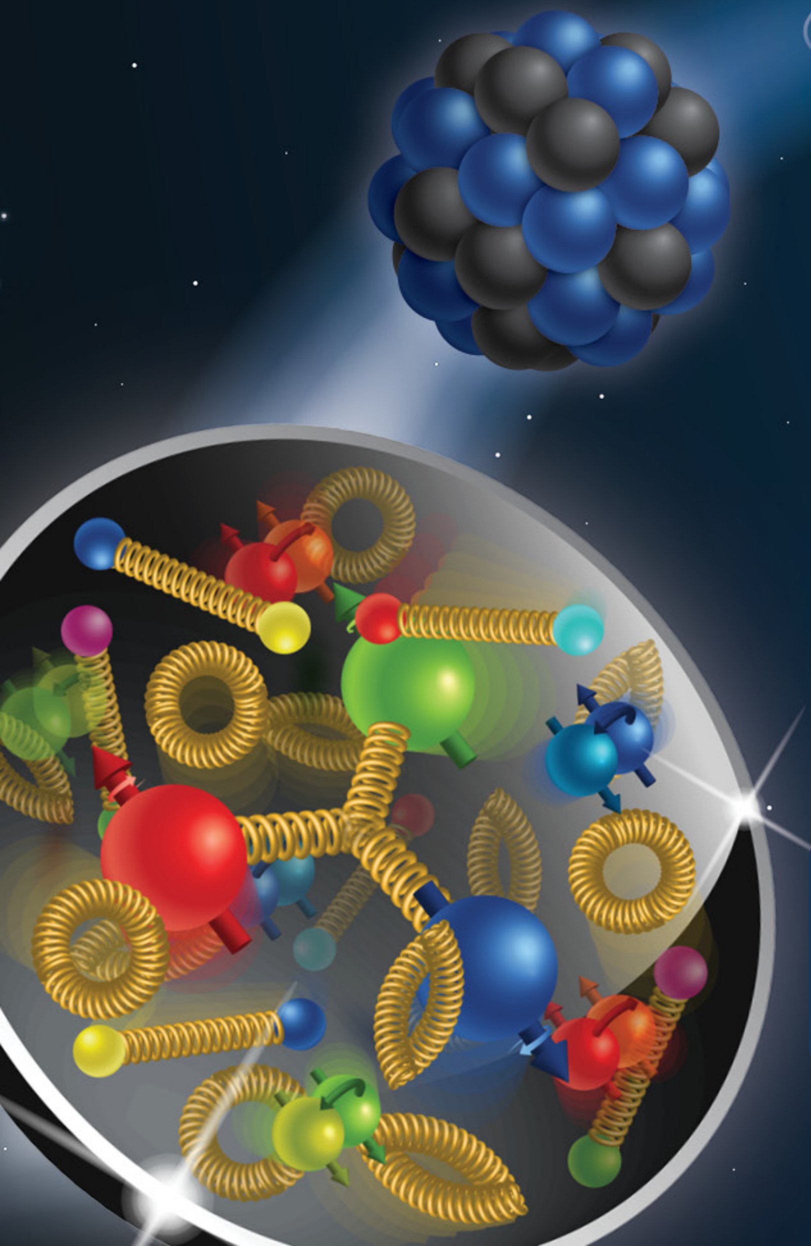


GPD Studies with Exclusive Processes at EIC

Salvatore Fazio

Brookhaven National Lab

Joint CFNS & RBRC Workshop on Physics and Detector Requirements at Zero-Degree of Colliders

Stony Brook University, NY

24-26 September 2019

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

Multi-dimensional Imaging of Quarks and Gluons

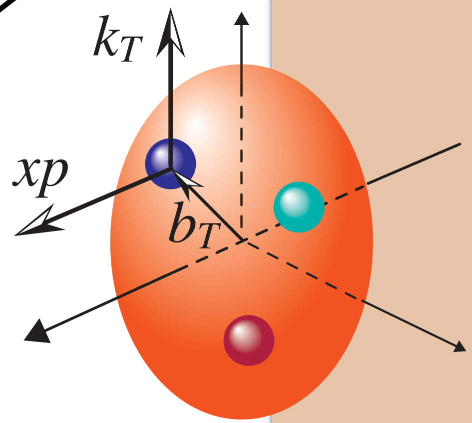
Wigner functions

$W(x, b_T, k_T)$

Momentum space

$\int d^2 b_T$

$f(x, k_T)$



Coordinate space

$\int d^2 k_T$

$f(x, b_T)$

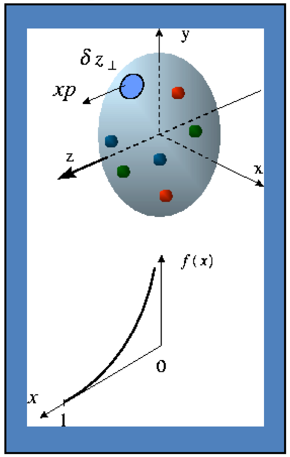
Spin-dependent 3D momentum space
From **SiDIS** & **DY / weak bosons**
→ **TMDs**

Spin-dependent 2D coordinate space
(transverse) + 1D (longitudinal momentum)
From **exclusive processes**
→ **GPDs**

Direct access to gluon elliptic Wigner fcn.
for gluons through diffractive di-jets measurements at an EIC under investigation
Yoshitaka Hatta, Bo-Wen Xiao, and Feng Yuan [Phys. Rev. Lett. 116, 202301 (2016)]
H. Mäntysaari, N. Mueller, B. Schenke [arXiv:1902.05087]

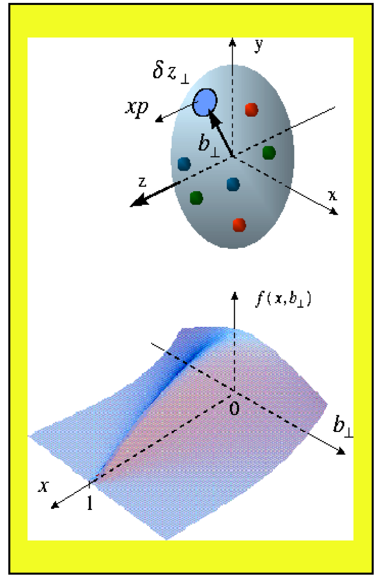
Generalized Parton Distributions

Longitudinal momentum & helicity distributions



$f(x)$

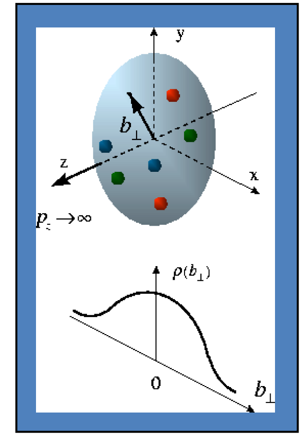
parton densities



$H(x, \xi, t)$

GPDs

transverse charge & current densities



$F_1(t)$

form factors

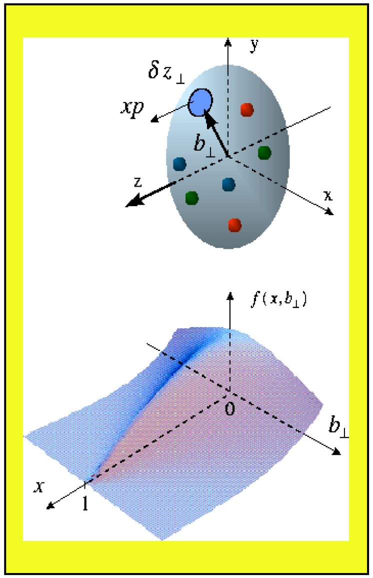
The nucleon (spin-1/2) has **four quark and gluon GPDs** (H, E and their polarized-proton versions $\widetilde{H}, \widetilde{E}$). Like usual PDFs, GPDs are non-perturbative functions **defined via the matrix**

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

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

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

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

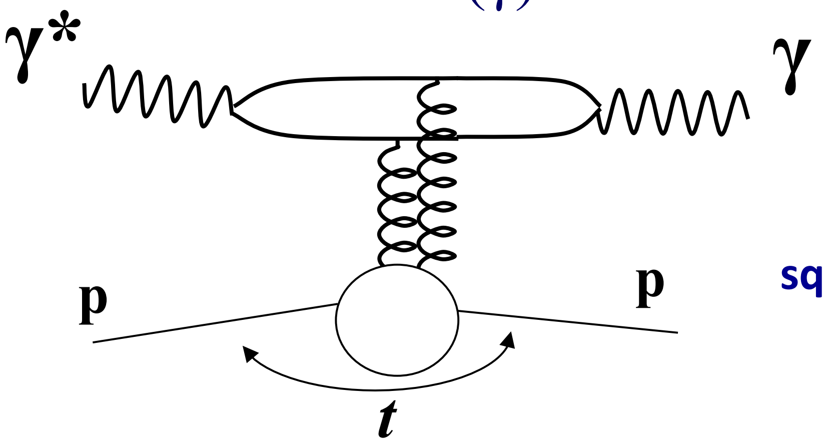
→ ***$\sin(\Phi_T - \phi_N)$***
governed by E and H

Requires a polarized proton-target

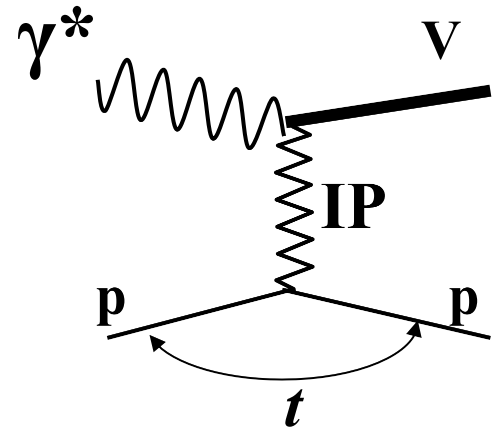
responsible for total orbital angular momentum through Ji sum rule
a window to the SPIN physics

