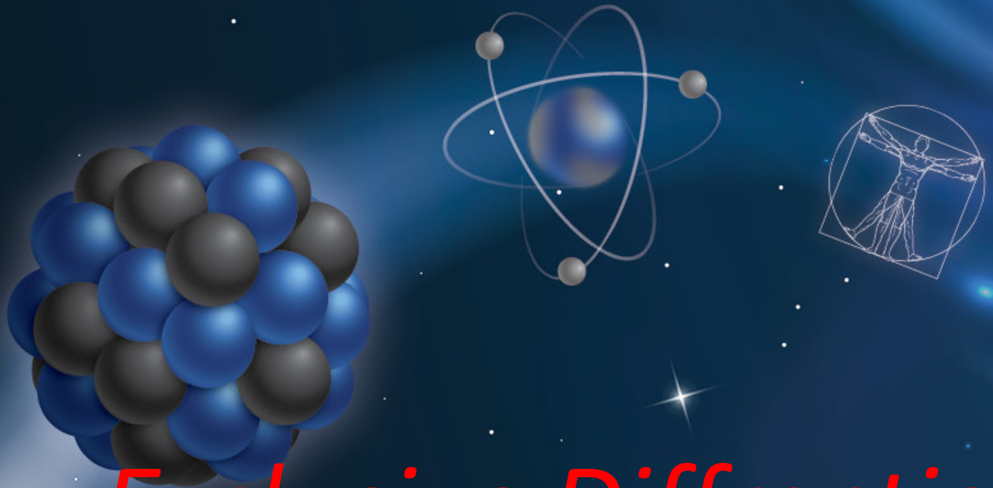


Exclusive Diffraction and GPDs at an EIC

Salvatore Fazio

Brookhaven National Lab

Workshop on the spectroscopy program at EIC and future accelerators

ECT*, Trento (Italy)

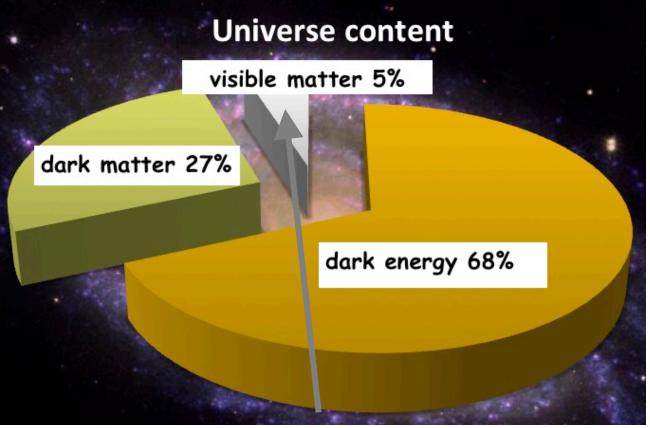
19-21 December 2018

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

Plan of the talk

- Introduction
- The Electron-Ion Collider Project
- DVCS @ EIC
  - Impact studies
- DVMP @ EIC
- Exclusive diffraction on Nuclei
  - imaging, saturation
- Summary

What do we know?



This is us !!!

protons, neutrons, electrons

Proton
10^{-15}m

Quarks and Gluons
10^{-17}m

increase
beam energy

To investigate the nucleon's partonic structure, the previous and only e+p collider, HERA, was built

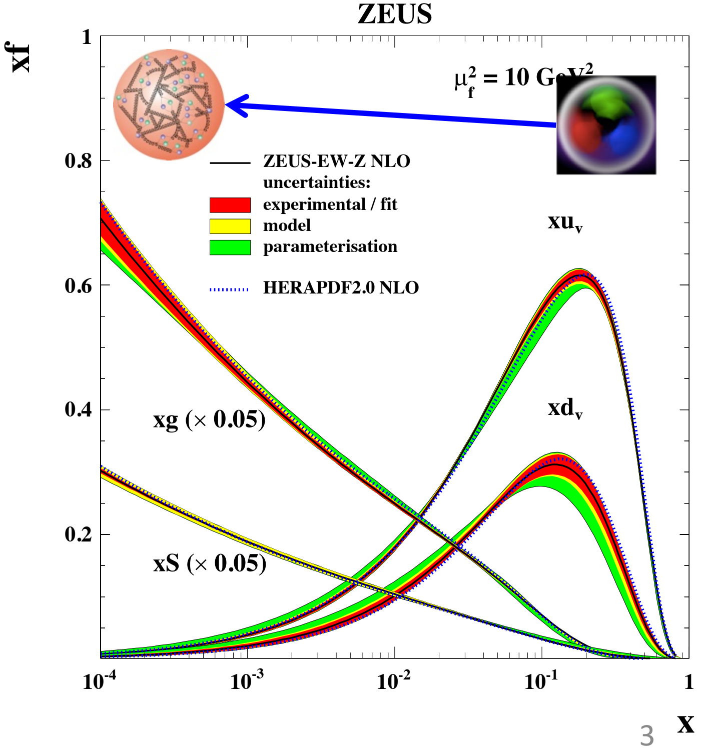
The x (of Bjorken) variable: fraction of the nucleon's momentum carried by the interacting parton

HERA's discovery: Gluon density dominates at x<0.1

Proton:

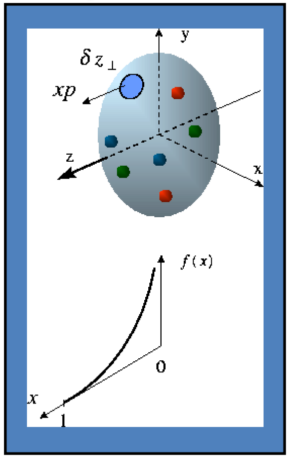
Quark-Masses: ~1% M_p

Mass of the "visible matter" is completely dominated by gluons, QCD dynamics



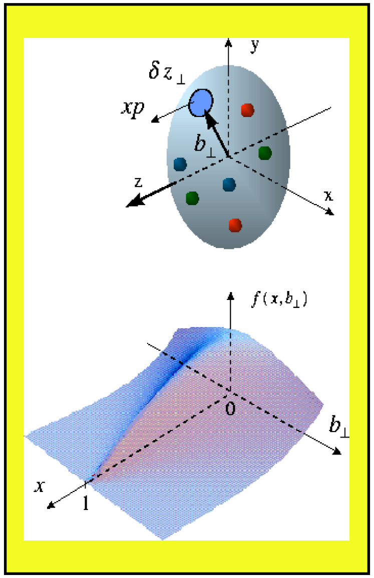
Generalized Parton Distributions

Longitudinal momentum & helicity distributions



$f(x)$

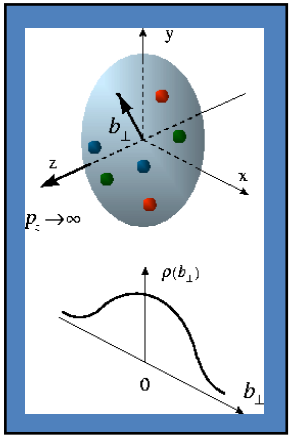
parton densities



$H(x,\xi,t)$

GPDs

transverse charge & current densities



$F_1(t)$

form factors

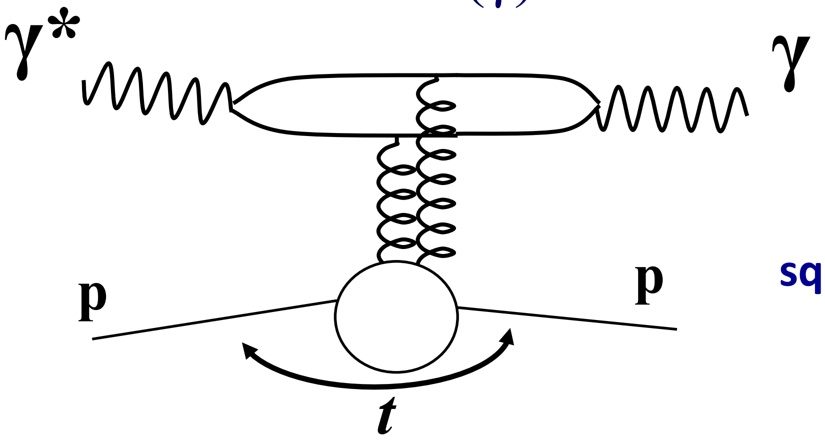
The nucleon (spin-1/2) has **four quark and gluon GPDs** (H, E and their polarized versions). Like usual PDFs, GPDs are non-perturbative functions **defined via the matrix elements of**

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

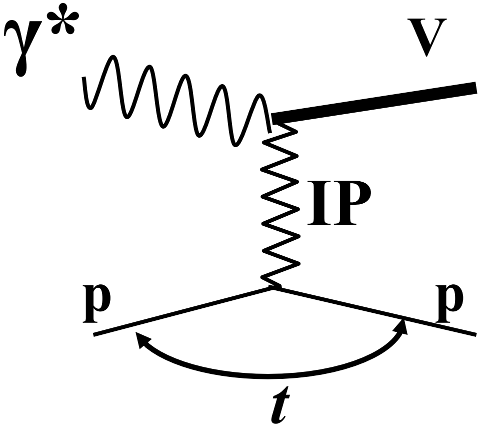
$$= \frac{1}{2\bar{P}^+}\left[H^q(x,\xi,t,\mu^2)\bar{u}(p')\gamma^+ u(p) + E^q(x,\xi,t,\mu^2)\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m_N}u(p)\right]$$

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**

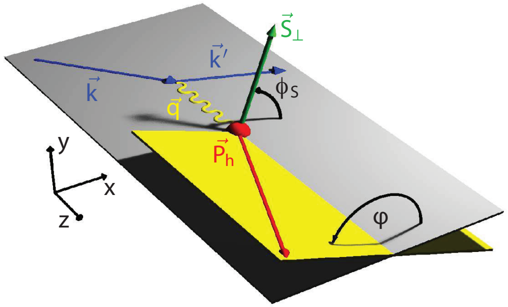
Alternative/complementary way to quark-flavor separation

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

Accessing the GPDs in exclusive processes

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

Dominated by H
slightly dependent on E

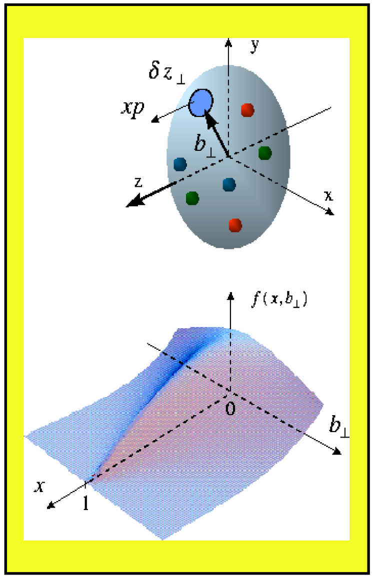


$$\varphi = \phi_h - \phi_l$$

Angle btw the production and scattering planes

$$\varphi_s = \Phi_T - \phi_h$$

Angle btw the scattering plane and the transverse pol. vector



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

Requires a positron beam
done @ HERA

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

sin(*$\Phi_T - \phi_N$*)
governed by E and H
Requires a polarized proton-target

Spin-Sum-Rule in PRF: **from** g_1

$$\frac{1}{2} = J_q^z + J_g^z = \frac{1}{2}\Delta\Sigma + \sum_q \mathcal{L}_q^z + J_g^z$$

$$J_{q,g}^z = \frac{1}{2}\left(\int_{-1}^{1} x\,dx\left(H^{q,g} + E^{q,q}\right)\right)\Big|_{t\to 0}$$

responsible for orbital angular momentum
a window to the SPIN physics

Ingredients for a High Resolution “Femtoscope”

Large center-of-mass coverage:

Access to wide kinematic range in x and Q^2

Polarized electron and hadron beams:

- access to spin structure of nucleons and nuclei
- Spin vehicle to access the 3D spatial and momentum structure of the nucleon
- Full specification of initial and final states to probe q-g structure of NN and NNN interaction in light nuclei

Nuclear beams:

- Accessing the highest gluon densities → amplification of saturation phenomena

High luminosity:

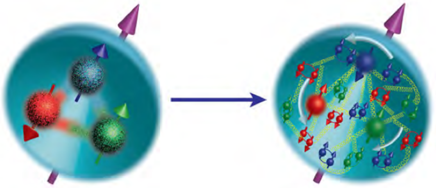
- Detailed mapping the 3D spatial and momentum structure of nucleons and nuclei
- Access to rare probes

All these requirement will be addressed by a future **Electron-Ion Collider**

Most Compelling Physics Goals

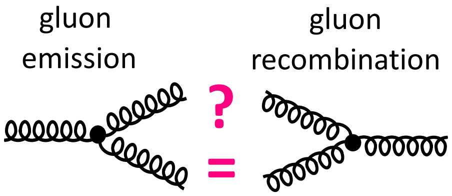
How are sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

- How do the nucleon properties emerge from them and their interactions?



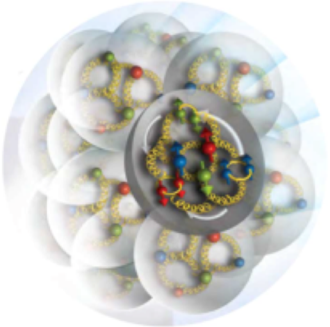
What happens to the gluon density in nuclei?

- Does it saturate at high energy?
- Does this saturation give rise to a gluonic matter with universal properties in all nuclei, even proton?



How does a dense nuclear environment affect the quarks and gluons, and their correlations and their interactions?

- How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?
- How do the confined hadronic states emerge from these quarks and gluons?
- How do the quark-gluon interactions create nuclear binding?



