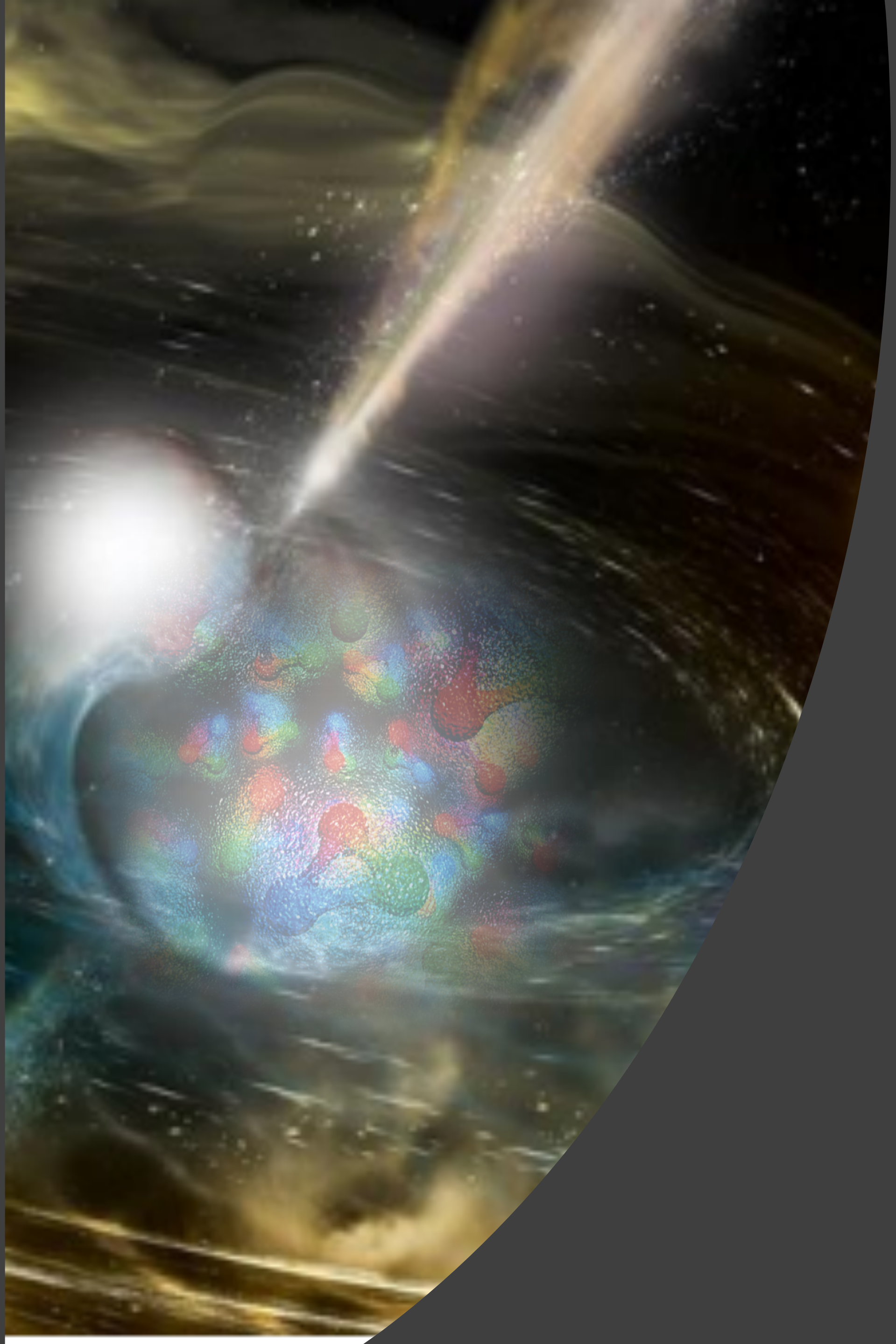
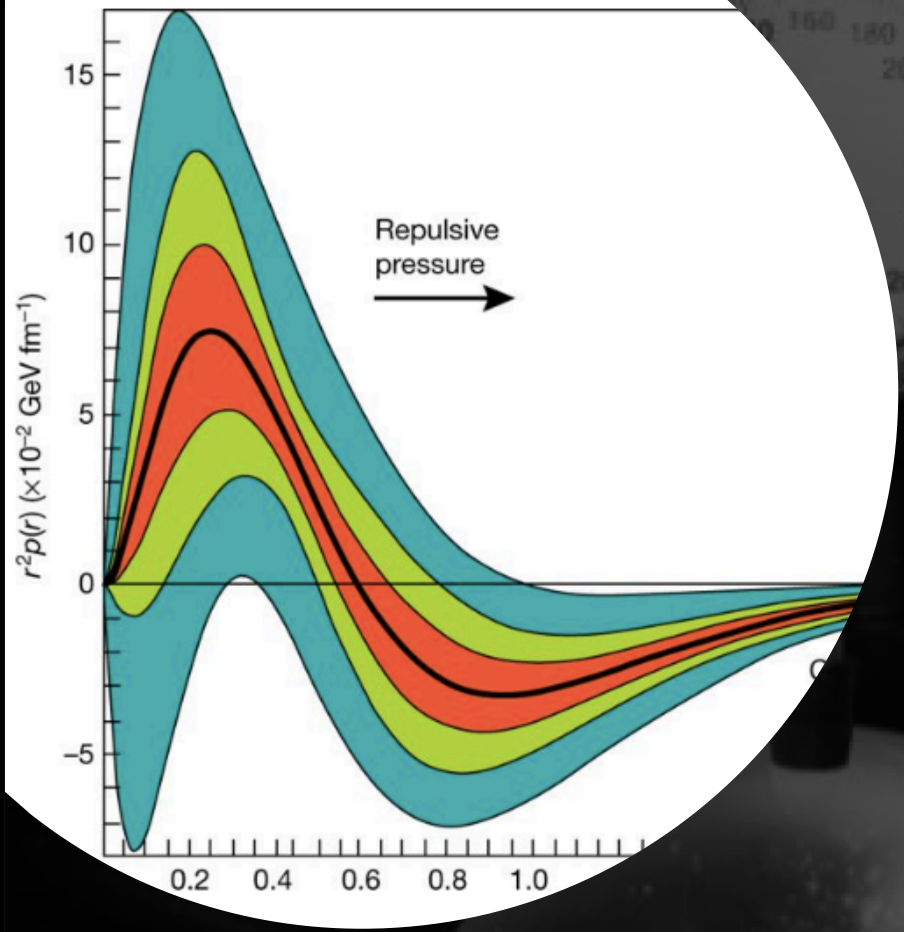


New ML-based Analysis of Deeply Virtual Exclusive Processes

A.I. for Nuclear Physics Workshop
March 4-6, 2020 and
EIC 1st YR Meeting
March 19, 2020

