Extracting General Parton Distributions from exclusive measurements at the future EIC

Salvatore Fazio

Università della Calabria & INFN Cosenza

UNIVERSITÀ DELLA CALABRIA
Dipartimento di FISICA

INFN Gruppo Collegato di Cosenza
Istituto Nazionale di Fisica Nucleare

ePIC

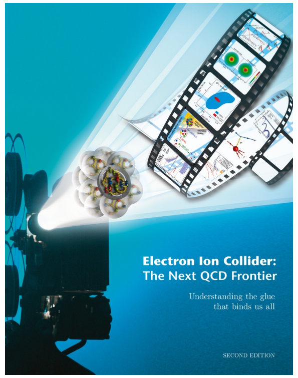
XXIX Cracow EPIPHANY Conference

Cracow - January 16-19, 2023

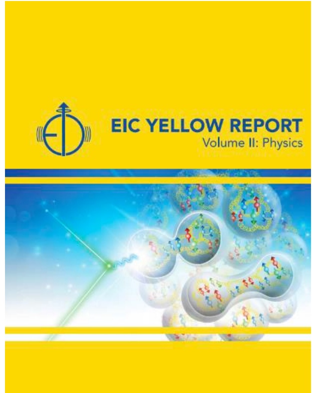
Outline

- 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
  - I will try to give appropriate credits

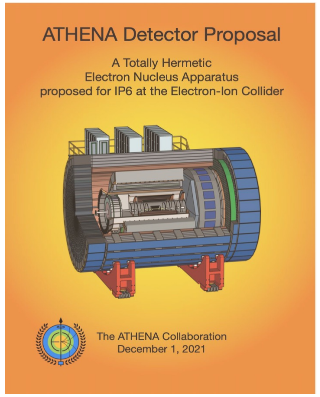
INT Report
arXiv:1108.1713



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



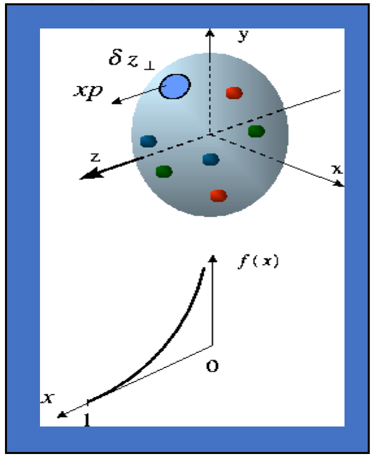
EIC Yellow Report
Nucl.Phys.A 1026 (2022) 122447



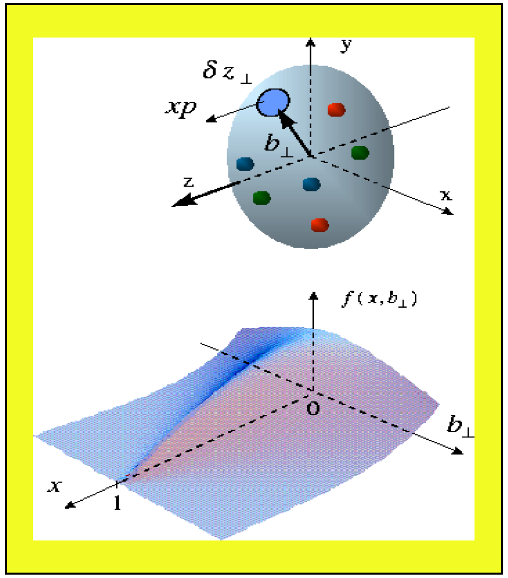
ATHENA:
JINST 17 (2022) 10, P10019
ECCE: arXiv:2209.02580
CORE: arXiv:2209.00496

Generalized Parton Distributions

Longitudinal momentum & helicity distributions

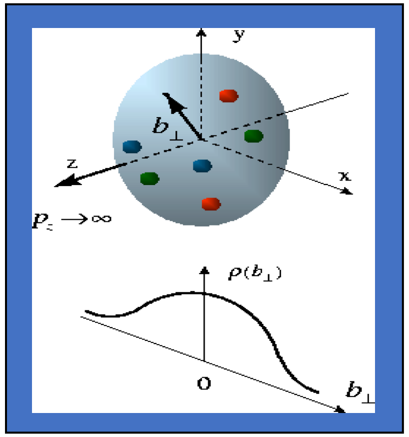


$f(x)$ **parton densities**



$H(x,\xi,t)$ **GPDs**

transverse charge & current densities



$F(t)$ **form factors**

See Talks by:
J. Wagner
F. Kunne
K.P. Kumericki
K. Cichy
W. Broniowski

The nucleon (spin-1/2) has **four quark and gluon GPDs** (H, E and their polarized-proton versions $\tilde{H}, \tilde{E}$). Like usual PDFs, GPDs are non-perturbative functions **defined via the matrix elements of** well-defined **parton operators**:

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

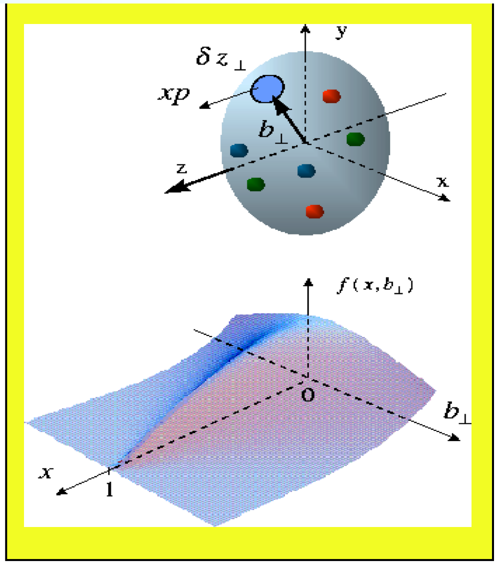
$$= \frac{1}{2\bar{P}^+}\left[H^q(x,\xi,t,\mu^2)\bar{u}(p')\gamma^+ u(p) + E^q(x,\xi,t,\mu^2)\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m_N}u(p)\right]$$

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(Φ$_T$–ϕ$_N$)*** **governed by E and H**

[Requires a polarized proton target]

Responsible for total orbital angular momentum through Ji sum rule:

a window to the SPIN physics

$$\sum_{q=u,d,s} J^q(Q^2) + J^G(Q^2) = \frac{1}{2}\hbar$$

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

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

→ **Done @ HERA**

[Requires a positron beam]

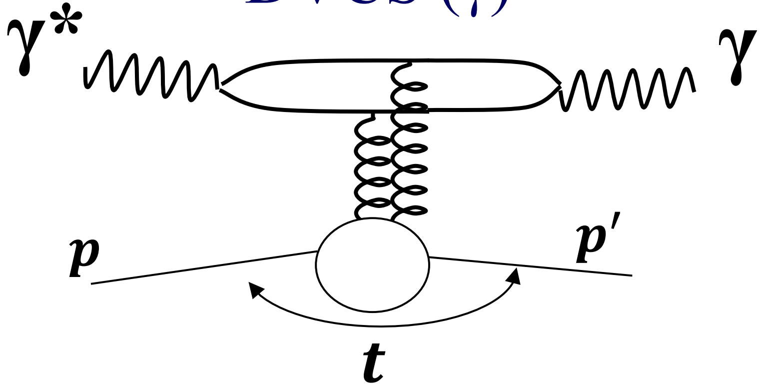
Alternatively: measure Time-like Compton Scattering (TCS)

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)]

Accessing GPDs in exclusive processes

DVCS (γ)

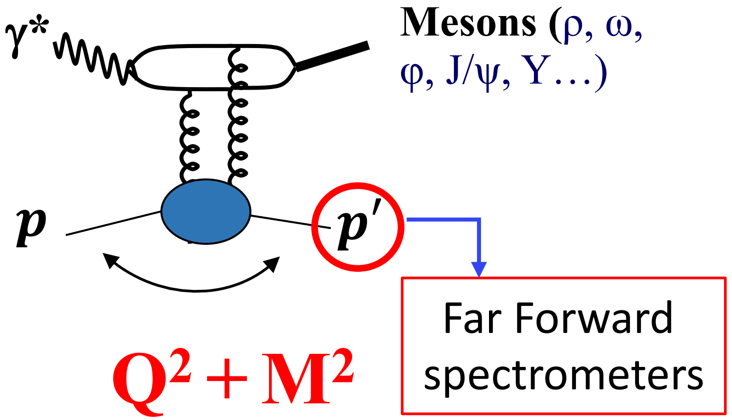


Scale: Q^2

4-momentum transfer at the *p* vertex:

$$t = (p' - p)^2$$

TCS (dilepton) and VM (ρ, ω, φ, J/ψ,



$Q^2 + M^2$

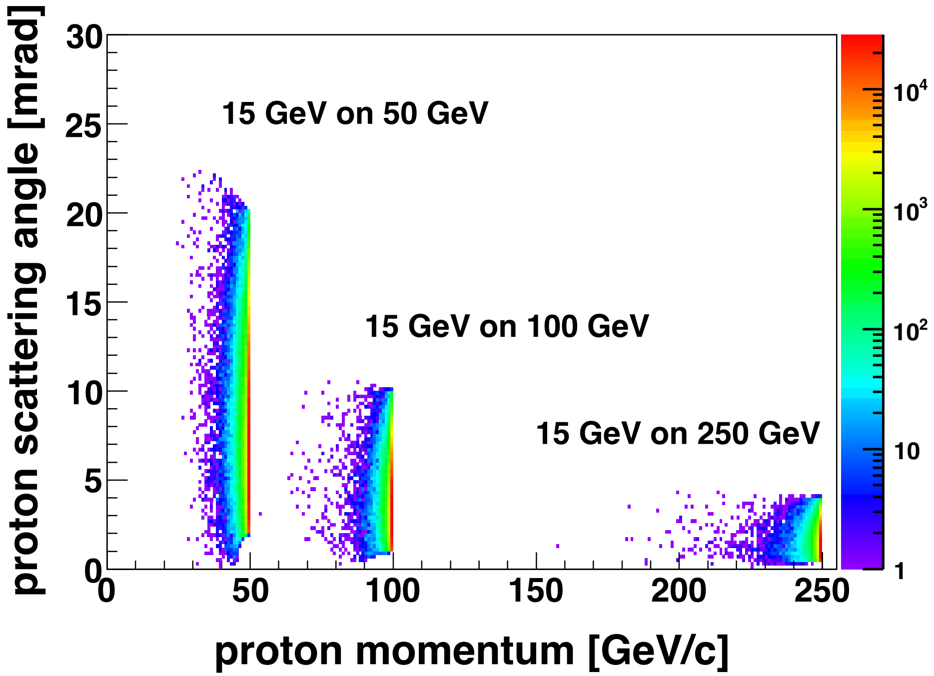
DVCS:

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

HEMP & TCS:

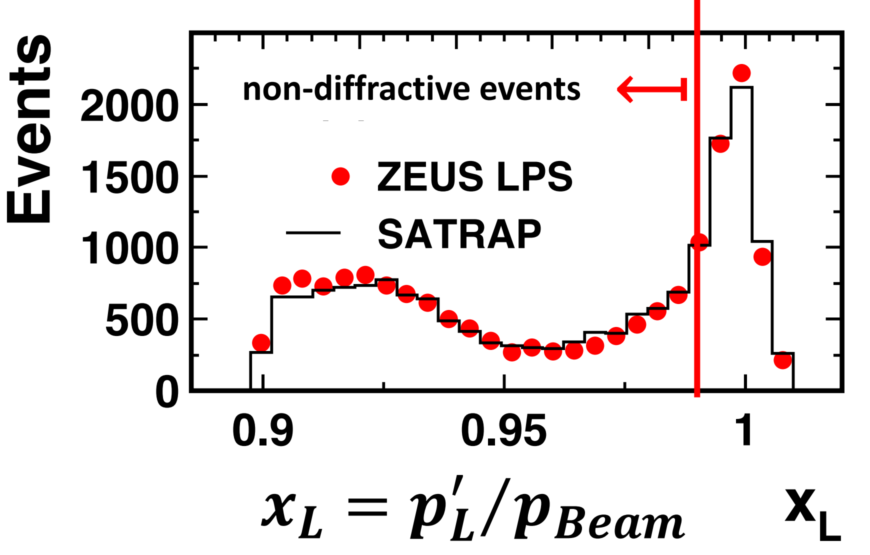
- Uncertainty of wave function
- J/Psi → direct access to gluons, $c\bar{c}$ pair produced via quark(gluon)-gluon fusion
- Light VMs → quark-flavor separation
- Psedoscalars → helicity-flip GPDs
- TCS → *Re*(A)

Scattered proton measurement



See talk by A. Jentsch

ZEUS Coll, JHEP 06 (2009) 074



@ 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

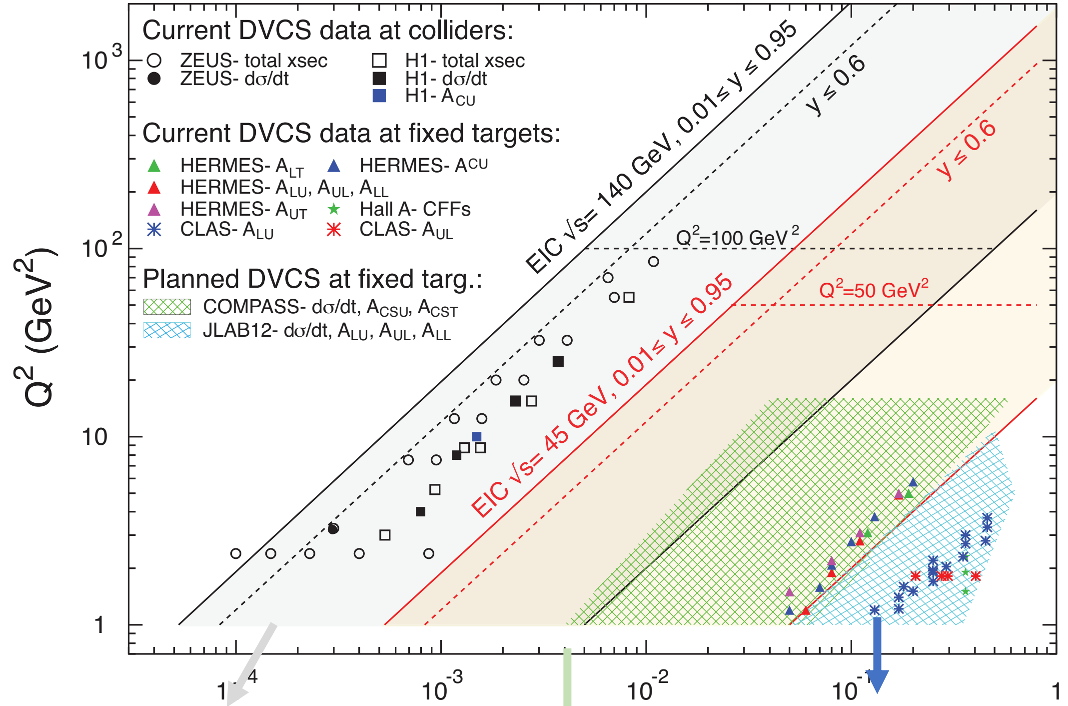
→ RPs are high resolution movable small tracking detectors (Si strips, Si pixels…), a crucial component

→ Magnets aperture limits larger angles acceptance

→ Smaller angles acceptance limited by beam divergence and emittance

→ rule of thumb keep 10s between RP and beam

DVCS at the EIC



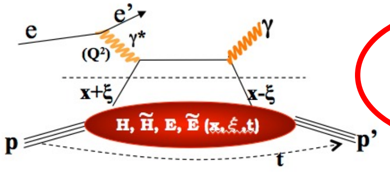
Overlap with HERA:
Large impact on current fits at low x

Intermediate region:
Fine mapping of the GPDs evolution

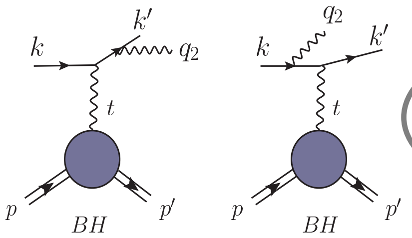
Overlap with JLAB12:
Sanity check

HERA results limited by lack of statistics

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



DVCS signal



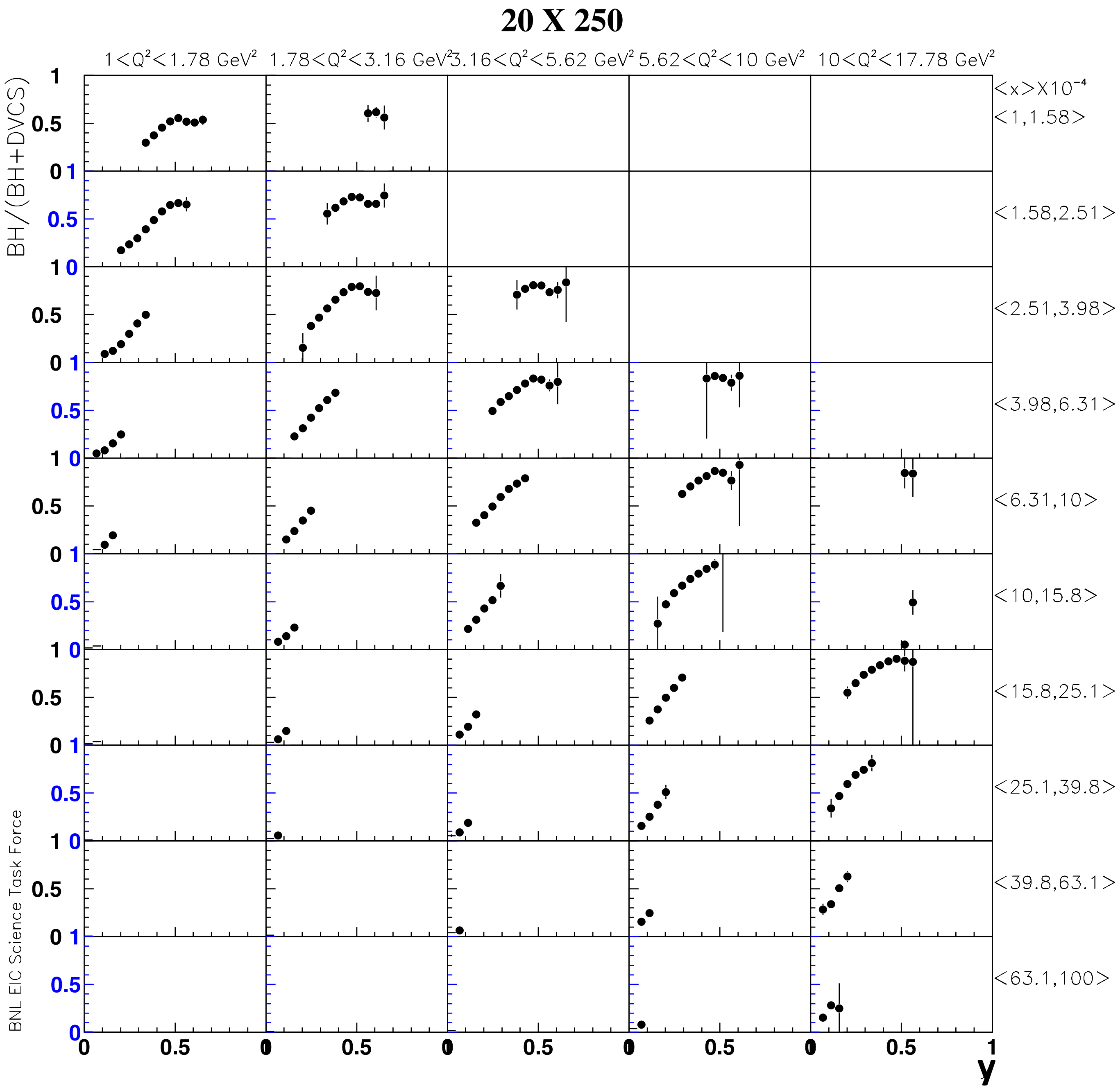
Bethe-Heitler QED bkgd.

Comprehensive EIC studies

- **Signal extraction "a la HERA"**
- **xSec meas.: Specific requirements to suppress BH**
  → keep BH/sample below 60% at high energies
- **Radiative Corrections evaluated**
- **detector acceptance & smearing**
- **t-slope: b=5.6 compatible with H1 data**
- **|t|-binning is (3*resolution)**
- **5% systematic uncertainties**

