DVCS at an Electron Ion Collider

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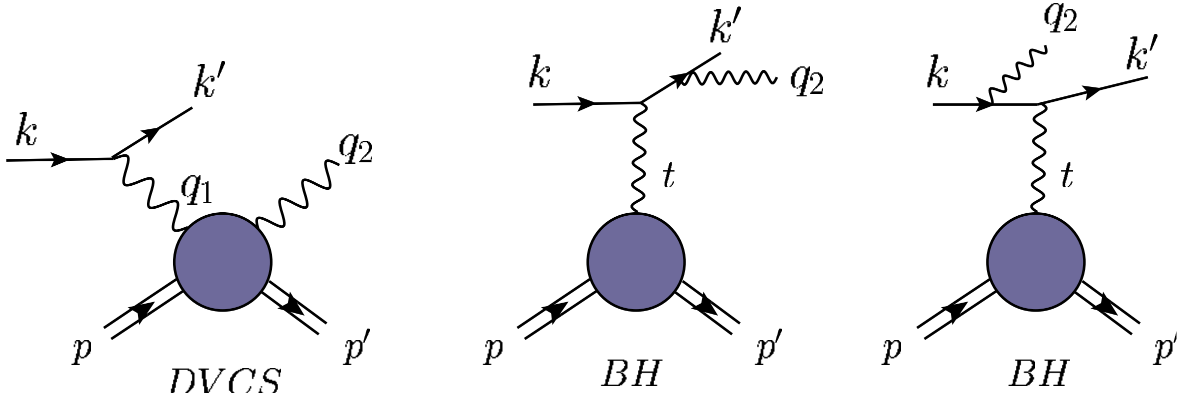


International workshop on

Deeply Virtual Compton Scattering: From Observables to GPDs

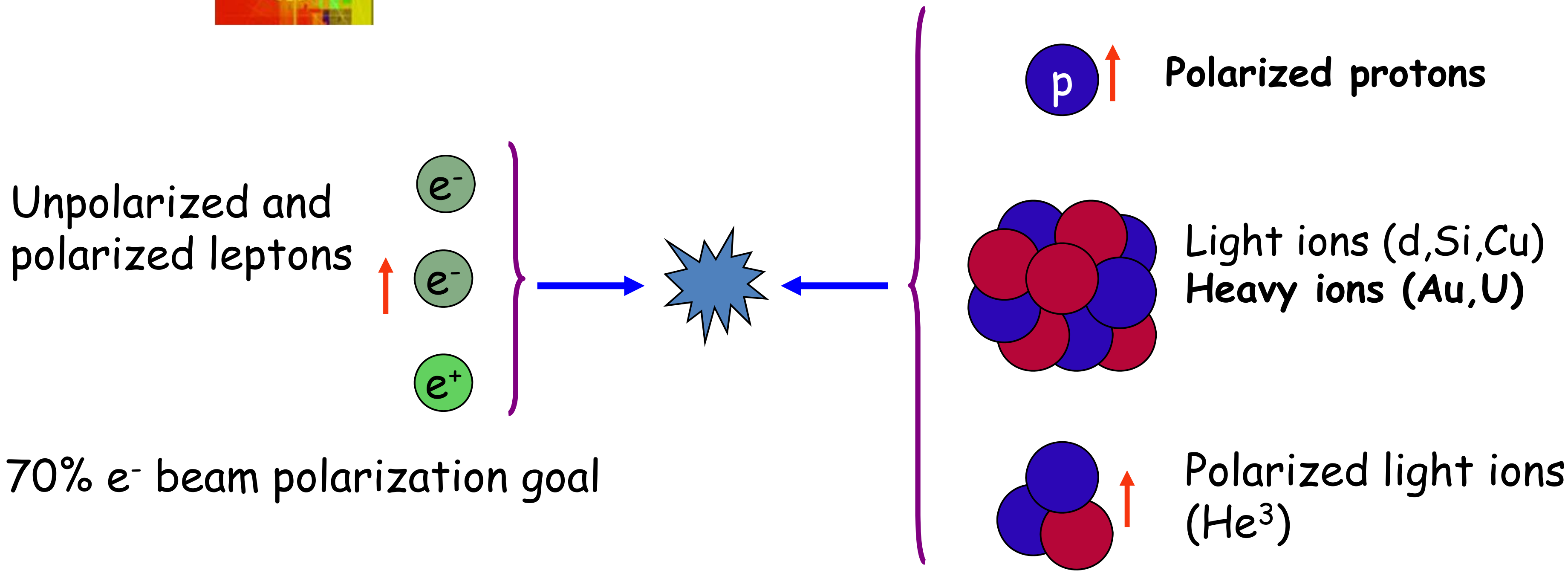
Ruhr-Universität Bochum, February 10-12, 2014

Plan of the talk

- The EIC Machine designes
- Measuring DVCS @ EIC
  - Bethe-Heitler subtraction
  - Account for Initial State Radiation
  - White Paper results and more
- How luminosity hungry we are?
- Requirements for an ideal EIC detector
- Summary

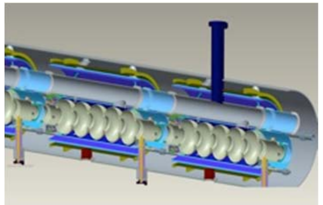
The EIC idea

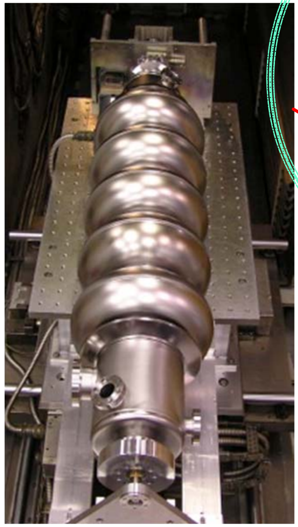
Electron Ion Collider project (EIC) -> 2 options: Brookhaven National Laboratory (eRHIC)
Thomas Jefferson National Laboratory (ELIC)

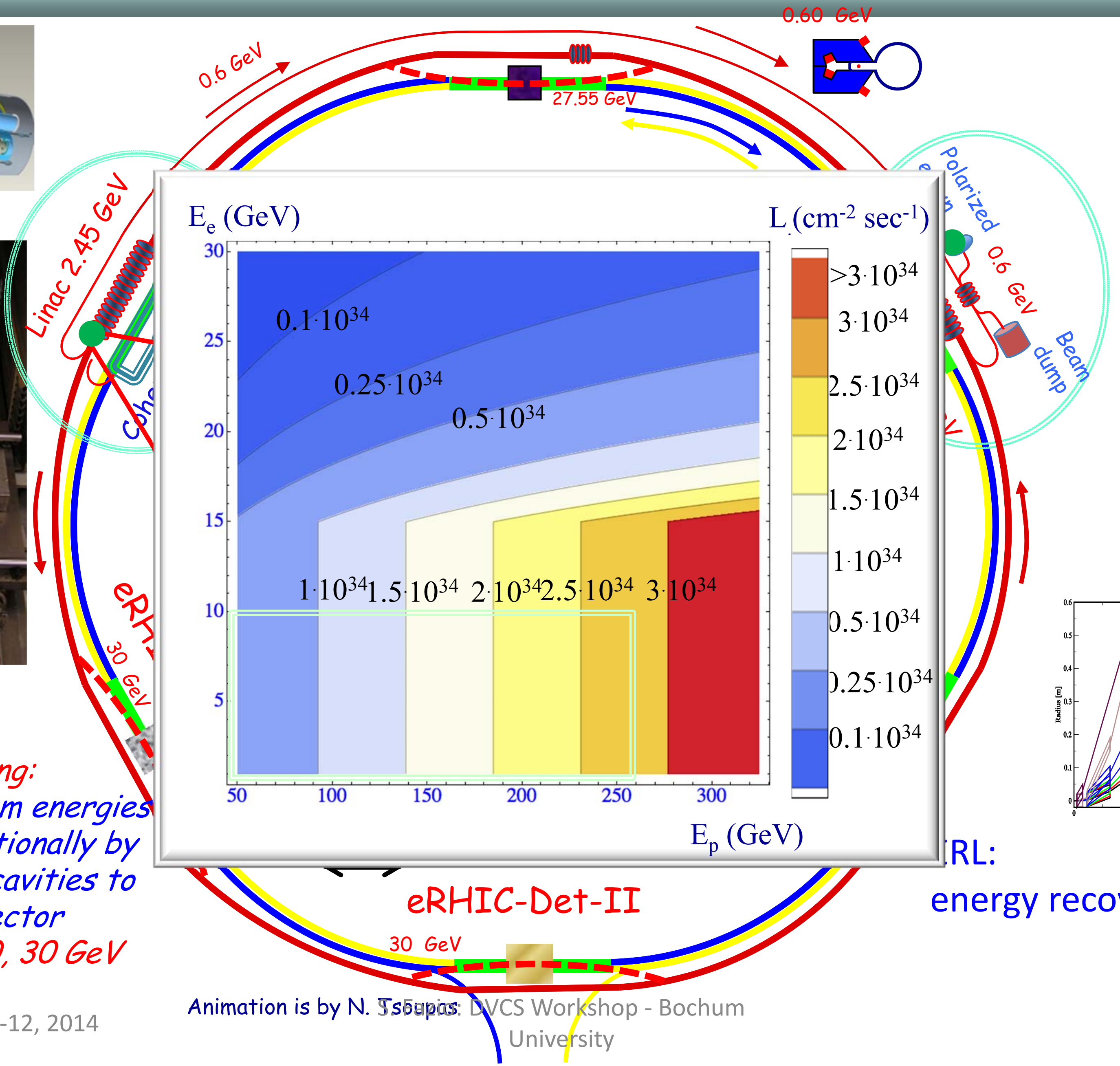


Mission: Studying the Physics of Strong Color Fields

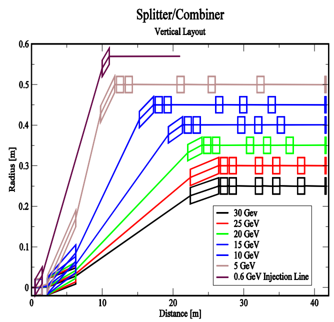
The eRHIC project







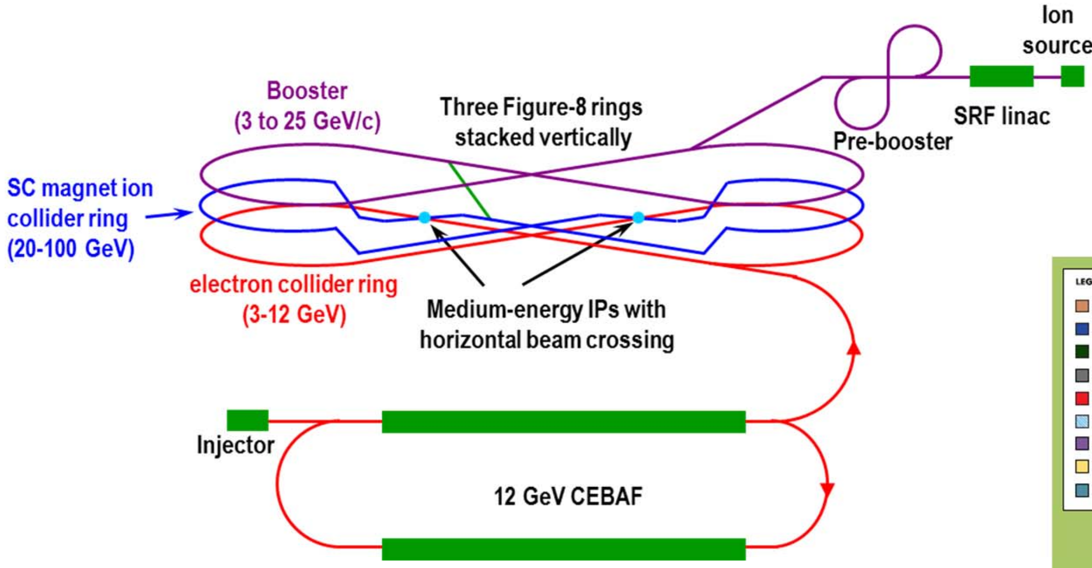
Staging:
All lepton beam energies scale proportionally by adding SRF cavities to the injector
E_o=5, 10, 20, 30 GeV

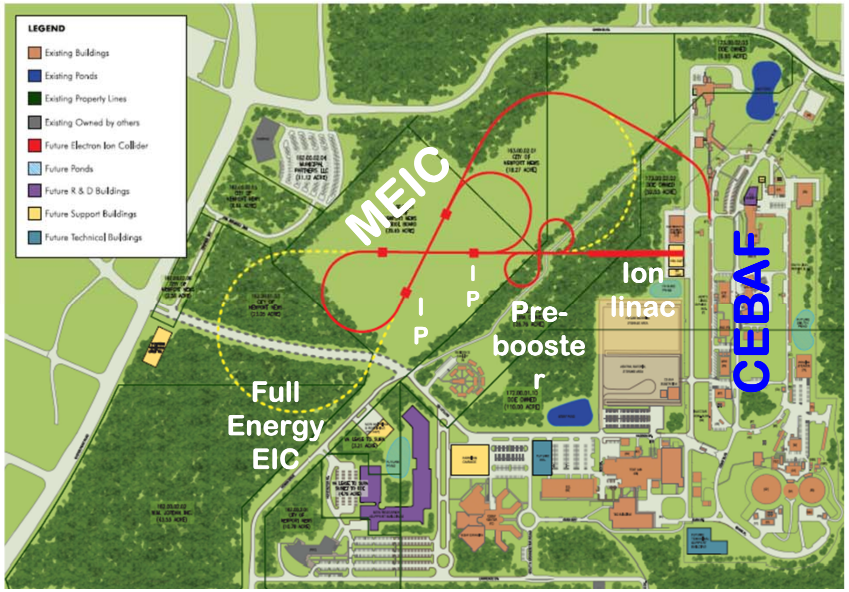


ERL:
energy recovery linac

Animation is by N. Tsoupas

Medium Energy EIC @ JLab





JLab Concept:

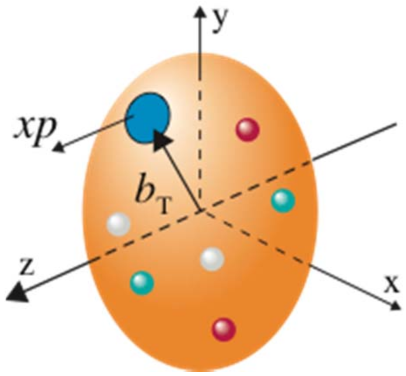
- Initial configuration (MEIC):
  - 3-11 GeV on 20-100 GeV ep/eA collider
  - fully-polarized, longitudinal and transverse
  - luminosity: up to few x 10^{34} e-nucleons cm^{-2} s^{-1}
- Upgradable to higher energies

250 GeV protons + 20 GeV electrons

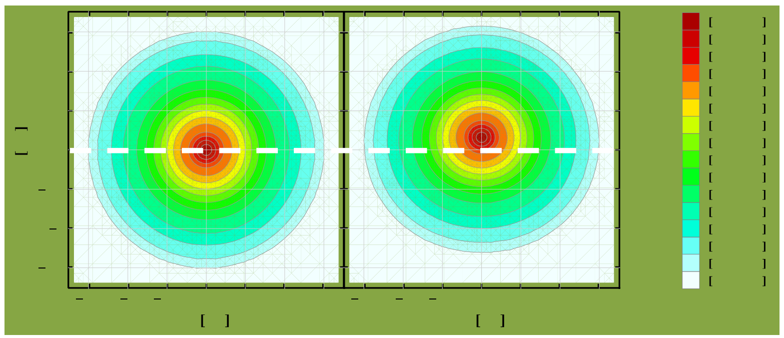
(2+1)-Dimensional imaging of the proton

Open questions:

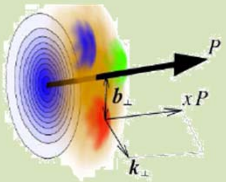
- PDFs do not resolve transverse coordinate or momentum space
- In a fast moving nucleon the longitudinal size squeezes like a `pizza' but transverse size remains about 1 fm



Goal: nucleon tomography!



Proton imaging

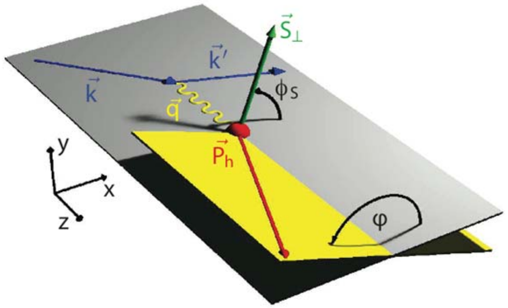


- what is the spatial distribution of quarks and gluons in nucleons/nuclei
- Possible window to orbital angular momentum

Accessing the GPDs

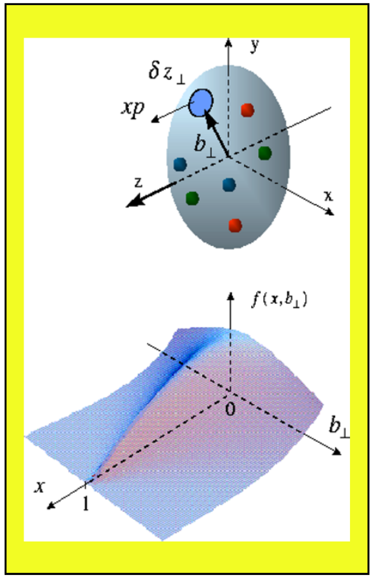
$$\frac{d\sigma}{dt} \sim A_0\left[|H|^2(x,t,Q^2) - \frac{t}{4M_p^2}|E^2|(x,t,Q^2) \right]$$

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 at eRHIC**

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

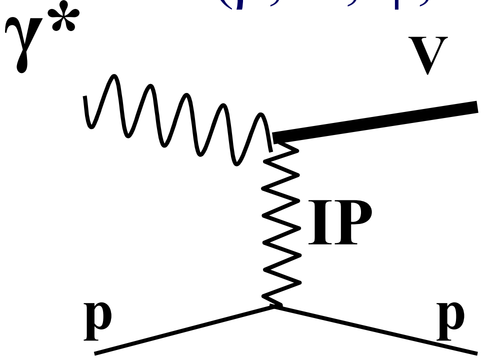
Dominated by H
slightly dependent on E

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

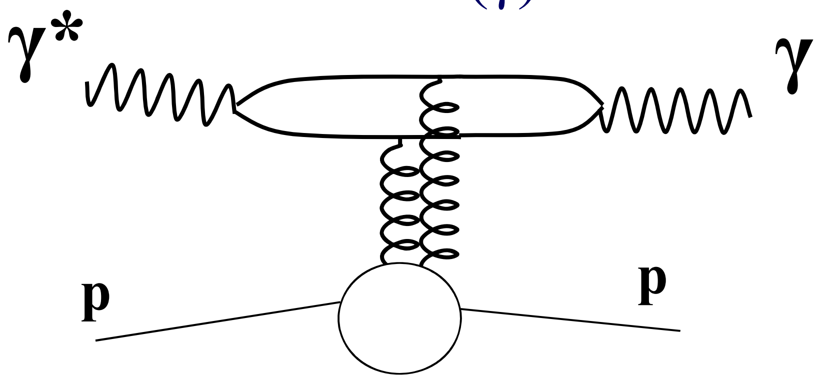
sin($\Phi_T - \phi_N$)
governed by E and H

Deeply Virtual Compton Scattering

VM (ρ, ω, φ, J/ψ, Y)



DVCS (γ)



Scale: $Q^2 + M^2$ ⟷ Q^2

Q^2 gives the lever arm

DVCS properties:

- **Similar to VM production, but γ instead of VM in the final state**
- **Very clean experimental signature**
- **Not affected by VM wave-function uncertainty**
- **Hard scale provided by Q^2**
- **Sensitive to both quarks and gluons**

A GOLDEN MEASUREMENT!

