Measuring GPDs at EIC

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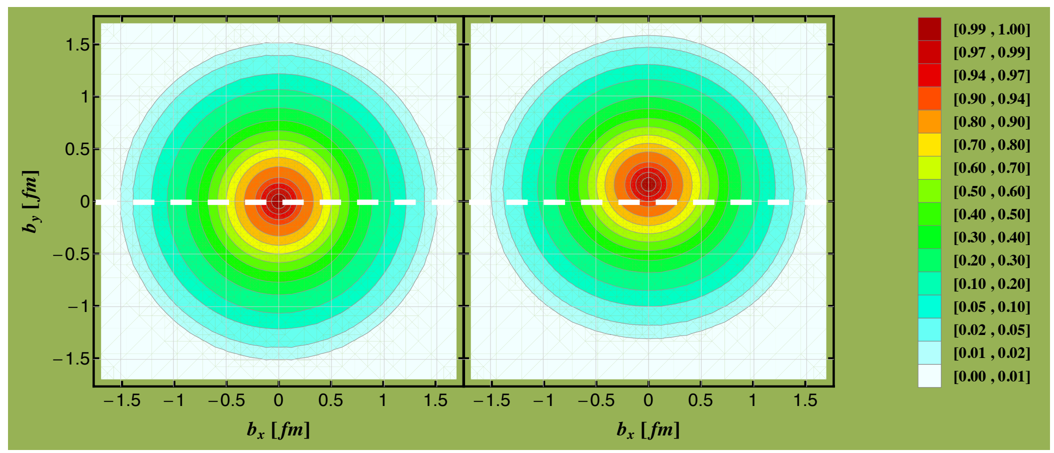
"Dante's Purgatory"



POETIC

Physics Opportunities @ an Electron Ion Collider

Indiana University, Bloomington IN

August 20-22, 2012

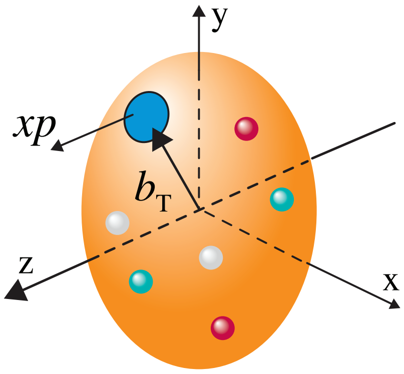
Plan of the talk

- Introduction to GPDs
- Detector requirements
- GPDs and DVCS
  - Bethe-Heitler subtraction
  - |t|-differential cross sections
  - Charge and spin asymmetries
- Imaging with an EIC (the impact!)
- Imaging the gluons: J/ψ
- Summary

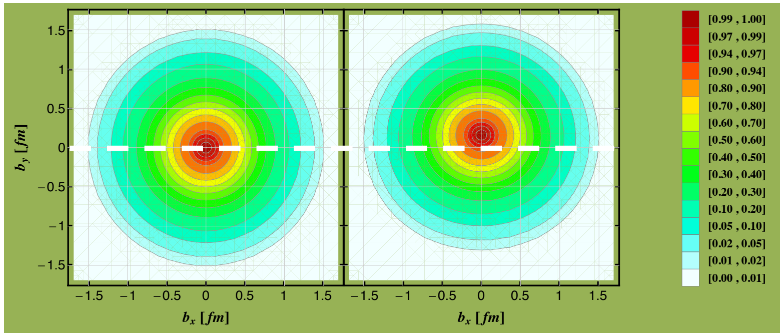
(2+1)-Dimensional imaging of the proton

Open questions:

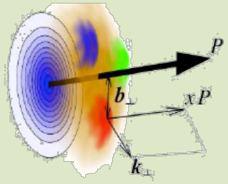
- **PDFs do not resolve transverse coordinate or momentum space**
- **In a fast moving nucleon the longitudinal size squeezes like a `pizza' but transverse size remains about 1 fm**



Goal: nucleon tomography!



Proton imaging



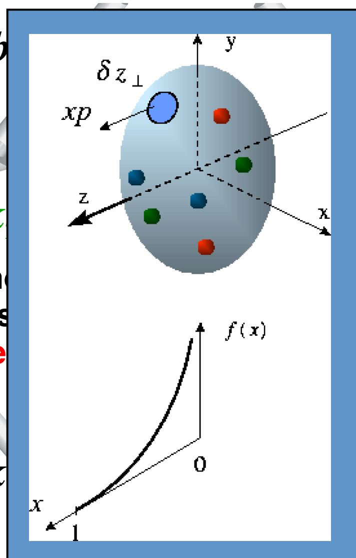
- what is the spatial distribution of quarks and gluons in nucleons/nuclei
- Possible window to orbital angular momentum

(2+1)-D imaging of the proton

Longitudinal momentum & helicity distributions

$\int d^2 b$

$\int d^2 k_T$



$f(x,k$

transverse m
distributions
semi–inclusive

$f(x,b_T)$

ct parameter
stributions

$\int d^2 k$

$\int d^2 b_T$

$f(x)$

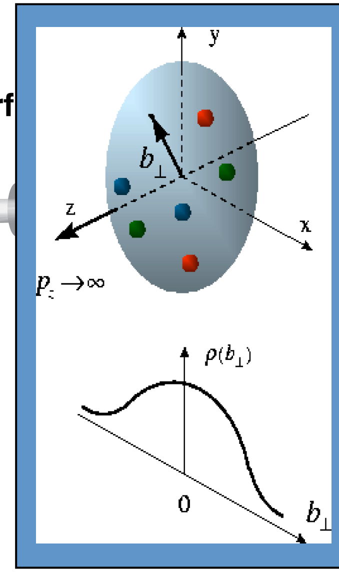
parton densities

inclusive and semi–inclusive processes

transverse charge & current densities

Fourier trf

$b_T \leftrightarrow \Delta$

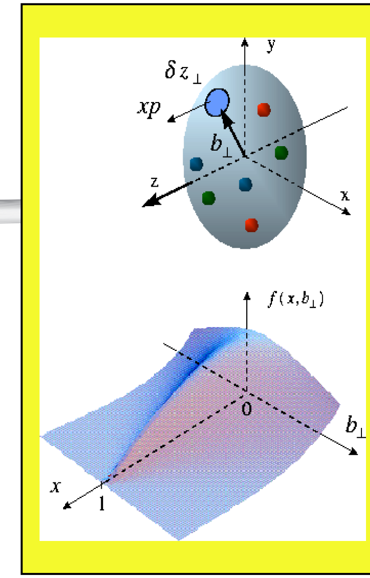


$F_1(t)$

form factors

elastic scattering

$\xi = 0$



$A_{n,0}(t) + 4\xi A_{n,2}(t) + ...$

generalized form factors

lattice calculations

Wigner Distribution
$W(x,r,k_t)$

3D picture in coordinate space

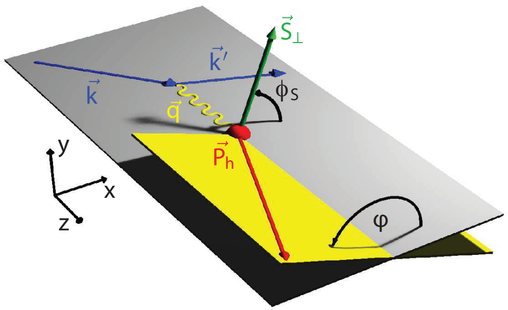
generalized parton distributions

→ exclusive reaction like DVCS and VMP

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

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

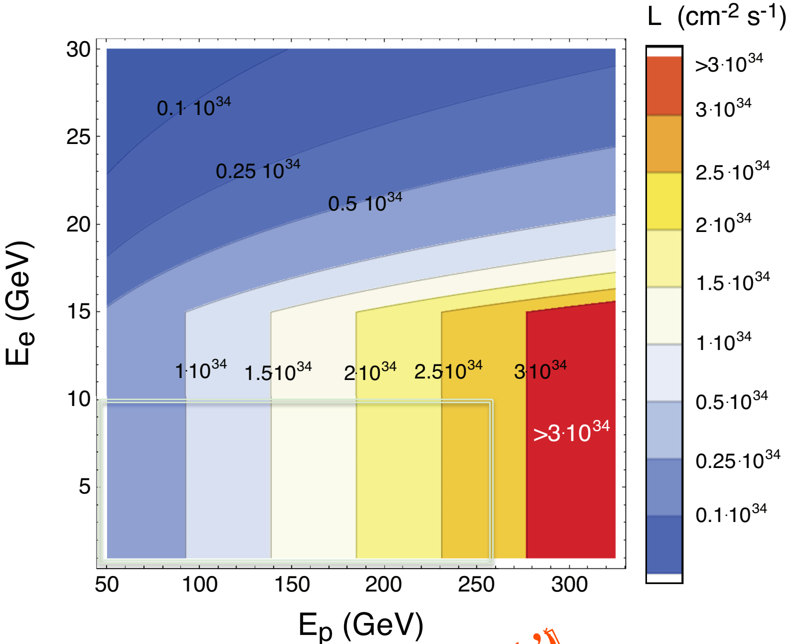
$\sin(\Phi_T - \phi_N)$
governed by E and H

EIC

Why EIC is unique:

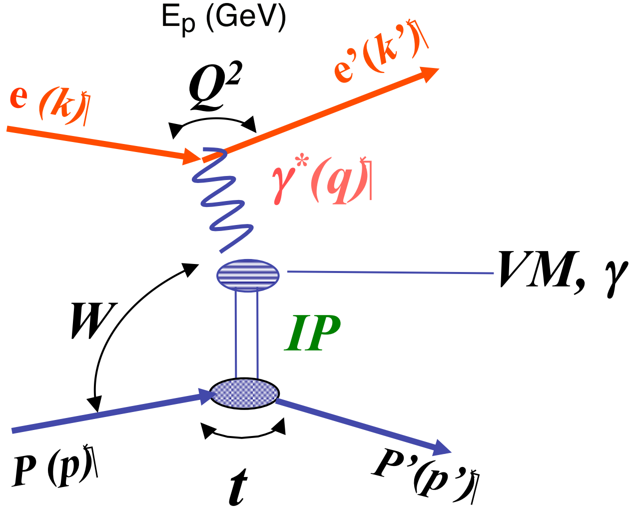
- 5 - 20 GeV electrons on 100-250 (130) GeV protons (nuclei). Polarization of electrons and protons (nuclei)
- Lumi: ~10^{34} $cm^{-2}s^{-1}$ (stage 1–ep pol)

Important for exclusive DIS:
- Dedicated forward instrumentation
- High tracker coverage
- Very High lumi!



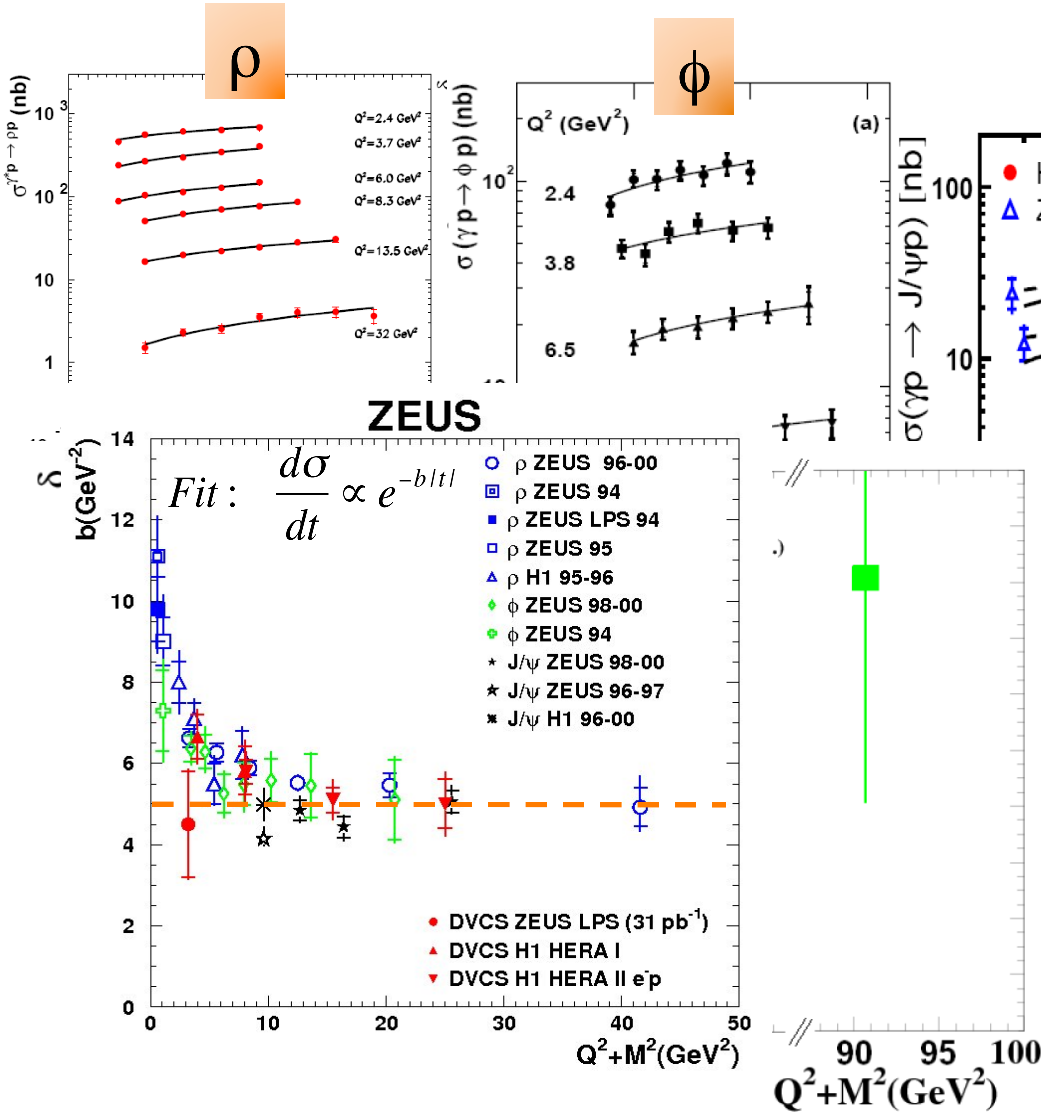
What are the detector requirements:

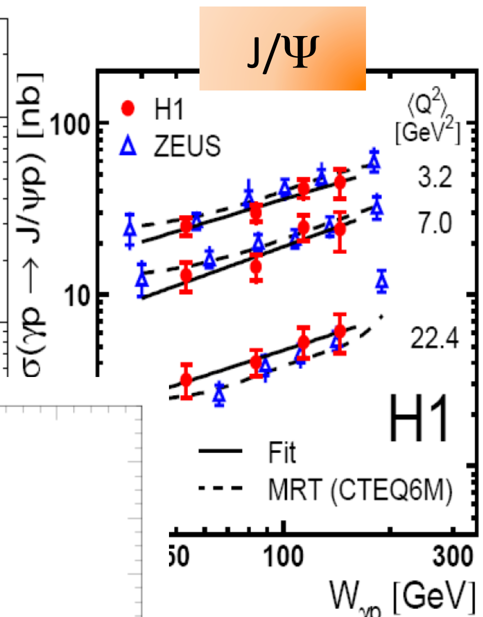
Important for exclusive diffraction:
- Hermetic Central Tracking Detector (Si pixels)
- Good em calorimeter resolution with fine granularity
- Preshower em cal → π^0 background
- Very forward calorimetry
- **Roman pots (and with excellent acceptance)**

