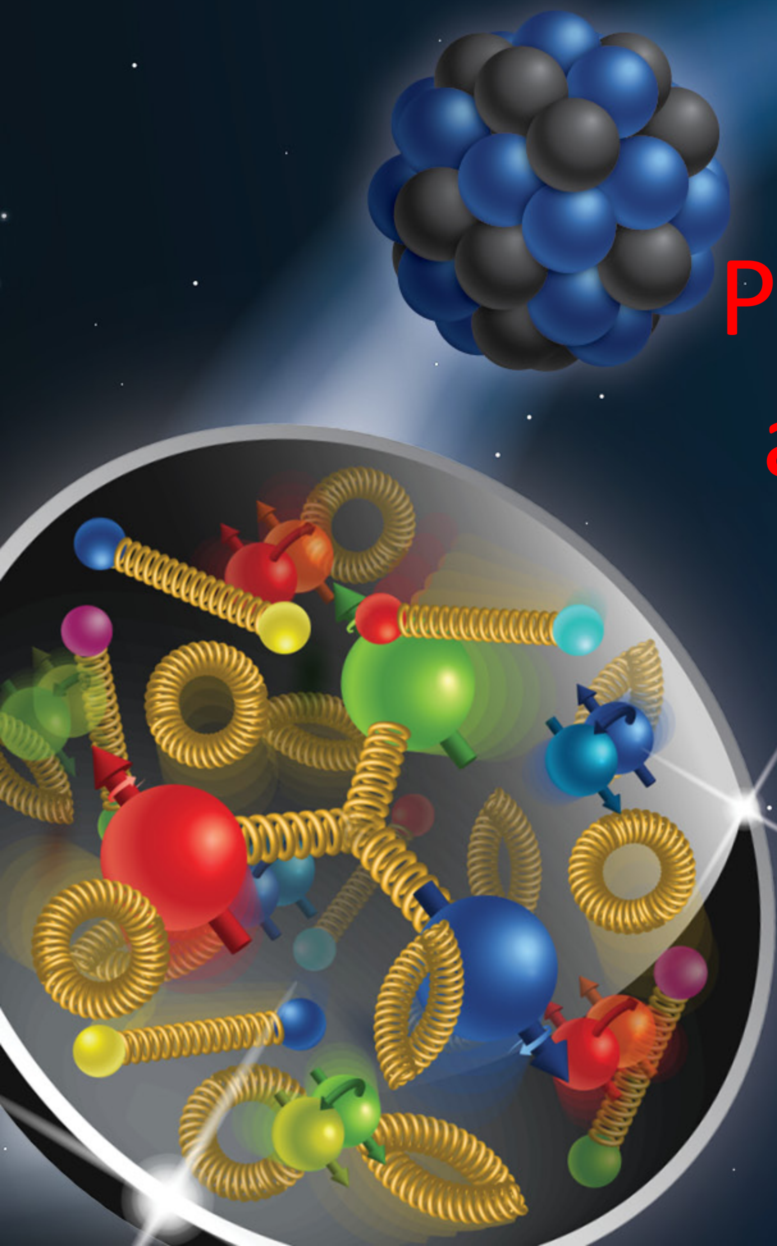


Partonic Spatial Imaging at an Electron-Ion Collider

J.H. Lee & Salvatore Fazio

BNL

Initial Stages 2019

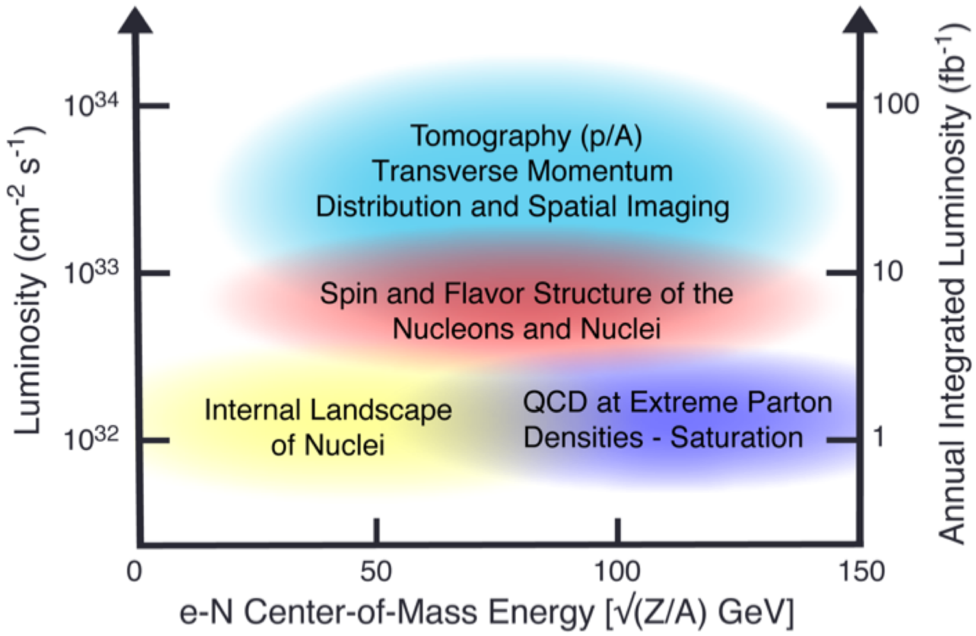
New York NY

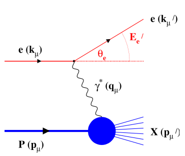
24-28 June 2019

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

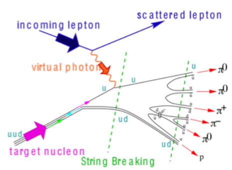
EIC: key physics and measurements





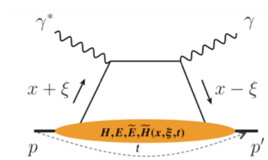
Inclusive DIS

measure scattered electron with high precision



Semi-inclusive DIS

detect the scattered lepton and final state (jets, hadrons, correlations in final state)



Exclusive processes

all particles in the event identified (diffraction)

Talk by E. Sichtermann on Friday

Multi-dimensional Imaging of Quarks and Gluons

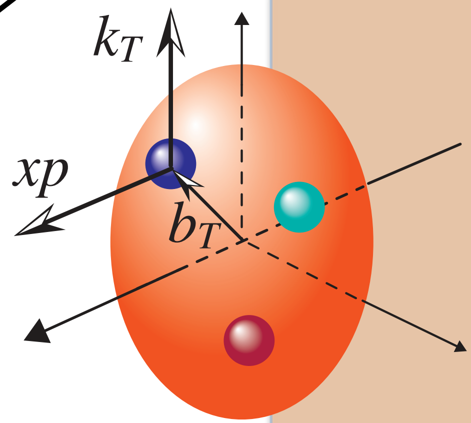
Wigner functions

$W(x, b_T, k_T)$

Momentum space

$\int d^2 b_T$

$f(x, k_T)$



Coordinate space

$\int d^2 k_T$

$f(x, b_T)$

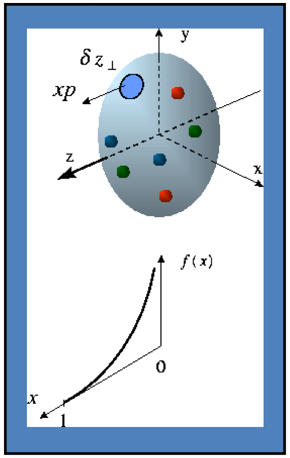
Spin-dependent 3D momentum space images from semi-inclusive scattering
→ **T**ransverse **M**omentum **D**istributions

Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering
→ **G**eneralized **P**arton **D**istributions

Direct access to $W(x, b_T, k_T)$
for gluons through diffractive dijet measurements at an EIC under investigation
Y. Hatta, B. Xiao, and F. Yuan [PRL 116, 202301 (2016)]
H. Mäntysaari, N. Mueller, B. Schenke [PRD 99 074004 (2019)]

