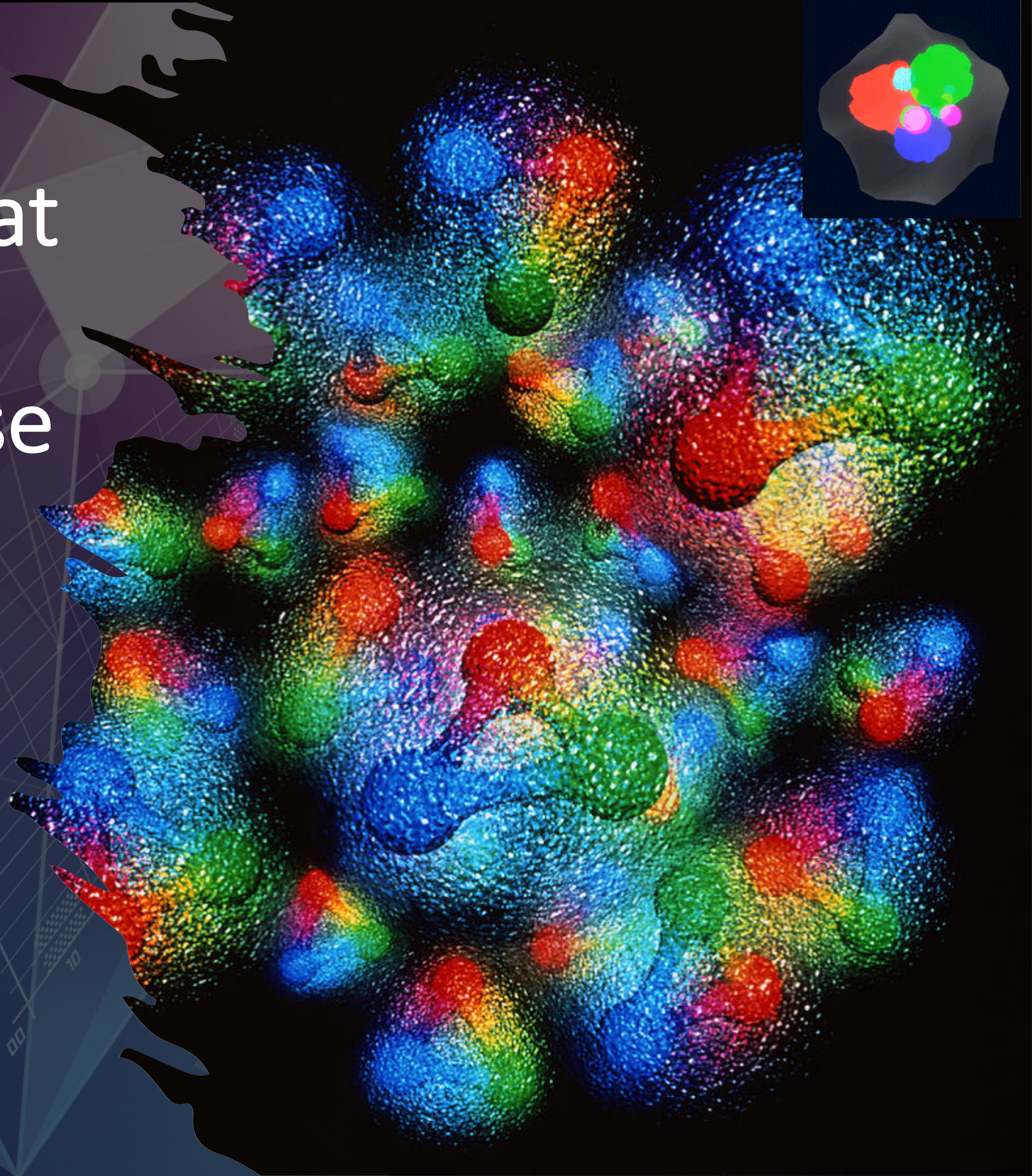
Unique opportunities at Jlab 12+GeV: Longitudinal/Transverse separation in DVES

Simonetta Liuti



UNIVERSITY OF VIRGINIA 1819
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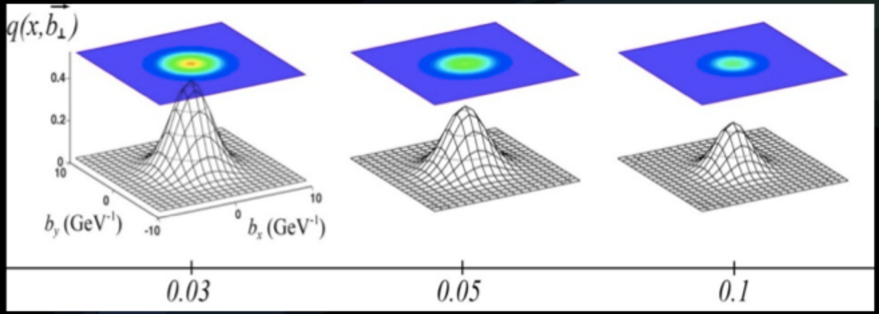
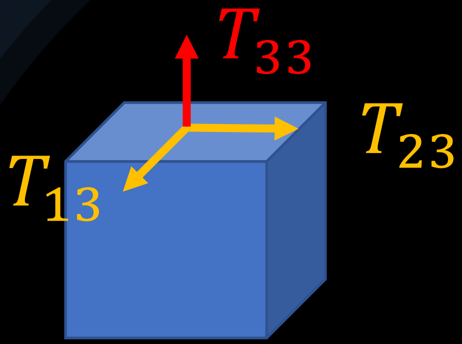
CENTER for NUCLEAR FEMTOGRAPHY

- Quark and Gluon Imaging

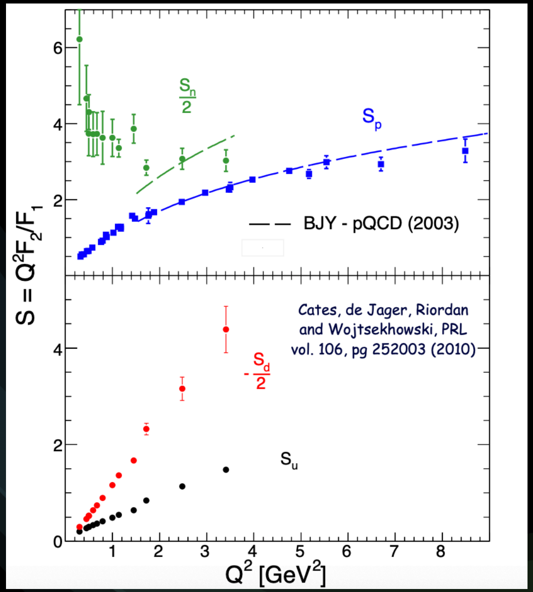


M. Defurne

- The proton spin and its internal forces (dynamics)

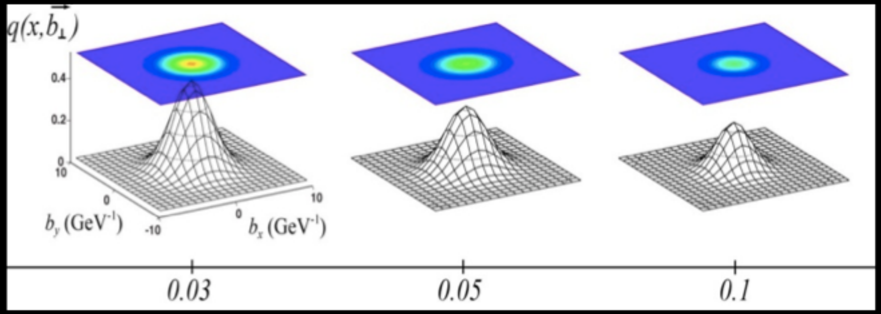


- Mechanisms of flavor dependence in nucleons and nuclei

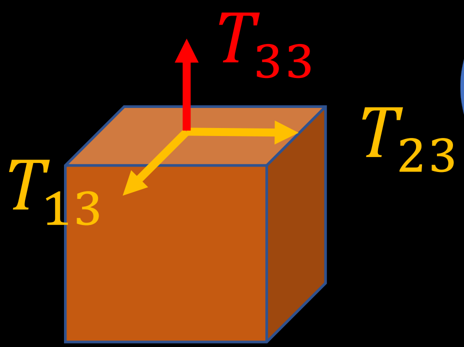


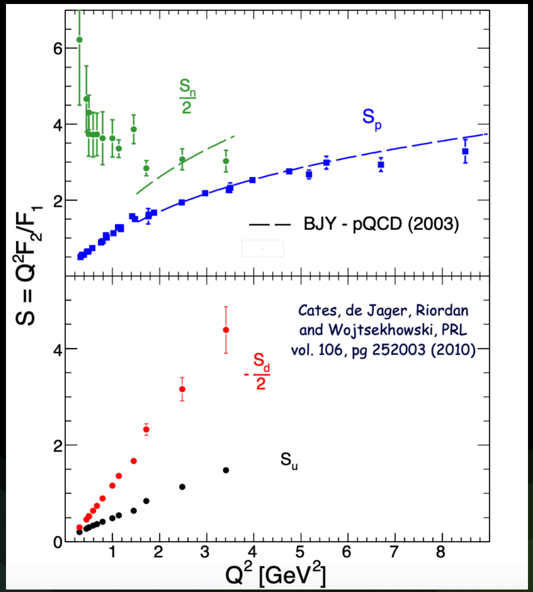
G. Cates et al. (2010)

