DVCS and GPD extraction with EIC

Salvatore Fazio

Brookhaven National Lab

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BROOKHAVEN NATIONAL LABORATORY

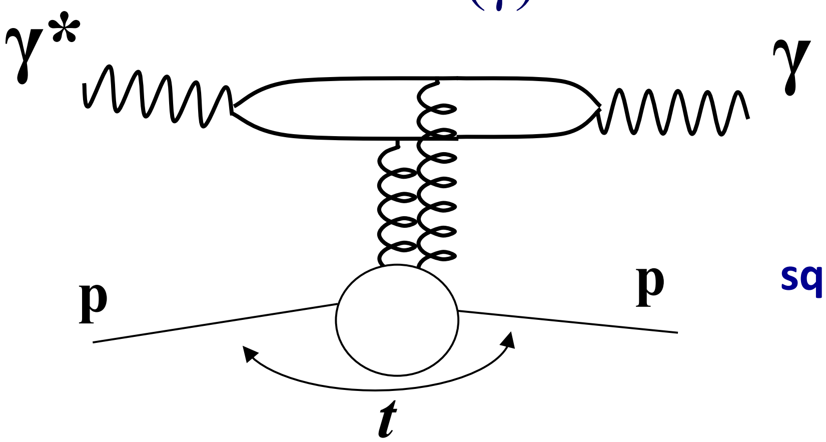
U.S. DEPARTMENT OF ENERGY | Office of Science

Plan of the talk

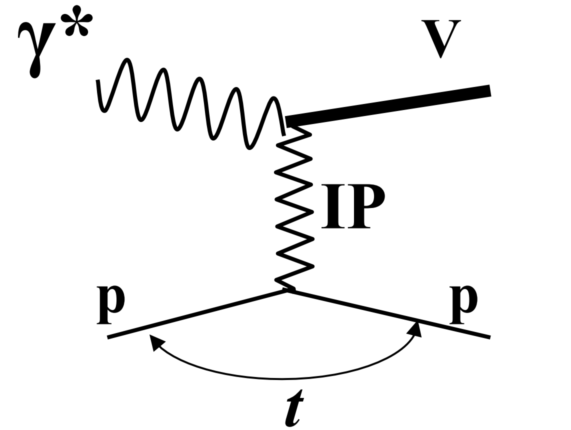
- Imaging with an EIC
- DVCS
  - Experimental techniques
  - Impact studies
- DVMP
- Nuclei (imaging, saturation)
- Summary

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

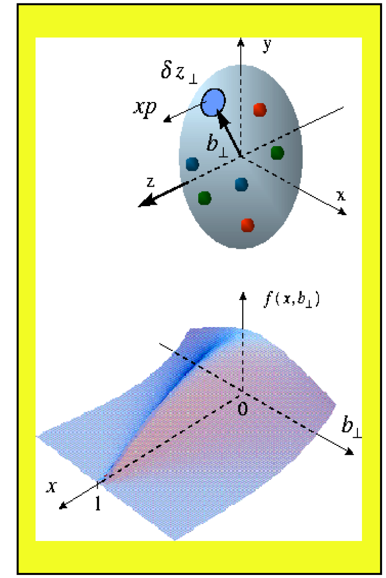
Alternative/complementary way to quark-flavor separation

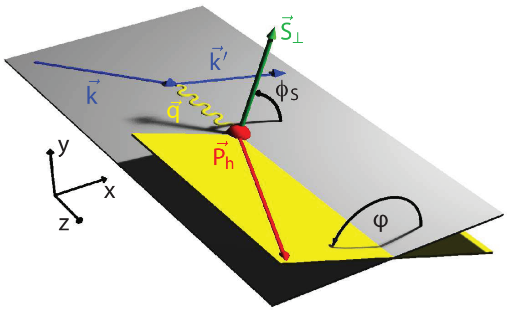
DVCS on a real neutron target → polarized Deuterium or He^3

Accessing the GPDs in exclusive processes

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

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

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

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

responsible for orbital angular momentum
a window to the SPIN physics

Spin-Sum-Rule in PRF:

from g_1

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

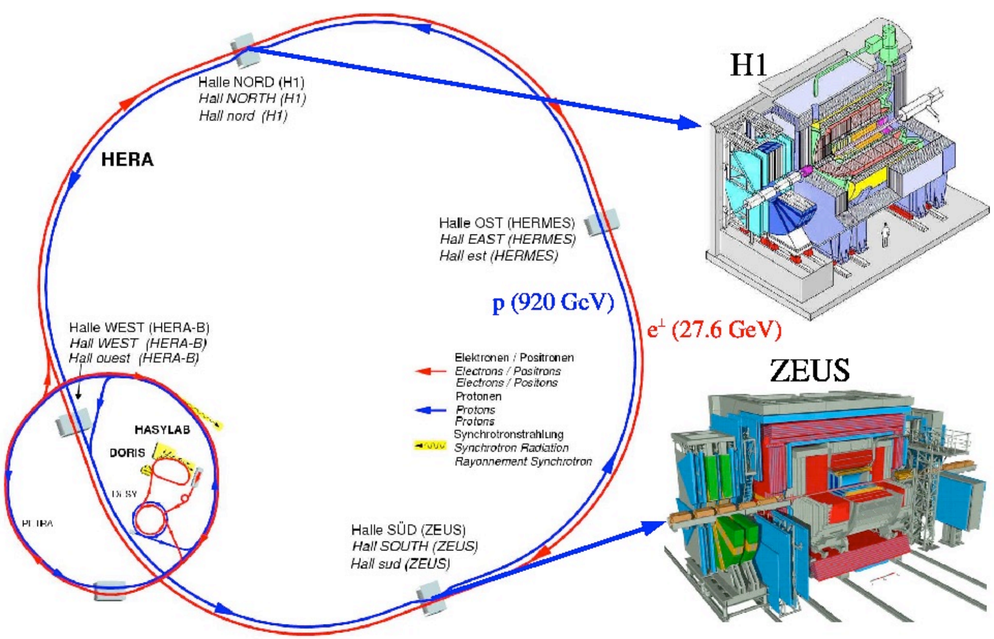
$$J_{q,g}^z = \frac{1}{2}\left(\int_{-1}^{1} x\,dx \left(H^{q,g} + E^{q,q} \right) \right)_{t \to 0}$$

The HERA Collider and experiments

- 27.5 GeV electrons/positrons on 920 GeV protons →$\sqrt{s}$=318 GeV
- 2 collider experiments: **H1 and ZEUS**
- HERA I: 16 pb^{-1} e-p, 120 pb^{-1} e+p
  HERA II (after lumi upgrade): 500 pb^{-1}, polarisation of e+,e-

- **Fixed target experiment**
- **Intense program on DVCS!**

Closed July 2007, still lot of excellent data to analyse…

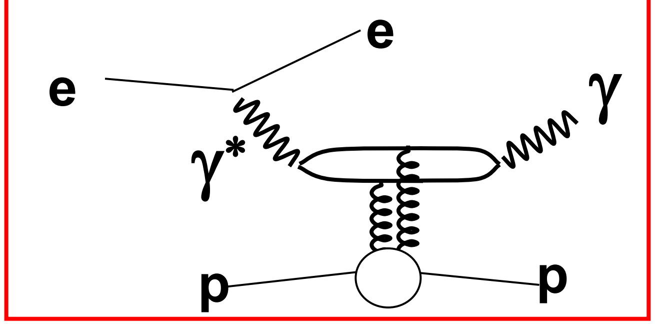


Detectors not originally designed for forward physics, but diffraction at HERA is great success story!

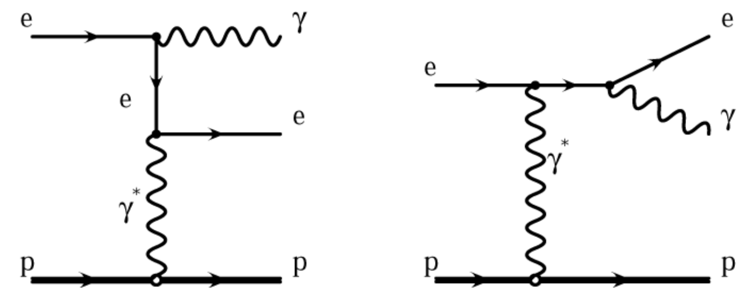
ZEUS forward instrumentation no longer available in HERA II

DVCS @ ZEUS - Strategy

DVCS

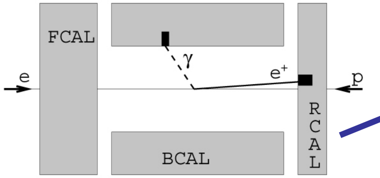


BH

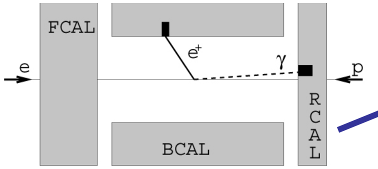


two electromagnetic candidates (ordered in energy) and up to one track

BH must be removed **[uncertainty on BH xsec ~ 3%]**



γ sample: no tracks matching to the second candidate — **Signal sample (DVCS+BH)**

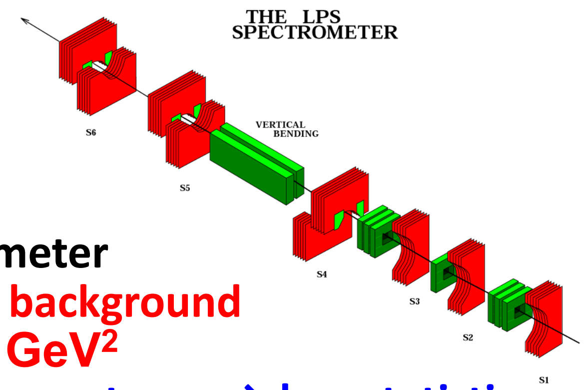


e sample: a track match to the second candidate — **Control sample (BH+ dilepton + J/ψ)**

Wrong-sign sample: a negative track match to the second candidate — **Control sample (dilepton + J/ψ)**

Kinematic region:
$1.5 < Q^2 < 100$ GeV^2
$40 < W < 170$ GeV

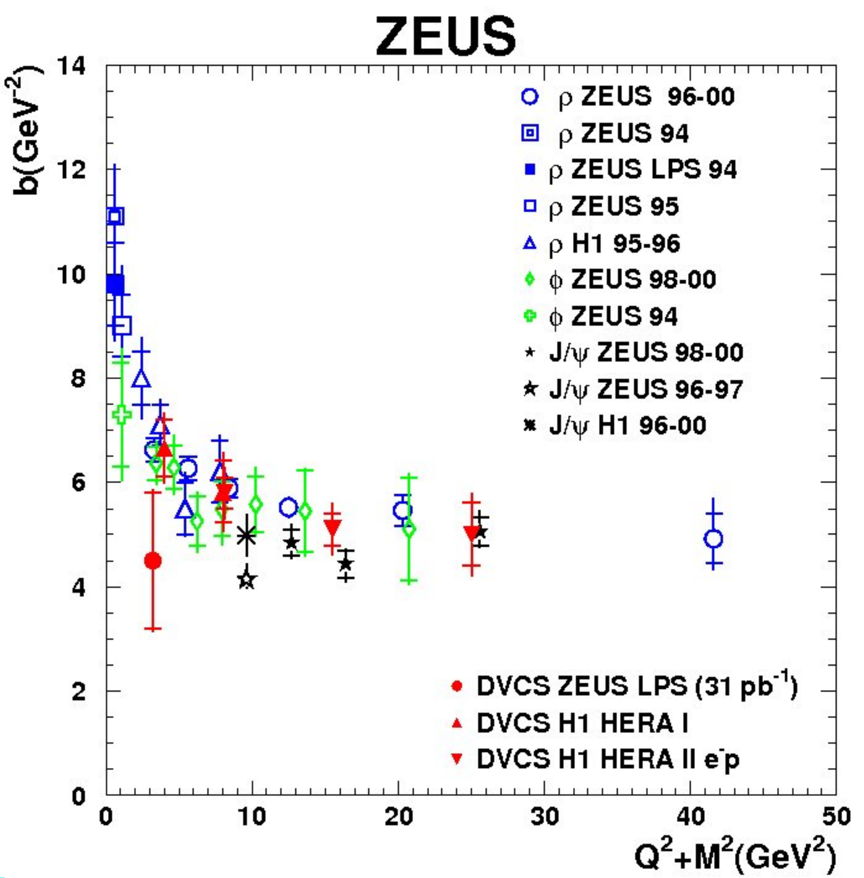
DVCS: *t* dependence – RPs



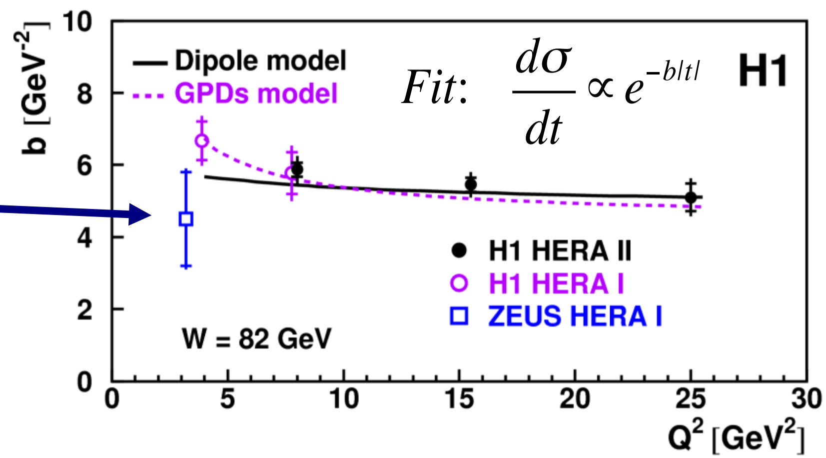
Roman Pots spectrometer

- 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}



direct measurement of the outgoing proton 4-momentum using the Leading Proton Spectrometer (roman pots)



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

Ingredients for a High Resolution “Femtoscope”

Large center-of-mass coverage:
Access to wide kinematic range in x and Q^2

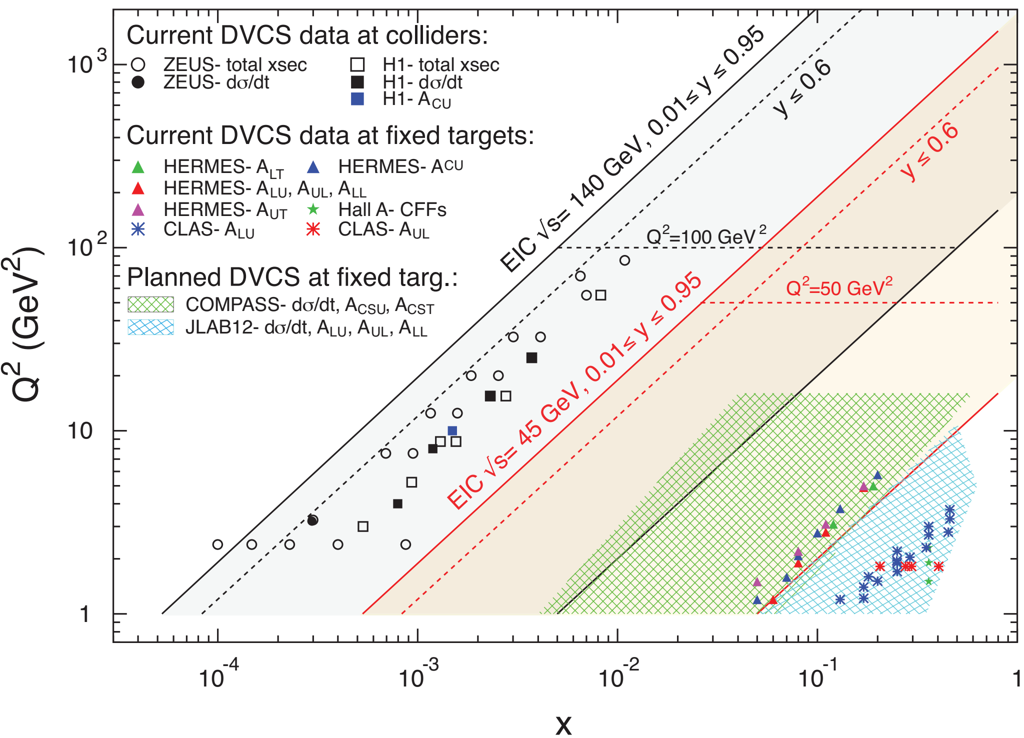
Polarized electron and hadron beams:
- access to spin structure of nucleons and nuclei
- Spin vehicle to access the 3D spatial and momentum structure of the nucleon
- Full specification of initial and final states to probe q-g structure of NN and NNN interaction in light nuclei

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 must be addressed by a future **Electron-Ion Collider**