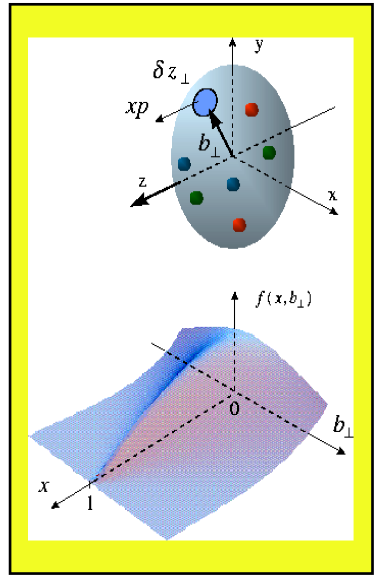
Generalized Parton Distributions

Longitudinal momentum & helicity distributions



$f(x)$

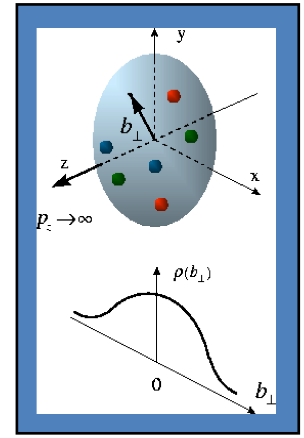
parton densities



$H(x,\xi,t)$

GPDs

Transverse charge & current densities



$F_1(t)$

form factors

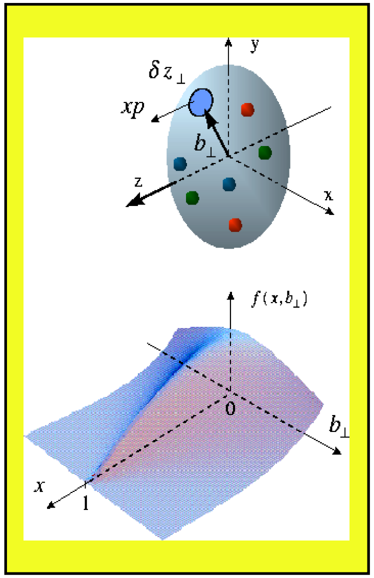
The nucleon (spin-1/2) has **four quark and gluon GPDs** (H, E and their polarized-proton versions $\widetilde{H}, \widetilde{E}$). Like usual PDFs, GPDs are non-perturbative functions **defined via the matrix**

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

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

Accessing the GPDs in exclusive processes

$H^{q,g}(x,\xi,t)$	$E^{q,g}(x,\xi,t)$	*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*	



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

Dominated by H
slightly dependent on E

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

→ **Requires a positron beam**
done @ HERA

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

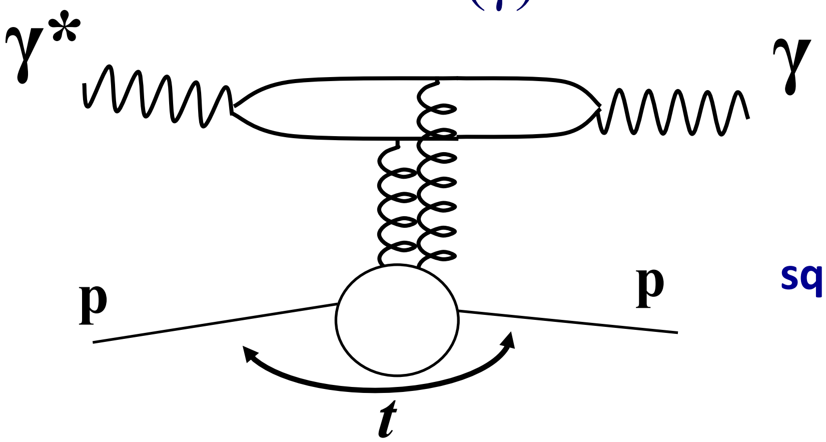
→ ***sin(Φ$_T$−φ$_N$)***
governed by E and H

Requires a polarized proton-target

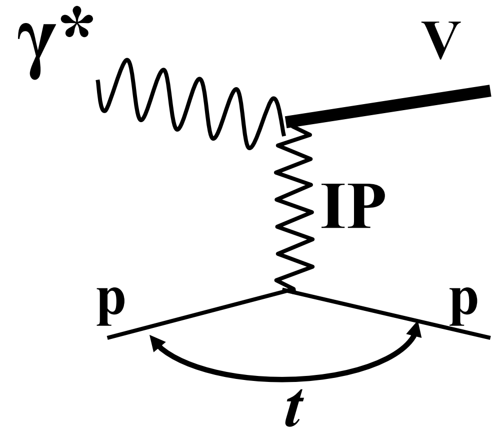
responsible for total orbital angular momentum through Ji sum rule
a window to the SPIN physics

Exclusive Vector Meson and real photon production

DVCS (γ)



HEMP (ρ, ω, φ, J/ψ, Υ, π^0)



square 4-momentum at the *p* vertex:

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

Scale: Q^2 ⟷ $Q^2 + M^2$

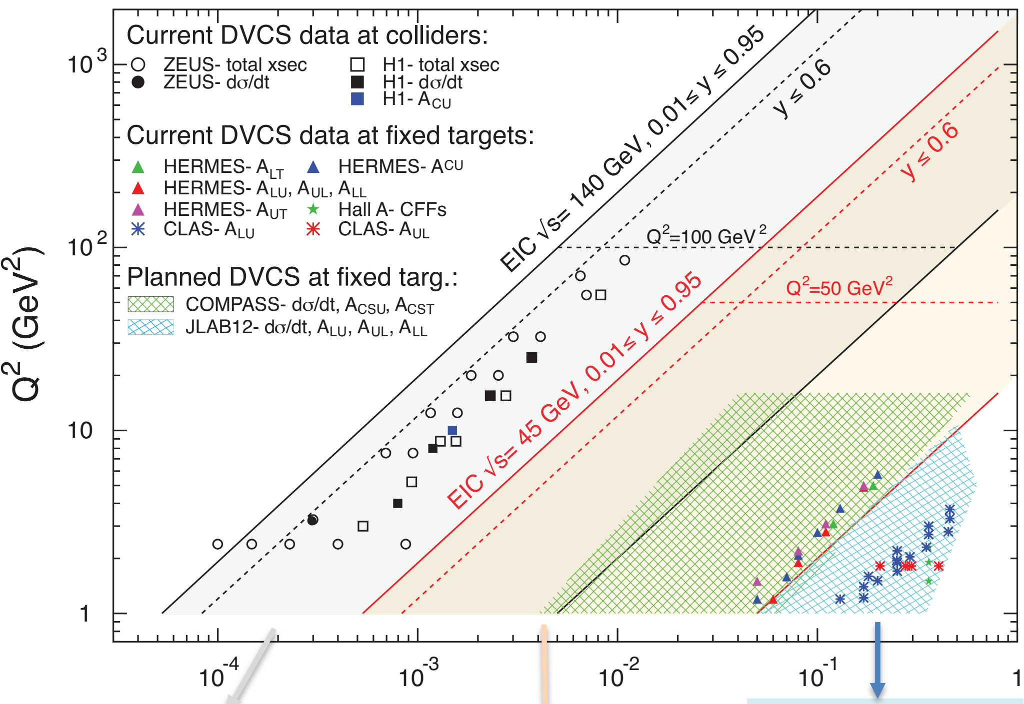
Deeply Virtual Compton Scattering:

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

Hard Exclusive Meson Production:

- Uncertainty of wave function
- J/Psi, Y → direct access to gluons
- Light VMs → quark-flavor separation
- Scalar mesons → quark-flavor in $\tilde{H}$, $\tilde{E}$

DVCS at an EIC



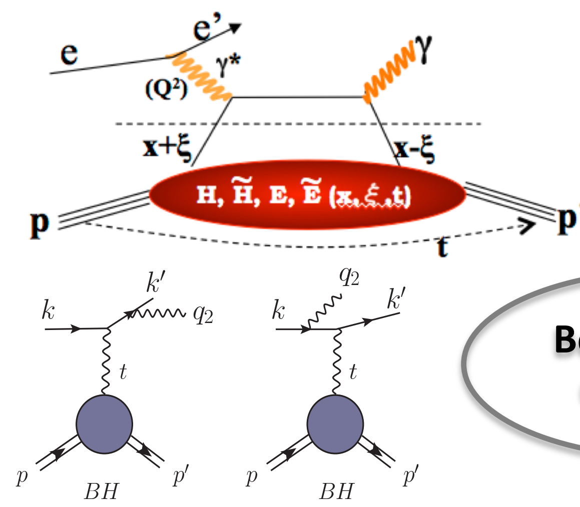
Overlap with HERA: Large impact on current fits at low x

Intermediate region: Fine mapping of the GPDs evolution

Overlap with JLAB12: Sanity check

HERA results limited by lack of statistics

EIC: the first machine to measure cross sections and asymmetries



DVCS signal

Bethe-Heitler QED bkgd.