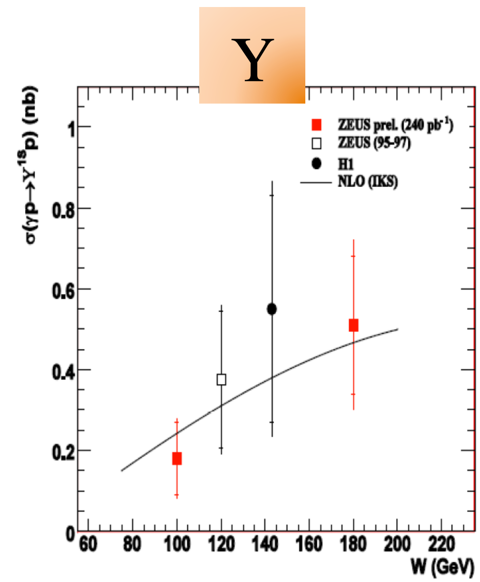


Vector Meson Production

W & t dependences: probe transition from soft → hard regime







$\sigma \sim W^{\delta}$

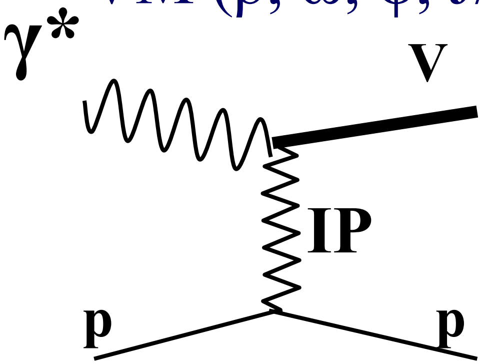
$\sigma \sim e^{-b|t|}$

➡ steep energy dependence of σ in presence of the hard scale

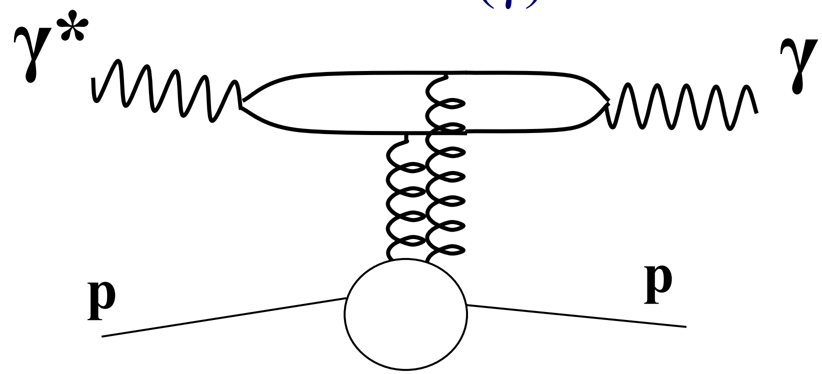
➡ universality of b-slope parameter: point-like configurations dominate

Deeply Virtual Compton Scattering

VM (ρ, ω, φ, J/ψ, Y)



DVCS (γ)



Scale: $Q^2 + M^2$ ⟷ Q^2

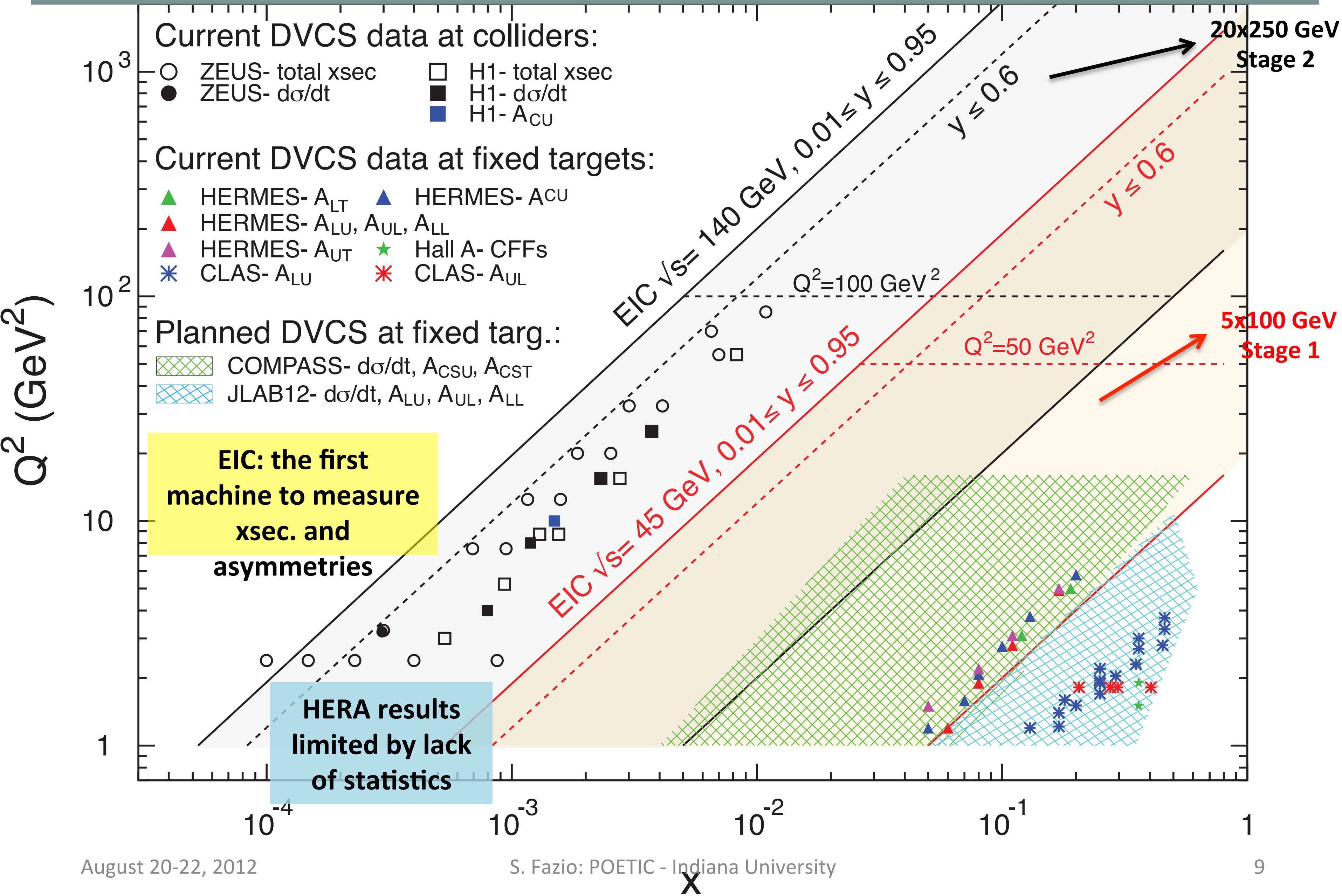
Q^2 gives the lever arm

A GOLDEN MEASUREMENT!

DVCS properties:

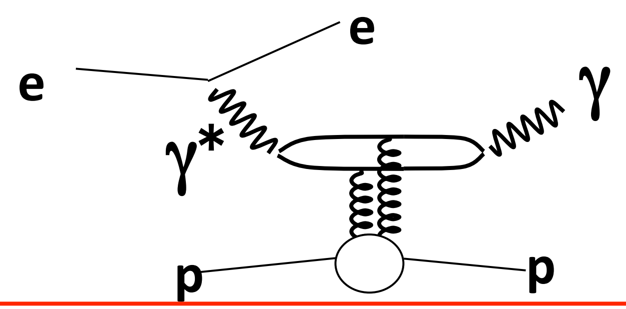
- Similar to VM production, but γ instead of VM in the final state
- Very clean experimental signature
- Not affected by VM wave-function uncertainty
- Hard scale provided by Q^2
- Sensitive to both quarks and gluons

DVCS phase-space

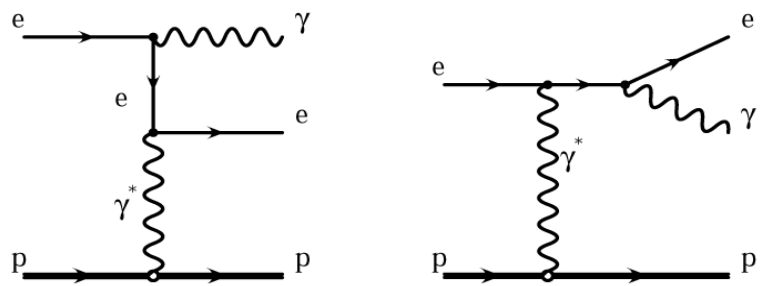


DVCS - BH

DVCS



BH



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

$$|\mathcal{I}_{\mathcal{BH}}|^2 = \frac{e^6}{x^2 y^2 (1+\varepsilon^2)^2 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{BH} + \sum_{n=1}^{2} c_n^{BH} \cos(n\phi) + s_1^{BH} \sin(\phi) \right\}$$

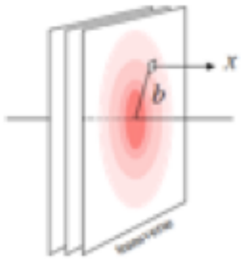
$$|\mathcal{I}_{\mathcal{DVCS}}|^2 = \frac{e^6}{y^2 Q^2} \left\{ c_0^{DVCS} + \sum_{n=1}^{2} \left[c_n^{DVCS} \cos(n\phi) + s_n^{DVCS} \sin(n\phi) \right] \right\}$$

$$|\mathcal{I}|^2 = \frac{\pm e^6}{x y^3 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{\mathcal{I}} + \sum_{n=1}^{3} c_n^{\mathcal{I}} \cos(n\phi) + s_1^{\mathcal{I}} \sin(\phi) \right\}$$

- DVCS cross section measurement -> BH must be removed
- Asymmetry measurement -> BH must be part of the sample (we need the interference term)

DVCS – cross section measurement

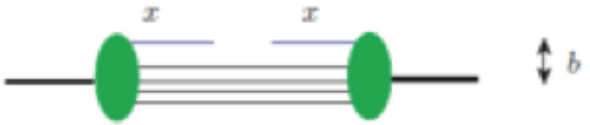
|t|-differential cross section is a very powerful tool



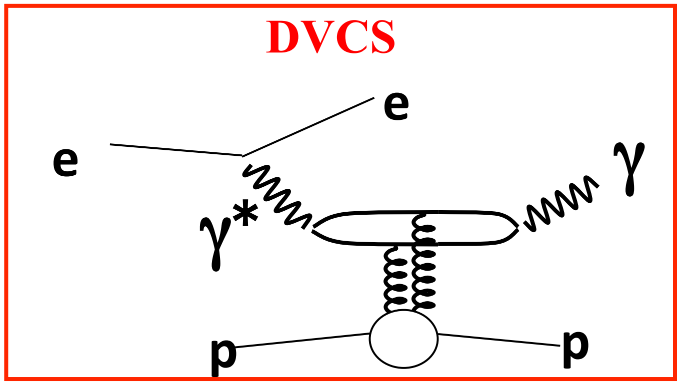
- Gives precise access to GPD H
- Fourier transform -> direct imaging in impact parameter space

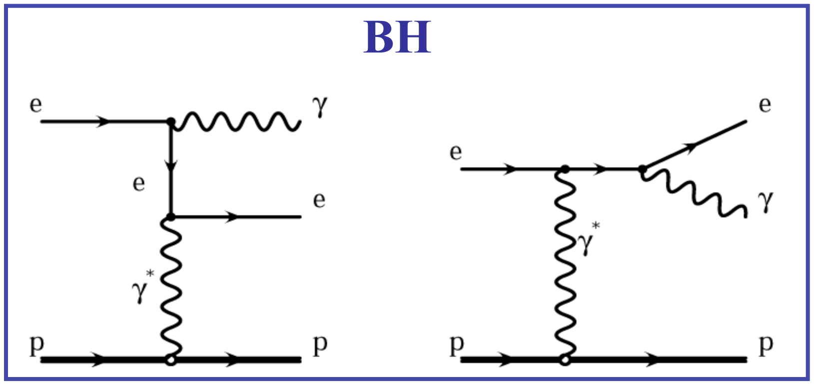
$$q(x, b^2) \approx \int dt e^{-ibt} \frac{d\sigma}{dt}$$