DVCS at an EIC



HERA results limited by lack of statistics

EIC: the first machine to measure cross sections and asymmetries

✧ **EIC will provide sufficient luminosity to bin in multi-dimensions**

✧ **Wide x and Q^2 range needed to extract GPDs**

E.C. Aschenauer, S. F., K. Kumerički, D. Müller
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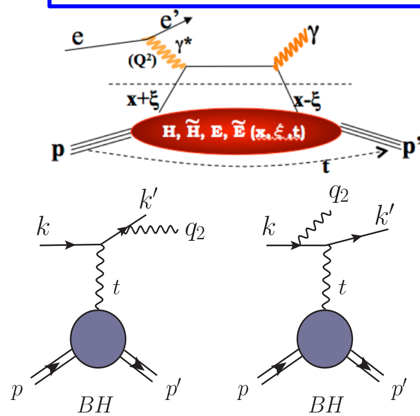


DVCS signal

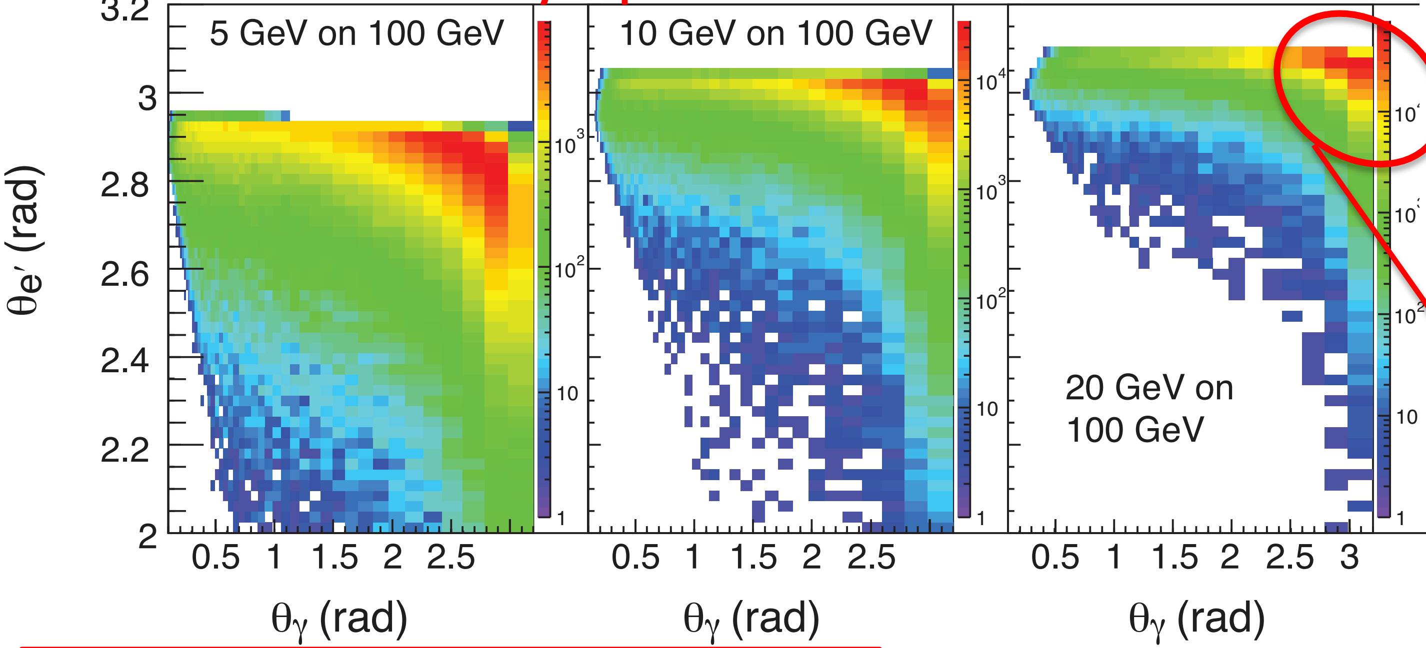
Bethe-Heitler QED bkgd.

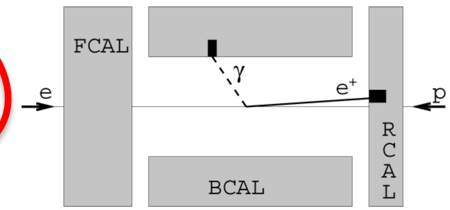
Comprehensive EIC studies

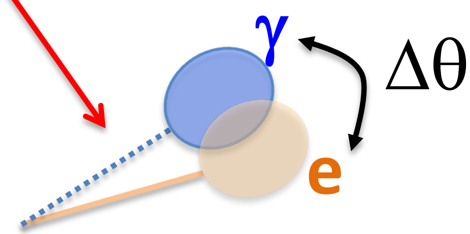
- **Signal extraction "a la HERA"**
- **xSec meas.: Specific requirements to suppress BH**
  → keep BH/sample below 60% at high energies
- **Radiative Corrections evaluated**
- **detector acceptance & smearing**
- **t-slope: b=5.6 compatible with H1 data**
- **|t|-binning is (3*resolution)**
- **5% systematic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

DVCS – clusters separation in rapidity

Very important: hermetic tracker







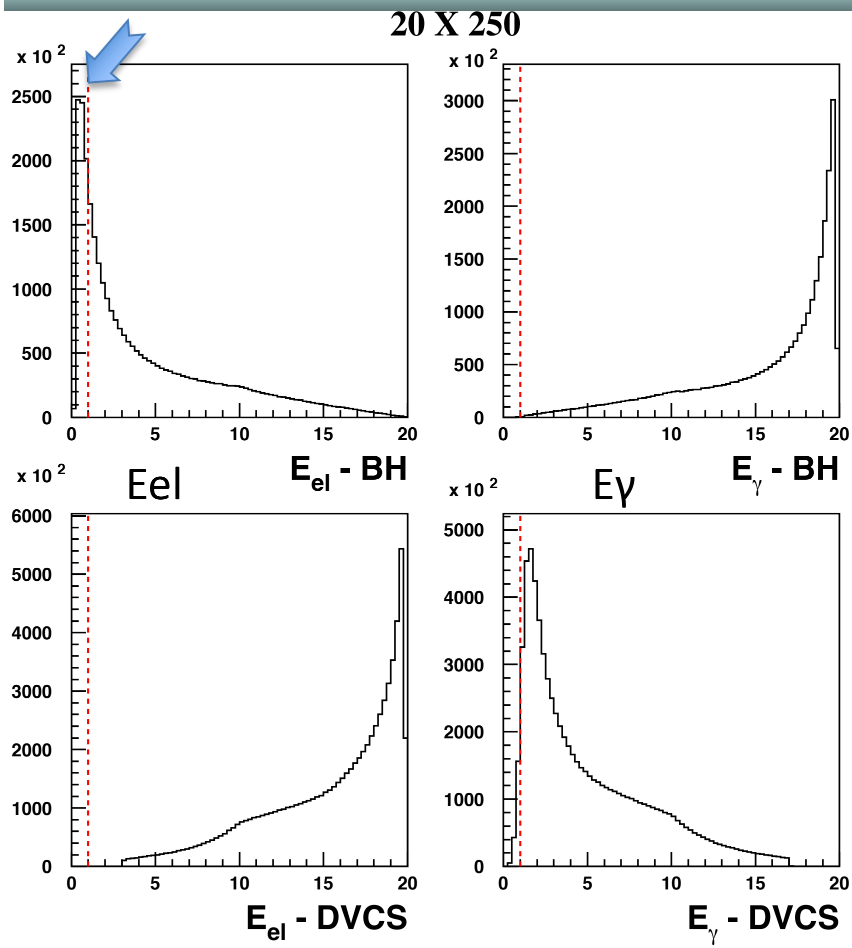
N.B. - Need for a emCAL with a very fine granularity, to distinguish clusters down to $\Delta\theta$=1 deg

This is also important for $\Delta\phi$ 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 $\pi^0 \rightarrow \gamma\gamma$

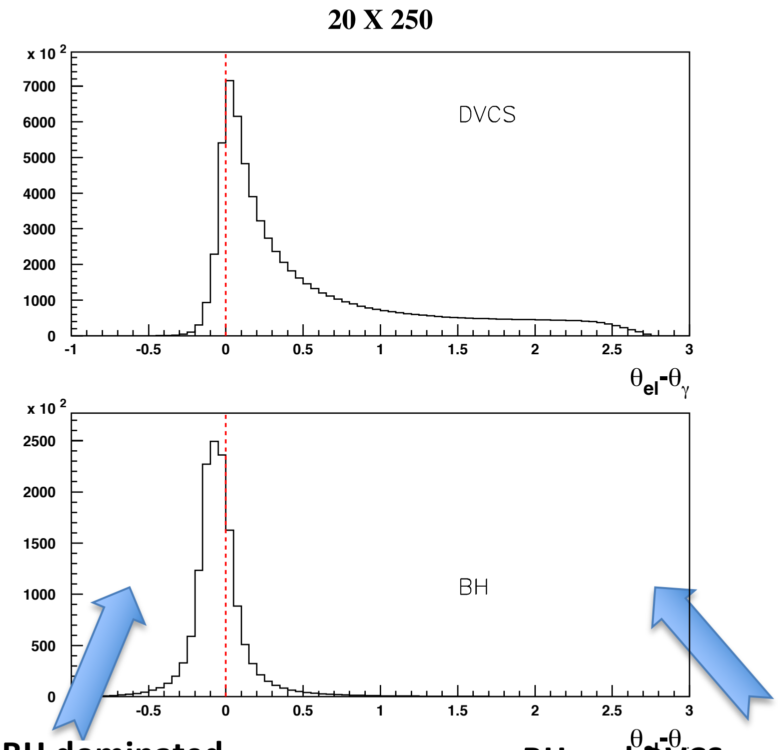
BH suppression



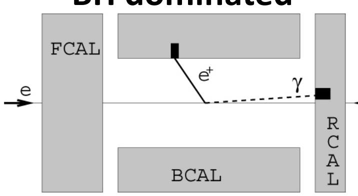
Eel

Eγ

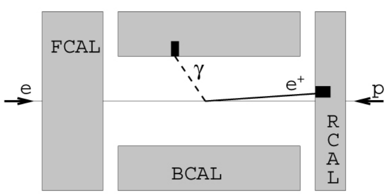
BH electron has very low energy (often below 1 GeV)



BH dominated



BH and DVCS

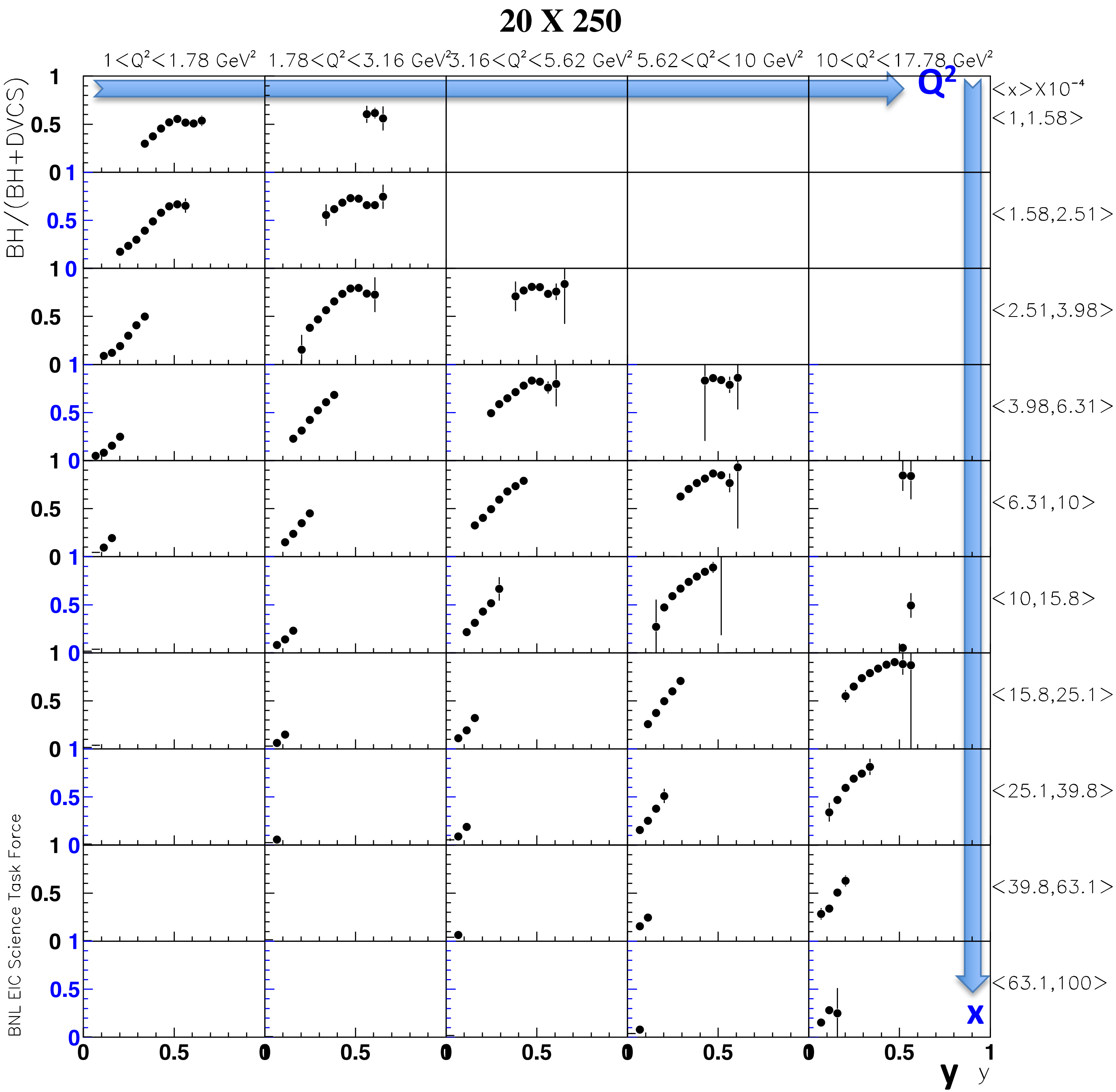


> **Important:** **em Cal must discriminate clusters above noise down to 1 GeV**

DVCS: most of the γ are less "rear" than e ($\theta_{el}-\theta_\gamma$) > 0 → rejects most of the BH

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

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

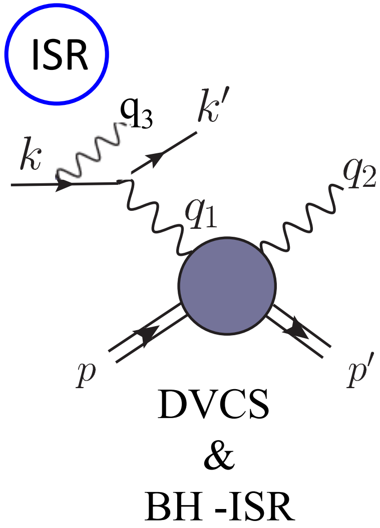
BH subtraction will be relevant at lower energies and large y, in some of the x-Q^2 bin

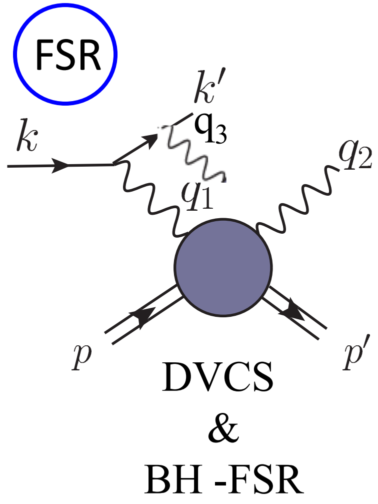
BUT…

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

Radiative effects





Initial State Radiation (ISR):

photon collinear to the incoming beam and goes down the beam line

→ this contribution can only be estimated via MC

→ this causes a correction of the kinematics (x and Q^2) and some systematic uncertainty

