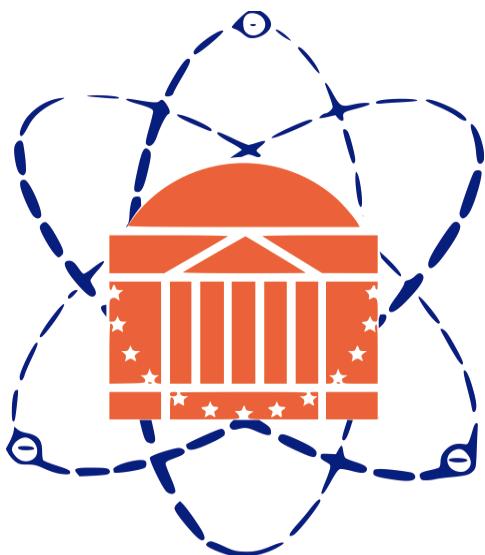
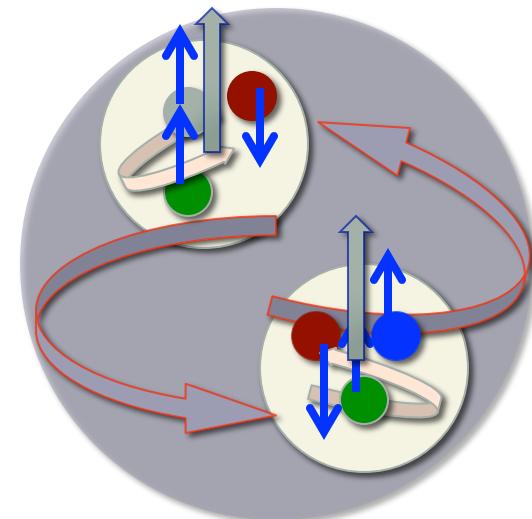


GPDS: THEORY AND PHENOMENOLOGY

EICUG MEETING
CATHOLIC UNIVERSITY OF AMERICA
JULY 30-AUGUST 3, 2018



Simonetta Liuti
University of Virginia



Outline

1. Physics goals: quarks and gluons imaging, mass, spin, nuclear structure
2. Theory: Fourier transforms, merging information from lattice, models/parametrizations, the question of OAM; QCD factorization and k_T dependence
3. A new concerted effort,
 1. not just one centralized umbrella hub but a variety of approaches handbook/white paper with benchmarks → central hub stifles creativity
 2. Extraction from experiments at EIC: beyond standard numerical methods
4. Impact on BSM searches
5. Conclusions and Outlook

1. PHYSICS GOALS

Generalized Parton Distributions are not just your Mother Distributions:



- 1 GPDs define a **new way of thinking** strongly interacting systems
- 2 GPDs define a **new paradigm** that allows us to access questions that we couldn't afford asking before

what is the origin of mass and spin?
- 3 GPDs represent a **phenomenological link** that allows us to measure what could only be explored through lattice QCD before

what is the spatial structure of hadrons/imaging/femtography?
- 4 GPDs connect to **complex phase space distributions**: to observe them requires to step up data analyses from the standard methods used so far

New numerical/analytic/quantum computing methods to evaluate and interpret Wigner distributions

How does the proton get its mass and spin?

$$\mathcal{L}_{QCD} = \bar{\psi} (i\gamma_\mu D^\mu - m) \psi - \frac{1}{4} F_{a,\mu\nu} F_a^{\mu\nu}$$

The mass generated by the Higgs mechanism is very far in value from the characteristic scale of strongly interacting matter

Invariance of \mathcal{L}_{QCD} under **translations** and **rotations**

Energy Momentum Tensor

from **translation** inv. 

$$T_{QCD}^{\mu\nu} = \frac{1}{4} \bar{\psi} \gamma^{(\mu} D^{\nu)} \psi + Tr \left\{ F^{\mu\alpha} F_\alpha^\nu - \frac{1}{2} g^{\mu\nu} F^2 \right\}$$

Angular Momentum Tensor

from **rotation** inv. 

$$M_{QCD}^{\mu\nu\lambda} = x^\nu T_{QCD}^{\mu\lambda} - x^\lambda T_{QCD}^{\mu\nu}$$

QCD Energy Momentum Tensor and Angular Momentum

Energy density

$$\vec{S} = \vec{E} \times \vec{B}$$

$\frac{E^2 + B^2}{2}$	S_x	S_y	S_z
S_x	σ_{xx}	σ_{xy}	σ_{xz}
S_y	σ_{yx}	σ_{yy}	σ_{yz}
S_z	σ_{zx}	σ_{zy}	σ_{zz}

Momentum density

Shear stress

$$M^{\mu\nu\lambda} = x^\nu T^{\mu\lambda} - x^\lambda T^{\mu\nu}$$

Angular Momentum density

Matrix element in spherically symmetric systems

(Jaffe and Manohar, NPB 1990; X.Ji, PRL 1997)

$$t = (p - p')^2 = \Delta^2$$

$$S=0$$

$$\langle p' \mid T^{\mu\nu} \mid p \rangle = 2 \left[A(t) P^{\mu\nu} + C(t) (\Delta^2 g^{\mu\nu} - \Delta^{\mu\nu}) \right] + \tilde{C}(t) g^{\mu\nu}$$

$S=1/2$

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

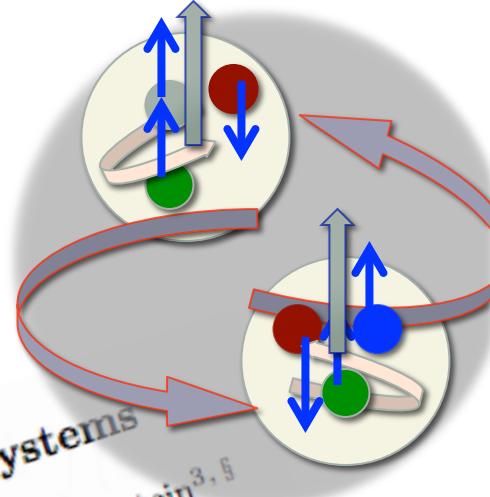
+ $C(t) [\Delta^2 g^{\mu\nu} - \Delta^{\mu\nu}] \bar{U}(p', \Lambda') U(p, \Lambda) + \tilde{C}(t) g^{\mu\nu} \bar{U}(p', \Lambda') U(p, \Lambda)$

Energy Momentum Tensor in a spin 1 system

(Taneja, Kathuria, SL, Goldstein, PRD86(2012))

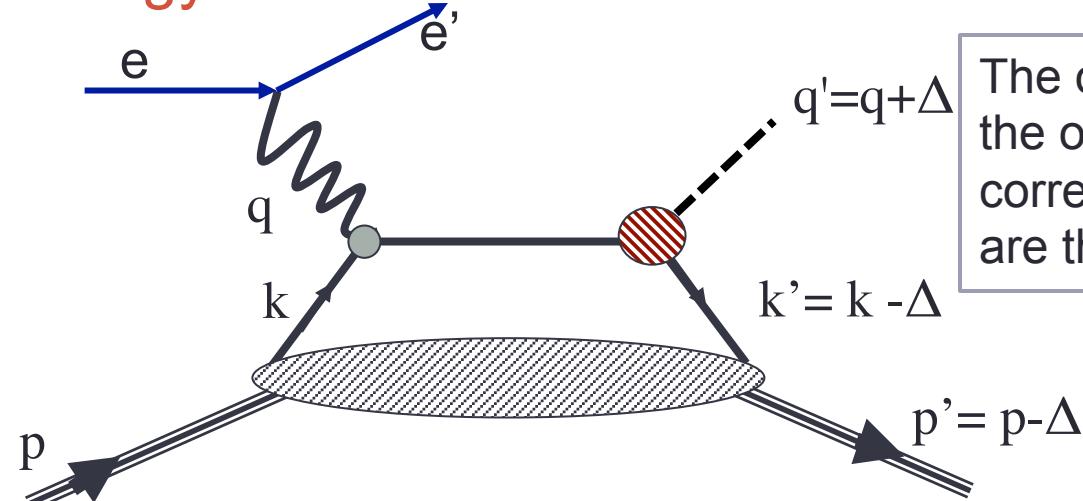
$$\begin{aligned}
 \langle p' | T^{\mu\nu} | p \rangle = & -\frac{1}{2} P^\mu P^\nu (\epsilon'^* \epsilon) \boxed{\mathcal{G}_1(t)} \\
 & - \frac{1}{4} P^\mu P^\nu \frac{(\epsilon P)(\epsilon'^* P)}{M^2} \boxed{\mathcal{G}_2(t)} - \frac{1}{2} [\Delta^\mu \Delta^\nu \\
 & \times \boxed{\mathcal{G}_3(t)} - \frac{1}{4} [\Delta^\mu \Delta^\nu \\
 & + \frac{1}{2} (\epsilon P) - \epsilon^\mu (\epsilon'^* P)) \Delta^\nu + \mu \leftrightarrow \nu] \boxed{\mathcal{G}_4(t)} \\
 & + 2g_{\mu\nu} (\epsilon P)(\epsilon'^* P) - (\epsilon'^*\epsilon^\mu \epsilon^\nu + \epsilon'^*\epsilon^\nu \epsilon^\mu) \Delta^2 \boxed{\mathcal{G}_6(t)} \\
 & + \frac{1}{2} [\epsilon'^*\epsilon^\mu \epsilon^\nu + \epsilon'^*\epsilon^\nu \epsilon^\mu] \boxed{\mathcal{G}_7(t)} + g^{\mu\nu} (\epsilon'^* \epsilon) M^2 \boxed{\mathcal{G}_8(t)} \quad (5)
 \end{aligned}$$

Angular momentum sum rule for spin one hadronic systems
Swadhin K. Taneja,^{1,*} Kunal Kathuria,^{2,†}, Simonetta Liuti,^{2,‡} and Gary R. Goldstein^{3,§}



GPDs and the Energy Momentum Tensor

Jaffe Manohar (1990) and Ji (1997) both saw that there was an off-forward part in the matrix element



The observables for
the off-forward
correlation function
are the GPDs

Ji went one step forward and noticed that for the quark and gluon operators defining angular momentum as

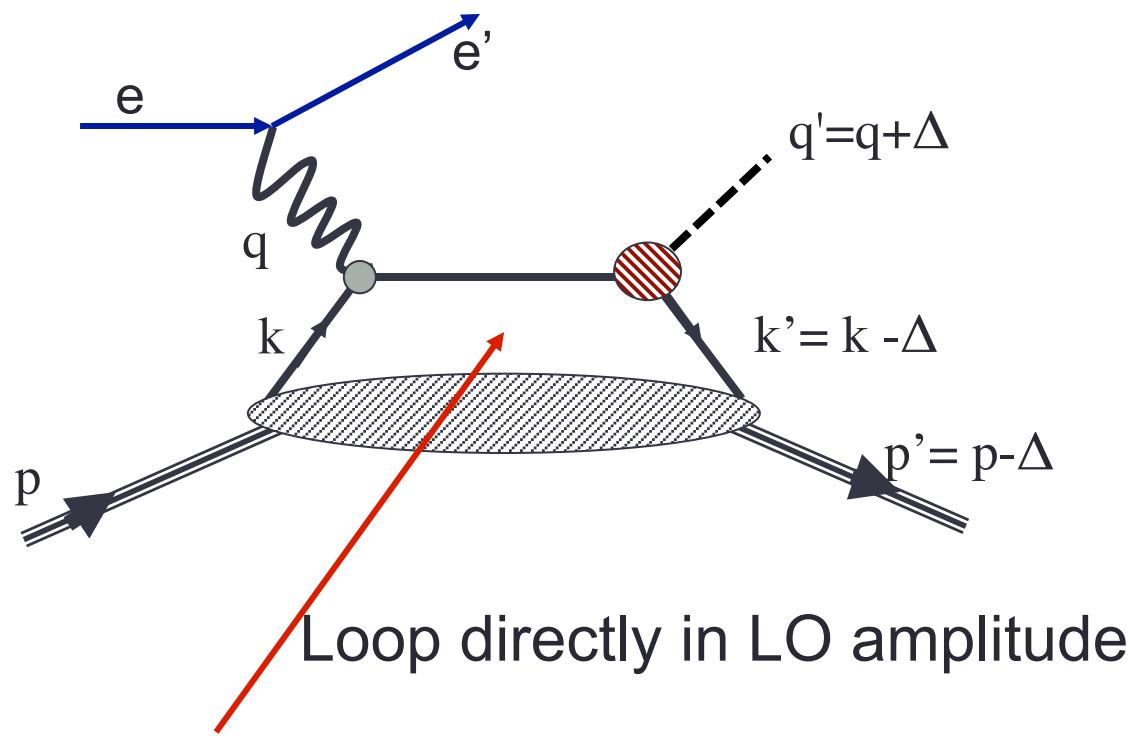
$$\langle P - \Delta, \Lambda' \mid \bar{q}(0)\gamma^+ \mathcal{W}(0, z) q(z^-) \mid P, \Lambda \rangle_{\mathbf{z}_T=0}$$

The off-forward matrix elements coincide with the ones for a specific correlation function

$$M^{+12} = q^\dagger \sigma^{12} q + q^\dagger \left[\vec{x} \times (-i\vec{D}) \right]^3 q + \left[\vec{x} \times (\vec{E} \times \vec{B}) \right]$$

quark field
gluon field

Deeply virtual photon/meson production



Loop directly in LO amplitude

$$(1) \frac{1}{(p+q)^2 - m^2 + i\epsilon} = PV \frac{1}{(p+q)^2 - m^2} - i\pi \delta((p+q)^2 - m^2)$$

Both Re and Im parts are present

(2) Quarks momenta and spins on LHS can be different from the RHS

OPE: Mellin Moments (X. Ji, 1998)

$$n_{\mu_1} \dots n_{\mu_n} \langle P' | O_q^{\mu_1 \dots \mu_n} | P \rangle = \overline{U}(P') \not{p} U(P) H_{qn}(\xi, t) + \overline{U}(P') \frac{\sigma^{\mu\alpha} n_\mu i \Delta_\alpha}{2M} U(P) E_{qn}(\xi, t)$$

helicity conserving

helicity flip

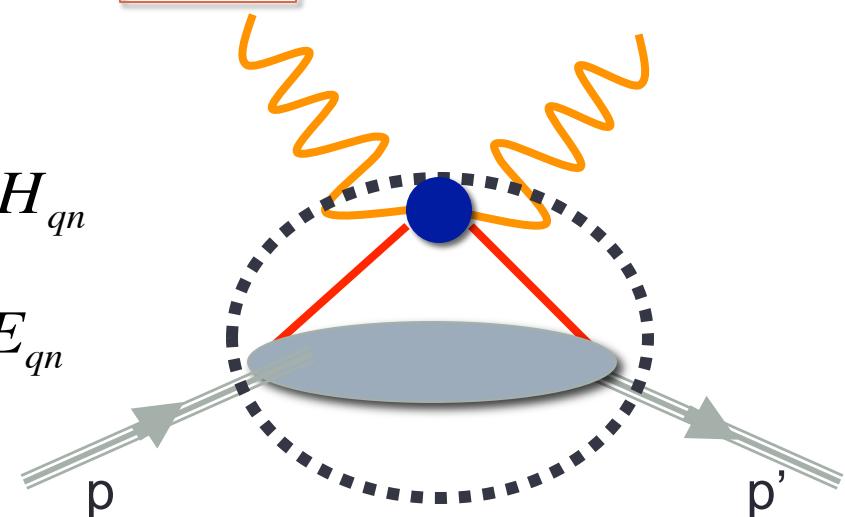
$$H_{qn}(\xi, t) = \sum_{i=0}^{\lfloor \frac{n-1}{2} \rfloor} A_{qn,2i}(t) (-2\xi)^{2i} + \text{Mod}(n+1, 2) C_{qn}(t) (-2\xi)^n$$

$$E_{qn}(\xi, t) = \sum_{i=0}^{\lfloor \frac{n-1}{2} \rfloor} B_{qn,2i}(t) (-2\xi)^{2i} - \text{Mod}(n+1, 2) C_{qn}(t) (-2\xi)^n.$$

