Hadron femtography with exclusive processes from early data at ePIC

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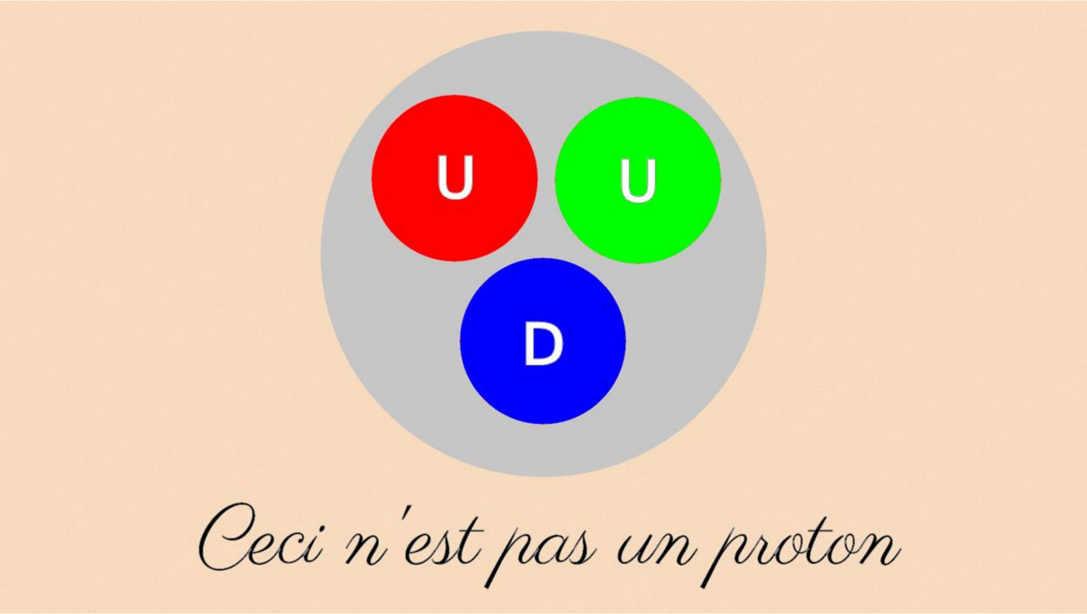


Towards improved hadron femtography with hard exclusive reactions, edition V,

University of Virginia, Charlottesville VA, July 20-24, 2026

EIC science pillars

See R. Ent

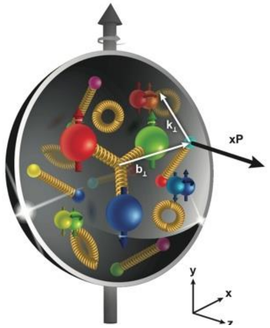
The EIC will unravel the different contribution from the quarks, gluons and orbital angular momentum

SPIN is one of the fundamental properties of matter.
All elementary particles, but the Higgs carry spin.
Spin cannot be explained by a static picture of the proton
It is the interplay between the intrinsic properties and interactions of quarks and gluons

Does the mass of visible matter emerge from quark-gluon interactions?

Atom: Binding/Mass = 0.00000001
Nucleus: Binding/Mass = 0.01
Proton: Binding/Mass = 100

For the proton the EIC will determine an important term contributing to the proton mass, the so-called "QCD trace anomaly



How can we understand their dynamical origin in QCD?
What is the relation to Confinement

How are the quarks and gluon distributed in space and momentum inside the nucleon & nuclei?

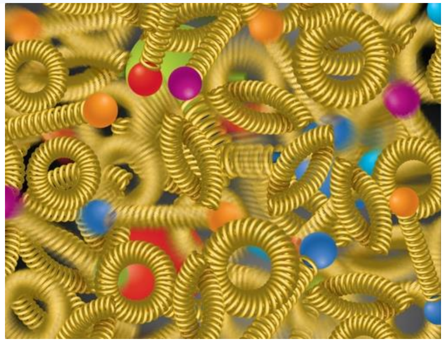
How do the nucleon properties emerge from them and their interactions?

How do the confined hadronic states emerge from quarks and gluons?

Is the structure of a free and bound nucleon the same?

How do quarks and gluons, interact with a nuclear medium?

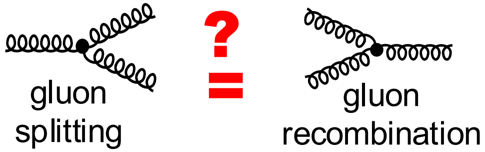
How do the quark-gluon interactions create nuclear binding?



What happens to the gluon density in nuclei? Does it saturate at high energy?

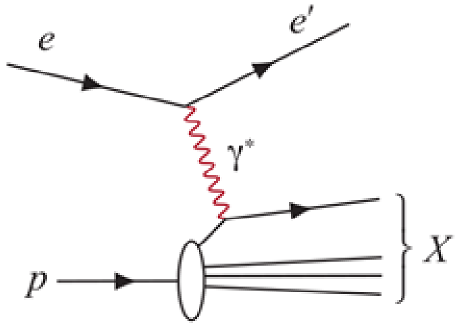
How many gluons can fit in a proton?

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?



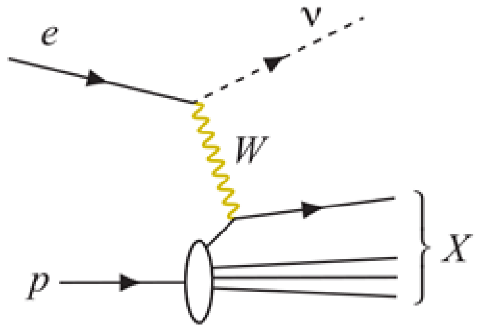
What process must be measured?

DIS event kinematics - scattered electron or final state particles (CC DIS, low y)



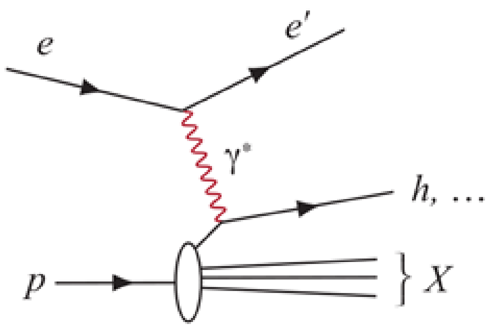
Neutral Current DIS

- Detection of scattered electron with high precision - event kinematics



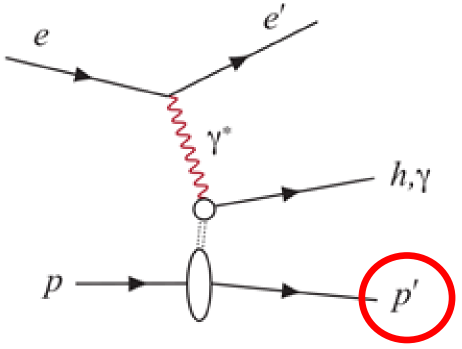
Charged Current DIS

- Event kinematics from the final state particles (Jacquet-Blondel method)



Semi-Inclusive DIS

- Precise detection of scattered electron in coincidence with at least 1 hadron



Exclusive Processes

- Detection of all particles in event

Parton Distributions in nucleons and nuclei

QCD at Extreme Parton Densities - Saturation

Spin and Flavor structure of nucleons and nuclei

Tomography Transverse Momentum Dist.

QCD at Extreme Parton Densities - Saturation

Tomography Spatial Imaging

$\int \mathcal{L}dt$:

$\sim 1\ \mathrm{fb}^{-1}$

$\sim 10\ \mathrm{fb}^{-1}$

$\sim 100\ \mathrm{fb}^{-1}$

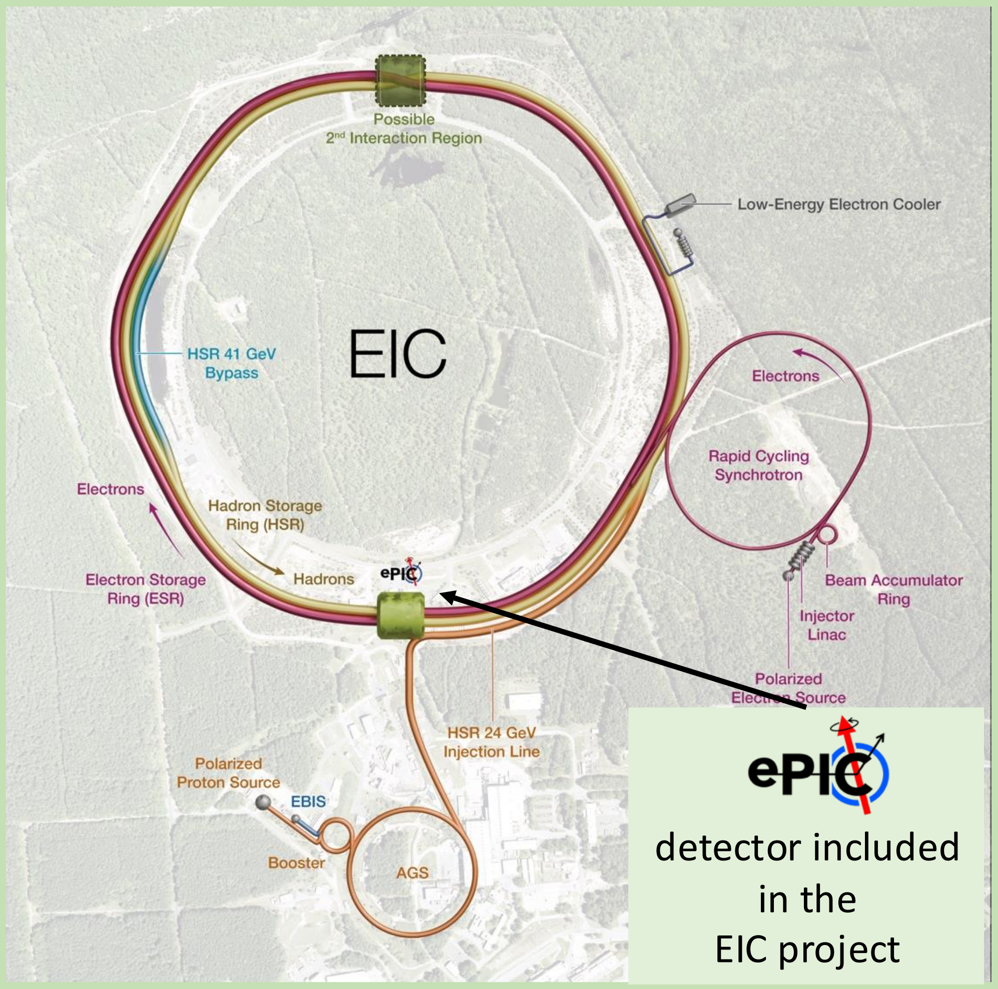
The Electron-Ion Collider

A DOE approved project!
Could be the only new collider in the coming ~20-30 years

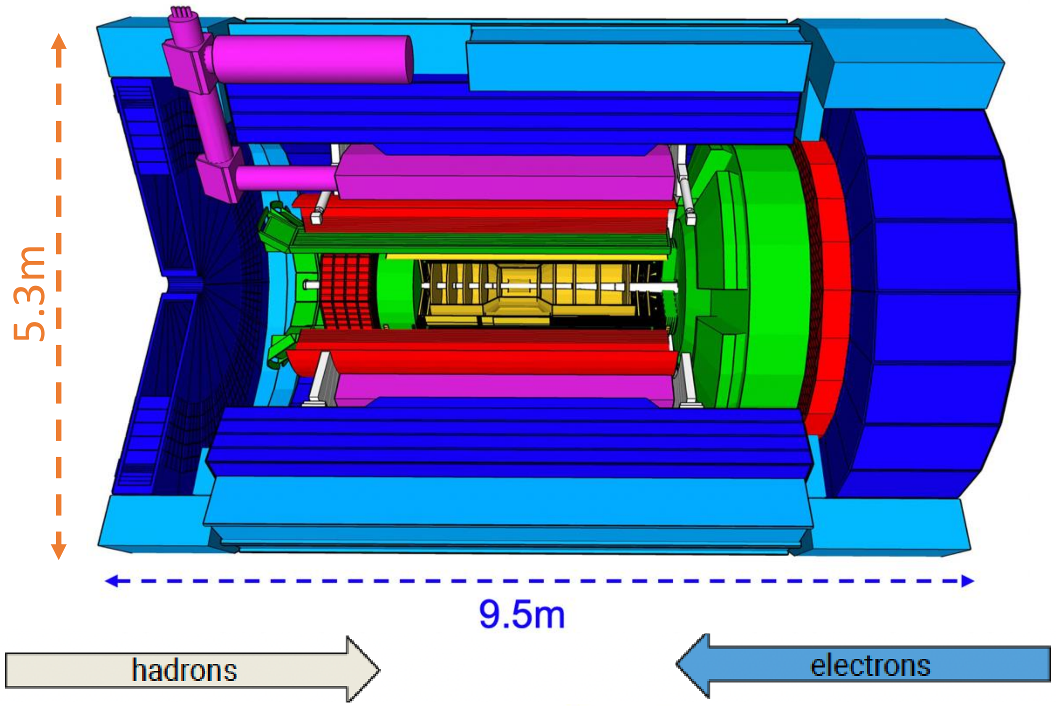
See R. Ent

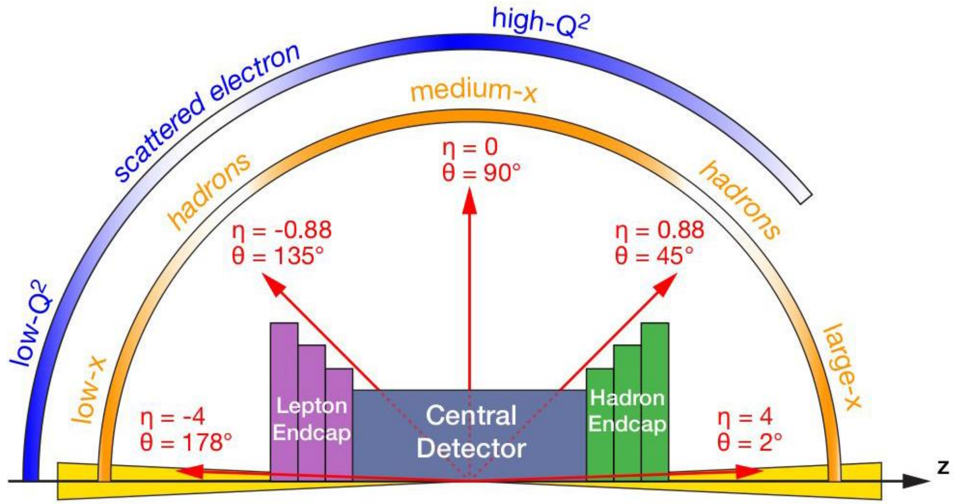
- ✓ Add a 5 to 18 GeV electron storage ring
- ✓ Two interaction regions, IP6 and IP8
- ✓ High Luminosity: 10^{33}-10^{34} $cm^{-2}s^{-1}$ (~10^2-10^3 * HERA)
- ✓ Flexible √s = 29-100 GeV (per nucleon) upgradable to 141 GeV
- ✓ Highly polarized (~70%) $e^{\uparrow}, p^{\uparrow}, d^{\uparrow}, He^{\uparrow}$, flexible spin pattern
- ✓ Wide variety of nuclear beams: (D to U)

World's first Polarized electron-proton/light ion and electron-Nucleus collider



The ePIC detector





Tracking

- **New 1.7 T solenoid**
- Si MAPS (vertex, barrel, forward, backward disks)
- MPGDs (μRWELL/μMegas) (barrel, forward, backward disks)

Particle identification

- High performance DIRC (barrel)
- Dual radiator (aerogel+gas) RICH (forward)
- Proximity focusing RICH (aerogel) (backward)
- TOF (~30ps): AC-LGAD (barrel and forward)