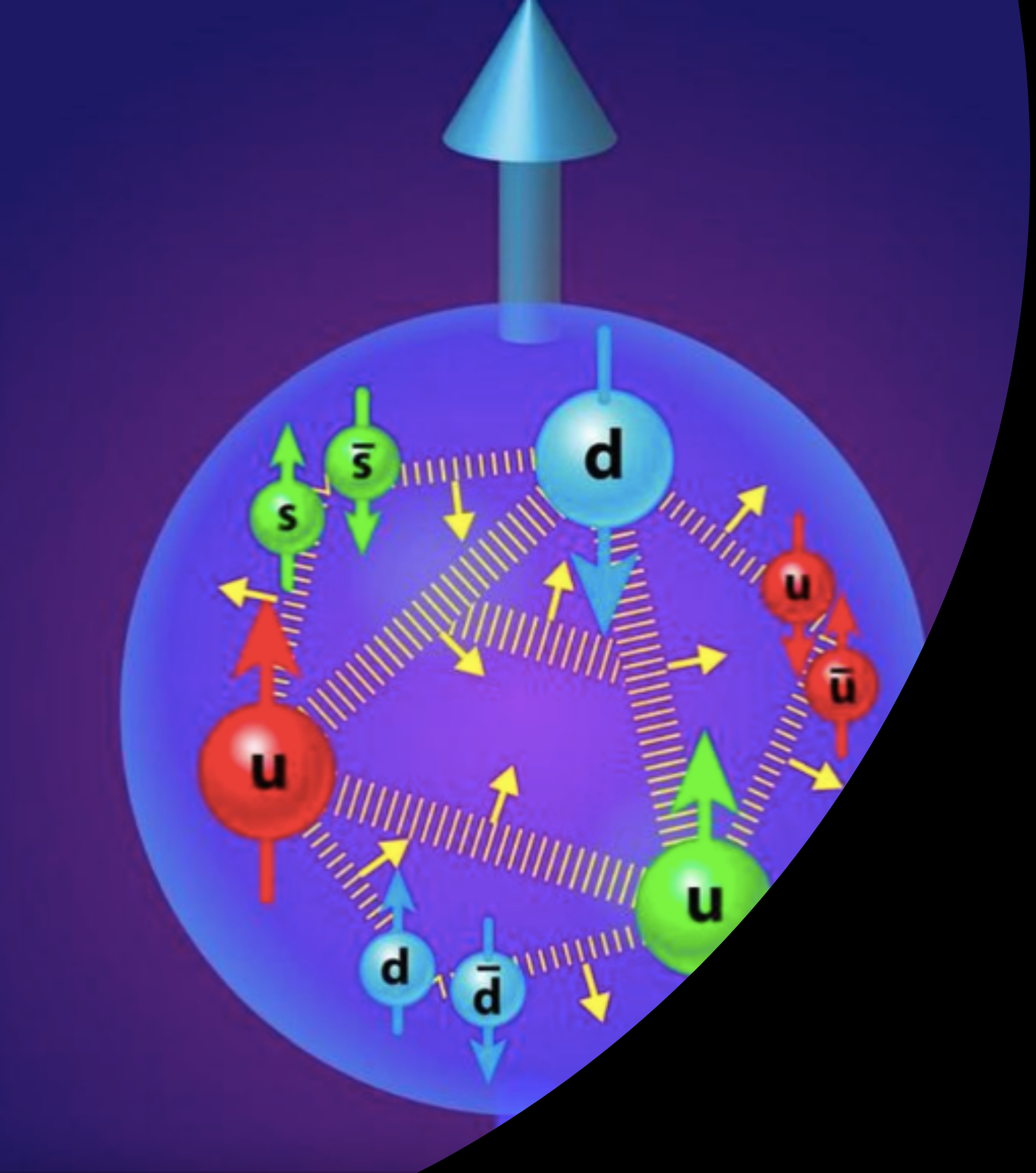
SIMONETTA LIUTI

UNIVERSITY OF VIRGINIA



Burkert, Elouadrhiri, Girod, Nature 557, 396 (2018)

- **"The average peak pressure near the center is about 10^{35} pascals, which exceeds the pressure estimated for the most densely packed known objects in the Universe, neutron stars"**



How is the pressure distribution extracted from data?

(How does the proton/neutron get its mass and spin?)

Introducing the complete formalism

arXiv:1903.05742

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

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(Dated: April 6, 2019)

We provide the general expression of the cross section for exclusive deeply virtual photon electroproduction from a spin 1/2 target using current parameterizations of the off-forward correlation function in a nucleon for different beam and target polarization configurations up to twist three accuracy. All contributions to the cross section including deeply virtual Compton scattering, the Bethe-Heitler process, and their interference, are described within a helicity amplitude based framework which is also relativistically covariant and readily applicable to both the laboratory frame and in a collider kinematic setting. Our formalism renders a clear physical interpretation of the various components of the cross section by making a connection with the known characteristic structure of the electron scattering coincidence reactions. In particular, we focus on the total angular momentum, J_z, and on the orbital angular momentum, L_z. On one side, we uncover an avenue to a precise extraction of J_z, given by the combination of generalized parton distributions, $H + E$, through a generalization of the Rosenbluth separation method used in elastic electron proton scattering. On the other, we single out for the first time, the twist three angular modulations of the cross section that are sensitive to L_z. The proposed generalized Rosenbluth technique adds constraints and can

Phys. Rev. D (2020)

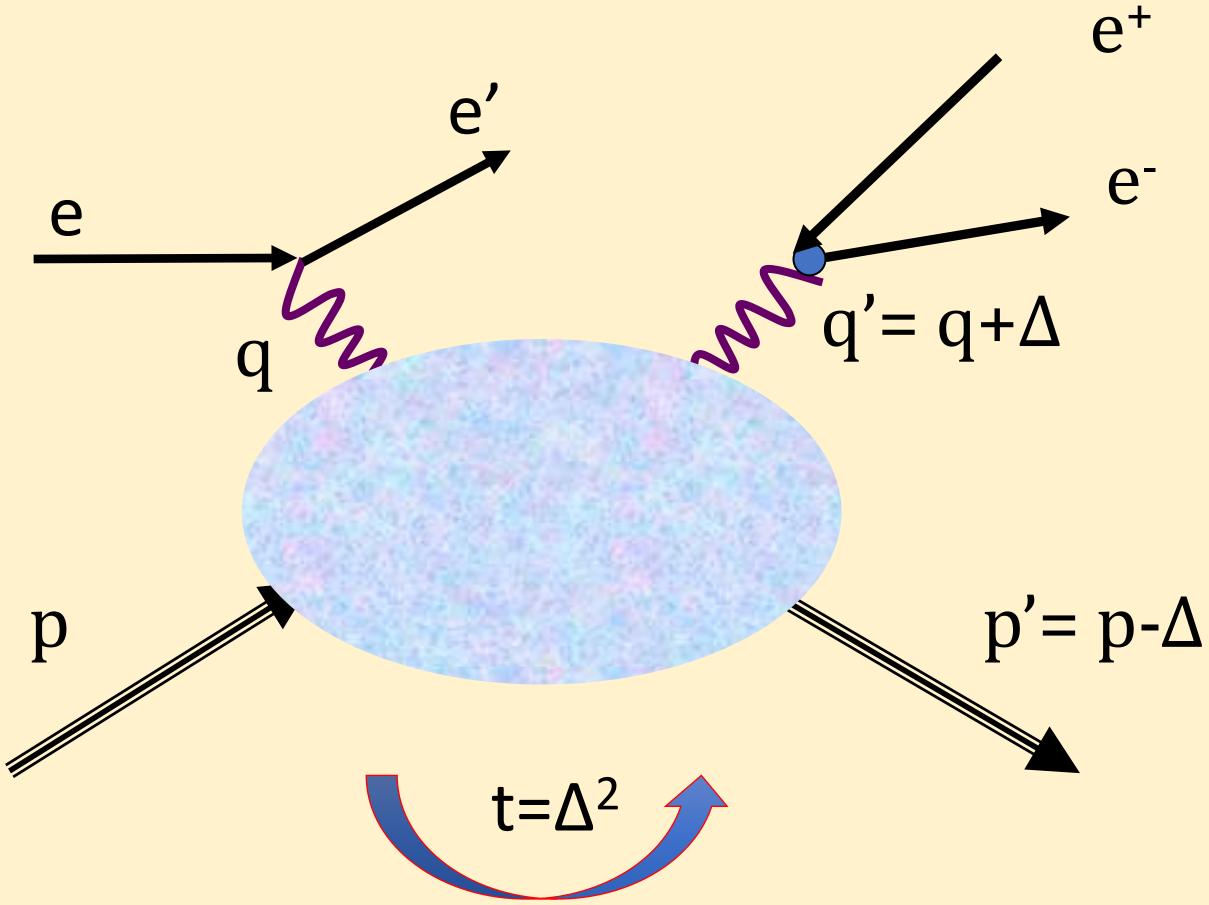
- ✓ Supersedes previous work by Belitsky Kirchner Mueller and Kumericki Mueller