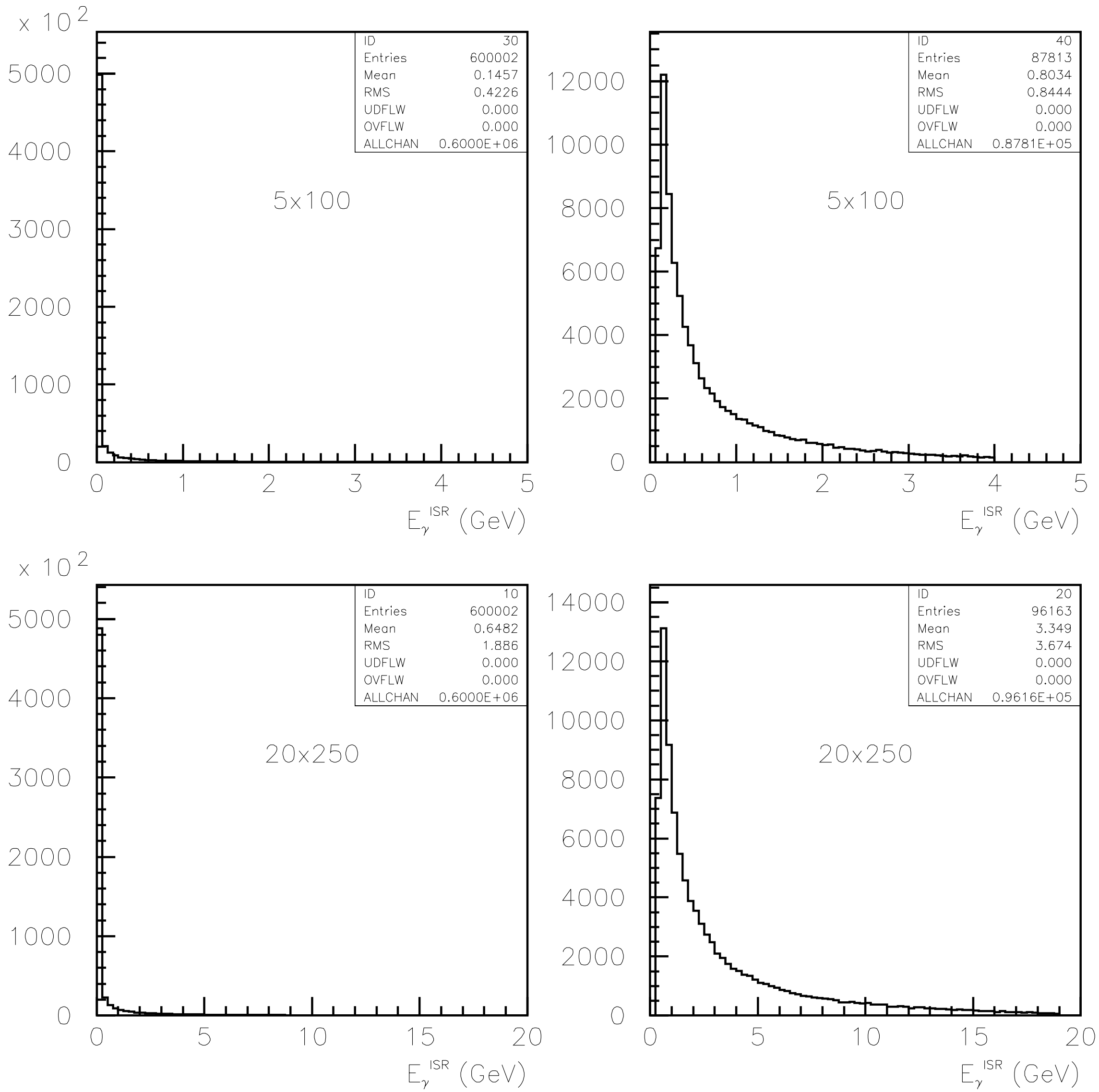
→ **EIC: ONLY 15% of the events radiate a photon with > 2% energy of the incoming electron Independentely of C.o.M energy and Q^2 (see back up slide)**

Final State Radiation (FSR):

photon collinear to the outgoing scattered lepton

- if lepton is band only little in magnetic field, EM-cluster of photon and lepton collapse to one
  - → no contribution (total electron energy measured correctly)
- if photon and lepton are separated enough in magnetic field, it leads to 3 EM-clusters in event
  - → no contribution (event will not pass DVCS selection criteria)

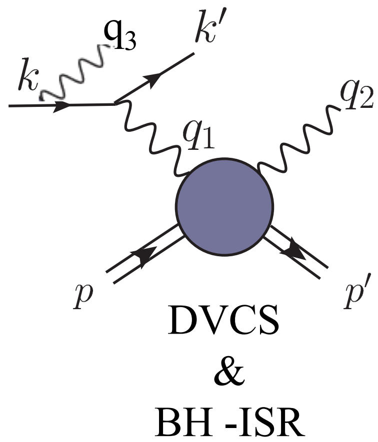
Contribution from ISR



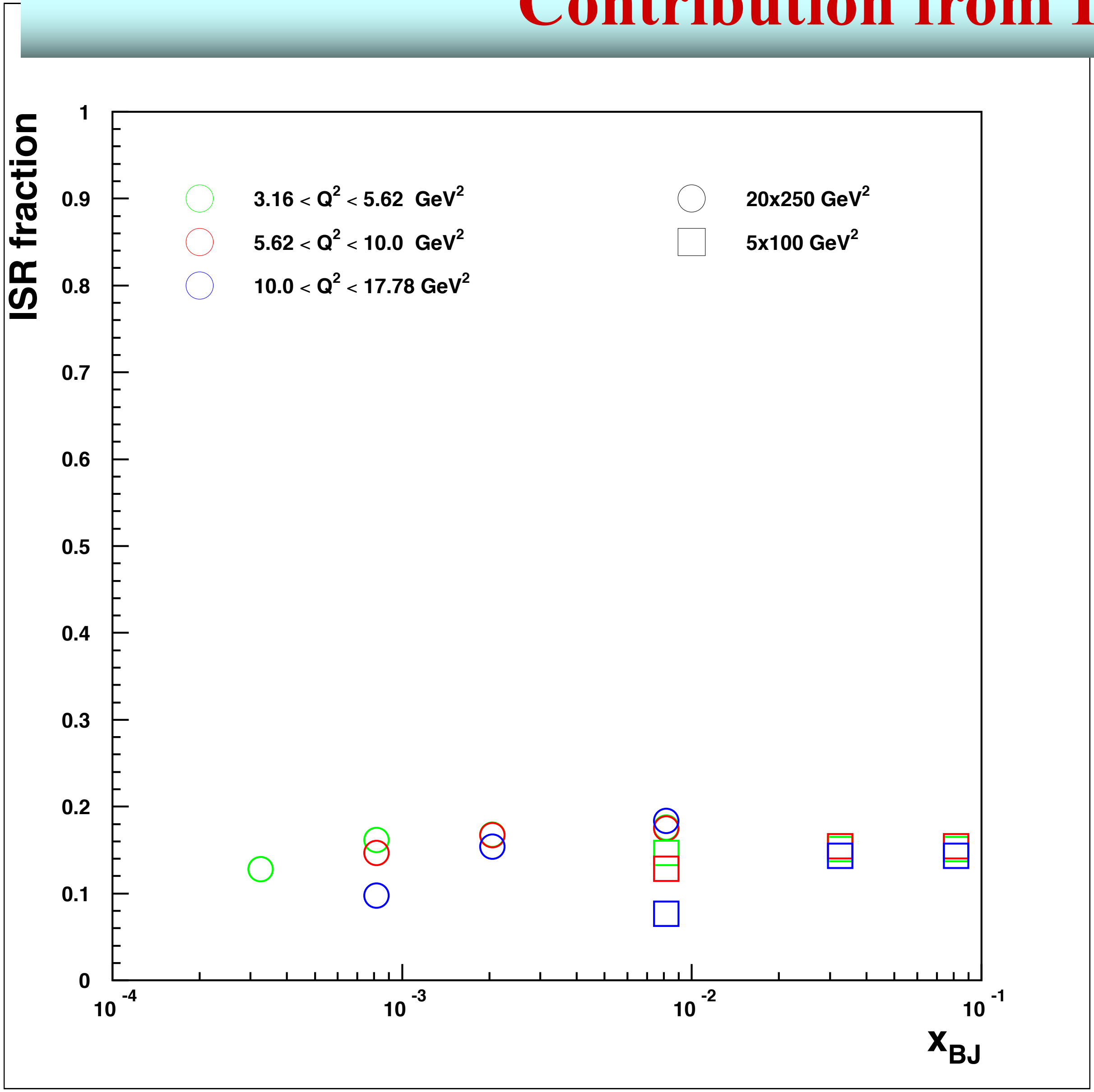
the energy spectrum of the emitted ISR photon for two different EIC beam energy combinations.

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.



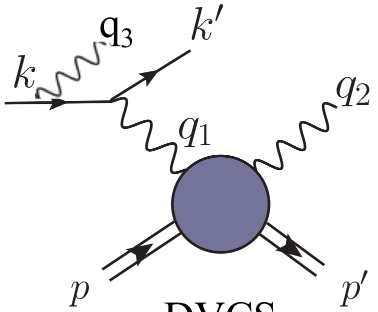
Contribution from ISR



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

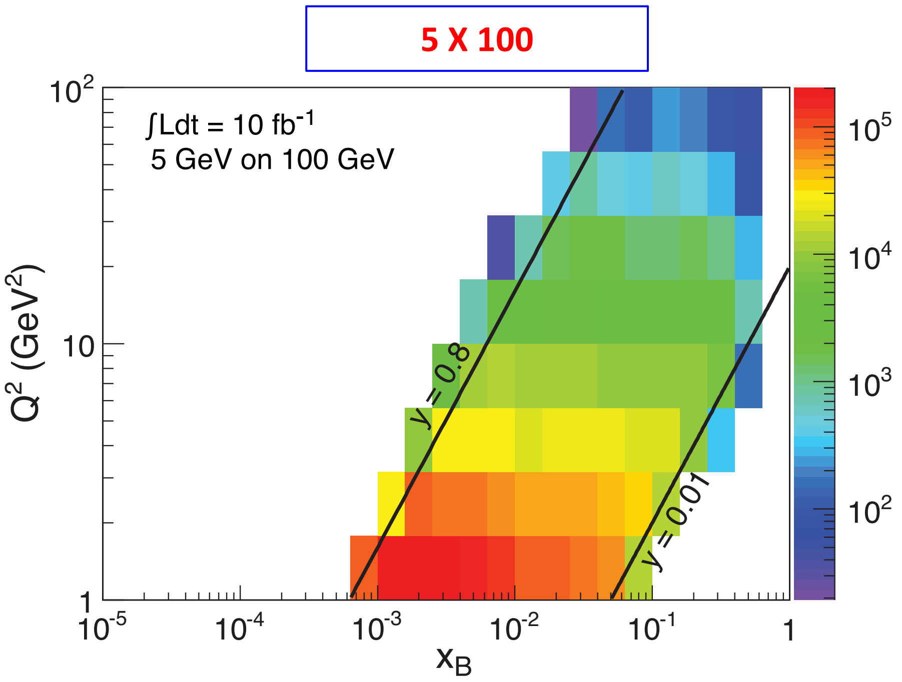
ISR photons with **$E_\gamma < 0.02\ E_e$** do not result in a significant correction for the event kinematics.

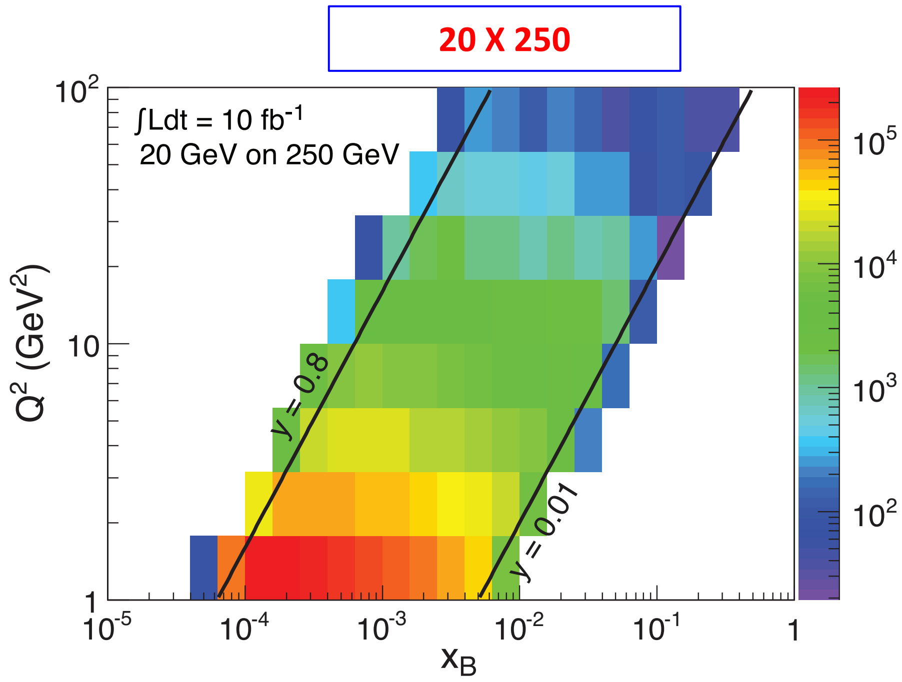


DVCS & BH -ISR

DVCS at a high luminosity collider

- ✧ **EIC will provide sufficient lumi to bin in multi-dimensions**
- ✧ **wide x and Q^2 range needed to extract GPDs**





… we can do a fine binning in Q2 and W… and even in |t|

Data simulation & event selection

Acceptance criteria

- for Roman pots: 0.03< |t| < 0.88 GeV^2
- for |t| > 1GeV2 detect recoil proton in main detector
- 0.01 < y < 0.85 GeV^2
- η < 5

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]

0.01 < |t| < 0.85 GeV^2

(Low-|t| sample)

- **Very high statistics**
- **Systematics will dominate!**
- **Within Roman pots acceptance**

1.0 < |t| < 1.5 GeV^2

(Large-|t| sample)

- **Xsec goes down exponentially**
- **requires much longer data taking**

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

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

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

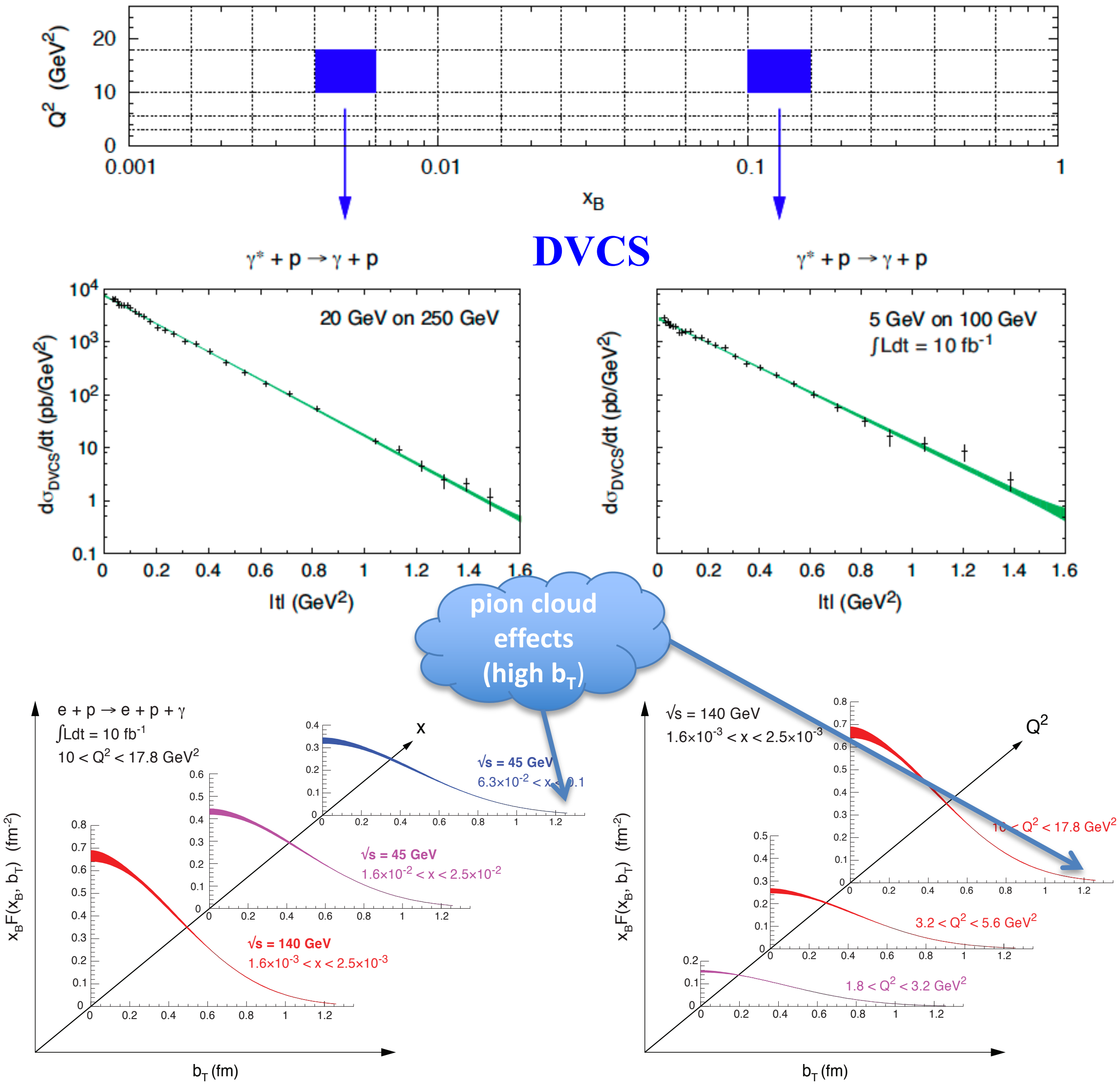
➢ Systematic uncertainty assumed to be ~5% (having in mind experience from HERA)

