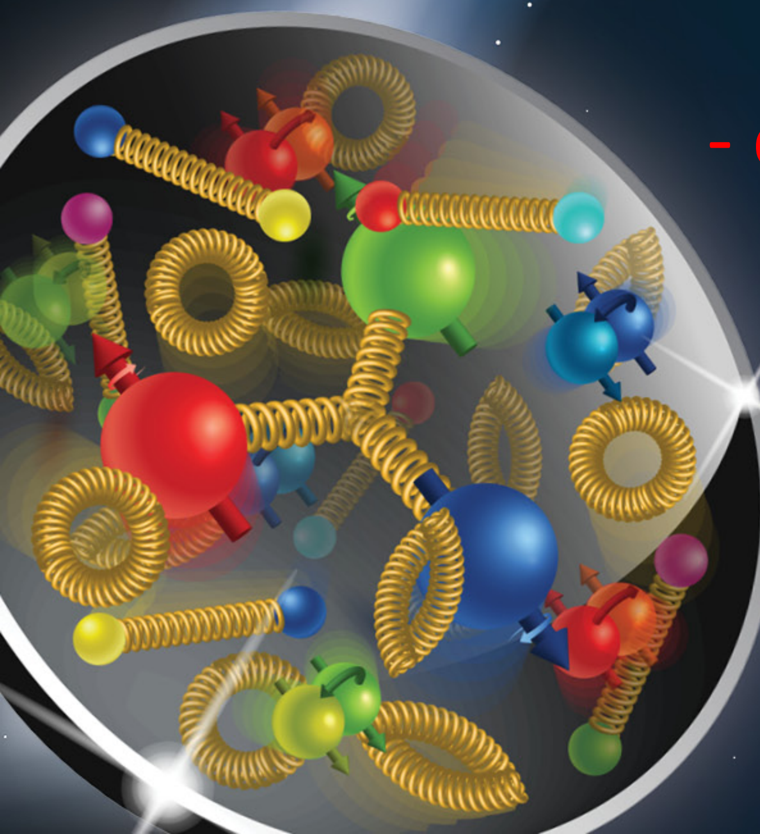
Studies of partonic spatial imaging at an Electron-Ion Collider - current status and future plans -



Salvatore Fazio
Brookhaven National Lab

EIC Users' Group Meeting
Paris, France
23-27 July 2019

BROOKHAVEN NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY | Office of Science

Multi-dimensional Imaging of Quarks and Gluons

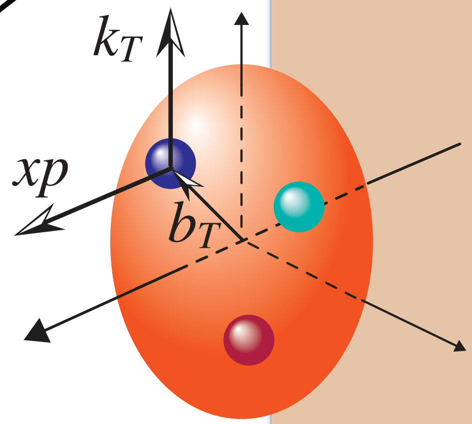
Wigner functions

$W(x, b_T, k_T)$

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**

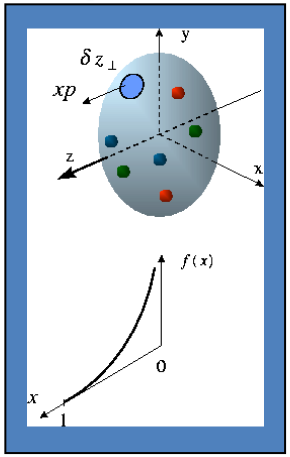
Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum)
From **exclusive processes**
→ **GPDs**

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

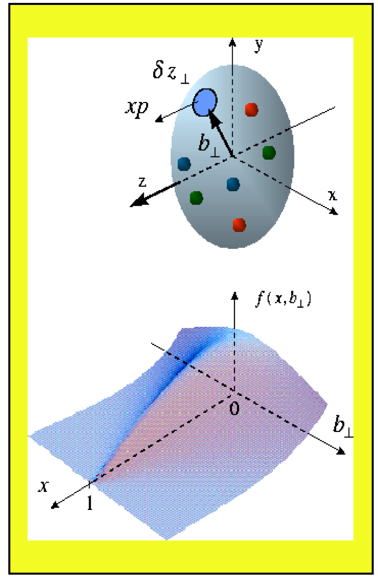
See P. Sznajder's plenary talk

Longitudinal momentum & helicity distributions



$f(x)$

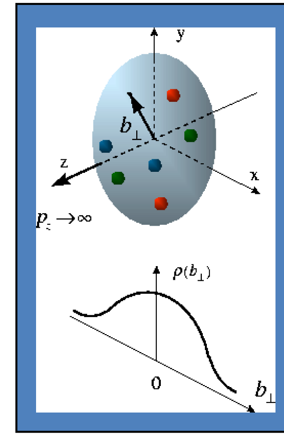
parton densities



$H(x,\xi,t)$

GPDs

transverse charge & current densities



$F_1(t)$

form factors

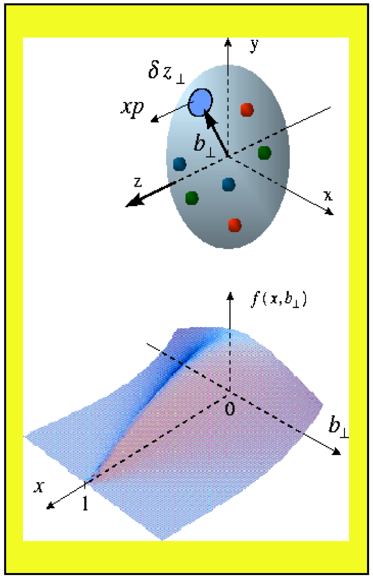
The nucleon (spin-1/2) has **four quark and gluon GPDs** (H, E and their polarized-proton versions $\widetilde{H}, \widetilde{E}$). Like usual PDFs, GPDs are non-perturbative functions **defined via the matrix**

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

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

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

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

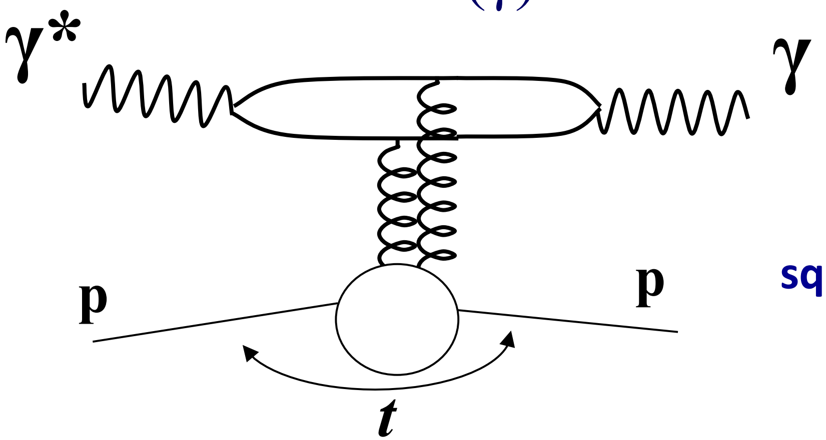
→ ***$sin(\Phi_T - \phi_N)$***
governed by E and H

Requires a polarized proton-target

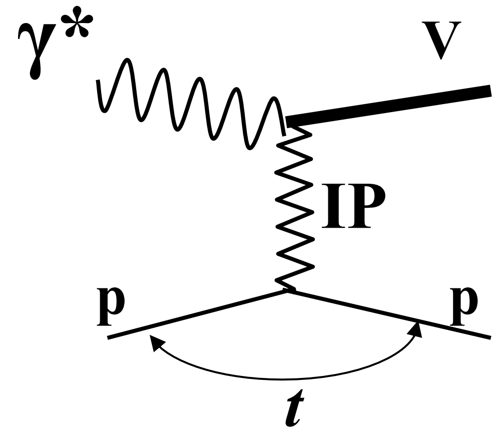
responsible for total orbital angular momentum through Ji sum rule
a window to the SPIN physics

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)

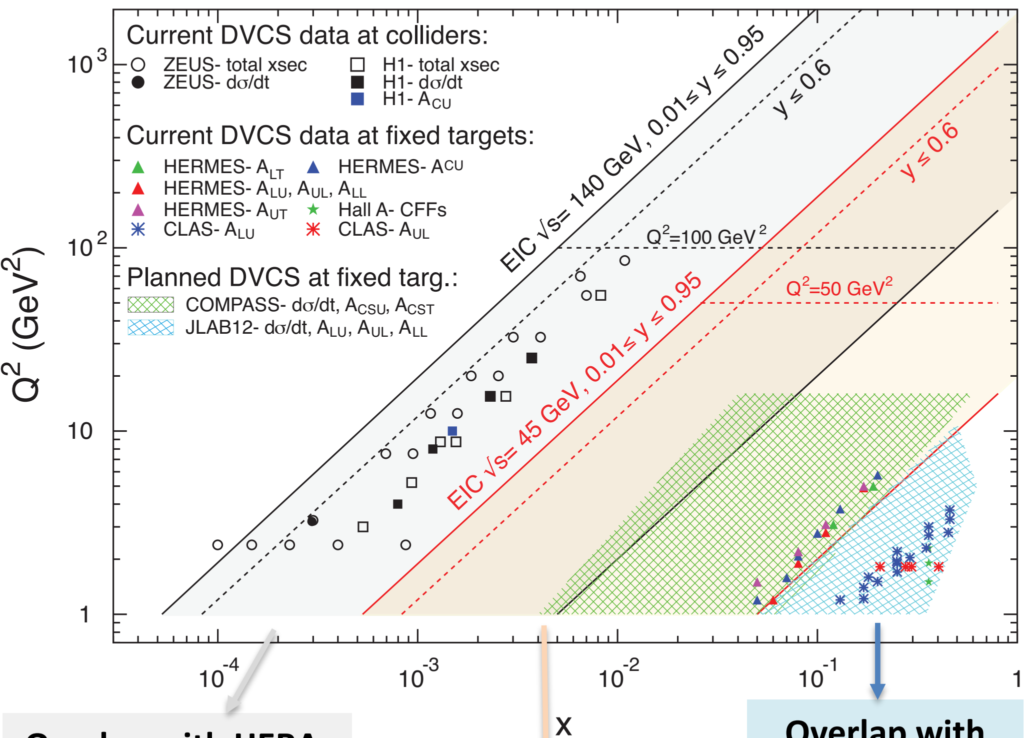
VMP:

