SIMONETTA LIUTI
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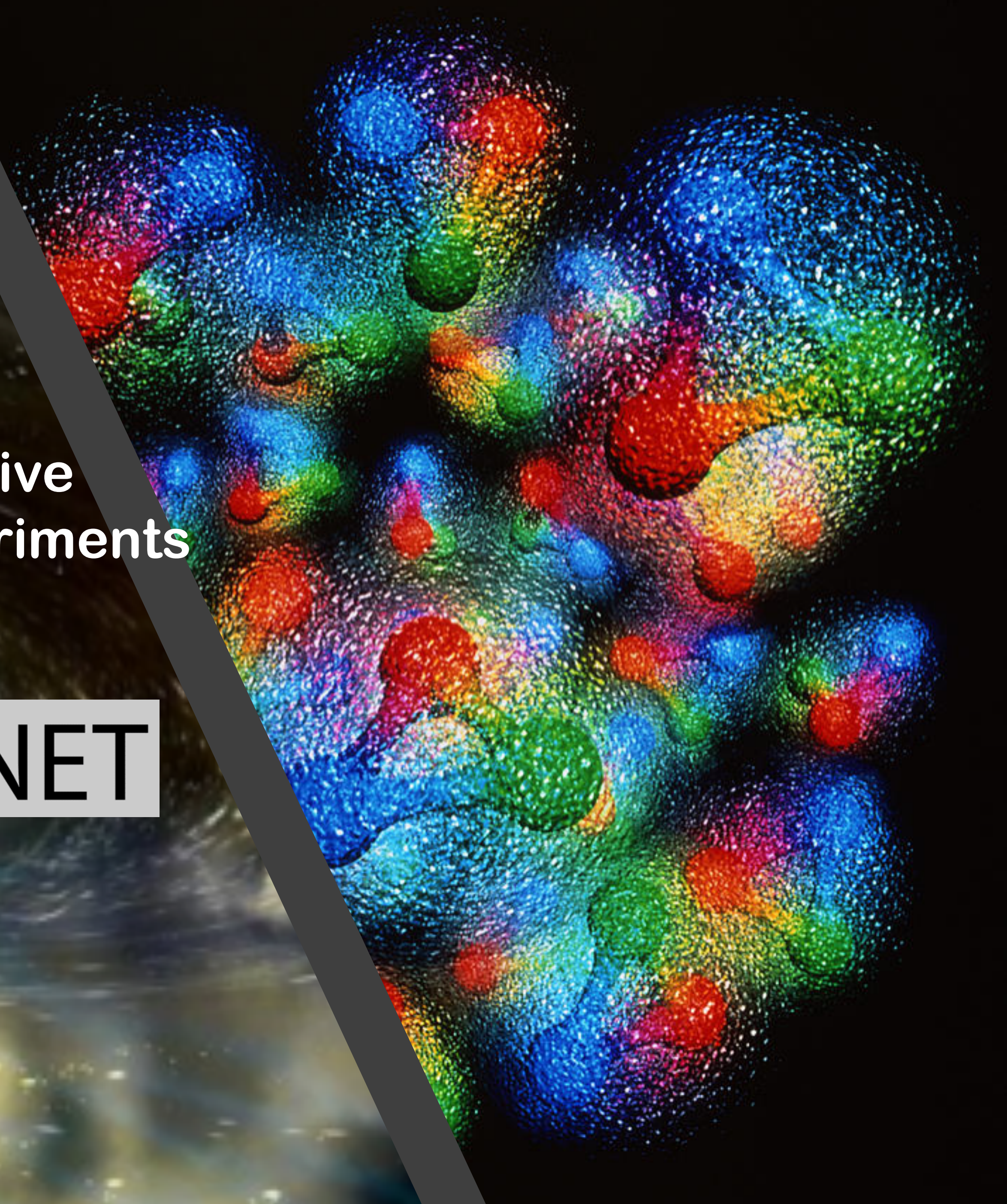
The Femtography Project: Comprehensive framework for deeply virtual exclusive experiments

FemtoNET



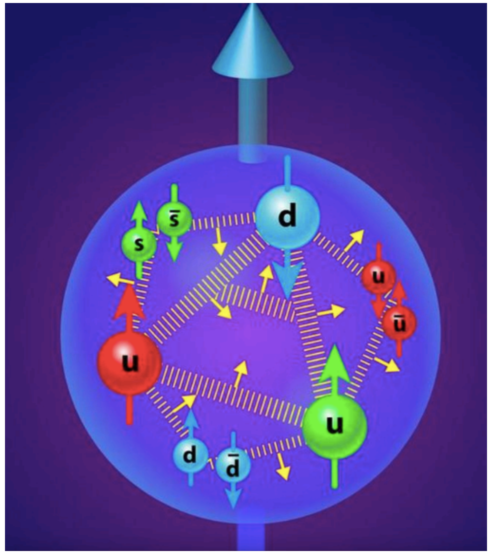
Snowmass
October 28, 2020

GPDs and Deeply Virtual Exclusive Experiments

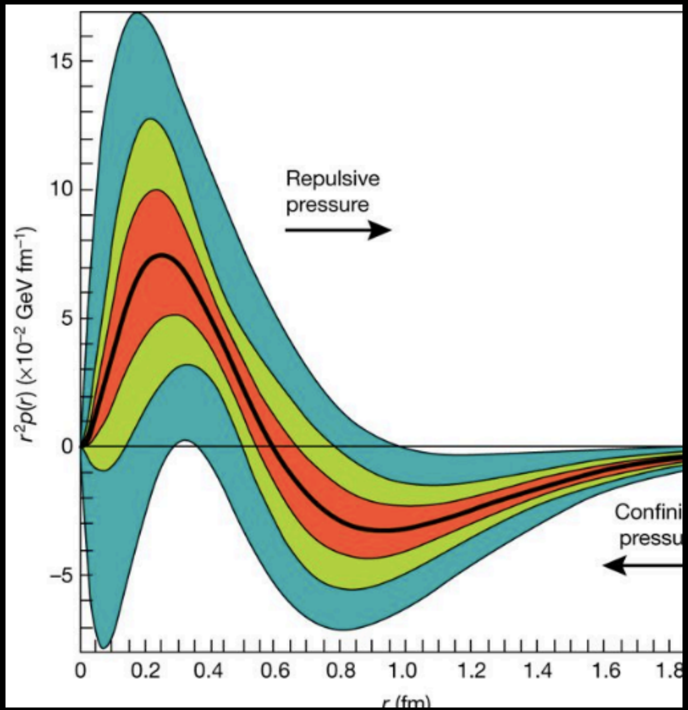
A new paradigm that will allow us to both penetrate and visualize the deep structure of visible matter, answering questions that we couldn't even afford asking before

$$\frac{1}{2}\int_{-1}^{1} dx\,x\,[H_q(x,0,0) + E_q(x,0,0)] = J_q$$

X. Ji, 1997



How does the proton/neutron get its mass and spin and how do we test this dynamics?