- ✓ The main advantages are :

    - ✓ Covariance (not just Lab frame): a desirable feature for the EIC
    - ✓ Transparent description of observables that ties into the TMD and other coincidence experiments picture

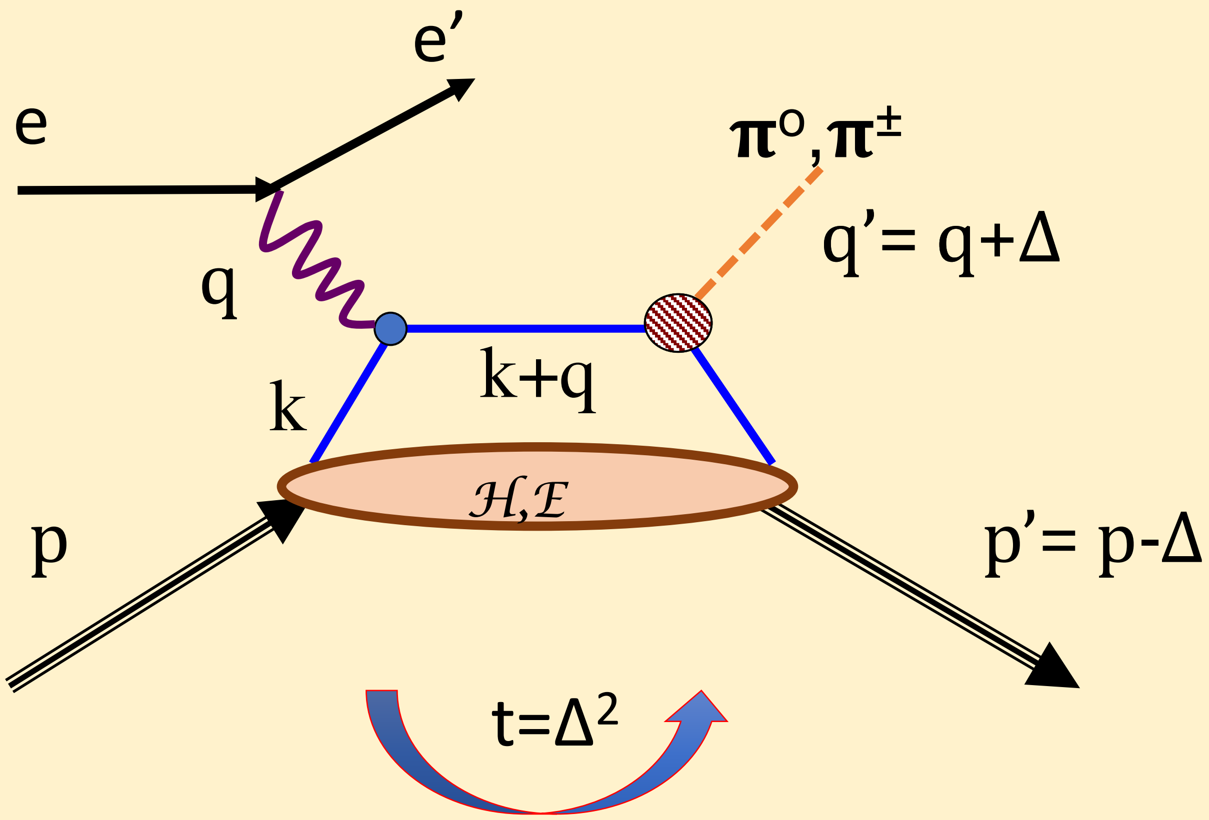
A multi-step, multi-prong process

- Deeply Virtual Compton Scattering
- Timelike Compton Scattering



A multi-step, multi-prong process

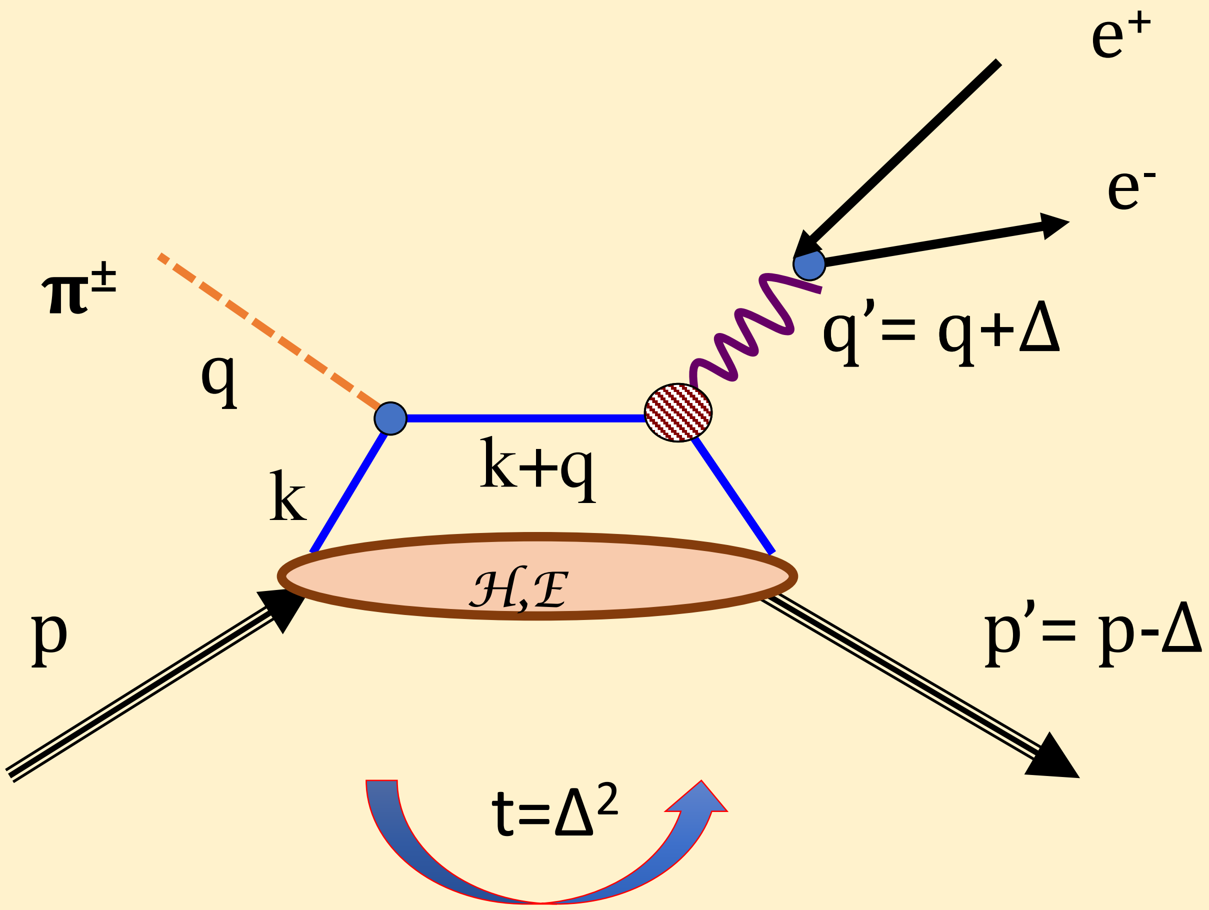
- Deeply Virtual Meson Production
- Exclusive Drell Yan