Common thread



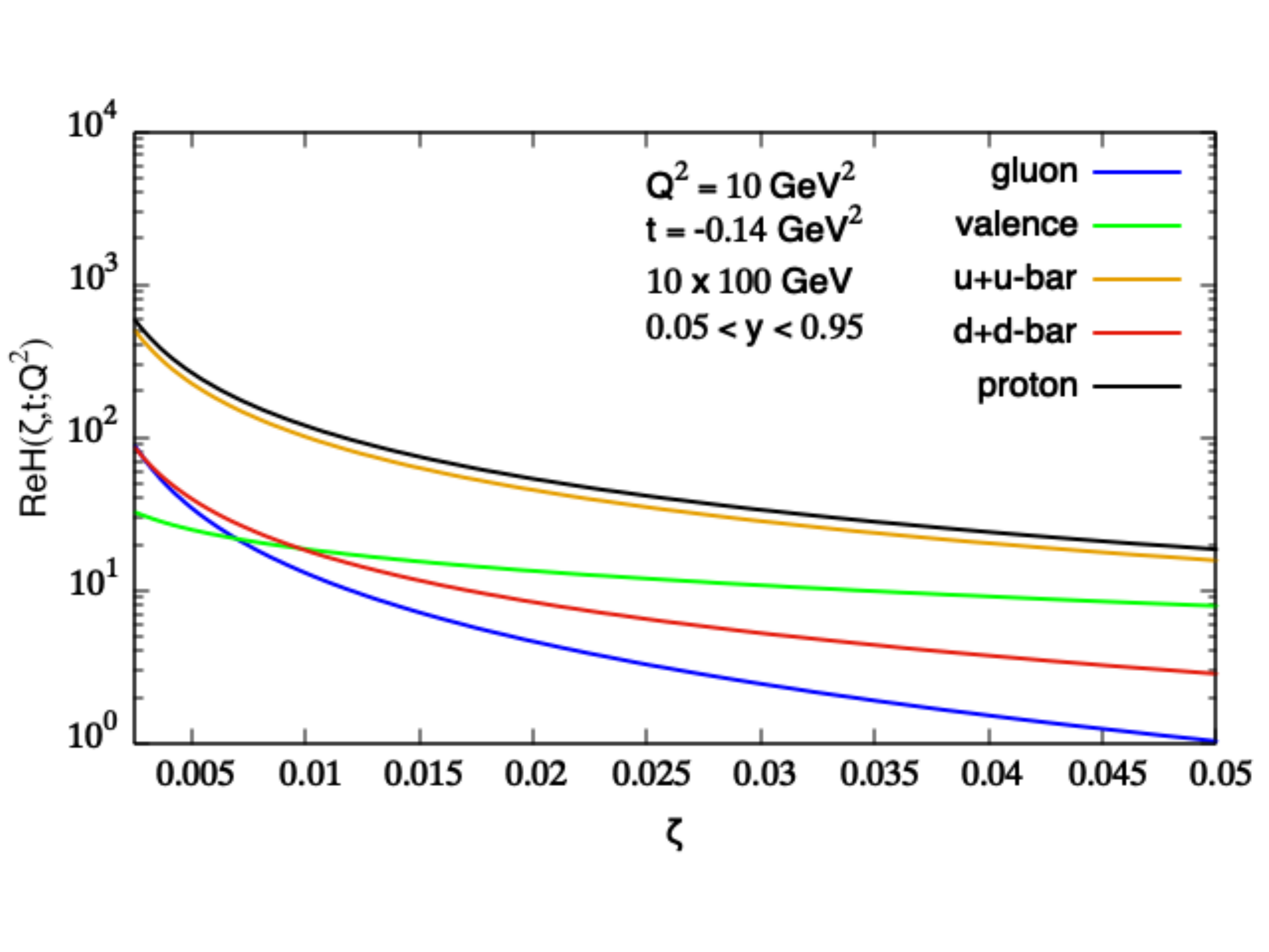
Probing QCD at scattering amplitude level