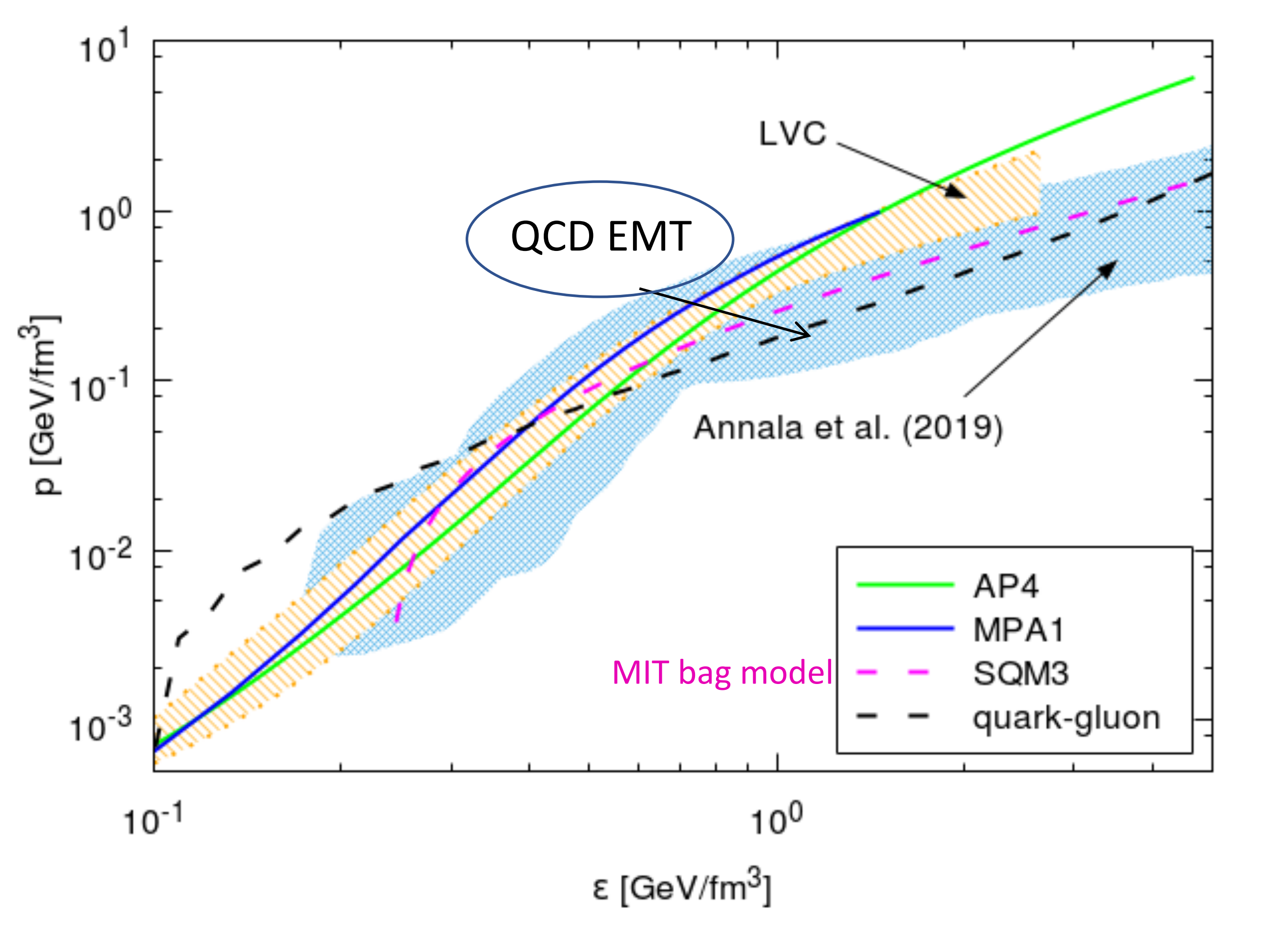
"The average peak pressure near the center is about 10^{35} pascals, which exceeds the pressure estimated for the most densely packed known objects in the Universe, neutron stars"

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

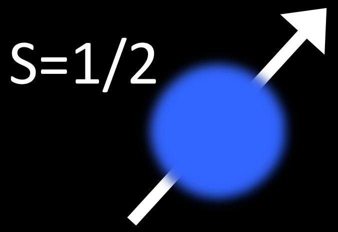
How do we measure pressure and forces inside the proton?

M. Polyakov, 2003

The Jlab extraction of the pressure measurement helps us understand the EoS of neutron stars



A. Rajan, T. Gorda, SL, K. Yagi, submitted for publication



(X. Ji, 1997)

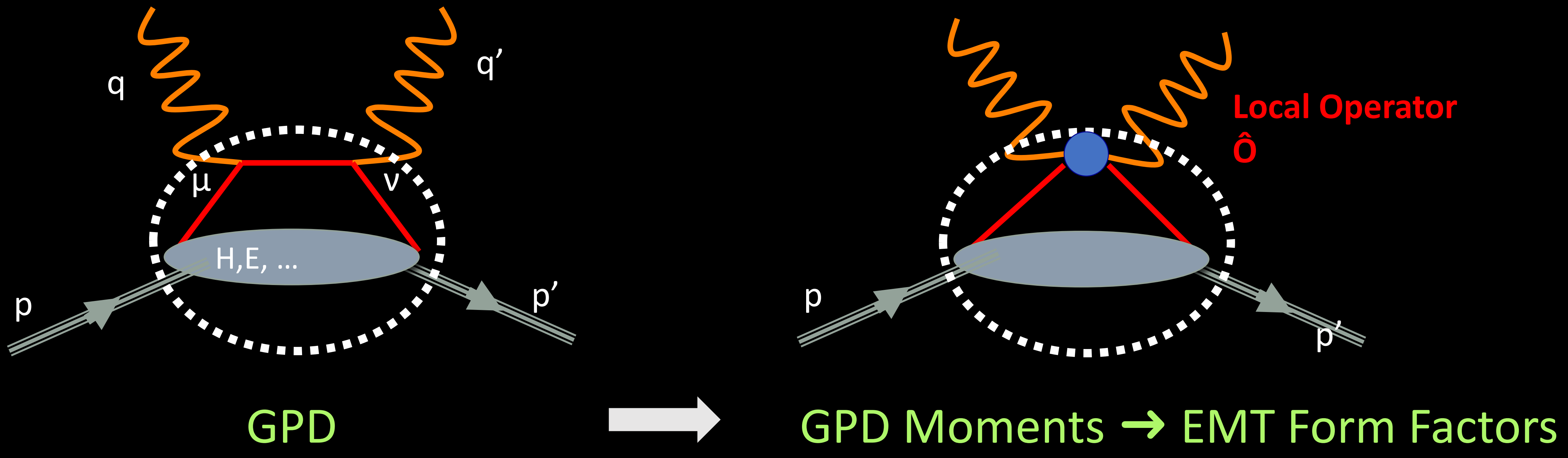
$$\langle p', \Lambda \mid T^{\mu\nu} \mid p, \Lambda \rangle = A(t)\bar{U}(p', \Lambda')[\gamma^{\mu} P^{\nu} + \gamma^{\nu} P^{\mu}]U(p, \Lambda) + B(t)\bar{U}(p', \Lambda')i\,\frac{\sigma^{\mu(\nu}\Delta^{\nu)}}{2M}U(p, \Lambda)$$
$$+C(t)[\Delta^2 g^{\mu\nu} - \Delta^{\mu\nu}]\bar{U}(p', \Lambda')U(p, \Lambda) + \widetilde{C}(t) g^{\mu\nu}\bar{U}(p', \Lambda')U(p, \Lambda)$$

