3D Tomography of the Nucleon Using GPDs

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CENTER *for* NUCLEAR FEMTOGRAPHY

FemtoNET

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Outline

- What is Femtography?
- Theoretical Motivation
- 3 Dimensional Imaging
- Experiment and Femtography
- Additional Tools for Imaging

What is Femtography?

Femtography - is **data driven visualizations** of the phase space distribution of the quarks and gluons inside of the proton using a variety of **deeply virtual exclusive processes**.

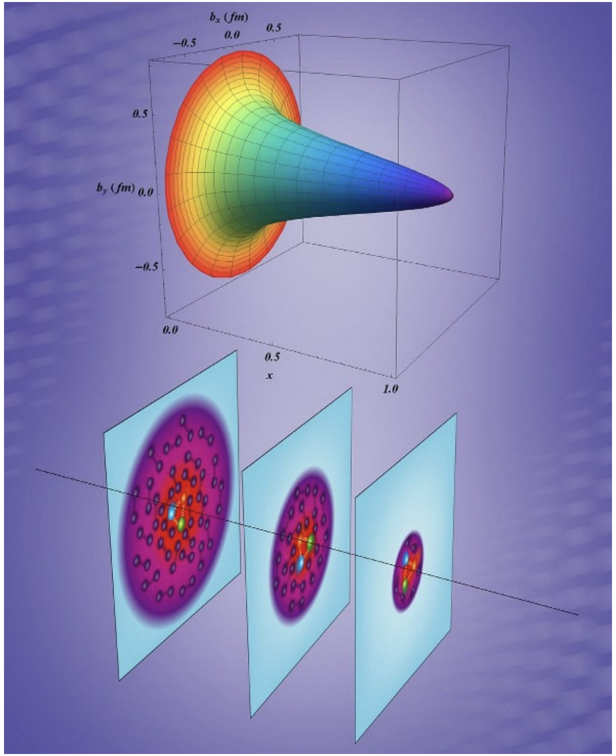


Image credit: **Rafael Dupre**

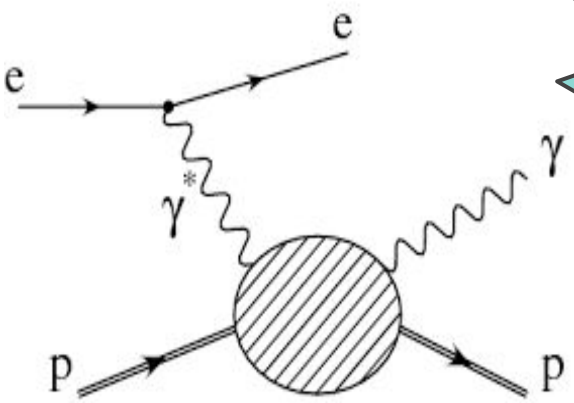
Nature of Deeply Virtual Exclusive Processes

A **new paradigm** for measuring the fundamental properties of nuclei by probing the quantum mechanical **phase space distributions** of the quarks and gluons.

Where does the proton spin come from?

$$J^q = \int dx x [H^q(x,0,0) + E^q(x,0,0)]$$

Kyle's Talk

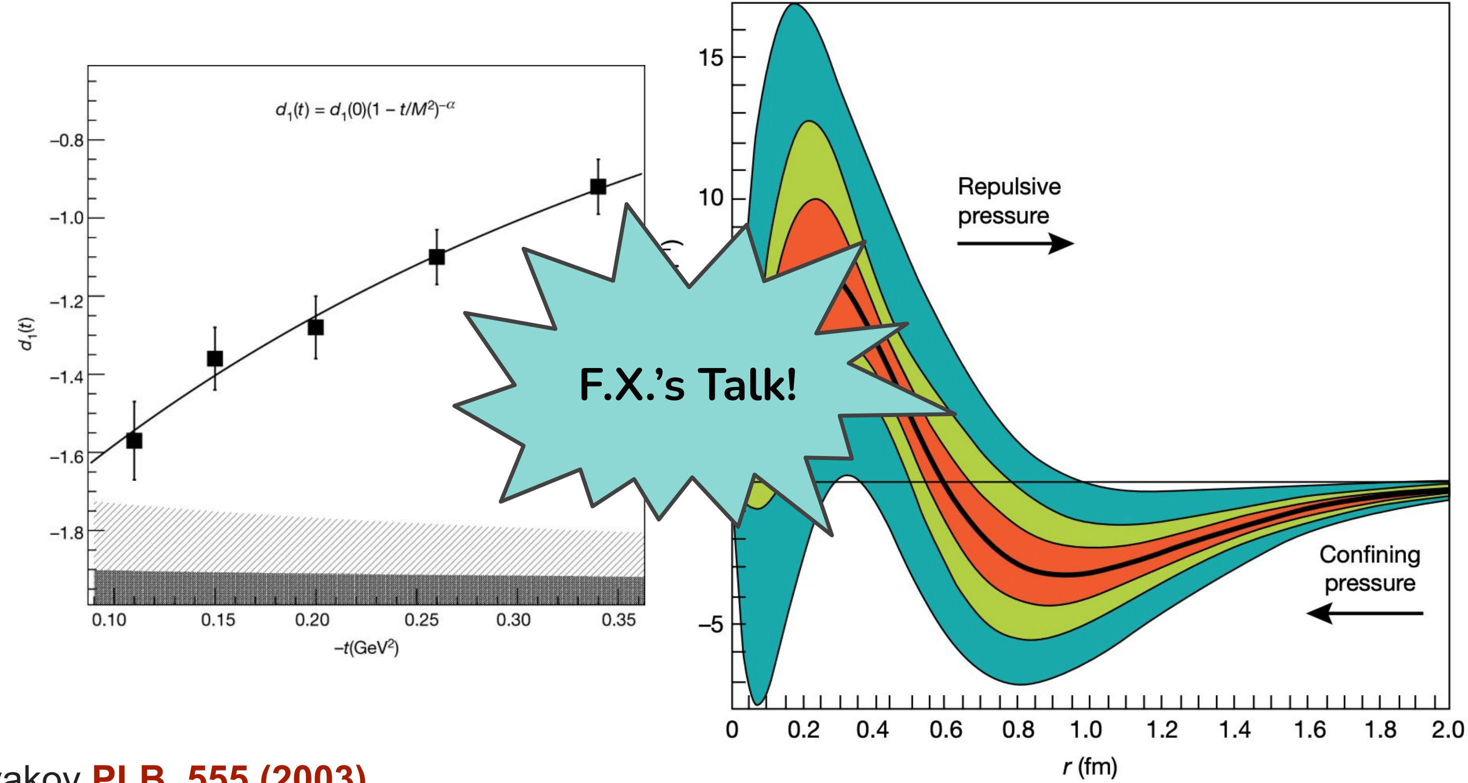


$$J^i_{q,g} = \frac{1}{2}\epsilon^{ijk} \int d^3x M^{0jk}$$

$$J^i_{q,g} = \frac{1}{2}\epsilon^{ijk} \int d^3x (T^{0k}_{q,g} x^j - T^{0j}_{q,g} x^k)$$

X. Ji **PRL. 78 (1997)**

The mechanical properties of nuclei: pressure in the proton?



