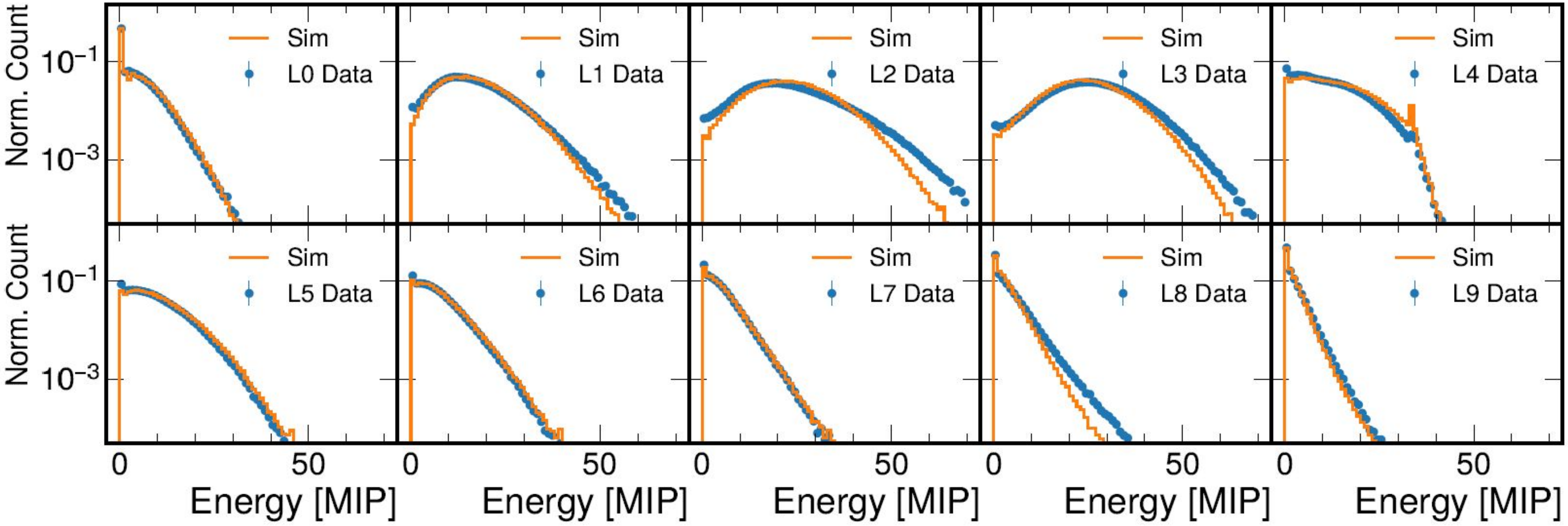


First beam test with positron beam at JLab (Jan 2023)





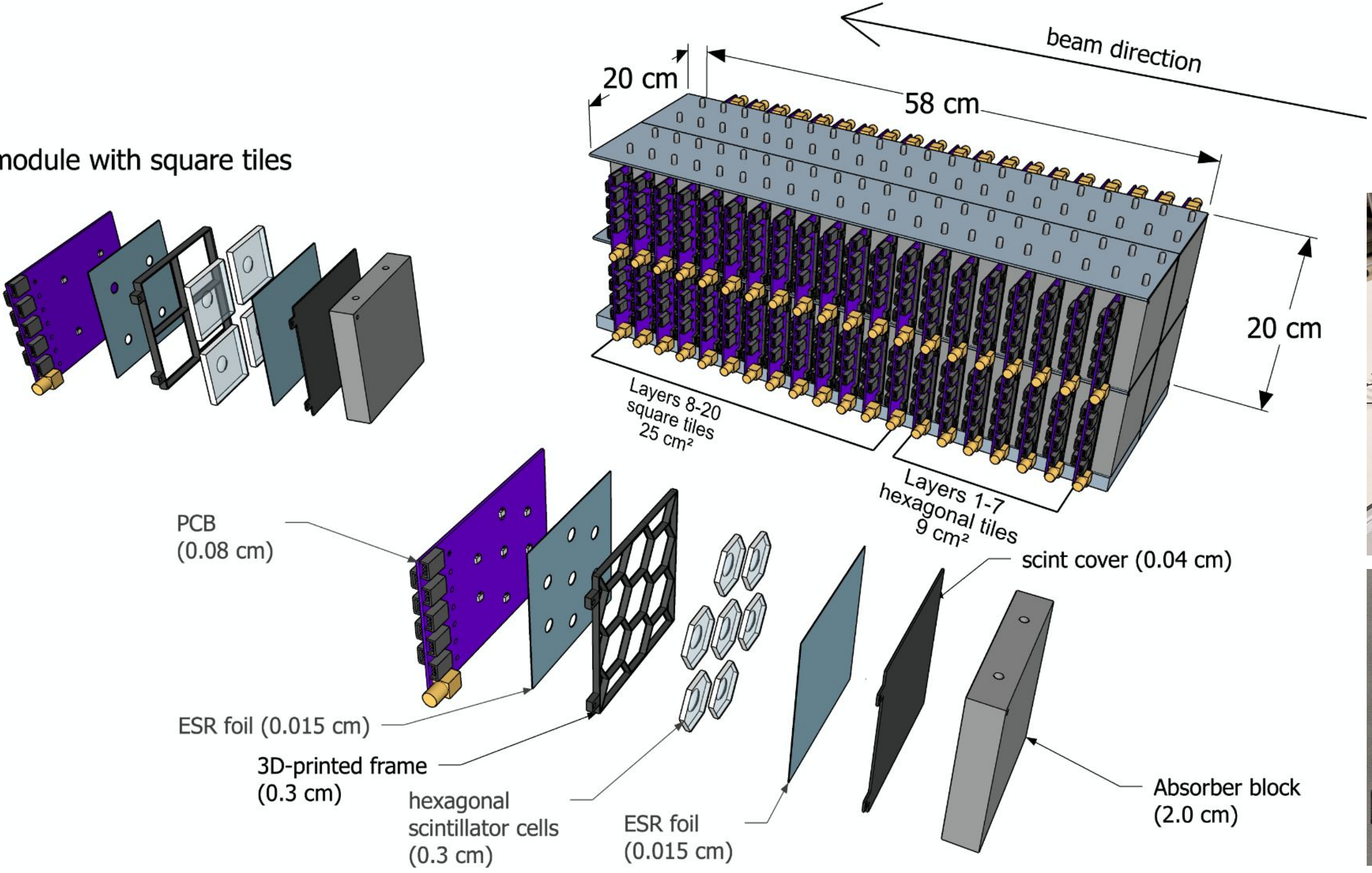
Measured energy spectra per layer (4 GeV positron)