gives distribution of quarks with



- longitudinal momentum fraction x
- transverse distance b from proton center

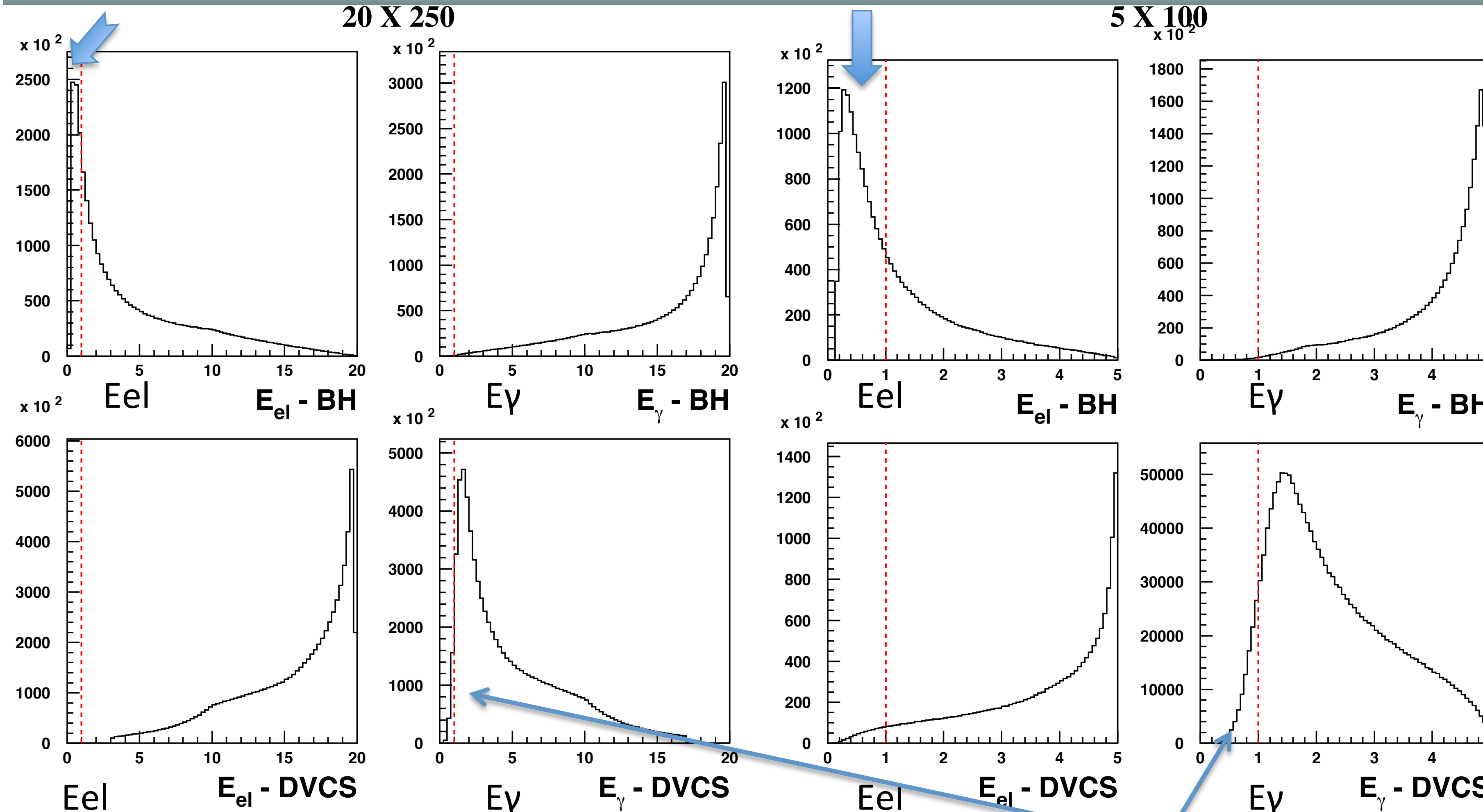




BH background must be removed in measuring the DVCS cross section

Uncertainty on proton form factor → **uncertainty on BH xsec ~ 3% (at LO)**

BH rejection

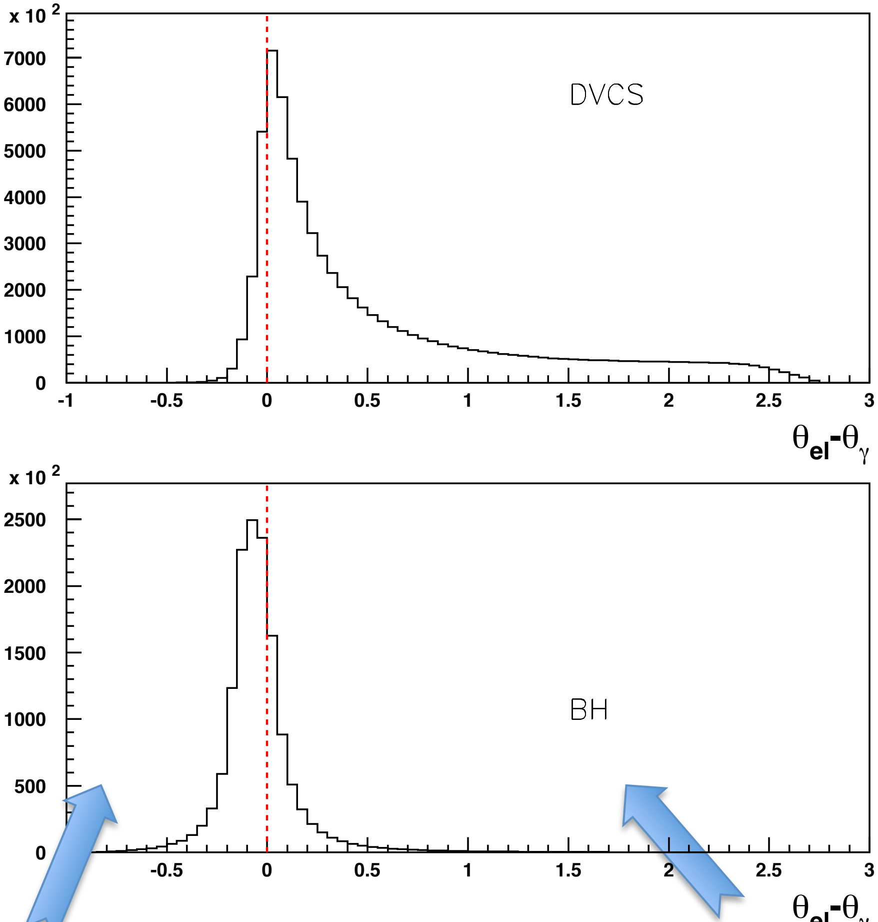


1. **BH electron has very low energy (often below 1 GeV)**
2. **Photon for BH (ISR) goes often forward (trough the beam pipe)**

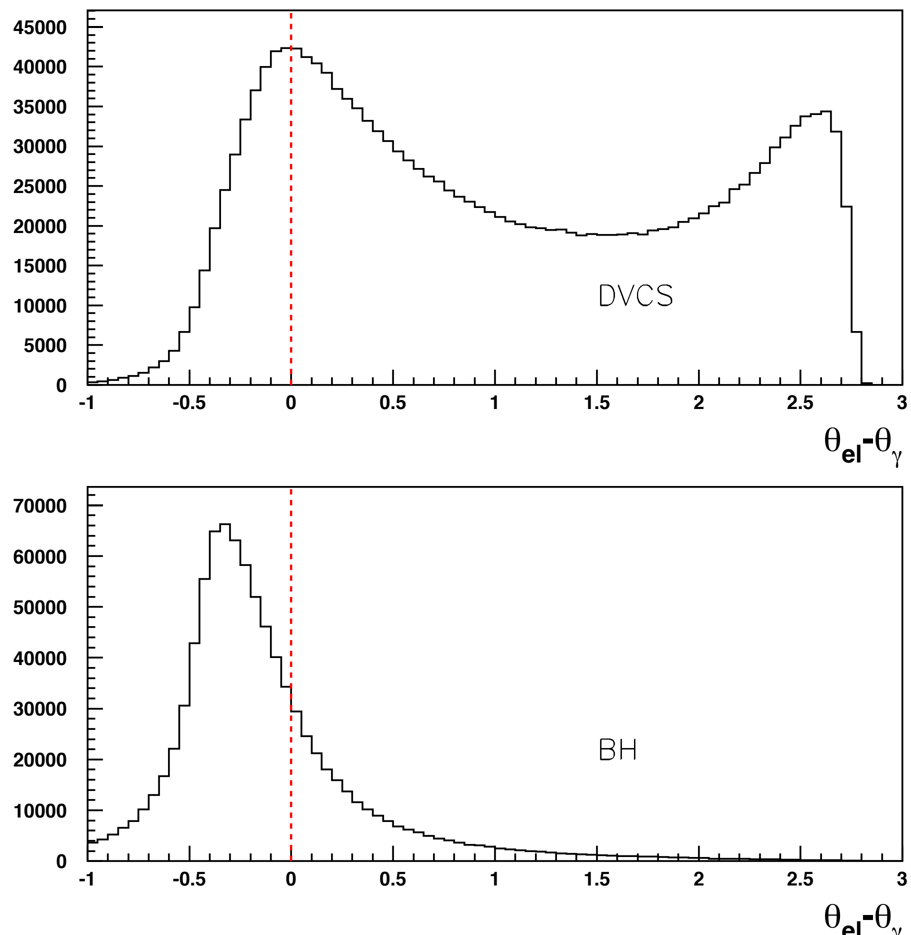
Important: em Cal must discriminate clusters above noise down to 1 GeV

BH rejection

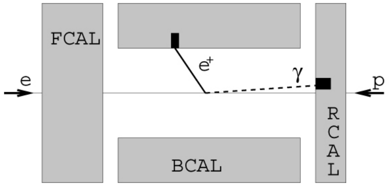
20 X 250



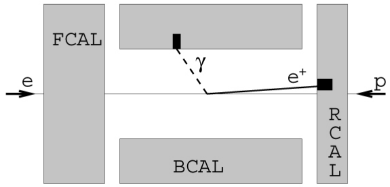
5 X 100



BH dominated

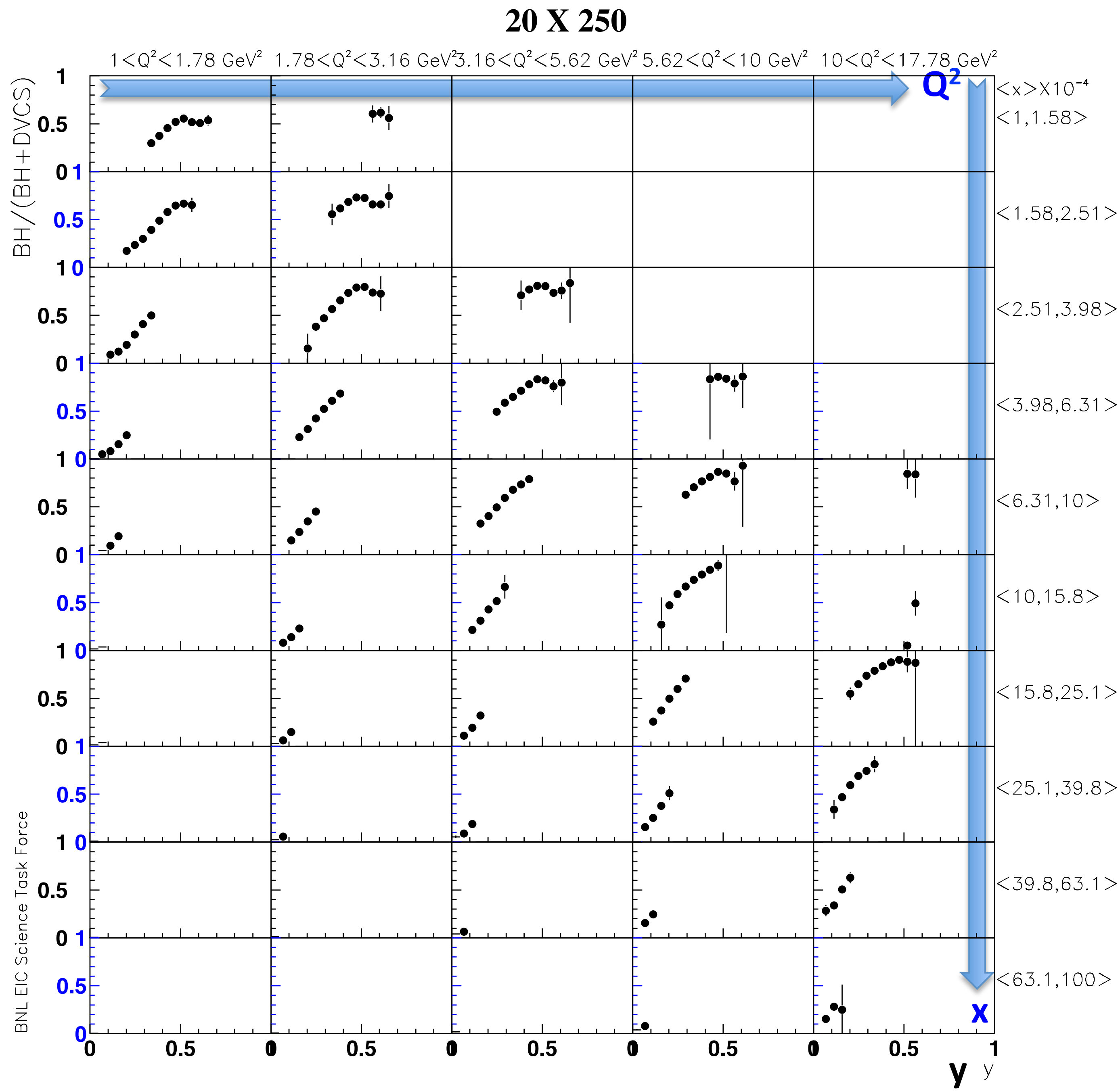


BH and DVCS



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

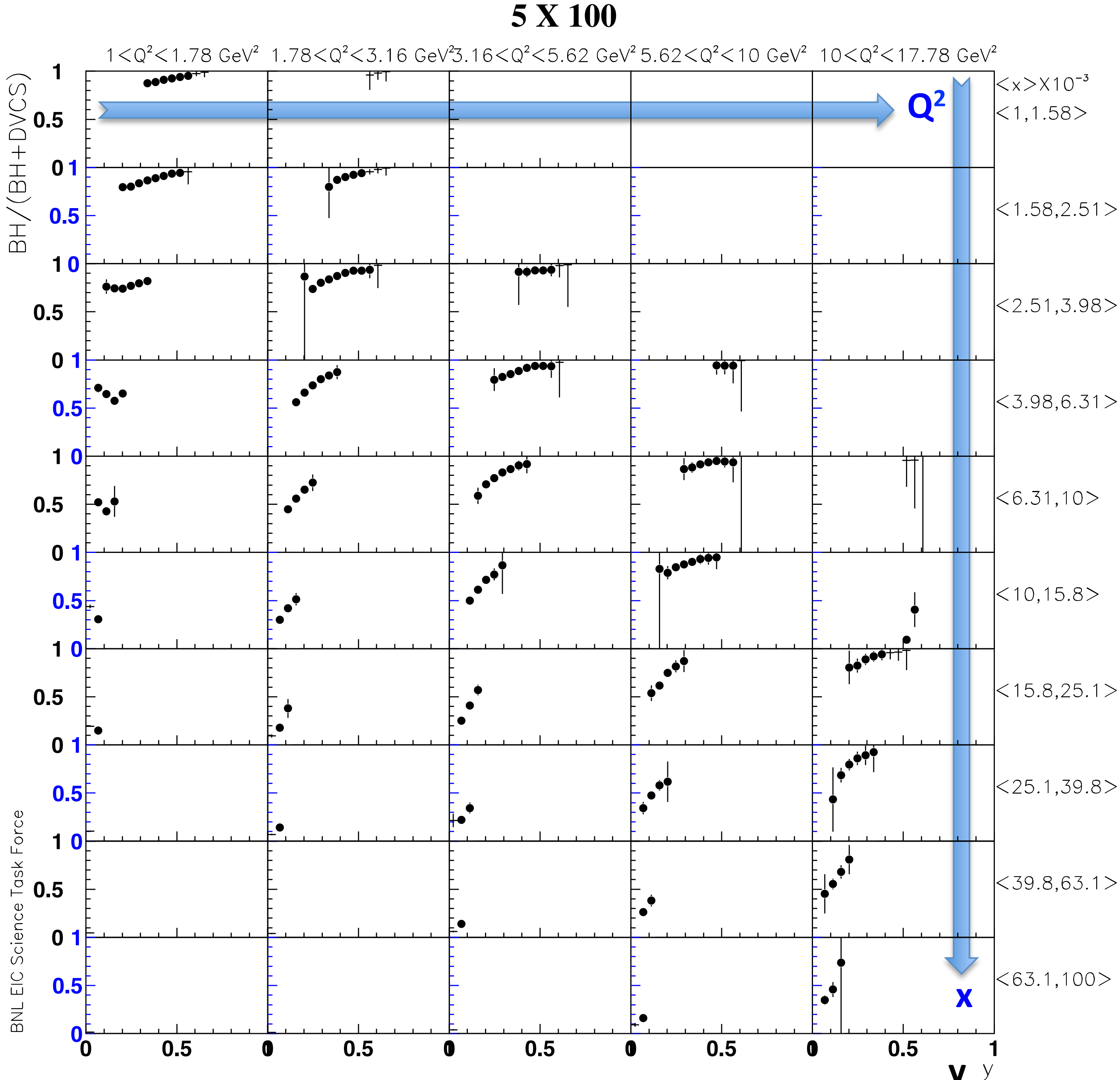
BH fraction



Stage 2

BH subtraction will be not an issue for y<0.6

BH fraction



Stage 1

BH subtraction will be relevant in stage 1, at large y, depending on the x-Q^2 bin

