Multidimensional partonic imaging at the future Electron-Ion Collider

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ePIC

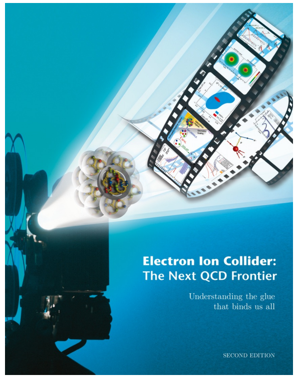
The 16th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon – MENU 2023

Mainz - October 16-20, 2023

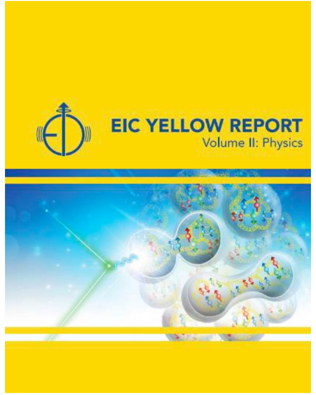
> 15 years of studies!

- More than a decade of studies:
  - INT report (2010)
  - White Paper (2015)
  - Yellow Report (2020)
  - Detector pre-proposals (2021-22)
  - ePIC Collaboration (> 2022)
- Presentation based on the work of many
  - Includes independent impact and performance studies

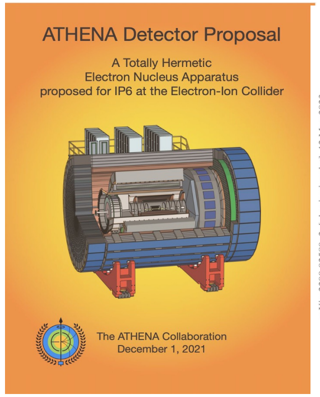
INT Report
arXiv:1108.1713



EIC Withe Paper
Eur. Phys. J. A (2016) 52: 268



EIC Yellow Report
Nucl.Phys.A 1026 (2022) 122447



ECCE: arXiv:2209.02580
ATHENA: JINST 17 (2022) 10, P10019
CORE: arXiv:2209.00496

The Electron-Ion Collider

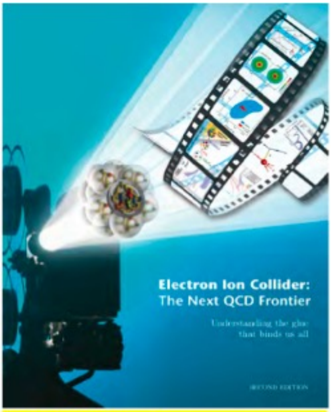
For e-N collisions at the EIC:

✓ **High Luminosity:** up to 10^{34} cm^{-2}sec^{-1}
100-1000 times HERA

✓ **Flexible √s** = 30-140 GeV (per nucleon)

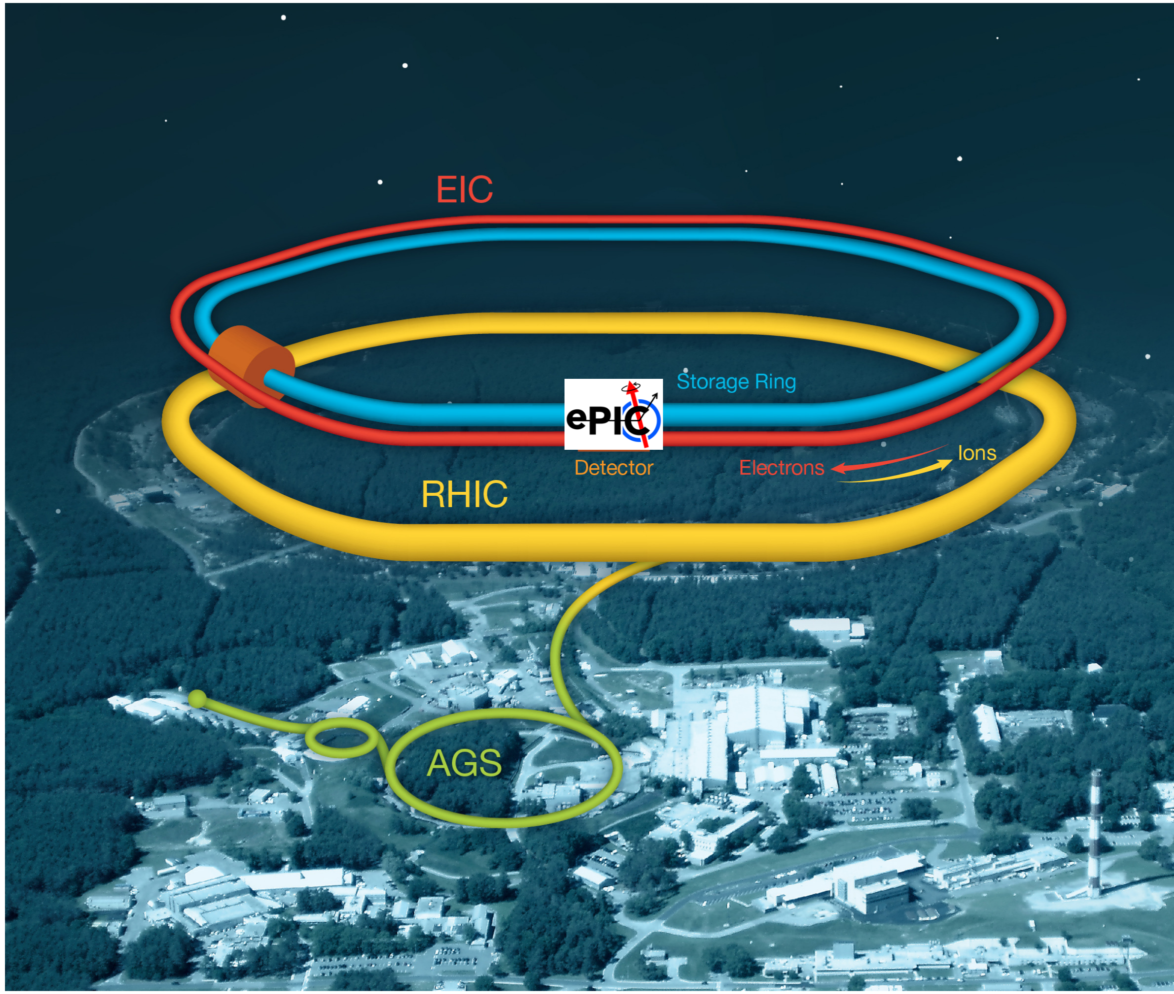
✓ **Highly polarized beams:** e (80%); p, D/^{3}He (70%)

✓ **Wide range of nuclear beams:** (D to Pb/U)

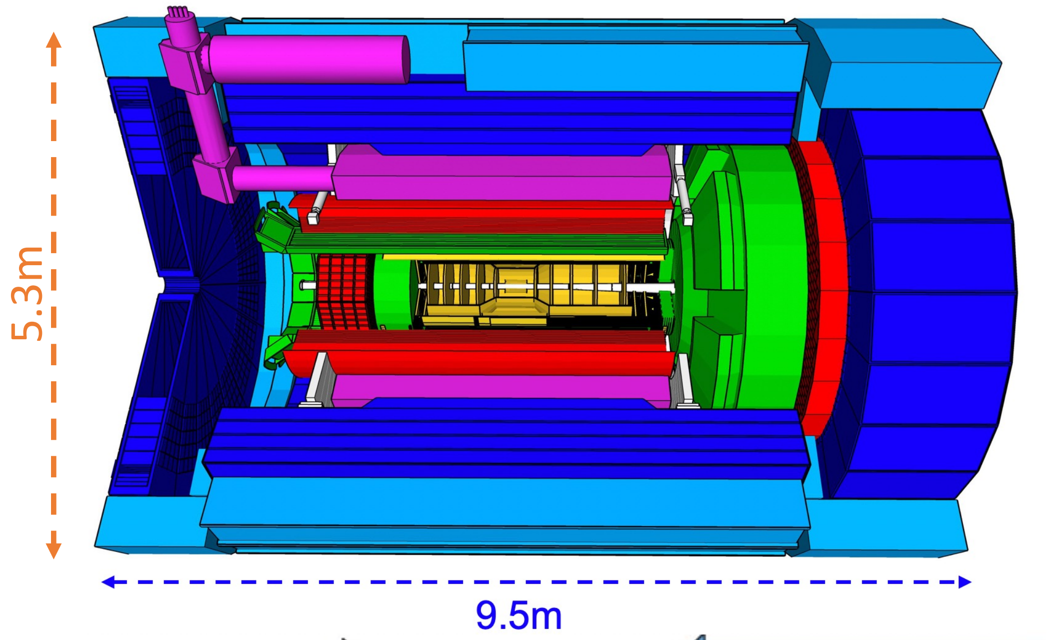


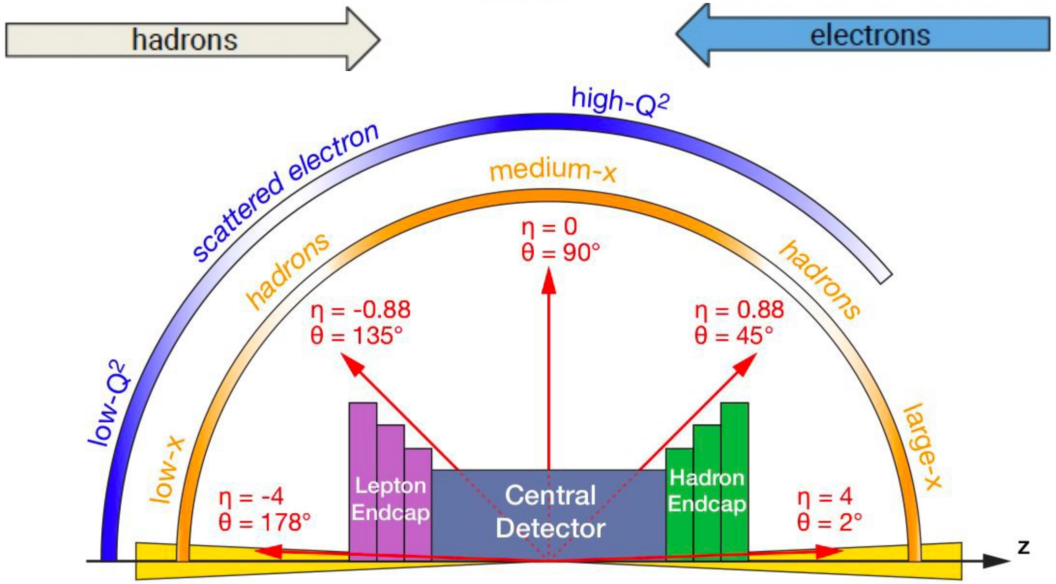
1212.1701.v3
A. Accardi et al
Eur. Phy. J. A, 52 9(2016)

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

Multidimensional imaging of quarks and gluons

Wigner functions

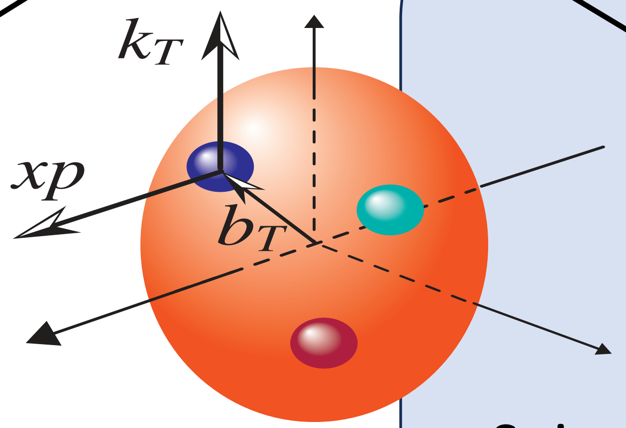
offer unprecedented insight into confinement and chiral symmetry breaking

$W(x,b_T,k_T)$

Momentum space

$\int d^2b_T$

$f(x,k_T)$



$\int d^2k_T$

Coordinate space

$f(x,b_T)$

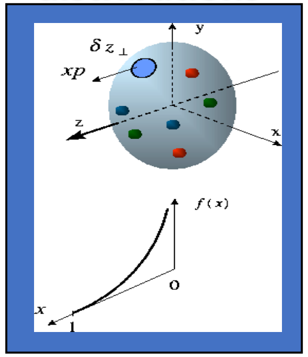
Spin-dependent 3D **momentum space** images from **semi-inclusive scattering** → Transverse-Momentum Depentent distributions (**TMDs**)

see also A. Vossen's talk

Spin-dependent 2D **coordinate space** (transverse) + 1D (longitudinal momentum) images from **exclusive scattering** →Generalized Parton Distributions (**GPDs**)

