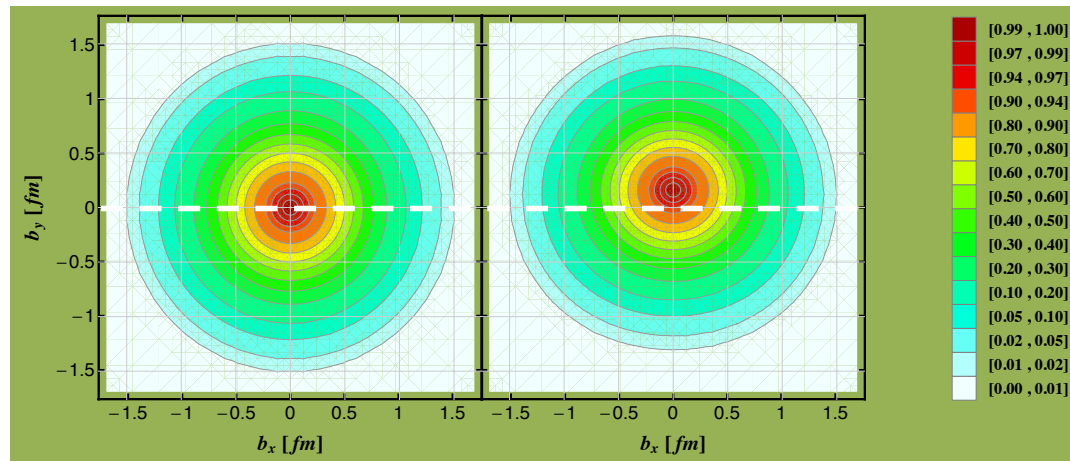
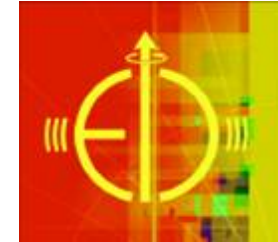


GPDs at an Electron Ion Collider

BROOKHAVEN
NATIONAL LABORATORY



Salvatore Fazio
Brookhaven National Laboratory
Upton, New York
(for the BNL EIC Science Task Force)



DIFFRACTION 2012

Puerto del Carmen, Lanzarote – Canary Islands

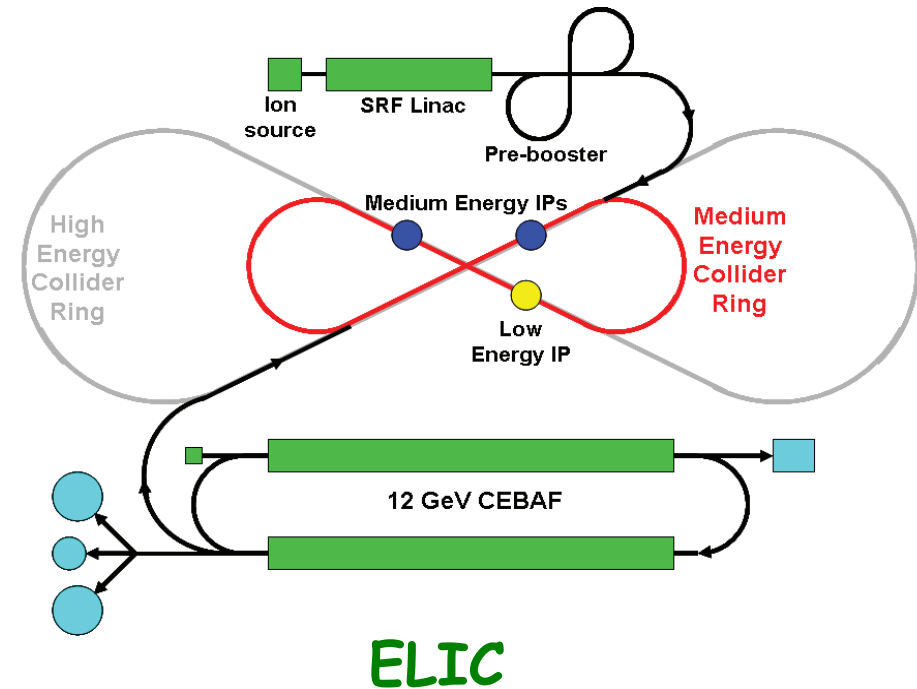
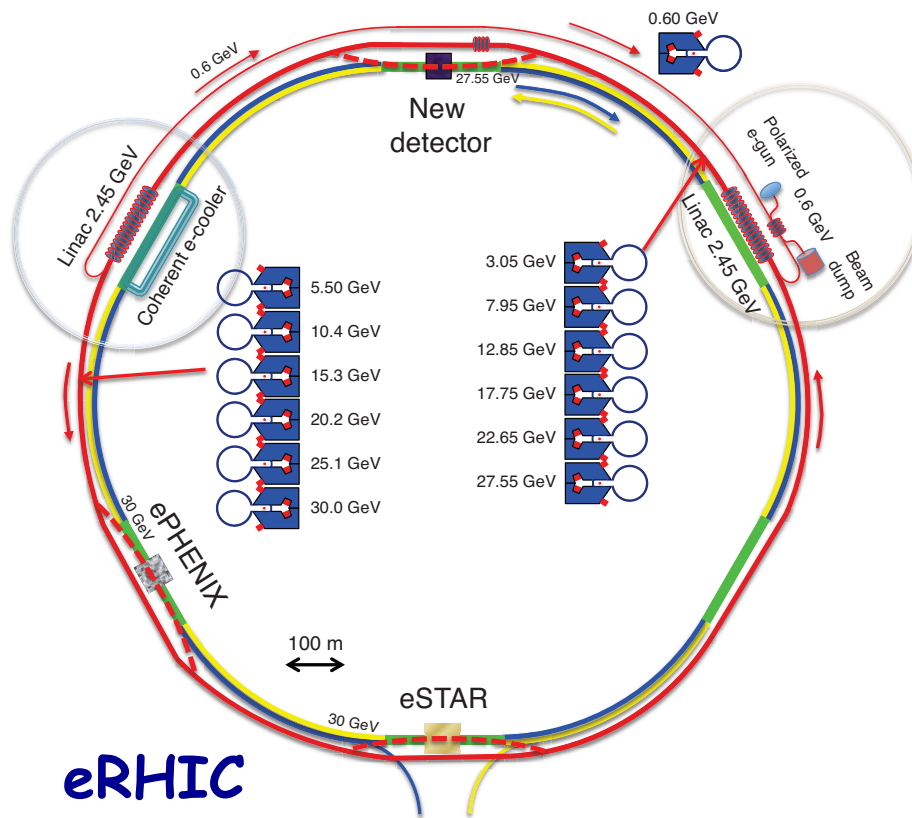
September 10-15, 2012



The EIC project

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

Thomas Jefferson National Laboratory (ELIC)

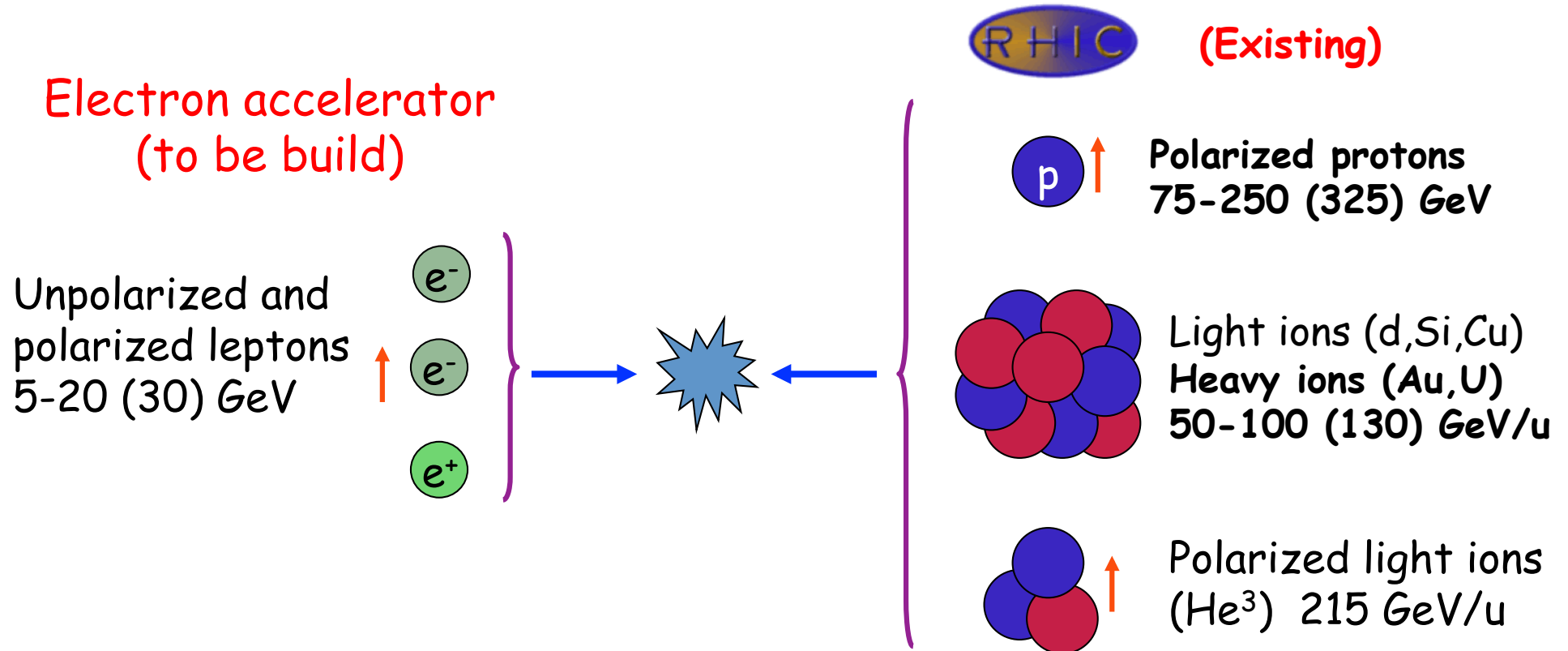


Center mass energy range: $\sqrt{s}=28-200$ GeV

High beam polarization for both hadrons and electrons

Mission: Studying the Physics of Strong Color Fields

The eRHIC idea



Center mass energy range: $\sqrt{s}=28-200$ GeV

EIC/eRHIC – experimental features

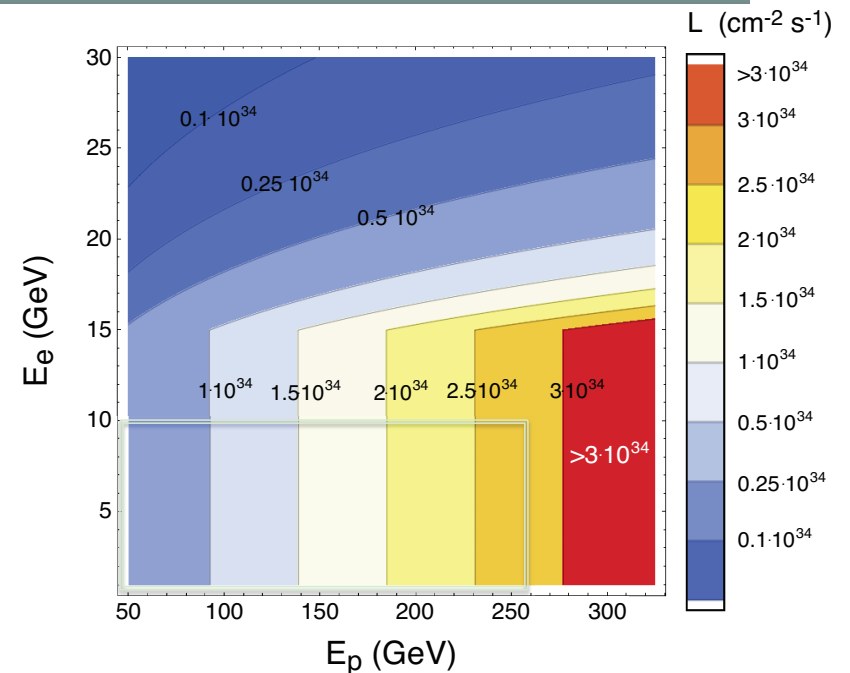
Why EIC is unique:

□ 5 - 30 GeV electrons on 75-250 GeV (50-100GeV) protons (nuclei). Polarization of electrons and protons (nuclei)

□ Lumi: $\sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

Important for exclusive DIS:

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



EIC/eRHIC – experimental features

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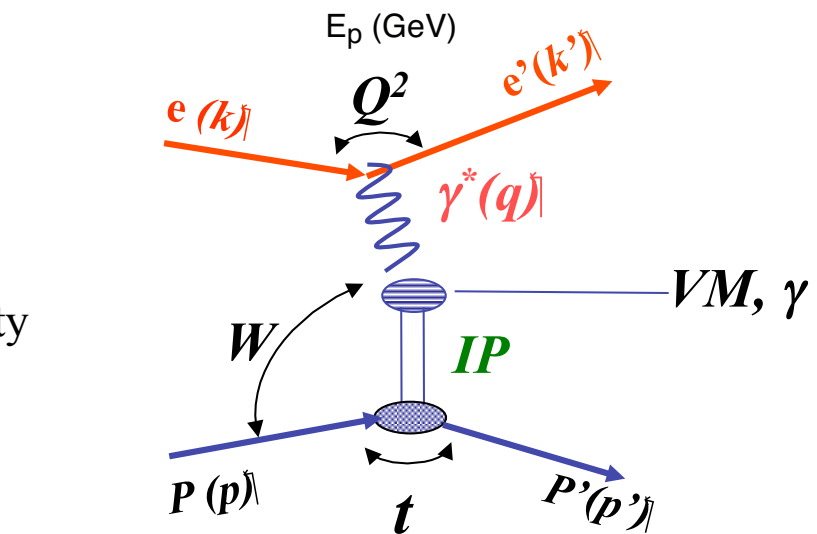
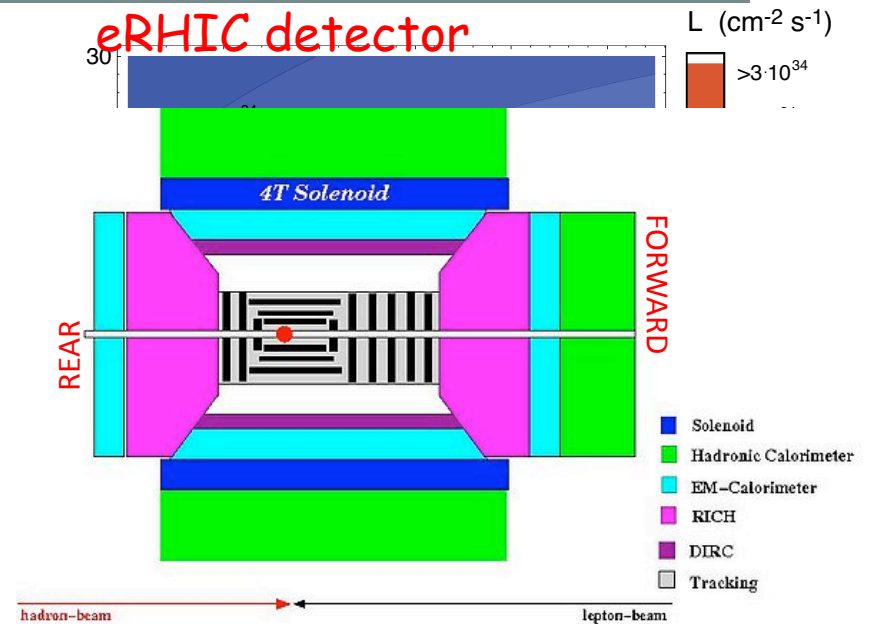
Important for exclusive DIS:

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

What are the detector requirements:

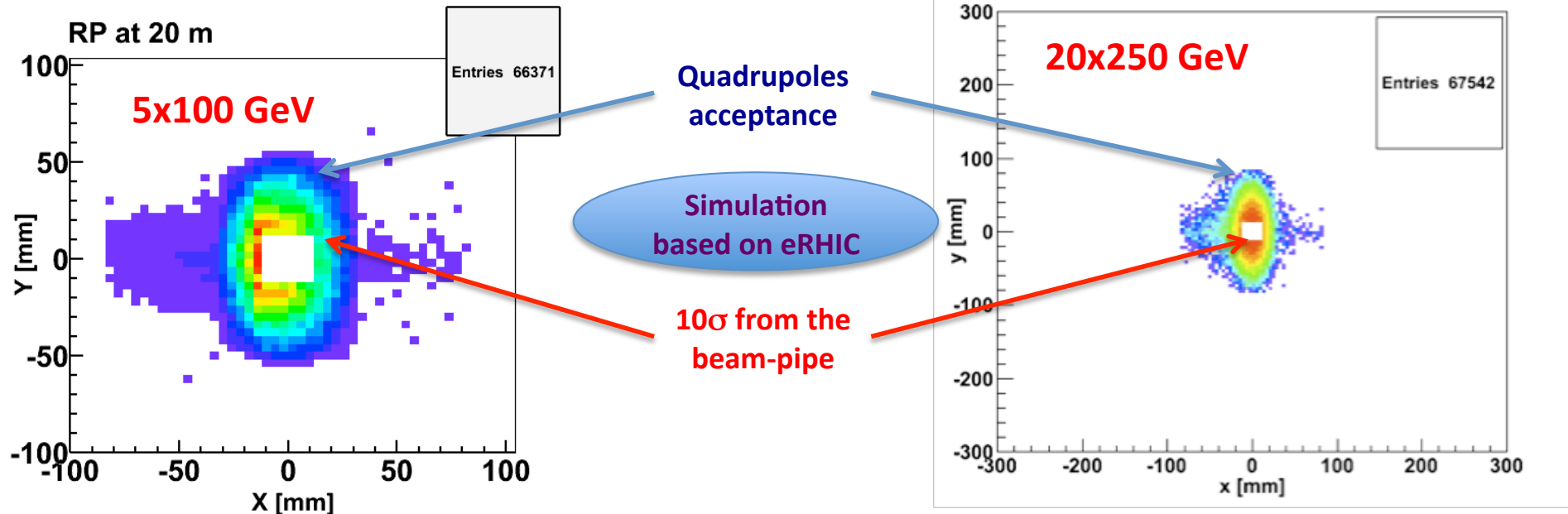
Important for exclusive diffraction:

- Hermetic Central Tracking Detector
- Good EM calorimeter resolution with fine granularity
- Preshower em cal $\rightarrow \pi^0$ background
- Very forward calorimetry
- **Roman pots (and with excellent acceptance)**



Direct $|t|$ measurement – Roman Pots

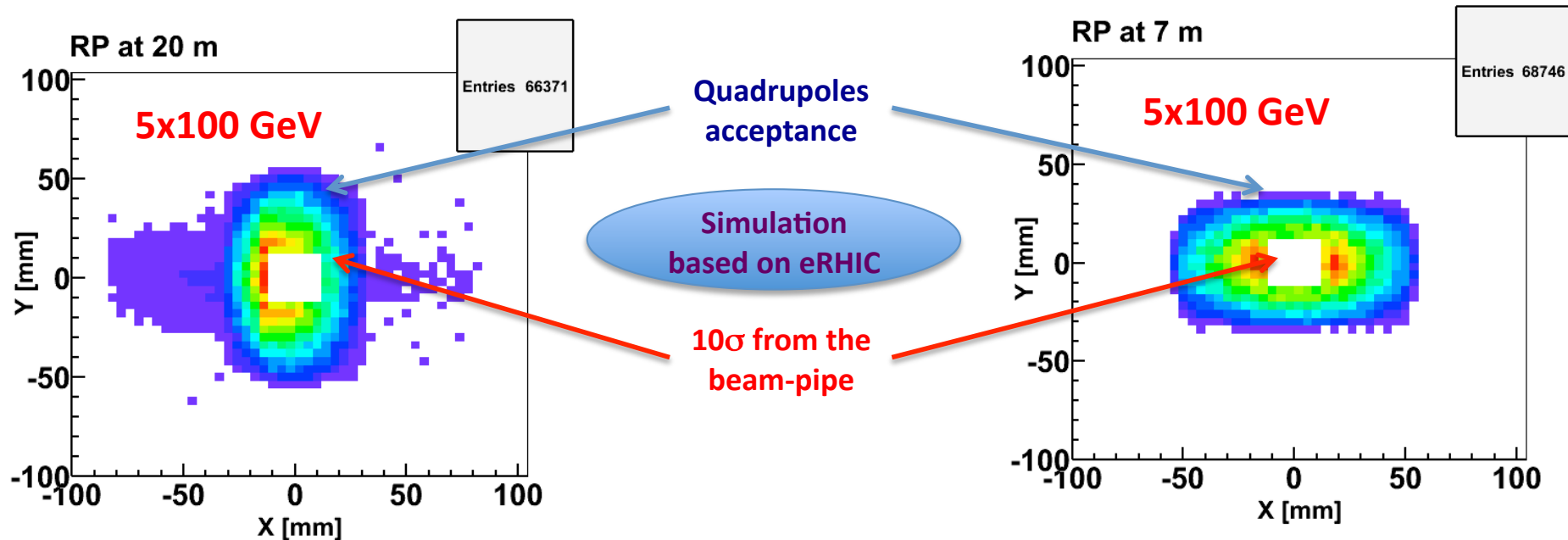
Accepted in “Roman Pot” (example) at $s=20\text{m}$



- high- $|t|$ acceptance mainly limited by magnet aperture
- low- $|t|$ acceptance limited by beam envelop ($\sim 10\sigma$)
- $|t|$ -resolution limited by
 - beam angular divergence $\sim 100\mu\text{rad}$ for small $|t|$
 - uncertainties in vertex (x,y,z) and transport
 - $\sim <5\text{-}10\%$ resolution in t (RP at STAR)

Direct $|t|$ measurement – Roman Pots

Accepted in “Roman Pot” (example) at $s=20\text{m}$

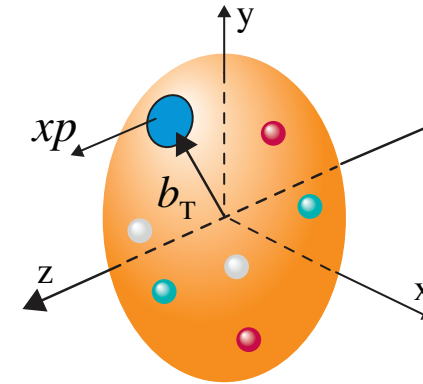


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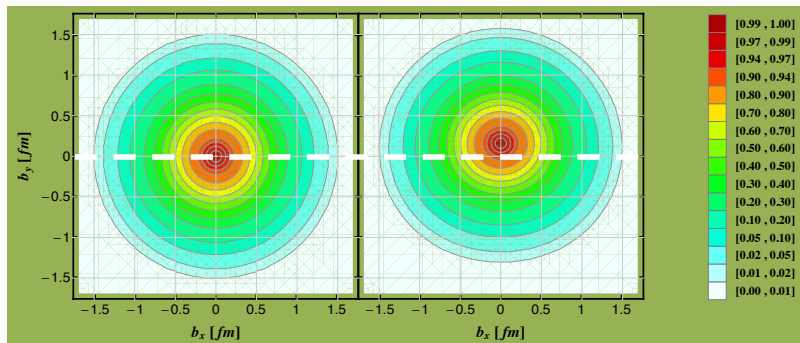
(2+1)-Dimensional imaging of the proton

Open questions:

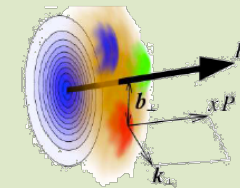
- ⊙ PDFs do not resolve transverse coordinate or momentum space
- ⊙ In a fast moving nucleon the longitudinal size squeezes like a 'pizza' but transverse size remains about 1 fm



Goal: nucleon tomography!



Proton imaging



what is the spatial distribution of quarks and gluons in nucleons/nuclei

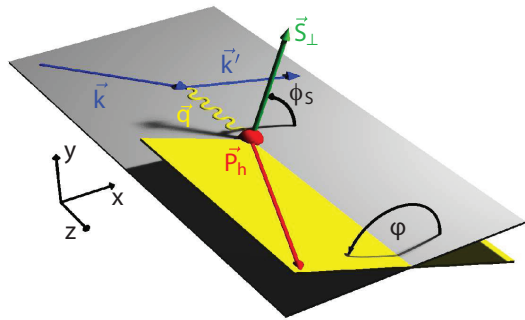


Possible window to orbital angular momentum

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**



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

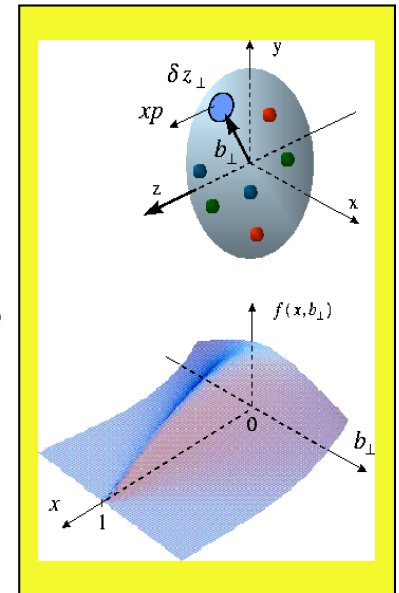
Angle btw the production
and scattering planes

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

Angle btw the scattering plane
and the transverse pol. vector

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

Requires a positron
beam at eRHIC



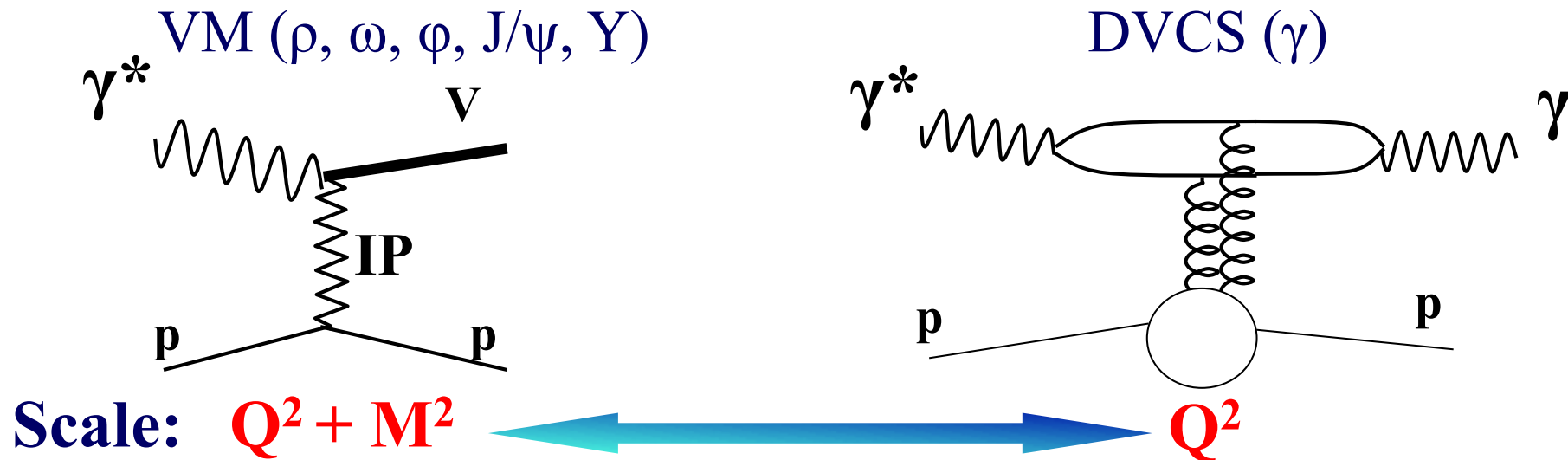
$$A_{LU} \propto y \left[F_1(t) H(\xi, \xi, t, Q^2) - \frac{t}{4M^2} F_2(t) E(\xi, \xi, t, Q^2) + \dots \right]$$