M. V. Polyakov **PLB. 555 (2003)**
M. V. Polyakov, P. Schweitzer **Int.J.Mod.Phys. A33 (2018)**
V. Burkert, L. Elouadrhiri, F.X. Girod ***Nature* v. 557 (2018)**

Phase Space (Wigner) Distributions in the Proton

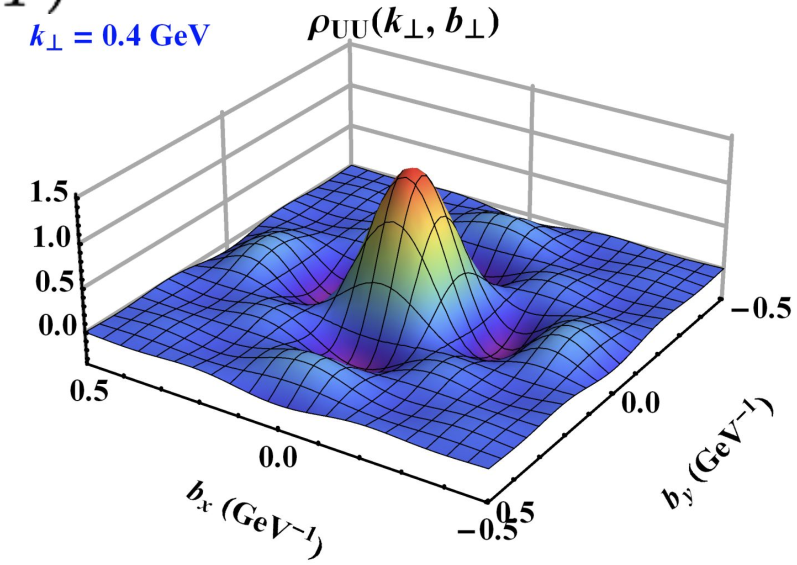
Wigner Distribution $W(x, \vec{k_T}, \vec{b_T})$

$b_T \to \Delta_T$

Generalized Transverse Momentum Distribution Functions $W(x, \vec{k_T}, \vec{\Delta_T})$

$\int d^2 k_T$

Generalized Parton Distribution Functions $H(x, \vec{\Delta_T})$



A.V. Belitsky, X. Ji, F. Yuan **PRD. 69 (2003)**
Ji, Xiong, Yuan **PRD 88 (2013) (gluon)**

Lorce and Pasquini **PRD.84 (2011)**
Lorce and Pasquini **JHEP 1309 (2013) (gluon)**
More, Mukherjee, Nair, **PRD. 95 (2017)**

Generalized parton distributions

$$F^{[\Gamma]}_{\Lambda,\Lambda'}(x,\xi,t) = \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ikz} \langle p',\Lambda'|\overline{\psi}(-\frac{z}{2})\Gamma \mathcal{W}(-\frac{z}{2},\frac{z}{2}|n)\psi(\frac{z}{2})|p,\Lambda\rangle\Big|_{z^+=z_T=0}$$

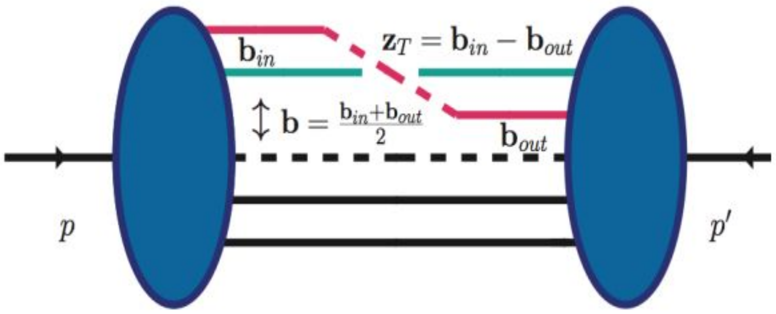


Image credit: A. Rajan, M. Engelhardt, S. Liuti **PRD 98 (2018)**

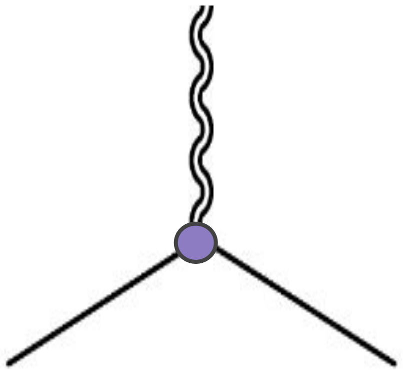
b_T Relative average transverse position from the center of momentum of the system ⟺ Δ_T

k_T Relative average transverse momentum (integrated) ⟺ z_T

X. Ji **PRL. 78 (1997)**
A. Radyushkin **PRD. 56 (1997)**
D. Muller, et. al. **(1994)**
M. Diehl **Phys.Rep. (2003)**

Energy Momentum Tensor Form Factors

$$\langle P'|T^{\mu\nu}_{q,g}|P\rangle = \overline{U}(P')[A_{q,g}(\Delta^2)\gamma^{(\mu}\overline{P}^{\nu)} + B_{q,g}(\Delta^2)\overline{P}^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha/2M$$
$$+C_{q,g}(\Delta^2)(\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2)/M + \overline{C}_{q,g}(\Delta^2)g^{\mu\nu}M]U(P)$$

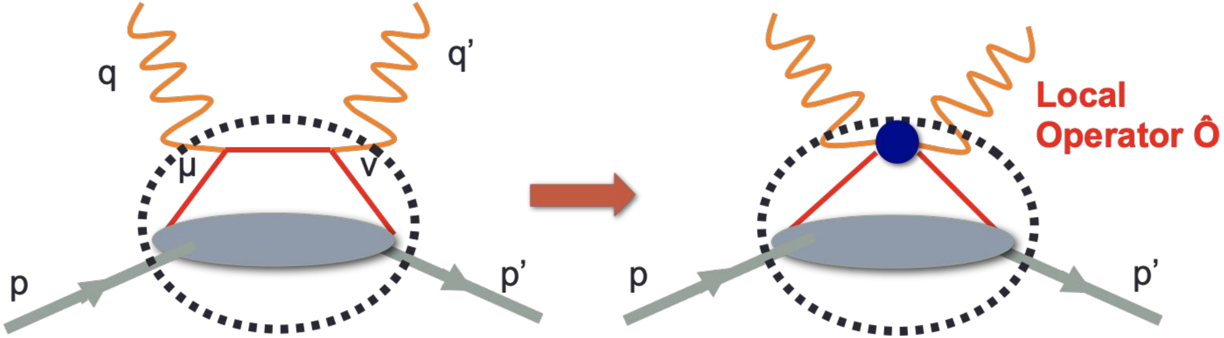


p $\quad$ $p' = p - \Delta$

X. Ji **PRL. 78 (1997)**

The matrix elements of the energy momentum tensor can be parameterized by **form factors** describing elastic scattering of a graviton off a proton.