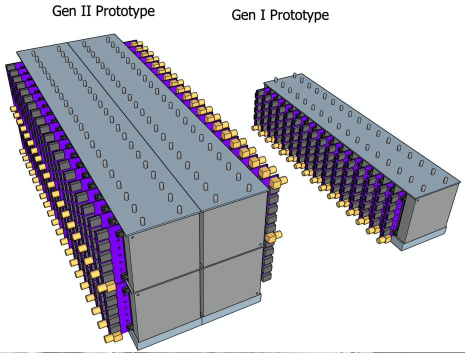


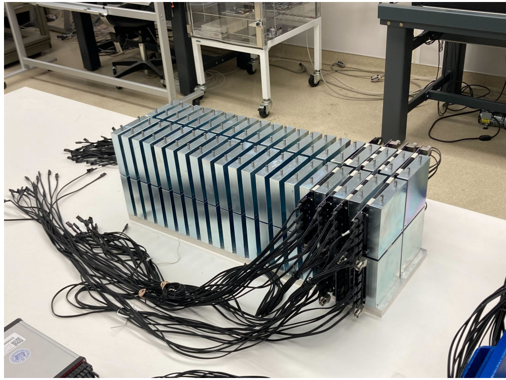
“Beam Test of the First Prototype of SiPM-on-Tile Calorimeter Insert for the EIC Using 4 GeV Positrons at JLab”
M. Arratia et al. (arXiv:2309.00818)

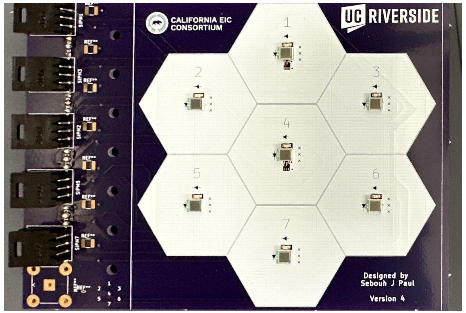
Generation II prototype (~400 channels)