- 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

Alternative/complementary way to quark-flavor separation

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

DVCS at an EIC

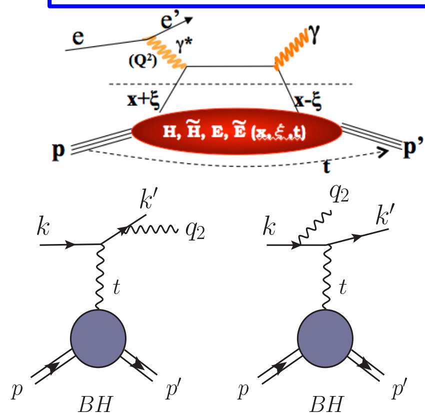


Overlap with HERA: Large impact on current fits at low x

Intermediate region: Fine mapping of the GPDs evolution

Overlap with JLAB12: Sanity check

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



DVCS signal

Bethe-Heitler QED bkgd.

HERA results limited by lack of statistics

EIC: the first machine to measure cross sections and asymmetries

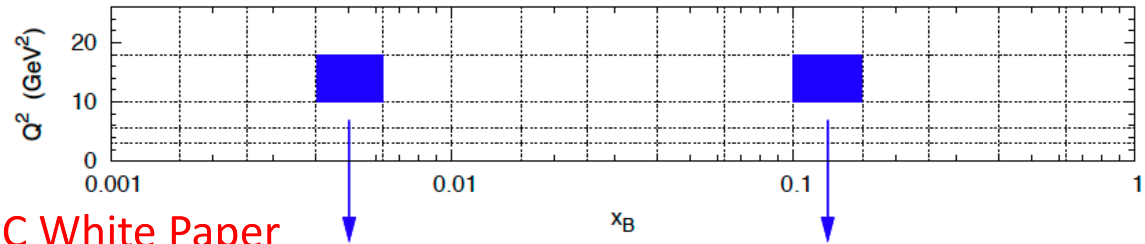
Comprehensive EIC studies

- 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 & J/ψ differential cross section

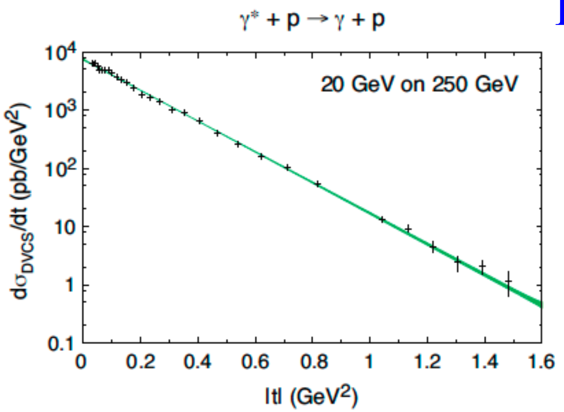
$$\int L = 10 fb^{-1}$$

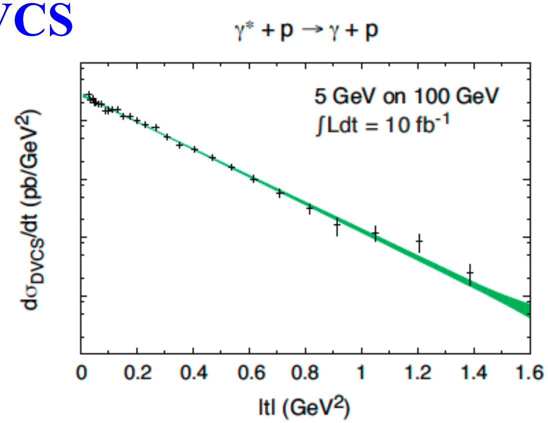
- **Measurement dominated by systematics**
- Fine binning in a wide range of x-Q^2 needed for GPDs
- Fourier transform of dσ/dt → partonic profiles