Connection between Local Operators and GPDs



$$\int dx x H(x,\xi,t) = A(t) + \xi^2 C(t) \qquad \int dx x E(x,\xi,t) = B(t) - \xi^2 C(t)$$

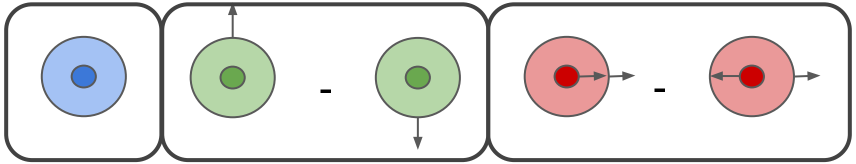
Image credit: **Simonetta Liuti**

X. Ji, W. Melnitchouk, X. Song **PRD 56 (1997)**

Momentum Space to Transverse Position Space

Probability density of finding a quark at transverse position b from the center of momentum as a function of quark and proton polarization.

$$\rho^q_{\Lambda\lambda}(\mathbf{b}) = H_q(\mathbf{b}^2) + \frac{b^i}{M}\epsilon_{ij} S^j_T \frac{\partial}{\partial b} E_q(\mathbf{b}^2) + \Lambda\lambda \widetilde{H}_q(\mathbf{b}^2)$$



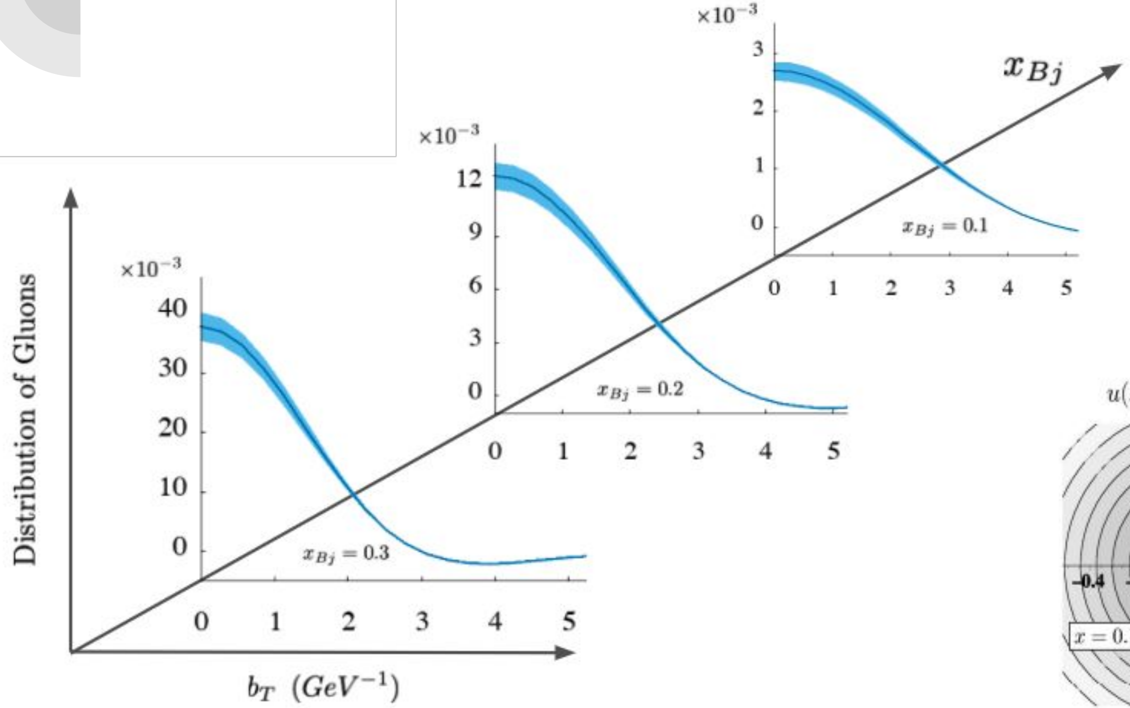
$$\rho^q_{\Uparrow}(x, b_T) = \int \frac{d^2\Delta_T}{(2\pi)^2} \left[H(x,0,t) - \frac{1}{2M} E(x,0,t) \frac{\partial}{\partial b_y} \right] e^{-i\Delta_T \cdot b_T}$$

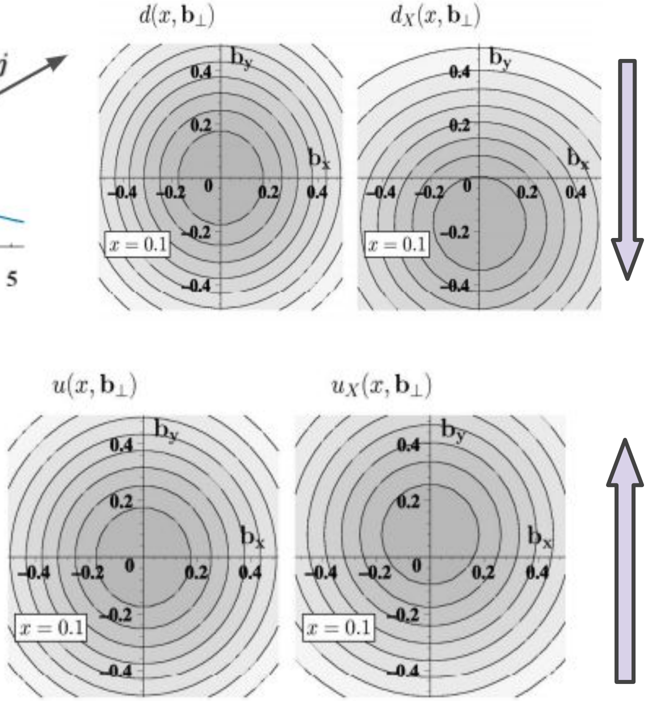
M. Burkardt **PRD. 62 (2000)**
M. Burkardt ***Int.J.Mod.Phys.A* 18 (2003)**

Transverse polarization shifts the unpolarized distribution proportional to the GPD E.