EIC: the first machine to measure cross sections and asymmetries

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



BH contamination

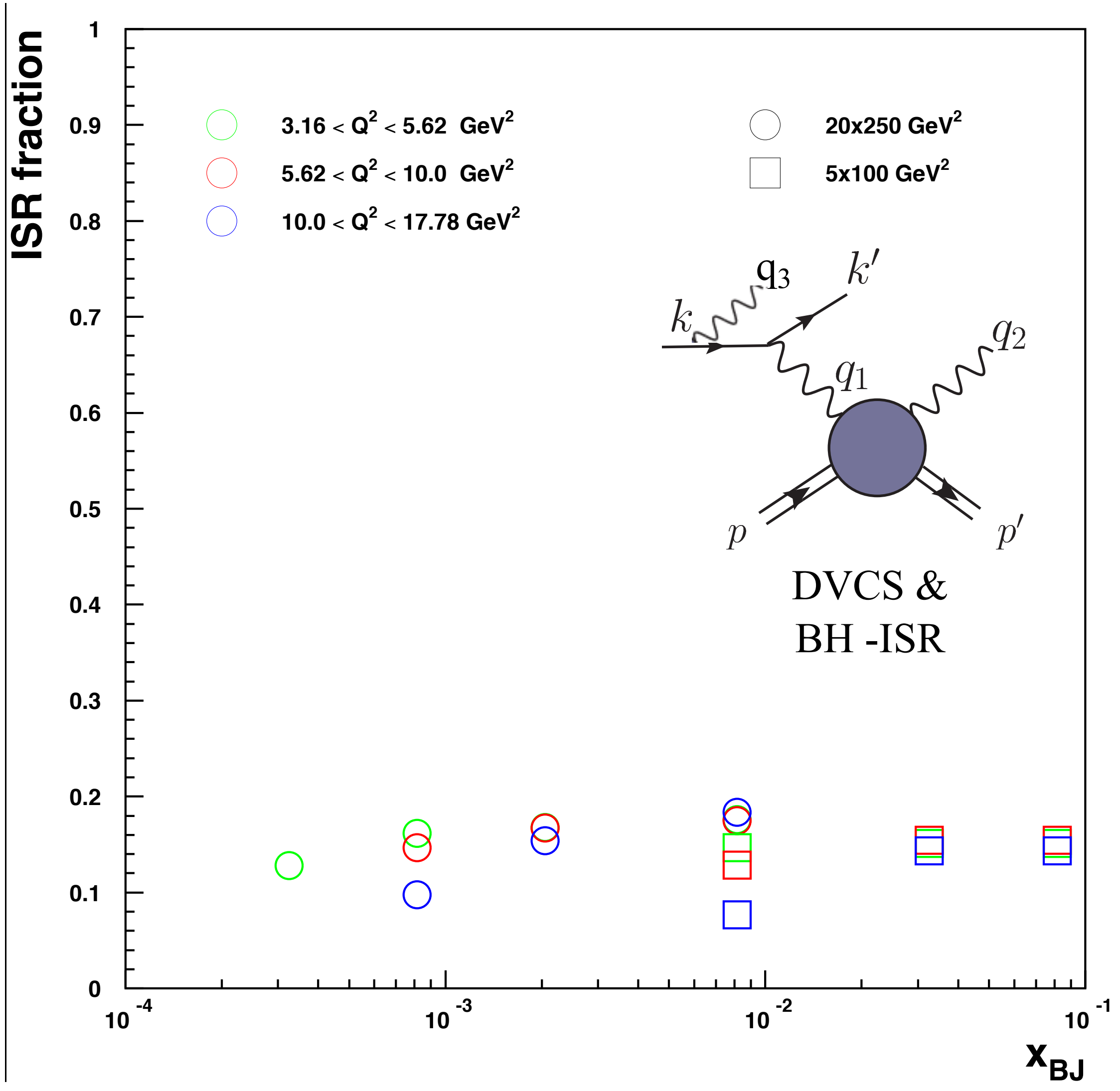
Special selection criteria can be optimized to suppress BH below 80%

- **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

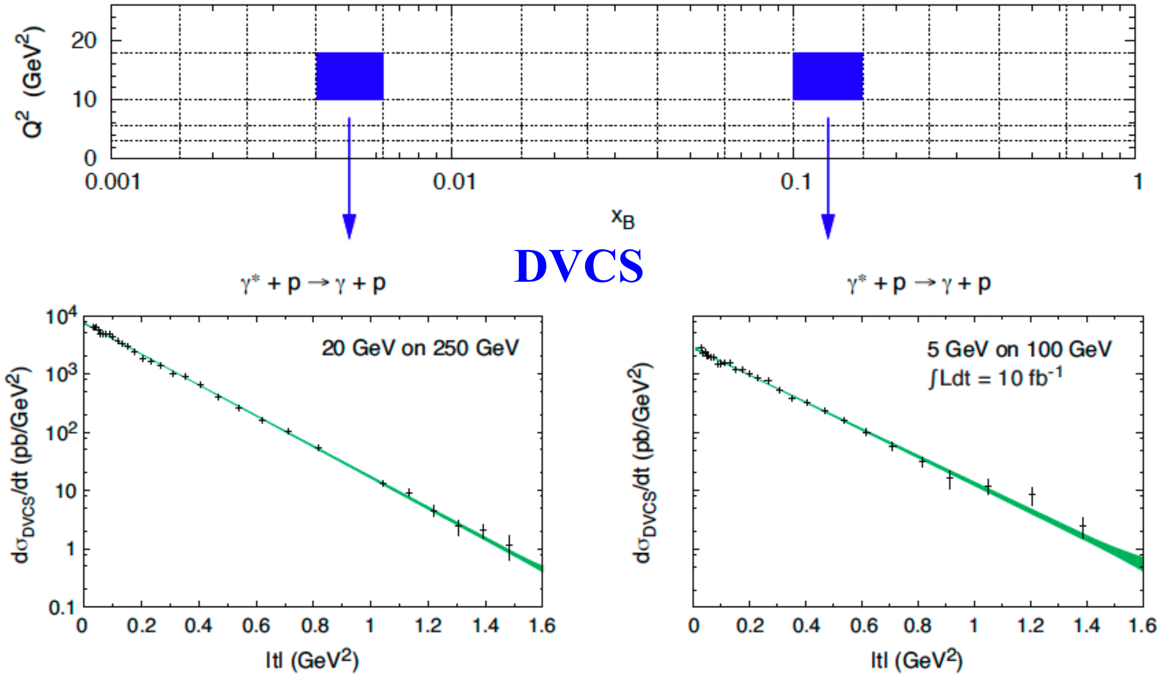
- **ONLY 15% of the events emit a photon with > 2% energy of the incoming electron**
- **ISR photons with $E_\gamma < 0.02\ E_e$ do not result in a significant correction for the event kinematics**

[JHEP09(2013)093]

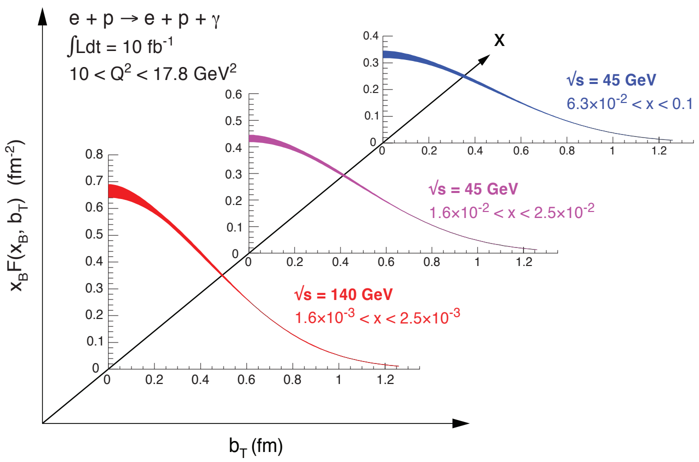
DVCS – differential cross section

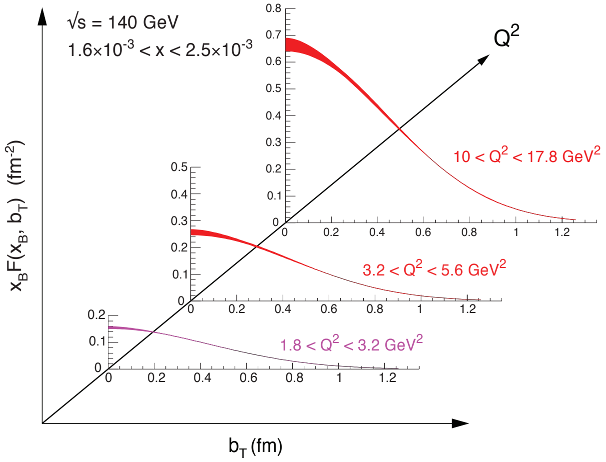
$$\int L = 10 fb^{-1}$$

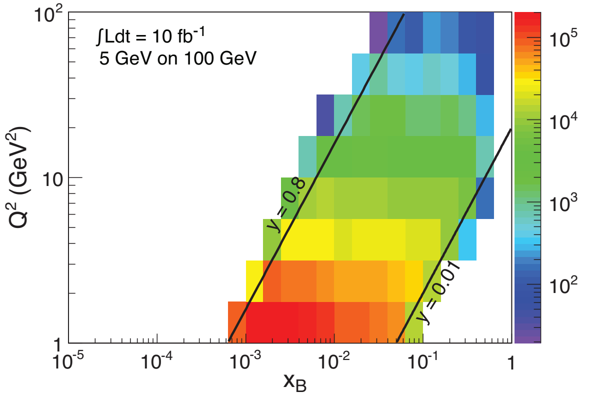
EIC White Paper

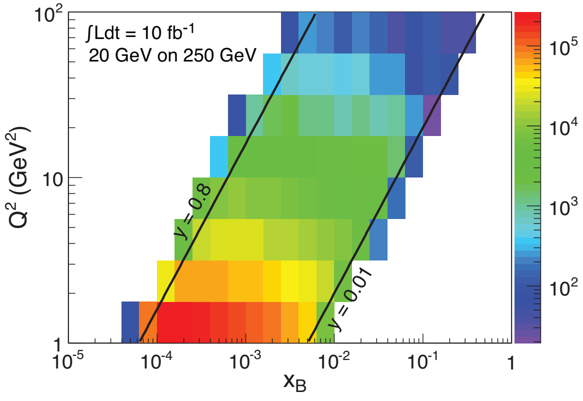


- **L = 10 fb^{-1} per energy configuration**
- **Measurement dominated by systematics**
- Fine binning in a wide range of x-Q^2 needed for GPDs
- **Assumed t-range:** $0.03 < |t|\ (GeV^2) < 1.6$
- Fourier transform of dσ/dt → partonic profiles







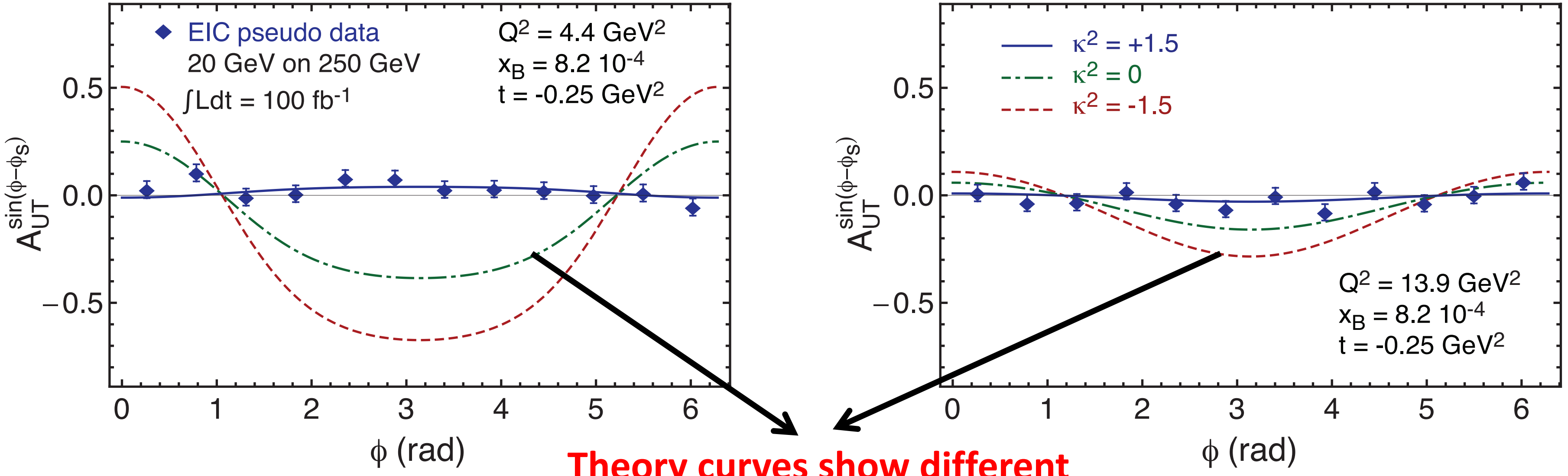


DVCS – Transverse T. Spin Asymmetry

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

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

[JHEP09(2013)093]



