Prospects for Exclusives / GPDs at an EIC

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CENTER for NUCLEAR FEMTOGRAPHY

FemtoNET

EICUG: 2nd Detector Meeting

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FemtoNet

Phenomenology

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Lattice QCD

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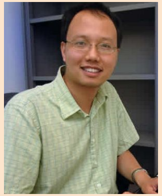
Machine Learning



Yaohang Li
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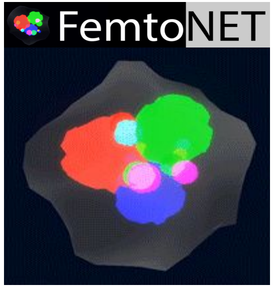

Students

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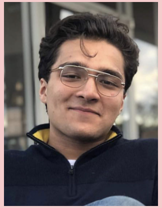

Joshua Bautista
Univ. of Va.

FemtoNet Analysis Framework

https://femtonet.phys.virginia.edu/ (under construction)

FemtoViz

A visualization web app to easily plot and compare calculated GPDs from a model calculation.

FemtoEvolve

A framework for perturbative QCD evolution of generalized parton distributions.

FemtoNN

A code release for neural network framework for femtography and extracting information.

FemtoNet Publications

Machine Learning

- Deep Learning Analysis of Deeply Virtual Exclusive Photoproduction **PRD 104 (2021)**
- Benchmarks for a Global Extraction of Information from Deeply Virtual Exclusive Scattering Experiments **arXiv:2207.10766 (submitted to PRD)**
- VAIM - CFF: A variational autoencoder inverse mapper solution to Compton form factor extraction from deeply virtual exclusive reactions **(in progress)**
- Deep learning partonic angular momentum through VAIM **(in progress)**

Phenomenology

- Extraction of generalized parton distribution observables from deeply virtual electron proton scattering experiments **PRD 101 (2020)**
- Theory of deeply virtual Compton scattering off the unpolarized proton **PRD 105 (2022)**
- Novel Rosenbluth extraction framework for Compton form factors from deeply virtual exclusive experiments **PLB 829 (2022)**
- Parametrization of quark and gluon generalized parton distributions in a dynamical framework **PRD 105 (2022)**
- Deeply virtual Compton scattering from fixed target to collider settings **(in progress)**

Outline

- Physics Motivation
- Exclusive Cross Sections
- Predictions
- Outlooks/Conclusions

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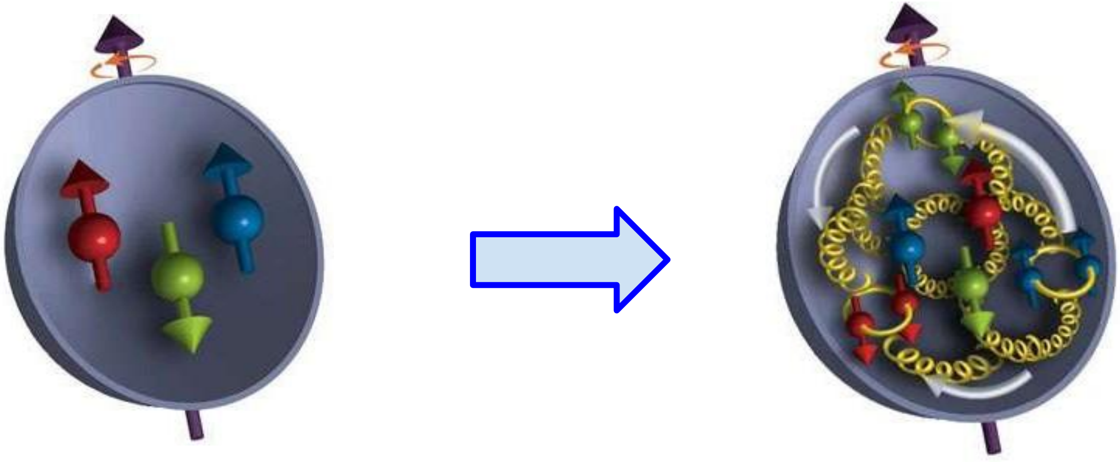
Spin as an emergent phenomena of QCD dynamics



The naive parton model cannot explain the origin of hadronic properties such as spin.

Orbital motion (dynamics) of the quarks and gluons could be the answer.

How do we describe <u>orbital angular momentum</u> of partons?