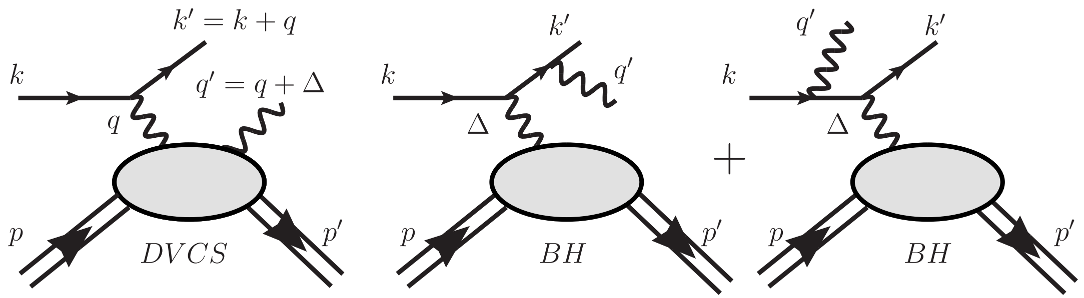


A multi-step, multi-prong process

Deeply Virtual Meson Production

Exclusive Drell Yan





$$\frac{d^5\sigma}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} = \frac{\alpha^3}{16\pi^2(s-M^2)^2\sqrt{1+\gamma^2}}|T|^2 ,$$

$$T(k,p,k',q',p') = T_{DVCS}(k,p,k',q',p') + T_{BH}(k,p,k',q',p'),$$

DVCS

twist two GPDs

twist three GPDs

$$\frac{d^5\sigma_{DVCS}}{dx_{Bj}\,dQ^2\,d|t|\,d\phi\,d\phi_S} = \frac{\alpha^3}{16\pi^2(s-M^2)^2\sqrt{1+\gamma^2}}\left|T_{DVCS}\right|^2$$

$$= \frac{\Gamma}{Q^2(1-\epsilon)}\Big\{ \boxed{F_{UU,T}} + \boxed{\epsilon F_{UU,L}} + \epsilon\cos 2\phi F_{UU}^{\cos 2\phi}$$

$$+ \sqrt{\epsilon(\epsilon+1)}\left[\cos\phi \boxed{F_{UU}^{\cos\phi}} + \sin\phi\, \cancel{F_{UU}^{\sin\phi}}\right]$$

$$+ \lambda_e \sqrt{2\epsilon(1-\epsilon)}\sin\phi \boxed{F_{LU}^{\sin\phi}}$$

$$+ S_L\left[\cancel{F_{UL}} + \sqrt{\epsilon(\epsilon+1)}\sin\phi \boxed{F_{UL}^{\sin\phi}} + \epsilon\sin 2\phi F_{UL}^{\sin 2\phi}\right]$$

$$+ \lambda_e \sqrt{1-\epsilon^2}\boxed{F_{LL}} + 2\lambda_e\sqrt{\epsilon(1-\epsilon)}\cos\phi \boxed{F_{LL}^{\cos\phi}}$$

$$+ |S_T|\Big[\sin(\phi-\phi_S)\left(\boxed{F_{UT,T}^{\sin(\phi-\phi_S)}} + \boxed{\epsilon F_{UT,L}^{\sin(\phi-\phi_S)}}\right)$$

$$\epsilon\sin(\phi+\phi_S)\boxed{F_{UT}^{\sin(\phi+\phi_S)}} + \epsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)}$$

$$+\sqrt{2\epsilon(1+\epsilon)}\left(\sin\phi_S \boxed{F_{UT}^{\sin\phi_S}} + \sin(2\phi-\phi_S)\boxed{F_{UT}^{\sin(2\phi-\phi_S)}}\right)\Big]$$

$$+ \lambda_e\, S_L\Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)\boxed{F_{LT}^{\cos(\phi-\phi_S)}} + \sqrt{2\epsilon(1-\epsilon)}\cos\phi_S \boxed{F_{LT}^{\cos\phi_S}}$$

$$+\sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)\boxed{F_{LT}^{\cos(2\phi-\phi_S)}}\Big]\Big\}$$

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}	$UT^{\sin(\phi-\phi_s)},\ LT^{\cos(\phi-\phi_s)}$	$UL^{\sin\phi},\ LL^{\cos\phi},\ UT^{\cos\phi},\ UT^{\sin\phi}$
H+E	2	-	-	-	$UU^{\cos\phi},\ LU^{\sin\phi},\ UL^{\sin\phi},\ LL^{\cos\phi},\ UT^{\cos\phi},\ UT^{\sin\phi}$
$\mathbf{2\widetilde{H}_{2T} + E_{2T}} - \xi \widetilde{E}_{2T}$	3	UU	$f^{\perp}$	$UU^{\cos\phi},\ LU^{\sin\phi}$	UU, LU
$\mathbf{2\widetilde{H}'_{2T} + E'_{2T}} - \xi \widetilde{E}'_{2T}$	3	LL	$g_L^{\perp}$	$UU^{\cos\phi},\ LU^{\sin\phi}$	UU, LU
$\mathbf{H_{2T}} + \frac{\mathbf{t_o - t}}{\mathbf{4M^2}} \widetilde{\mathbf{H}}_{\mathbf{2T}}$	3	UT	$f_T^{(*)}, f_T^{\perp\,(*)}$	$UU^{\cos\phi},\ UL^{\cos\phi},\ LU^{\sin\phi},\ LL^{\cos\phi}$	UU, LU
$\mathbf{H'_{2T}} + \frac{\mathbf{t_o - t}}{\mathbf{4M^2}} \widetilde{\mathbf{H}}'_{\mathbf{2T}}$	3	LT	$g'_T, g_T^{\perp}$	$UU^{\cos\phi},UL^{\cos\phi},\ LU^{\sin\phi},\ LL^{\cos\phi}$	UU, LU
$\widetilde{\mathbf{E}}_{\mathbf{2T}} - \xi E_{2T}$	3	UL	$f_L^{\perp\,(*)}$	$UU^{\cos\phi},\ UL^{\cos\phi},\ LU^{\sin\phi},\ LL^{\cos\phi}$	UU, LU, UT
$\widetilde{\mathbf{E}}'_{\mathbf{2T}} - \xi E'_{2T}$	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

Orbital angular momentum

Spin Orbit

Transverse Orbital angular momentum

Newly accessible configurations!