Mellin Moments

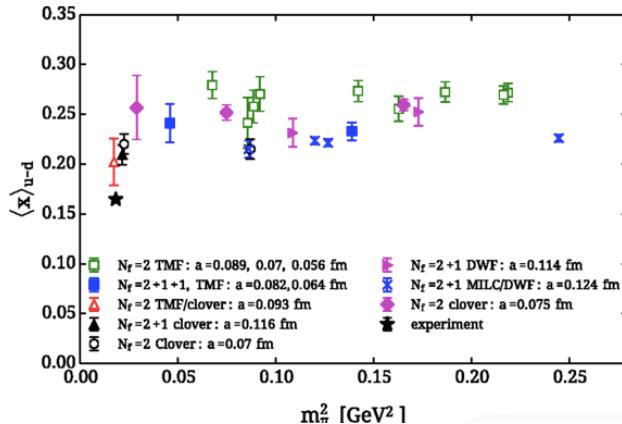
$$\int_{-1}^1 dx x^{n-2} H_q(x, \xi, t) = H_{qn}$$

$$\int_{-1}^1 dx x^{n-2} E_q(x, \xi, t) = E_{qn}$$

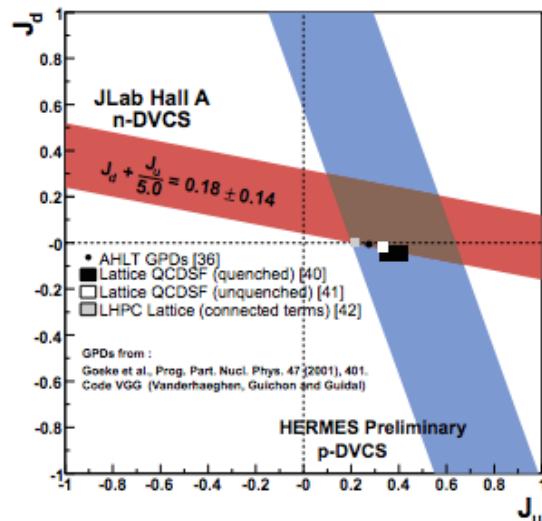


ETMC, Phys. Rev. D 92 , 114513 (2015)

A_{20}



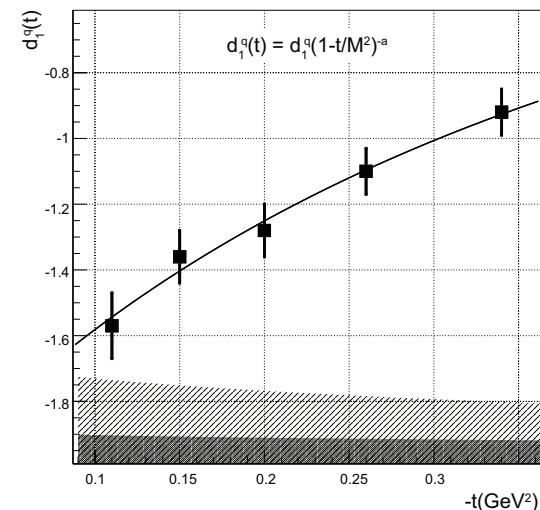
B_{20}



Jlab Hall A, Mazouz et al. PRL (2007)

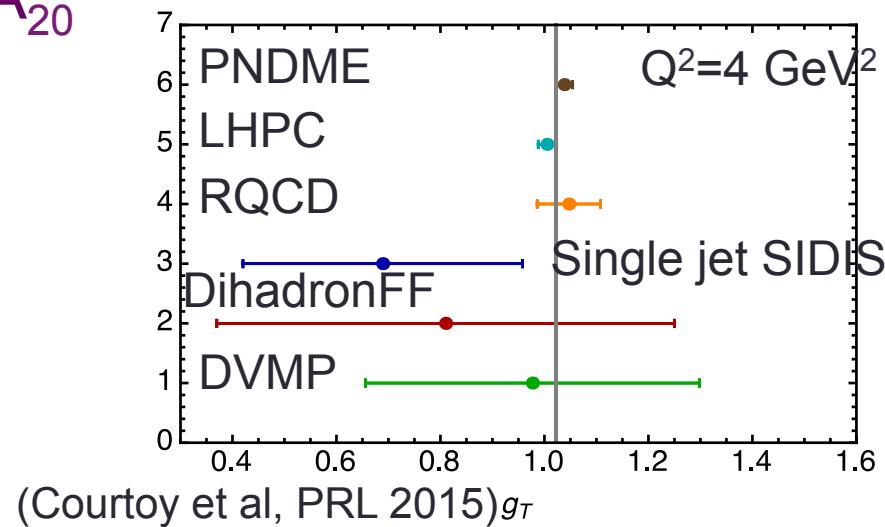
Jlab Hall B, Burkert et al., Nature (2018)

C_{20}



\tilde{A}_{20}

Chiral Odd sector



To understand both **mass** and **spin** we need to be able to **describe and measure** both **space** and **momentum** distributions of **quarks** and **gluons** inside the proton

Color charge Flux tube

“light (quark) pair creation seems to occur non-localized and instantaneously.”

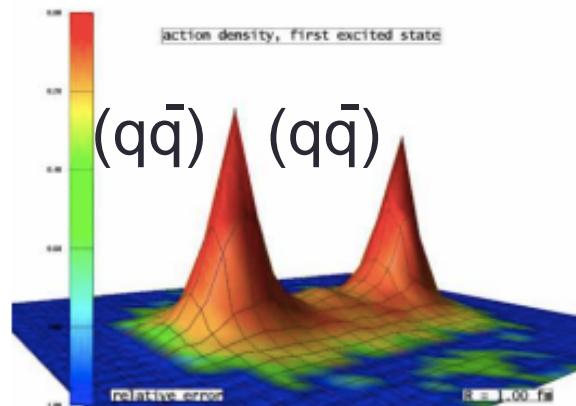
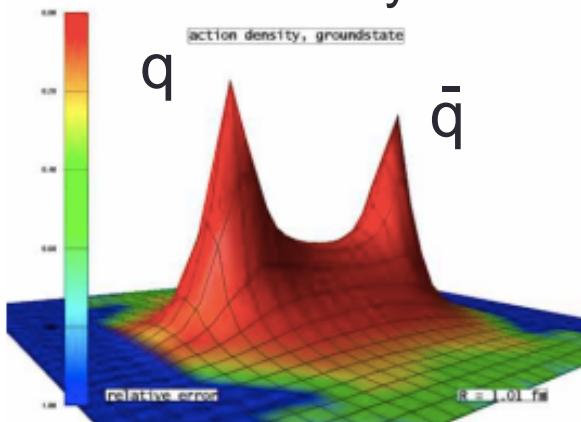
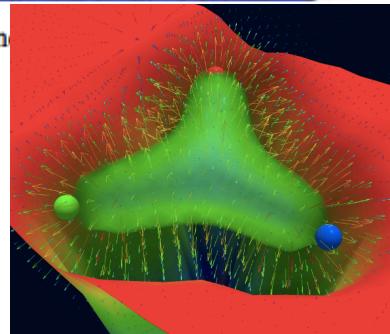
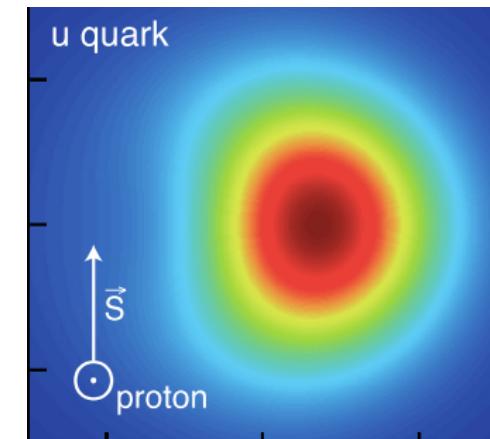


Figure 3: Action density distribution for the ground

G. Bali et al., PoS LAT2005 (2006)
F. Bissey, et al. PRD76 (2007)



Quark spatial density distribution in transv. polarized proton

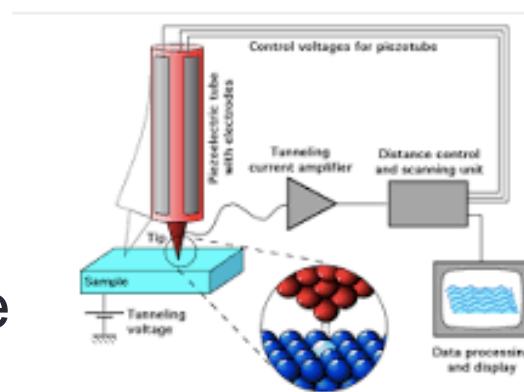


We cannot “see” structures at the atomic level with an optical microscope because we are limited by the size of the wavelength of visible light ($>400\text{nm}$)



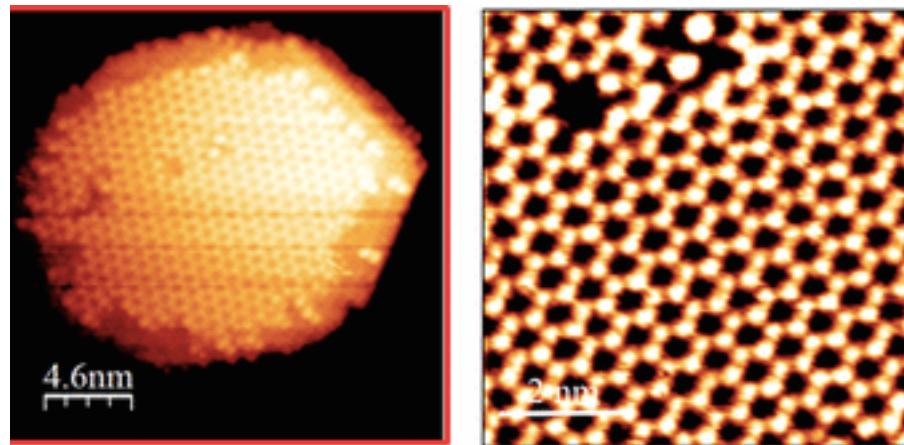
Transmission Electron Microscope: by scattering electrons -- with a much smaller wavelength -- allows us to reconstruct pictures of microscopic particles

Scanning Probe Microscope: we monitor the tunneling current between the probe and the surface of a sample, as the tip scans the surface



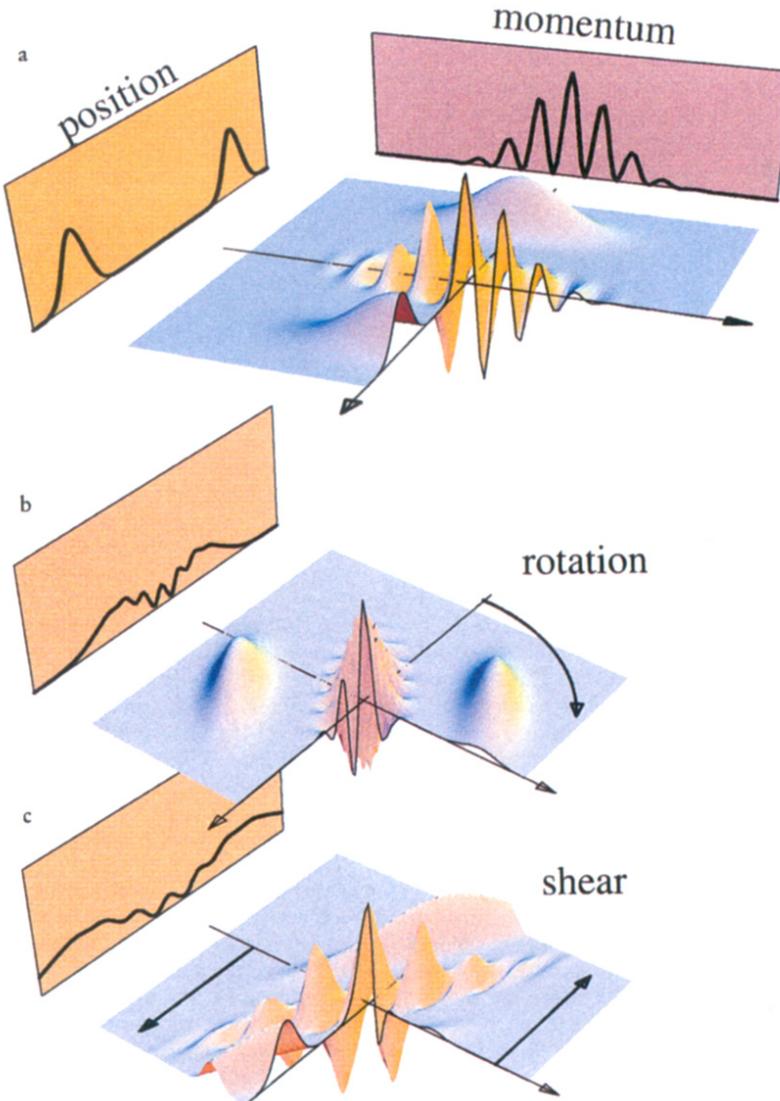
We can now image the structure of matter in 3D at the atomic level ($1 \text{\AA} = 10^{-10} \text{ m} = 0.1 \text{ nm}$)

