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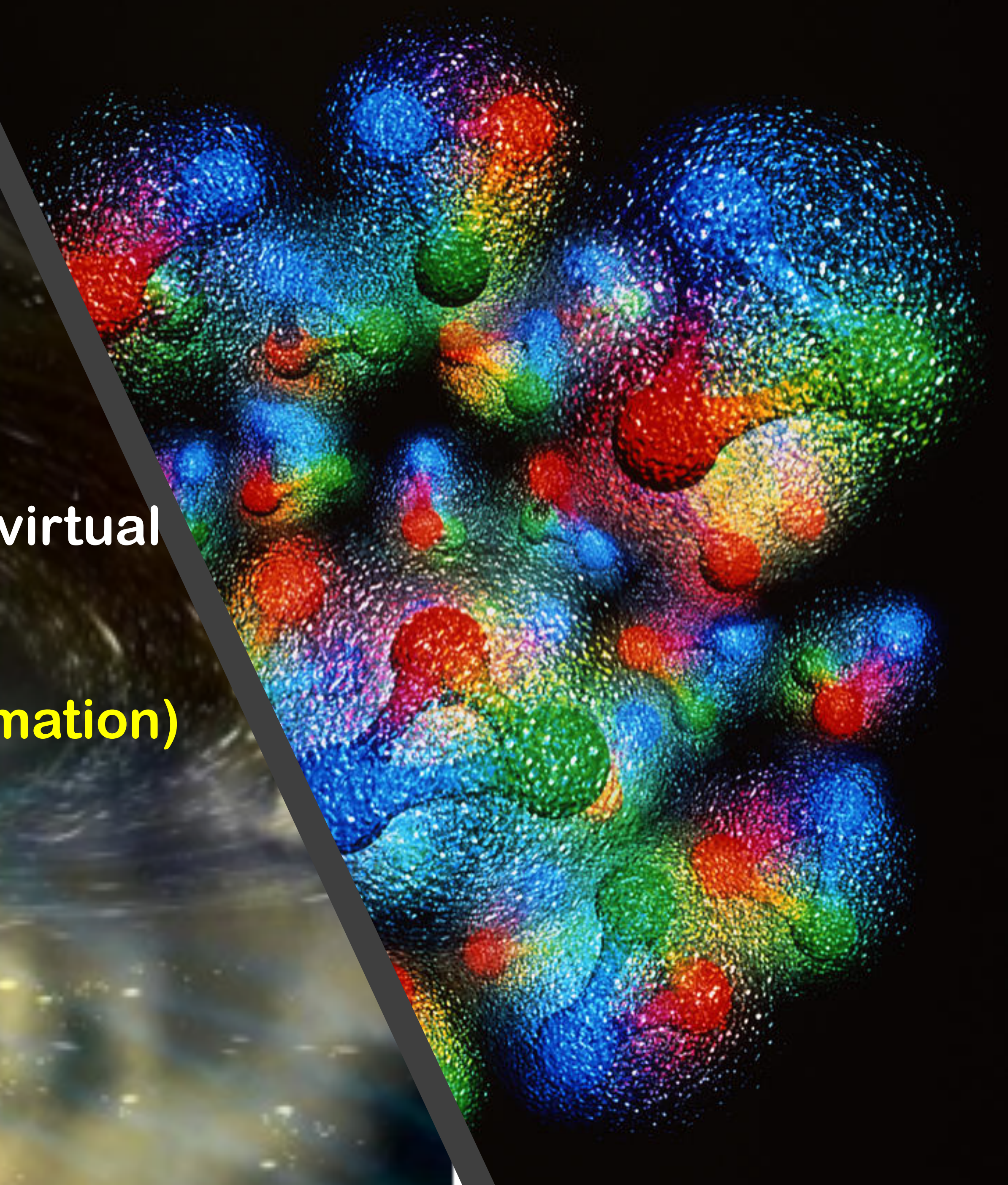
FemtoNET

Comprehensive framework for deeply virtual exclusive experiments

(Walking back from the $Q^2 \rightarrow \infty$ approximation)

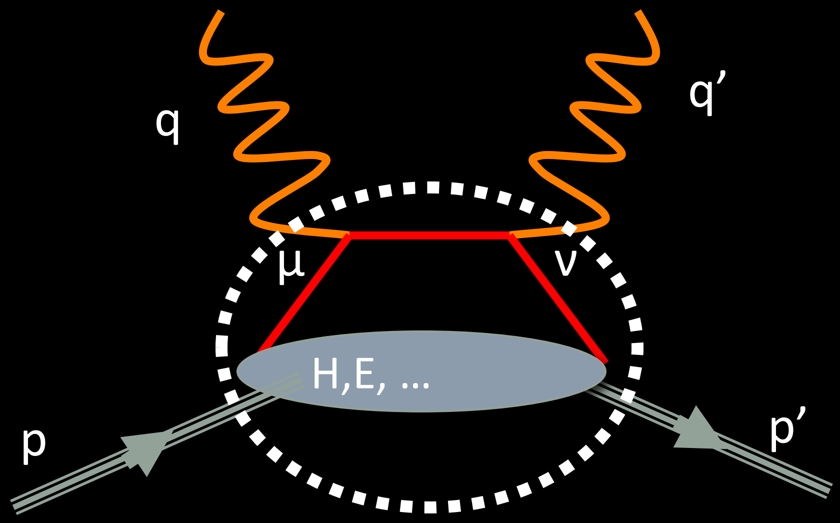
QCD Evolution
UCLA, May 10-14, 2021



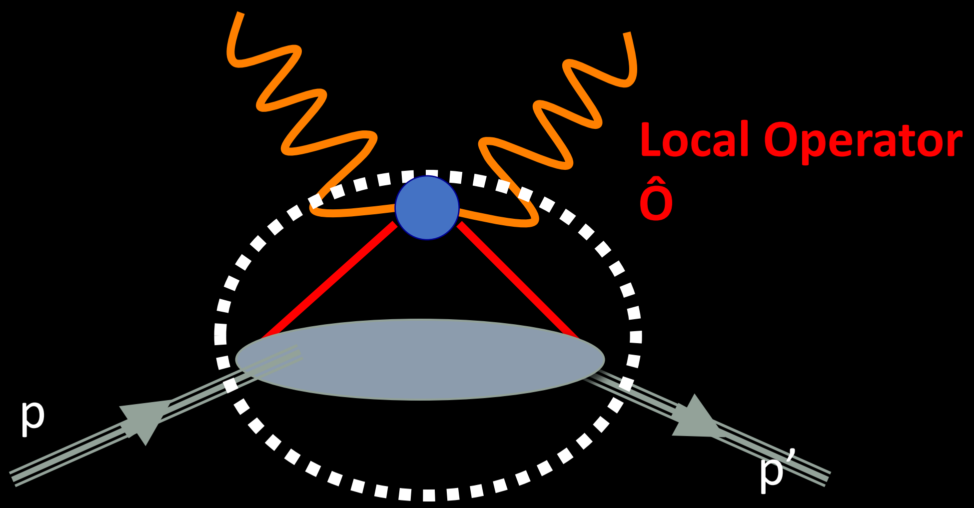
GPDs and Deeply Virtual Exclusive Experiments

A new paradigm that will allow us to both penetrate and visualize the deep structure of visible matter, answering questions that we couldn't even afford asking before

EMT matrix elements from Generalized Parton Distributions Moments (X.Ji,1997)