for the EIC pp physics case

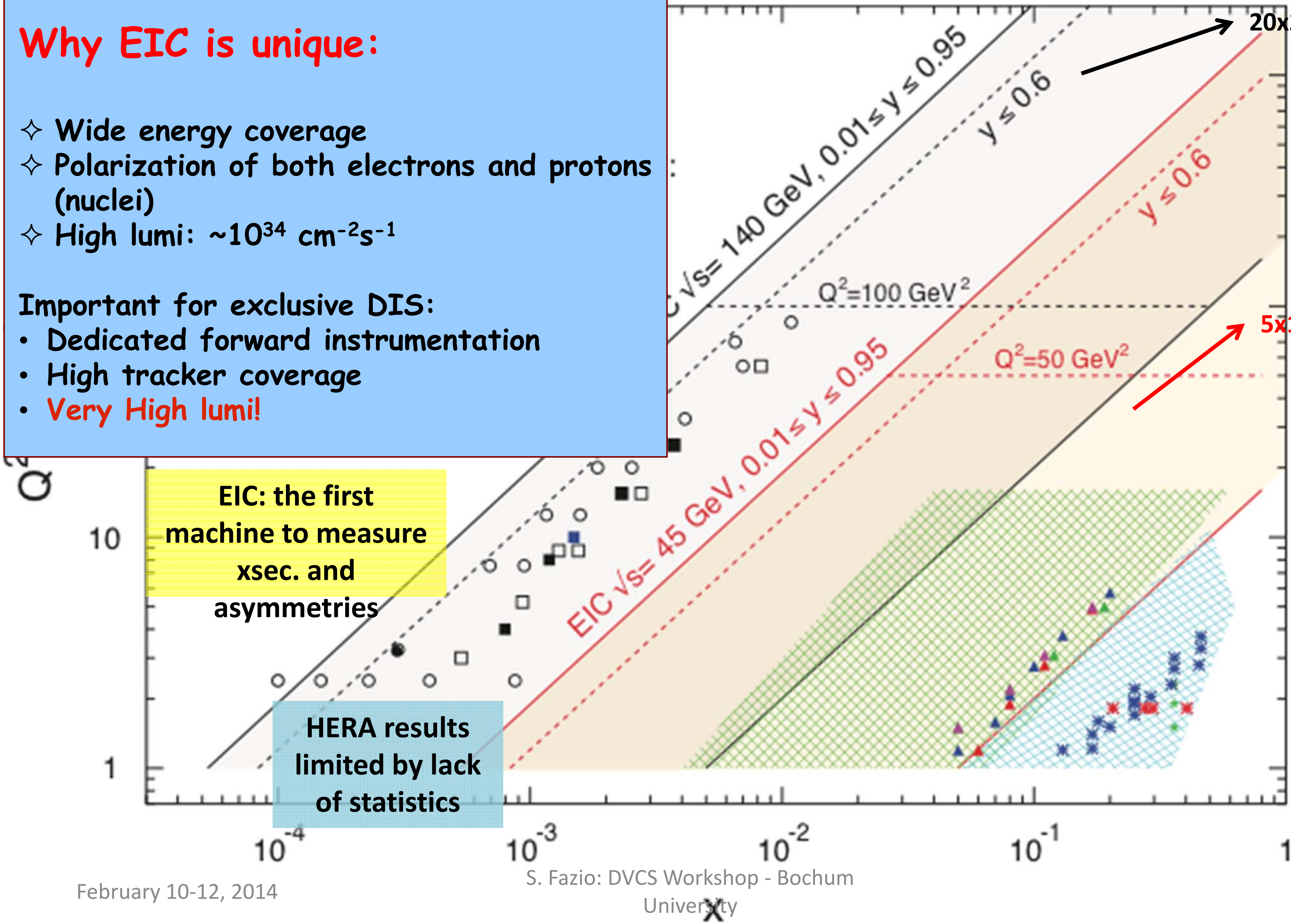
DVCS at EIC

Why EIC is unique:

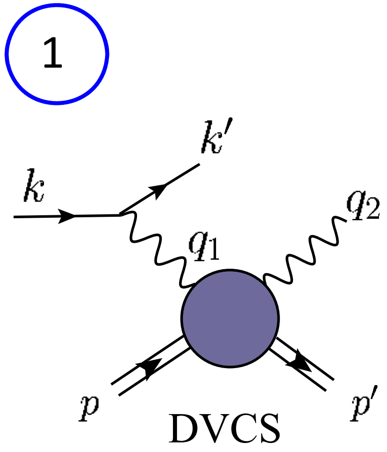
✧ Wide energy coverage
✧ Polarization of both electrons and protons (nuclei)
✧ High lumi: ~10^{34} $cm^{-2}s^{-1}$

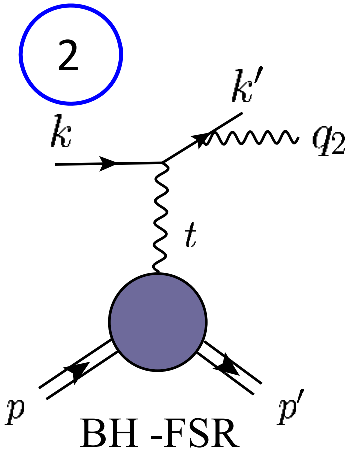
Important for exclusive DIS:

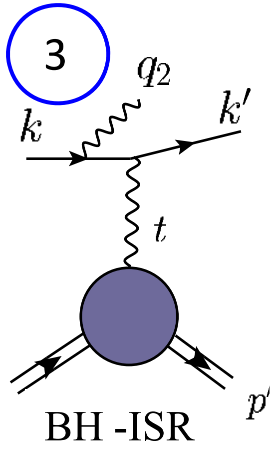
- Dedicated forward instrumentation
- High tracker coverage
- Very High lumi!

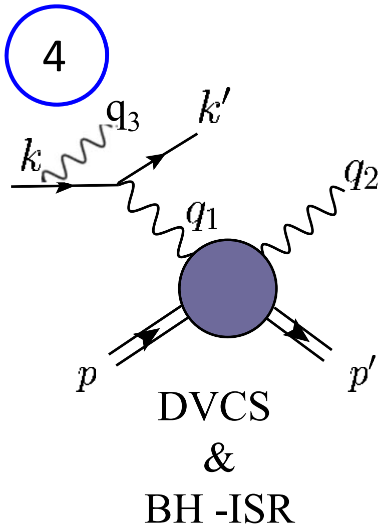


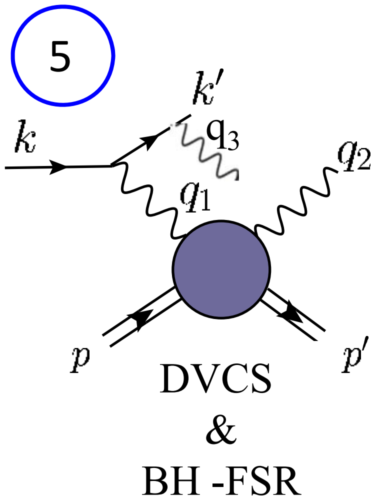
Processes to be considered











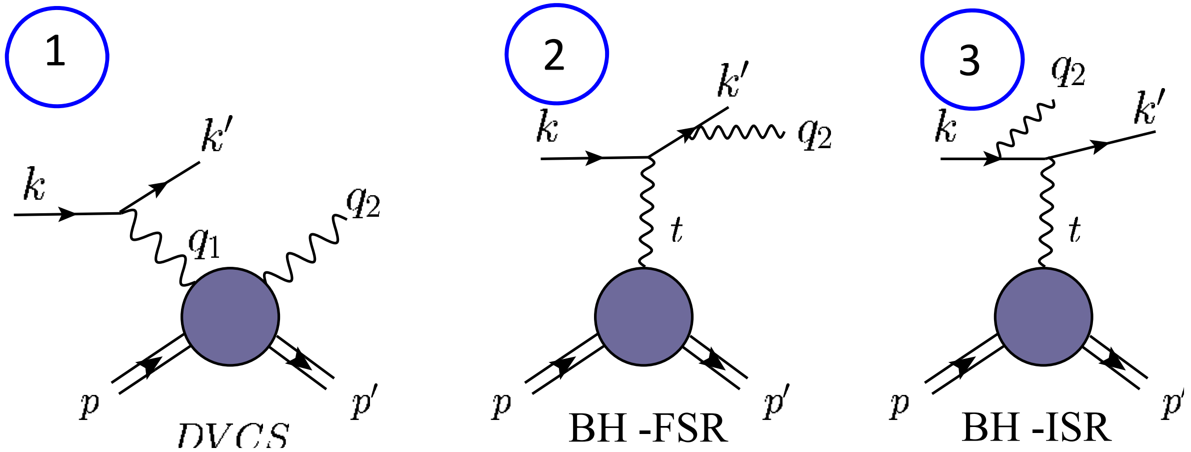
DVCS and Bethe-Heitler have the same final state topology

$$d\sigma \sim \left| \mathcal{A}_{DVCS} + \mathcal{A}_{BH} + \mathcal{A}_{INT} \right|$$

The relevant processes are:

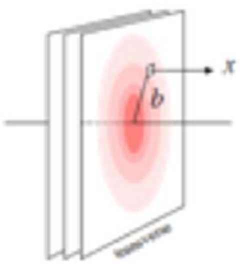
- DVCS (1)
- BH initial (3) and final (2) state rad.
- ISR (4) and FSR (5) in DVCS

DVCS - BH



$$\frac{d\sigma}{dxdyd|t|d\phi d\varphi} = \frac{\alpha^3 x_B y}{16|e^3|\pi^2 Q^2\sqrt{1+\varepsilon^2}}\left|\mathcal{A}_{DVCS} + \mathcal{A}_{BH} + \mathcal{A}_{INT}\right|$$

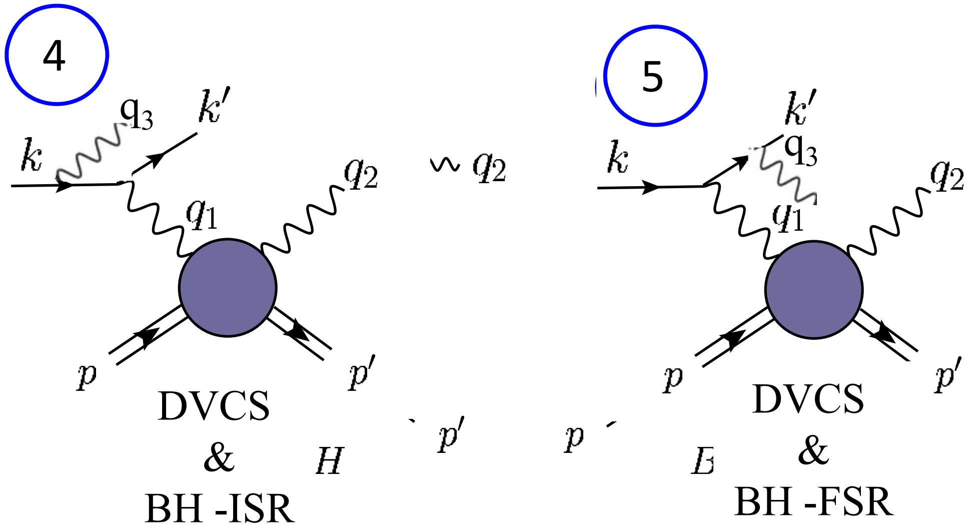
- **|t|-differential cross section is a very powerful tool**
  - **Gives precise access to GPD H**
  - **Fourier transform -> direct imaging in impact parameter space**



$$q(x,b^2) \approx \int dt e^{-ibt} \frac{d\sigma}{dt}$$

- DVCS cross section measurement -> BH must be removed [**uncertainty on BH xsec ~ 3%**]
- Asymmetry measurement -> BH must be part of the sample (we need the interference term)

What can be done experimentally to suppress BH



process 4:(ISR):

The photon is collinear to the outgoing scattered lepton

- ❖ if lepton bands little in magnetic field, EM-cluster of photon and lepton collapse to one
  - → no contribution (event will not pass DVCS selection criteria)

process 2:(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

- ❖ if photon and lepton are separated enough in magnetic field the cuts on slides 10 & 11 help to suppress the contribution
  - → remaining contribution needs to be estimated by MC and subtracted

process 5:(FSR):

The photon is collinear to the incoming beam and goes down the beam line (event will not pass selection criteria)

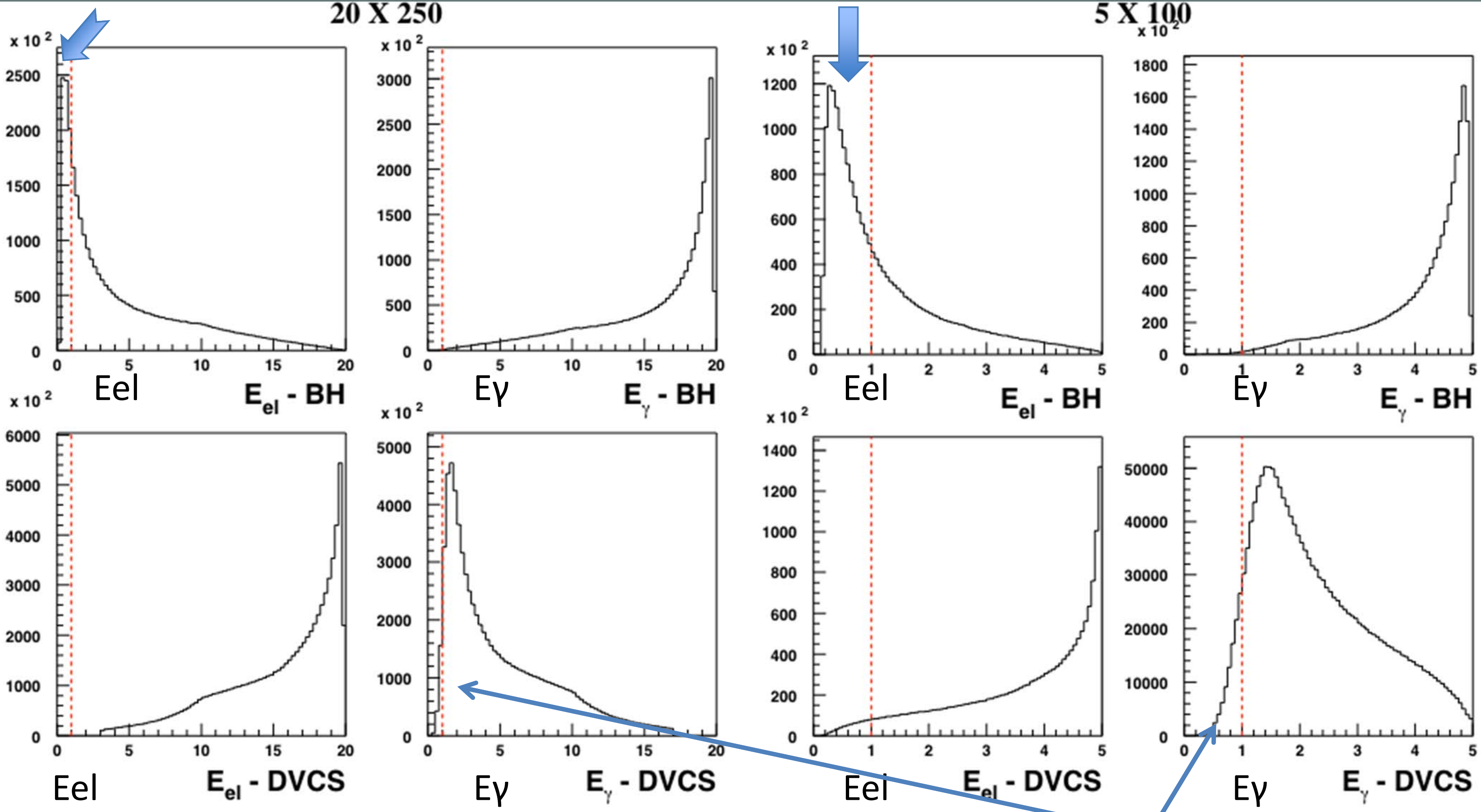
process 3:(FSR):

photon collinear to the outgoing scattered lepton

→ no/very small contribution

- ❖ 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)

BH rejection

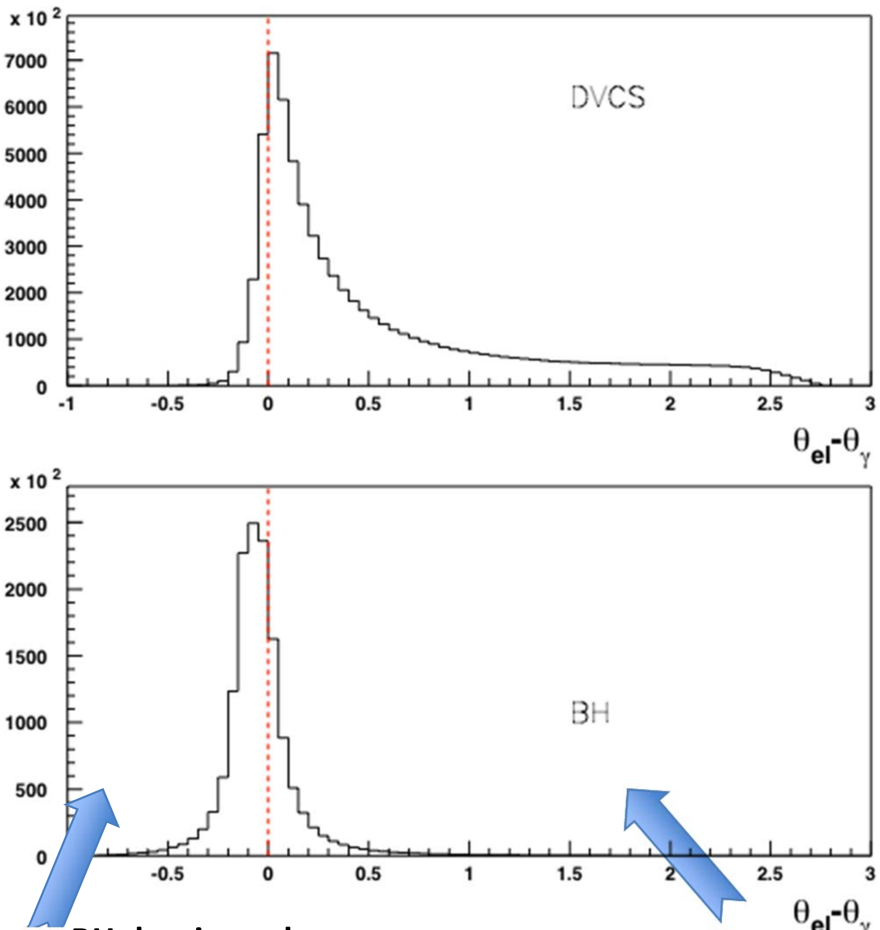


1. **BH electron has very low energy (often below 1 GeV)**
2. **Photon for BH (ISR) goes often forward (trough the beam pipe)**