Hexagonal-MoS₂ nanocrystallites

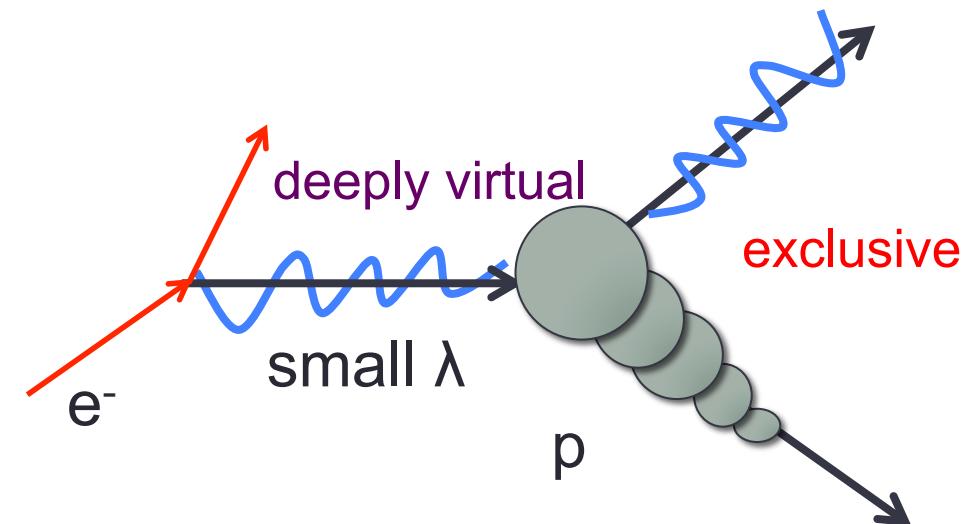


Petra Reinke et al. (Material Science Dept. UVa , Nanoletters (2017)

Key Theory Development: Wigner/phase space distributions at the femtoscale

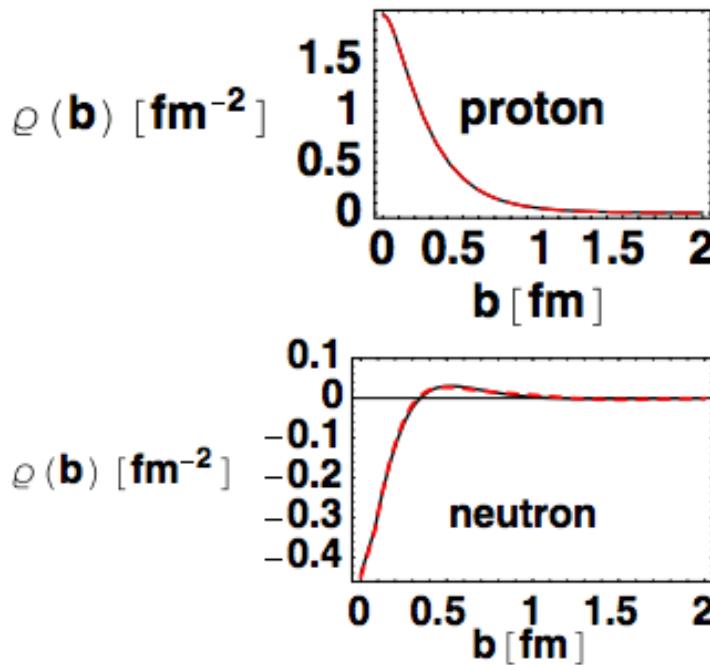


Key Experimental Probe: a specific class of high energy scattering experiments



Surprise: re-evaluation of nucleon charge density

G. Miller, 2007



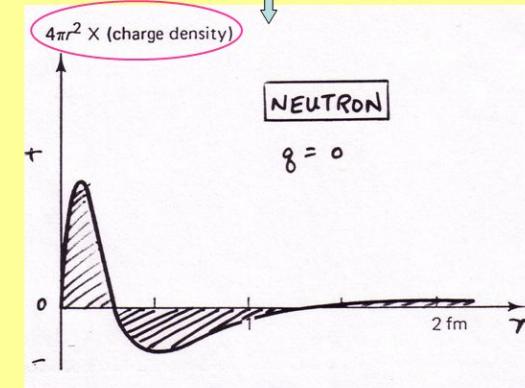
Neutron “textbook” density

What does negative $\langle r^2 \rangle$ mean?

4

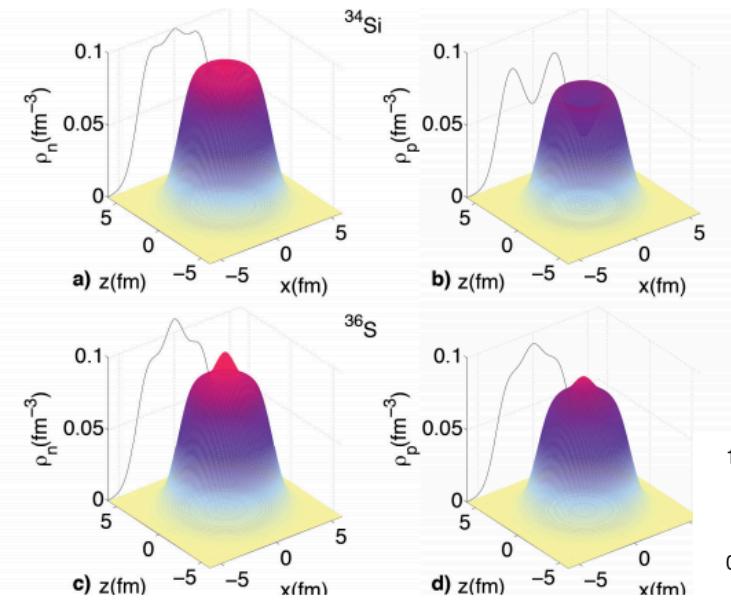
$$\langle r^2 \rangle \equiv \int r^2 \rho(r) d^3r = \int r^2 (4\pi r^2 \rho(r)) dr$$

- charge density must have both -ve and +ve regions, since net charge = 0
- integral is weighted with $r^2 \rightarrow$ more negative charge at large radius

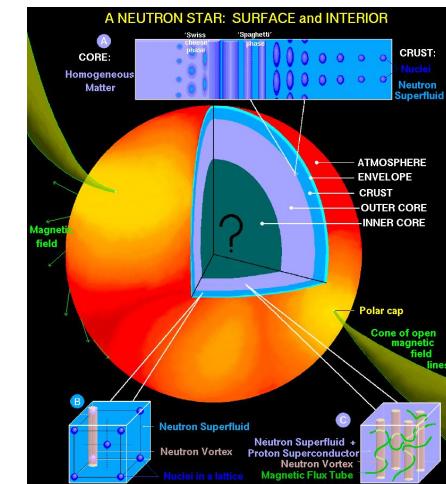
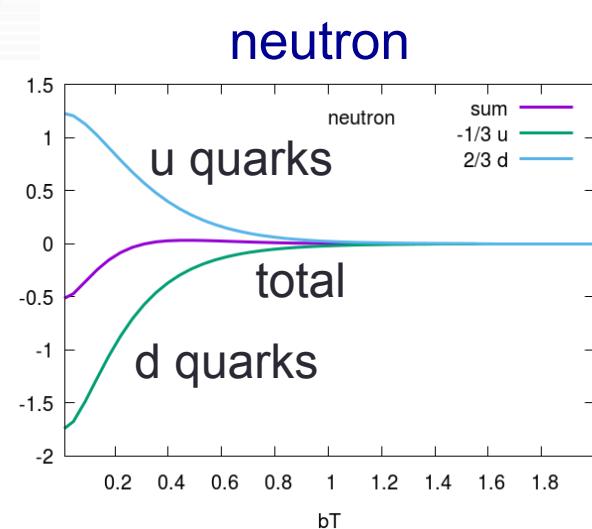


Unpolarized

Re-interpreting and imaging the proton and neutron densities at the femtoscale can impact both the nuclear density distributions and the equation of state of neutron stars as we explore and understand the core of the neutron



A. Mutschler et al., Nature (2017)

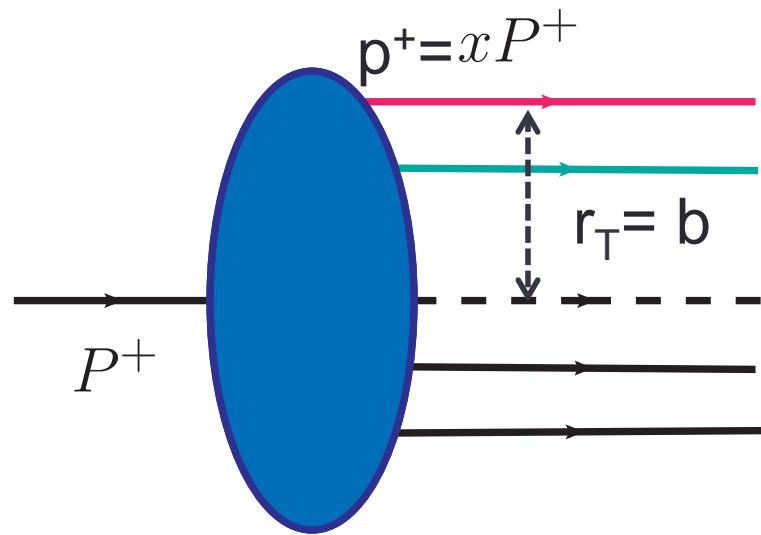


A. Rajan, S.L.

2.THEORY

Definitions, Connection with lattice QCD, OAM

The Proton Relativistic Wave Function: Poincaré Invariance



Center of P^+

$$\vec{R}_T = \frac{1}{P^+} \sum_i (x_i P^+) \vec{r}_T^i$$

- P^+ plays the role of mass
- “The subgroup of the Poincaré group that leaves the surface $z^+=\text{const}$ invariant, is isomorphic to the Galilean group in 2D”
- We can disentangle the transverse components from the time components in boosts → boosts in transverse plane are kinematical

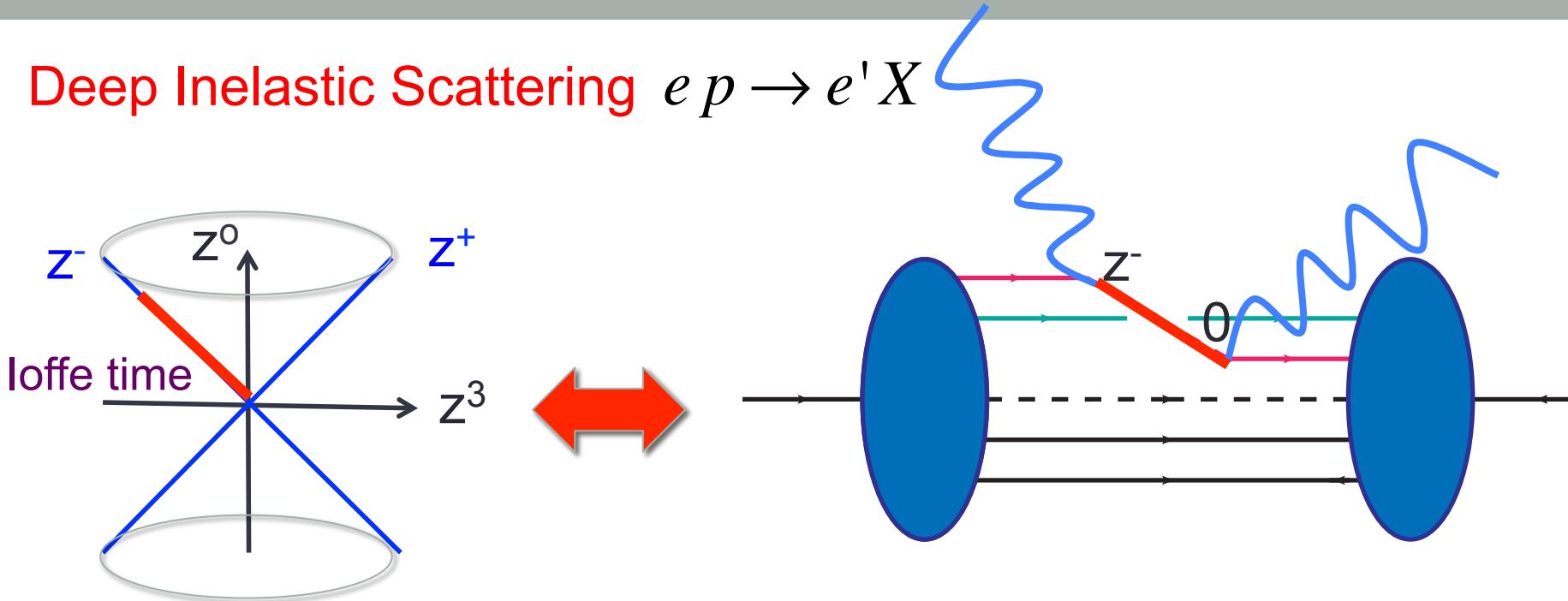
Implication

We can map out **faithfully** the spatial quark distributions in the transverse plane (no modeling/approximation)

$$q(x, \vec{b}) = \frac{dn}{dxd^2\vec{b}}$$

Soper (1977), Burkardt (2001)

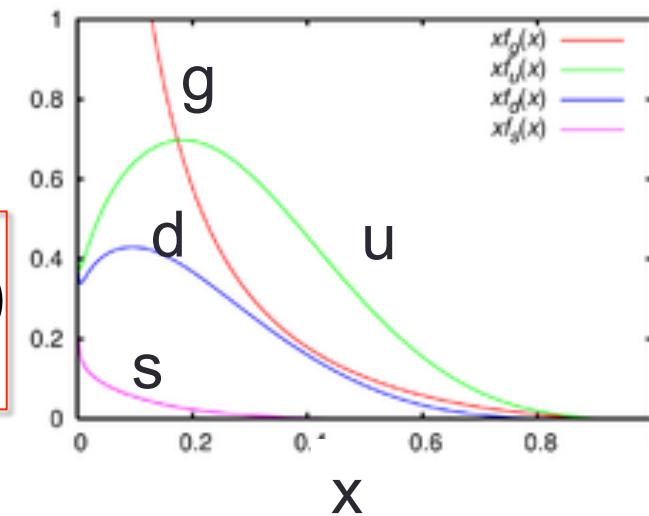
Deep Inelastic Scattering $e p \rightarrow e' X$