GPD

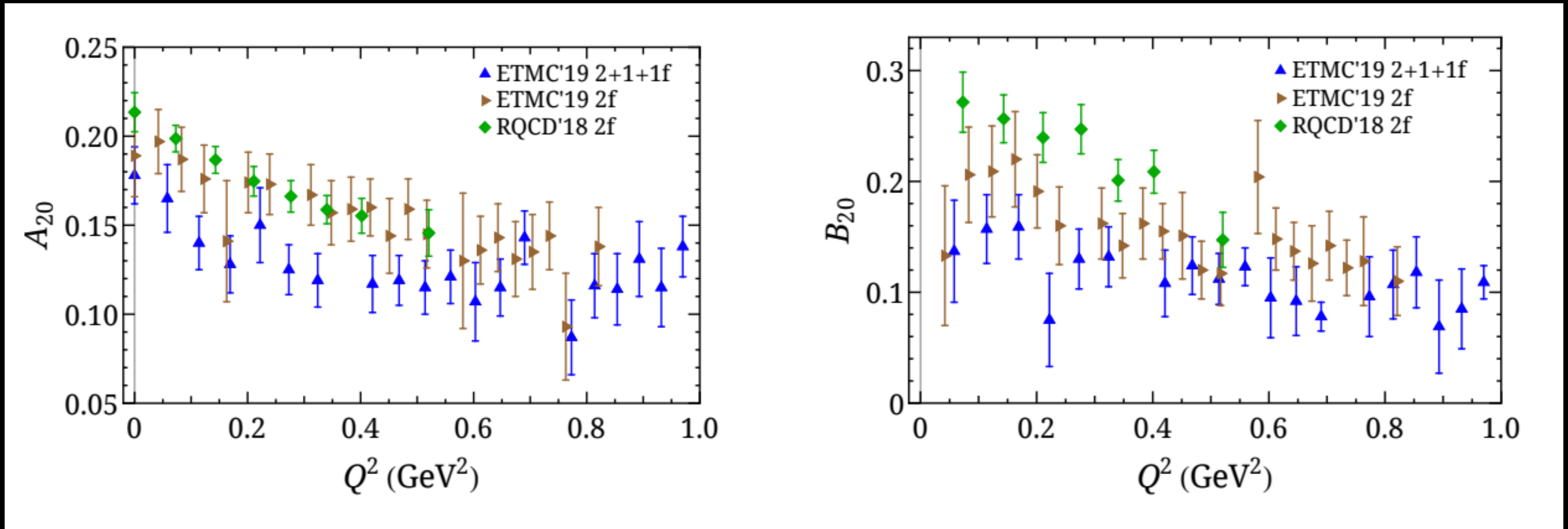


GPD Moments → EMT Form Factors

- Large momentum transfer $Q^2 >> M^2$ → "deep"
- Large Invariant Mass $W^2 >> M^2$ → equivalent to an "inelastic" process

EMT form factors	GPD Moments	Physical variable
$\frac{1}{2}(A_q + B_q) = J_q$	$= \frac{1}{2}(A_{20} + B_{20})$	$J_q^i = \int d^3r \epsilon^{ijk} r_j T_{0k}$ Angular Momentum
$A_q = \langle x_q \rangle$	$= A_{20}$	$A_q = \langle x_q \rangle = A_{20}$ Momentum
$C_q = \text{Internal Forces}$	$= C_{20}$	$\int d^3r \left(r^i r^j - \delta^{ij} r^2\right) T_{ij}$ Pressure

u-d



arXiv 2006.08636

Lorentz Invariance Relation

$L_q(x)$ $\qquad\qquad$ L_q

$$F_{14}^{(1)} = -\int_x^1 dy\,(\tilde{E}_{2T} + H + E) \;\Rightarrow\; -L_q = \int_0^1 dx F_{14}^{(1)} = \int_0^1 dx\, x G_2$$

- ✓ Twist 3 GPD notation from Meissner, Metz and Schlegel, JHEP(2009)
- ✓ We confirm and corroborate the global/integrated OAM result deducible from Ji, Xiong, Yuan PRD88 (2013)

see M. Engelhardt talk

- A. Rajan, A. Courtoy, M. Engelhardt, S.L., PRD (2016)
- A. Rajan, M. Engelhardt, S.L., PRD (2018)

Twist 3 Transverse Angular Momentum Sum Rule

$$J_q = L_q + \frac{1}{2}\Delta\Sigma_q$$

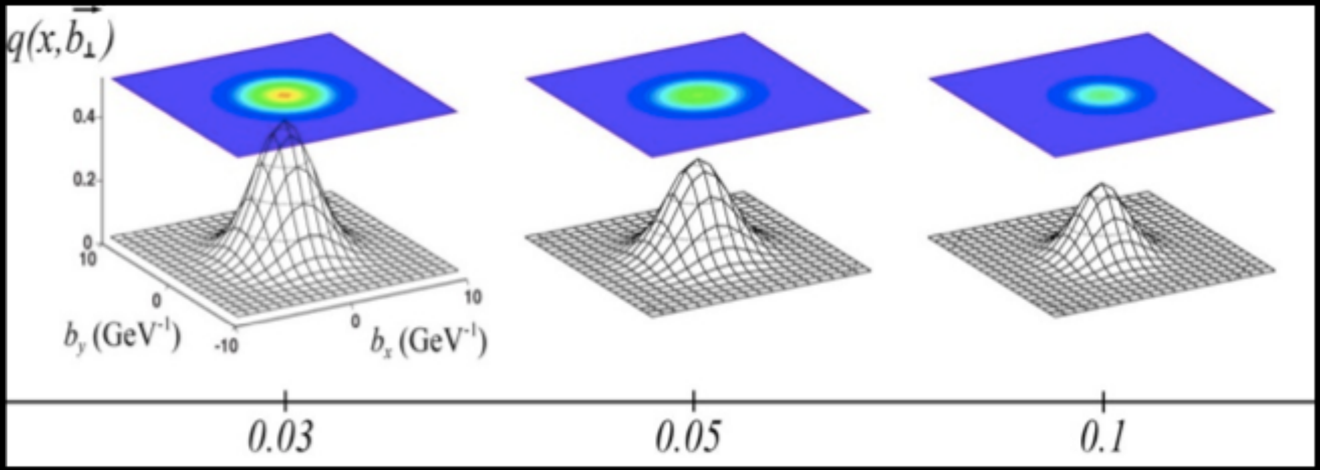
A. Rajan, M. Engelhardt, SL, *to be submitted*

$$\underbrace{\frac{1}{2}\int dx\, x(H+E) - \frac{1}{2}\int dx\, \mathcal{M}_T}_{J_T} = \underbrace{\int dx\, x\left(\widetilde{E}_{2T} + H + E + \frac{H_{2T}}{\xi}\right)}_{L_T} + \underbrace{\frac{1}{2}\int dx\, g_T - \frac{1}{2}\int dx\, x\mathcal{A}_T}_{S_T}$$

See also recent paper by Guo, Ji, Shiells 2101.05243

see M. Engelhardt talk

Measuring the Nucleon Gravitomagnetic Form Factors



graph from M. Defurne

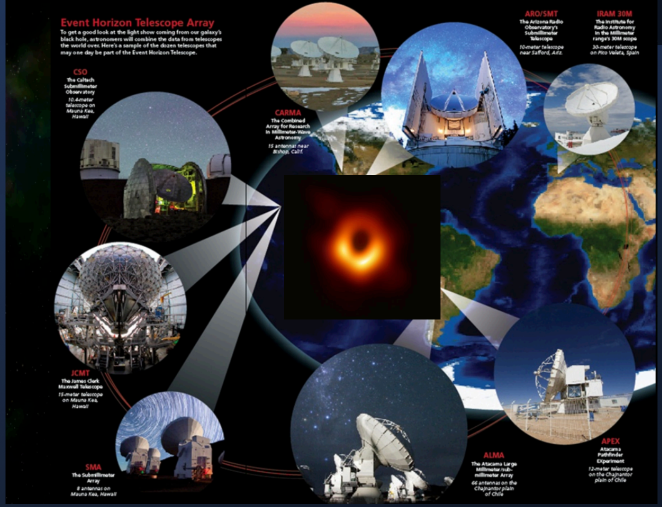
A multi-step, multi-prong process that compares to imaging a black hole

- Main idea: use DVCS, TCS, DVMP… and related processes as probes

- Precision: high luminosity in a wide kinematic range is key!