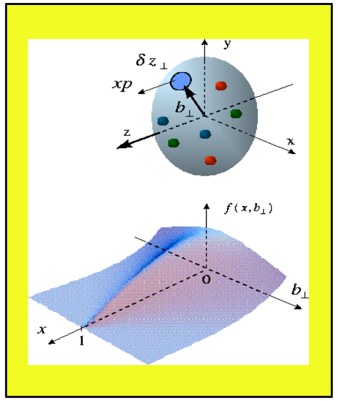
Generalized Parton Distributions

Longitudinal momentum & helicity distributions



$\boldsymbol{f(x)}$

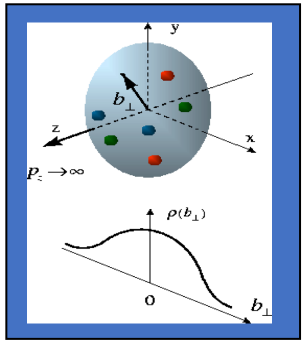
parton densities



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

GPDs

transverse charge & current densities



$\boldsymbol{F(t)}$

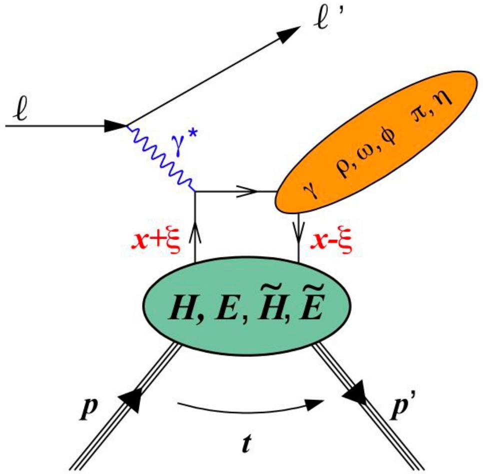
form factors

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**:

$$
\begin{aligned}
F^q &= \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ix\bar{P}^+z^-} \langle p'|\bar{q}(-\frac{1}{2}z)\gamma^+ q(\frac{1}{2}z)|p\rangle|_{z^+=0,\mathbf{z}=0} \\
&= \frac{1}{2\bar{P}^+}\left[H^q(x,\xi,t,\mu^2)\bar{u}(p')\gamma^+ u(p) + E^q(x,\xi,t,\mu^2)\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m_N}u(p)\right]
\end{aligned}
$$



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

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

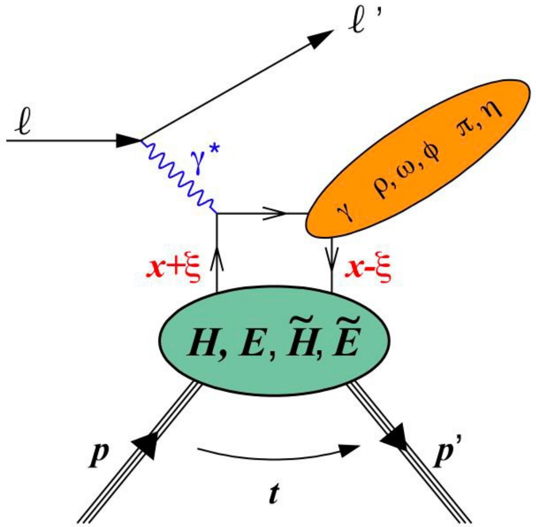
Connection to the **proton spin**: $J_q = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{1} dx\, x[H^q(x,\xi,t) + E^q(x,\xi,t)]$ $\qquad J_q = \frac{1}{2}\Delta\Sigma + L_q$

[X.D. Ji, Phys. Rev. Lett. 78, 610 (1997)]

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, Υ → 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

H^q E^q

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

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

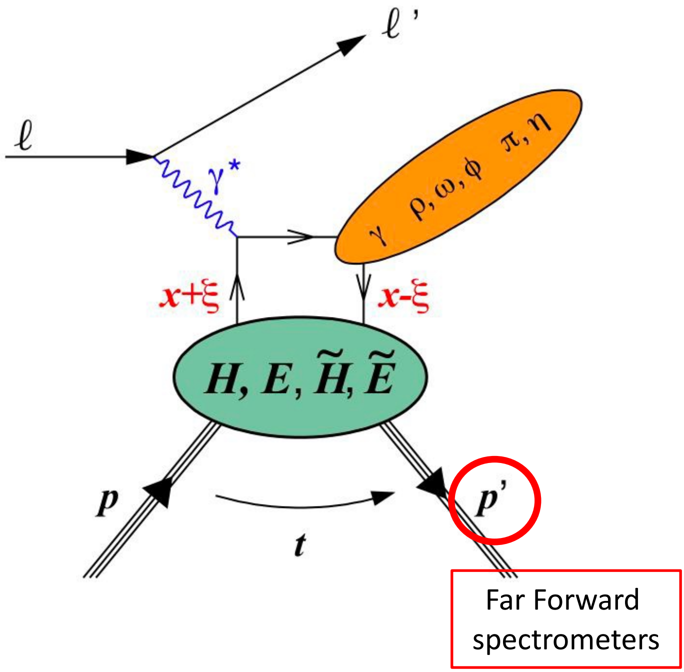
π^0	2Δu□Δd
η	2Δu–Δd

Accessing GPDs

$H^{q,g}(x,\xi,t)$	$E^{q,g}(x,\xi,t)$	*for sum over parton helicities*
$\widetilde{H}^{q,g}(x,\xi,t)$	$\widetilde{E}^{q,g}(x,\xi,t)$	*for difference over parton helicities*
nucleon helicity conserved	*nucleon helicity changed*	

The nucleon (spin-1/2) has **four quark and gluon GPDs**

Plus four helicity flip ones.



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

Dominated by H slightly dependent on E

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

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

[Requires a polarized proton target]

Responsible for total orbital angular momentum through Ji sum rule

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

Done @ HERA

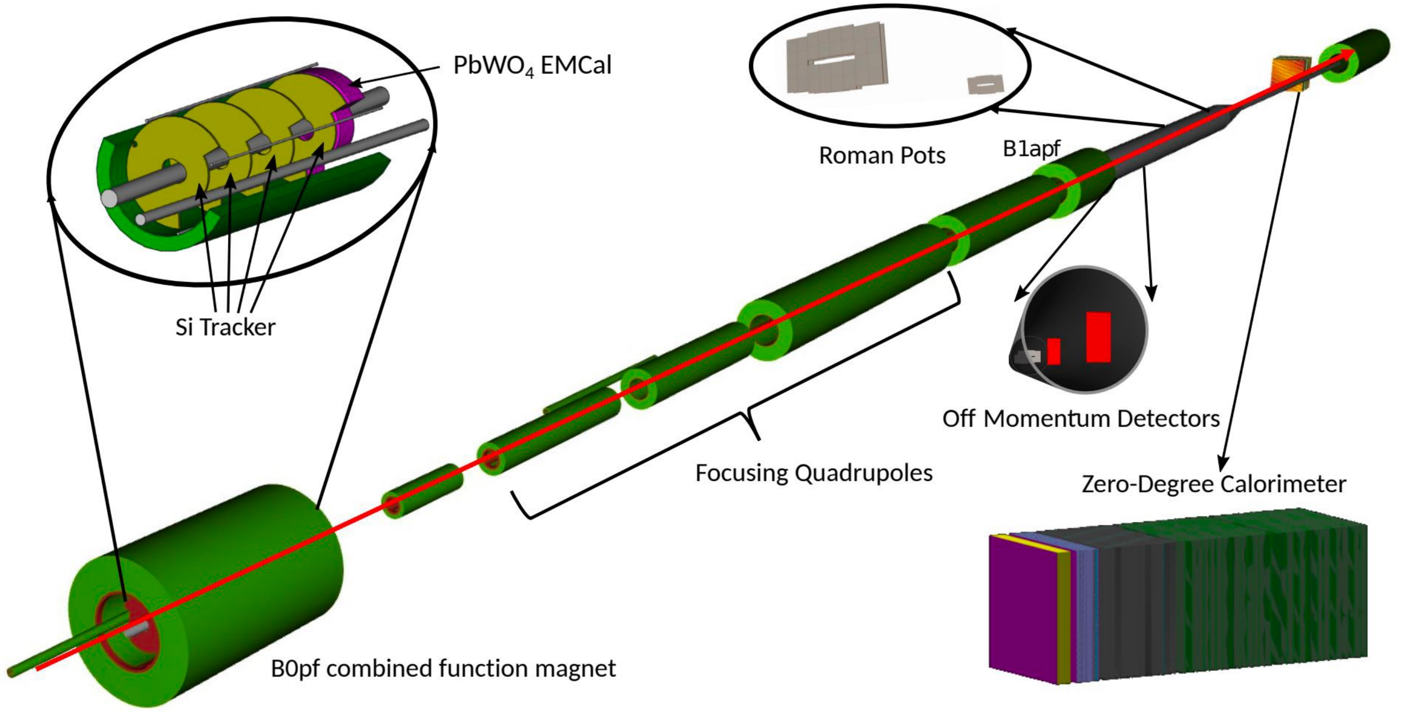
[Requires a positron beam]

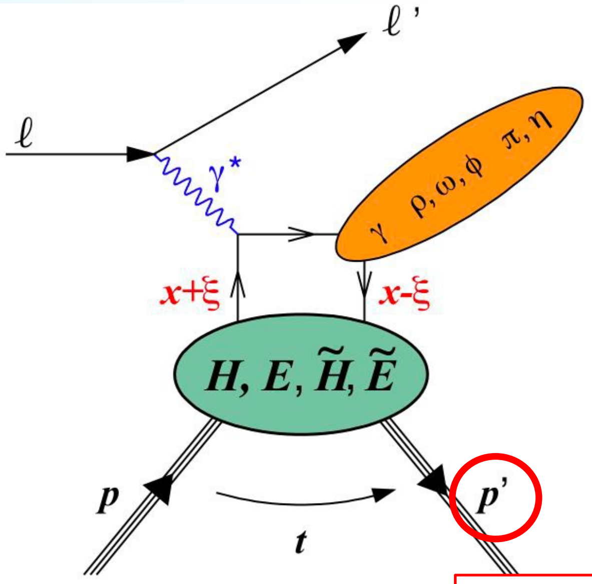
Alternatively: measure Time-like Compton Scattering (TCS)

Re(A) related to D-term, “last global unknown property” of a hadron, related to distribution of forces inside the nucleon

[M. V. Polyakov and P. Schweitzer, Int. J. Mod. Phys. A 33, no. 26, 1830025 (2018)]

Far forward detectors





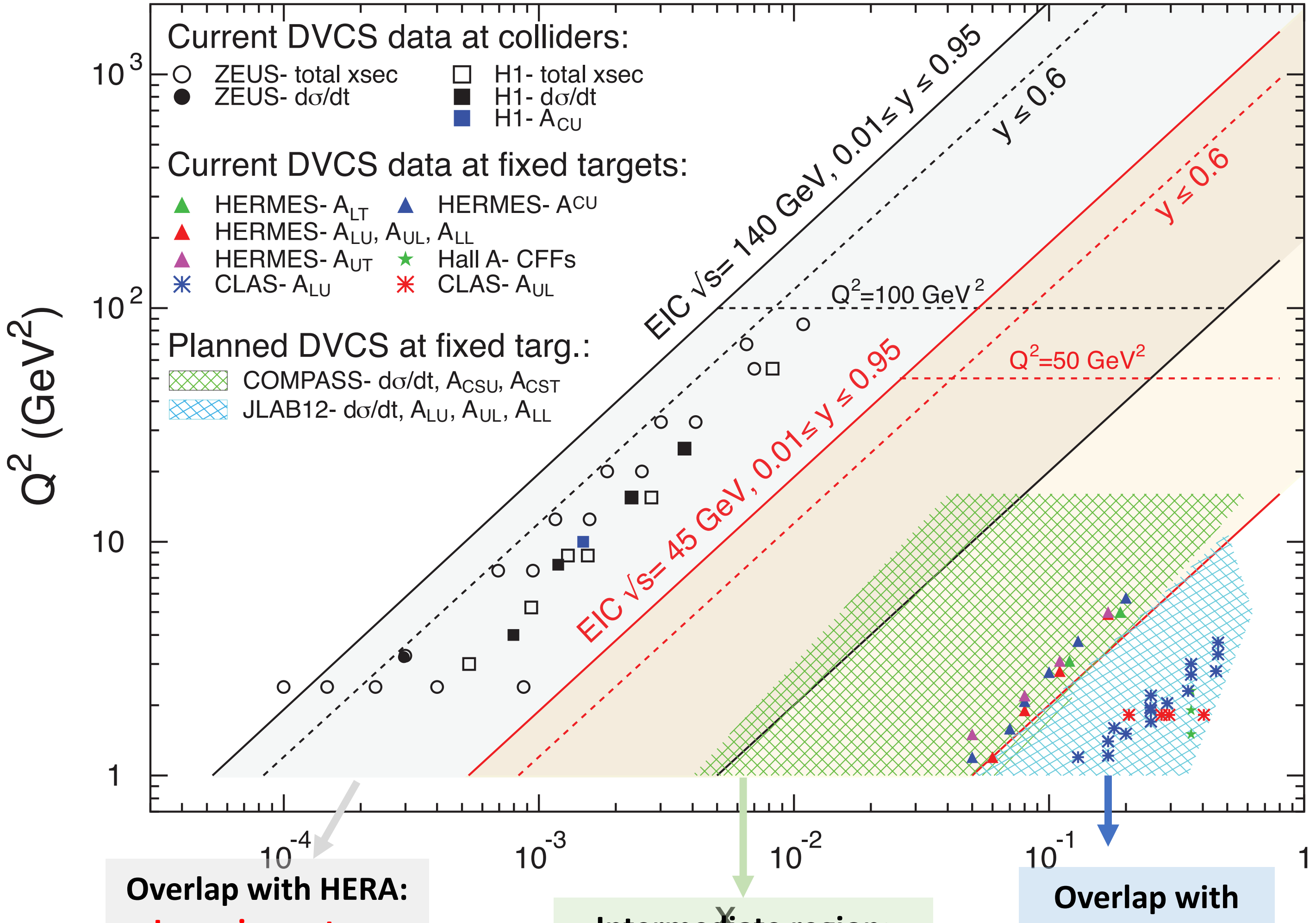
Far Forward spectrometers

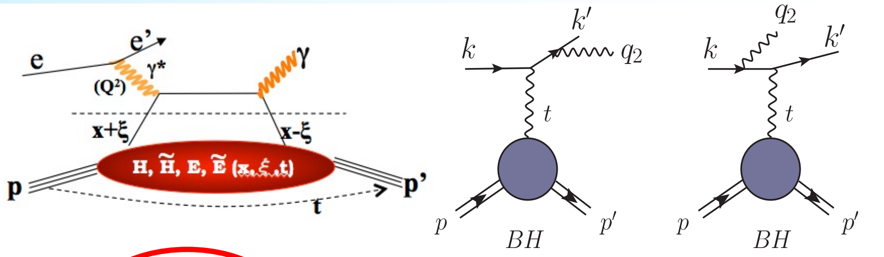
Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	θ < 5.5 mrad (η > 6)
Roman Pots (2 stations)	0.0 < θ < 5.0 mrad (η > 6)
Off-Momentum Detectors (2 stations)	θ < 5.0 mrad (η > 6)
B0 Detector	5.5 < θ < 20.0 mrad (4.6 < η < 5.9)

The impact parameter information encoded in $t = (p' - p)^2$

- Require accurate measurement of t across a wide range in ep collisions
- Scattered protons measured by
  - Roman Pots (low t)
  - B0 (higher t)

DVCS at the EIC





DVCS signal

Bethe-Heitler QED bkgd.