Theory curves show different assumptions for E

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

Transversely polarized protons: sin($\Phi_T - \phi_N$)

gives access to GPD E

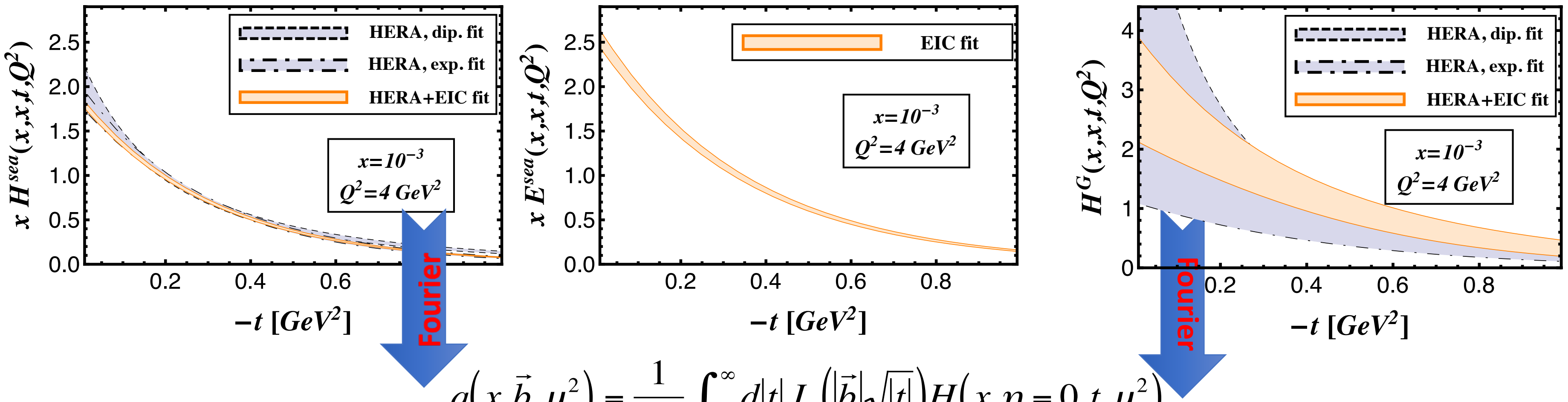
Access to orbital angular momentum through "Ji sum rule"

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

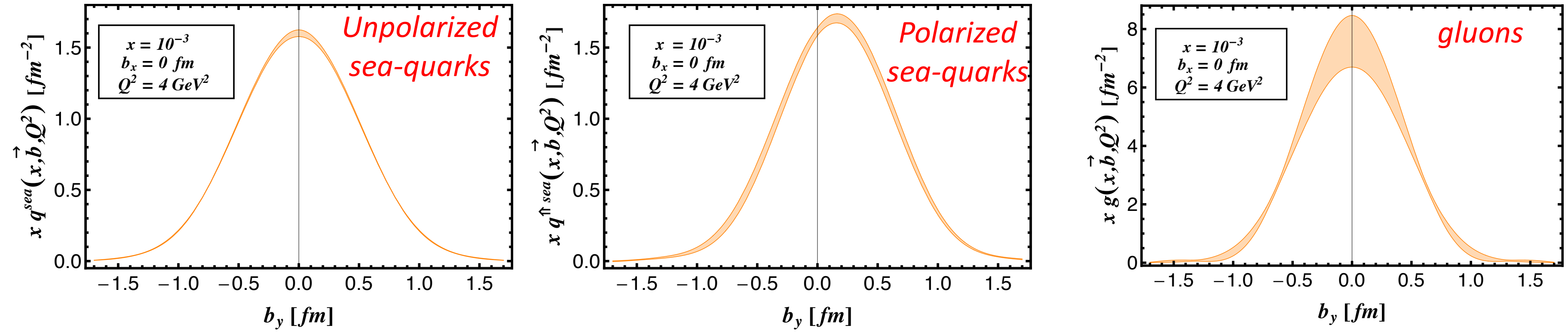
$$\sum_{q=u,d,s} J^q(Q^2) + J^G(Q^2) = \frac{1}{2}\hbar$$

DVCS-based spatial imaging

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



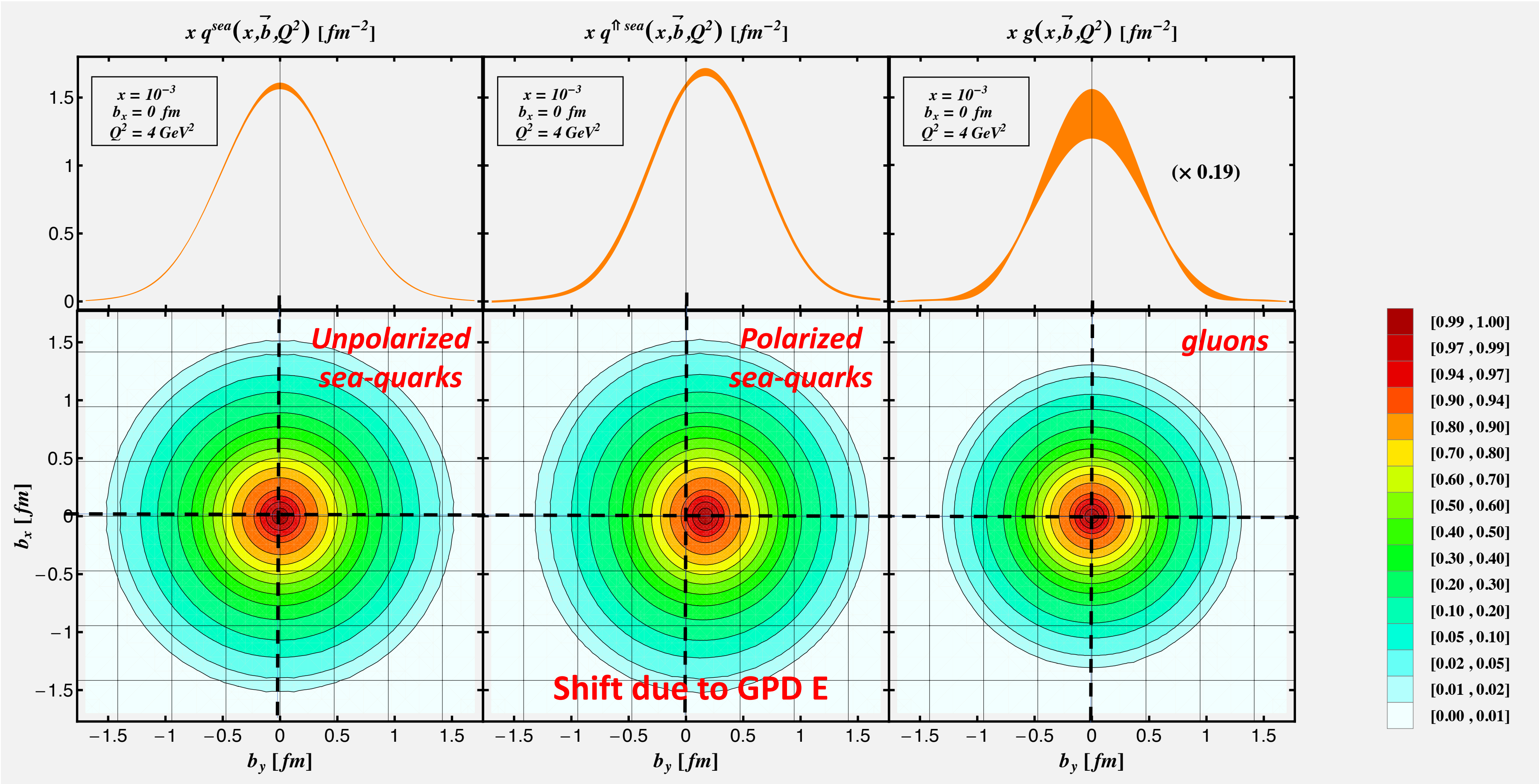
$$q\left(x,\vec{b},\mu^2\right) = \frac{1}{4\pi}\int_0^\infty d|t|\, J_0\left(\left|\vec{b}\right|\sqrt{|t|}\right) H\left(x,\eta=0,t,\mu^2\right)$$



- ➢ **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)**

DVCS-based spatial imaging

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



- **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!

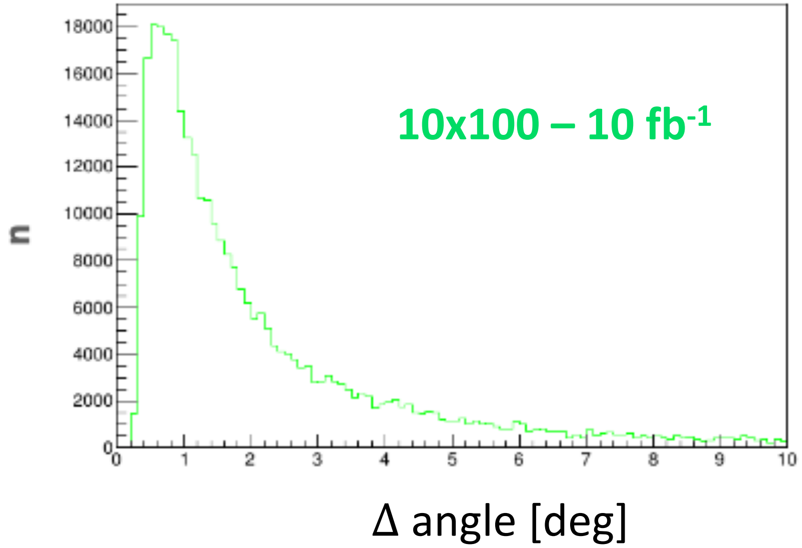
- Gluon GPD H can be much improved by including J/ψ
- Access to gluon GPD E → orbital momentum (Ji sum rule)
- Flavor Separation of GPDs (VMP and/or DVCS on deuteron)
- Nuclear imaging (modification of GPDs in p+A collisions)