Generalized Parton Distributions

It was shown that the **quantum correlation functions** that can describe the consequences of orbital dynamics of partons in the nucleon are the 3D generalized parton distributions (GPDs).

$$F^{[\Gamma]}_{\Lambda,\Lambda'}(x,\xi,t) = \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle p',\Lambda'|\overline{\psi}\Big(-\frac{z}{2}\Big)\Gamma\mathcal{W}\Big(-\frac{z}{2},\frac{z}{2}|n\Big)\psi\Big(\frac{z}{2}\Big)|p,\Lambda\rangle\Big|_{z^+=z_T=0}$$

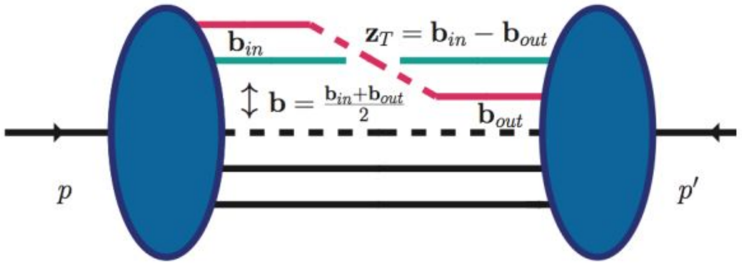


Image credit: A. Rajan, M. Engelhardt, S. Liuti **PRD 98 (2018)**

$$t = (p'-p)^2$$

$$\xi = \frac{(p'-p)^+}{(p'+p)^+}$$

New information on parton dynamics!

X. Ji **PRL. 78 (1997)**
A. Radyushkin **PRD. 56 (1997)**

D. Muller, et. al. **(1994)**
M. Diehl **Phys.Rep. (2003)**

What are the possibilities?

$$T^{\mu\nu}_{QCD} = \frac{1}{4}\,\overline{\psi}\gamma^{(\mu}D^{\nu)}\psi + Tr\left\{F^{\mu\alpha}F^{\nu}_{\alpha} - \frac{1}{2}g^{\mu\nu}F^2\right\}$$

$$\begin{bmatrix} T^{00} & T^{01} & T^{02} & T^{03} \\ T^{10} & T^{11} & T^{12} & T^{13} \\ T^{20} & T^{21} & T^{22} & T^{23} \\ T^{30} & T^{31} & T^{32} & T^{33} \end{bmatrix}$$

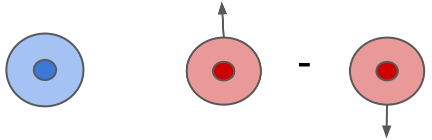
Energy Density

Momentum Density

Pressure Distribution

Shear Forces

There is a connection between GPDs and the EMT of QCD, meaning GPDs can describe the **total angular momentum.**



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

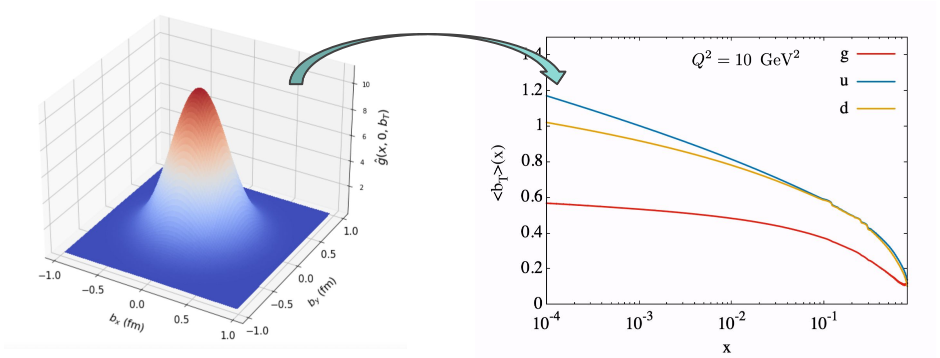
X. Ji, W. Melnitchouk, X. Song **PRD 56 (1997)**
X. Ji, **PRD. 55 (1997)**