HERA results limited by lack of statistics

EIC: the first machine to measure cross sections and asymmetries

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

Overlap with HERA:
Large impact on current fits at low x

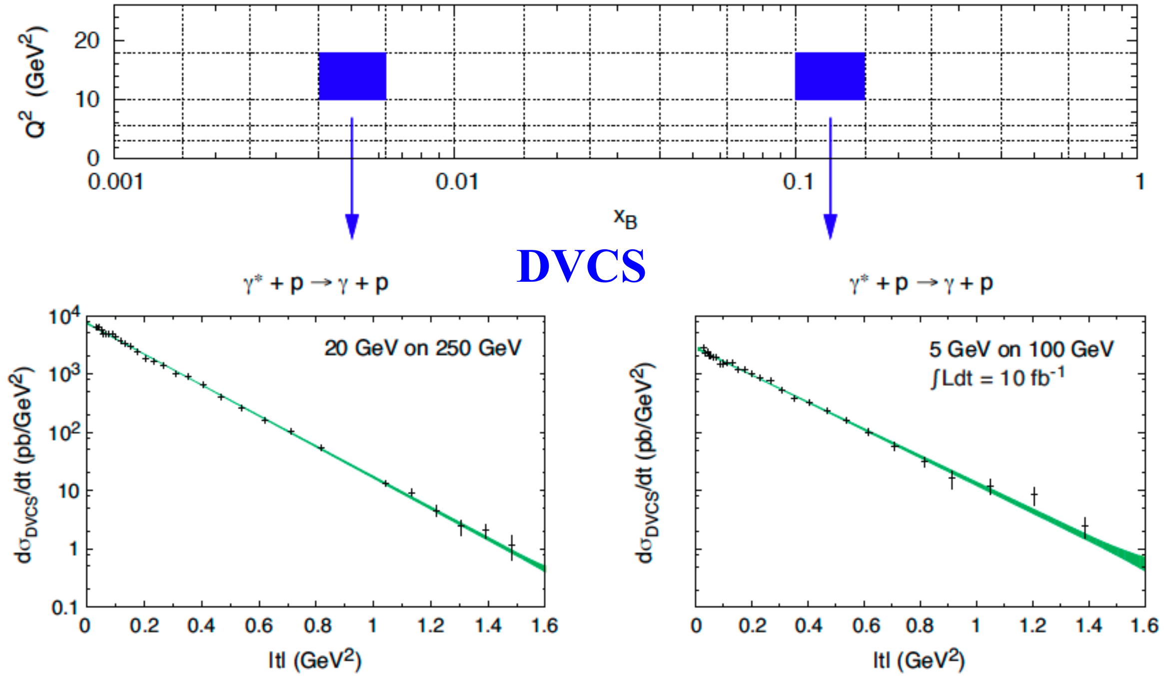
Intermediate region:
Fine mapping of the GPDs evolution

Overlap with JLAB12:
Sanity check

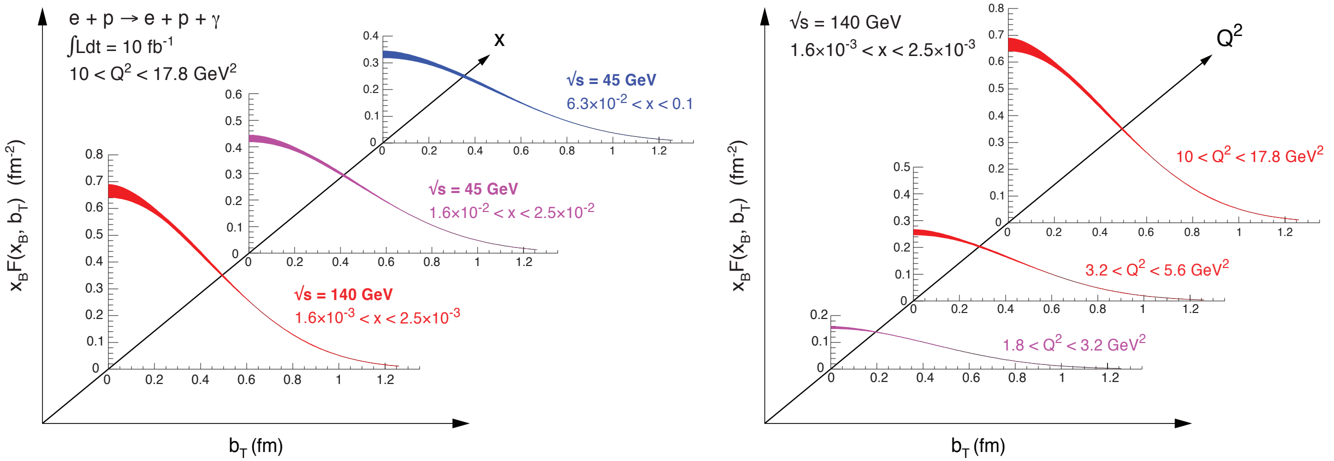
DVCS – differential cross section

$$\int L = 10fb^{-1}$$

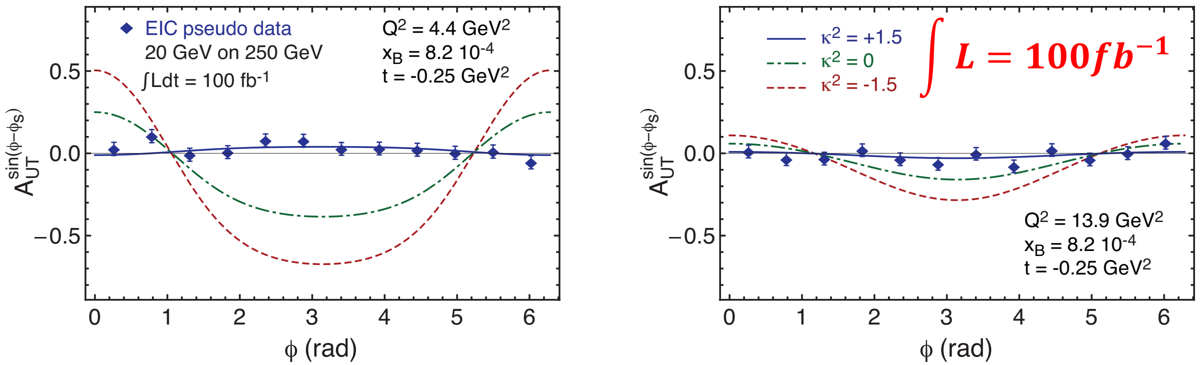
EIC White Paper



- **L = 10 fb^{-1} per energy configuration**
- **Measurement dominated by systematics**
- Fine binning in a wide range of x-Q^2 needed for GPDs
- **Assumed t-range:** $0.03 < |t|\ (\mathrm{GeV}^2) < 1.6$
- Fourier transform of $d\sigma/dt$ → partonic profiles



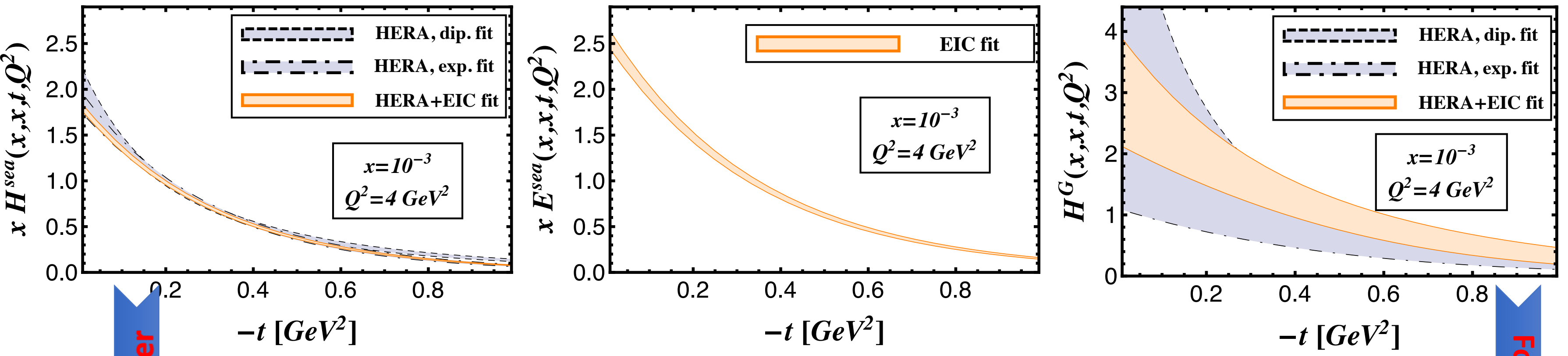
E.C. Aschenauer, S. F., K. Kumerički, D. Müller [JHEP09(2013)093]



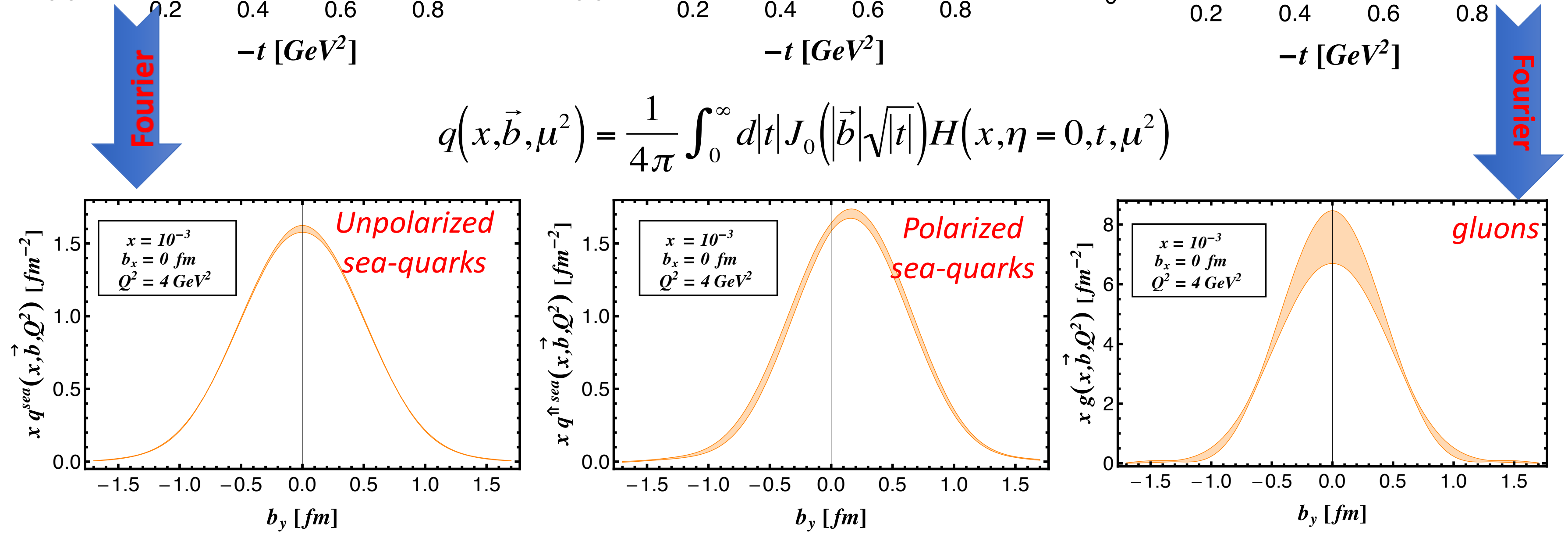
Theory curves show different assumptions for E

DVCS-based spatial imaging

E.C. Aschenauer, S. F., K. Kumerički, D. Müller [JHEP09(2013)093]



$$q\left(x,\vec{b},\mu^2\right)=\frac{1}{4\pi}\int_0^\infty d|t|\,J_0\left(|\vec{b}|\sqrt{|t|}\right)H\left(x,\eta=0,t,\mu^2\right)$$



- A global fit over all mock data was done, based on: [Nuclear Physics B 794 (2008) 244–323]
- Known values *q(x)*, *g(x)* are assumed for H^q, H^g (at t=0 forward limits E^q, E^g are unknown)

- **Take this with a grain of salt!**
  - **Depends on models, simulations…**
  - **It's a proof of principle to show accuracy of a possible extraction**

Much still to be investigated!