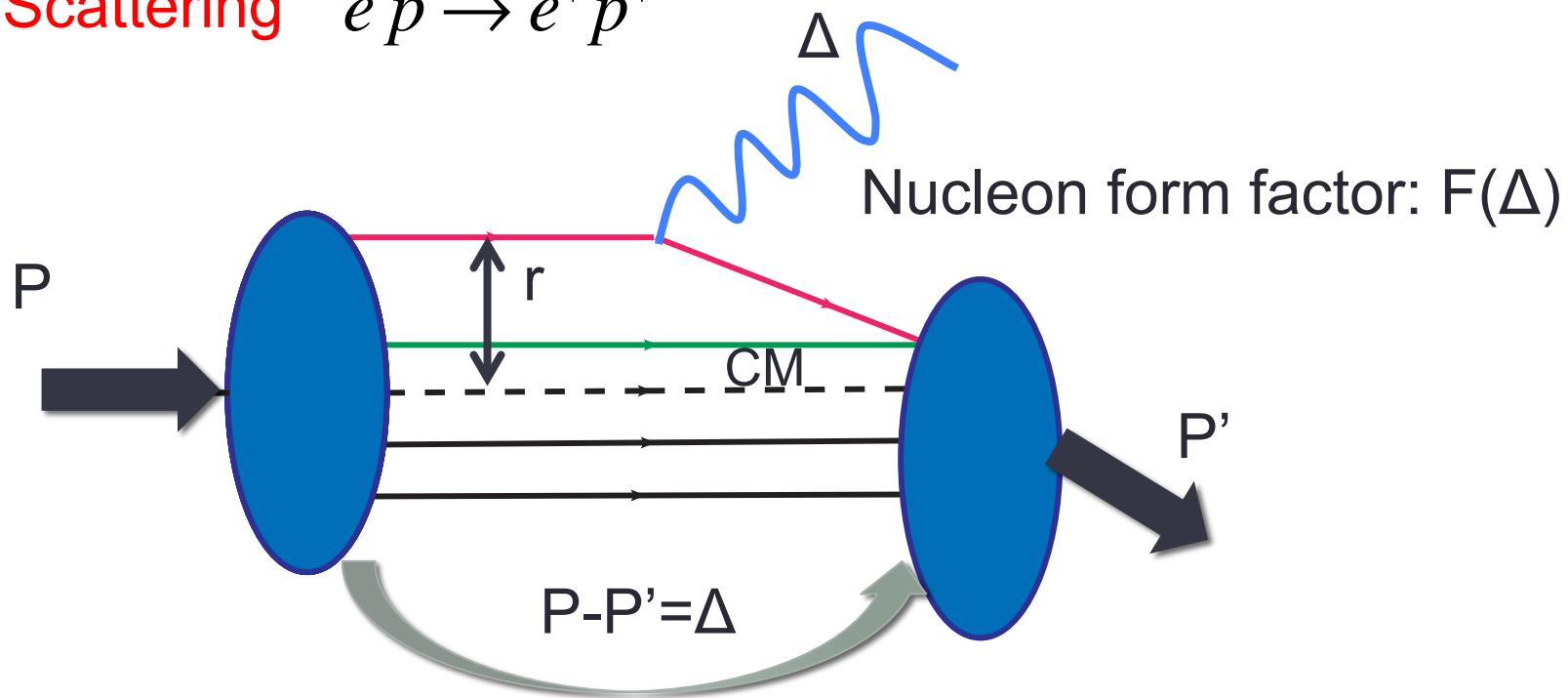
z^- is conjugate to $p^+ = xP^+$

➡

$$\int d^2 b q(x, b) \equiv q(x)$$



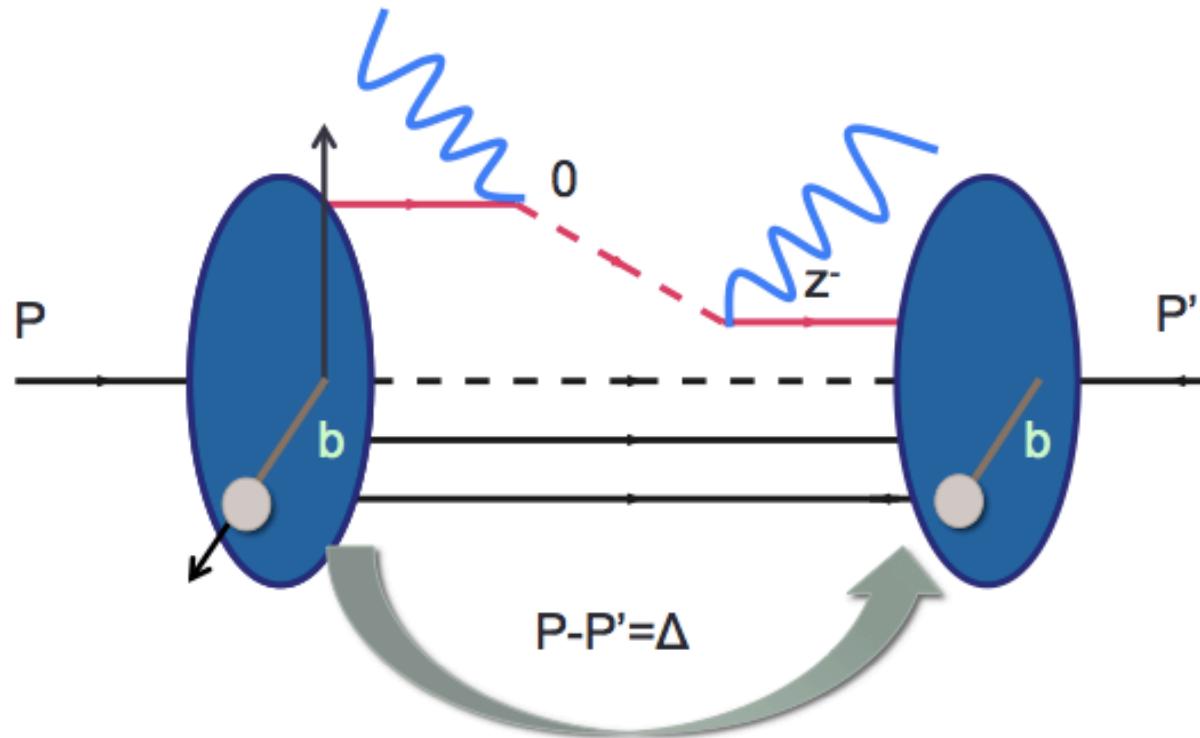
Elastic Scattering $e p \rightarrow e' p'$



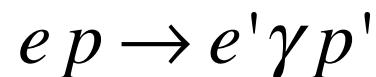
In a non relativistic approximation

$$F(\Delta) = \int d^3 \vec{r} e^{i \vec{r} \cdot \vec{\Delta}} q(\vec{r})$$

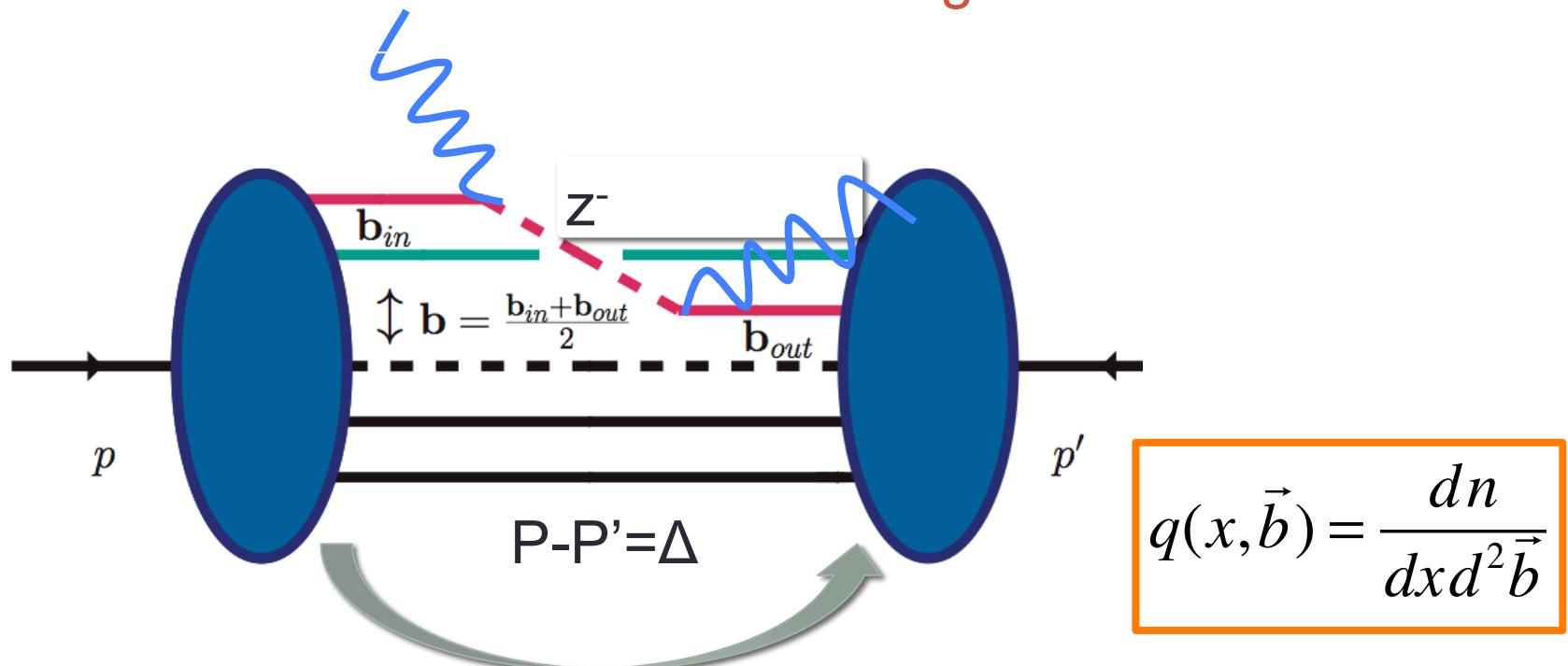
Space-time picture of the off-forward correlation function



$$\langle P - \Delta, \Lambda' | \bar{q}(0)\gamma^+ \mathcal{W}(0, z) q(z^-) | P, \Lambda \rangle_{\mathbf{z}_T=0}$$



A new generation of **deeply virtual** **exclusive** experiments probing **two** distinct distance scales will allow us to image **fermi size** structure



- Δ_T Fourier conjugate of \mathbf{b} = transverse position of the quark inside the proton
- xP^+ Fourier conjugate of z^- = LC distance traveled by the struck quark between the initial and final photon scattering

GPDs involve two types of distance

$$H^q(\textcolor{blue}{x}, 0, \Delta) = \int \frac{dz^-}{2\pi} e^{i\textcolor{blue}{x} P^+ z^-} \langle P - \Delta, \Lambda' | \bar{q}(0) \gamma^+ q(\textcolor{red}{z}^-) | P, \Lambda \rangle_{\mathbf{z}_T=0}$$

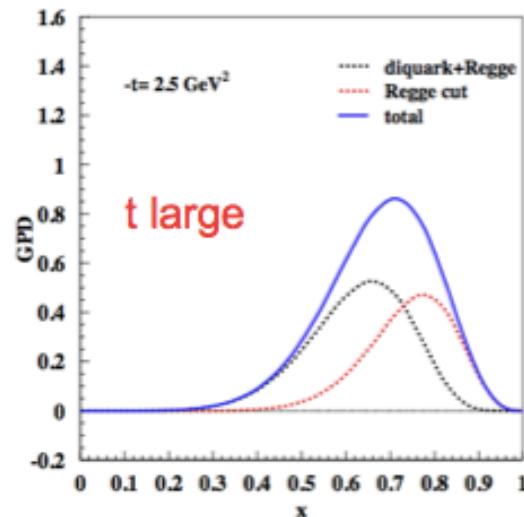
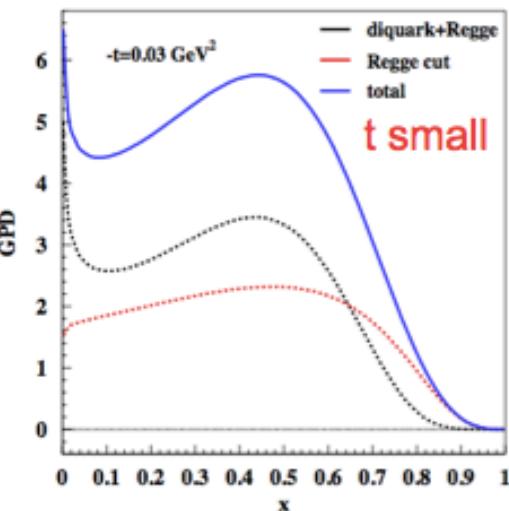
x distribution → Fourier transform of non-diagonal density distribution in $\textcolor{red}{z}^-$

Δ distribution → Fourier transform of diagonal density distribution in $\textcolor{blue}{b}$

$$\bar{q}_+^\dagger(0, \textcolor{pink}{b}) q_+(z^-, \textcolor{pink}{b}) \rightarrow \rho(0, \textcolor{pink}{b}; z^-, \textcolor{pink}{b})$$

$H^u(x, 0, \Delta)$

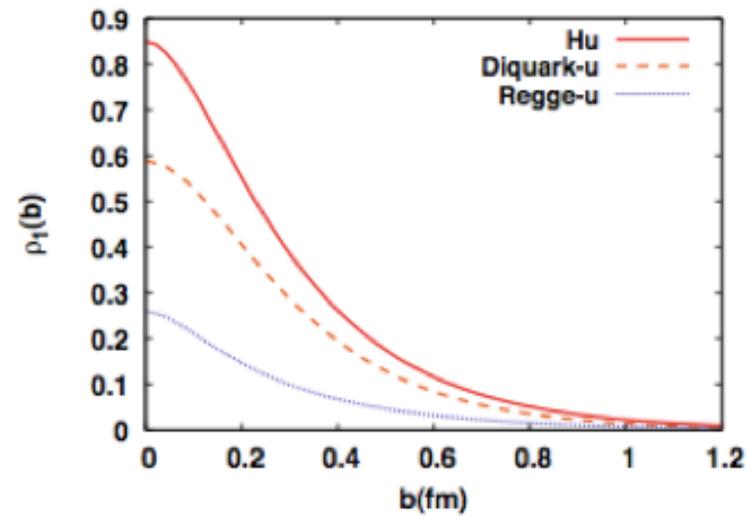
x dependence



O. Gonzalez-Hernandez et al., PRC88 (2013)

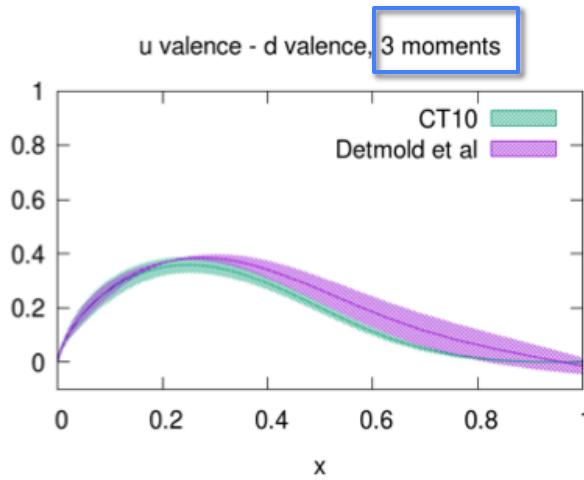
$$F^q(t \equiv \Delta^2) = \int dx H^q(x, 0, \Delta) \rightarrow \rho^q(b)$$

density distribution on transverse plane

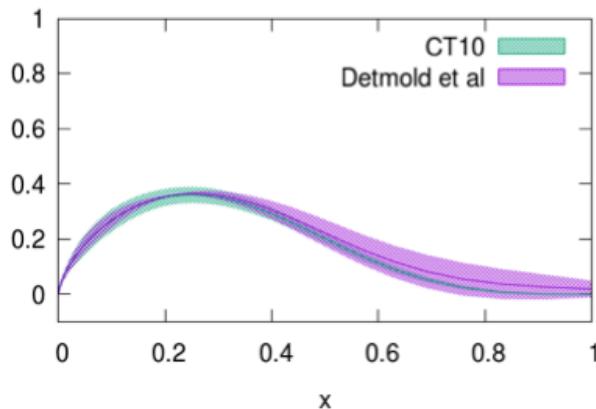


1. x -dependent reconstruction using Ioffe time distributions and lattice QCD moments (S.L. and A. Rajan)