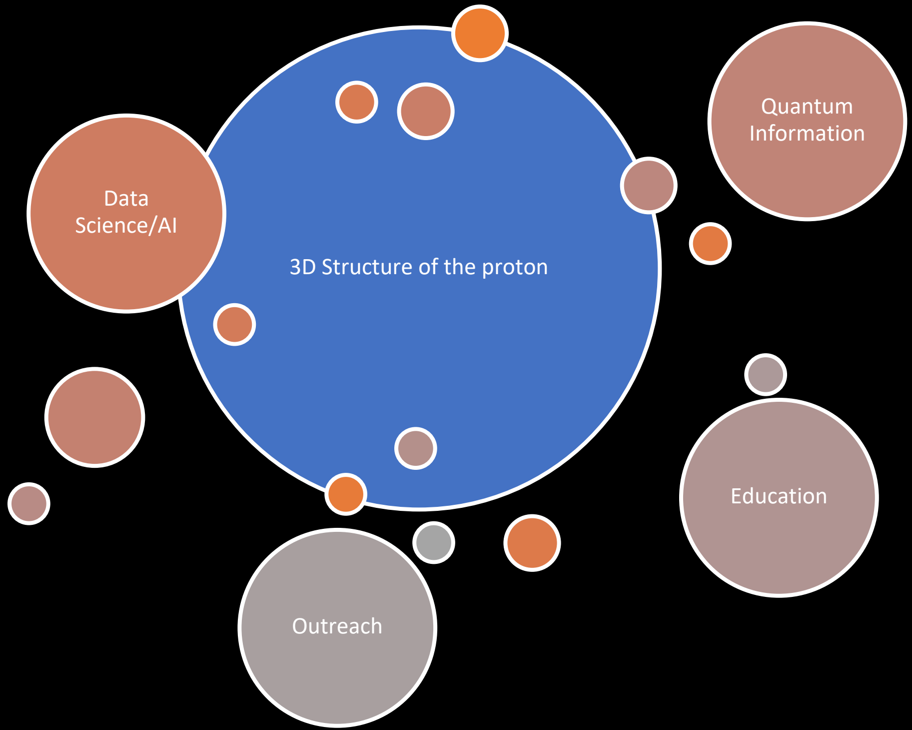
- Data Management: unprecedented amount of data need new AI based techniques to handle the image making

Event Horizon Telescope



It took nearly two decades to achieve !

Center for Nuclear Femtography (CNF)



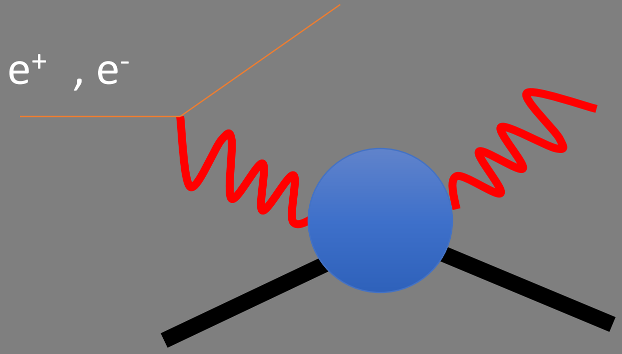
Since its foundation (UVA, 2018) CNF has funded multiple projects on femtography/extraction of information the 3D structure of the proton from

- Experimental data management
- ML & AI
- Inverse problem
- Lattice QCD calculations
- Outreach

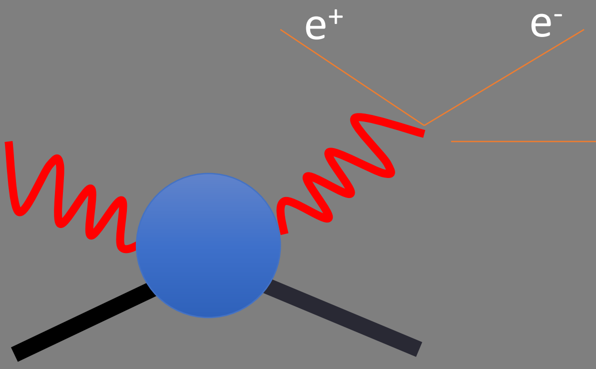
Presently organizing efforts into a larger collaboration, involving institutions and labs across the country

https://www.femtocenter.org/

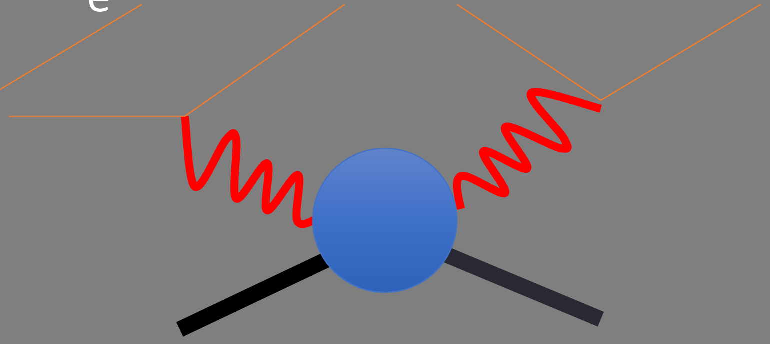
Harnessing/coordinating information from all channels



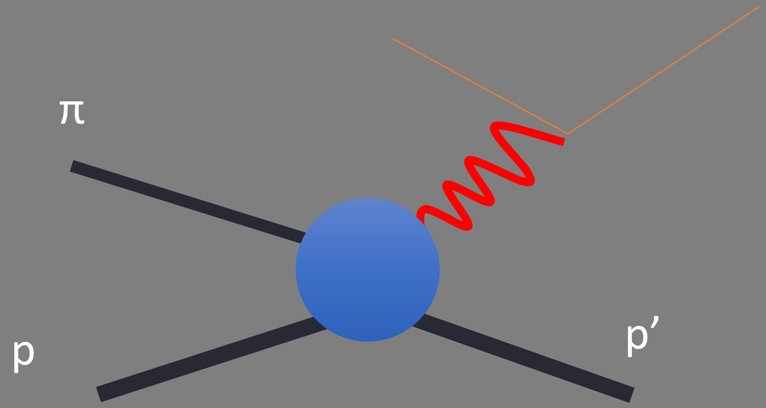
DVCS, DVMP



TCS

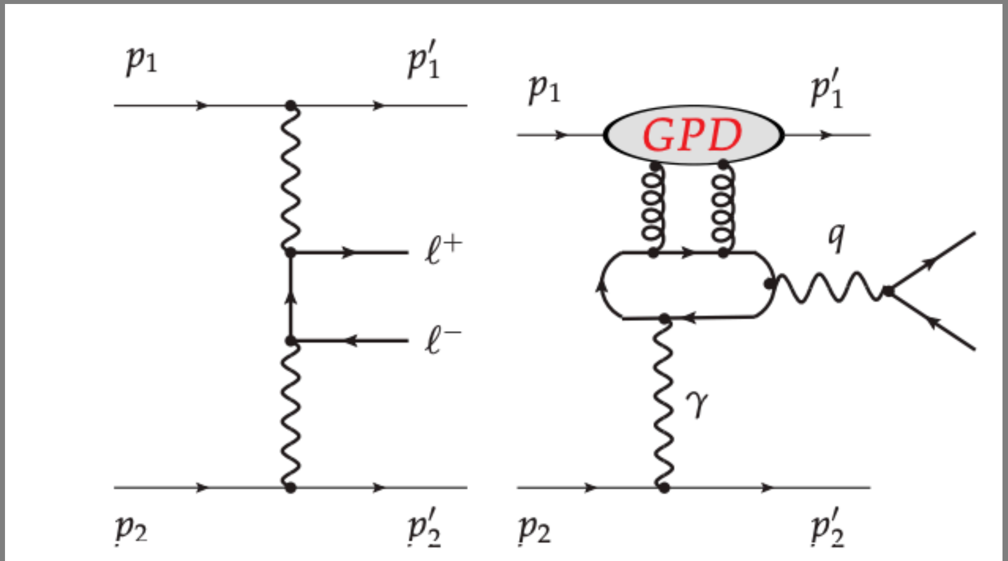


DDVCS



Exclusive pion induced DY (EDY)