Dominated by **H**
slightly dependent on **E**

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

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

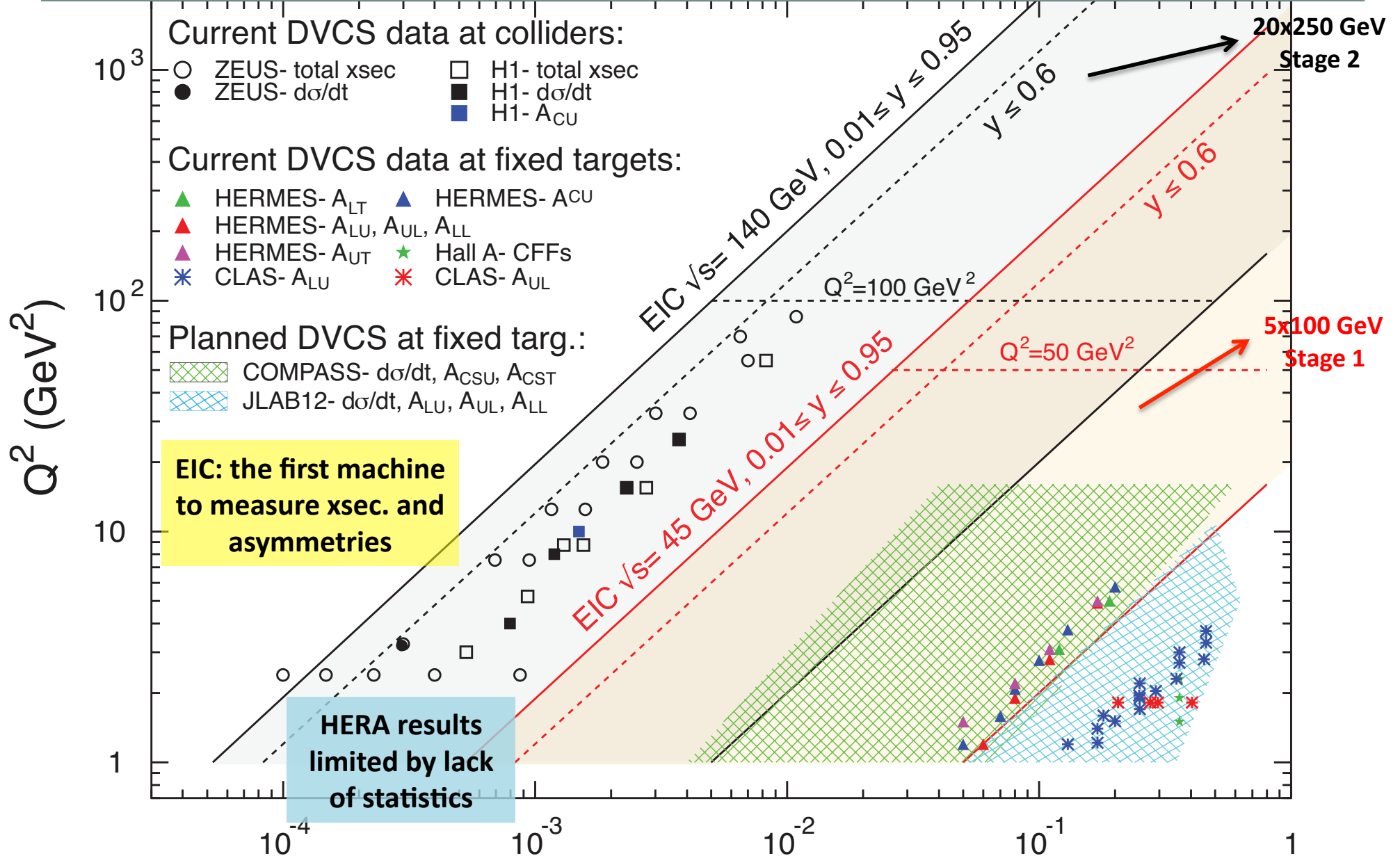
Deeply Virtual Compton Scattering



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 (via evolution)

DVCS phase-space



Scanning the phase space...

EIC lumi:

~10 fb⁻¹/year @ stage 1 – 5x100

~100 fb⁻¹/year @ stage 2 – 20x250

Acceptance criteria

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

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

- $y < 0.6$
- $(\theta_{\text{el}} - \theta_{\gamma}) > 0$
- $E_{\text{el}} > 1 \text{ GeV}^2$; $E_{\gamma} > 1 \text{ GeV}^2$

➤ Events smeared for expected resolution in t , Q^2 , x

➤ Systematic uncertainty assumed to be ~5%

➤ Overall systematic uncertainty from luminosity measurement not taken into account

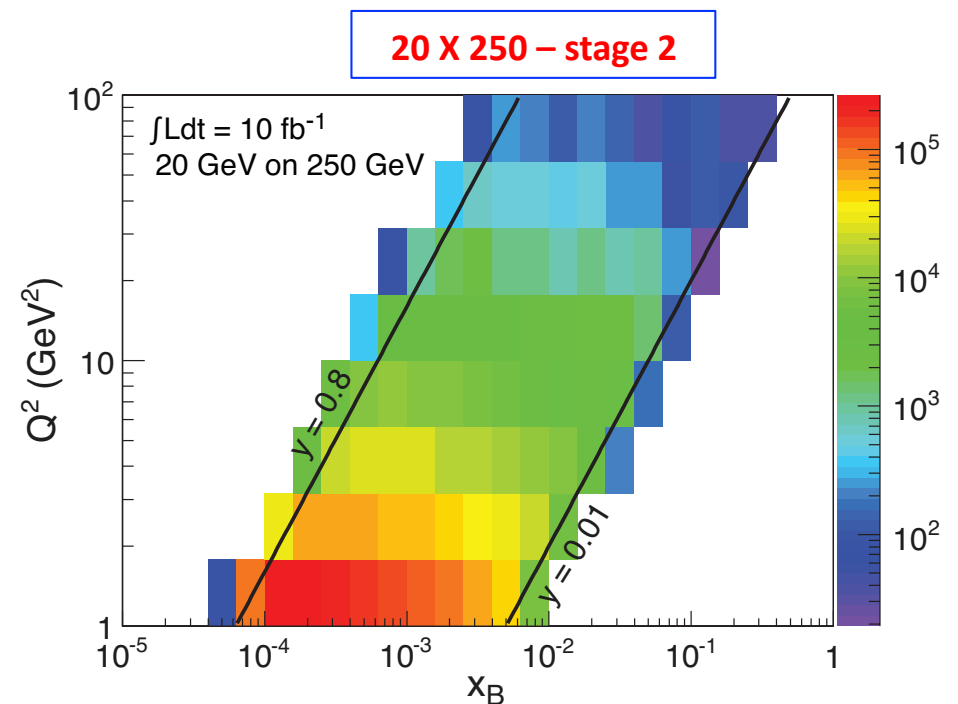
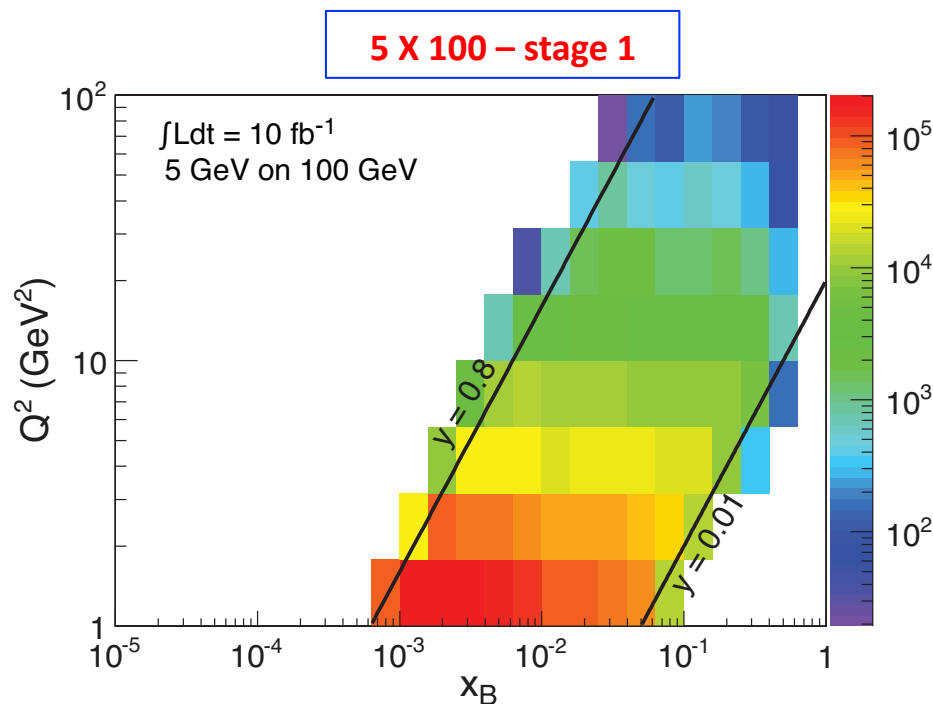
Scanning the phase space...

EIC lumi:

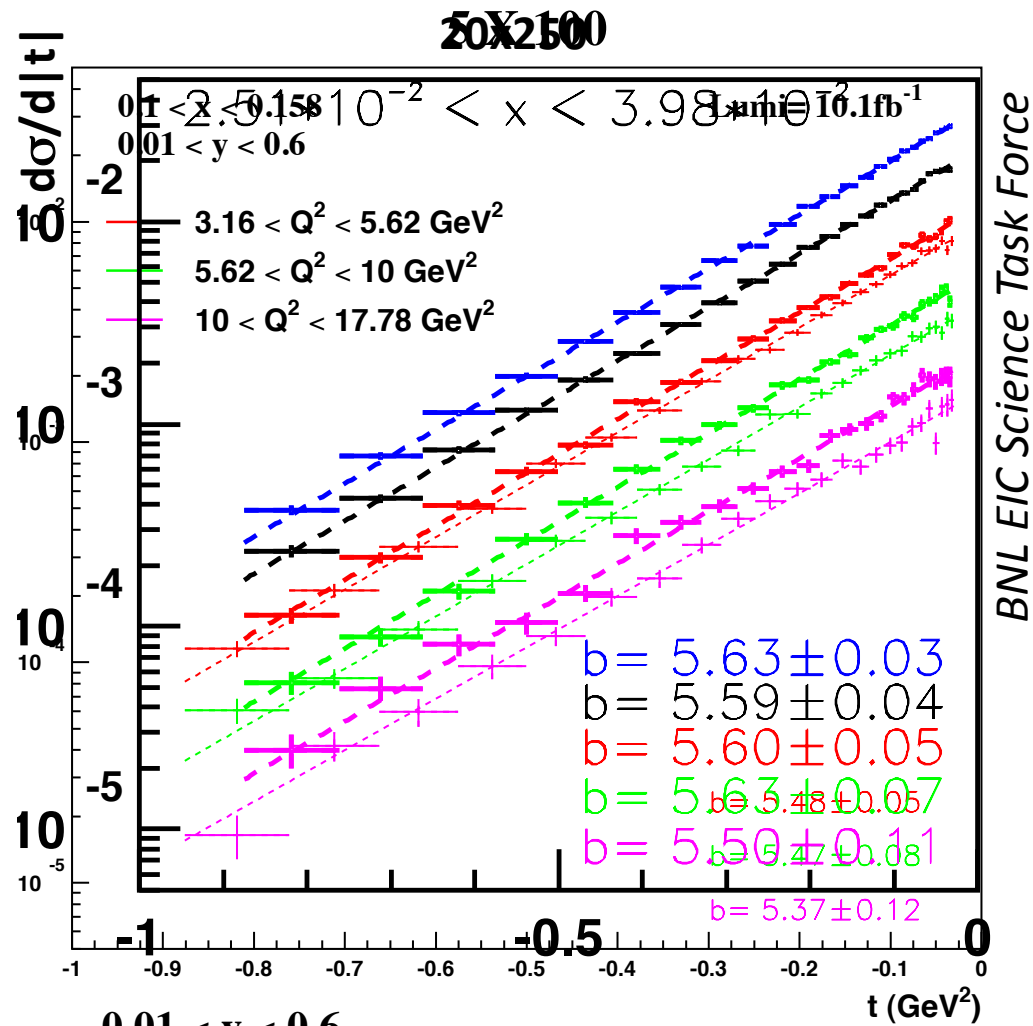
$\sim 10 \text{ fb}^{-1}/\text{year}$ @ stage 1 – 5x100

$\sim 100 \text{ fb}^{-1}/\text{year}$ @ stage 2 – 20x250

- ✧ 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 Q^2 and W ... and even in $|t|$



$\frac{d\sigma}{d|t|}$

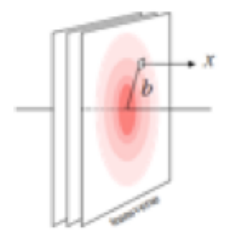
$$\frac{d\sigma}{d|t|} = \frac{\# evt}{\Delta_{bin} \cdot A \cdot \mathcal{L}} \sim e^{-bt}$$

b=5.6

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

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

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



- |t|-binning -> 3 * resolution (or higher)
- Statistical error down to 1%

EIC lumi:

~10 fb⁻¹/year @ stage 1 – 5x100

~100 fb⁻¹/year @ stage 2 – 20x250

dσ/d|t| - large |t|

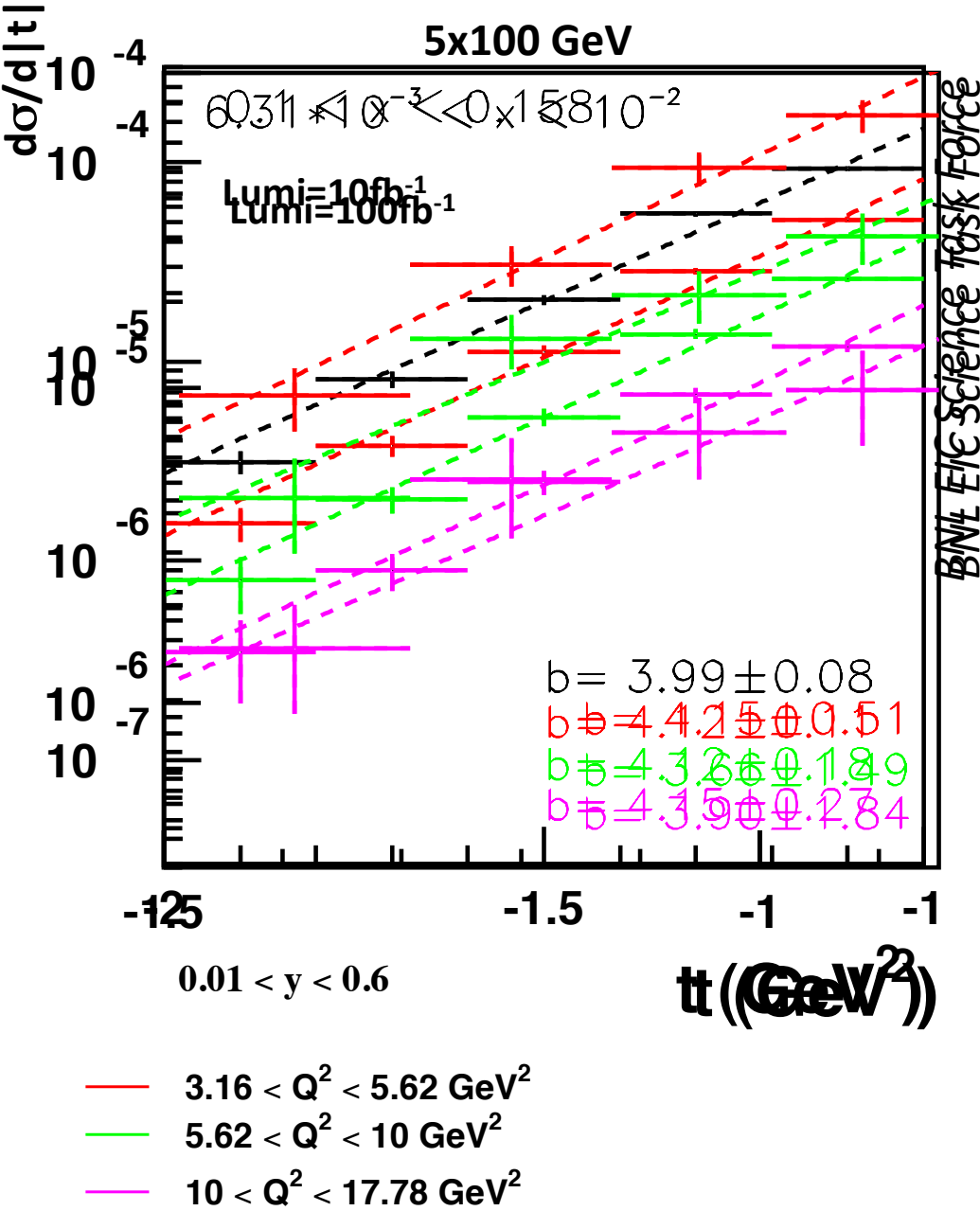
EIC lumi:
 ~10 fb⁻¹/year @ stage 1 – 5x100
 ~100 fb⁻¹/year @ stage 2 – 20x250

Dependence at large-|t| still unknown

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



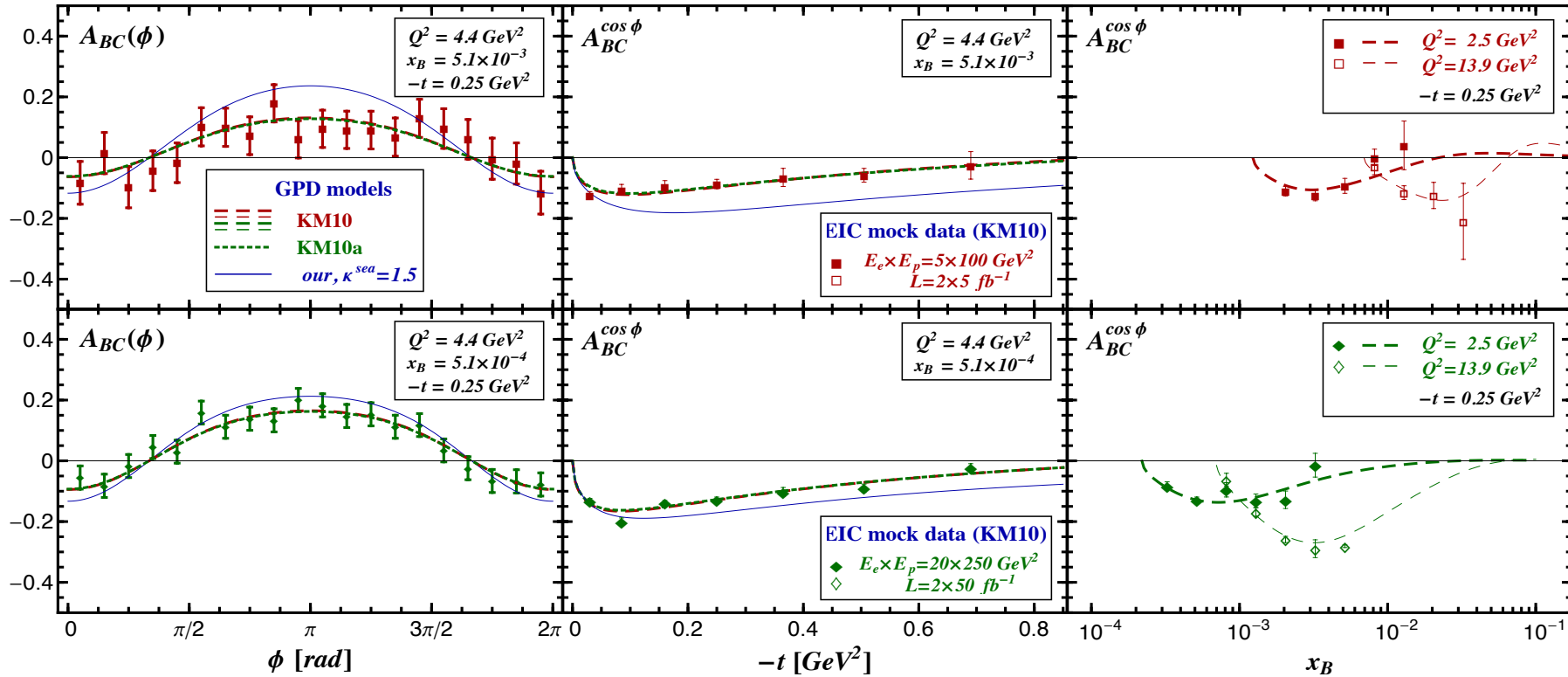
Very important to constrain GPDs



$$\frac{d\sigma}{dt} \propto \text{Im}(A) \rightarrow \text{GPD } H$$

Asymmetries

Unpolarized positron beam \rightarrow beam charge asymmetry (A_C)

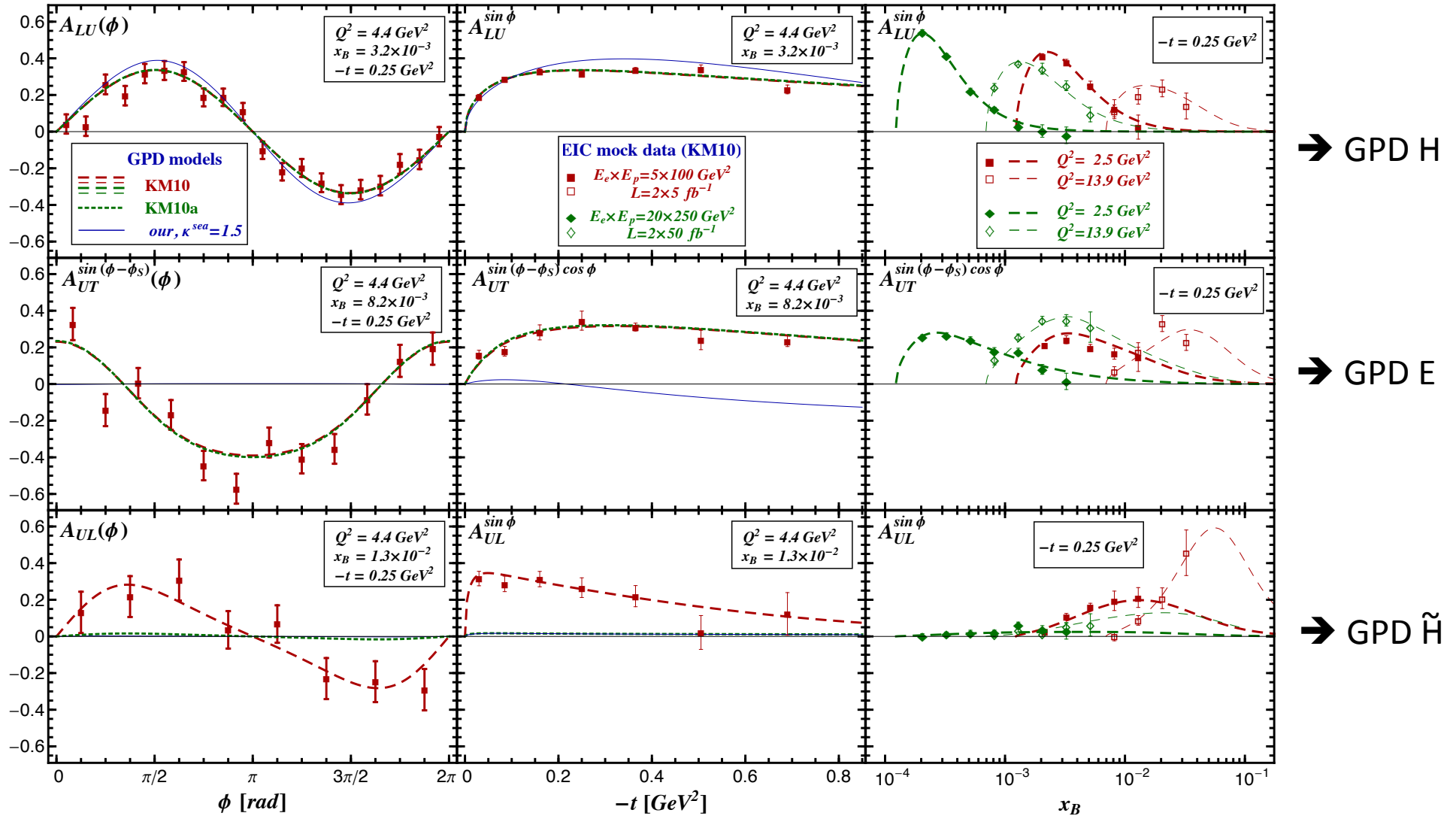


$$A_C \propto \text{Re}(A)$$

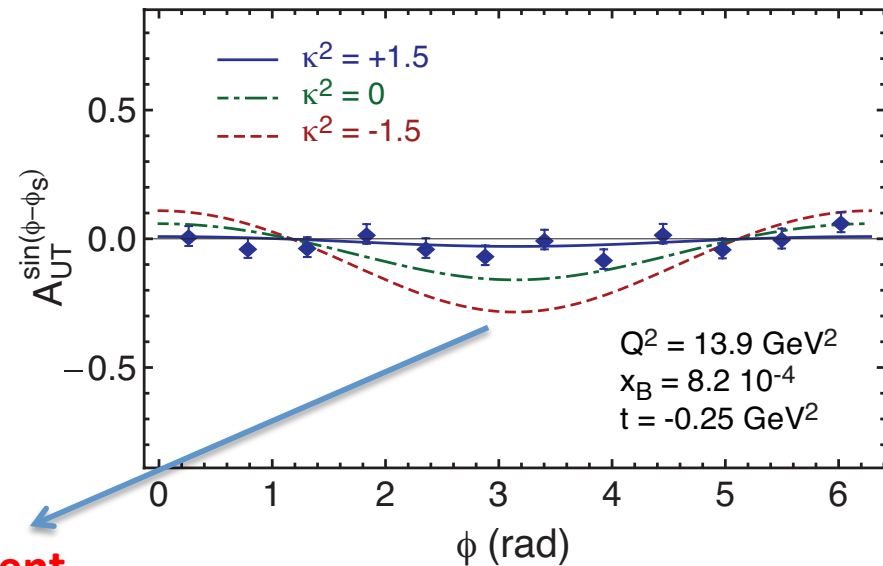
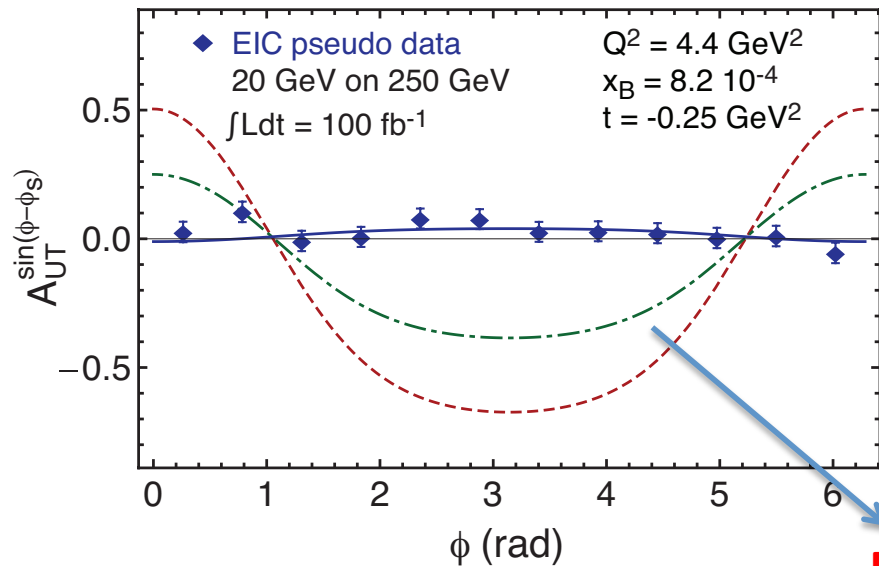
The complex Amplitude can be accessed

Asymmetries

Beam long. and transverse polarization → beam helicity asymmetries (A_{UL} , A_{LU} , A_{UT})