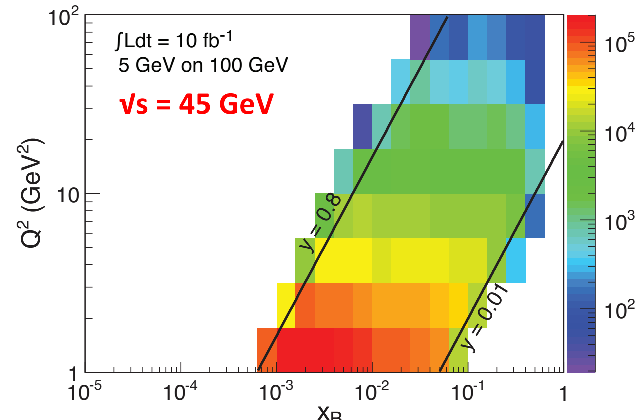


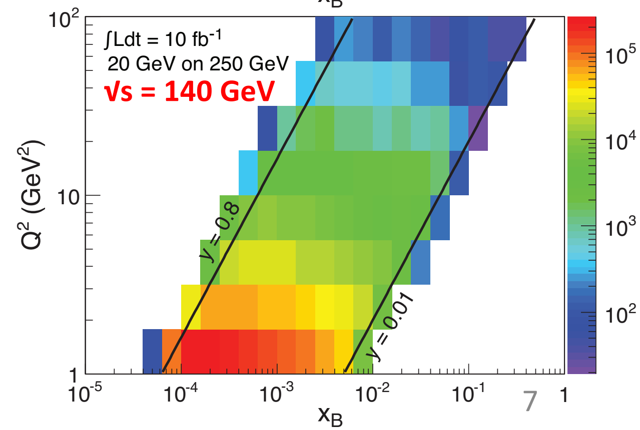
EIC White Paper

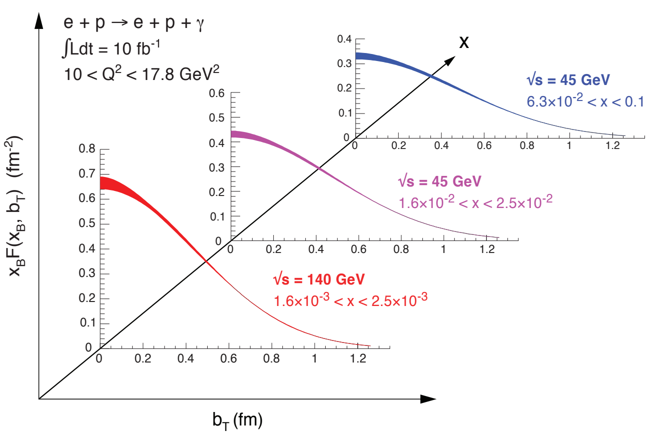
DVCS

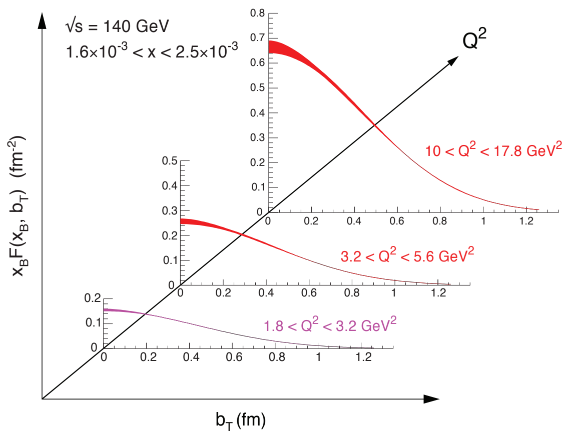








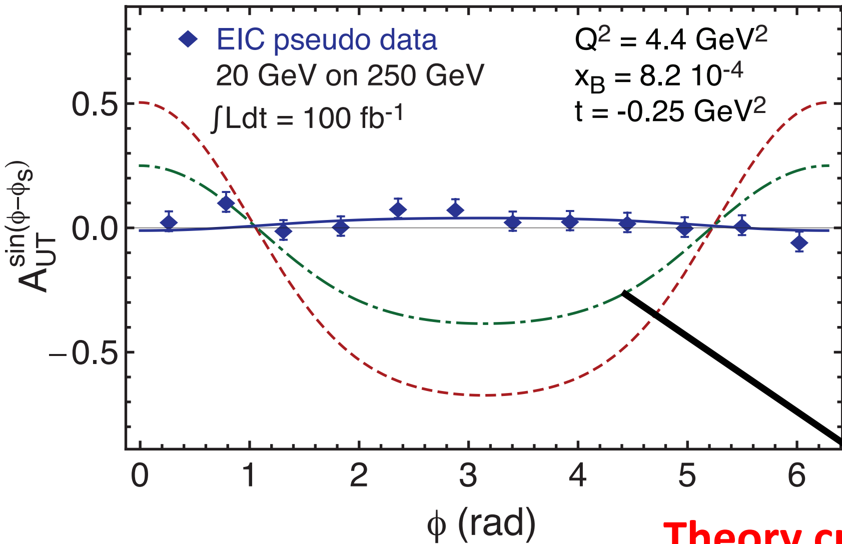


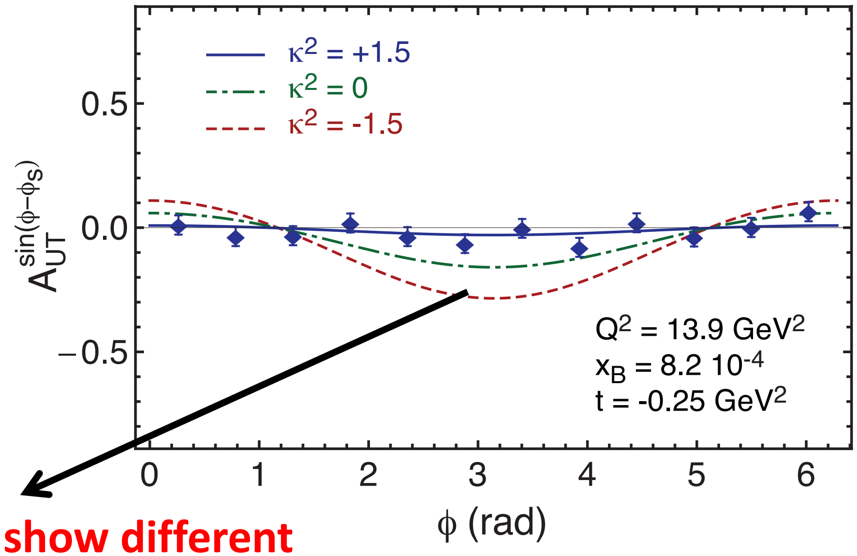


Transverse target-spin asymmetry

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

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





Theory curves show different assumptions for E

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

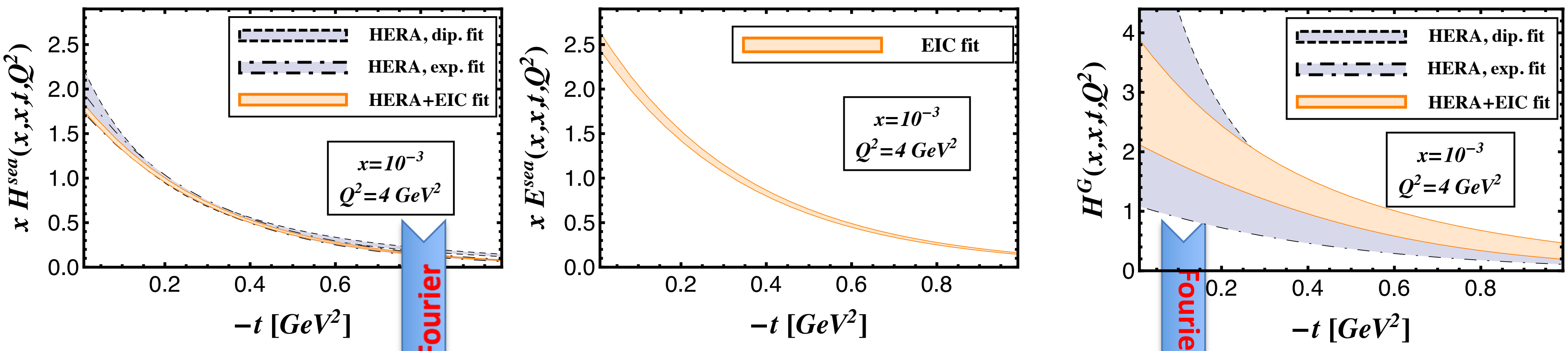
Transversely polarized protons: sin($\Phi_T - \phi_N$)
gives access to GPD E
Access to orbital angular momentum through "Ji sum rule"

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

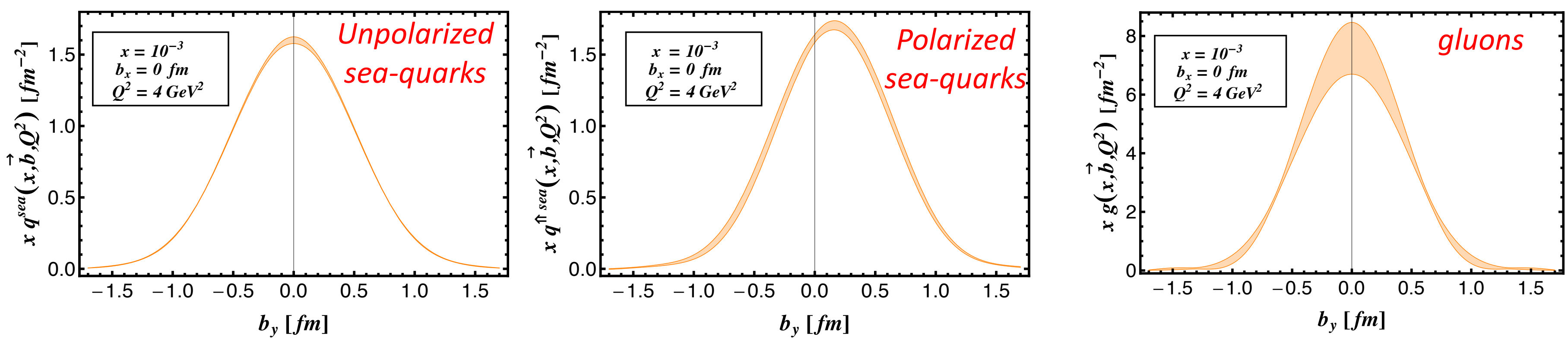
[X.D. Ji, Phys. Rev. Lett. 78, 610 (1997)]

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)

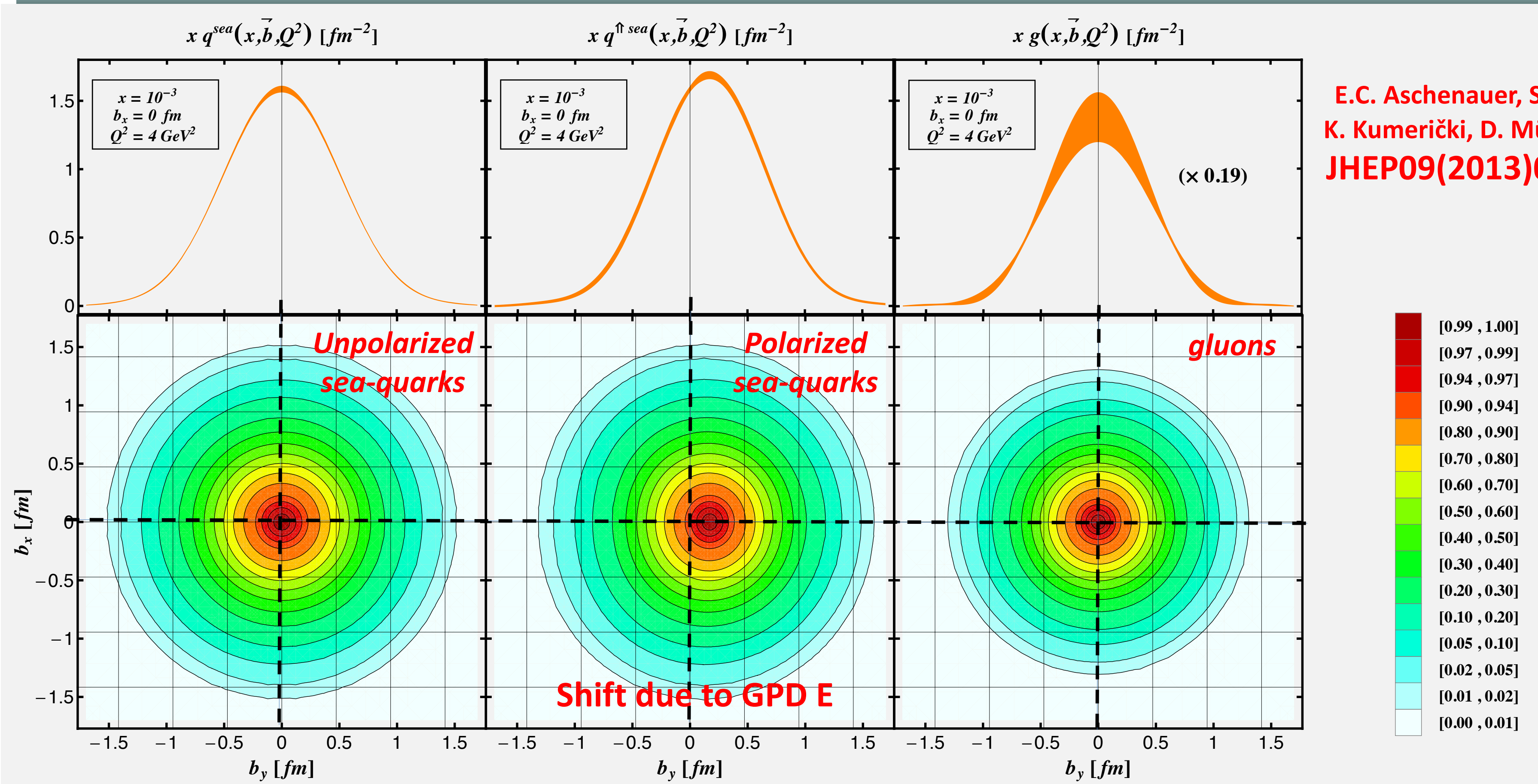


$$q\left(x,\vec{b},\mu^2\right) = \frac{1}{4\pi}\int_0^\infty d|t|\, J_0\left(\left|\vec{b}\right|\sqrt{|t|}\right) H\left(x,\eta=0,t,\mu^2\right)$$



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?