➢ Overall systematic uncertainty from luminosity measurement not taken into account

5 X 100 GeV → **10 fb^{-1}**

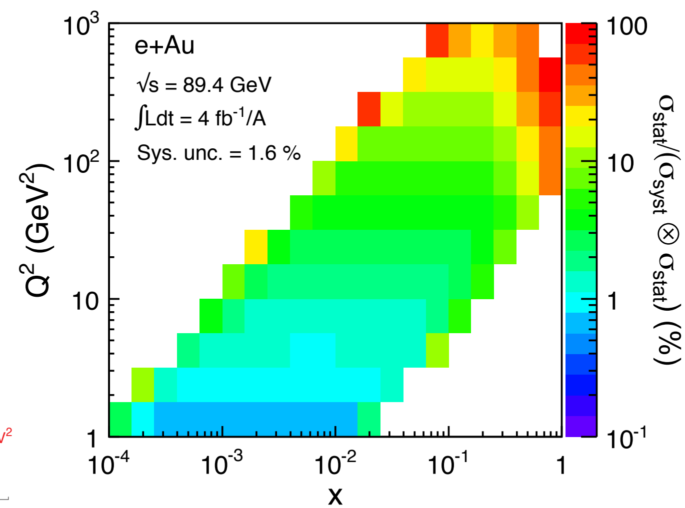
20 X 250 GeV → **10 fb^{-1}**

DVCS & J/ψ differential cross section



Luminosity: 10 fb^{-1}

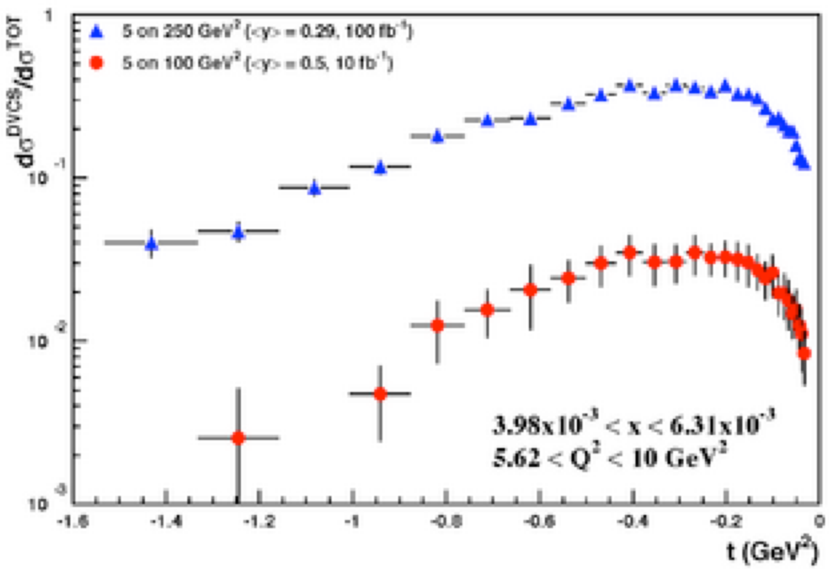
- **Measurement dominated by systematics**
- Fourier transf. of dσ/dt → partonic profiles

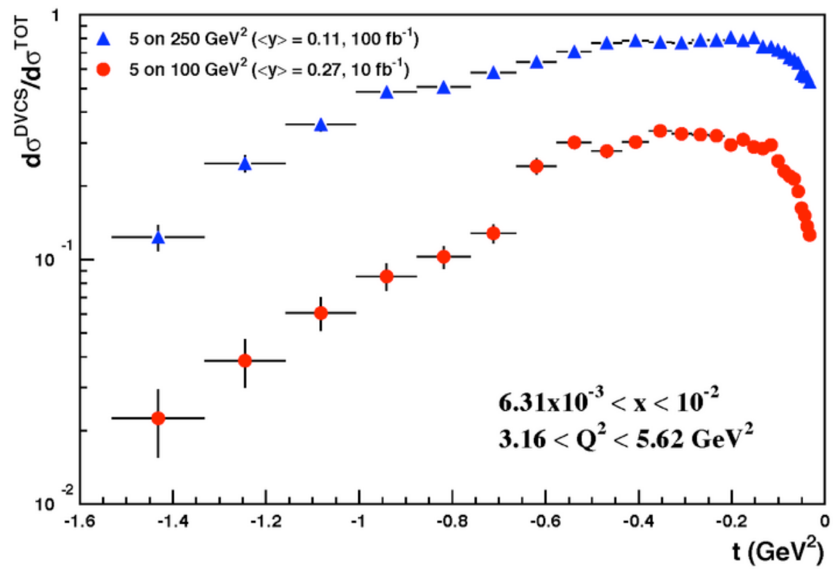


Rosenbluth separation

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

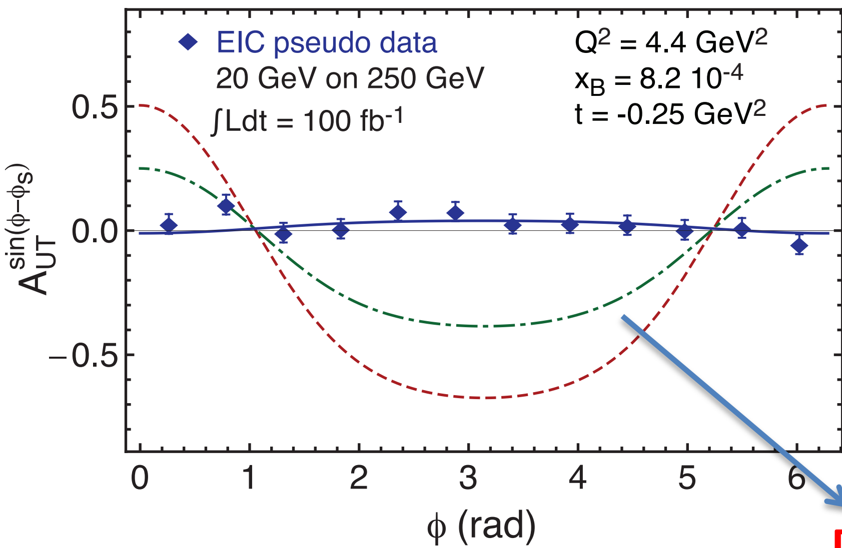
Rosenbluth separation of the electroproduction cross section into its parts

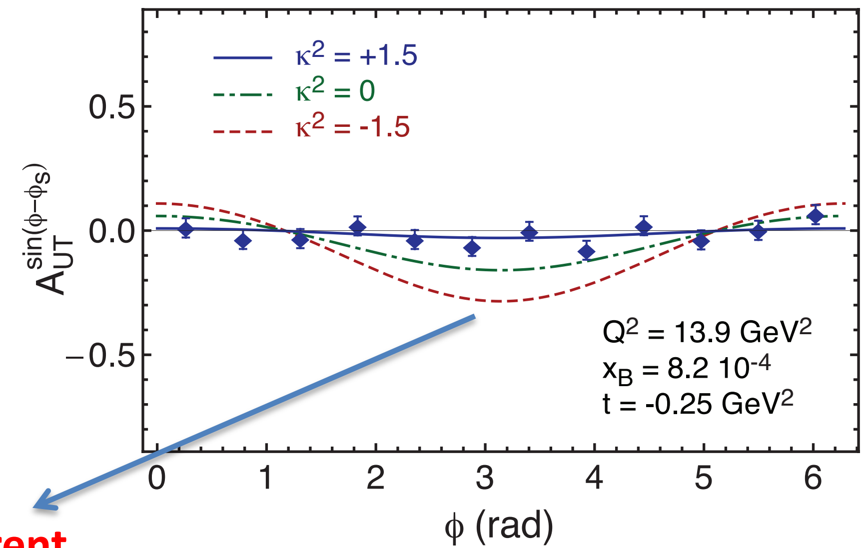




- The statistical uncertainties include all the selection criteria to suppress the BH
- exponential |t|-dependence assumed

Transverse target-spin asymmetry





Different assumptions for E

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

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

Spin-Sum-Rule in PRF: from g_1

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

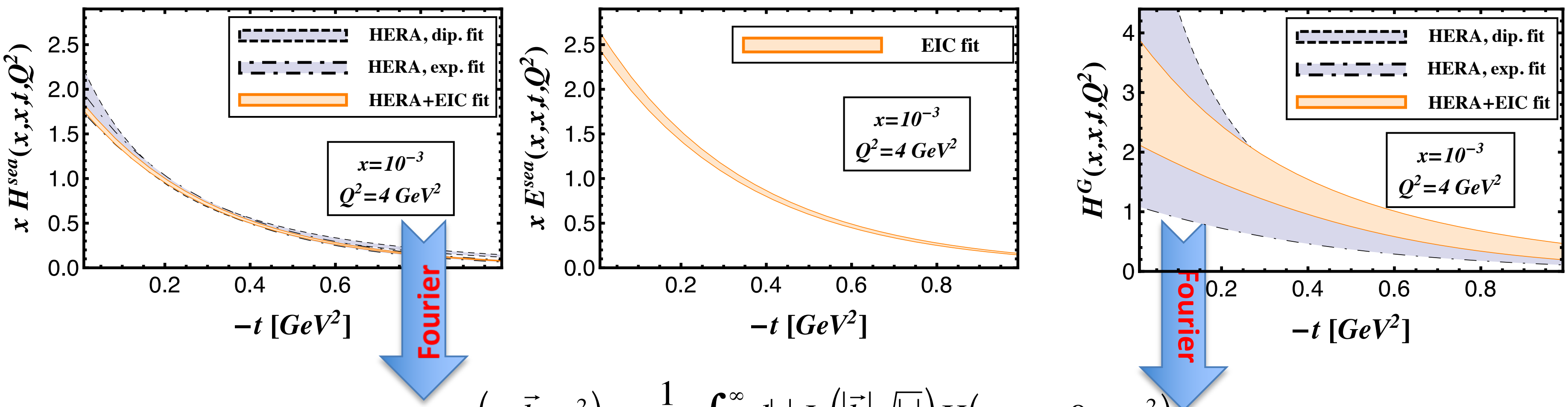
$$J_{q,g}^z = \frac{1}{2}\left(\int_{-1}^{1} x\,dx\left(H^{q,g} + E^{q,q}\right)\right)_{t\to 0}$$

Gives access to GPD E

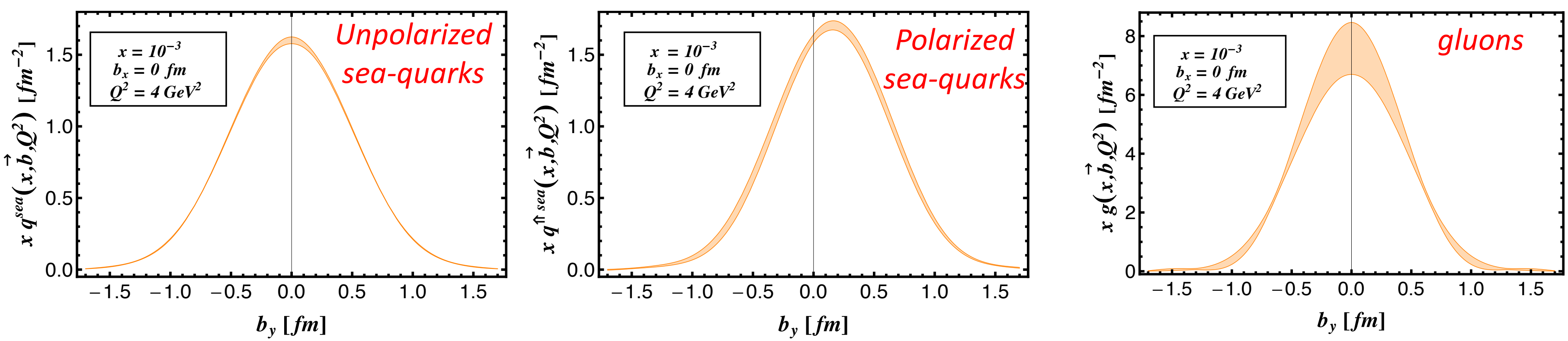
E.C. Aschenauer, S. F., K. Kumerički, D. Müller
JHEP09(2013)093

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)

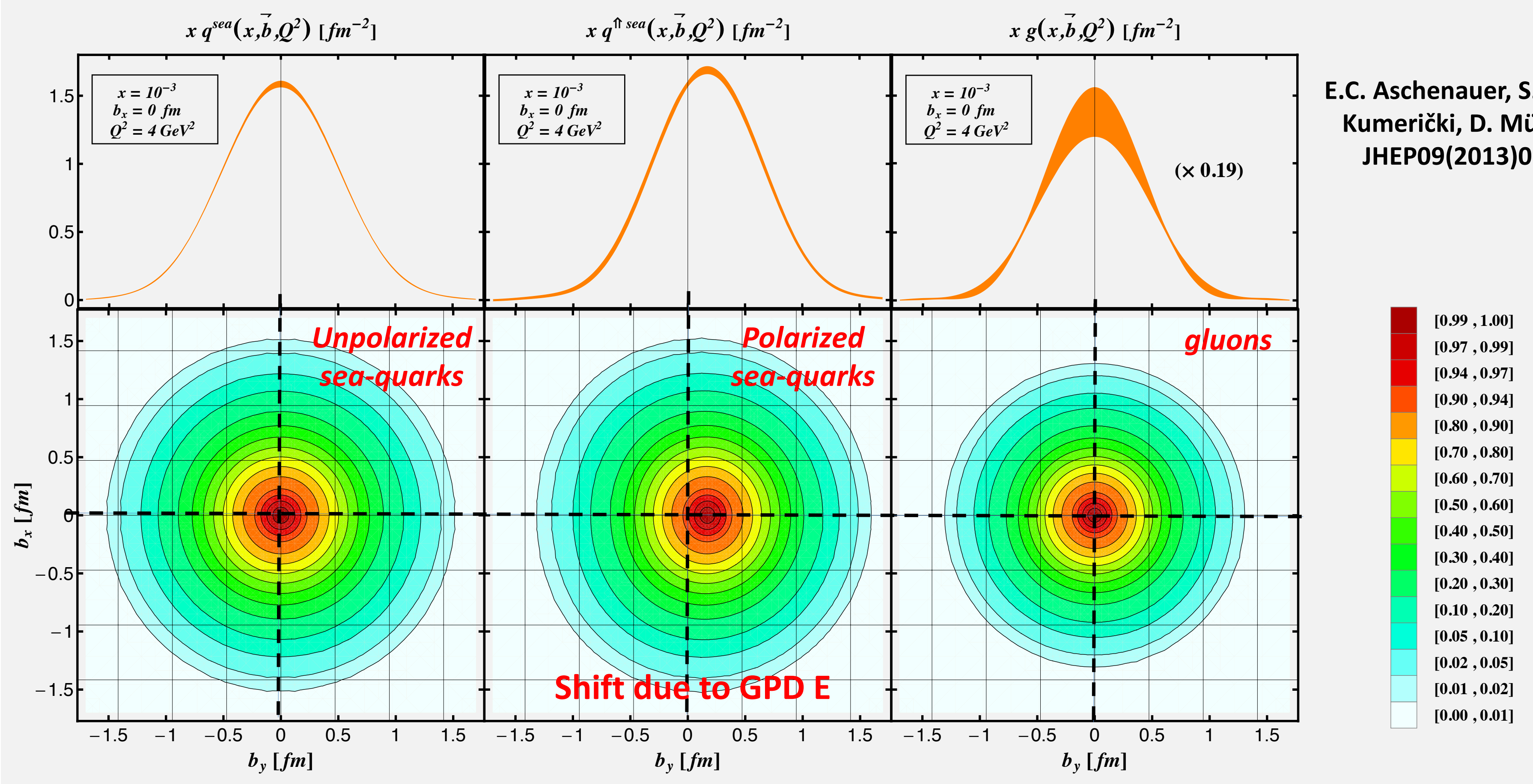


$$q\left(x,\vec{b},\mu^2\right)=\frac{1}{4\pi}\int_0^\infty d|t|\,J_0\left(|\vec{b}|\sqrt{|t|}\right)H\left(x,\eta=0,t,\mu^2\right)$$



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?