BH

$$\frac{d^5\sigma_{BH}}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} = \Gamma\left|T_{BH}\right|^2 = \frac{\Gamma}{t}\left\{F_{UU}^{BH} + (2\Lambda)(2h)F_{LL}^{BH} + (2\Lambda_T)(2h)F_{LT}^{BH}\right\}$$

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

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

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

…compared to BKM, NPB (2001)

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

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

(

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

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

(

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

(

BH-DVCS interference

$$\frac{d^5\sigma_{\mathcal{I}}}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} = e_l\Gamma\left(T^*_{BH}T_{DVCS} + T^*_{DVCS}T_{BH}\right)$$

$$= e_l\,\frac{\Gamma}{Q^2\mid t\mid}\left\{F^{\mathcal{I}}_{UU} + (2h)F^{\mathcal{I}}_{LU} + (2\Lambda)F^{\mathcal{I}}_{UL} + (2h)(2\Lambda)F^{\mathcal{I}}_{LL} + (2\Lambda_T)F^{\mathcal{I}}_{UT} + (2h)(2\Lambda_T)F^{\mathcal{I}}_{LT}\right\}$$

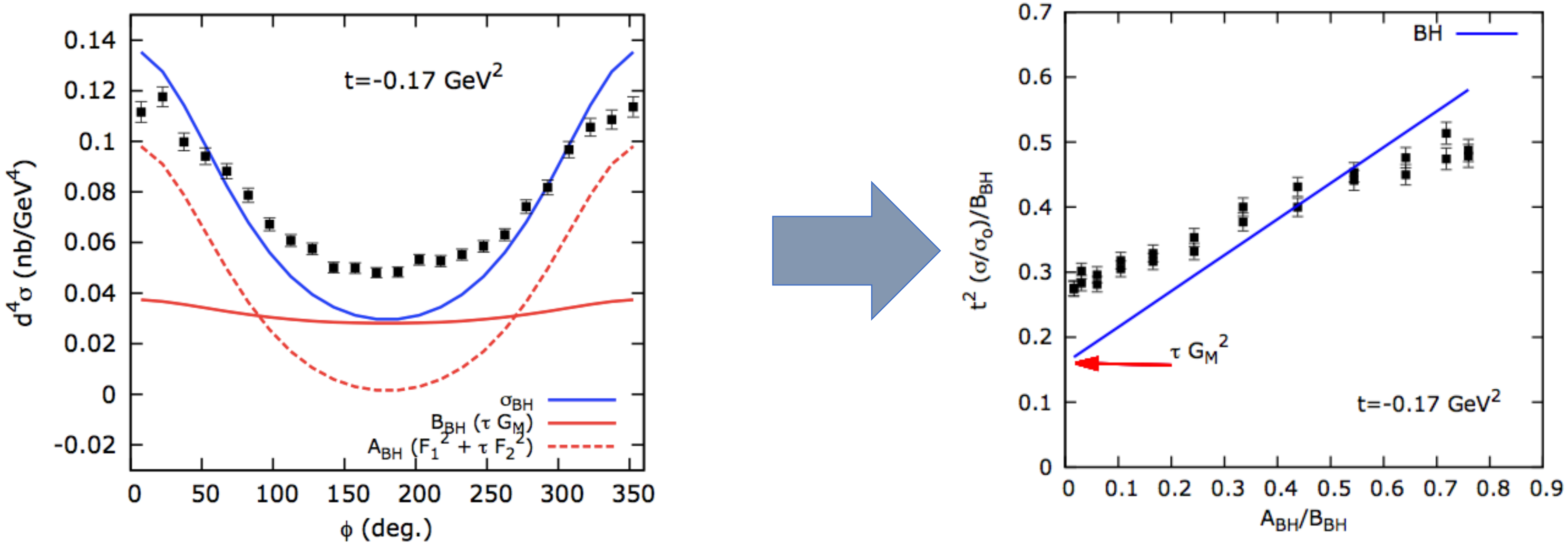
Unpolarized

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

$$F^{\mathcal{I},tw2}_{UU} = A^{\mathcal{I}}_{UU}\,\Re e\left(F_1\mathcal{H} + \tau F_2\mathcal{E}\right) + B^{\mathcal{I}}_{UU}G_M\,\Re e\left(\mathcal{H}+\mathcal{E}\right) + C^{\mathcal{I}}_{UU}G_M\,\Re e\widetilde{\mathcal{H}}$$

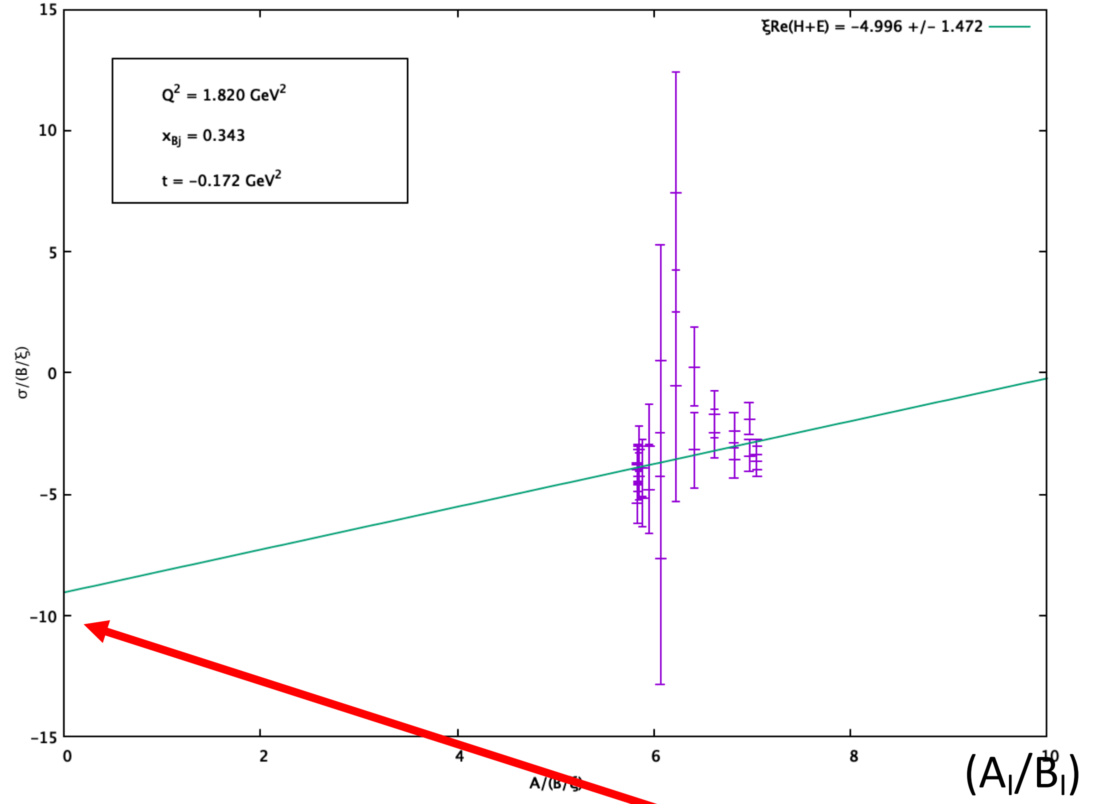
$$F^{\mathcal{I},tw3}_{UU} = \Re e\left\{A^{(3)\mathcal{I}}_{UU}\left[F_1(2\widetilde{\mathcal{H}}_{2T} + \mathcal{E}_{2T}) + F_2(\mathcal{H}_{2T} + \tau\widetilde{\mathcal{H}}_{2T})\right]\right.$$
$$\left. + B^{(3)\mathcal{I}}_{UU}G_M\,\widetilde{E}_{2T} + C^{(3)\mathcal{I}}_{UU}G_M\left[2\xi H_{2T} - \tau(\widetilde{E}_{2T} - \xi E_{2T})\right]\right\}$$

Rosenbluth separation for Bethe-Heitler contribution



$$\frac{d^5\sigma^{BH}_{unpol}}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} = \frac{\Gamma}{t^2}\left[A_{BH}\boxed{(F_1^2+\tau F_2^2)} + B_{BH}\boxed{\tau G_M^2(t)}\right]$$

