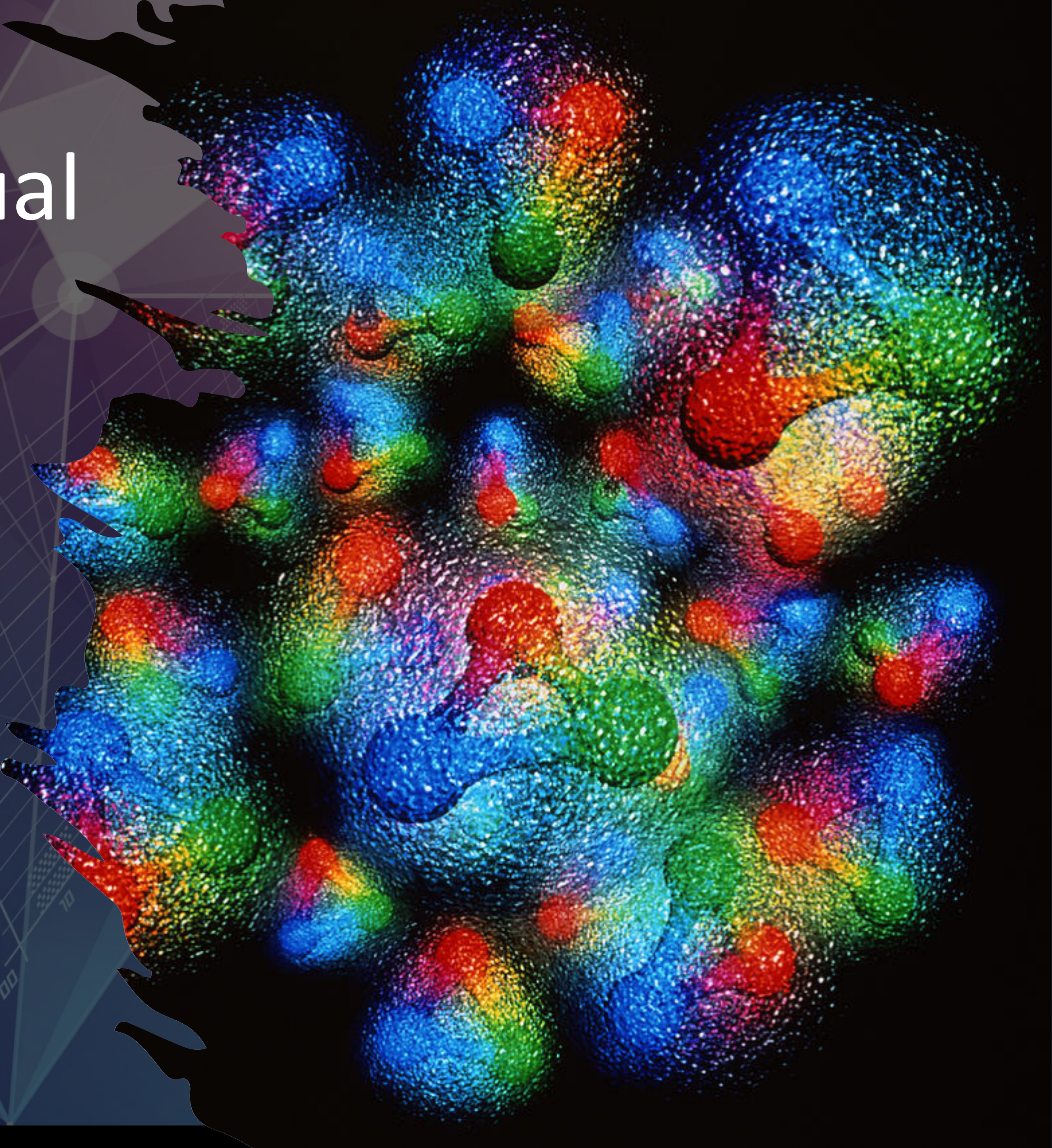
Theory of Deeply Virtual Exclusive Scattering

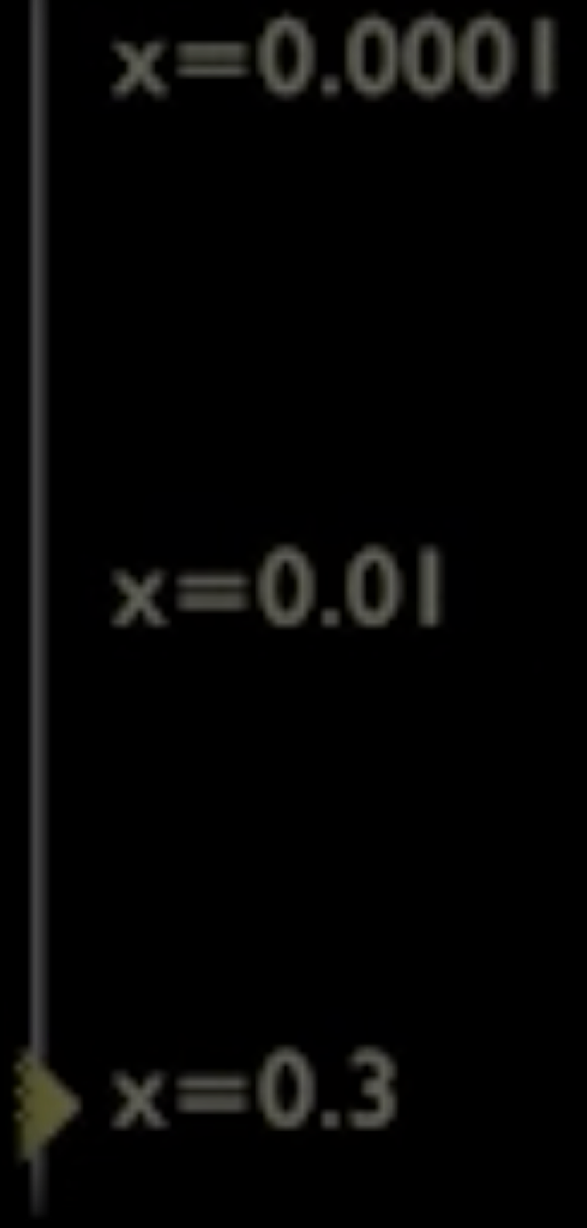
Simonetta Liuti

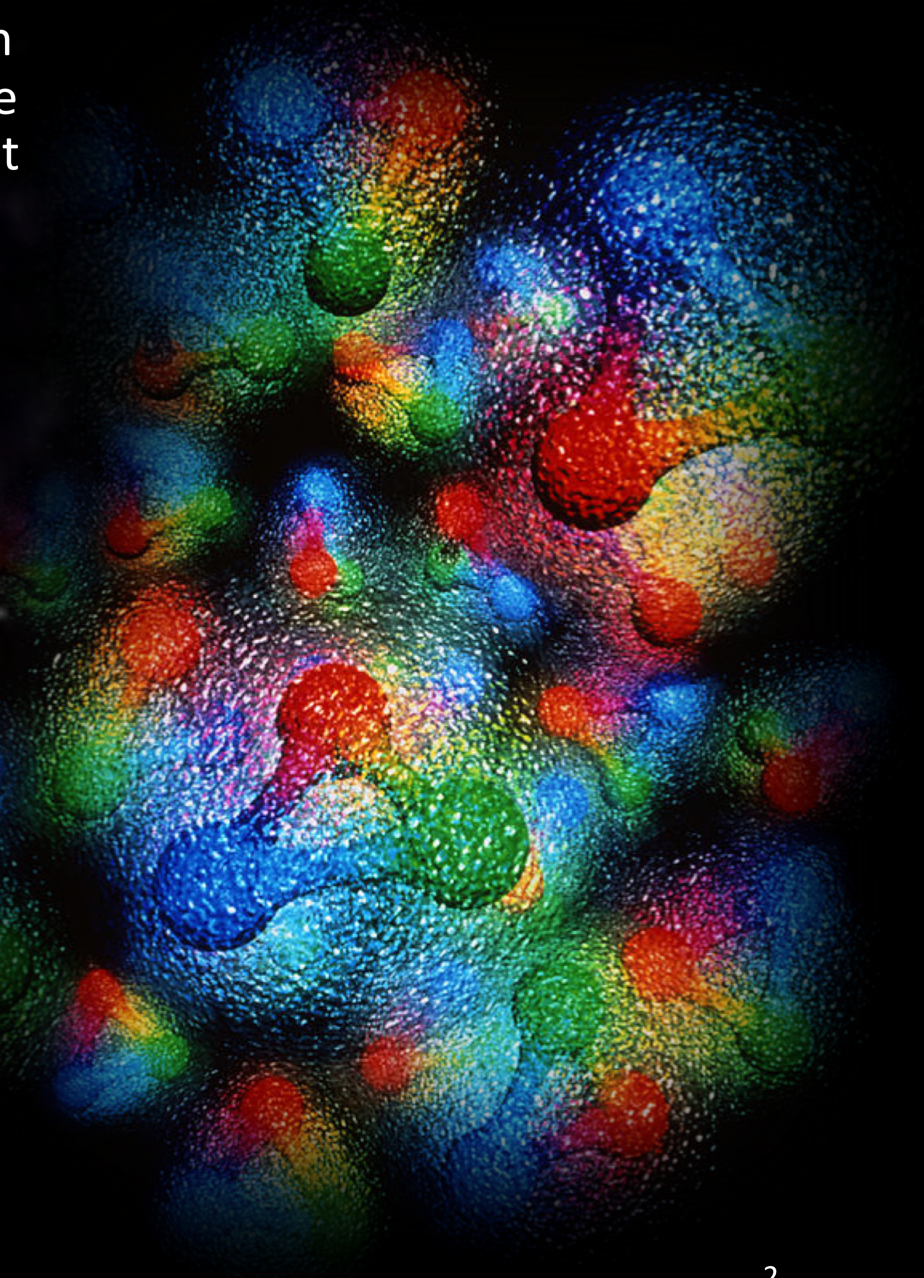


CENTER *for* NUCLEAR FEMTOGRAPHY

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





Physics Goals: rendering the spatial structure of the inside of the proton

What does it really take to have an image of the proton and can we really observe what goes on inside it?