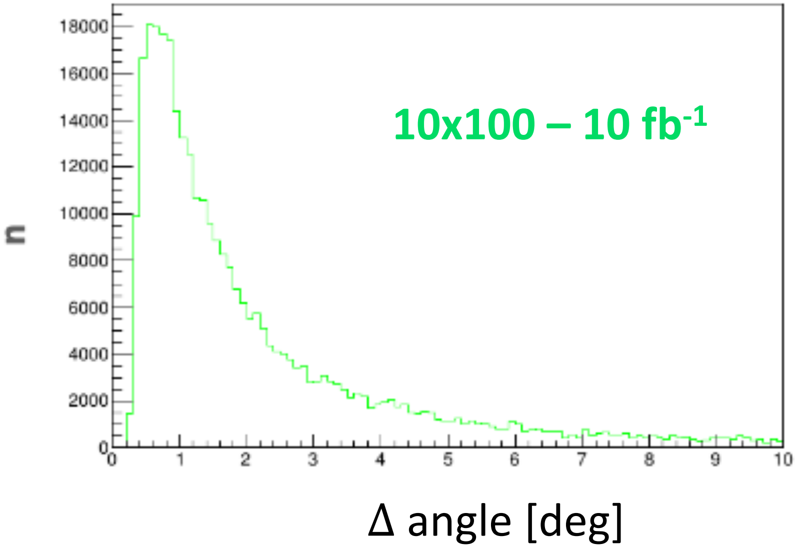
- Gluon GPD H can be much improved by including J/ψ
- Access to gluon GPD E → orbital momentum (Ji sum rule)
- Flavor Separation of GPDs (VMP and/or DVCS on deuteron)
- Nuclear imaging (modification of GPDs in p+A collisions)

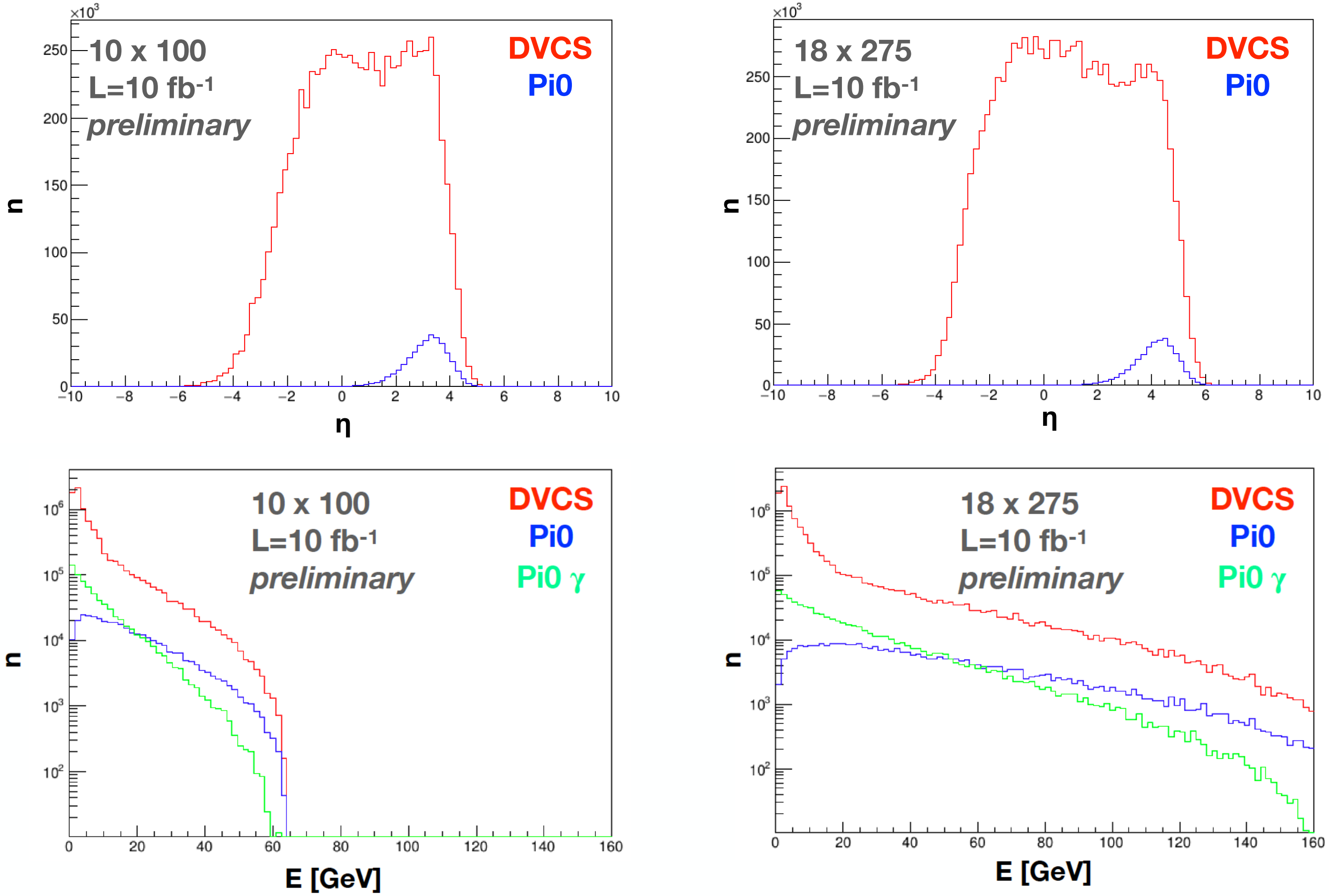
DVCS vs exclusive π^0

$\int L = 10\ fb^{-1}$

EIC Yellow Report

- Why we worry about a background from "$\pi^0 \rightarrow \gamma\gamma$" ?
  1) The two decay photons could merge into one
  2) One of the photons could go out of the acceptance
- Study based on Goloskokov-Kroll model





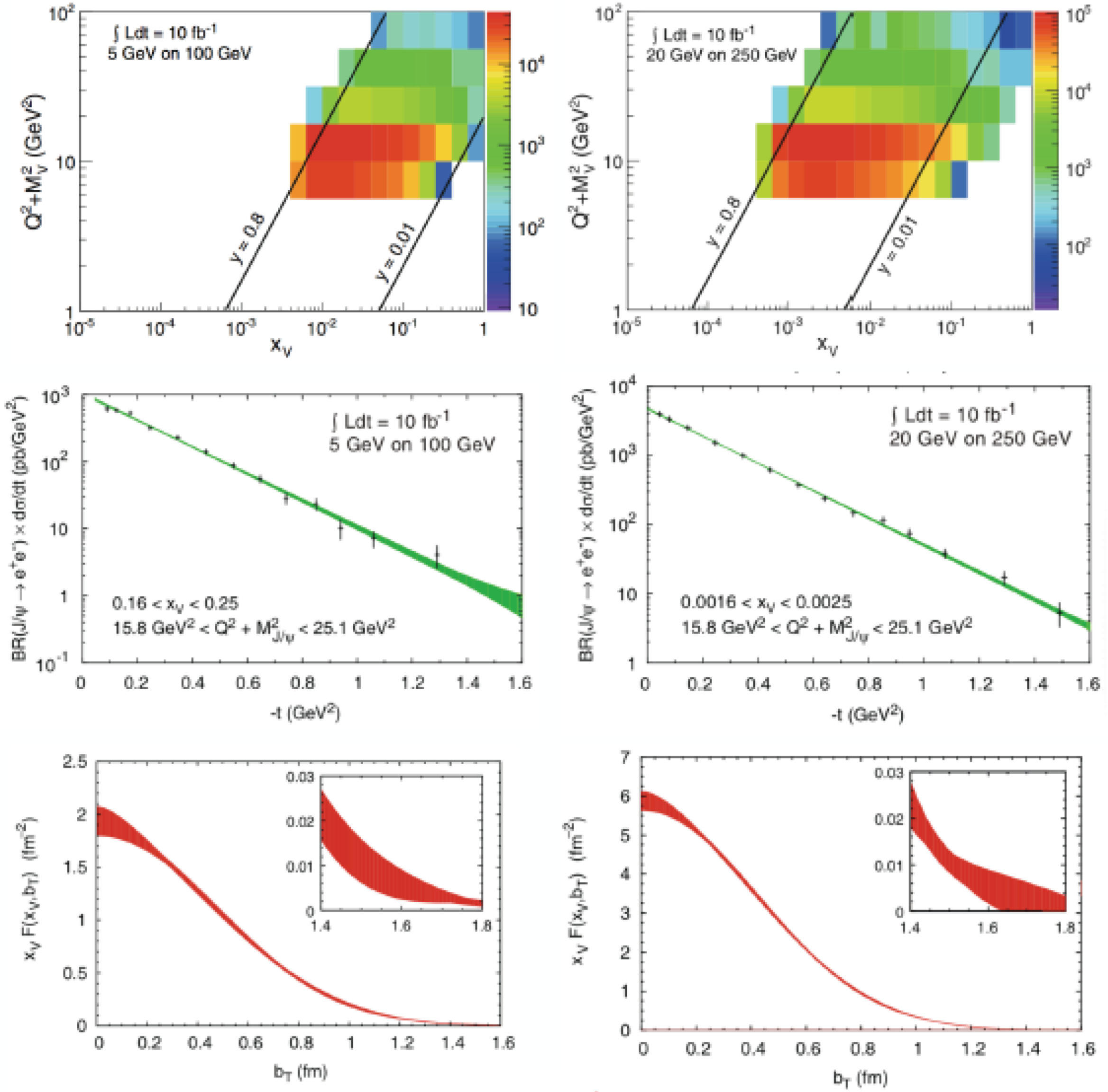
Take away message:

- π^0 x-sec lower than signal (DVCS)
- Min 2γ angle: ~0.2 deg
- Exclusive π^0 can reach high momentum/energy (but xSec decreases with meson's energy)

Imaging gluons with J/ψ

$\int L = 10\, fb^{-1}$

EIC White Paper



Average densities

Challenges of VMP

- Uncertainty on wave function
- measuring muon vs electron decay channel

○ **We simulated the J/ψ cross section, extracted the Fourier transform but never included it on GPDs fits**

➢ Measurement dominated by systematics at low |t|

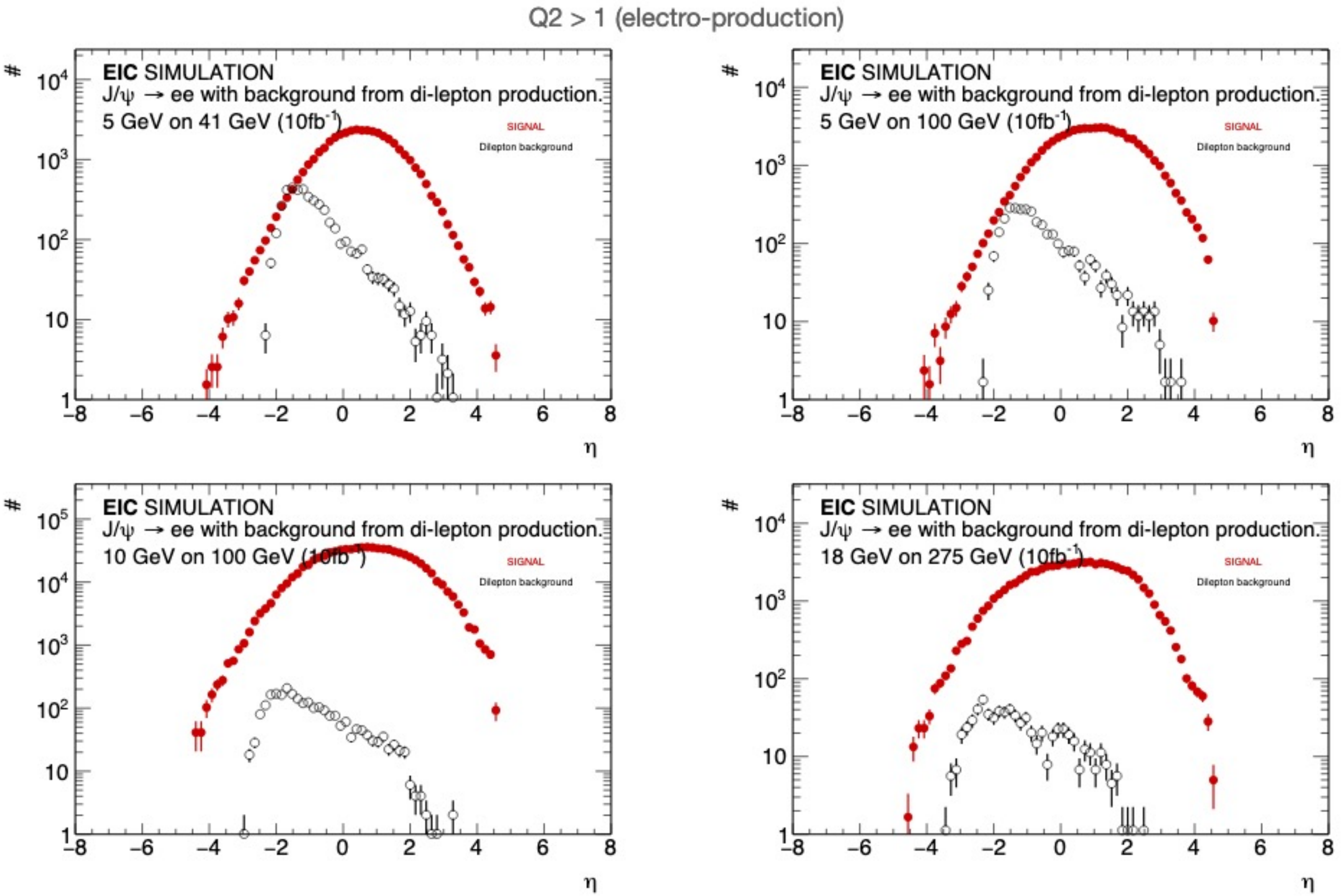
➢ **Large-$|t|$ spectrum would benefit of collecting more luminosity**

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

J/ψ signal vs background

$\int L = 10\ fb^{-1}$

EIC Yellow Report



Studies by: Sylvester Joosten (ANL)

Comparisons of **signal** and **di-lepton background** (empty circles)

- Basic analysis cuts applied
- **Electroproduction** (Q^2>1GeV^2): Di-lepton background under control at all energies for heavy mesons [J/ψ; Υ]
- **photoproduction** (Q^2~0): at lower energies, di-lepton higher that signal at backward rapidities: η<-2 (J/ψ) and η<-3 (Υ)