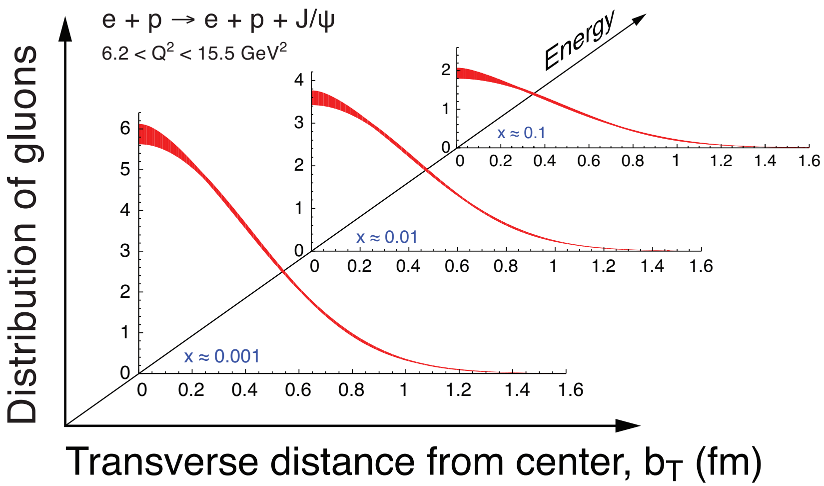
- GPD H-Gluon is nice but can be much better by including J/ψ
- Access to GPD E-gluon → orbital momentum (Ji sum rule)
- Flavor Separation of GPDs (VMP and/or DVCS on deuteron)
- Nuclear imaging (modification of GPDs in p+A collisions)

How to separate flavors?

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)

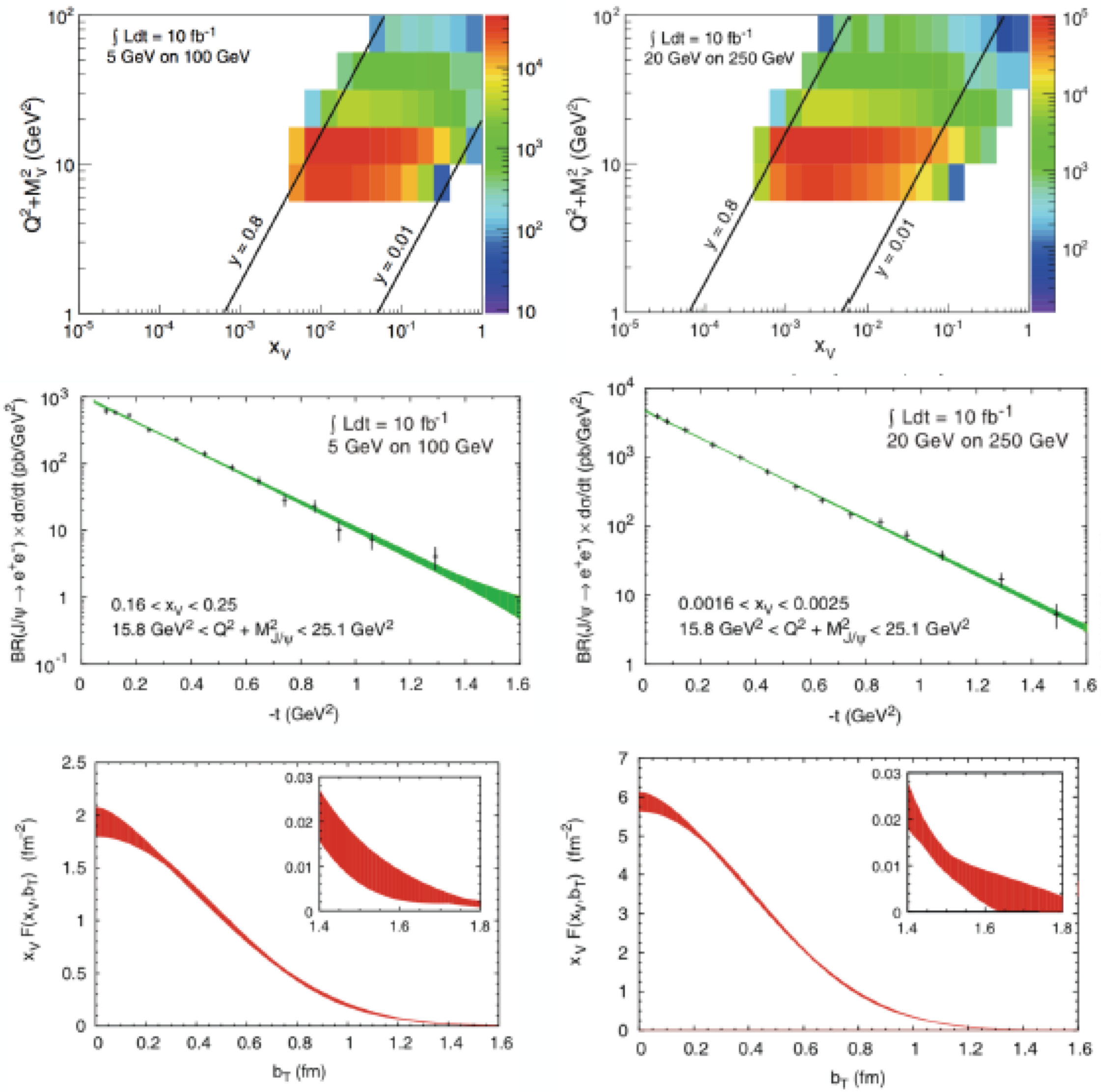
- Uncertainty on wave function
- measuring muons vs electron decay channel

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

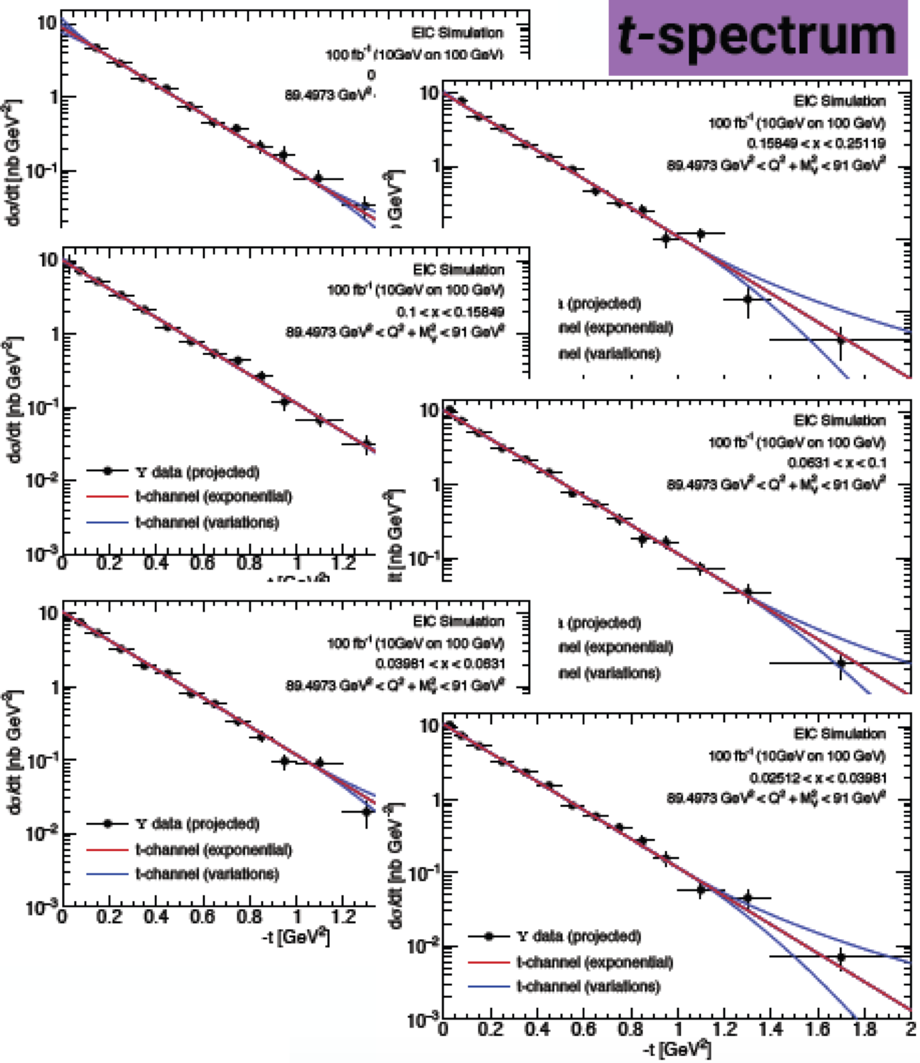
Average gluon densities

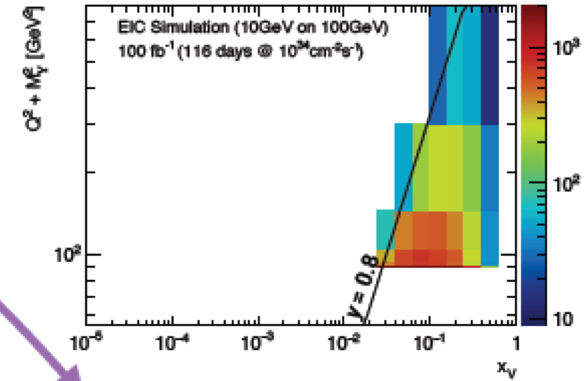
Imaging gluons with Y(1s)

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

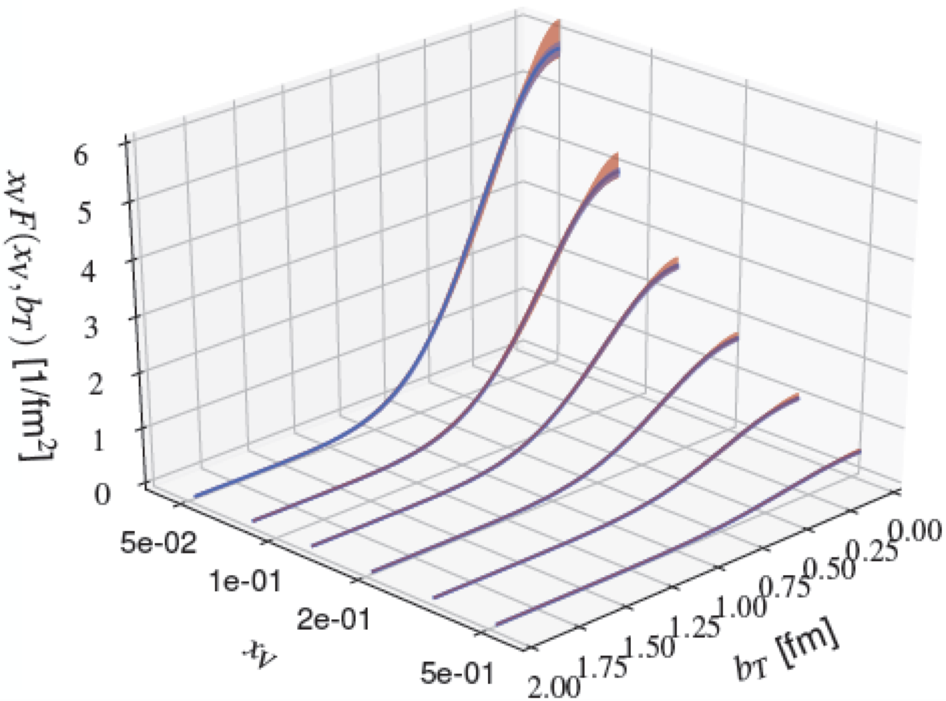
- Nominal EIC detector
- 10x more luminosity
- Electron and muon channels

***t*-spectrum**





Average gluon density:



Next-generation GPD studies with exclusive meson production at EIC

Center for Frontiers in Nuclear Science

Topical Workshop, CFNS, Stony Brook U., 4-6 June 2018
Organizers: Marie Boer, S. F., Lech Szymanowski, Christian Weiss
35 participants, 3 days of presentations and discussions
INDICO page: https://indico.bnl.gov/event/4346/

Objective: Assess potential of hard exclusive meson production and related processes for GPD studies and plan EIC simulations

- Concepts and interpretation: Quark/gluon imaging, energy-momentum tensor
- Reaction theory: QCD factorization, finite-size effects
- Experimental results: HERA, JLab 6 & 12 GeV, COMPASS; LHC UPC pA, future RHIC UPC plans
- EIC machine and detector requirements
- Simulation tools: Physics models, PARTONS framework, detector models

Next-generation GPD studies with exclusive meson production at EIC

Center for Frontiers in Nuclear Science

Outcomes

- **QCD factorization with finite-size effects provides realistic description of exclusive meson production**
  - Use in GPD & imaging studies
  - Need theoretical work: NLO corrections, relation between approaches

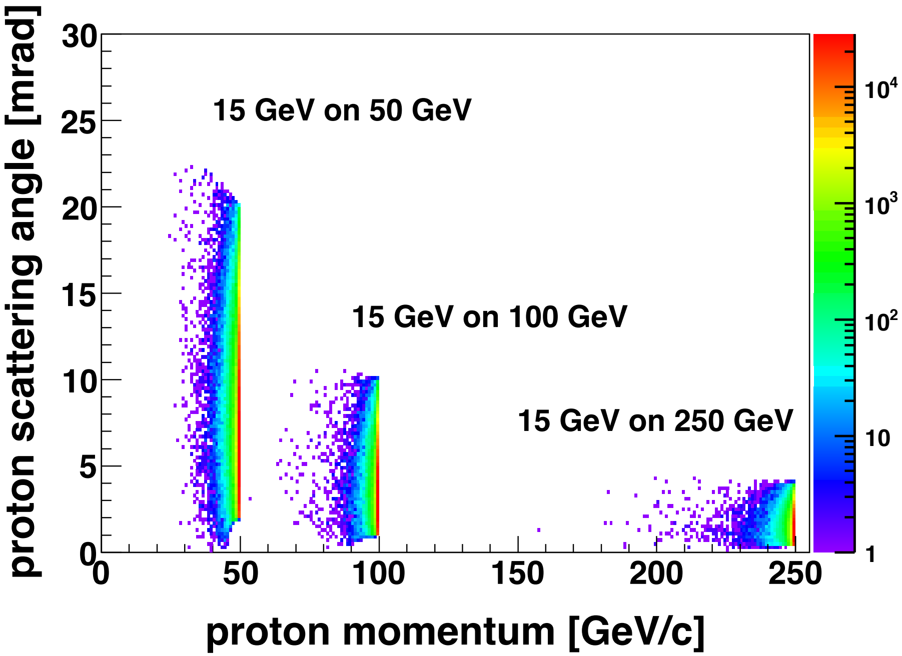
- **UPCs at LHC extend energy frontier in heavy quarkonium production**
  - LHCb, ALICE results for $\gamma + p \rightarrow J/\psi + p$ (up to $W \sim 1.5$ TeV)
  - Consistent with HERA data; no indications of nonlinear effects

- **Meson production could become essential tool for GPD studies at EIC**
  - Dedicated community, great interest

- **Next-level impact studies need GPD-based physics models**
  - Aim for GPD extraction with uncertainties

- **PARTONS project (H. Moutarde et al) can play important role in integrating GPD efforts at JLab12 and EIC**

Scattered Proton measurement



Remember:

Detector -4 to 4 in h

→ 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

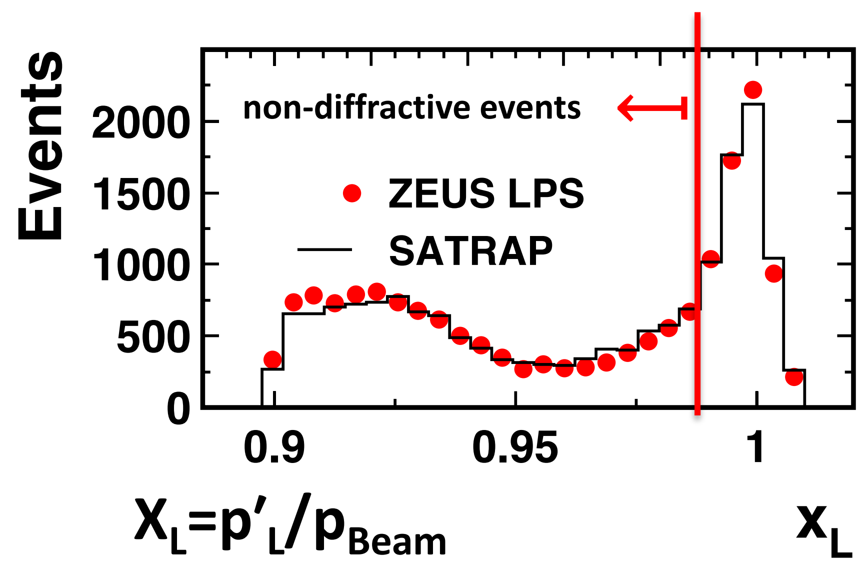
→ RPs are high resolution movable small tracking detectors (Si strips, Si pixels…), a crucial component

→ $\Theta < 10$ mrad

→ impact on large p_T-acceptance

→ small p_T-acceptance limited by beam divergence and immittance

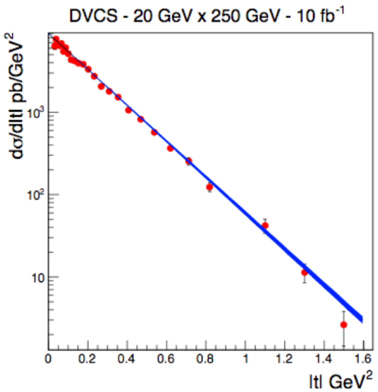
→ rule of thumb keep 10s between RP and beam