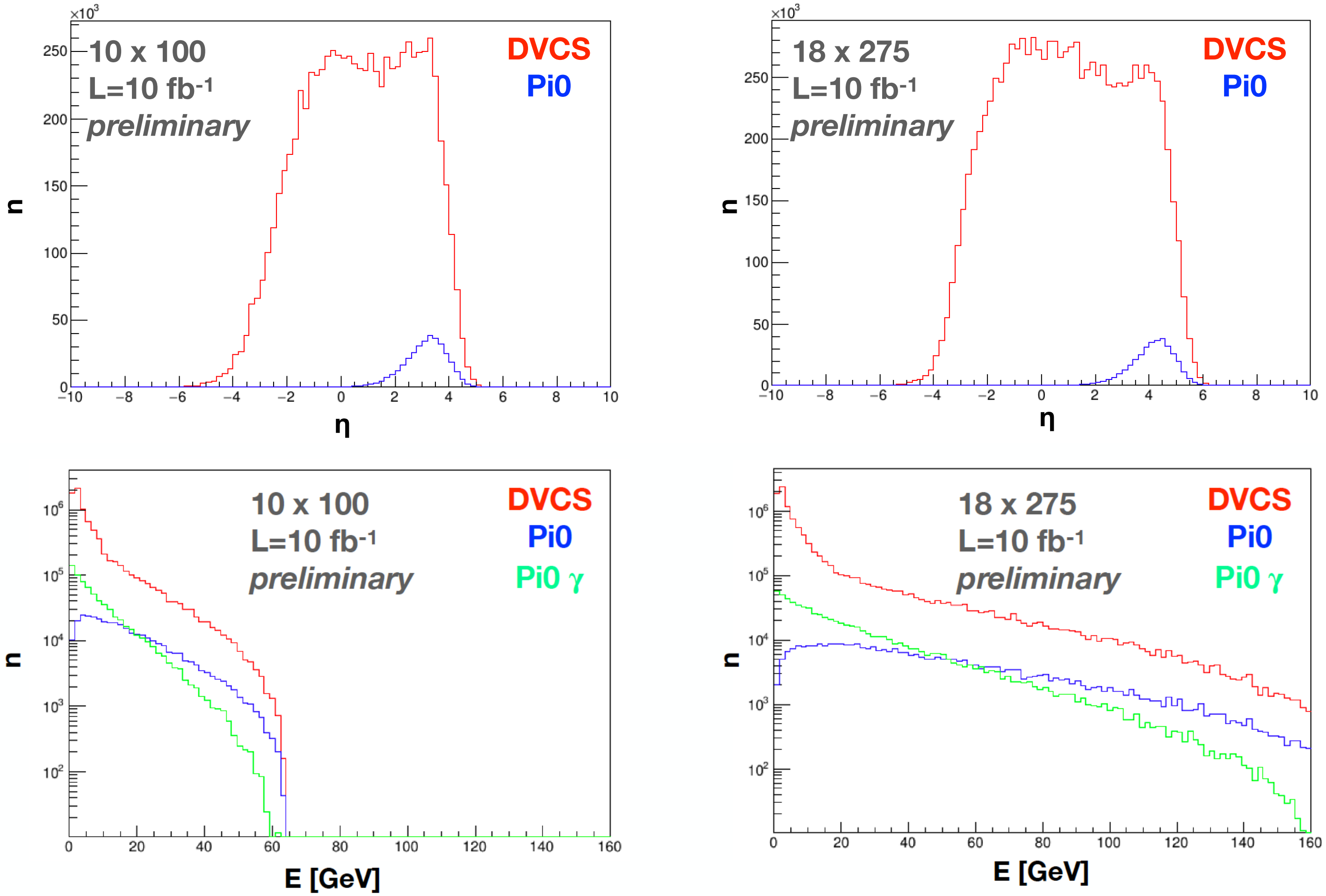
Impact of EIC (based on DVCS only):
✓ Excellent reconstruction of H^{sea}, and H^{g} (from $d\sigma/dt$)
✓ **Reconstruction of sea-quarks GPD E**

DVCS vs exclusive π^0

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

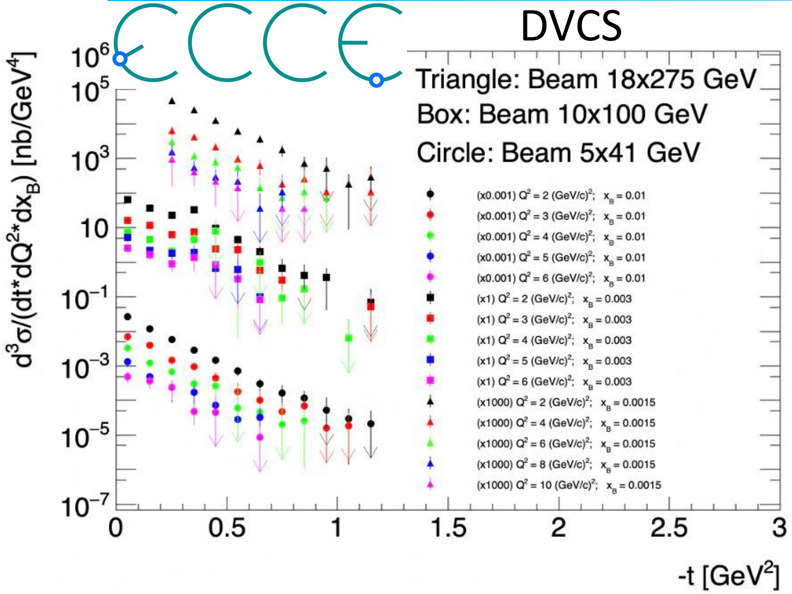


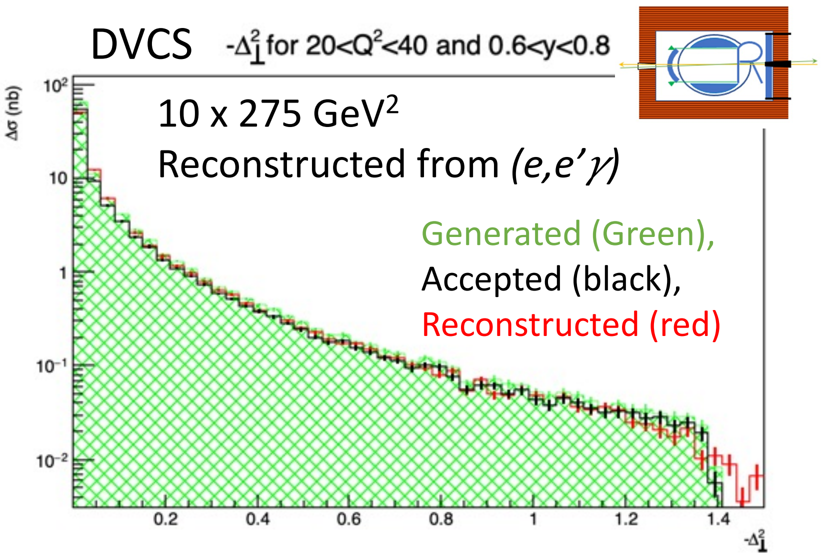


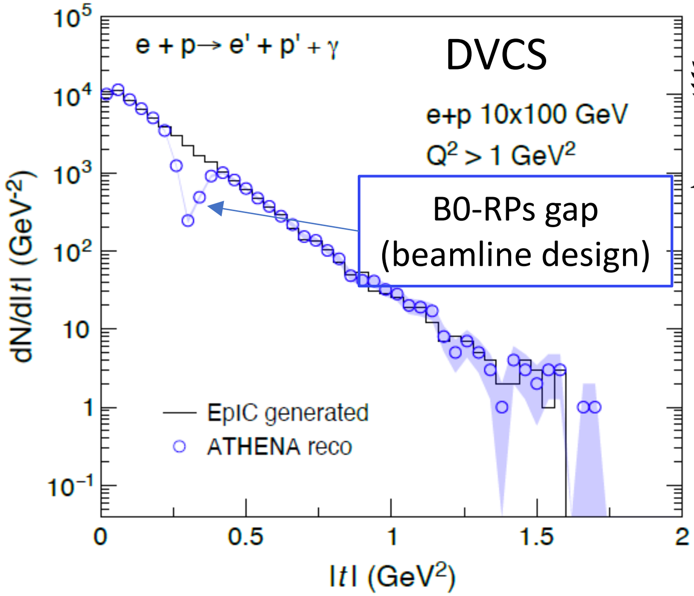
Take away message:

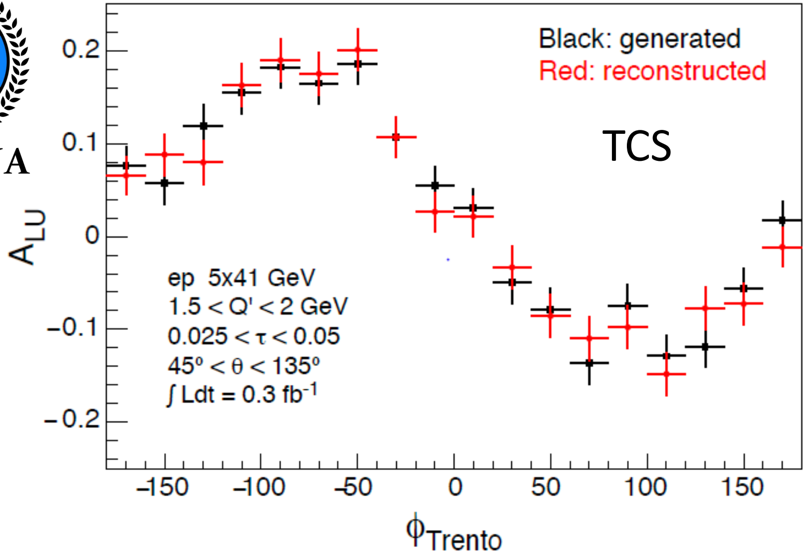
- π^0 x-sec lower than signal (DVCS)
- Min 2γ angle: ~0.2 deg
- Exclusive π^0 can reach high momentum/energy (but xSec decreases with meson's energy)

Detector pre-proposals – DVCS/TCS









Observables:

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

Asymmetries (DVCS & TCS):

GPDs via amplitude-level interference with Bethe-Heitler

Key:

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

Timelike Compton Scattering (TCS)