2+1 Dimensional Imaging in Impact Parameter Space

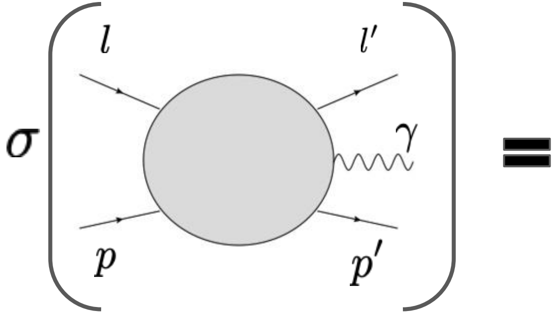
M. Burkardt **PRD. 66 (2002)**

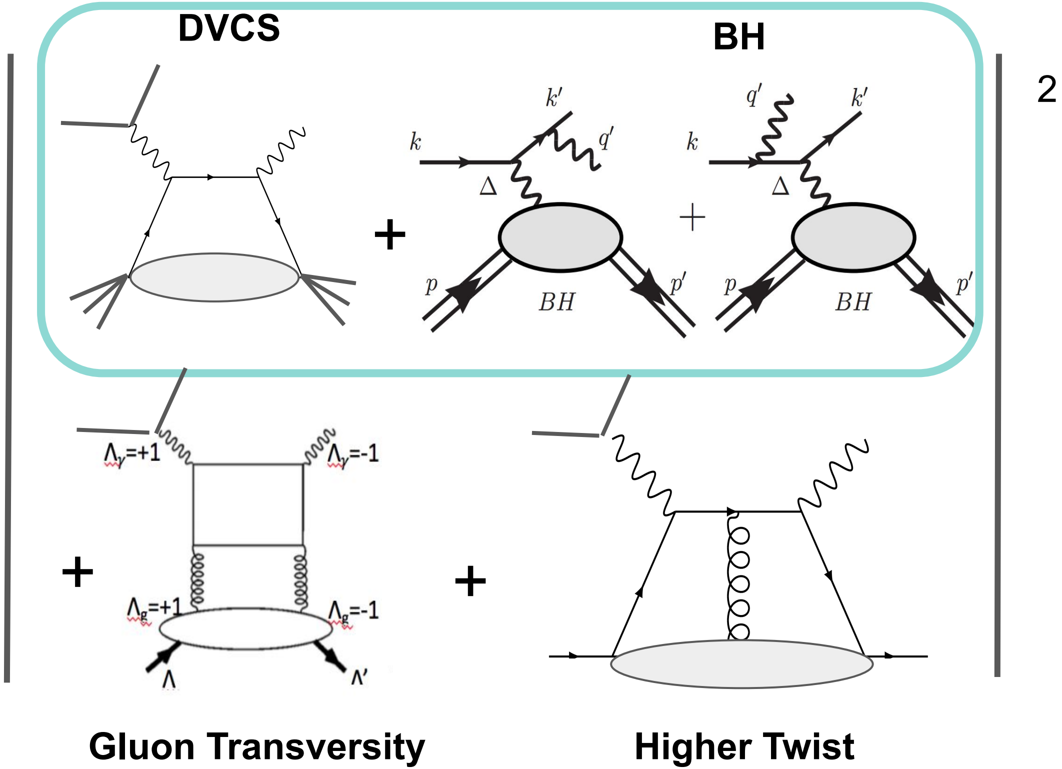




Gluon GPDs: B. Kriesten, P. Velie, E. Yeats, F.Y. Lopez, S. Liuti **arXiv:2101.01826**
Fourier Transforms: A. Rajan, B. Kriesten, S. Liuti **(in progress)**

Deeply Virtual Compton Scattering





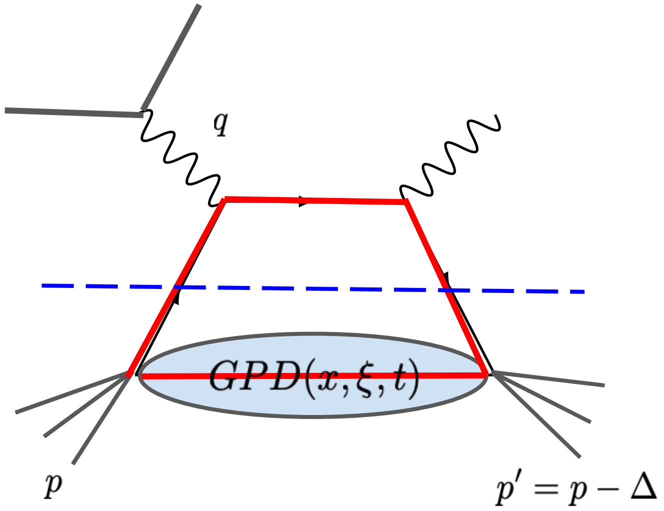
DVCS is known to probe **generalized parton distributions** and is accompanied by various background processes.

X. Ji, **PRD. 55 (1997)**

B.Kriesten, S.Liuti, et. al. **PRD. 101 (2020)**

Inverse Problem for Extracting GPDs?

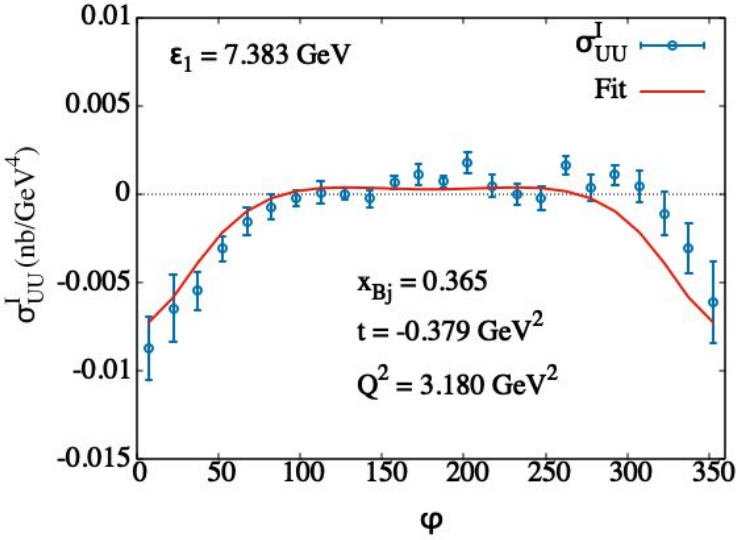
Issues with GPDs: they come convoluted with Wilson coefficient functions (Compton Form Factors) meaning we only have experimental access to integrals (ReCFF) or specific points in x (ImCFF) of these distributions.