BUT…

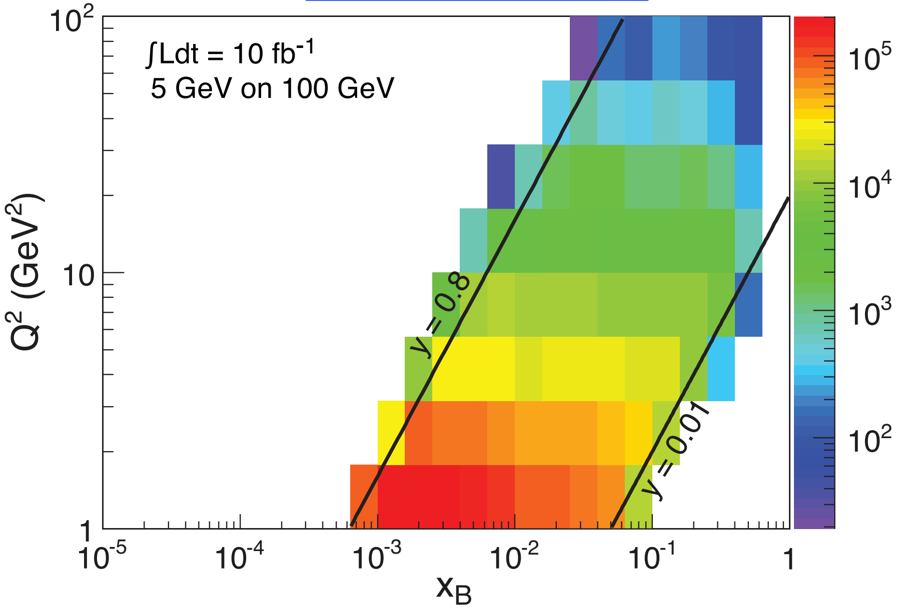
Stage 1-2 overlapping: x-sec. measurements in stage 2 at low-y can cross-check the BH subtrac. made in stage 1

Scanning the phase space…

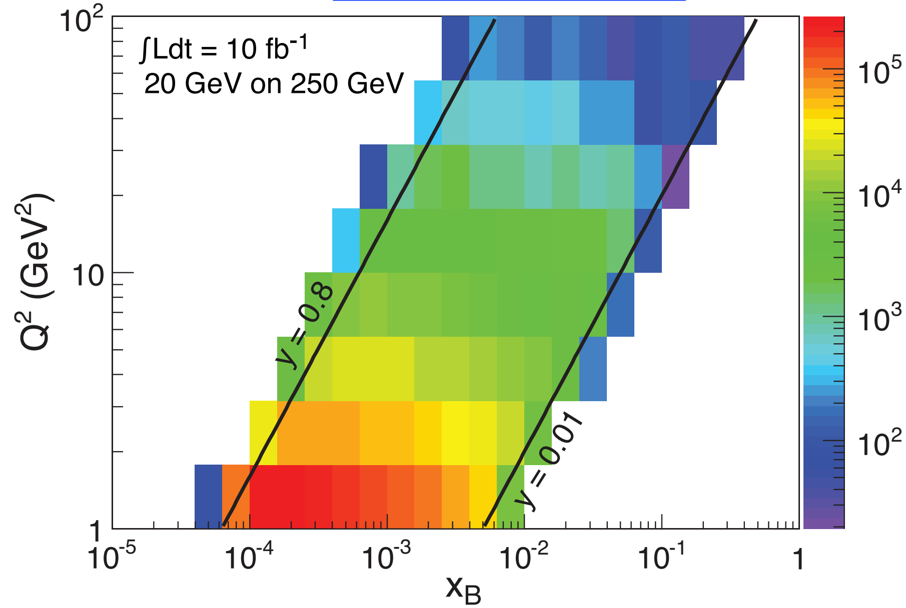
EIC lumi:
~10 fb^{-1}/year @ stage 1 – 5x100
~100 fb^{-1}/month @ stage 2 – 20x250

- **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

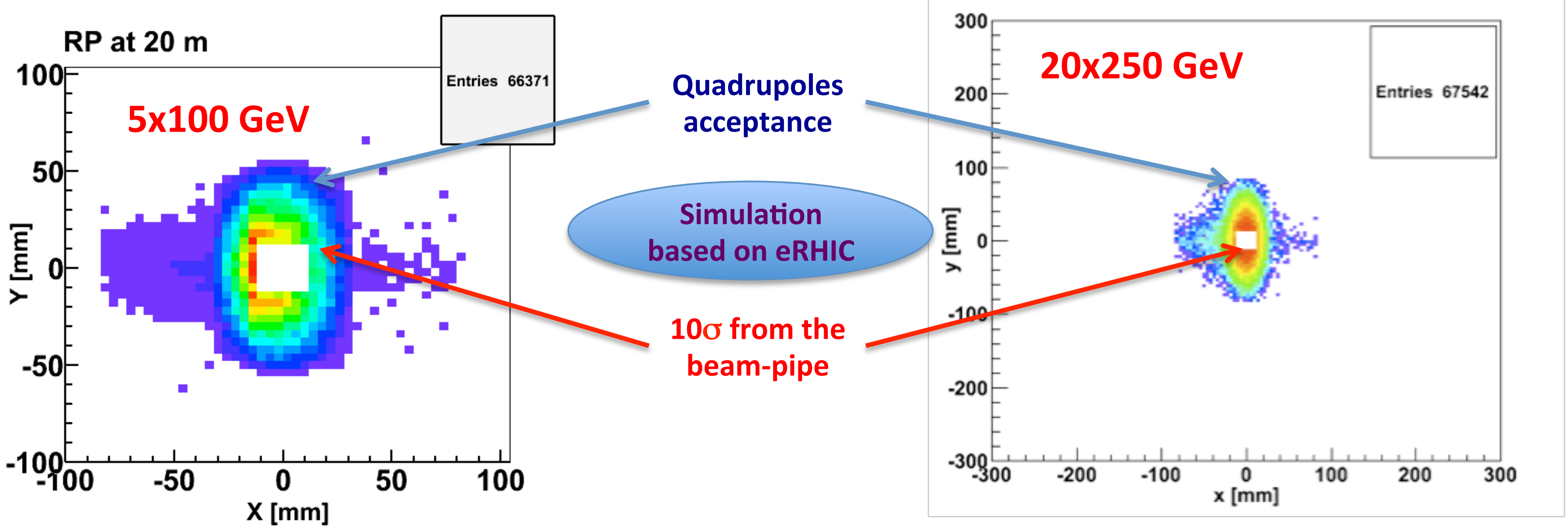


… we can do a fine binning in Q2 and W… and even in |t|

Direct |t| measurement – Roman Pots

Plots from J-H Lee

Accepted in"Roman Pot"(example) at s=20m



- high-|t| acceptance mainly limited by magnet aperture
- low-|t| acceptance limited by beam envelop (~10σ)
- |t|-resolution limited by
  - beam angular divergence ~100μrad for small |t|
  - uncertainties in vertex (x,y,z) and transport
  - ~<5-10% resolution in t (RP at STAR)

Data simulation & selection

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

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**

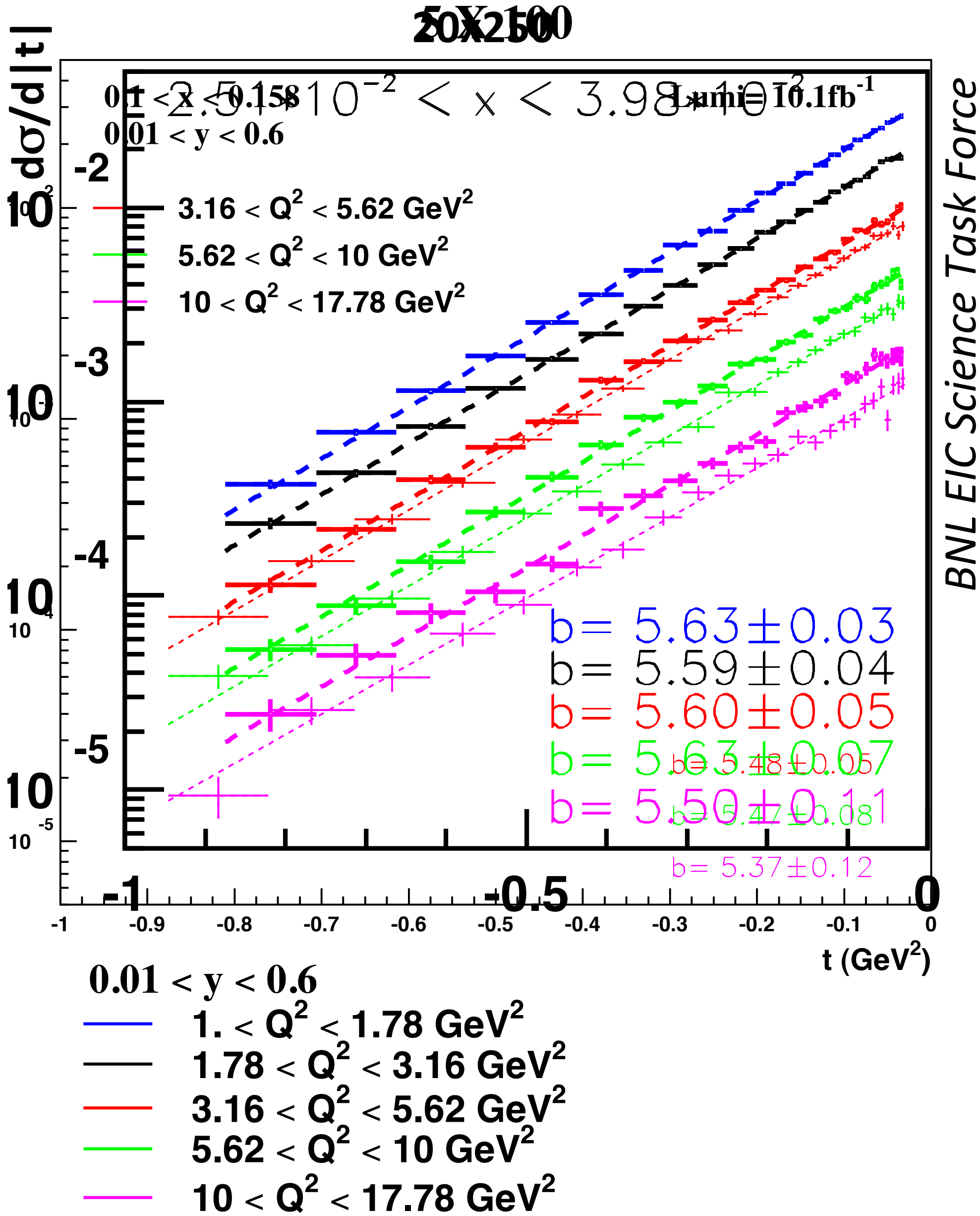
$1.0 < |t| < 1.5$ GeV^2

(Large-|t| sample)

- **Xsec goes down exponentially**
- **requires a year of data taking**
- **Main detector can be used in measuring |t|**

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

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



dσ/d|t|

$$\frac{d\sigma}{d|t|} = \frac{\# evt}{\Delta_{bin} \bullet A \bullet \mathcal{L}} \quad \sim e^{-bt}$$

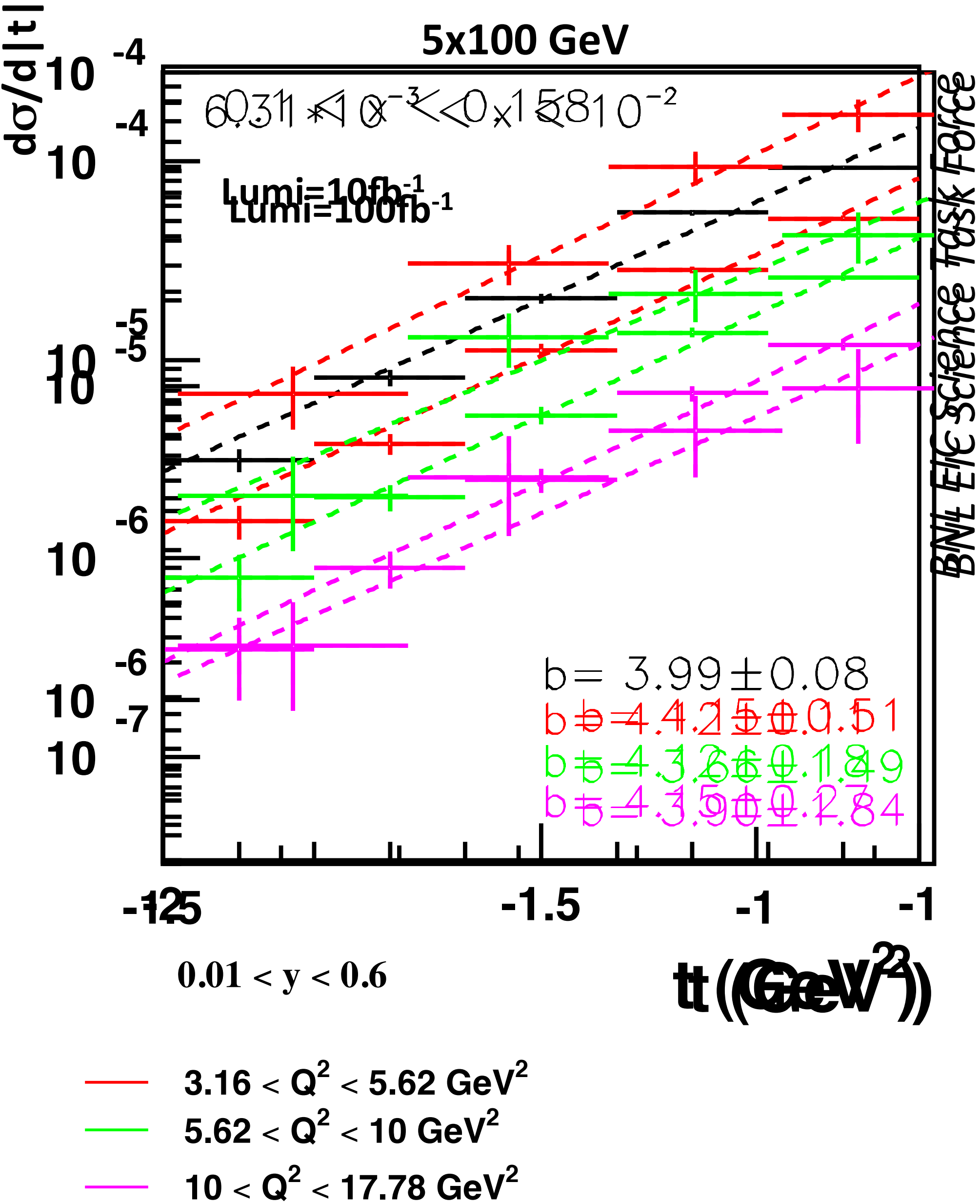
b=5.6

Specifications:

- **Statistical error down to 1%**
- **It uses smeared t values (5% momentum resol.)**
- **|t|-binning –> 3 * resolution (or higher)**