Impact of proton acceptance

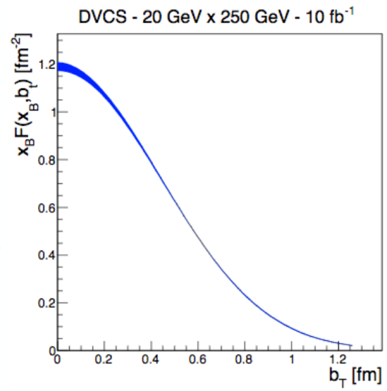
Measurement

Physics observable (cross-section vs impact parameter)



Plots from EIC White Paper:

Fourier transform

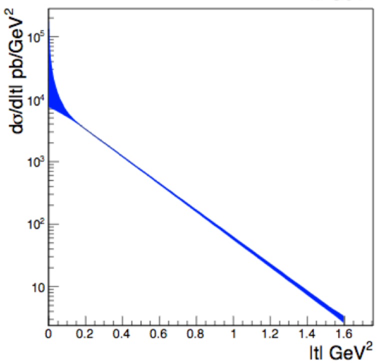


Requirement:

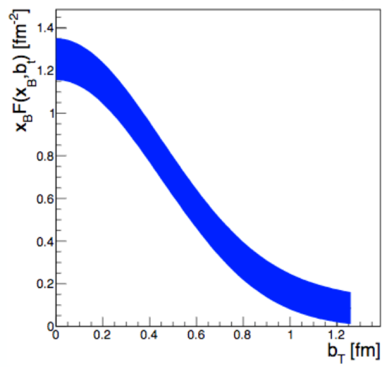
$\int L_{int}=10fb^{-1}$

$0.18 < p_t$ (GeV) < 1.3

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

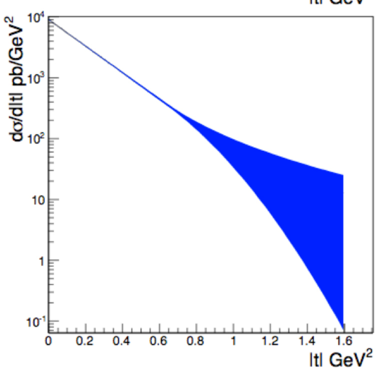


limited lower p_T-acceptance

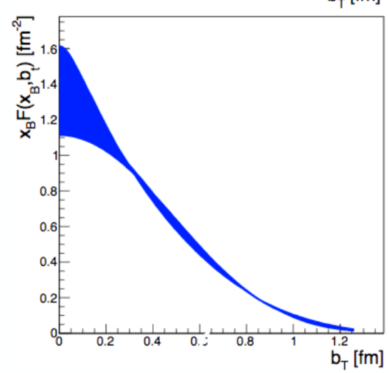


$\int L_{int}=10fb^{-1}$

$0.44 < p_T$(GeV) < 1.3



limited higher p_T-acceptance



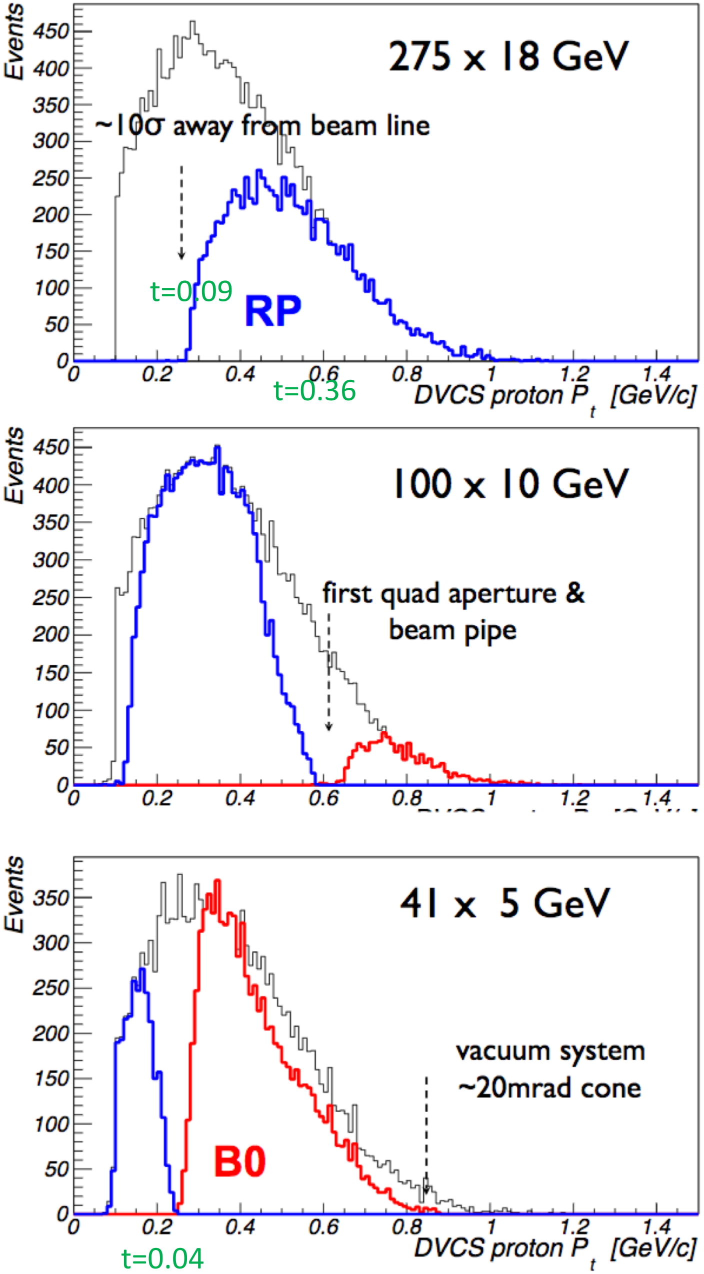
$\int L_{int}=10fb^{-1}$

$0.18 < p_T$ (GeV) < 0.8

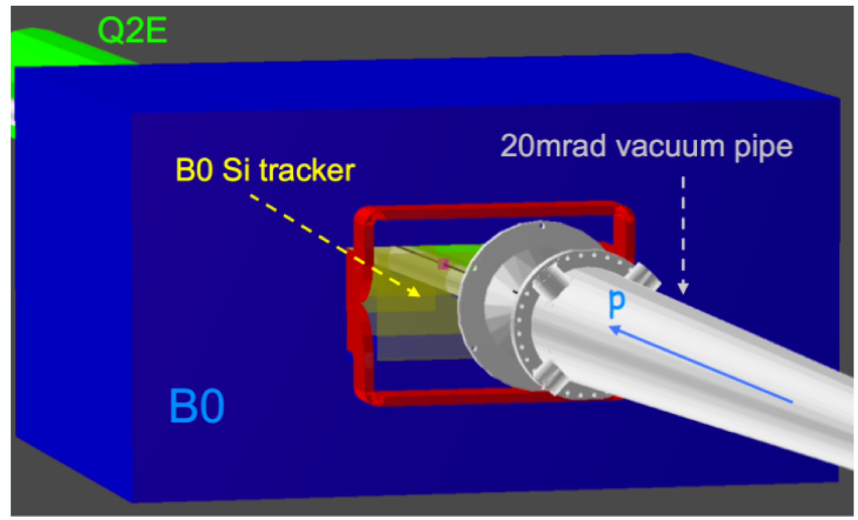
We need large acceptance Proton spectrometers!

Proton acceptance with eRHIC

J.H. Lee
EIC Users Meeting

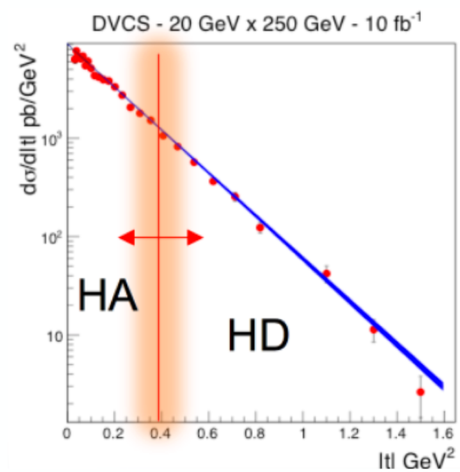


p_T acceptance for forward scattered protons from exclusive reactions



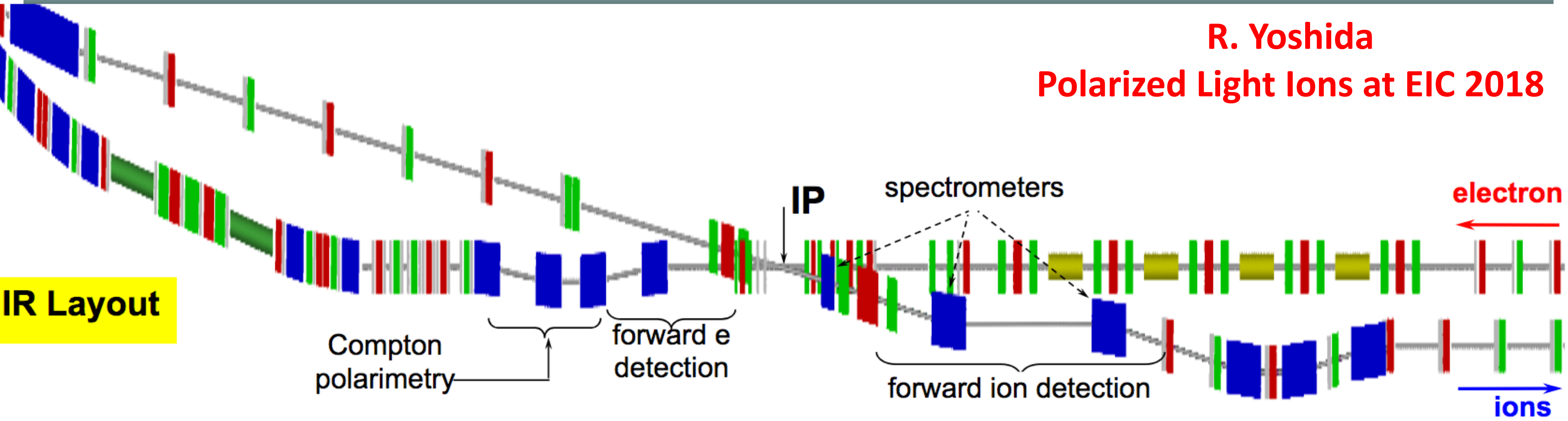
- Plots: HD (high divergence) mode
- Acceptance gap between RP and B0 will be further optimized

Accept 0.3 < p_T< 1.3 GeV and higher
→ Low p_T-part can be filled in with HA (high acceptance, smaller beam divergence) running mode



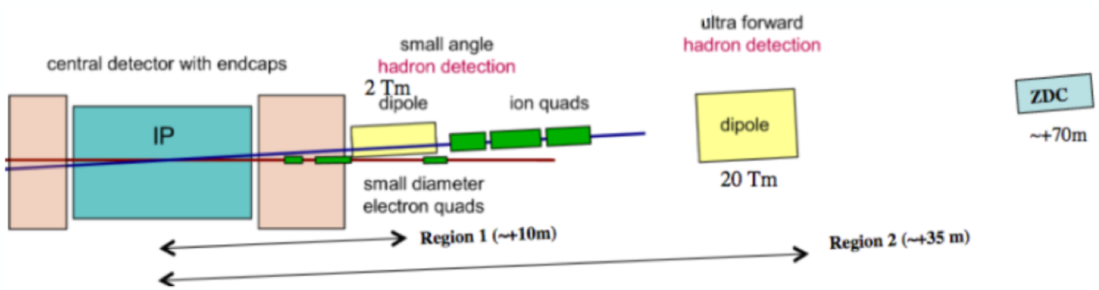
Proton acceptance with JLEIC

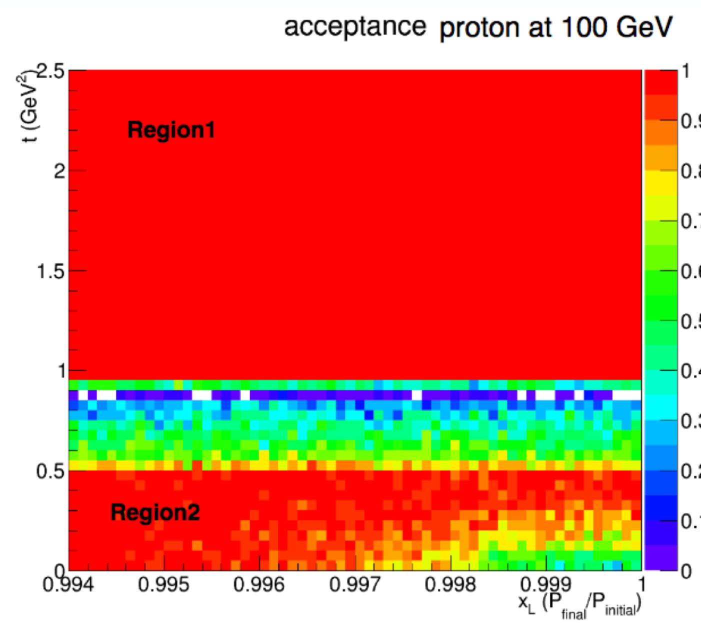
R. Yoshida
Polarized Light Ions at EIC 2018



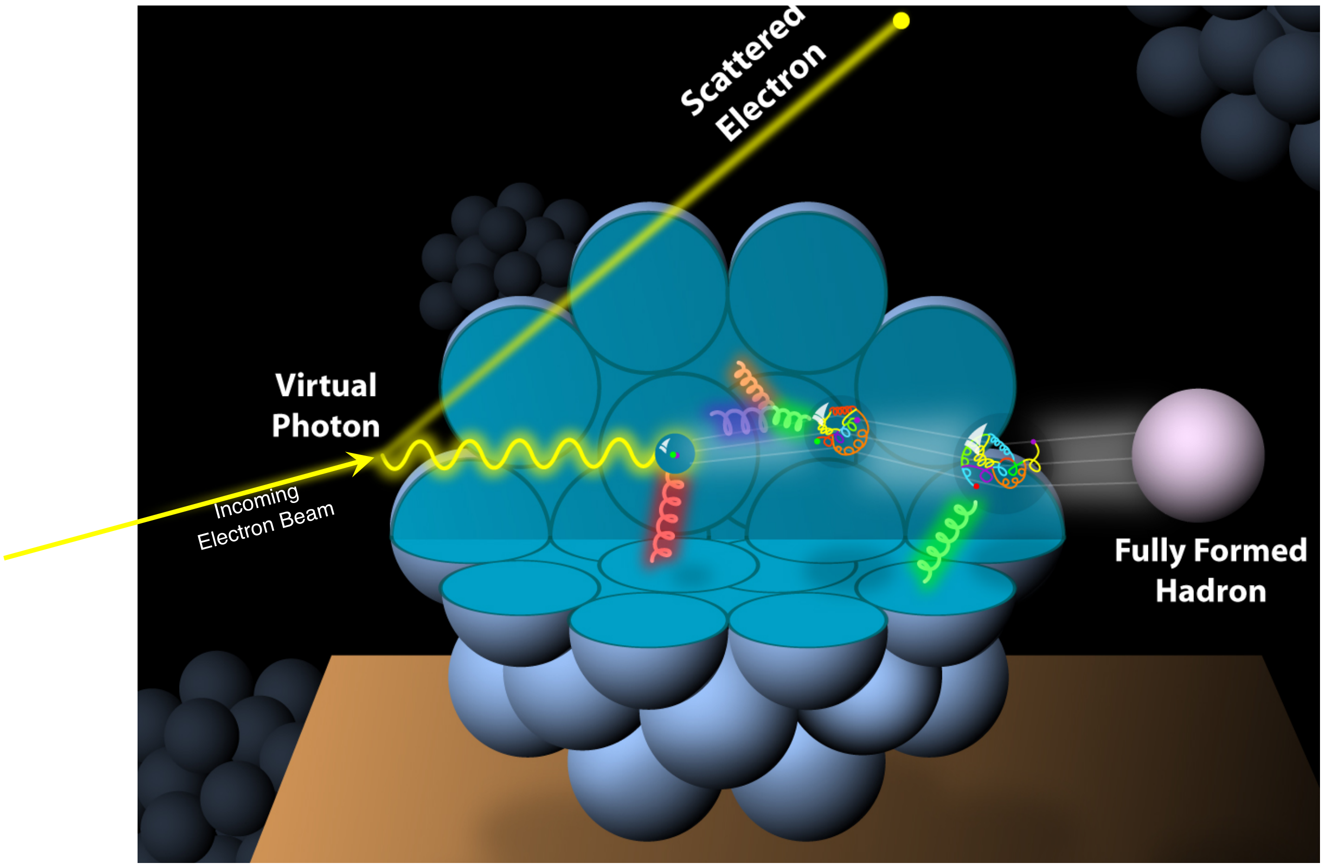
Two forward charged hadron detector regions:

- Region 1: Small dipole covering scattering angles from 0.5 up to a few degrees (before quads)
- Region 2: Far forward, up to one degree, for particles passing through (large aperture) accelerator quads. Use second dipole for precision measurement. (Hi Res)

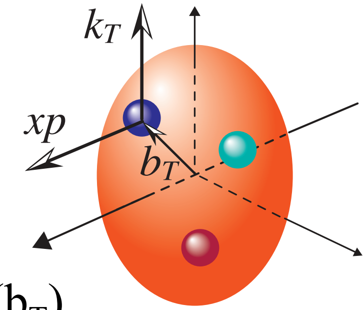




And What about nuclei?