Comprehensive EIC studies

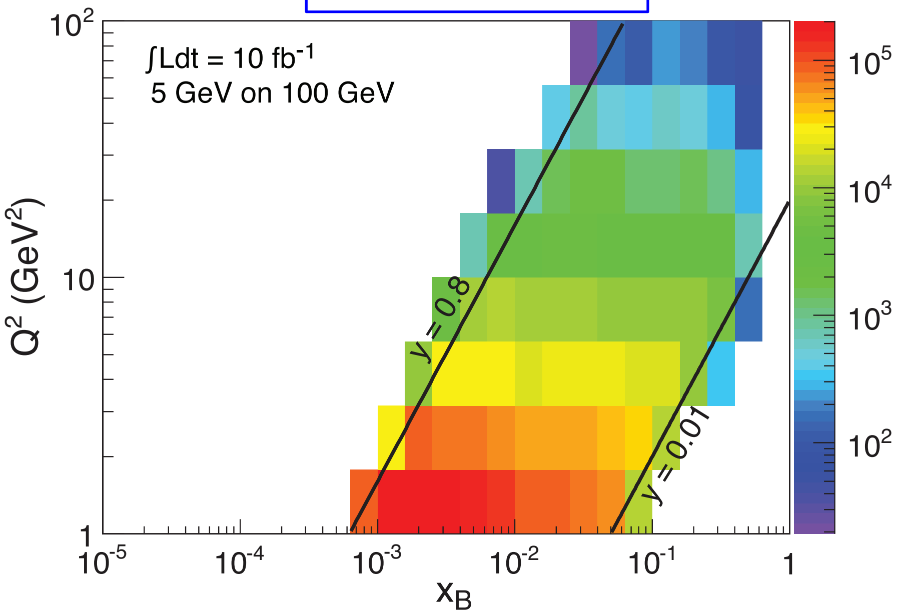
- Signal extraction "a la HERA"
- xSec meas.: Specific requirements to suppress BH
  → keep BH/sample below 60% at high energies
- Radiative Corrections evaluated
- detector acceptance & smearing
- t-slope: b=5.6 compatible with H1 data
- |t|-binning is (3*resolution)
- 5% systematic uncertainties

DVCS at a high luminosity collider

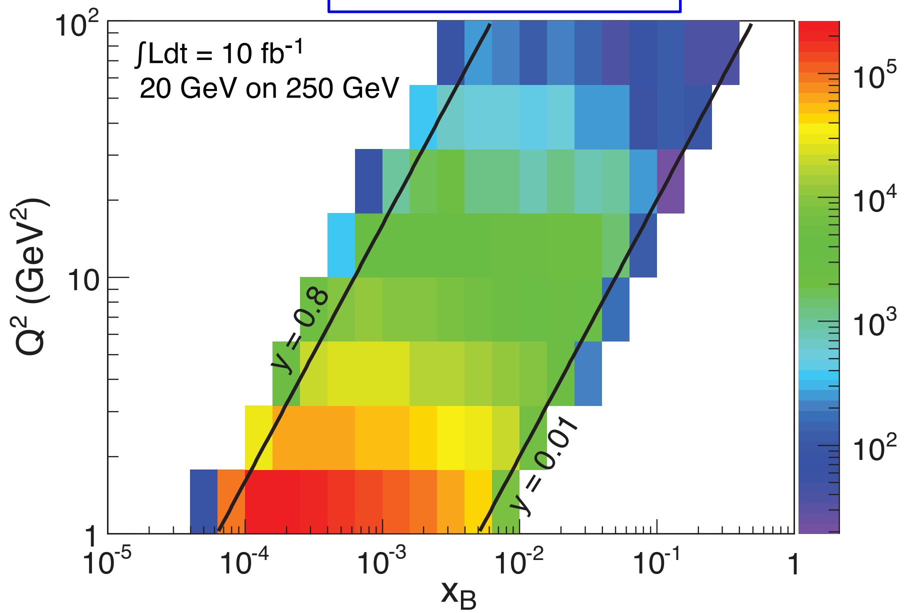
The code MILOU by E. Perez, L Schoeffel, L. Favart [arXiv:hep-ph/0411389v1]
is Based on a GPDs convolution by: A. Freund and M. McDermott [http://durpdg.dur.ac.uk/hepdata/dvcs.html]

- ✧ EIC will provide sufficient luminosity for multi-dimensions
- ✧ wide x and Q^2 range needed to extract GPDs

√s = 45 GeV

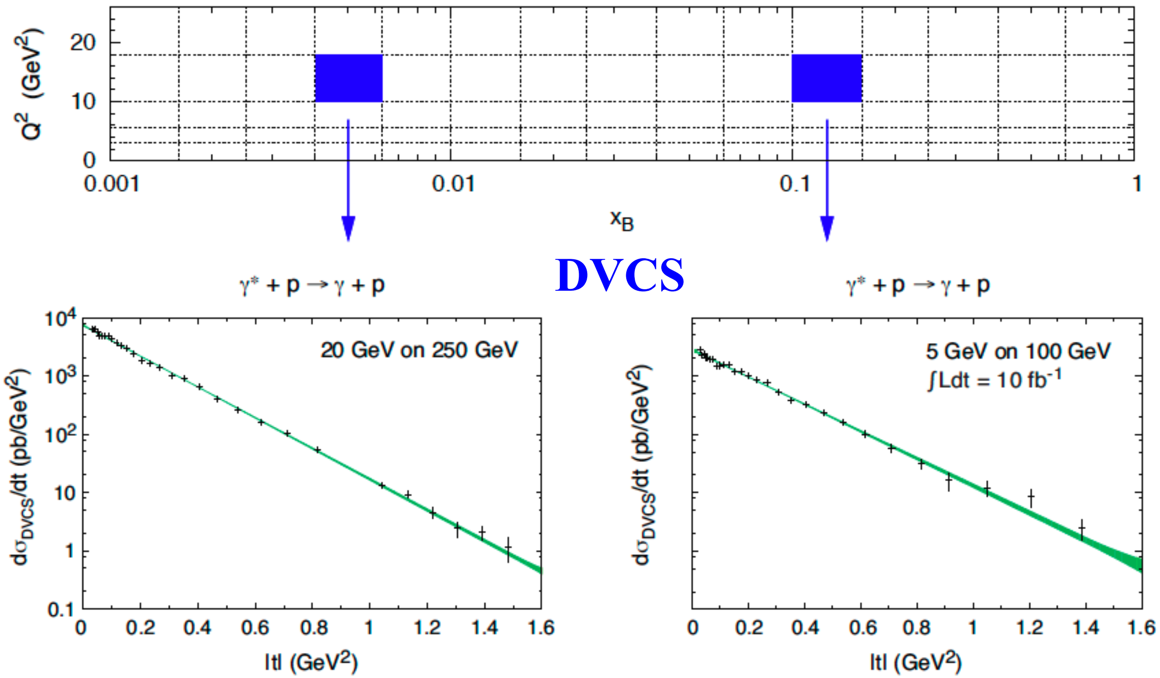


√s = 140 GeV



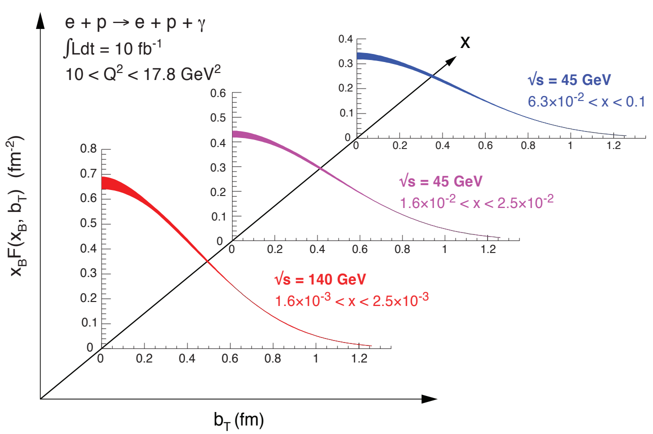
… we can do a fine binning in Q^2 and W… and in |t|

