Gluon Spatial Distributions in the Nucleon

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FemtoNET

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Femtography of the nucleon

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

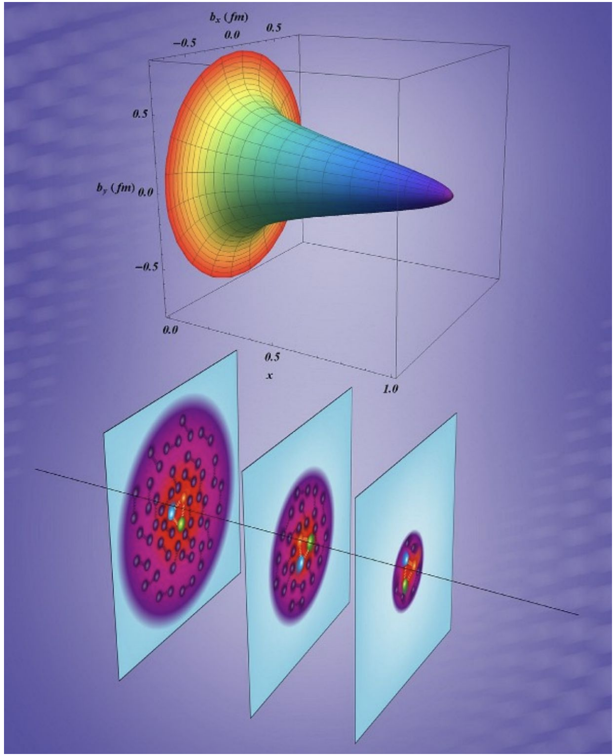


Image credit: **Rafael Dupre**

Generalized parton distributions

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

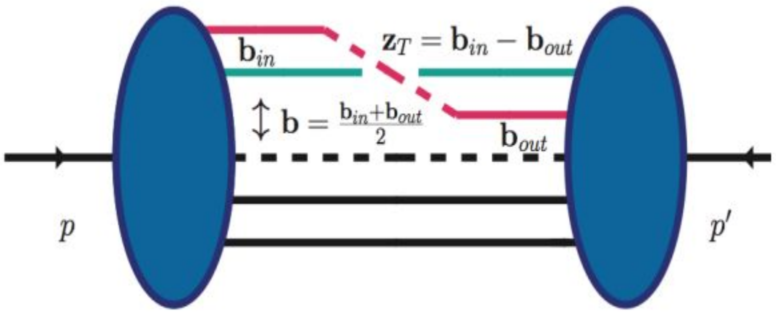


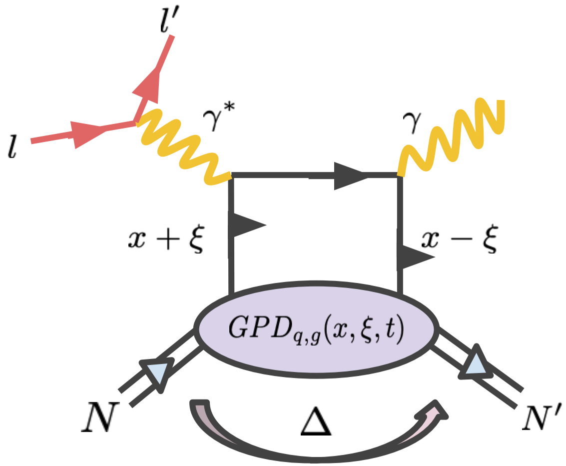
Image credit: A. Rajan, M. Engelhardt, S. Liuti **PRD 98 (2018)**

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

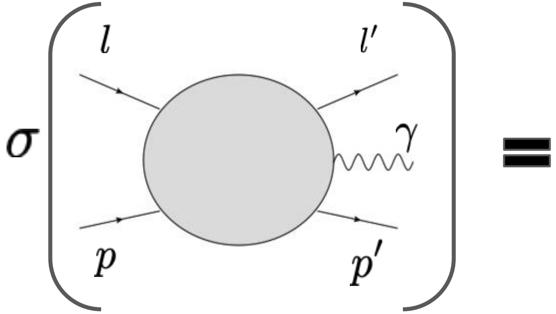
X. Ji **PRL. 78 (1997)**
A. Radyushkin **PRD. 56 (1997)**
D. Muller, et. al. **(1994)**
M. Diehl **Phys.Rep. (2003)**