off-forward

q and g not separately conserved

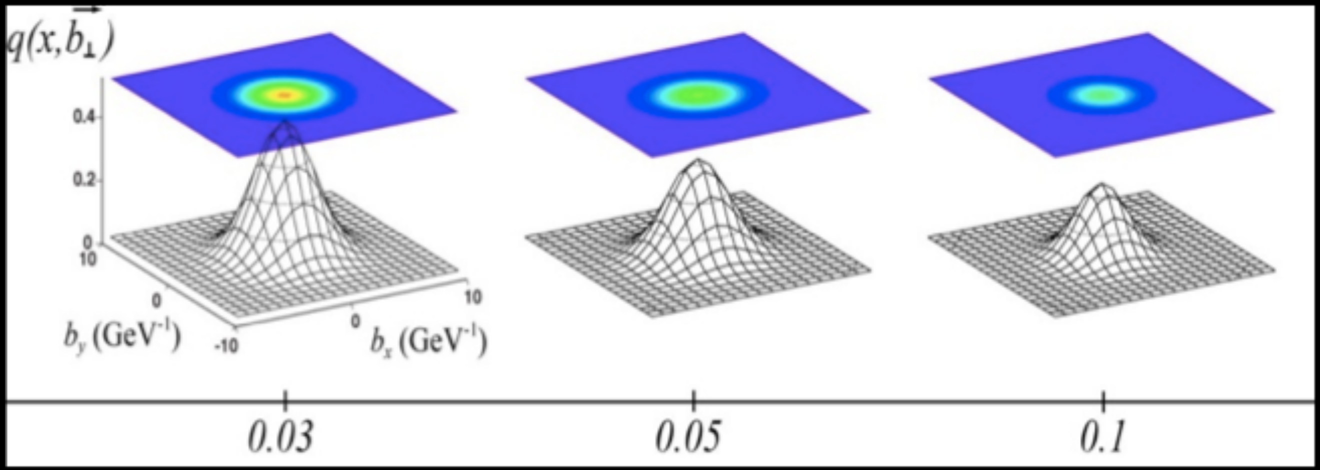
$$P = \frac{p + p'}{2}$$
$$\Delta = p' - p = q - q'$$
$$t = (p - p')^2 = \Delta^2$$

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



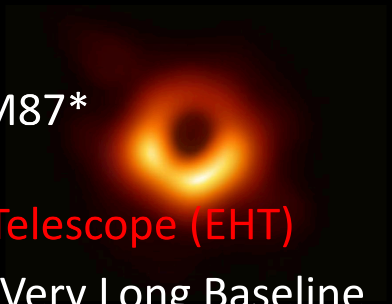
- Large momentum transfer $Q^2 >> M^2$ ➔ “deep”
- Large Invariant Mass $W^2 >> M^2$ ➔ equivalent to an “inelastic” process

Measuring the Nucleon Gravitomagnetic Form Factors



graph from M. Defurne

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



Event Horizon Telescope (EHT)

- ✓ Main idea: Very Long Baseline Interferometry (VLBI), an array of smaller telescopes synchronized to focus on the same object and act as a giant telescope
- ✓ Precision: large aperture (many telescopes widely spaced) and high frequency radio waves
- ✓ Data Management: 5 petabytes physically transported to a central location. Data from all eight sites were combined to create a composite set of images, revealing for the first time M87*'s event horizon.

It took nearly two decades to achieve !

Jefferson Lab@12 GeV

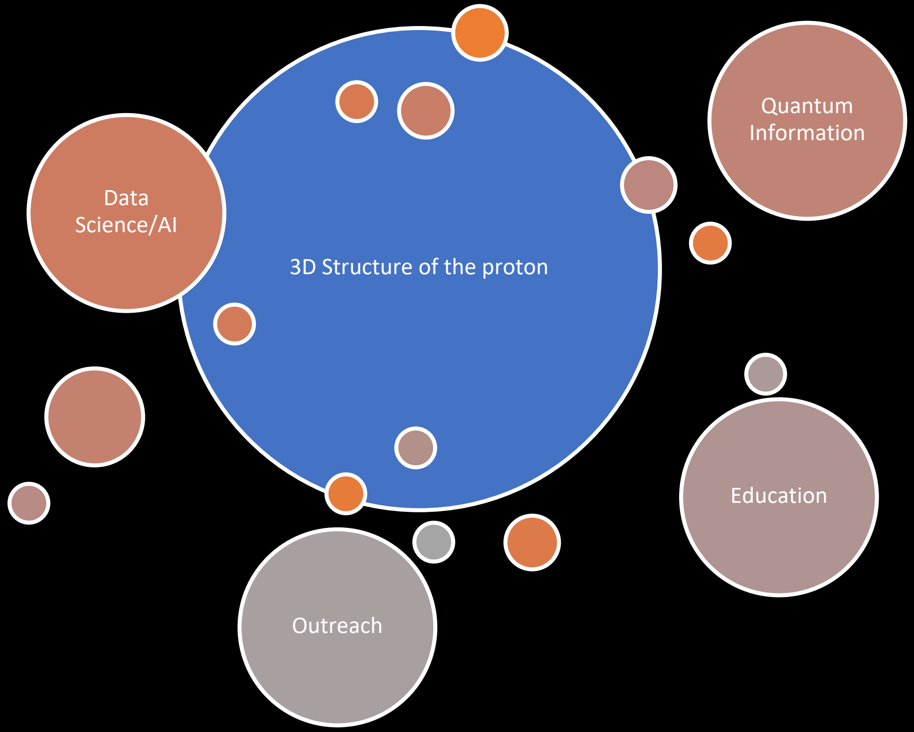
- ✓ Main idea: use DVCS, TCS, DVMP… and related processes as probes
- ✓ Precision: high luminosity in a wide kinematic range is key!
- ✓ Data Management: unprecedented amount of data need new AI based techniques to handle the image making

In the course of 10 years, first proton image!

Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
Hadron spectra as probes of QCD	0	2	1	3	0	**6**
Transverse structure of the hadrons	6	3	3	1	0	**13**
Longitudinal structure of the hadrons	2	3	7	0	0	**12**
3D structure of the hadrons	5	9	6	0	0	**20**
Hadrons and cold nuclear matter	8	5	7	0	1	**21**
Low-energy tests of the Standard Model and Fundamental Symmetries	3	1	0	1	2	**7**
Total	**24**	**23**	**24**	**5**	**3**	**79**

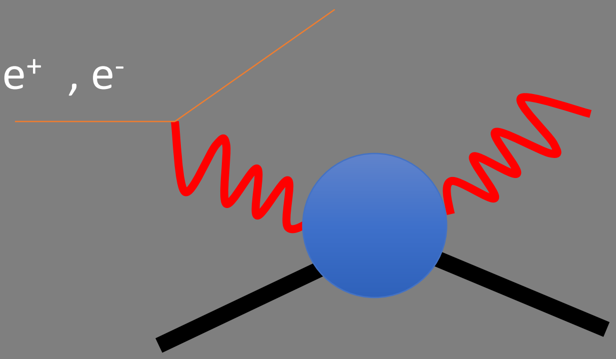
Center for Femtography (CNF)

SURA

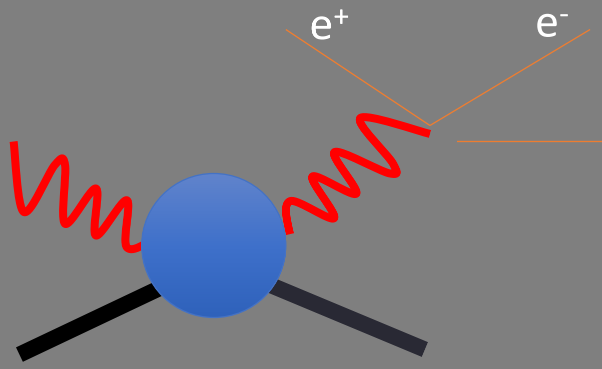


- CNF has funded multiple projects on Femtography
- Covering different areas
  - Experimental data
  - ML & AI
  - Inverse problems
  - Lattice calculations
  - …
- Total funding exceeding $0.5M per year
- Presently moving into a larger collaboration, involving people outside VA.