Spatial Densities

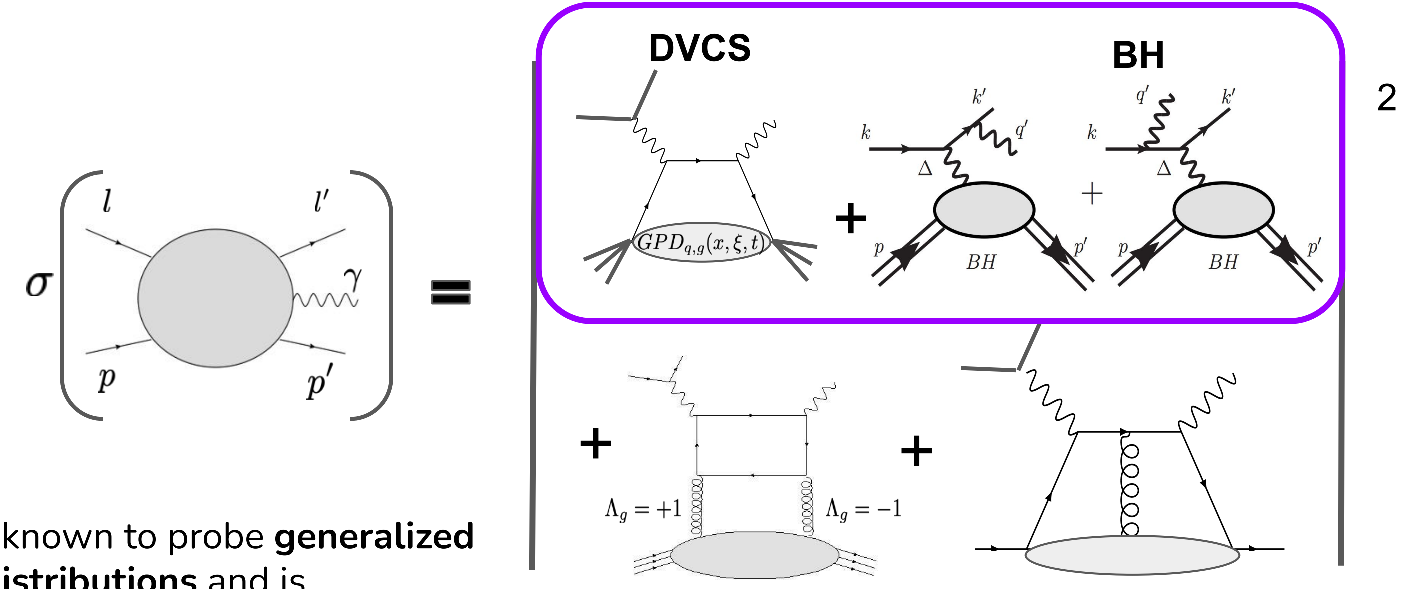
$$\rho^q_{\Lambda\lambda}(\mathbf{b}) = H_q(\mathbf{b}^2) + \frac{b^i}{M}\epsilon_{ij}S^j_T\frac{\partial}{\partial b}E_q(\mathbf{b}^2) + \Lambda\lambda\widetilde{H}_q(\mathbf{b}^2)$$

Through Fourier transform of the momentum transfer, we have access to the **spatial distribution** of the partons in the hadron.

M. Burkardt **PRD. 62 (2000)**
M. Burkardt ***Int.J.Mod.Phys.A* 18 (2003)**



How to measure GPDs? Deeply virtual Compton scattering



Gluon Transversity

Higher Twist

DVCS is known to probe **generalized parton distributions** and is accompanied by various background processes.

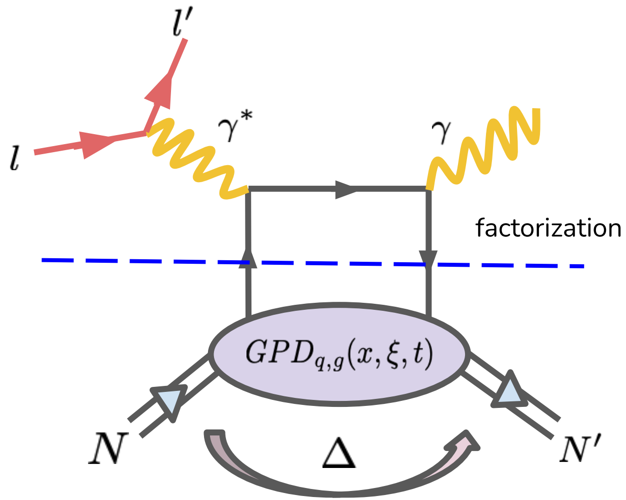
X. Ji, **PRD. 55 (1997)**

B.Kriesten, S.Liuti, et. al. **PRD. 101 (2020)**

Important, but reserved for later ...

However … there's a catch!

In the DVCS cross section, **GPDs** come convoluted with Wilson coefficient functions (Compton Form Factors) meaning we only have experimental access to integrals (ReCFF) or specific points in x (ImCFF) of these distributions.



$$\mathcal{H}^q(\xi,t) = \boxed{e_q^2 P.V. \int_{-1}^{+1} dx \left[\frac{1}{\xi - x} - \frac{1}{\xi + x}\right] H^q(x,\xi,t)} + \boxed{i\pi e_q^2 H^{q+\bar{q}}(\xi,\xi,t)}$$

Not the same integral for angular momentum!