Imaging the gluons in nuclei



Diffractive physics in eA

→ Measure spatial gluon distribution in nuclei

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

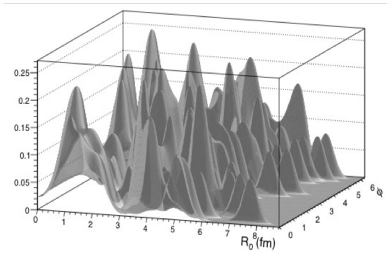
→ Momentum transfer $t = |p_{Au} - p_{Au'}|^2$

Hot topic:

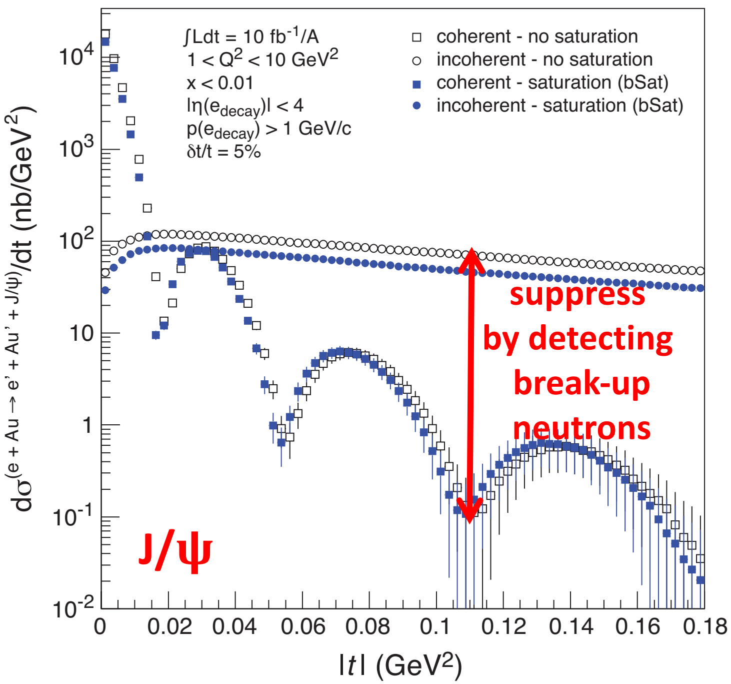
- ➤ Lumpiness of source?
- ➤ Just Wood-Saxon+nucleon $g(b_T)$

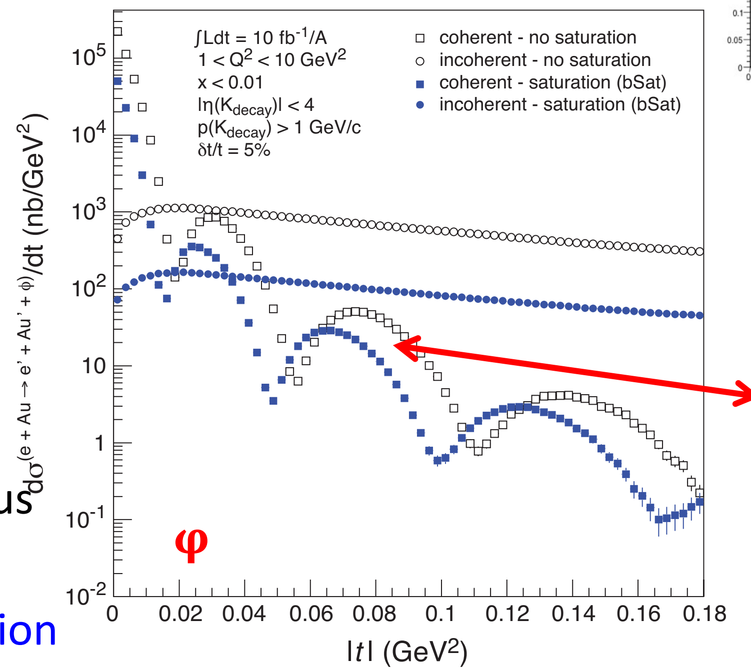
❑ coherent part probes “shape of black disc”

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



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



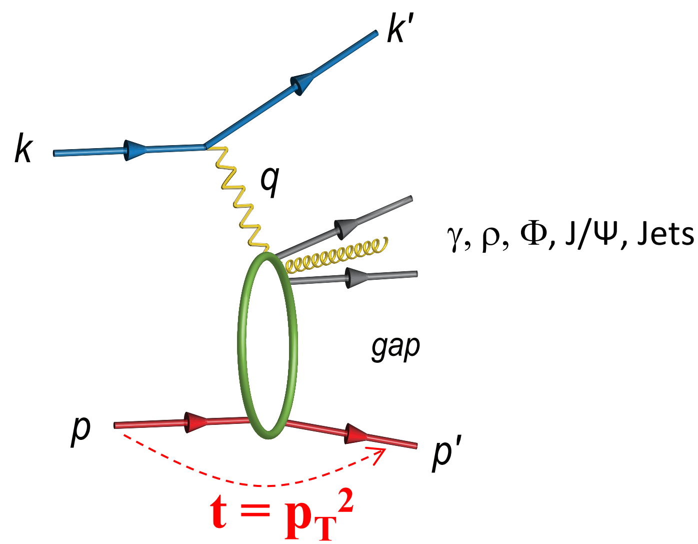


Sensitive to saturation effects!

Physics requires forward scattered nucleus needs to stay intact

→ Veto breakup through neutron detection

Detector Requirements for Exclusive Reactions in ep/eA



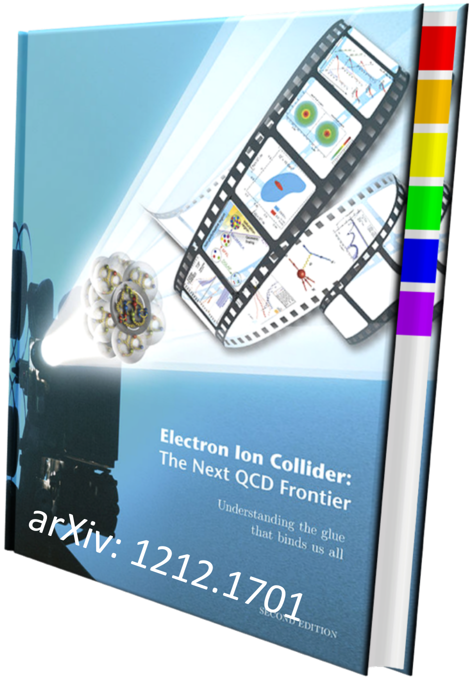
- Exclusivity criteria:
  - Large rapidity coverage or tracker and Calorimeter (ballpark $-4.5 < \eta < 4.5$)
  - Reconstruction of all particles in event
    - wide coverage in t ($=p_T^2$) → Roman pots
- eA: large acceptance for neutrons from nucleus break-up
  - Zero Degree Calorimeter
    - veto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

Summary

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

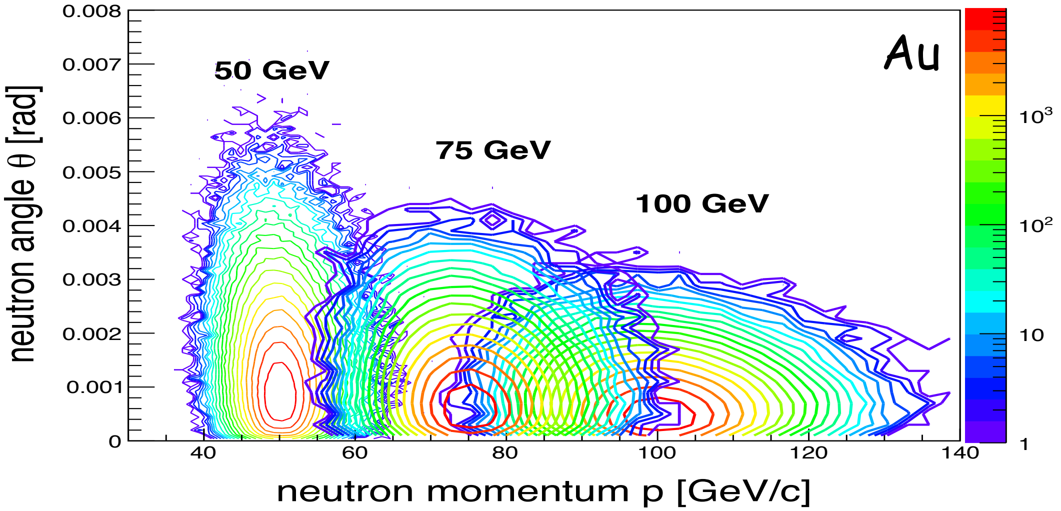
- Accurate 2+1D imaging of the polarized and unpolarized quarks and gluons inside the hadrons, and their correlations
- Investigate the proton-spin decomposition puzzle (orbital angular momentum)
- Study of GPDs in nuclei (and possible gluon saturation effects)

EIC science program will profoundly impact our understanding of nucleon structure and the glue



Back up

Forward scattered neutrons

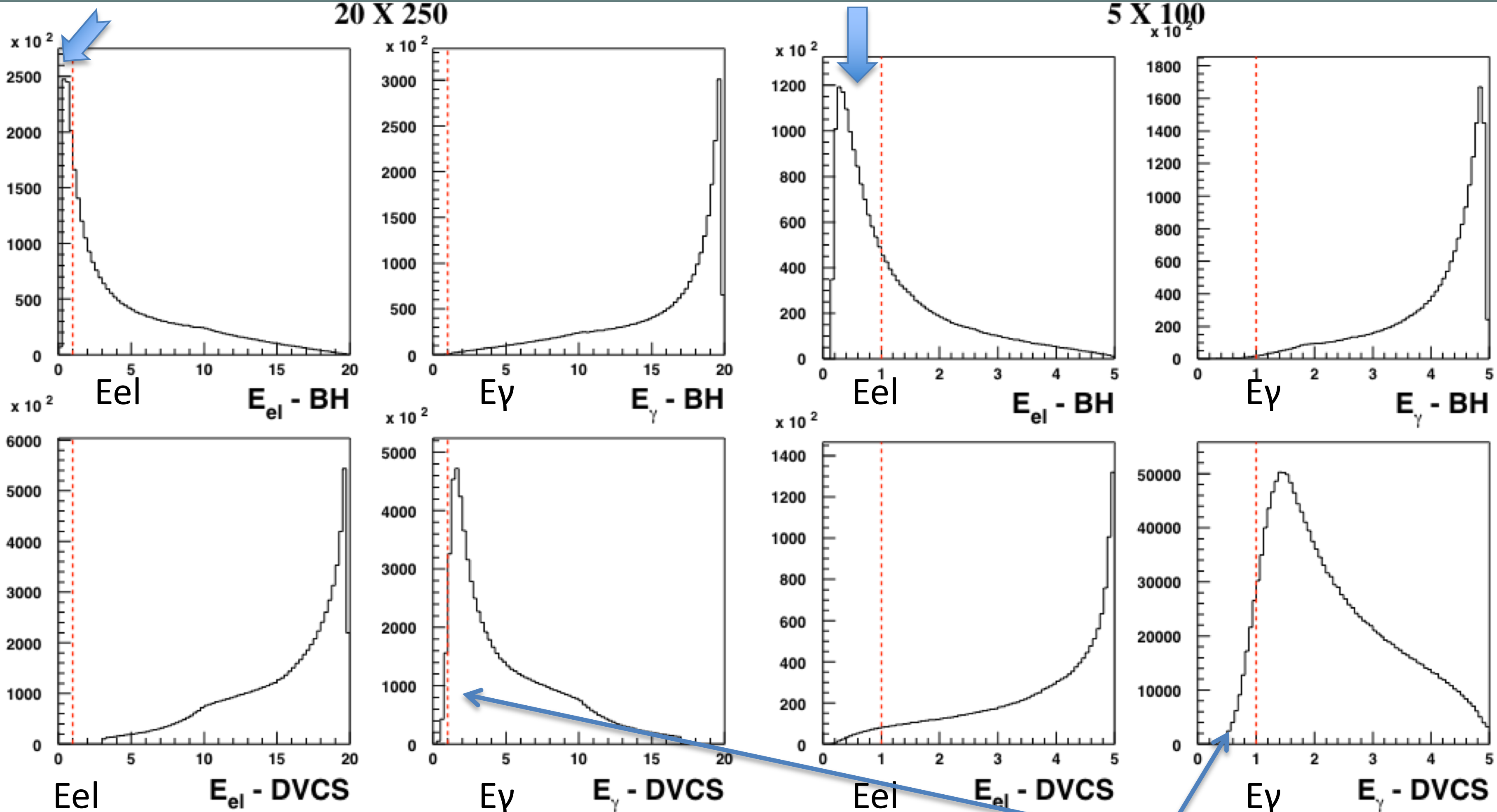


Requirements:

- Need at +/- 4 mrad beam element free cone before the zero degree calorimeter to detect the breakup neutrons
- Neutrons are also critical to reconstruct collisions geometry
  L. Zheng, ECA, J-H. Lee arXiv:1407.8055
  → precision neutron energy reconstruction → transverse size of **ZDC**

E.C. Aschenauer

BH rejection

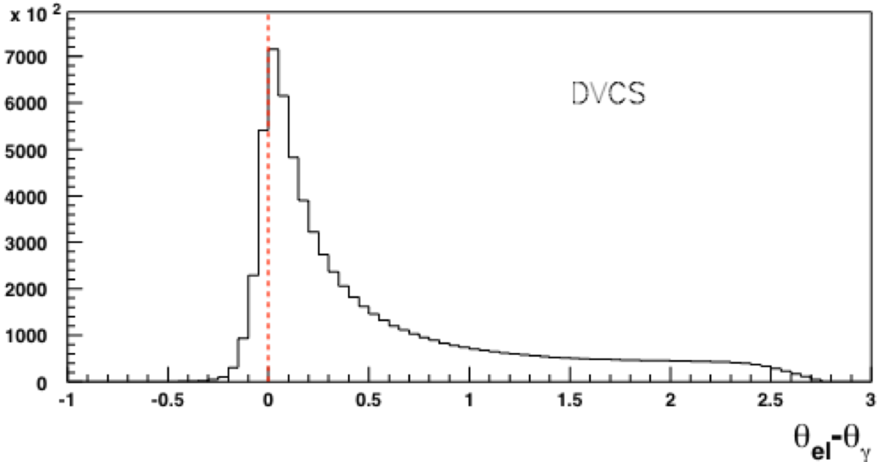


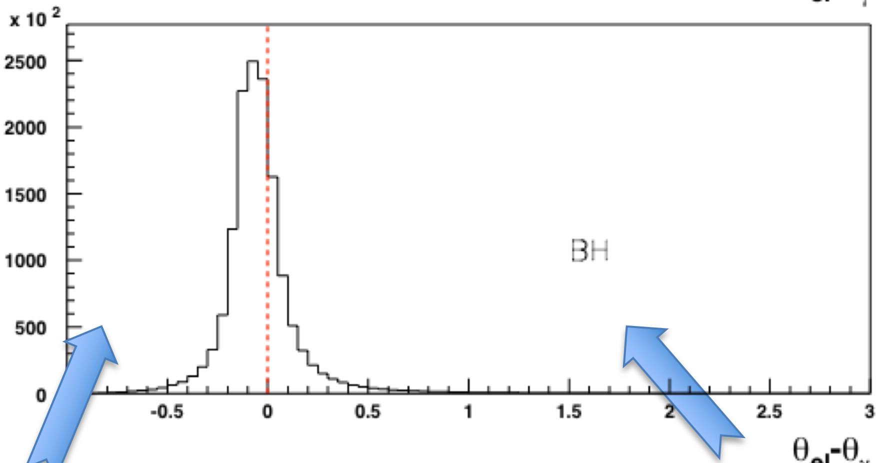
1. **BH electron has very low energy (often below 1 GeV)**
2. **Photon for BH (ISR) goes often forward (trough the beam pipe)**