The Electron Ion Collider

Two proposals for realization of the Science Case

For e-N collisions at the EIC:

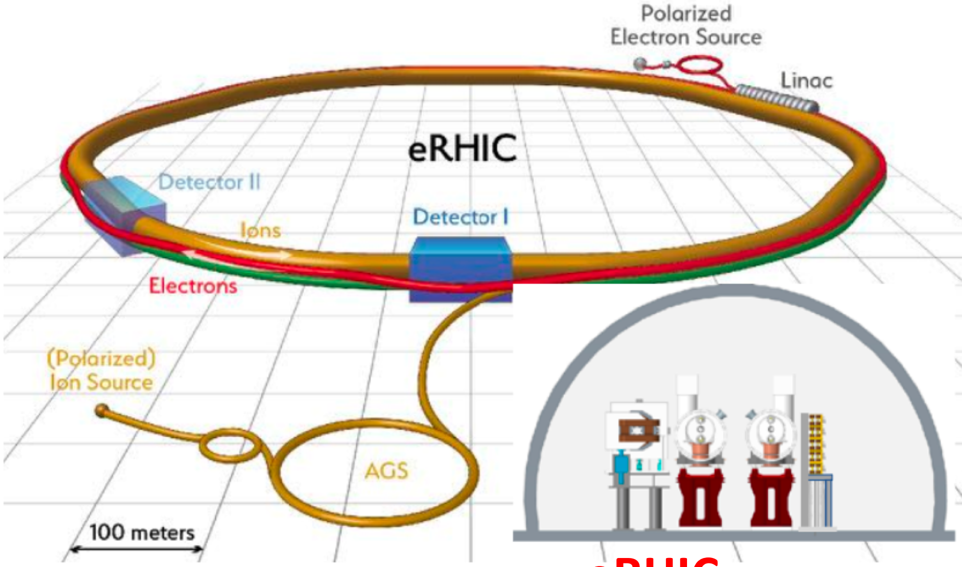
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ Luminosity $L_{ep} \sim 10^{34}$ cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ $\sqrt{s}$ = 20-100 (140) GeV Variable CoM

For e-A collisions at the EIC:

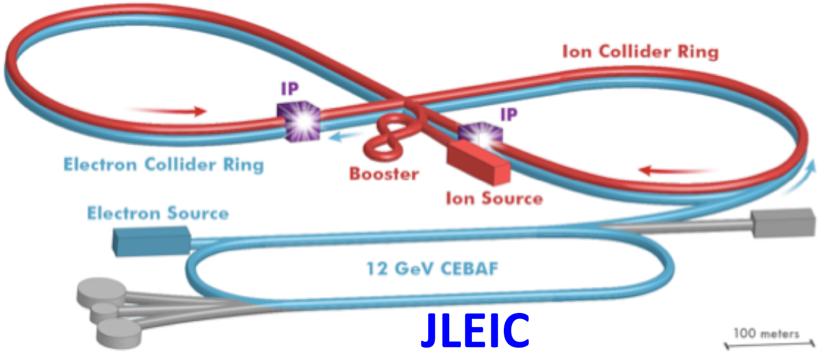
- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e+p
- ✓ Variable center of mass energy

World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

Both designs use DOE's significant investments in infrastructure



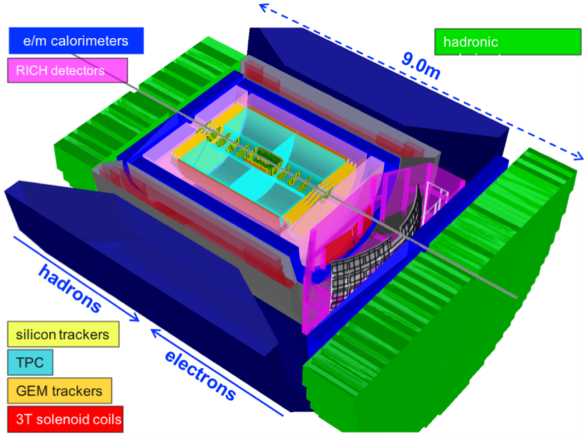
eRHIC
Brookhaven National Lab



JLEIC
Thomas Jefferson National Lab

“General-purpose” detector concepts

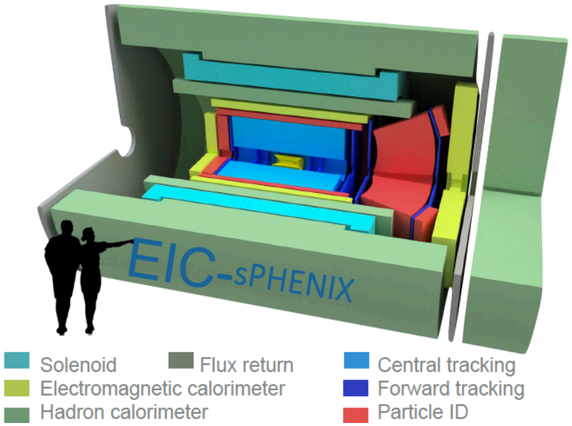
Brookhaven: BEAST



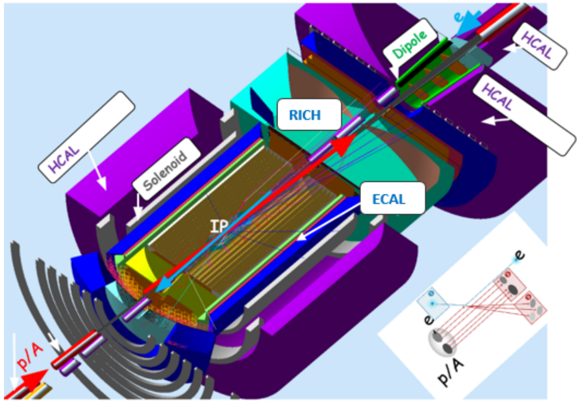
Overall detector requirements:

- ☐ **Large acceptance in pseudorapidity**: -4.5 ≲ η ≲ 4.5
- ☐ Equal coverage of tracking and EM-calorimetry
- ☐ High performance PID to separate p, K, π on track level
- ☐ High precision low mass tracking
- ☐ Forward instrumentation for protons and neutrons
- ☐ High control on systematic effects

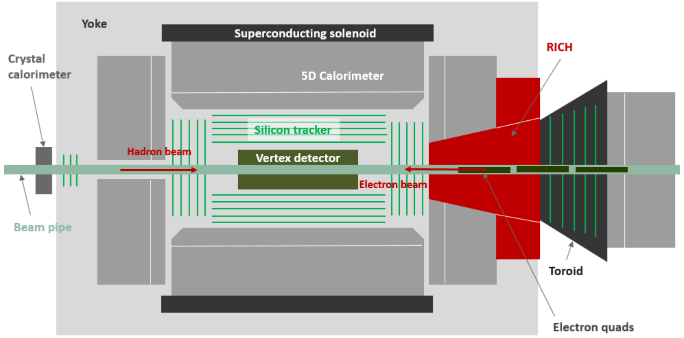
Brookhaven: EIC-sPHENIX



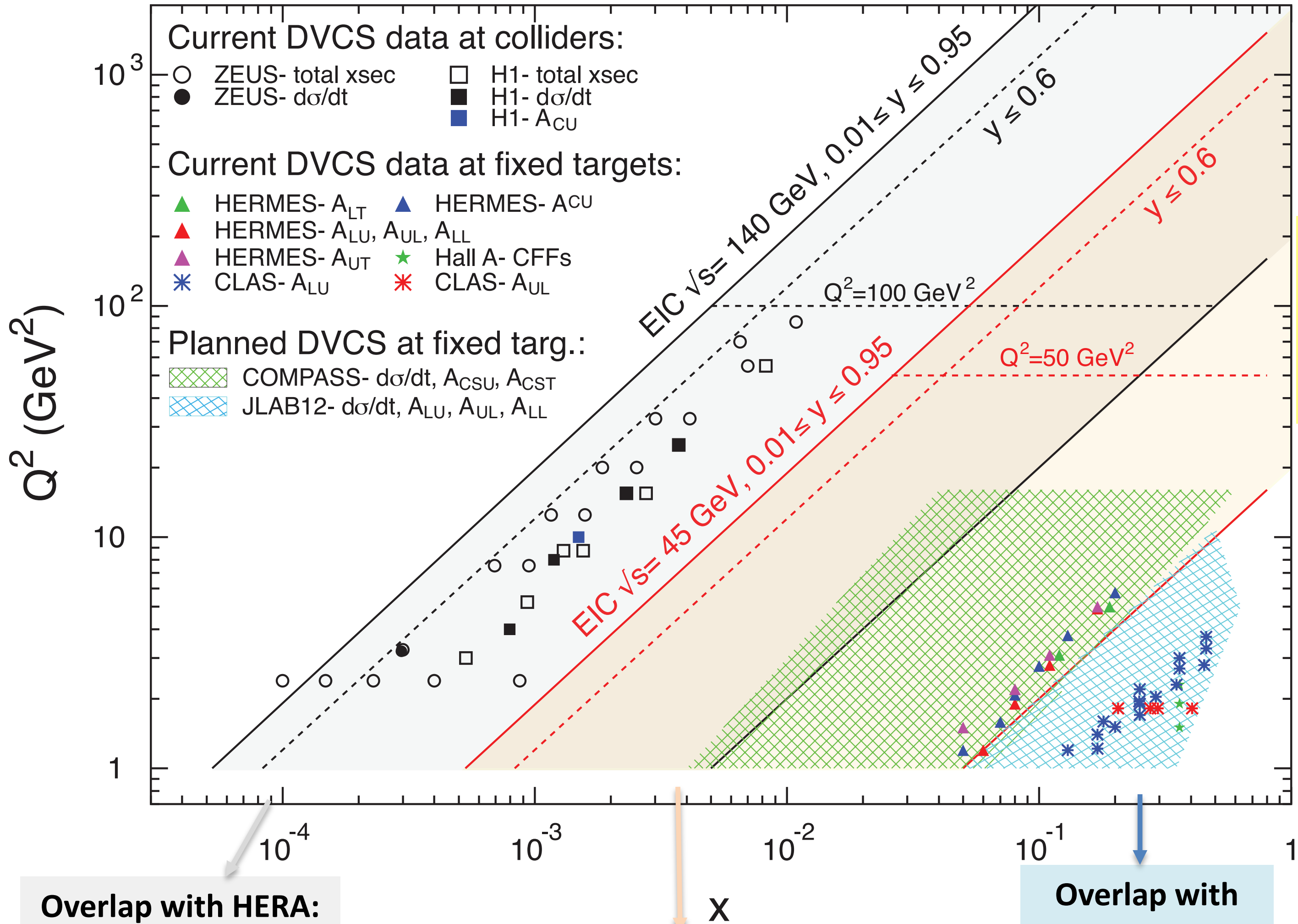
Jefferson lab: JLEIC



Argonne: TOPSiDE



DVCS at an EIC



HERA results limited by lack of statistics

EIC: the first machine to measure cross sections and asymmetries

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

Intermediate region:
Fine mapping of the GPDs evolution

Overlap with JLAB12:
Sanity check

Current data:
See C. Van Hulse' Talk

Data simulation & event selection

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]

Acceptance criteria

- for Roman pots: 0.03< |t| < 1.5 GeV^2
- 0.01 < y < 0.85 GeV^2
- $\eta < 5$

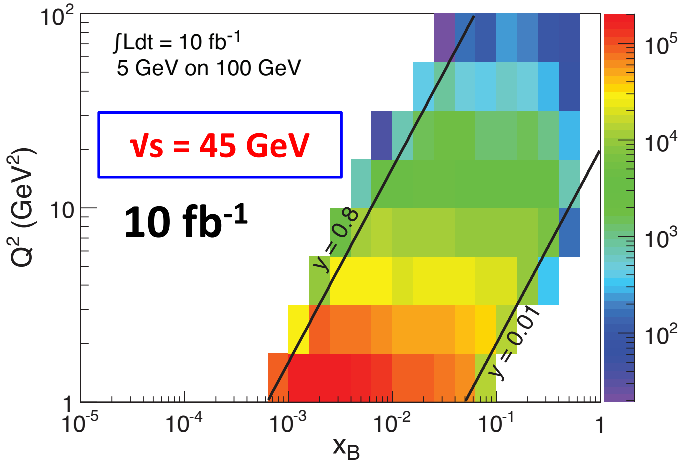
➢ BH rejection criteria (applied to x-sec. measurements)

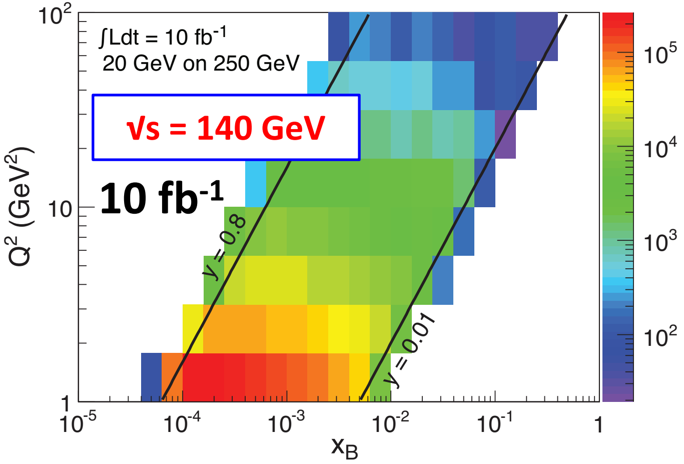
- y < 0.6
- $(\theta el-\theta\gamma) > 0$
- Eel>1GeV^2; Eel>1GeV^2

➢ Events smeared for expected resolution in t, Q2, x

➢ Systematic uncertainty assumed to be ~5% (having in mind experience from HERA)