Exclusive Vector Meson and real photon production

DVCS (γ)



VM (ρ, ω, φ, J/ψ, Y)



square 4-momentum at the *p* vertex:

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

Scale: Q^2 ⟷ $Q^2 + M^2$

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)]

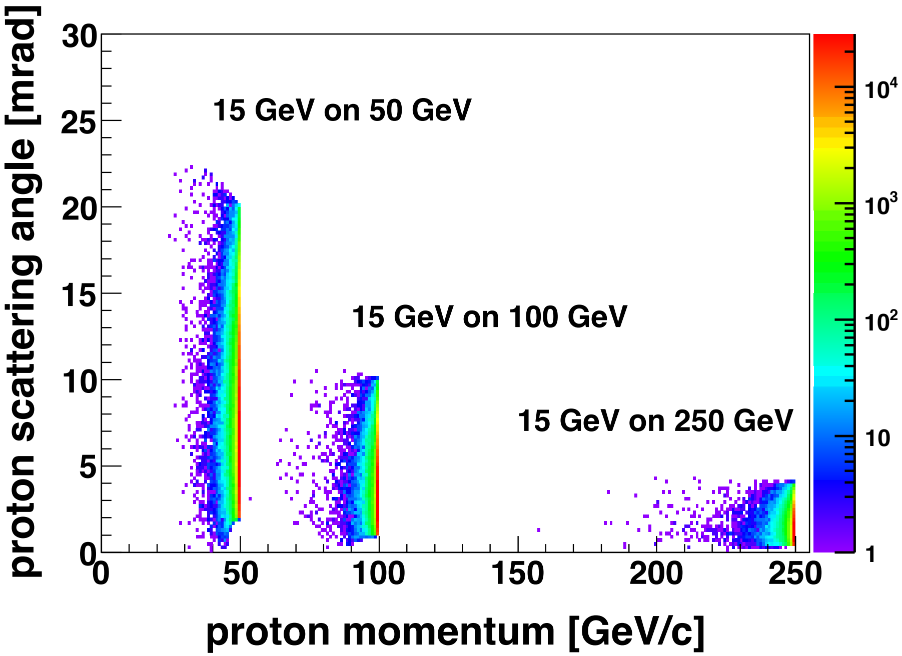
HEMP:

- 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

Alternative/complementary way to quark-flavor separation

DVCS on a real neutron target → polarized Deuterium or He^3

Scattered Proton measurement



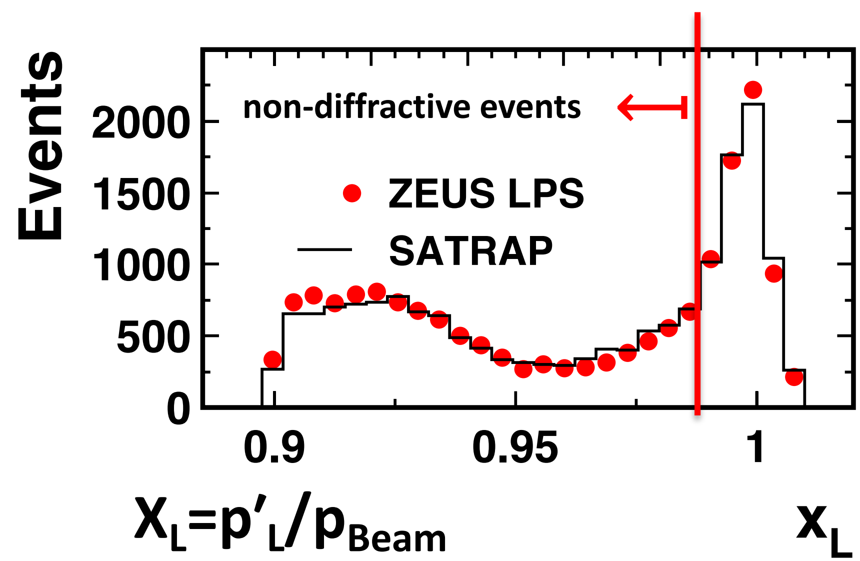
Remember:

p_T of proton critical for physics

$p_T = p' \sin(\Theta)$

$p'_L > 97\%$ of p_{Beam}

ZEUS Coll, JHEP 06 (2009) 074



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

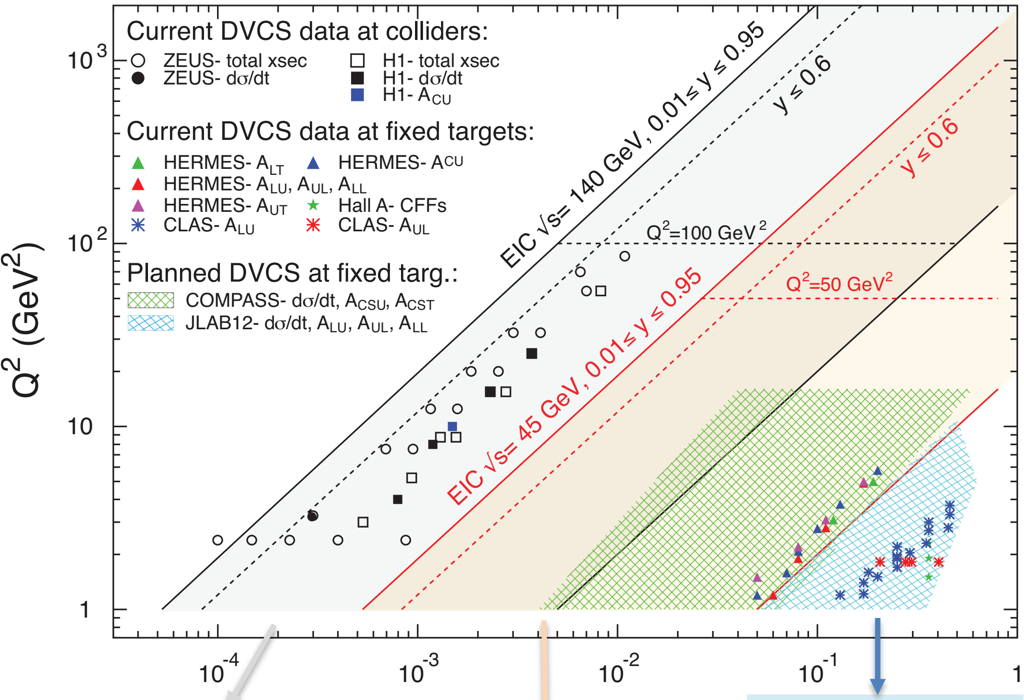
→ Θ < 10 mrad

→ impact on large p_T-acceptance

→ small p_T-acceptance limited by beam divergence and immittance

→ rule of thumb keep 10s between RP and beam

DVCS at an EIC



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

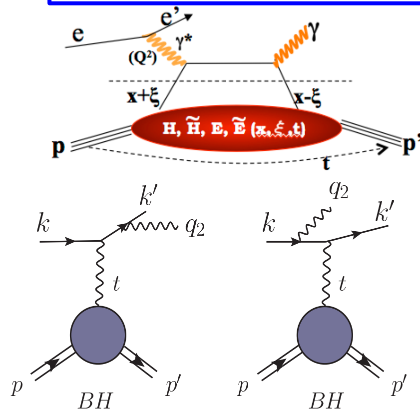
Intermediate region: **Fine mapping of the GPDs evolution**