See also Z.Panjsheeri's talk

Physics Goals: Quark and gluon angular momentum and the origin of the spin crisis

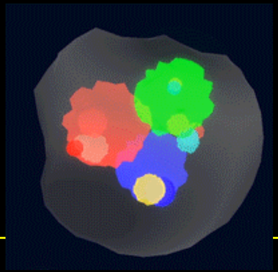
$$J_q + J_g = L_q + \frac{1}{2}\Sigma_q + J_g = \frac{1}{2}$$

1. How do we access the longitudinal and transverse components with measurements/**observables?**

2. **The role of QCD: are these twist-two or twist-three** quark and gluon distributions and why? What is the role of Q^2 evolution?
   M. Engelhardt's talk

The EXCLAIM project

(EXCLusives with Artificial Intelligence and Machine learning)



DOE funded collaboration, Co-PIs:

Computer Science/Machine Learning: Douglas Adams, Gia Wei Chern, Brandon Kriesten , Yaohang Li

Experiment: Marie Boer, Andrei Kim, Tanja Horn

Lattice QCD: Michel Engelhardt, Huey Wen Lin

Phenomenology/ Theory: Aurore Courtoy, Gary Goldstein, SL, Pavel Nadolsky, Matt Sievert, Dennis Sivers

UVA students: Joshua Bautista, Adil Khawaja, Zaki Panjsheeri

In the process of hiring several postdocs!

OUR PROGRAM

1. To develop *physics informed* networks that include *theory constraints* in *deep learning* models.

2. ML is not treated as a set of “black boxes” whose working is not fully controllable

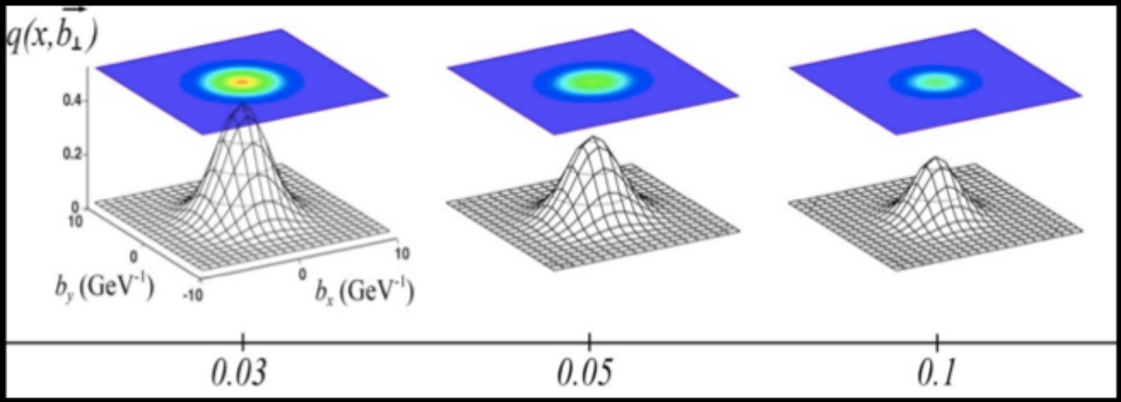
3. Utilize concepts in *information theory and quantum information theory* to interpret the working of ML algorithms necessary to extract information from data

4. At the same time, use ML methods as a testing ground for the working of quantum information theory in deeply virtual exclusive processes, as well as for inclusive processes

The first step is to define the benchmarks for a Global Analysis of Deeply Virtual Exclusive Experiments to allow us to compare results among different groups

The aim is not to come up with the "best" prediction for each observable and a global theoretical uncertainty

"Benchmarking" means choosing a common subset of observables and evaluating a few specific sources of error



graph from M. Defurne

M. Almaeen et al. arXiv 2207.10766

A possible set of theory constraints on ML based analyses

Hard constraints

"built into the architecture of the network"

- network invertibility
- choice of **activation functions**
- defining customized neural network layers