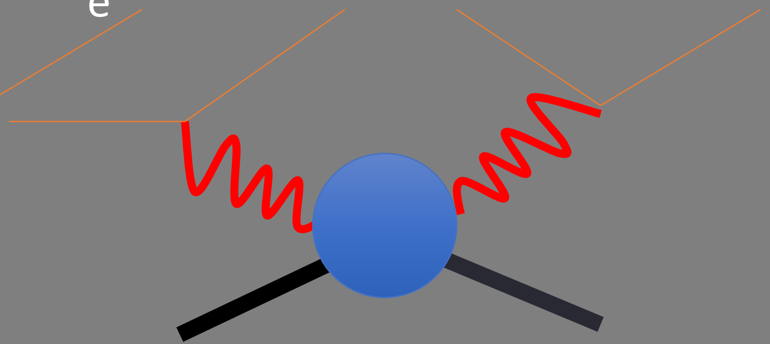
Harnessing/coordinating information from all channels



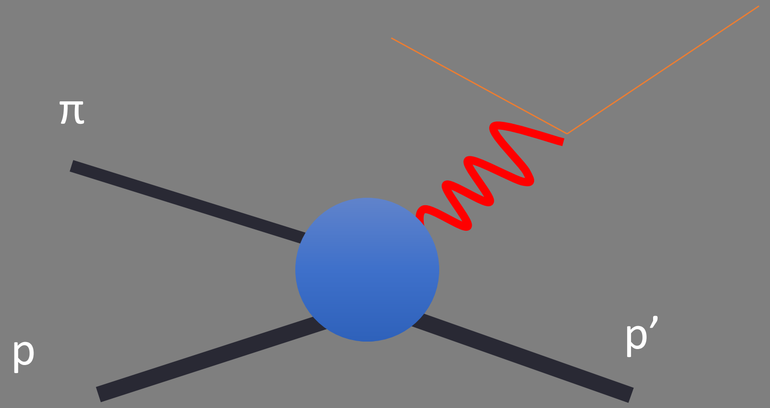
DVCS, DVMP



TCS

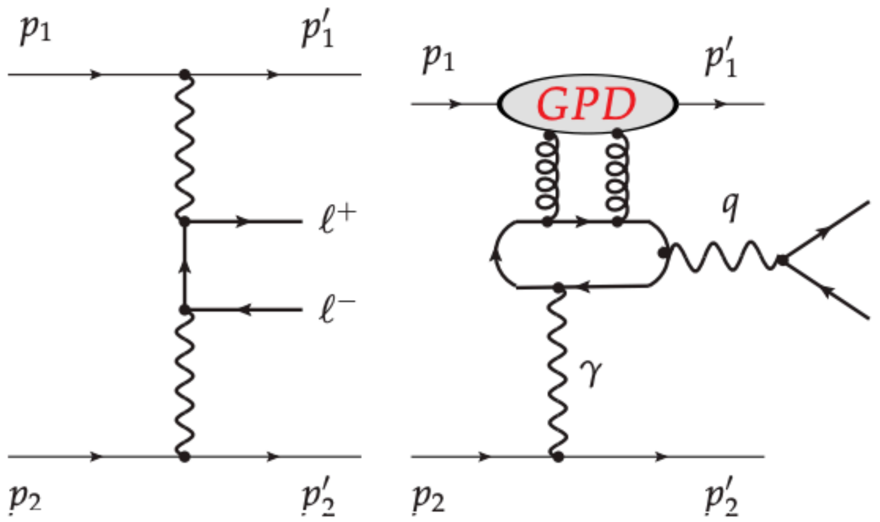


DDVCS



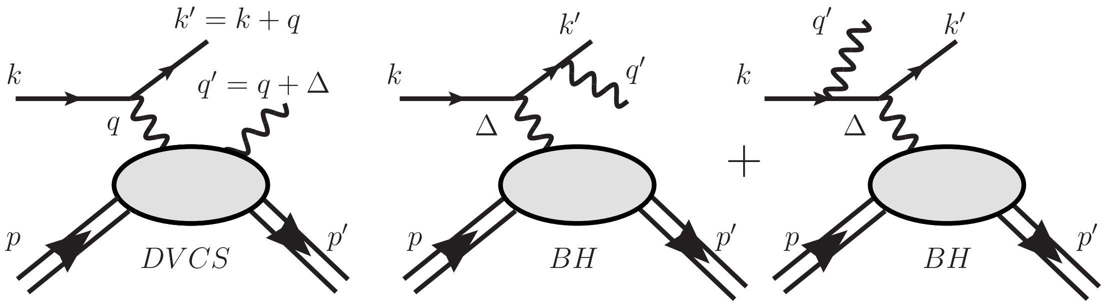
Exclusive pion induced DY (EDY)

Sawada et al., PRD93 (2016)



(a) BH (b) TCS with gluon GPDs

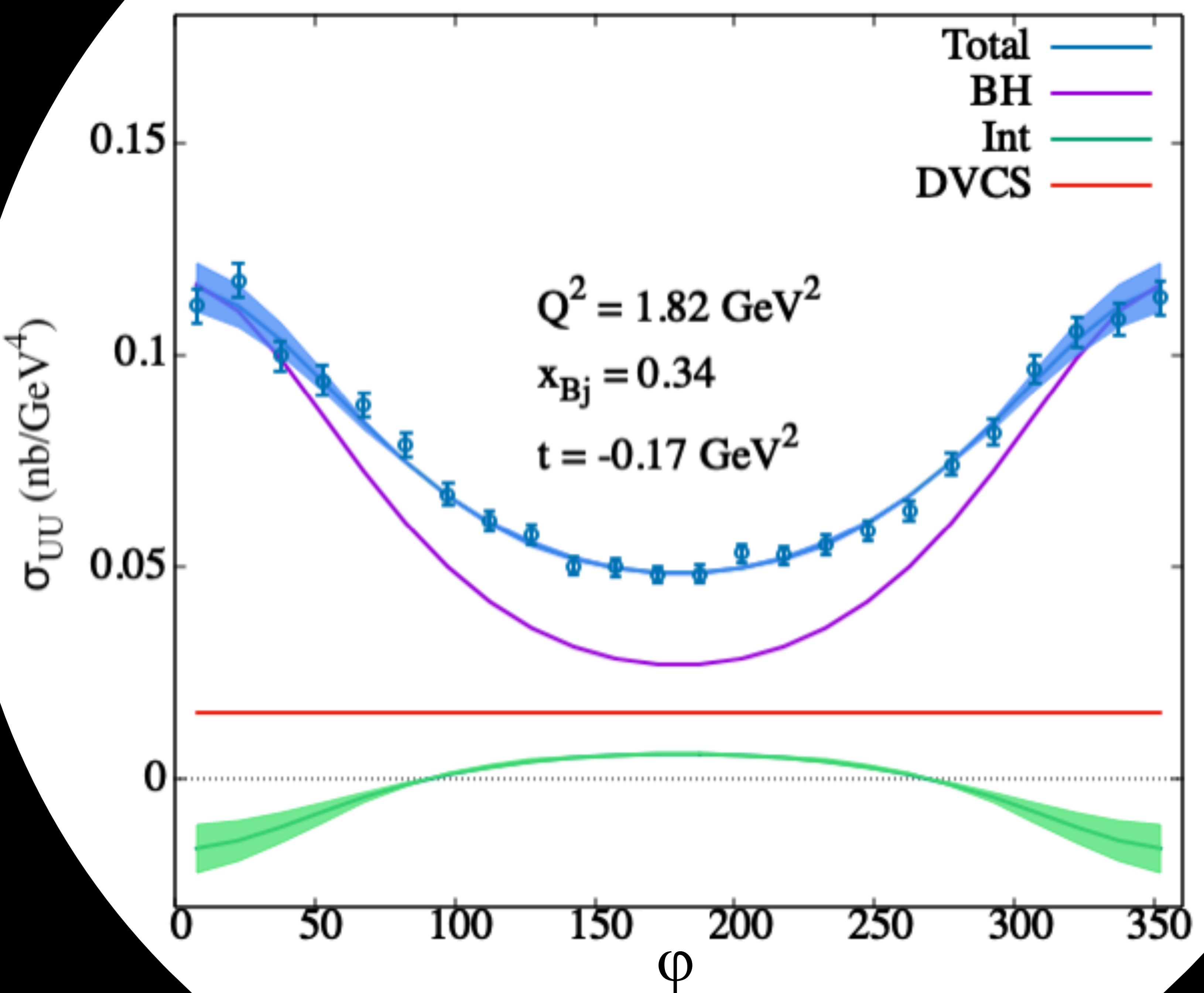
We need a robust framework for the cross section, where kinematic limits are under control (beyond “harmonics” model)