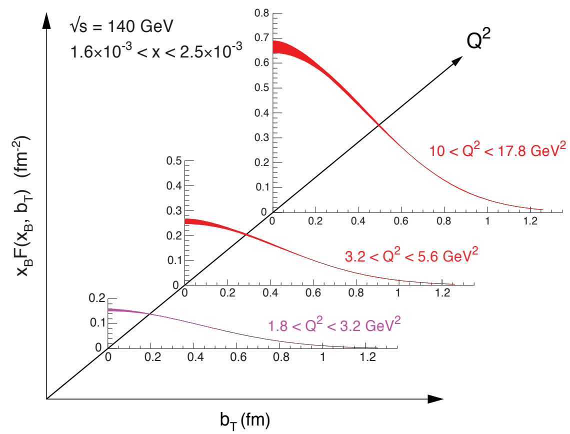
DVCS differential cross section



Luminosity: 10 fb^{-1}

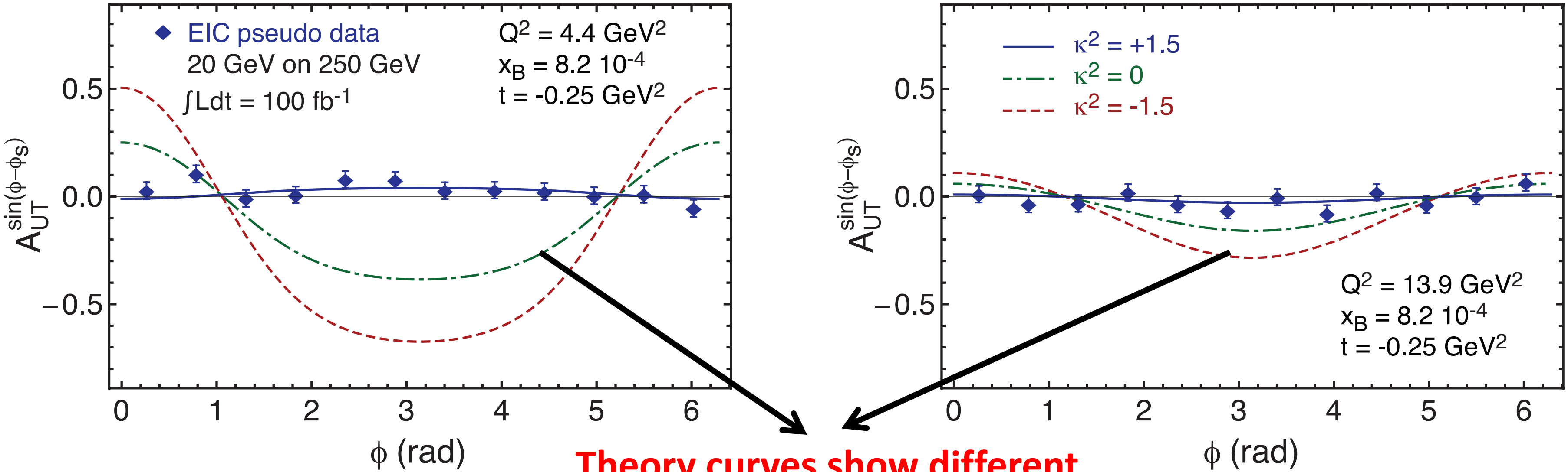
- **Measurement dominated by systematics**
- Fourier transf. of dσ/dt → partonic profiles





Transverse target-spin asymmetry

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



Theory curves show different assumptions for E

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

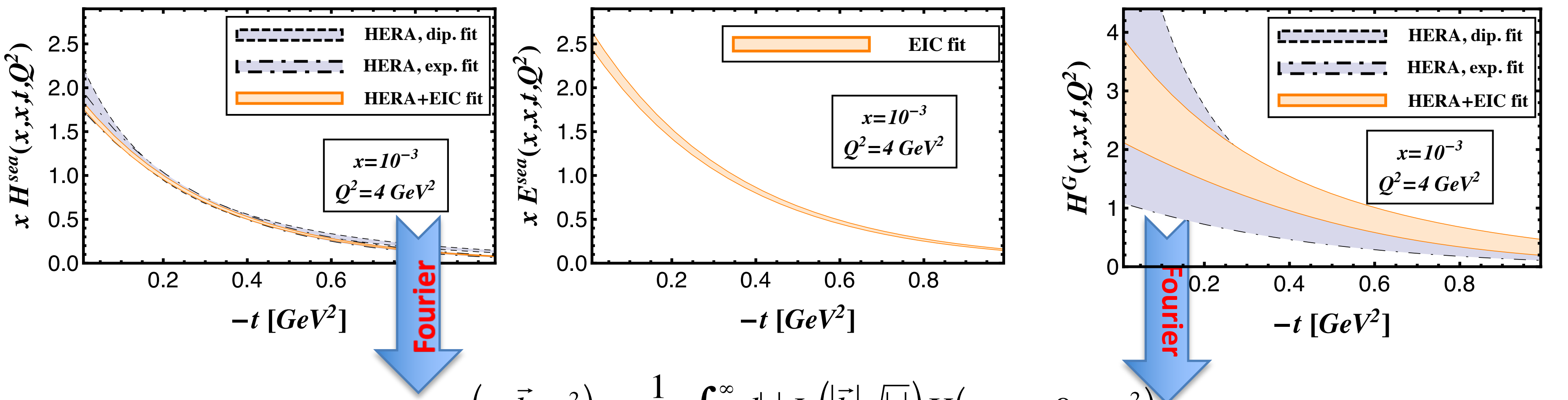
Transversely polarized protons: sin($\Phi_T - \phi_N$)
gives access to GPD E
Access to orbital angular momentum through "Ji sum rule"

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

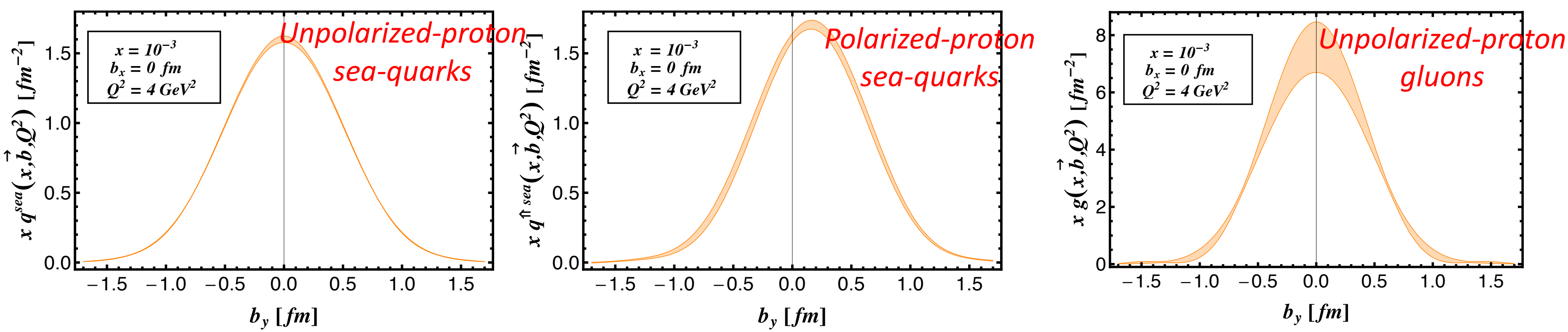
[X.D. Ji, Phys. Rev. Lett. 78, 610 (1997)]

DVCS-based imaging

- 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)