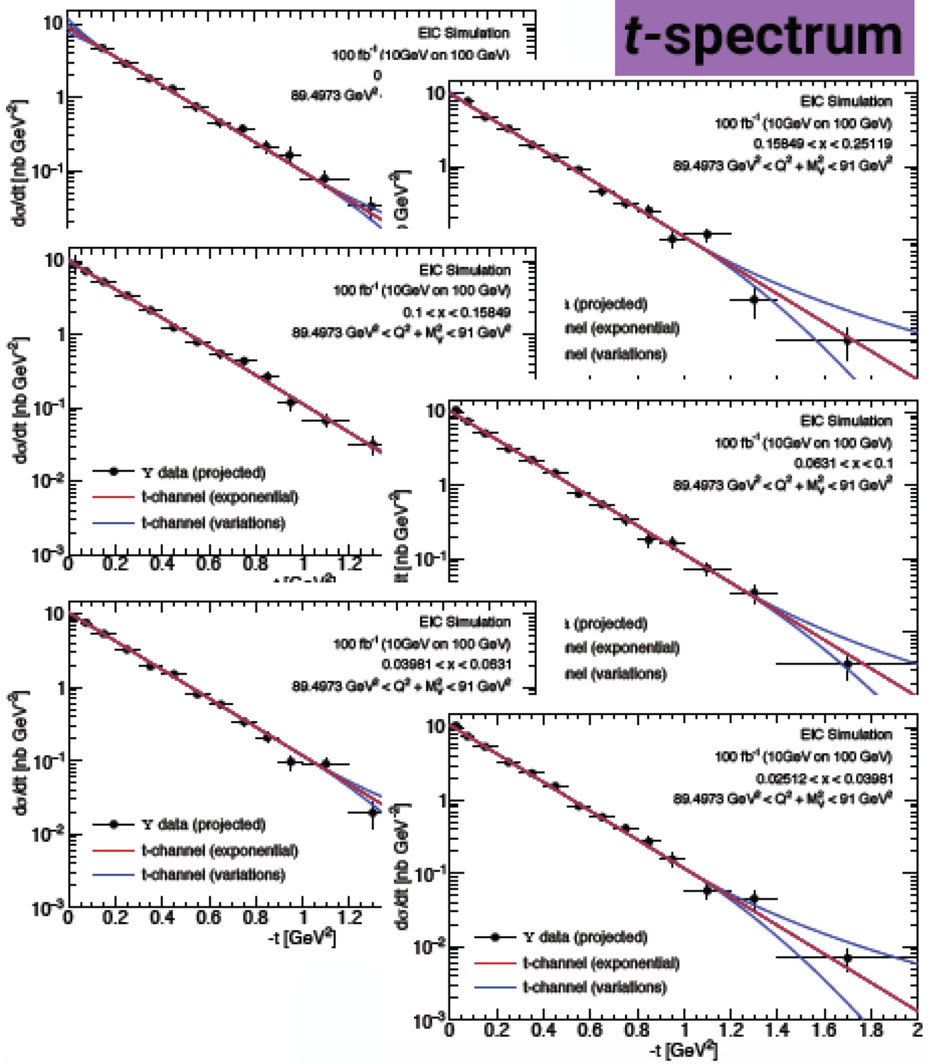
Imaging gluons with Υ(1s)

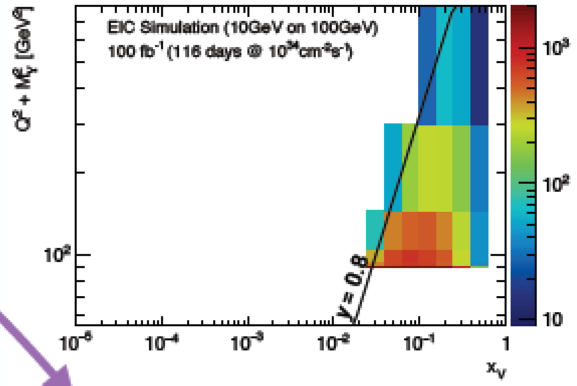
$\int L = 100\ fb^{-1}$

EIC Yellow Report

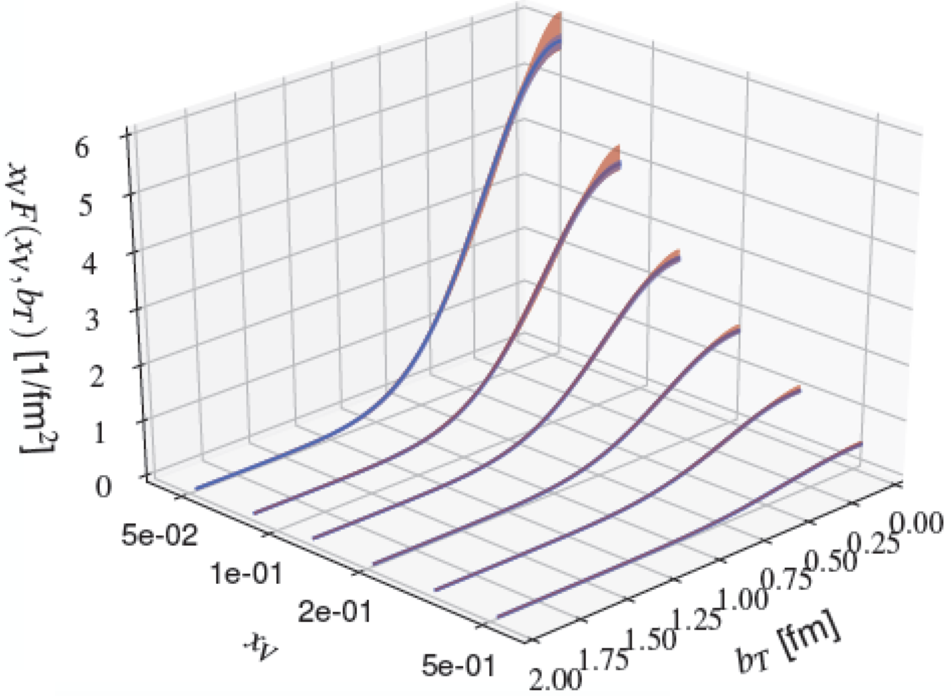
- ☆ Nominal EIC detector
- ☆ 10x more luminosity
- ☆ Electron and muon channels

t-spectrum





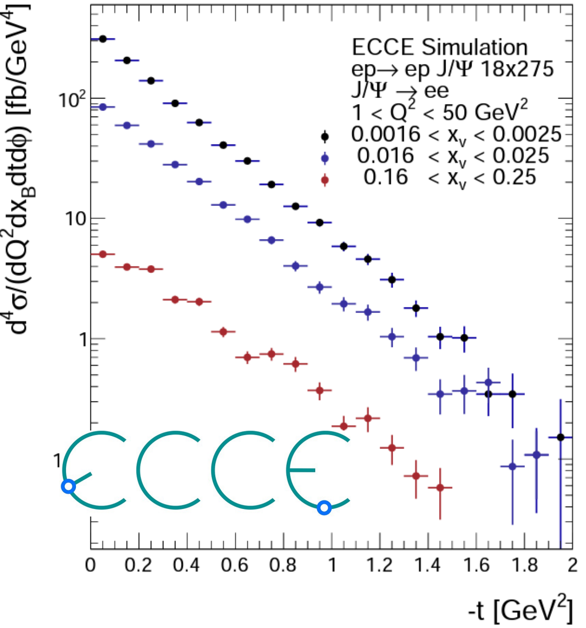
Average gluon density:

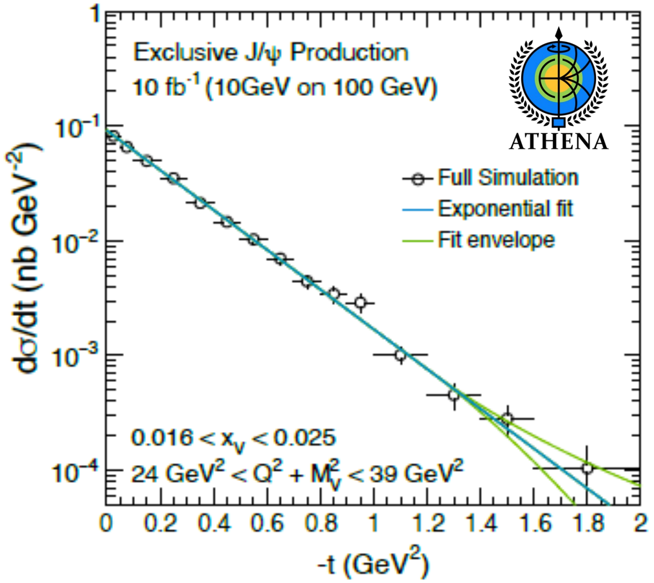


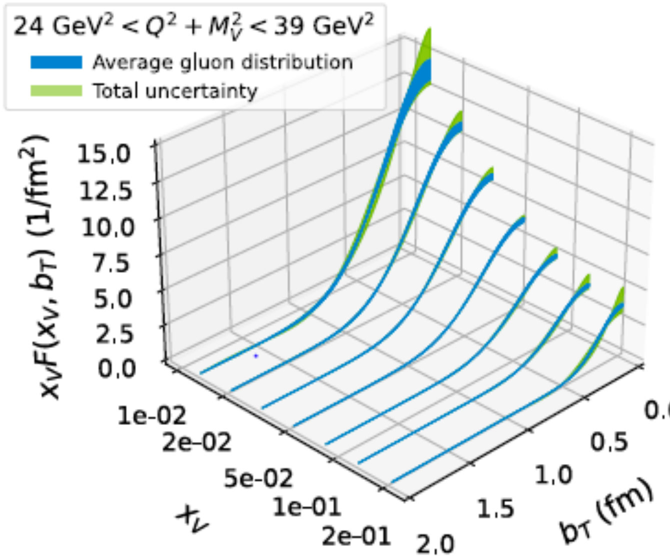
Studies by:
Sylvester Joosten (ANL)

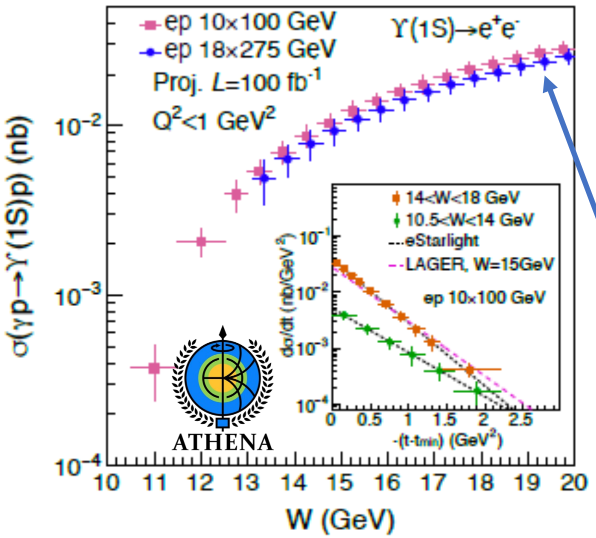
Detector Proposals- VMs

$\vec{e} + \vec{p} \rightarrow e + p + \vec{V}$









$\boxed{\int L = 100 fb^{-1}}$

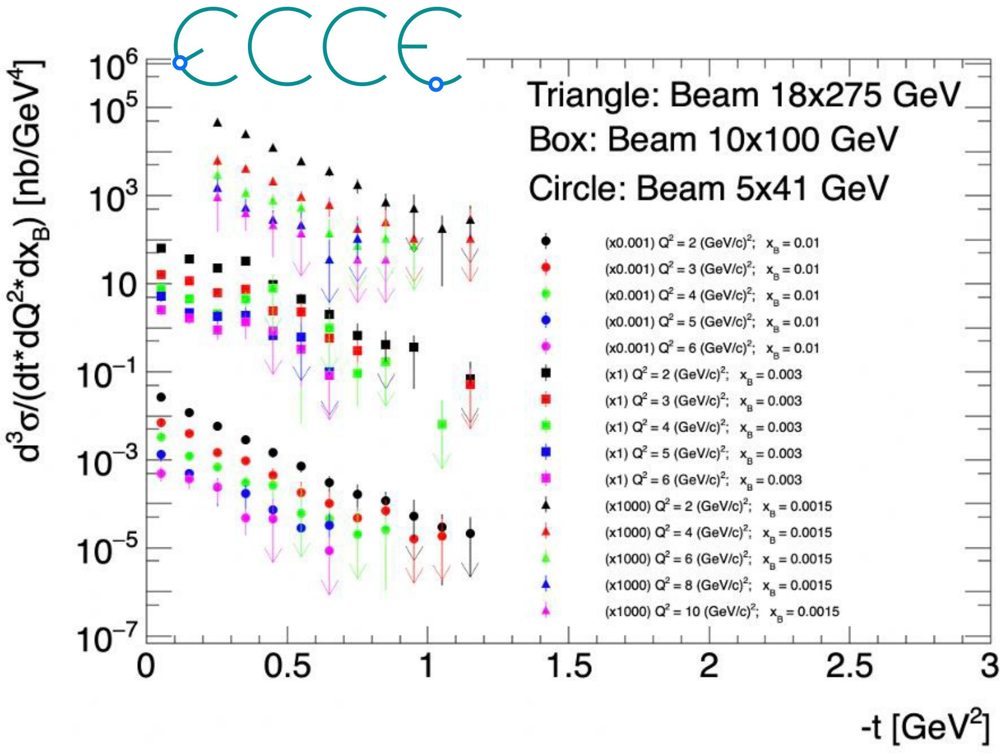
Υ Photopoduction near threshold
-> origin of p-mass

Key:

- γ/π^0 separation in ECAL for DVCS
- Acceptance and low material for VM decay leptons
- Resolution of lepton pair inv. mass
- Muon id
- Scattered electrons over full kinem.
- t- lever arm in FF spectrometers