Sawada et al., PRD93 (2016)



(a) BH (b) TCS with gluon GPDs

Based on…

Extraction of Generalized Parton Distribution Observables from Deeply Vir… Electron Proton Scattering Experiments

Brandon Kriesten,[*] Simonetta Liuti,[†] Liliet Calero Diaz,[‡] Dustin Keller,[§] and Andrew Meyer[¶]

Department of Physics, University of Virginia, Ch

Gary R. Goldstein

Department of Physics and Astronomy, Tufts Univ

J. Osvaldo Gonzalez-Her

INFN, Torino

(Dated: April 6, 201

arXiv:1903.05742

We provide the general expression of the cross section
troproduction from a spin 1/2 target using current param
function in a nucleon for different beam and target pola
accuracy. All contributions to the cross section includin
Bethe-Heitler process, and their interference, are describe
work which is also relativistically
in a collider kinematic setting. C
components of the cross section
the electron scattering coinciden
tum, J_z, and on the orbital angu
extraction of J_z, given by the c
generalization of the Rosenbluth
the other, we single out for the
that are sensitive to L_z. The pr
be extended to additional observ

Theory of Deeply Virtual Compton Scattering off the Unpolarized Proton

Brandon Kriesten[*] and Simonetta Liuti[†]

Department of Physics, University of Virginia, Charlottesville, VA 22904, USA.

Using the helicity amplitudes formalism, we study deeply virtual exclusive electron photoproduction off an unpolarized nucleon target, $ep \rightarrow e'p'\gamma$, through a range of kinematic settings for the initial electron energy in the laboratory system, 6 GeV, 11 GeV and 24 GeV, which are ideal for studying the 3D quark structure of the nucleon. We use a reformulation of the cross section that brings to the forefront the defining features of the $ep \rightarrow e'p'\gamma$ process as a *coincidence scattering* experiment, where the observables are expressed as bilinear products of the independent helicity amplitudes which completely describe the process in terms of the electric, magnetic and axial currents for the nucleon. These different contributions to the cross section are checked against the Fourier harmonics-based formalism which has provided so far the underlying mathematical framework to study Deeply virtual Compton scattering and related experiments. Using two different sets of the

Proton Compton Form Factors $\mathcal{H}$ and $\mathcal{E}$ from the Rosenbluth Separation Technique in Deeply Virtual Exclusive Photoproduction

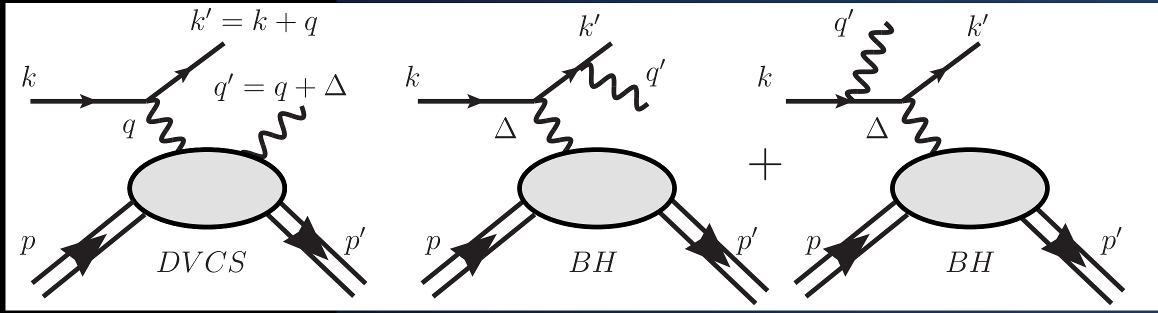
Brandon Kriesten,[*] Simonetta Liuti,[†] and Andrew Meyer[‡]

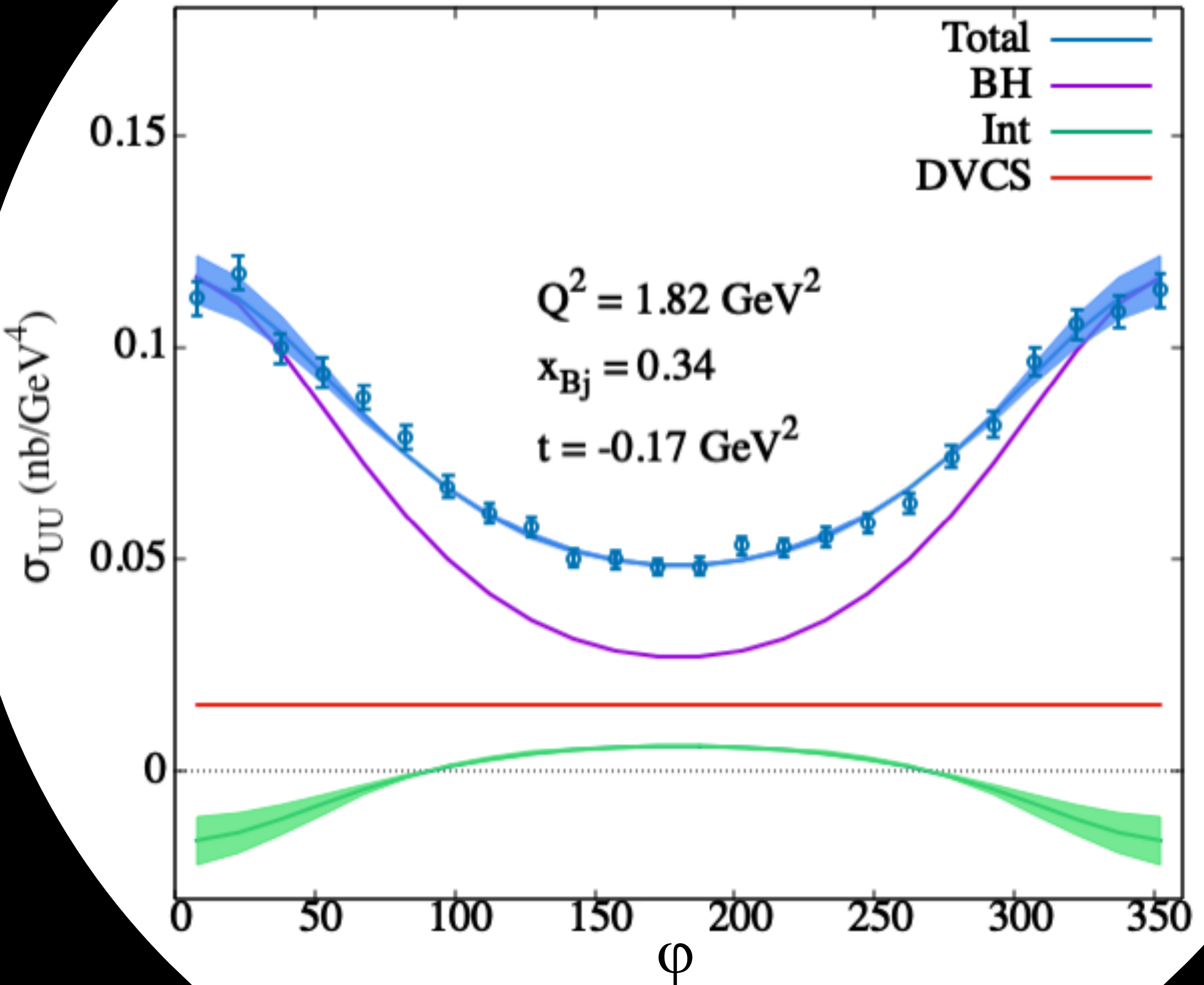
Department of Physics, University of Virginia, Charlottesville, VA 22904, USA.