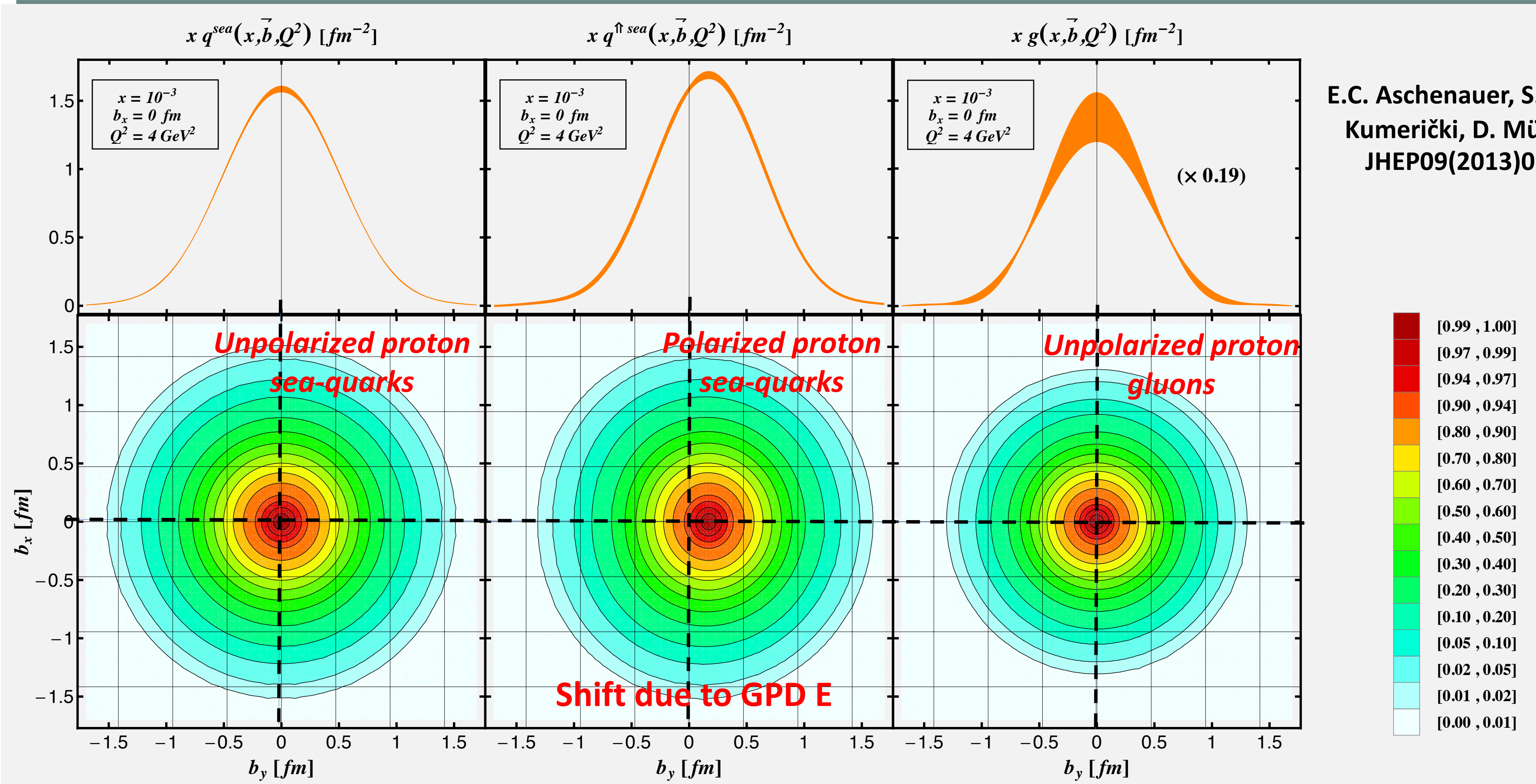


$$q\left(x,\vec{b},\mu^2\right)=\frac{1}{4\pi}\int_0^\infty d|t|\,J_0\left(\left|\vec{b}\right|\sqrt{|t|}\right)H\left(x,\eta=0,t,\mu^2\right)$$



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

Spatial Imaging – as in the EIC White Paper



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

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**

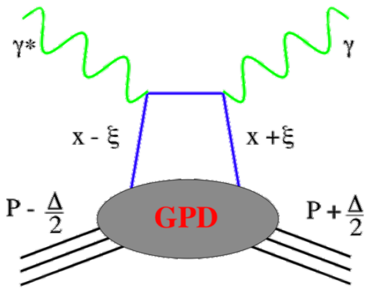
Other capabilities still to be evaluated?

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

How to separate flavors?

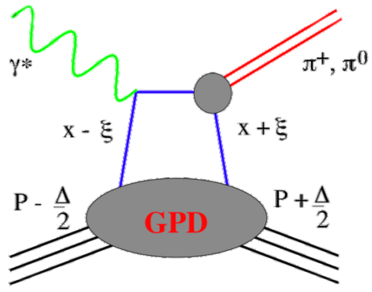
Hard Exclusive Meson Production (HEMP) → a powerful tool!

quantum numbers of final state ➡ select different GPD



DVCS

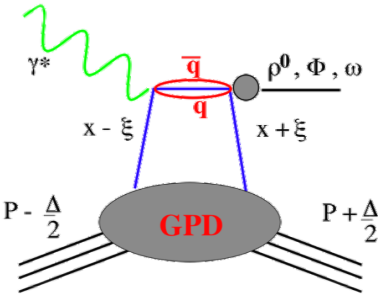
$H^q \; E^q \quad \widetilde{H}^q \quad \widetilde{E}^q$



pseudo-scalar mesons

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

π^0	2Δu+Δd
η	2Δu–Δd



vector mesons

$H^q \; E^q$

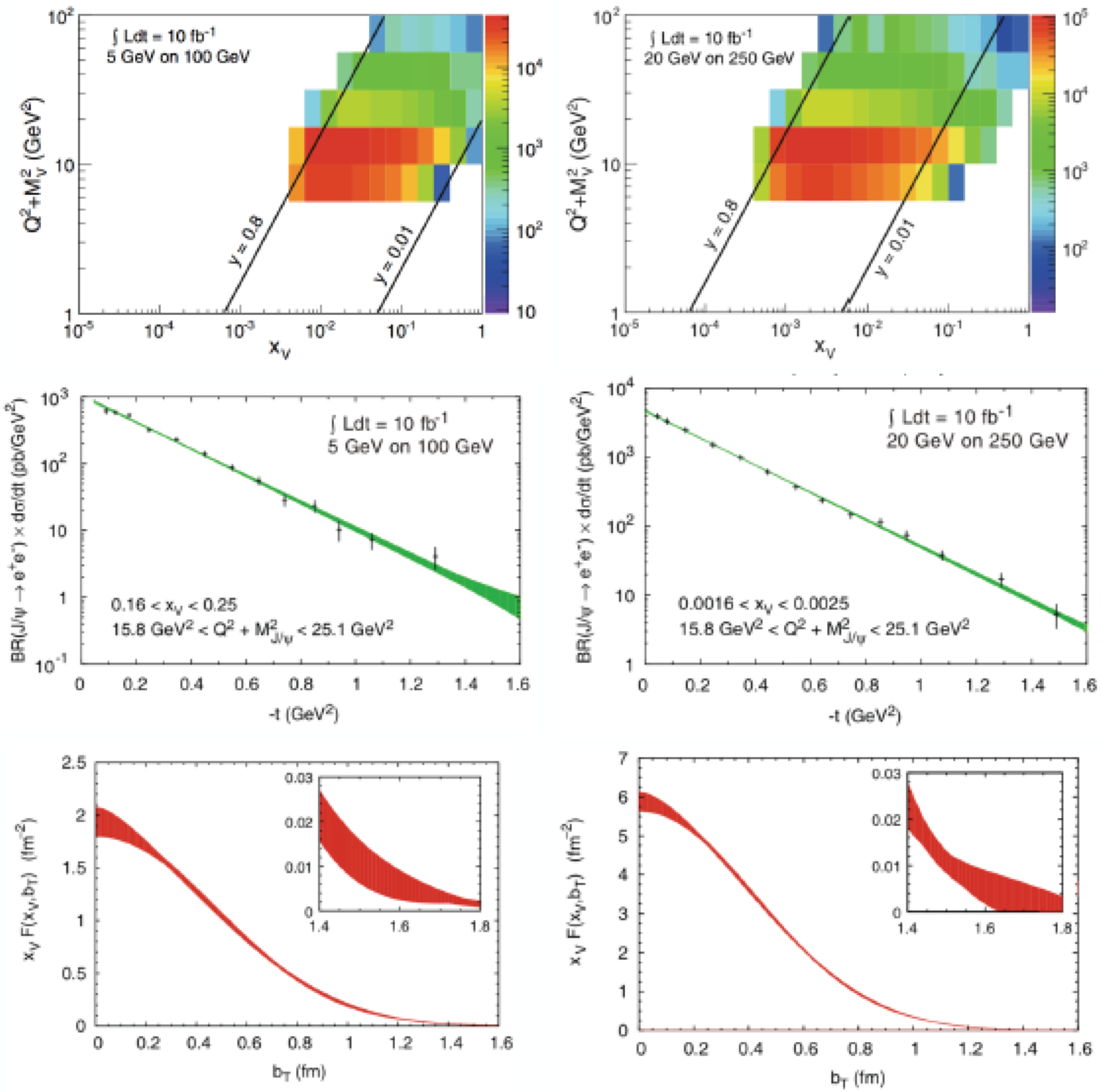
ρ^0	2u+d, 9g/4
ω	2u–d, 3g/4
ϕ	s, g
ρ^+	u–d
J/ψ, Υ	g