Detector Proposals- DVCS/TCS

Key:
- Acceptance (including FF)
- γ/π^0 separation in ECAL
- t- lever arm in FF spectrometers

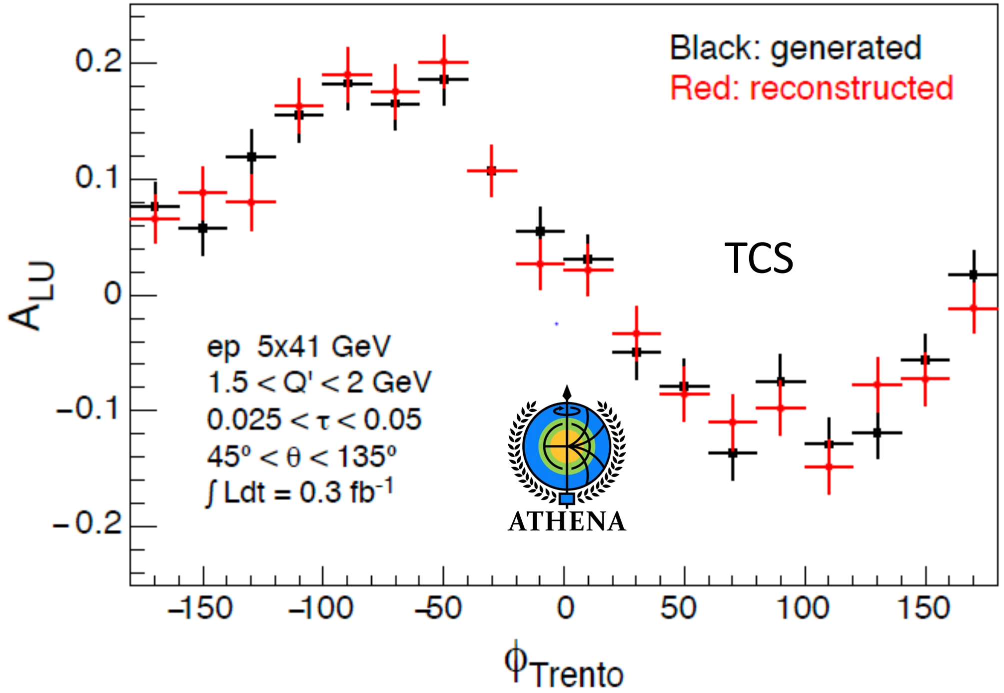


Observables:

$d\sigma/dt$; A_{LU}; A_{UT}

Asymmetries (DVCS & TCS):

GPDs via amplitude-level interference with BH

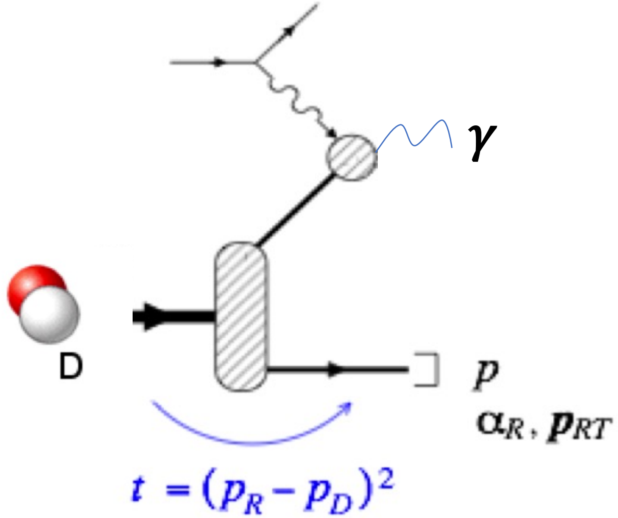


Timelike Compton Scattering (TCS)

$\gamma p \rightarrow \gamma^* p \; (\gamma^* \rightarrow l^+ l^-)$

- Q': invariant mass of $l^+ l^-$
- $\tau = Q^2 = \left(s - m_p^2\right)$ equivalent to x_B

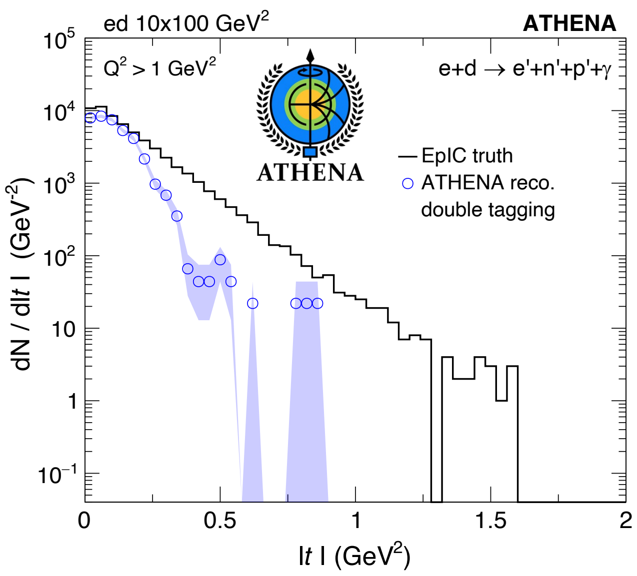
Study of neutrons with light nuclei

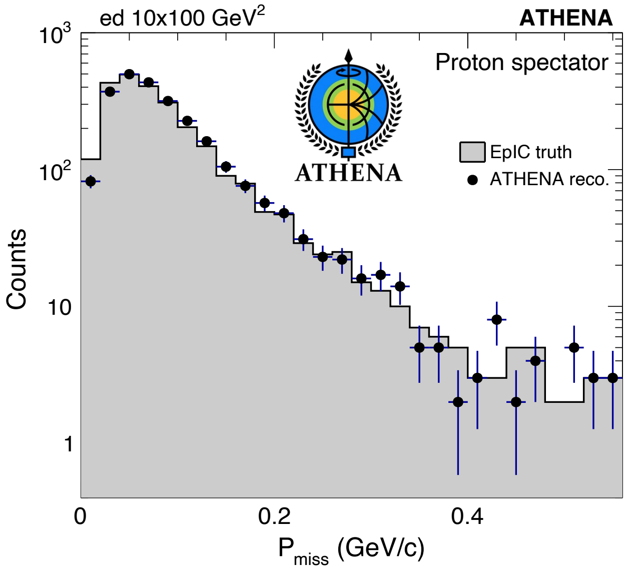


- Possibility to study neutron structure
- DVCS on neutron compared to proton is important for flavor u/d separation

DVCS on incoherent D (D breaks up) but coherent on the neutron, the "double tagging" method

- **Tag DIS on a neutron (by the ZDC)**
- **Measure the recoil proton momentum**
- Gives you a free neutron structure, not affected by final state interactions





ATHENA – DVCS on e+D:

- 80-90% acceptance at low |t|,
- |t|-acceptance loss at higher value mostly due to the loss in tagging the active neutron in ZDC.
- Alternatively, |t| can be measured via scattered *e* and γ → higher acceptance at large |t|.
- Proton momentum is well reconstructed

Multidimensional imaging of quarks and gluons

Wigner functions

offer unprecedented insight into confinement and chiral symmetry breaking

$W(x, b_T, k_T)$

Momentum space

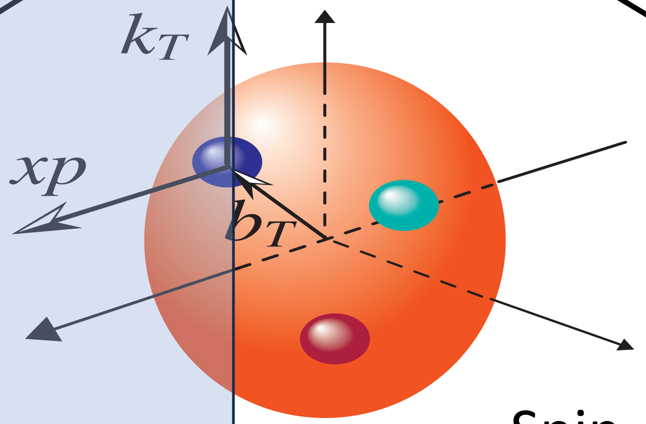
$\int d^2 b_T$

$f(x, k_T)$

$\int d^2 k_T$

Coordinate space

$f(x, b_T)$



Spin-dependent 3D **momentum space** images from **semi-inclusive scattering** → **TMDs**

Spin-dependent 2D **coordinate space** (transverse) + 1D (longitudinal momentum) images from **exclusive scattering** → **GPDs**

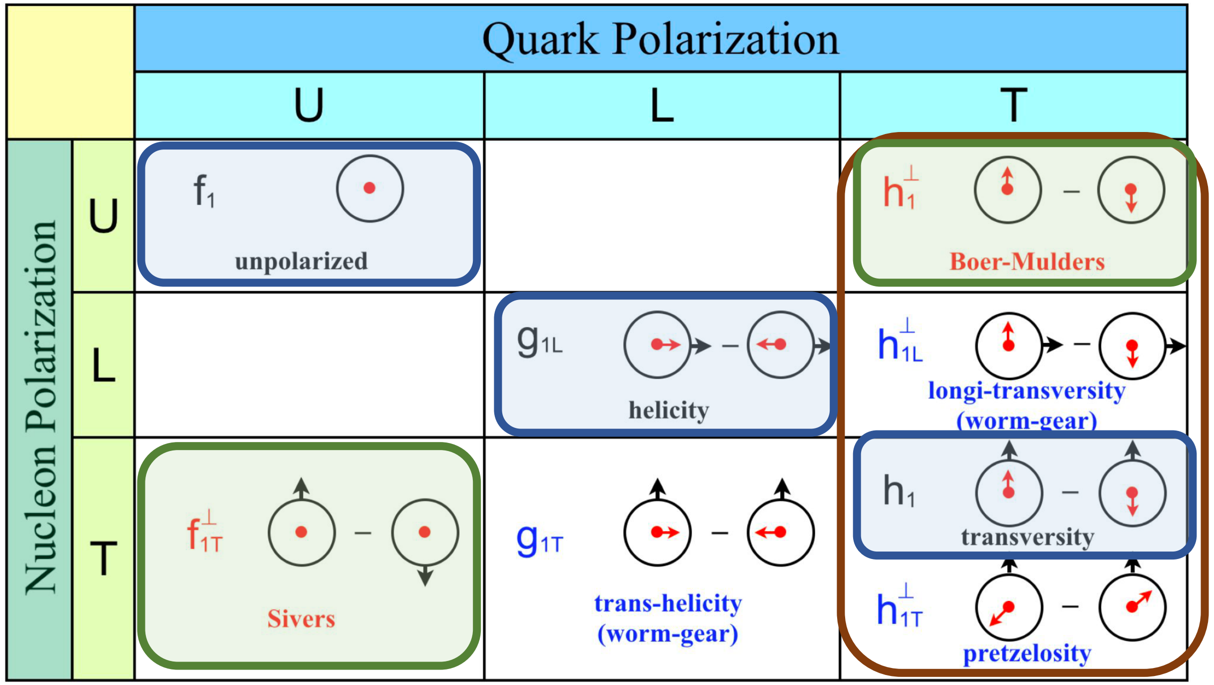
TMDs

TMDs surviving integration over k_T

Time-reversal odd TMDs describing **strength of spin-orbit correlations**

Chiral odd TMDs

Note: off-diagonal part vanishes without parton's transverse motion



Non-zero strength of spin-orbit correlations non-zero → indication of parton OAM

- **Sivers:** correlations of transverse-spin direction and the parton transverse momentum
- **Boer-Mulders:** correlations of parton transverse spin and parton transverse momentum
- Collins: fragmentation of a transversely polarized parton into a final-state hadron

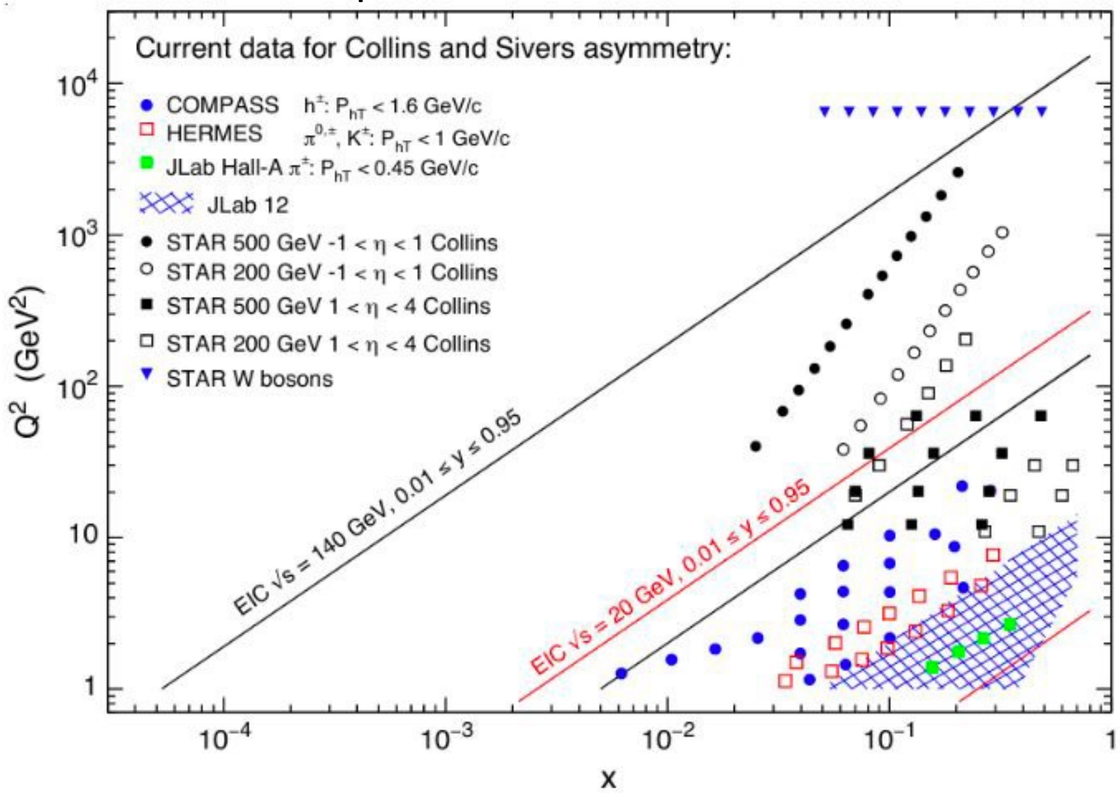
Momentum tomography

EIC will access TMDs primarily through SIDIS for single hadrons, as well as other semi-inclusive processes with the production of di-hadrons and jets