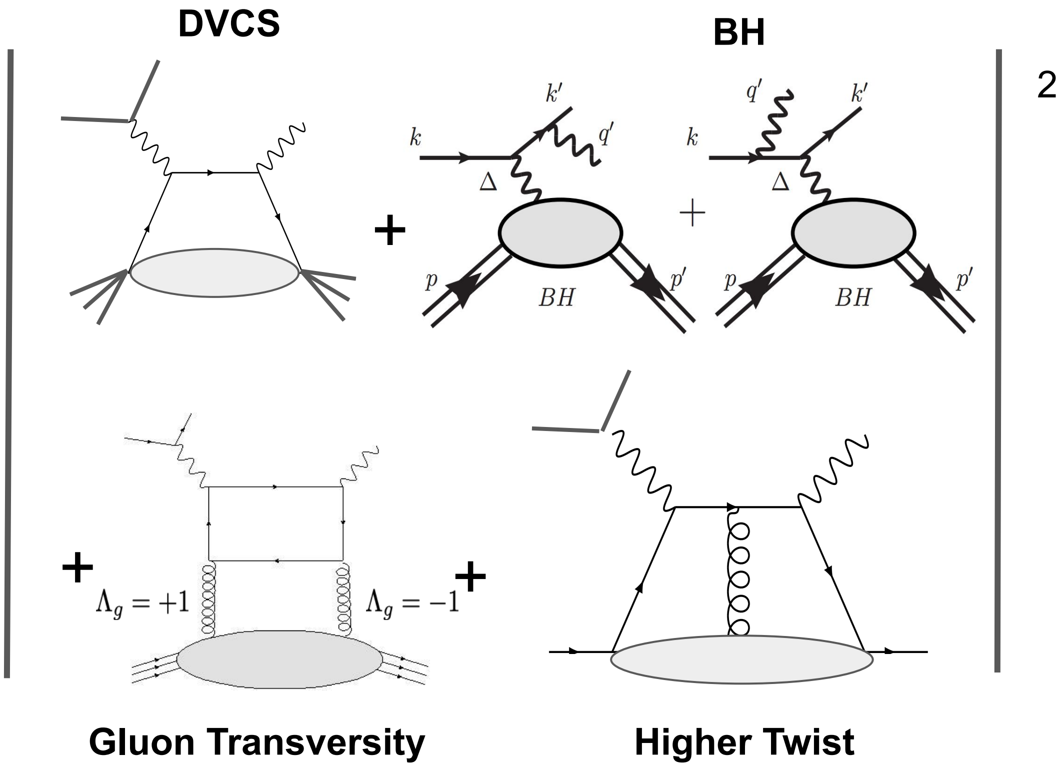
How do we image the gluon distribution in the proton?



Deeply virtual exclusive processes represent a **new paradigm** for measuring the fundamental properties of nuclei by probing the quantum mechanical **phase space distributions** of the quarks and gluons.

Deeply Virtual Compton Scattering



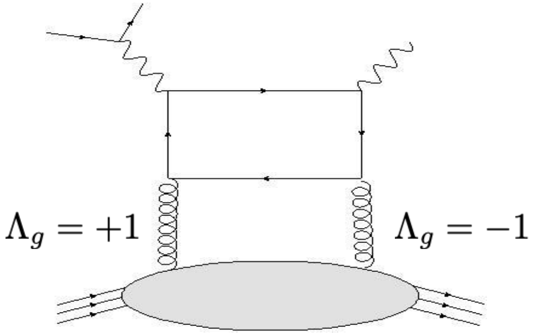


DVCS is known to probe **generalized parton distributions** and is accompanied by various background processes.