EIC lumi:
~10 fb^{-1}/year @ stage 1 – 5x100
~100 fb^{-1}/month @ stage 2 – 20x250

dσ/d|t| - large |t|



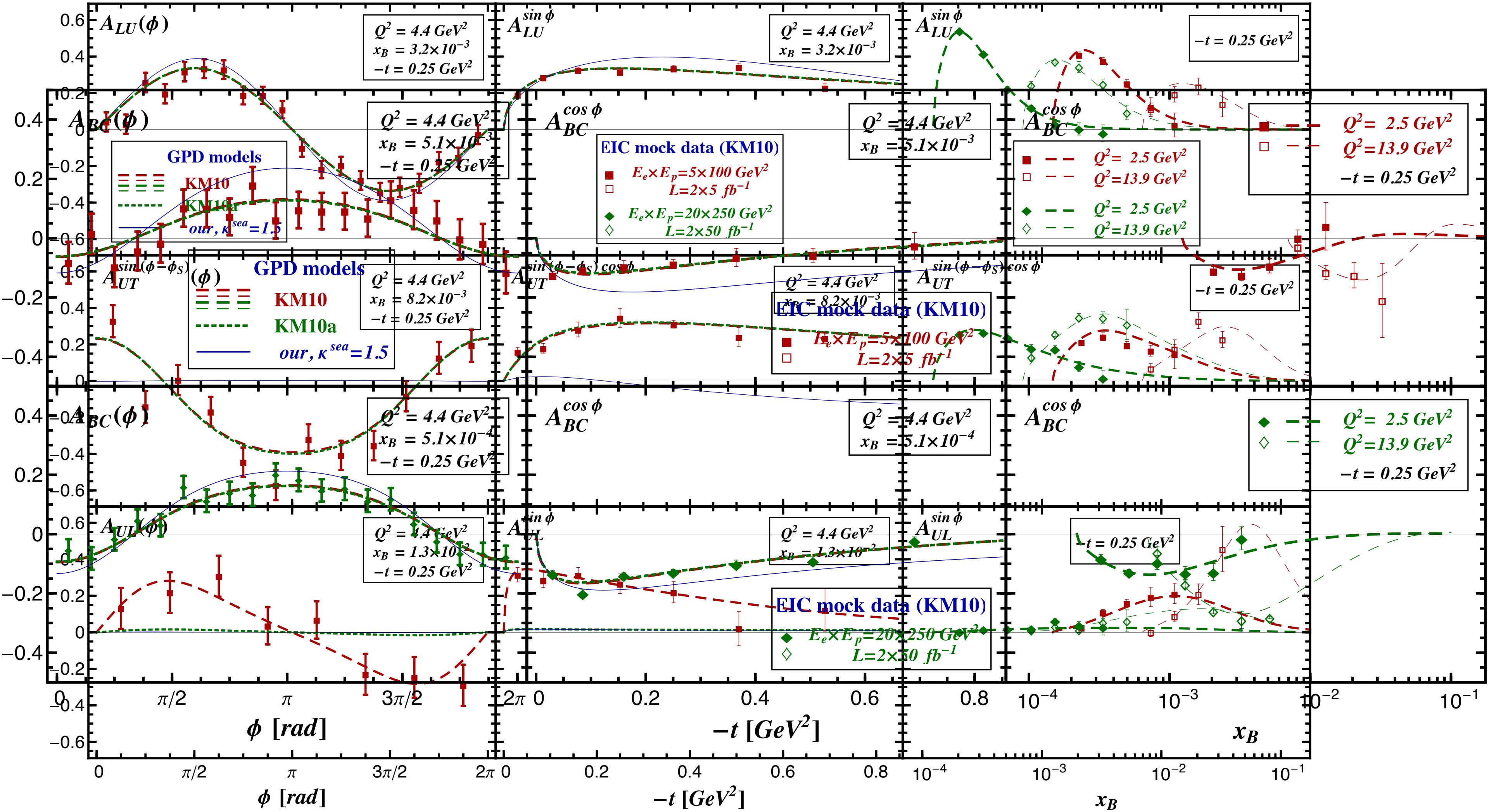
EIC lumi:
~10 fb^{-1}/year @ stage 1 – 5x100
~100 fb^{-1}/month @ stage 2 – 20x250

Dependence at large-|t| still unknown

Measurements possible also at large-|t| with a sufficient precision

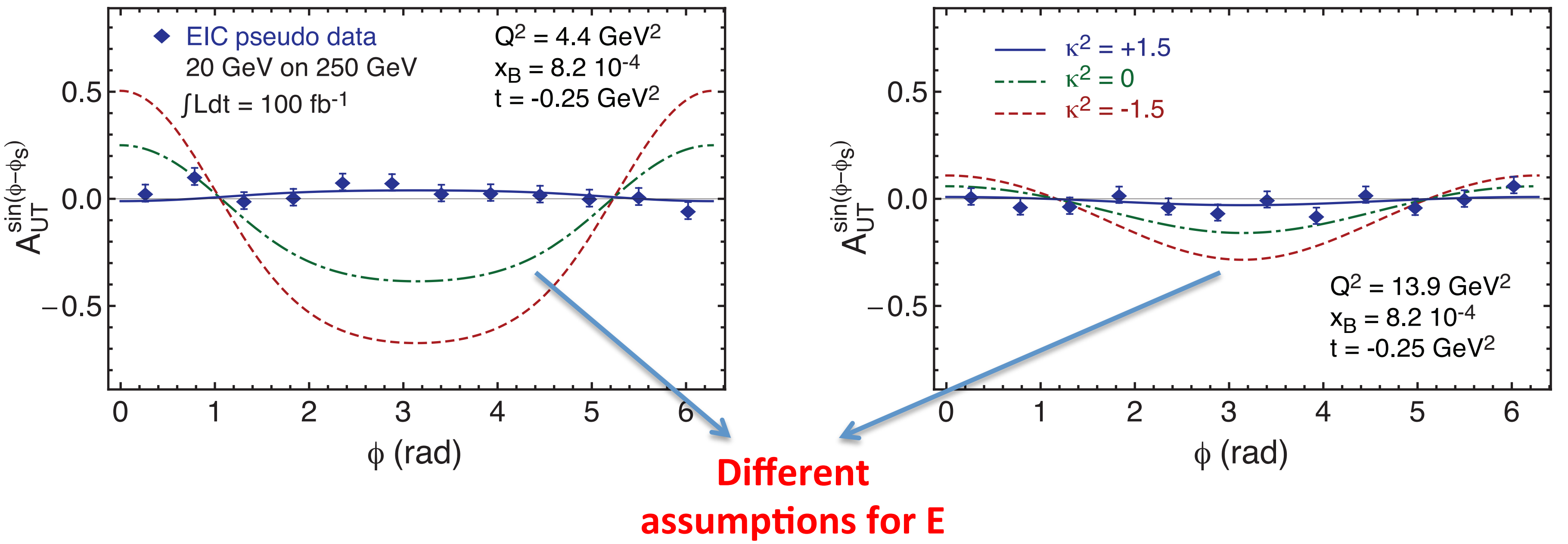
Very important to constrain GPDs

Asymmetries



Plots from D. Mueller

Transverse target-spin asymmetry



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

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

Gives access to GPD E

Imaging

Plots from D. Mueller

- Obtain the GPDs from global fits on present data and pseudo-data

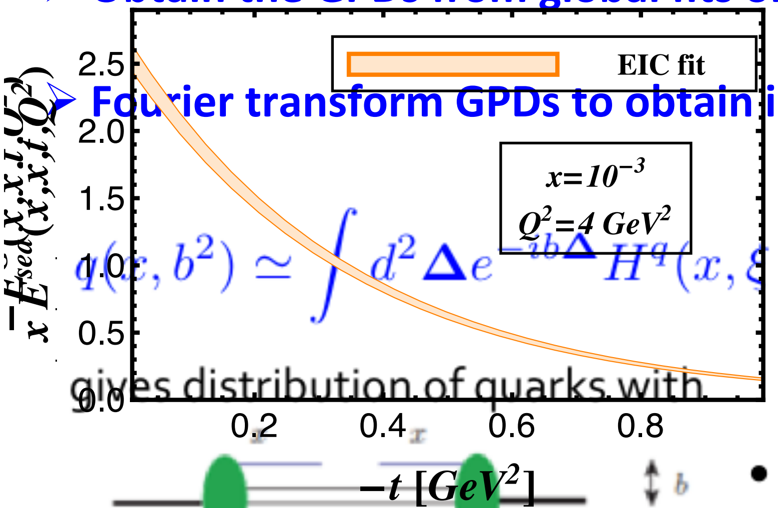
...FIT...

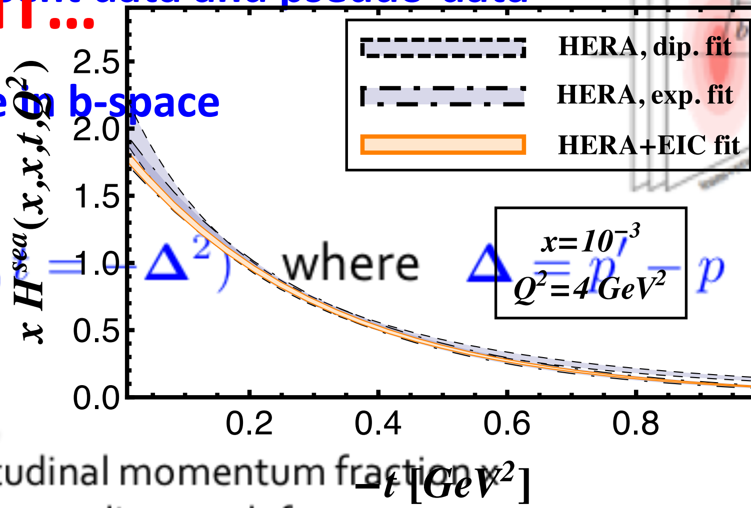
- Fourier transform GPDs to obtain image in b-space

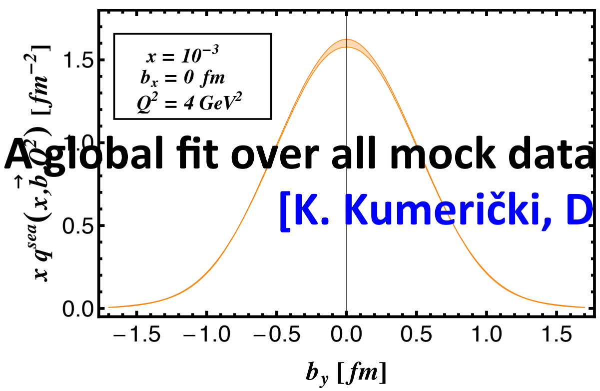
$$q(x, b^2) \simeq \int d^2\Delta\, e^{-ib\Delta} H^q(x, \xi = 0, t = -\Delta^2) \quad \text{where} \quad \Delta = p' - p$$

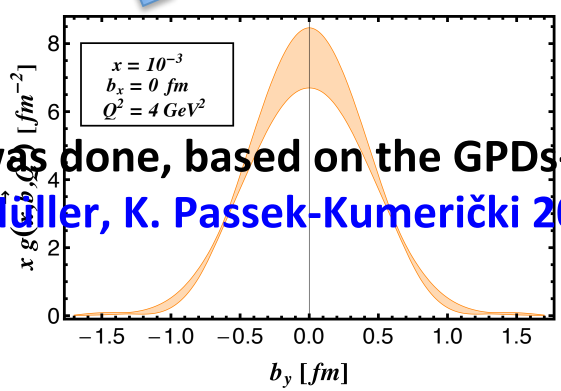
gives distribution of quarks with

- longitudinal momentum fraction x
- transverse distance b from proton center









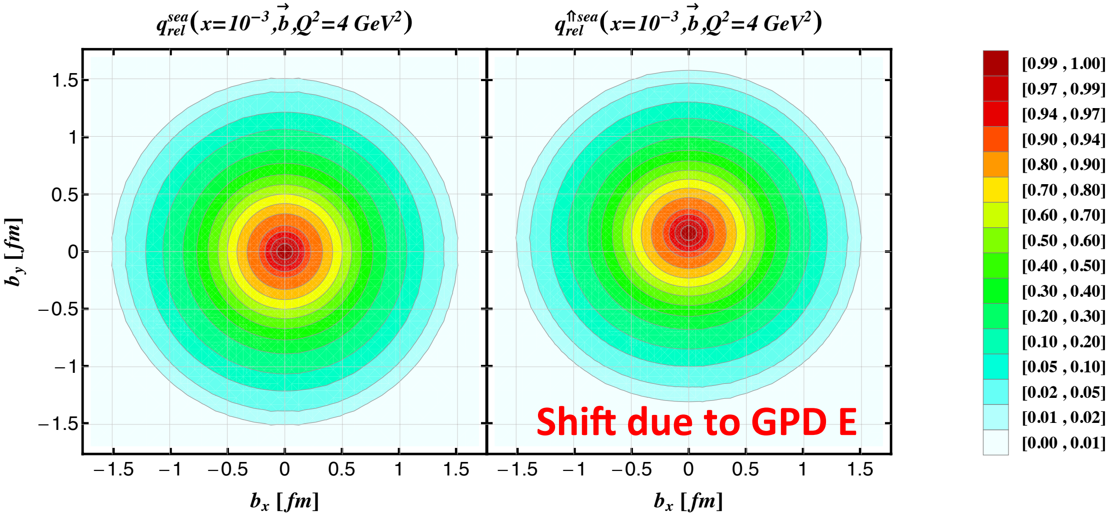
A global fit over all mock data was done, based on the GPDs-based model:

[K. Kumerički, D Müller, K. Passek-Kumerički 2007]

Errors are extrapolated for: $|t| \to 0$; $|t| > 1.5$ GeV^2

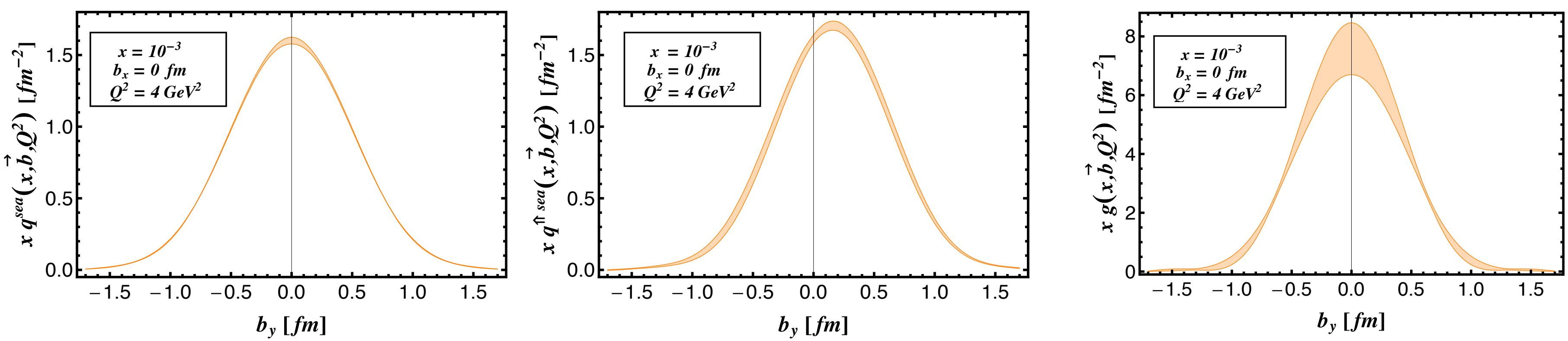
$$q\left(x,\vec{b},\mu^2\right) = \frac{1}{4\pi}\int_0^\infty d|t|\, J_0\left(\left|\vec{b}\right|\sqrt{|t|}\right) H\left(x,\eta=0,t,\mu^2\right)$$