Rosenbluth Separated Data for BH-DVCS

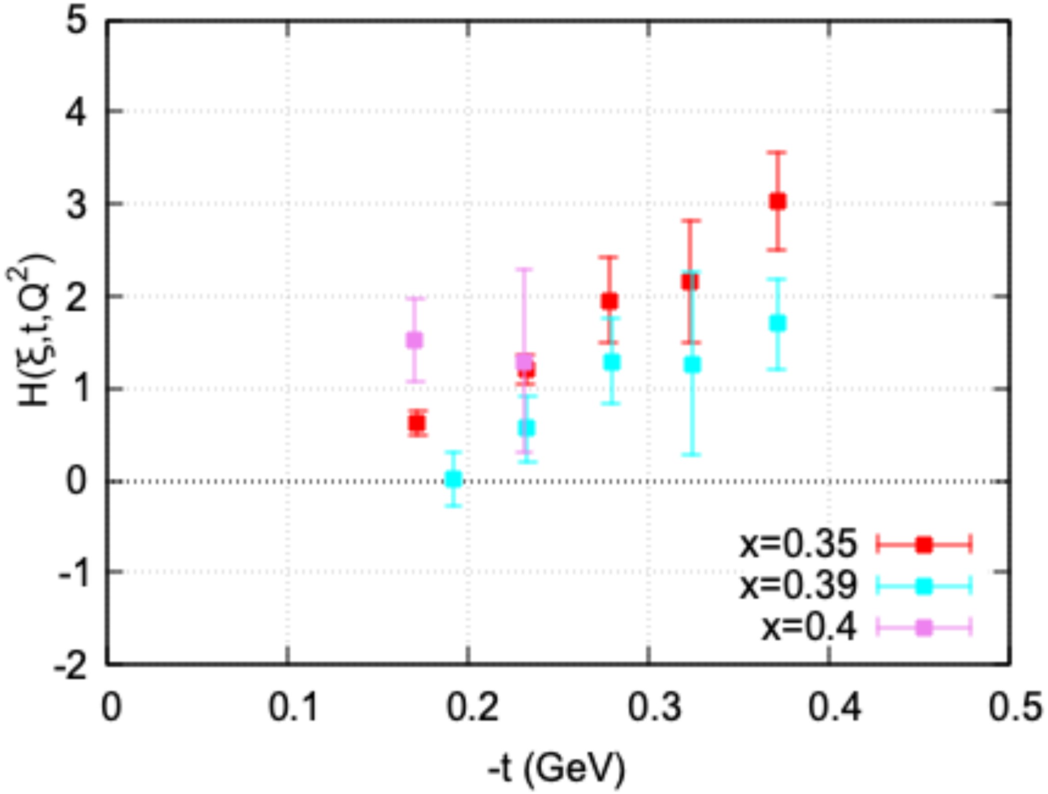


Hall A data, Defurne

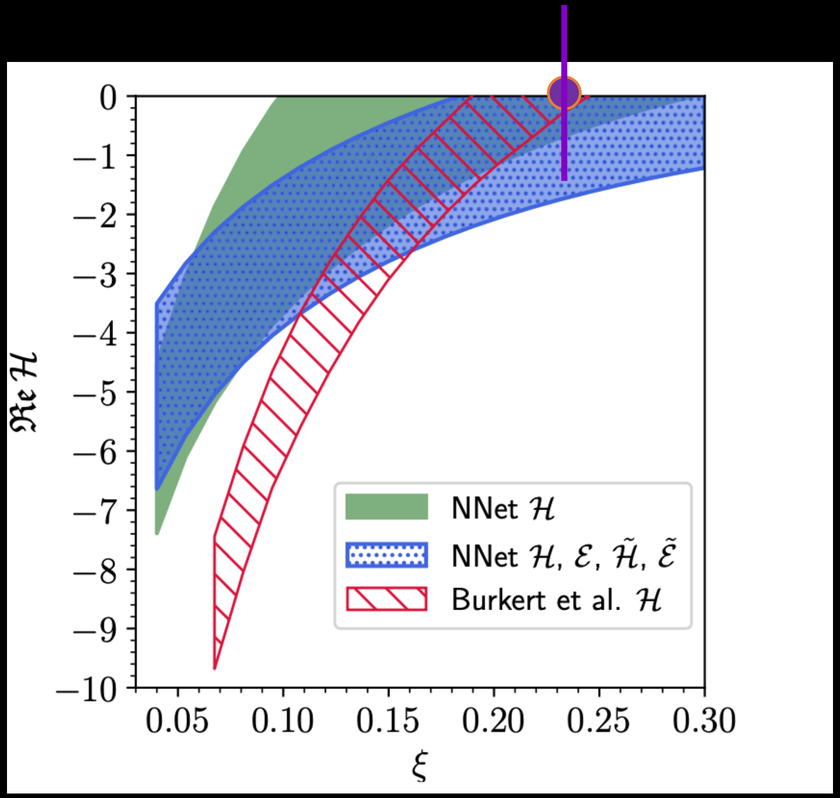
$G_E^2+\boldsymbol{\tau}\, G_M^2$ $\quad$ G_M^2 $\quad$ $G_M\, G_A$

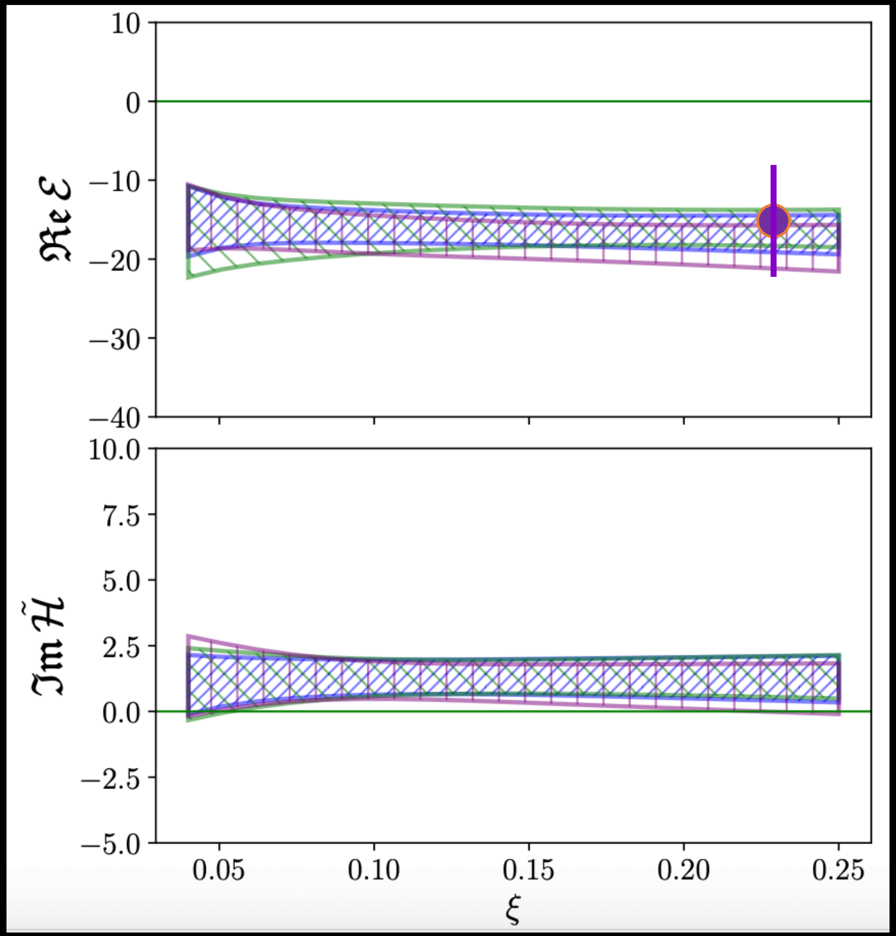
$$\frac{d^5\sigma^{\mathcal{I}}_{unpol}}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} = \frac{\Gamma}{Q^2(-t)}\left[A_{\mathcal{I}}\boxed{(F_1\Re e\mathcal{H}+\tau F_2\Re e\mathcal{E})}+B_{\mathcal{I}}\boxed{G_M\,\Re e(\mathcal{H}+\mathcal{E})}+C_{\mathcal{I}}\boxed{G_M\,\Re e\widetilde{\mathcal{H}}}\right]$$