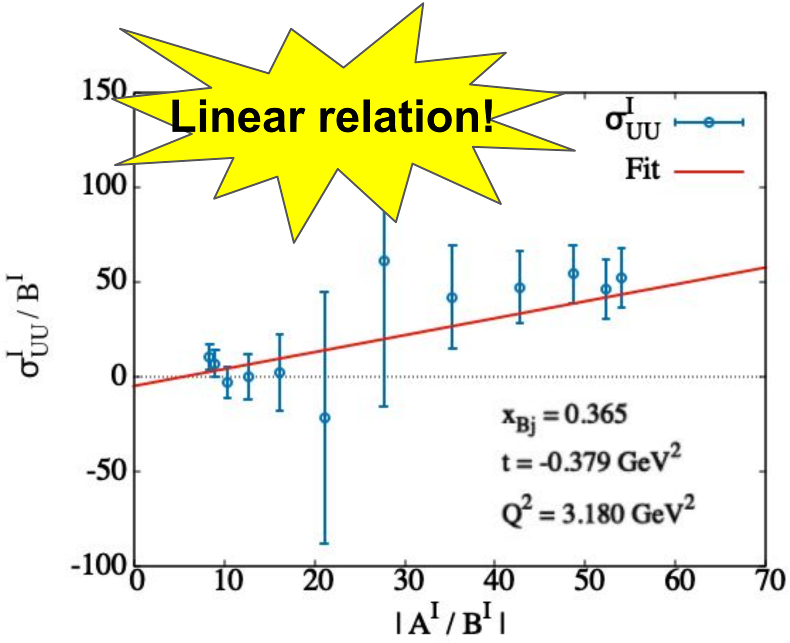


$$\int_{-1}^{+1} dx \frac{F^q(x,\xi,t)}{x-\xi+i\epsilon} = \mathcal{P}\int_{-1}^{+1} dx \frac{F^q(x,\xi,t)}{x-\xi} - i\pi F(\xi,\xi,t)$$

Rosenbluth Separation using DVCS Data

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

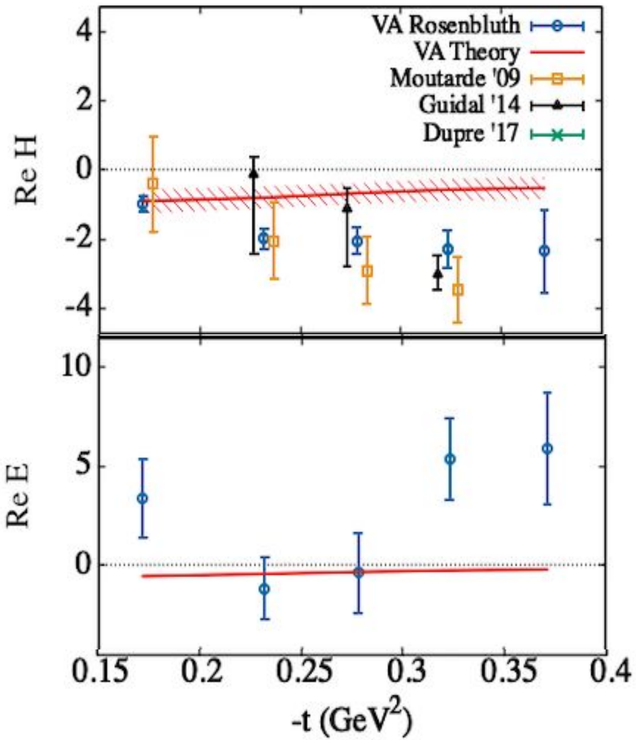




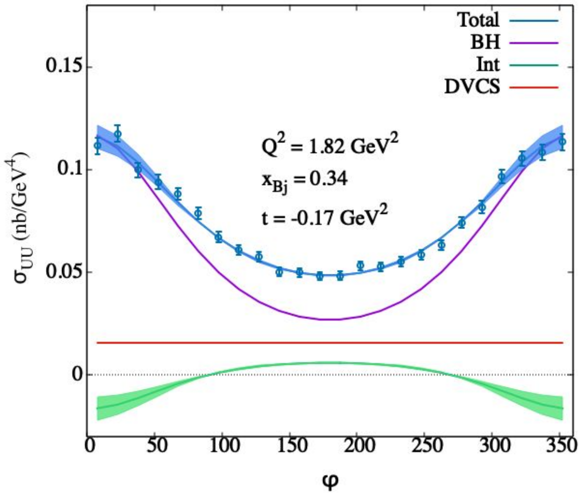
B. Kriesten, S. Liuti, A. Meyer **arXiv: 2011.04484**
B.Kriesten, S. Liuti **arXiv: 2004.08890**

Data: F. Georges et. al. **Ph.D. Thesis (2018)**

CFF Extractions: A comparison of methods



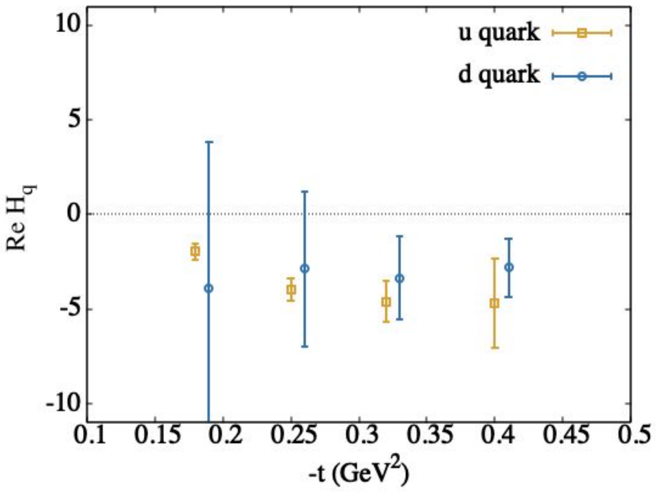
All CFF extractions use the same data, but with different extraction methods and cross section formula you extract different values and different size error bars.



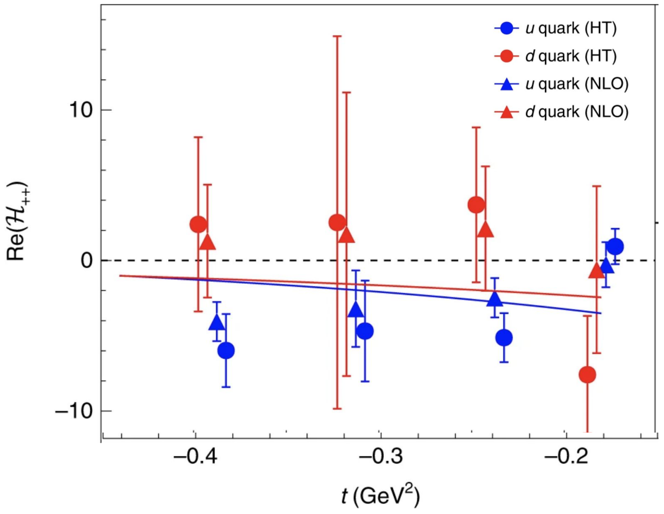
B. Kriesten, S. Liuti, A. Meyer **arXiv: 2011.04484**