What we want to measure: $$\frac{d\sigma}{dx\,dQ^2\,dz\,d\phi_S\,d\phi_h\,dp_T^h}$$

- **6-fold differential cross sections in SIDIS**
- **Azimuthal asymmetries and their modulations**

EIC Yellow Report: kin. reach for Sivers and Collins

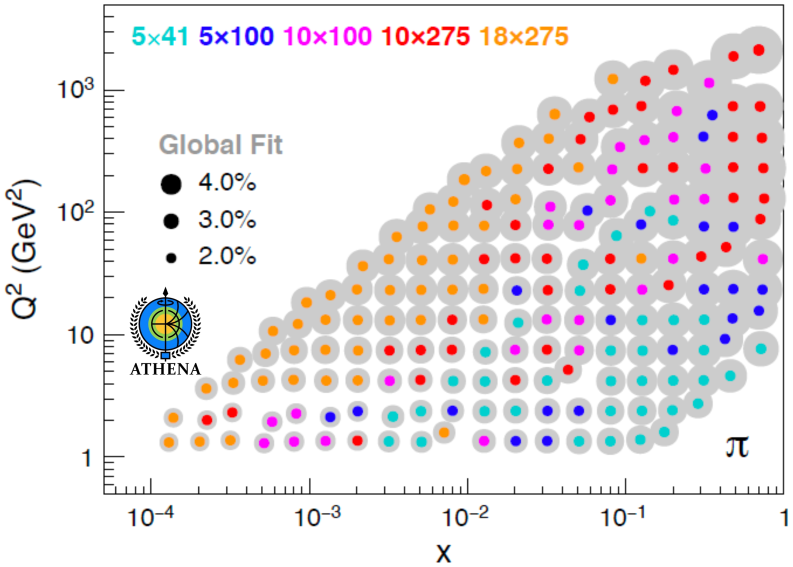


EIC envisions a rich program to probe spin-orbit effects within the proton and during hadronization, and explore the 3D spin structure of the proton in momentum space

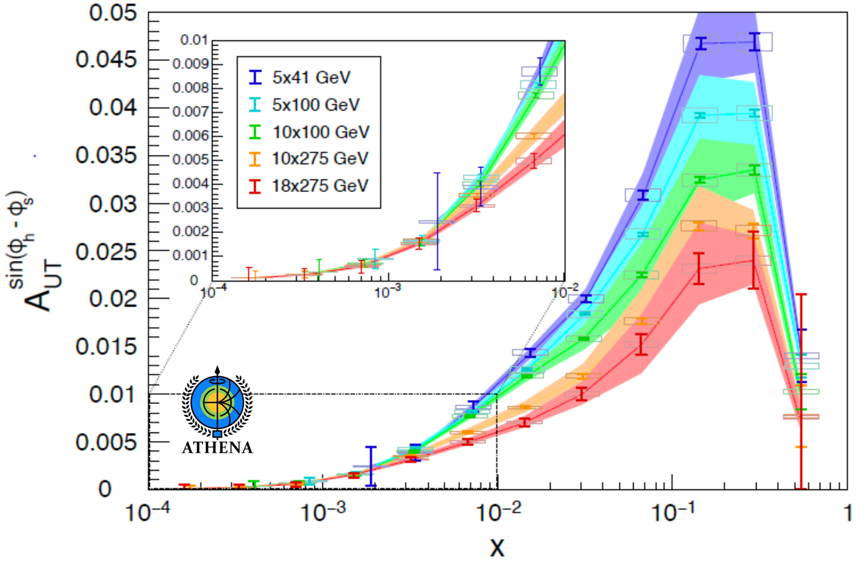
- Extends the SiDIS kinematic coverage of an order ~2 in both x and Q^2

Momentum tomography – SIDIS, Heavy Flavor, Jets

Unpolarized cross section uncertainties

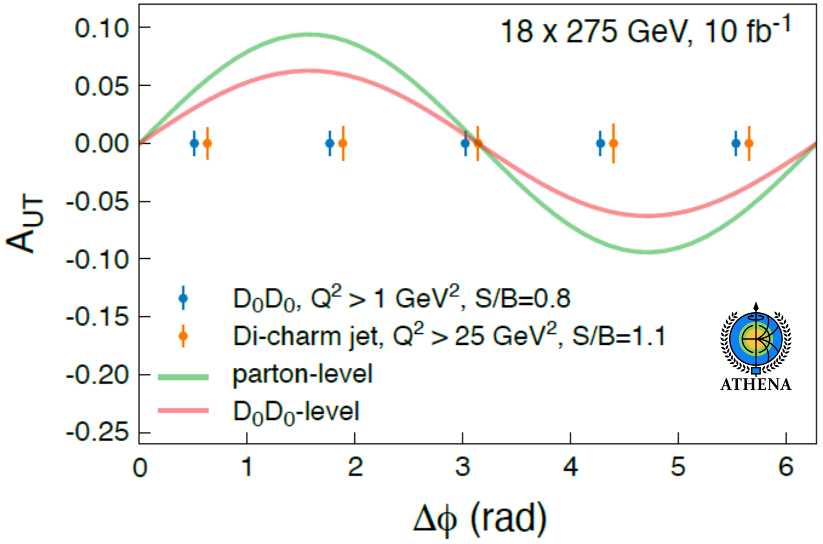


Projected Sievers asymmetries

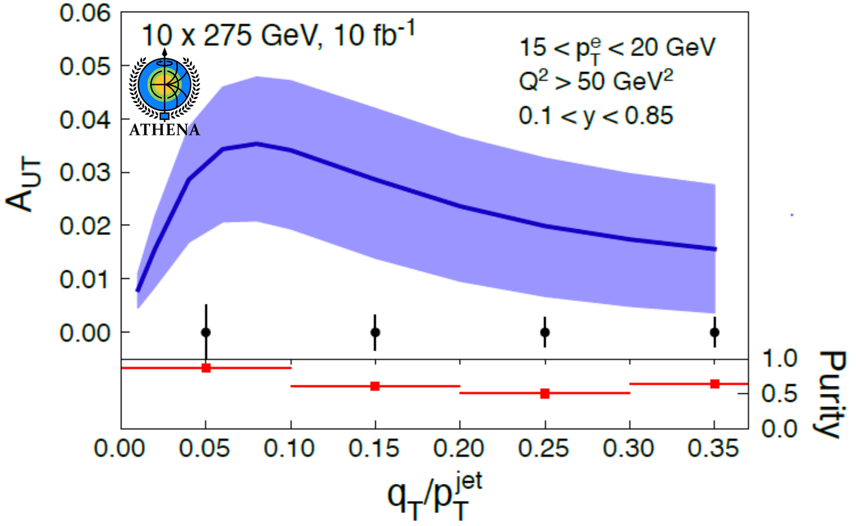


Heavy flavor

Sensitivity for Sivers in di-charm



Sensitivity for Sivers in **lepton-jet**



Jets:

- excellent proxies for partons
- probe **quark TMDs** without convolution with FF
- di-jets can probe **gluon Sivers**

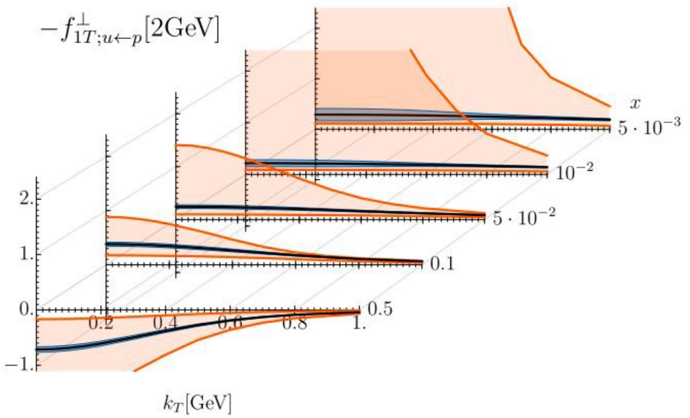
Key det. performance:

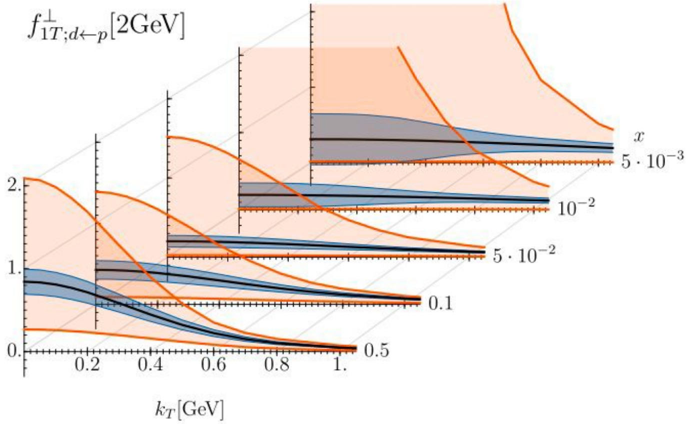
- Azimuthal acceptance
- PID
- Acceptance
- Vertexing (heavy flavor)
- Quality of tracking
- HCal (for jets)

TMDs: Impact Studies

Expected impact on *u* and *d* quark Sivers distributions

R. Seidl, et al. (ECCE), Nucl.Instrum.Meth.A 1049 (2023) 168017



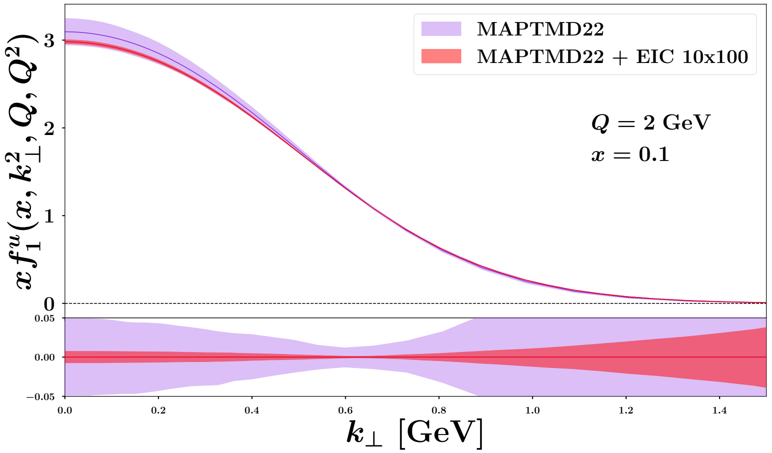


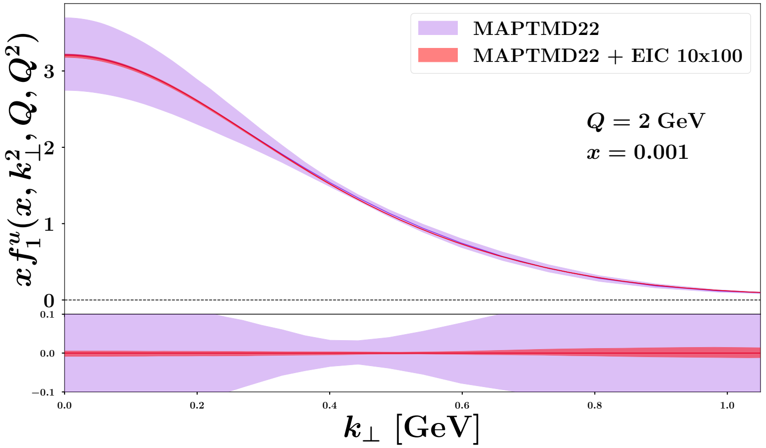
- Valence region TMDs still have significant uncertainties
- Severe lack of experimental data for sea quarks and gluons
- **EIC has transformative potential for understanding the proton's 3D structure in momentum space**

Expected impact unpolarized *u* quark

Map Collaboration impact studies

Courtesy of A. Bacchetta & M. Radici





see also A. Vossen's talk

Summary

e+p(A) physics program at EIC provides an unprecedented opportunity to study quarks and gluons in free protons and nuclei

Imaging in coordinate space

- Accurate 2+1D imaging of the polarized and unpolarized quarks and gluons inside the hadrons, and their correlations
  - extraction of the whole set of GPDs from DVCS, TCS and HEMP
  - access to gluons, orbital momentum, D-term, proton mass

Imaging in momentum space

- Precise measurements of SiDIS and jets over an extended phase space
  - Impact studies show transformative potential for TMDs studies

New excitement ahead

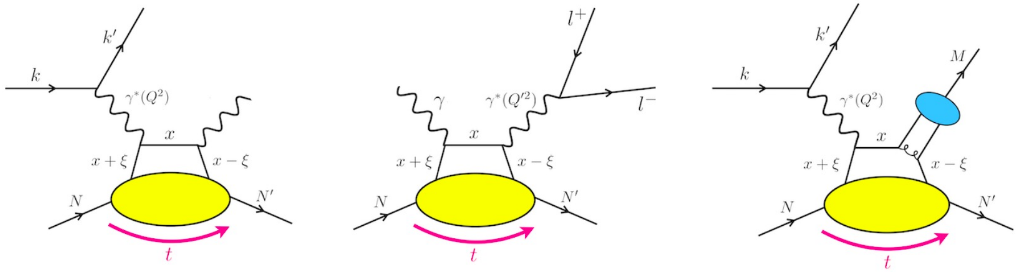
- New generators and common platforms
- Event reconstruction at the ePIC experiment being finalized
  - New, more realistic, impact studies
- Extraction of GPDs from light nuclei is being investigated at ePIC