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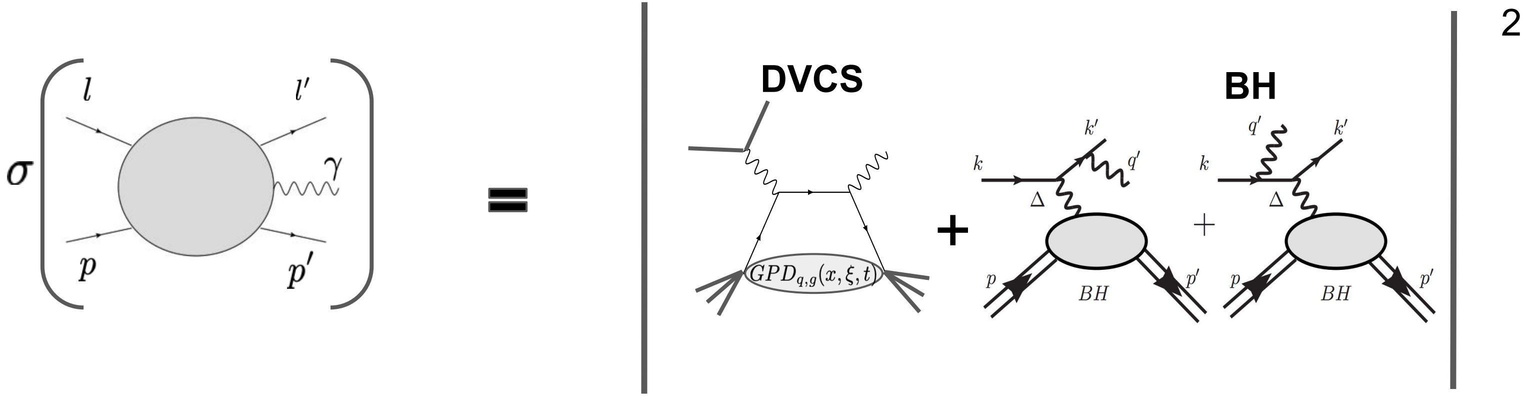
Focus on these amplitudes

$$\sigma = \sigma_{BH} + \sigma_{DVCS} + \sigma_{\mathcal{I}}$$



B.Kriesten, S.Liuti, et. al. **PRD. 101 (2020)**

What does the DVCS cross section look like?

The cross section has three components that contribute to leading order

$$\sigma_{BH}(x_{Bj},t,Q^2,E_b,\phi) = \frac{\Gamma}{t}\left[A_{UU}^{BH}(F_1^2+\tau F_2^2) + B_{UU}^{BH}\tau G_M^2(t)\right]$$

No CFFs

$$\begin{aligned}\sigma_{\mathcal{I}}(x_{Bj},t,Q^2,E_b,\phi) = \frac{\Gamma}{Q^2 t}\Big[&A_{\mathcal{I}}(x_{Bj},t,Q^2,E_b,\phi)\Big(F_1(t)\boxed{\Re e\mathcal{H}(x_{Bj},t,Q^2)} + \tau F_2(t)\boxed{\Re e\mathcal{E}(x_{Bj},t,Q^2)}\Big)\\ &+ B_{\mathcal{I}}(x_{Bj},t,Q^2,E_b,\phi)G_M(t)\Big(\boxed{\Re e\mathcal{H}(x_{Bj},t,Q^2)} + \boxed{\Re e\mathcal{E}(x_{Bj},t,Q^2)}\Big)\\ &+ C_{\mathcal{I}}(x_{Bj},t,Q^2,E_b,\phi)G_M(t)\boxed{\Re e\widetilde{\mathcal{H}}(x_{Bj},t,Q^2)}\Big]\end{aligned}$$

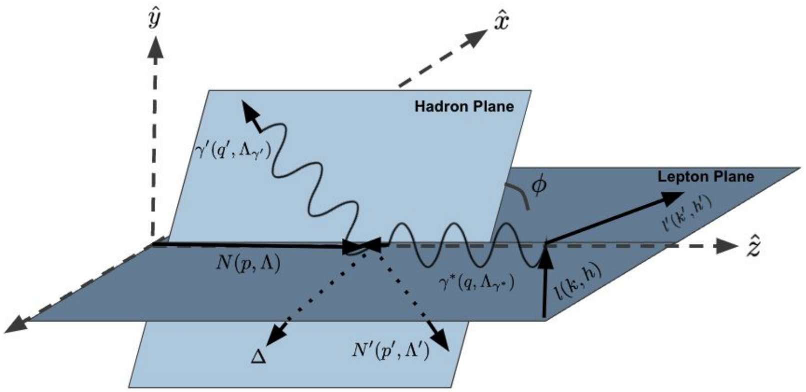
Linear CFFs: 3

$$\begin{aligned}\sigma_{DVCS}(x_{Bj},t,Q^2,E_b,\phi) = \frac{\Gamma}{Q^2}\frac{2}{1-\epsilon}\Big[&(1-\xi^2)\boxed{\Big[(\Re e\mathcal{H})^2 + (\Im m\mathcal{H})^2 + (\Re e\widetilde{\mathcal{H}})^2 + (\Im m\widetilde{\mathcal{H}})^2\Big]}\\ &+ \frac{t_o - t}{4M^2}\Big[\boxed{(\Re e\mathcal{E})^2 + (\Im m\mathcal{E})^2 + \xi^2(\Re e\widetilde{\mathcal{E}})^2 + \xi^2(\Im m\widetilde{\mathcal{E}})^2}\Big]\\ &- 2\xi^2\boxed{\Big(\Re e\mathcal{H}\,\Re e\mathcal{E} + \Im m\mathcal{H}\Im m\mathcal{E} + \Re e\widetilde{\mathcal{H}}\,\Re e\widetilde{\mathcal{E}} + \Im m\widetilde{\mathcal{H}}\Im m\widetilde{\mathcal{E}}\Big)}\Big]\end{aligned}$$

Quadratic CFFs: 8

Very complicated to disentangle all of the various pieces!