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

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

Gluon Transversity Observables in DVCS



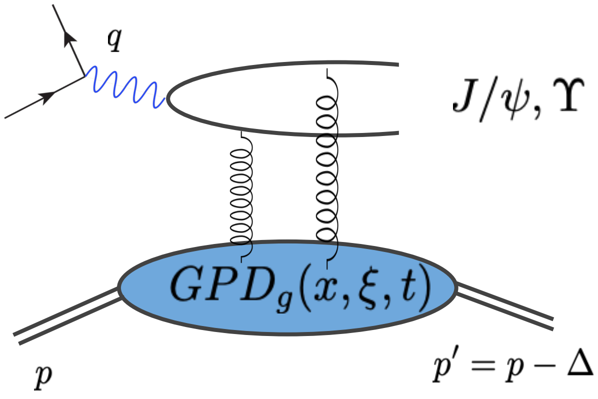
Accessing the **chiral-odd** gluon structure of the nucleon

$$
\begin{aligned}
F_{UU}^{\cos 2\phi} = & -2\frac{\alpha_S}{2\pi}\sqrt{1-\xi^2}\,\frac{t_0-t}{4M^2}\,\Re\mathrm{e}\Bigg[\sqrt{1-\xi^2}\left(\widetilde{\mathcal{H}}_T^g + (1-\xi)\frac{\mathcal{E}_T^g + \widetilde{\mathcal{E}}_T^g}{2}\right)\left(\mathcal{H} + \widetilde{\mathcal{H}} - \frac{\xi^2}{1-\xi^2}(\mathcal{E}+\widetilde{\mathcal{E}})\right)^* \\
& + \sqrt{1-\xi^2}\left(\widetilde{\mathcal{H}}_T^g + (1+\xi)\frac{\mathcal{E}_T^g - \widetilde{\mathcal{E}}_T^g}{2}\right)\left(\mathcal{H} - \widetilde{\mathcal{H}} - \frac{\xi^2}{1-\xi^2}(\mathcal{E}+\widetilde{\mathcal{E}})\right)^* \\
& + \frac{\sqrt{t_0-t}}{2M}\left(\widetilde{\mathcal{H}}_T^g + (1+\xi)\frac{\mathcal{E}_T^g - \widetilde{\mathcal{E}}_T^g}{2}\right)\left(\mathcal{E} + \xi\widetilde{\mathcal{E}}\right)^* \\
& - \sqrt{1-\xi^2}\left(\mathcal{H}_T^g + \frac{t_0-t}{M^2}\widetilde{\mathcal{H}}_T^g - \frac{\xi^2}{1-\xi^2}\mathcal{E}_T^g + \frac{\xi}{1-\xi^2}\widetilde{\mathcal{E}}_T^g\right)\left(\mathcal{E} - \xi\widetilde{\mathcal{E}}\right)^*\Bigg]
\end{aligned}
$$

Exclusive Measurements of Gluon Distributions

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

Gluon GPDs enter the vector meson production cross section.
Y. Guo, X. Ji, Y. Liu **arXiv:2103.11506**

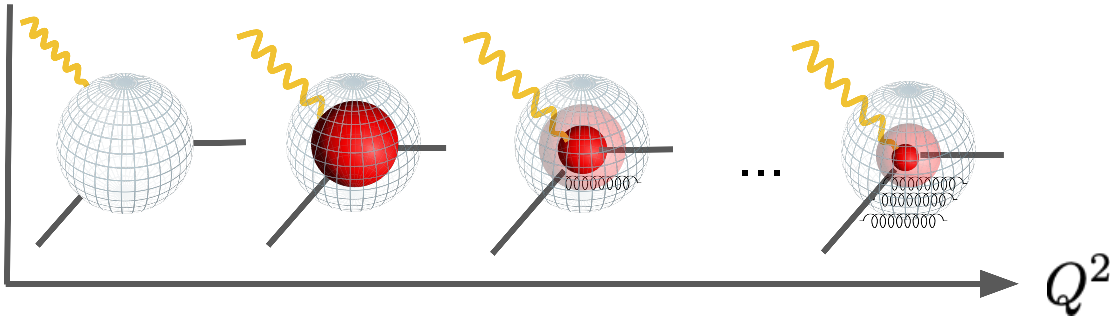


EIC White Paper **arXiv: 1212.1701**

$$\frac{d\sigma}{dt} \propto \left(1 - \frac{t}{4M^2}\right) E_2^2 - 2E_2(H_2 + E_2) + (1-\xi^2)(H_2+E_2)^2$$