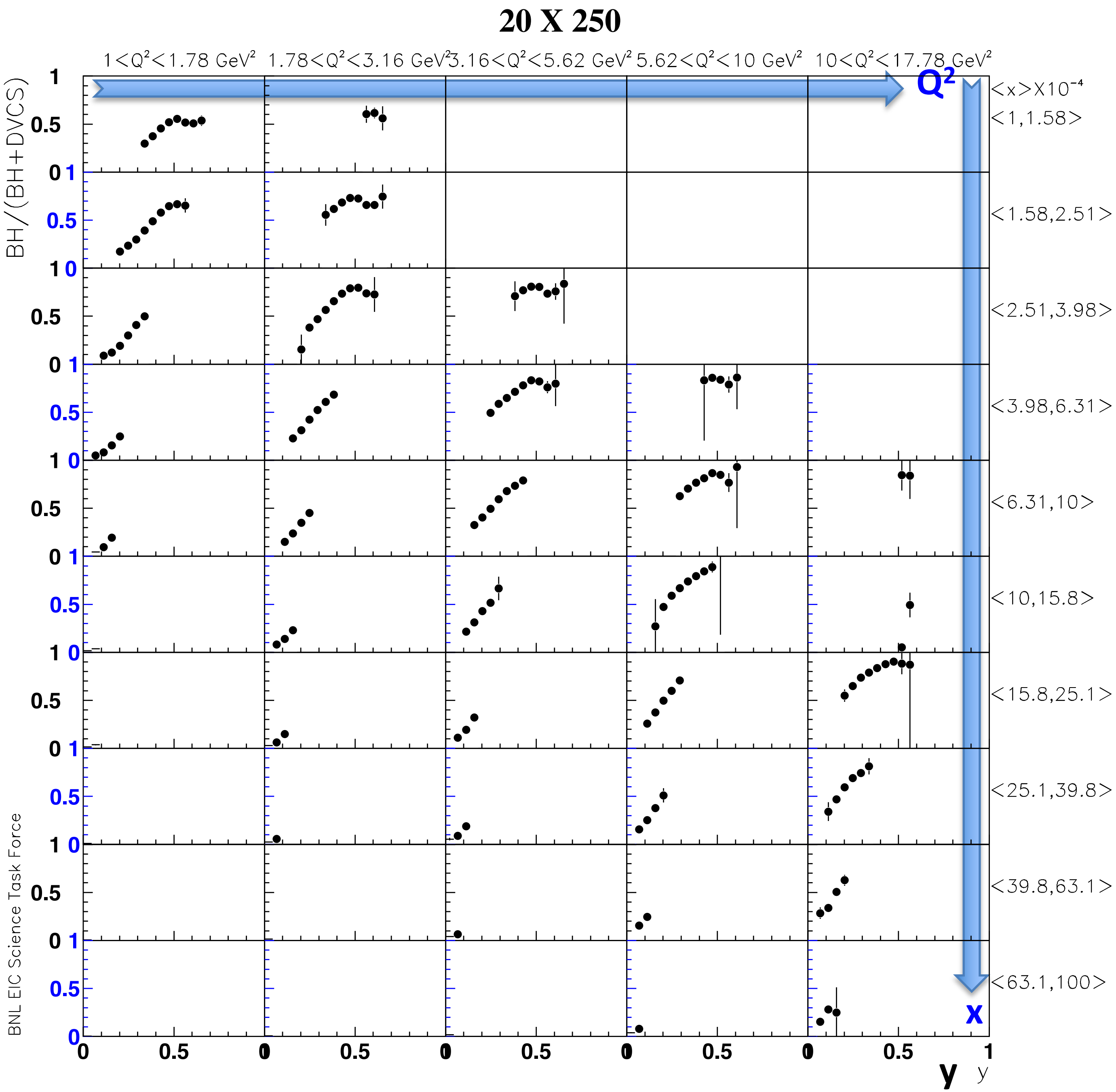
➢ Overall systematic uncertainty from luminosity measurement not taken into account





✧ EIC will provide sufficient lumi to bin in multi-dimensions

✧ wide x and Q2 range needed to extract GPDs



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

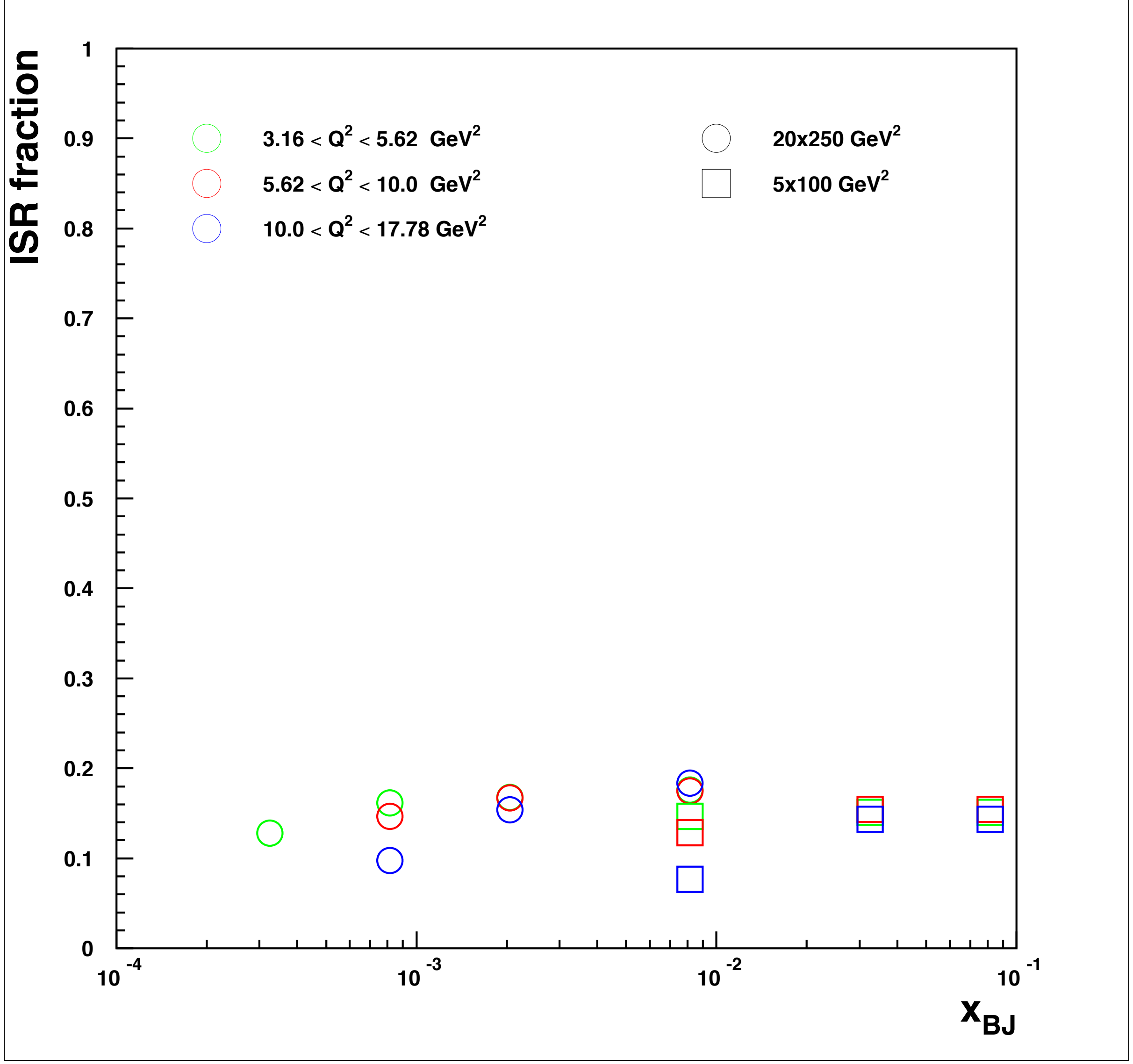
BH subtraction will be relevant at lower energies and large y, in some of the x-Q² bin

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

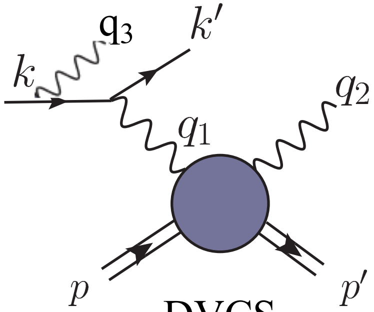
Contribution from ISR



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

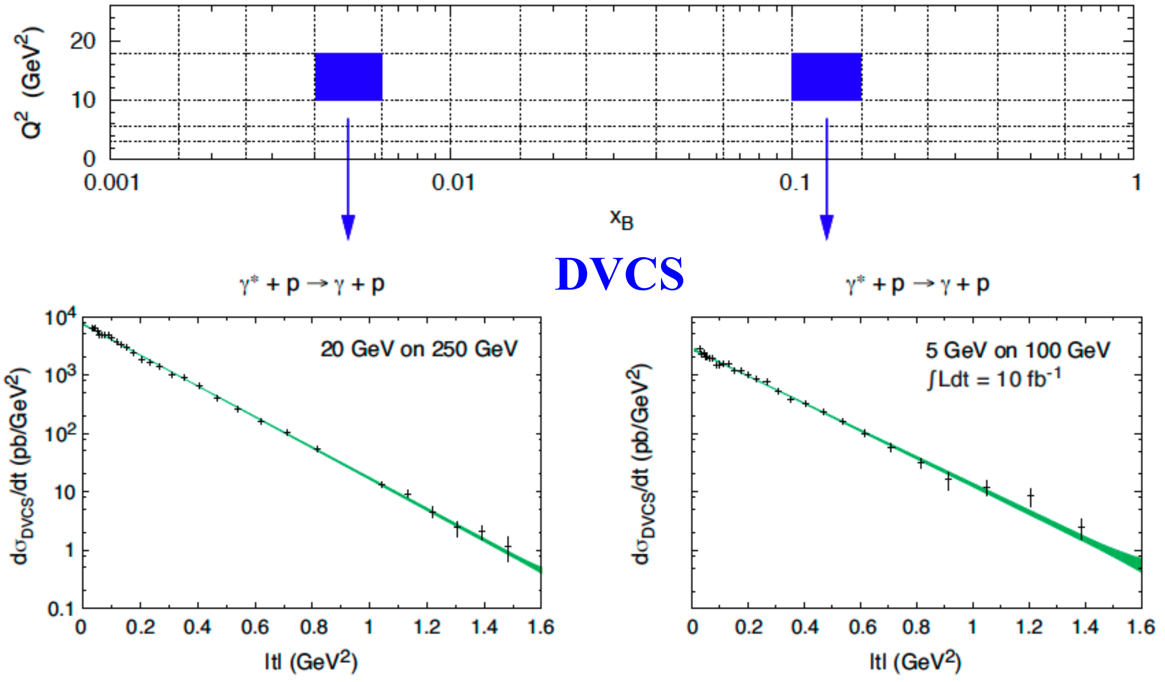
ONLY 15% of the events emit a photon with > 2% energy of the incoming electron

ISR photons with **E_γ < 0.02 E_e** do not result in a significant correction for the event kinematics.

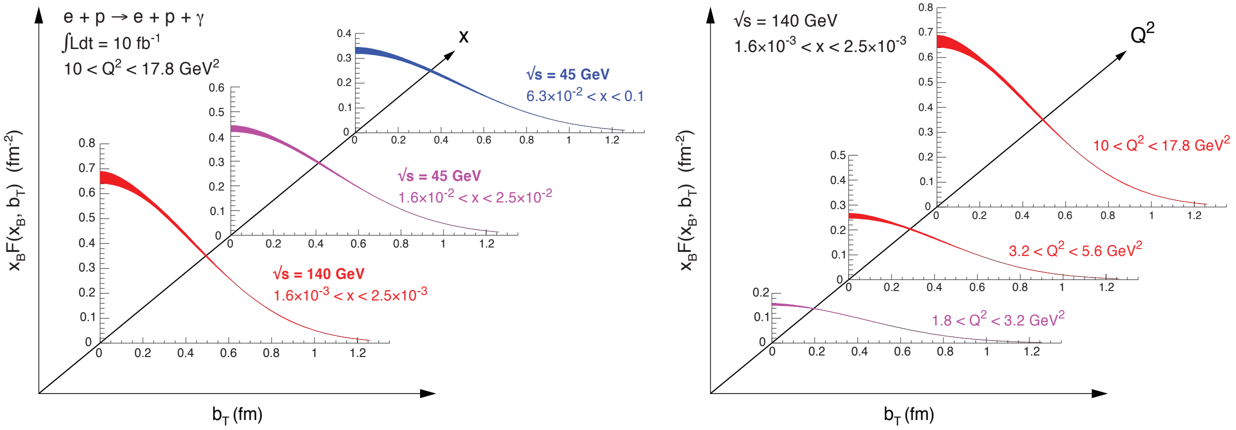


DVCS
&
BH -ISR

DVCS & J/ψ differential cross section



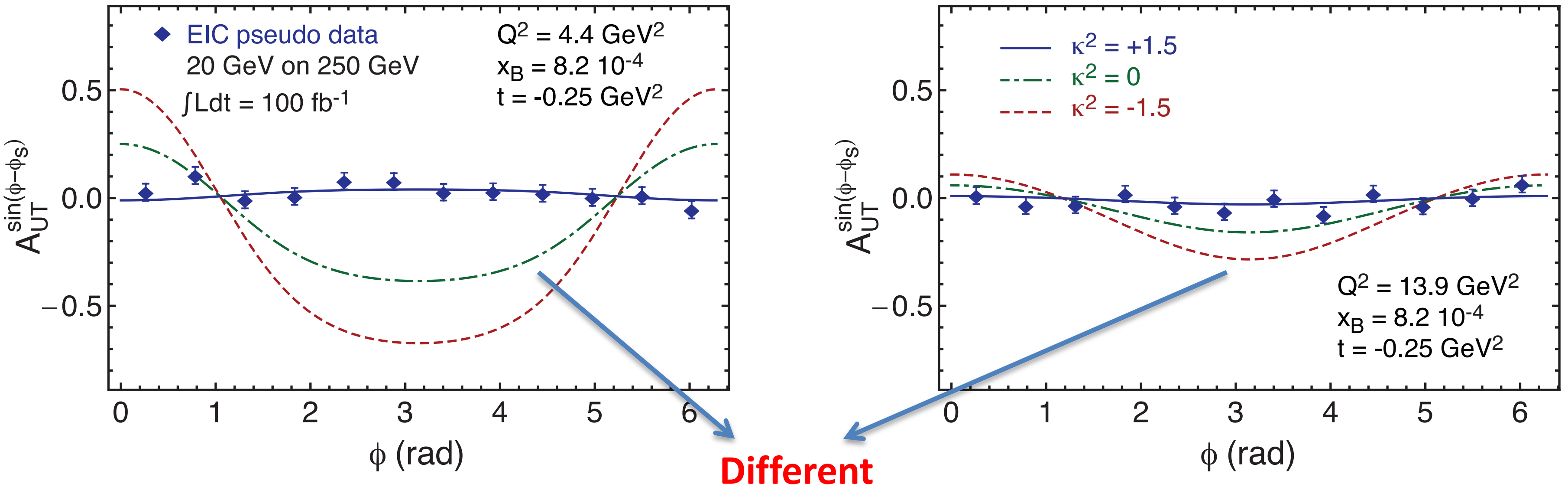
DVCS



Luminosity: 10 fb^{-1}

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

Transverse target-spin asymmetry



Different assumptions for E

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

$\sin(\Phi_T - \phi_N)$

governed by E and H

Spin-Sum-Rule in PRF: from g_1

$$\frac{1}{2} = J_q^z + J_g^z = \frac{1}{2}\Delta\Sigma + \sum_q \mathcal{L}_q^z + J_g^z$$