Focus on this today

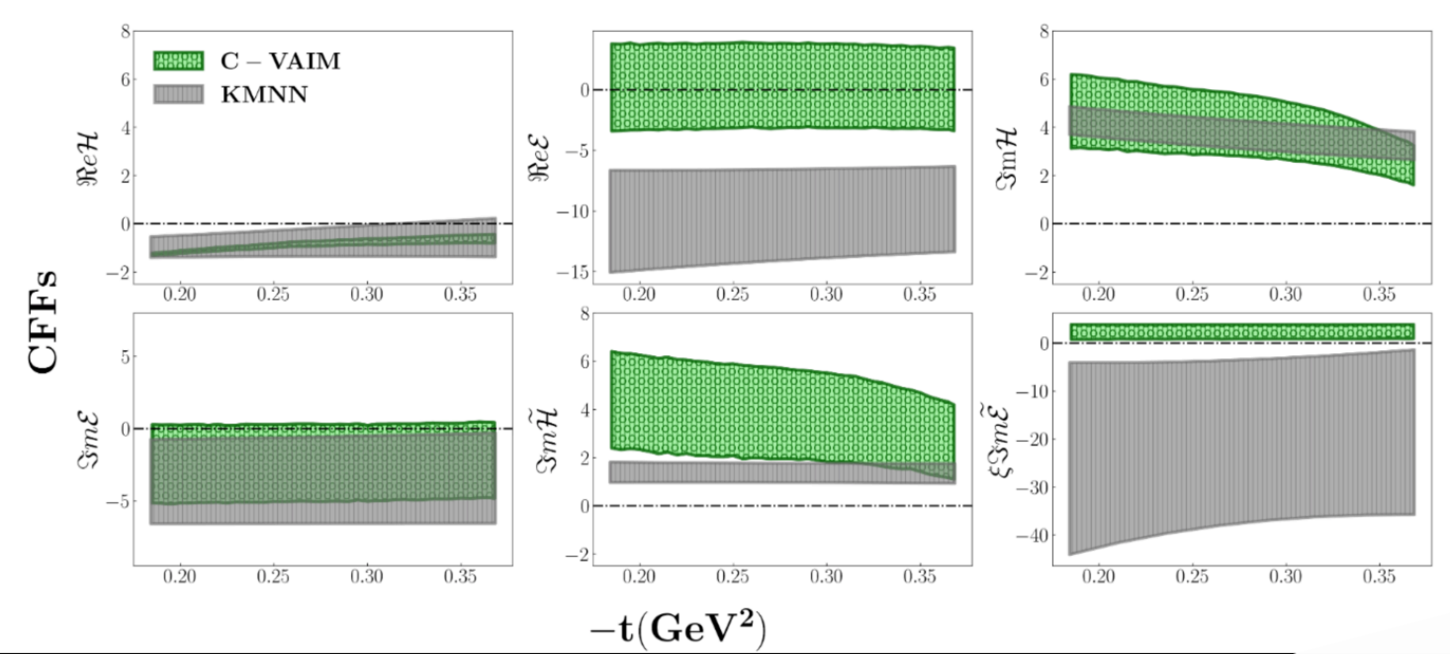
Soft constraints

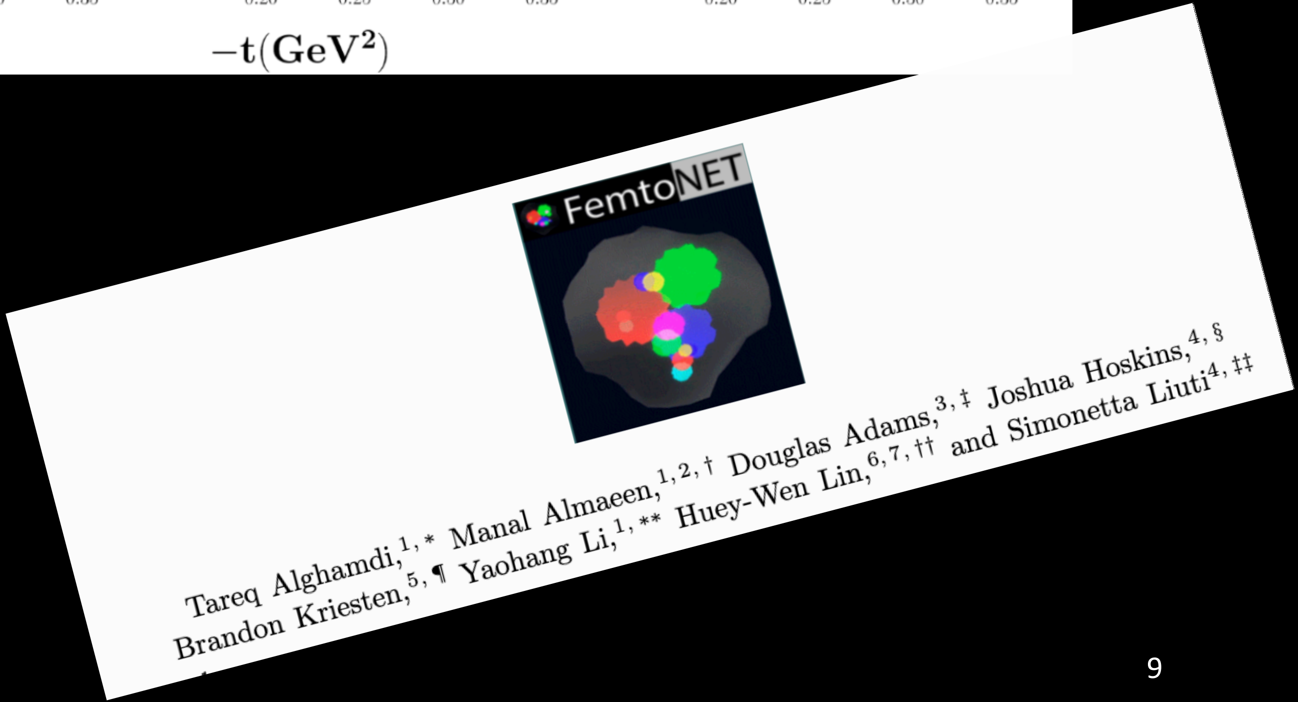
"adding additional terms to the loss function that can be learned to minimize and generate physics weighted parameters"

1. Cross section structure
2. Lorentz invariance
3. Positivity constraints
4. Forward kinematic limit, defined by $\xi, t \rightarrow 0$, to PDFs, when applicable
5. $\mathfrak{Re}$-$\mathfrak{Im}$ connection of CFFs through dispersion relations with proper consideration of threshold effects

Variational Autoencoder Inverse Mapper (VAIM

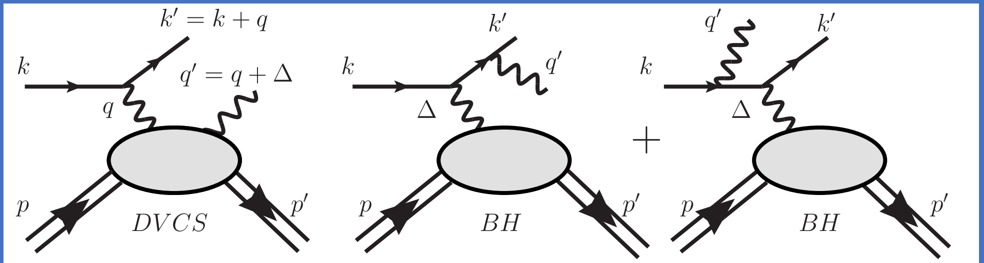
- Point for discussion: in order to compare results from different approaches we need to define the **benchmarks!!!!**





- We need a robust framework for DVES processes cross section, where kinematic limits are under control

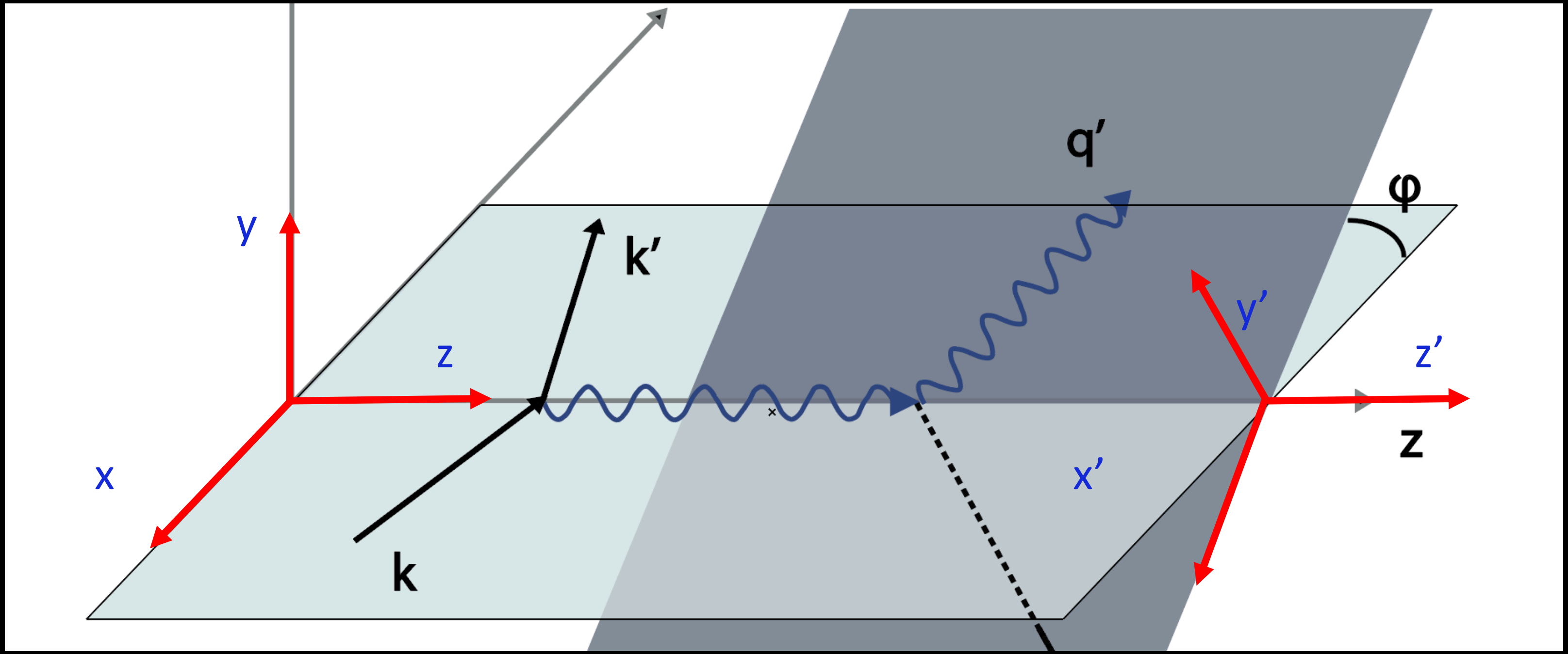
$$\frac{d^5\sigma}{dx_{Bj}dQ^2d|t|d\phi d\phi_S} = \frac{\alpha^3}{16\pi^2(s-M^2)^2\sqrt{1+\gamma^2}}\left|T\right|^2 ,$$



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

The hadronic tensor is evaluated in the rotated frame

DVCS



In lepton plane

$$\varepsilon^{\Lambda_{\gamma^*}=\pm 1} \equiv \frac{1}{\sqrt{2}}(0;\mp 1, i, 0),$$

$$\varepsilon^{\Lambda_{\gamma^*}=0} \equiv \frac{1}{Q}(|\,\vec{q}\,|;0,0,q_0) = \frac{1}{\gamma}(\sqrt{1+\gamma^2};0,0,1),$$