E.M. Calorimetry

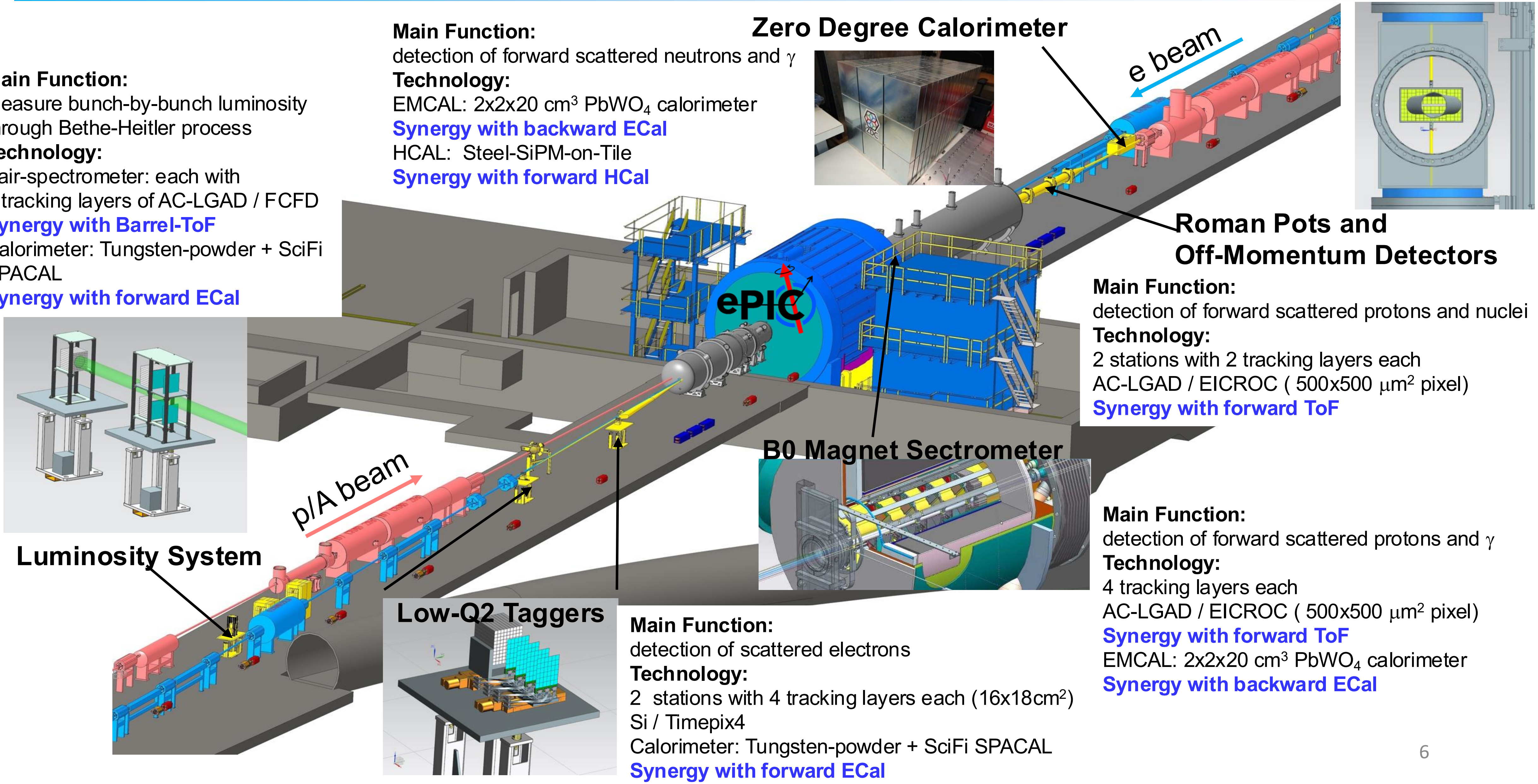
- Imaging EMCAL (barrel)
- W-powder/ScFi (forward)
- $PbWO_4$ crystals (backward)

Hadronic Calorimetry

- Fe/Scint reuse from sPHENIX (barrel)
- Steel/Scint - W/Scint (backwards/forward)

DAQ: streaming/triggerless with AI

Far forward/backwards detectors



Luminosity System

Main Function:
measure bunch-by-bunch luminosity through Bethe-Heitler process
Technology:
Pair-spectrometer: each with
2 tracking layers of AC-LGAD / FCFD
Synergy with Barrel-ToF
Calorimeter: Tungsten-powder + SciFi SPACAL
Synergy with forward ECal

Zero Degree Calorimeter

Main Function:
detection of forward scattered neutrons and γ
Technology:
EMCAL: 2x2x20 cm^3 $PbWO_4$ calorimeter
Synergy with backward ECal
HCAL: Steel-SiPM-on-Tile
Synergy with forward HCal

Roman Pots and Off-Momentum Detectors

Main Function:
detection of forward scattered protons and nuclei
Technology:
2 stations with 2 tracking layers each
AC-LGAD / EICROC (500x500 μm^2 pixel)
Synergy with forward ToF

B0 Magnet Sectrometer

Main Function:
detection of forward scattered protons and γ
Technology:
4 tracking layers each
AC-LGAD / EICROC (500x500 μm^2 pixel)
Synergy with forward ToF
EMCAL: 2x2x20 cm^3 $PbWO_4$ calorimeter
Synergy with backward ECal

Low-Q2 Taggers

Main Function:
detection of scattered electrons
Technology:
2 stations with 4 tracking layers each (16x18cm^2)
Si / Timepix4
Calorimeter: Tungsten-powder + SciFi SPACAL
Synergy with forward ECal

The ePIC Collaboration

A truly global pursuit for a new experiment at the EIC

27 Countries

187 Institutions and counting!

1150+ scientists and counting!


BNL – January 2026

Structure of Physics Analysis at ePIC

PHYSICS ANALYSIS COORDINATORS
Salvatore Fazio (Calabria/INFN) – Charlotte Van Hulse (VU Brussel)
Rosi Reed (Lehigh) - deputy

INCLUSIVE PHYSICS
Win Lin (Stony Brook)
Tyler Kutz (Mainz)

SEMI-INCLUSIVE PHYSICS
Anselm Vossen (Duke)
Oleg Eyser (BNL)

JETS AND HEAVY FLAVOR
Shyam Kumar (Bari)
Austin Baty (Illinois- Chicago)

EXCLUSIVE, DIFFRACTION AND TAGGING
Stephen Kay (York)
Jan Vanek (New Hampshire)

BSM AND PRECISION EW
Zuhal Seyma Demiroglu (Stony Brook)
Jae Nam (BNL)

Ingredients we need:

- A flexible collider (EIC)
- A versatile general-purpose detector (ePIC)
- An engaged and enthusiastic International Collaboration

- PAC/Conveners in blue joining in August, pending vote by the ePIC C.C. Council
- PWGs at ePIC typically meet by-weekly
- Global Physics Analysis Coordination by-weekly

Exclusive in e+A: see M. Kesler

Preliminary Technical Design Report – Chapter 4

Connects processes with the NAS pillars (provides a table)

Presents global performance and tools:

- Electron identification
- Photon measurement
- Hadron identification
- Jets reconstruction
- Muon identification

Discuss the detector performance in measuring physics processes:

- Inclusive
- Semi-inclusive
- Exclusive and diffractive
- Hard probes (heavy flavor and jets)

For each process the influence of **beam background** is being investigated

ePIC Early Science Report

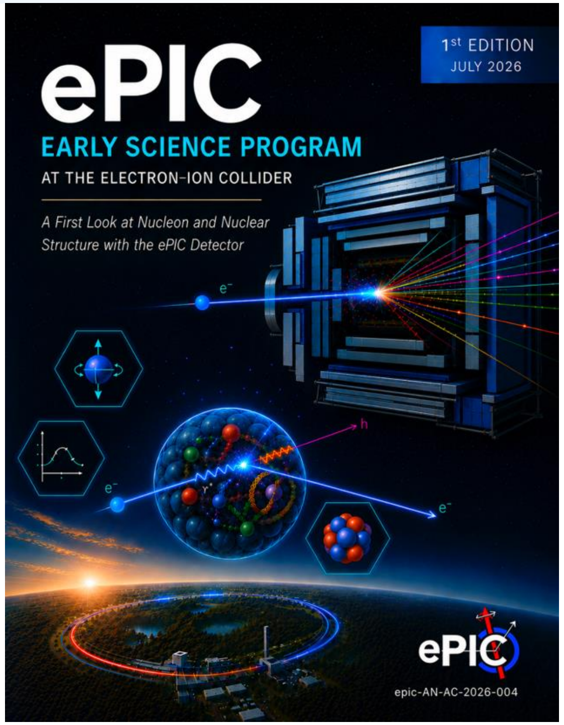
- The EIC will ramp up gradually — luminosity, beam energies, species and polarization arrive in stages during the early years of running
- In June 2025 BNL & JLab Associate Lab Directors charged ePIC to summarize the science achievable with early data, before full machine capability
- This report answers that charge using the **full Geant4 detector ePIC simulation** and **official ePIC event reconstruction**

○ **Main takeway:**

- Even before full design parameters, ePIC will deliver world-leading insights, and lay the foundation for the complete EIC science mission
- Early running also establishes the validated reconstruction, calibration and analysis methods for the full EIC program

○ The ESR has been submitted to the JLAB and BNL ALDs for comments

- a public version will be soon published on arXiv and a special issue of NIM-A



ESR - v3.2

EIC Early Running Conditions

- **Assumptions:**
  - Running 30 weeks/year
  - 2.5 hour turn around time
  - 80% facility availability
- **Lower electron-beam energy also possible:**
  - ep 5x100: 0.5 fb-1/year
  - eAu 5x110: 2 fb-1/year
  - eAg 5x110: 2 fb-1/year

Species	Beam energy (GeV)	Integrated luminosity	Electron-beam polarization	Hadron-beam polarization
e+Ag	9×115	1.0 fb^{-1}	NO	N/A
e+D	9×130	1.5 fb^{-1}	LONG	NO
$e+p$	9×130	1.0 fb^{-1}	LONG	TRANS and/or LONG
$e+p$	9×275	2.5 fb^{-1}	LONG	TRANS and/or LONG
e+Au	9×100	1.0 fb^{-1}	LONG	N/A
$e+^3$He	9×166	1.5 fb^{-1}	LONG	TRANS and/or LONG

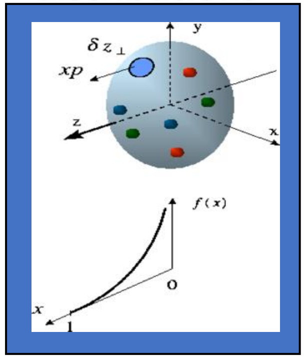
Table 1: EIC Early Science Matrix. The eA luminosity is per nucleon.