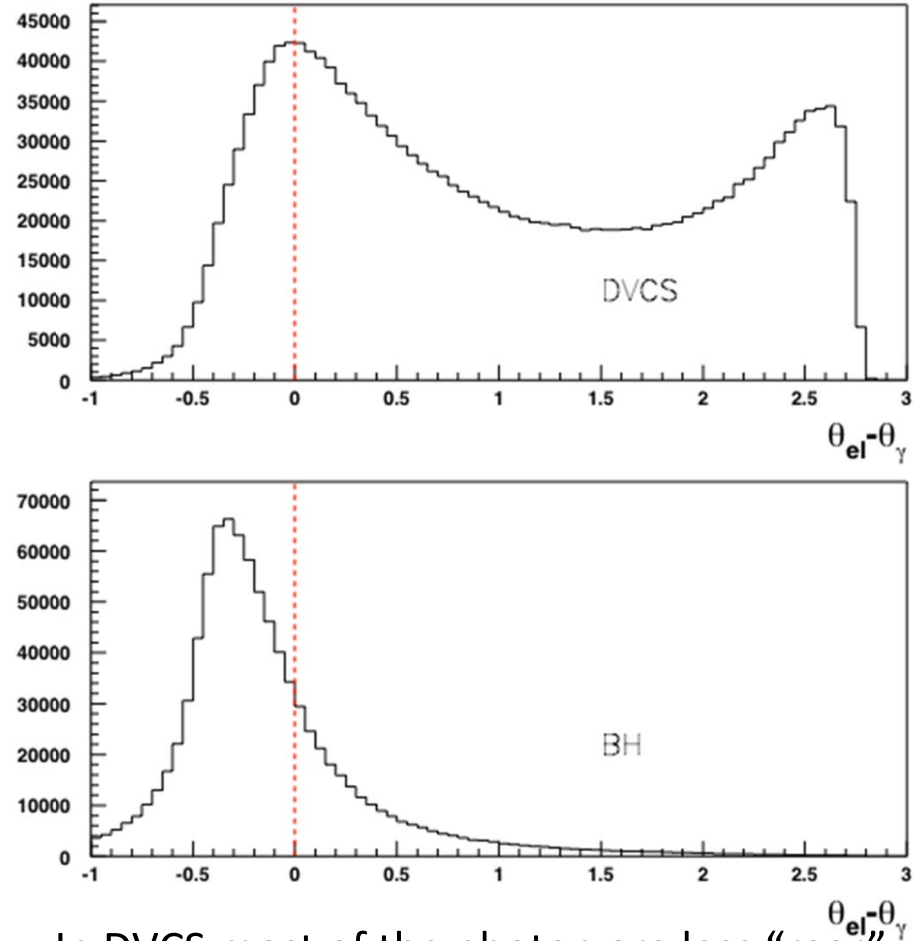
Important: em Cal must discriminate clusters above noise down to 1 GeV

BH rejection

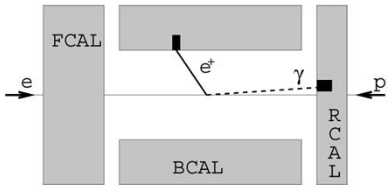
20 X 250



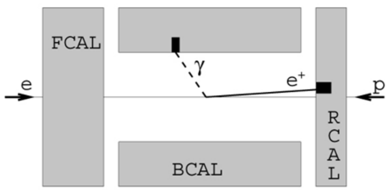
5 X 100



BH dominated

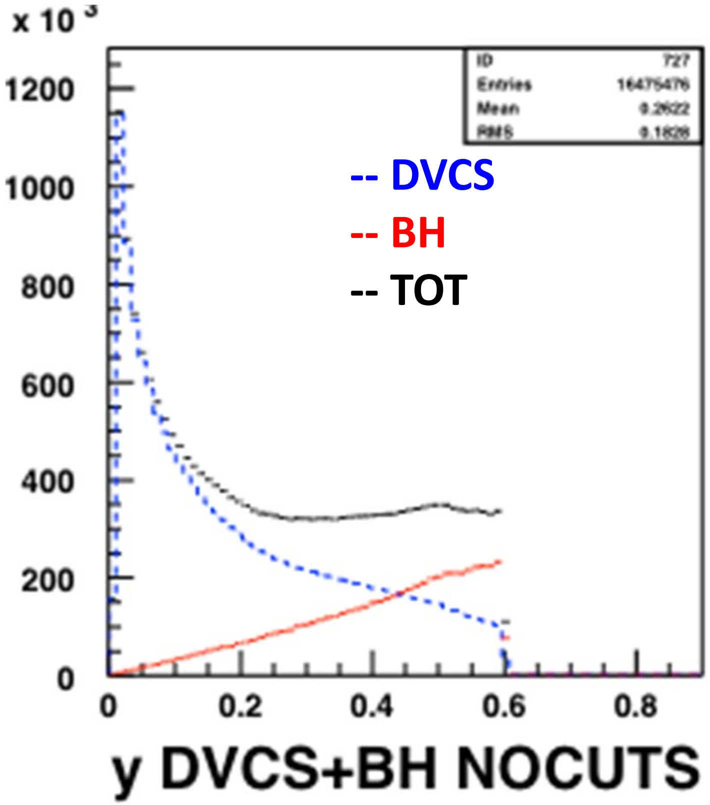


BH and DVCS

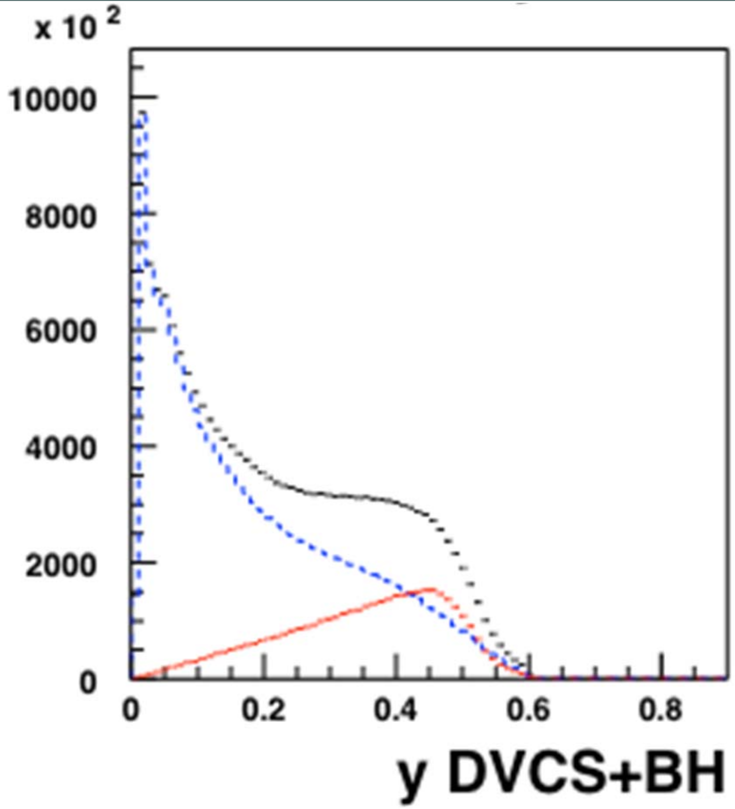


In DVCS most of the photon are less “rear”
Than the electrons:
(θel-θγ) > 0 → rejects most of the BH

BH rejection



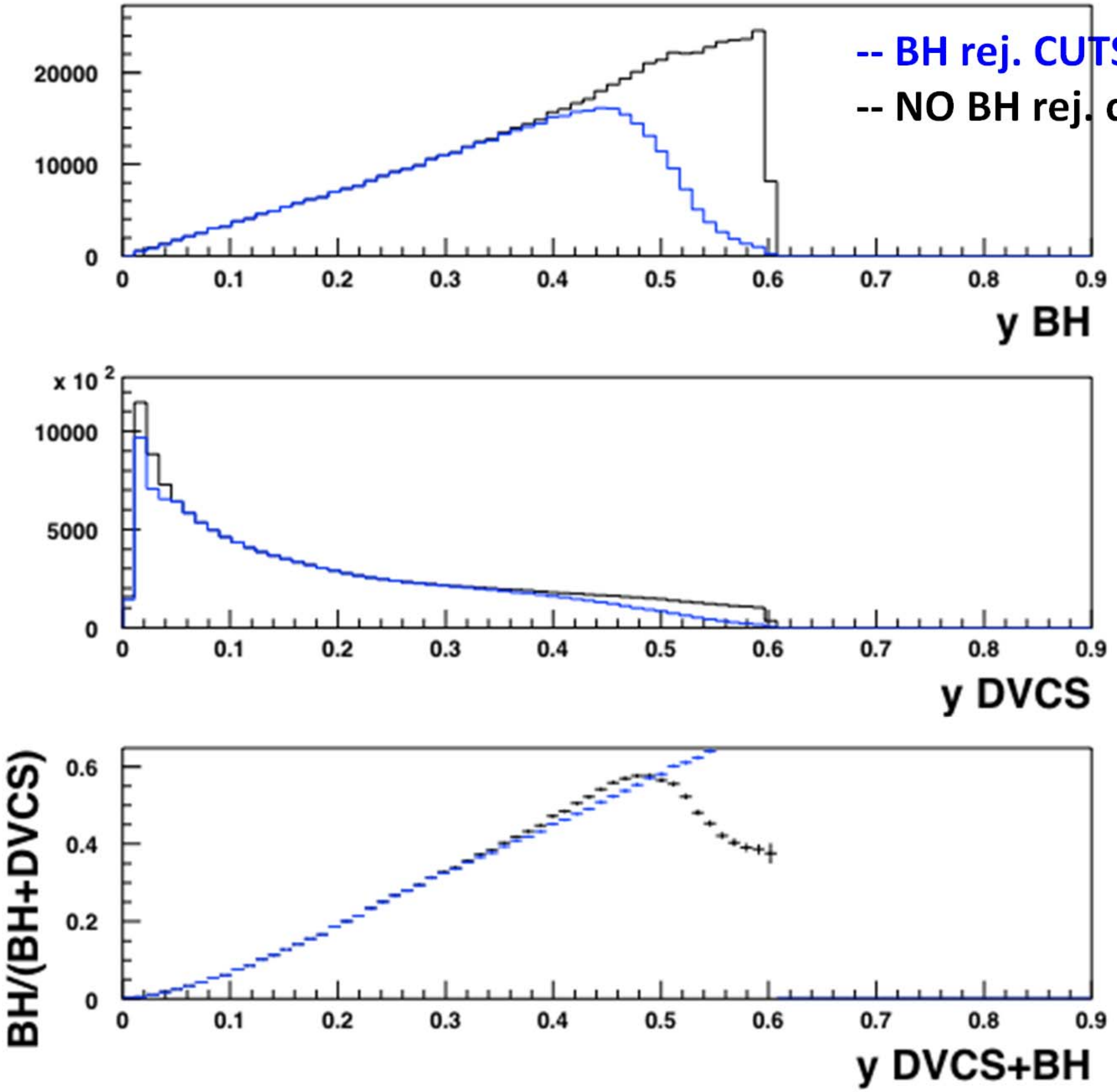
20x250



0.01 < y < 0.6
$10^{-4} < x < 0.1$
0.01 < |t| < 1.0 GeV2
1.0 < Q2 < 100 GeV2
No BH rejection cuts cuts applied

all kinematic cuts applied plus:
Theta_el – Theta_g > 0
Theta_el < pi – 0.02
Theta_g < pi – 0.02
E_el > 1 GeV
E_g > 1 GeV

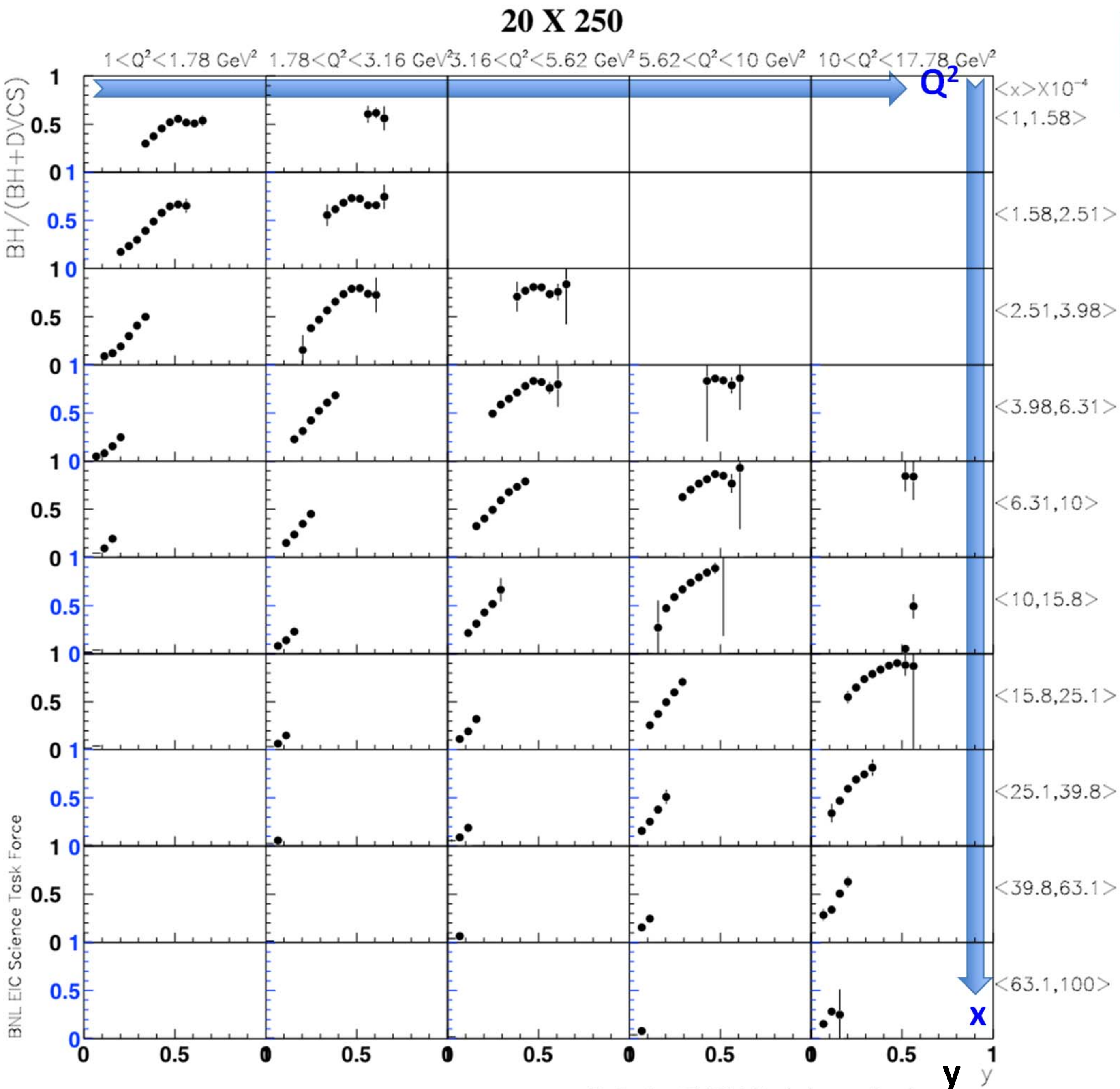
BH rejection



20 x 250 GeV^2

cuts keep BH below 60% at large y > 0.5

BH fraction

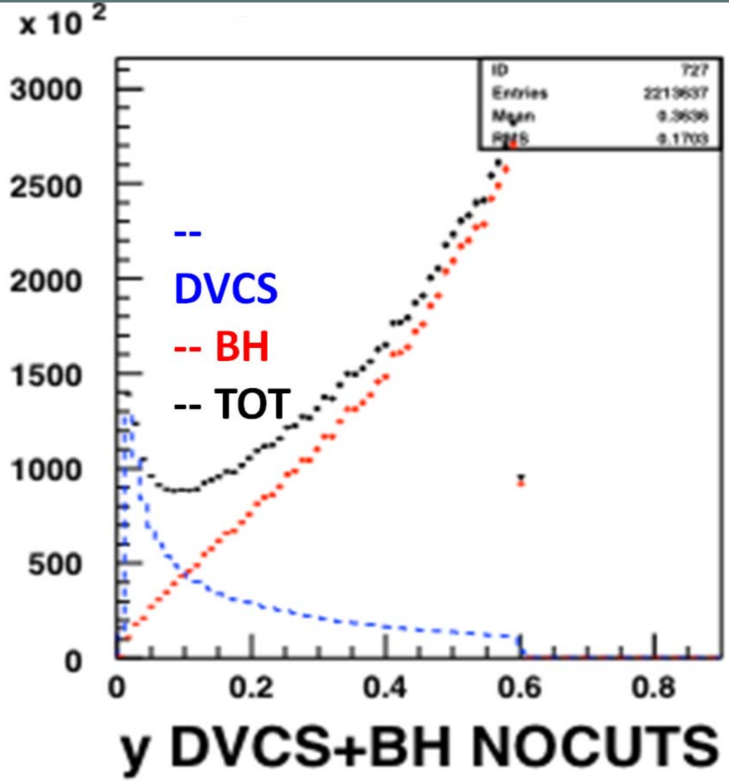


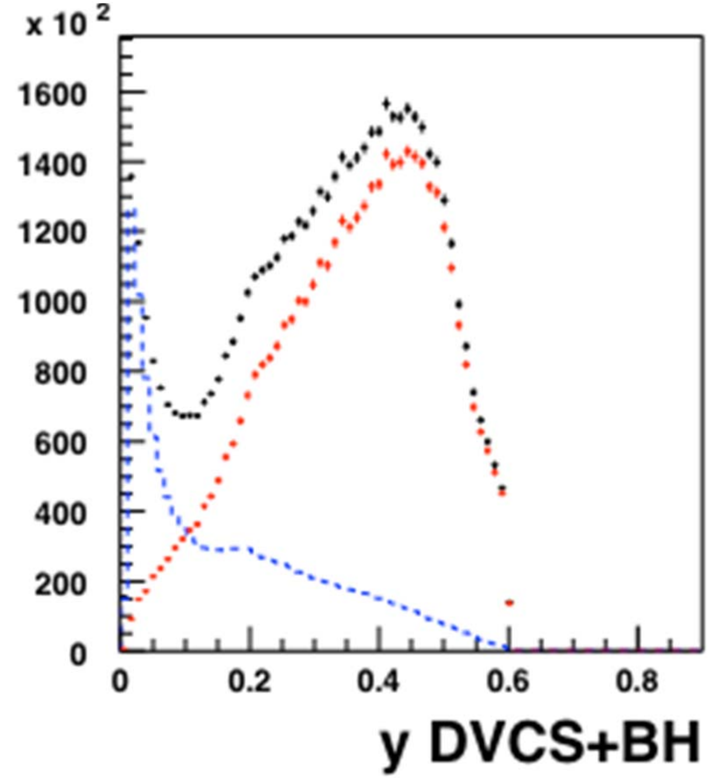
20 x 250 GeV²

BH subtraction will be not an issue for y<0.6

BH rejection

5x100





0.01 < y < 0.6
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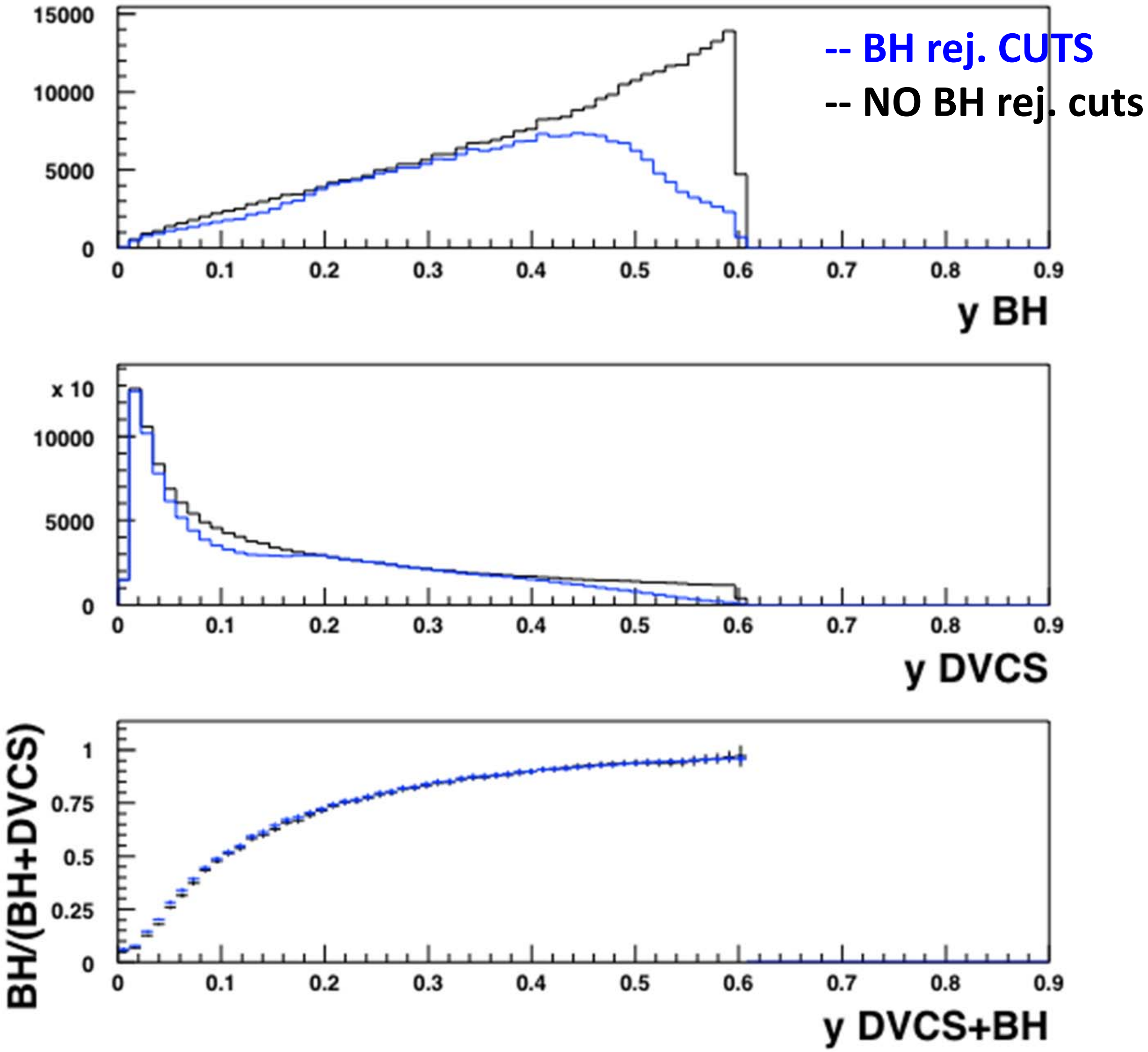
1.0 < Q2 < 100 GeV2
No BH rejection cuts cuts applied