finer granularity, hexagon shapes, high-quality material, UV LED



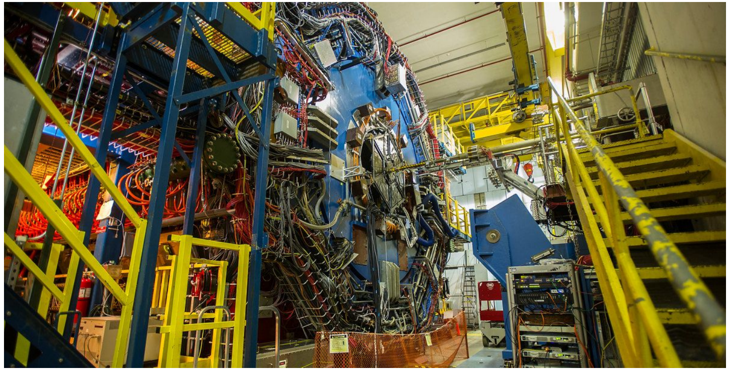




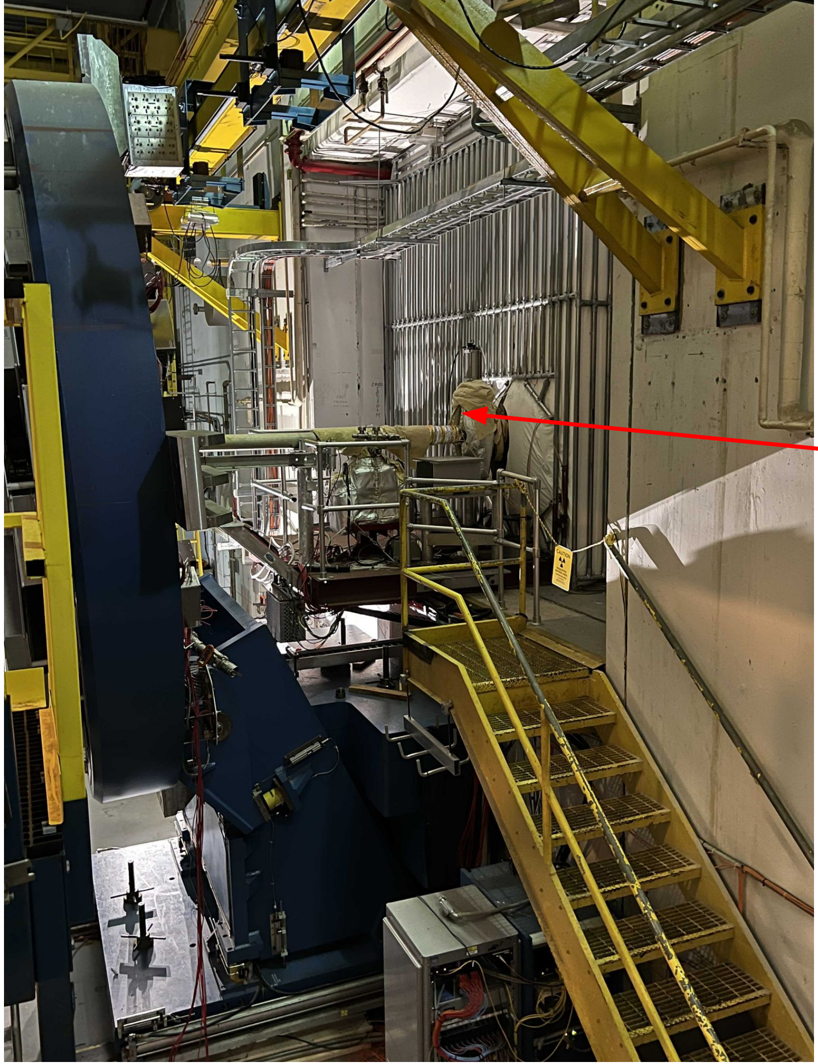


Planned test at BNL

Brookhaven
National Laboratory



STAR detector at RHIC

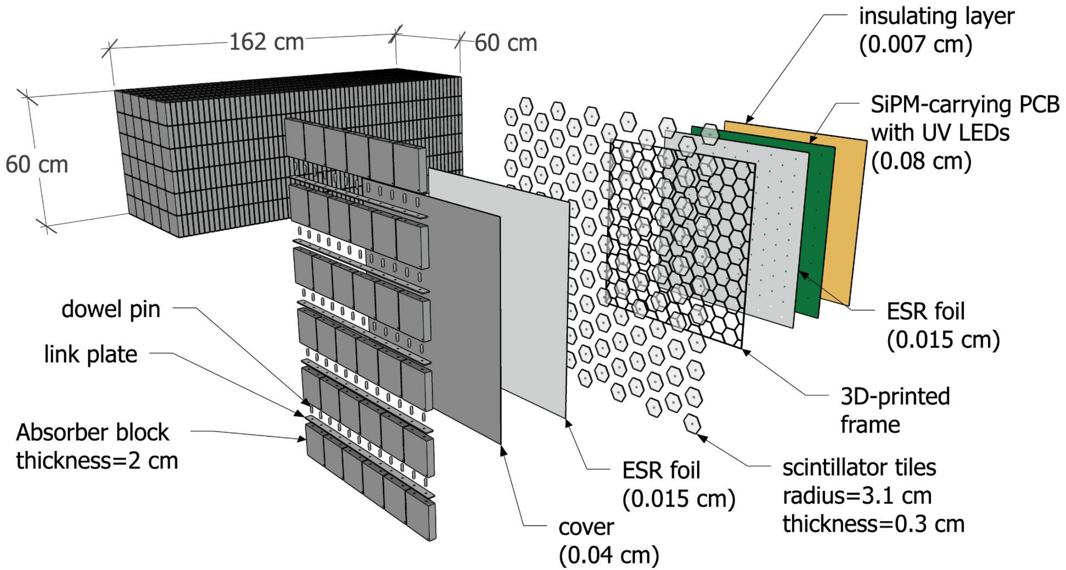


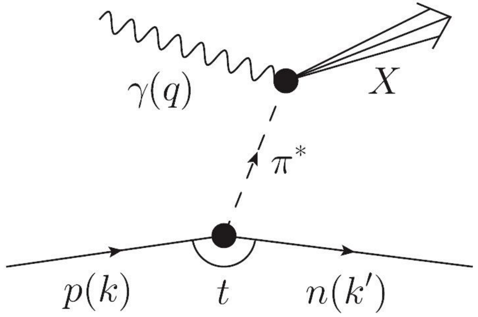
We plan to mount of detector here

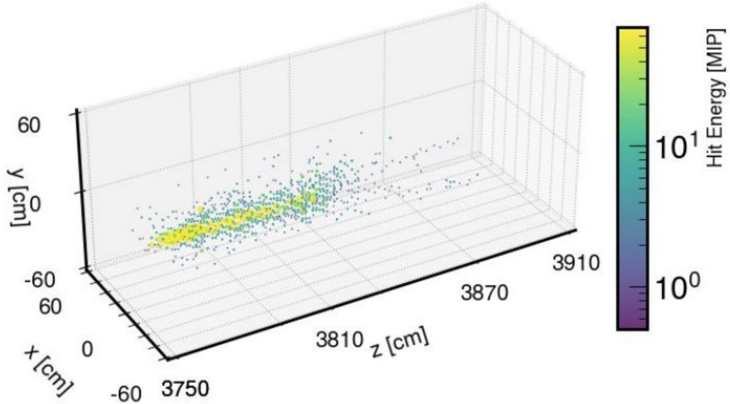
During the last RHIC run (200 GeV pp collisions) in 2024

Zero Degree Calorimeter (ZDC)

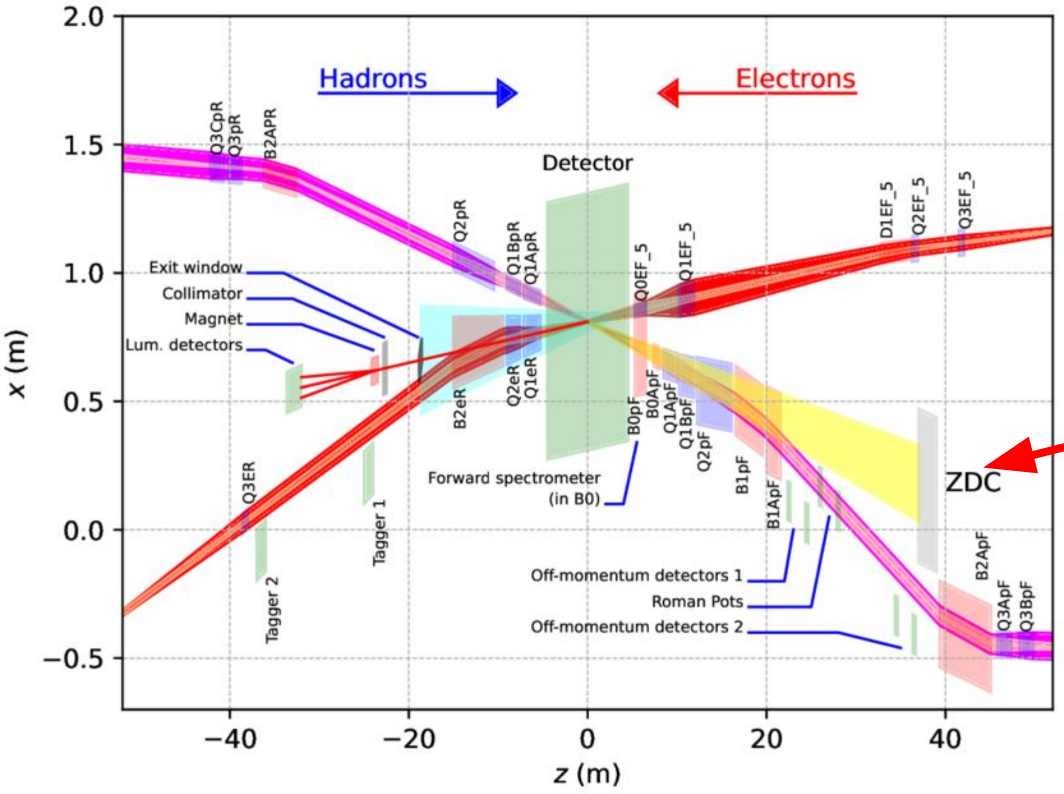
Goal: to measure angle and energy of neutrons at small angles





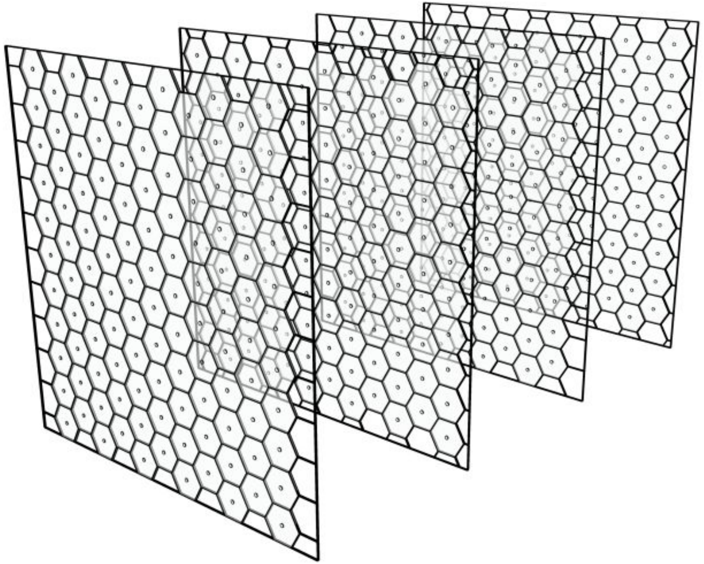


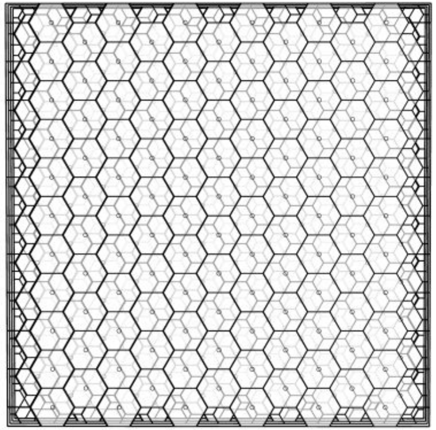
The EIC central detector is “a small” part of a highly integrated accelerator/detector complex