We present an extraction from available Deeply Virtual Compton Scattering data on an unpolarized proton target, of the imaginary and real parts of the Compton Form Factors H, E, and, separately the combination, $H + E$. The latter is essential for the extraction of angular momentum. The extraction technique is a generalization of the Rosenbluth separation method which exploits the linear dependence in the kinematic coefficients of the reduced cross section to independently determine the Compton form factors as the slope and intercept.

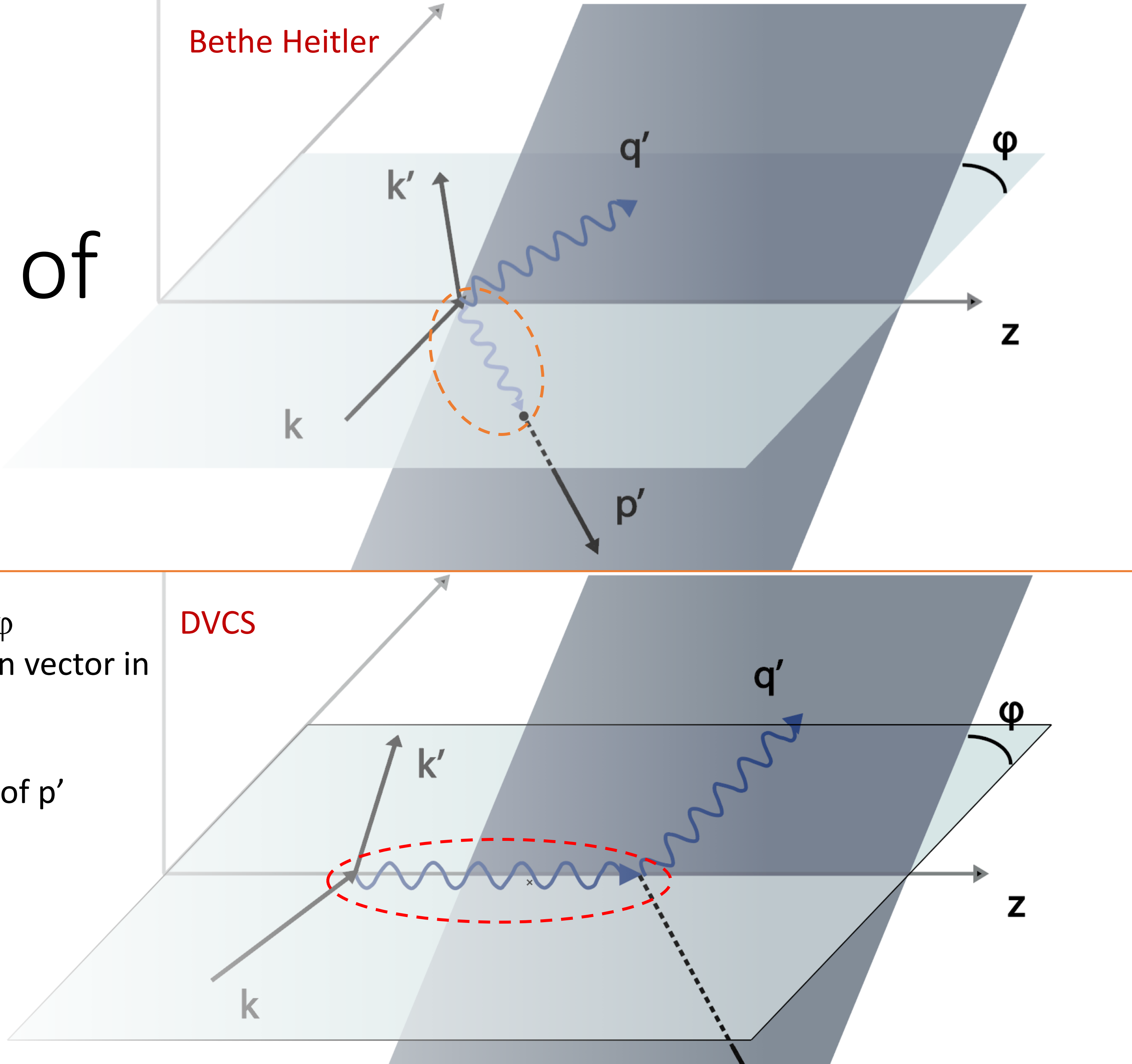
We need a robust framework for the cross section, where kinematic limits are under control (beyond "harmonics" model)

- **B. Kriesten et al,** *Phys.Rev. D* 101 (2020)
- **B. Kriesten and S. Liuti,** arXiv 2004.08890




Total
BH
Int
DVCS
$Q^2 = 1.82$ GeV^2
$x_{Bj} = 0.34$
$t = -0.17$ GeV^2
σ_{UU} (nb/GeV^4)
0.15
0.1
0.05
0
0
50
100
150
200
250
300
350
φ

Demystification of harmonics formalism



- In DVCS the virtual photon is along the z axis: φ dependence from usual rotation of polarization vector in helicity amp
- In BH the virtual photon is along the direction of p’
- Mismatch complicates the BH-DVCS term

BH

$$\frac{d^5\sigma^{BH}_{unpol}}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} \equiv \frac{\Gamma}{t}F^{BH}_{UU} = \frac{\Gamma}{t}\left[A(y,x_{Bj},t,Q^2,\phi)\left(F_1^2+\tau F_2^2\right) + B(y,x_{Bj},t,Q^2,\phi)\tau G_M^2(t)\right]$$

$$A = \frac{16\,M^2}{t(k\,q')(k'\,q')}\left[4\tau\left((k\,P)^2+(k'\,P)^2\right) - (\tau+1)\left((k\,\Delta)^2+(k'\,\Delta)^2\right)\right]$$

$$B = \frac{32\,M^2}{t(k\,q')(k'\,q')}\left[(k\,\Delta)^2+(k'\,\Delta)^2\right],$$

$$\epsilon_{BH} = \left(1+\frac{B}{A}(1+\tau)\right)^{-1}$$

…compared to ELASTIC SCATTERING

$$\left(\frac{d\sigma}{d\Omega}\right)_0 = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \frac{\epsilon (G_E^N)^2 + \tau (G_M^N)^2}{\epsilon(1+\tau)},$$

where $N = p$ for a proton and $N = n$ for a neutron, (
the recoil-corrected relativistic point-particle (Mott)
and τ, ϵ are dimensionless kinematic variables:

$$\tau = \frac{Q^2}{4m_N^2}, \quad \epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1},$$

J. Arrington, G. Cates, S. Riordan, Z. Ye, B. Wojsetowski, A. Puckett …

…compared to BKM, NPB (2001)

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

$$\begin{aligned} c_{0,\mathrm{unp}}^{\mathrm{BH}} = 8K^2 &\left\{ (2+3\epsilon^2)\frac{Q^2}{\Delta^2}\left(F_1^2 - \frac{\Delta^2}{4M^2}F_2^2\right) + 2x_{\mathrm{B}}^2(F_1+F_2)^2 \right\} \\ &+ (2-y)^2 \left\{ (2+\epsilon^2)\left[\frac{4x_{\mathrm{B}}^2 M^2}{\Delta^2}\left(1+\frac{\Delta^2}{Q^2}\right)^2 \right.\right. \\ &\qquad \left. + 4(1-x_{\mathrm{B}})\left(1+x_{\mathrm{B}}\frac{\Delta^2}{Q^2}\right)\right]\left(F_1^2 - \frac{\Delta^2}{4M^2}F_2^2\right) \\ &\qquad + 4x_{\mathrm{B}}^2\left[x_{\mathrm{B}} + \left(1 - x_{\mathrm{B}} + \frac{\epsilon^2}{2}\right)\left(1-\frac{\Delta^2}{Q^2}\right)^2 \right. \\ &\qquad \left.\left. - x_{\mathrm{B}}(1-2x_{\mathrm{B}})\frac{\Delta^4}{Q^4}\right](F_1+F_2)^2 \right\} \\ &+ 8(1+\epsilon^2)\left(1 - y - \frac{\epsilon^2 y^2}{4}\right) \\ &\quad \times \left\{ 2\epsilon^2\left(1-\frac{\Delta^2}{4M^2}\right)\left(F_1^2 - \frac{\Delta^2}{4M^2}F_2^2\right) - x_{\mathrm{B}}^2\left(1-\frac{\Delta^2}{Q^2}\right)^2 (F_1+F_2)^2 \right\}, \end{aligned}$$