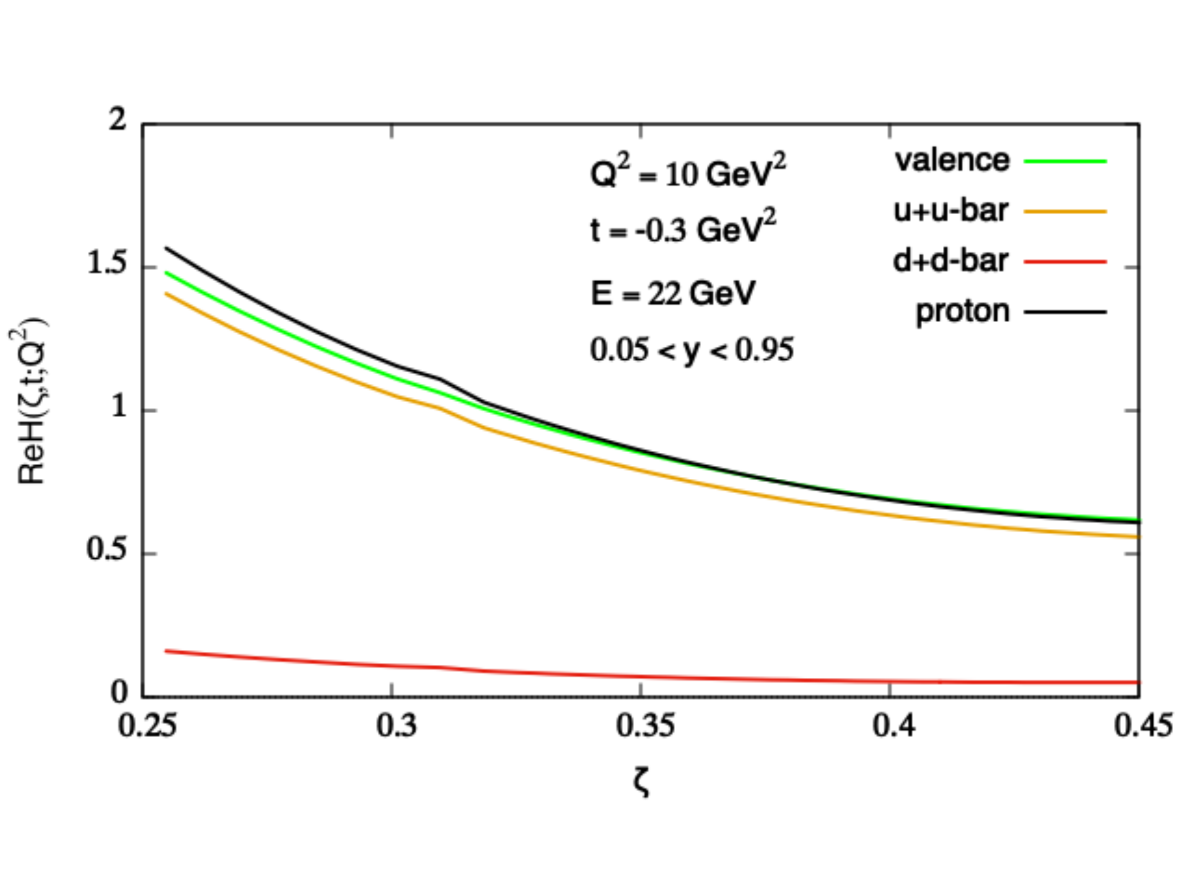
Outstanding questions

1. How do we separate the various flavor components at leading order (twist)

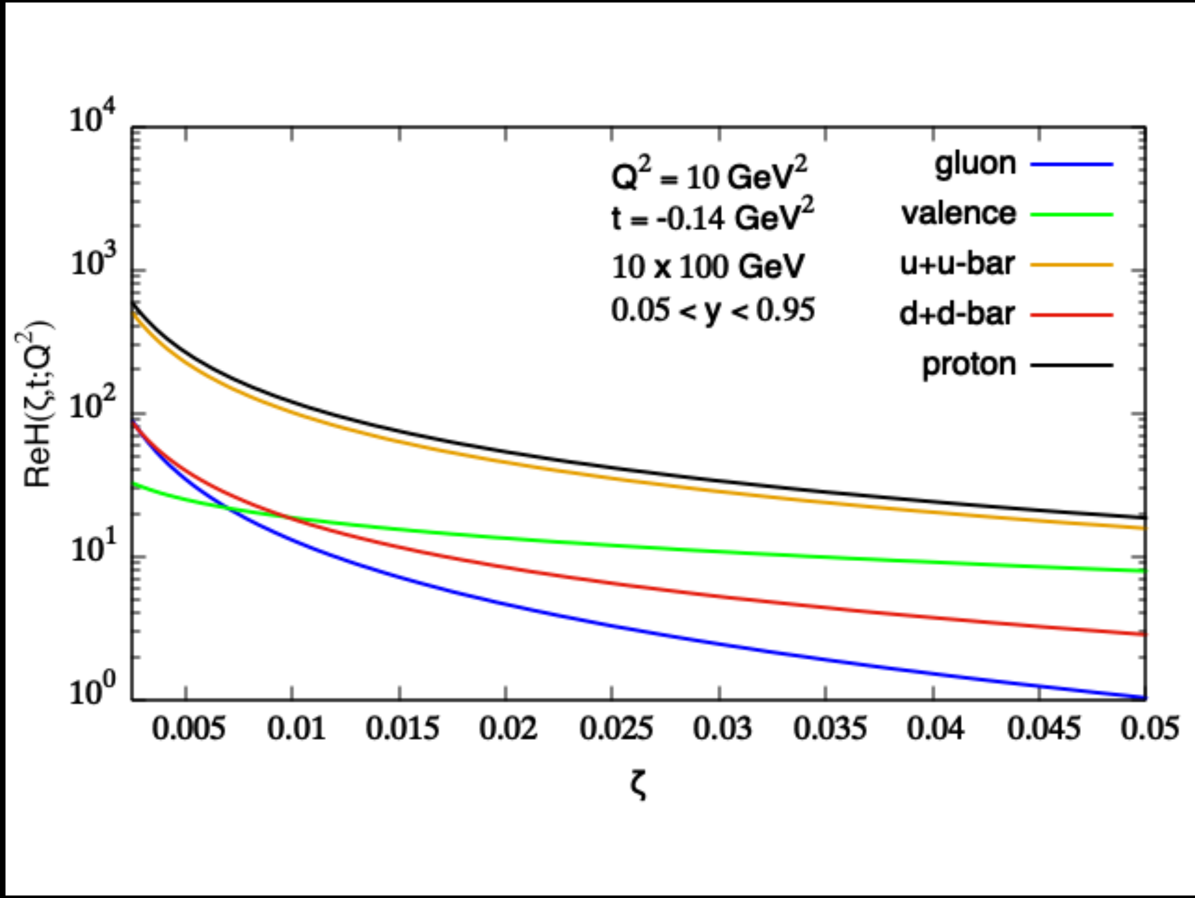


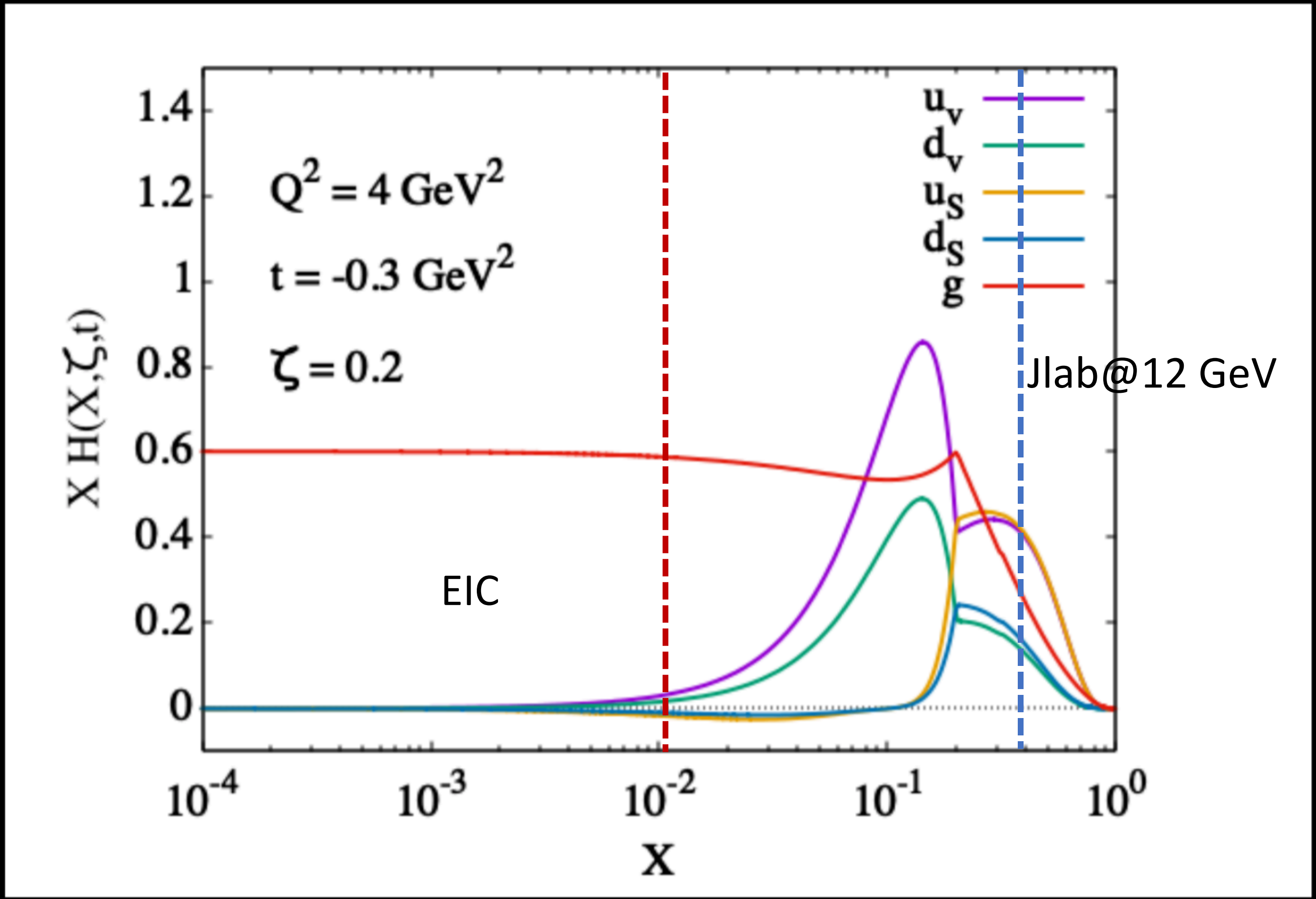
B. Kriesten and S. Liuti, *in preparation*

Jlab @22 GeV



EIC





All GPDs

- B. Kriesten, P. Velie, E. Yeats, F. Y. Lopez and S. Liuti, *Phys. Rev D 105 (2022)*, arXiv:2101.01826

10/31/20

Twist -3 GPDs

Outstanding questions

2. How do we separate twist two and twist three components?

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

(*) T-odd

B. Kriesten and S. Liuti, *Phys.Rev. D105 (2022),* arXiv 2004.08890

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

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

Information on longitudinal angular momentum

$$\begin{array}{cccc} J_L & = & L_L & + & S_L \\ \frac{1}{2}\int dx\, x(H+E) & = & \int dx\, x(\widetilde{E}_{2T}+H+E) & + & \frac{1}{2}\int dx\, \widetilde{H} \\ & = & -\int dx\, F_{14}^{(1)} & + & \frac{1}{2}\int dx\, \widetilde{H} \end{array}$$

Information on quark spin orbit: $\boldsymbol{L}\cdot\boldsymbol{S}$

$$\frac{1}{2}\int dx x\widetilde{H} + \frac{m_q}{2M}\kappa_T^q = \int dx x(2\widetilde{H}'_{2T} + E'_{2T} + \widetilde{H}) + \frac{1}{2}e_q$$