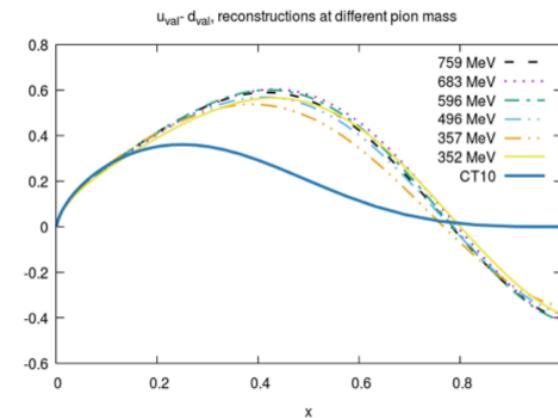
PDFs



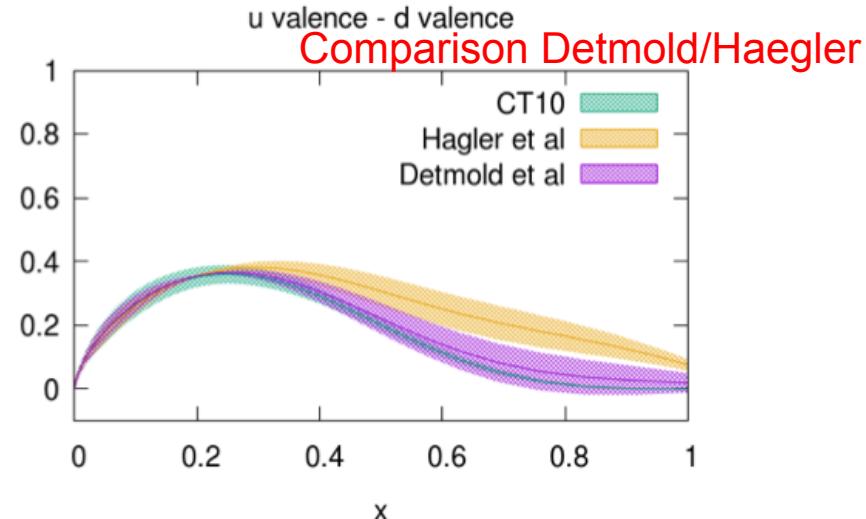
u valence - d valence, 4 moments



W. Detmold et al., Eur.Phys.J.3 (2001), Mod.Phys.Lett. A18 (2003)



LHPC (Ph. Hägler et al.) Phys.Rev. D77 (2008)



x

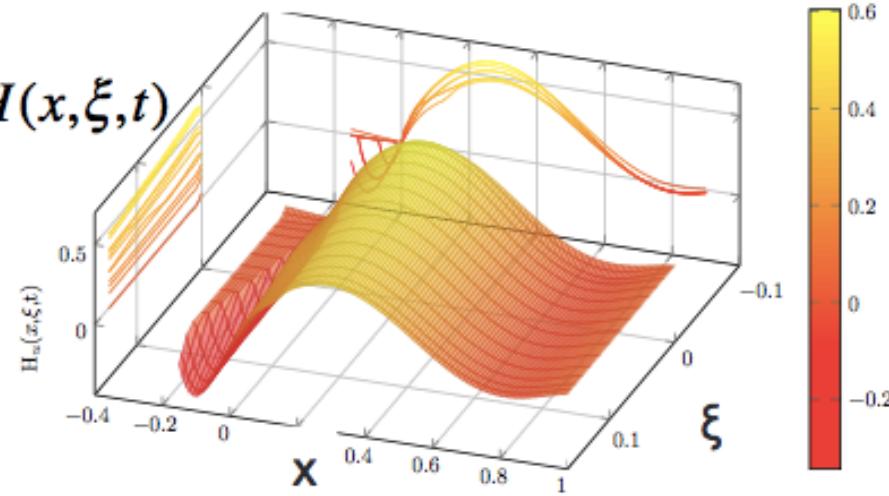
First stab at GPDs...

$$\overline{H}_{02}(X_{02}) = 3A_{10} - 6A_{20} + 3 \left[A_{30} + \left(\frac{2\zeta}{2-\zeta} \right)^2 A_{32} \right],$$

$$\overline{H}_{12}(X_{12}) = 6A_{20} - 6 \left[A_{30} + \left(\frac{2\zeta}{2-\zeta} \right)^2 A_{32} \right],$$

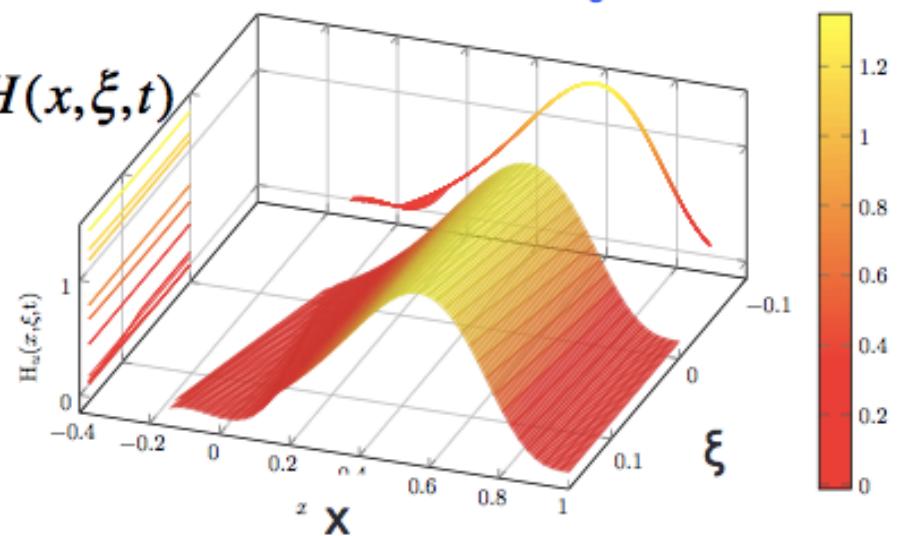
$$\overline{H}_{22}(X_{22}) = 3A_{30} + \left[\left(\frac{2\zeta}{2-\zeta} \right)^2 A_{32} \right].$$

$t = 0.1 \text{ GeV}^2, Q^2=4 \text{ GeV}^2$

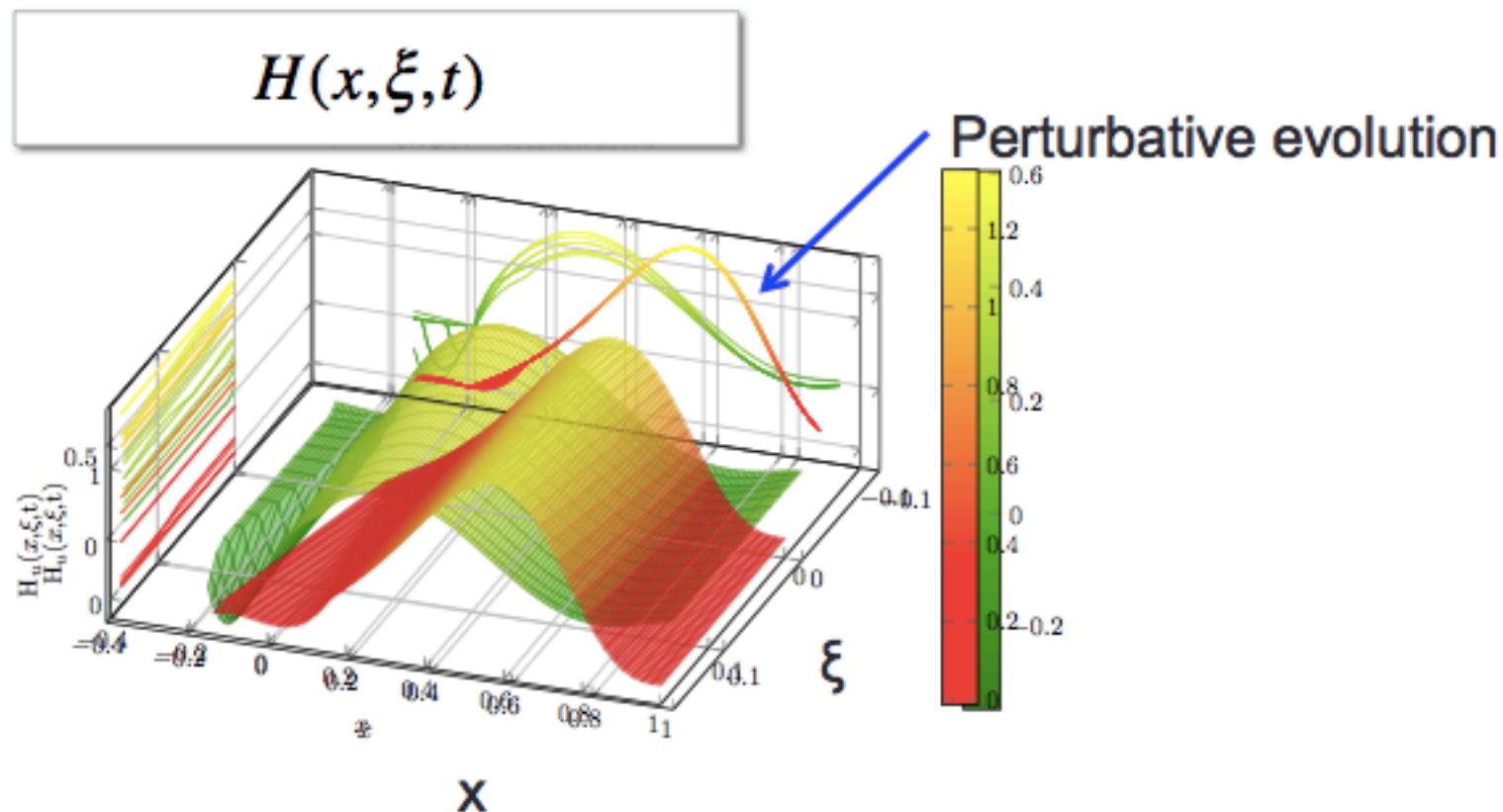


Reconstructed

$t = 0.1 \text{ GeV}^2, Q_0^2 = 0.1 \text{ GeV}^2$



Model



In summary ...

- Knowing the longitudinal (LC) momentum dependence allows us to separate out the transverse plane where Poincarè invariance applies
- We can then **scan the transverse plane** by measuring the scattered photon and proton with momentum transfer Δ

Based on

Parton transverse momentum and orbital angular momentum distributions

¹Physics Department, University of Virginia,^{2,†} Michael Engelhardt,^{3,‡} and Simonetta Liuti^{4,§}

²Catedrática CONACyT, Departamento de Física, Centro de Investigación y de Estudios Avanzados, Apartado Postal 14-740, 07000 México D.F., México

³T-
Department of Physics, New Mexico State University, Box 30001 MSC 3D,

⁴Physics Depa

Lorentz Invariance and QCD Equation of Motion Relations for Generalized Parton Distributions and the Dynamical Origin of Proton Orbital Angular Momentum

Abha Rajan,^{1,*} Michael Engelhardt,^{2,†} and Simonetta Liuti^{3,‡}

¹University of Virginia - Physics Department, 382 McCormick Rd., Charlottesville, Virginia 22904 - USA

²New Mexico State University - Department of Physics, Box 30001 MSC 3D, Las Cruces NM, 88003 - USA

³University of Virginia - Physics Department, 382 McCormick Rd., Charlottesville, Virginia 22904 - USA
and Laboratori Nazionali di Frascati, INFN, Frascati, Italy.

The quark integral of a W and momenta forward Com explicit link t transverse m determinatior orbital angul polarized tar

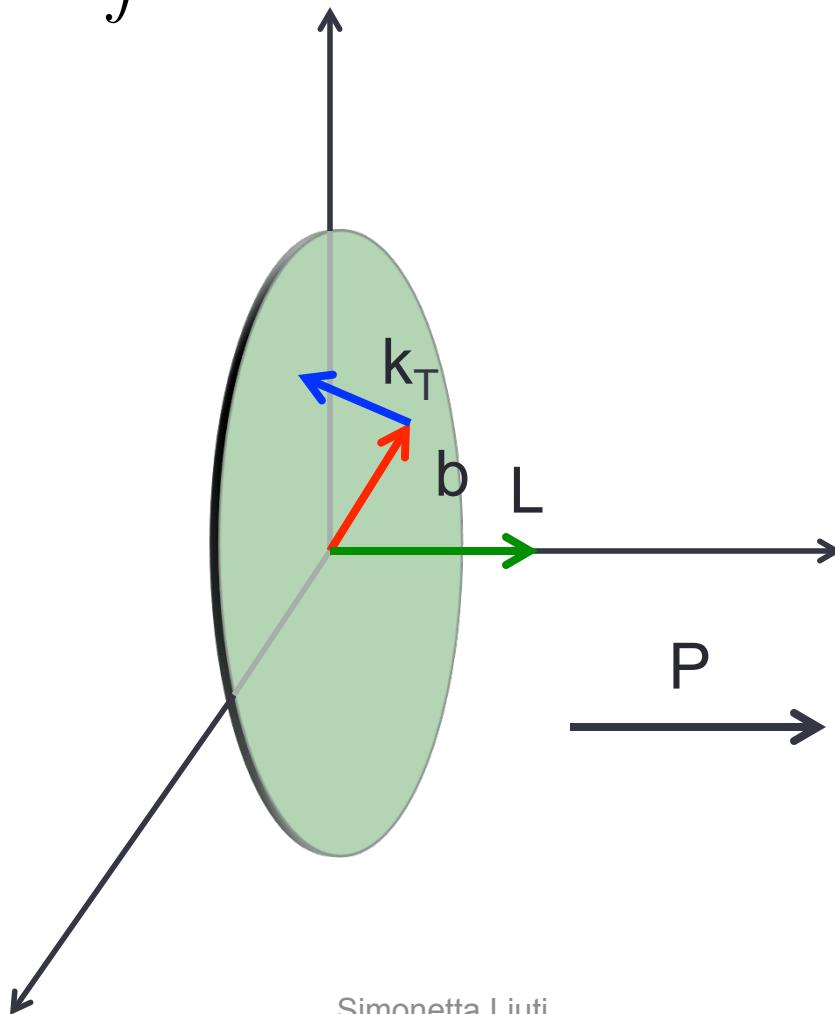
DOI: 10.1103

We derive new Lorentz Invariance and Equation of Motion Relations between twist-three Generalized Parton Distributions (GPDs) and moments in the parton transverse momentum, k_T , of the parton longitudinal momentum fraction x . Although GTMDs in principle define the observables for partonic orbital motion, experiments that can unambiguously detect them appear remote at present. The relations presented here provide a solution to this impasse in that, e.g., the orbital angular momentum density is connected to directly measurable twist-three GPDs. Out of 16 possible Equation of Motion relations that can be written in the T-even sector, we focus on three helicity configurations that can be detected analyzing specific spin asymmetries: two correspond to longitudinal proton polarization and are associated with quark orbital angular momentum and spin-orbit correlations; the third, obtained for transverse proton polarization, is a generalization of the relation obeyed by the g_2 structure function. We also exhibit an additional relation connecting the off-forward extension of the Sivers function to an off-forward Qiu-Sterman term.