DVCS Scattering Planes and the role of phase



$$\sigma_{DVCS} = \sum_{\Lambda^{(1)}_{\gamma^*}, \Lambda^{(2)}_{\gamma^*}} L_h^{\Lambda^{(1)}_{\gamma^*}, \Lambda^{(2)}_{\gamma^*}} H_\Lambda^{\Lambda^{(1)}_{\gamma^*}, \Lambda^{(2)}_{\gamma^*}}$$

Where the lepton tensor carries no phase because it is all on the lepton plane.

$$H_\Lambda^{\Lambda^{(1)}_{\gamma^*}, \Lambda^{(2)}_{\gamma^*}} = \sum_{\Lambda'} F_{\Lambda\Lambda'}^{\Lambda^{(1)}_{\gamma^*}, \Lambda^{(2)}_{\gamma^*}} = \sum_{\Lambda'} \sum_{\Lambda_{\gamma'}} \left[f_{\Lambda,\Lambda'}^{\Lambda^{(1)}_{\gamma^*}, \Lambda_{\gamma'}} \right]^* f_{\Lambda,\Lambda'}^{\Lambda^{(2)}_{\gamma^*}, \Lambda_{\gamma'}}$$

Where the proton/photon helicity amplitudes have a phase given as

$$f_{\Lambda,\Lambda'}^{\Lambda_{\gamma^*}, \Lambda_{\gamma'}} \propto e^{-i(\Lambda_{\gamma^*} - \Lambda - \Lambda_{\gamma'} + \Lambda')\phi}$$

Given that we are overlapping helicity amplitudes with same incoming proton, outgoing proton, and real photon; then the hadron tensor acquires a total phase

$$H_\Lambda^{\Lambda^{(1)}_{\gamma^*}, \Lambda^{(2)}_{\gamma^*}} \propto e^{i(\Lambda^{(1)}_{\gamma^*} - \Lambda^{(2)}_{\gamma^*})\phi}$$

B.Kriesten, S.Liuti, et. al. **PRD. 101 (2020)**

DVCS Cross Section

$$\varepsilon_\mu^{\Lambda_\gamma^*}(hadron) = e^{-i\Lambda_\gamma^*\phi}\varepsilon_\mu^{\Lambda_\gamma^*}(lepton)$$

$$\begin{aligned}
\frac{d^5\sigma_{DVCS}}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} &= \Gamma|T_{DVCS}|^2 \\
&= \frac{\Gamma}{Q^2(1-\epsilon)}\Big\{F_{UU,T} + \epsilon F_{UU,L} + \epsilon\cos 2\phi F_{UU}^{\cos 2\phi} + \sqrt{\epsilon(\epsilon+1)}\cos\phi F_{UU}^{\cos\phi} \\
&+ (2h)\sqrt{2\epsilon(1-\epsilon)}\sin\phi F_{LU}^{\sin\phi} \\
&+ (2\Lambda)\Big[\sqrt{\epsilon(\epsilon+1)}\sin\phi F_{UL}^{\sin\phi} + \epsilon\sin 2\phi F_{UL}^{\sin 2\phi} \\
&+ (2h)\Big(\sqrt{1-\epsilon^2}F_{LL} + 2\sqrt{\epsilon(1-\epsilon)}\cos\phi F_{LL}^{\cos\phi}\Big)\Big] \\
&+ (2\Lambda_T)\Big[\sin(\phi-\phi_S)\Big(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\Big) \\
&\quad + \epsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)} \\
&\quad + \sqrt{2\epsilon(1+\epsilon)}\Big(\sin\phi_S F_{UT}^{\sin\phi_S} + \sin(2\phi-\phi_S)F_{UT}^{\sin(2\phi-\phi_S)}\Big)\Big] \\
&\quad + (2h)(2\Lambda_T)\Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos\phi_S F_{LT}^{\cos\phi_S} \\
&\quad\quad + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}
\end{aligned}$$