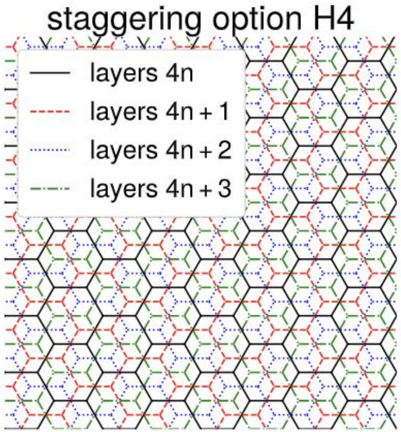


40 m away from interaction point

Position resolution improved through staggering







Staggering leads to partial overlap that can be used to define "subcells". Algorithms can estimate subcell energy according to neighbour info

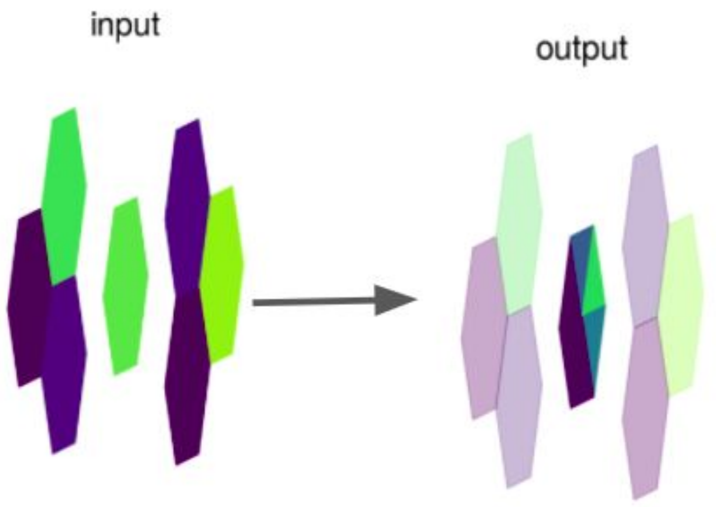
HEXPLIT Algorithm

$$W_i = \prod_{j=1}^{N-1} \max(E_j, \delta),$$

Product over overlapping cells, *j*, in neighboring layers

$$E_i = E_{\text{tile}} W_i / \sum_j W_j.$$