NB: ePIC to be installed year-1 (exception for roman pots and OMD)

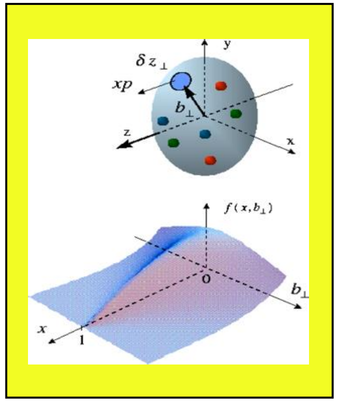
- **For comparison:** HERA delivered 0.5fb^{-1} each to H1 and ZEUS in its lifetime

Generalized Parton Distributions (GPDs)

Longitudinal momentum & helicity distributions

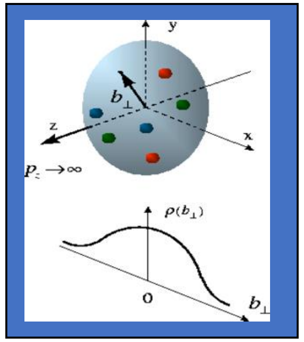


$\boldsymbol{f(x)}$
parton densities



$\boldsymbol{H(x,\xi,t)}$
GPDs

transverse charge & current densities



$\boldsymbol{F(t)}$
form factors

N / q	U	L	T
U	H		E_T
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	H_T $\tilde{H}_T$

Spin-½ hadron: **4 chiral-even** (H, E and their polarized-hadron versions $\widetilde{H}$, $\tilde{E}$) and **4 chiral-odd** ($H_T, E_T, \widetilde{H}_T, \tilde{E}_T$) quark and gluon **GPDs at leading twist**

Like usual PDFs, GPDs are non-perturbative functions **defined via the matrix elements of parton operators**:

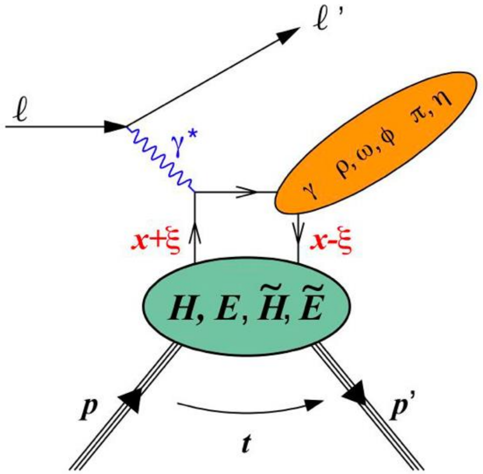
$$F^q = \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ix\bar{P}^+z^-} \langle p'|\bar{q}(-\frac{1}{2}z)\gamma^+ q(\frac{1}{2}z)|p\rangle|_{z^+=0,\mathbf{z}=0}$$

$$= \frac{1}{2\bar{P}^+}\left[H^q(x,\xi,t,\mu^2)\bar{u}(p')\gamma^+u(p) + E^q(x,\xi,t,\mu^2)\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m_N}u(p)\right]$$

- Experimental access to GPDs via Compton Form Factors (CFFs)

$$\mathcal{H}(\xi,t) = \sum_q e_q^2 \int_{-1}^{1} dx\, H^q(x,\xi,t)\left(\frac{1}{\xi - x - i\varepsilon} - \frac{1}{\xi + x - i\varepsilon}\right)$$

- Measure t-differential cross sections and asymmetries in exclusive processes

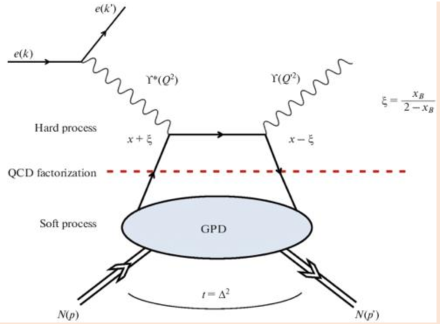


Mandelstam variable: $t = -(p' - p)^2$

Accessing GPDs in exclusive processes

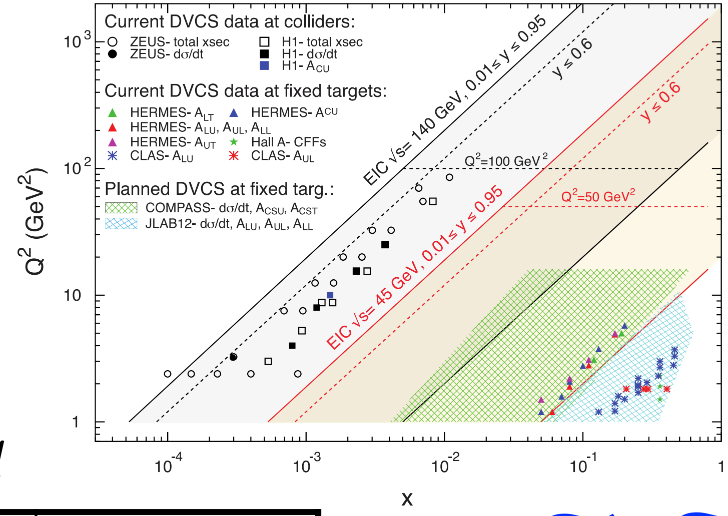
Real photon (DVCS):

- Very clean experimental signature
- No VM wave-function uncertainty
- Hard scale provided by Q^2
- Access to the whole set of GPDs
- Sensitive to both quarks and gluons [via Q^2 dependence of xsec (scaling violation)]



Hard Exclusive Meson Production (HEMP):

- Uncertainty of wave function
- Hard scale provided by $Q^2 + M^2$
- J/Psi, Y → direct access to gluons, $c\bar{c}$, or $b\bar{b}$ pairs produced via $q(g) - g$ fusion
- Light VMs → quark-flavor separation
- Psedoscalars → helicity-flip GPDs



Only possible at EIC: from valence quark region, deep into the sea!

$H^q \; E^q$

ρ^0	2u+d, 9g/4
ω	2u–d, 3g/4
ϕ	s, g
ρ^+	u–d
J/ψ, Y	g

$\widetilde{H^q} \; \widetilde{E^q}$

π^0	2Δu+Δd
η	2Δu–Δd

Key detector performance:

- γ/π^0 separ. in ECAL for DVCS
- Acceptance and low material for VM decay leptons
- Resol. of lepton pair invariant mass
- Scattered electrons over full kinematics
- t- lever arm in FF spectrometers

What kind of observables we need?

We got them all but one!

$$\frac{d\sigma}{dt} \sim A_0 \left[|H|^2(x,t,Q^2) - \frac{t}{4M_p^2} |E^2|(x,t,Q^2) \right]$$

A_{LU}

Dominated by H
slightly dependent on E

Both access the imaginary part of the amplitude

$$A_{UT} \propto \sqrt{\frac{-t}{4M^2}} \left[F_2(t) H(\xi,\xi,t,Q^2) - F_1(t) E(\xi,\xi,t,Q^2) + \dots \right]$$

sin(*$\Phi_T - \phi_N$*)
governed by E and H

[Requires a polarized proton target]

$$A_C = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \propto Re(A)$$

Done @ HERA

[Requires a positron beam → not in EIC baseline]

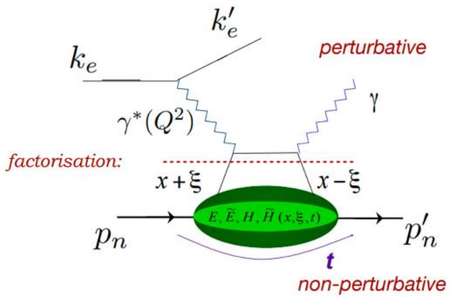
A_{LL}

provides access to the real part of the amplitude, but it is primarily sensitive to the real part of the ***axial*** **CFF,** $\mathrm{Re}(\tilde{\mathcal{H}})$

Highlights on exclusive measurements in e+p collisions at ePIC

- ALL IS A WORK IN PROGRESS!
- Software framework, event reconstruction, tools... are being finalized and are evolving as we speak!