Data: M. Defurne et.al. **PRC (2015)**

Flavor Separation using Neutron DVCS Data



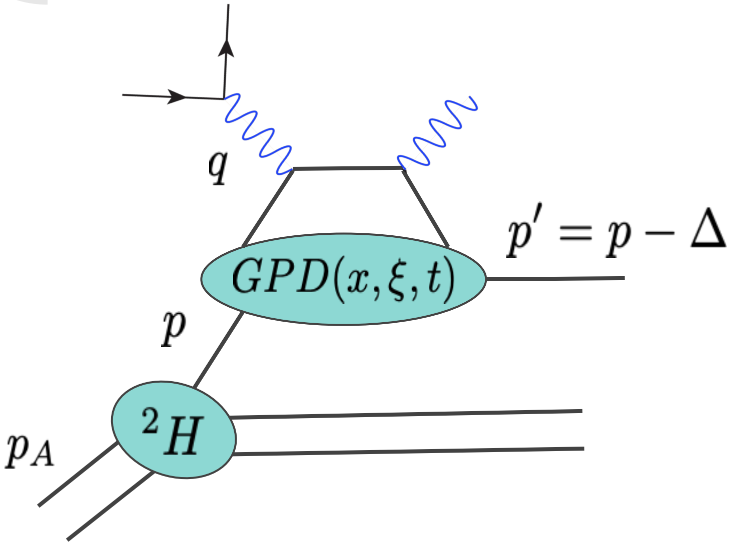
B. Kriesten, S. Liuti **(in progress)**



M. Benali, et. al. **Nature Physics 16, (2020)**

Using a combination of proton and neutron data we can flavor separate CFFs where an EIC will help constrain the neutron DVCS errors.

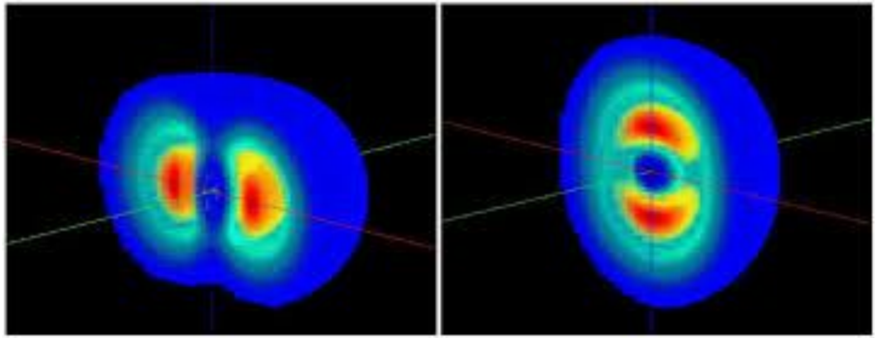
DVCS on Light Nuclei



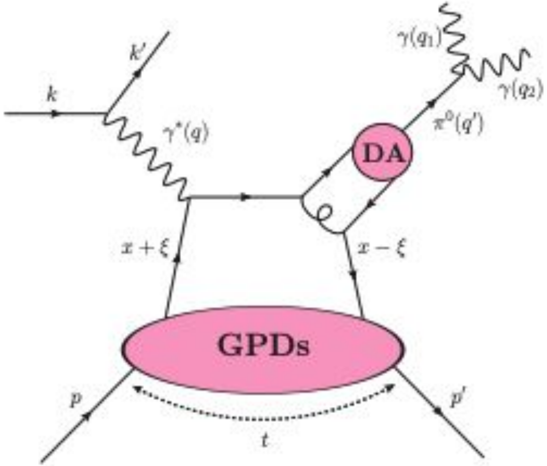
S. Taneja, K. Kathuria, S Liuti, and G.R. Goldstein **PRD. 86 (2012)**

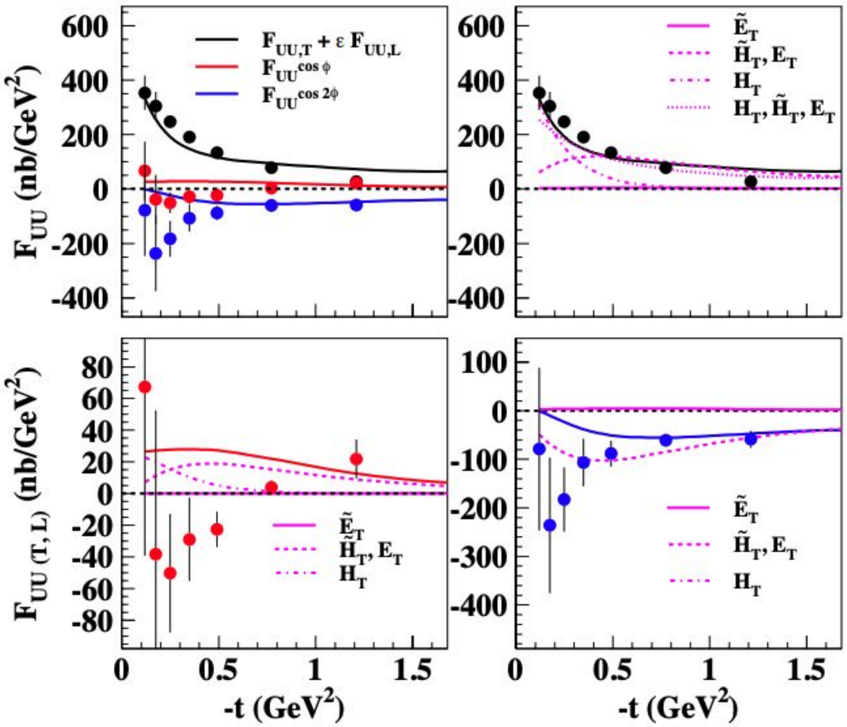
Using the Spin-1 Energy Momentum Tensor, a similar angular momentum sum rule has been developed for the Spin-1 deuteron

$$J_q = \frac{1}{2}\int dx\, x H_2^q(x, 0, 0)$$



pi0 electroproduction and Chiral Odd GPDs





Ahmad, Goldstein, Liuti **PRD.79 (2009)**

Goloskokov, Kroll **EPJA (2011)**

Data: Bedlinsky et. al. **PRL. 109, (2012)**

Deeply Virtual pi0 Production Q2 dependence

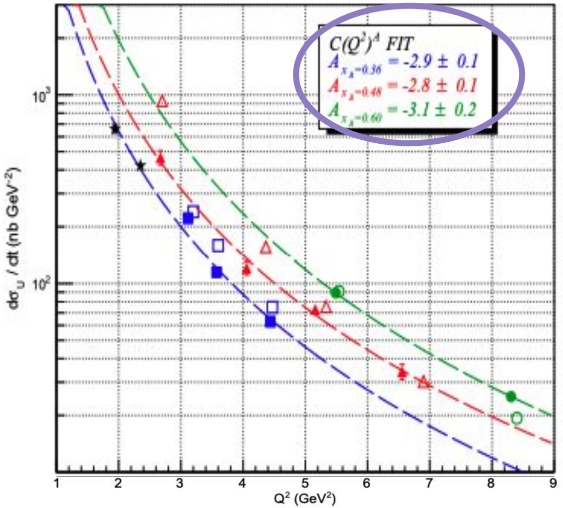
Chance to study scaling effects and the scattering mechanism of pi0 electroproduction.