DVCS on protons and neutrons also separates quark u/d flavors

- **We do not have a real neutron target → Use Deuterium**

Imaging gluons with J/ψ

EIC White Paper

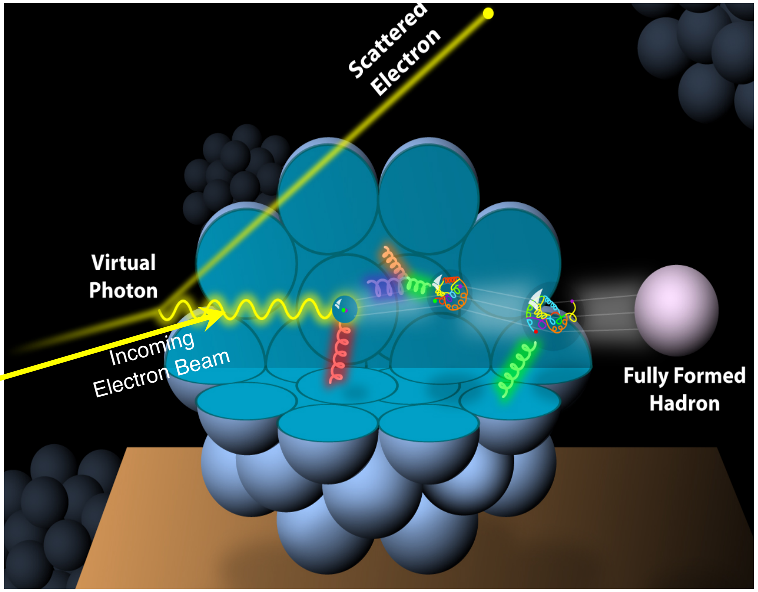


Luminosity: 10 fb^{-1}

- Measurement dominated by systematics
- Fourier transf. of dσ/dt → partonic profiles

Average gluon densities

Nuclear PDFs and GPDs
an Electron-Ion Collider (EIC)



- How does the nuclear environment affect the distribution of quarks and gluons and their interaction in nuclei?
- Where does the saturation of the gluon density set in?

Imaging the gluons in nuclei

Diffractive physics in eA

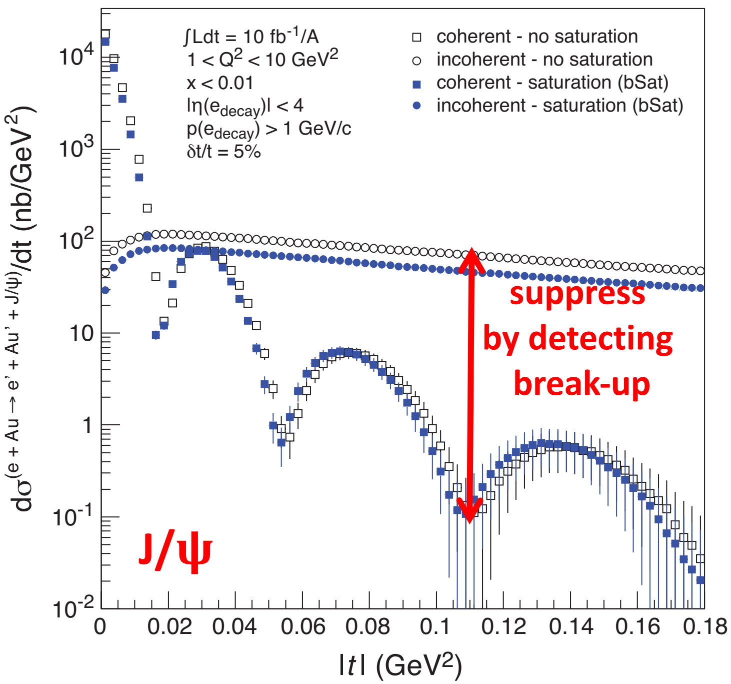
→ Measure spatial gluon distribution in nuclei

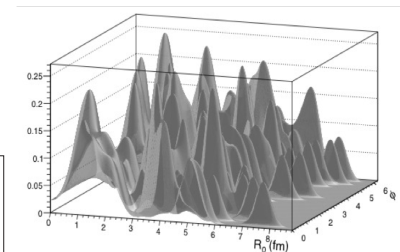
→ Reaction: e + Au → e′ + Au′ + J/ψ, φ, ρ

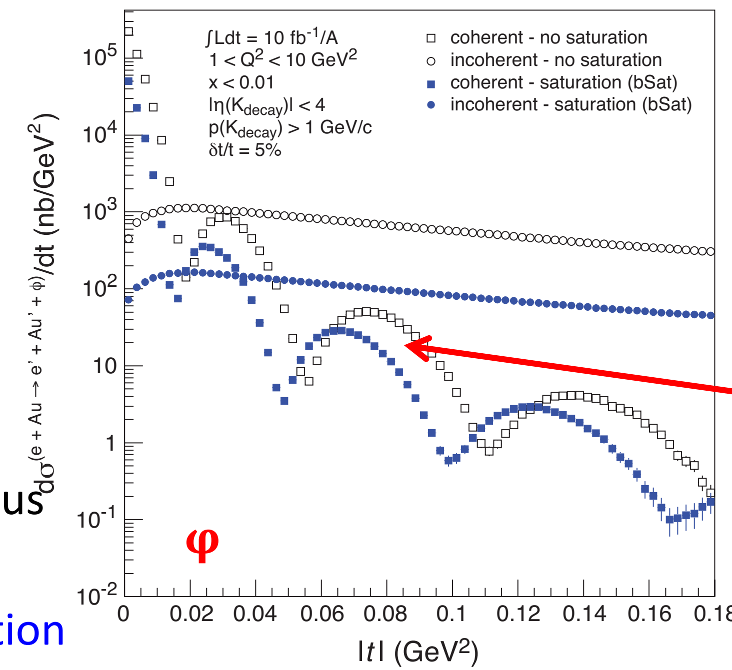
→ Momentum transfer t = |p_{Au}-$p_{Au'}$|^2

❑ coherent part probes shape/size of the source

❑ incoherent part (large t) sensitive to lumpiness of the source [= proton] (fluctuations, hot spots, ...)







Sensitive to saturation effects!