In rotated plane a phase ϕ appears

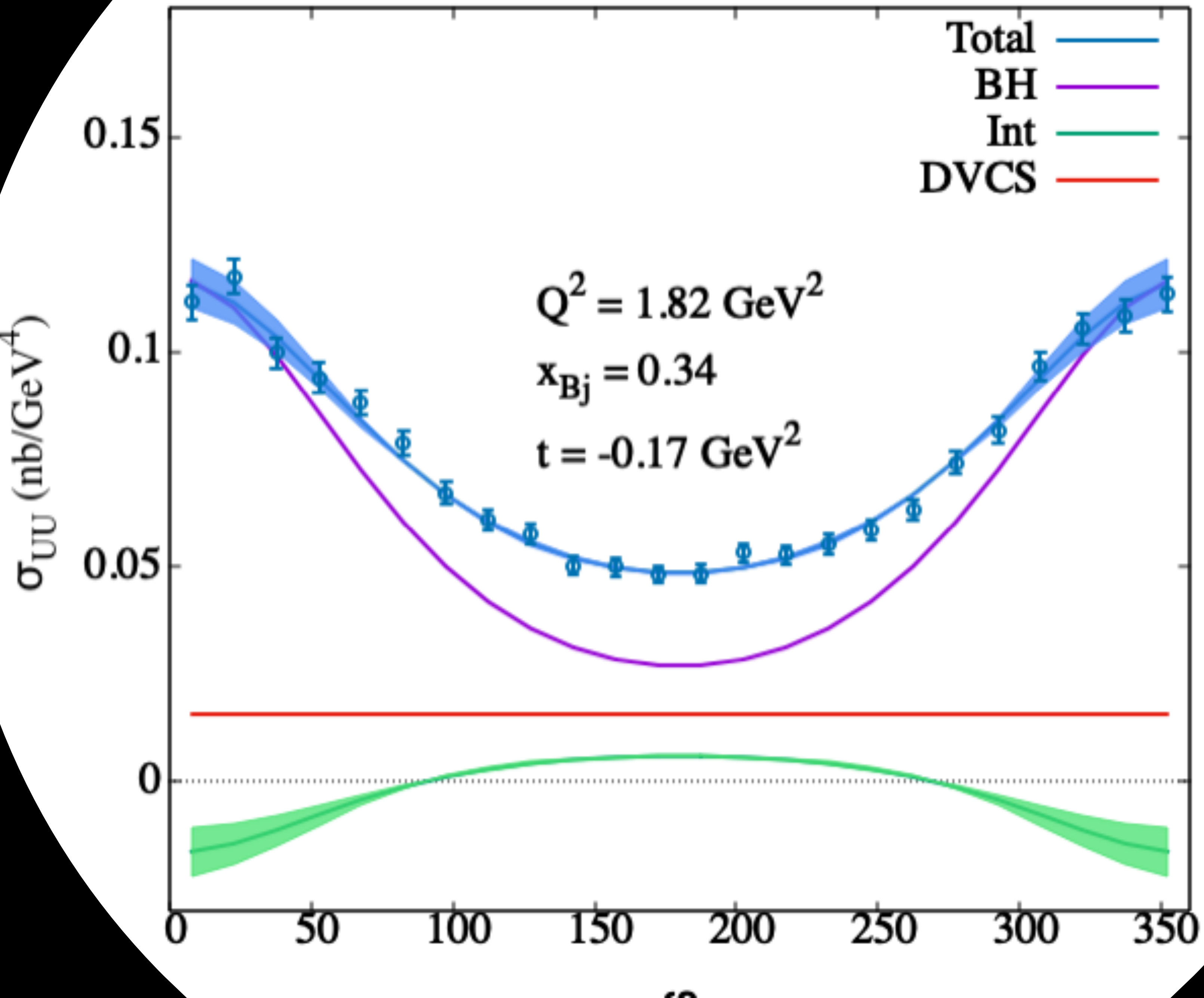
$$\varepsilon^{\Lambda_{\gamma^*}=\pm 1} \rightarrow \frac{e^{-i\Lambda_{\gamma^*}\phi}}{\sqrt{2}}(0,\mp 1, i, 0)$$

1) We differ from the BKM formalism (and all who followed) by a QED phase in the interference term

2) The QED phase is important because it demarcates QCD genuine twist-two from twist-three effects

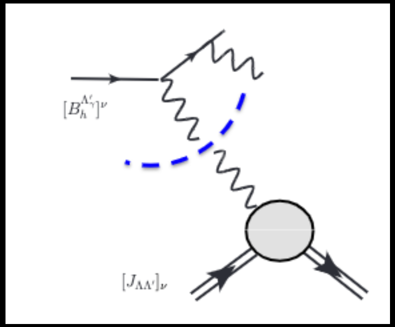
3) We use the formalism of the helicity amplitudes which does not generate “harmonics”

Example: Unpolarized DVCS



Parametrization of **BH** contribution

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



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

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

$$\begin{aligned}A =& \frac{16\,M^2}{t(k\,q')(k'\,q')}\left[4\tau\Big((k\,P)^2 + (k'\,P)^2\Big) - (\tau+1)\Big((k\,\Delta)^2 + (k'\,\Delta)^2\Big)\right] \\ B =& \frac{32\,M^2}{t(k\,q')(k'\,q')}\left[(k\,\Delta)^2 + (k'\,\Delta)^2\right],\end{aligned}$$