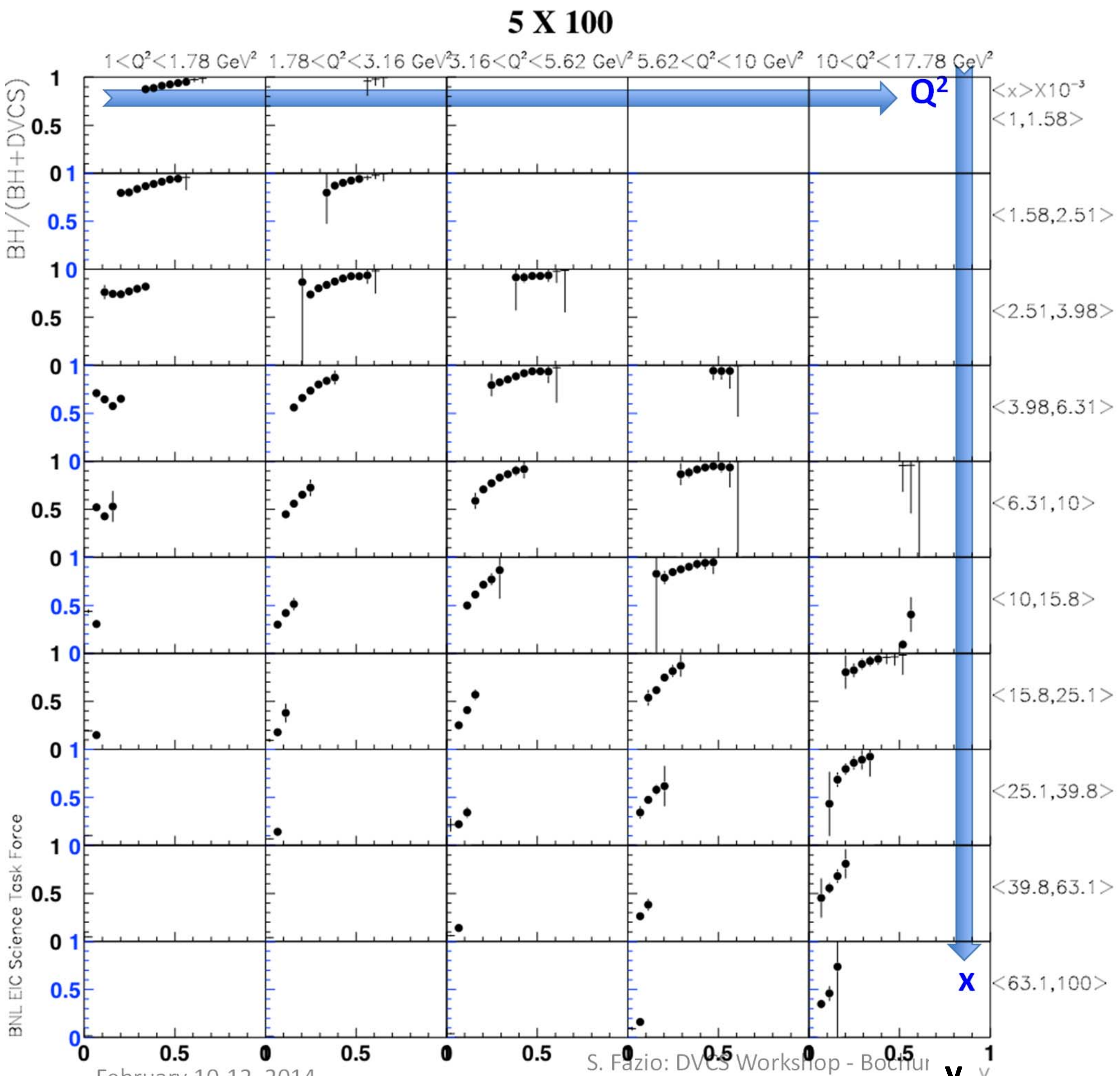
All kinematic cuts applied plus:
Theta_el – Theta_g > 0
Theta_el < pi – 0.02
Theta_g < pi – 0.02
E_el > 1 GeV
E_g > 1 GeV

BH rejection



5 x 100 GeV^2

BH rejection cut not very effective at low energies



BH fraction

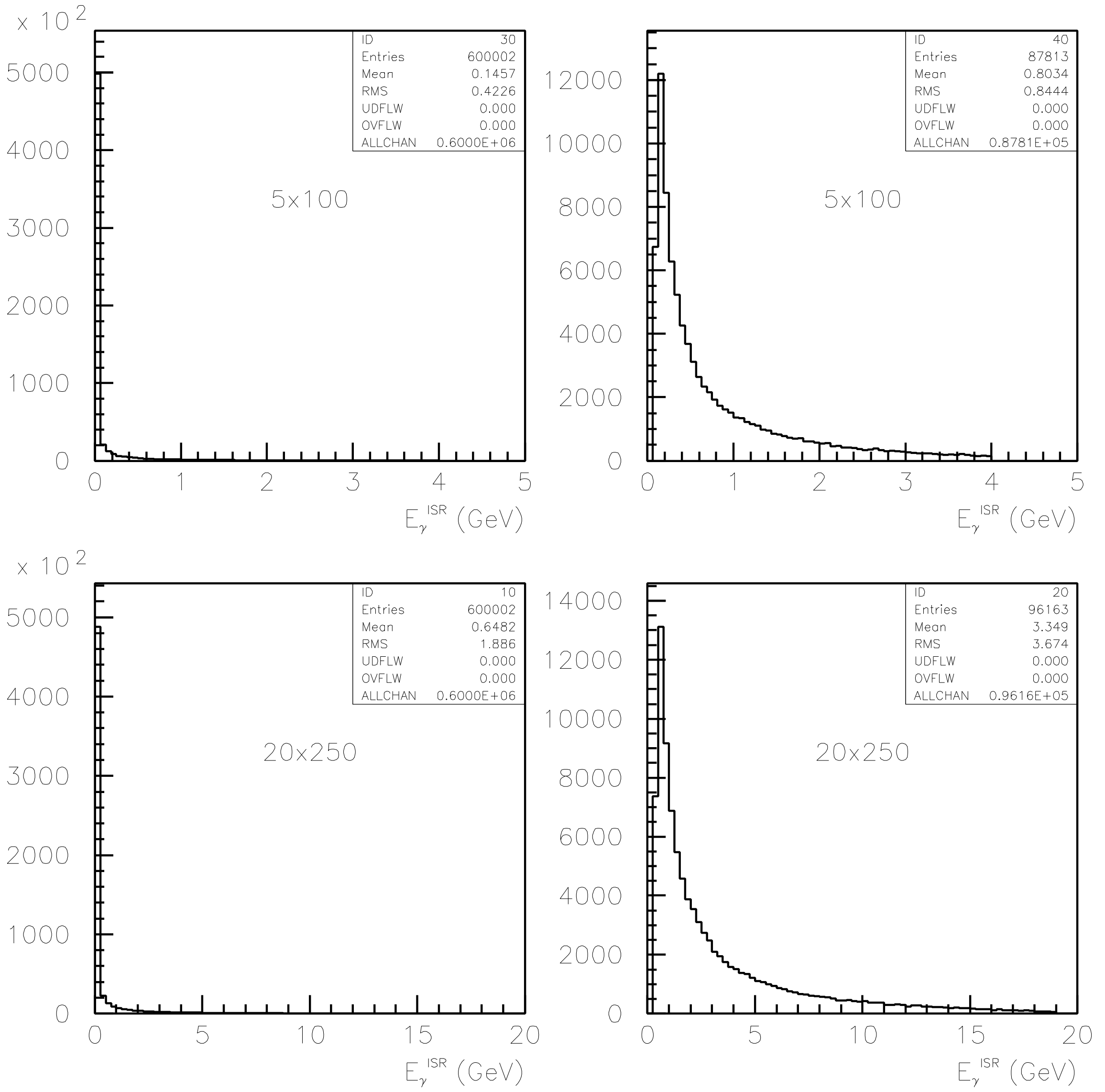
5 x 100 GeV^2

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

BUT…

Stage 1-2 overlapping:
x-sec. measurements in stage 2 at low-y can cross-check the BH subtrac. made in stage 1

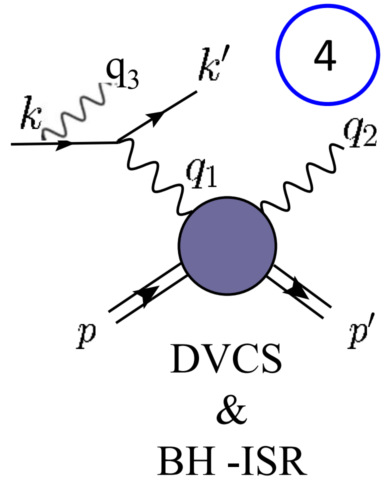
Contribution from ISR



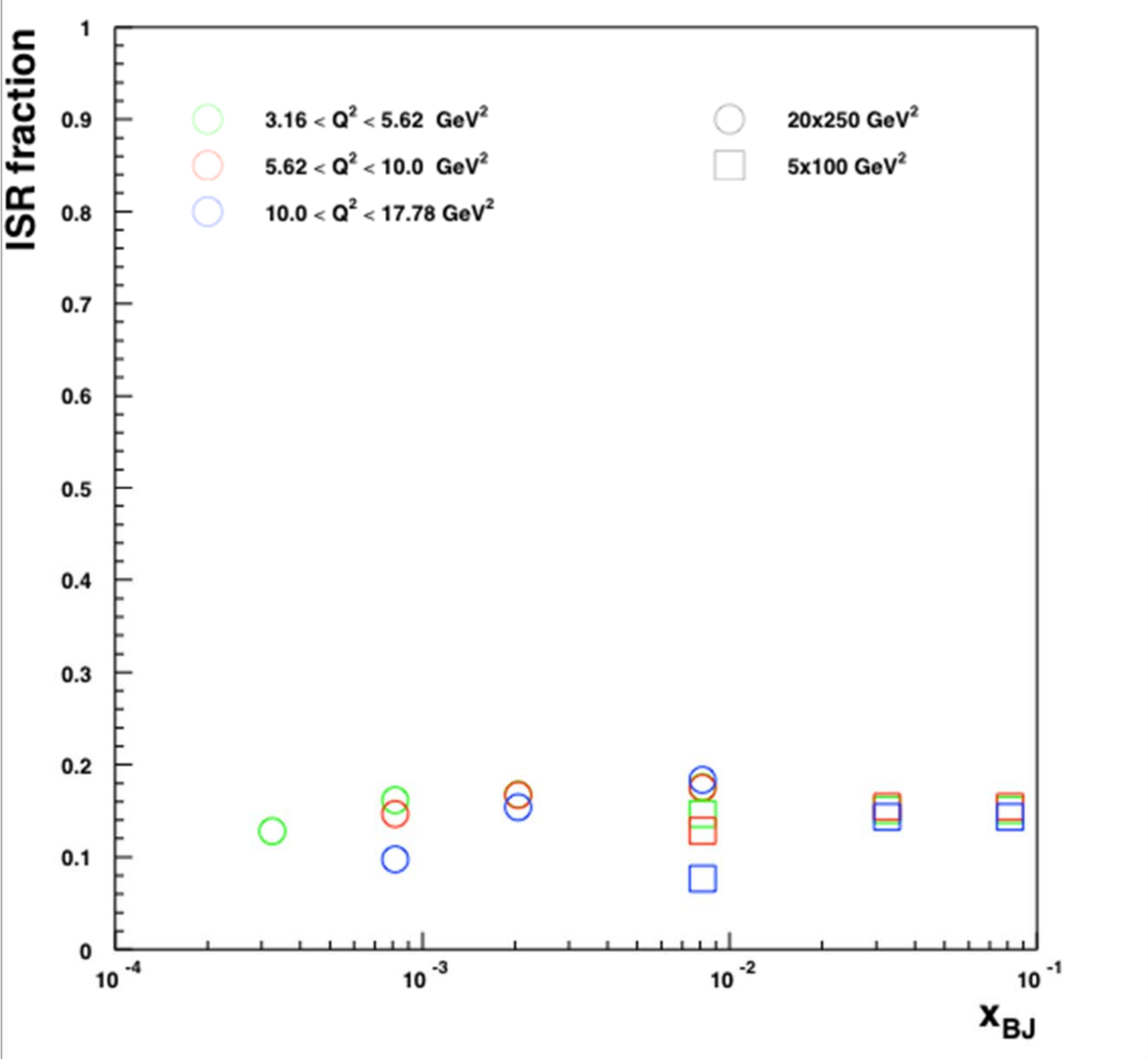
the energy spectrum of the emitted BH photon in process 4 for two different EIC beam energy combinations.

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 process 4 (ISR events) for 3 Q^2-bins as fct of x for 2 EIC beam energy combinations.

Only ISR with $E_\gamma = 0.02\ E_e$

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

BH – what we did and will do

- ✓ We applied BH rejection cuts as done at HERA. These cuts will be optimized as soon as the EIC detector is designed.

- ✓ We have assigned a 5% systematic uncertainty, and that accounts also for the uncertainties in subtracting BH from DVCS via a MC method.

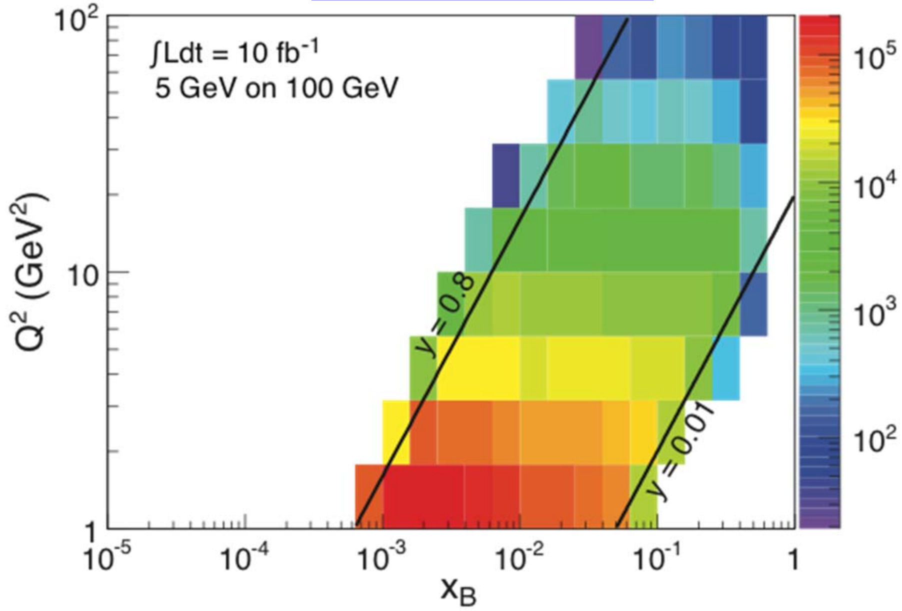
- ✓ Three of our theorist colleagues (H. Spiesberger, M. Stratmann and M. Hentschinski) currently working on the calculation of NLO BH, meaning to radiate a 2^{nd} photon from the electron line, which was estimated by M. Vanderhagen et al. to be a few %.