E_e = 5.75 GeV Q^2 = 1.8 GeV^2 x_{Bj} = 0.34



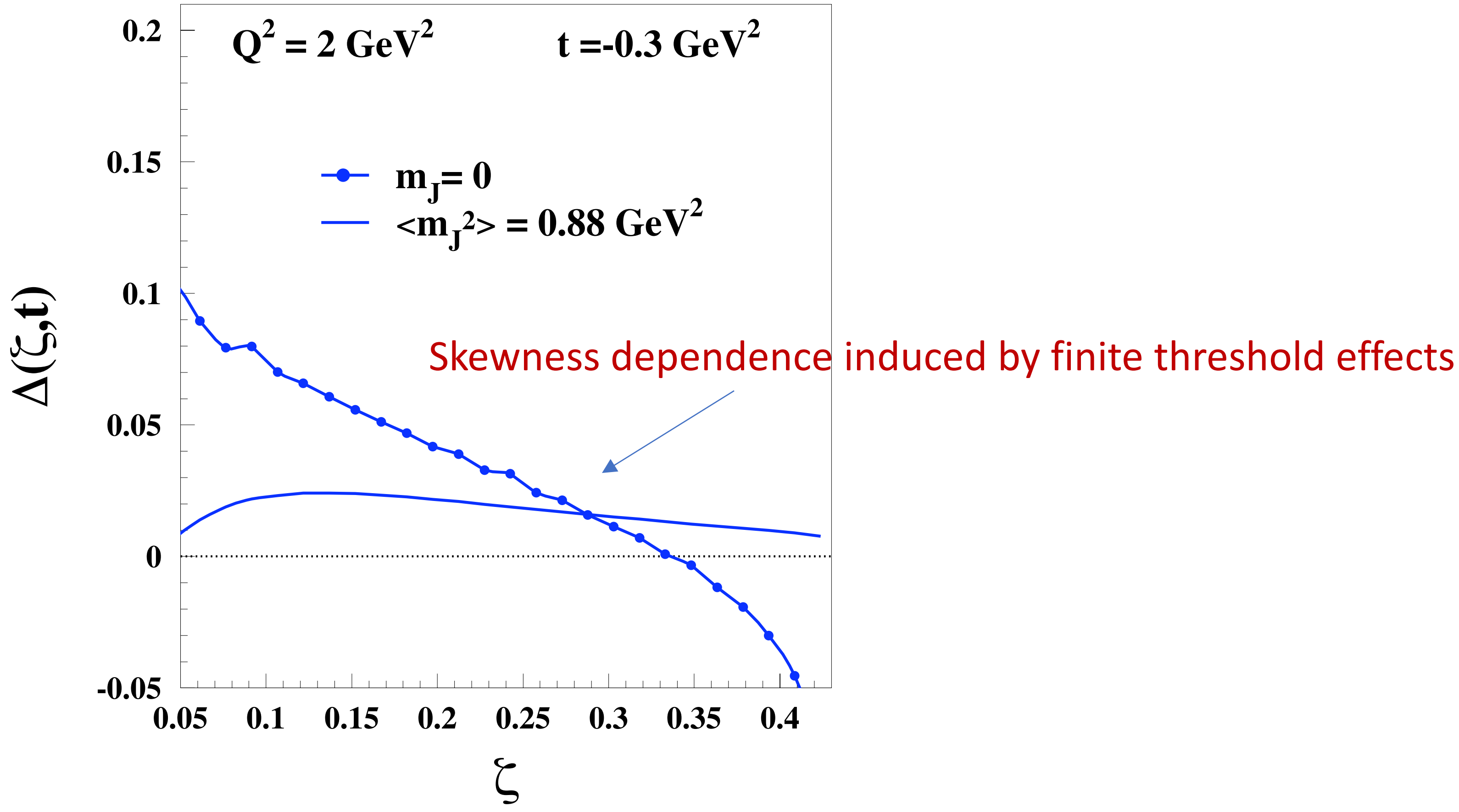
Comparison with other/BKM based analyses





$$\mathrm{Re}\,\mathcal{H}^{(\pm)}(\xi,t) = \frac{1}{\pi}\Big[P.V.\int_{-1}^{\xi_{\rm th}} dx\,\frac{H^{(\pm)}(x,x,t)}{x-\xi} + \int_{\xi_{\rm th}}^{+1} dx\,\frac{H^{(\pm)}_{\rm unphys}(x,x,t)}{x-\xi}\Big],$$

Impact on pressure extraction through dispersion relations



Phys.Rev. D80 (2009) 071501

Center for Nuclear Femtography Project at Jefferson Lab

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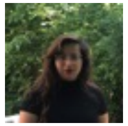

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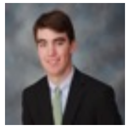

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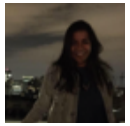

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EIC Center at Jefferson Lab

Gabriel Niculescu
James Madison University

Abha Rajan
University of Virginia

***
Red: Undergraduate
Blue: Graduate

The University of Virginia is stepping up this truly interdisciplinary effort

Data Science

3D Structure of the proton

Quantum Information

Latttice QCD

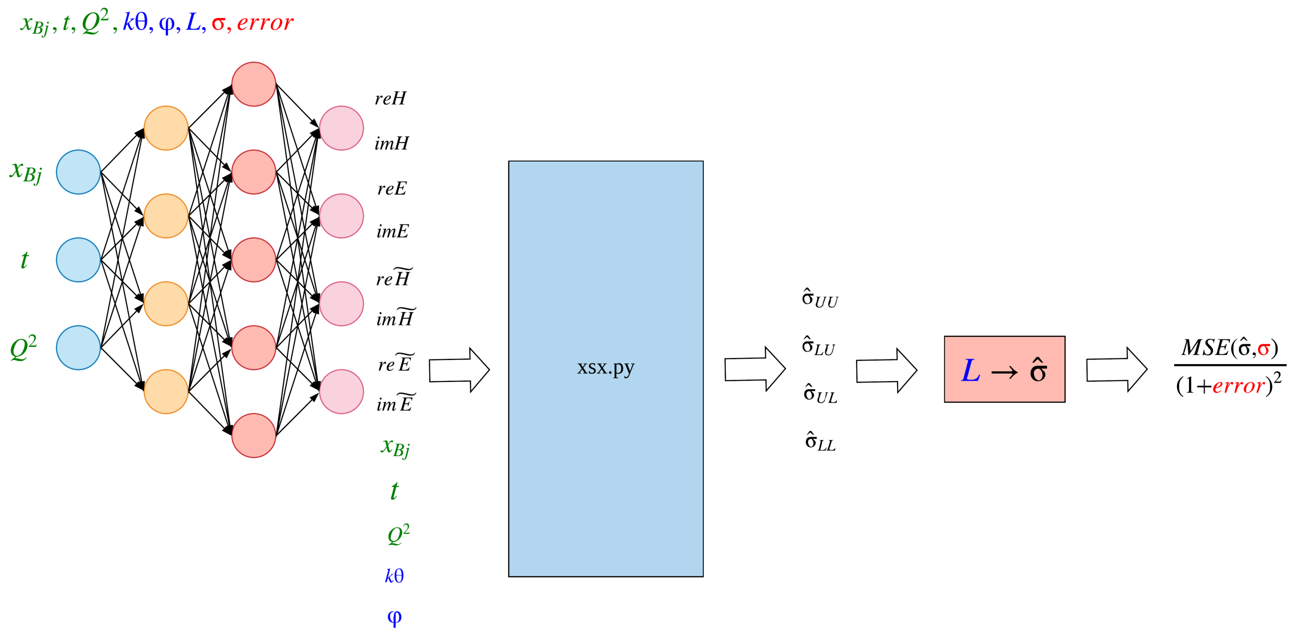
Education

Outreach

Femtography Imaging with Neural Networks (FINN)

Strategy:

1. A fully connected neural network maps input kinematic data to a vector of eight form factors (see diagram).
2. Use a code developed by our Data Analysis Team to evaluate the cross sections and in terms of the CFFs.