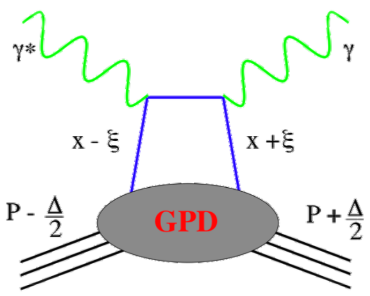
- GPD H-Gluon is nice but can be much better by including J/ψ
- Access to GPD E-gluon → orbital momentum (Ji sum rule)
- Flavor Separation of GPDs (VMP and/or DVCS on deuteron)
- Nuclear imaging (modification of GPDs in p+A collisions)

Time to move on…

How to separate flavors?

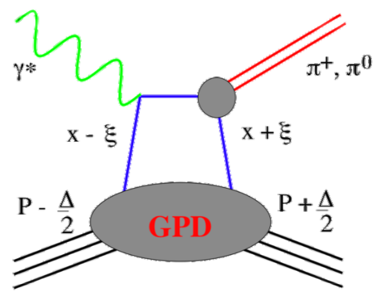
Hard Exclusive Meson Production (HEMP) → a powerful tool!

quantum numbers of final state ➡ select different GPD



DVCS

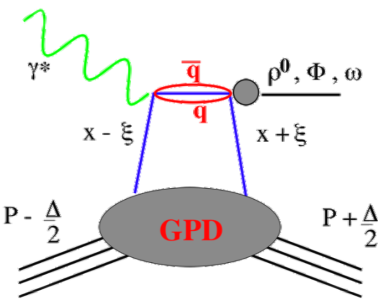
$H^q \; E^q \quad \widetilde{H}^q \quad \widetilde{E}^q$



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

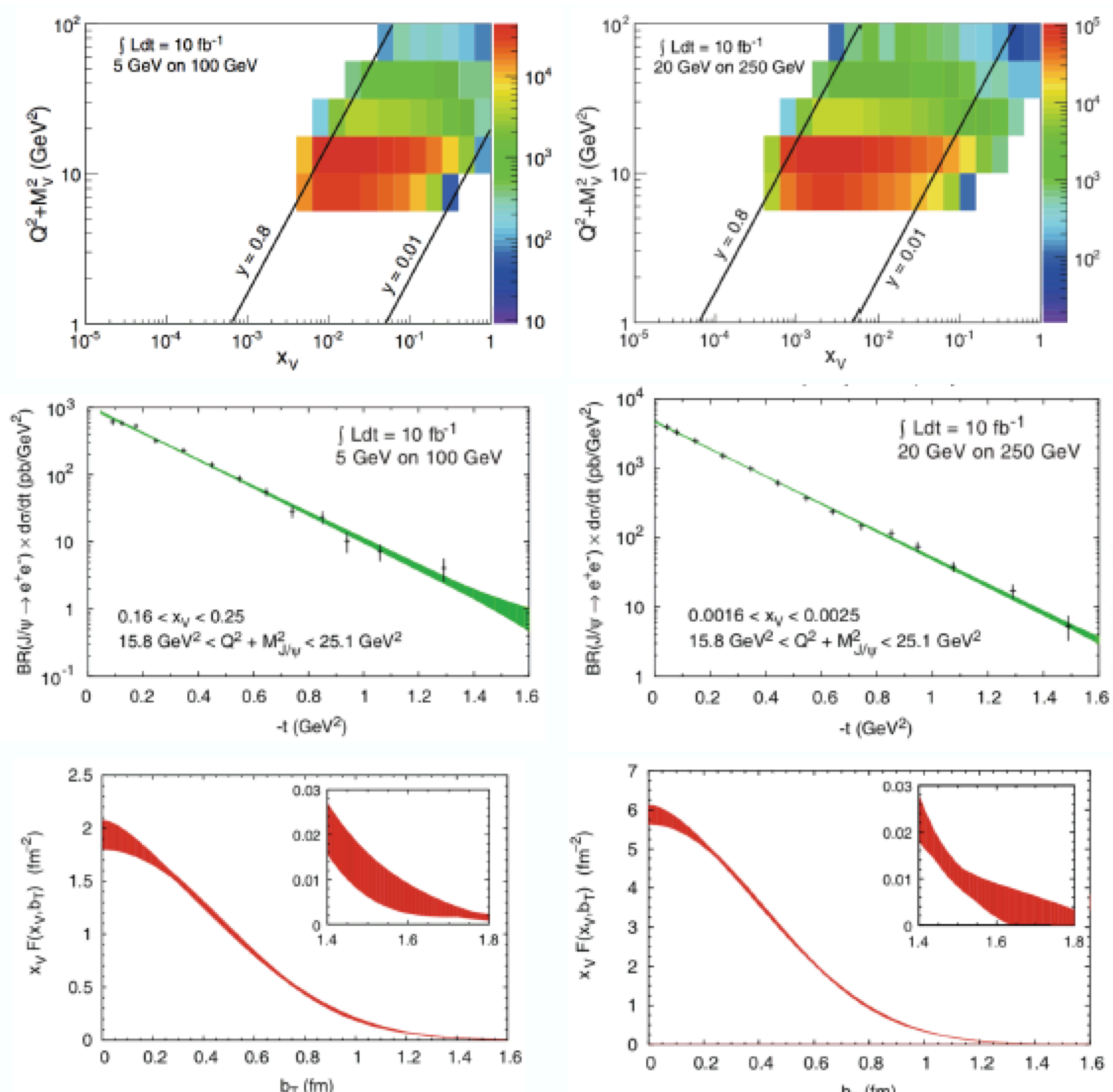
DVCS on protons and neutrons also separates quark u/d flavors

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

Imaging gluons with J/ψ

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

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!

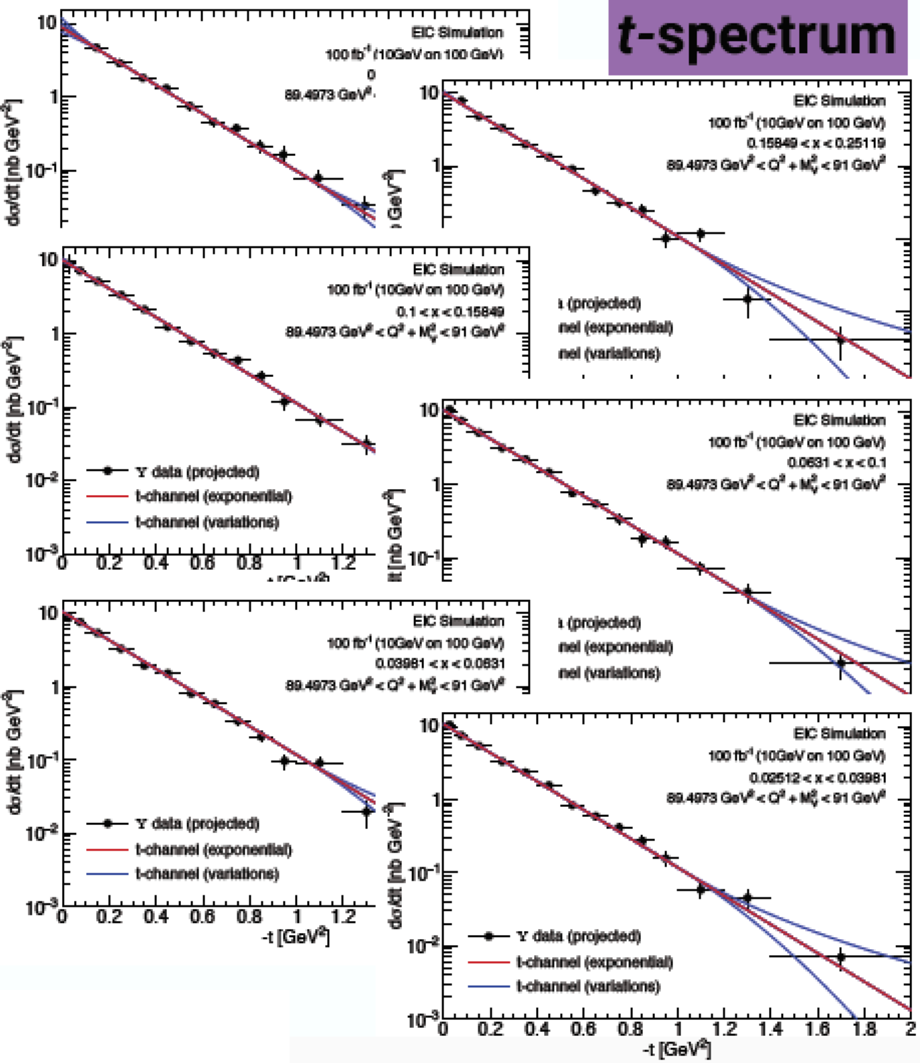
Imaging gluons with Υ(1s)