Imaging

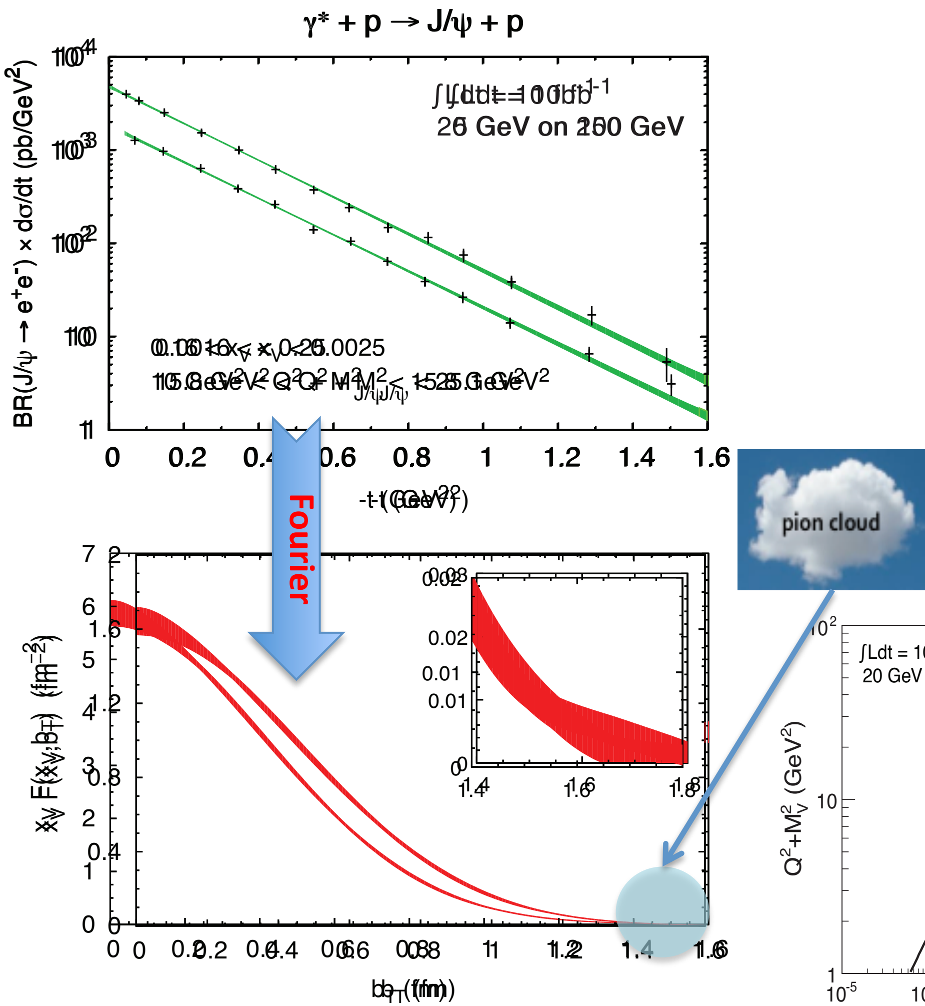


- A global fit over all mock data was done, based on the GPDs-based model:
  [K. Kumerički, D Müller, K. Passek-Kumerički 2007]
- Known values *q(x)*, *g(x)* are assumed for H^q, H^g (at t=0 forward limits E^q, E^g are unknown)
- Excellent reconstruction of H^{sea}, H^{sea} and good reconstruction of H^g (from $d\sigma/dt$)
- Reconstruction of GPD E (connection to the orbital momentum g-sum role)

Plots from D. Mueller

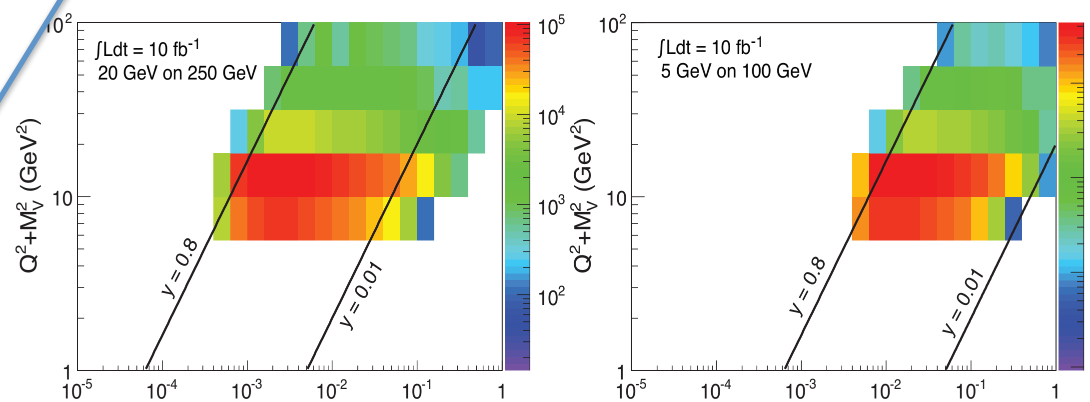


J/ψ



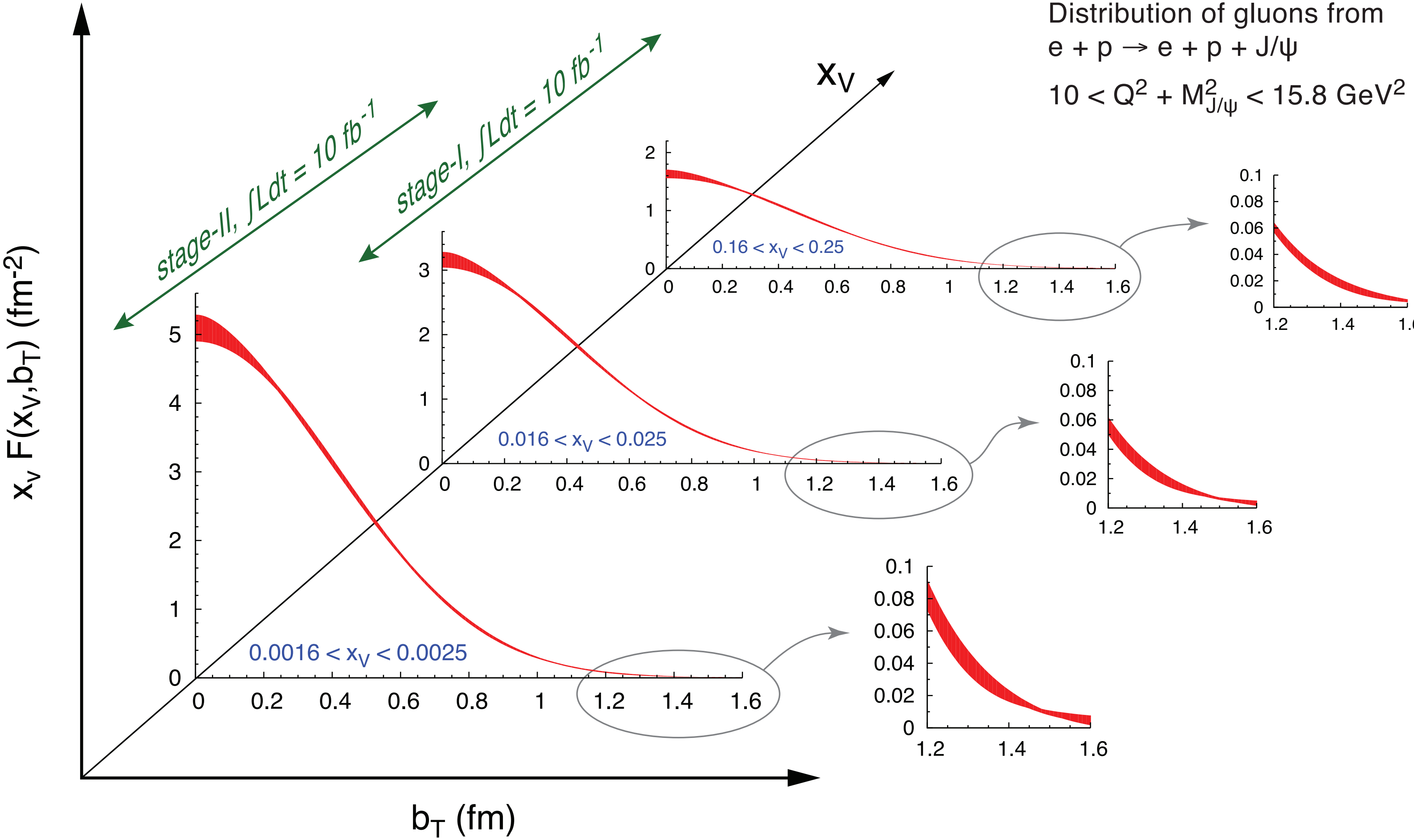
γ*p -> J/ψ p

- 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
$e + p \rightarrow e + p + J/\psi$

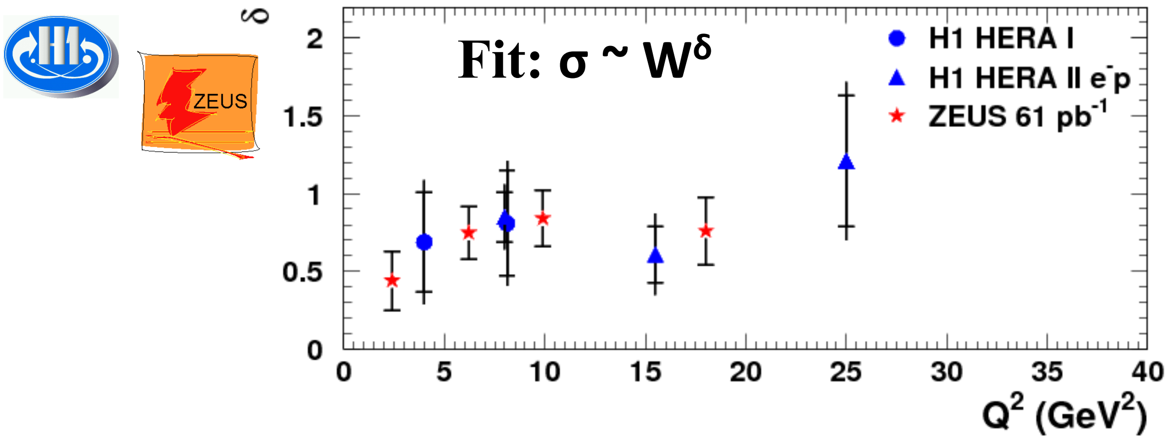
$10 < Q^2 + M^2_{J/\psi} < 15.8\ GeV^2$

Summary

- A lot of experience carried over from HERA
- DVCS can be used to drive the requirements for a dedicated new detector
- Simulation shows how an EIC can much improve our knowledge of GPDs
- A fine binning of x-sec and symmetries will be possible, uncertainties mostly dominated by systematics
- Large potential for an accurate 2+1D imaging of the polarized and unpolarized quarks and gluons inside the hadrons (and nuclei!)

Back up

DVCS @ HERA

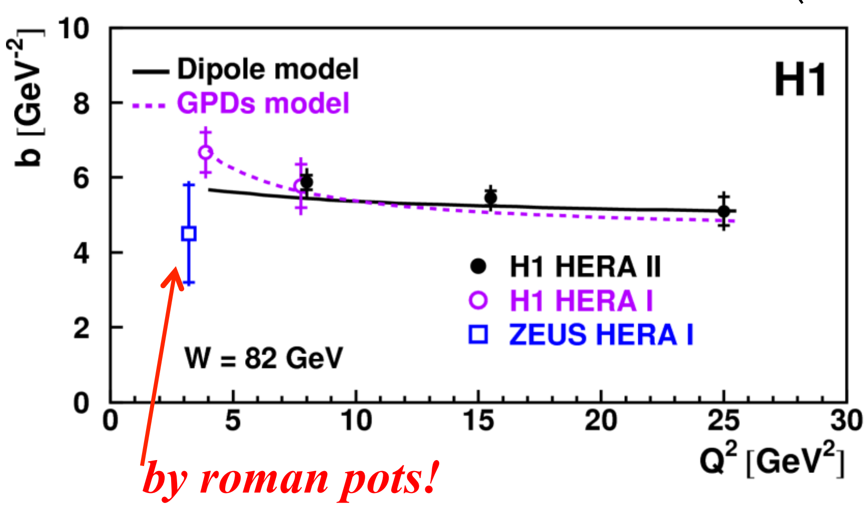


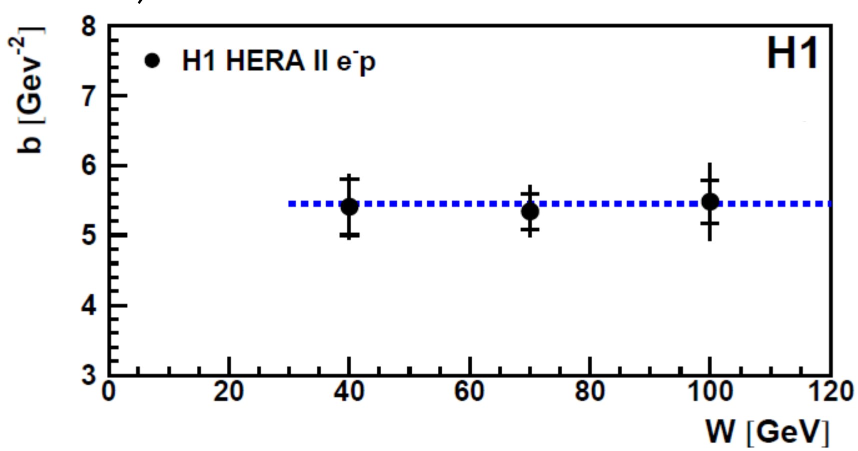
***Q²* dependence for the *W* slope not clear within the uncertainties!**

ZEUS: JHEP05(2009)108
H1: Phys.Lett.B659:796-806,2008

t measured indirectly: $t \sim \left(P_{T\gamma}^2 + P_{T_e}^2\right)^2$

$Fit: \dfrac{d\sigma}{dt} \propto e^{-b|t|}$





No evidence for *W* dependence of *b*

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:

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

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

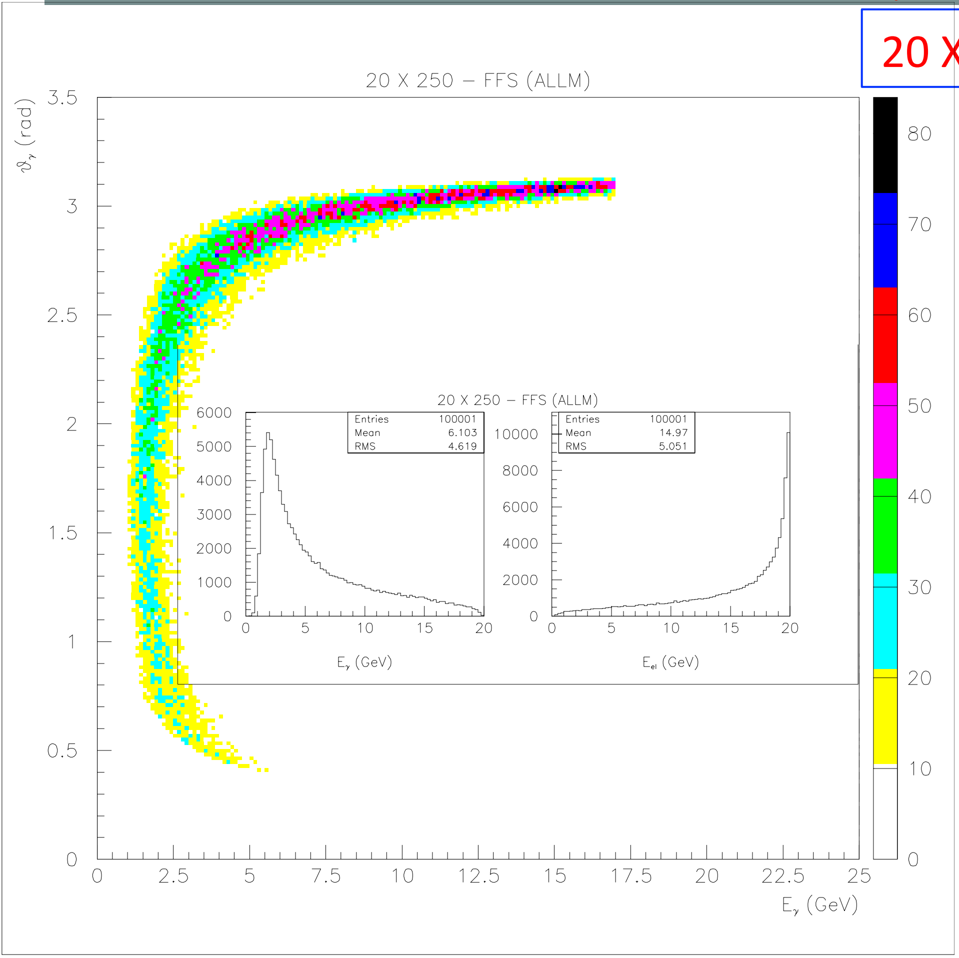
- ✓ $\frac{d\sigma}{d|t|} = \exp\left(B\left(Q^2\right)t\right)$ -> The B slope is allowed to be costant or to vary with Q^2