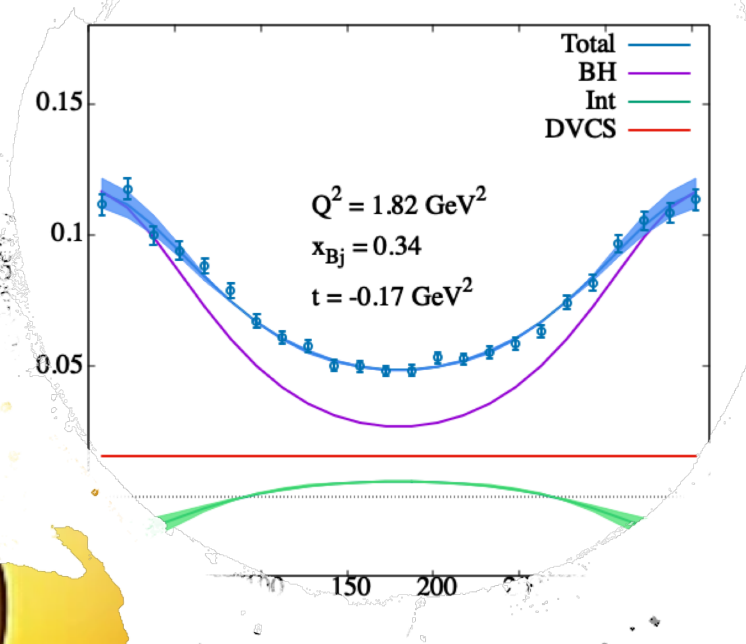


B. Kriesten et al, *Phys.Rev. D* 101 (2020)
B. Kriesten and S. Liuti, arXiv 2004.08890

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

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


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



A comprehensive formalism for the observables is necessary setting up the scene to enable discovery

DVCS

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

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

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

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

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

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

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

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

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

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

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

twist two GPDs

twist three GPDs

U

L

T

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 $\widetilde{\mathrm{H}}$

NEW!! Orbital Angular Momentum L

NEW!! Spin Orbit correlation L ·S

→ 1/Q correction to E

→ 1/Q correction to $\widetilde{\mathrm{E}}$

(*) T-odd

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

BH

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

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

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

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

…compared to ELASTIC SCATTERING

10/28/20

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

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 …

BH-DVCS interference

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

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

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

Twist 3 BH-DVCS interference

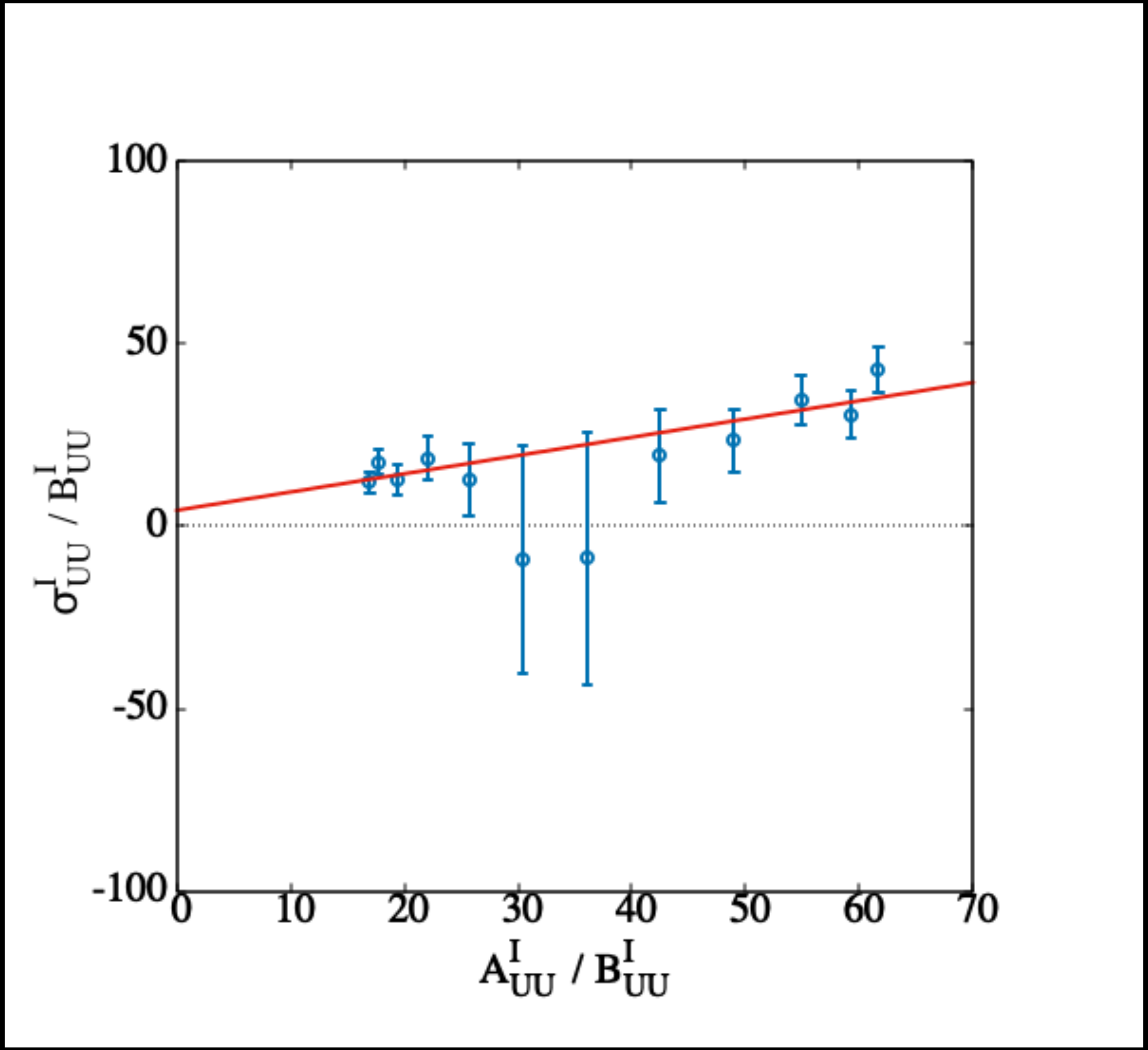
$$F_{UU}^{\mathcal{I}} = F_{UU}^{\mathcal{I},tw2} + \frac{K}{\sqrt{Q^2}} F_{UU}^{\mathcal{I},tw3}$$