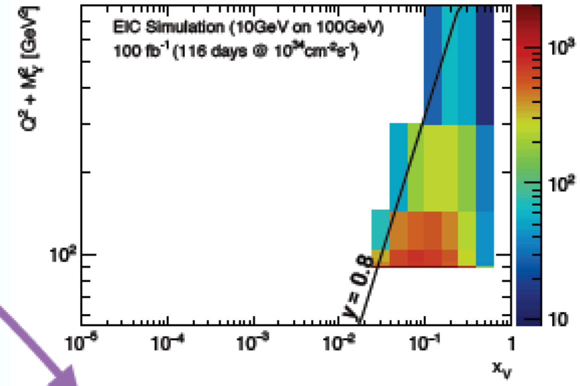
$$\int L = 100 fb^{-1}$$

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

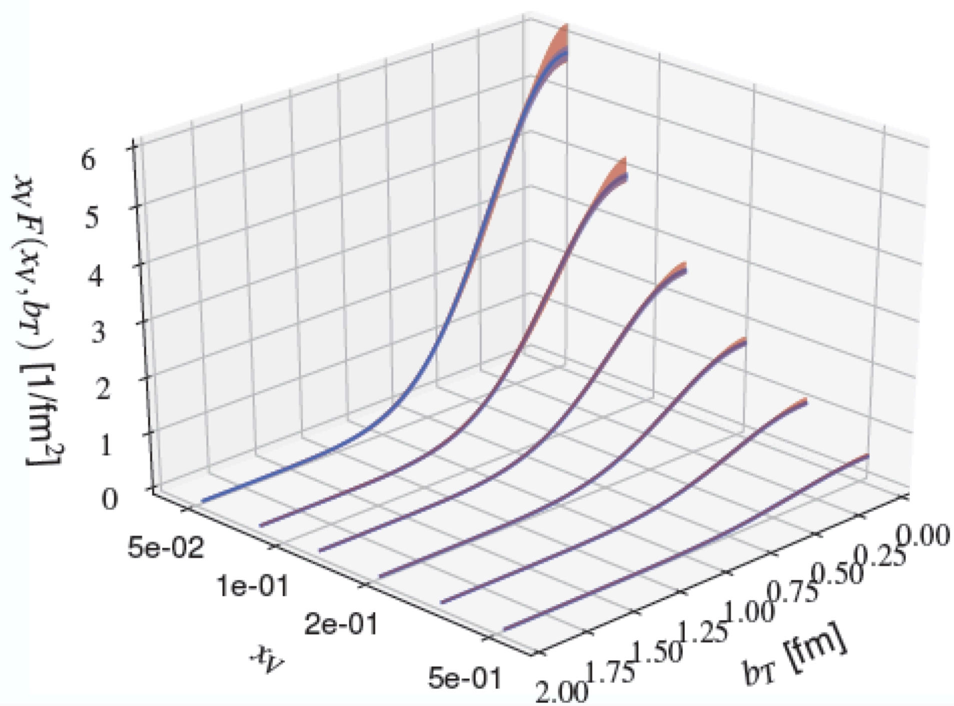
- ☆ Nominal EIC detector
- ☆ 10x more luminosity
- ☆ Electron and muon channels

***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

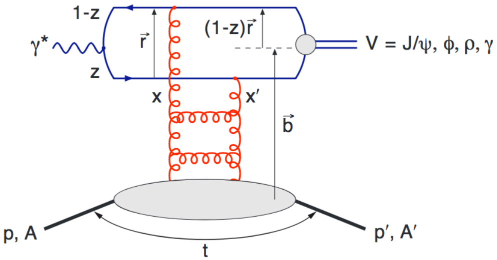
Warsaw – NCBJ, 22-25 January 2019
https://events.ncbj.gov.pl/event/8/

- **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



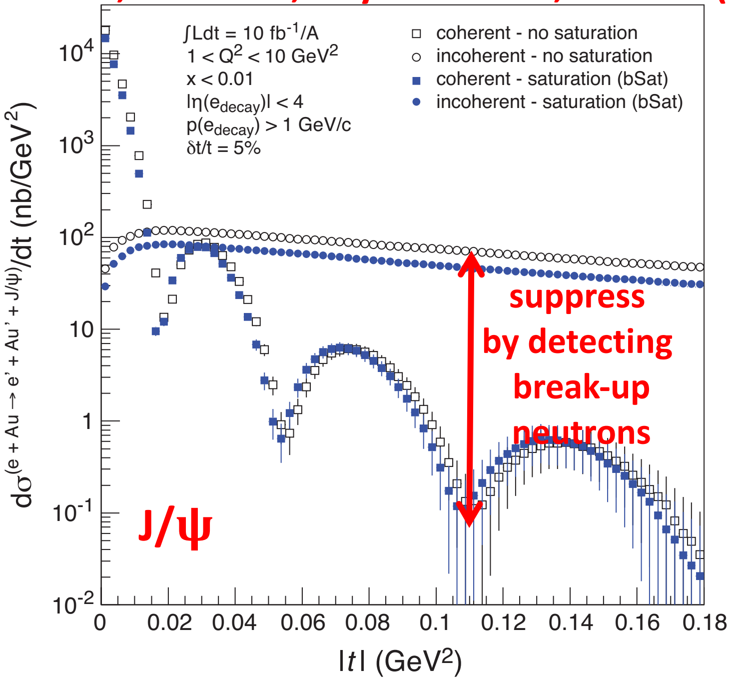
Diffractive physics in eA

→ Measure spatial gluon distribution in nuclei

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

→ Momentum transfer t = |pAu-pAu′|^2

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



Coherent requires forward scattered nucleus needs to stay intact

→ Veto breakup through neutron detection

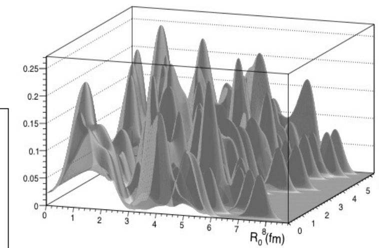
Hot topic:

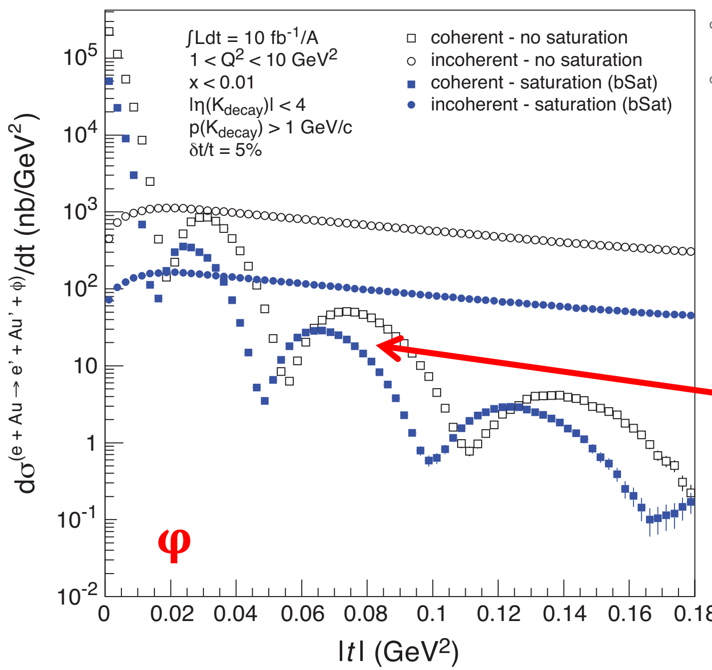
- ➤ Lumpiness of source?
- ➤ Just Wood-Saxon+nucleon g(b_T)

❑ coherent part probes "shape of black disc"

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

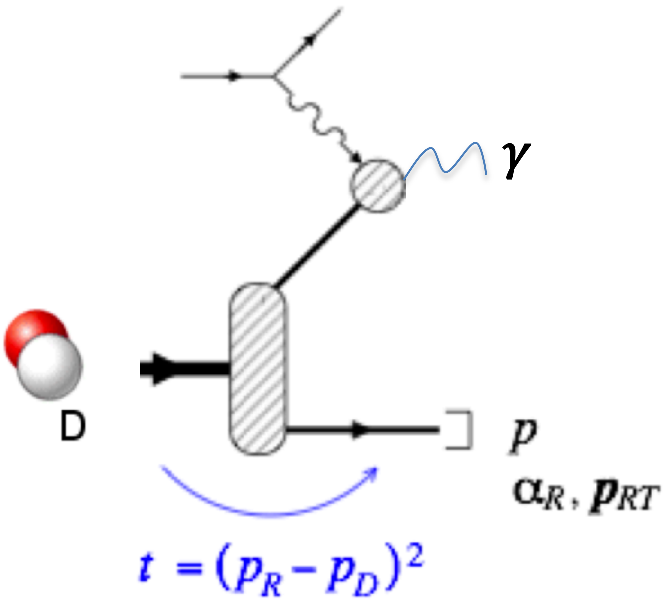
possible Source distribution with $b_T{}^g$ = 2 GeV^{-2}





Sensitive to saturation effects!