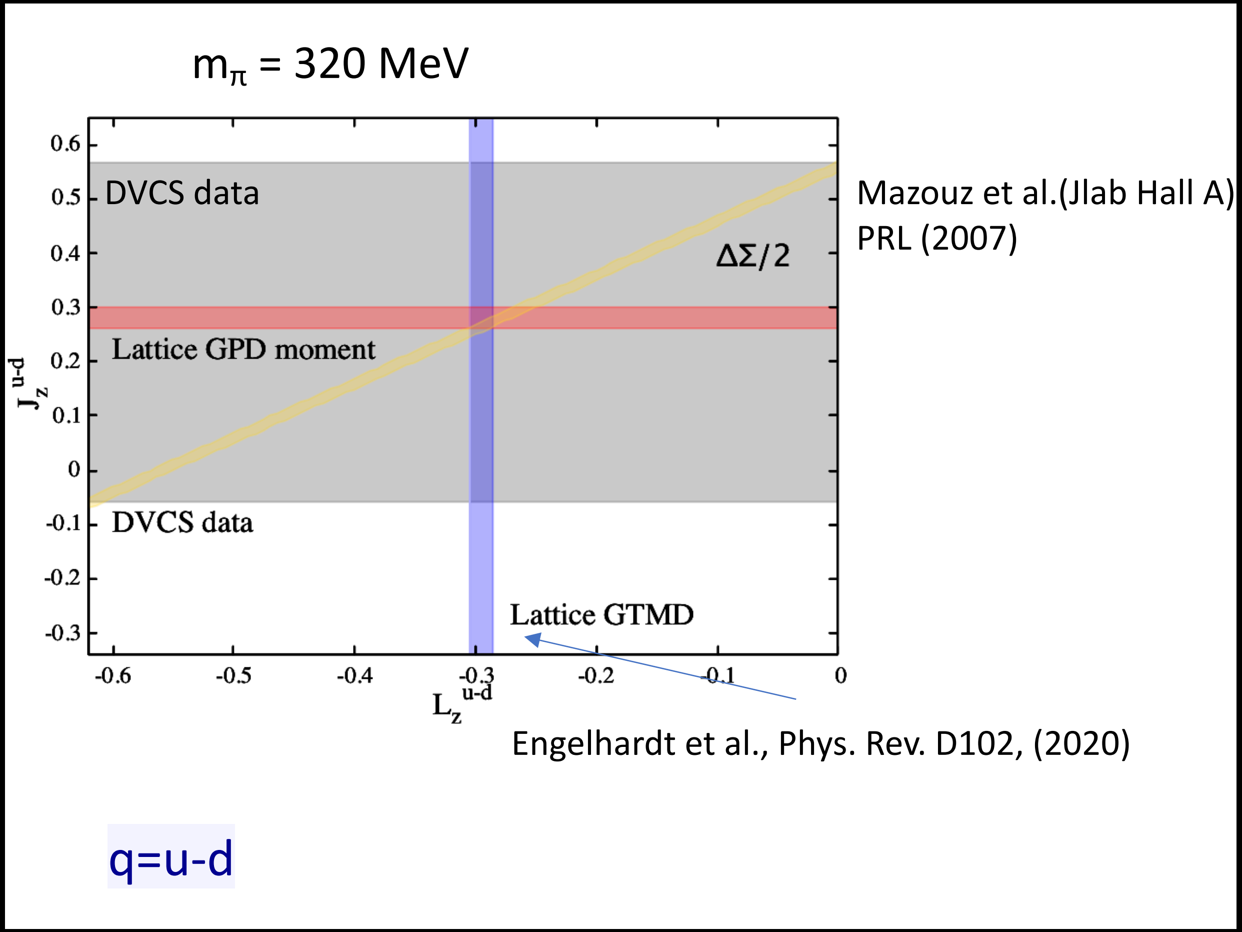
$$\underbrace{\frac{1}{2}\int dx x\widetilde{H} + \frac{m_q}{2M}\kappa_T^q}_{J_z S_z} = \underbrace{\int dx x(2\widetilde{H}'_{2T} + E'_{2T} + \widetilde{H})}_{L_z S_z} + \underbrace{\frac{1}{2}e_q}_{S_z S_z}$$