DVCS

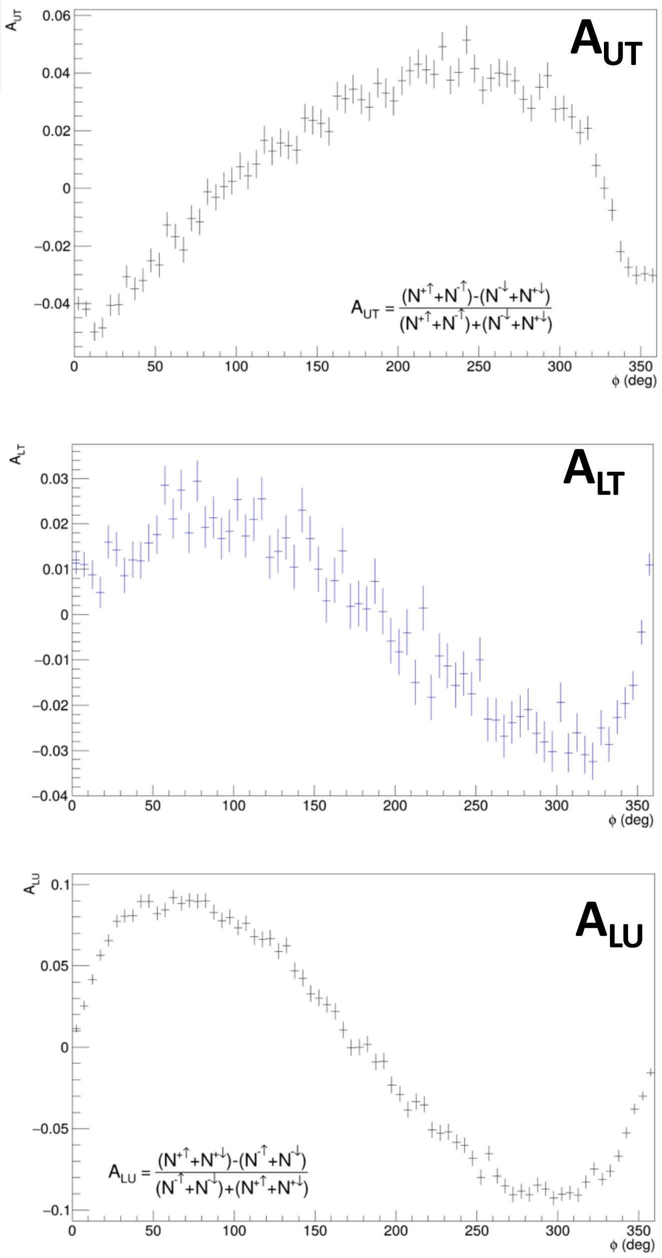


- EpIC generator v1.1.2 (link)
  - Mind: $EpIC \neq$ ePIC ☺
  - Purpose built generator for GPD-sensitive processes (DVCS, TCS, VMs, etc.)
  - Cross-sections evaluated from CFFs evaluated from models

- Event samples used: DVCS + BH + INT.
  - 1M events (5x41, 10x250, 18x275); 1.3M events (10x100, 10x130)
  - $1 < Q^2 < 100$ GeV^2; $0.01 < y < 0.9$; $10^{-5} < xB < 0.7$
  - Plots shown are for 10x130 GeV energy configuration

- Single particle cuts:
  - Electron: only 1 reconstructed and Q2 ≥ 1 GeV2
  - Photon: only 1 reconstructed
  - Proton: only 1 reconstructed in far forward detectors (B0 and RPs)
  - Full exclusivity (e'p'γ all reconstructed)
- Kinematic cuts:
  - $15 < (E - p_z) < 25$ GeV (reduces radiative effects)
  - $|M^2_{miss}| < 1$ GeV^2 (exclusivity)

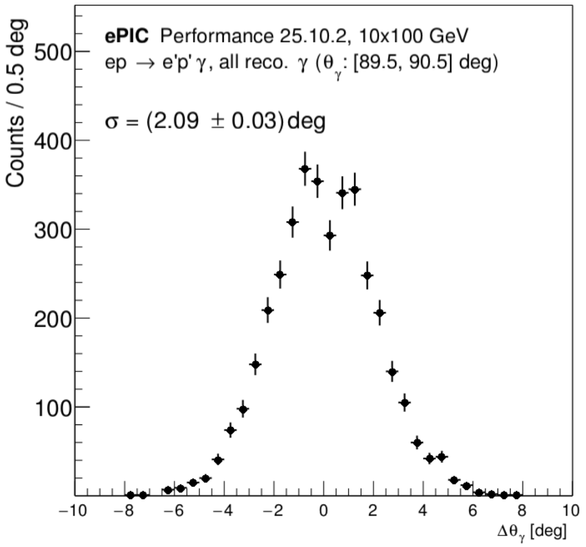
Generated level asymmetries

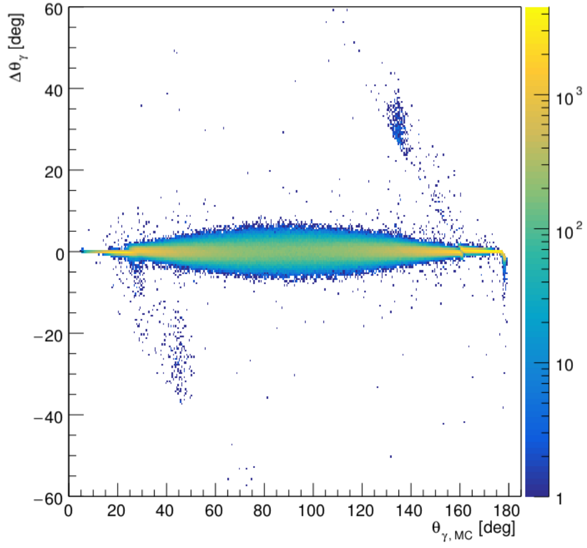


DVCS at ePIC – work in progress!

Proton momentum via f.f. spectrometers: roman pots (RPs) and B0

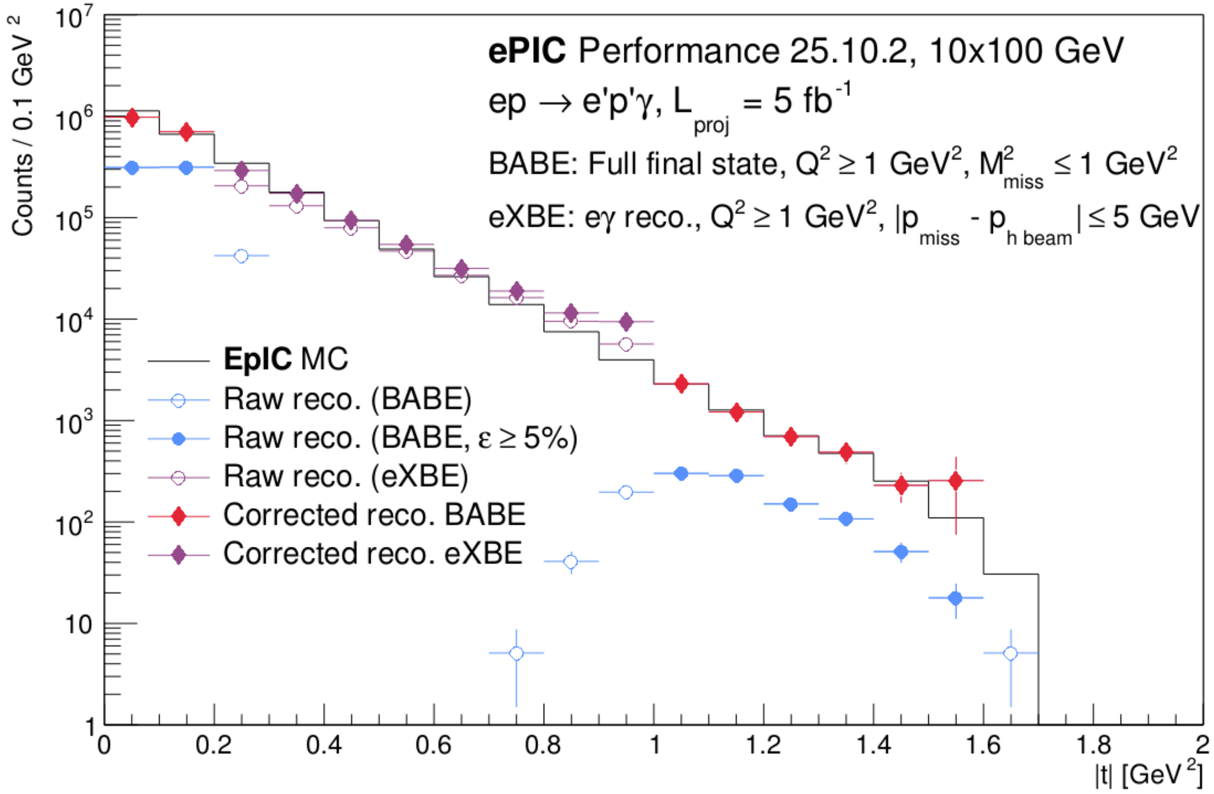
- Directly measured as: $t = -(p' - p)^2$