Physics requires forward scattered nucleus needs to stay intact

→ Veto breakup through forward detection

Talk by H. Mäntysaari this morning

Summary

We studied and quantified the capability of an EIC to provide high precision and fine binned DVCS and meson production measurements of both cross sections and asymmetries over a large phase-space. This opens an unprecedented possibility for

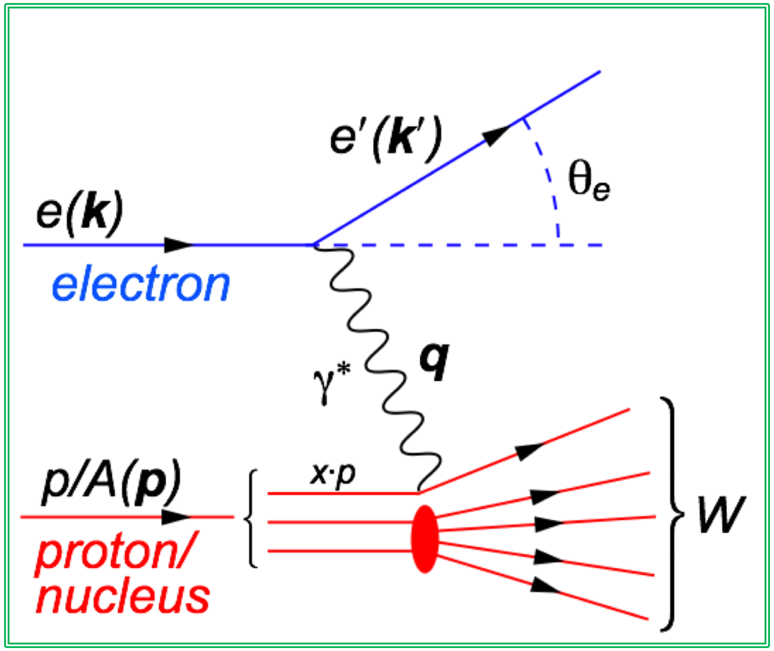
- Accurate 2+1D imaging of the polarized and unpolarized quarks and gluons inside the hadrons, and their correlations
- Investigate the proton-spin decomposition puzzle (total orbital angular momentum)

To come

- Include mesons in global fits (flavor separation, precision on gluons)
- Study of GPDs in nuclei (and possible gluon saturation effects)

Back up

Our Tool: Deep Inelastic Scattering



Kinematics:

$$Q^2 = 2E_eE'_e(1-\cos\theta_{e'}) = -(k-k')^2 = -q^2$$

Measure of resolution power

$$y = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right) \quad x = \frac{Q^2}{2pq} \quad \sqrt{s} = 2\sqrt{E_eE_p}$$

Measure of inelasticity

Measure of momentum fraction of struck quark

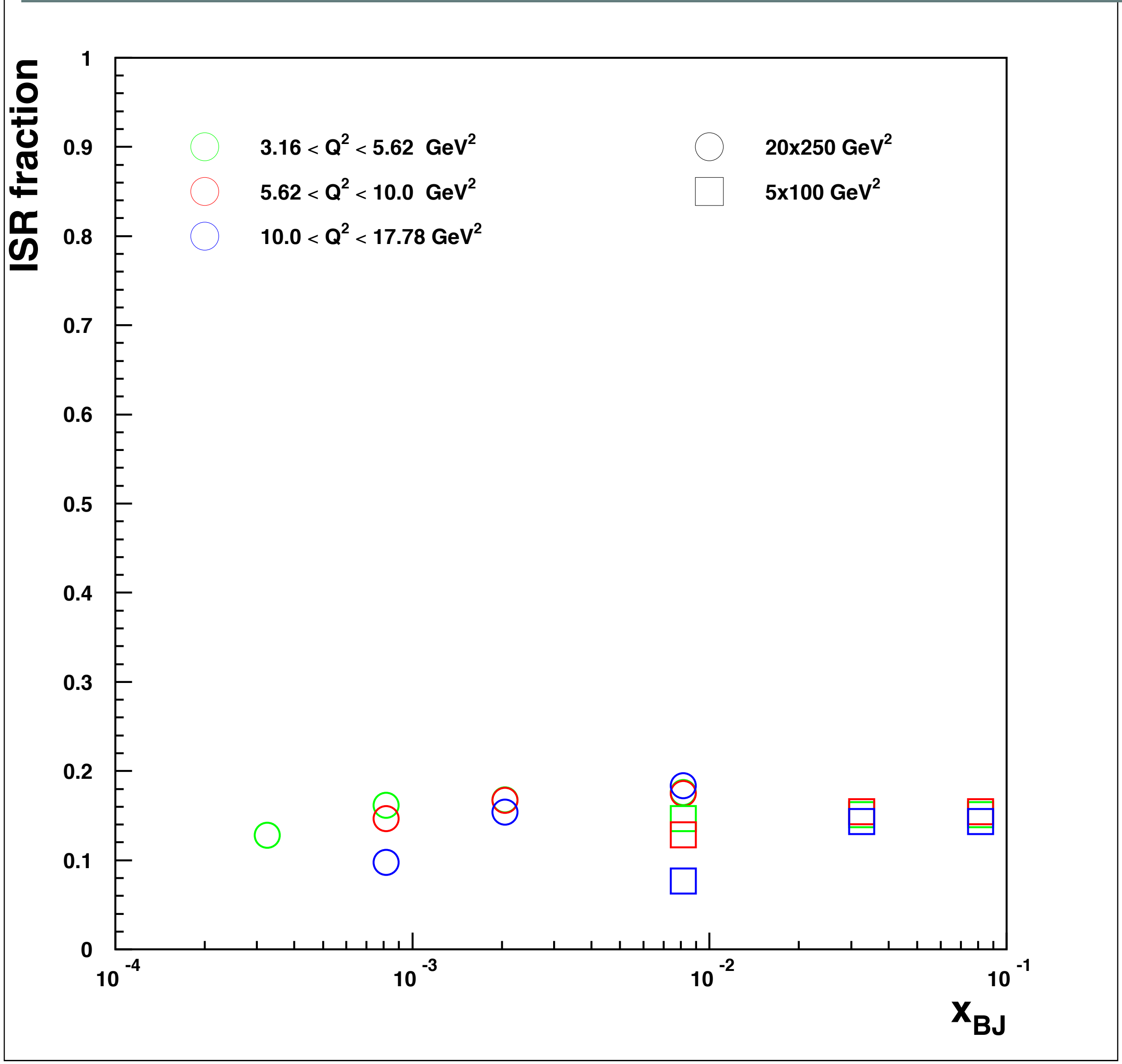
Center-of-mass energy of electron-hadron system

All variables are correlated: $Q^2 = s \cdot x \cdot y$

DIS:

- As a probe, electron beams provide unmatched precision of the electromagnetic interaction
- Direct, model independent, determination of kinematics of physics processes
- Indirectly probes gluons with high precision

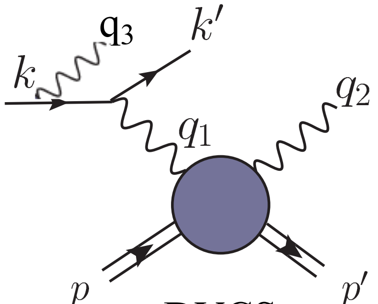
Contribution from ISR



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

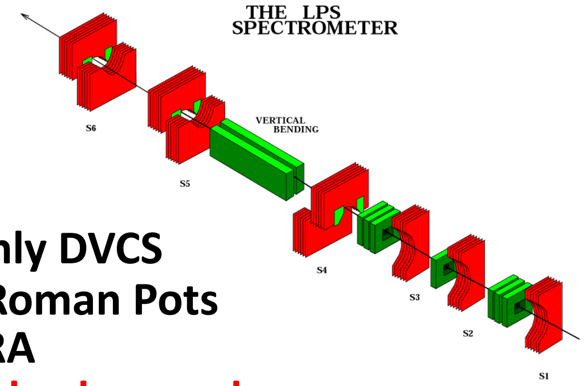
ONLY 15% of the events emit a photon with > 2% energy of the incoming electron