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

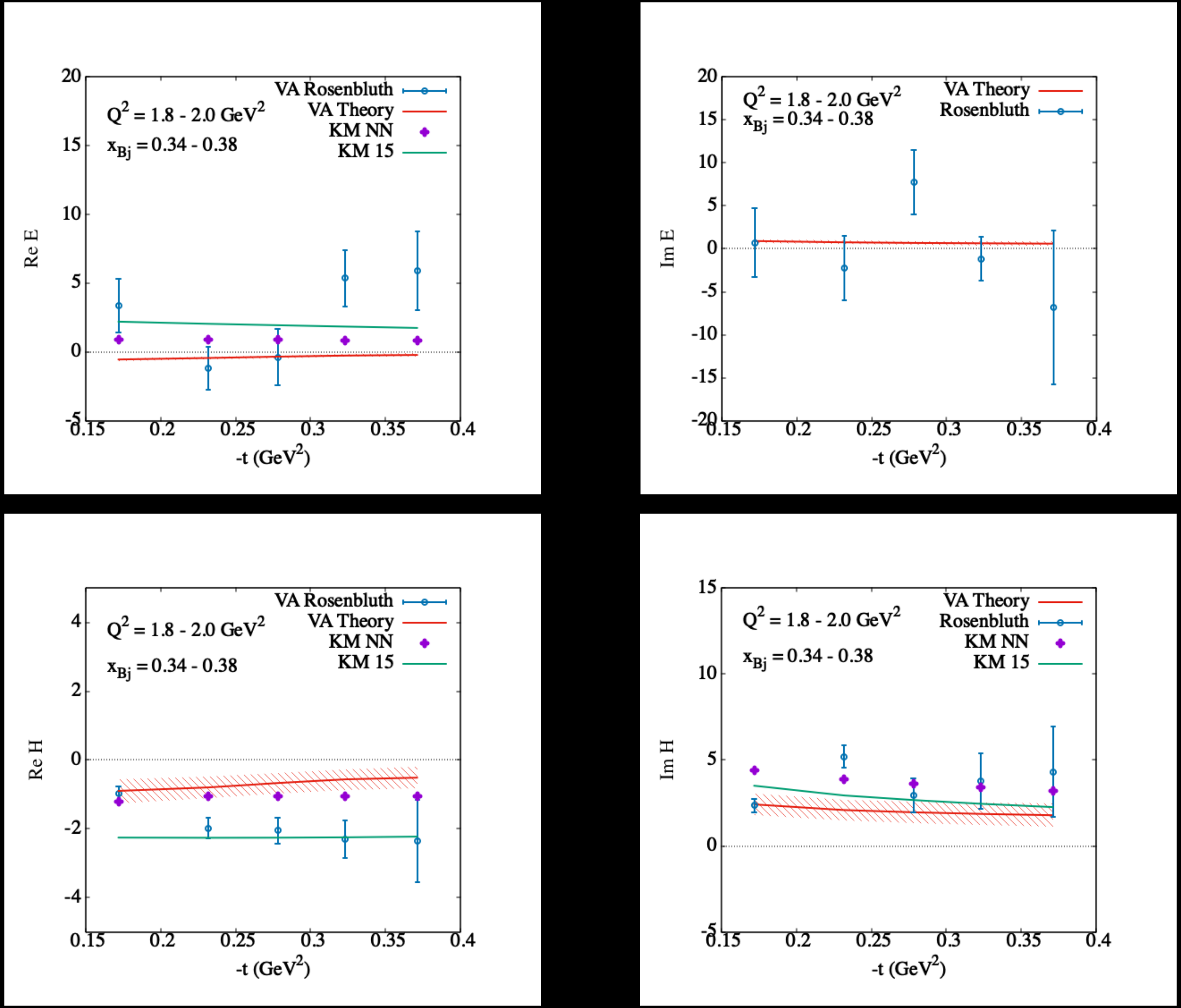
Orbital Angular Momentum

Need different dedicated study of observables!!

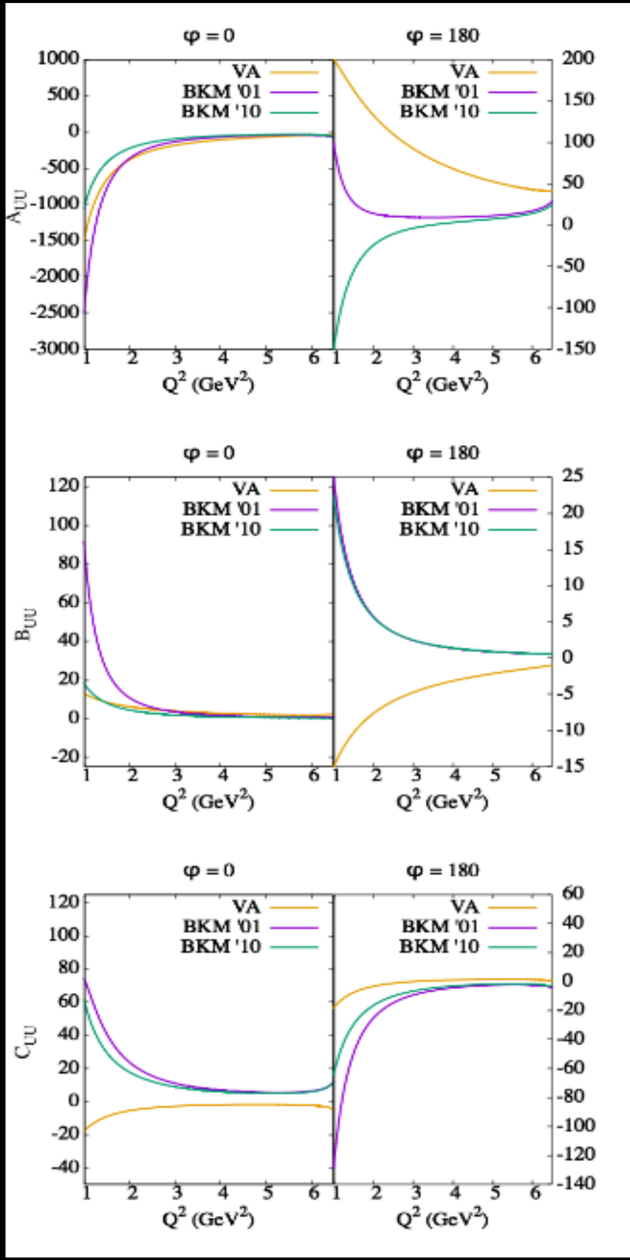
Rosenbluth Separated BH-DVCS interference data