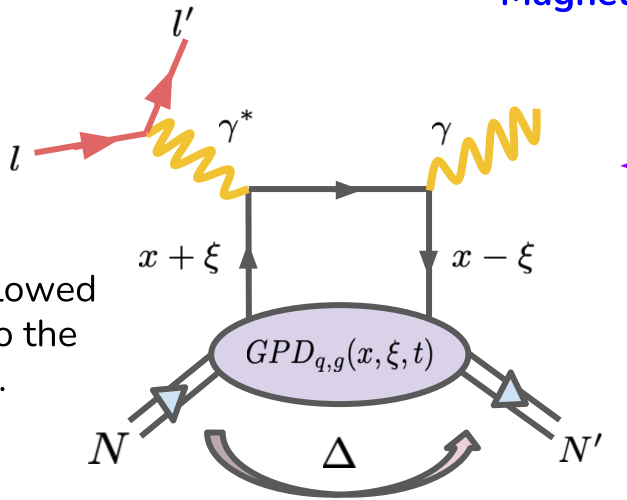
Interference and CFFs

$$\mathcal{I} = e_l \frac{\Gamma}{Q^2 \mid t \mid} \left\{ A^{\mathcal{I}}_{UU} \Re e(F_1 \mathcal{H} + \tau F_2 \mathcal{E}) + B^{\mathcal{I}}_{UU} G_M \Re e(\mathcal{H} + \mathcal{E}) + C^{\mathcal{I}}_{UU} G_M \Re e \widetilde{\mathcal{H}} + \frac{\sqrt{t_0 - t}}{Q} F^{\mathcal{I},tw3}_{UU} . \right\}$$

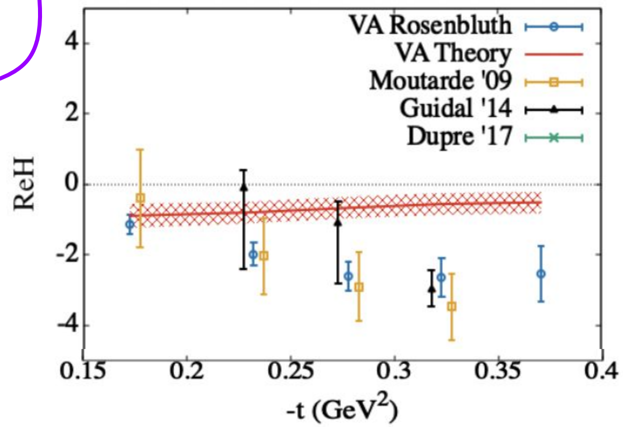
$$\mid T_{BH} \mid^2 = \frac{1}{t^2(1-\epsilon_{BH})} B_{BH} \left[F_T + \epsilon_{BH} F_L \right]$$

Magnetic Electric

Similar structure appear as in the Bethe-Heitler process, suggests **Rosenbluth separation** similar as in e-p scattering.



Axial vector contribution allowed by parity due to the second photon.



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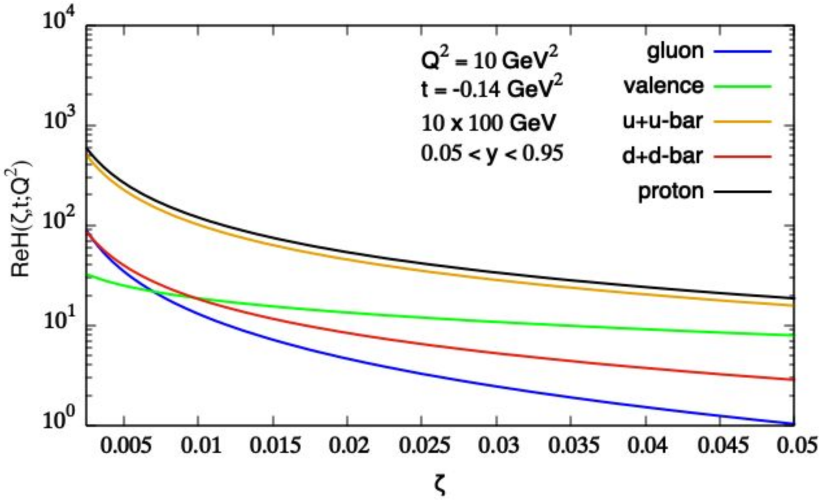
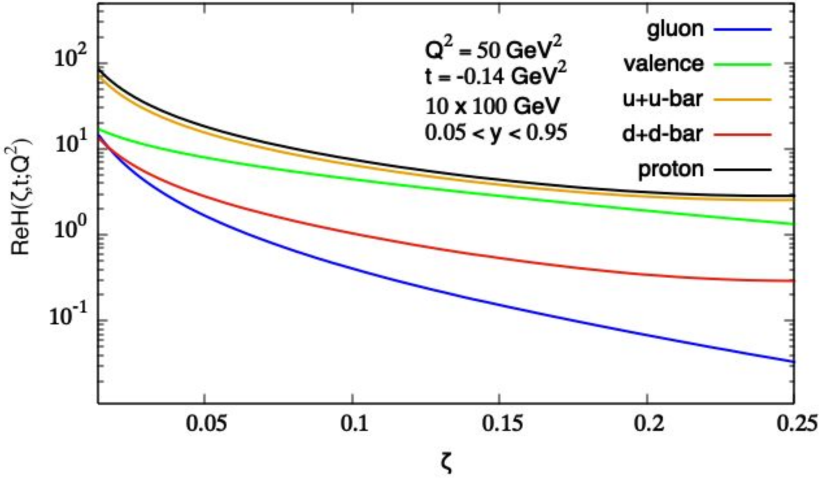
CFFs at an EIC … what are we measuring?