$$\frac{d\sigma_U}{dt} = \boxed{\frac{d\sigma_T}{dt}} + \epsilon \boxed{\frac{d\sigma_L}{dt}}$$

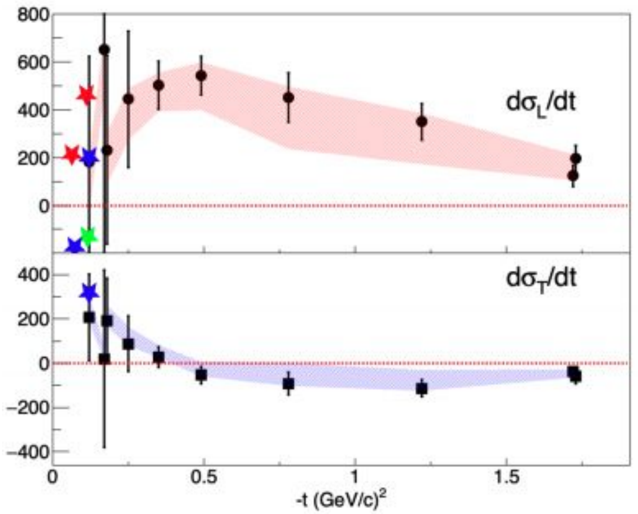
$$Q^{-8} \qquad Q^{-6}$$

J. Collins et. al. **PhysRevD.56.2982**

Data: M. Defurne et. al. **PRL 117 (2017)**
E. Fuchey **PRC 83 (2011)**
Bedlinsky et. al. **PRL. 109, (2012)**

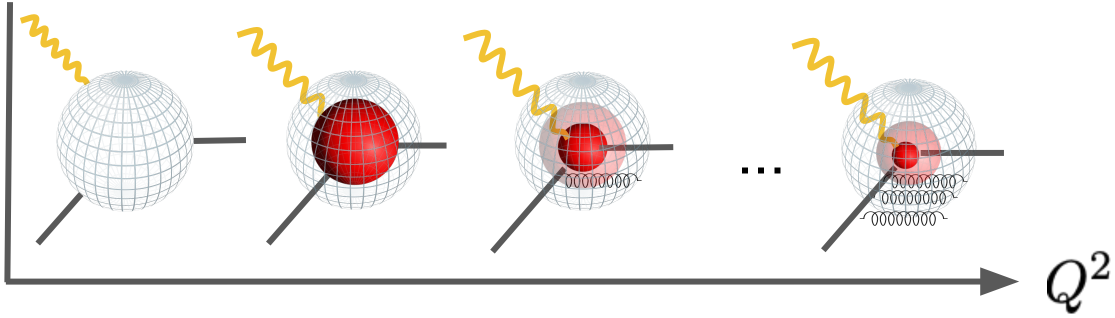


M. Dlamini et. al. **arXiv:2011.11125**



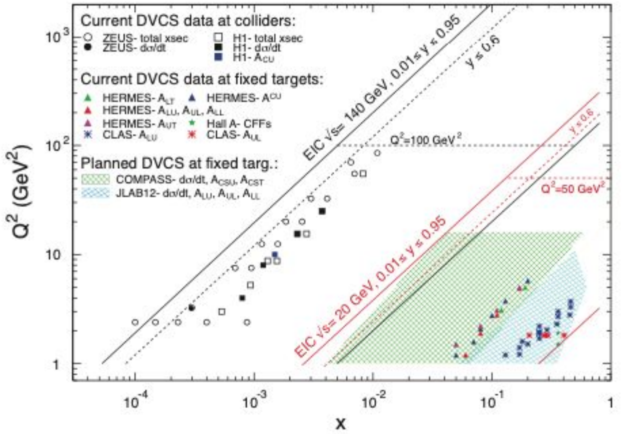
I. Korover, R. Milner **arXiv:2103:00611**

Where is the glue?



$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_S(Q^2)}{2\pi}\left[P_{QQ}\otimes F_2 + \boxed{2e^2 P_{QG}\otimes xg(x)}\right]$$

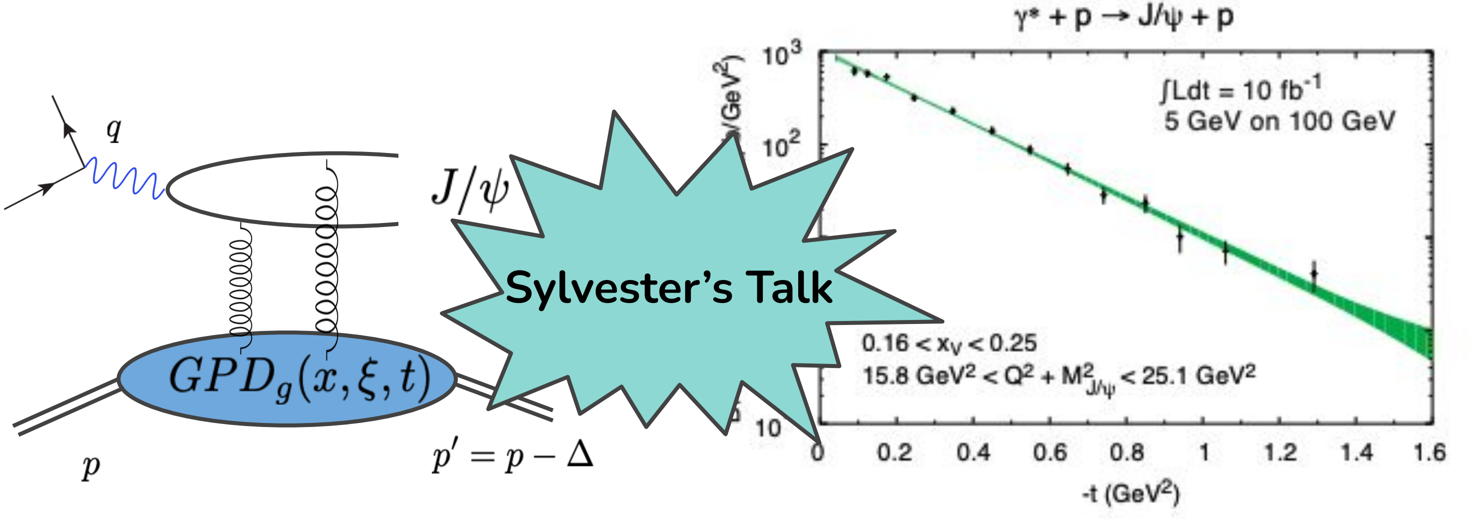
A **lever arm in Q2** hopefully allows us to use perturbative evolution to extract the gluon distribution.