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

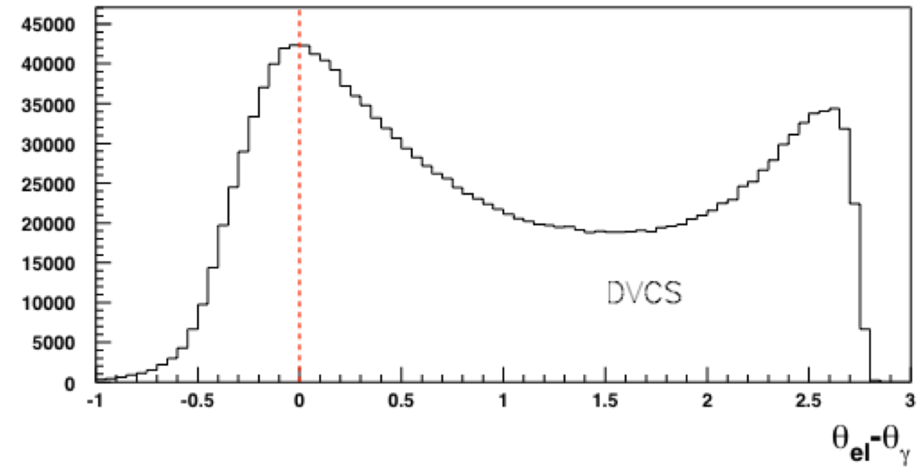
BH rejection

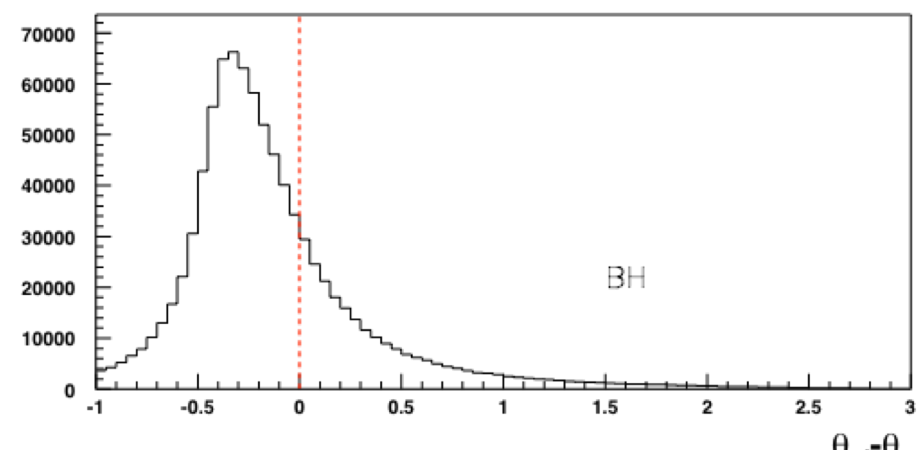
20 X 250



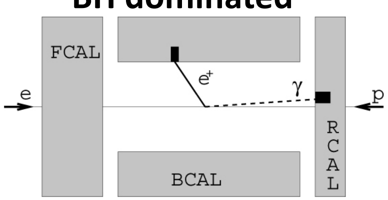


5 X 100

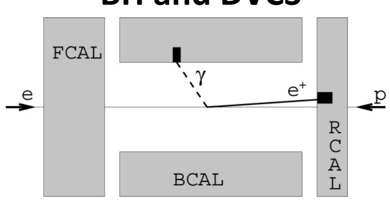




BH dominated

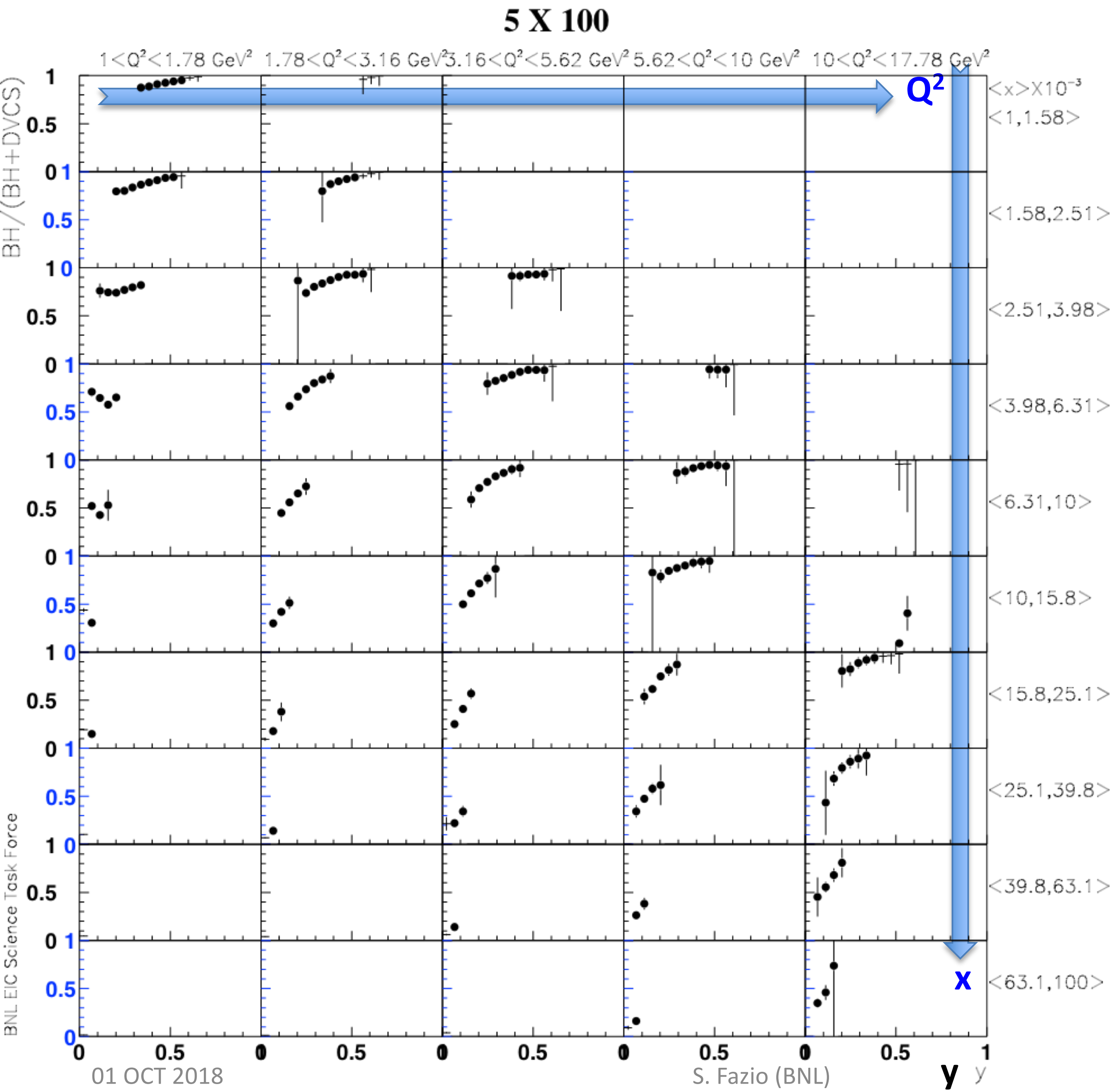


BH and DVCS



In DVCS most of the photon are less "rear"
Than the electrons:
$(\theta el-\theta\gamma) > 0$ → rejects most of the BH

BH fraction

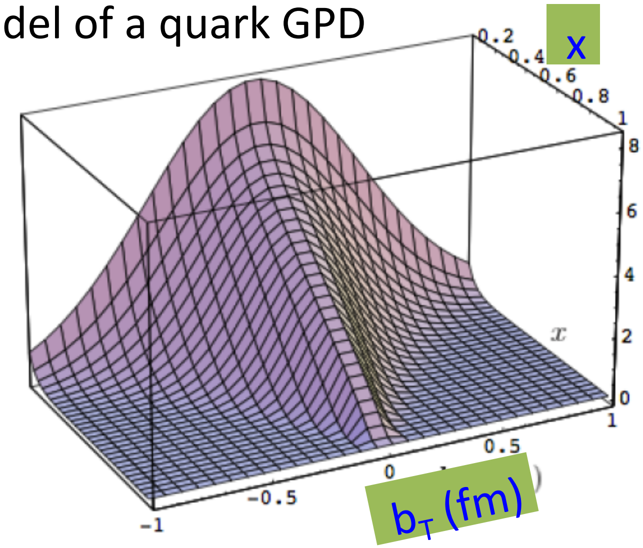


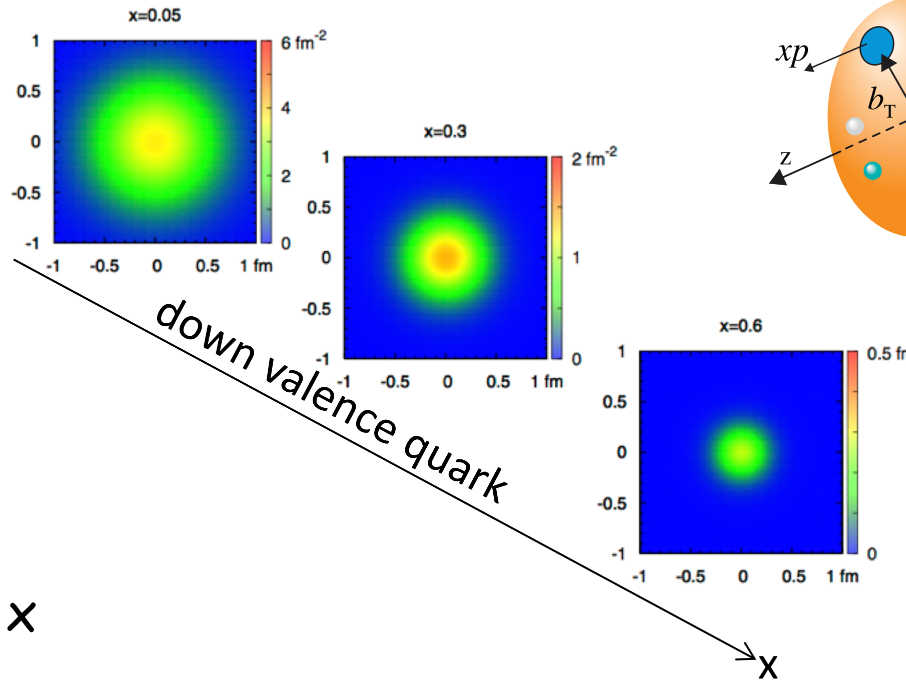
5 x 100 GeV^2

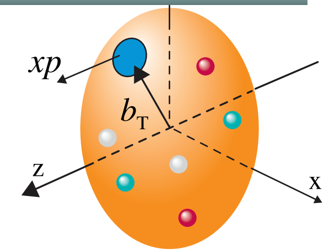
BH subtraction will be relevant at low beam-energies, at large y, depending on the x-Q^2 bin

radius vs x

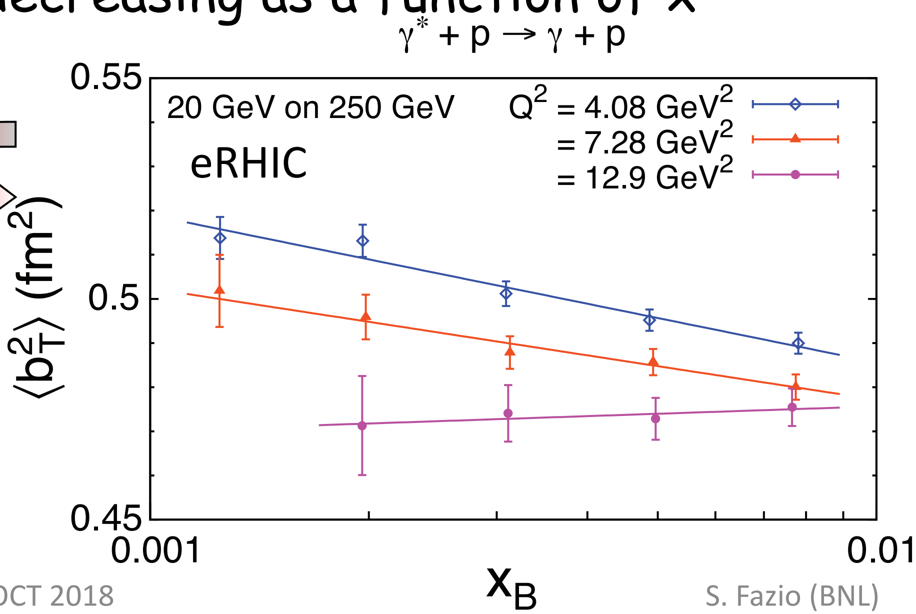
Model of a quark GPD







b_T decreasing as a function of x



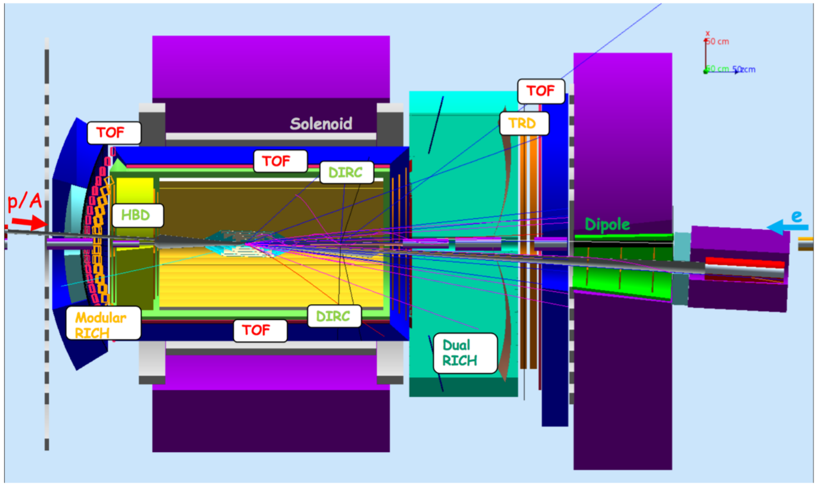
Valence (high x) quarks at the **center** → small b_T

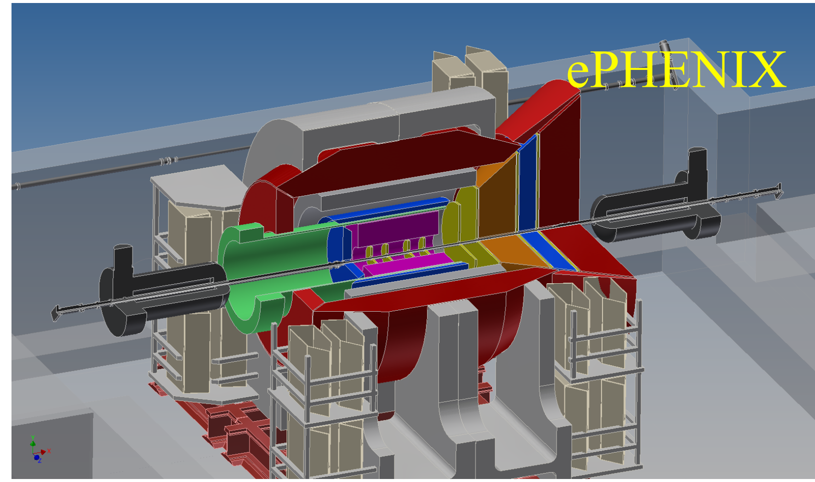
Sea (small x) quarks at the périphérie → high b_T ?

GLUONS ???

“General-porpose” detector general requirements

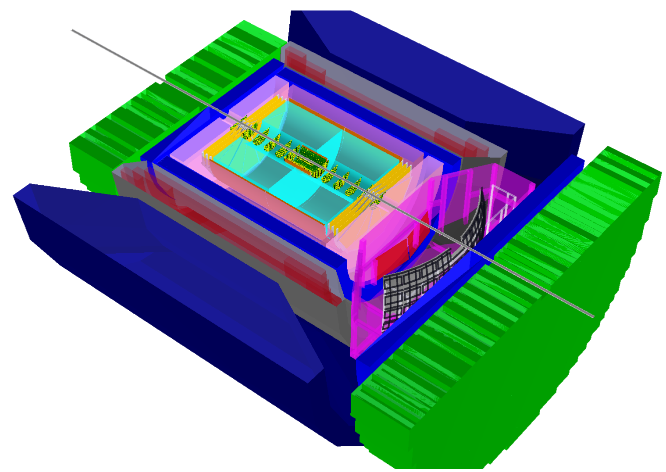
JLAB B. Sorrow **BNL**





Overall detector requirements:

- **Large acceptance in pseudorapidity**: $-4.5 \lesssim \eta \lesssim 4.5$
- 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



A model detector concept: BeAST (Brookhaven eA Solenoidal Tracker)

A full silicon detector concept also proposed by Argonne EIC Detector and R&D program
→ https://wiki.bnl.gov/conferences/index.php/EIC_R%25D