2. Partonic Orbital Angular Momentum: Wigner Distributions

$$L_q^{\mathcal{U}} = \int dx \int d^2\mathbf{k}_T \int d^2\mathbf{b} (\mathbf{b} \times \mathbf{k}_T)_z \mathcal{W}^{\mathcal{U}}(x, \mathbf{k}_T, \mathbf{b})$$

Hatta Burkardt
Lorce, Pasquini,
Xiong, Yuan
Mukherjee,
Rajan,
S.L.

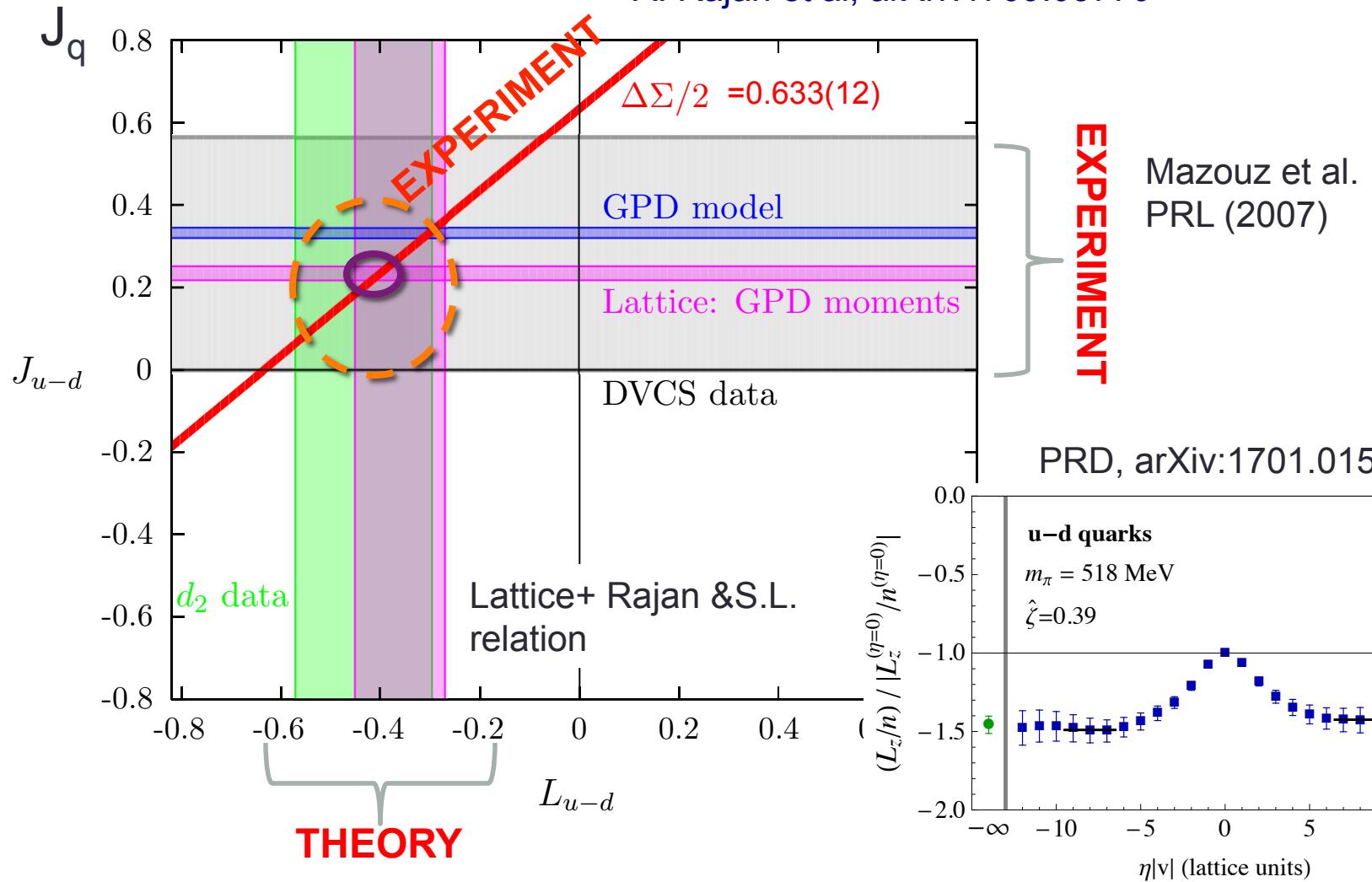


Quark sector :

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

A. Rajan et al, PRD (2016) arXiv:1601.06117

A. Rajan et al, arXiv:1709.05770



Possible Observable for L_q

$$\frac{1}{M} \int d^2 k_T k_T^2 F_{14}(x, 0, k_T^2, 0, 0) = \langle b_T \times k_T \rangle_3(x) \quad L_q(x)$$

k_T moment of a GTMD
(Lorce and Pasquini)

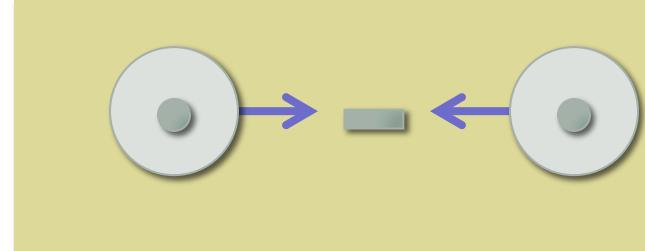
$$\begin{aligned}\xi &= 0 \\ k_T \cdot \Delta_T &= 0 \\ \Delta_T^2 &= 0\end{aligned}$$

CAN IT BE MEASURED?



Is there any observable that we can identify OAM with?

A New Relation



A. Rajan, A. Courtoy, M. Engelhardt, S.L., PRD (2016),
 A. Rajan, M. Engelhardt, S.L., submitted to PRD arXiv:1709.05770

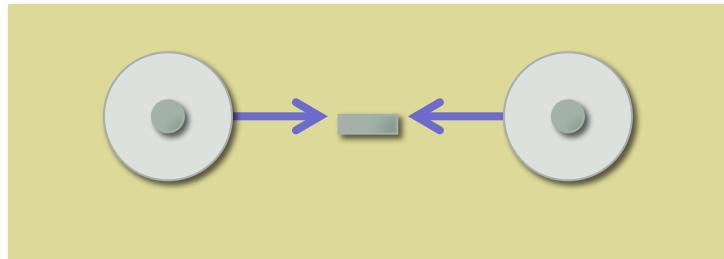
$$\frac{1}{M} \int d^2 k_T k_T^2 F_{14}(x, 0, k_T^2, 0, 0) = - \int_x^1 dy \left[\tilde{E}_{2T} + H + E \right]$$

Through Generalized Lorentz Invariance Relation (LIR)
 F_{14} is connected to twist 3 GPDs

* Different notation! $G_2 \rightarrow \tilde{E}_{2T} + H + E$
 Polyakov et al. Meissner, Metz and Schlegel, JHEP(2009)

Access to Angular Momentum Sum Rule $J_q = L_q + \frac{1}{2}\Delta\Sigma_q$

A. Rajan et al, arXiv:1709.05770



Beam Target Spin Correlation: unpolarized quark density in a longitudinally polarized proton

$$\tilde{E}_{2T} = - \int_x^1 \frac{dy}{y} (H + E) + \left[\frac{\tilde{H}}{x} - \int_x^1 \frac{dy}{y^2} \tilde{H} \right] + \left[\frac{1}{x} \mathcal{M}_{F_{14}} - \int_x^1 \frac{dy}{y^2} \mathcal{M}_{F_{14}} \right]$$

$L = J - S + 0$

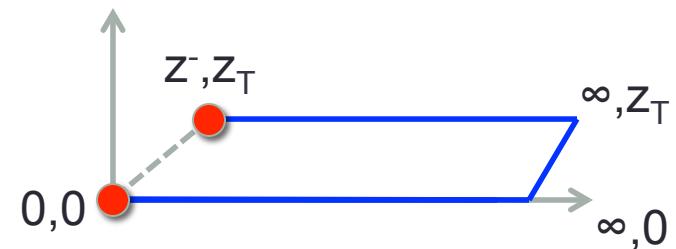
Diagram illustrating the decomposition of \tilde{E}_{2T} into components:

- New! From DVCS**: Points to the first term $-\int_x^1 \frac{dy}{y} (H + E)$.
- DVCS (Ji, '97)**: Points to the second term $\left[\frac{\tilde{H}}{x} - \int_x^1 \frac{dy}{y^2} \tilde{H} \right]$.
- Polarized ep $g_1(x)$** : Points to the third term $\left[\frac{1}{x} \mathcal{M}_{F_{14}} - \int_x^1 \frac{dy}{y^2} \mathcal{M}_{F_{14}} \right]$.
- Color force/gauge link**: Points to the zeroth term 0 .

Generalized LIR

$$\frac{1}{M} \int d^2 k_T k_T^2 F_{14}(x, 0, k_T^2, 0, 0) = - \int_x^1 dy \left[\tilde{E}_{2T} + H + E \right]$$

Generalized LIR for a staple link



$$\frac{d}{dx} \int d^2 k_T \frac{k_T^2}{M^2} F_{14} = \tilde{E}_{2T} + H + E + \mathcal{A}$$

LIR violating term

**Directly
calculable!**

$$A_{F_{14}} = v^{-\frac{(2P^+)^2}{M^2}} \int d^2 k_T \int dk^- \left[\frac{k_T \cdot \Delta_T}{\Delta_T^2} (A_{11}^F + x A_{12}^F) + A_{14}^F + \frac{k_T^2 \Delta_T^2 - (k_T \cdot \Delta_T)^2}{\Delta_T^2} \left(\frac{\partial A_8^F}{\partial(k \cdot v)} + x \frac{\partial A_9^F}{\partial(k \cdot v)} \right) \right]$$

Interpretation

$M_2(v^-)$

Force acting on quark

$$\int dx \int d^2 k_T \mathcal{M}_{\Lambda' \Lambda}^{i,S} = i \epsilon^{ij} g v^- \frac{1}{2P^+} \int_0^1 ds \langle p', \Lambda' | \bar{\psi}(0) \gamma^+ U(0, sv) F^{+j}(sv) U(sv, 0) \psi(0) | p, \Lambda \rangle$$

$$\int dx \int d^2 k_T \mathcal{M}_{\Lambda' \Lambda}^{i,A} = -g v^- \frac{1}{2P^+} \int_0^1 ds \langle p', \Lambda' | \bar{\psi}(0) \gamma^+ \gamma^5 U(0, sv) F^{+i}(sv) U(sv, 0) \psi(0) | p, \Lambda \rangle$$

Non zero only for staple link

$M_3(v=0)$

$$\int dx x \int d^2 k_T \mathcal{M}_{\Lambda' \Lambda}^{i,S} = \frac{ig}{4(P^+)^2} \langle p', \Lambda' | \bar{\psi}(0) \gamma^+ \gamma^5 F^{+i}(0) \psi(0) | p, \Lambda \rangle$$

$$\int dx x \int d^2 k_T \mathcal{M}_{\Lambda' \Lambda}^{i,A} = \frac{g}{4(P^+)^2} \epsilon^{ij} \langle p', \Lambda' | \bar{\psi}(0) \gamma^+ F^{+j}(0) \psi(0) | p, \Lambda \rangle$$

Relations between derivatives

$$\frac{d}{dv^-} \mathcal{M}_{\Lambda\Lambda'}^{i,S(n=2)} \Big|_{v^- = 0} = i(2P^+) \mathcal{M}_{\Lambda\Lambda'}^{i,A(n=3)}$$

$$\frac{d}{dv^-} \mathcal{M}_{\Lambda\Lambda'}^{i,A(n=2)} \Big|_{v^- = 0} = -i(2P^+) \mathcal{M}_{\Lambda}^{i,S(n=3)}$$

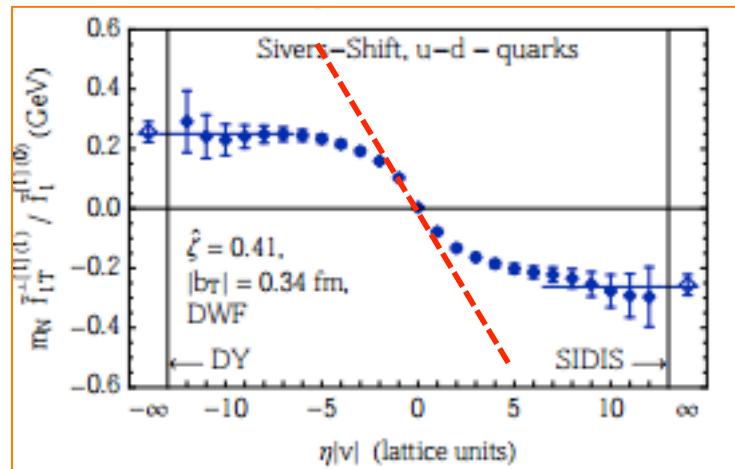
Proton transverse spin configuration

Genuine twist three d_2

$$\frac{d}{dv^-} \left[\int dx F_{12}^{(1)} \right]_{v^- = 0} = \frac{d}{dv^-} \int dx \mathcal{M}_{F_{12}} \Big|_{v^- = 0} = i(2P^+) \int dx x \frac{\Delta_i}{\Delta_T^2} (\mathcal{M}_{++}^{i,A} - \mathcal{M}_{--}^{i,A}) = \mathcal{M}_{G_{12}}^{n=3}$$