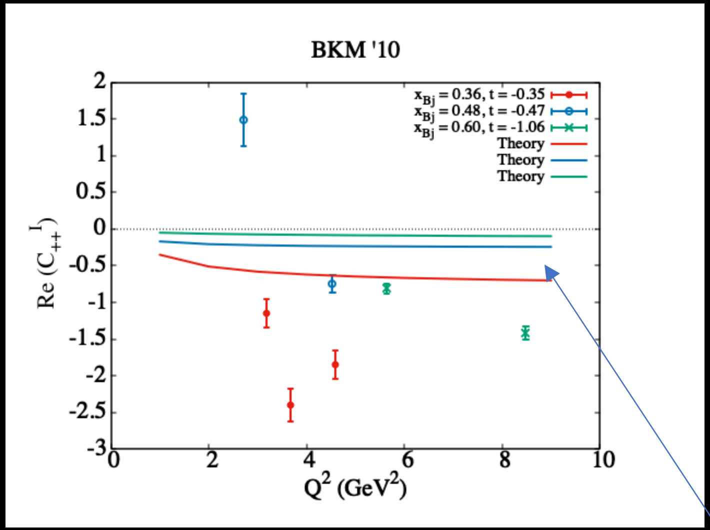
Compton Form Factors



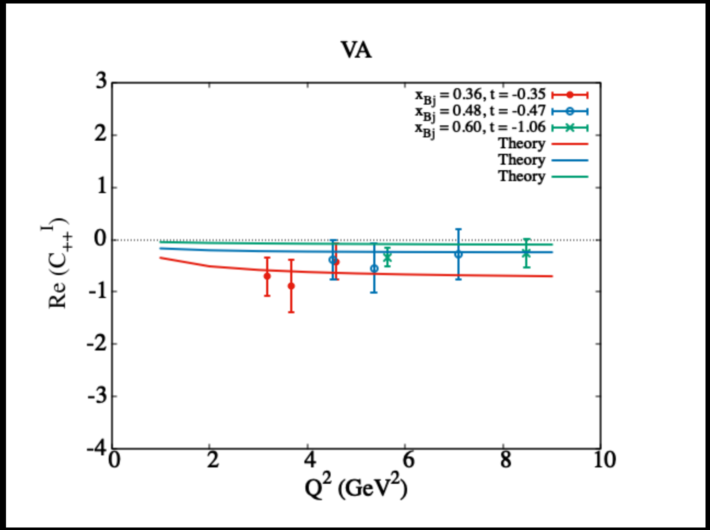
Impact on Q^2 dependence: Brandon Kriesten's talk