Overlap with JLAB12: **Sanity check**

HERA results limited by lack of statistics

EIC: the first machine to measure cross sections and asymmetries

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



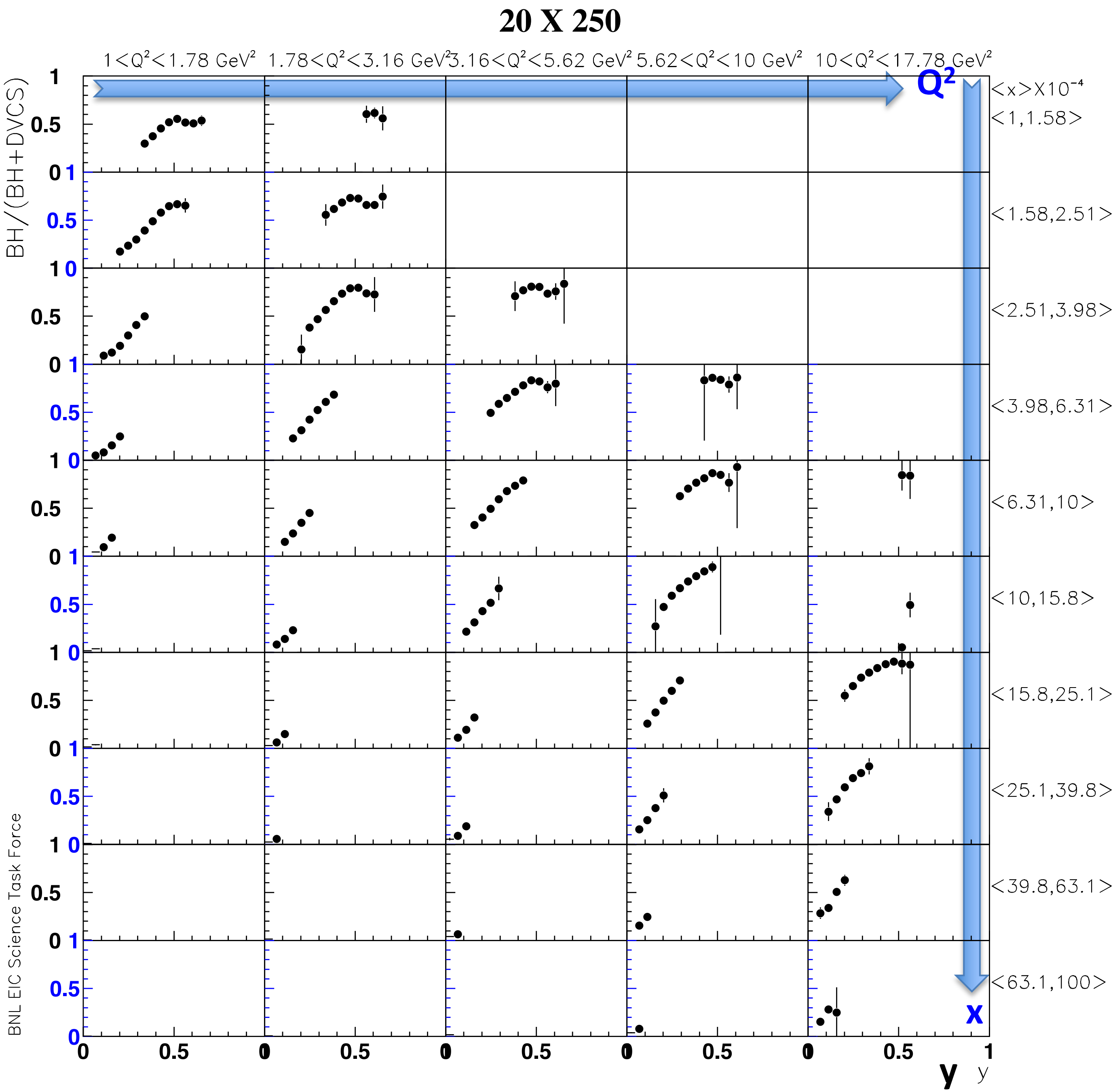
DVCS signal

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**

BH fraction



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

20 x 250 GeV²

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-Q² bin

BUT…

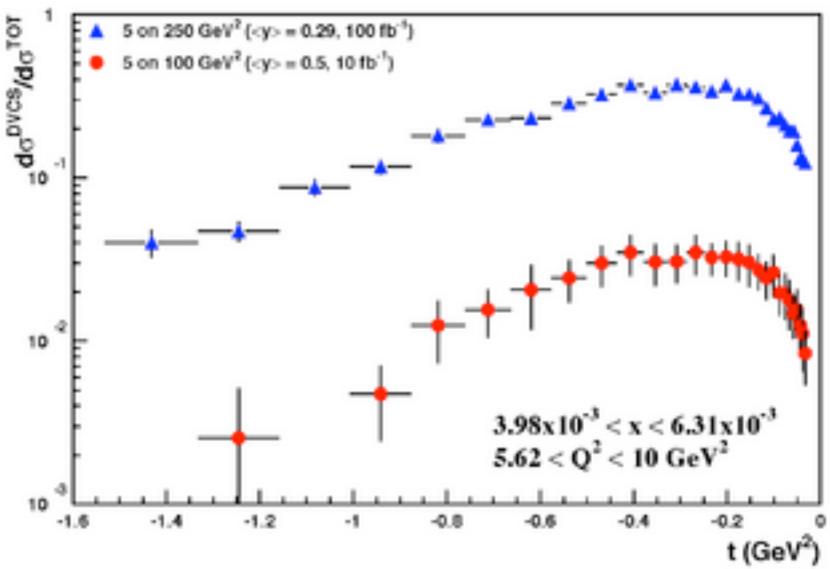
higher-lower √s kin. overlapping:

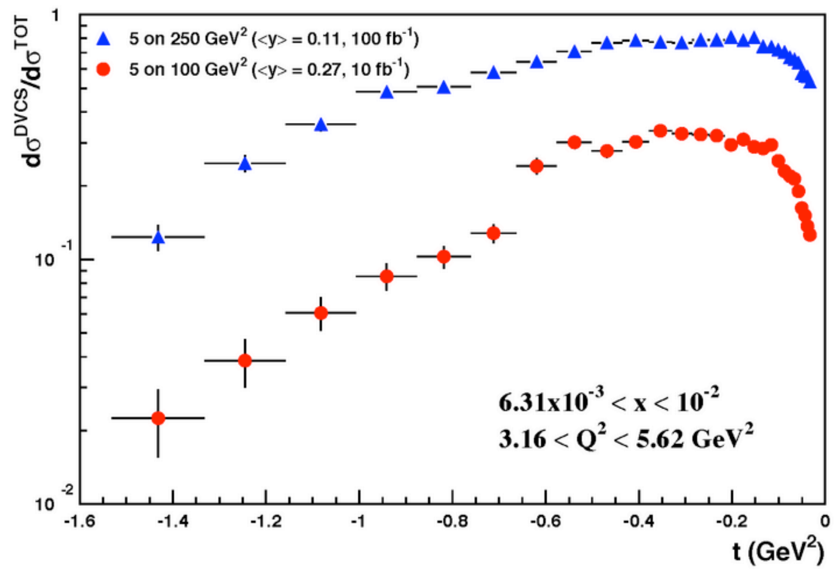
x-sec. measurements at a higher √s at low-y can cross-check the BH subtraction made at lower √s

Rosenbluth separation

$$d\sigma = \mathrm{d}\sigma_{DVCS} + \mathrm{d}\sigma_{BH} + \mathrm{d}\sigma_{INT}$$

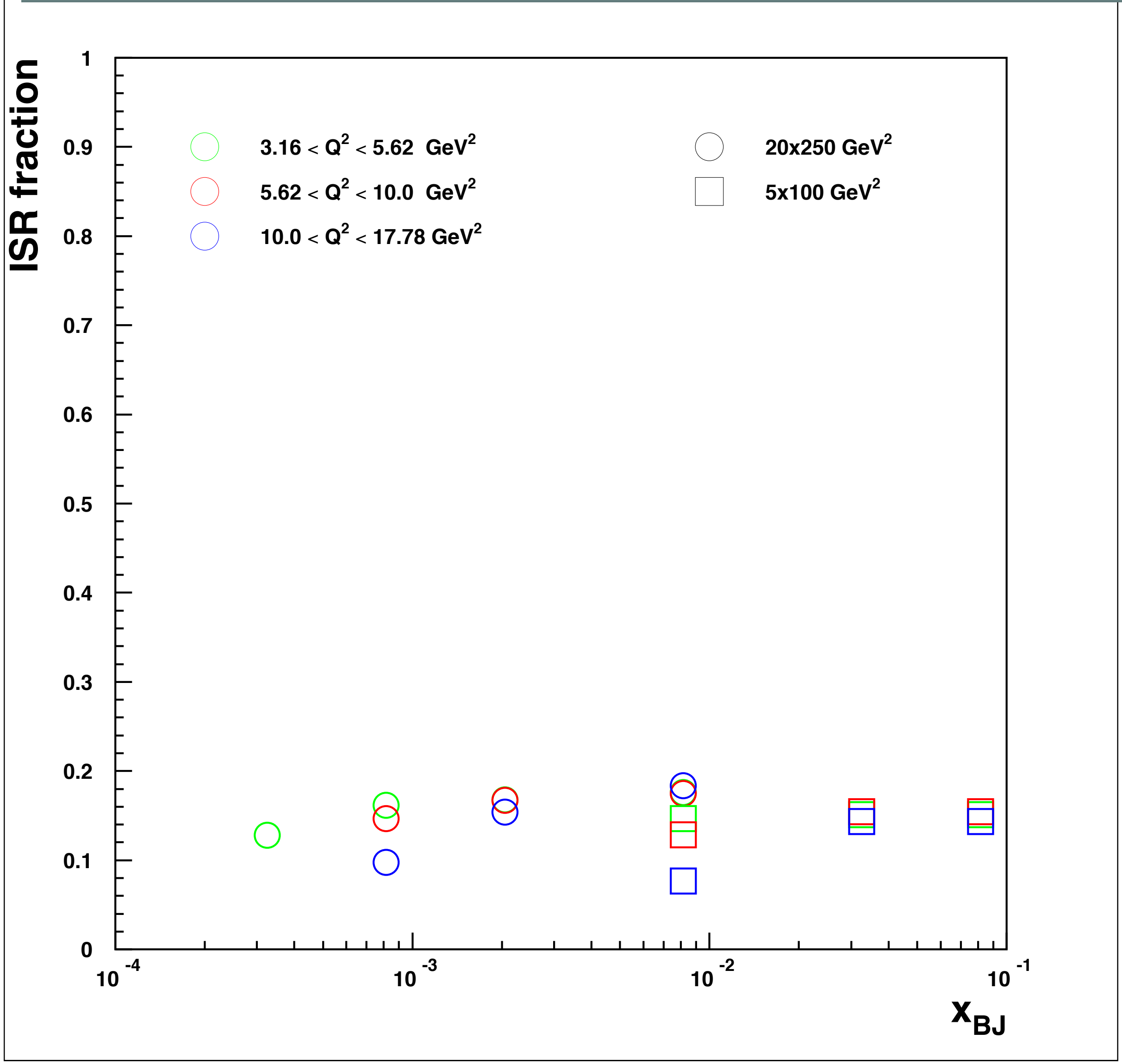
Rosenbluth separation of the electroproduction cross section into its parts





- The statistical uncertainties include all the selection criteria to suppress the BH
- exponential |t|-dependence assumed