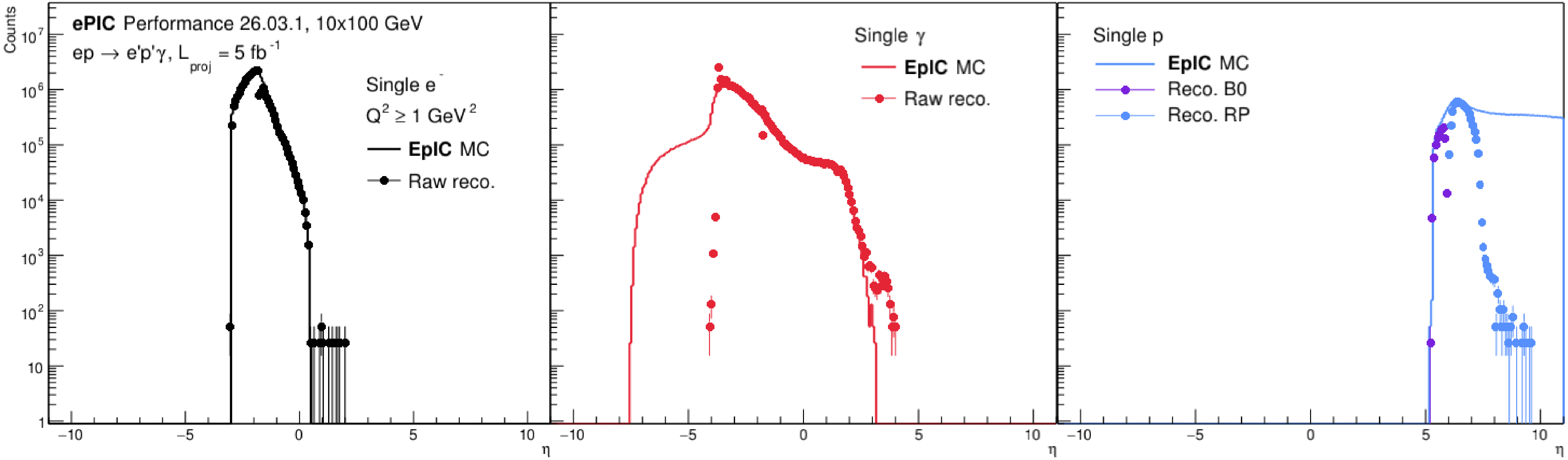
Reconstructed minus generated track polar angle

- for all reconstructed DVCS photons (left)
- vs the generated photon θ (right)



Generated and reconstructed t-distributions for fully-exclusive DVCS events

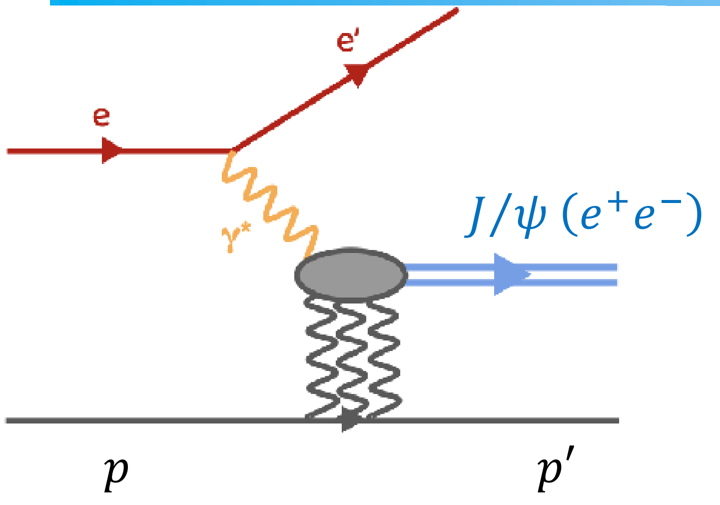
DVCS at ePIC – work in progress!



Electron, photon – **central barrel** and (mostly) **forward endcap**
Proton

Proton – **B0/RP [FF spetrometers]**
(beam-energy dependent)
→ 5x41 – 94% B0, 6% RP
→ 10x100 – 3% B0, 97% RP
→ 10x130 – same as 10x100
→ 18x275 – 100% RP

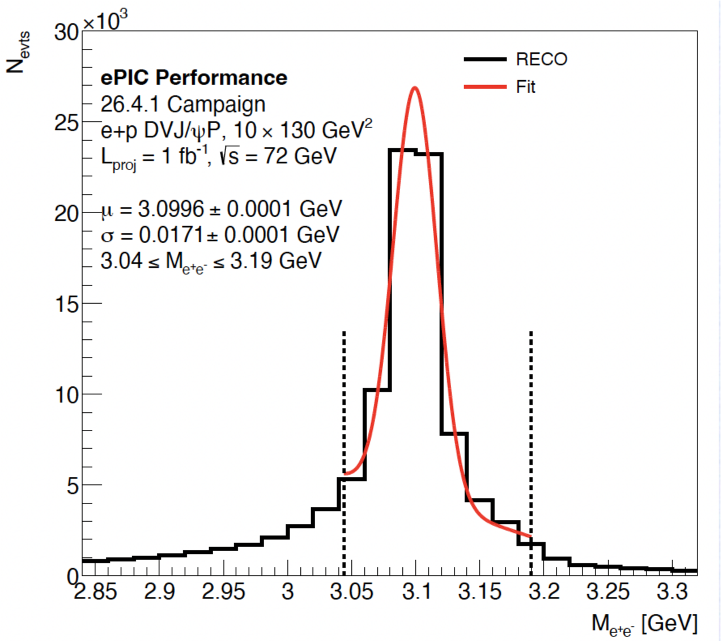
J/PSI at ePIC – work in progress!



- Dominated by gluon exchange →direct sensitivity to gluon GPDs
- Heavy charm mass provides a hard scale

- Generator: lAger 3.6.1-1.-0
- Beam energies: 10 x 130 GeV

excellent mass resolution and signal purity

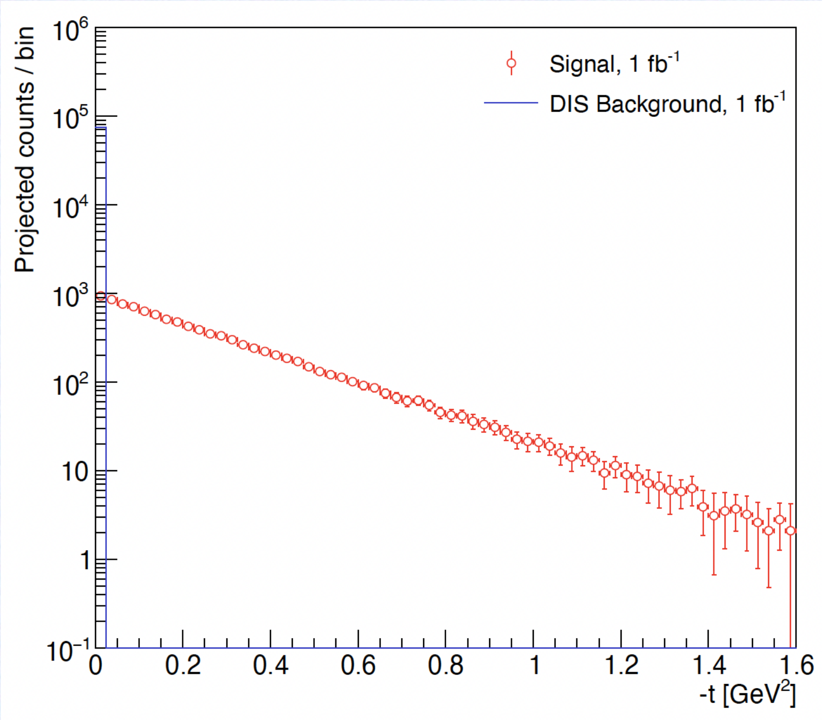


- Proton in far forward spectrometers: B0 or RPs
- Exclusivity: ll final state particles are reconstructed
- Event selection
  - Exactly two oppositely charged tracks Identified as electrons
  - Energy-momentum consistency: $0.8 < E/p < 1.2$
  - Invariant mass: $2.7 < M_{e^+e^-} < 3.4$ GeV (good J/ψ candidate)
  - Longitudinal energy balance: $15 < E - p_z < 25$ GeV