A.V. Belitsky et al. / Nuclear Physics B 629 (2002) 323–392

$$\begin{aligned} c_{1,\mathrm{unp}}^{\mathrm{BH}} = 8K(2-y) &\left\{ \left(\frac{4x_{\mathrm{B}}^2 M^2}{\Delta^2} - 2x_{\mathrm{B}} - \epsilon^2\right)\left(F_1^2 - \frac{\Delta^2}{4M^2}F_2^2\right) \right. \\ &\quad \left. + 2x_{\mathrm{B}}^2\left(1 - (1-2x_{\mathrm{B}})\frac{\Delta^2}{Q^2}\right)(F_1+F_2)^2 \right\}, \end{aligned}$$

$$c_{2,\mathrm{unp}}^{\mathrm{BH}} = 8x_{\mathrm{B}}^2 K^2 \left\{ \frac{4M^2}{\Delta^2}\left(F_1^2 - \frac{\Delta^2}{4M^2}F_2^2\right) + 2(F_1+F_2)^2 \right\}.$$

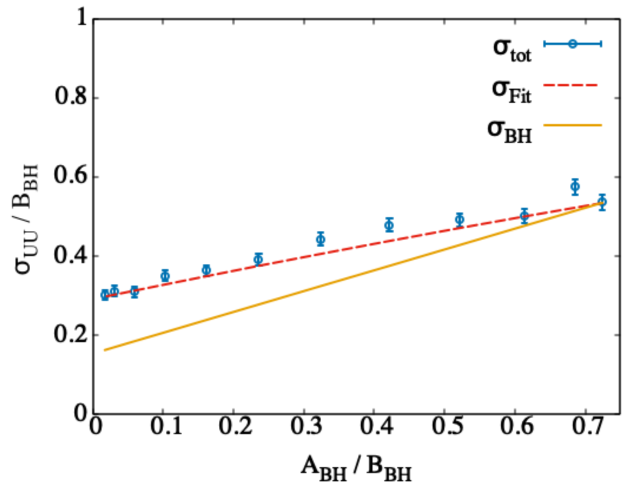
$$F_{UU}^{\mathcal{I}} = F_{UU}^{\mathcal{I},tw2} + \frac{K}{\sqrt{Q^2}} F_{UU}^{\mathcal{I},tw3}$$

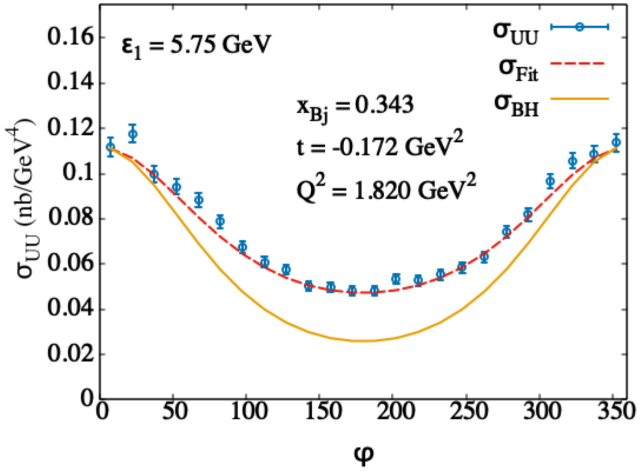
BH-DVCS interference

$$F_{UU}^{\mathcal{I},tw2} = A_{UU}^{\mathcal{I}} \Re e \left(F_1 \mathcal{H} + \tau F_2 \mathcal{E}\right) + B_{UU}^{\mathcal{I}} G_M \Re e \left(\mathcal{H} + \mathcal{E}\right) + C_{UU}^{\mathcal{I}} G_M \Re e \widetilde{\mathcal{H}}$$

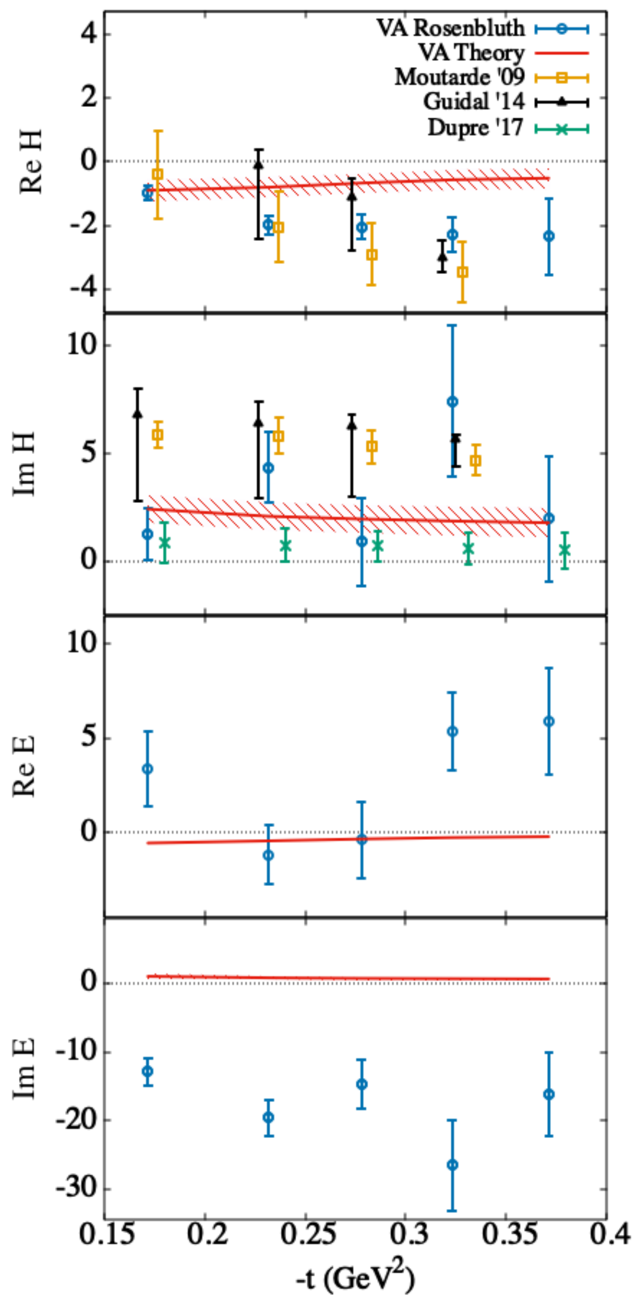
$A_{UU}{}^{I}$ $B_{UU}{}^{I}$ $C_{UU}{}^{I}$ are φ dependent coefficients