…compared to ELASTIC SCATTERING

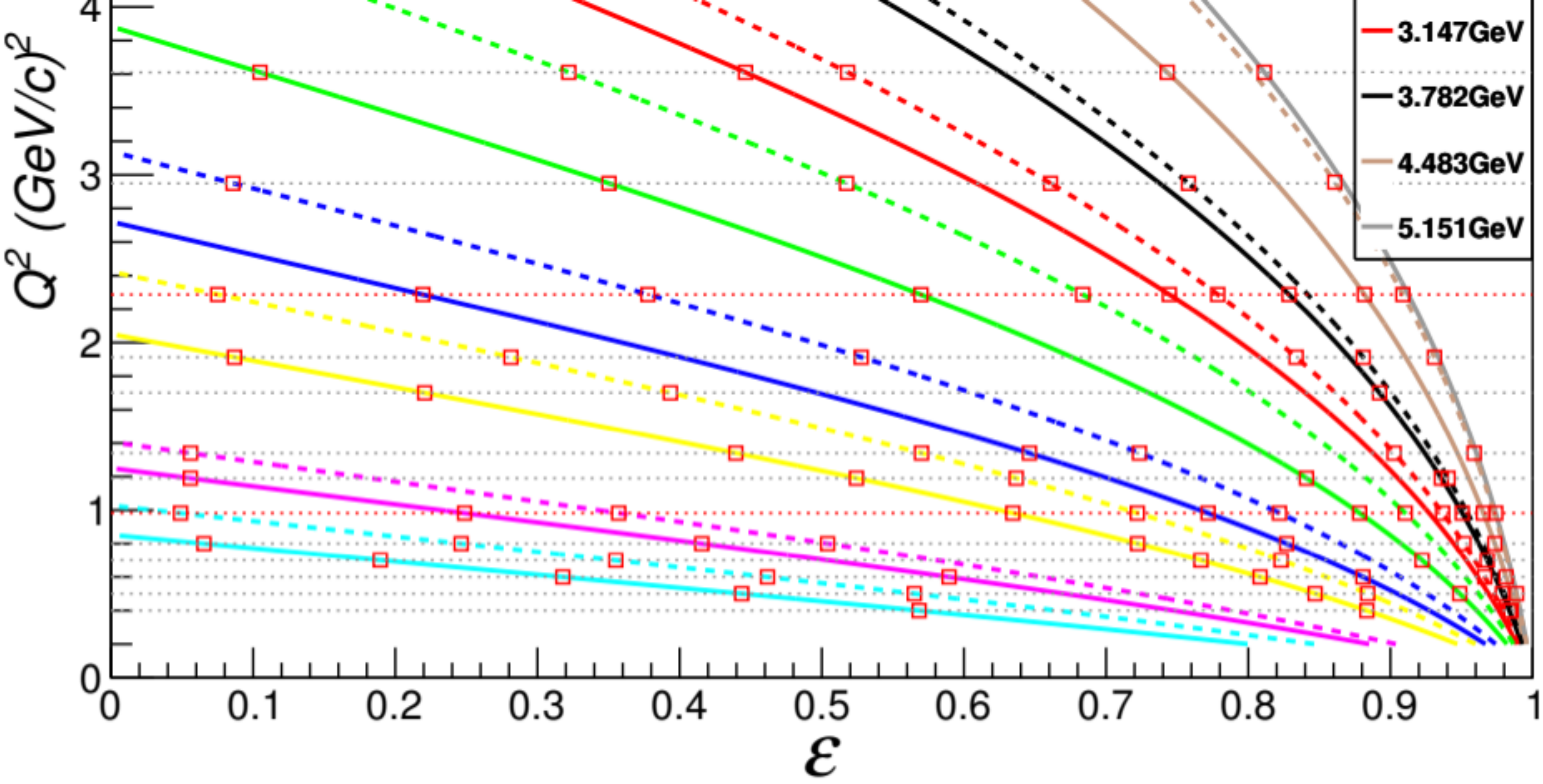
10/21/21

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

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 …

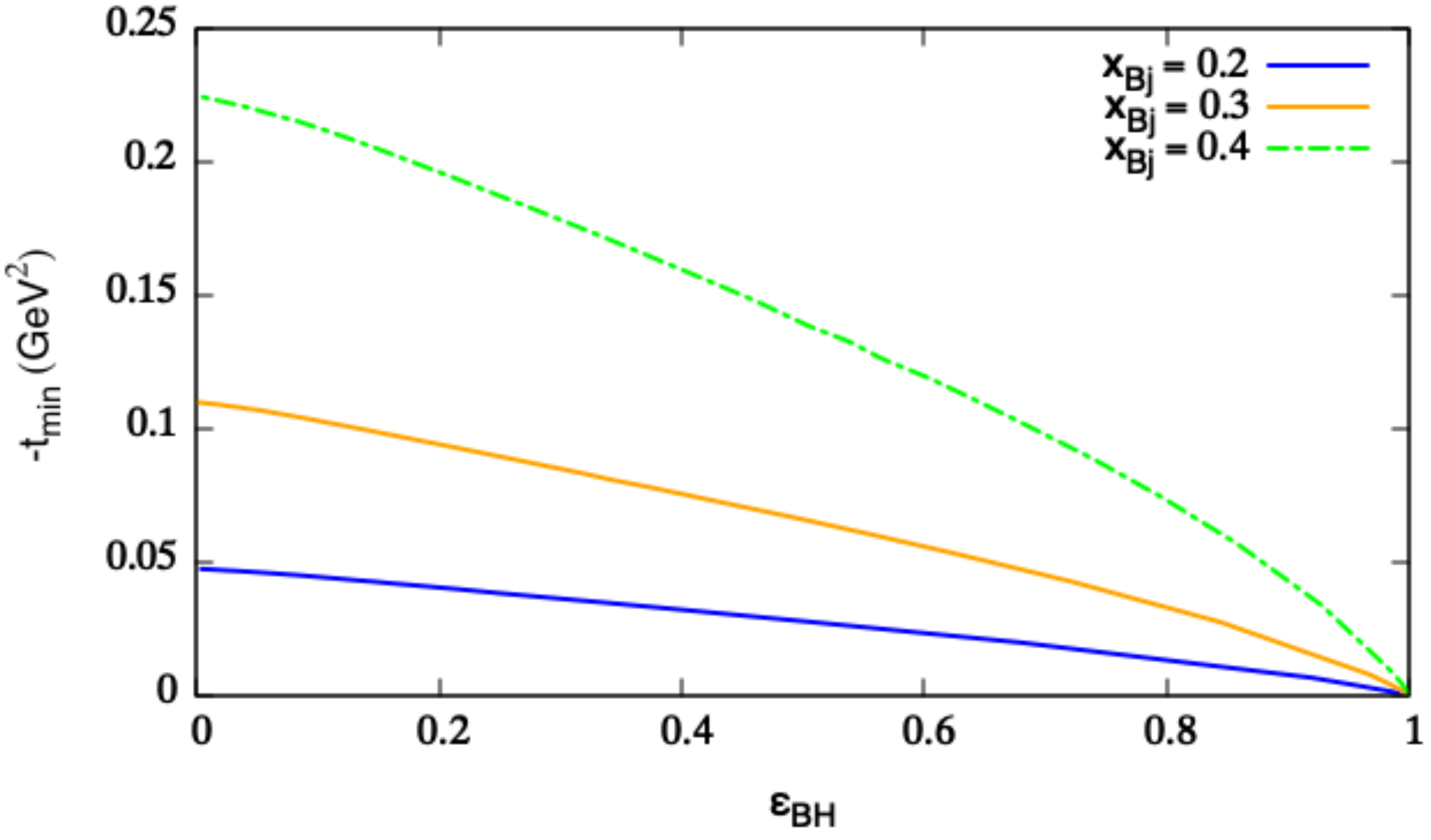


igure 3.2: The E05-017 nominal kinematic coverage. The solid and dashed lines are constan

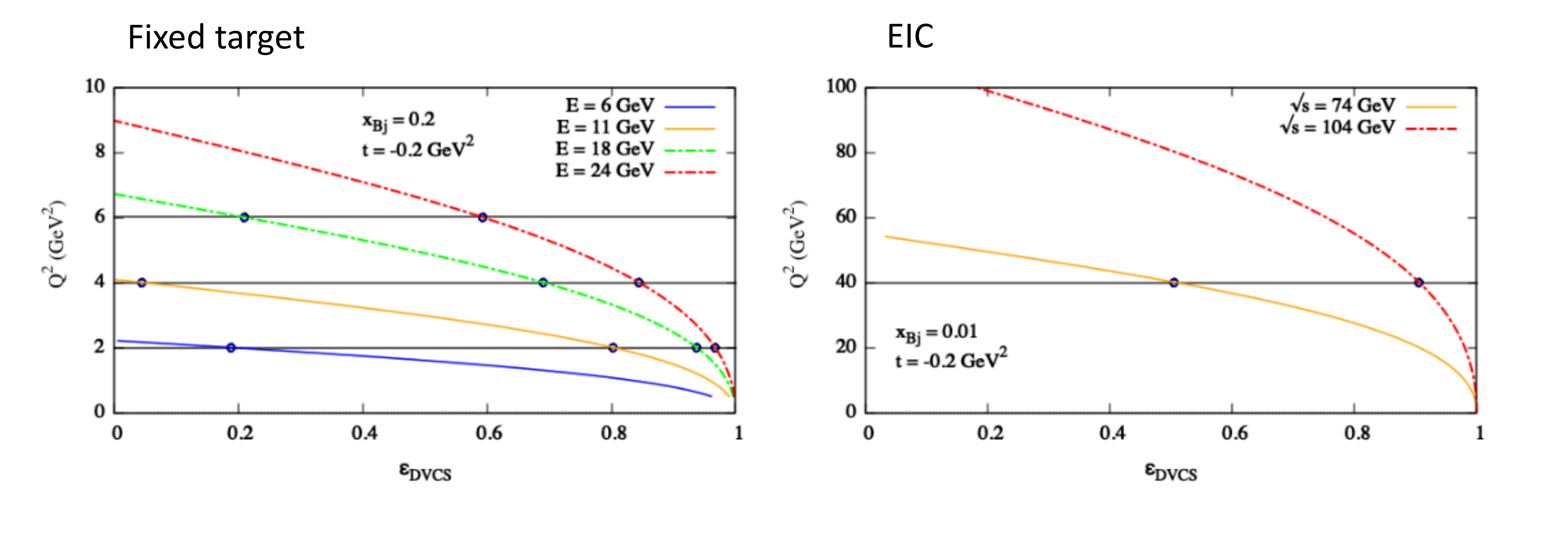
tings.

M. Yurov, Ph.D. thesis

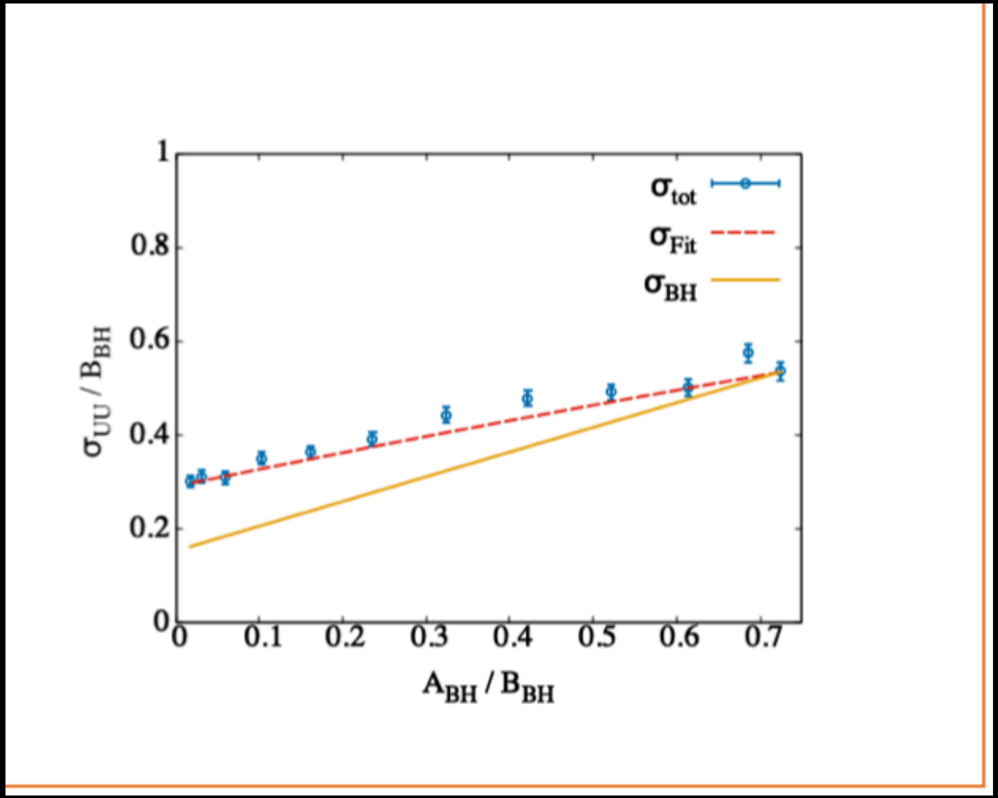
E= 6 GeV


0.25
0.2
0.15
0.1
0.05
0
$-t_{min}$ (GeV^2)
0
0.2
0.4
0.6
0.8
1
ε_{BH}
x_{Bj} = 0.2
x_{Bj} = 0.3
x_{Bj} = 0.4

DVCS


Fixed target
EIC
$x_{Bj} = 0.2$
$t = -0.2\ \mathrm{GeV}^2$
E = 6 GeV
E = 11 GeV
E = 18 GeV
E = 24 GeV
$Q^2\ (\mathrm{GeV}^2)$
ε_{DVCS}
$\sqrt{s}$ = 74 GeV
$\sqrt{s}$ = 104 GeV
$x_{Bj} = 0.01$
$t = -0.2\ \mathrm{GeV}^2$

Rosenbluth separation



- 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

How do we separate twist two and twist three components?