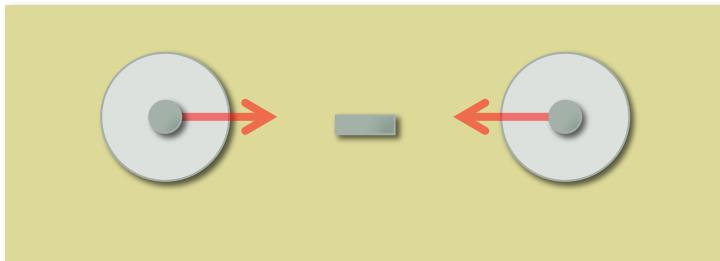
$$\frac{d}{dv^-} \int dx G_{12}^{(1)} \Big|_{v^- = 0} = \frac{d}{dv^-} \int dx \mathcal{M}_{G_{12}} \Big|_{v^- = 0} = i(2P^+) \int dx x \frac{\Delta_i}{\Delta_T^2} (\mathcal{M}_{++}^{i,S} + \mathcal{M}_{--}^{i,S}) = \mathcal{M}_{F_{12}}^{n=3}$$

Slope of Sivers function in staple length



Other correlations: quark and gluon spin-orbit

A. Rajan et al, arXiv:1709.05770



Beam Target Spin Correlation: longitudinally polarized quark density in an unpolarized proton

$$\frac{1}{2} \int dx x \tilde{H} = (L_z S_z)_q + \frac{1}{2} e_q - \frac{m_q}{2M} \kappa_T^q$$

chiral odd magnetic moment

Chiral symmetry breaking test!

x moments

M_1

$$\boxed{\int dx \tilde{E}_{2T} = - \int dx (H + E)}$$

$$\Rightarrow \int dx (\tilde{E}_{2T} + H + E) = 0$$

M_2

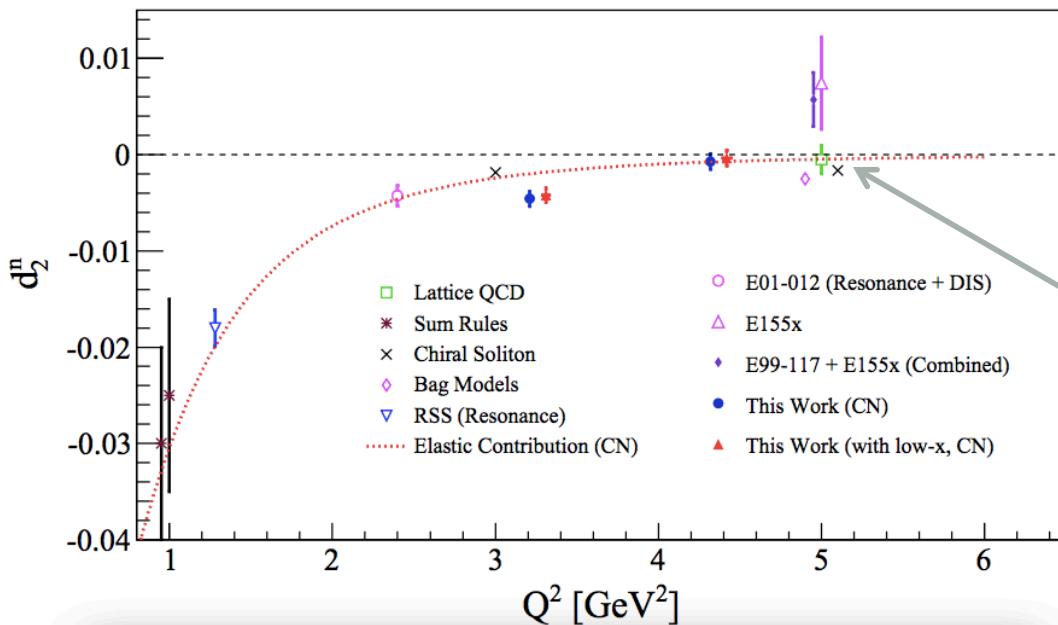
OAM Sum Rule

$$\boxed{\int dxx \tilde{E}_{2T} = -\frac{1}{2} \int dxx (H + E) - \frac{1}{2} \int dx \tilde{H}}$$

M_3

$$\boxed{\int dxx^2 \tilde{E}_{2T} = -\frac{1}{3} \int dxx^2 (H + E) - \frac{2}{3} \int dxx \tilde{H}}$$

$$-\frac{2}{3} \int dxx \mathcal{M}_{F_{14}}$$



Generalized Burkhardt Cottingham

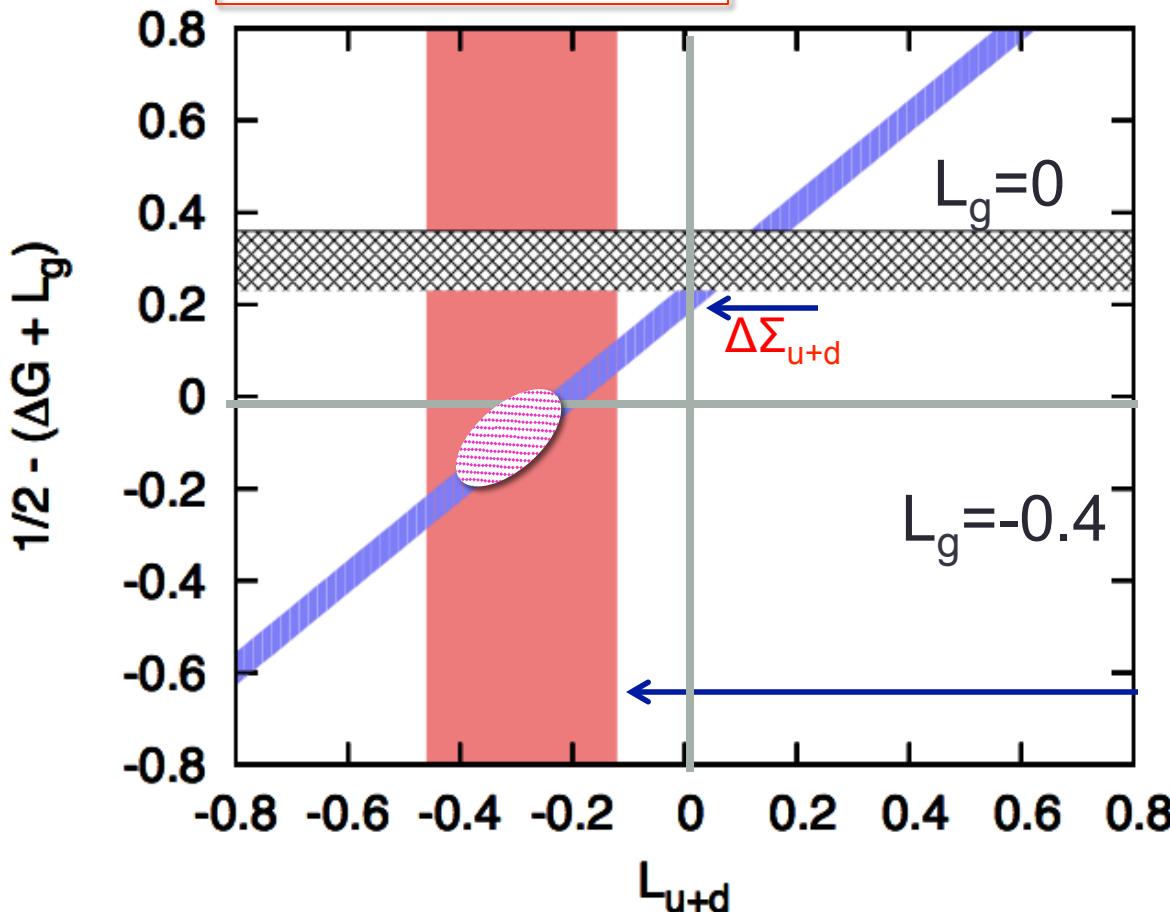
Genuine twist three d_2

Lattice calculation

EIC → Adding gluons: Jaffe Manohar Sum Rule

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

$$\boxed{\frac{1}{2} - (\Delta G + L_g^{JM})} = L_q^{JM} + \frac{1}{2}\Delta\Sigma_q$$

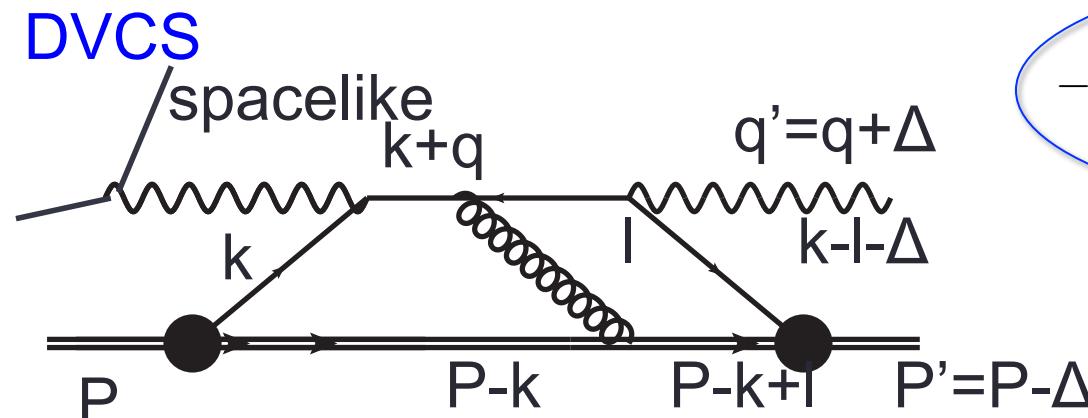


Using the “estimated” measured value of ΔG

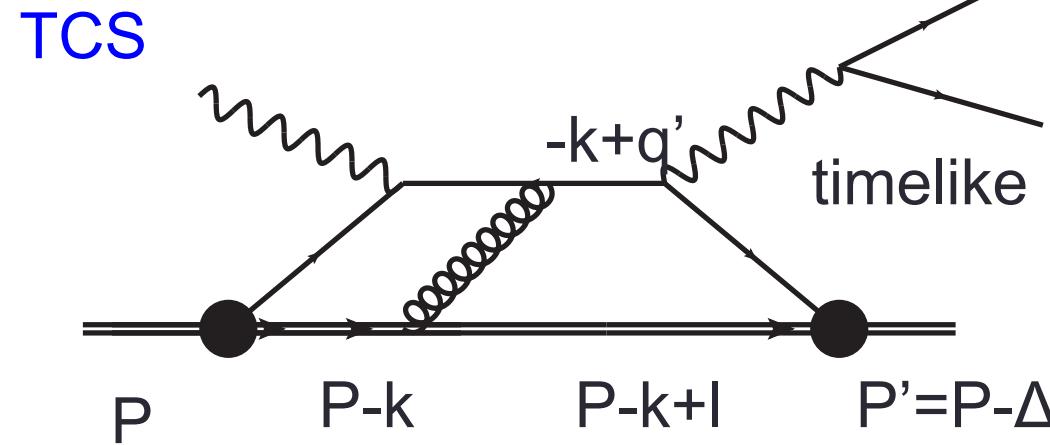
M. Engelhardt, preliminary
Lattice QCD evaluation
of GTMD F_{14} + gauge
link

A probe of QCD at the amplitude level: color forces!

$$\tilde{E}_{2T} = \tilde{E}_{2T}^{WW} + \tilde{E}_{2T}^{(3)} + \tilde{E}_{2T}^{LIR}$$



$$- \left[\frac{1}{x} \mathcal{M}_{F_{14}} - \int_x^1 \frac{dy}{y^2} \mathcal{M}_{F_{14}} \right] - \int_x^1 \frac{dy}{y} \mathcal{A}_{F_{14}}$$



Test Universality!

B. Kriesten, in progress

Finally, nuclei

To appear in PRL

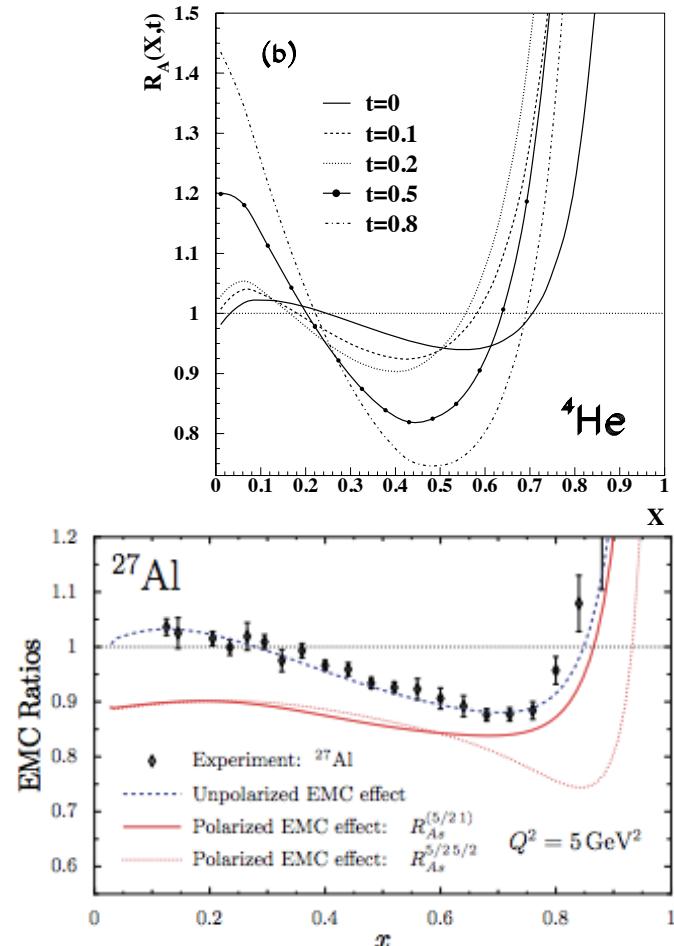
First Exclusive Measurement of Deeply Virtual Compton Scattering off ${}^4\text{He}$: Toward the 3D Tomography of Nuclei

M. Hattawy,^{1,2} N.A. Baltzell,^{1,3} R. Dupré,^{1,2,*} K. Hafidi,¹ S. Stepanyan,³
 S. Bultmann,⁴ R. De Vita,⁵ A. El Alaoui,^{1,6} L. El Fassi,⁷ H. Egiyan,³ F.X. Girod,³
 M. Guidal,² D. Jenkins,⁸ S. Liuti,⁹ Y. Perrin,¹⁰ B. Torayev,⁴ and E. Voutier^{10,2}
 (The CLAS Collaboration)

Inspired by original studies of spin 0 GPDs:
 SL & Taneja, PRD70 (2004), PRC72 (2005),
 PRC72R (2005)

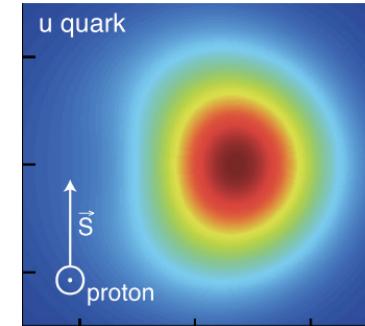
In progress/Future

The spin-orbit term can shed light on the origin of the polarized EMC effect
 (work in progress with I. Cloet)



➤ Spin and 3D structure of Deuteron

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



Nucleon (Ji, 1997)

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

Deuteron (Taneja, Kathuria, SL, Goldstein, 2012)

Spin 1 nucleus GPD related to deuteron form factor, G_M :
measurable with transverse polarized target
(Crabb, Day, Keller)

2. Energy Density

Quark mass term implies measuring scalar interaction in the proton: what are the observables?

$$H_q = \langle \bar{\psi}(-i \mathbf{D} \cdot \boldsymbol{\gamma})\psi \rangle$$

-- twist three pdf elusive

$$H_g = \left\langle \frac{1}{2}(E^2 + B^2) \right\rangle$$

-- twist three GPD

$$H_m = \left\langle m \bar{\psi} \left(1 + \frac{1}{4}\gamma_m \right) \psi \right\rangle$$

$$H_a = \left\langle \frac{1}{4}\beta(g)(E^2 - B^2) \right\rangle$$

-- connection with tensor interaction (G. Goldstein, O. Gonzalez-Hernandez, S.L.)