- Rosenbluth Separated BH-DVCS interference data

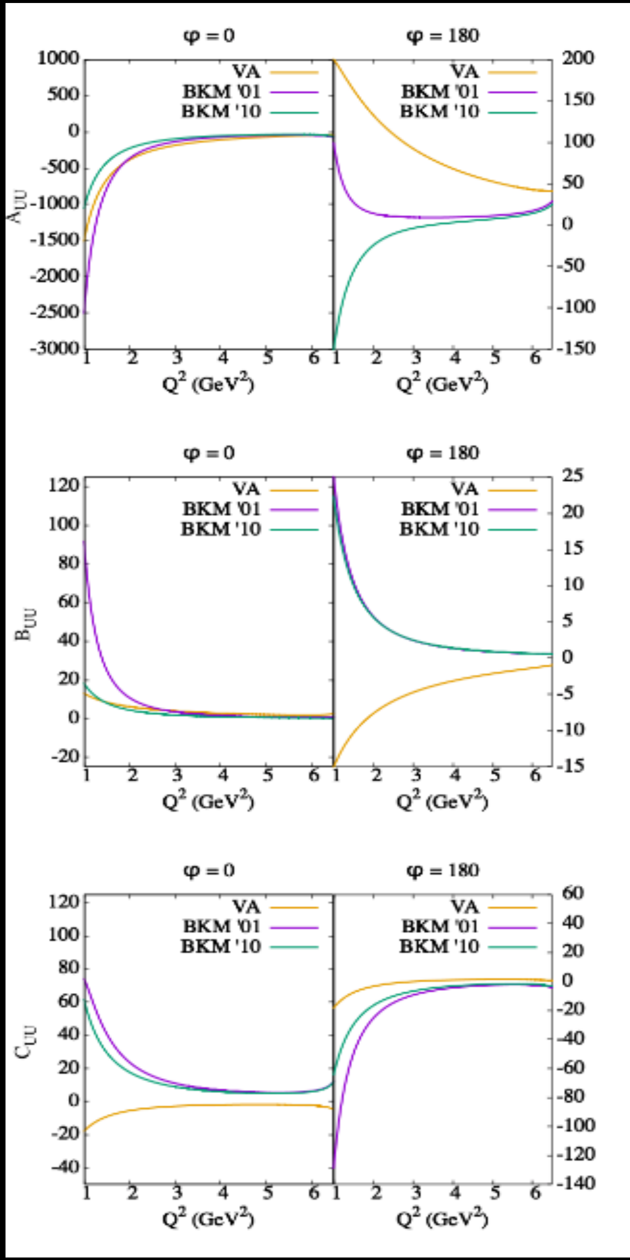


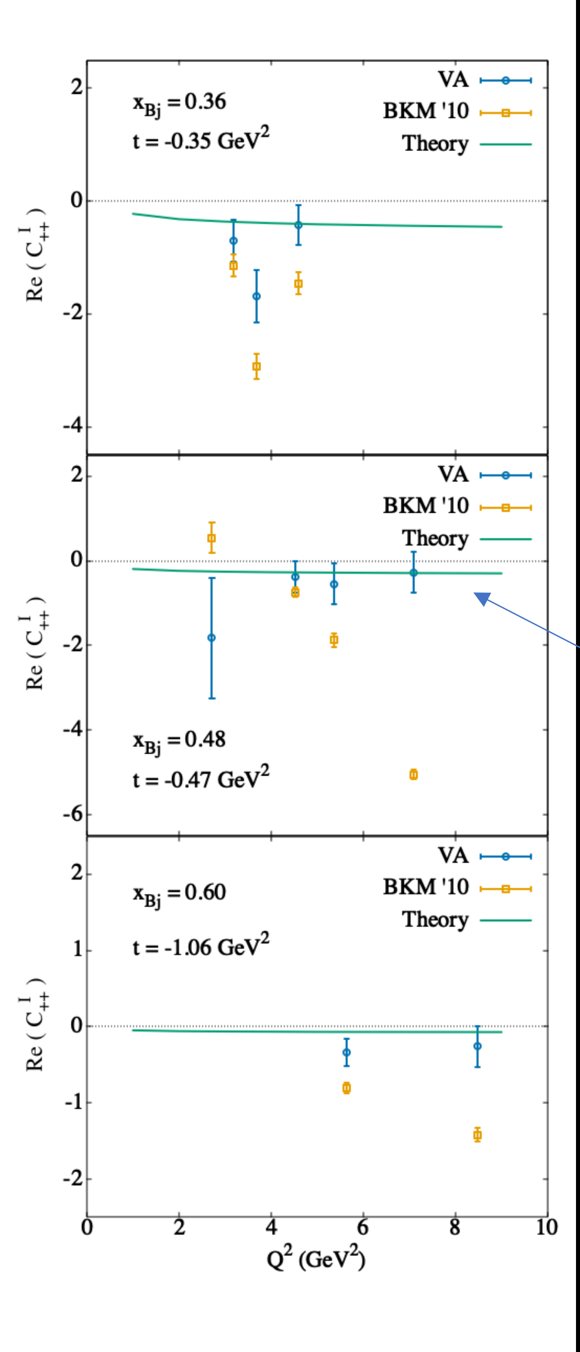


Compton Form Factors



Q^2 dependence





pQCD Evolution

Holistic approach to observables

GPD	Twist	$P_q P_p$	TMD	$P_{Beam} P_p$ (DVCS)	$P_{Beam} P_p$ ($\mathcal{I}$)
$\mathbf{H}+\frac{\xi^2}{1-\xi}E$	2	UU	f_1	$UU,\ LL,\ UT^{\sin(\phi-\phi_s)},\ LT^{\cos(\phi-\phi_s)}$	$UU^{\cos\phi},\ LU^{\sin\phi}$
$\widetilde{\mathbf{H}}+\frac{\xi^2}{1-\xi}\widetilde{E}$	2	LL	g_1	$UU,\ LL,\ UT^{\sin(\phi-\phi_s)},\ LT^{\cos(\phi-\phi_s)}$	$UU^{\cos\phi},\ UL^{\cos\phi},\ LU^{\sin\phi},\ LL^{\sin\phi},\ UT^{\frac{\cos\phi}{\sin\phi}},\ LT^{\cos\phi}$
$\mathbf{E}$	2	UT	$f_{1T}^{\perp(*)}$	$UT^{\sin(\phi-\phi_s)},\ LT^{\cos(\phi-\phi_s)}$	$UU^{\cos\phi},\ LU^{\sin\phi},\ UT,\ LT,\ UT^{\cos\phi},\ UT^{\sin\phi}$
$\widetilde{\mathbf{E}}$	2	LT	g_{1T}	$UT^{\sin(\phi-\phi_s)},\ LT^{\cos(\phi-\phi_s)}$	$UL^{\sin\phi},\ LL^{\cos\phi},\ UT^{\cos\phi},\ UT^{\sin\phi}$
$\mathbf{H+E}$	2	-	-	-	$UU^{\cos\phi},\ LU^{\sin\phi},\ UL^{\sin\phi},\ LL^{\cos\phi},\ UT^{\cos\phi},\ UT^{\sin\phi}$
$2\widetilde{\mathbf{H}}_{\mathbf{2T}}+\mathbf{E}_{\mathbf{2T}}-\xi\widetilde{E}_{2T}$	3	UU	$f^{\perp}$	$UU^{\cos\phi},\ LU^{\sin\phi}$	UU, LU
$2\widetilde{\mathbf{H}}'_{\mathbf{2T}}+\mathbf{E}'_{\mathbf{2T}}-\xi\widetilde{E}'_{2T}$	3	LL	$g_L^{\perp}$	$UU^{\cos\phi},\ LU^{\sin\phi}$	UU, LU
$\mathbf{H}_{\mathbf{2T}}+\frac{\mathbf{t_o-t}}{\mathbf{4M^2}}\widetilde{\mathbf{H}}_{\mathbf{2T}}$	3	UT	$f_T^{(*)}, f_T^{\perp(*)}$	$UU^{\cos\phi},\ UL^{\cos\phi},\ LU^{\sin\phi},\ LL^{\cos\phi}$	UU, LU
$\mathbf{H}'_{\mathbf{2T}}+\frac{\mathbf{t_o-t}}{\mathbf{4M^2}}\widetilde{\mathbf{H}}'_{\mathbf{2T}}$	3	LT	$g'_T, g_T^{\perp}$	$UU^{\cos\phi},UL^{\cos\phi},\ LU^{\sin\phi},\ LL^{\cos\phi}$	UU, LU
$\mathbf{E}_{\mathbf{2T}}-\xi E_{2T}$	3	UL	$f_L^{\perp(*)}$	$UU^{\cos\phi},\ UL^{\cos\phi},\ LU^{\sin\phi},\ LL^{\cos\phi}$	UU, LU, UT
$\widetilde{\mathbf{E}}'_{\mathbf{2T}}-\xi\widetilde{E}'_{2T}$	3	LU	$g^{\perp(*)}$	$UU^{\cos\phi},\ UL^{\cos\phi},\ LU^{\sin\phi},\ LL^{\cos\phi}$	UU, LU, UT
$\widetilde{\mathbf{H}}_{\mathbf{2T}}$	3	UT_x	$f_T^{\perp(*)}$	$UU^{\cos\phi},\ UL^{\cos\phi},\ LU^{\sin\phi},\ LL^{\cos\phi}$	UU, LU, UT
$\widetilde{\mathbf{H}}'_{\mathbf{2T}}$	3	LT_x	$g_T^{\perp}$	$UU^{\cos\phi},\ UL^{\cos\phi},\ LU^{\sin\phi},\ LL^{\cos\phi}$	UU, LU, UT

Transverse OAM

OAM

Spin Orbit

Newly accessible configurations!