Calculations are done to ensure 0.05 < y < 0.95 for configuration 10 x 100 GeV

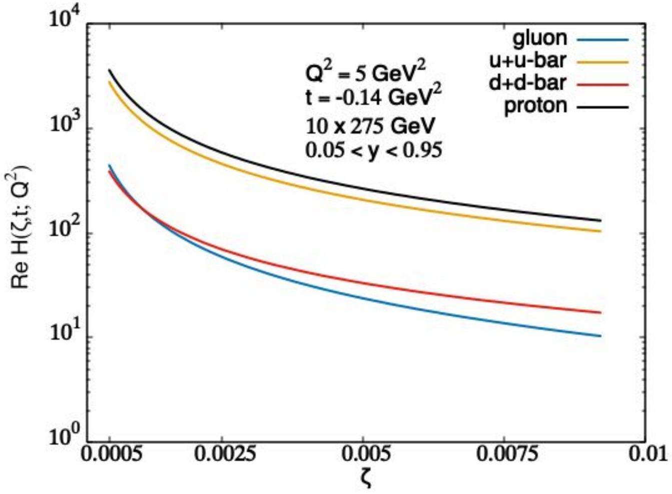




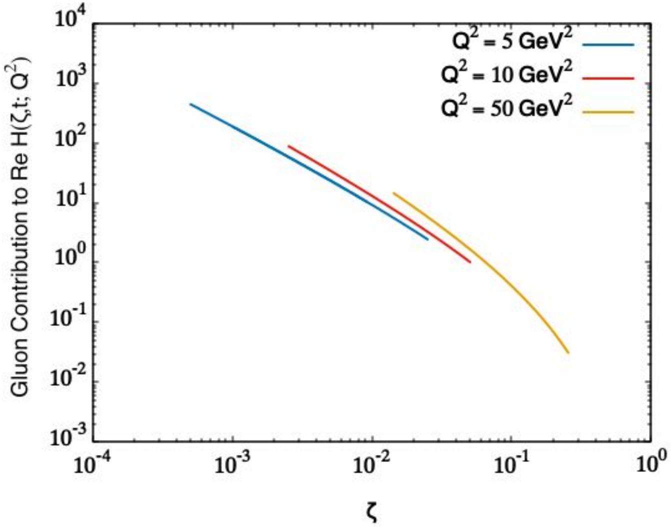
Role of gluons and quark sea …

CFFs at an EIC … what are we measuring?

Calculations are done to ensure $0.05 < y < 0.95$ for configuration 10 x 275 GeV

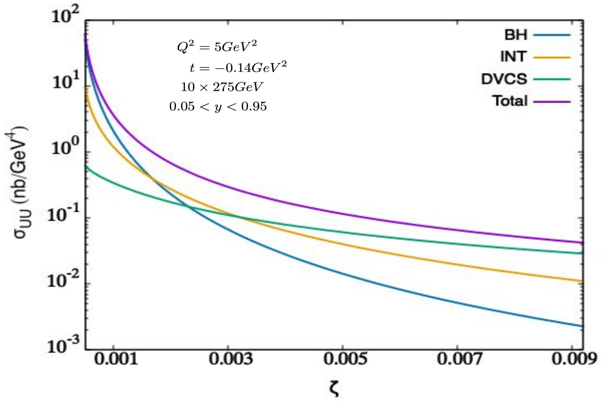


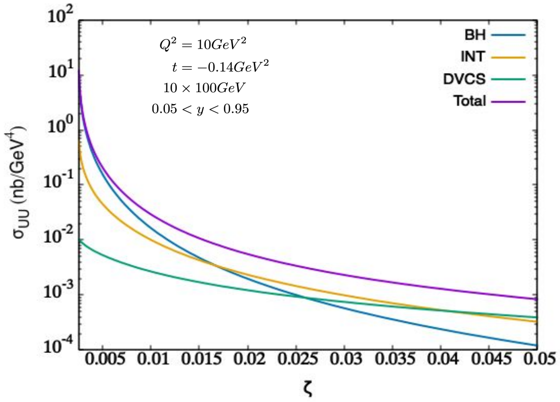
Total contributions of the gluon combining 10 x 275 and 10 x 100 GeV.