Measuring neutron via spectator tagging

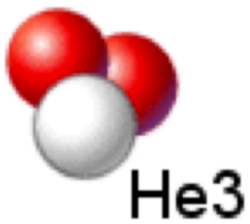


- Possibility to study neutron structure
- DVCS on neutron compared to proton is important for flavor separation

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

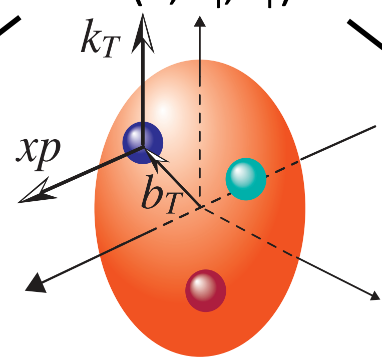
Direct access to Wigner function

Wigner function

$W(x,b_T,k_T)$ QCD genetic map

$\int d^2b_T$ $\int d^2k_T$

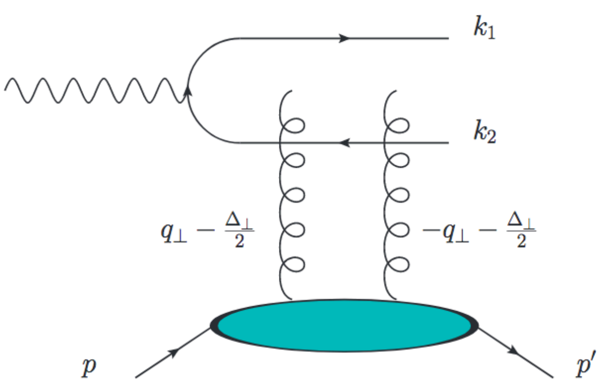
Momentum space



Coordinate space

$f(x,k_T)$
TMDs

$f(x,b_T)$
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**

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 “old” 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 $200 fb^{-1}$ collected at a lower and a top $\sqrt{s}$ energy needed cover the W.P.’s GPDs program on e+p.

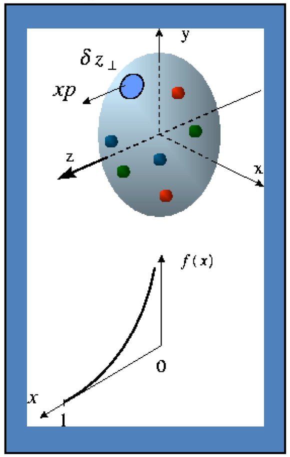
New excitement ahead

- 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)
- Gluon elliptic Wigner fcn.!

Back up

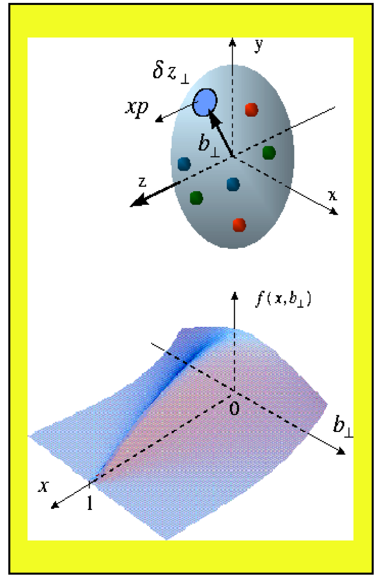
Generalized Parton Distributions

Longitudinal momentum & helicity distributions



$f(x)$

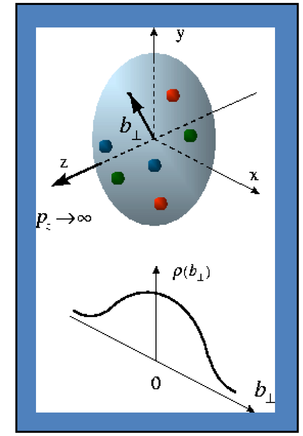
parton densities



$H(x,\xi,t)$

GPDs

transverse charge & current densities



$F_1(t)$

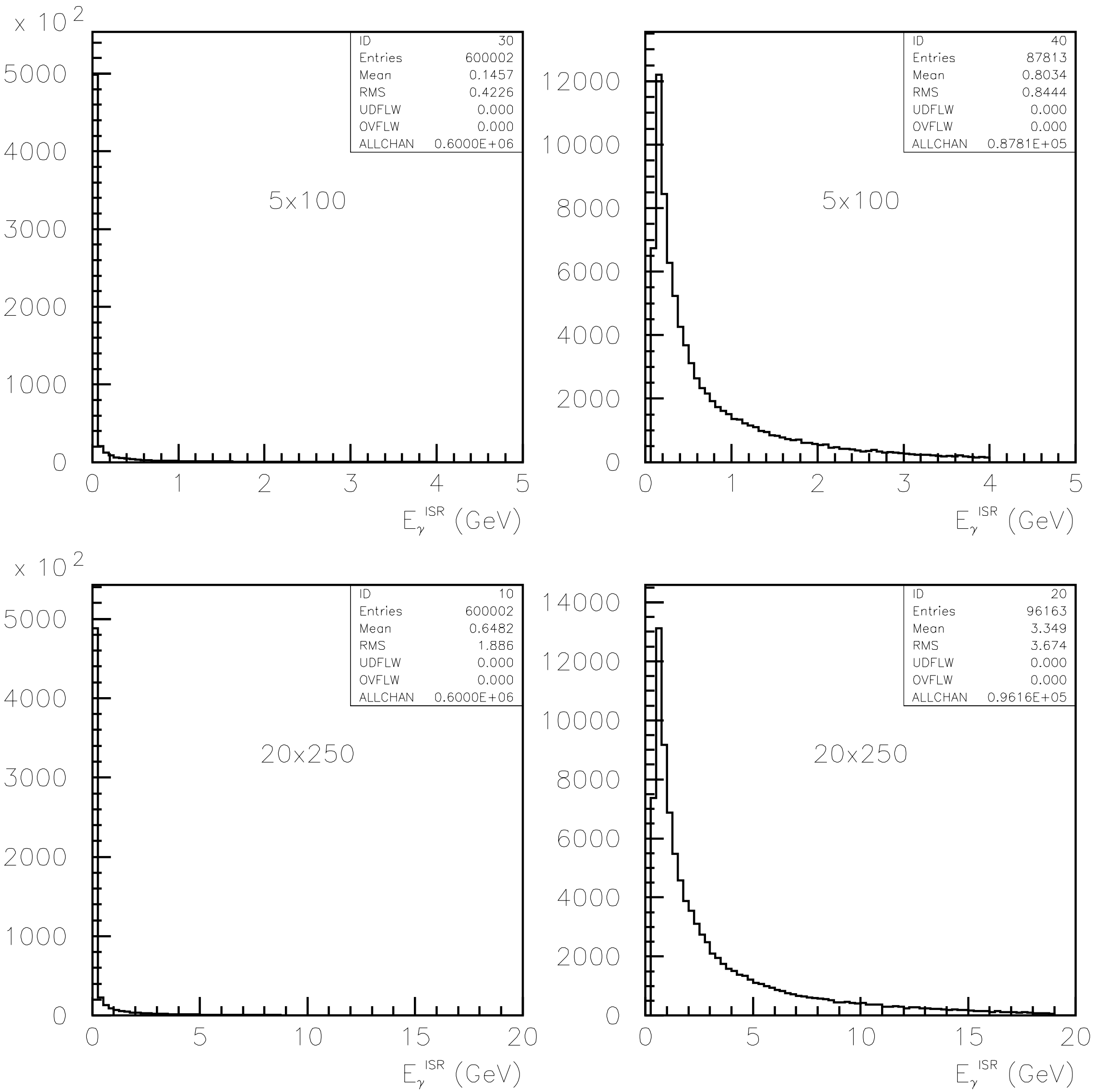
form factors

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

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

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

Contribution from ISR

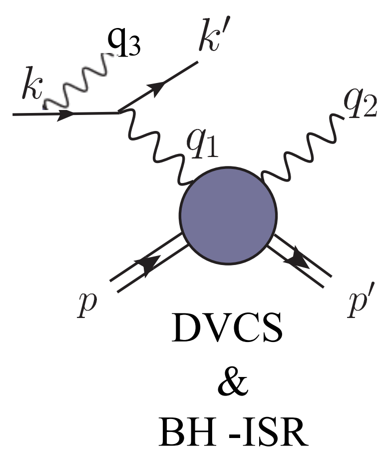


the energy spectrum of the emitted ISR photon for two different EIC beam energy combinations.

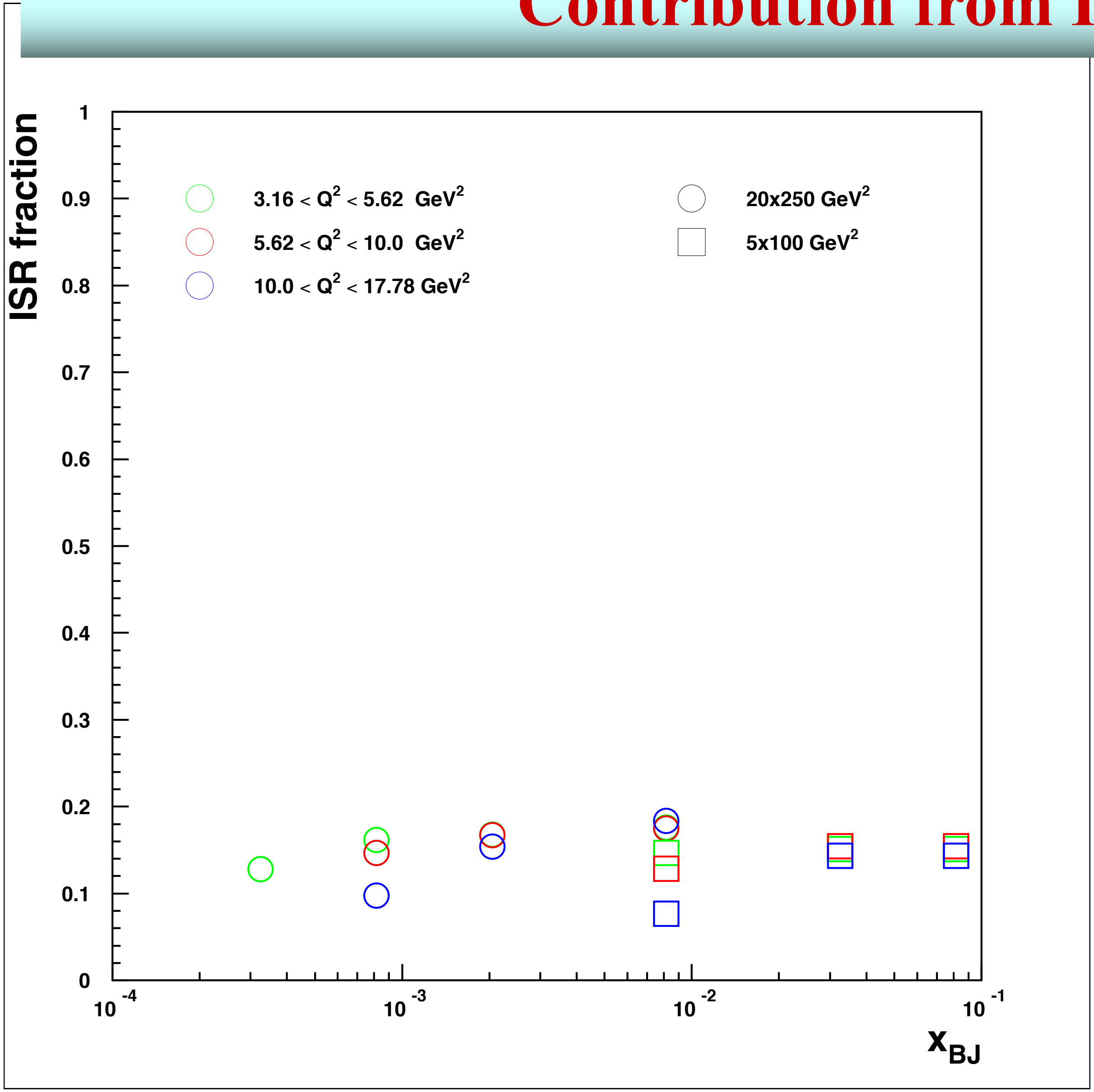
the right plots show the same photon spectra but requiring