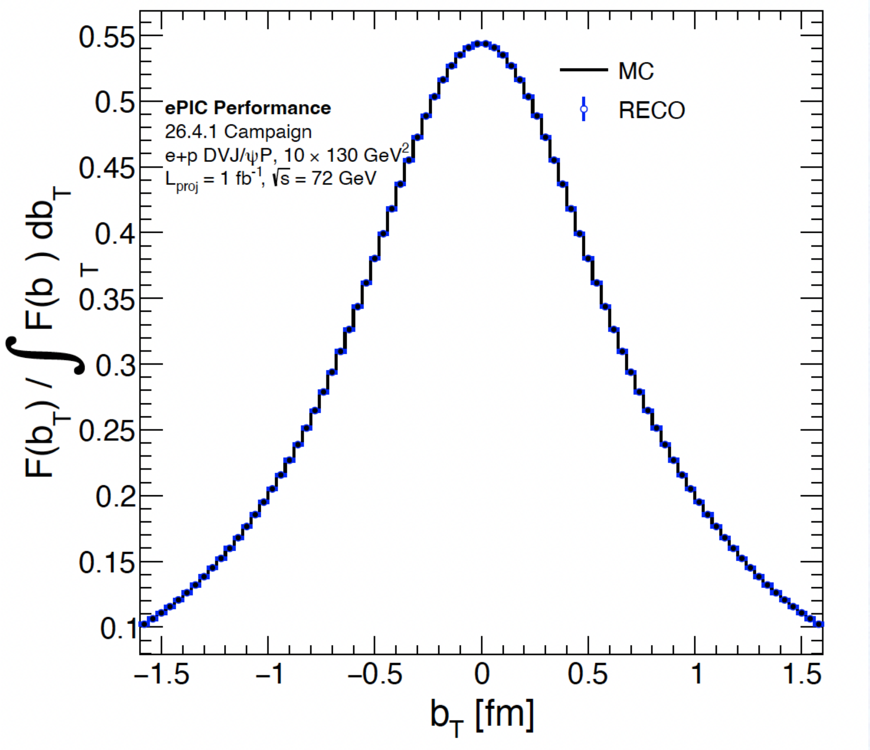
J/PSI at ePIC – work in progress!

- Direct access to gluon GPDs
- Needs to be binned in x and Q^2:
  - Total kinematic bins: 4 Q^2 bins x 11 x bins → 44 (Q^2, x) bins being used for early science studies

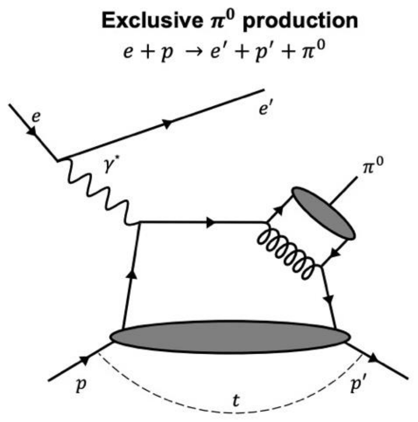
t-differential x-section with 1 fb^{-1}



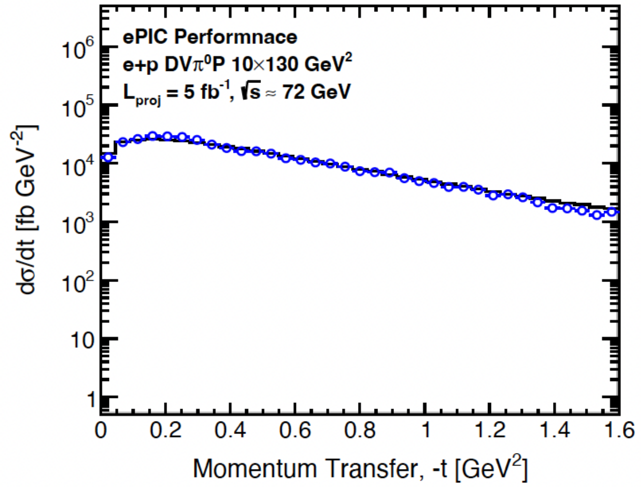
Fourier transformation extracts spattial distribution



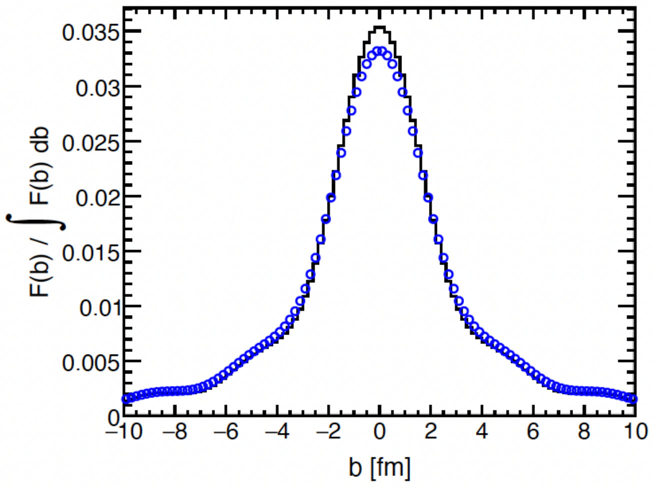
π^0 at ePIC



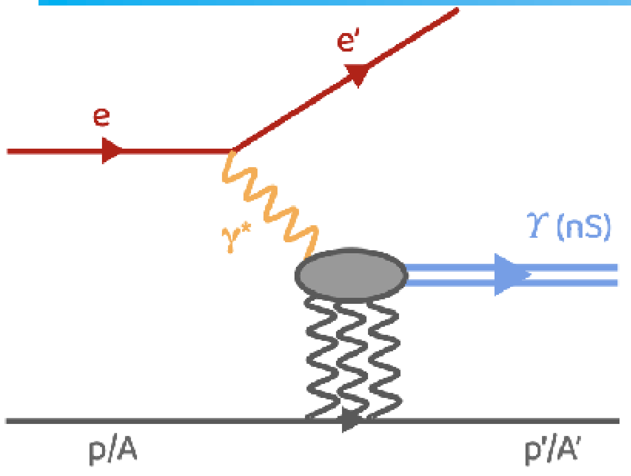
- **Imaging:** Probe chiral-odd GPDs (quark-helicity flip)
- **Spin:** Quark orbital angular momentum [PRL 133, 051901]
  - Azimuthal asymmetries sensitive to quark orbital angular momentum
- Public analysis note: [epic-AN-AC-2025-002]
- EpIC generator v1.1.2 (link) - 10 x 130 GeV