The white paper luminosity

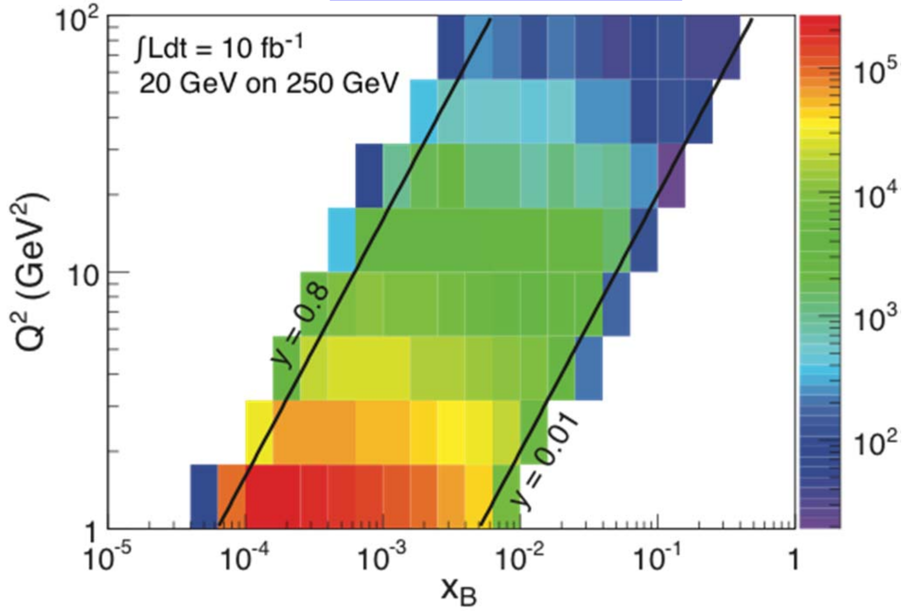
EIC lumi:
~10 fb^{-1} [1 year @ 5x100]
~100 fb^{-1} [1 year @ 20x250]

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

5 X 100 – stage 1



20 X 250 – stage 2



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

Data simulation & 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: $0.03 < |t| < 0.88$ GeV^2
- for $|t| > 1$GeV2 detect recoil proton in main detector
- $0.01 < y < 0.85$ 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

$0.01 < |t| < 0.85$ GeV^2 (Low-|t| sample)

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

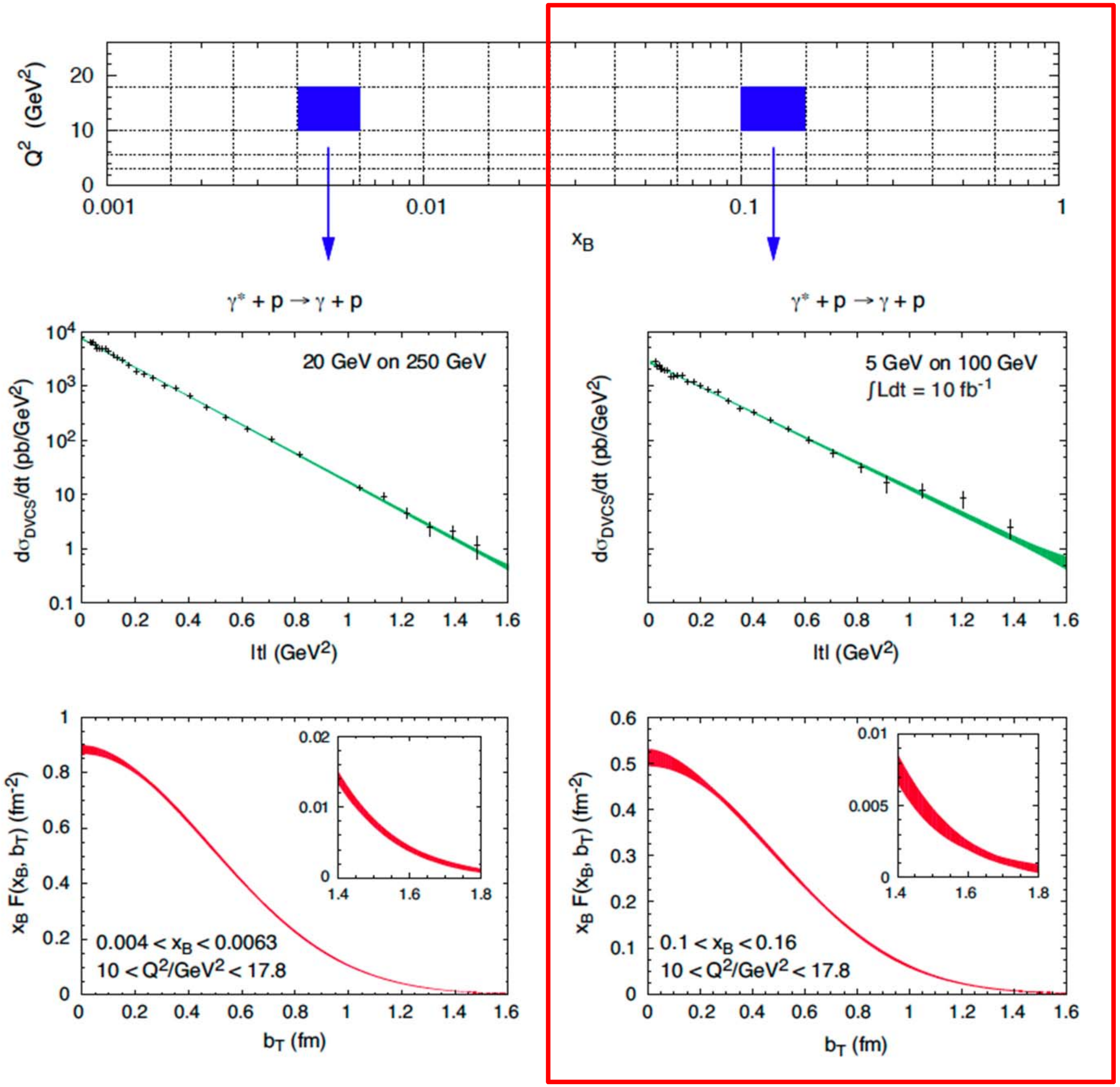
$1.0 < |t| < 1.5$ GeV^2 (Large-|t| sample)

- Xsec goes down exponentially
- requires much longer data taking

Stage 1: 5 X 100 GeV → **~10 fb^{-1} (~ 10 months)**

Stage 2: 20 X 250 GeV → **~100 fb^{-1} (~ 1 year)**

From the EIC white paper



~ 1 year of data taking

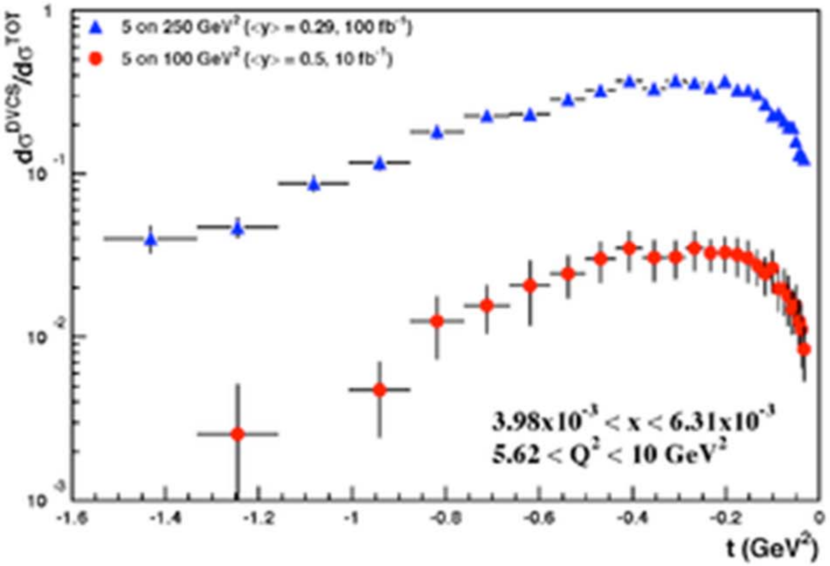
Simulation:

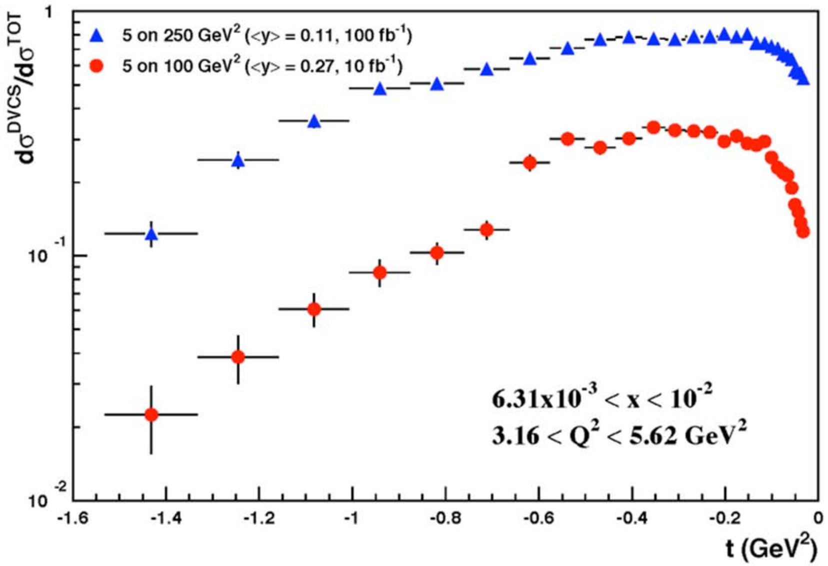
- **y>0.01 (detector acceptance)**
- **Detector smearing**
- **The |t|-binning is (3*reso)**
- **Exponential |t|-dependence exp(B*|t|)**
- **B-slope=5.6 compatible with H1 data, to facilitate Dieter's global fitting**
- **5% systematic uncertainties**

Rosenbluth separation

$$\frac{d\sigma}{dxdyd\,|\,t\,|\,d\phi d\varphi} = \frac{\alpha^3 x_B y}{16\left|e^3\right|\pi^2 Q^2\sqrt{1+\varepsilon^2}}\left|\mathcal{A}_{DVCS} + \mathcal{A}_{BH} + \mathcal{A}_{INT}\right|$$

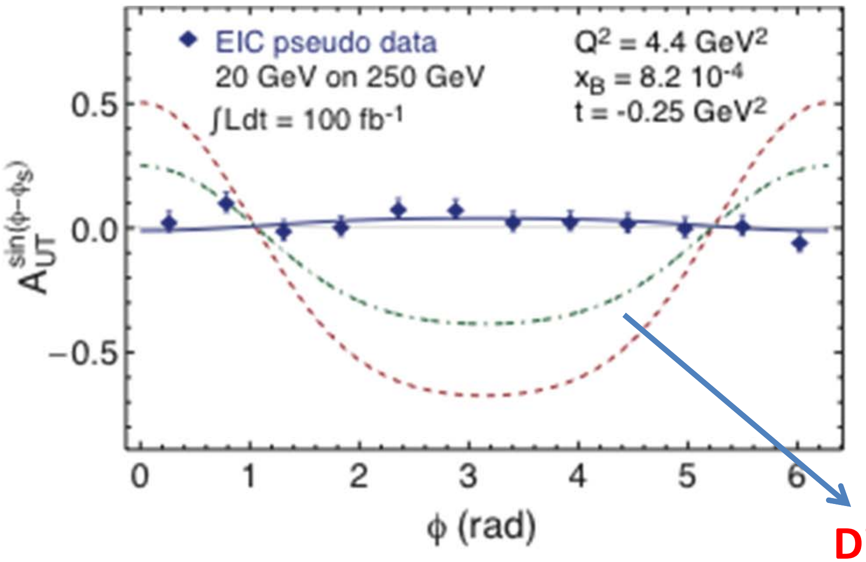
To access GPD H, we need a Rosenbluth separation of the electroproduction cross section into its parts

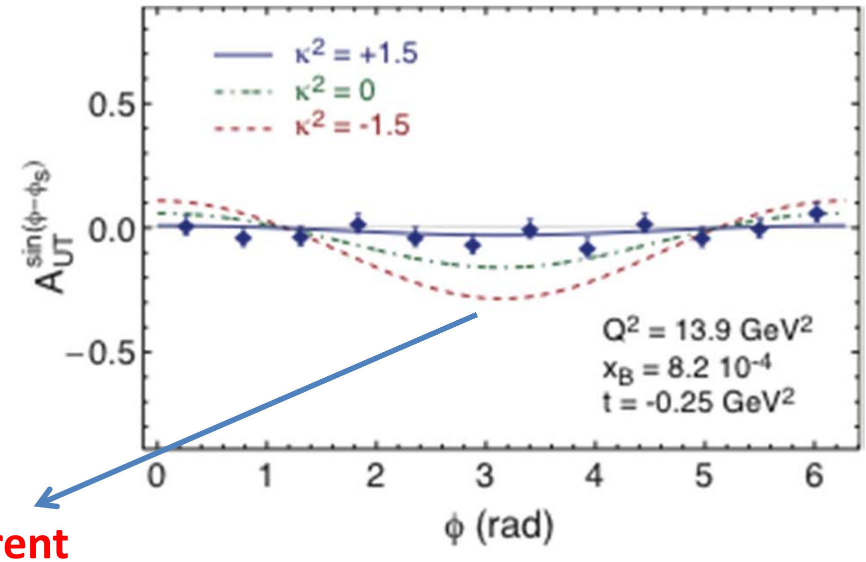




- The statistical uncertainties include all the selection criteria to suppress the BH
- exponential |t|-dependence assumed

Transverse target-spin asymmetry





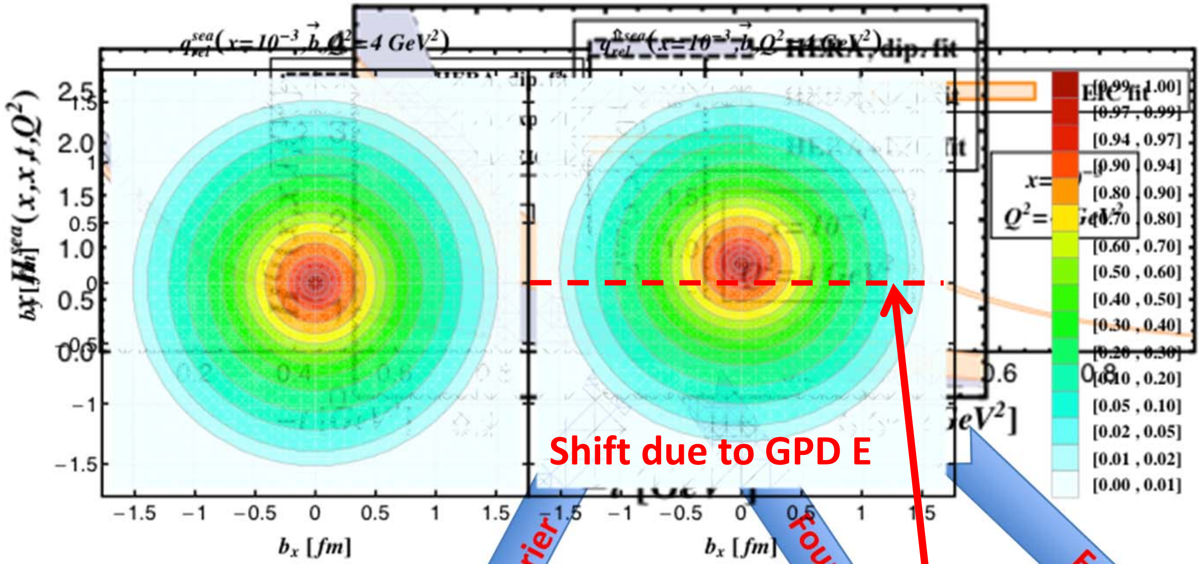
Different assumptions for E

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

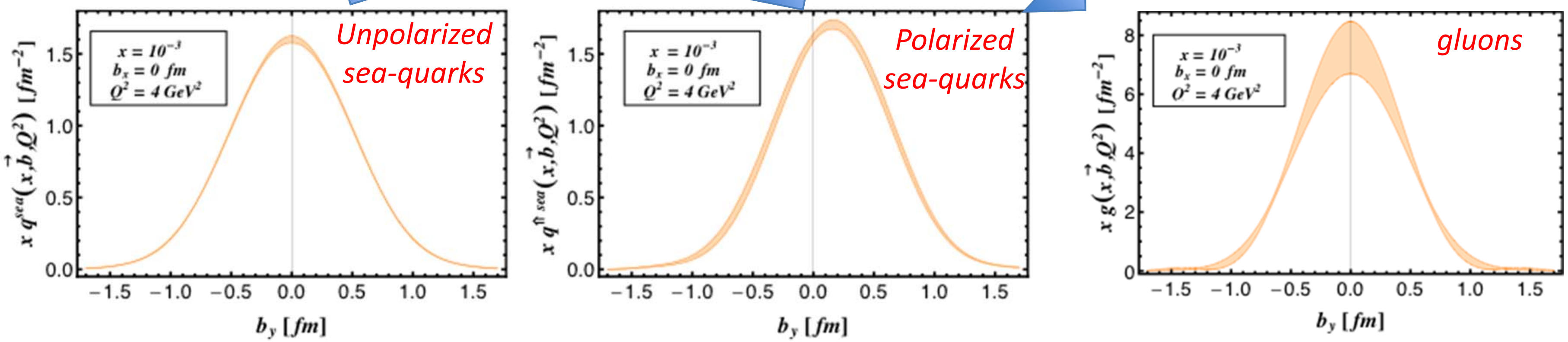
$sin(\Phi_T-\phi_N)$
governed by E and H

Gives access to GPD E

Imaging



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



- A global fit over all mock data was done, based on the GPDs-based model: [K. Kumerički, D Müller, K. Passek-Kumerički 2007]
- Known values *q(x)*, *g(x)* are assumed for H^q, H^g (at t=0 forward limits E^q, E^g are unknown)

Impact of eRHIC:

- ✓ Excellent reconstruction of H^{sea}, and H^g (from $d\sigma/dt$)
- ✓ Reconstruction of GPD E (connection to the orbital momentum g-sum role)

Paper on DVCS at EIC

JHEP

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Deeply virtual Compton scattering at a proposed high-luminosity Electron-Ion Collider

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ABSTRACT: Several observables for the deeply virtual Compton scattering process have been simulated in the kinematic regime of a proposed Electron-Ion Collider to explore the possible impact of such measurements for the phenomenological access of generalized parton distributions. In particular, emphasis is given to the transverse distribution of sea quarks and gluons and how such measurements can provide information on the angular momentum sum rule. The exact lepton energy loss dependence for the unpolarized t-differential electroproduction cross section, needed for a Rosenbluth separation, is also reported.

KEYWORDS: QCD Phenomenology, Deep Inelastic Scattering (Phenomenology)

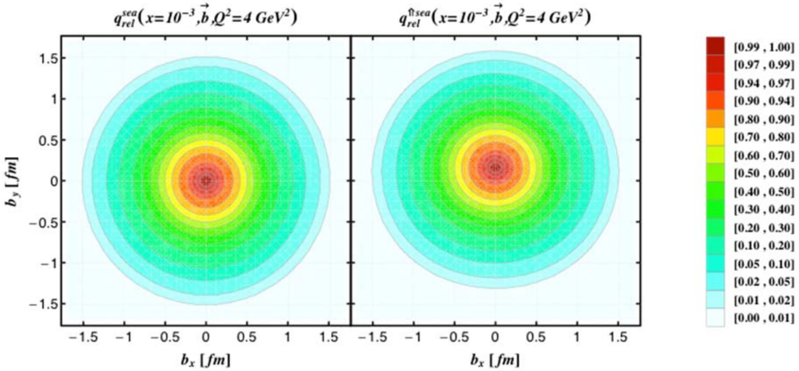
ARXIV EPRINT: 1304.0077

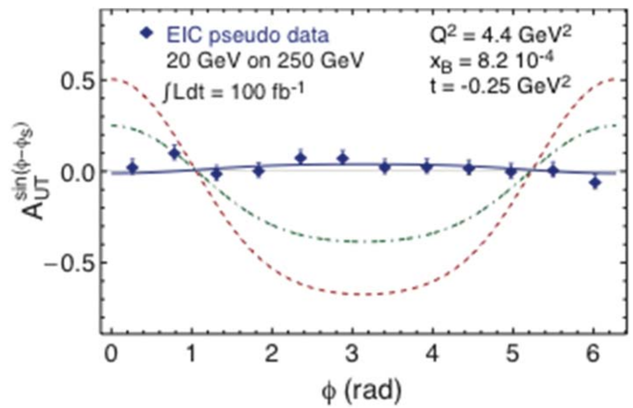
JHEP09(2013)093

For all details and more recently published paper

E.C. Aschenauer, S. Fazio, K. Kumericki, and D. Muller

JHEP09(2013)093 [arXiv:1304.0077]





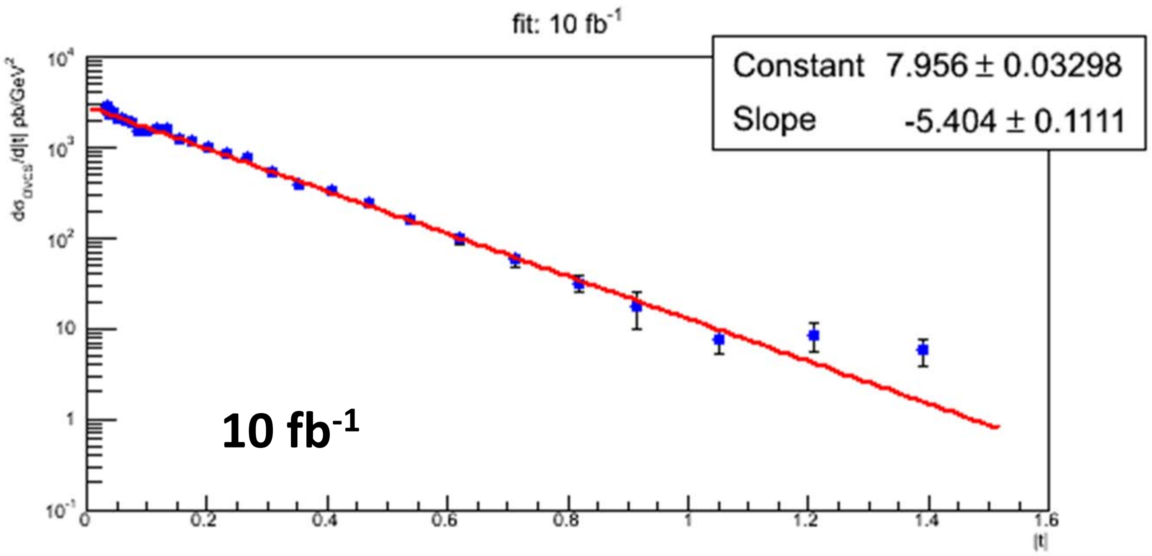
what can we do if 1 fb^{-1} ?