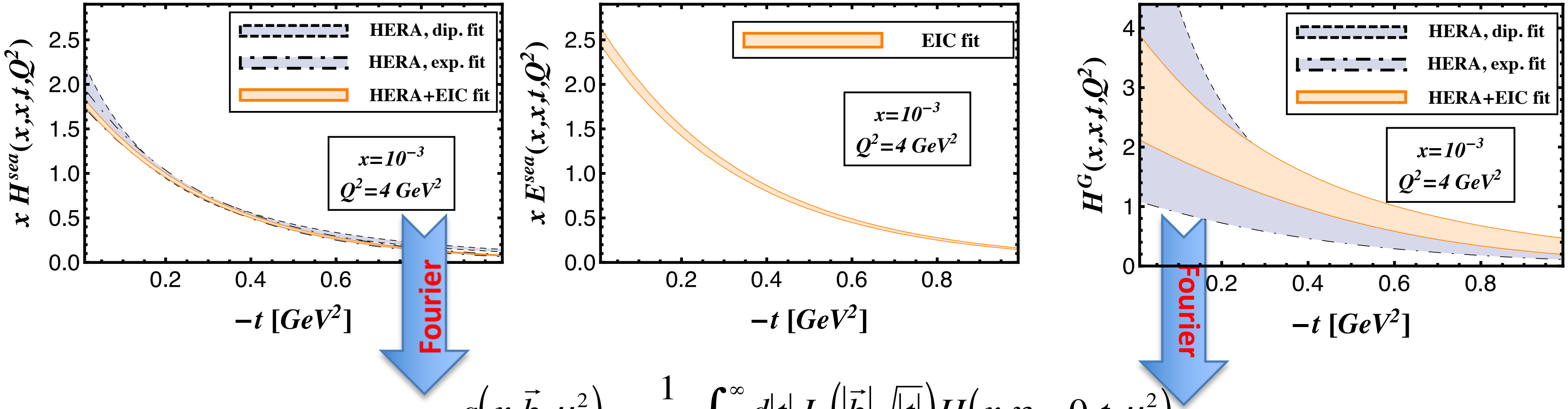
$$J_{q,g}^z = \frac{1}{2}\left(\int_{-1}^{1} x\,dx\left(H^{q,g} + E^{q,q}\right)\right)\Bigg|_{t\to 0}$$

Gives access to GPD E

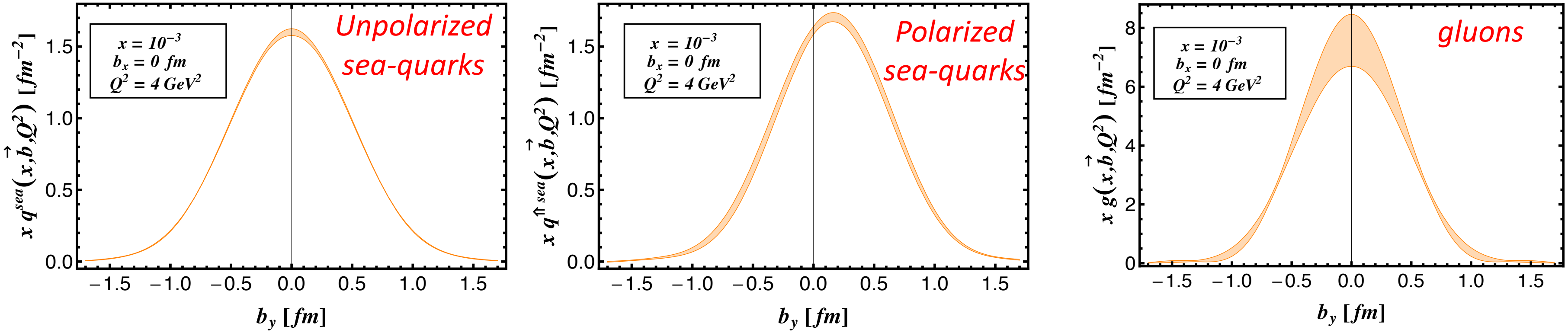
E.C. Aschenauer, S. F., K. Kumerički, D. Müller
JHEP09(2013)093

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)**

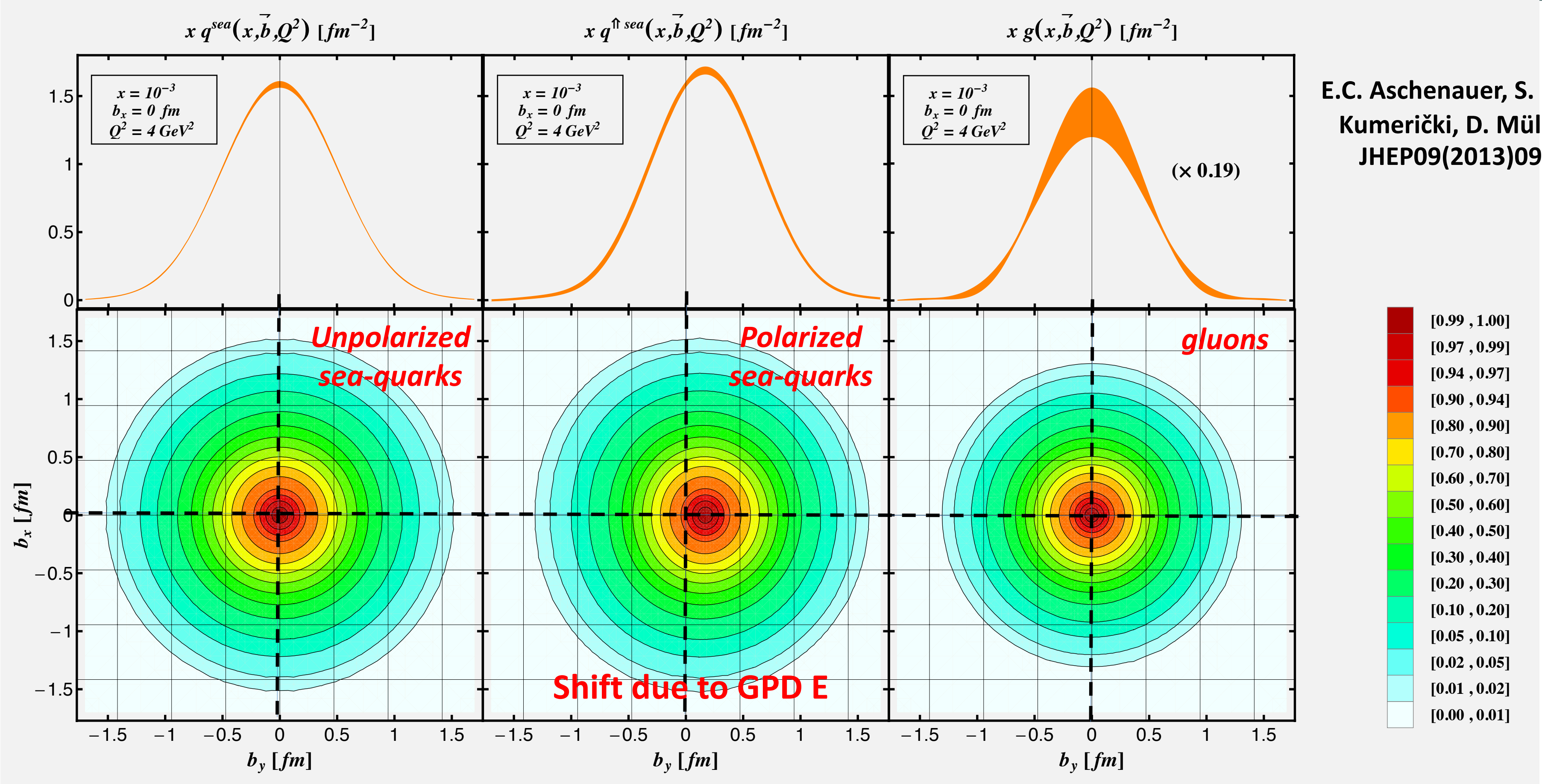


$$q\left(x,\vec{b},\mu^2\right)=\frac{1}{4\pi}\int_0^\infty d|t|\,J_0\left(\left|\vec{b}\right|\sqrt{|t|}\right)H\left(x,\eta=0,t,\mu^2\right)$$



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**

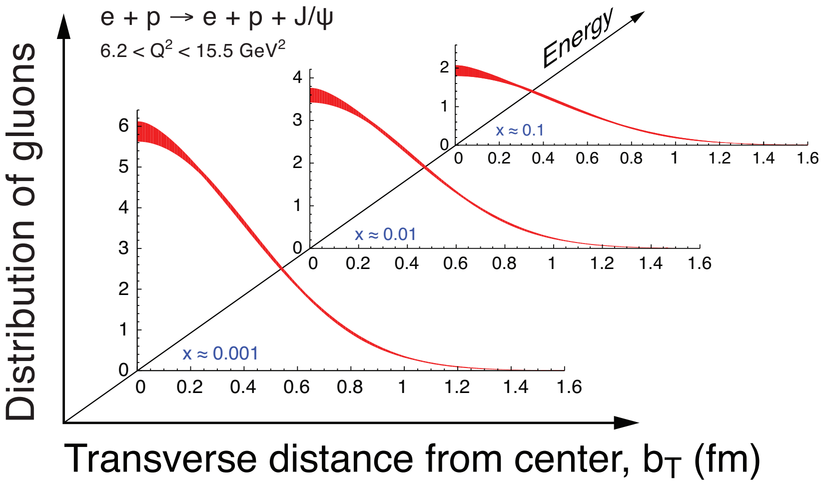
Other capabilities still to be evaluated?

- 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?

Method 1 – VMP

rho0: 2u+d 9/4g
omega: 2u-d /4g
phi: s,g
rho+: u-d
J/psi: g



We simulated the J/Psi cross section and the Fourier transform but never included it on GPDs fits

Challenges of VMP (if compared to DVCS)

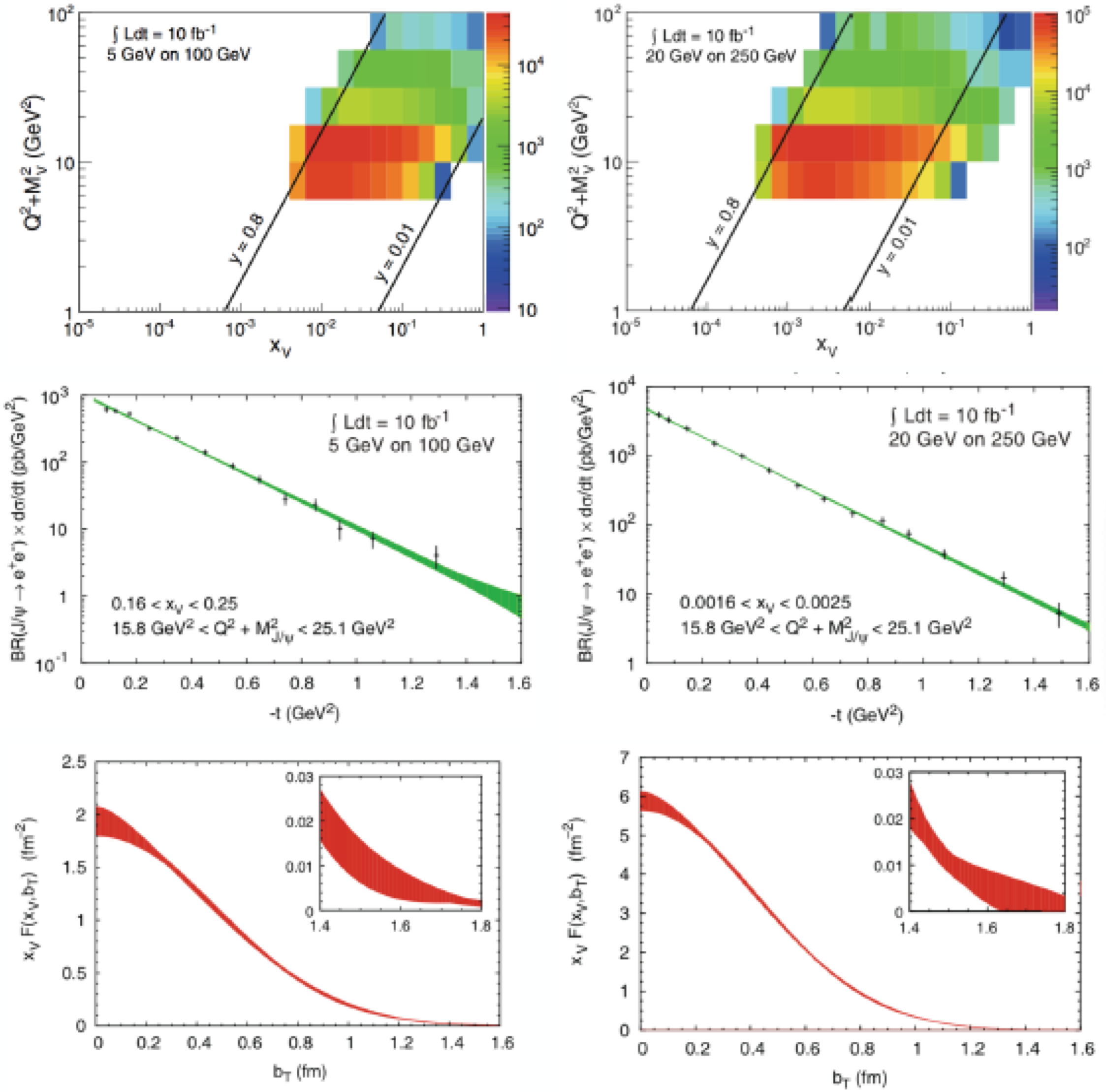
- Uncertainty on wave function
- measuring muons vs electron decay channel