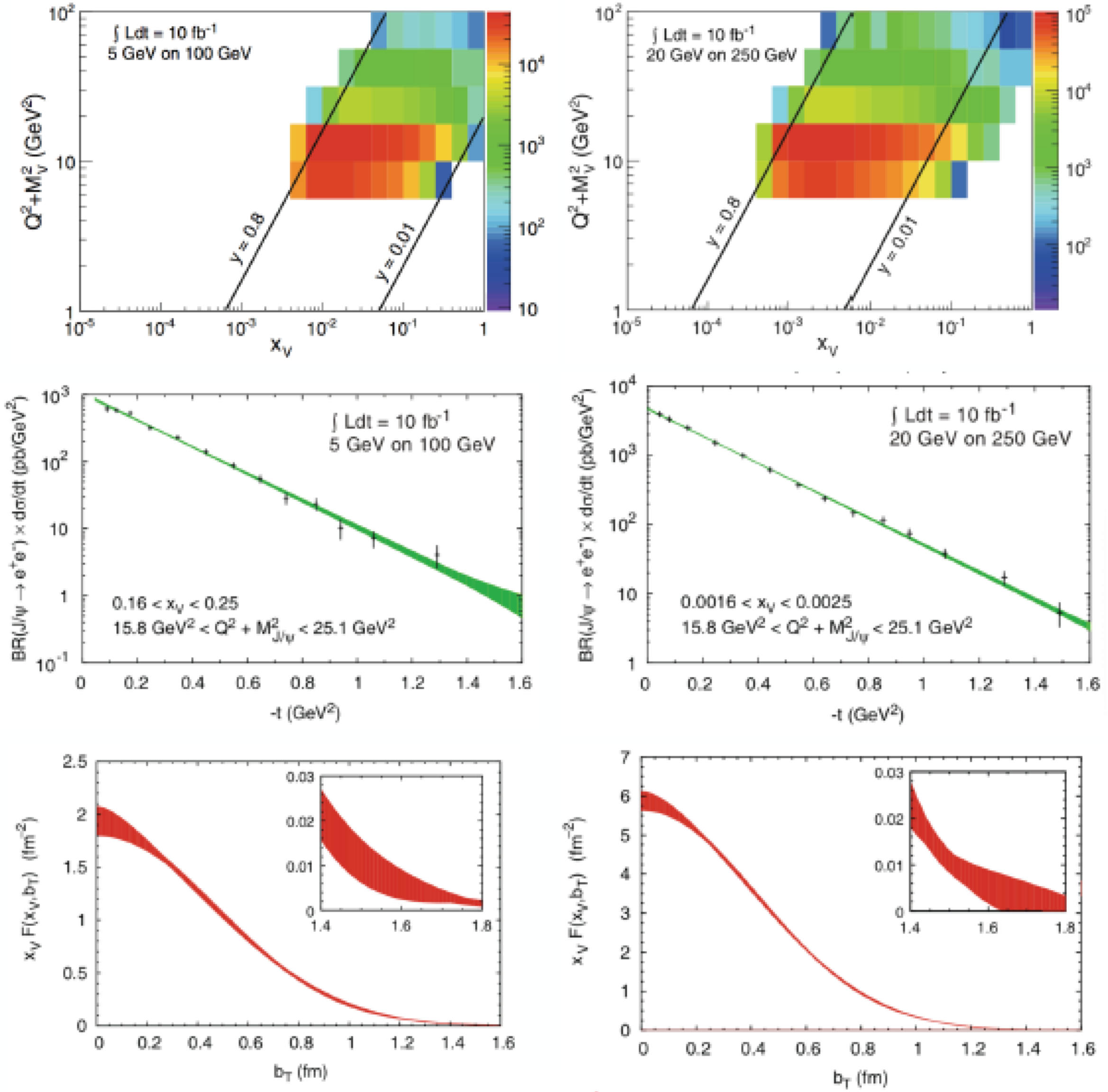
$\gamma p \rightarrow \gamma^* p\ (\gamma^* \rightarrow l^+ l^-)$

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

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**

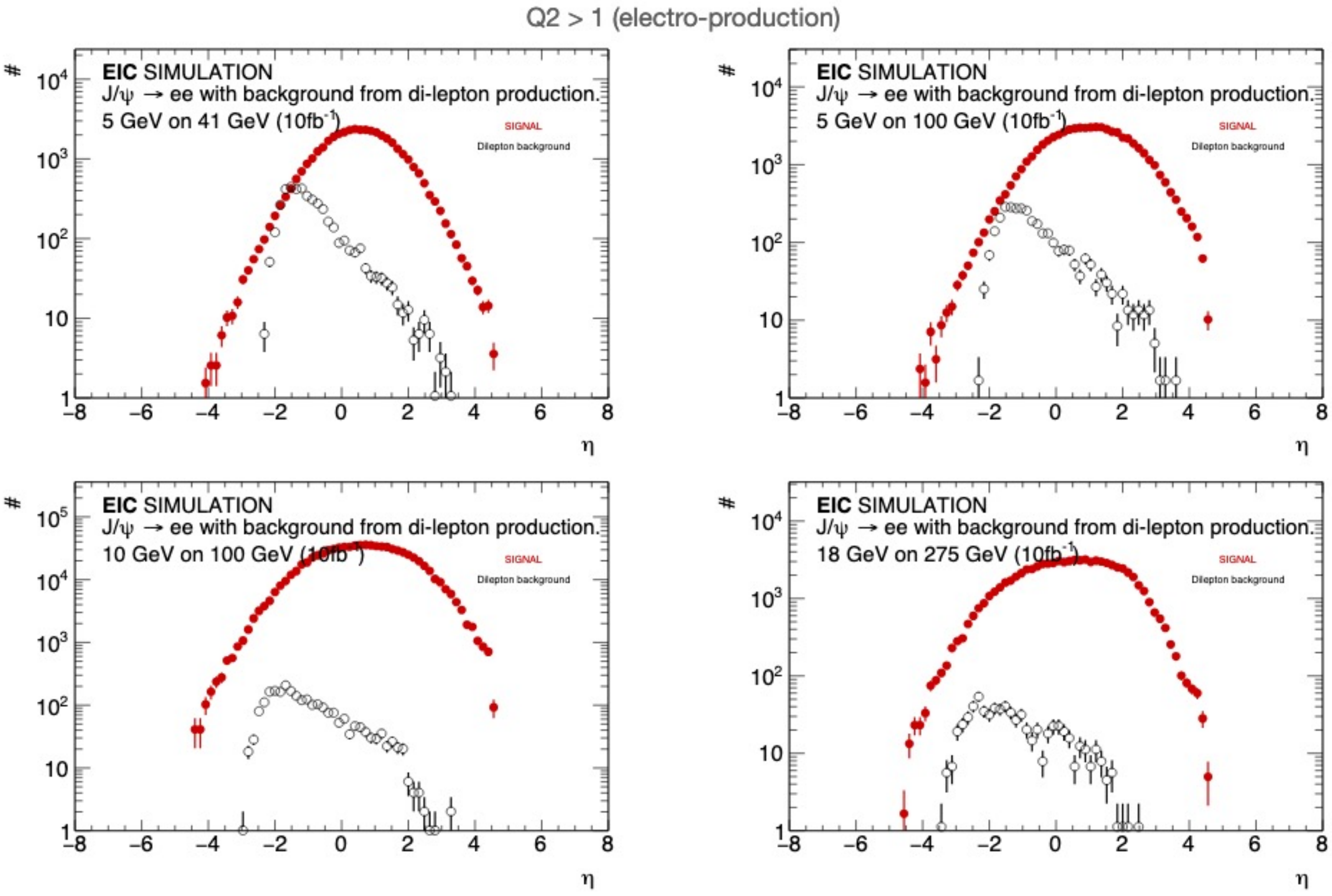
➢ Measurement dominated by systematics at low |t|

➢ **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

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)