Different scenarios can lead to lower luminosity machines. How luminosity hungry is the DVCS measurement for a precise constraining of the GPDs?

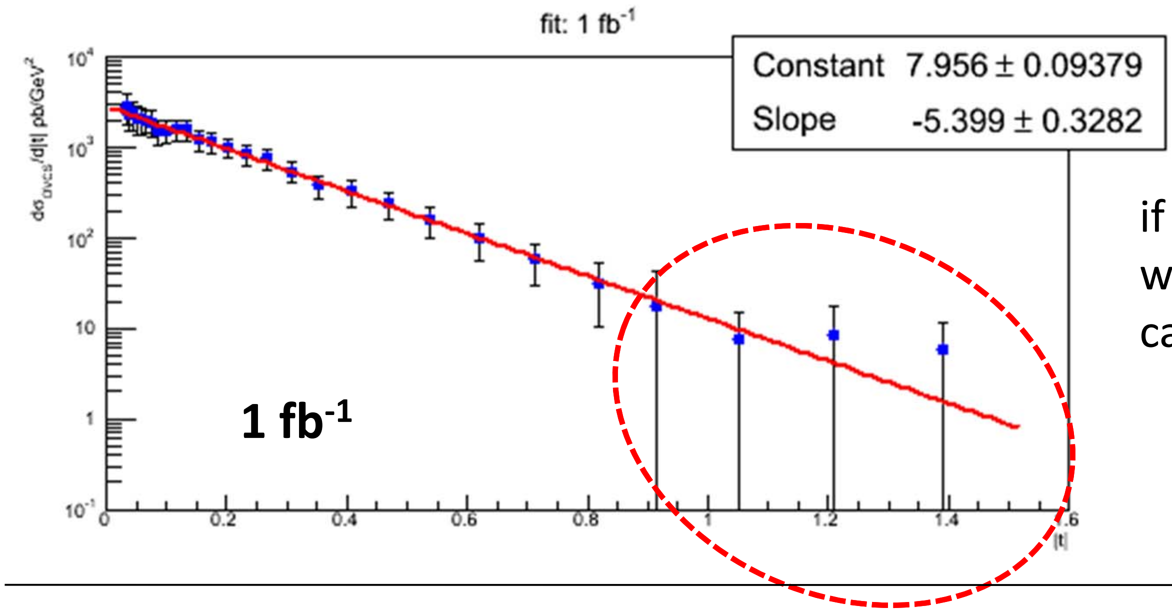
Can we do already some imaging with an integrated lumi of 1fb^{-1} ?

- **5% systematic uncertainty and added in quadrature to the statistical uncertainty**
- **Exponential fit: A*exp(B*t) gives the values and errors of the normalization A and the slope B plus the correlation coefficient c**
- **The fitted values (A, dA, B, dB, c) are used to compute errors using method of eigenvector distributions and then the error bands for the cross section and the partonic distribution using the Fourier Bessel function integral (Markus Dihel's code used for the white paper). This code, in calculating the error bars, considers the |t| range achievable experimentally and extrapolates beyond**

We want to study the impact of having only a low energy – low luminosity eRHIC at hand

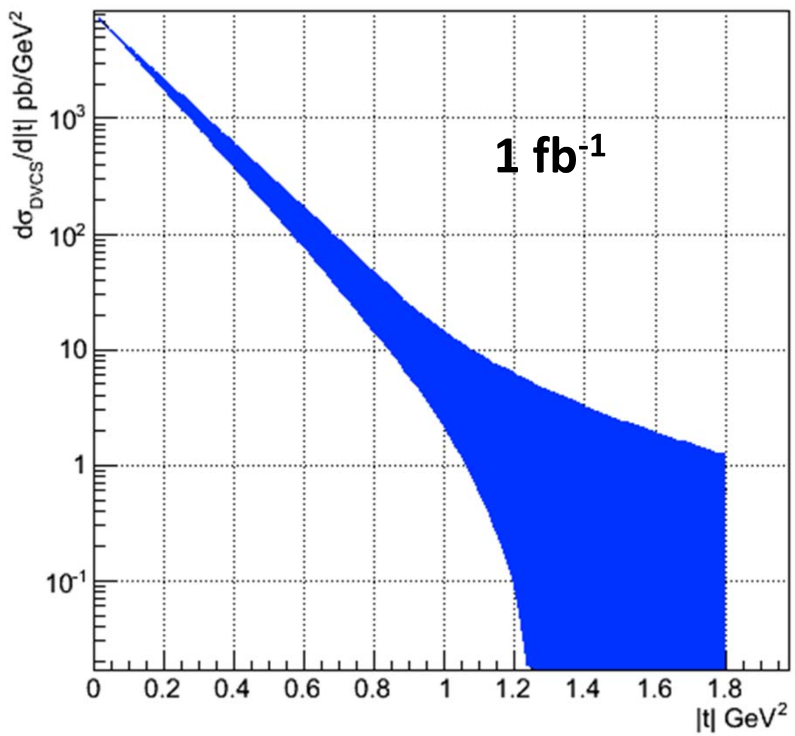


Beam energy: 5x100 GeV^2
10 < Q^2 < 17.78 GeV^2
0.1 < x < 0.158

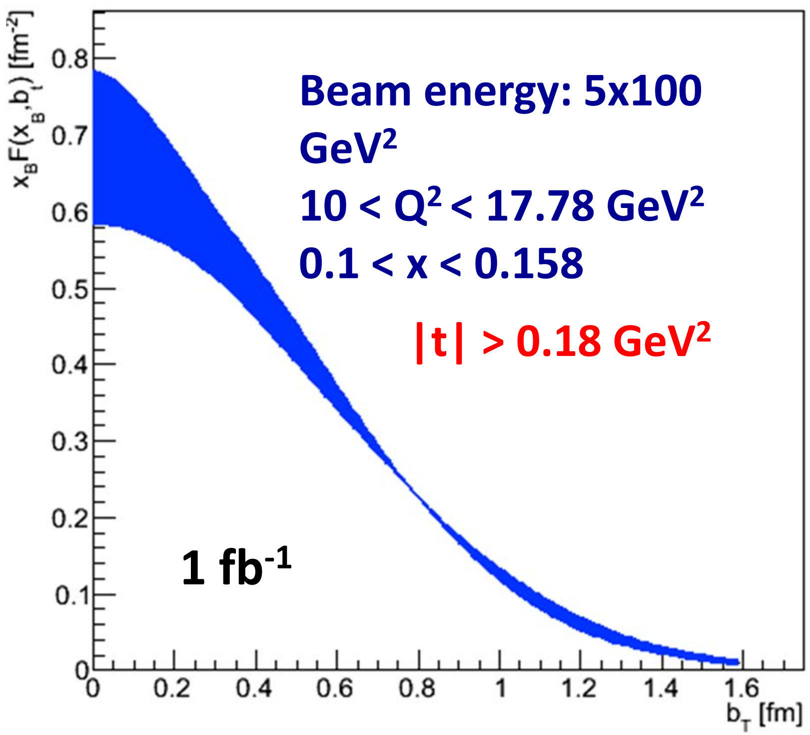


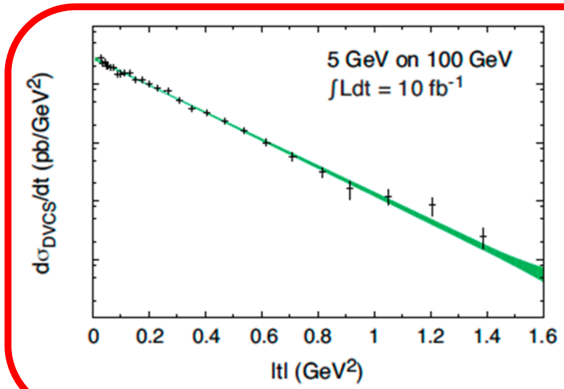
if we collect one order less lumi: with 1 fb^{-1} only the |t|<0.85 GeV^2 can be measured

DVCS - differential cross section



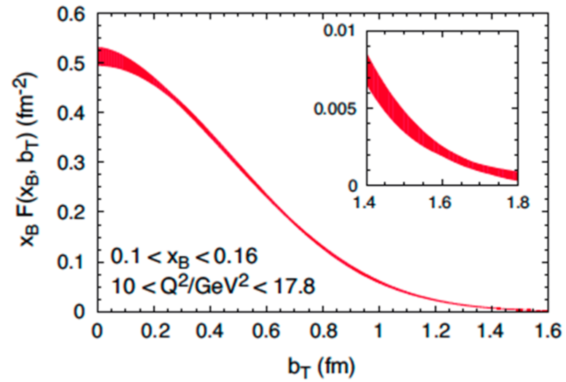
DVCS - parton distribution





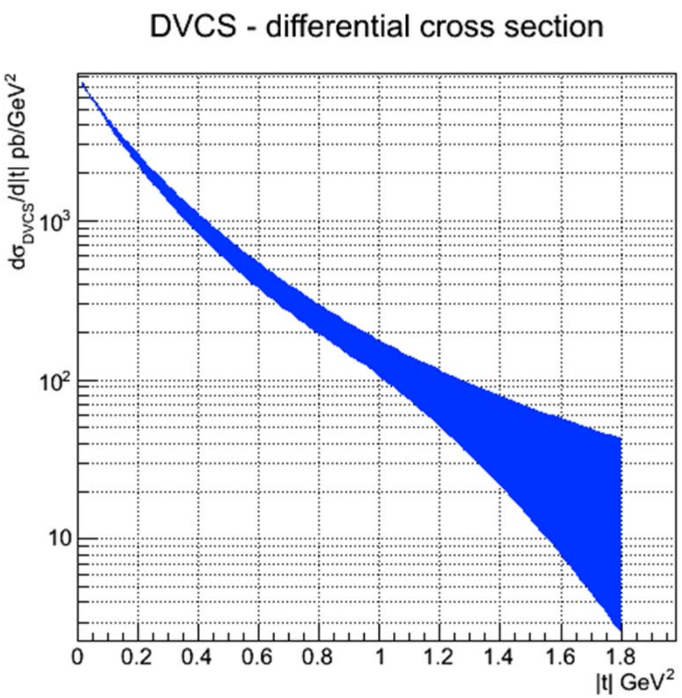
TO BE COMPARED WITH
(white paper)

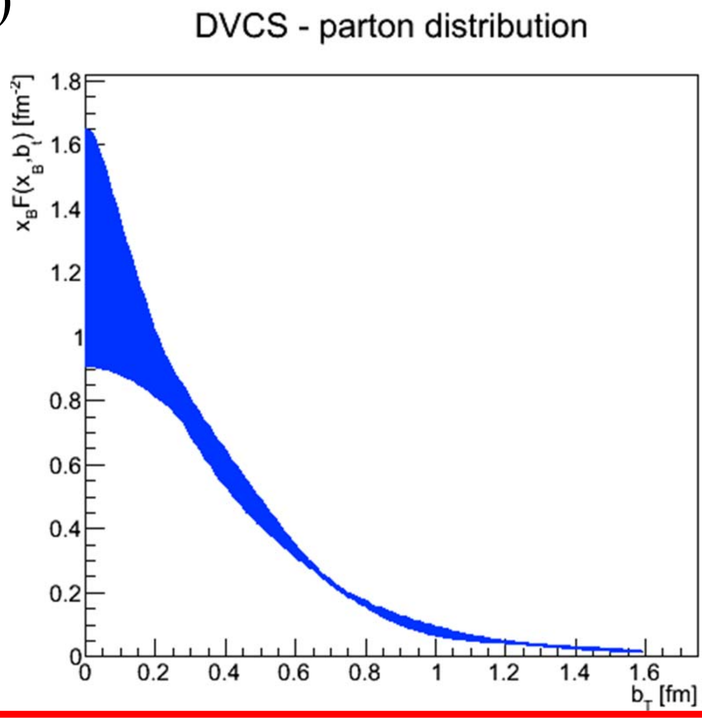
~ 1 y of data taking

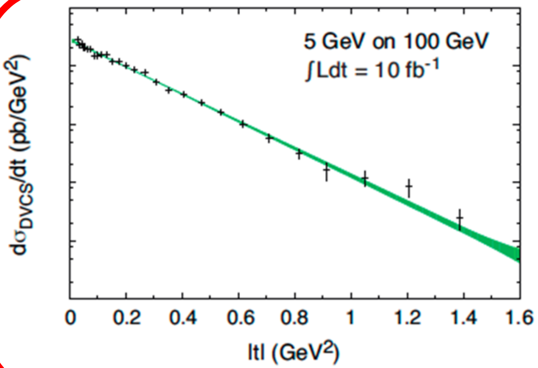


The same exercise as in the previous slide but this time assuming a dipole dependence instead of an exponential one.

$$func. = \frac{A}{(1 + B \cdot |t|)^2}$$

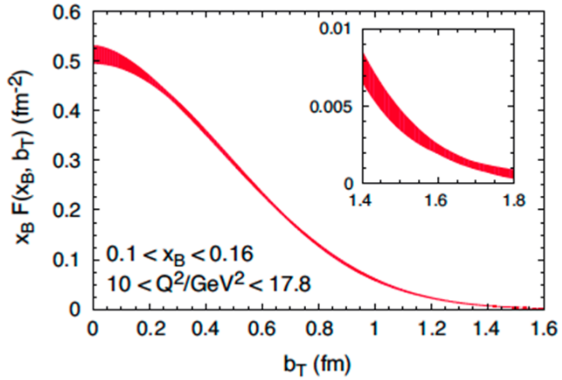




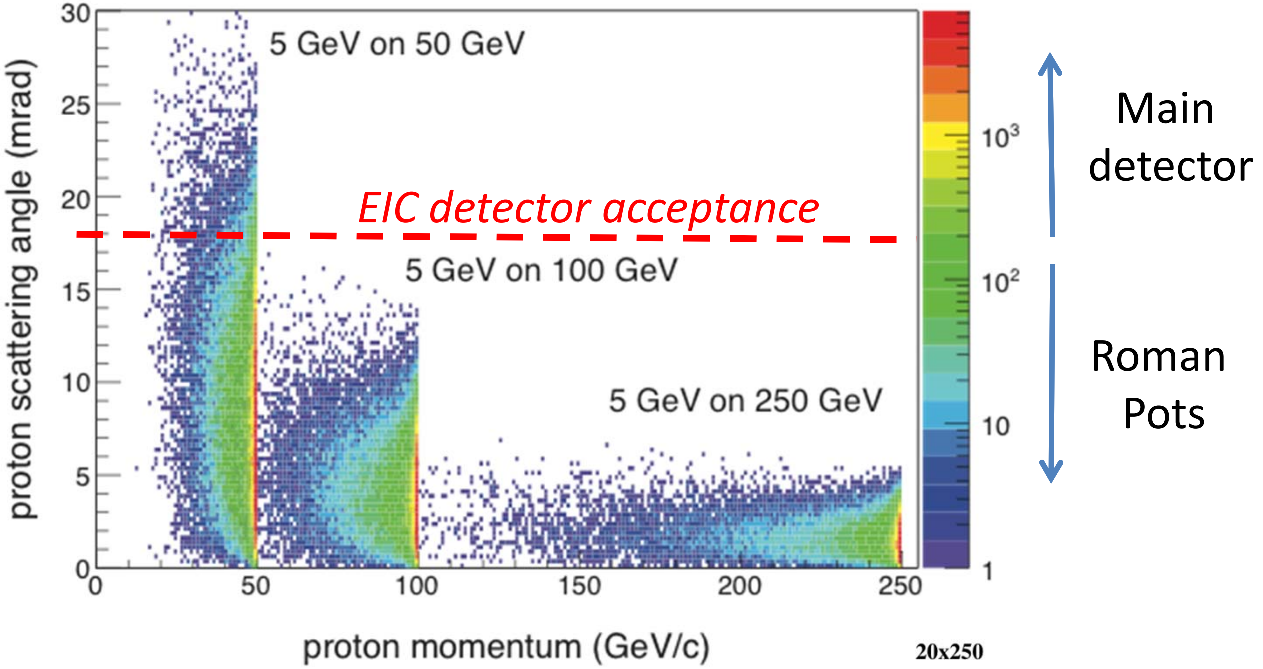


TO BE COMPARED WITH (white paper)

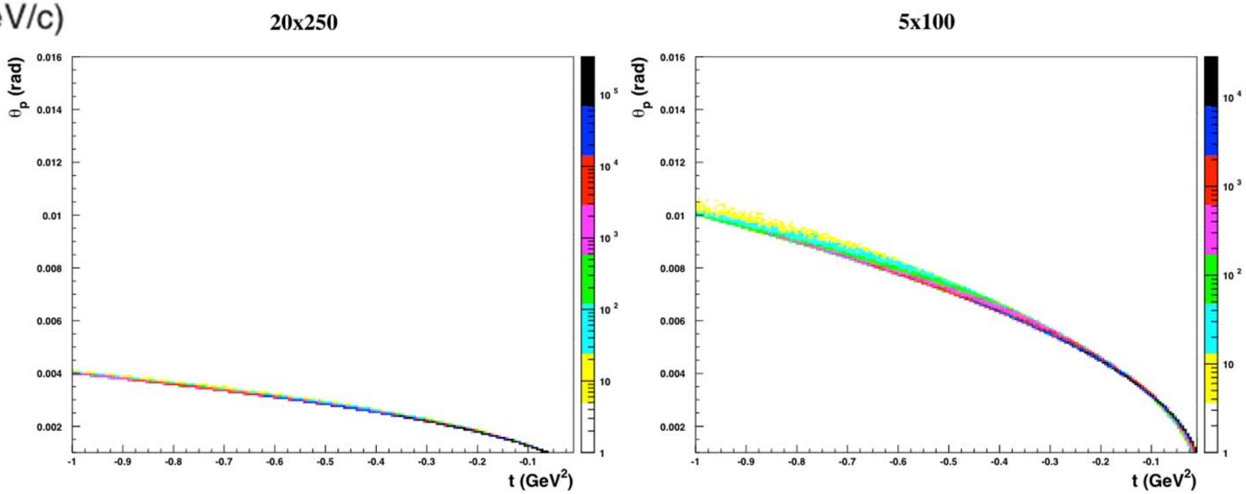
~ 1 y of data taking



Proton acceptance



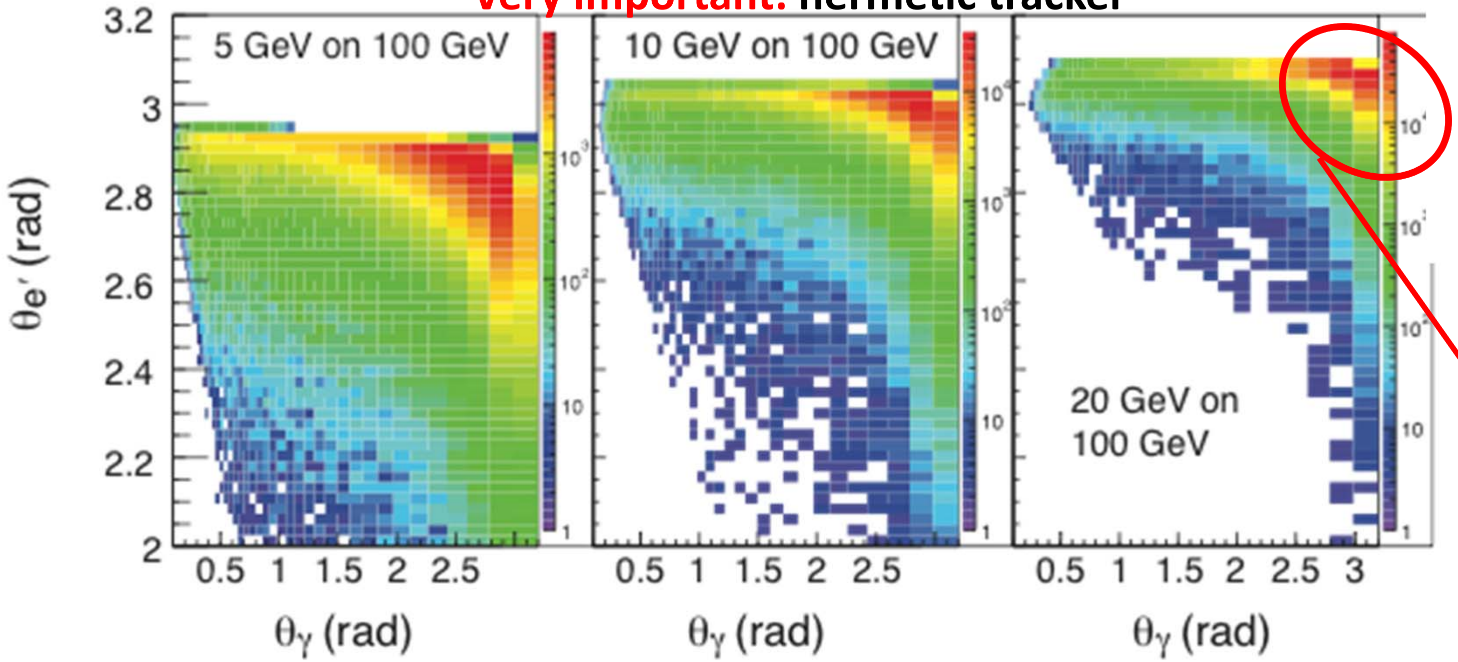
leading protons are never in the main detector acceptance at EIC (stage 1 and stage 2)

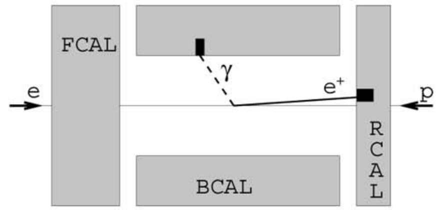


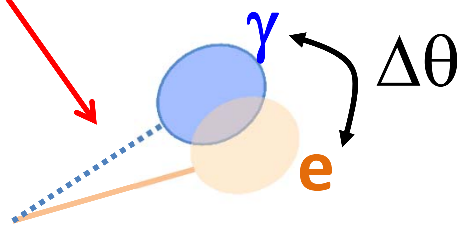
NB: need to measure leading protons in RP in the whole |t|-range

DVCS – clusters discrimination

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 an 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 $\pi^0 \rightarrow \gamma\gamma$

Summary of detector requirements

What are the basic requirements for a suitable detector?