EIC Yellow Report **arXiv: 2103.05419**
EIC White Paper **arXiv: 1212.1701**

Exclusive Measurements of Gluon Distributions

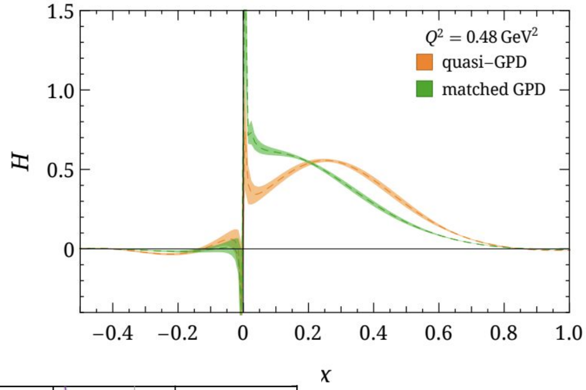
Exclusive electroproduction of vector mesons (such as the J/psi) can also probe the gluon content of nuclei



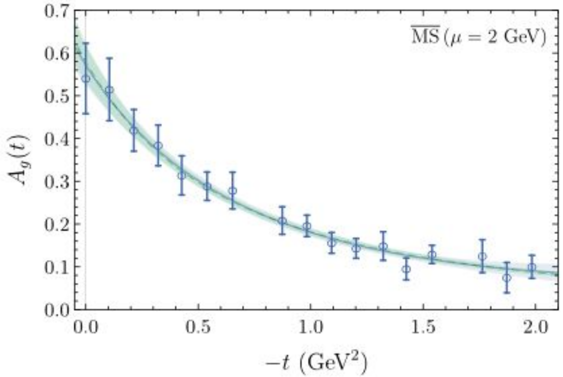
EIC White Paper **arXiv: 1212.1701**

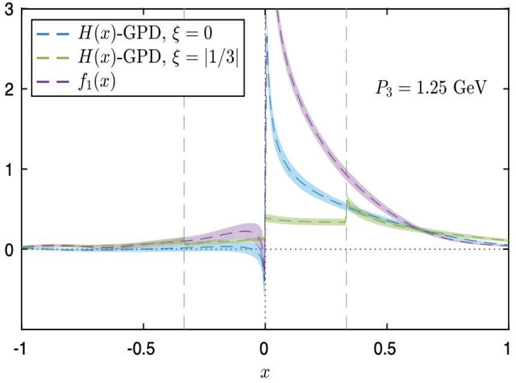
Additional Tools: Constraints from Lattice QCD

H.W. Lin **arXiv:2008:12474**

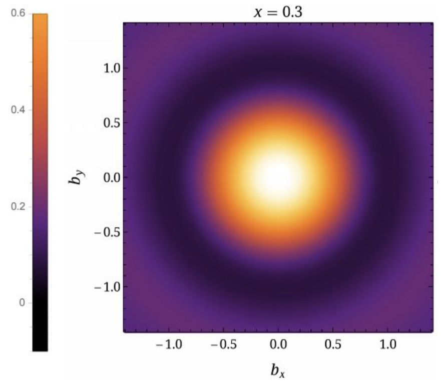


P.E. Shanahan, W. Detmold **PRD 99 (2019)**



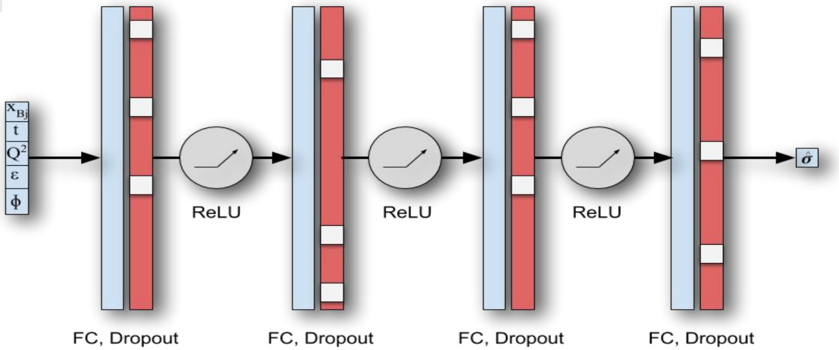


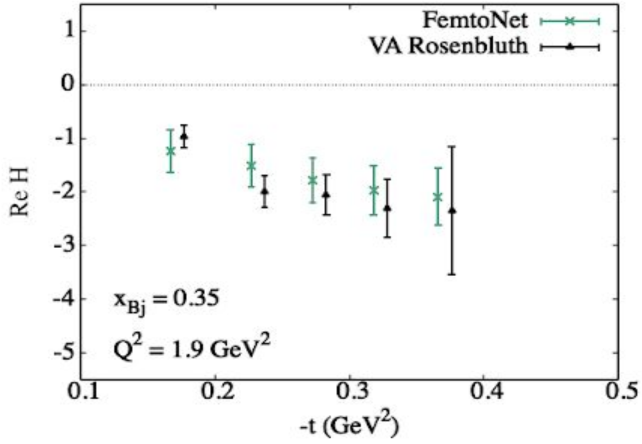
ETMC **PRL 125 (2020)**

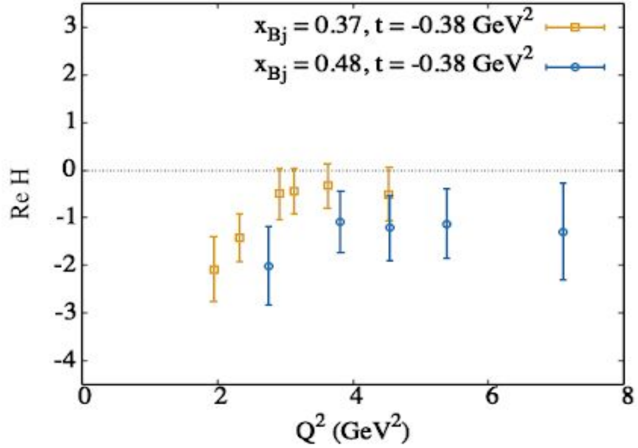


Lattice QCD can place **constraints** on extracted gluon observables through calculated moments.

Additional Tools: Femtography using Artificial Intelligence







Why do we need a deep neural network?

- DNN provide **efficient** and **accurate** predictions in the range of the data while disentangling **complex final states** with a **large number of observables**.

J. Grigsby, B. Kriesten, S. Liuti, et. al. **arXiv: 2012.04801**
J. Grigsby, B. Kriesten, S. Liuti, et. al. **(in progress)**

Conclusions

- An EIC will help us explore **new kinematic regimes** for femtography using a variety of exclusive processes to place constraints on the quark and gluon distributions.

- Femtography is **extremely difficult**, there are many steps from cross sections -> images.

    - Some of these connections are well defined but **CFFs -> GPDs** (inverse problem) must be explored using additional data analysis tools.

- Creating femtographic images will require **coalitions of experts** including experimentalists, theorists, data scientists, machine learning experts, lattice QCD specialists, and visualization experts to work together.