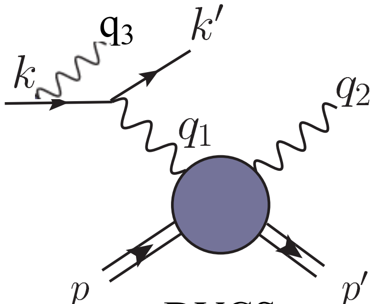
Contribution from ISR



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

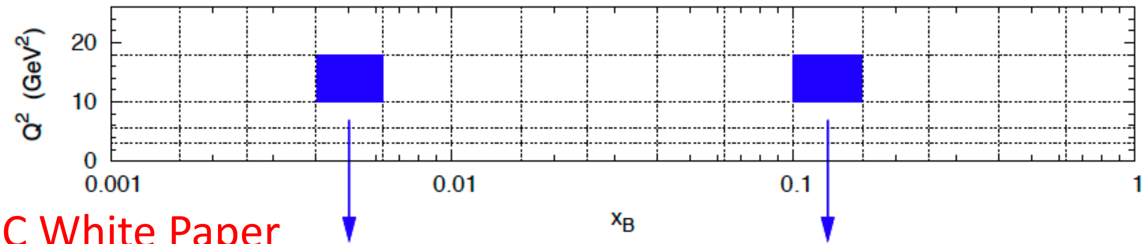
ONLY 15% of the events emit a photon with > 2% energy of the incoming electron

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



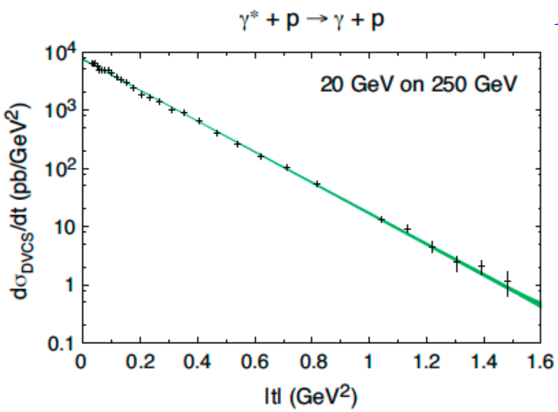
DVCS differential cross section

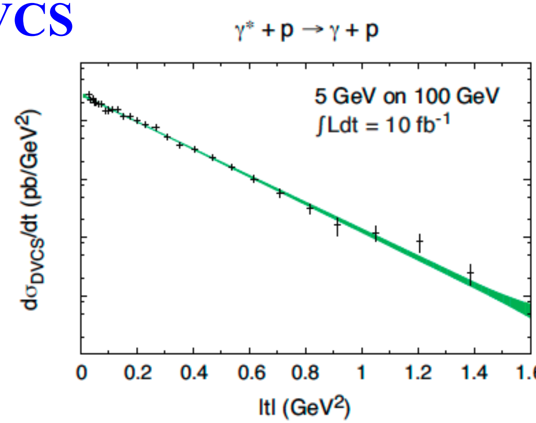
$$\int L = 10 fb^{-1}$$



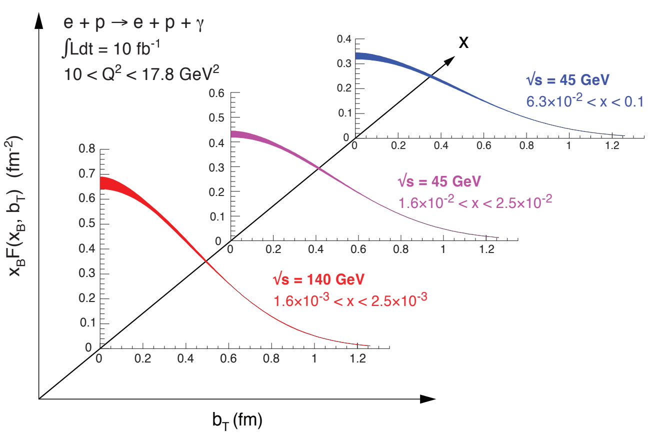
EIC White Paper

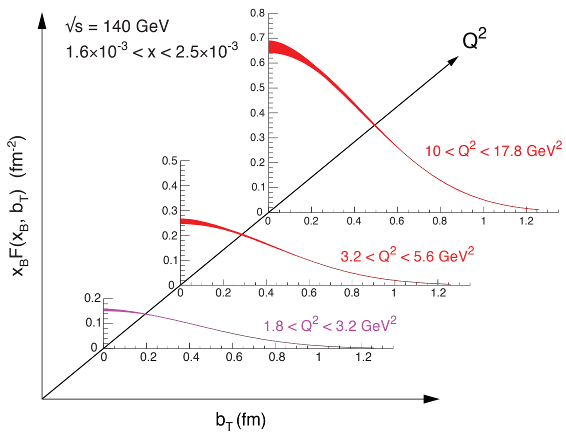
DVCS

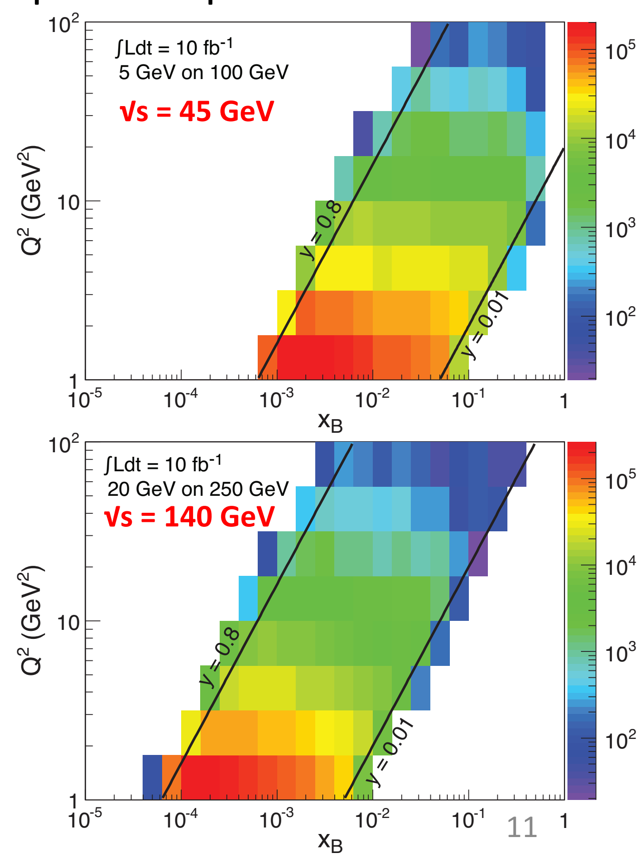




- **Measurement dominated by systematics**
- Fine binning in a wide range of x-Q^2 needed for GPDs
- Fourier transform of $d\sigma/dt$ → partonic profiles

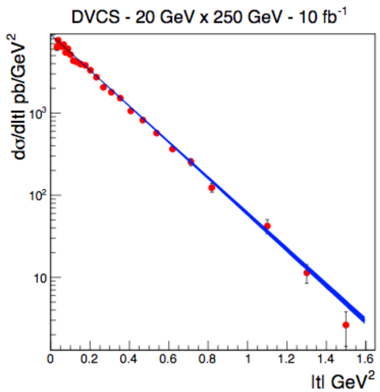




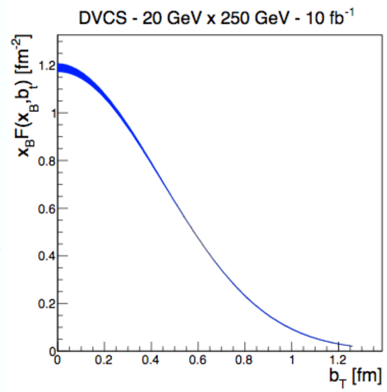


Impact of proton acceptance

Measurement



Physics observable (cross-section vs impact parameter)



Plots from EIC White Paper:

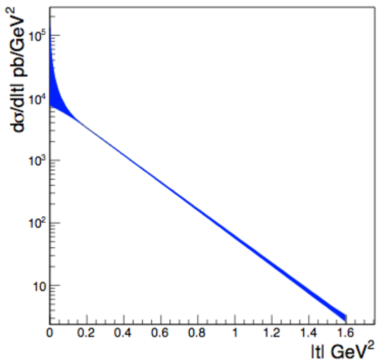
Fourier transform

Requirement:

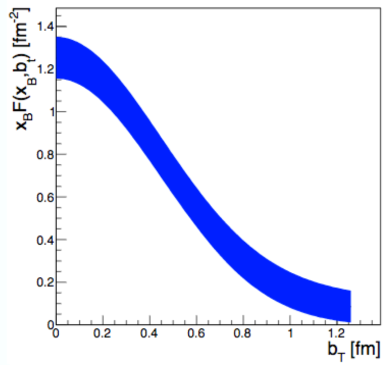
$\int L_{int} = 10 fb^{-1}$

$0.18 < p_t$ (GeV) < 1.3

$0.03 < |t|$ (GeV^2) < 1.6

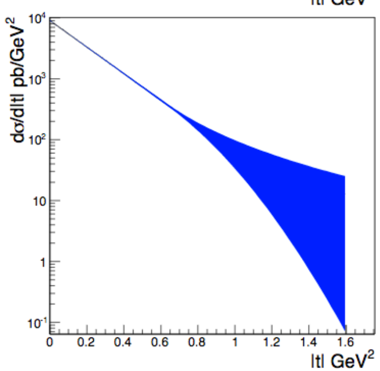


limited lower p_T-acceptance

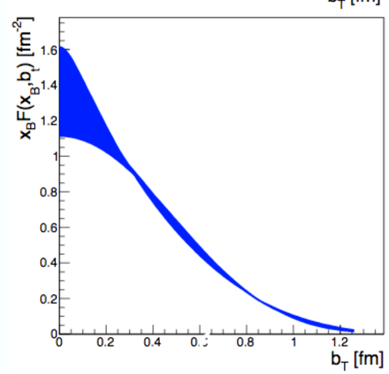


$\int L_{int} = 10 fb^{-1}$

$0.44 < p_T$(GeV) < 1.3



limited higher p_T-acceptance



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

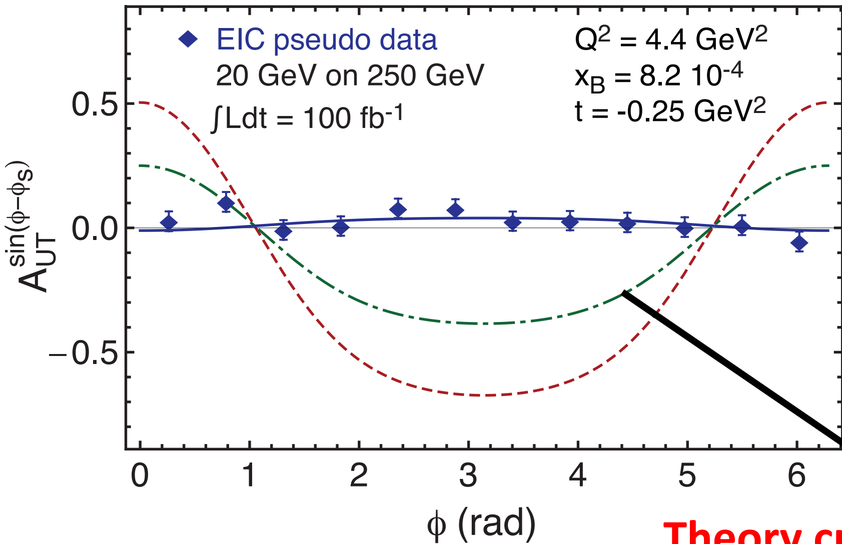
$0.18 < p_T$ (GeV) < 0.8

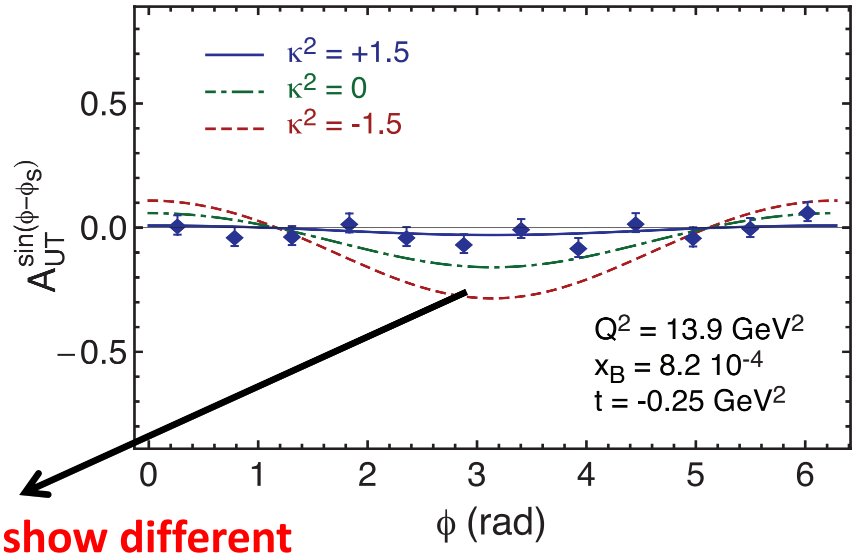
We need a proton spectrometer with large acceptance!

Transverse target-spin asymmetry

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

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





Theory curves show different assumptions for E

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

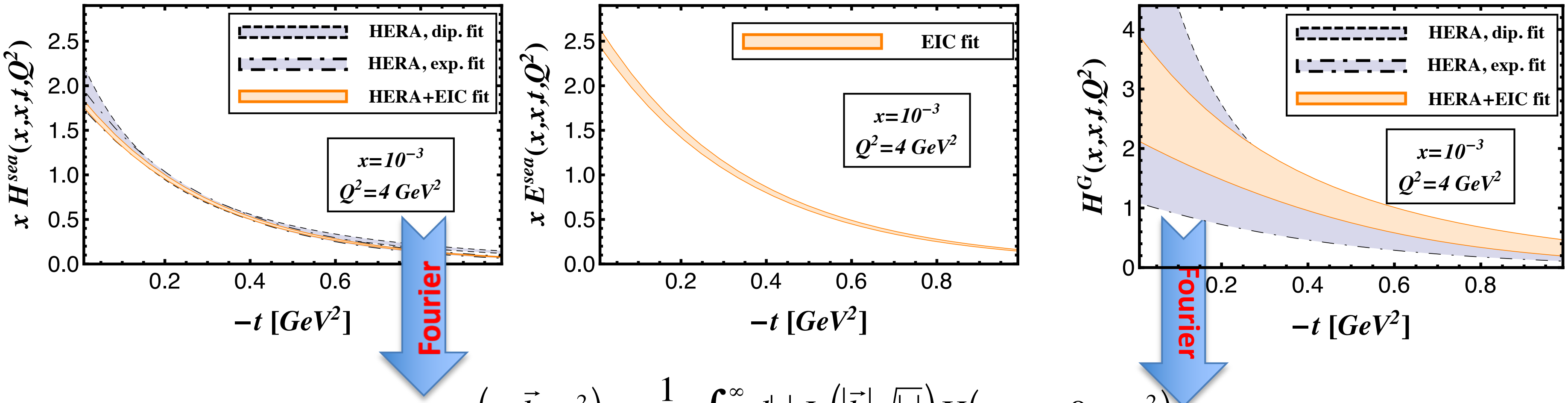
Transversely polarized protons: $sin(\Phi_T - \phi_N)$
gives access to GPD E
Access to orbital angular momentum through "Ji sum rule"

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

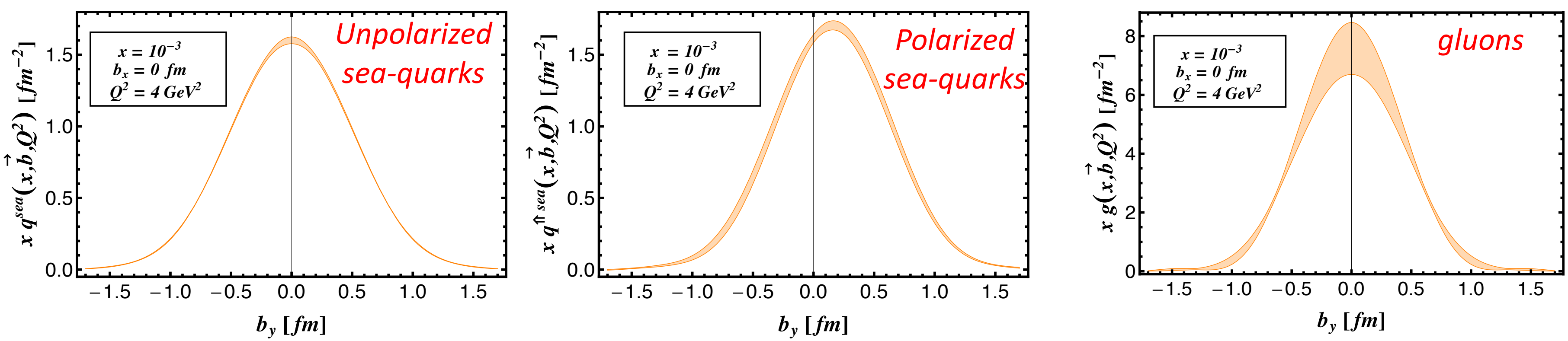
[X.D. Ji, Phys. Rev. Lett. 78, 610 (1997)]

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)