Important for exclusive DIS:

- Hermetic Central Tracking Detector
- Electromagnetic calorimeter with good energy resolution and fine granularity
  - Measure low energy clusters down to ~900 MeV
  - Rear Encap → capable of discriminating clusters down to $\Delta\theta = 1$deg
- Preshower em cal → π^0 background
- Forward hadronic calorimeter → rapidity gap and p.dis. background
- Roman pots (and with excellent acceptance, ~5% momentum resolution)

Outlook: we need a full detector simulation to better evaluate systematics and better constraining resolution requirements

An EIC detector CONCEPT

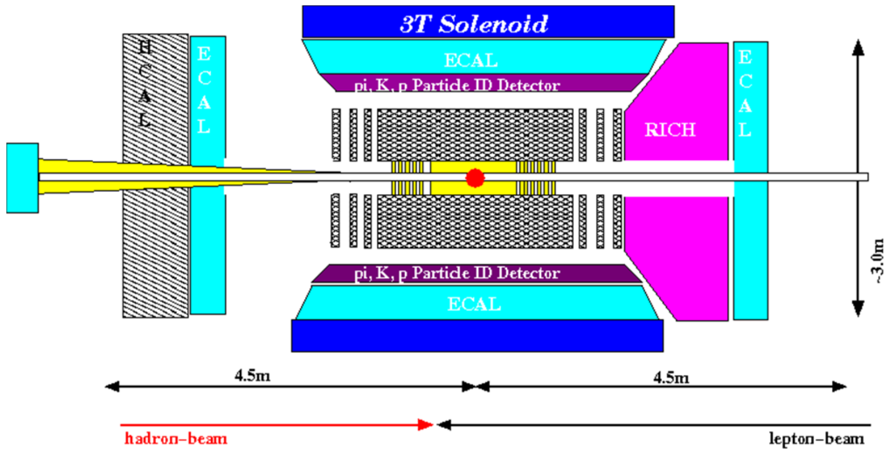
Extremely wide physics program puts stringent **requirements** on detector performance

- high acceptance -5 < η < 5
- good PID (π,K,p and lepton) and vertex resolution
- same rapidity coverage for tracking and calorimeter
  → good momentum resolution, lepton PID
- low material density because of low scattered lepton p
  → minimal multiple scattering and brems-strahlung
- very forward electron and proton/neutron detection
- Fully integrated in machine IR design

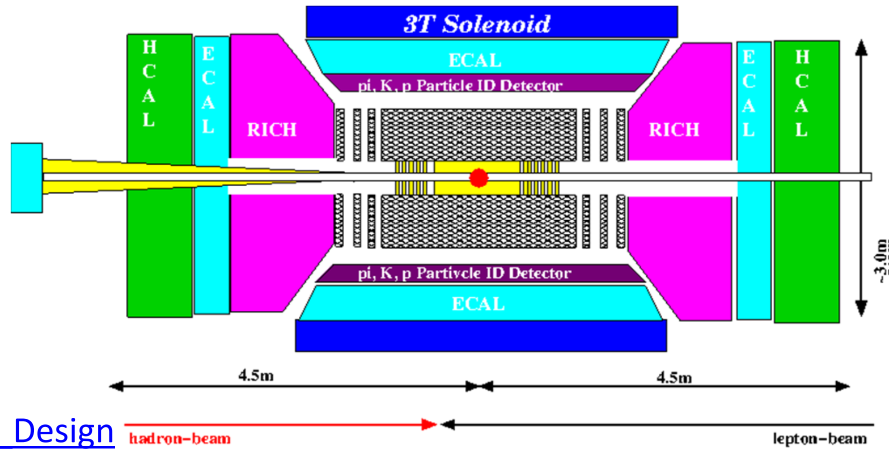
Full Geant4 Model based on Generic EIC R&D detector concepts

https://wiki.bnl.gov/eic/index.php/DIS:_What_is_important
https://wiki.bnl.gov/eic/index.php/ERHIC_Dedicated_Detector_Design

Phase-I (5 – 10 GeV):



Phase-II (>10 GeV):



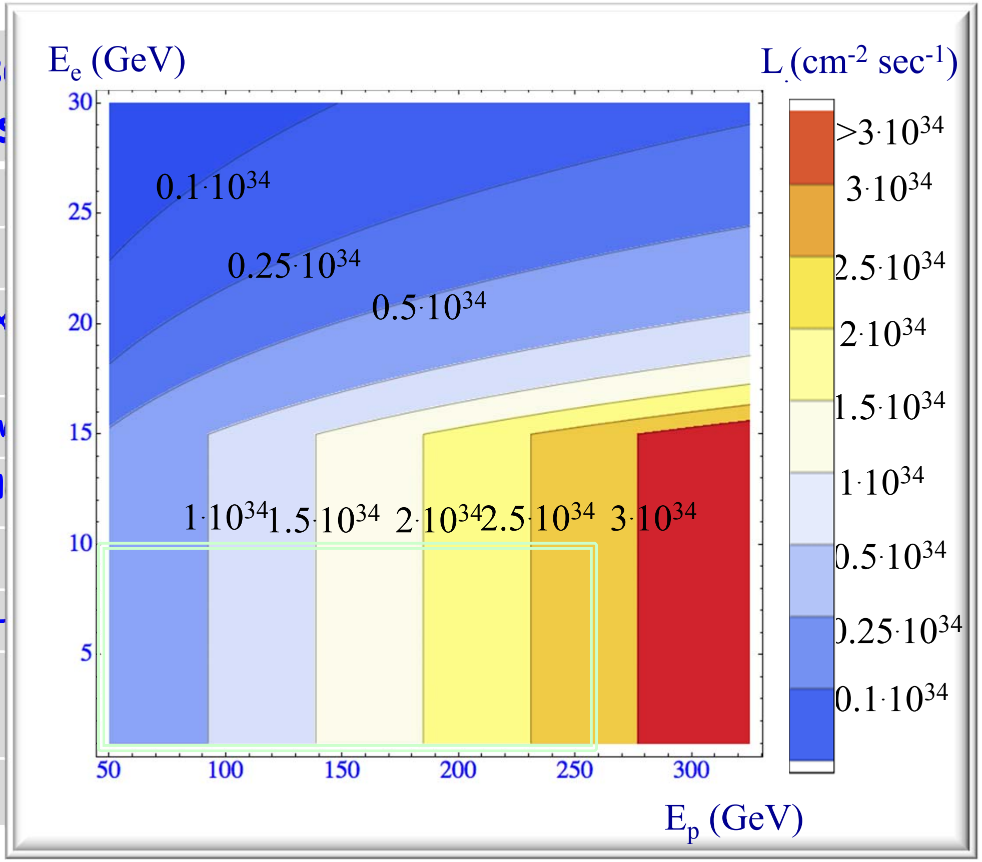
Summary

- **Simulation shows how an EIC can much improve our knowledge of GPDs**
- **Subtraction of BH, important for xsec measurement, has been studied in detail as well as ISR corrections to DVCS.**
- **With the large luminosity collected as in the white paper, a fine binning of x-sec and symmetries will be possible, uncertainties mostly dominated by systematics leading to an accurate 2+1D imaging of the polarized and unpolarized quarks and gluons inside the hadrons**
- **if we assume the collection of only 1 fb^{-1}, measurements at large-|t| will be lost and the impact on the quality of the imaging will be drastically reduced, especially at lower impact parameter values**

Back up

eRHIC Design Parameters

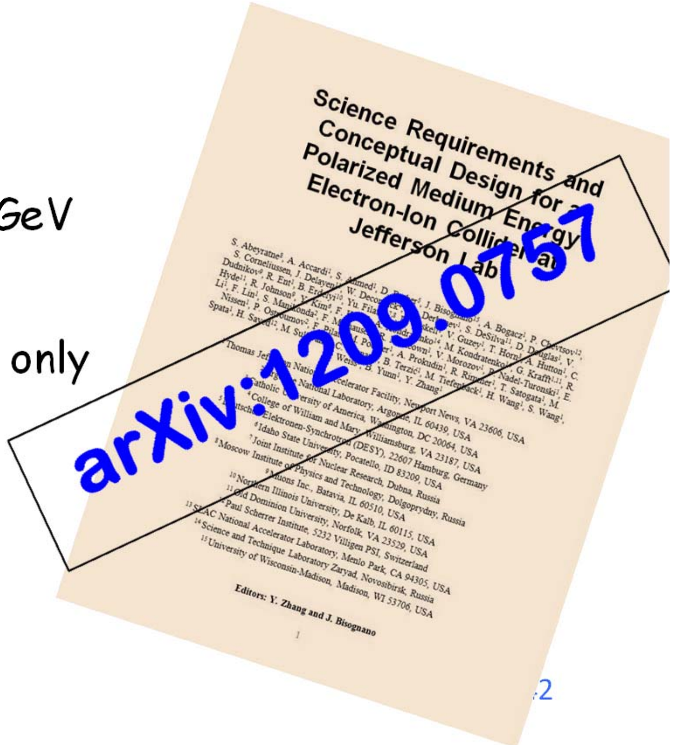
Challenge	Increas the s
Polarized electron gun	
Coherent Electron Cooling	
Multi-pass SRF ERL	5 x 30
Crab crossing	New
Understanding beam-beam effects	N
β*=5 cm	
Multi-pass SRF ERL	2-
Feedback for kink instability suppression	
Space charge effect compensation	



- Hourglass the pinch effects are included. Space charge effects are compensated.
- Energy of electrons can be selected at any desirable value at or below 30 GeV
- The luminosity does not depend on the electron beam energy below or at 20 GeV
- The luminosity falls as E_e^{-4} at energies above 20 GeV
- The luminosity is proportional to the hadron beam energy: $L \sim E_h/E_{top}$

MEIC Design Parameters

- **Energy**
  - Full coverage of *s* from a few 100 to a few 1000 GeV^2
  - Electrons 3-12 GeV, protons 20-100 GeV, ions 12-40 GeV/u
- **Ion species**
  - Polarized light ions: p, d, ^{3}He, and possibly Li
  - Un-polarized light to heavy ions up to A above 200 (Au, Pb)
- **Up to 2 detectors**
  - Two at medium energy ions: one optimized for full acceptance, another for high luminosity
- **Luminosity**
  - Greater than 10^{34} cm^{-2}s^{-1} per interaction point
  - Maximum luminosity should optimally be around $\sqrt{s}$=45 GeV
- **Polarization**
  - At IP: longitudinal for both beams, transverse for ions only
  - All polarizations >70% desirable
- **Upgradeable to higher energies and luminosity**
  - 20 GeV electron, 250 GeV proton, and 100 GeV/u ion



MC simulation

Written by E. Perez, L Schoeffel, L. Favart [arXiv:hep-ph/0411389v1]

The code MILOU is Based on a GPDs convolution by:
A. Freund and M. McDermott [All ref.s in: http://durpdg.dur.ac.uk/hepdata/dvcs.html]

✓GPDs, evolved at NLO by an indipendent code which provides tables of CFF
- at LO, the CFFs are just a convolution of GPDs:

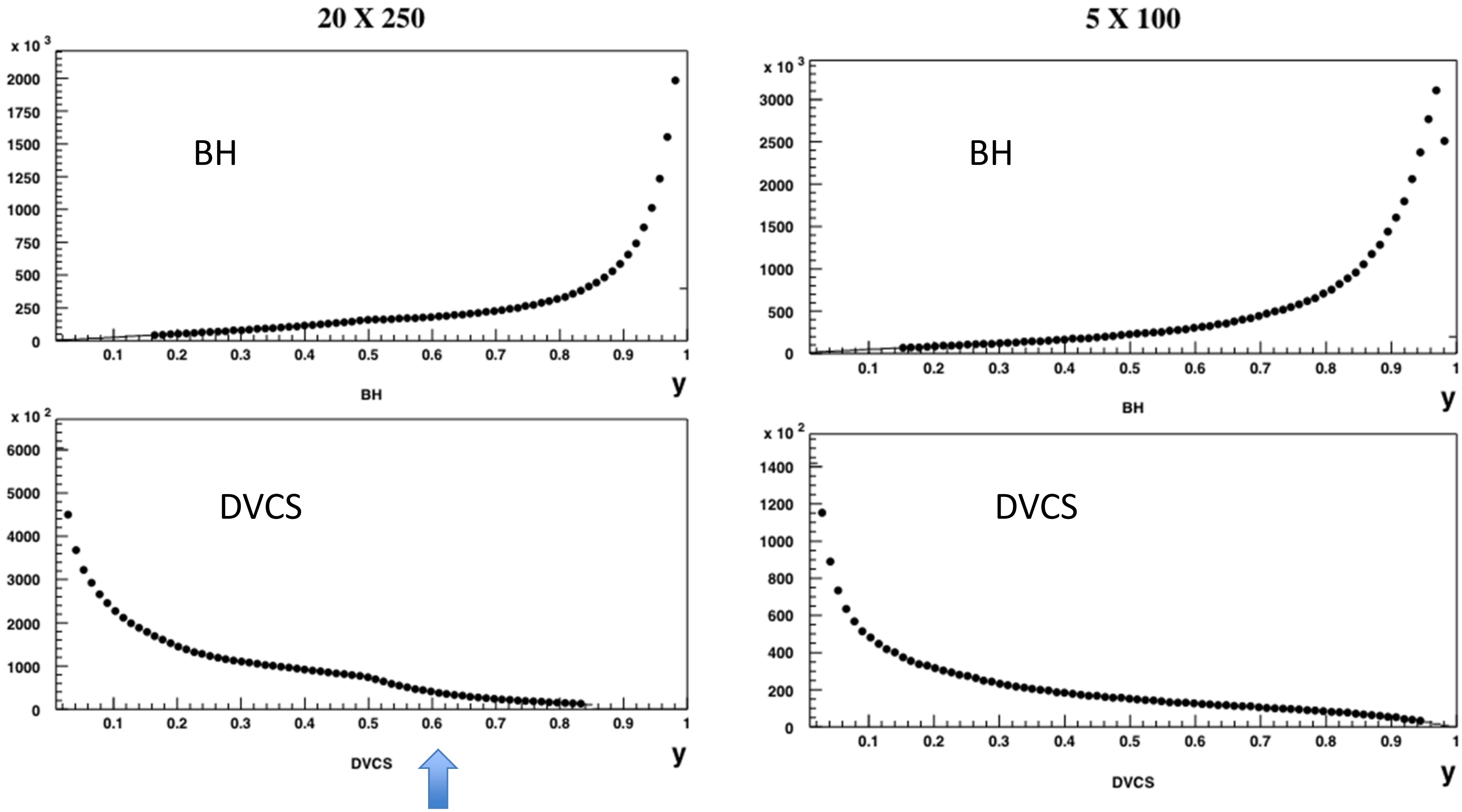
$$\mathscr{H}(\xi, Q^2, t) = \sum_{u,d,s} \int_{-1}^{1} \left[\frac{e_i^2}{1 - x/\xi - i\varepsilon} \pm \{\xi \to -\xi\} \right] H_i(x, \xi, Q^2, t) dx$$

✓provide the real and imaginary parts of Compton form factors (CFFs), used to calculate cross sections for DVCS and DVCS-BH interference.