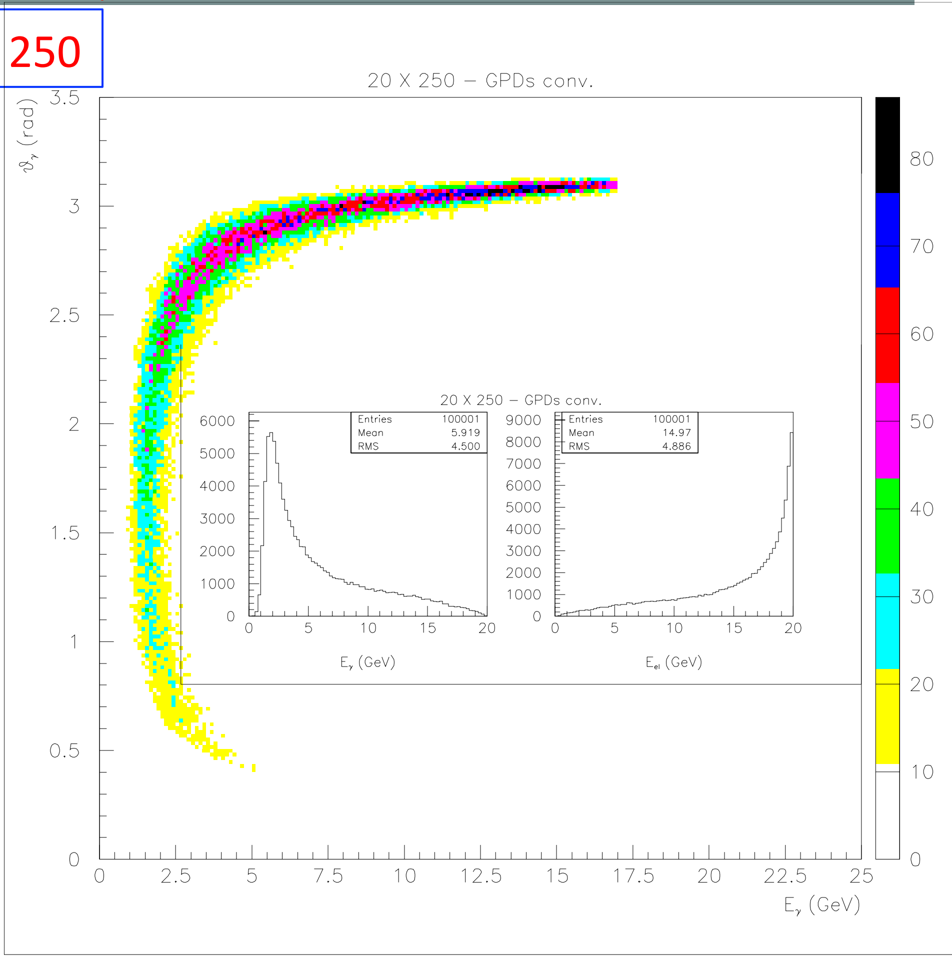
- ✓Proton dissociation ($ep \to e \gamma Y$) can be included