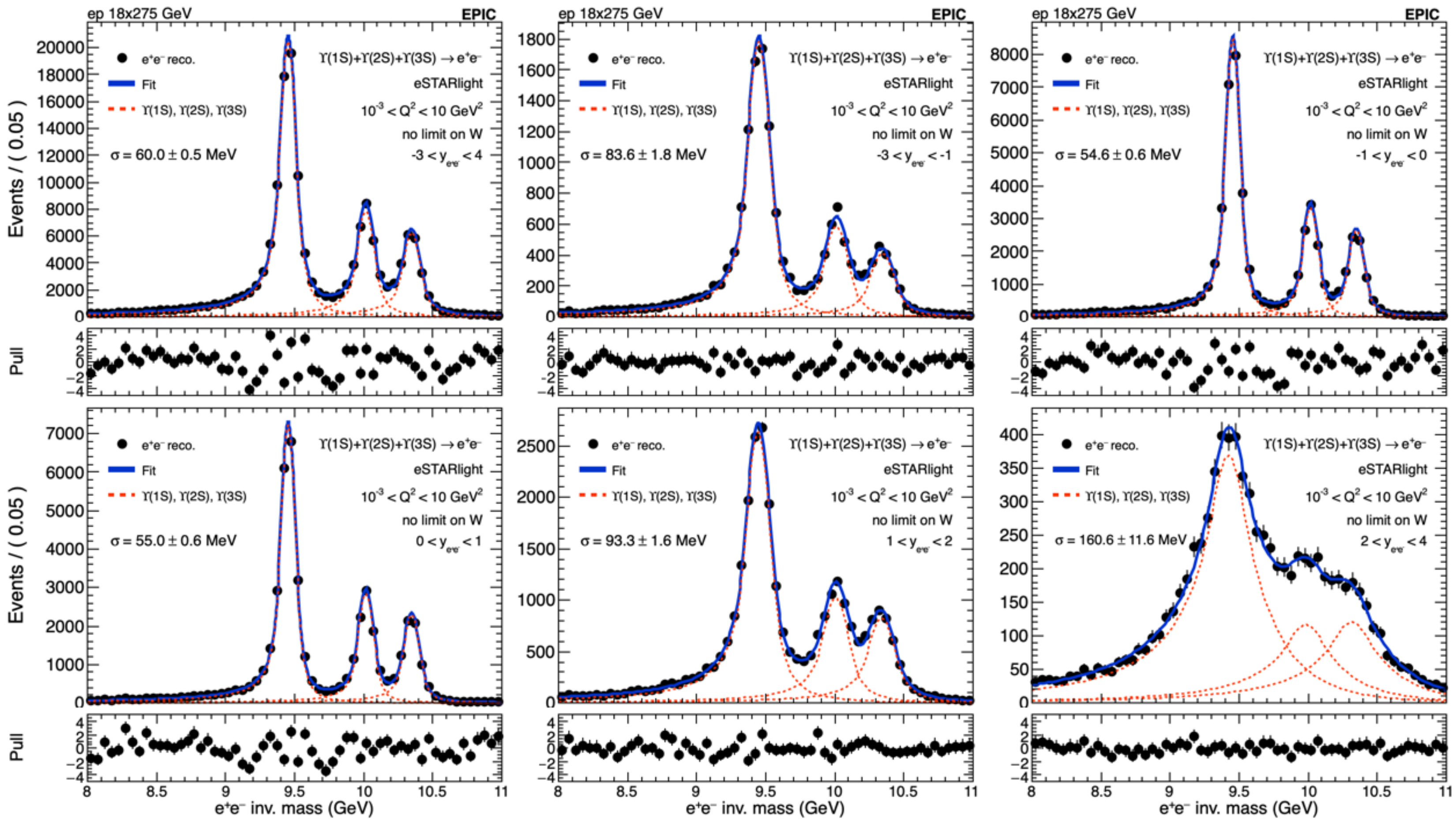
- **Event selection:**
  - Scattered **electron** detected (Tracker + Calorimeter)
    - $0.8 < E/p < 1.2$
  - Scattered **proton** detected in FF spectromenters (B0 or RPs)
  - Neutral pion ($\pi^0 \to \gamma\gamma$):
    - two photons in mid- and forward ecals
    - $0.096 < m_{\gamma\gamma} < 25$ GeV
  - Kinematic cuts:
    - $15 < (E - p_z) < 25$ GeV (reduces radiative effects)
    - $|M^2_{miss}| < 1$ GeV^2 (exclusivity)



ϒ at ePIC – work in progress!



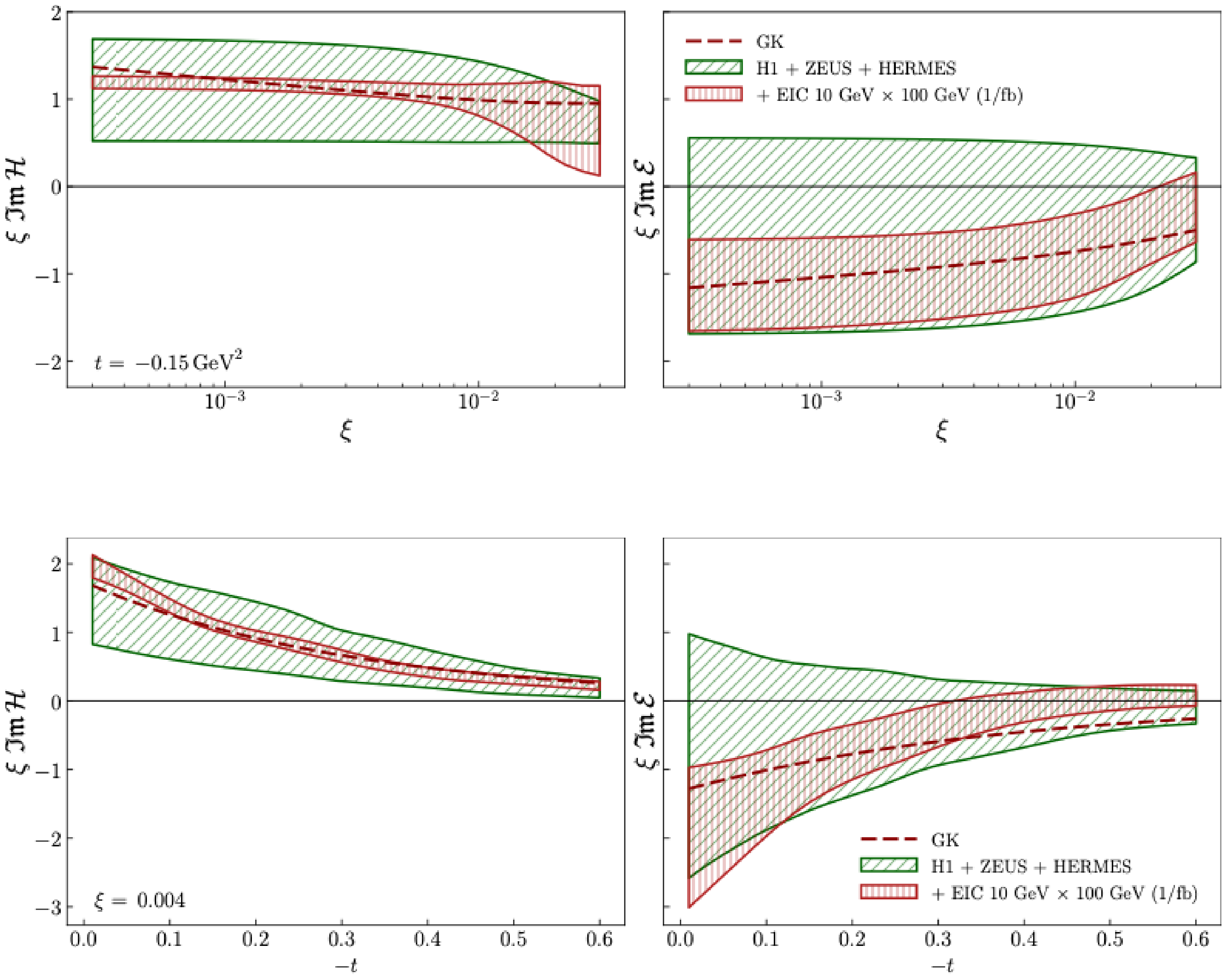
$$\Upsilon(1S), \Upsilon(2S), \Upsilon(3S) \rightarrow e^+e^-$$



- Sensitivity to gluon distributions
- Challenges: tracking resolution is crucial
- First studies at low Q^2
  - Ratio yields 1 : 0.45 : 0.33 from STARlight paper
  - Fitted with the **Double-Sided Crystal Ball function**
  - $m_{\Upsilon nS} = m_{\Upsilon 1S} \frac{\mathrm{PDGmass}_{nS}}{\mathrm{PDGmass}_{1S}}$

left -> right: Different rapidity intervals

Early science: impact on CFFs



- Impact based on **DVCS only** and **no polarized protons** in the analysis
- Figures based on [*PRD* 112 (2025) 3, 036010]
- CFFs extracted by training an ensemble of neural nets on HERA data only (green slanted dashes) and additionally on simulated EIC data (red vertical dashes) at $Q^2 = 4\ \mathrm{GeV}^2$
- psudo-data used for the published paper, and based on fast smearing of ePIC and full simulation of FF detectors, are now rescaled to $1\mathrm{fb}^{-1}$ before fitting
- **Main takeaways:**
  - DVCS Beam spin asymmetries provide quantitative constraints for improving extraction of CFFs
  - Starts to pave the way for full EIC GPD program

Summary

- ✓ The EIC provides an unprecedented opportunity for the ultimate understanding of QCD
- ✓ The ePIC Collaboration was formed in Spring ‘22 with a successful merging of several proposal efforts
- ✓ Rich opportunities for hadron tomography **from the inception** of the EIC/ePIC running
  - ✓ *t*-differential cross sections and spin asymmetries (with all helicity configurations) can be **precisely measured** at ePIC
  - ✓ Sizable impact on CFFs of a proton
  - ✓ Access to gluon GPDs
  - ✓ Set the bases for the whole hadron femptoscopy program at ePIC

New excitement ahead

- o Event reconstruction at the ePIC experiment being finalized & novel analysis tools being developed
  - New, more realistic, impact studies
  - TDR has a chapter on physics studies
  - Report on Early Science
  - NIM A special issue