✓ $\frac{d\sigma}{d|t|} = \exp(B(Q^2)t)$ -> The B slope is allowed to be costant or to vary with Q^2

✓Proton dissociation ($ep \to e\gamma Y$) can be included

✓Other non-GPD based models are implemented like FFS, DD



- BH dominates at large y.
- DVCS dropes with y

Uncertainties on BH calculations

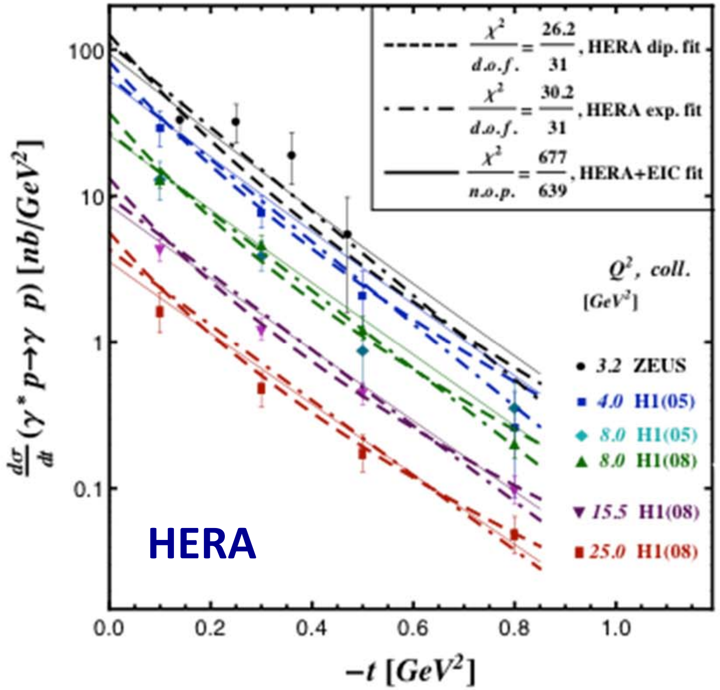
- to calculate the BH cross section correction to a process one needs
  - the proton form factor
    - there are many papers on this (arXiv:1209.0683)
    - the current systematic uncertainty is in the order of 3%
  - a precise parameterization of the total cross section
    - This is most likely the biggest uncertainty because DVCS cross section fraction of the total photon electro production cross section is not very well known
      - and iterative method should help to keep the uncertainties minimal

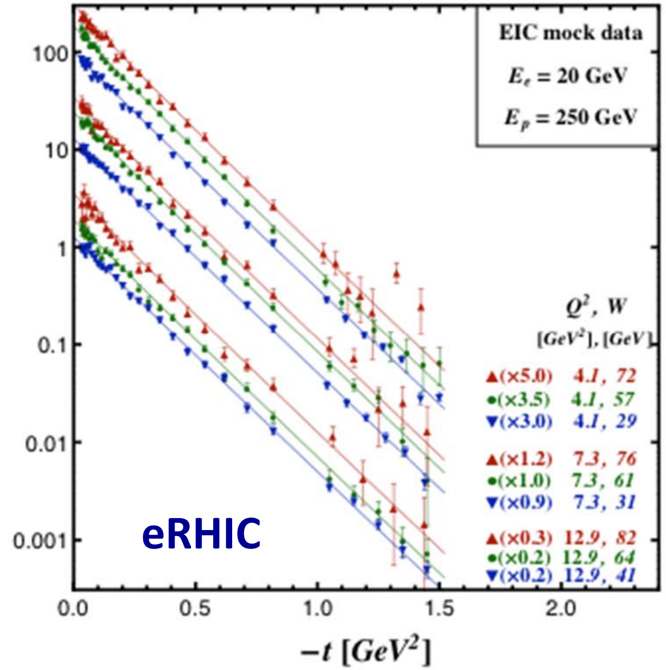
t-xsec (ep -> γp)

Selection criteria:

$0.01 < y < 0.6$
$\theta\gamma < 2x10^{-2}$ rad
$\theta el < 2x10^{-2}$ rad
$E\gamma > 1$ GeV
$Eel > 1$ GeV

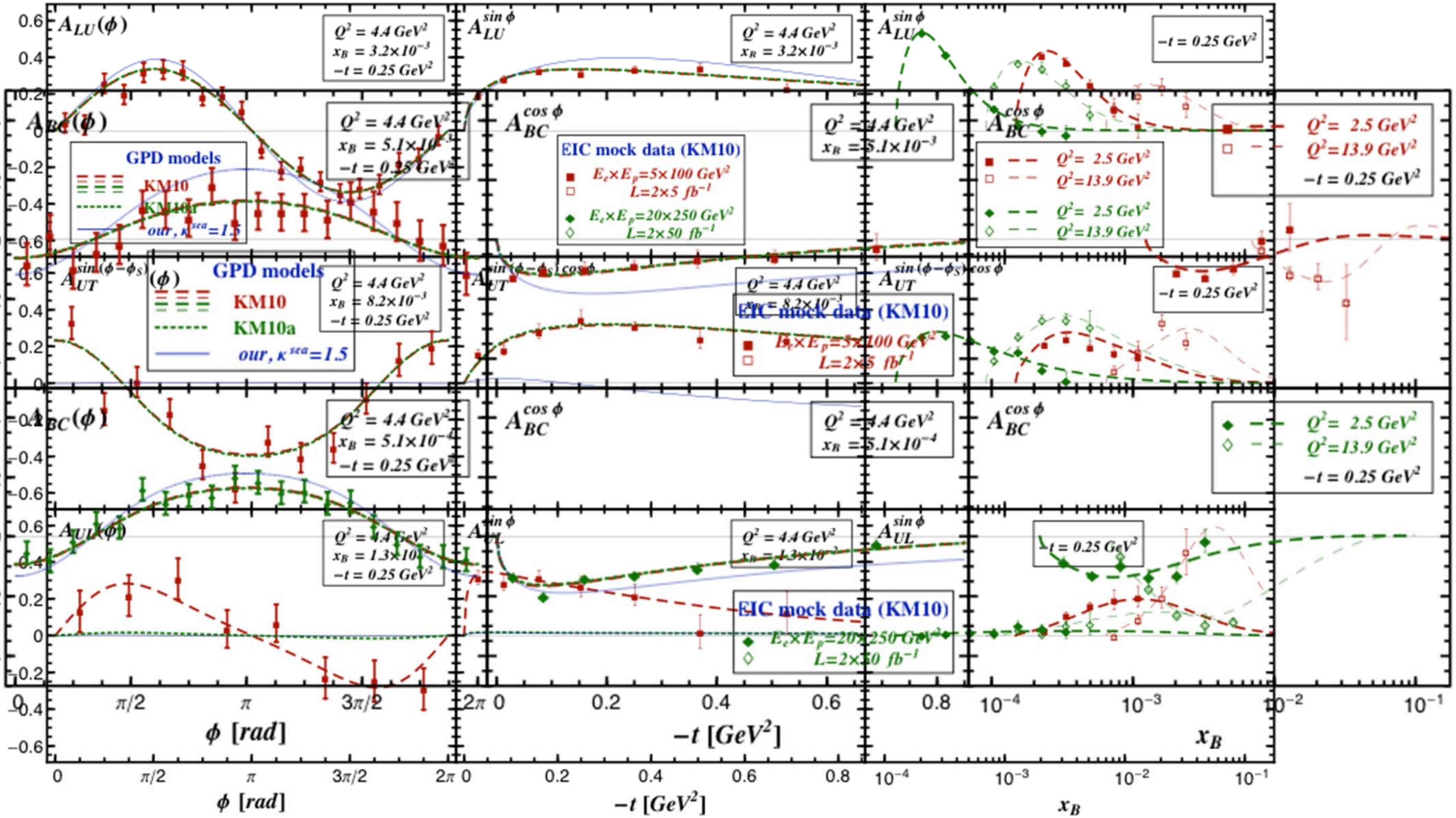
$\sim e^{-bt}$ b=5.6 GeV^{-2}





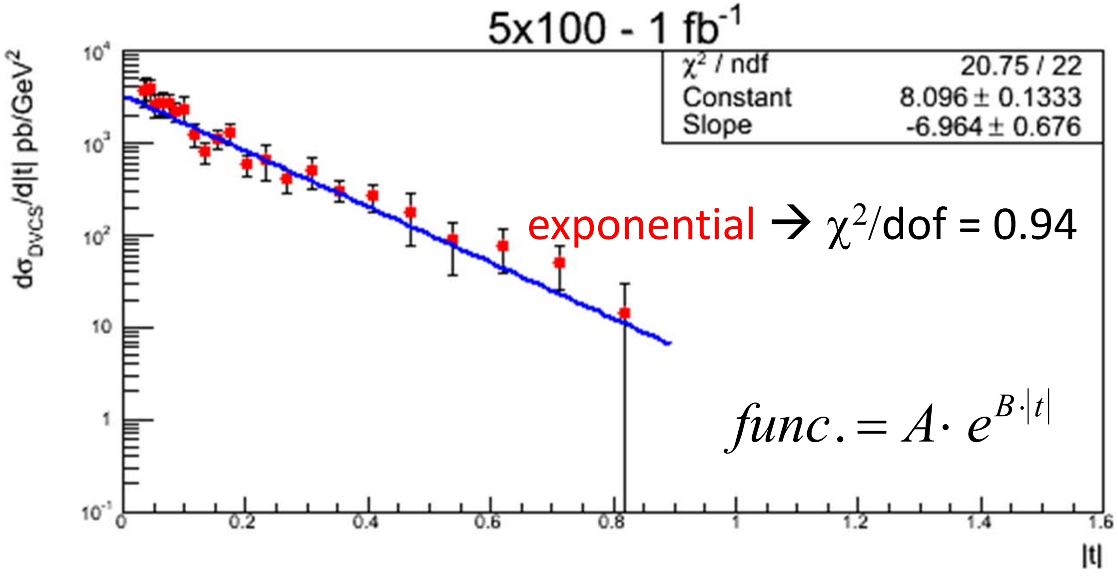
10 x-bins ; 5 Q^2-bins

Asymmetries



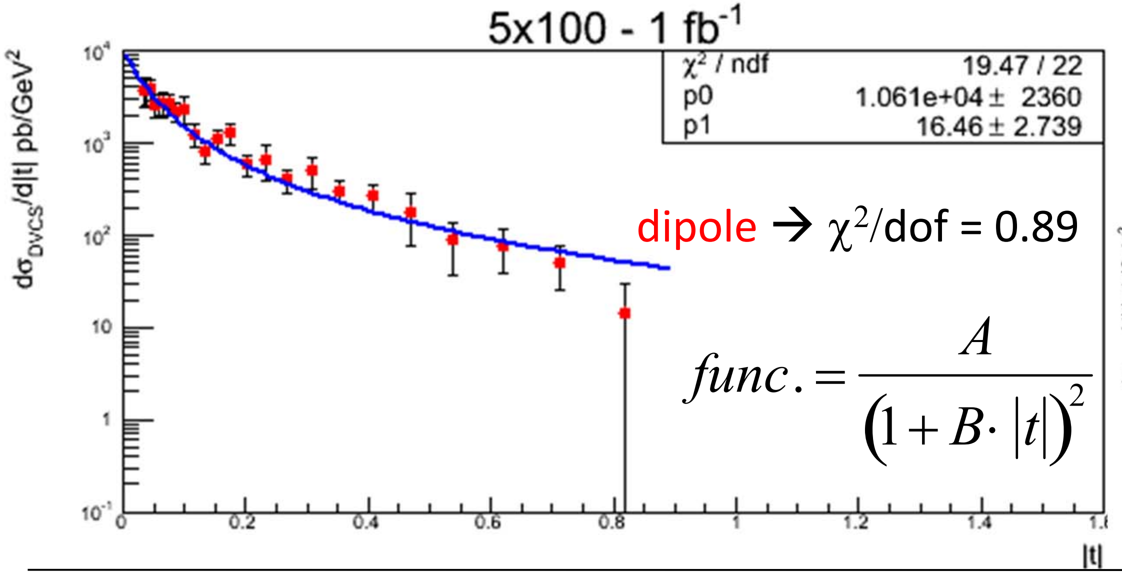
Plots from D. Mueller

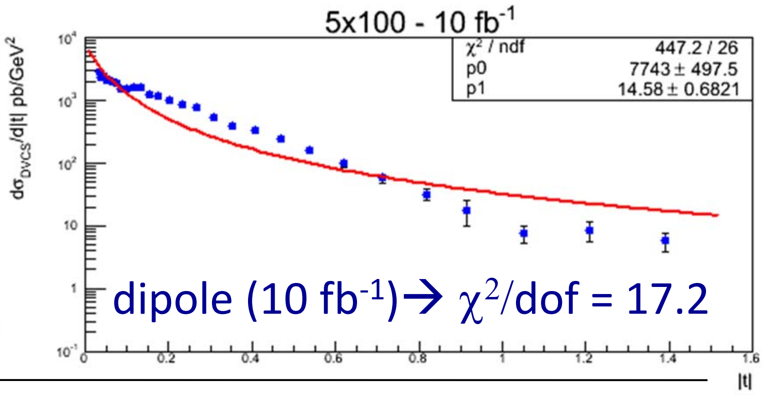
What if dσ/dt follows a dipole dependence rather than en exponential? Can we discriminate between the two with 1 fb^{-1} ?



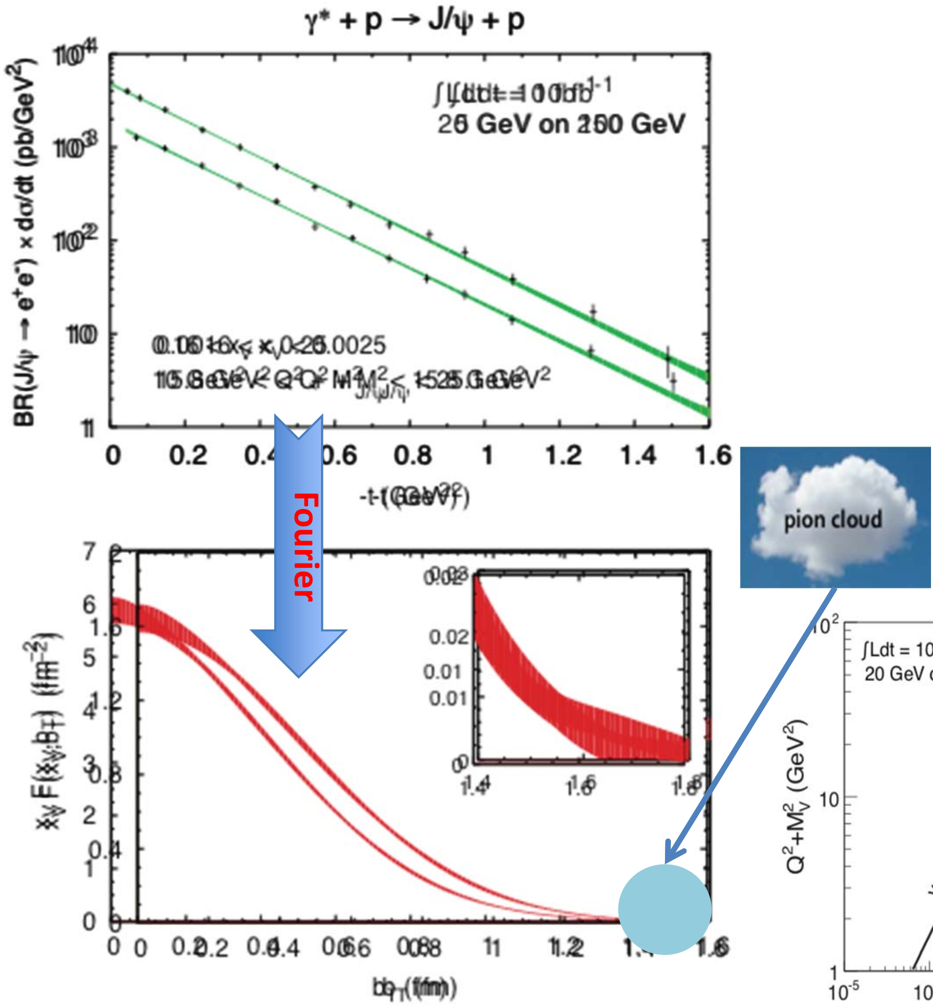
*Lets try to fit a dipole parameterization and superimpose it to the data generated according to an exponential A*exp(B*|t|)*

Beam energy: 5x100 GeV^2
$10 < Q^2 < 17.78$ GeV^2
$0.1 < x < 0.158$



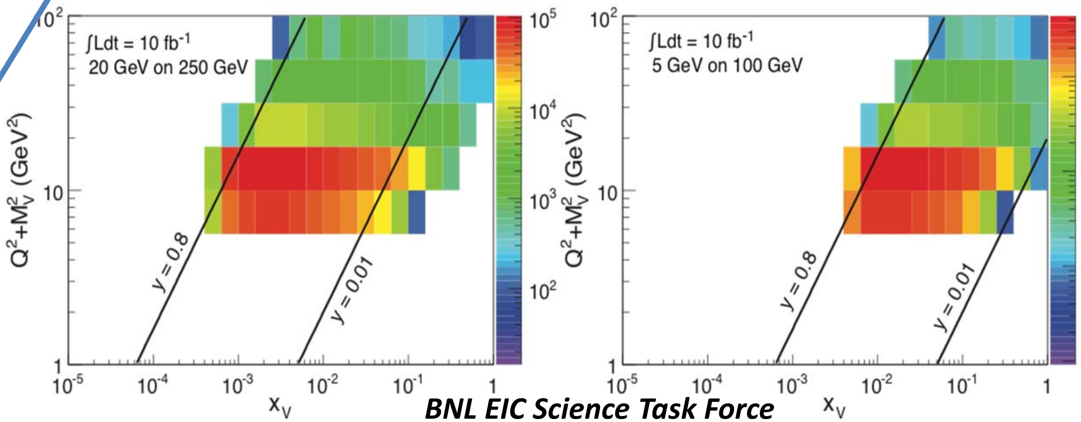


J/ψ



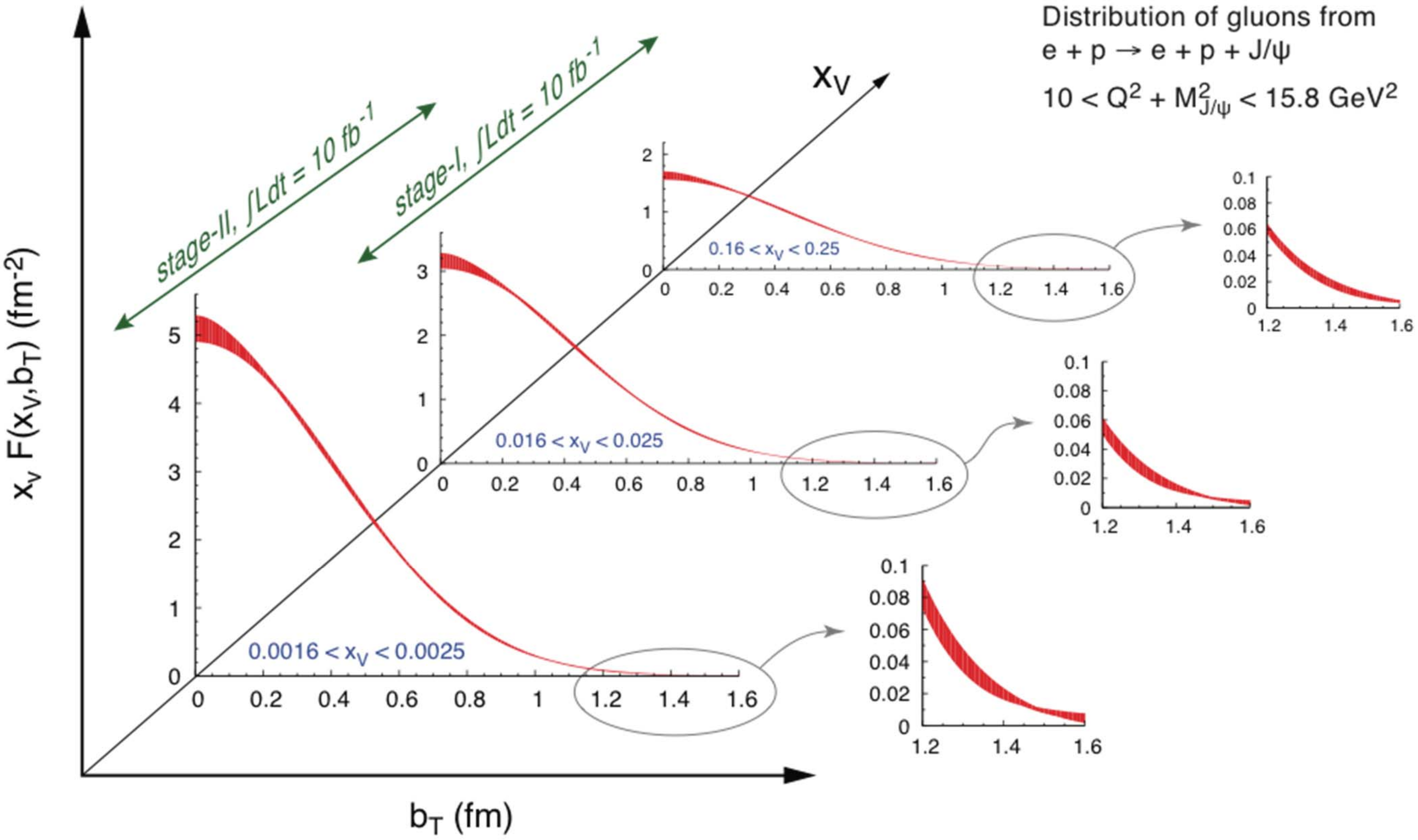
$\gamma^*p \rightarrow J/\psi\ p$

- pseudo-data generated using a version of Pythia tuned to J/ψ data from HERA
- wave function uncert. (non-relativistic approximation)
- mass provides hard scale
  - Sensitive to gluons
  - Both photo- and electro-production can be computed



BNL EIC Science Task Force

J/ψ



Distribution of gluons from
e + p → e + p + J/ψ
10 < Q2 + M2J/ψ < 15.8 GeV2
stage-II, ∫Ldt = 10 fb-1
stage-I, ∫Ldt = 10 fb-1
xV
xV F(xV,bT) (fm-2)
bT (fm)
0.0016 < xV < 0.0025
0.016 < xV < 0.025
0.16 < xV < 0.25