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

θ_γ vs E_γ

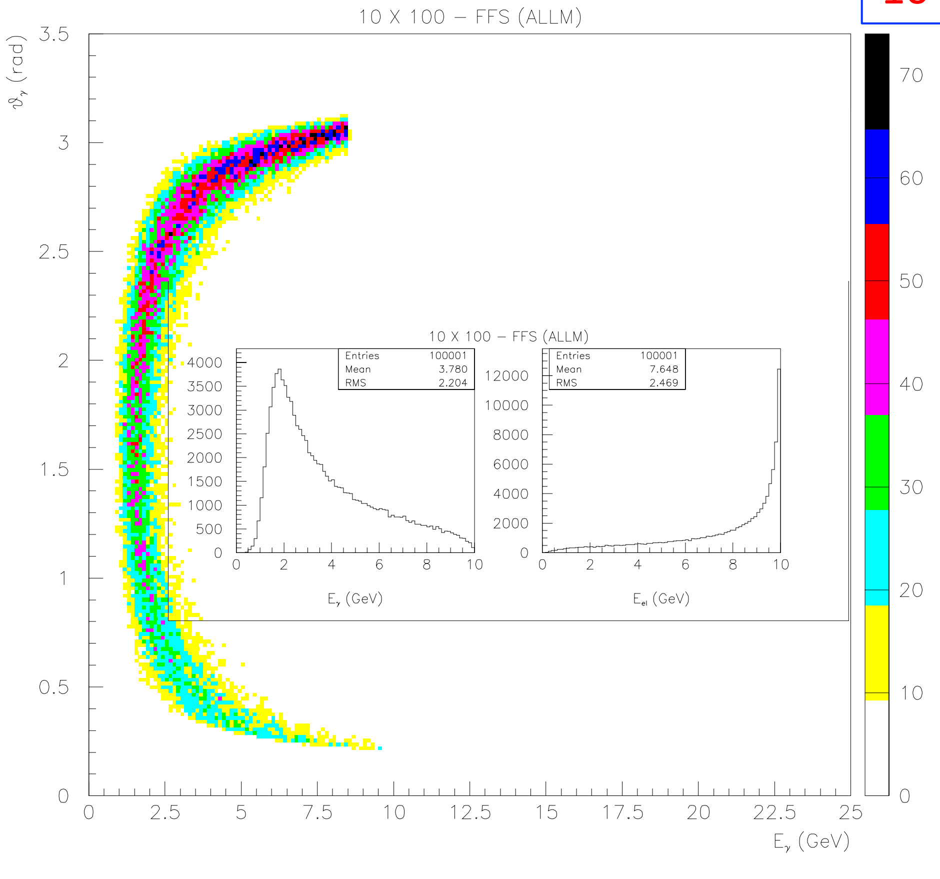
20 X 250

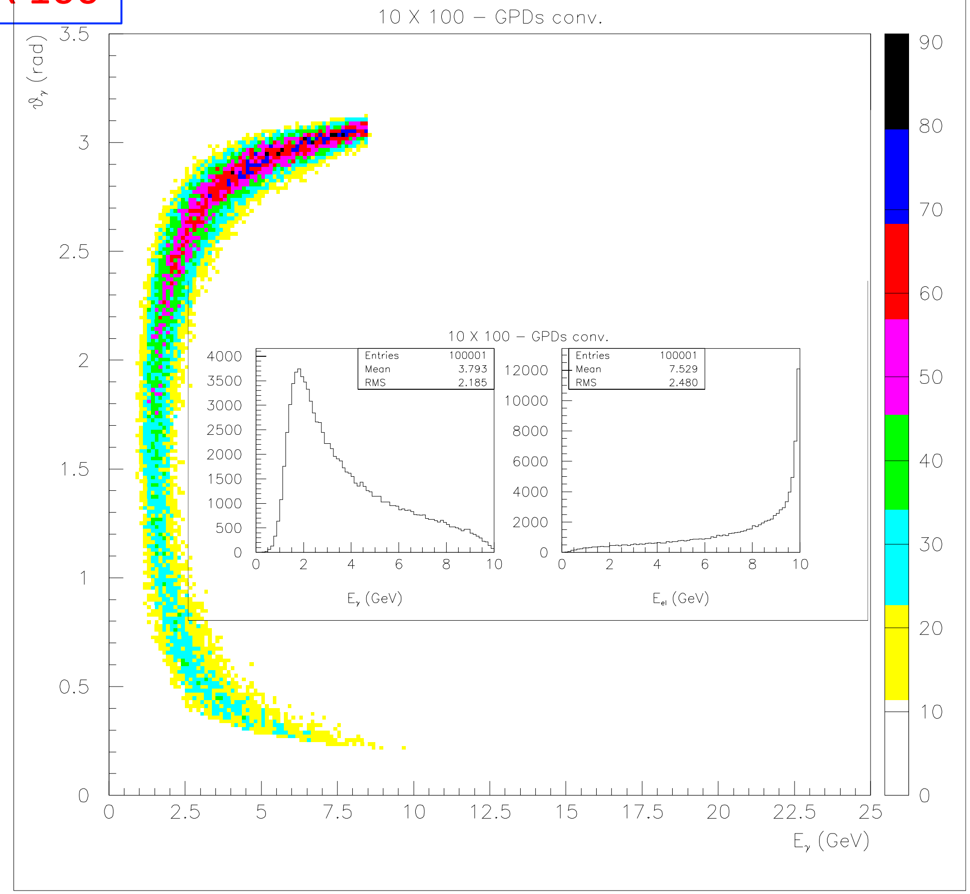




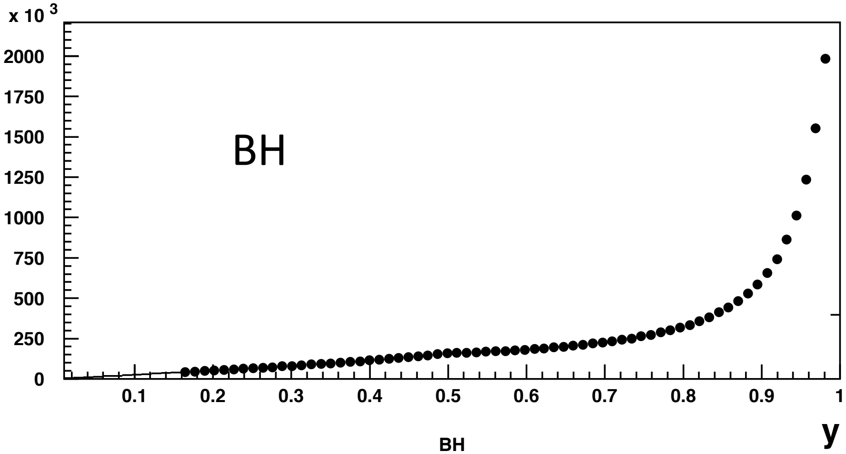
θ_γ vs E_γ

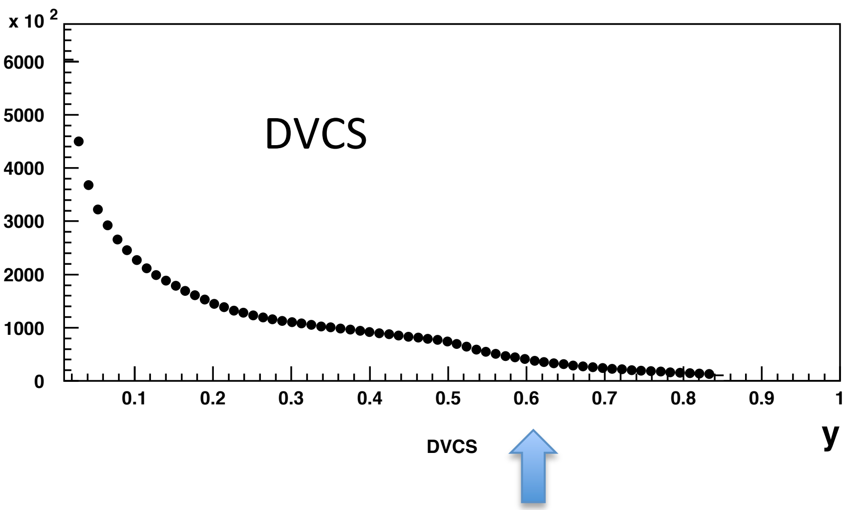
10 X 100



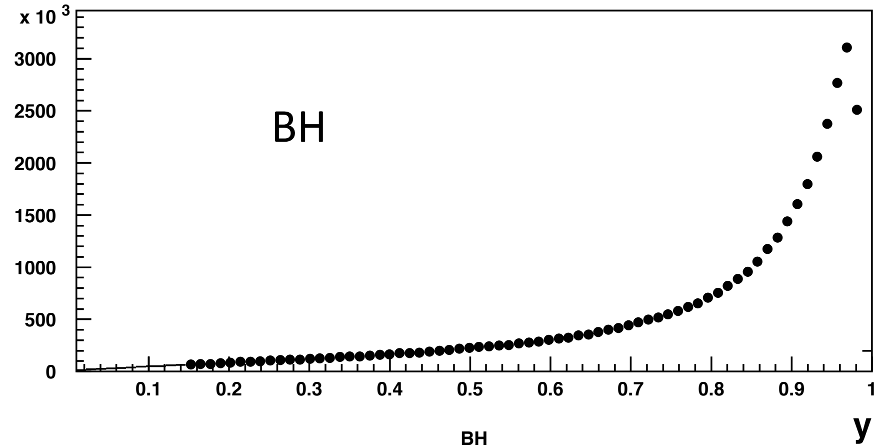


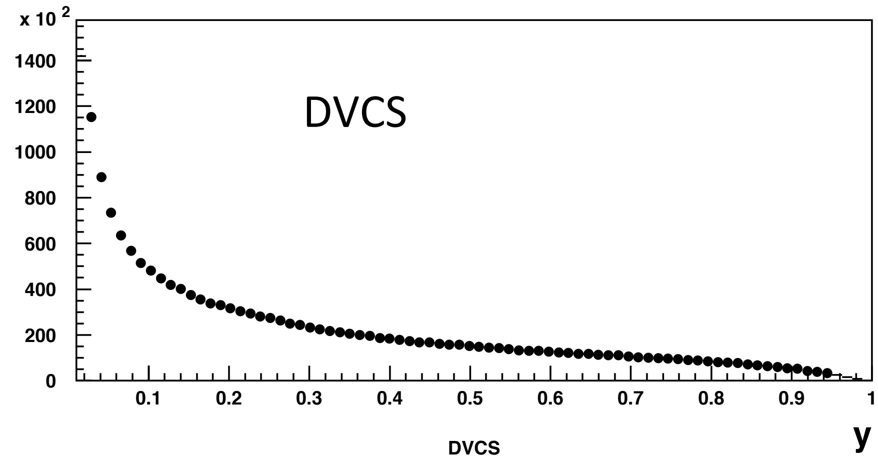
20 X 250





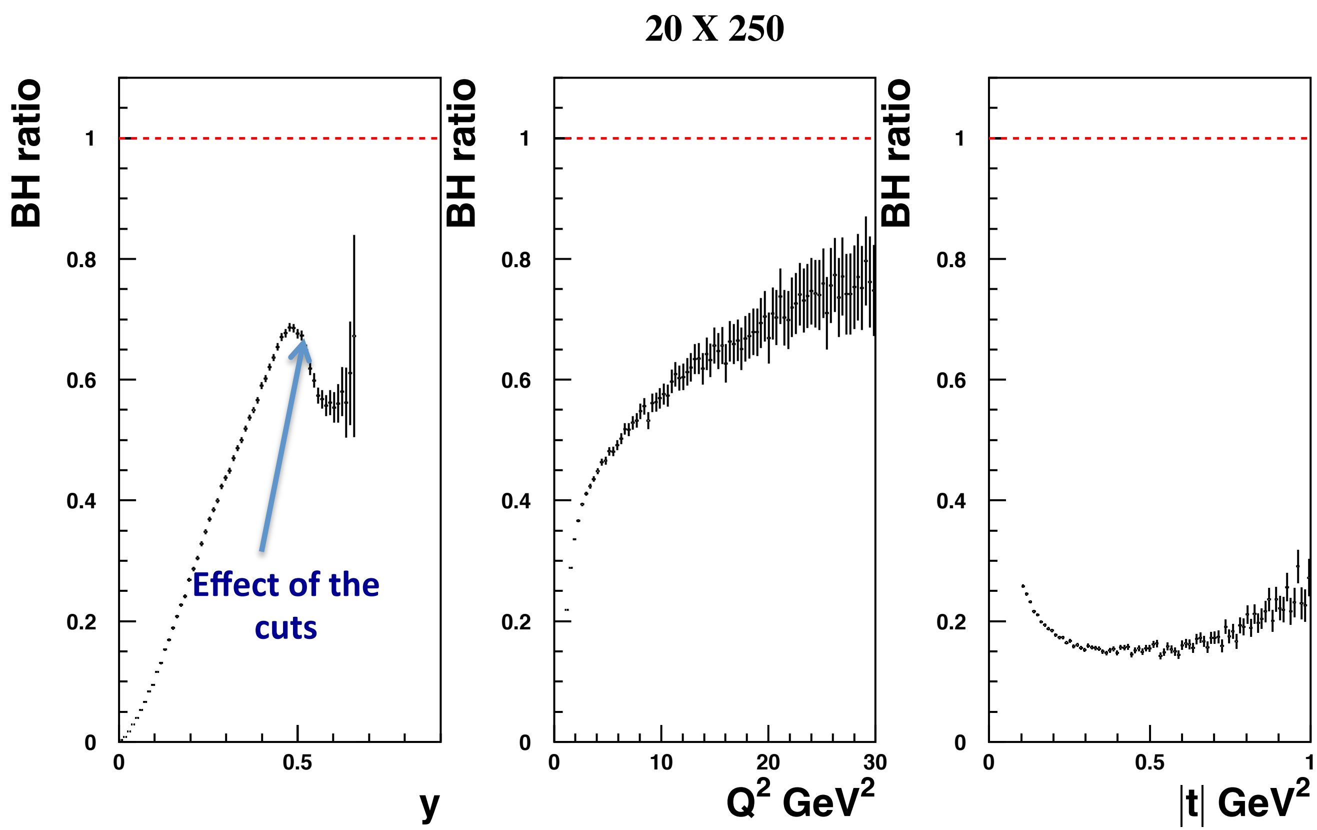
5 X 100





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

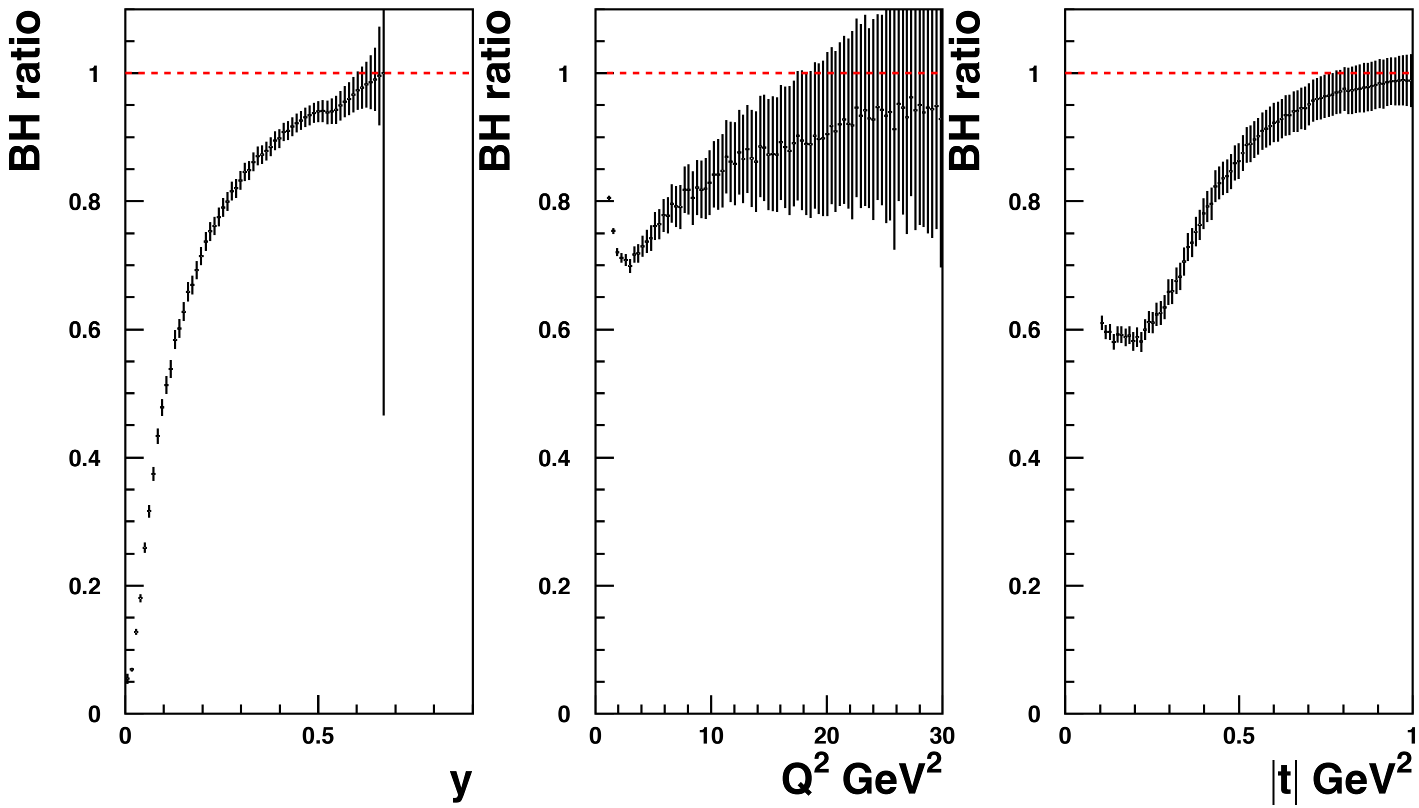
BH fraction - overall



The effect of the cut for the 20x250 conf. is that BH never exceeds 70% of the sample

BH fraction - overall

5 X 100



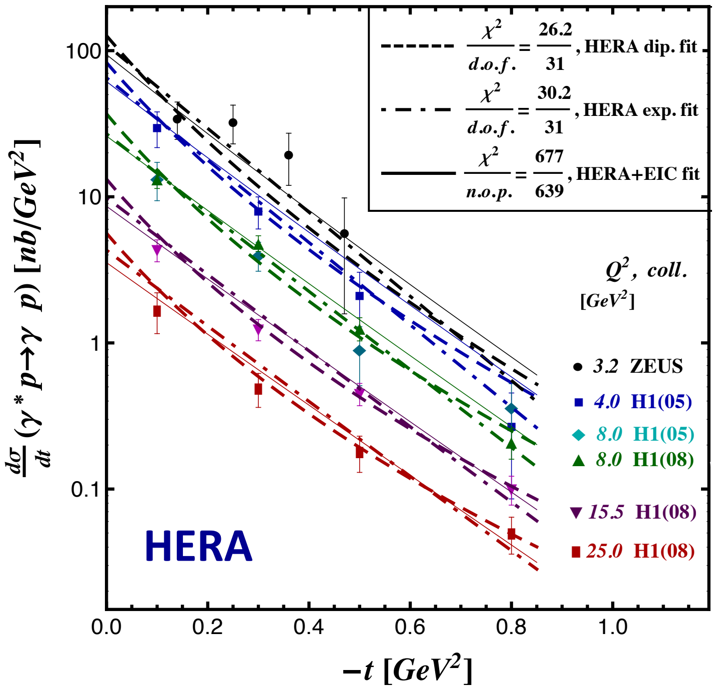
for the 5x100 conf. is that BH can be a problem at large y and large t, depending on the bin

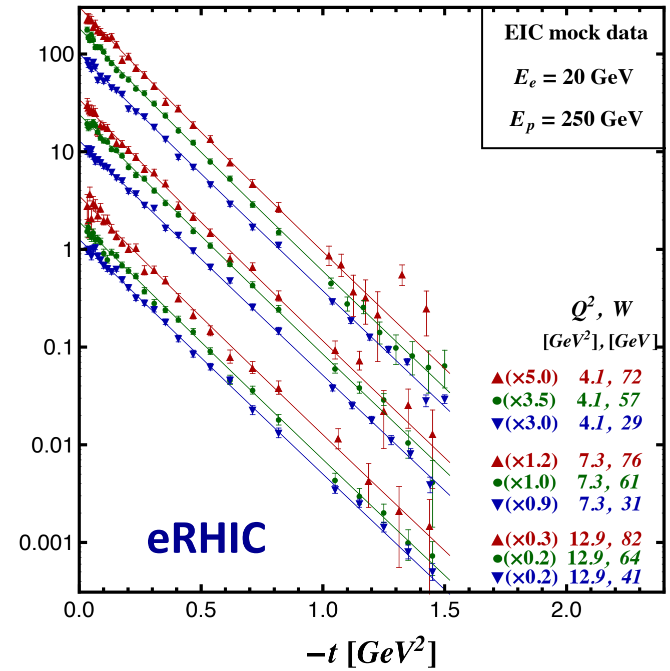
t-xsec (ep -> γp)

Selection criteria:

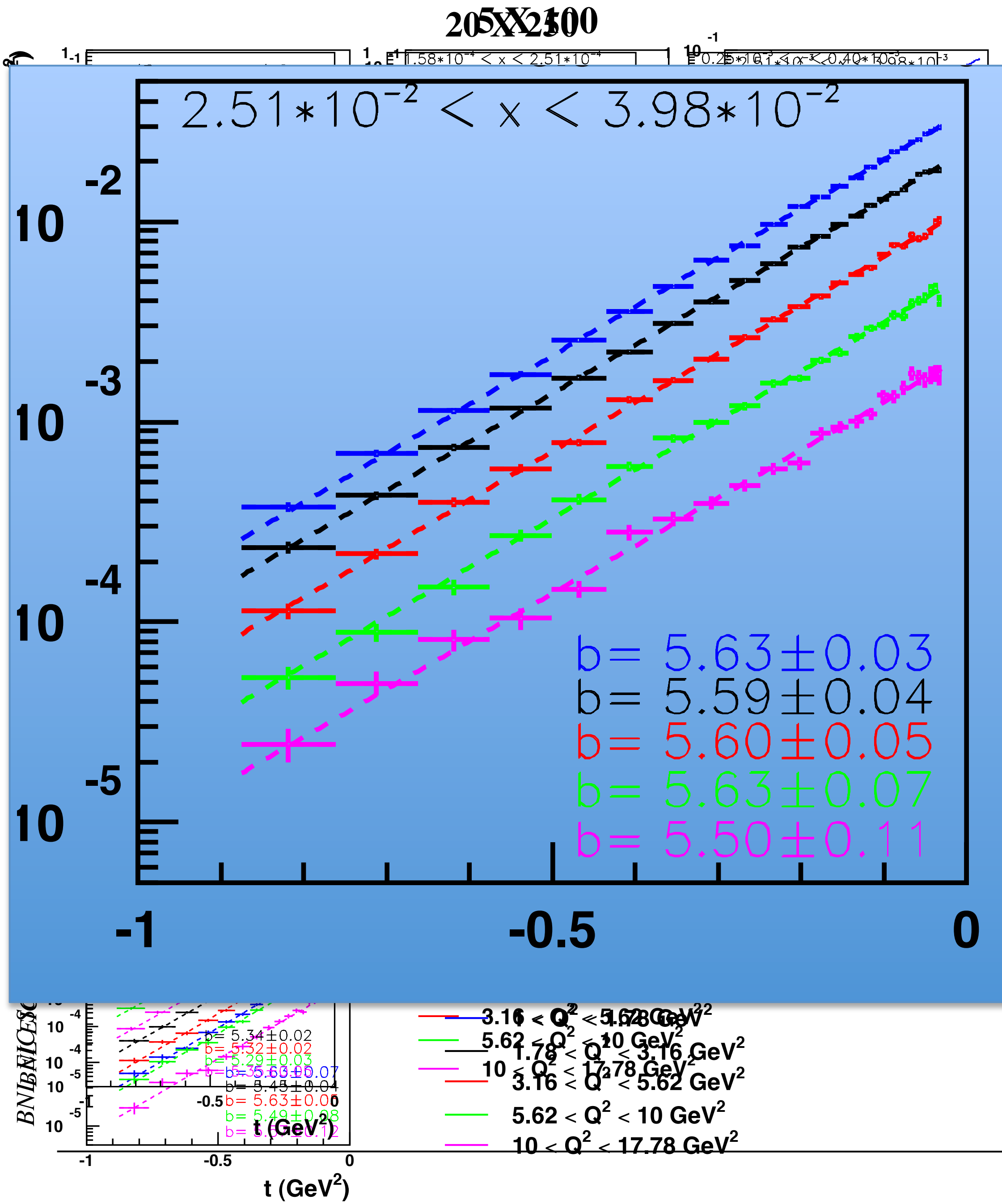
$0.01 < y < 0.6$
$\theta\gamma < 2\times10^{-2}$ rad
$\theta el < 2\times10^{-2}$ rad
$E\gamma > 1$ GeV
$Eel > 1$ GeV

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





10 x-bins ; 5 Q^2-bins



dσ/d|t|

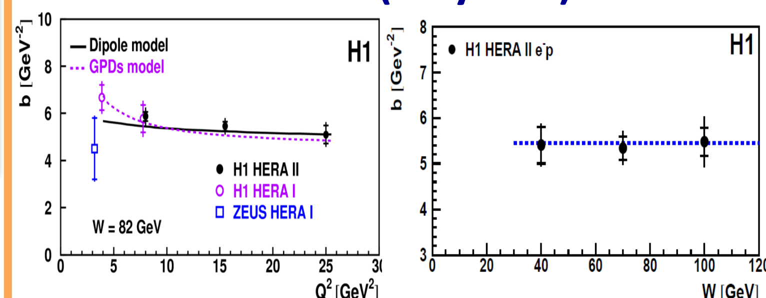
$$\frac{d\sigma}{d|t|} = \frac{\# evt}{\Delta_{bin} \bullet A \bullet \mathcal{L}} \quad \sim e^{-bt}$$

b=5.6

Specifications:

- **Statistical error down to 1%**
- **It uses smeared t values (5% momentum resol.)**
- **|t|-binning –> 3 * resolution (or higher)**

DVCS |t|-slope @ HERA (15 years)



- Electron and photon clusters are ofter very close!
- can affect the phi distribution reconstruction!

Crucial!

Our em cal must distinguish two clusters within the order of 1 deg

More studies on-going…