Method 2 – DVCS on protons and neutrons

- **We do not a real neutron target → Use Deuterium (D)**
- **We incoherent DVCS on D (D can break up) but coherent on n (tagged by ZDC)**
- **One still needs J/psi to directely access the gluons and extract Eg**

Imaging gluons with J/ψ

EIC White Paper



Luminosity: 10 fb^{-1}

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

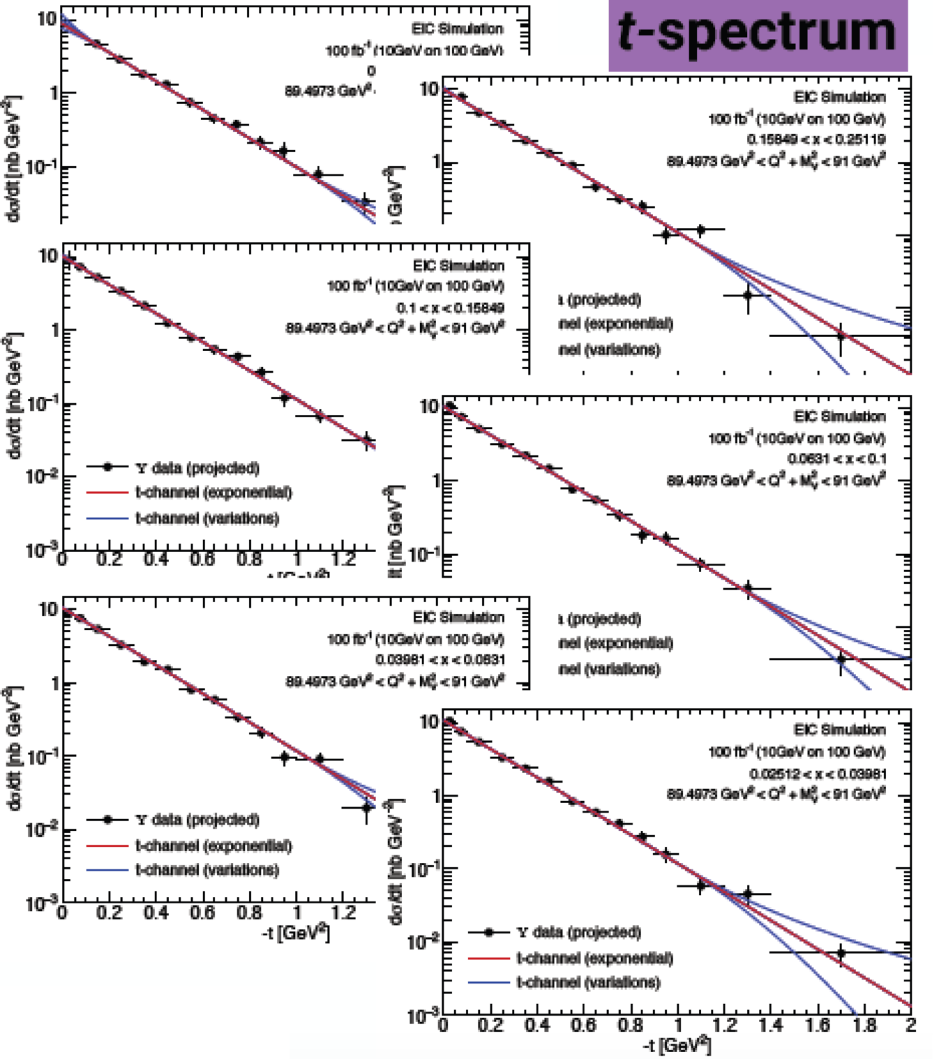
Average gluon densities

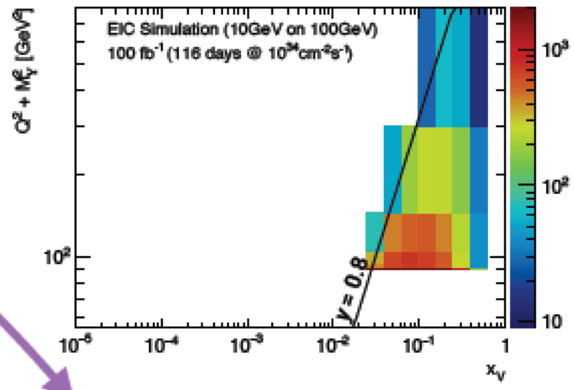
Imaging gluons with Y(1s)

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

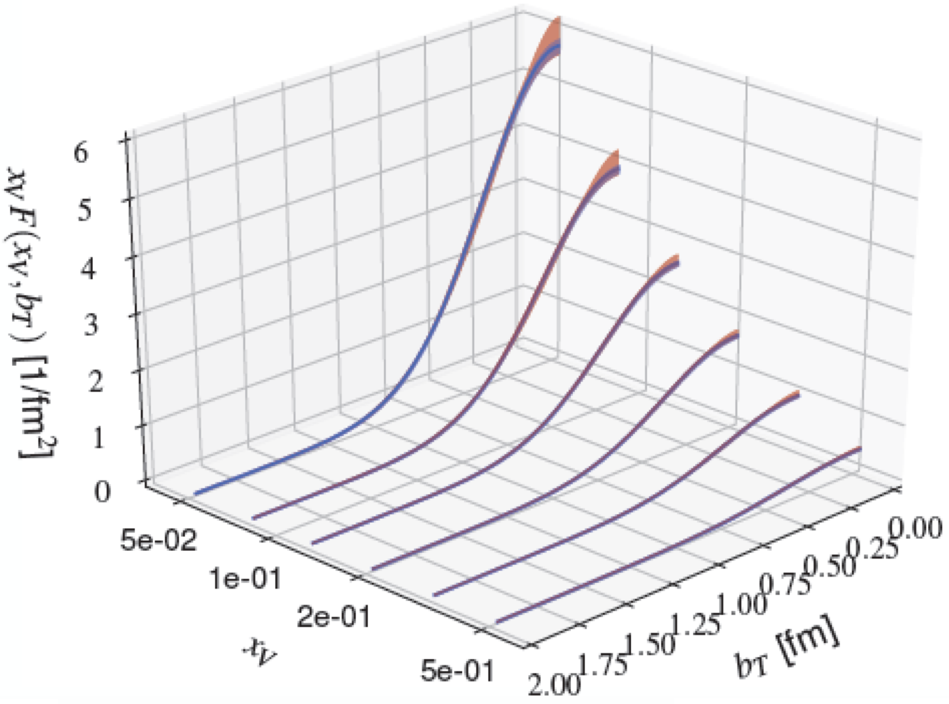
- ☆ Nominal EIC detector
- ☆ 10x more luminosity
- ☆ Electron and muon channels

***t*-spectrum**

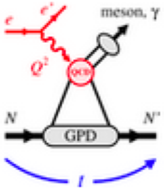




Average gluon density:



Topical Workshops



Center for Frontiers in Nuclear Science

Next-generation GPD studies with exclusive meson production at EIC

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

- **Meson production could become essential tool for GPD studies at EIC**
  Dedicated community, great interest
- **Next-level impact studies need GPD-based physics models**
- **PARTONS project (H. Moutarde et al) can play important role in integrating GPD efforts at JLab12 and EIC**

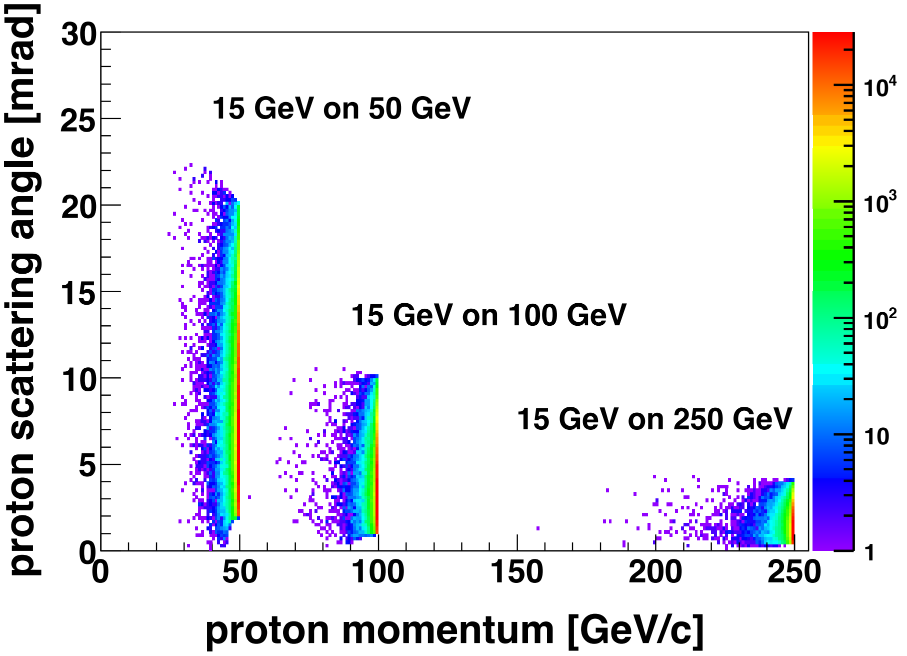
Follow-up Workshop: Warsaw (Poland), January 22-25 2019

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

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

https://events.ncbj.gov.pl/event/8/

Scattered Proton measurement



Remember, main detector is 35 mrad from beam line

→ so not seen in main detector

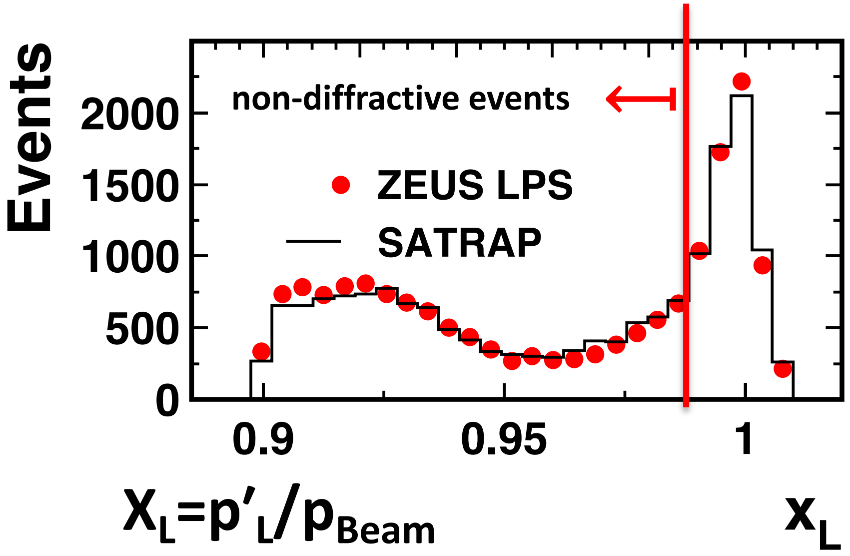
→ need different detection technology

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

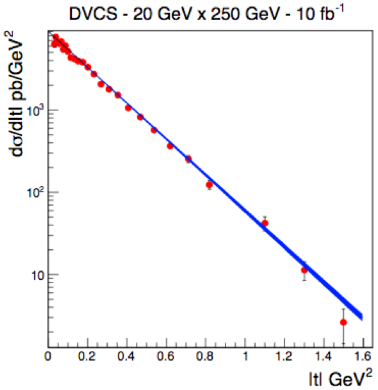
→ small p_T-acceptance limited by beam divergence and immittance

→ rule of thumb keep 10s between RP and beam

Impact of proton acceptance

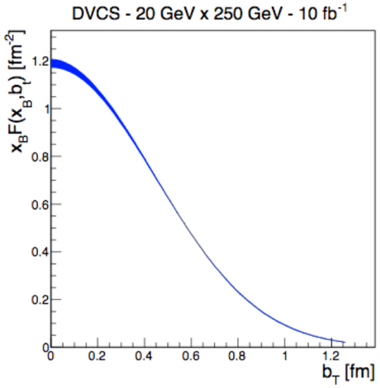
Measurement

Physics observable (cross-section vs impact parameter)



Plots from
EIC White Paper:

Fourier transform

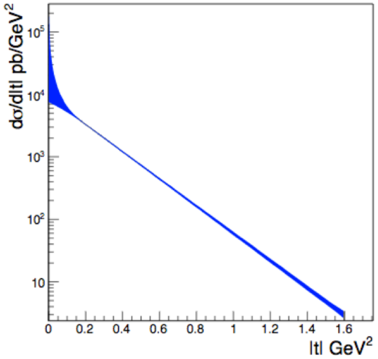


Requirement:

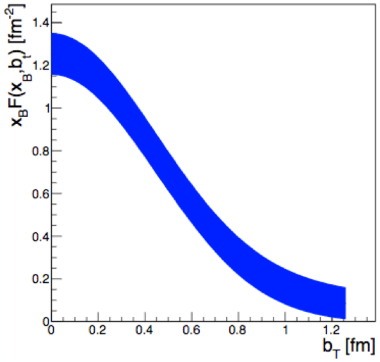
$\int L_{int}$=10fb^{-1}

$0.18 < p_t$ (GeV) < 1.3

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

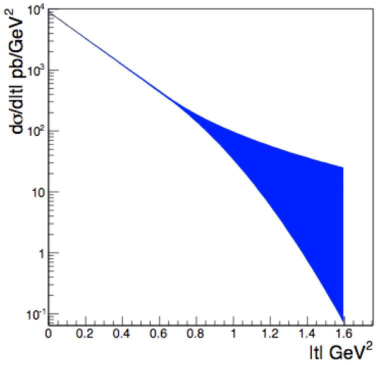


limited
lower
p_T-acceptance

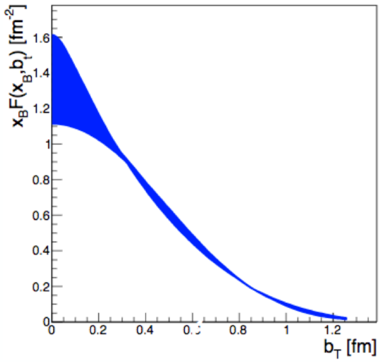


$\int L_{int}$=10fb^{-1}

$0.44 < p_T$(GeV) < 1.3



limited
higher
p_T-acceptance

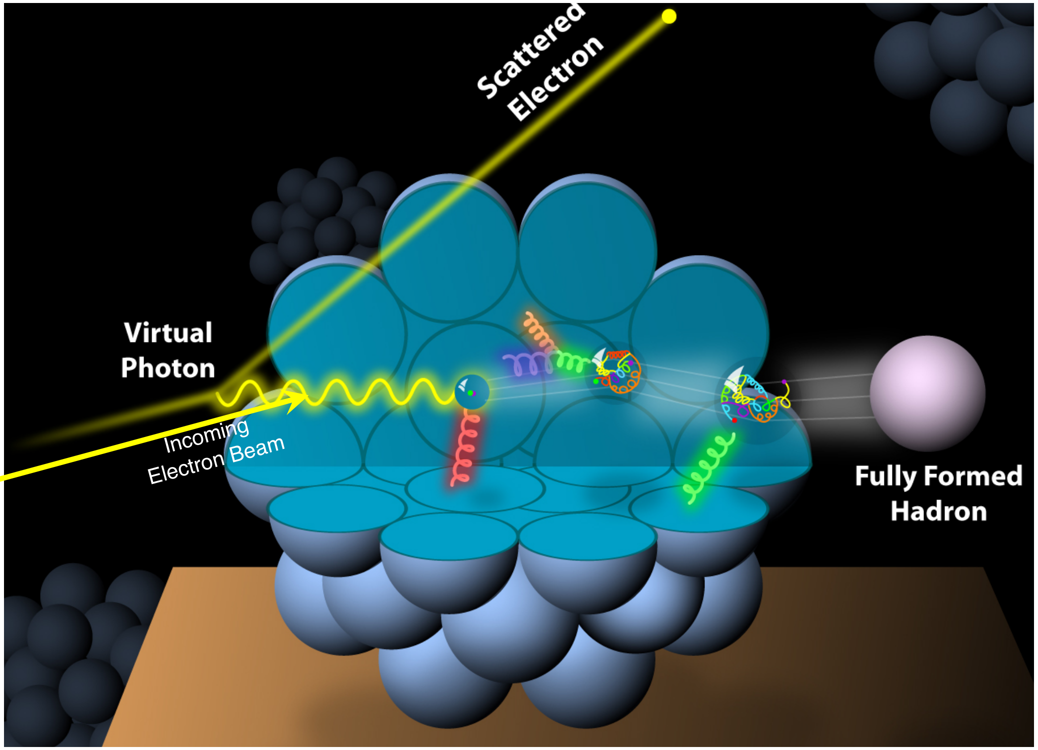


$\int L_{int}$=10fb^{-1}

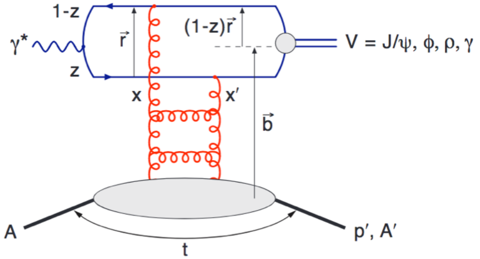
$0.18 < p_T$ (GeV) < 0.8

We need a proton spectrometer with large acceptance!

Nuclear PDFs and GPDs
an Electron-Ion Collider (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

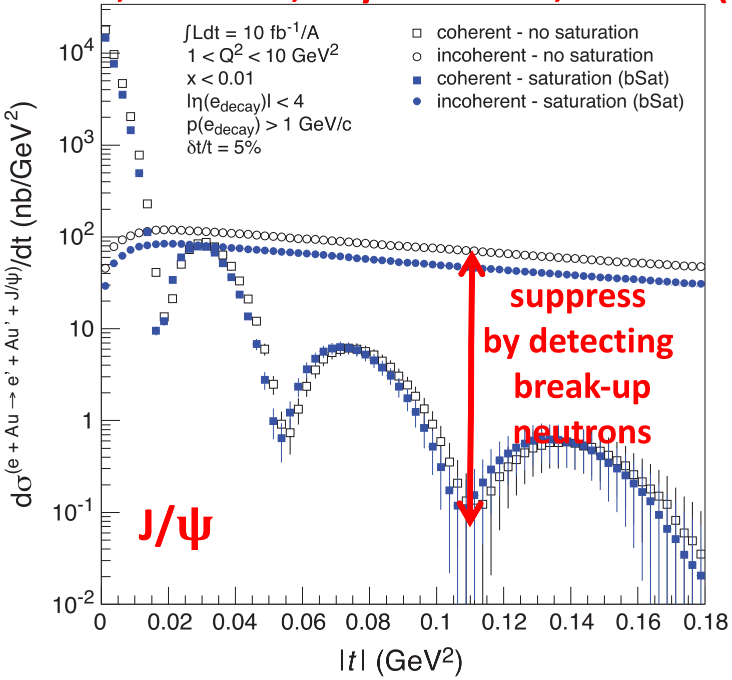
T. Toll, T. Ullrich, Phys.Rev. C87, 024913 (2013)

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, ...)

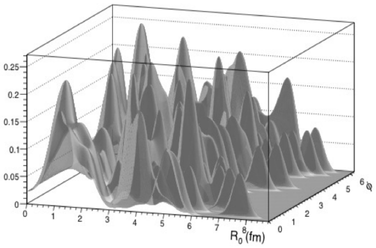


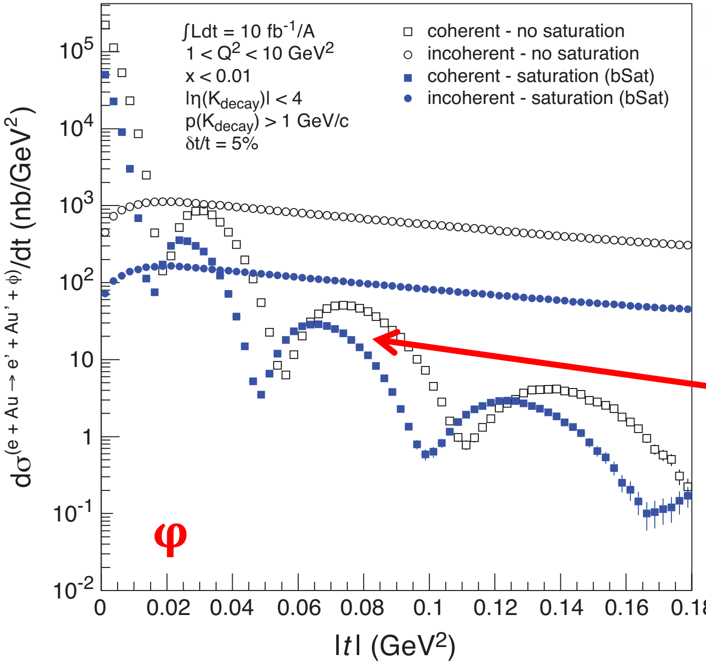
suppress by detecting break-up neutrons

Coherent requires forward scattered nucleus needs to stay intact

→ Veto breakup through neutron detection

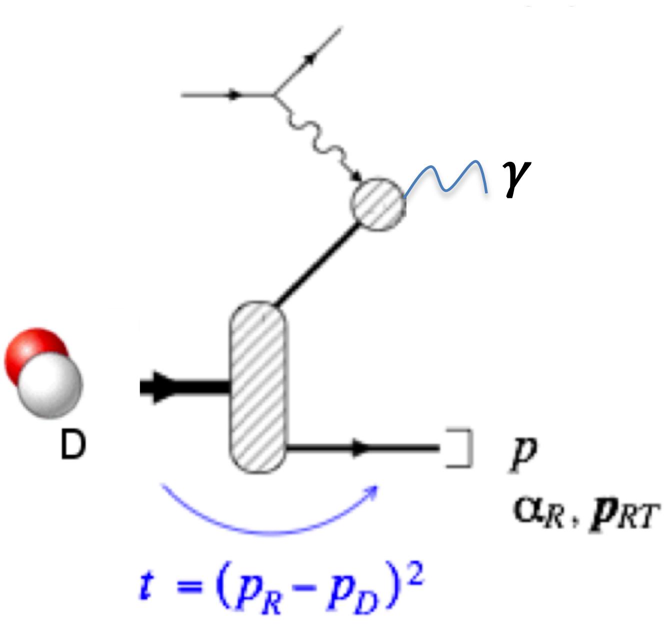
possible Source distribution with b_T^g = 2 GeV^{-2}





Sensitive to saturation effects!

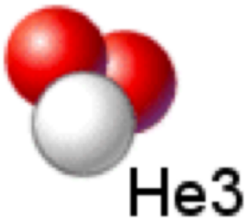
Measuring neutron via spectator tagging



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

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

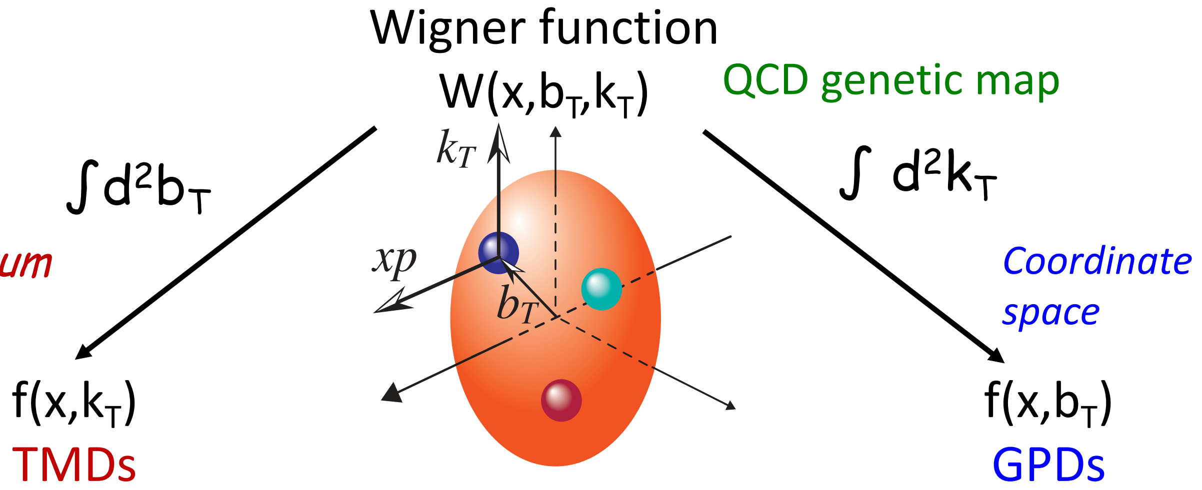
- **Tag DIS on a neutron (by the ZDC)**
- **Measure the recoil proton momentum**
- **The recoil proton momentum cone is**
  - $\alpha_R = (E_R + p_{R||})/(E_D + p_{D||})$ **and** p_{RT}
- Gives you a free neutron structure, not affected by final state interactions



Polarized He3 also experimentally easy, proton contributions cancel out!

Direct access to Wigner function

C. Van Hulse' Talk



Wigner function

$W(x,b_T,k_T)$

QCD genetic map

$\int d^2b_T$

Momentum space

$f(x,k_T)$

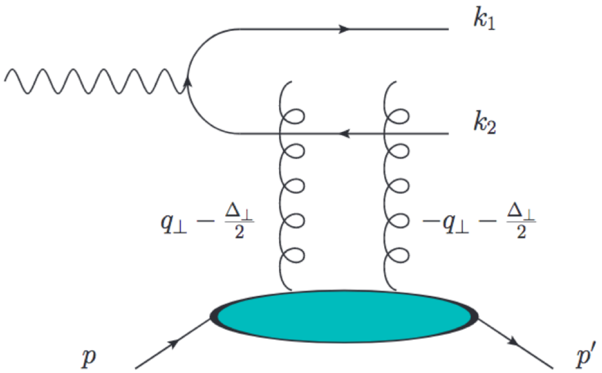
TMDs

$\int d^2k_T$

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 EIC physics beyond the W.P.!**
- **EIC impact studies still be done**