Transverse target-spin asymmetry



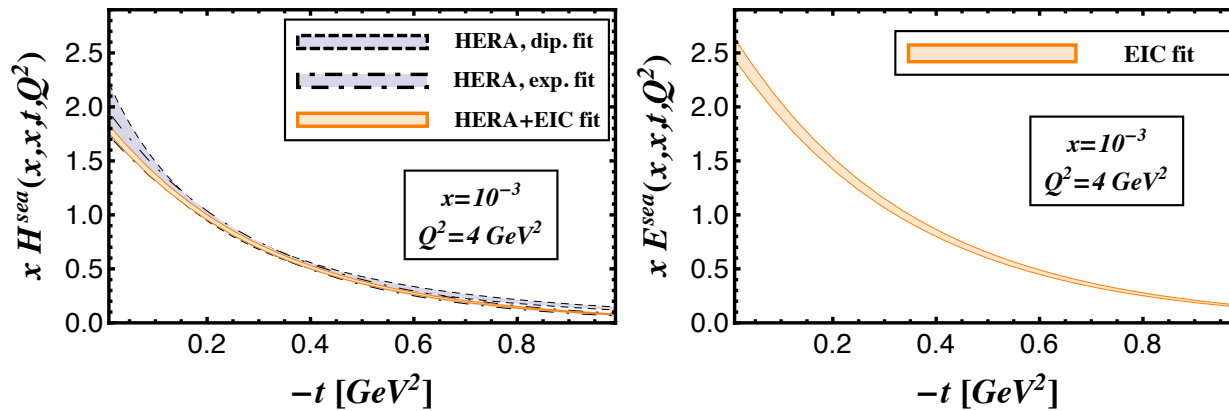
Different assumptions for E

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

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

Gives access to GPD E

Imaging



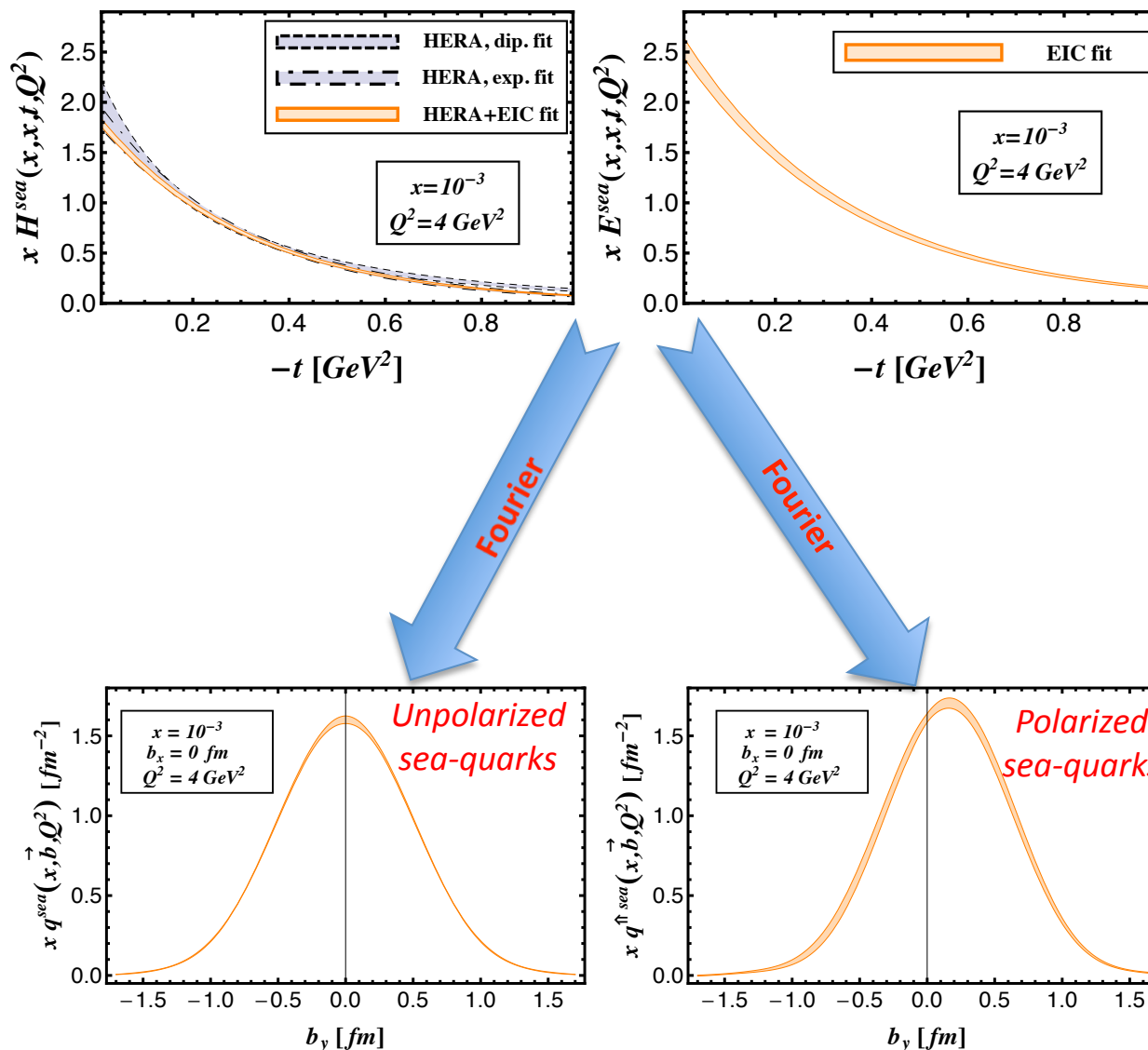
- A global fit over all mock data was done, based on the GPDs-based model: [K. Kumerički, D Müller, K. Passek-Kumerički 2007]
- Known values $q(x)$, $g(x)$ are assumed for H^q , H^g (at $t=0$ forward limits E^q , E^g are unknown)

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)

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

Imaging

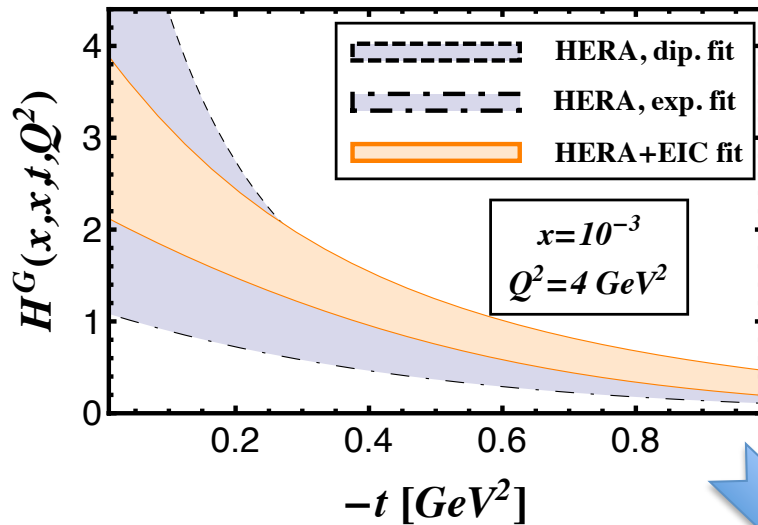


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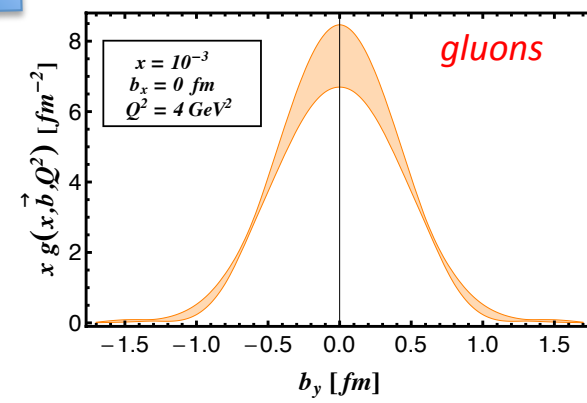
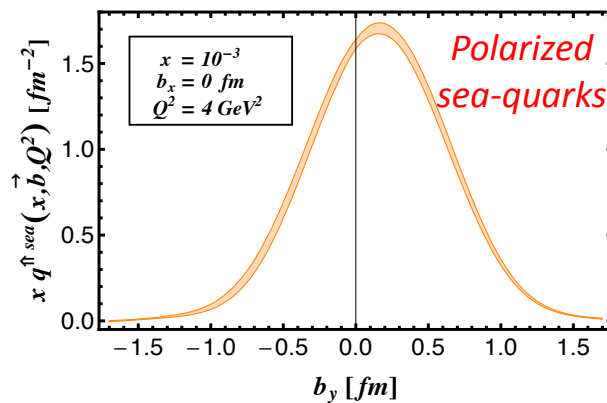
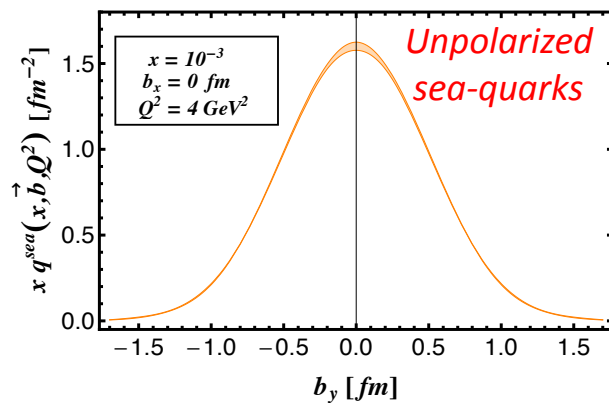


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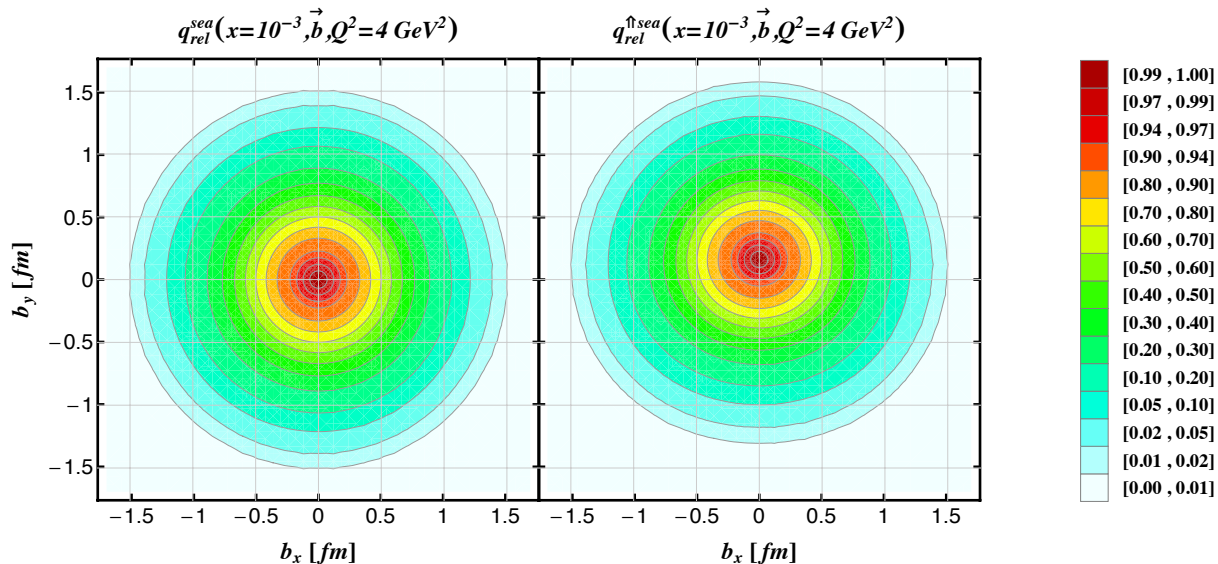
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Fourier



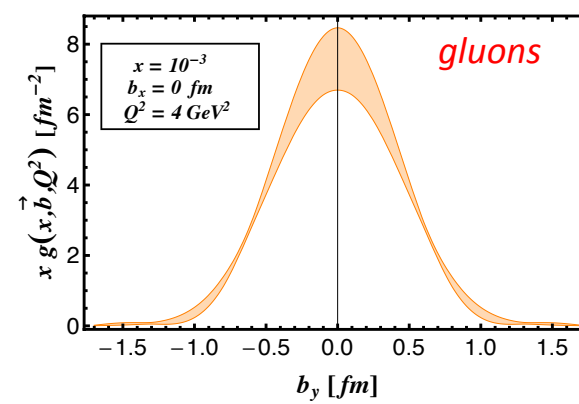
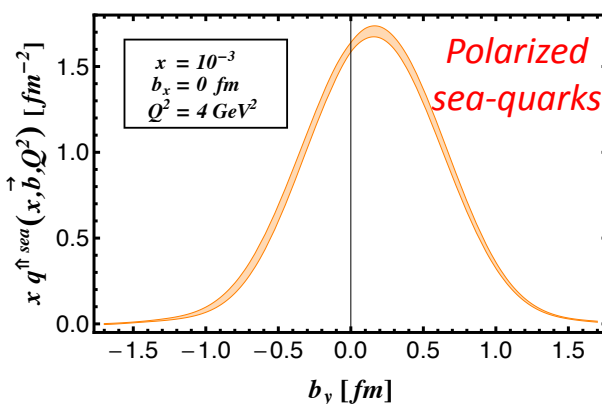
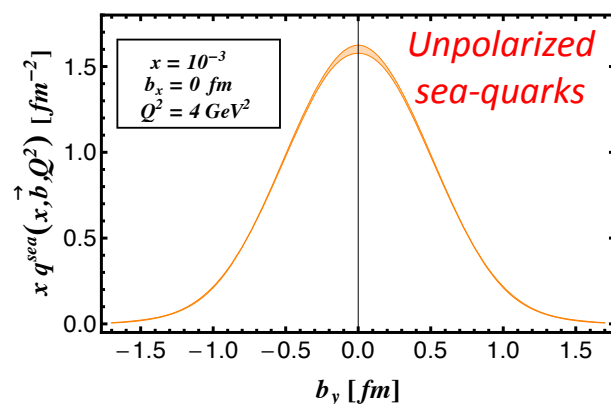
Imaging