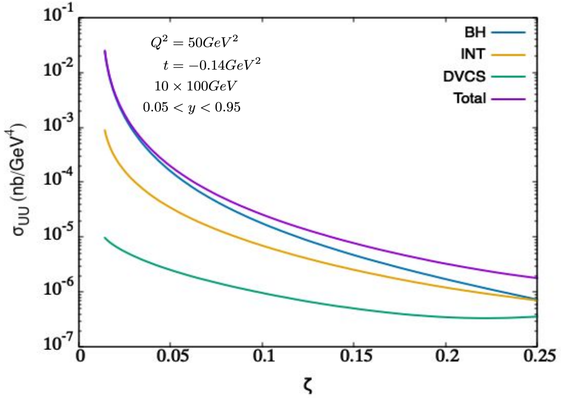


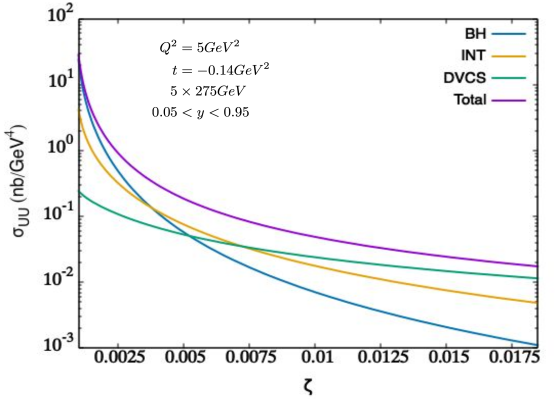
Cross Sections

$\phi = 180$









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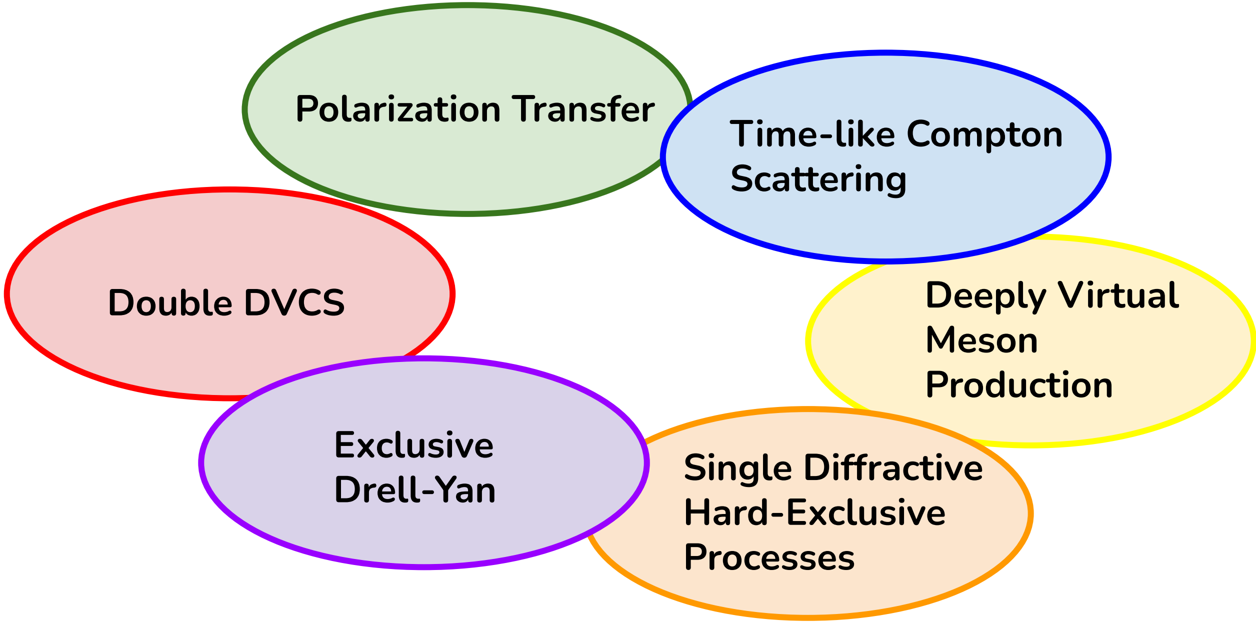
Opportunities for New Observables



Many new avenues for experimental observables, development of formalism in a clear and concise manner with studies of impact on hadronic properties is crucial. A framework to connect these observables in a multi-channel global analysis.

Conclusions

- An EIC will help us explore **new kinematic regimes** for femtography using a variety of exclusive processes to place constraints on the quark and gluon distributions.

- Femtography is **difficult**, there are many steps from cross sections -> physical properties. A multi-channel global analysis scanning a wide range of kinematics for various exclusive scattering observables will widen the prospects for GPD analysis.

- A thorough understanding of the unpolarized cross section is necessary for an analysis of polarization observables and benchmarking future extractions.