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	$g_L^\perp$	$2\widetilde{H}'_{2T} + E'_{2T}$
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	$f_T^{(*)}$	$H_{2T} + \tau \widetilde{H}_{2T}$
	$\widetilde{H}_T^{(3)}$	LT	g'_T	$H'_{2T} + \tau \widetilde{H}'_{2T}$

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

1/Q correction to H

1/Q correction to $\widetilde{\text{H}}$

NEW!! Orbital Angular Momentum L

NEW!! Spin Orbit correlation $L \cdot S$

NEW!! Transverse OAM L_T

Transverse spin

(*) T-odd

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

8/8/23

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

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

A. Rajan, O. Alkassasbeh, M. Engelhardt, S.L., (2023)

Twist three GPD Physical interpretation

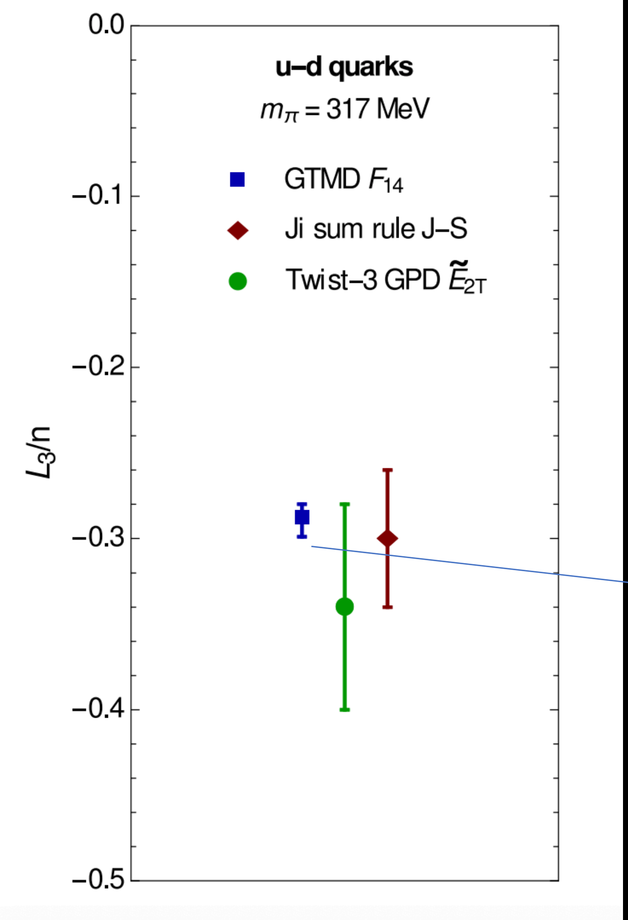
$$
\begin{array}{ccccc}
J_L & = & L_L & + & S_L \\
\frac{1}{2}\int dx\, x(H+E) & = & \boxed{\int dx\, x(\widetilde{E}_{2T}+H+E)} & + & \frac{1}{2}\int dx\, \widetilde{H} \\
 & = & \boxed{-\int dx\, F_{14}^{(1)}} & + & \frac{1}{2}\int dx\, \widetilde{H}
\end{array}
$$

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

*Twist 3 GPD notation from Meissner, Metz and Schlegel, JHEP(2009)

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

lattice

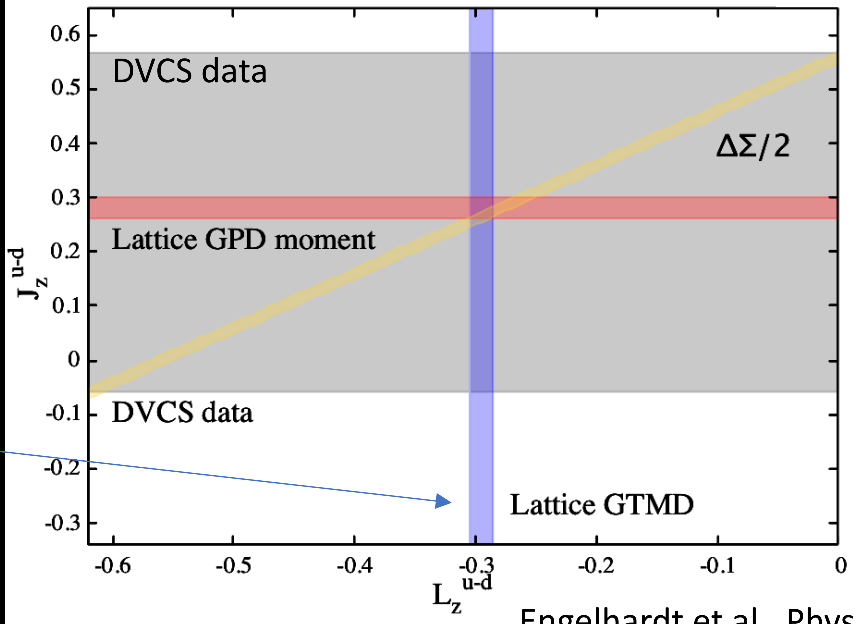


M. Engelhardt, Lattice 2023

experiment vs. lattice

m_π = 320 MeV

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



Mazouz et al.
Jlab Hall A
PRL (2007)

Engelhardt et al., Phys. Rev. D102, (2020)

q=u-d

Quark Spin Orbit: $L \cdot S$: emerging role of chiral properties

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

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

*Twist 3 GPD notation from Meissner, Metz and Schlegel, JHEP(2009)

Transverse Angular Momentum Sum Rule

O. Alkassasbeh, M. Engelhardt, SL and A. Rajan, (2022) soon on arXiv

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

To understand the working of twist three better, we started looking in more detail into a SPIN 0 target: ^{4}He

$$W^{[\gamma^+]} = H_A(x, \xi, t)$$

ee parametrization from [23],

$$W^{[\gamma^i]} = \frac{\Delta^i}{P^+} H_A^{(3)}(x, \xi, t)$$

$$W^{[\gamma^i \gamma_5]} = \frac{i\varepsilon_T^{ij} \Delta^j}{P^+} \boxed{\widetilde{H}_A^{(3)}(x, \xi, t)}$$

New type of correlation

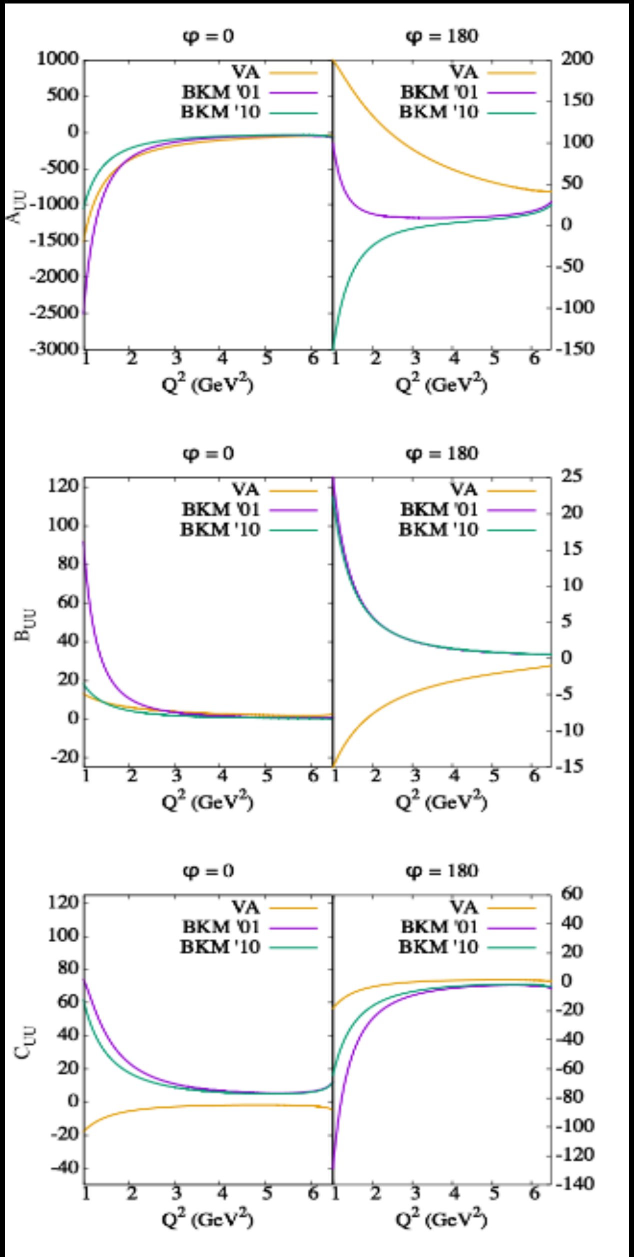
How do we identify the new twist-three correlations inside observables? Put the "physics" back into the process!!