Information on transverse angular momentum

O. Alkassasbeh, M. Engelhardt, SL and A. Rajan, (2023)

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

Putting this all together: what we know from measurements and lattice

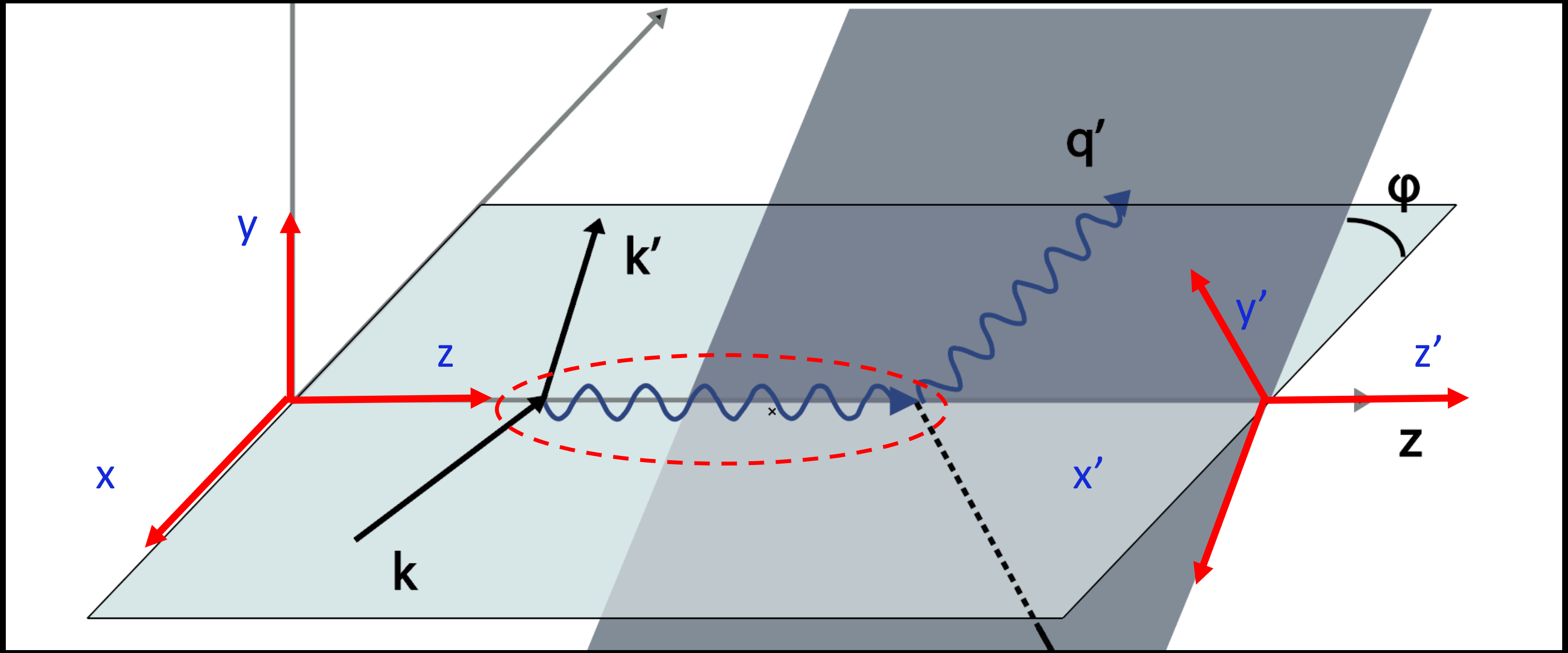


$$J_q = L_q + \frac{1}{2}\Delta\Sigma_q$$

1) The ability to perform L/T separations is important

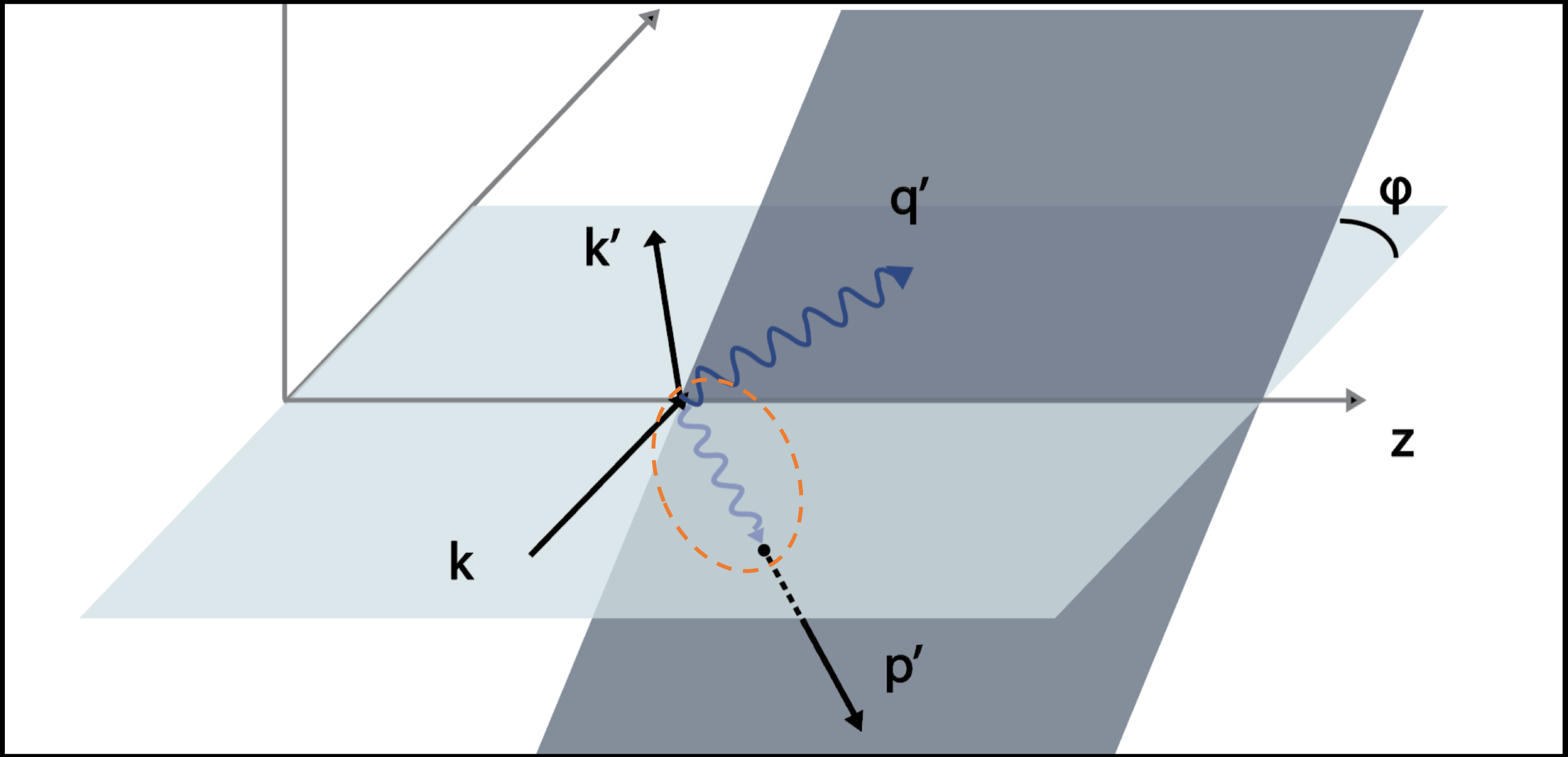
2) To understand the cross section we need to understand the f dependence

DVCS



The hadronic tensor is evaluated in the rotated frame

Bethe Heitler



Contribution to cross section

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

$$F_L = \varepsilon_L^{\mu\,*} \varepsilon_L^{\nu} \, \frac{1}{4M^2} W_{\mu\nu}^{BH} = G_E^2$$
$$F_T = \varepsilon_T^{\mu\,*} \varepsilon_T^{\nu} \, \frac{1}{4M^2} W_{\mu\nu}^{BH} = \tau G_M^2$$

$$\epsilon_{BH} = \left(1 + \frac{B_{BH}}{A_{BH}} (1+\tau) \right)^{-1} = \frac{1}{1 + \left[\frac{2\tau}{1+\tau} \frac{(kP)^2 + (k'P)^2}{(k\Delta)^2 + (k'\Delta)^2} - \frac{1}{2} \right]^{-1}}$$