$E_\gamma = 0.02 * E_e$

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



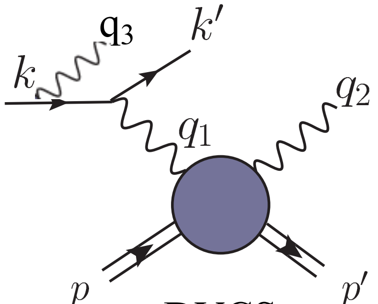
Contribution from ISR



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.

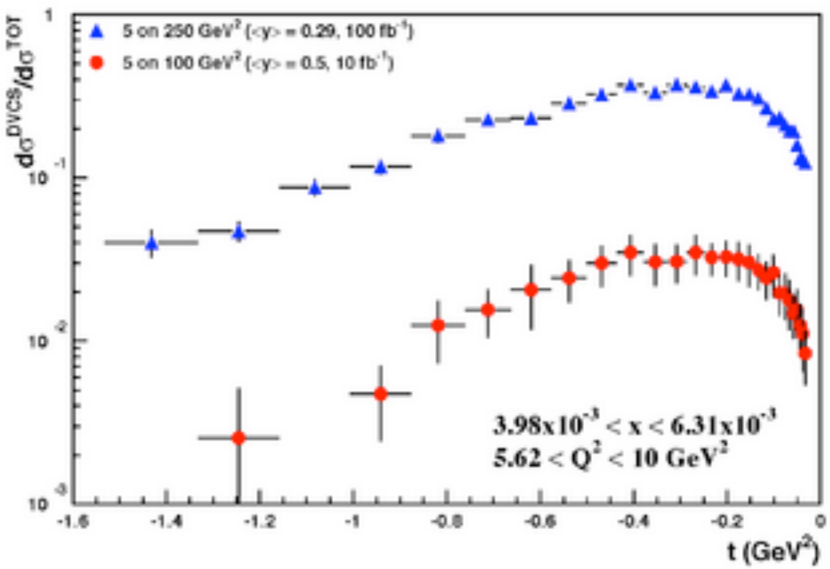


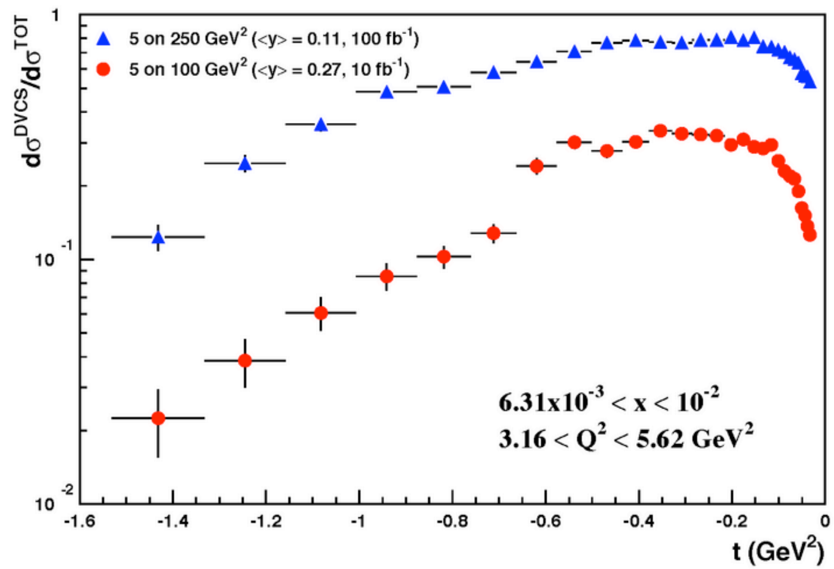
DVCS
&
BH -ISR

Rosenbluth separation

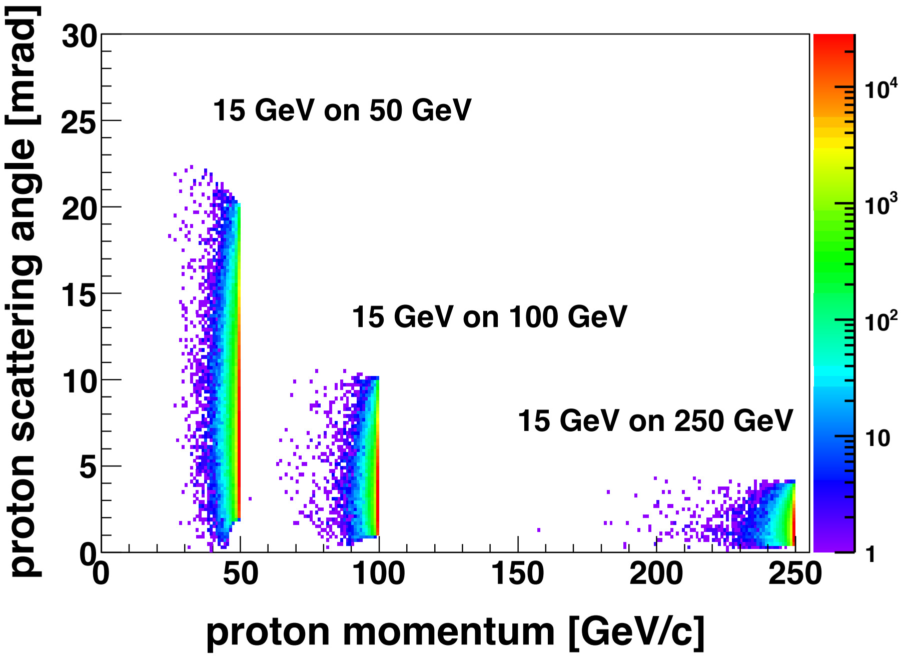
$$d\sigma = \mathrm{d}\sigma_{DVCS} + \mathrm{d}\sigma_{BH} + \mathrm{d}\sigma_{INT}$$

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



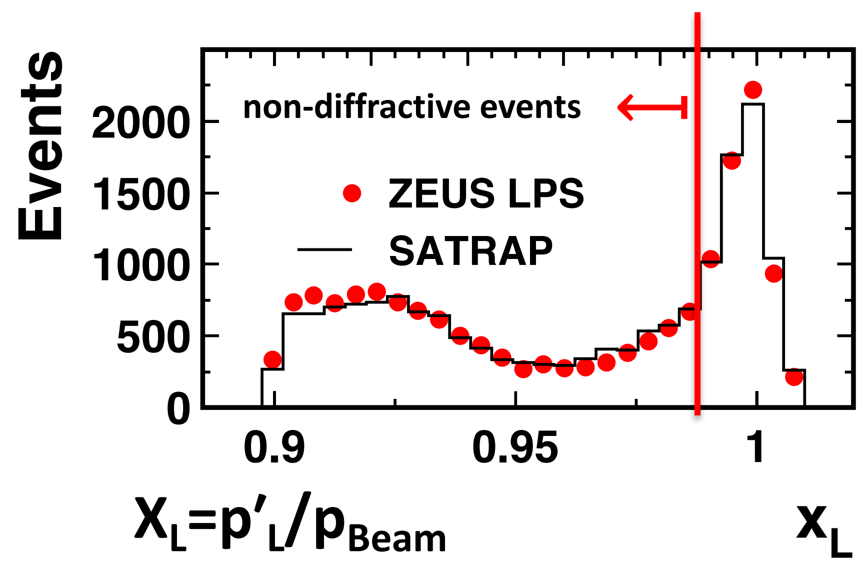
Remember:

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

→ $\Theta < 10$ mrad

→ impact on large p_T-acceptance

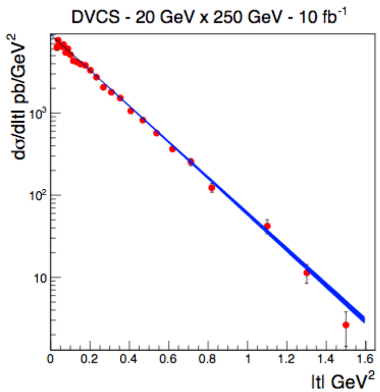
→ small p_T-acceptance limited by beam divergence and immittance