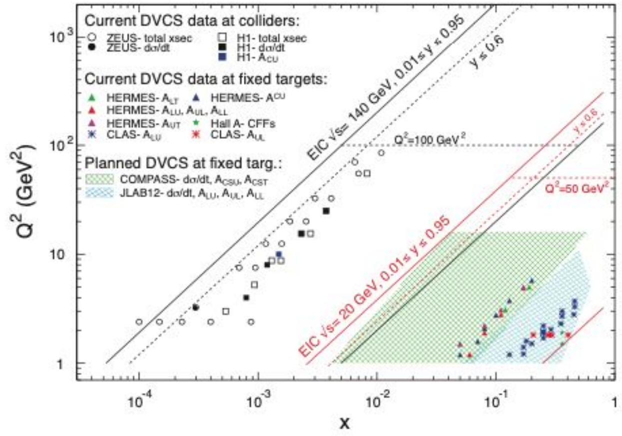
$$E_2 = \int_0^1 dx E_g(x,\xi,t) \quad H_2 = \int_0^1 dx H_g(x,\xi,t)$$

Gluon distributions through scaling violations



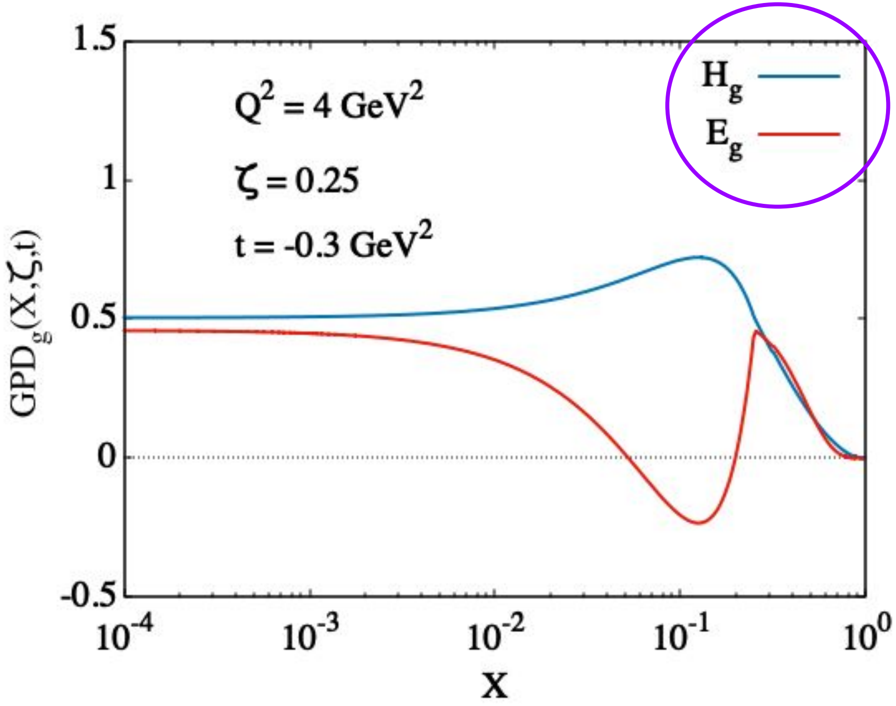
$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_S(Q^2)}{2\pi}\left[P_{QQ}\otimes F_2 + 2e^2 P_{QG}\otimes xg(x)\right]$$