Kriesten et al., Phys.Rev.D 101 (2020)
Kriesten and SL , 2004.08890

Twist 3 GPDs Physical Interpretation

GPD	$P_q P_p$	TMD	Ref. 1
$H^{\perp}$	UU	$f^{\perp}$	$2\widetilde{H}_{2T} + E_{2T}$
$\widetilde{H}_L^{\perp}$	LL	$g_L^{\perp}$	$2\widetilde{H}'_{2T} + E'_{2T}$
$H_L^{\perp}$	UL	$f_L^{\perp\,(*)}$	$\widetilde{E}_{2T} - \xi E_{2T}$
$\widetilde{H}^{\perp}$	LU	$g^{\perp\,(*)}$	$\widetilde{E}'_{2T} - \xi E'_{2T}$
$H_T^{(3)}$	UT	$f_T^{(*)}$	$H_{2T} + \tau \widetilde{H}_{2T}$
$\widetilde{H}_T^{(3)}$	LT	g'_T	$H'_{2T} + \tau \widetilde{H}'_{2T}$

→ 1/Q correction to H

→ 1/Q correction to $\widetilde{H}$

NEW!! Orbital Angular Momentum L

NEW!! Spin Orbit correlation L ·S

→ 1/Q correction to E

→ 1/Q correction to $\widetilde{E}$

(*) T-odd

[1] Meissner, Metz and Schlegel, JHEP(2009)

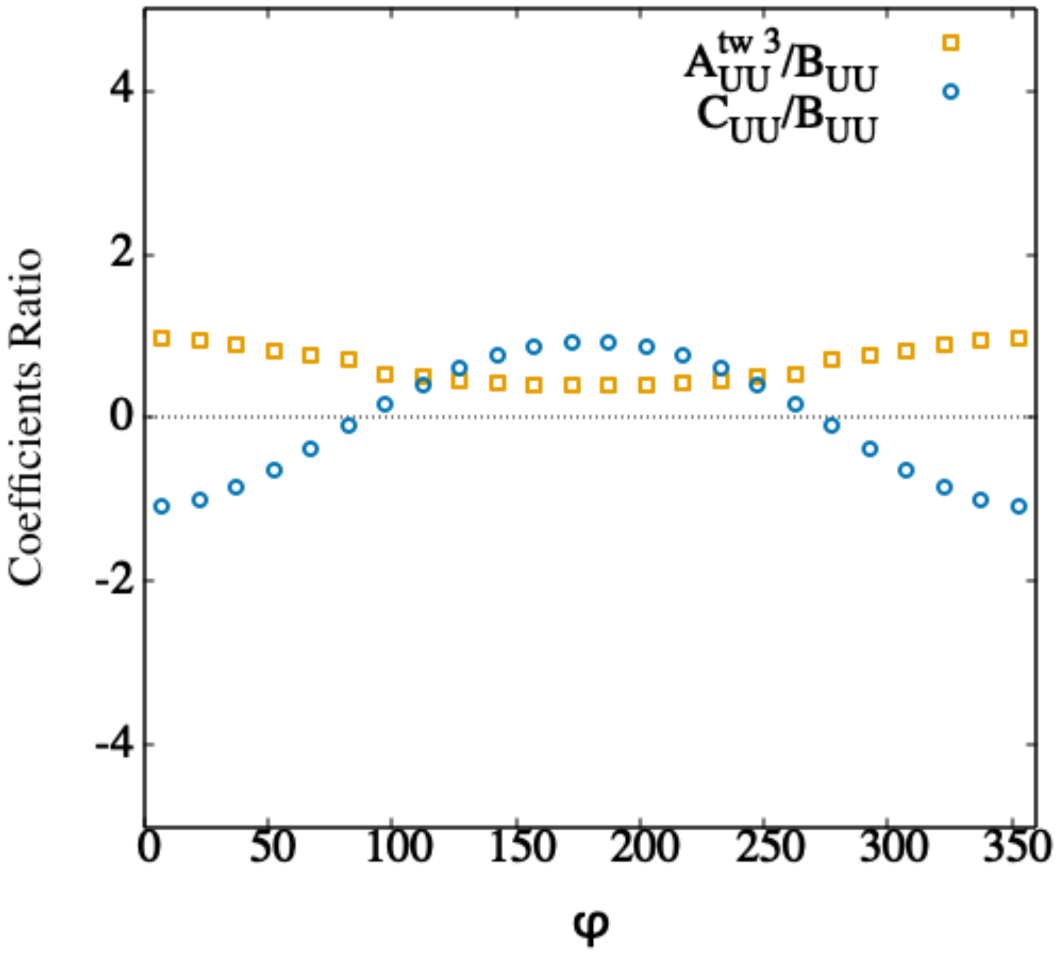
Twist 3
BH-DVCS interference

$$F_{UU}^{\mathcal{I}} = F_{UU}^{\mathcal{I},tw2} + \frac{K}{\sqrt{Q^2}} F_{UU}^{\mathcal{I},tw3}$$

$$F_{UU}^{\mathcal{I},tw3} = A_{UU}^{(3)\mathcal{I}} \left[F_1 \left(\Re e(2\widetilde{\mathcal{H}}_{2T} + \mathcal{E}_{2T}) - \Re e(2\widetilde{\mathcal{H}}'_{2T} + \mathcal{E}'_{2T}) \right) + F_2 \left(\Re e(\mathcal{H}_{2T} + \tau \widetilde{\mathcal{H}}_{2T}) - \Re e(\mathcal{H}'_{2T} + \tau \widetilde{\mathcal{H}}'_{2T}) \right) \right]$$
$$+ B_{UU}^{(3)\mathcal{I}} G_M \left(\Re e \widetilde{\mathcal{E}}_{2T} - \Re e \widetilde{\mathcal{E}}'_{2T} \right)$$
$$+ C_{UU}^{(3)\mathcal{I}} G_M \left[2\xi (\Re e \mathcal{H}_{2T} - \Re e \mathcal{H}'_{2T}) - \tau \left(\Re e (\widetilde{\mathcal{E}}_{2T} - \xi \mathcal{E}_{2T}) - \Re e \left(\widetilde{\mathcal{E}}'_{2T} - \xi \mathcal{E}'_{2T} \right) \right) \right]$$

Orbital Angular Momentum

Twist 3 is very small



But we can extract it by comparing DVCS and TCS data (work in progress)

What I left out

- Nuclei: ^{4}He and deuteron GPDs
- π^0 electroproduction as a means to access the tensor charge and transversity GPDs
- Machine Learning

CONCLUSIONS

Immense discovery potential as we uncover the mechanical properties the of the proton and observe its spatial images through deeply virtual exclusive experiments

To observe, evaluate and interpret GPDs and Wigner distributions at the subatomic level requires stepping up data analyses from the standard methods

developing new numerical/analytic/quantum computing methods

Center for Nuclear Femtography

A comprehensive formalism for the observables (cross sections and asymmetries) does not imply “tedious QED-based calculation-hard to code-easier if approximated”