Summary on GPDs

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

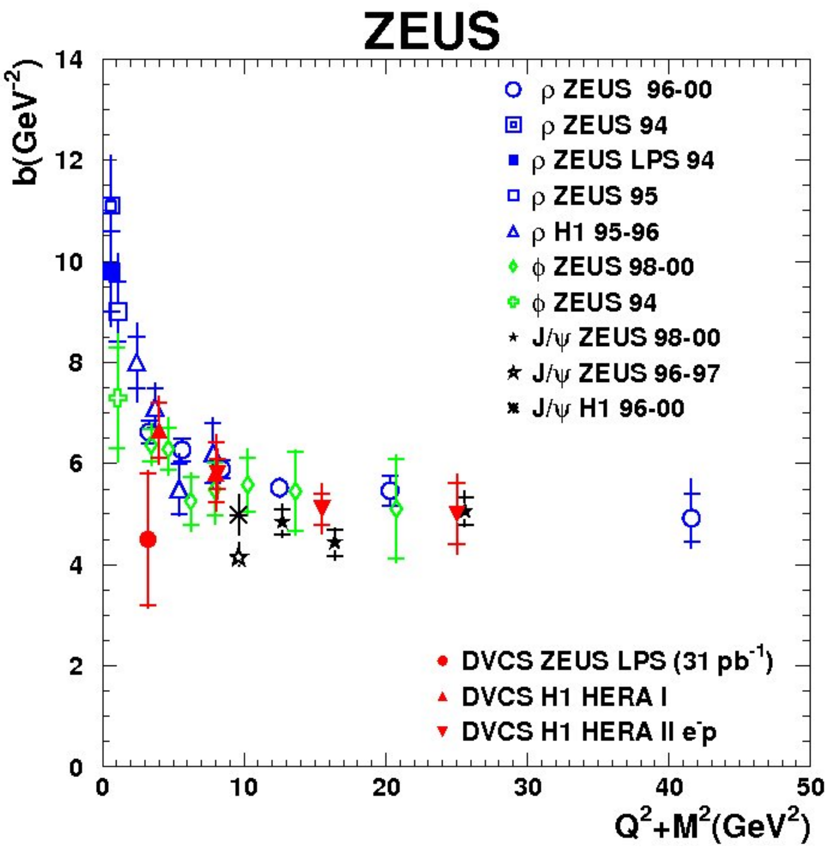
- Accurate 2+1D imaging of the polarized and unpolarized quarks and gluons inside the hadrons, and their correlations
- Investigate the proton-spin decomposition puzzle (orbital angular momentum

To do list

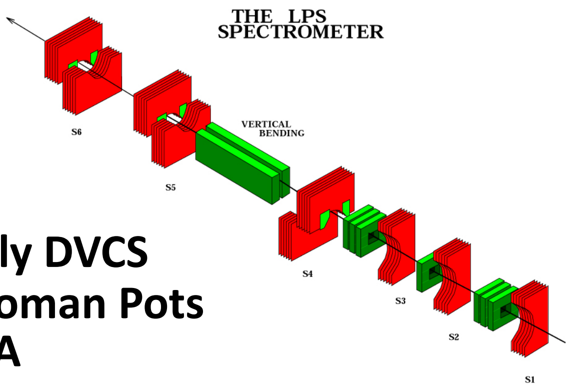
- Include VMP in global fits (flavor separation, precision on gluons)
- Study of GPDs in nuclei (and possible gluon saturation effects)
- Wigner fcn.

Back up

DVCS & VMPs at HERA



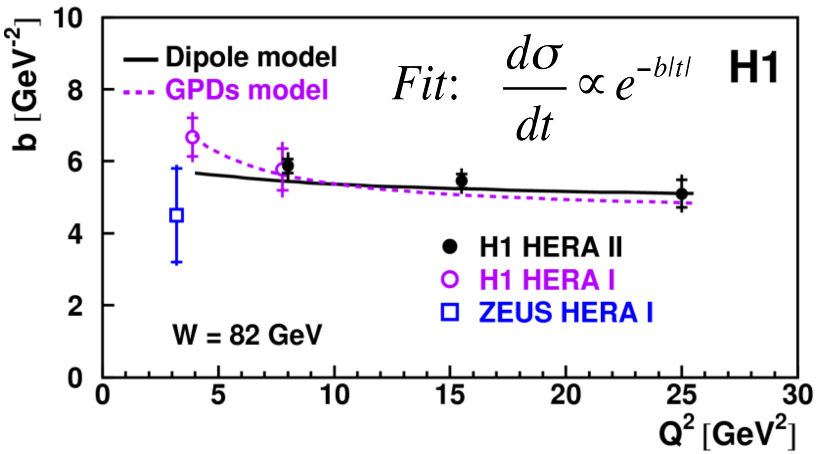
dσ/dt measured for the first time by a direct measurement of the outgoing proton 4-momentum using the Leading Proton Spectrometer (roman pots)



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

- **No p-dissociation background**
- **0.08 < |t| < 0.53 GeV²**
- **Low geometrical acceptance → low statistics**

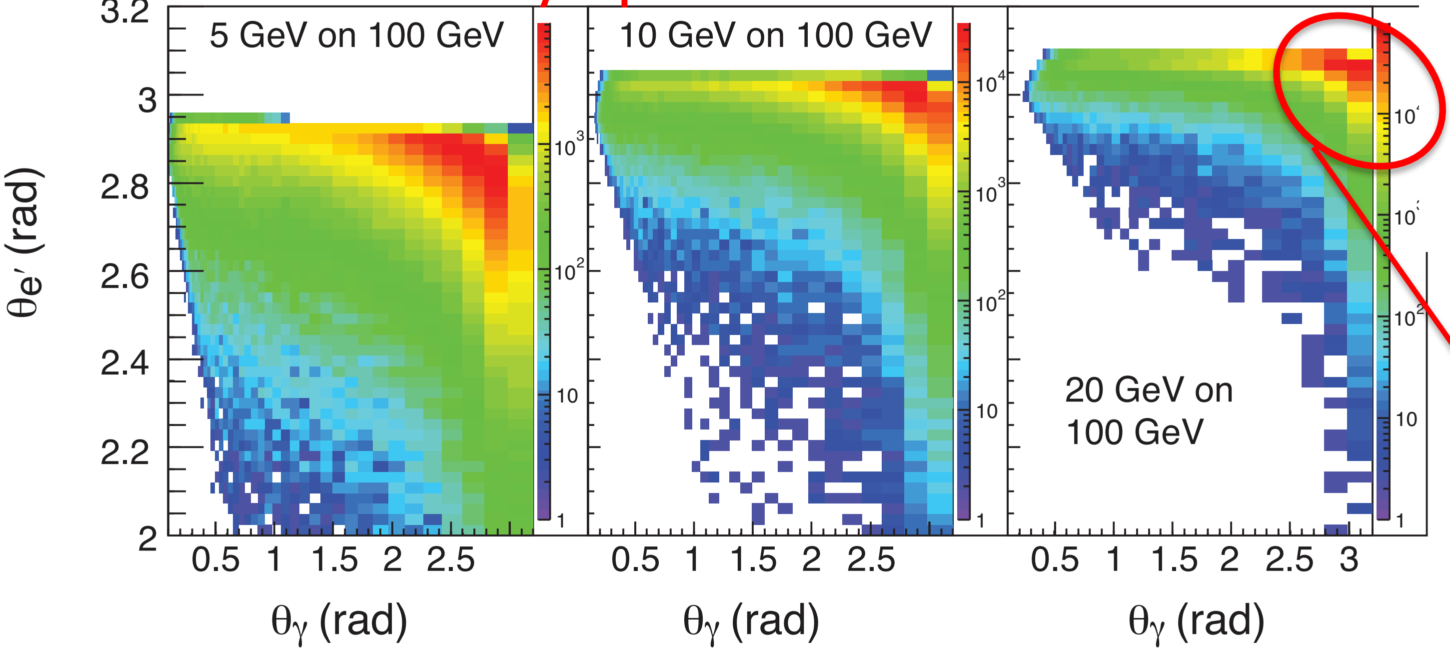
This detector was removed after the HERA II upgrade → $\mathcal{L}$ = 31 pb^{-1}

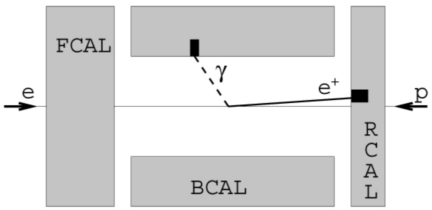


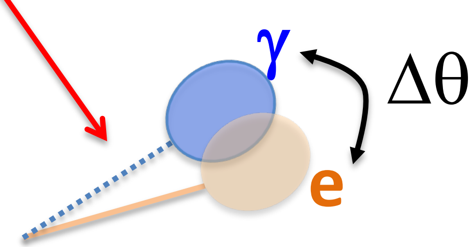
The ZEUS result still statistically compatible with H1, but hints for a flatter trend

DVCS – clusters separation in rapidity

Very important: hermetic tracker







N.B. - **Need for a emCAL with a very fine granularity, to distinguish clusters down to Δθ=1 deg**

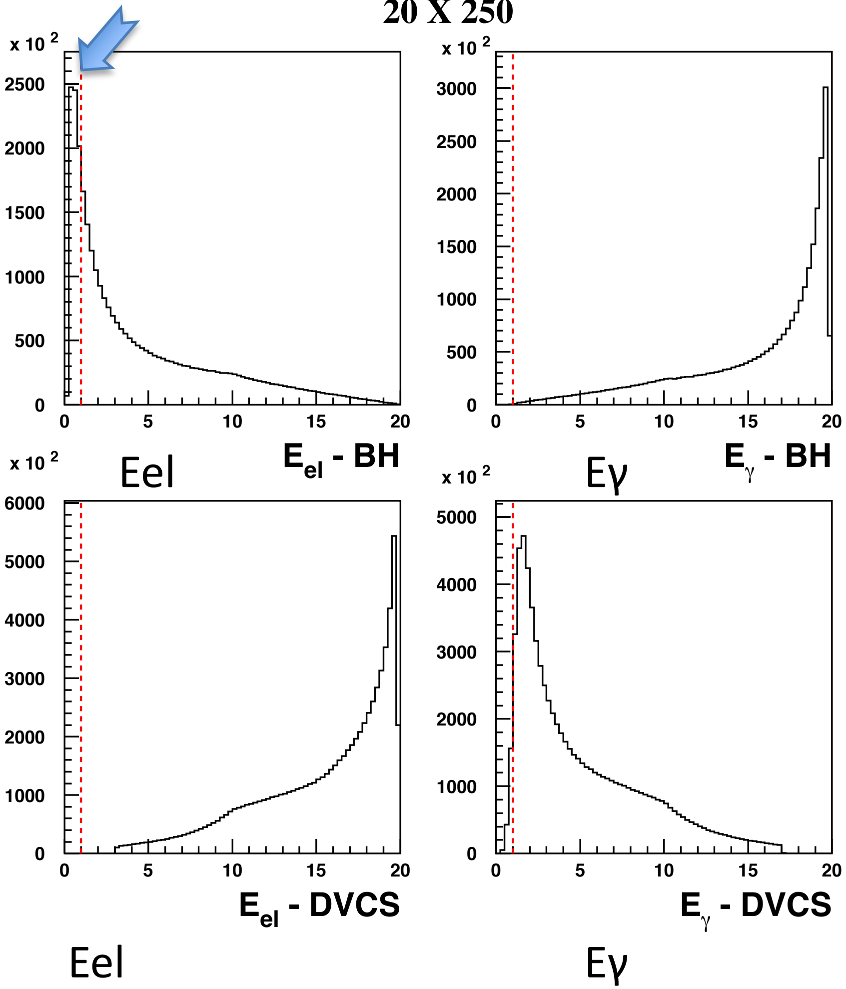
This is also important for Δϕ calculation in asymmetries measurement and for BH rejection in the xsec measurement

N.B. – when electron lies at a very small angle its track can be missing

A pre-shower calorimeter needed to control background from $\pi^0 \rightarrow \gamma\gamma$

BH suppression

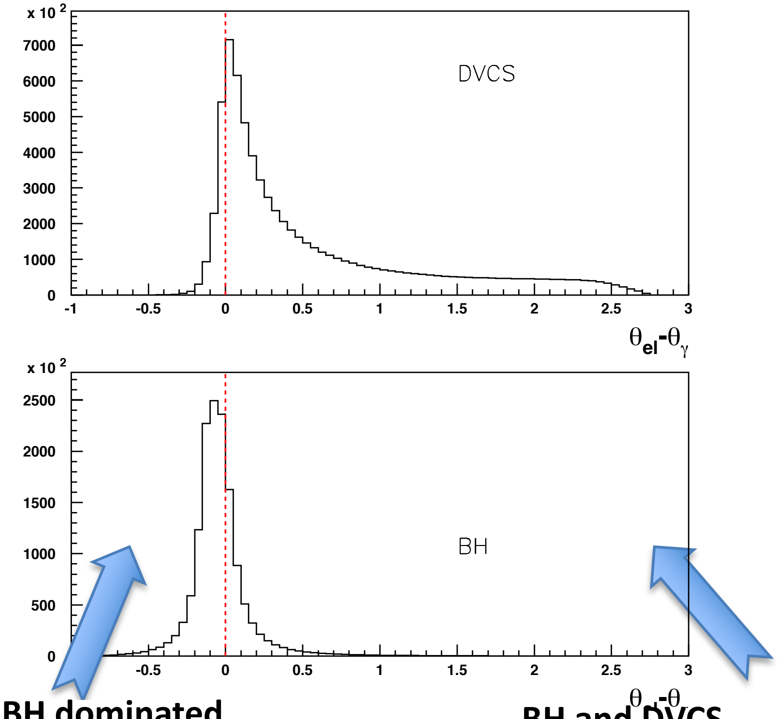
20 X 250



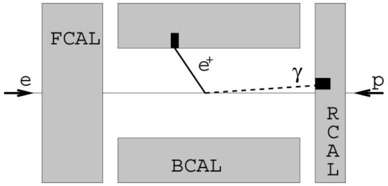
BH electron has very low energy (often below 1 GeV)