Re H



Re H



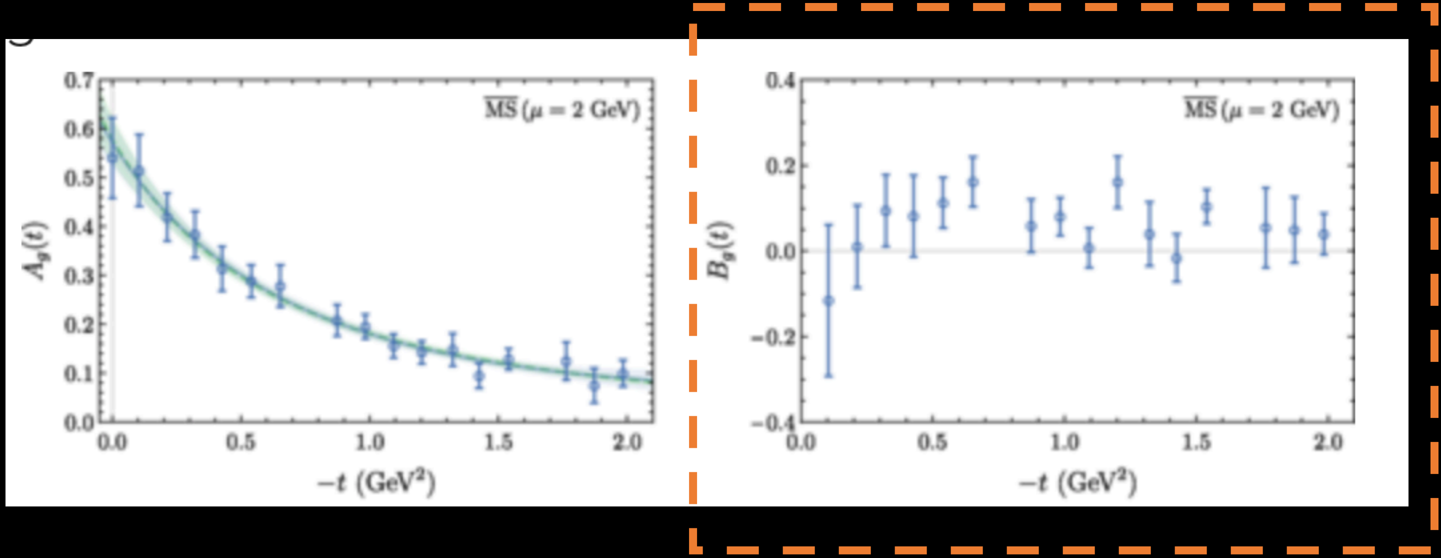
pQCD Evolution

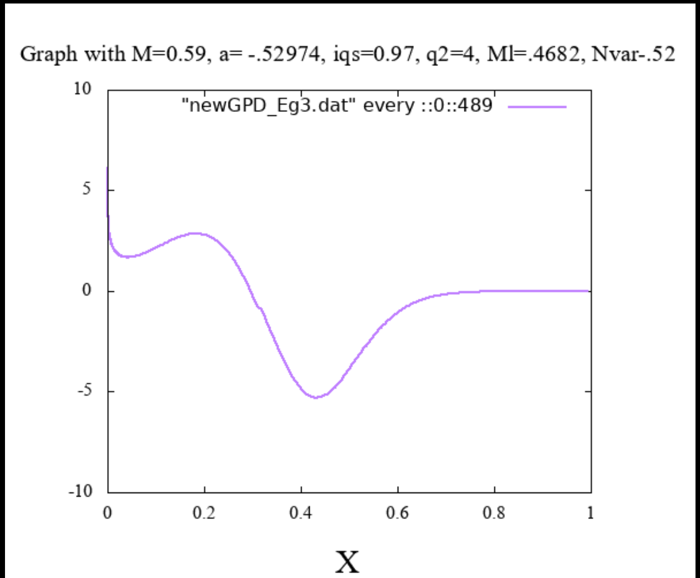
Moving Towards EIC, LHCSpin

Gluon GPDs $J_g + \Sigma_q J_q = \frac{1}{2}$ H_g, E_g

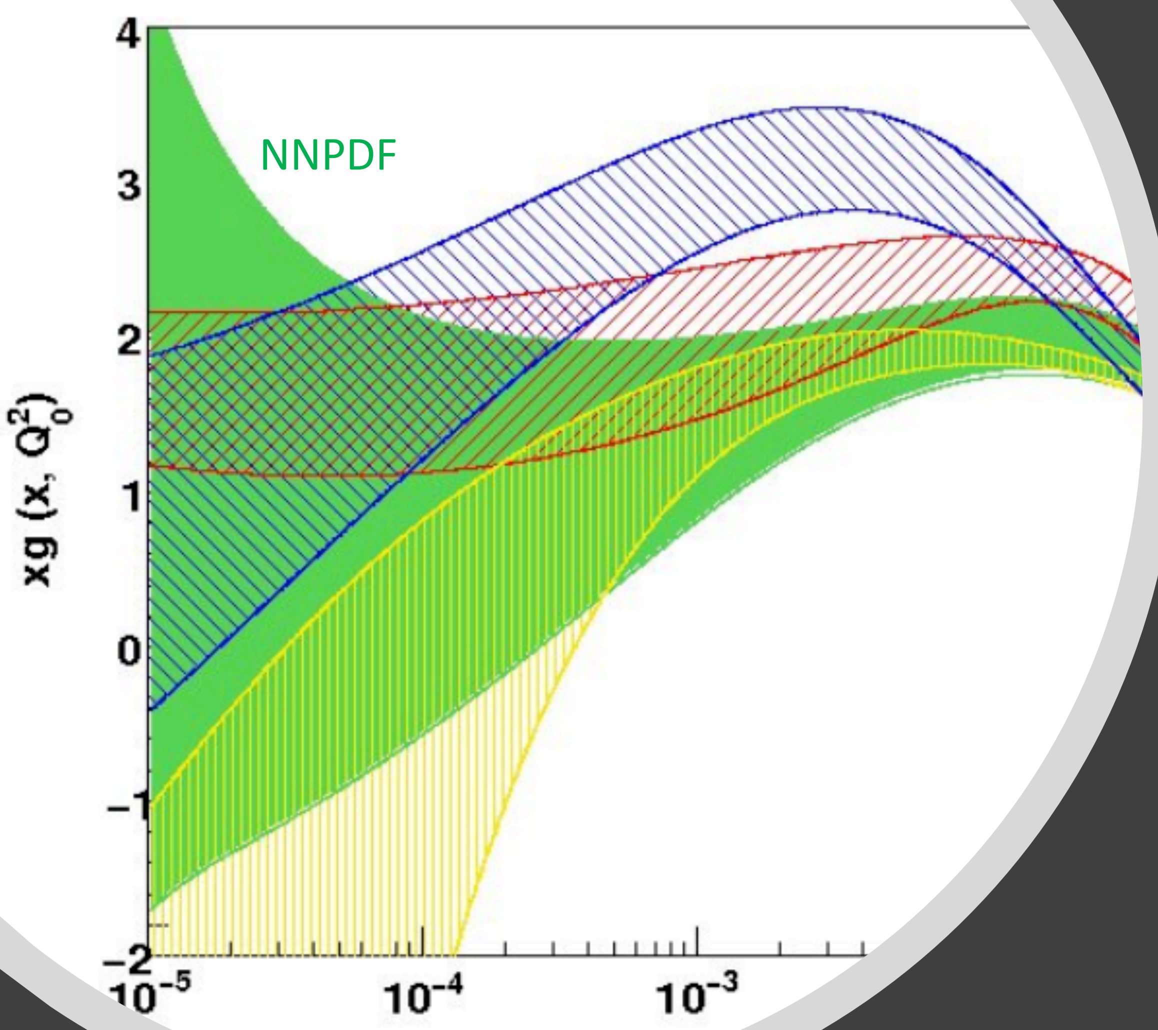
Accessed through PQCD evolution and J/ψ production

Parametrizations/models merging information from lattice QCD





UVA "state of the art results" (B. Kriesten, P. Velie. E. Yeats, F. Yepez)



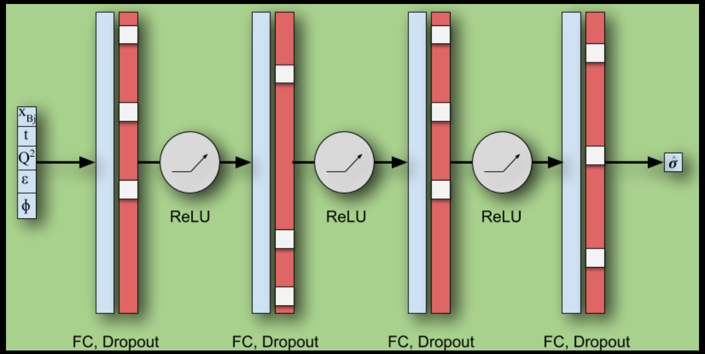
Extracting information from data with standard methods is painstakingly slow: can we use ML/AI?

Brandon Kriesten (UVA), Jake Grigsby (UVA), Pete Alonzi (DS, UVA), Matthias Burkardt (NMSU), Joshua Hoskins (Mary Washington U.), SL

UVA Strategy: supervised learning algorithm augmented by unsupervised (UMAP) method

➢ Using Deep Neural Networks for regression

- The model is a multilayered perceptron (MLP) with 4 hidden layers, each followed by a rectified inear unit (ReLU) activation function



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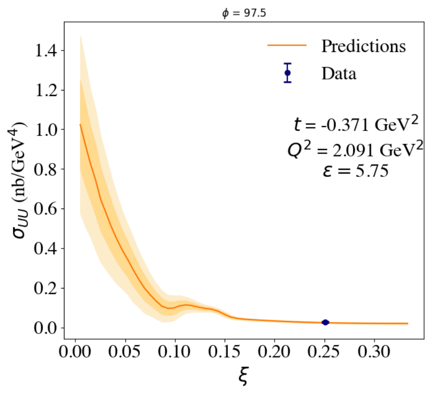
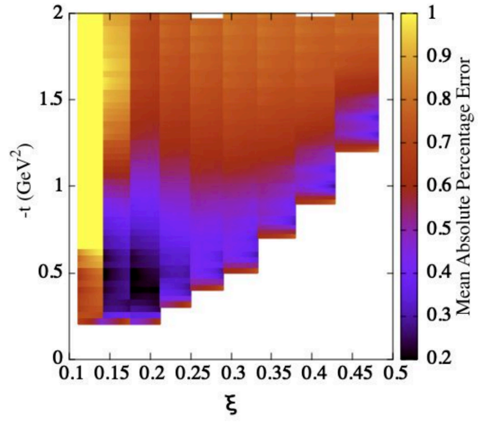
- Once the model is trained, we can use it to make predictions about the value of the cross section in a given kinematic region. The cross section at a point (x_{Bj}, t, Q^2, E, ϕ) is computed by a forward pass of the network. This operation is parallelizable and can run efficiently on a GPU

- We estimate the model's uncertainty by performing many forward passes per prediction point, with Dropout turned on.

Role of Noise and Uncertainty

- We are not restricted to kinematic bins that have already been measured - the model learns to extrapolate between existing bins.
- We can sweep through regions where data do not exist, and use the model's uncertainty estimate to advise our use of its predictions
- This creates a distribution of predictions, and we use the mean and standard deviation of that distribution to estimate uncertainty
- (Gal & Ghahramani, 2016)





	UU				LU			
	Standard		Feature Engineering		Standard		Feature Engineering	
Method	Median Error (%)	Accuracy (%)	Median Error (%)	Accuracy (%)	Median Error (%)	Accuracy (%)	Median Error (%)	Accuracy (%)
Linear	238.87	1.61	347.77	0.53	239.37	22.44	289.60	24.02
SVR	57.70	15.86	58.92	13.17	94.92	43.70	68.55	59.06
Random Forest	32.90	24.73	32.27	26.88	62.87	59.45	**63.65**	59.06
KNN	19.84	37.63	**20.93**	34.41	**62.36**	60.24	68.09	56.69
DNN	**19.11**	**61.3**	21.56	**60.5**	145.86	**62.0**	150.62	**65.8**

This model will be open-sourced

What I left out

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

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