$$A_{BH} = \frac{8M^2}{t(kq')(k'q')} \Big[4\tau \Big((kP)^2 + (k'P)^2 \Big) - (1+\tau) \Big((k\Delta)^2 + (k'\Delta)^2 \Big) \Big],$$
$$B_{BH} = \frac{16M^2}{t(kq')(k'q')} \Big[(k\Delta)^2 + (k'\Delta)^2 \Big]$$

…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:

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

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

…compared to BKM, NPB (2001)

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

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

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

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

BH-DVCS interference

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

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

Twist 3 BH-DVCS interference

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

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

Orbital Angular Momentum

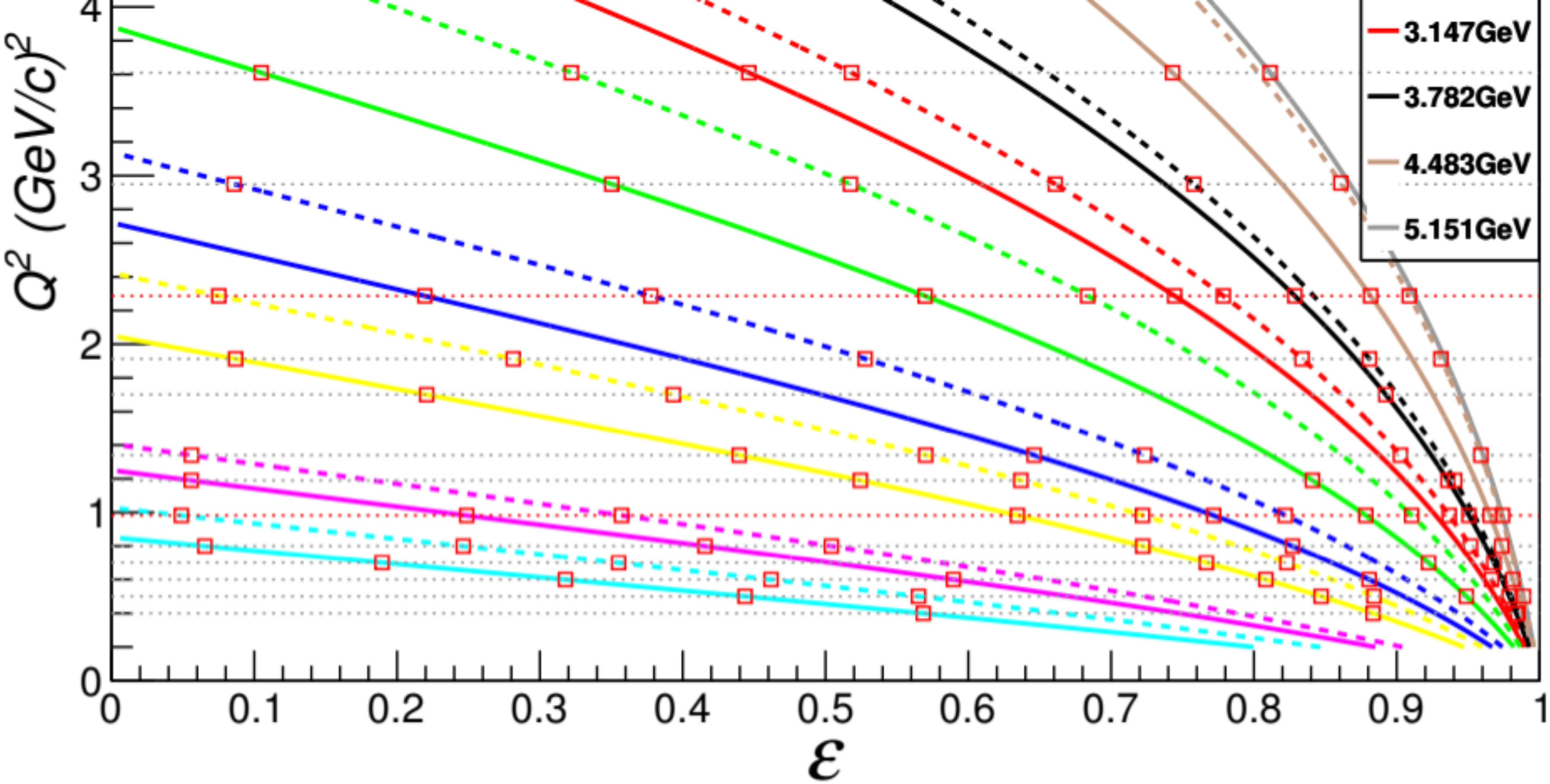
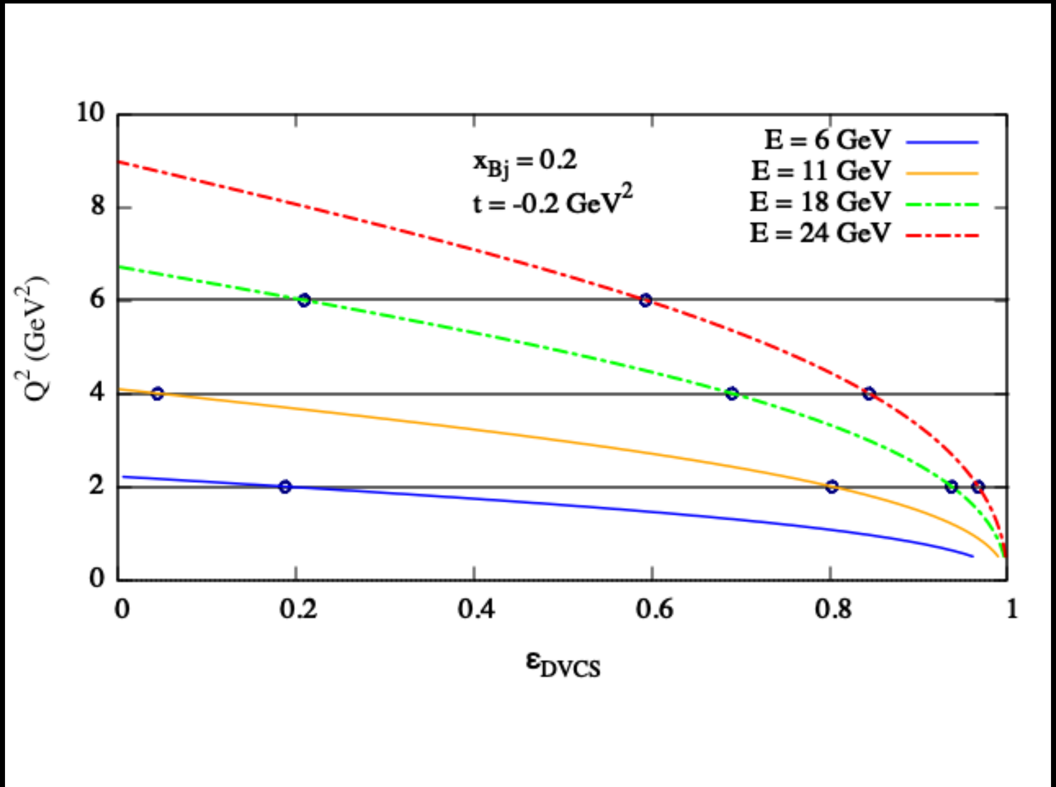