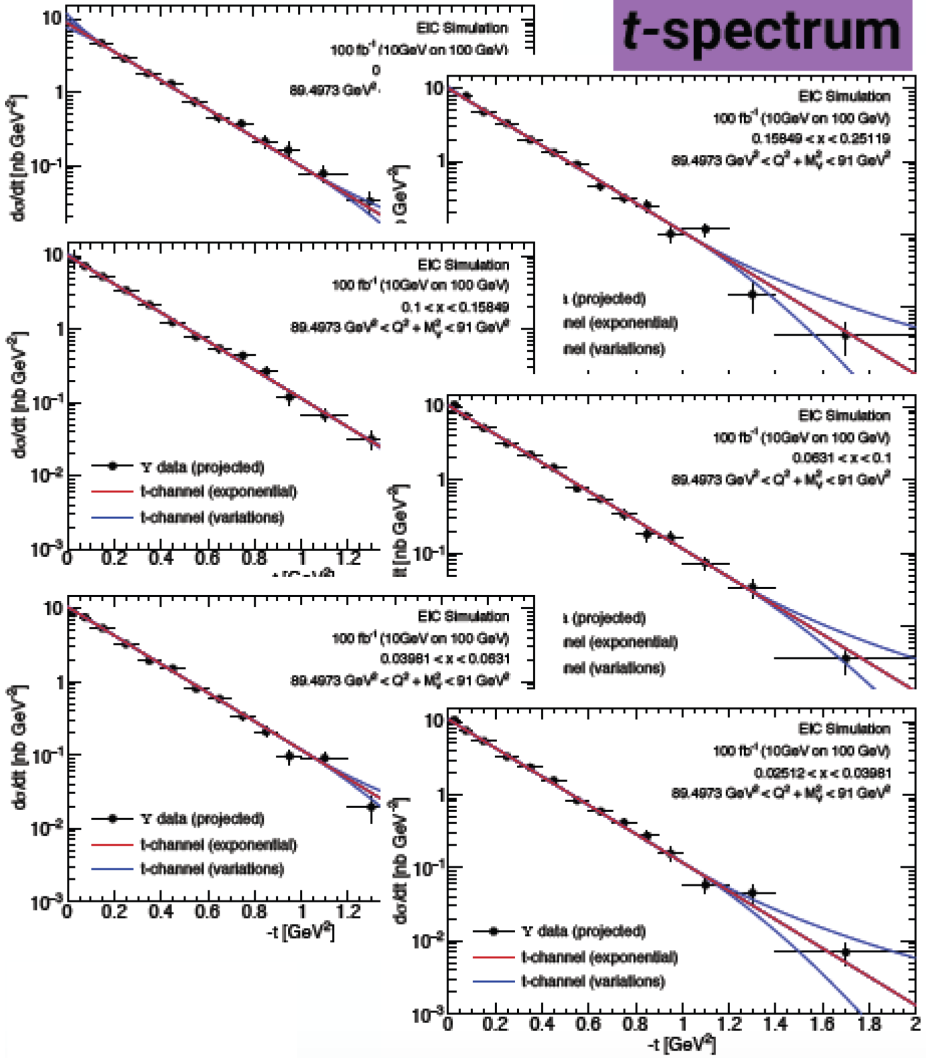
Imaging gluons with $\Upsilon(1s)$

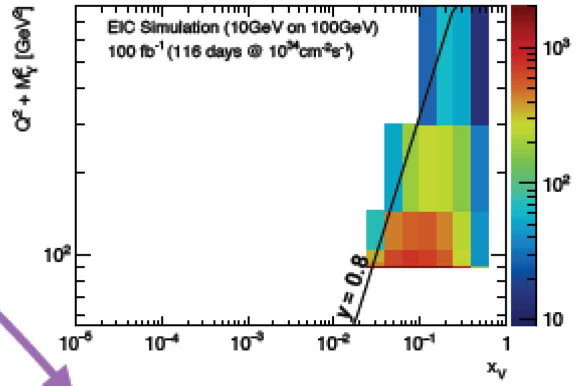
$$\int L = 100\ fb^{-1}$$

EIC Yellow Report

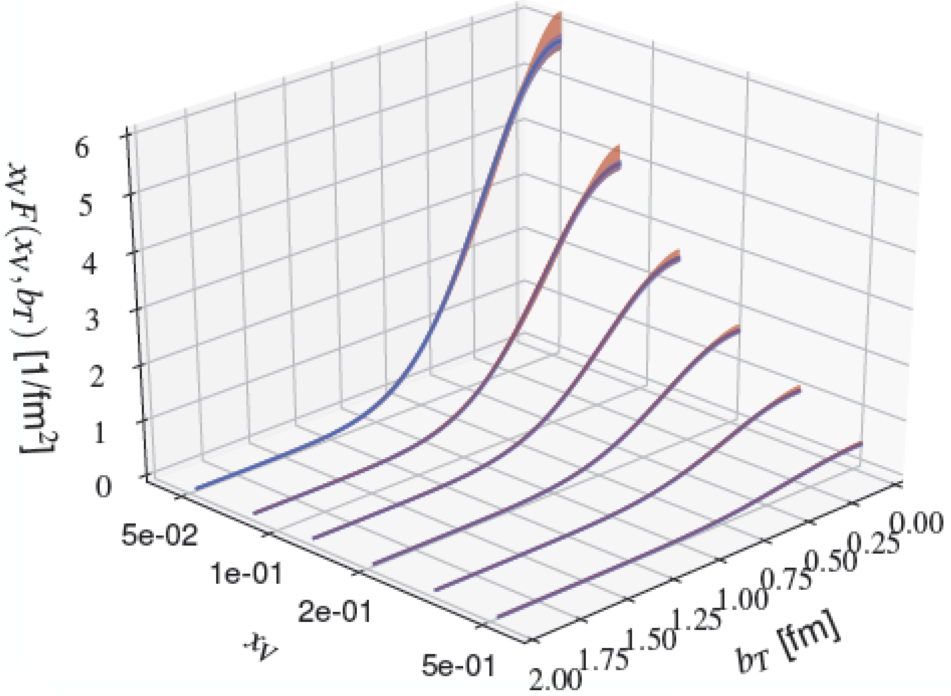
- Nominal EIC detector
- 10x more luminosity
- Electron and muon channels

t-spectrum





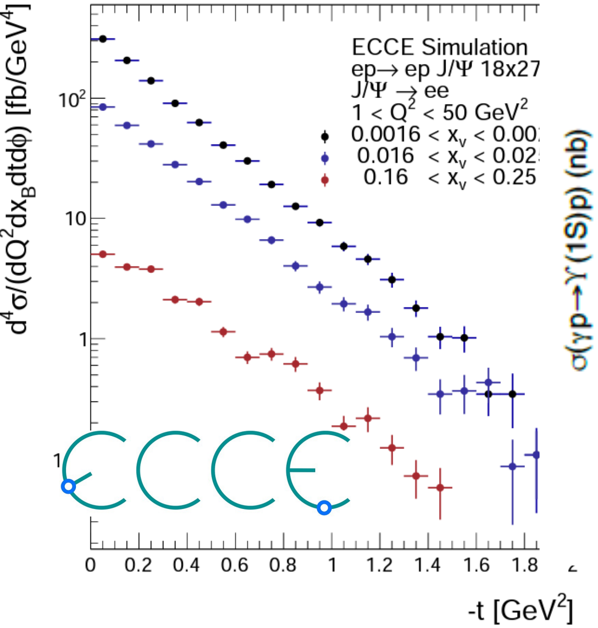
Average gluon density:

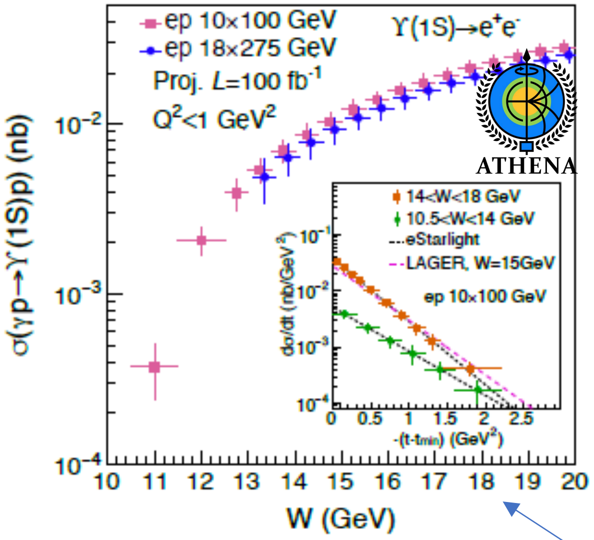


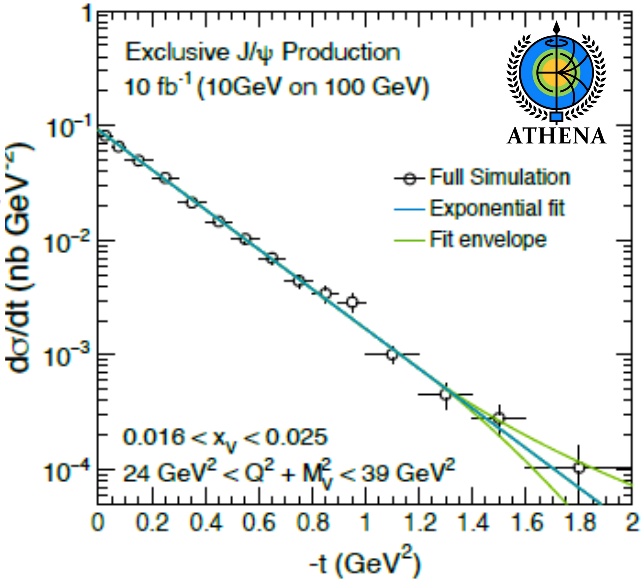
Studies by:
Sylvester Joosten (ANL)

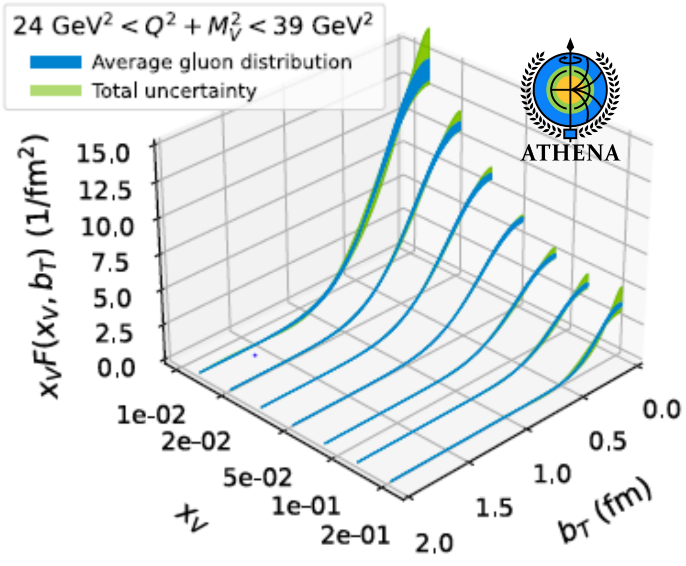
Detector Proposals- VMs

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

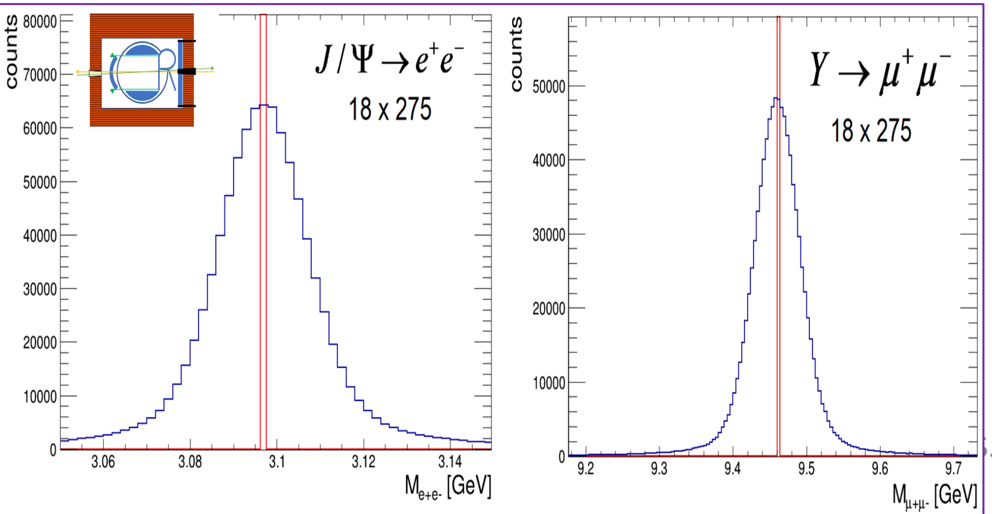








VMs invariant mass at CORE



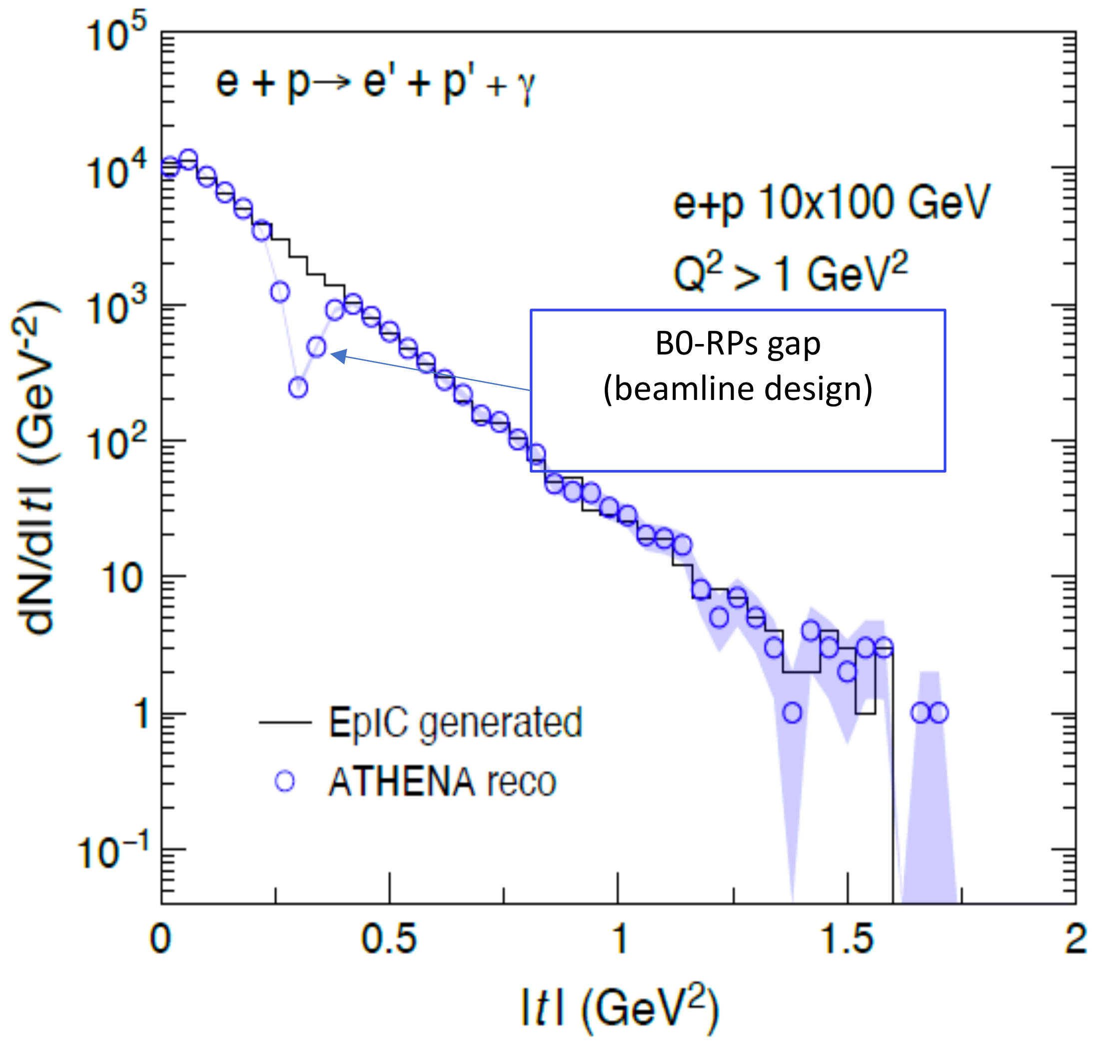
Υ Photopoduction near threshold and electro-production ($Q^2 < 1$ GeV^2) -> origin of *p*-mass