Example: BH-DVCS interference

From harmonics to physically meaningful observables

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

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



Nuclei from spin 0, ½, 1 will help us disentangle many new spin correlations!

There is a rich program ahead of us

But again the problem is in the observable

Observable

$$A_{UT} \sim \mathrm{Im}\{H_1^* H_5 + (H^*{}_1 + \frac{1}{6} H^*{}_5)(H_2 - H_4)\}$$

We can access J !

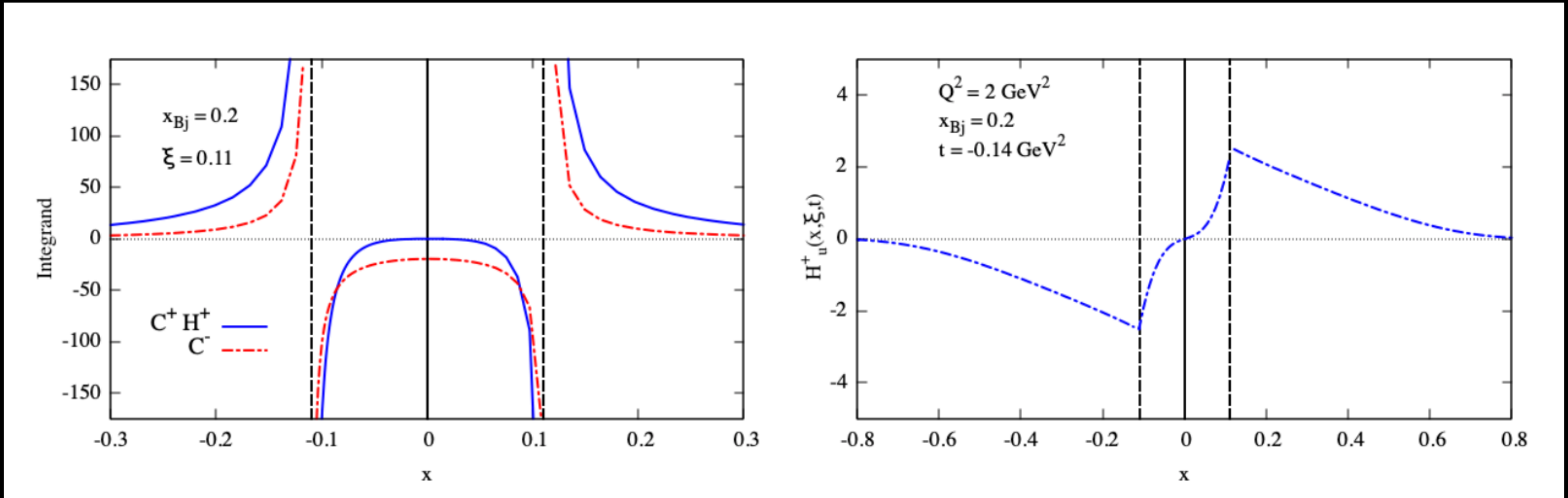
Title: "*Microscopic description of deeply virtual Compton scattering off spin-0 nuclei,*"
Authors: S. Liuti and S. K. Taneja,
Journal: Phys. Rev. C **72**, 032201 (2005)

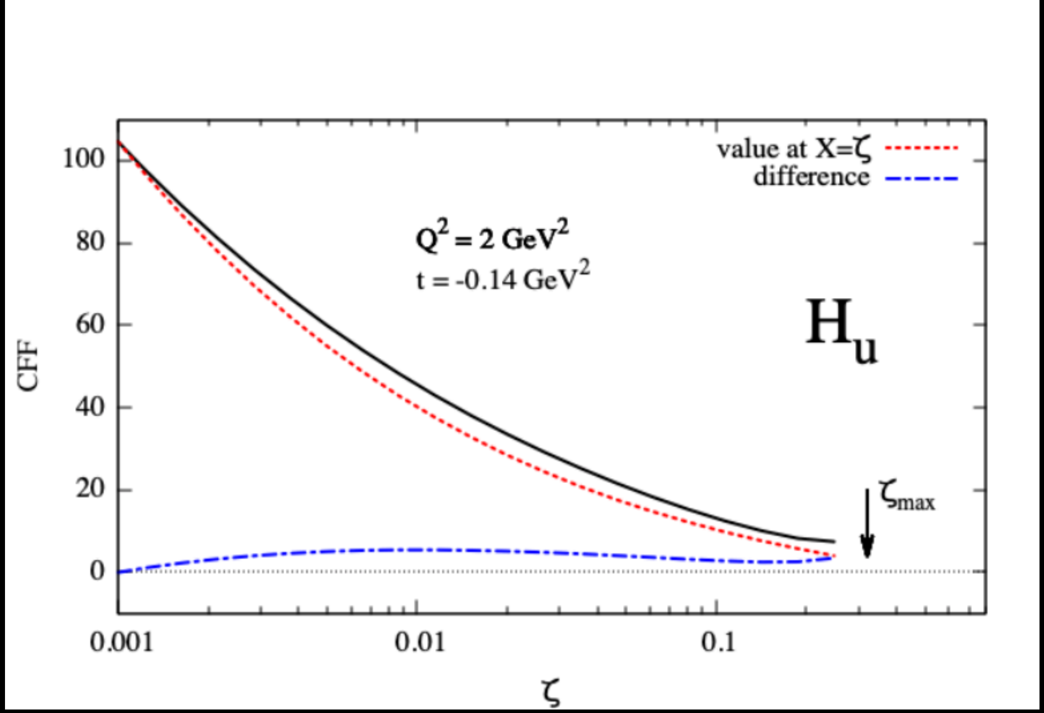
Title: "*Angular momentum sum rule for spin one hadronic systems*"
Authors: S. K. Taneja, K. Kathuria, S. Liuti and G. R. Goldstein,
Journal: Phys. Rev. D **86**, 036008 (2012); arXiv:1101.0581 [hep-ph]

Finally, what types of GPDs are we extracting?