Figure 3.2: The E05-017 nominal kinematic coverage. The solid and dashed lines are constan
...ings.

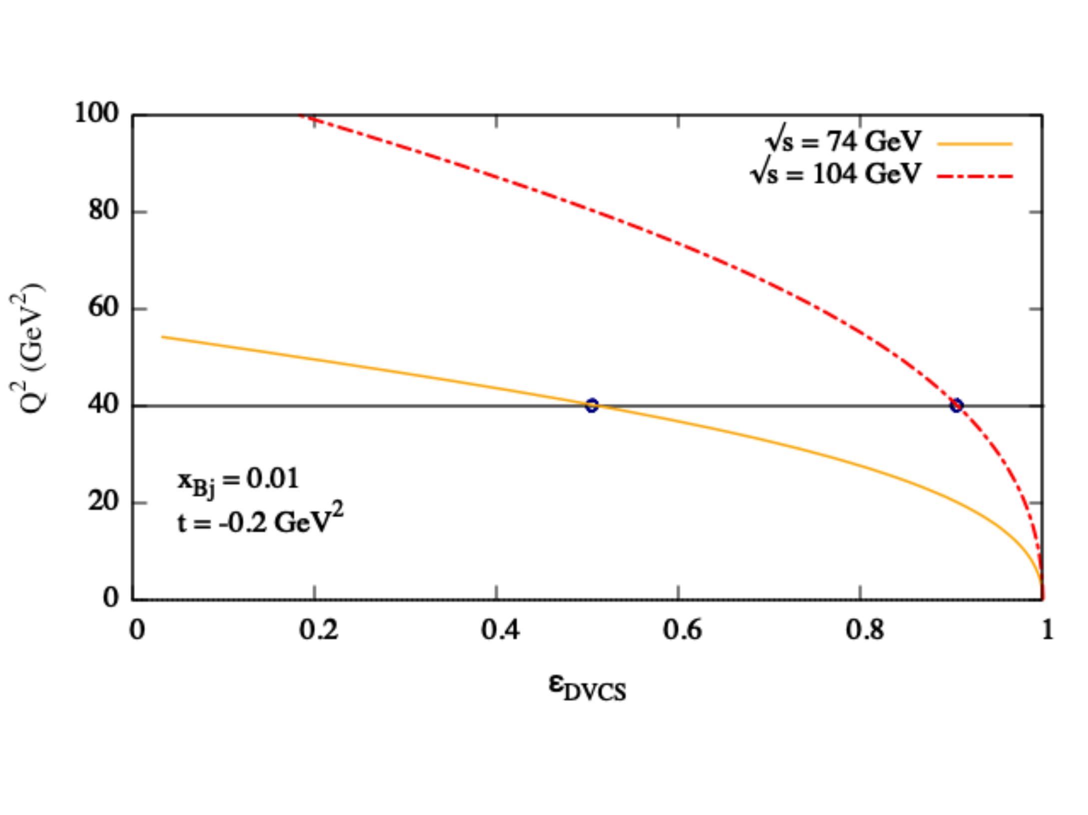
M. Yurov, Ph.D. thesis

DVCS

Jlab

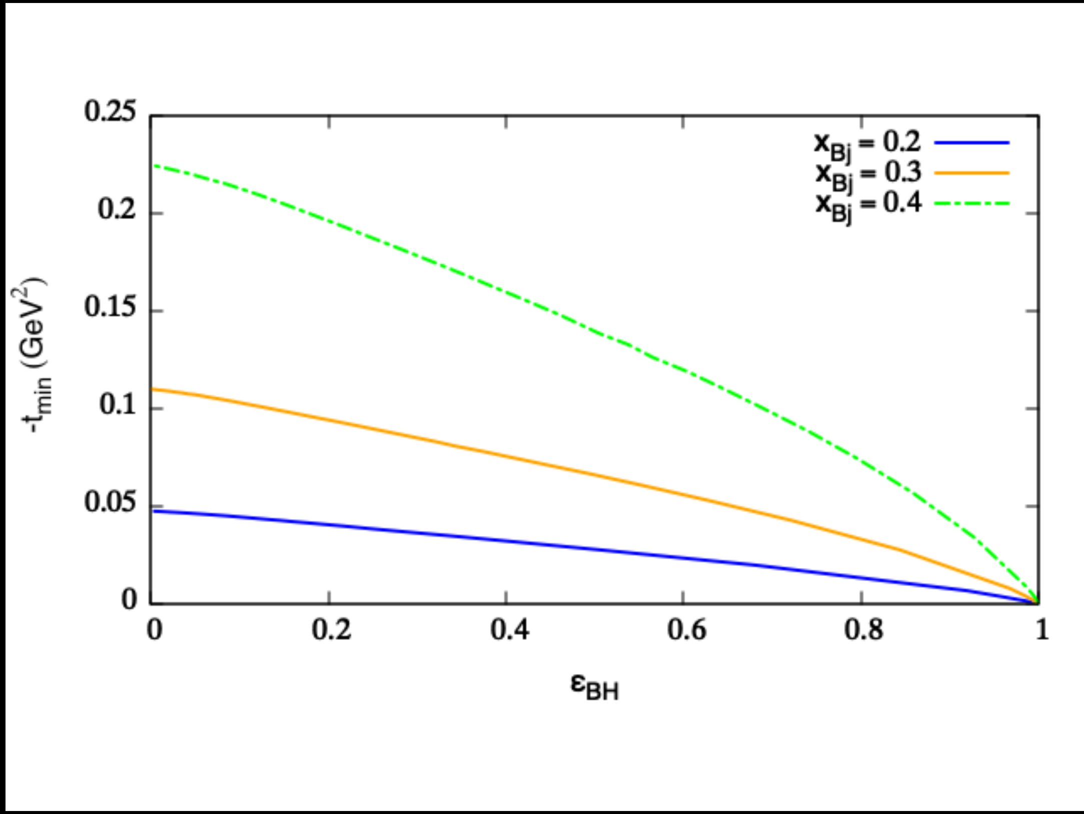


EIC

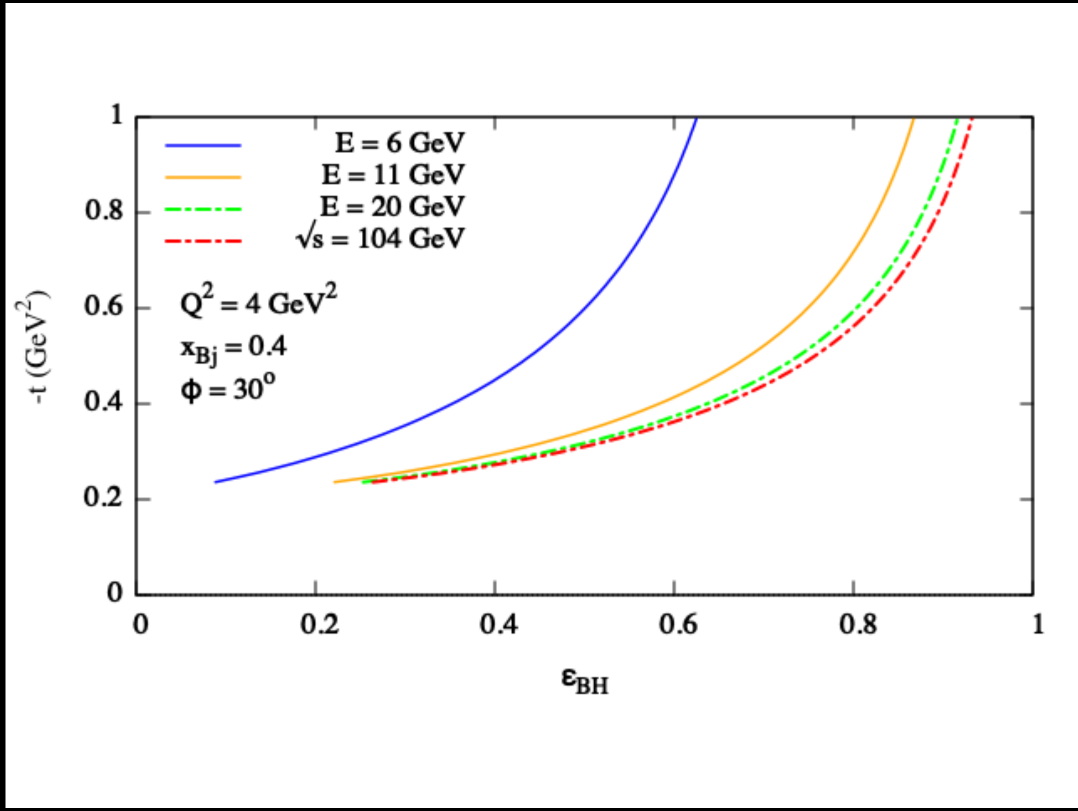


BH

Jlab

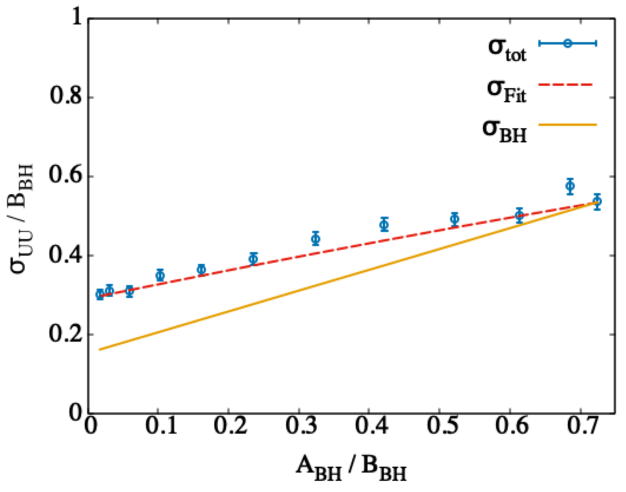


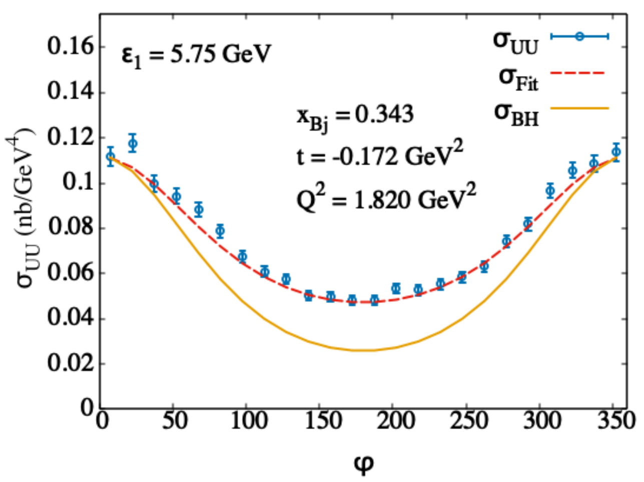
Jlab to EIC



Streamlined description of cross section

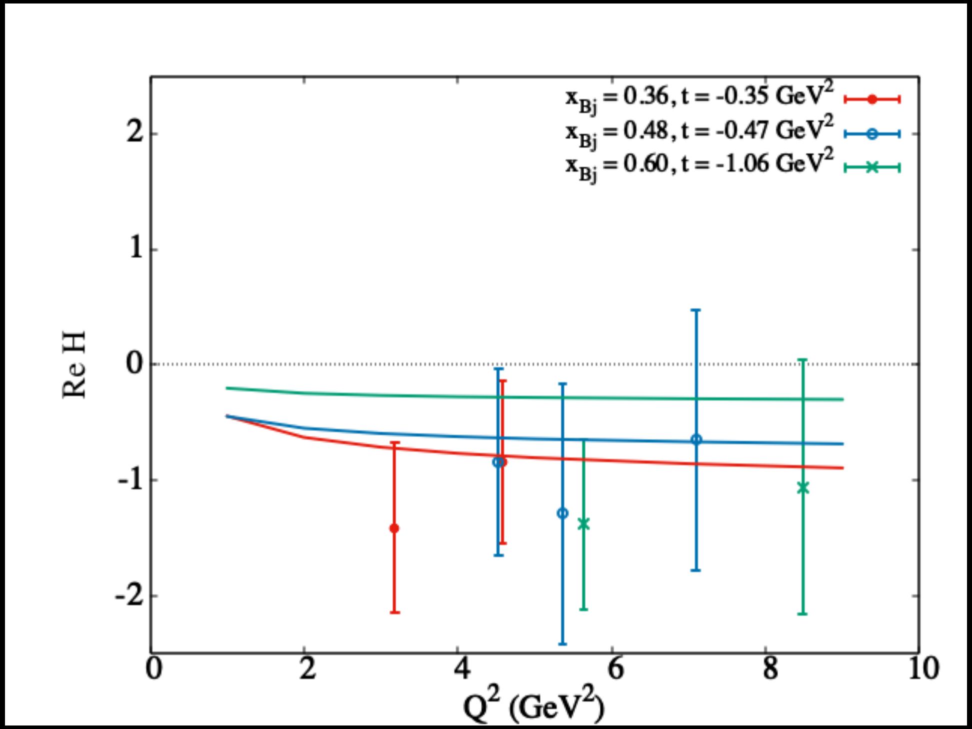
- Rosenbluth Separated BH-DVCS interference data