Key:

- 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

- Plot made with full simulation
- DVCS events simulated using EpIC



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

Observables:

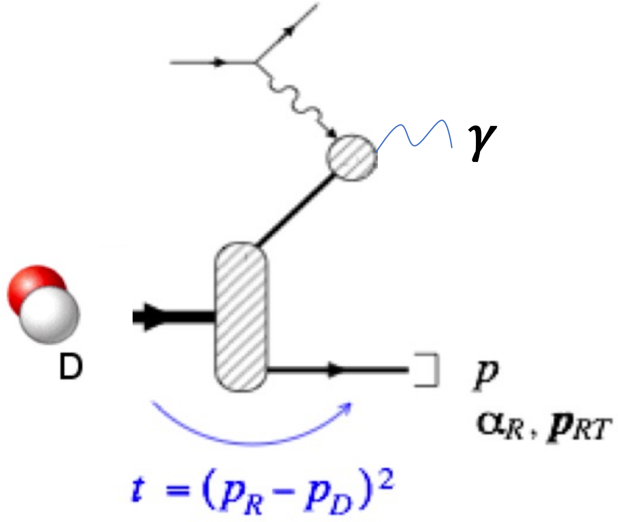
$d\sigma/dt$; A_{LU}; A_{UT}

Asymmetries (DVCS & TCS):

GPDs via amplitude-level interference with Bethe-Heitler

Study of neutrons with light nuclei

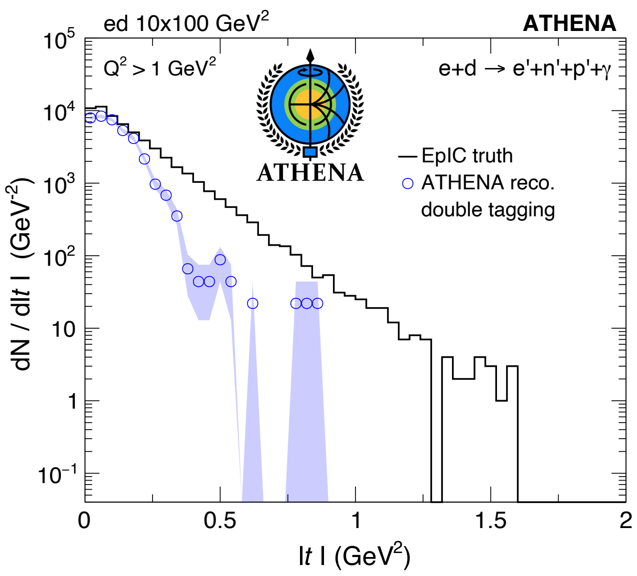
See talk by A. Jentsch

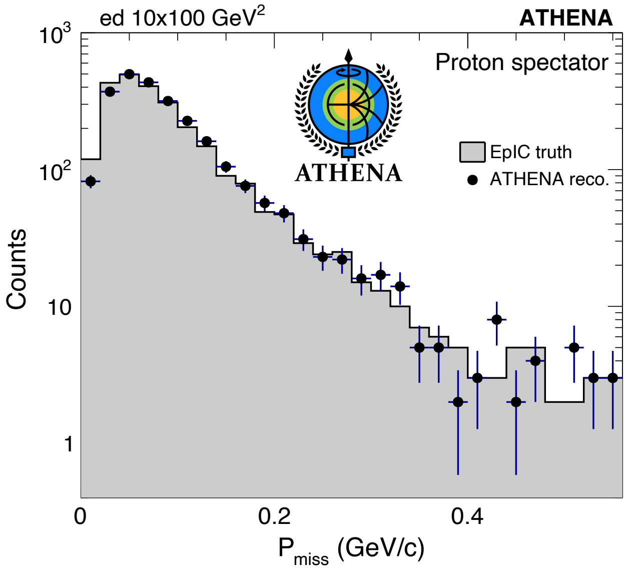


- Possibility to study neutron structure
- DVCS on neutron compared to proton is important for flavor u/d separation

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:

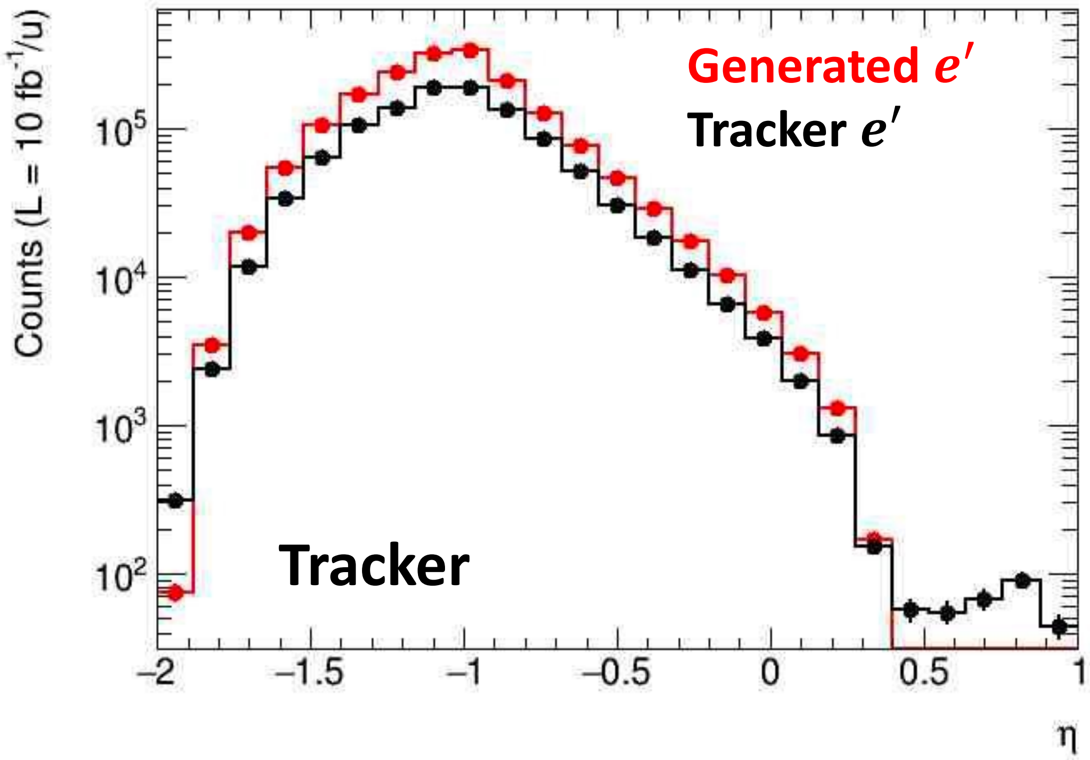
- 80-90% acceptance at low |t|,
- |t|-acceptance loss at higher value mostly due to the loss in tagging the active neutron in ZDC.
- Alternatively, |t| can be measured via scattered e and γ → higher acceptance at large |t|.
- Proton momentum is well reconstructed

DVCS with ^{4}He

Study by Gary Penman

Process which can give understanding of EMC effect, and tomographic view of nucleons.

- Pure DVCS illustrated by “Handbag Mechanism”
- TOPEG MC generator: by Perugia+Orsay
- Detector simulation: EpIC with fun-4-all
- Electron detection (tracker):
  - electron: # of tracks in internal Si tracker = 1
  - electron acceptance ~= 88.3%
- Photon detection (ECAL):
  - # ele tracks = 1 && # ECAL hits > 0 && max cluster energy: E_{max} > 250 MeV
  - photon acceptance ~= 86.1%

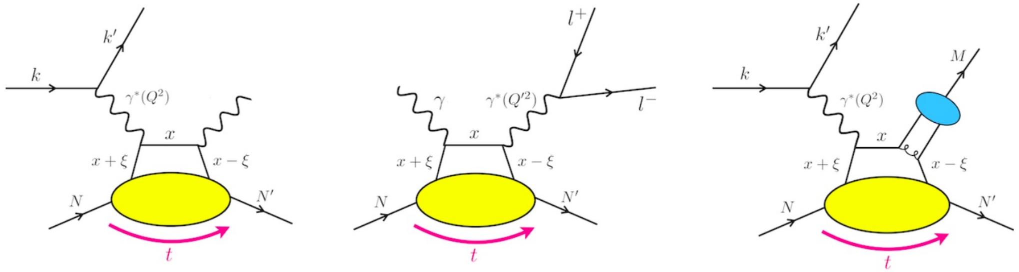


The EpIC generator: a new tool!

GPDs → CFFs → Observables

See Talk by V. Martinez-Fernandez

- 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



The near future: impact studies!

- We aim at performing new impact studies for extracting GPDs, similarly to what was done in JHEP09(2013)093, now with:
  - geant-4 simulation of the ePIC detector response and realistic event reconstruction
  - BH subtraction in xsec and π^0 background studies
  - state of art models: GK and KM20
  - we should reassess pi0 with a full simulation
- Status of ePIC detector simulation:
  - full GEANT4 bases simulation exists: DD4HEP, Jana2 (EICRecon) ...
- EpIC generator:
  - fully replaces MILOU & MILUO 3D. Maintained, using state or art models
  - Anyone encouraged to use it: arXiv:2205.01762
  - Future development: add more mesons, light ions (D, He) including incoherent D

o Everyone is welcome to collaborate to physics studies! (even if not joining the ePIC coll.)