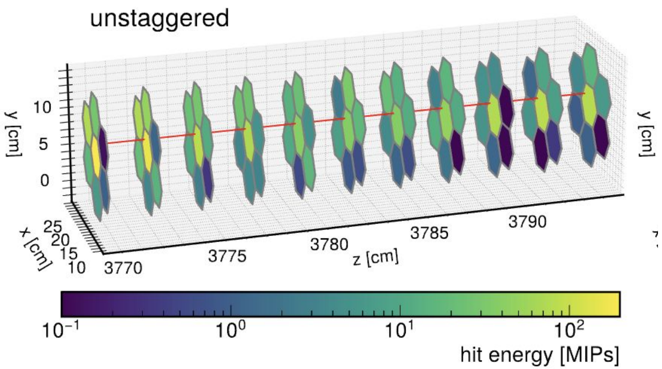
Energy in a given subcell, *i*

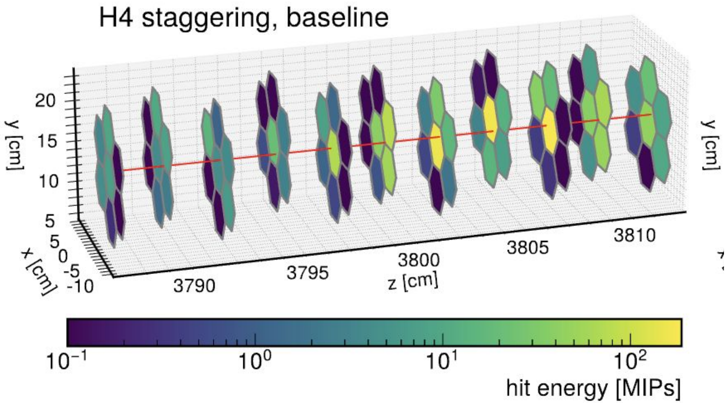


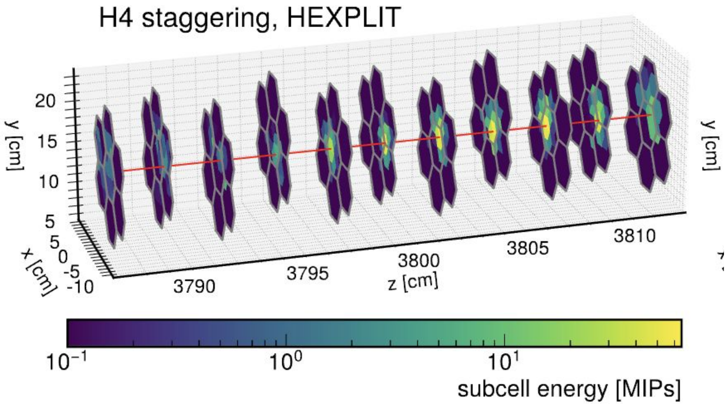
S. Paul, M. Arratia arXiv:2308.06939

Unstaggered | Staggered

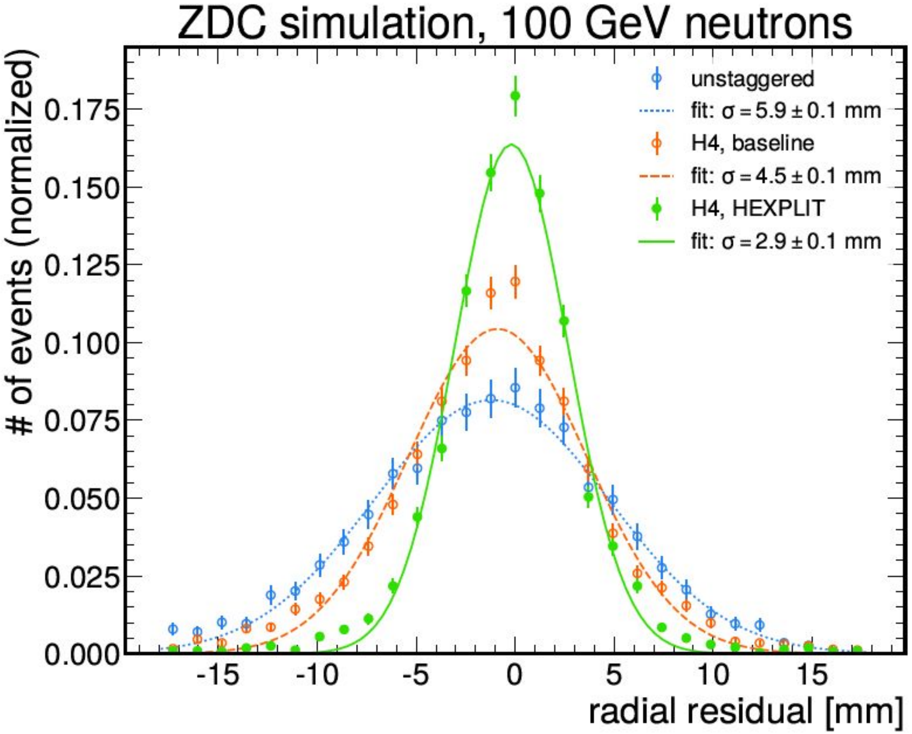
Core of 100 Gev neutron shower

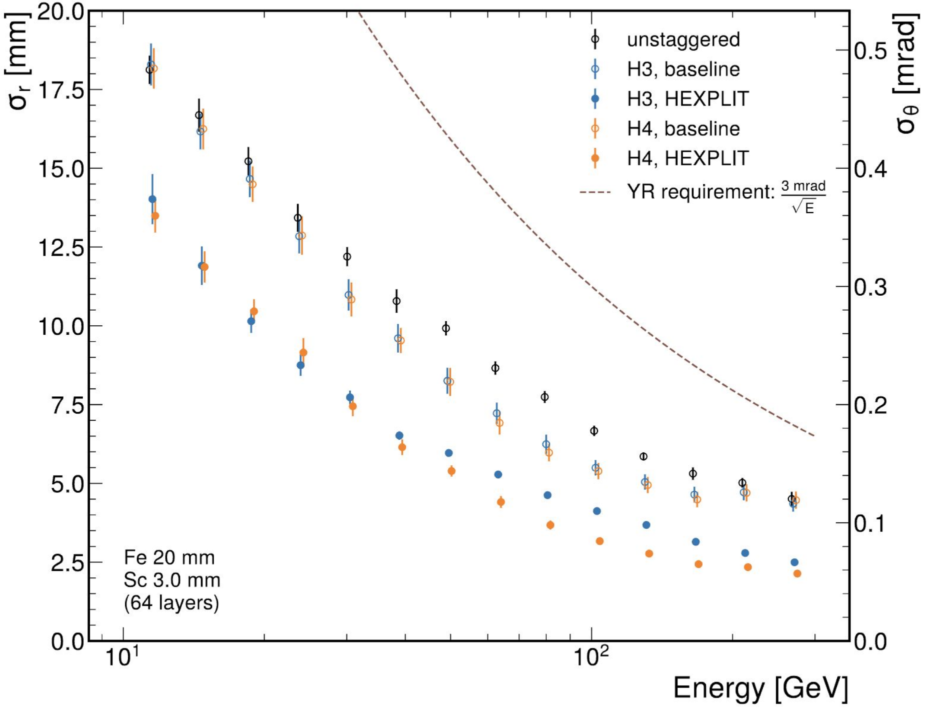




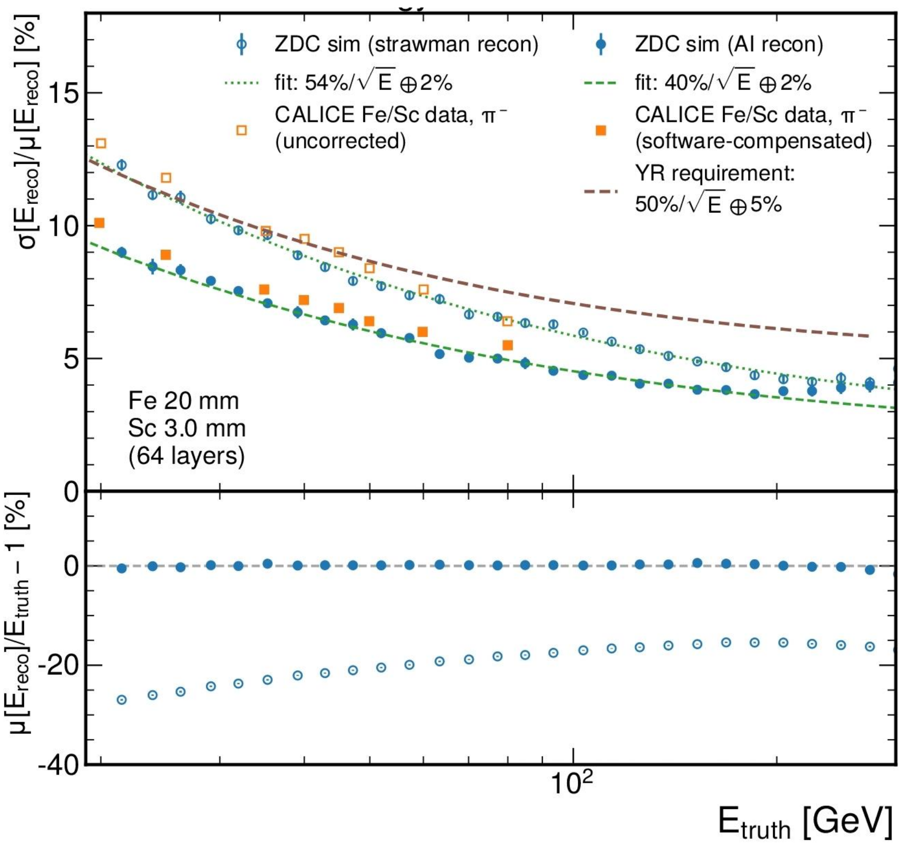


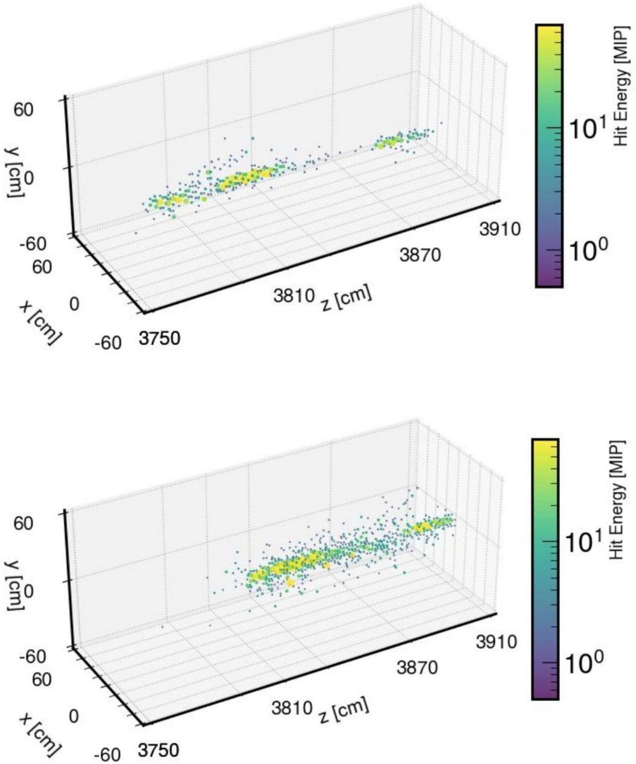
A factor of 2 improvement over unstaggered design