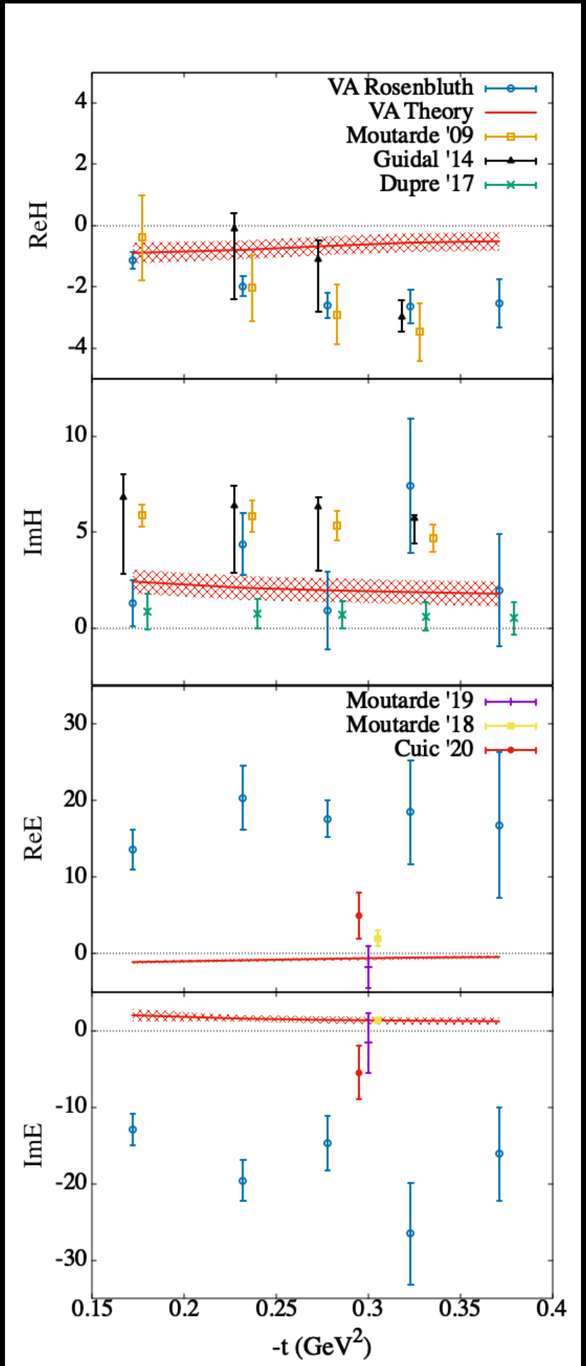


2.B. Kriesten, S. Liuti and A. Meyer, *Phys. Lett. B**829**, (2022)*

Compton Form Factor Extraction



Q^2 dependence



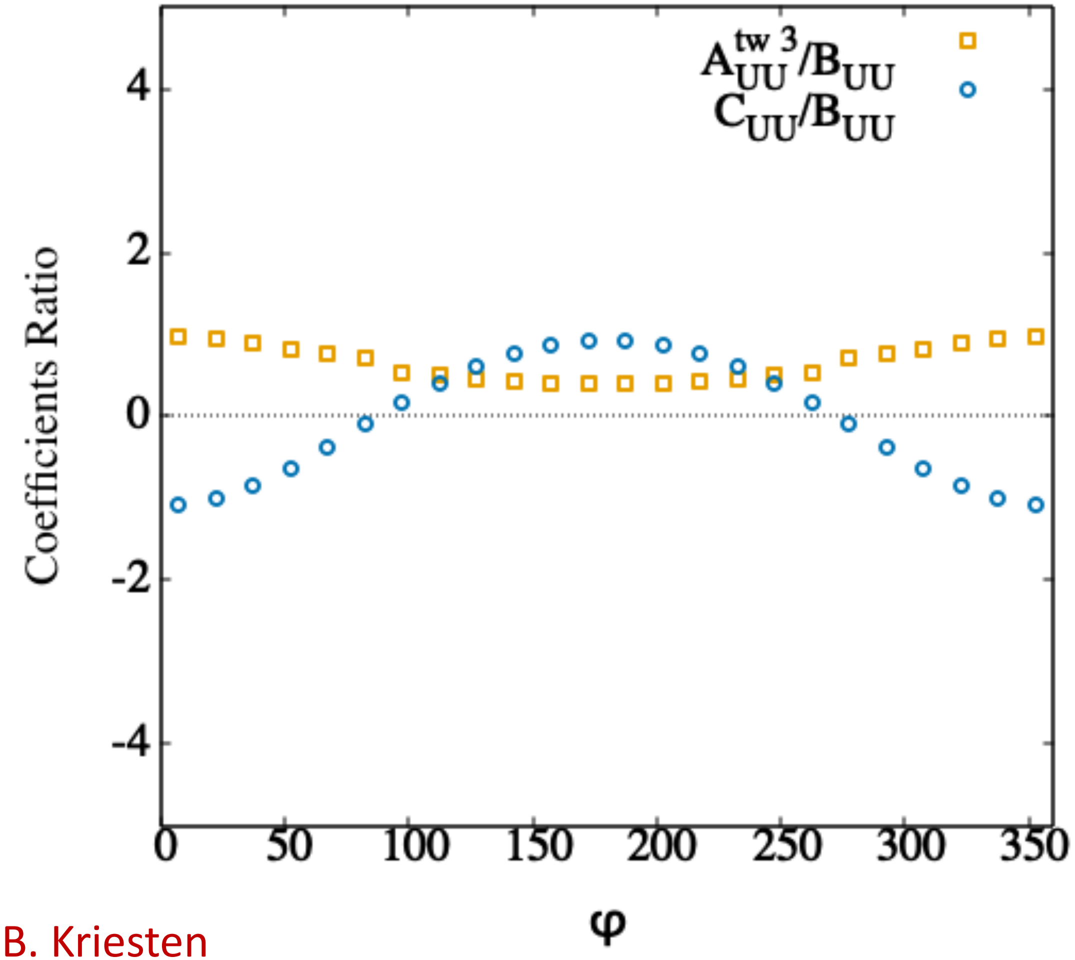
Re H

Im H

Re E

Im E

First estimate: Twist 3 seems small



B. Kriesten

There is more:

What type of information can we extract from data?

Demystification of “ghost GPDs”

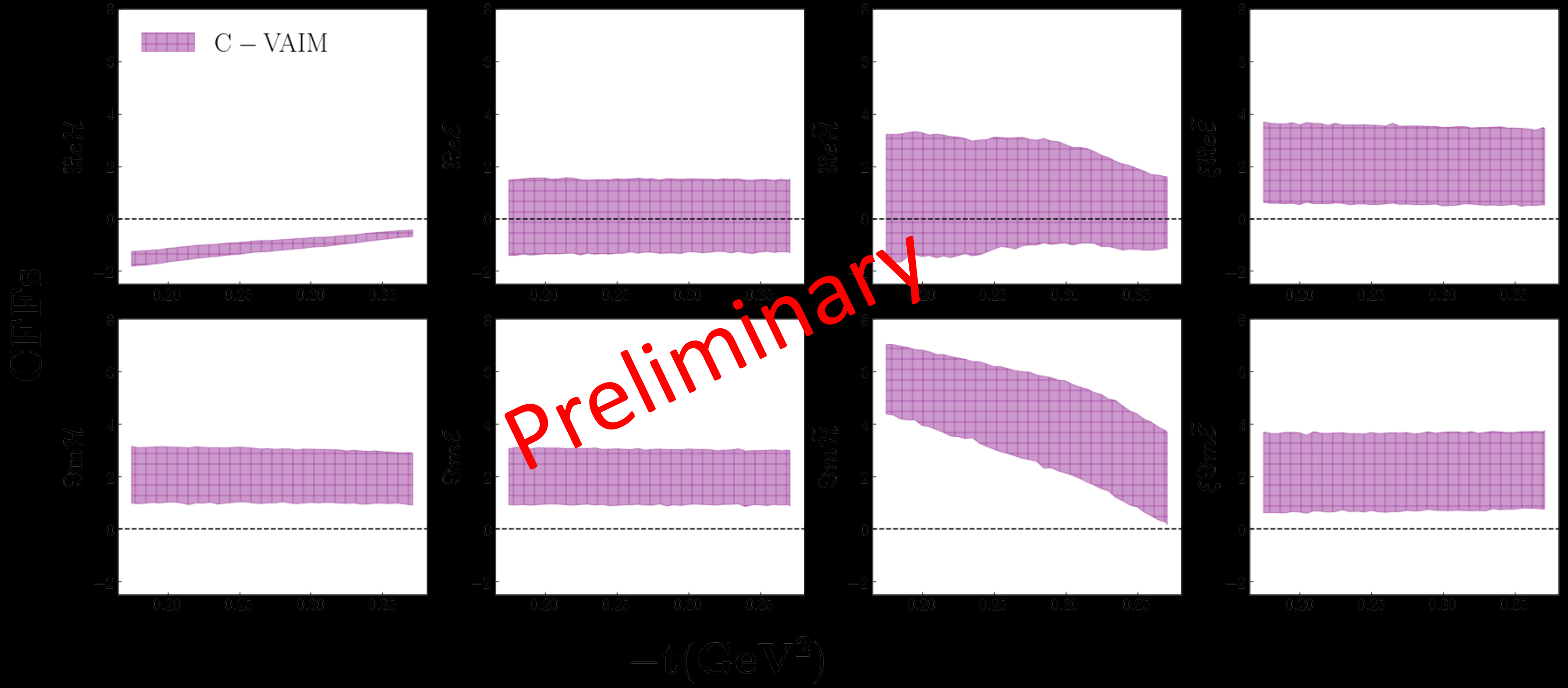
Bringing this further: ML based approach merging and organizing information from experiment and lattice with a faithful uncertainty representation (uncertainty quantification)
(collaboration with B. Kriesten, M. Almaeen, Yaohang Li, H-W. Lin)

- Evaluation of CFFs from experiment
- Extraction of GPDs from CFFs

Femtonet group: We are developing a new concept of physically informed NN (PHINN) through

1) Constraints on the variables/observables

2) NN design/architecture



C − VAIM
CFFs
Preliminary
−t(GeV²)

DVCS formalism

- B. Kriesten et al, *Phys.Rev. D* 101 (2020)
- B. Kriesten and S. Liuti, *Phys.Rev. D105 (2022),* arXiv 2004.08890
- B. Kriesten and S. Liuti, Phys. Lett. B829 (2022), arXiv:2011.04484

ML

- J. Grigsby, B. Kriesten, J. Hoskins, S. Liuti, P. Alonzi and M. Burkardt, Phys. Rev. D104 (2021)
- M. Almaeen, J. Grigsby, J. Hoskins, B. Kriesten, Y. Li, H-W. Lin and S. Liuti, ``Benchmarks for a Global Extraction of Information from Deeply Virtual Exclusive Scattering,'' arXiv 2207.10766

GPD Parametrization for global analysis

- B. Kriesten, P. Velie, E. Yeats, F. Y. Lopez and S. Liuti,

Phys. Rev D 105 (2022), arXiv:2101.01826