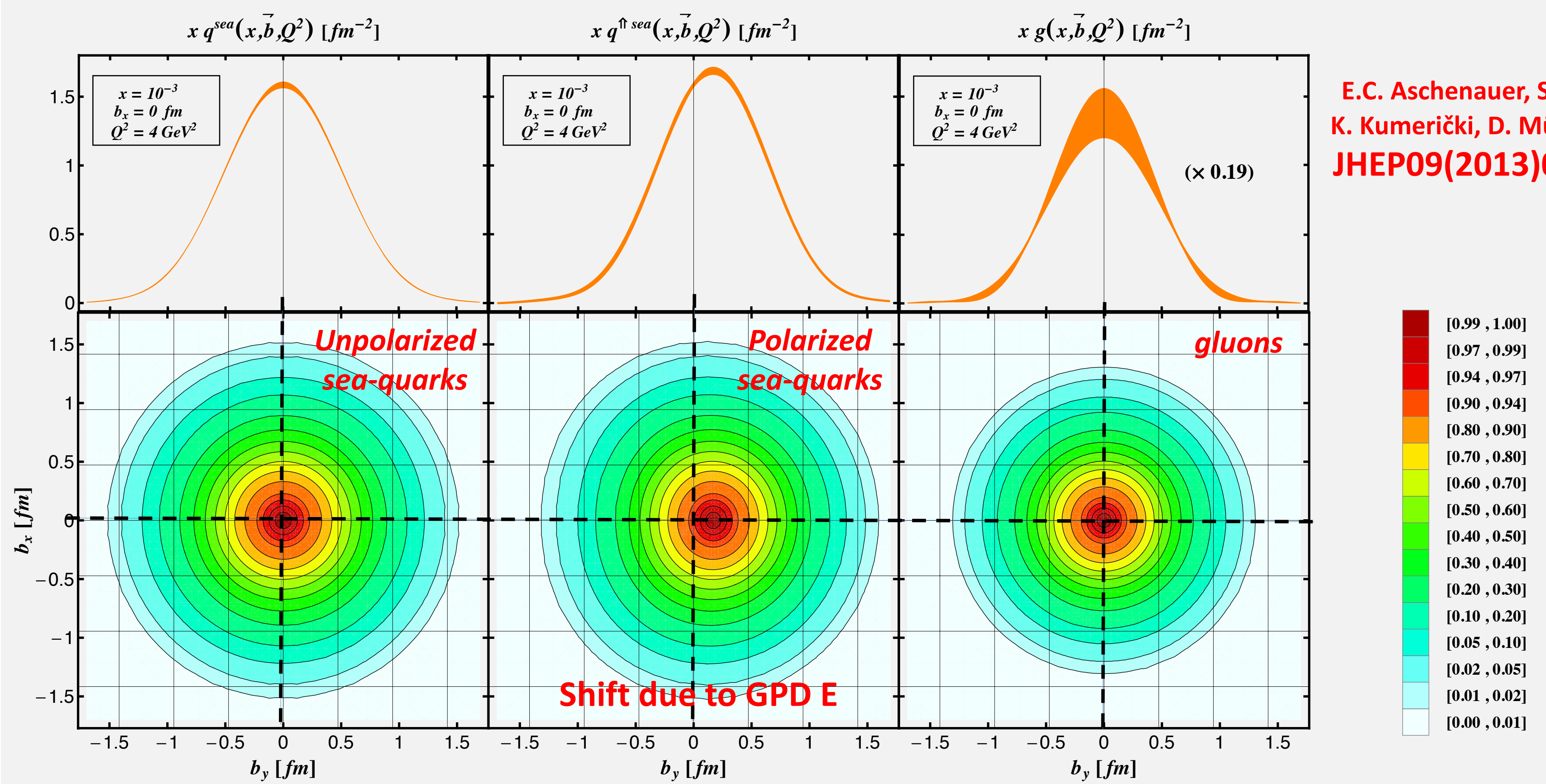


$$q\left(x,\vec{b},\mu^2\right) = \frac{1}{4\pi}\int_0^\infty d|t|\, J_0\left(|\vec{b}|\sqrt{|t|}\right) H\left(x,\eta=0,t,\mu^2\right)$$



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**

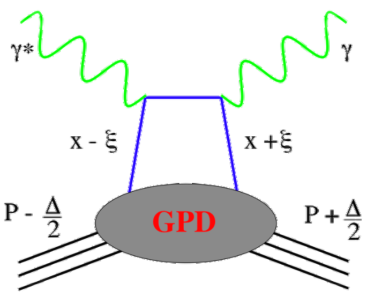
Other capabilities still to be evaluated?

- 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)

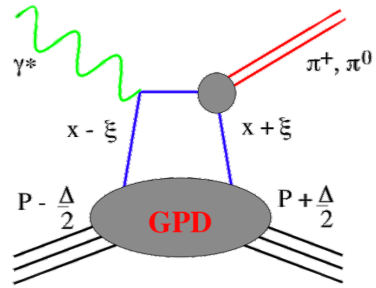
How to separate flavors?

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

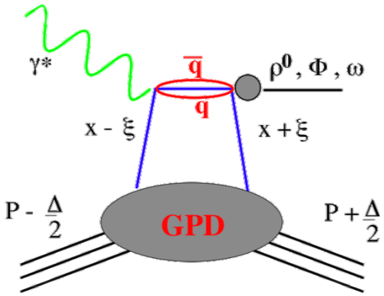
quantum numbers of final state → select different GPD



DVCS



pseudo-scalar mesons



vector mesons

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

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

π^0	2Δu+Δd
η	2Δu–Δd

$H^q \; E^q$

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

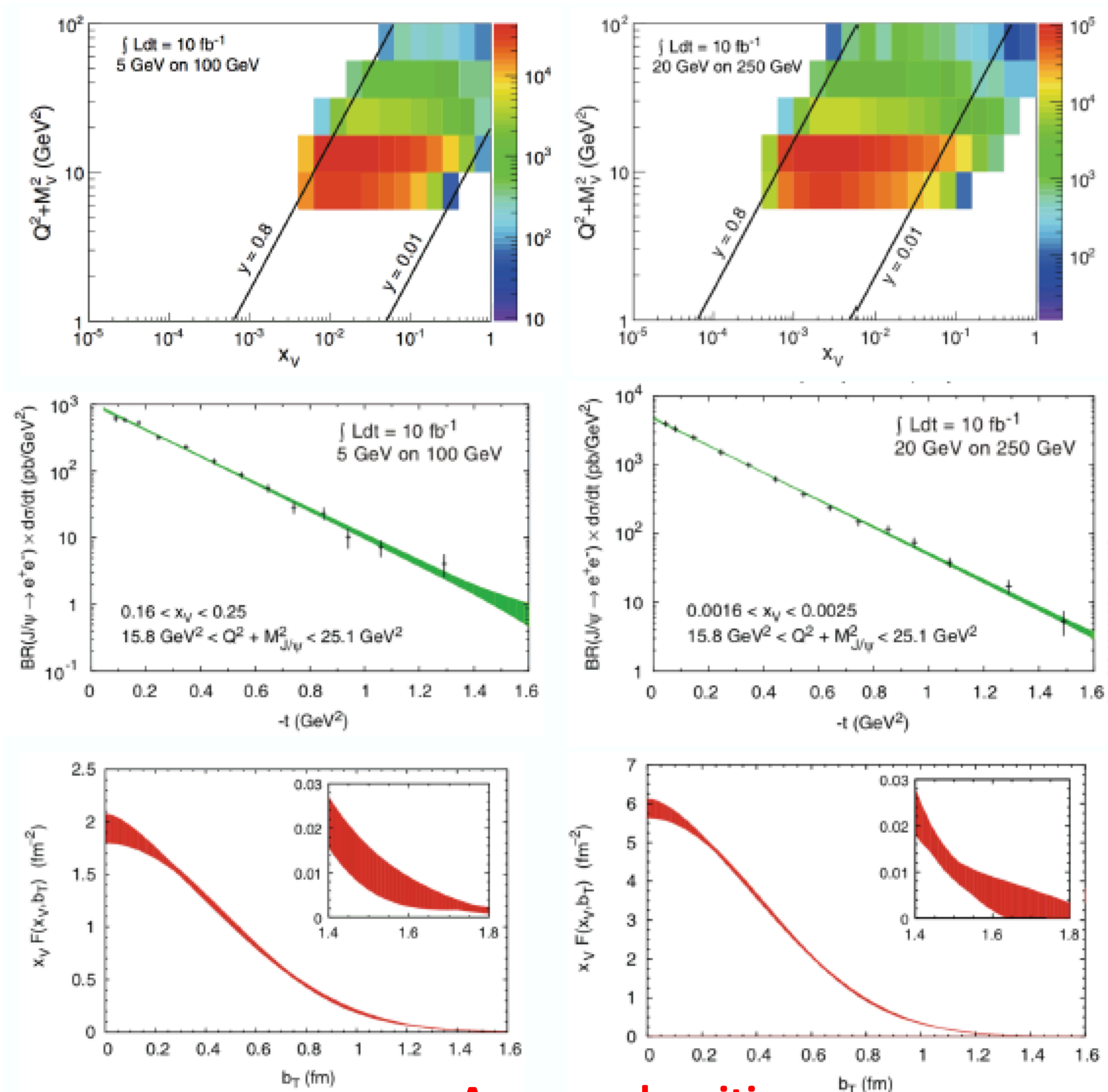
DVCS on protons and neutrons also separates quark u/d flavors

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

Imaging gluons with J/ψ

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

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 and 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!

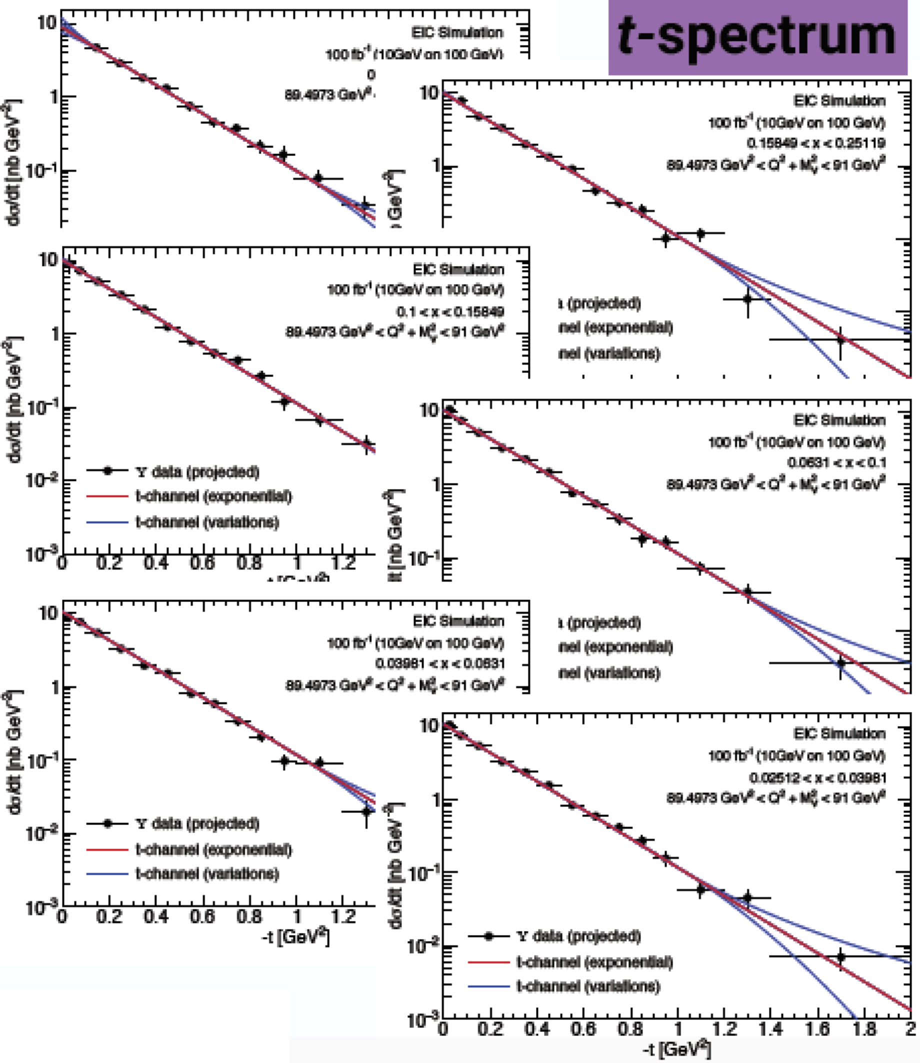
Imaging gluons with Υ(1s)