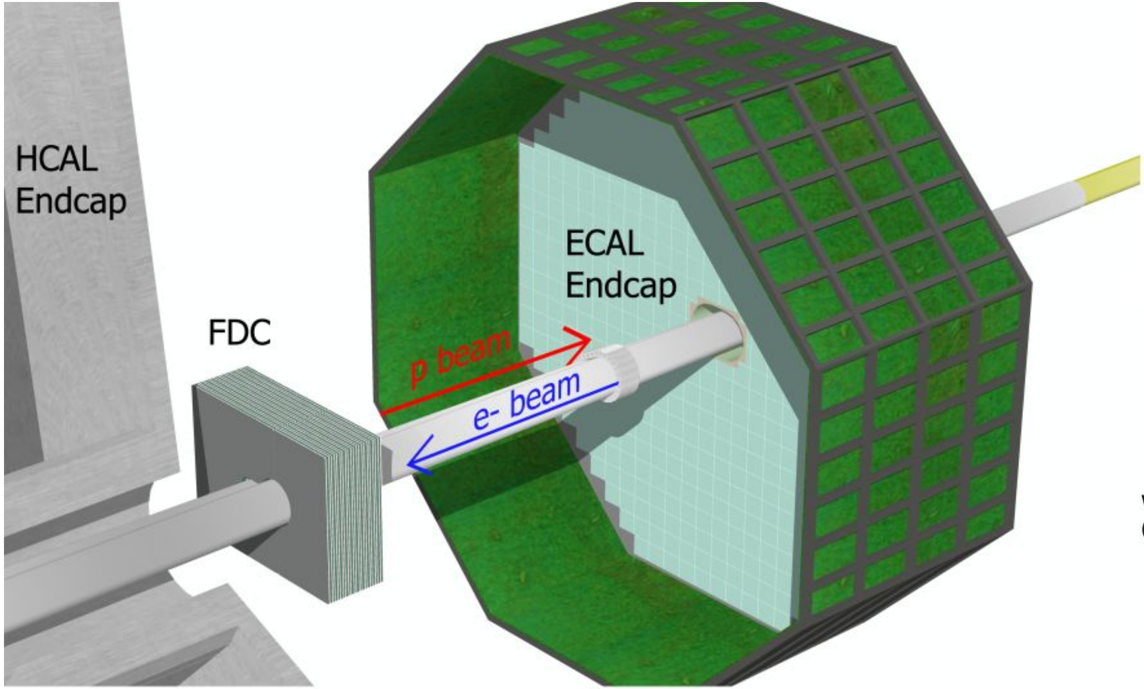


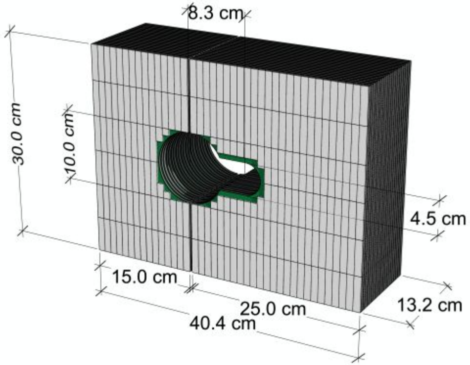
Energy reconstruction with Graph-Neural Network

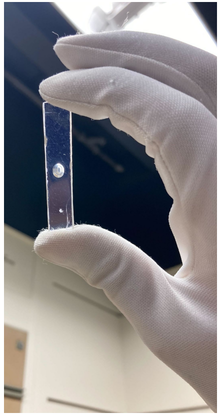


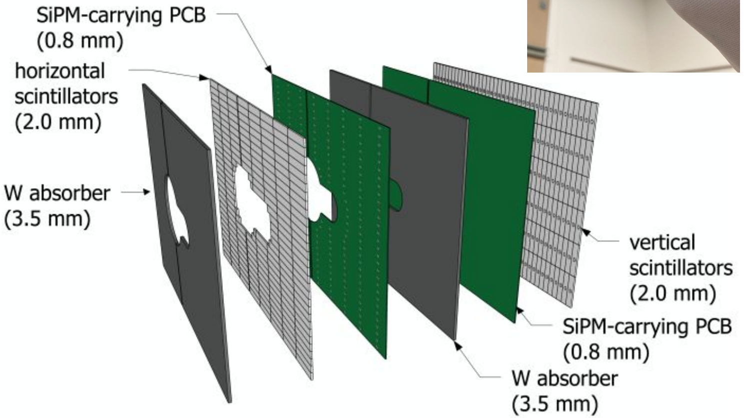


Few Degree Calorimeter (FDC)