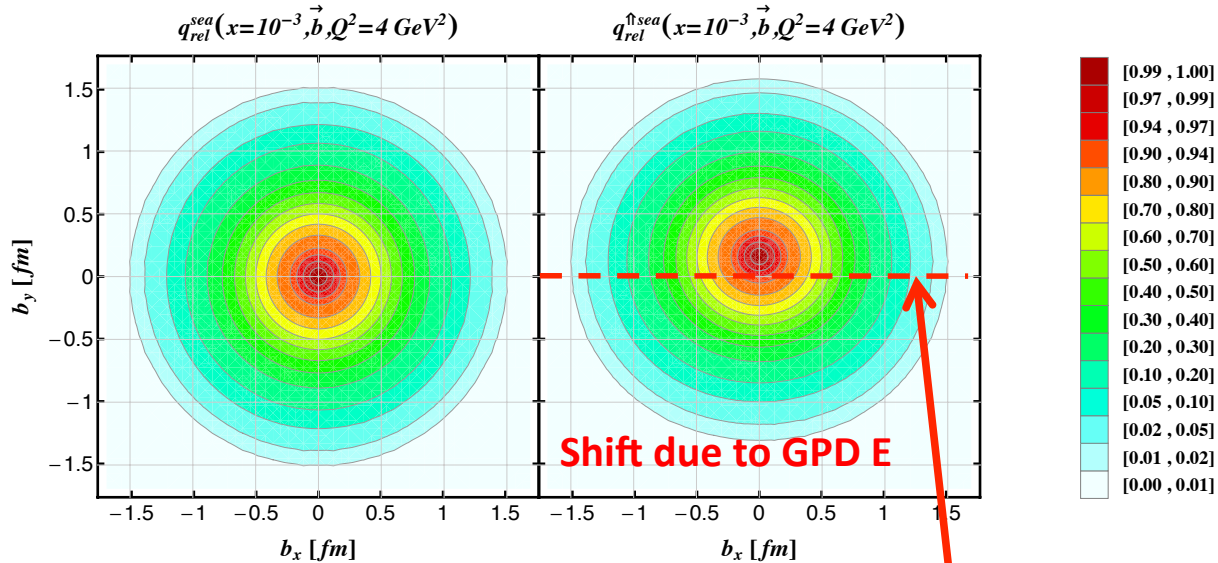
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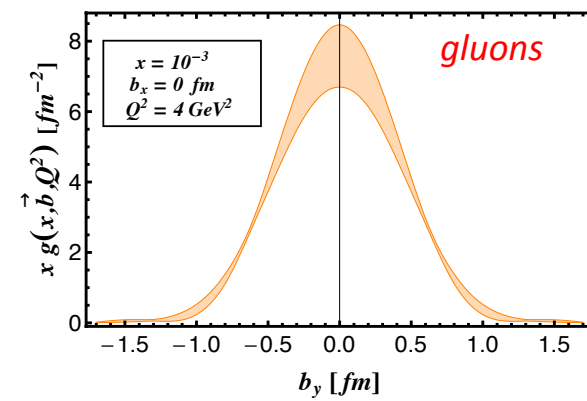
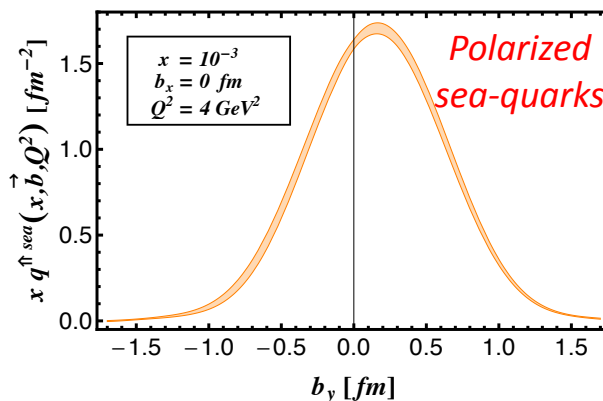
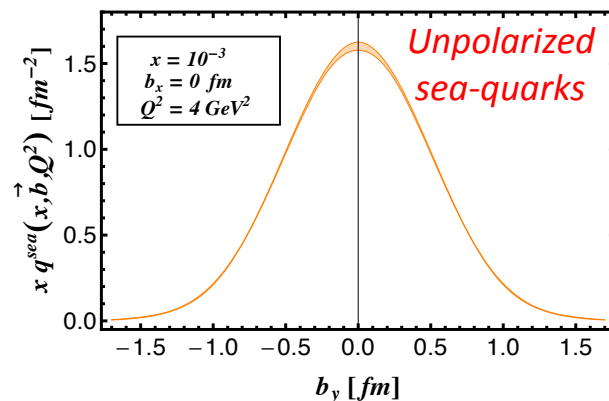
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All details and more to appear in:

Deeply Virtual Compton Scattering at a proposed high-luminosity Electron-Ion-Collider

E. Aschenauer¹, S. Fazio¹, K. Kumerički², D. Müller^{1,3}

¹ *Physics Department, Brookhaven National Lab, Upton, US*

² *Department of Physics, University of Zagreb, Zagreb, Croatia*

³ *Institut für Theoretische Physik II, Ruhr-University Bochum, Bochum, Germany*

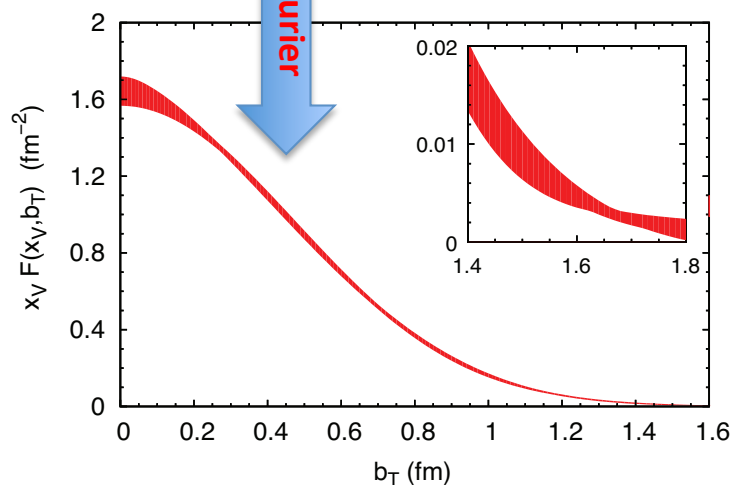
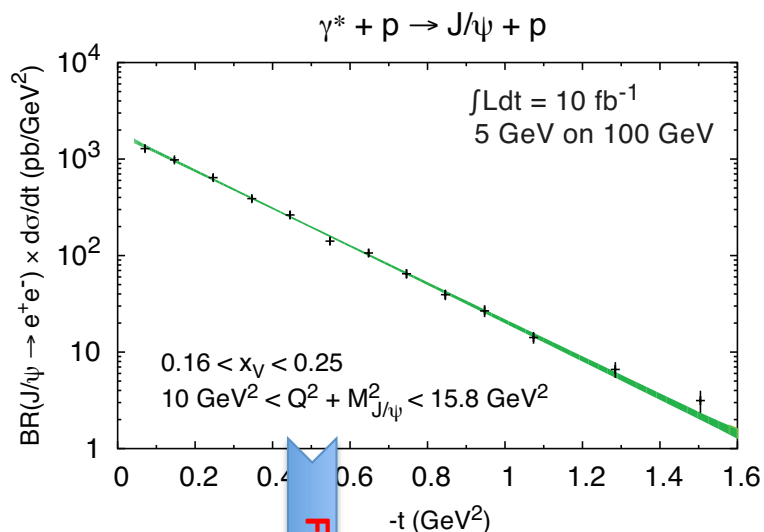
Coming soon...

Abstract

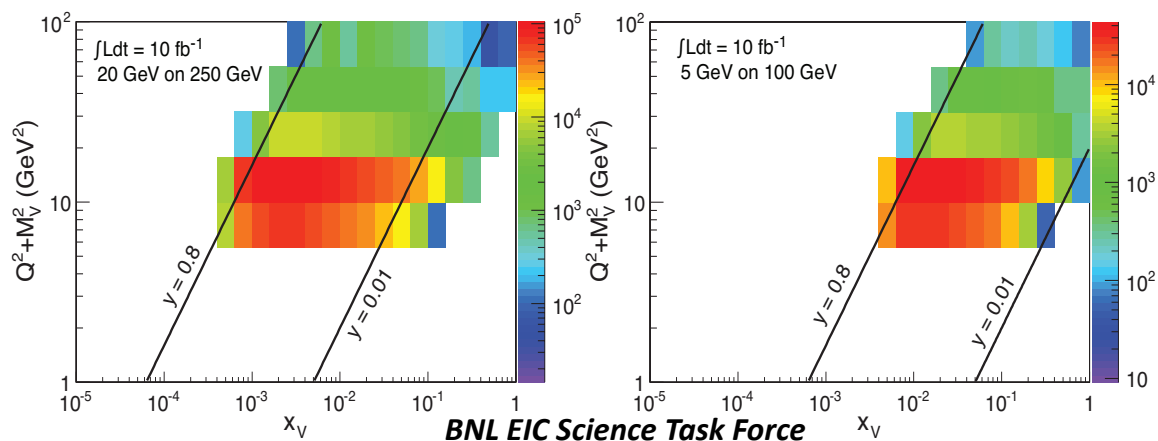
We simulate deeply virtual Compton scattering at a proposed electron-ion-collider and explore the possible impact of such measurements for the phenomenological access of generalized parton distributions. In particular we give emphasize to the transverse distribution of sea quarks and gluons and show that such measurements will provide information on the angular momentum sum rule.

J/ψ

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

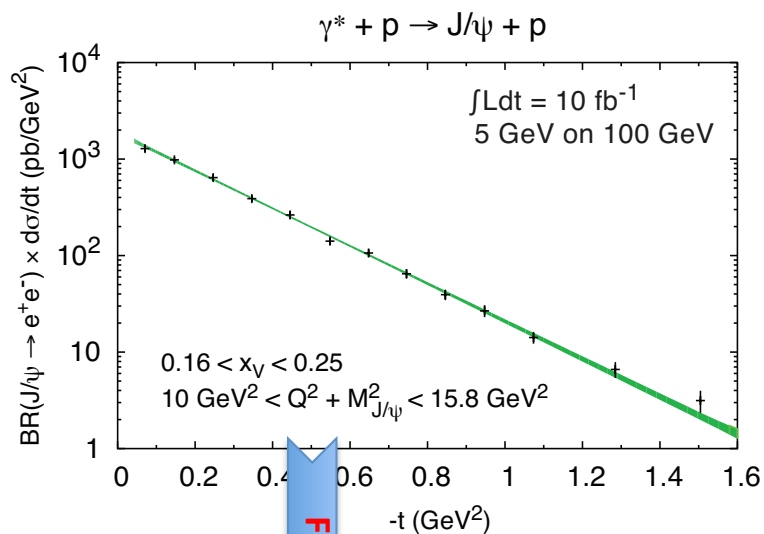


- pseudo-data generated using a version of Pythia tuned to J/ψ data from HERA
- wave function uncert. (non-relativistic approximation)
- mass provides hard scale
 - Sensitive to gluons
 - Both photo- and electro-production can be computed

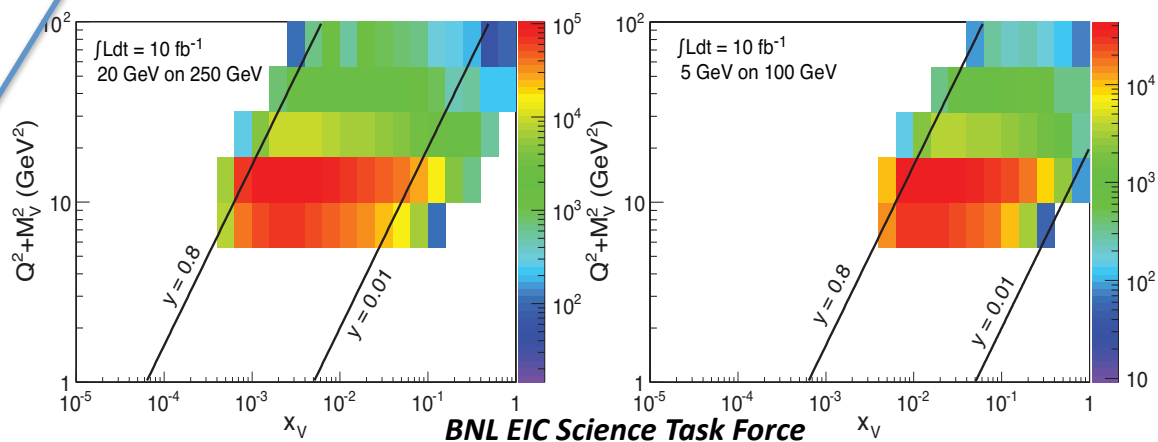
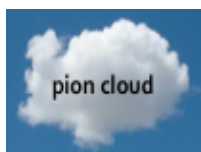
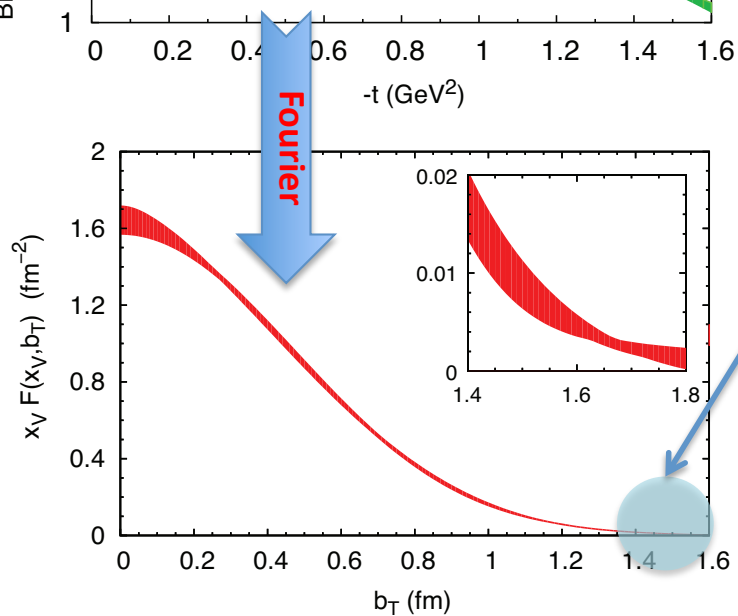