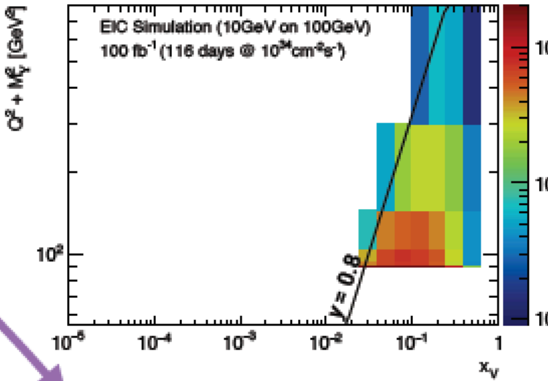
$$\int L = 100 fb^{-1}$$

S. Joosten, Z.-E. Meziani
2018 EICUG Meeting

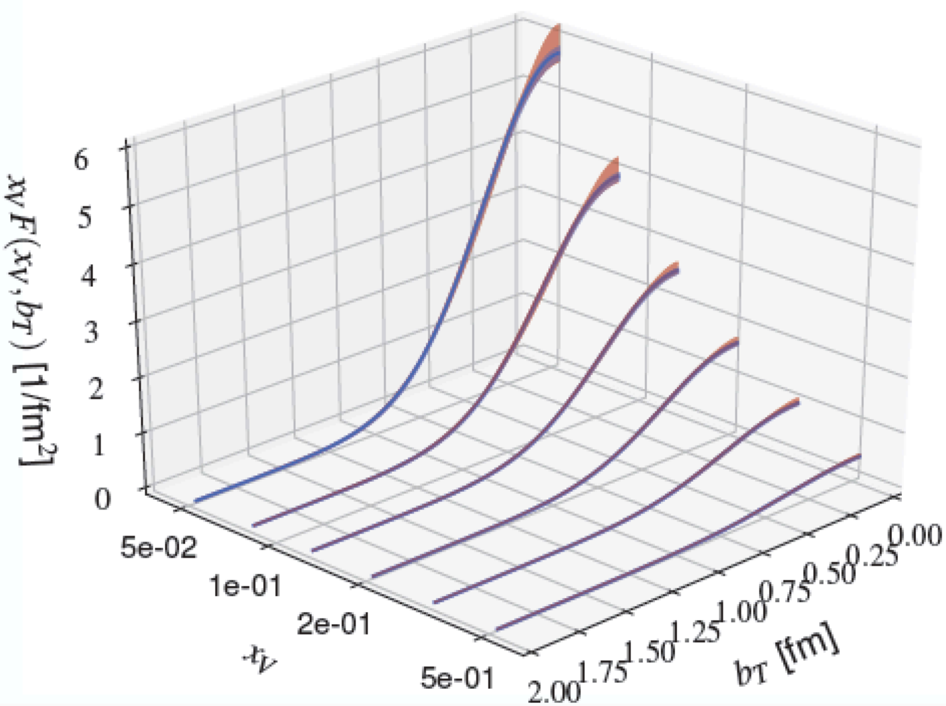
- Nominal EIC detector
- 10x more luminosity
- Electron and muon channels

t-spectrum

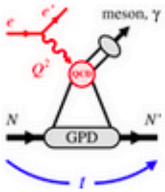




Average gluon density:



Series of workshops organized aiming at future studies



Center for Frontiers in Nuclear Science

Next-generation GPD studies with exclusive meson production at EIC

CFNS – Stony Brook U., 4-6 June 2018
https://indico.bnl.gov/event/4346/

Prospects for extraction of GPDs from global fits of current and future data

22-25 January 2019
Heavy Ion Laboratory (Cyklotron)
Europe/Warsaw timezone

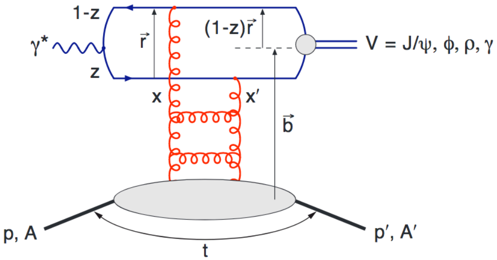
Warsaw – NCBJ, 22-25 January 2019
https://events.ncbj.gov.pl/event/8/

- **Next-level impact studies need GPD-based NLO models which include mesons!**

  Aim for GPD extraction with uncertainties

- **Common shared platforms** (E.g. PARTONS by H. Moutarde et al.) **can play important role in integrating GPD efforts at JLab12 and EIC**

Imaging the gluons in nuclei



Diffractive physics in eA

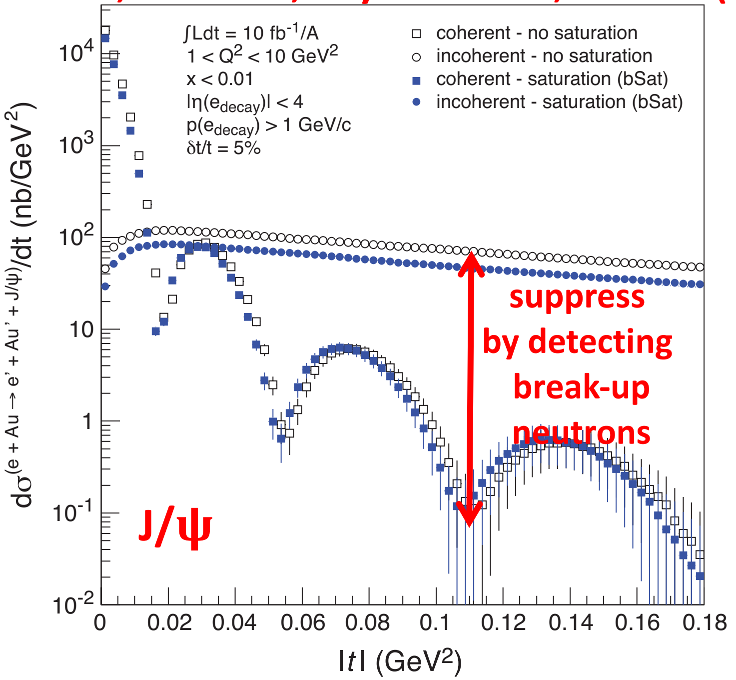
→ Measure spatial gluon distribution in nuclei
→ Reaction: e + Au → e′ + Au′ + J/ψ, φ, ρ
→ Momentum transfer $t = |p_{Au} - p_{Au'}|^2$

Hot topic:

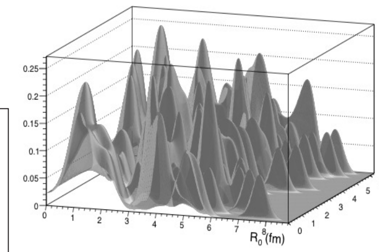
- ➢ Lumpiness of source?
- ➢ Just Wood-Saxon+nucleon $g(b_T)$

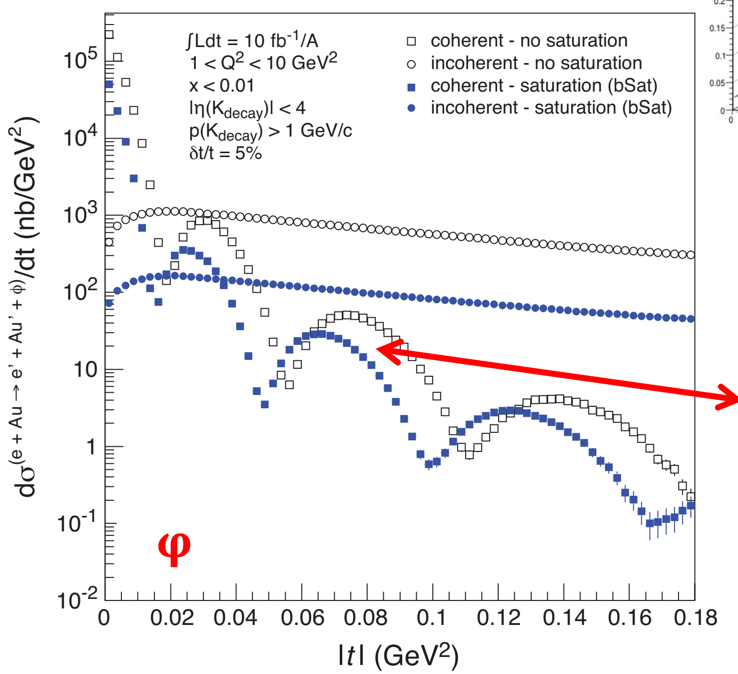
❑ coherent part probes "shape of black disc"
❑ incoherent part (large t) sensitive to "lumpiness" of the source [= proton] (fluctuations, hot spots, ...)

T. Toll, T. Ullrich, Phys.Rev. C87, 024913 (2013)



possible Source distribution with $b_T{}^g = 2\ GeV^{-2}$



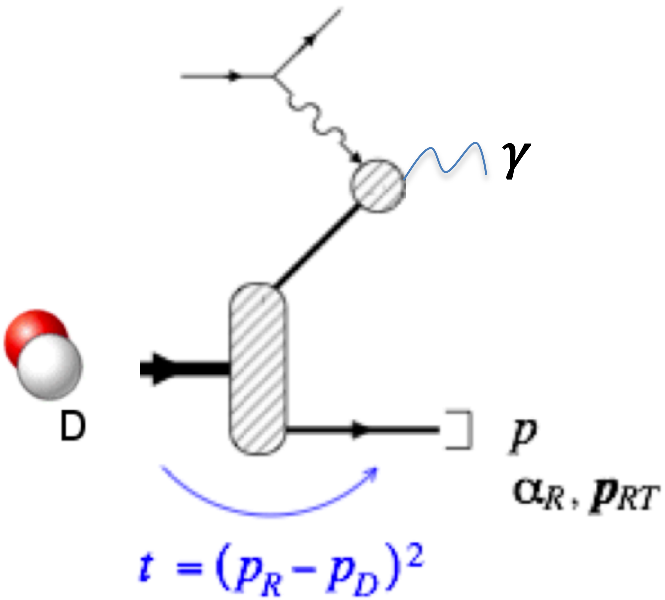


Sensitive to saturation effects!