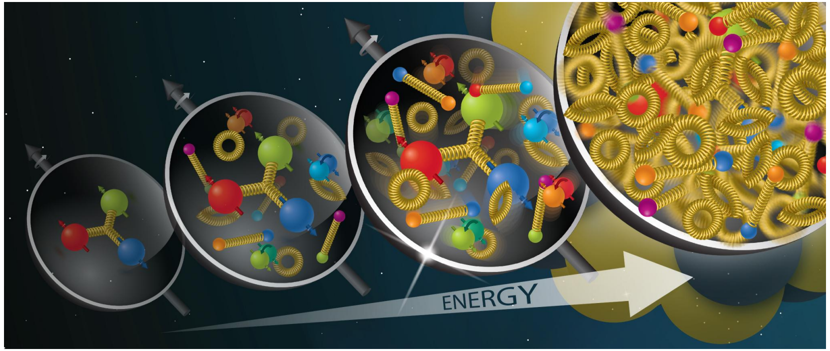


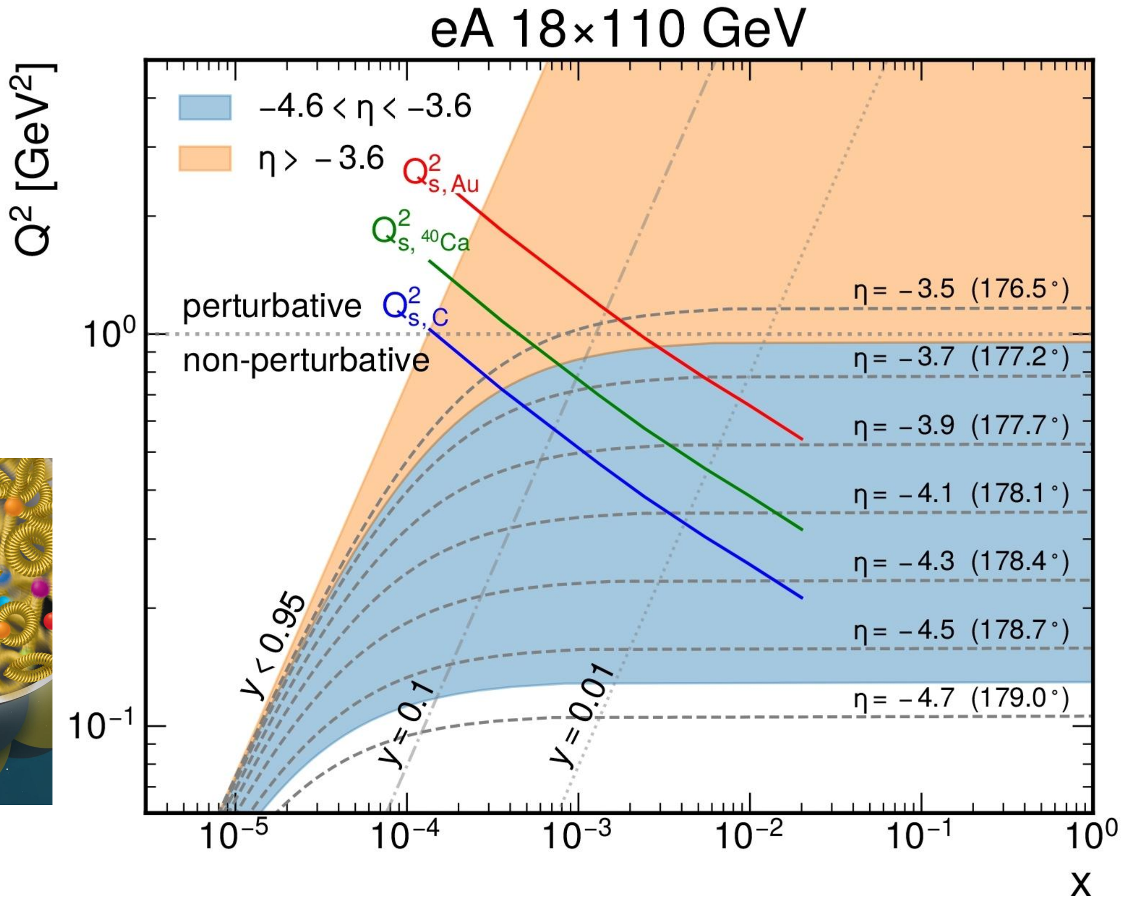




M. Arratia et al. arXiv:2307.12531

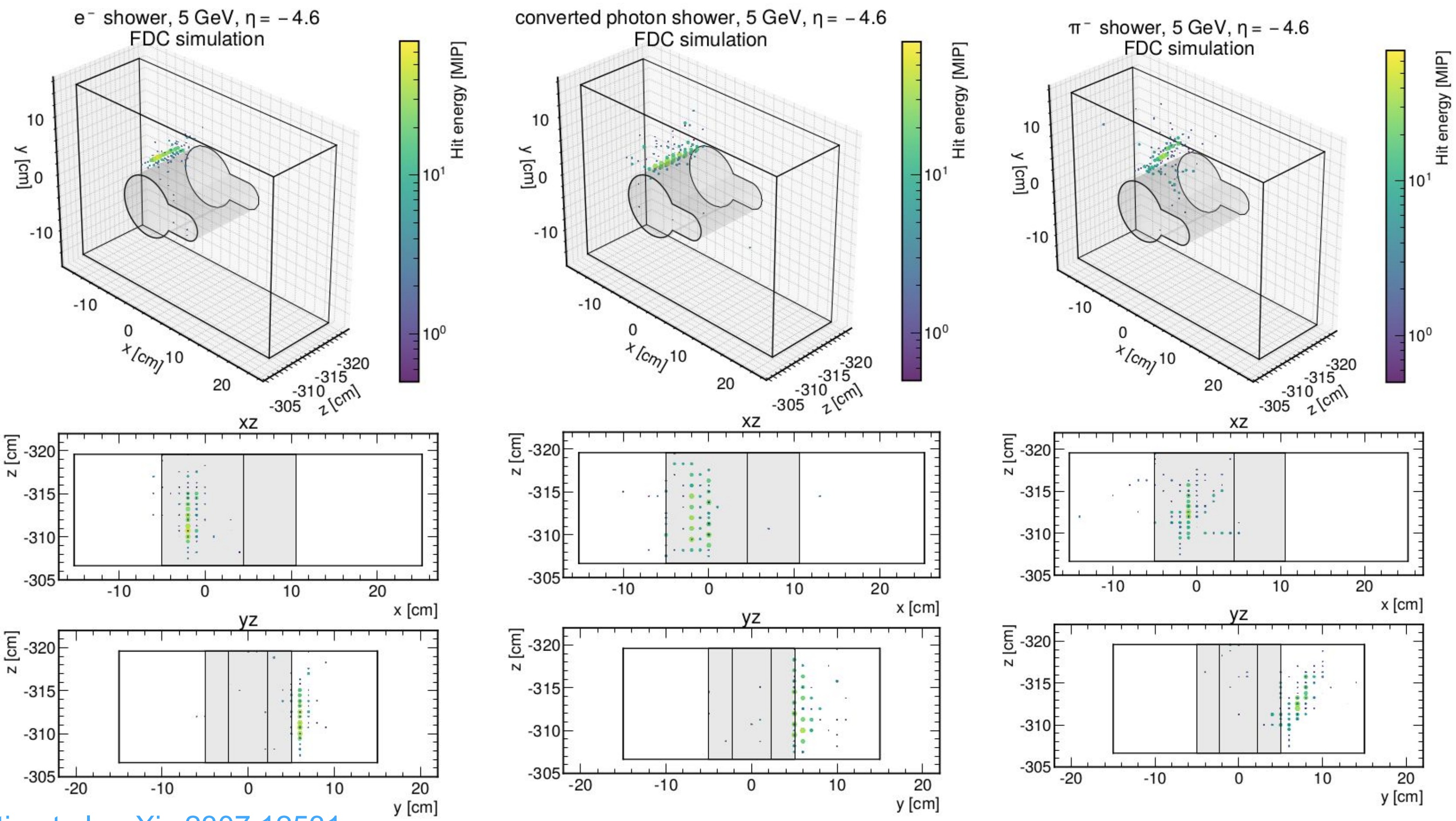
Motivation: search for "gluon Saturation"