BACKUP

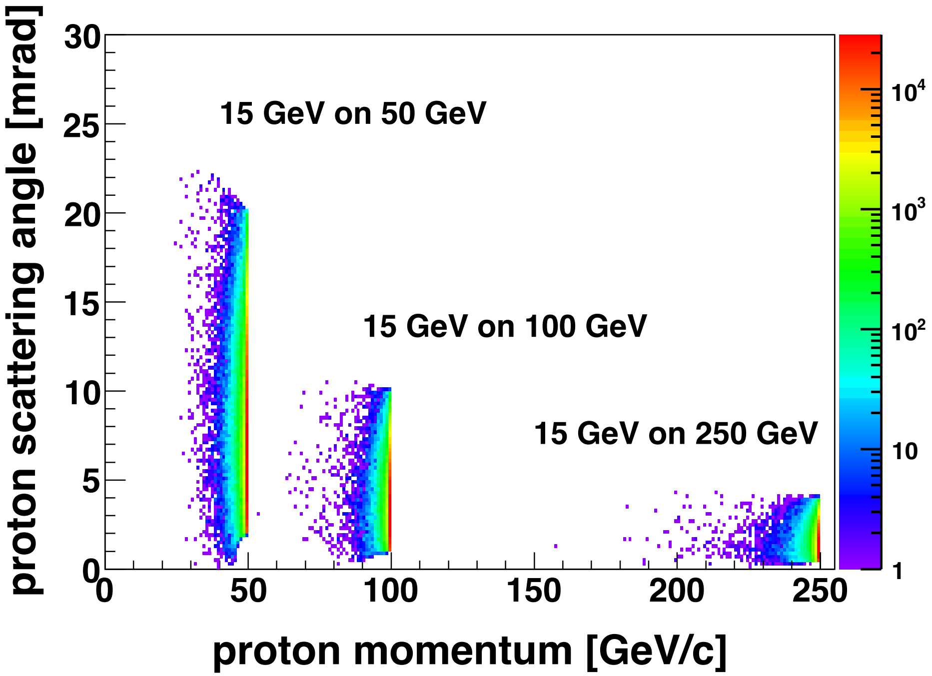
The EpIC generator: a new tool!

GPDs → CFFs → Observables

- Authors: E.C. Achenauer, V. Batozskaya, S.F., K. Gates, H. Moutarde, D. Sokhan, H. Spiesberger, P. Sznajder
  - Eur. Phys. J. C 82 (2022) 9, 819
- EpIC: an event generator for exclusive reactions
  - Named after EIC and the philosopher *Epicurus*
  - we may have inspired the name for EIC detecor-1 ☺
- EpIC uses the PARTONS framework (http://partons.cea.fr), takes advantage of:
  - two state-of-art GPD models (GK, KM20)
  - flexibility for adding new models
- Multiple channels: DVCS, TCS, π^0
  - Initial and final state radiative corrections are implemented based on the collinear approximation
  - flexibility for adding all exclusive mesons

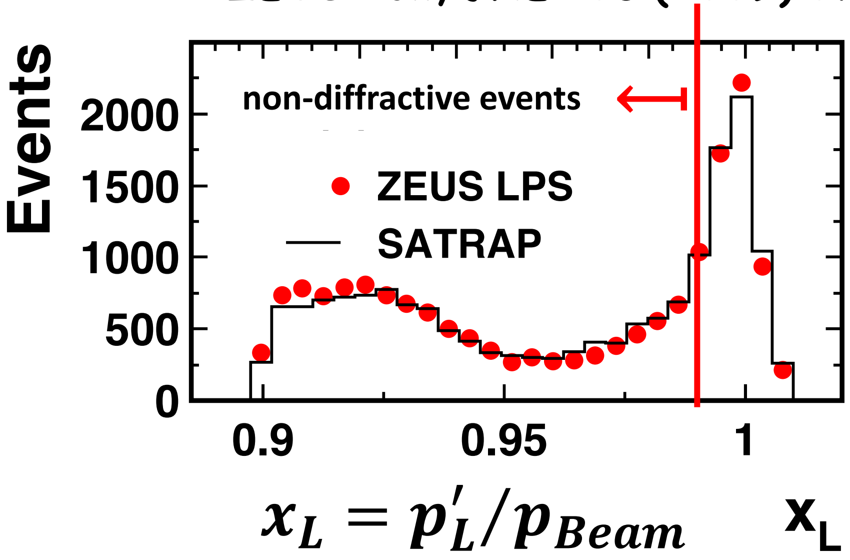


Scattered proton measurement



See talk by A. Jentsch

ZEUS Coll, JHEP 06 (2009) 074



$x_L = p'_L/p_{Beam}$

@ ePIC: Far Forward trackers:

- Roman Pots
- off-mom proton det.s,
- B0 tracker

Note:

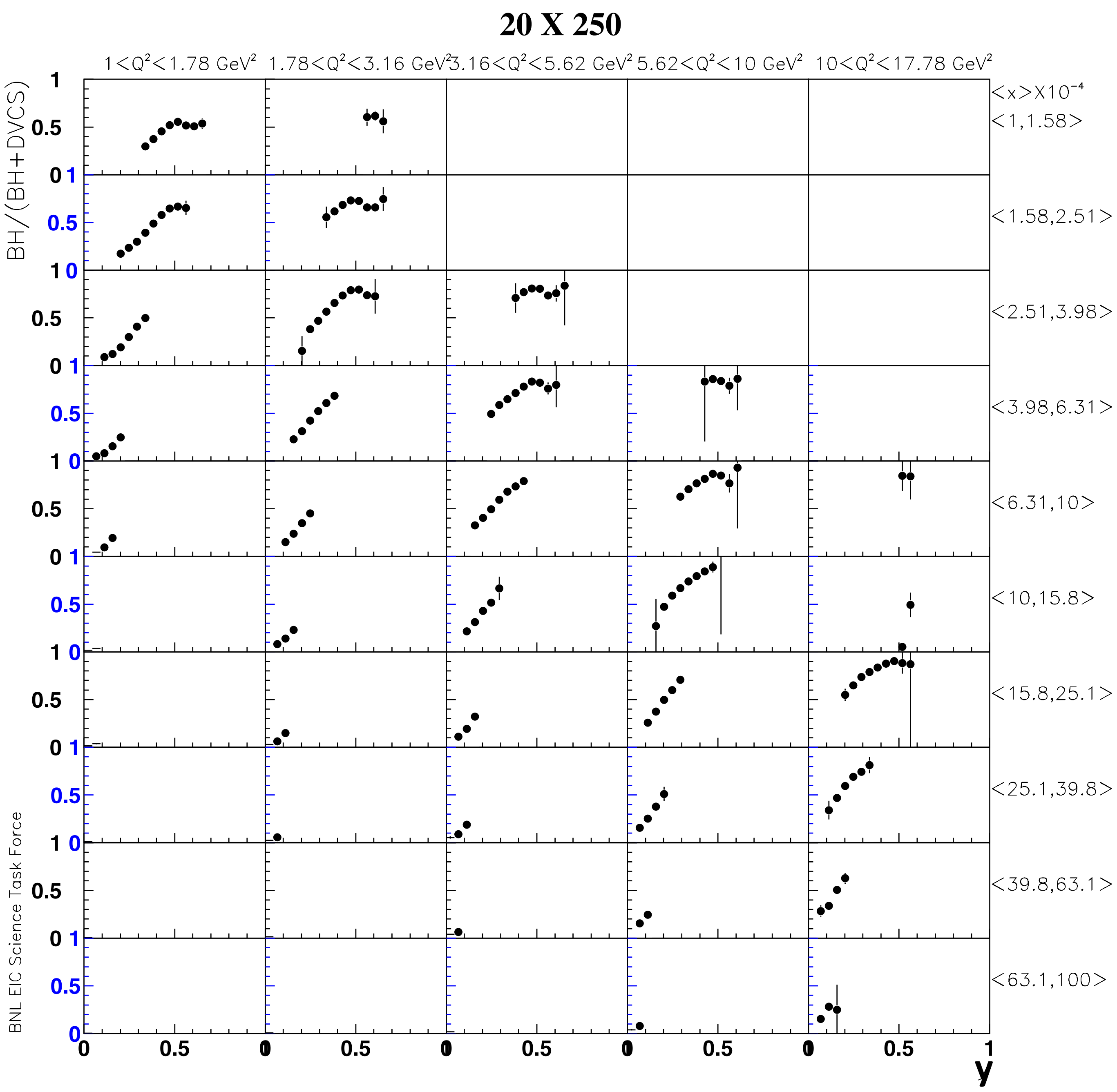
High energy colliders (HERA, Tevatron, LHC, RHIC) use Roman Pots to detect these protons

→ RPs are high resolution movable small tracking detectors (Si strips, Si pixels…), a crucial component

→ Magnets aperture limits larger angles acceptance

→ Smaller angles acceptance limited by beam divergence and emittance

→ rule of thumb keep 10s between RP and beam



BH contamination

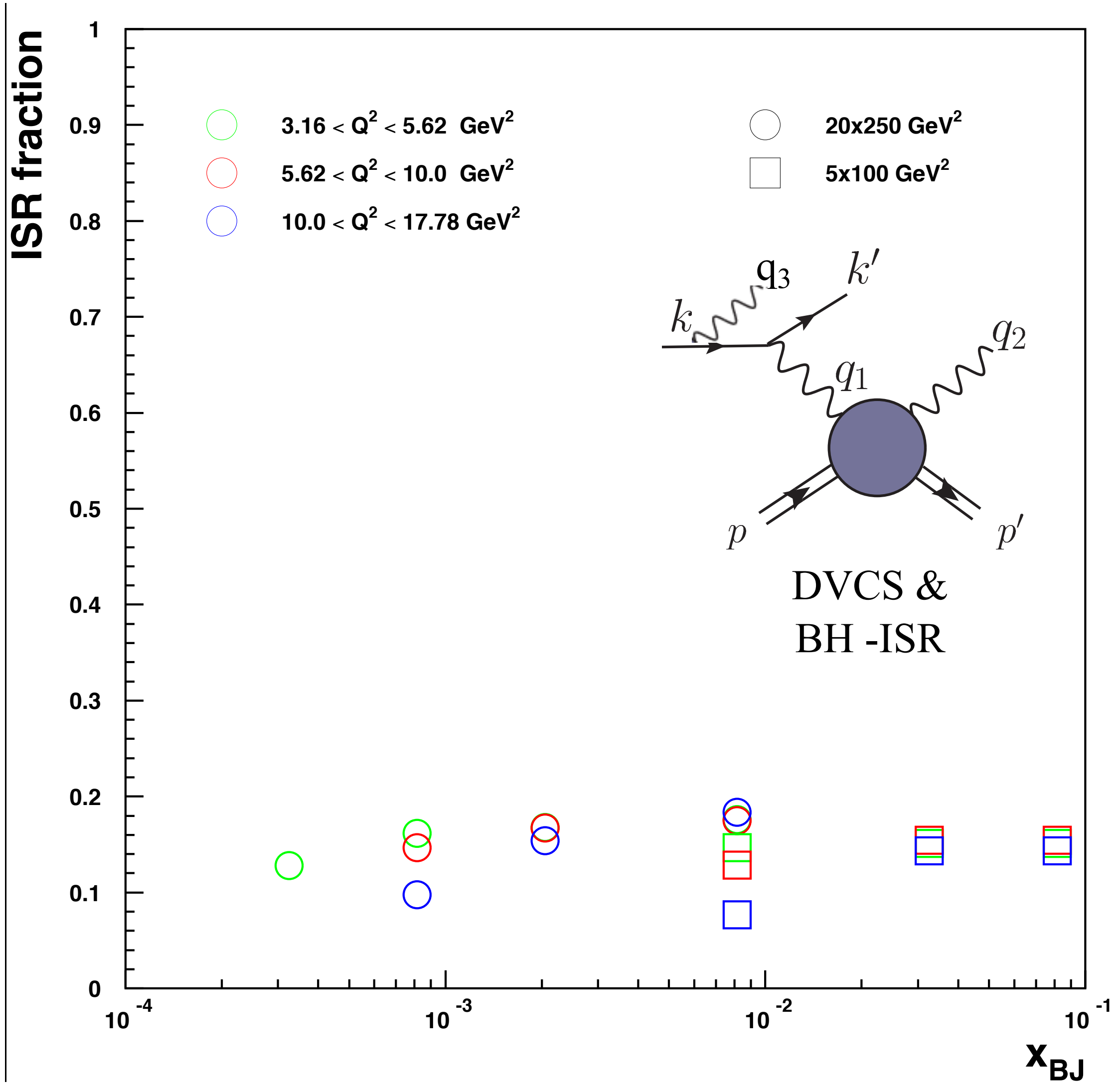
Special selection criteria can be optimized to suppress BH below 80%

- **But… more problematic at lower energies and larger *y*, in some *x*-Q^2 bins**

Generator: MILOU

Now confirmed by simulations with the novel EpIC generator

Initial state radiation



Photon collinear to the incoming beam and goes down the beam line

→this contribution can only be estimated via MC

→this causes a correction of the kinematics (x and Q^2) and some systematic uncertainty

Fraction of ISR events for three Q^2-bins vs. x for two EIC beam energy combinations

- **ONLY 15% of the events emit a photon with > 2% energy of the incoming electron**
- **ISR photons with $E_\gamma < 0.02\ E_e$ do not result in a significant correction for the event kinematics**

[JHEP09(2013)093]