→ rule of thumb keep 10s between RP and beam

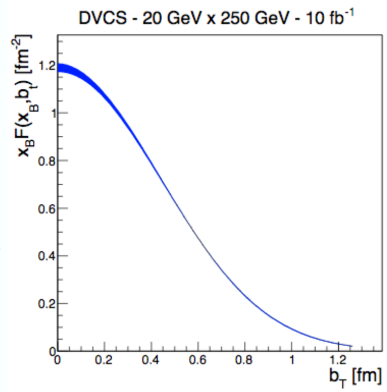
Impact of proton acceptance

Measurement

Physics observable (cross-section vs impact parameter)



Plots from EIC White Paper:

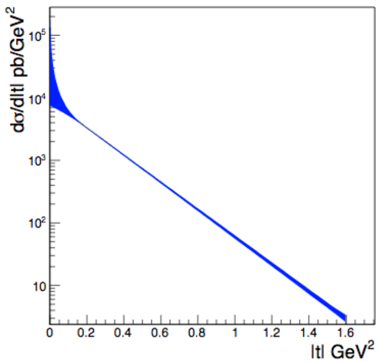


Requirement:

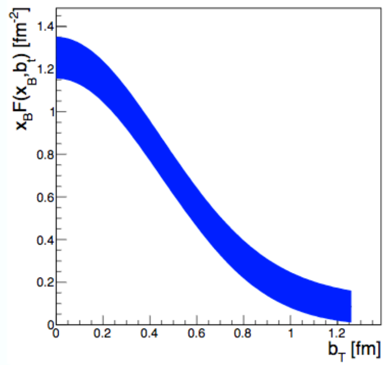
$\int L_{int} = 10 fb^{-1}$

$0.18 < p_t$ (GeV) < 1.3

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

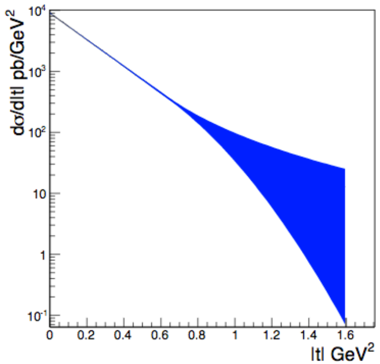


limited lower p_T-acceptance

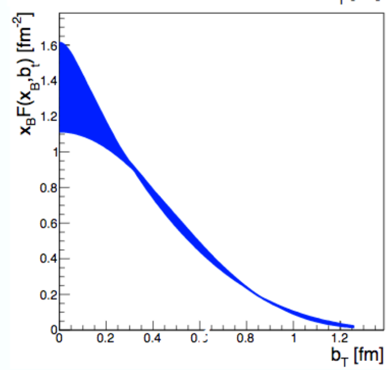


$\int L_{int} = 10 fb^{-1}$

$0.44 < p_T$(GeV) < 1.3



limited higher p_T-acceptance



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

$0.18 < p_T$ (GeV) < 0.8

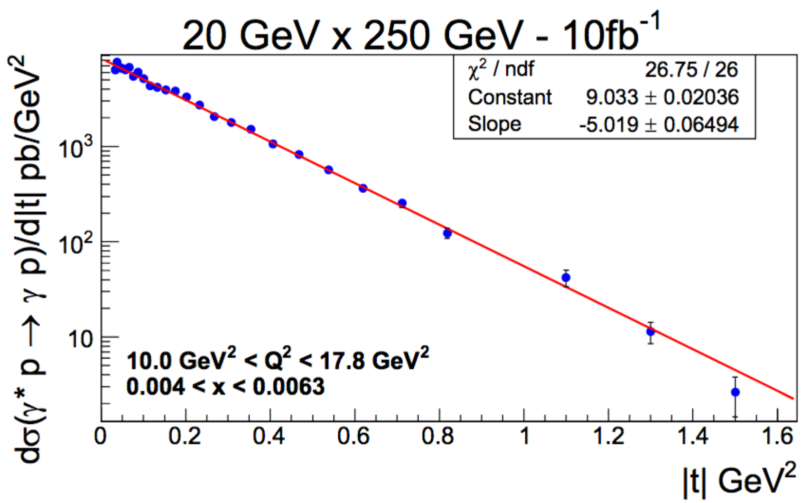
We need a proton spectrometer with large acceptance!

Impact of collected luminosity

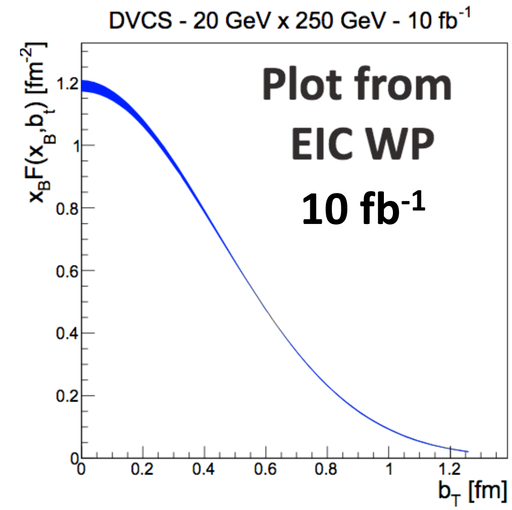
See also B. Mueller's talk

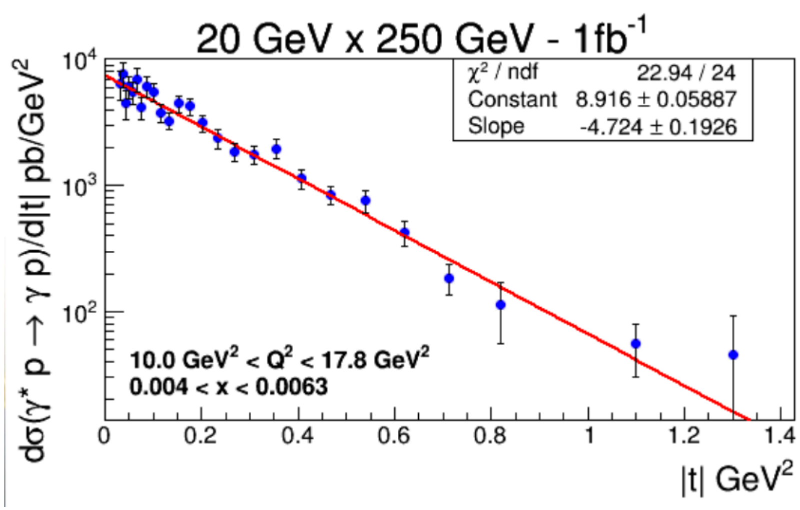
$0.18 < p_T < 1.3$ GeV

$10\ fb^{-1} \rightarrow 1\ fb^{-1}$

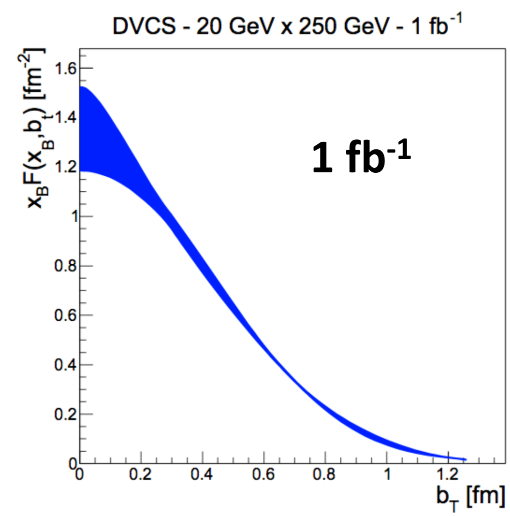


Fourier transform

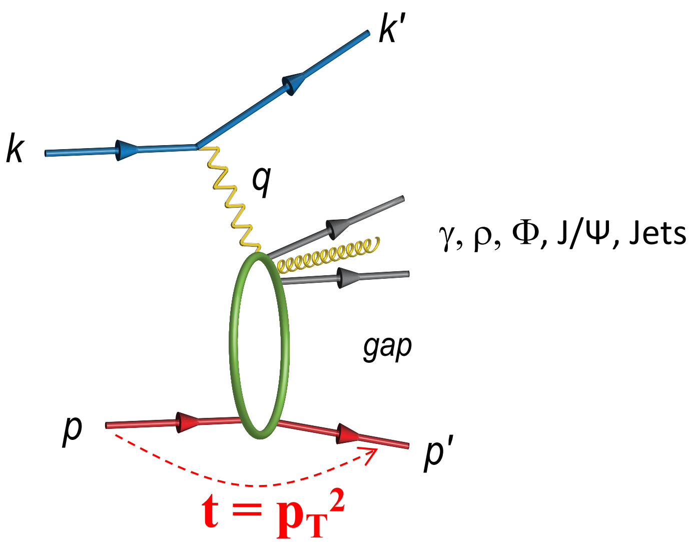




Fourier transform



Detector Requirements for Exclusive Reactions in ep/eA



- Exclusivity criteria:
  - Large rapidity coverage or tracker and Calorimeter (ballpark $-4.5 < \eta < 4.5$)
  - Reconstruction of all particles in event
    - wide coverage in t (=p_T^2) → Roman pots
- eA: large acceptance for neutrons from nucleus break-up
  - Zero Degree Calorimeter
    - veto nucleus breakup
    - determine impact parameter of collision