J/ψ

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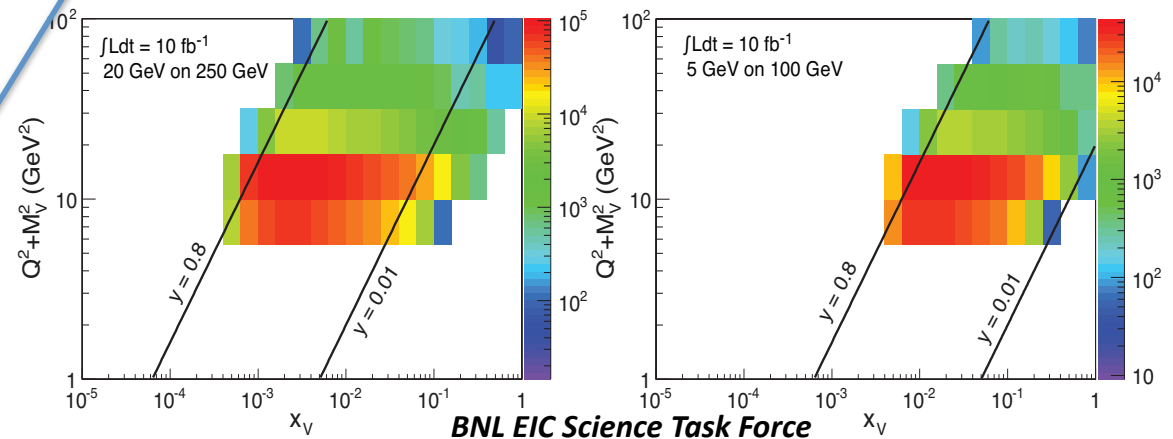
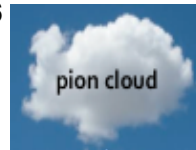
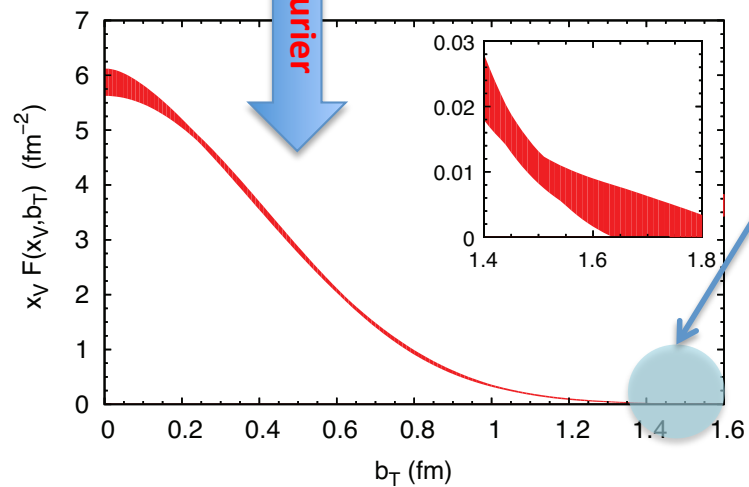
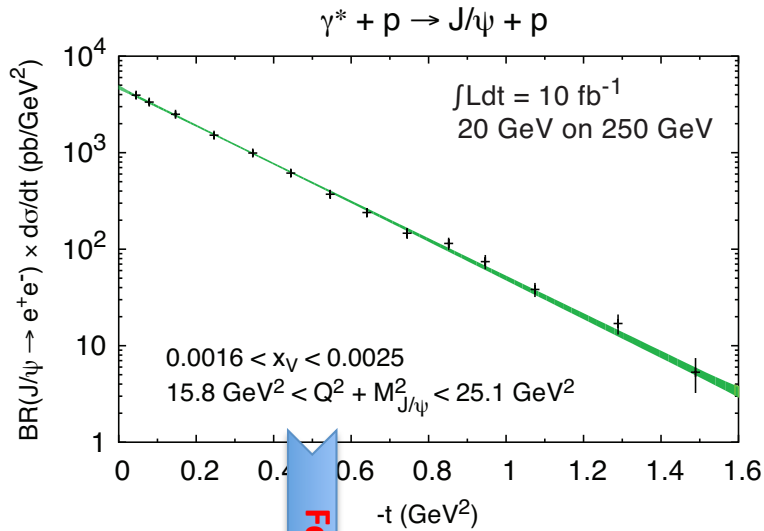


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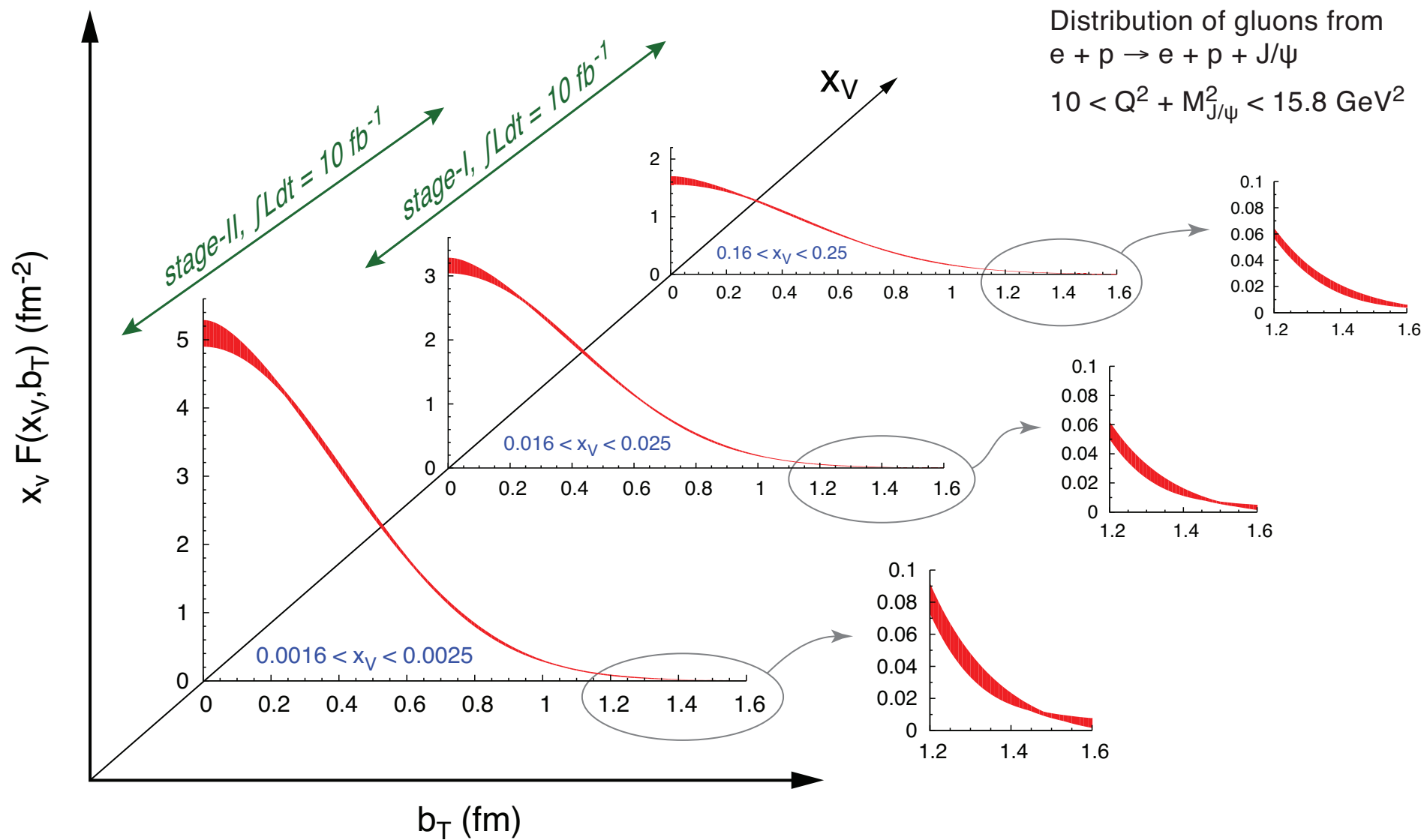
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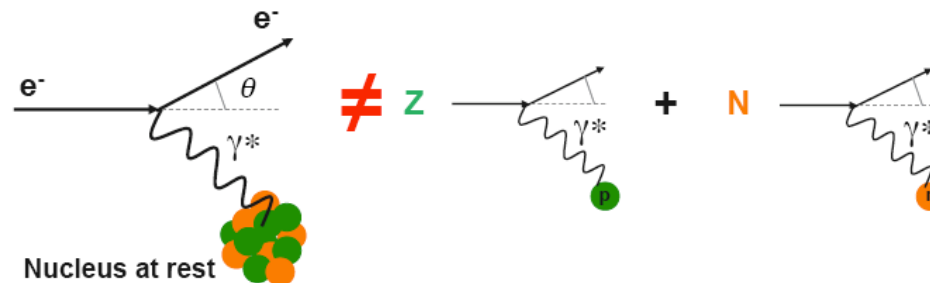
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- mass provides hard scale
 - Sensitive to gluons
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J/ψ



GPDs on nuclear targets

- ❑ How does the nuclear environment modify parton-parton correlations?
- ❑ How do nucleon properties change in the nuclear medium?

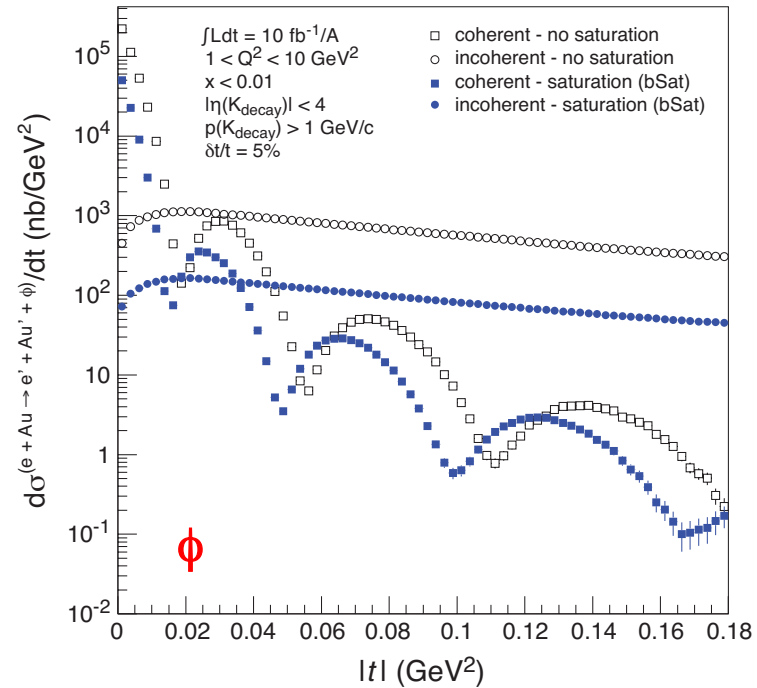
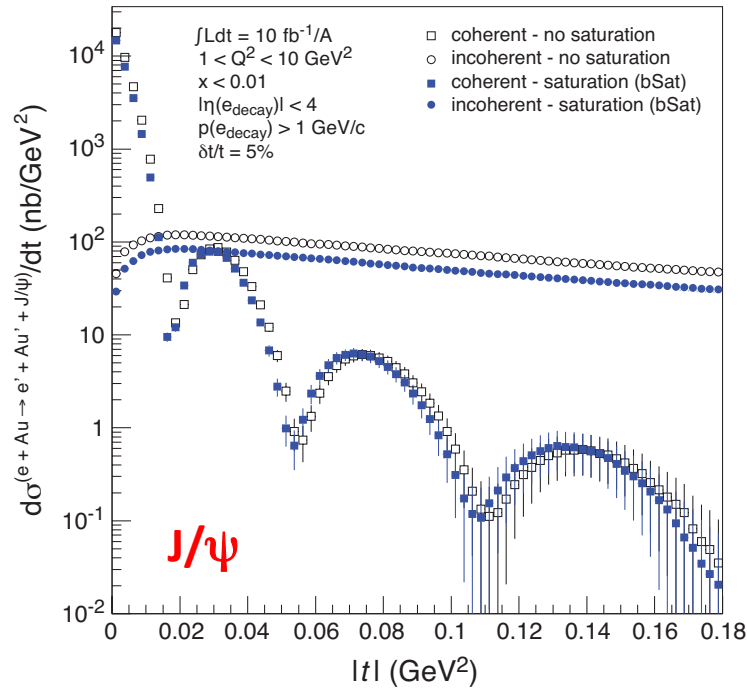


Nuclear GPDs \neq GPDs of free nucleon

- Diffraction in $e+p$:
 - ▶ coherent \Leftrightarrow p intact
 - ▶ incoherent \Leftrightarrow breakup of p
 - ▶ 15% of all events at HERA
- Diffraction in $e+A$:
 - ▶ coherent diffraction (nuclei intact)
 - ▶ breakup into nucleons (nucleons intact)
 - ▶ incoherent diffraction
 - ▶ Predictions: $\sigma_{\text{diff}}/\sigma_{\text{tot}}$ in $e+A \sim 25-40\%$

GPDs on nuclear targets

Exclusive VMP in e+A



- Low- t : coherent diffraction dominates - **gluon density**
- High- t : incoherent diffraction dominates - **gluon correlations**

Important: need good breakup detection efficiency to discriminate between the two scenarios

- Coherent events identified by vetoing nuclear break-up → **measure emitted neutrons in a ZDC**
- rapidity gap sufficient to identify coherent events

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!)**

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Brookhaven National Lab - EIC Science Task Force