Coherent requires forward scattered nucleus needs to stay intact

→ Veto breakup through neutron detection

Measuring neutron via spectator tagging

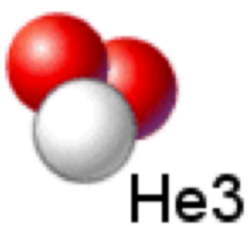


- Possibility to study neutron structure
- DVCS on neutron compared to proton is important for flavor separation

Using a Deuteron is the simplest case:

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**
- **The recoil proton momentum cone is**
  - $\alpha_R = (E_R + p_{R||})/(E_D + p_{D||})$ **and** p_{RT}
- Gives you a free neutron structure, not affected by final state interactions



Polarized He3 also experimentally easy but more complex theoretically

Luminosity & detector requirements

Luminosity requirements:

- xSec → 10 fb^{-1} -> enough for a good constrain of GPD H
- Asymmetries + Heavy Mesons --> 100 fb^{-1} **-> Essential for Eg**
- **Need for 100fb^{-1} dedicated run with transversely pol. Protons**
- **Two energies can cover the whole phase space**
- **200 fb^{-1} (scanning two √s) will be needed for the W.P.'s GPDs program on e+p collisions**

Requirements for forward spectrometers:

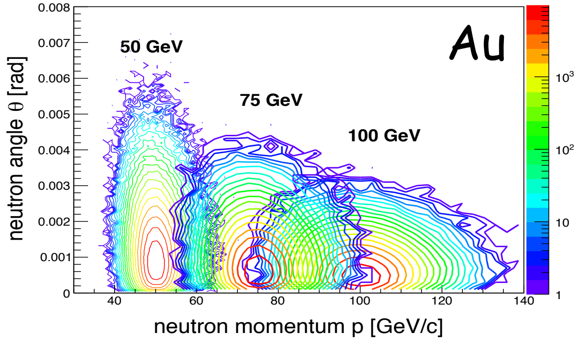
- |t| coverage in forward spectrometers **-> crucial**
- Largest possible geometrical acceptance **→ important to meet the lumi requirements**

EMCal:

- Discriminate a pair of photon clusters at angles > 40 mrad → suppress $\pi^0 \longrightarrow \gamma\gamma$

ZDC:

- Acceptance for neutrons down to θ = 6 mrad → Crucial to veto nuclear breakup
  - -> Coherent xSec in heavy ions
  - -> Double tagging in D and He3 -> neutron GPDs



Direct access to Wigner function

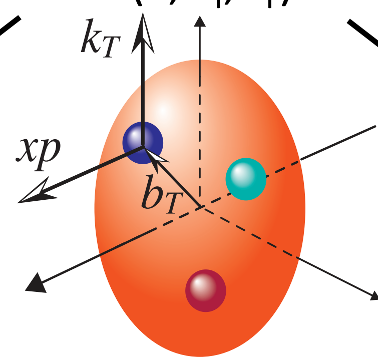
Wigner function

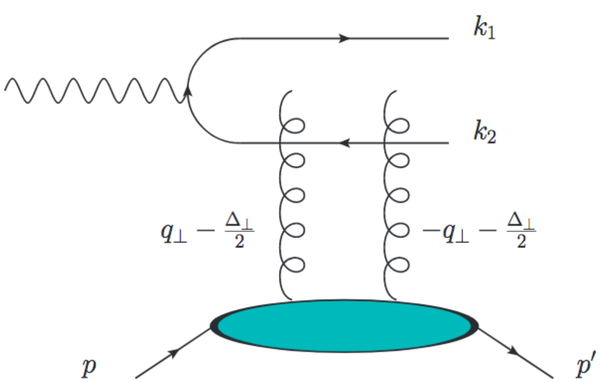
$W(x,b_T,k_T)$

QCD genetic map

$\int d^2b_T$ — *Momentum space* → $f(x,k_T)$ TMDs

$\int d^2k_T$ — *Coordinate space* → $f(x,b_T)$ GPDs





Process: exclusive di-jet production

First proposed in e+p scattering by:

Yoshitaka Hatta, Bo-Wen Xiao, and Feng Yuan,
Phys. Rev. Lett. 116, 202301 (2016)

Later extended to UPC:

Y. Hagiwara, Y. Hatta, R. Pasechnik, M. Tasevsky, and O. Teryaev
Phys. Rev. D 96, 034009 (2017)

- **New important peace of EIC physics beyond the W.P.!**
- **EIC impact studies still be done**
- **Warning: very low-p_T ~5 GeV^2 jets, formalism valid only for low-x ($x<10^{-3}$)**

Summary on GPDs

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

The studies from the EIC WP era… (DVCS)

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

Luminosity Requirements

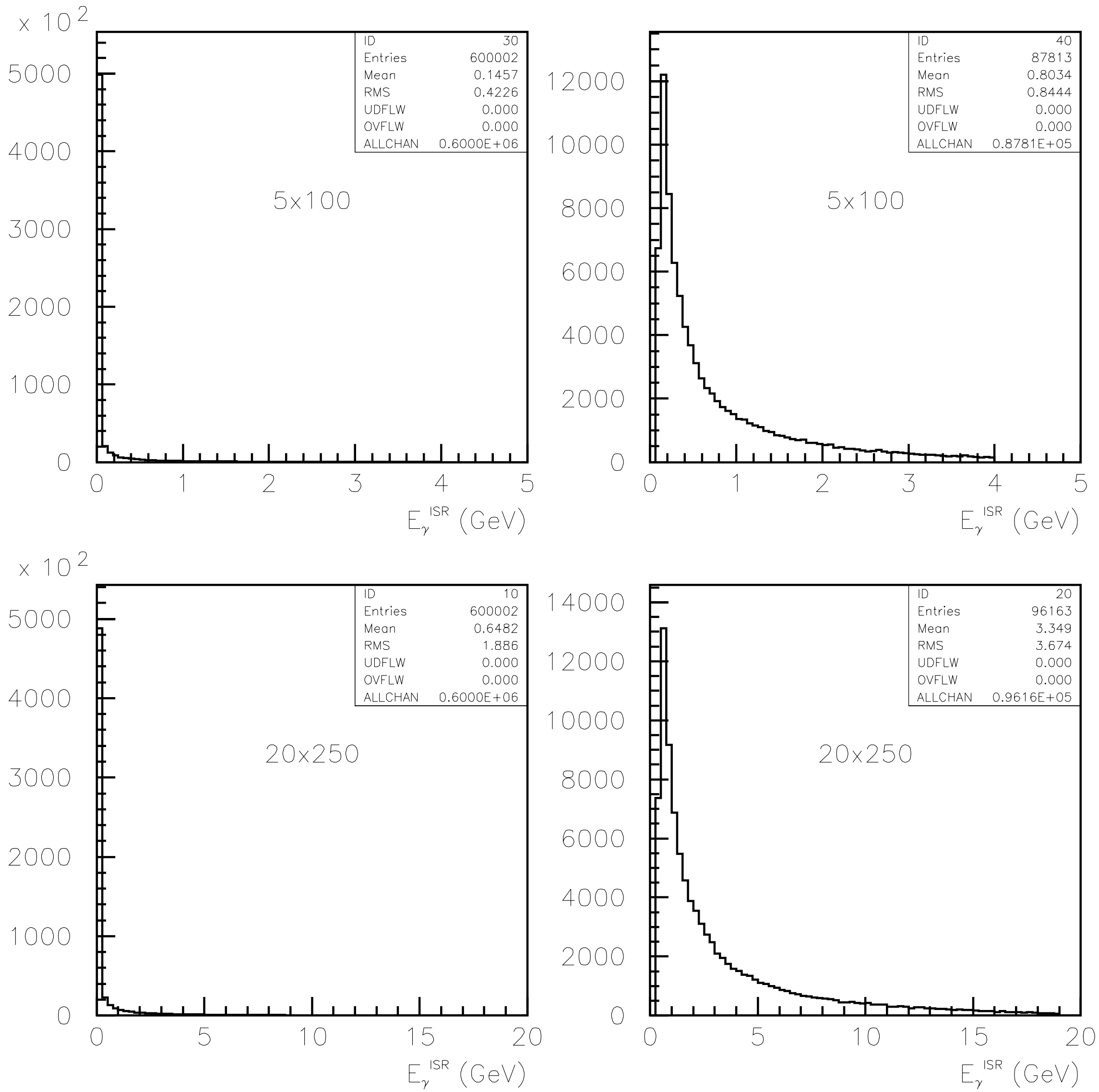
- A total of 200fb^{-1} collected at a lower and a top √s energy needed cover the W.P.'s GPDs program on e+p.

New excitement ahead

- Fully develop common framework platforms
- Include mesons in global fits (flavor separation, precision on gluons)
- Study of GPDs in nuclei (and possible gluon saturation effects)
- Extract the much-discussed *D*-term - the last "global unknown property" of a hadron, related to radial pressure distribution inside a nucleon
- Gluon elliptic Wigner fcn.!

Back up

Contribution from ISR



the energy spectrum of the emitted ISR photon for two different EIC beam energy combinations.

the right plots show the same photon spectra but requiring
$E_\gamma = 0.02 * E_e$

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