-- impact on BSM searches (A. Courtoy, S. Baessler, M. Gonzalez-Alonso, S.L., PRL (2015))

3. Shear Stress

Physics of the D-term (S.L. and S.K. Taneja)

$$\int_{-A}^A dx H^A(x, \xi, t) = F^A(t)$$

${}^4\text{He}$, spin 0!

$$\int_{-A}^A dxxH^A(x, \xi, t) = M_2^A(t) + \frac{4}{5}d_1^A(t)\xi^2,$$

\mathbf{d} represents the spatial distribution of the shears forces (Polyakov Shuvaev)

$$d^Q(0) = -\frac{m_N}{2} \int d^3r \ T_{ij}^Q(\vec{r}) \left(r^i r^j - \frac{1}{3} \delta^{ij} r^2 \right)$$

3. A NEW CONCERTED EFFORT

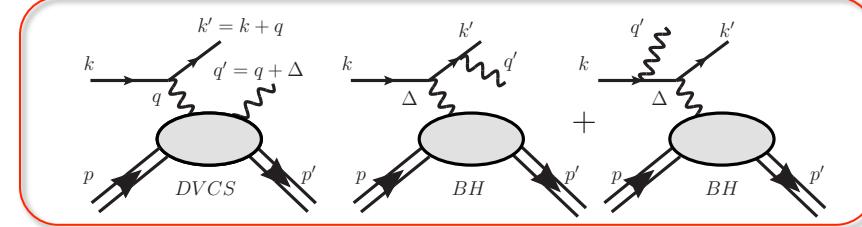
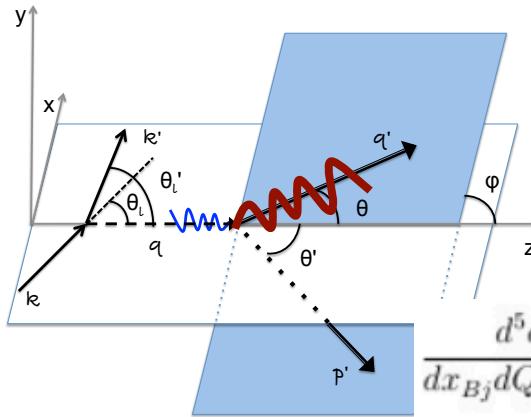
Multi-process, multi-variable analysis

- ✓ Deeply Virtual Compton Scattering
- ✓ Deeply Virtual Meson Production
- ✓ Timelike Compton Scattering
- ✓ Double DVCS
- ✓ DVCS, TCS with Recoil Polarization

(BTW...NEED EIC TO CARRY OUT THIS PROGRAM)

Deeply Virtual Compton Scattering

$$e p \rightarrow e' \gamma p'$$



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

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

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

$$+ (2h) \sqrt{2\epsilon(1-\epsilon)} \sin \phi F_{LU}^{\sin \phi} \left. \right]$$

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

$$+ (2h) \sqrt{1-\epsilon^2} F_{LL} + 2(2h) \sqrt{\epsilon(1-\epsilon)} \cos \phi F_{LL}^{\cos \phi} \left. \right]$$

$$+ |\vec{S}_\perp| \left[\sin(\phi - \phi_S) \left(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)} \right) \right. \\ \epsilon \sin(\phi + \phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \epsilon \sin(3\phi - \phi_S) F_{UT}^{\sin(3\phi-\phi_S)} \\ \left. + \sqrt{2\epsilon(1+\epsilon)} \left(\sin \phi_S F_{UT}^{\sin \phi_S} + \sin(2\phi - \phi_S) F_{UT}^{\sin(2\phi-\phi_S)} \right) \right] \\ + (2h) |\vec{S}_\perp| \left[\sqrt{1-\epsilon^2} \cos(\phi - \phi_S) F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)} \cos \phi_S F_{LT}^{\cos \phi_S} \right. \\ \left. + \sqrt{2\epsilon(1-\epsilon)} \cos(2\phi - \phi_S) F_{LT}^{\cos(2\phi-\phi_S)} \right] \} \quad (44)$$

GPD Content

(with Brandon Kriesten et al., in preparation)

$$F_{UU,T} = e^4 \left[(1 - \xi^2) (\|\mathcal{H}\|^2 + \|\bar{\mathcal{H}}\|^2) + \frac{\Delta_T^2}{M^2(1 - \xi^2)} (\|\mathcal{E}\|^2 + \xi^2 \|\bar{\mathcal{E}}\|^2) \right.$$

$$\left. - \xi^2 (\text{Re}(\mathcal{H})\text{Re}(\mathcal{E}) + \text{Re}(\bar{\mathcal{H}})\text{Re}(\bar{\mathcal{E}}) + \text{Im}(\mathcal{H})\text{Im}(\mathcal{E}) + \text{Im}(\bar{\mathcal{H}})\text{Im}(\bar{\mathcal{E}})) \right]$$

twist 2

$$F_{UU}^{\cos \phi} = e^4 \left(\frac{\sqrt{Q^2 + \nu^2} - \nu}{2P^+ Q^-} \right) \frac{\Delta_T^2}{4P^+} \left[\text{Re} \left(2\bar{\mathcal{H}}'_{2T} + \mathcal{E}'_{2T} + 2\bar{\mathcal{H}}_{2T} + \mathcal{E}_{2T} - \xi \bar{\mathcal{E}}_{2T} - \xi \bar{\mathcal{E}}'_{2T} \right) \text{Re} \left(\mathcal{H} - \frac{\xi^2}{1 - \xi^2} \mathcal{E} \right) \right.$$

twist 3

twist 2

spin-orbit

OAM

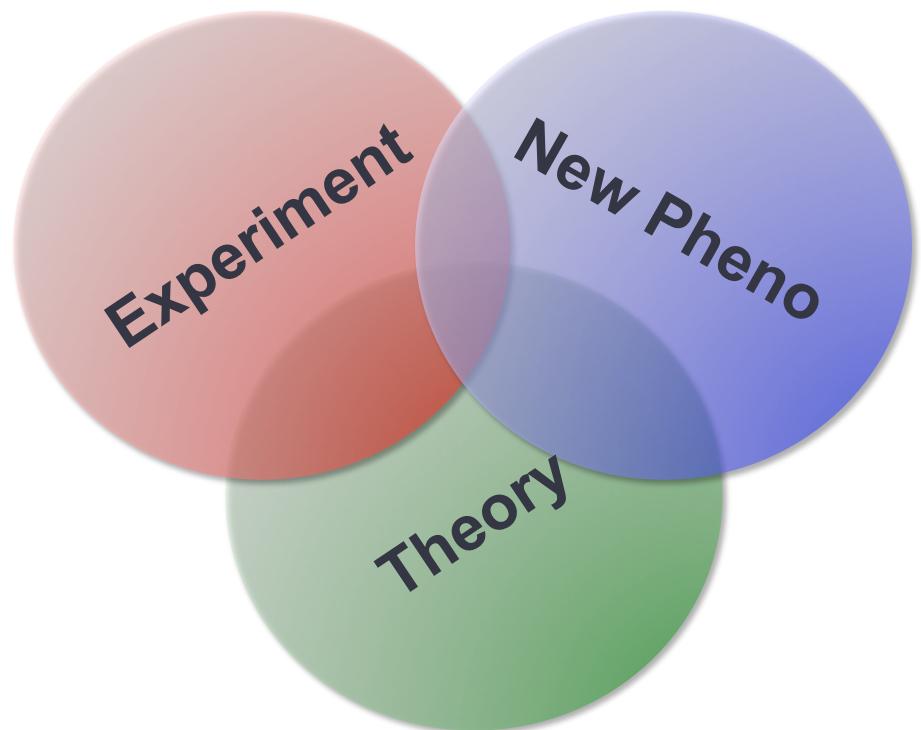
$$- \text{Re} \left(\xi \mathcal{E}'_{2T} + \xi \mathcal{E}_{2T} + \bar{\mathcal{E}}_{2T} + \bar{\mathcal{E}}'_{2T} \right) \text{Re} \left(\bar{\mathcal{H}} - \frac{\xi^2}{1 - \xi^2} \bar{\mathcal{E}} \right)$$

$$+ \text{Im} \left(2\bar{\mathcal{H}}'_{2T} + \mathcal{E}'_{2T} + 2\bar{\mathcal{H}}_{2T} + \mathcal{E}_{2T} - \xi \bar{\mathcal{E}}_{2T} - \xi \bar{\mathcal{E}}'_{2T} \right) \text{Im} \left(\mathcal{H} - \frac{\xi^2}{1 - \xi^2} \mathcal{E} \right)$$

$$- \text{Im} \left(\xi \mathcal{E}'_{2T} + \xi \mathcal{E}_{2T} + \bar{\mathcal{E}}_{2T} + \bar{\mathcal{E}}'_{2T} \right) \text{Im} \left(\bar{\mathcal{H}} - \frac{\xi^2}{1 - \xi^2} \bar{\mathcal{E}} \right) + \dots \right]$$

$$F_{UU}^{\sin \phi} = 0$$

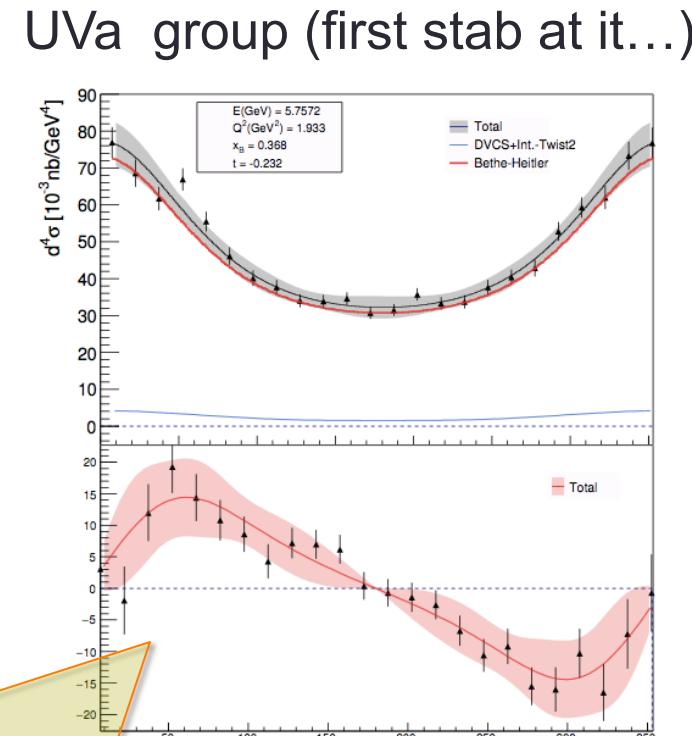
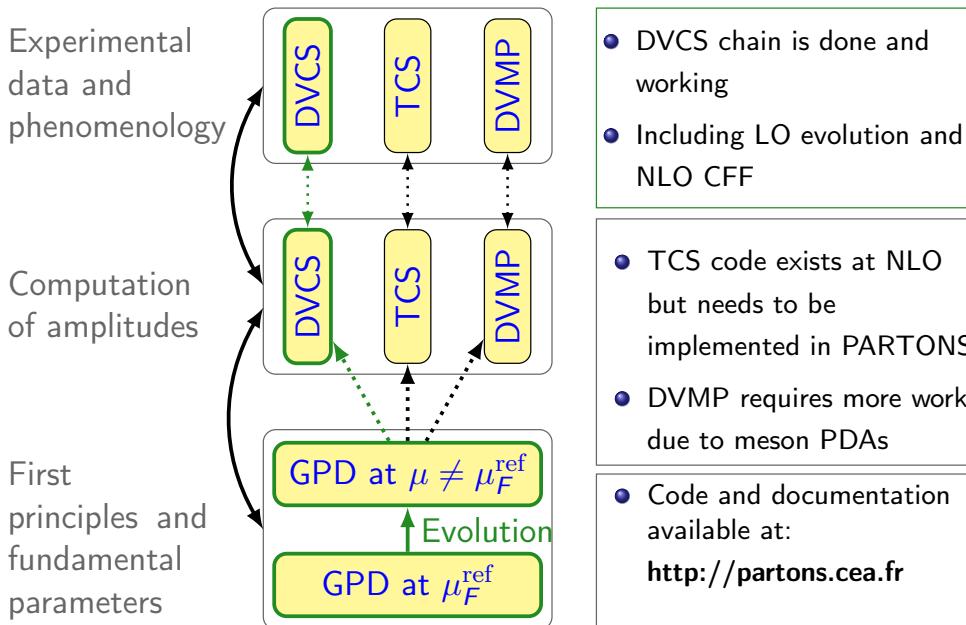
How do we detect all this?



New Analysis Groups

PARTONS: A GPDs dedicated Software

B. Berthou *et al.*, Eur.Phys.J. C78 (2018) no.6, 478



Need a variety of approaches (not just one scheme) to make progress!!

- Need to handle unprecedentedly large and varied volumes of data from different sources
- The analyses requirements call for an evolution of the standard physics methodologies.
- Infusion of Data Science methods into the physics analysis workflow provides that evolution.
- **No centralized hub!**
- White paper with benchmarks for all needed!

Conclusions and Outlook

A vast program ahead of us that can be explored only with an EIC

A global analysis will allow us to extract the spatial structure of the proton and neutron from measurements of hard electron proton scattering processes (DVMP, Dihadron electroproduction, single jet SIDIS). This program can be developed at the EIC!!!!

The possibility of obtaining the scalar and tensor form factors and charges directly from experiment with sufficient precision, gives an entirely different leverage to neutron beta decay searches

Hopefully experimental studies of the hard exclusive processes will fill the gap in our understanding of the strong forces creating our world as we see it.

M.Polyakov (hep-ph/0210165)

Hopefully experimental studies of the hard exclusive processes will fill the gap in our understanding of the strong forces creating our world as we see it.

Maxim Polyakov ([hep-ph/0210165](#))