Important: em Cal must discriminate clusters above noise down to 1 GeV

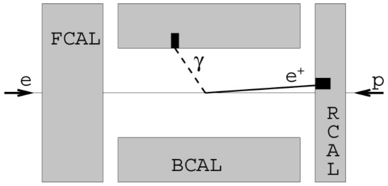
20 X 250



BH dominated



BH and DVCS



DVCS: most of the γ are less “rear” than e

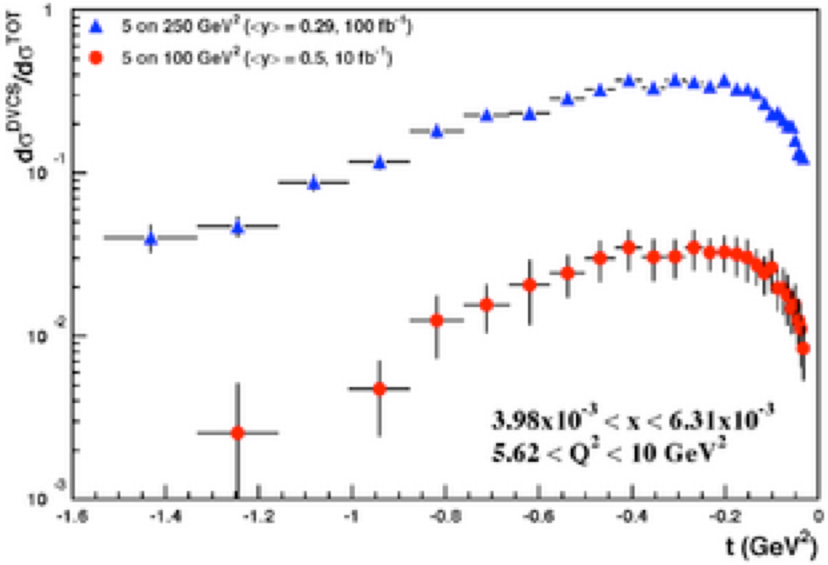
(θel-θγ) > 0 → rejects most of the BH

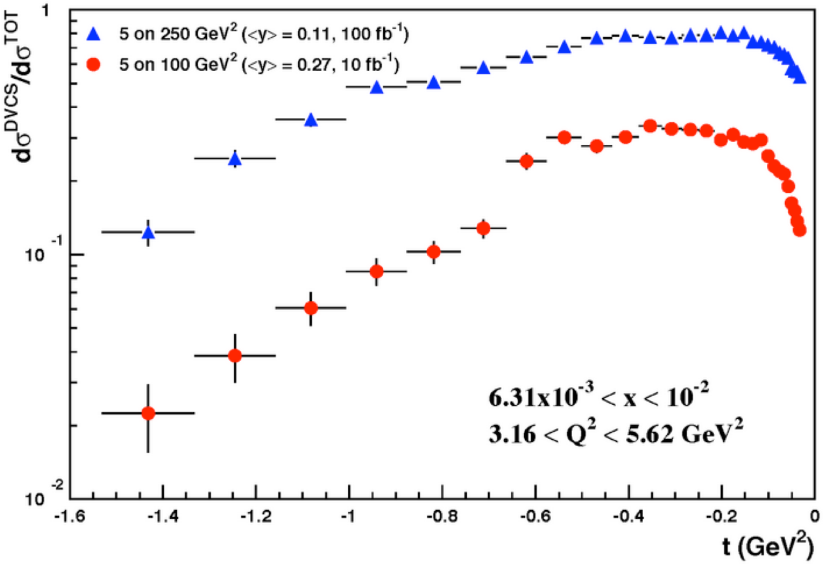
cuts keep BH below 60% of the sample even at large y > 0.5 – at high energies

Rosenbluth separation

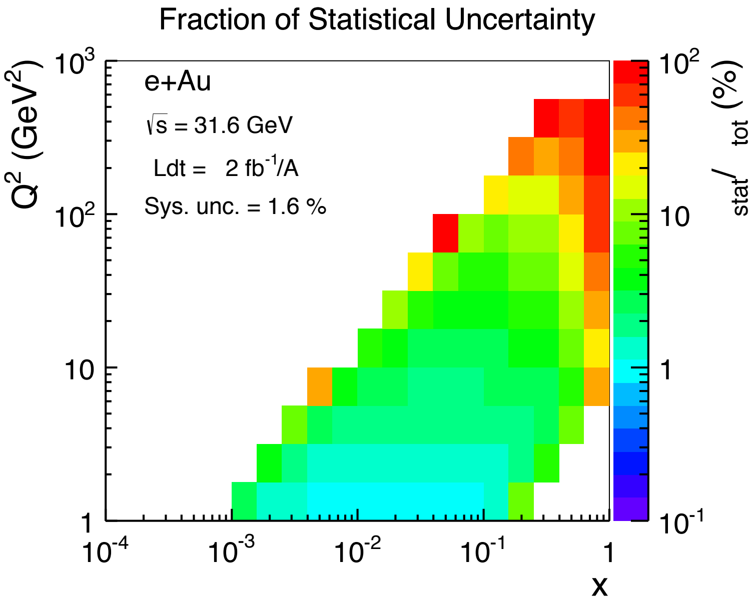
$$d\sigma = d\sigma_{DVCS} + d\sigma_{BH} + d\sigma_{INT}$$

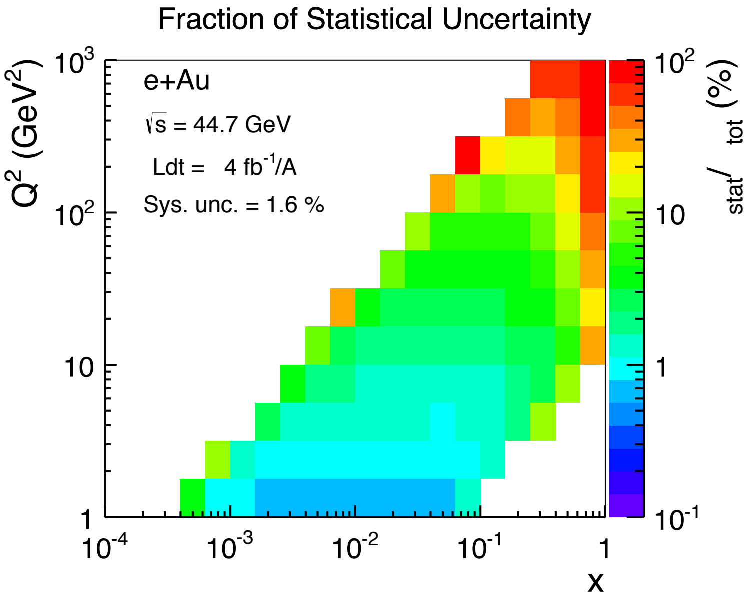
Rosenbluth separation of the electroproduction cross section into its parts

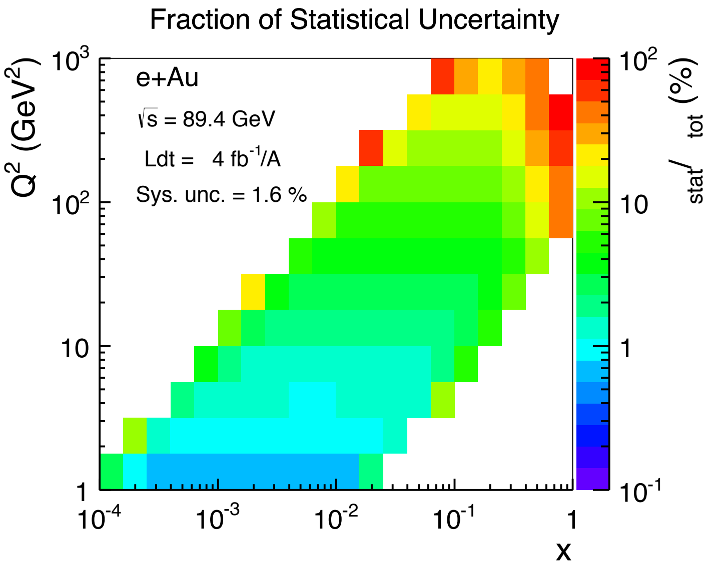




- The statistical uncertainties include all the selection criteria to suppress the BH
- exponential |t|-dependence assumed


Fraction of Statistical Uncertainty
e+Au
√s = 31.6 GeV
Ldt = 2 fb^{-1}/A
Sys. unc. = 1.6 %
Q^2 (GeV^2)
10^3
10^2
10
1
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x
10^2
10
1
10^{-1}
stat/ tot (%)


Fraction of Statistical Uncertainty
e+Au
√s = 44.7 GeV
Ldt = 4 fb^{-1}/A
Sys. unc. = 1.6 %
Q^2 (GeV^2)
10^3
10^2
10
1
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x
10^2
10
1
10^{-1}
stat/ tot (%)

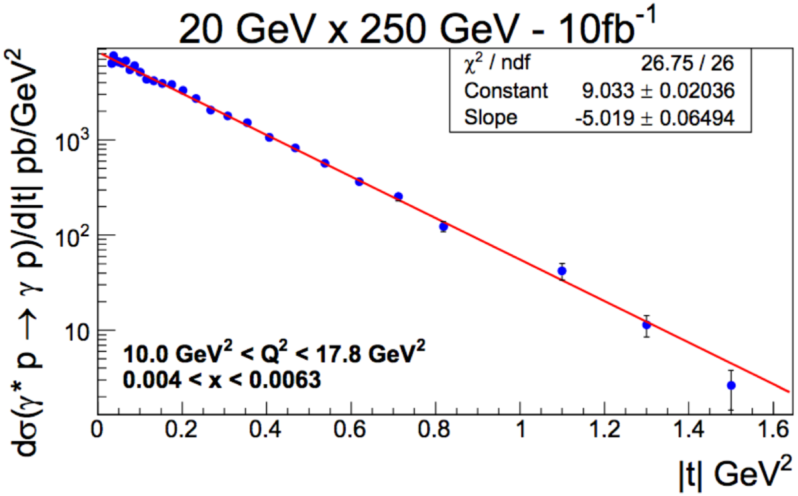

Fraction of Statistical Uncertainty
e+Au
√s = 89.4 GeV
Ldt = 4 fb^{-1}/A
Sys. unc. = 1.6 %
Q^2 (GeV^2)
10^3
10^2
10
1
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x
10^2
10
1
10^{-1}
stat/ tot (%)

Impact of collected luminosity

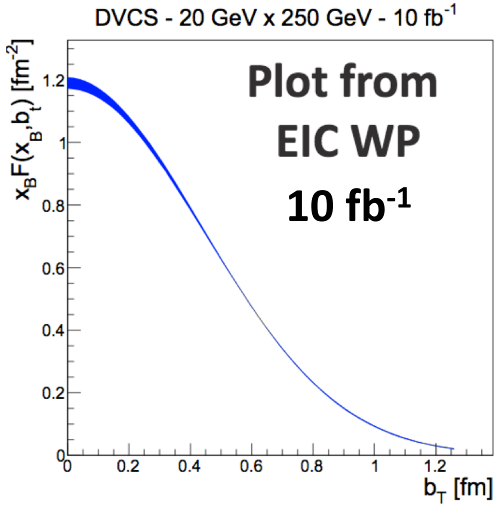
See also B. Mueller's talk

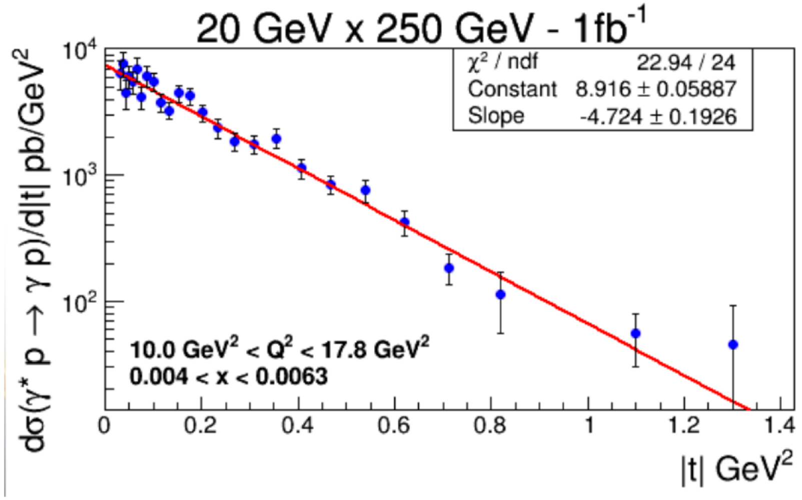
$0.18 < p_T < 1.3$ GeV

10 fb^{-1} → 1 fb^{-1}

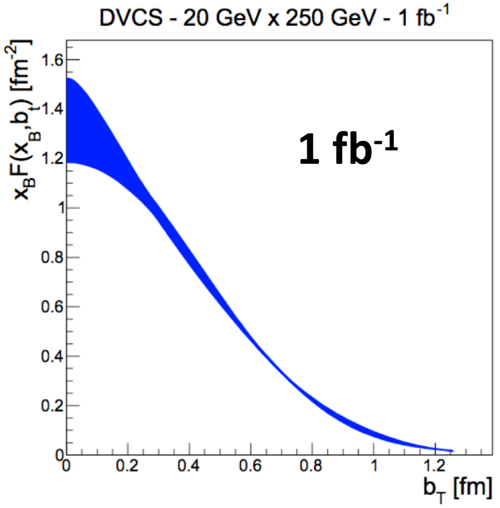


Fourier transform

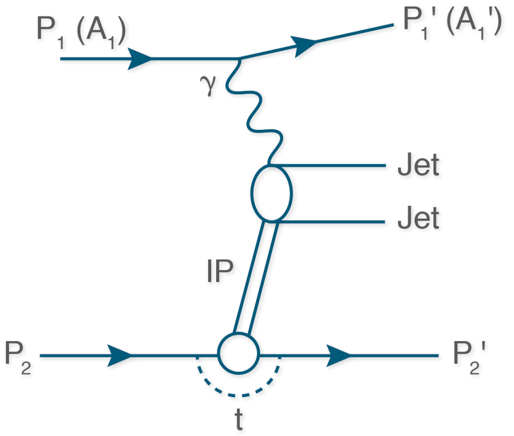




Fourier transform



Wigner function in UPC @ RHIC



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

Type of collisions: p+p, A+p (where the first p,A is the photon source)

Exclusivity requirements:

- Veto proton(nucleus) break up with RPs (ZDC)
- Use RPs to measure the scattered diffractive protons

LHC: C. Van Hulse' Talk

STAR @ RHIC:

→ ideal detector → large acceptance for low p_T di-jets (PRD**95**(2017)71103) + RPs

→ 2017 data: provides proof of principle

→ future **$p^{\uparrow}$+p RHIC runs** with upgrade of RP with curved edgeless sensors

→ factor of ~2 increase in acceptance

Estimated yield @ STAR: ~8000 events in p+p collisions at $\sqrt{s}$=510 GeV for a potential run 21/22 (Assumes RPs spectrometer upgrade)