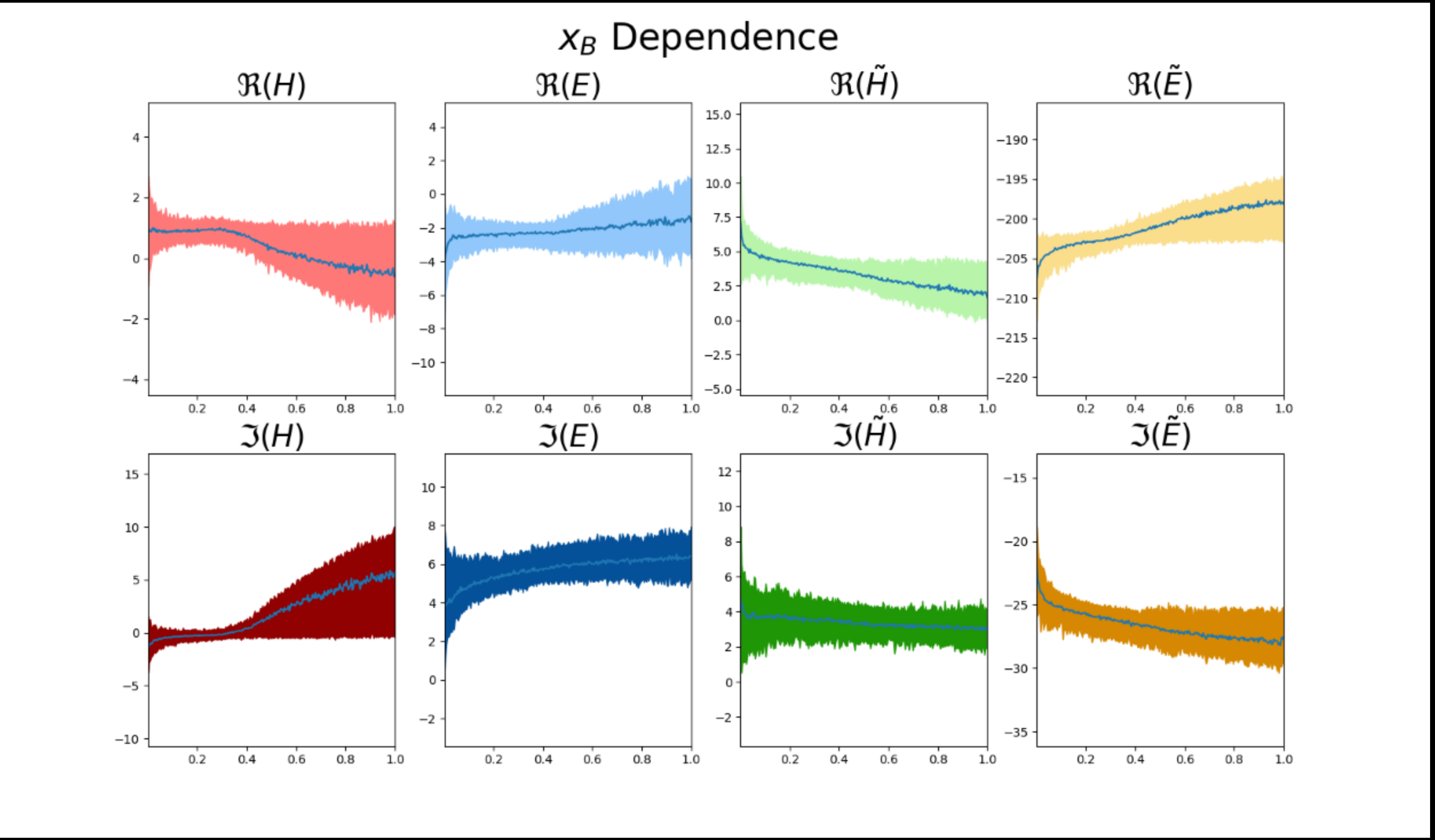
Jake Grigsby

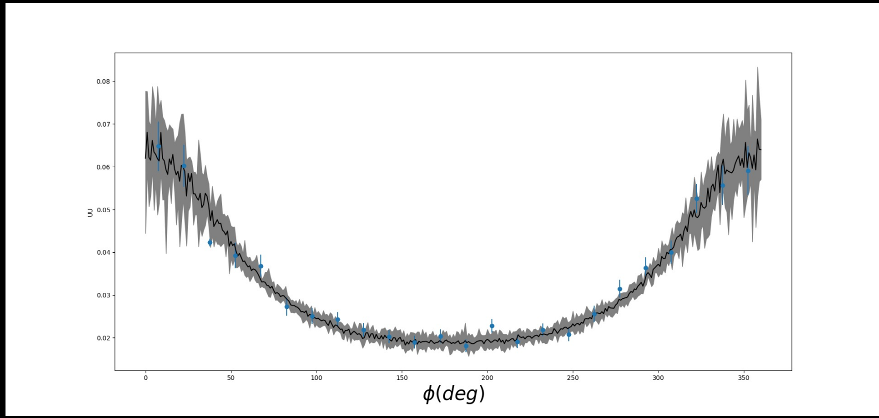
We translate the x-sec. code into TensorFlow

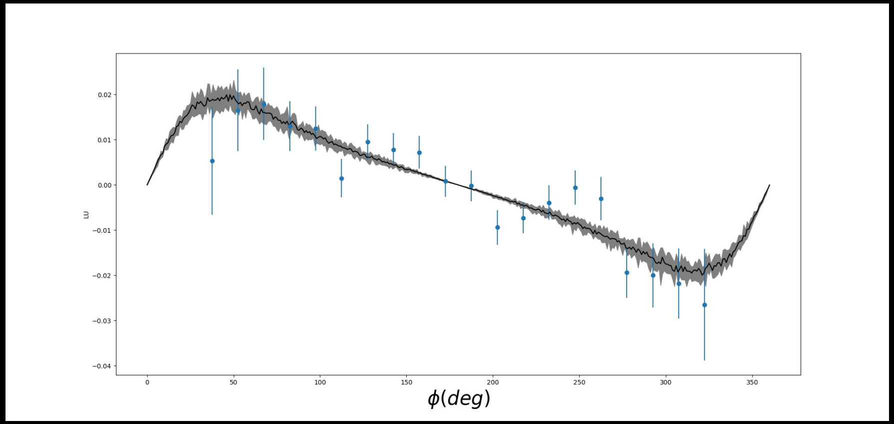
➔Automatically differentiable

➔At variance with other efforts we can train CFF extraction network with backpropagation and variants of stochastic gradient descent.

Compton Form factors







Conclusions and Outlook

We provide a new key to interpreting polarized degrees of freedom in deeply virtual exclusive experiments

Please check out our new formalism!!

arXiv:1903.05742