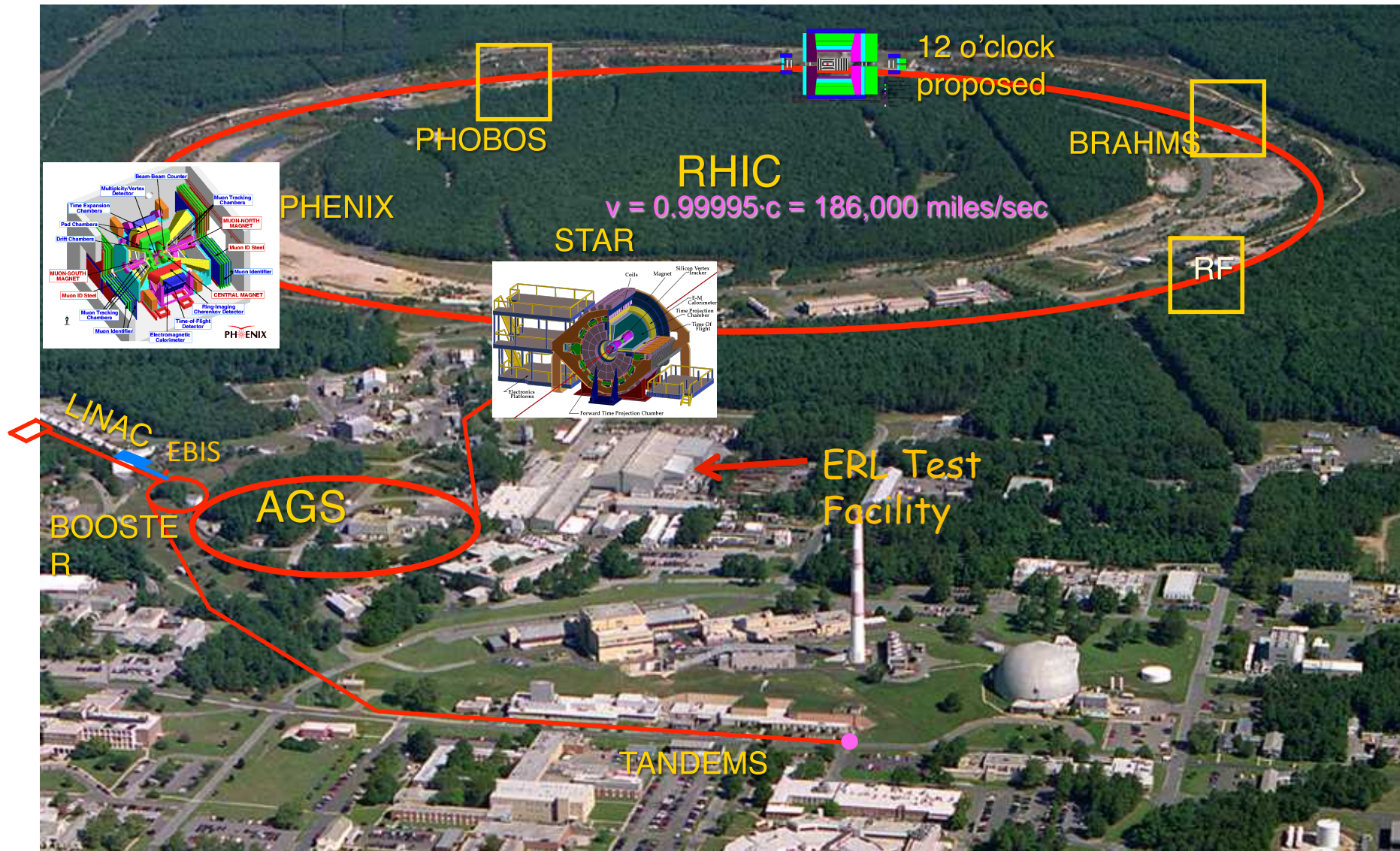
People: Elke Aschenauer, Thomas Ullrich, Thomas Burton, Ramiro Debbé, Jamie Dunlop, Salvatore Fazio, Wlodek Guryń, Matt Lamont, J. H. Lee, Dieter Mueller, Hubert Spiesberger, Marco Stratmann, Tobias Toll, Liang Zheng

Working groups: ep, eA, detector and machine design

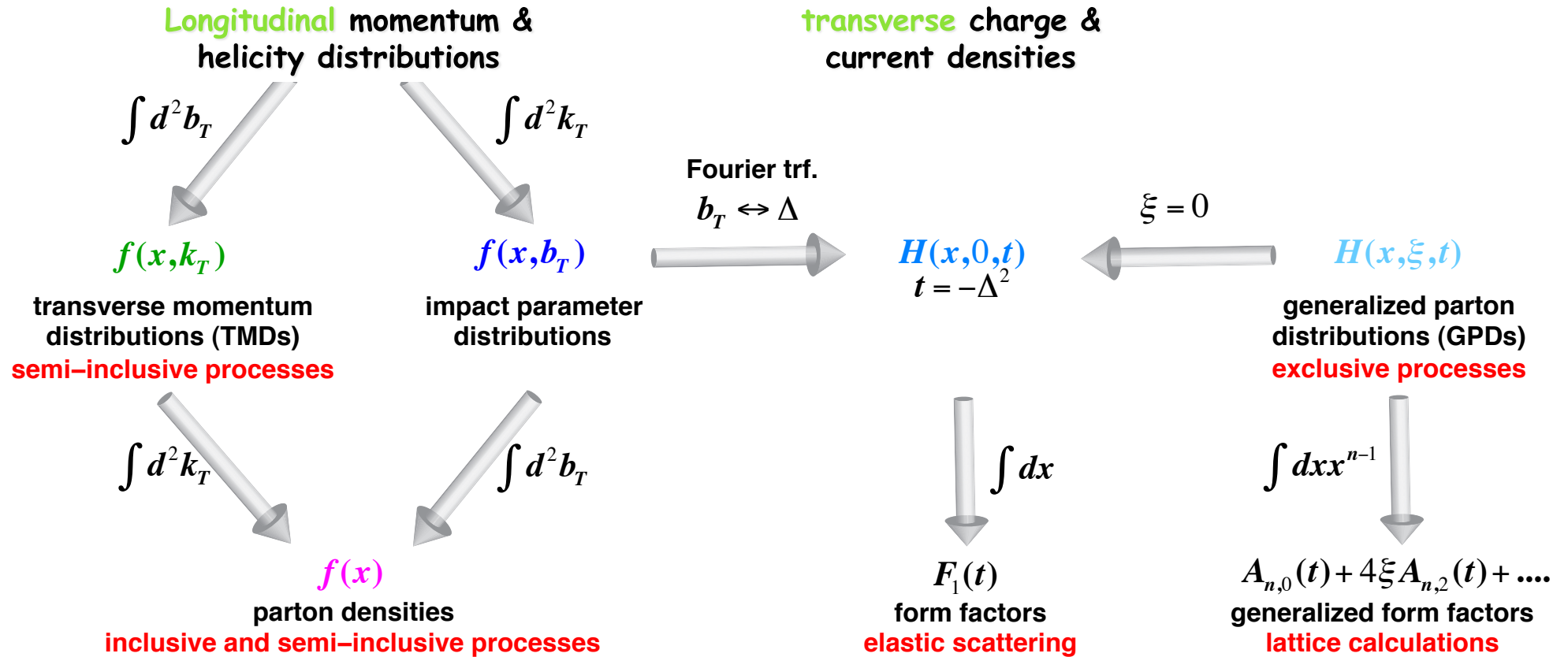
Web-page: https://wiki.bnl.gov/eic/index.php/Main_Page

Back up

The RHIC site @ BNL



(2+1)-D imaging of the proton



Wigner Distribution
 $W(x, r, k_+)$

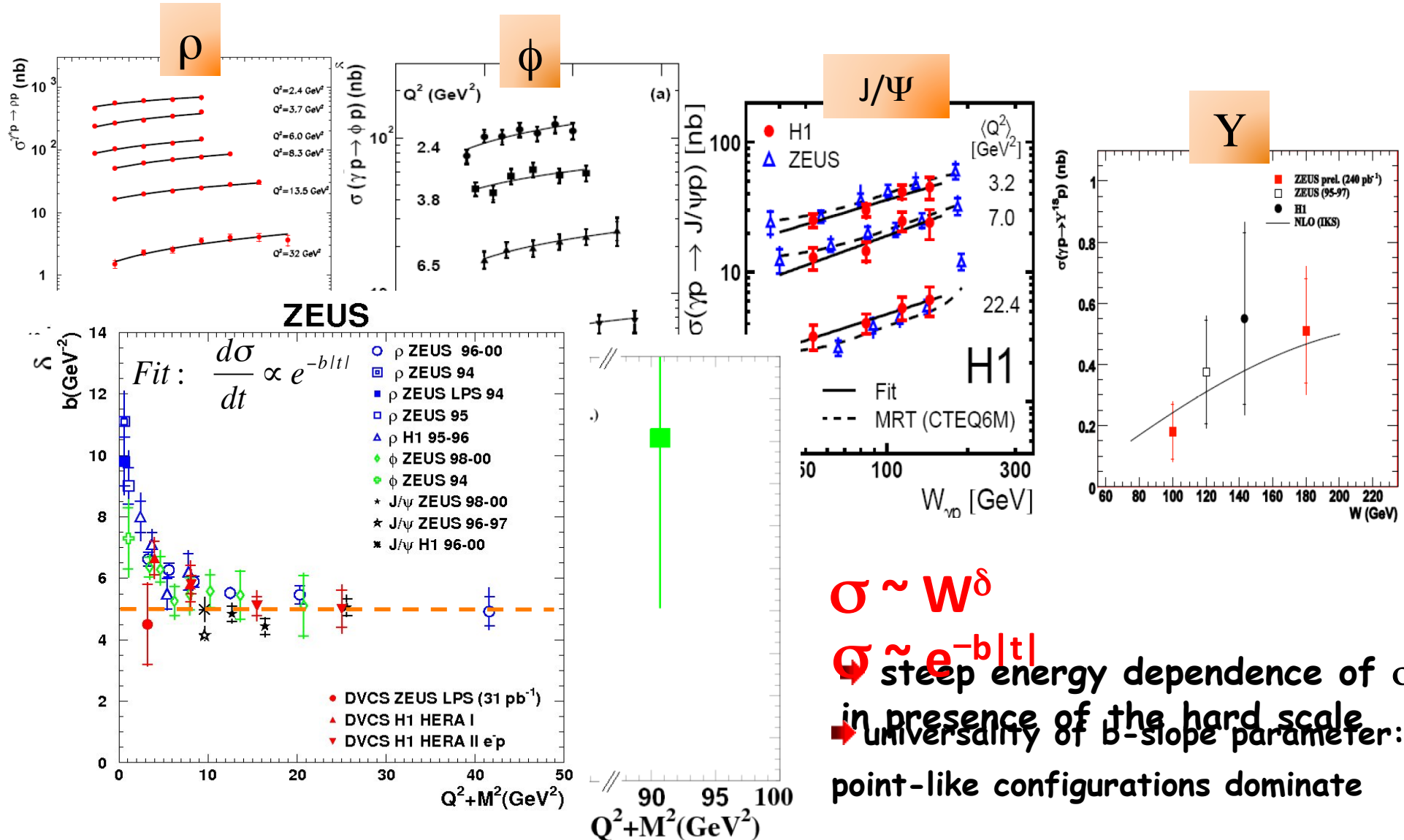


3D picture in coordinate space
generalized parton distributions
→ exclusive reaction like DVCS and VMP



Vector Meson Production

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



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 independent code which provides tables of CFF
 - at LO, the CFFs are just a convolution of GPDs:

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

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

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

$$\phi = \phi_N - \phi_l$$

$$\varphi = \Phi_T - \phi_N$$

$$\epsilon \equiv 2x \frac{m_N}{Q}$$

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

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

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

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

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

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

Data simulation & selection

Acceptance criteria

- for Roman pots: $0.03 < |t| < 0.88 \text{ GeV}^2$
- for $|t| > 1 \text{ GeV}^2$ detect recoil proton in main detector
- $0.01 < y < 0.85 \text{ GeV}^2$
- $\eta < 5$

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

- $y < 0.6$
- $(\theta_{e1} - \theta_{\gamma}) > 0$
- $E_{e1} > 1 \text{ GeV}^2$; $E_{e2} > 1 \text{ GeV}^2$

➤ Events smeared for expected resolution in t , Q^2 , x

➤ Systematic uncertainty assumed to be $\sim 5\%$ (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>]

$0.01 < |t| < 0.85 \text{ GeV}^2$

(Low- $|t|$ sample)

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

$1.0 < |t| < 1.5 \text{ GeV}^2$

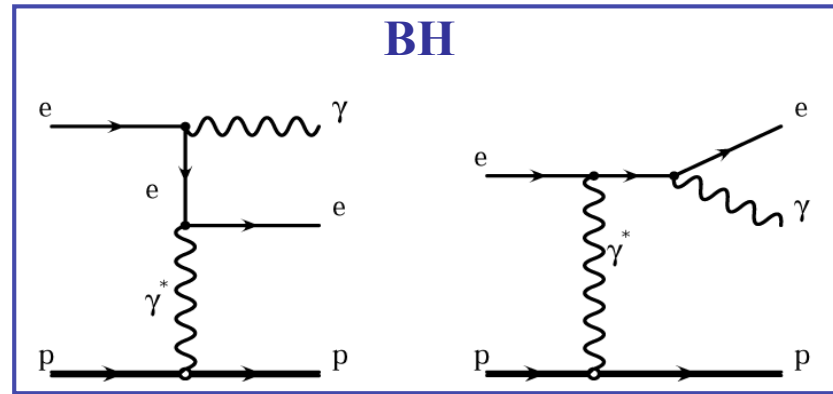
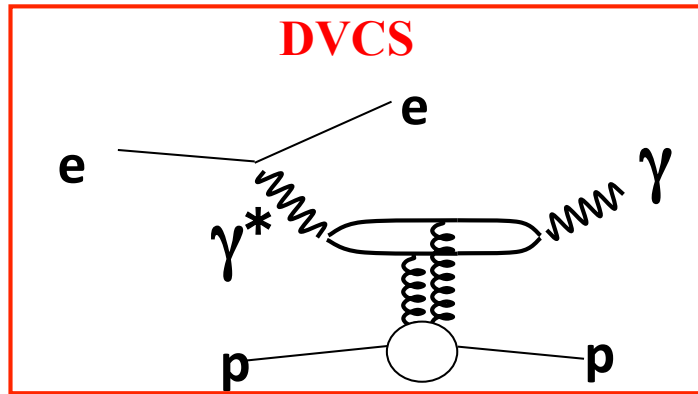
(Large- $|t|$ sample)

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

Stage 1: $5 \times 100 \text{ GeV} \rightarrow \sim 10 \text{ fb}^{-1}$ (~ 10 months)

Stage 2: $20 \times 250 \text{ GeV} \rightarrow \sim 100 \text{ fb}^{-1}$ (~ 1 year)

DVCS - BH



$$\frac{d\sigma}{dx dy d|t| d\phi d\varphi} \propto \left| \mathcal{J}_{DVCS} \right|^2 + \left| \mathcal{J}_{BH} \right|^2 + \left| \mathcal{J}_{int} \right|^2$$

DVCS cross section: BH becomes background -> must be removed

Uncertainty on proton form factor \rightarrow **uncertainty on BH xsec \sim 3% (at LO)**

Asymmetry measurement -> BH is the vehicle to study interference term

θ_γ vs E_γ

10 X 100