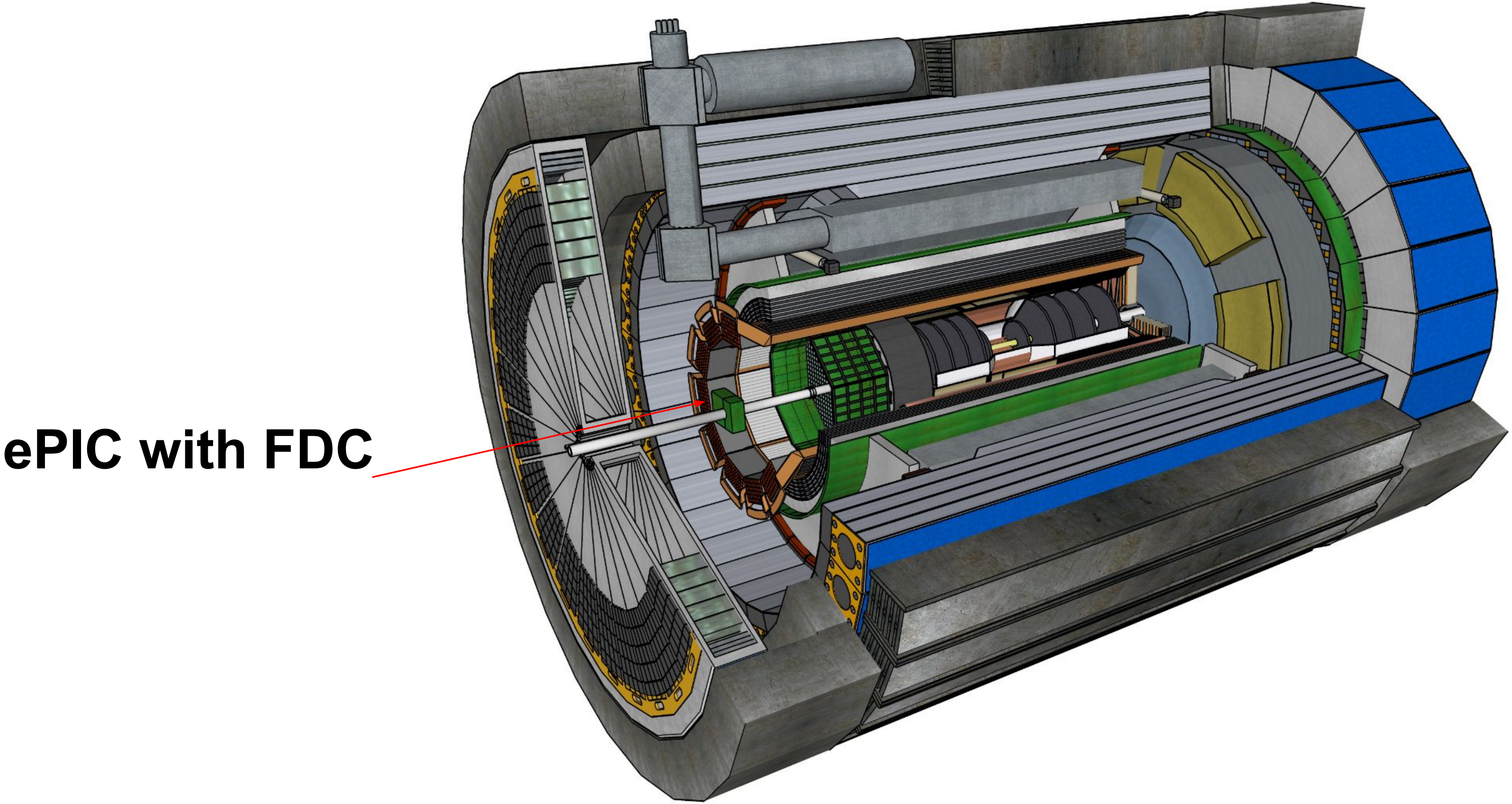


M. Arratia et al. arXiv:2307.12531

Highly granular shower shapes can yield standalone electron tagging



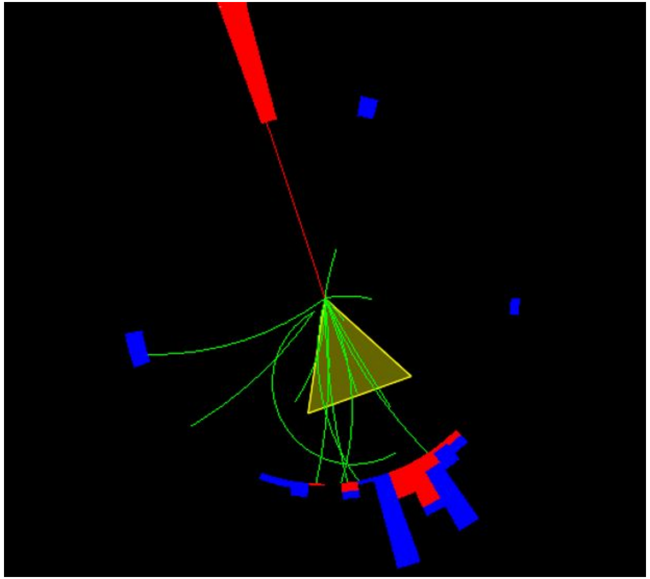
M. Arratia et al. arXiv:2307.12531

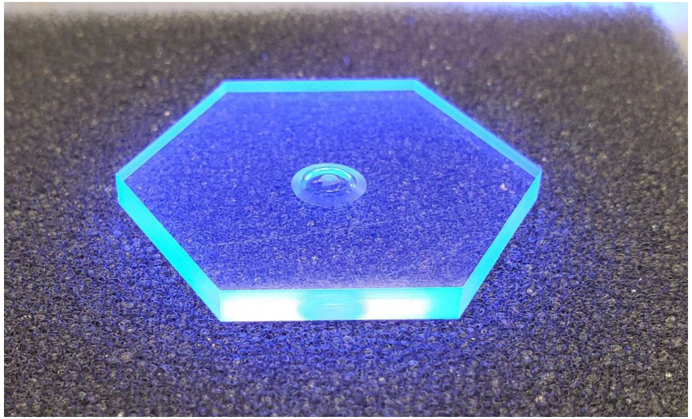

ePIC with FDC

Summary

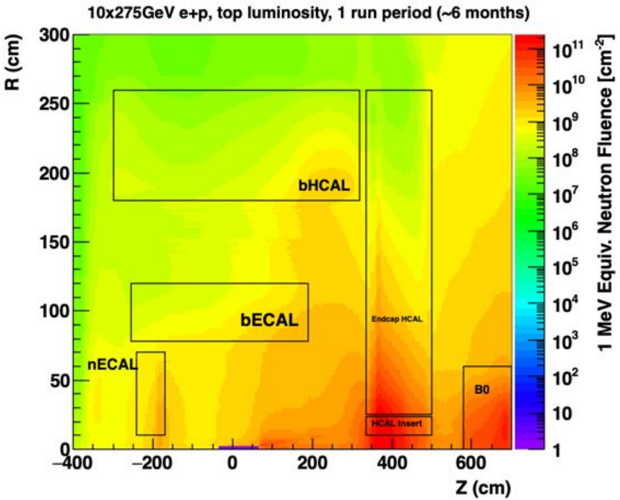
Jets will provide us with an exciting new tool for the quest of "Quantum Tomography" at the EIC

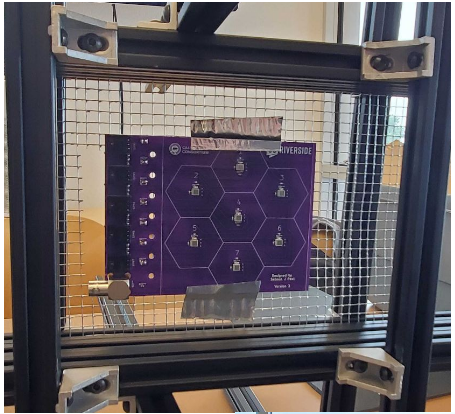
High-granularity calorimetry will enable key measurements in key kinematic regions at the EIC





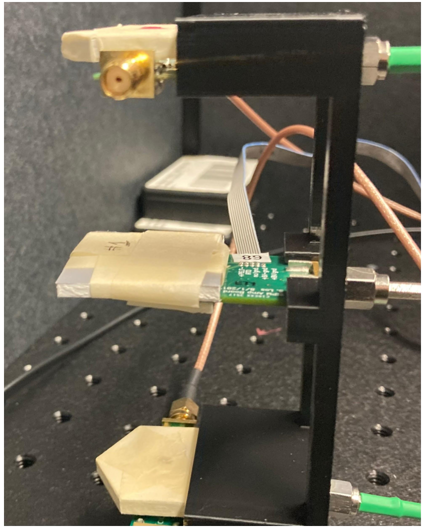
Radiation damage test at LBNL





SiPM-on-tile light-yield measurements

Cosmics



Sr-90