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



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

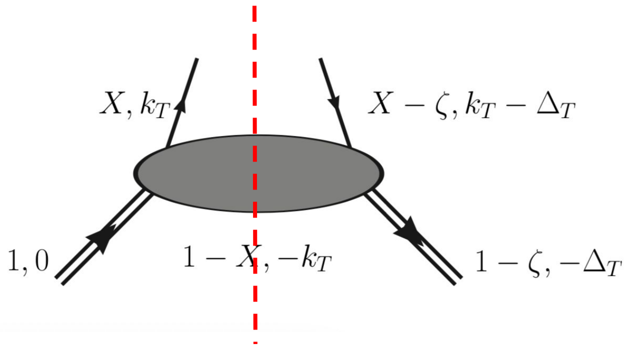
Flexible Gluon GPD Model

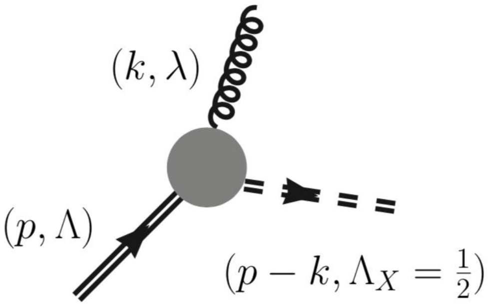


Allows us to calculate **gluon angular momentum** observables as they appear in experiment.

B. Kriesten, P. Velie, E. Yeats, F.Y. Lopez, S. Liuti **arXiv:2101.01826**

Reggeized Spectator Gluon GPD Model





$$A_{\Lambda'\lambda'_g,\Lambda\lambda_g} = \int \frac{d^2k_\perp}{1-X} \sum_{\Lambda_X} \phi^{*\Lambda_X}_{\lambda'_g\Lambda'}(k',p')\, \phi^{\Lambda_X}_{\lambda_g\Lambda}(k,p)$$

$$\phi^{\Lambda_X}_{\lambda_g\Lambda}(k,p) = \Gamma(k) \frac{\bar{U}_{\Lambda_X}(p-k)\, U_\Lambda(p)}{k^2 - m_g^2} \not{\epsilon}^*_{\lambda_g}(k)$$

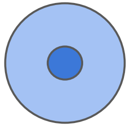
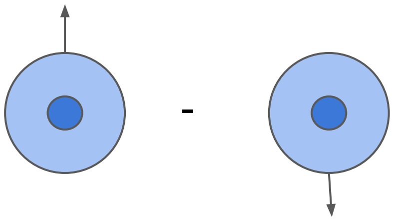
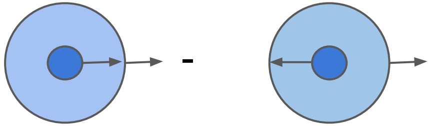
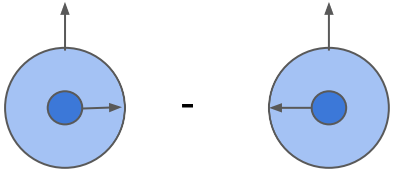
- 7 Fitted parameters and the initial scale for perturbative evolution.

$$H^g(X,\zeta,t) = \begin{cases} H^{M_\Lambda}_{M_X}(X,\zeta,t)\, R^{\alpha,\alpha'}_p(X,t), & \zeta \le X \le 1 \\ a_g X^2 - a_g \zeta X + H(\zeta,t), & 0 \le X < \zeta \\ 0 & -1+\zeta \le X < 0 \end{cases}$$

$$R^{\alpha,\alpha'}_p = X^{-[\alpha+\alpha'(1-X)^p t]}$$

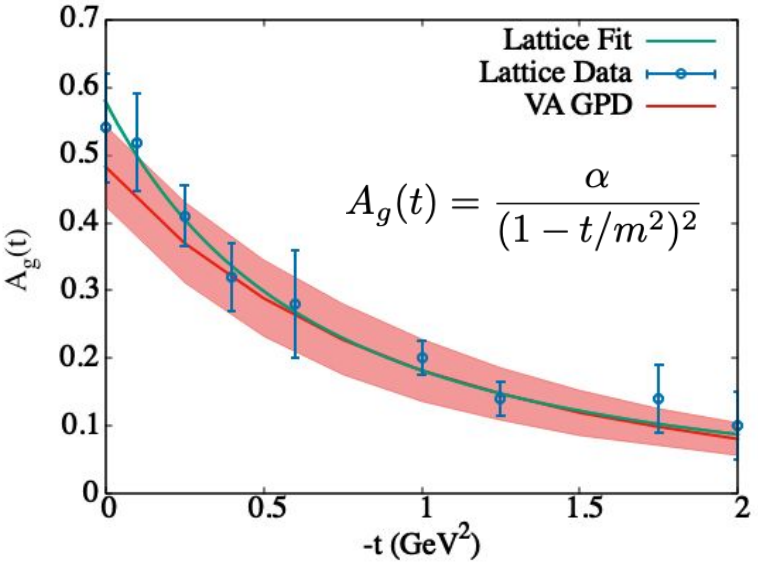
Quark Parametrization **PRD. 84 (2010), PRC 88 (2013)**