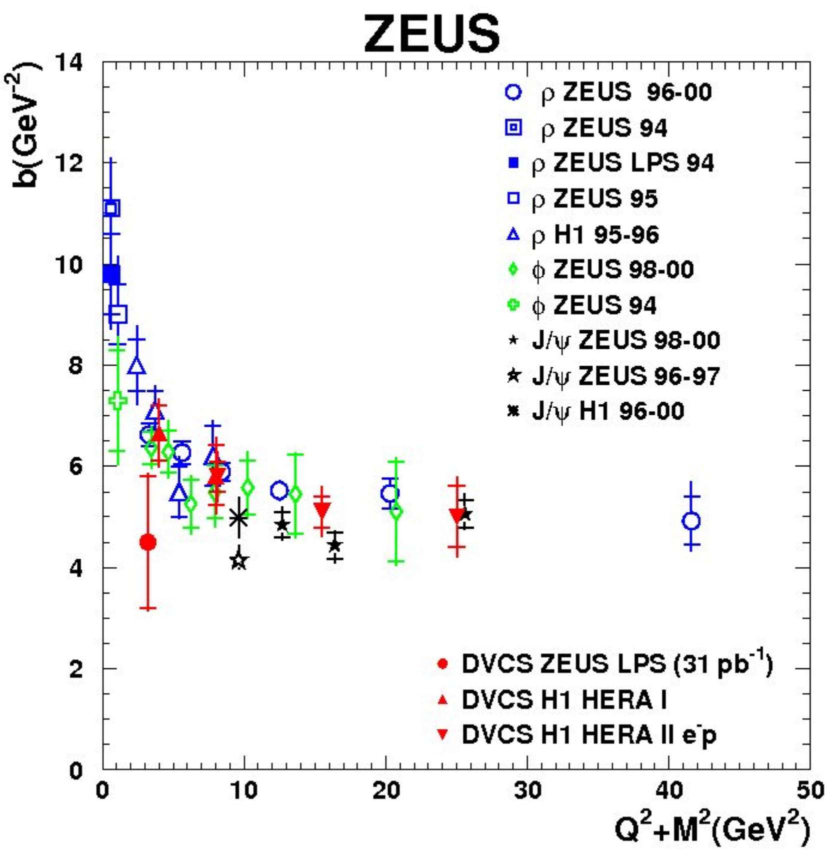
ISR photons with **$E_\gamma < 0.02\, E_e$** do not result in a significant correction for the event kinematics.



DVCS
&
BH -ISR

DVCS & VMPs at HERA



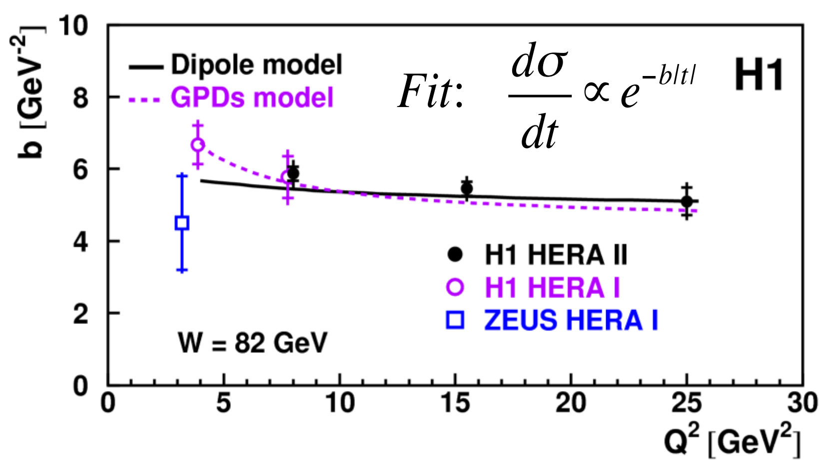


dσ/dt measured for the first time by a direct measurement of the outgoing proton 4-momentum using the Leading Proton Spectrometer (roman pots)

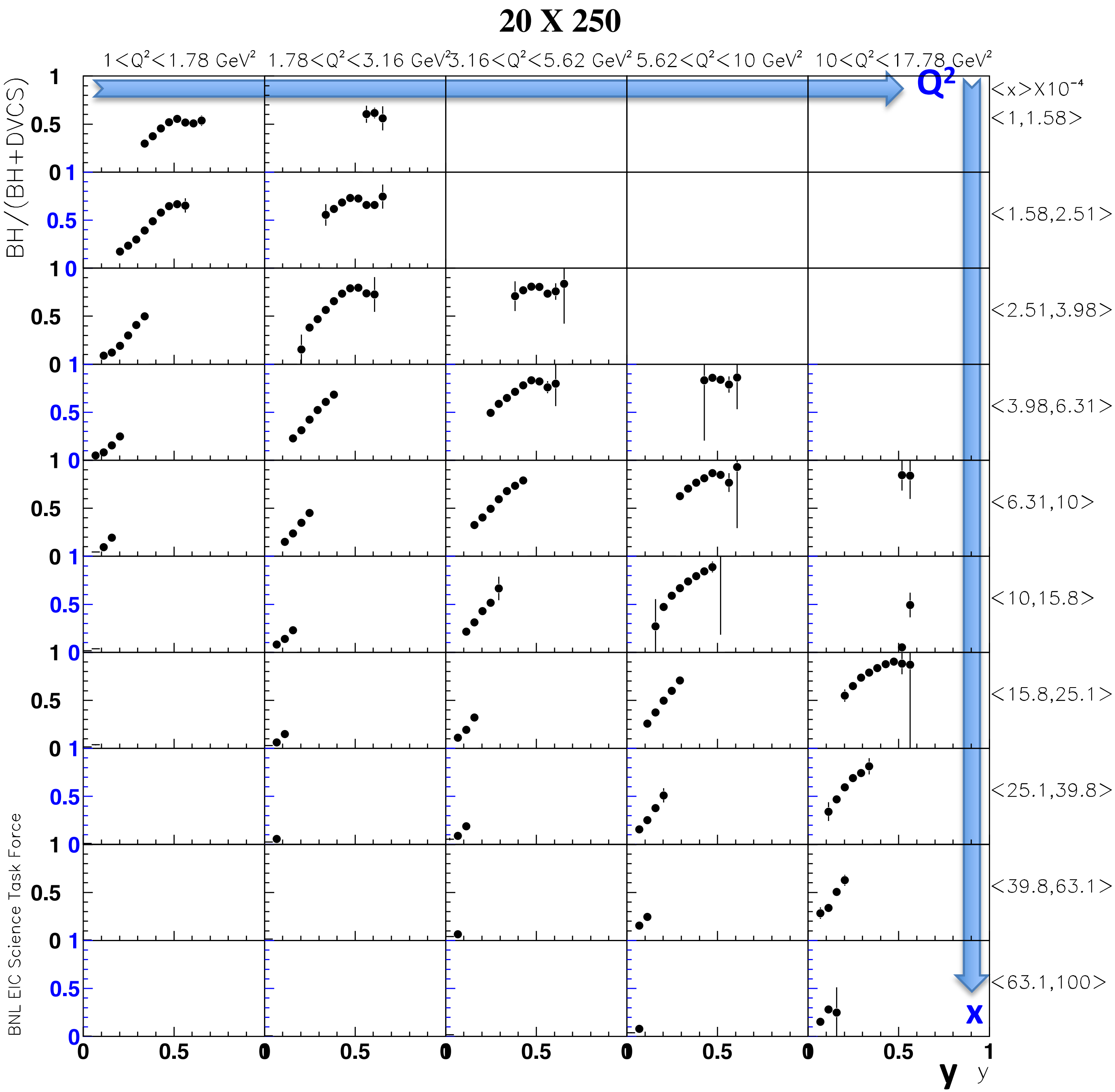
ZEUS released the only DVCS measurement with Roman Pots Spectrometer at HERA

- No p-dissociation background
- $0.08 < |t| < 0.53$ GeV^2
- Low geometrical acceptance → low statistics

This detector was removed after the HERA II upgrade → $\mathcal{L}$ = 31 pb^{-1}



The ZEUS result still statistically compatible with H1, but hints for a flatter trend



BH fraction

cuts keep BH below 60% of the sample at large y > 0.5

20 x 250 GeV^2

BH subtraction will be not an issue for y<0.6

BH subtraction will be relevant at lower energies and large y, in some of the x-Q^2 bin

BUT…

higher-lower √s kin. overlapping:

x-sec. measurements at a higher √s at low-y can cross-check the BH subtraction made at lower √s