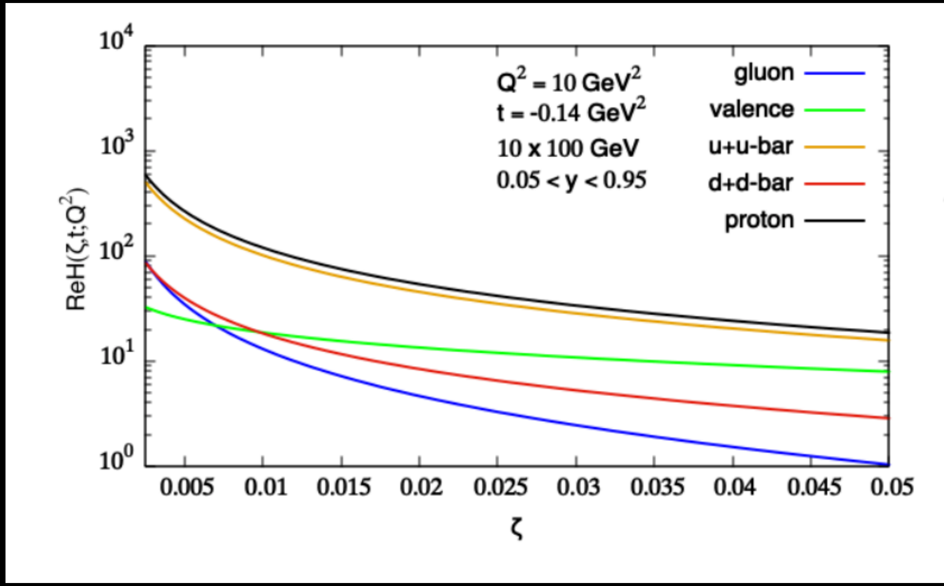
Kernels in convolution

“+”-distribution

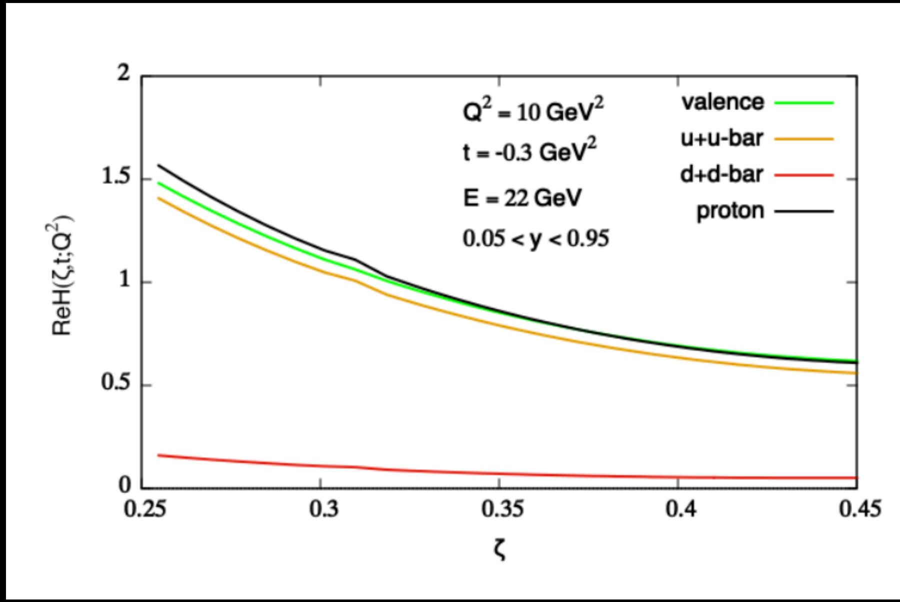



value at X=ζ
difference
$Q^2 = 2\ GeV^2$
$t = -0.14\ GeV^2$
H_u
ζ_{max}
CFF
100
80
60
40
20
0
0.001
0.01
0.1
ζ

EIC



Jlab 12 GeV+



CONCLUSIONS

- To obtain interesting new physical information on the spatial structure of the proton and atomic nuclei from exclusive experiments requires extending the number and type of deeply virtual exclusive reactions with multiple particles in the final state.

- Extracting information from data requires new methodologies and frameworks.

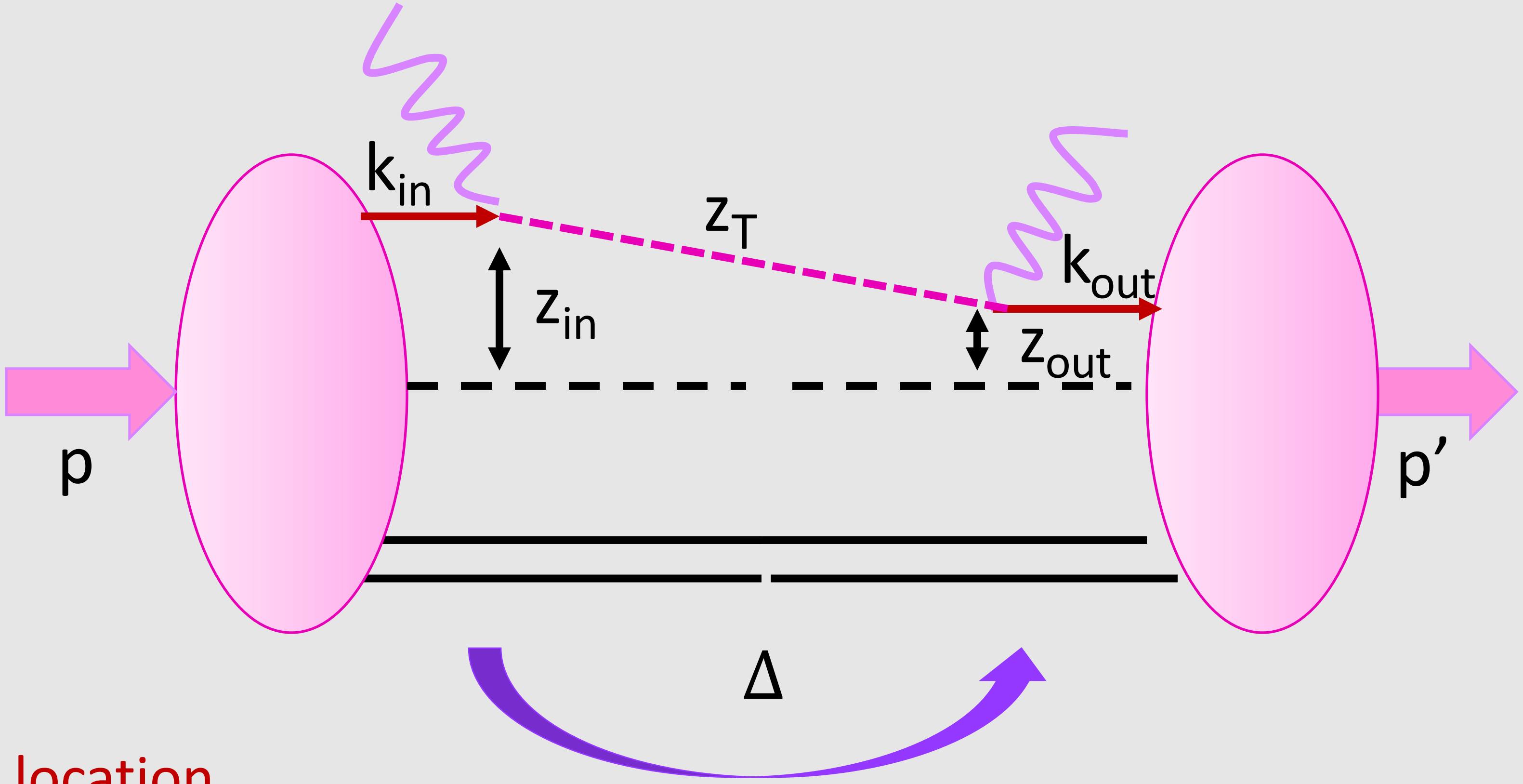
- Different efforts need to be benchmarked and coordinated

- I focused on the QED PHASE part of the cross section which plays a crucial role for distinguishing genuine twist-two from twist-three effects.

- If the cross section is written in terms of physically meaningful terms, we can understand more, and perform precise extractions as compared to a simple mathematical framework based on Fourier harmonics

Backup

Accessing transverse distances through Fourier transformation



Related to parton location

$$\begin{cases} b = \dfrac{z_{in} + z_{out}}{2} \\ \Delta = p - p' = ki_{n} \_ kou_{t} \end{cases}$$

Related to Ioffe “time”

$$\begin{cases} z_T = z_{in} - z_{out} \\ k_T = \dfrac{k_{in} + k_{out}}{2} \end{cases}$$

Example: Parametrization of Unpolarized DVCS cross section

$$|T_{UU}^{BH}|^2 = \frac{\Gamma}{t}\left[A_{UU}^{BH}\boxed{(F_1^2+\tau F_2^2)} + B_{UU}^{BH}\boxed{\tau G_M^2(t)}\right]$$

$$|T_{UU}^{\mathcal{I}}|^2 = \frac{\Gamma}{Q^2 t}\left[A_{UU}^{\mathcal{I}}\Re e\boxed{(F_1\mathcal{H}+\tau F_2\mathcal{E})} + B_{UU}^{\mathcal{I}}G_M\Re e\boxed{(\mathcal{H}+\mathcal{E})} + C_{UU}^{\mathcal{I}}\boxed{G_M\Re e\widetilde{\mathcal{H}}}\right]$$

$$|T_{LU}^{\mathcal{I}}|^2 = \frac{\Gamma}{Q^2 t}\left[A_{LU}^{\mathcal{I}}\Im m\boxed{(F_1\mathcal{H}+\tau F_2\mathcal{E})} + B_{LU}^{\mathcal{I}}G_M\Im m\boxed{(\mathcal{H}+\mathcal{E})} + C_{LU}^{\mathcal{I}}\boxed{G_M\Im m\widetilde{\mathcal{H}}}\right]$$

$$\begin{aligned}|T_{UU}^{DVCS}|^2 = \frac{\Gamma}{Q^2}\frac{2}{1-\epsilon}\Big[&(1-\xi^2)\left[(\Re e\mathcal{H})^2+(\Im m\mathcal{H})^2+(\Re e\widetilde{\mathcal{H}})^2+(\Im m\widetilde{\mathcal{H}})^2\right]\\ &+\frac{t_o-t}{4M^2}\left[(\Re e\mathcal{E})^2+(\Im m\mathcal{E})^2+\xi^2(\Re e\widetilde{\mathcal{E}})^2+\xi^2(\Im m\widetilde{\mathcal{E}})^2\right]\\ &-2\xi^2\left(\Re e\mathcal{H}\,\Re e\mathcal{E}+\Im m\mathcal{H}\Im m\mathcal{E}+\Re e\widetilde{\mathcal{H}}\,\Re e\widetilde{\mathcal{E}}+\Im m\widetilde{\mathcal{H}}\Im m\widetilde{\mathcal{E}}\right)\Big]\end{aligned}$$

- 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