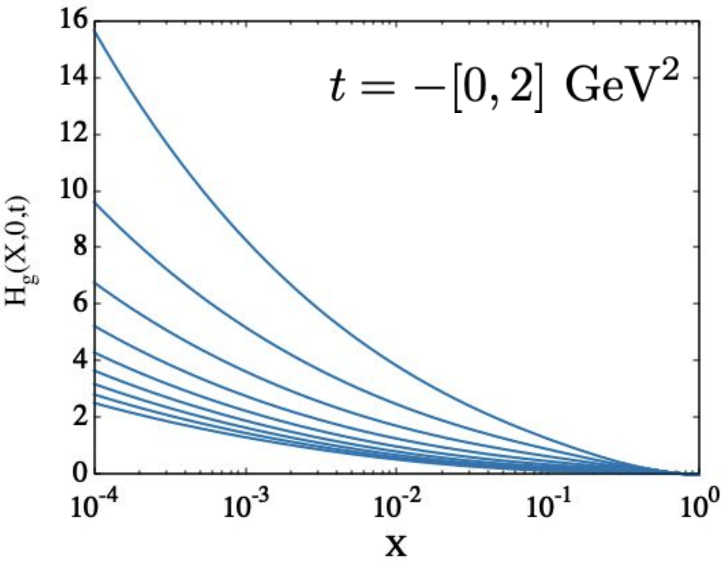
GPDs from Helicity Amplitudes

GPD	Phase	Helicity Composition
H	1	
$\Delta_T E$	$e^{i\phi}$	
$\widetilde{H}$	1	
$\xi \Delta_T \widetilde{E}$	$e^{i\phi}$	

Gluon GPD H(X,0,t)

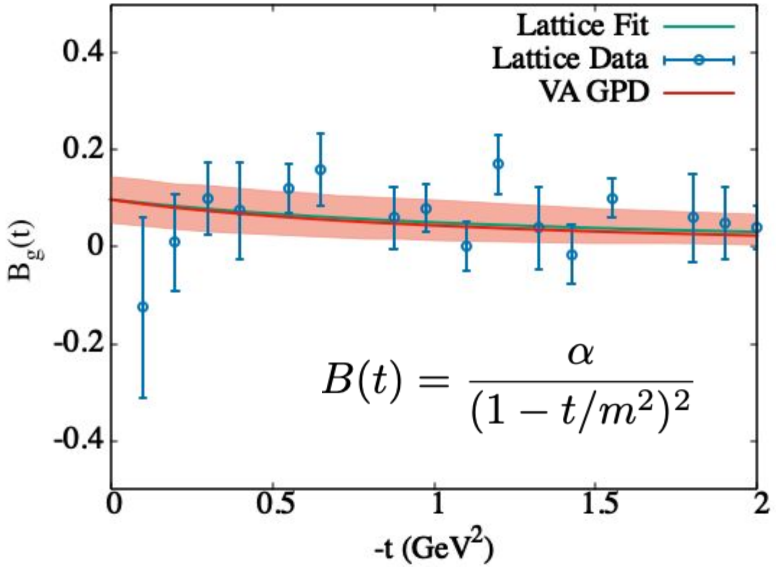
Dipole fit of Lattice QCD calculated moments (P.E. Shanahan, W. Detmold **PRD 99, (2019)**) allows us to fit the the gluon GPD t-dependence.

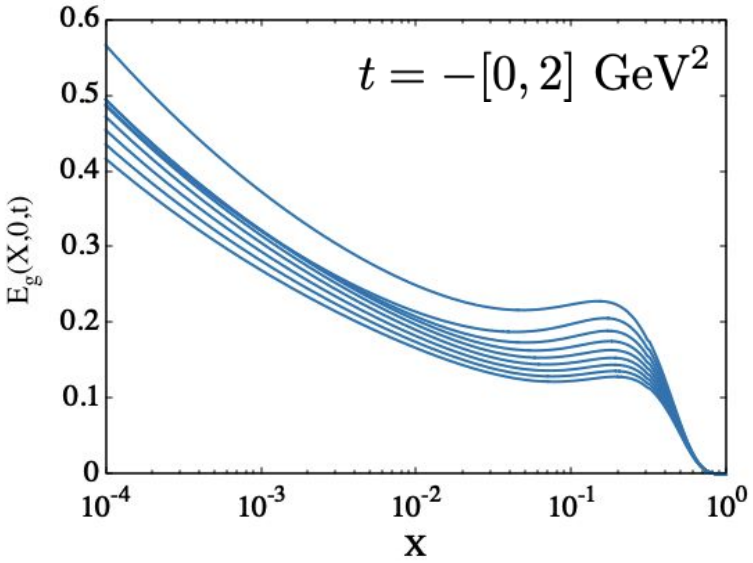




Gluon GPD E(X,0,t)

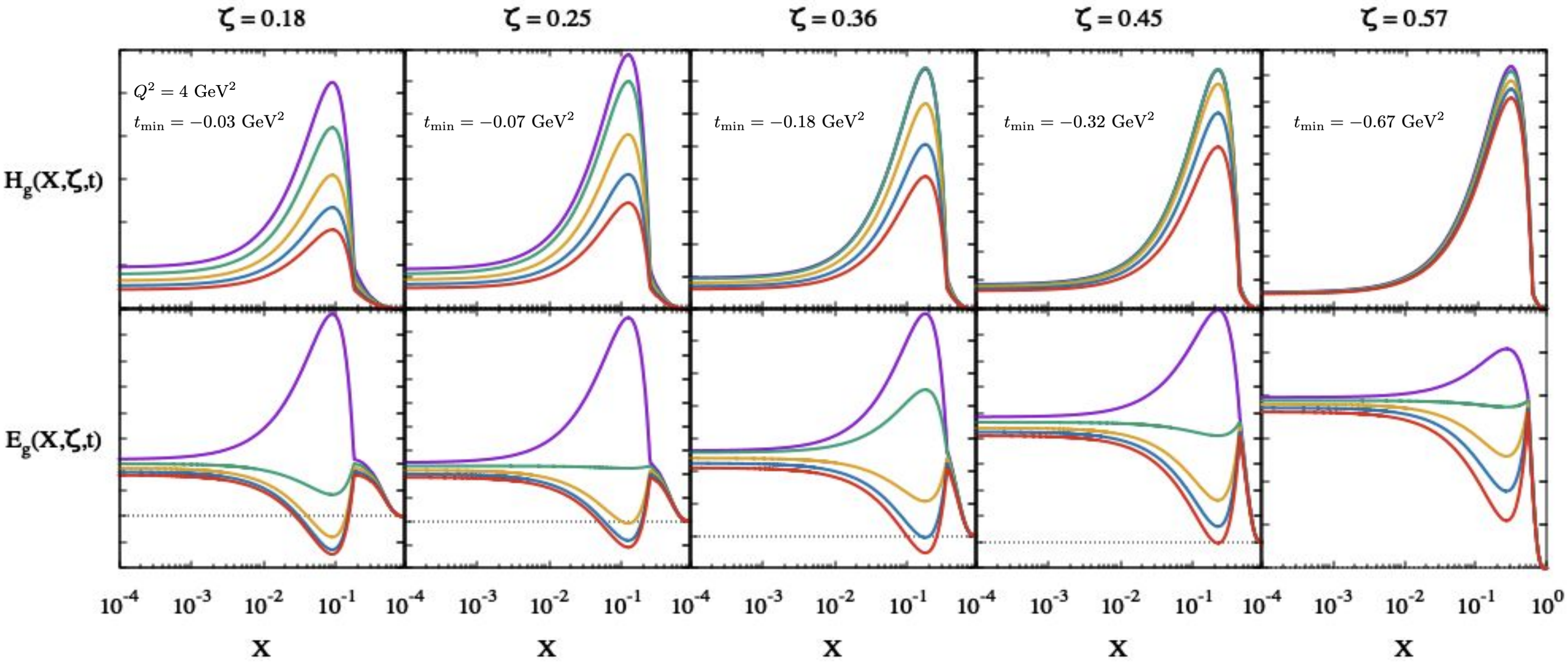
Similarly, we use a dipole fit of Lattice QCD calculated moments (P.E. Shanahan, W. Detmold **PRD 99, (2019)**) to fit the gluon GPD t-dependence, but there is **much flexibility in this fit**.





Full Gluon GPD

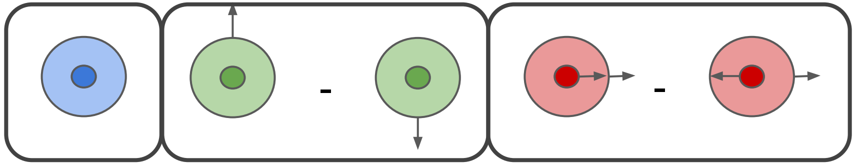
Allows us to calculate **gluon observables** as they appear in experimental cross sections.



Momentum Space to Transverse Position Space

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

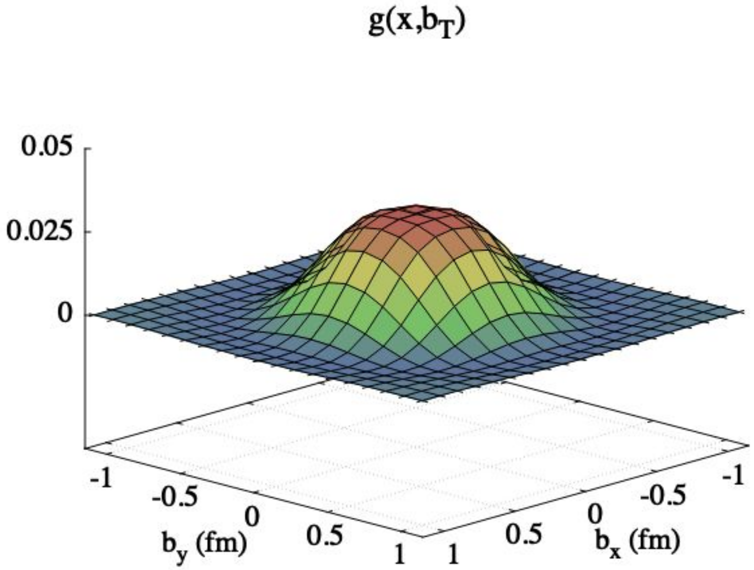
$$\rho^q_{\Lambda\lambda}(\mathbf{b}) = H_q(\mathbf{b}^2) + \frac{b^i}{M}\epsilon_{ij}S^j_T\frac{\partial}{\partial b}E_q(\mathbf{b}^2) + \Lambda\lambda\widetilde{H}_q(\mathbf{b}^2)$$



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

Gluon Transverse Position Space Images

Unpolarized gluon distribution in an unpolarized proton.



Conclusions

- Generalized Parton Distributions give us direct access to information of the fundamental properties of the nucleon contained in the EMT of QCD.

- Theoretical Models of GPDs are necessary to make estimates of the size of experimental observables and calculate sum rules such as those for OAM.

- Gluon GPD models will allow us to calculate cross sections for gluon pieces of DVCS cross sections at EIC kinematics.

- Using a flexible parametrization of gluon GPDs we can construct pictures of what we would expect gluon transverse spatial images to look like.