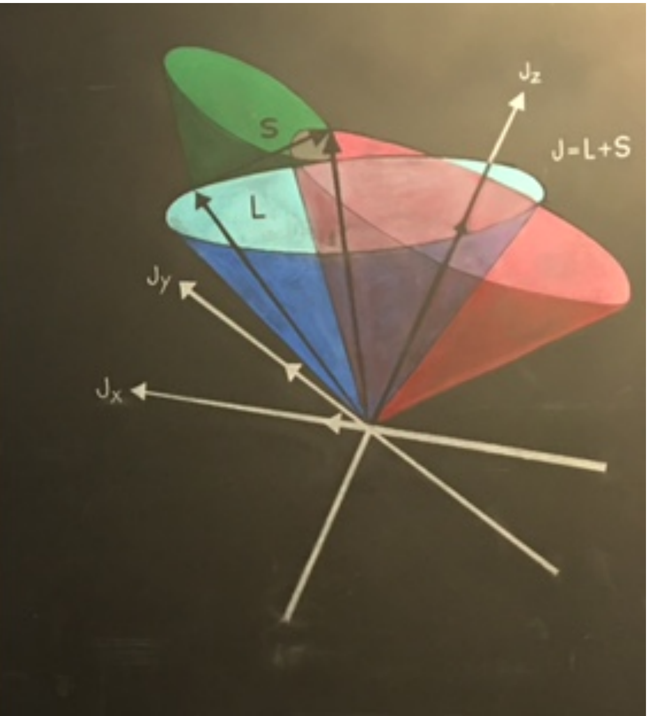
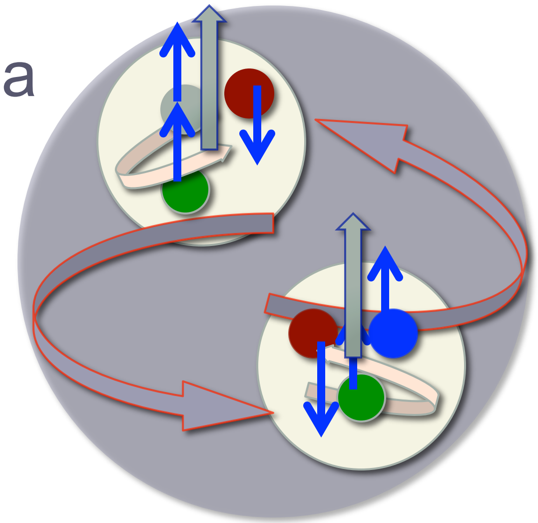
ON THE DYNAMICAL ORIGIN OF PARTONIC ANGULAR MOMENTUM

TRANSVERSITY 2017

DECEMBER 11-15, 2017



Simonetta Liuti
University of Virginia



Based on

PHYSICAL REVIEW D **94**, 034041 (2016)

Parton transverse momentum and orbital angular momentum distributions

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The quark … integral of a W… and momentu… forward Com… explicit link t… transverse m… determinatio… orbital angul… polarized tar…

DOI: 10.110…

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

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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 twist-two Generalized Transverse Momentum-Dependent Distributions (GTMDs), as a function 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.

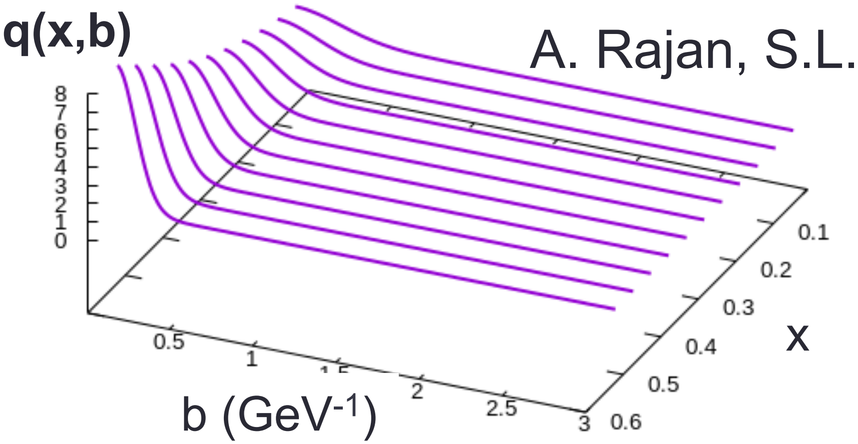
arXiv:1709.05770

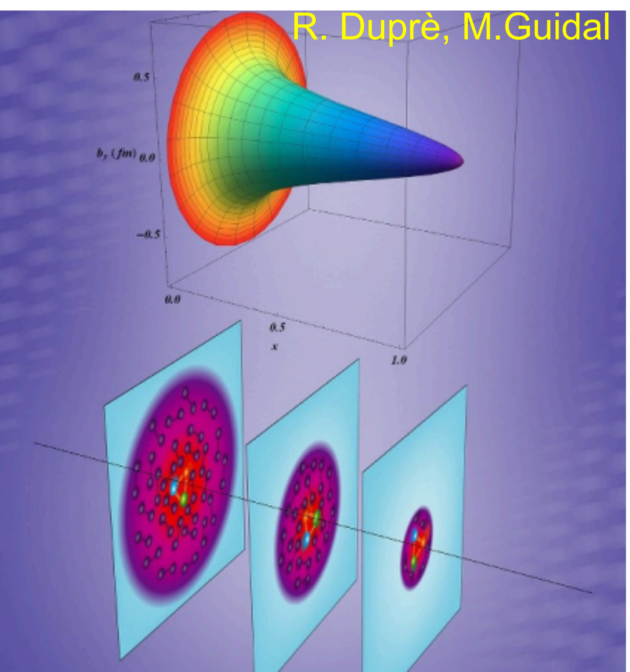
Outline

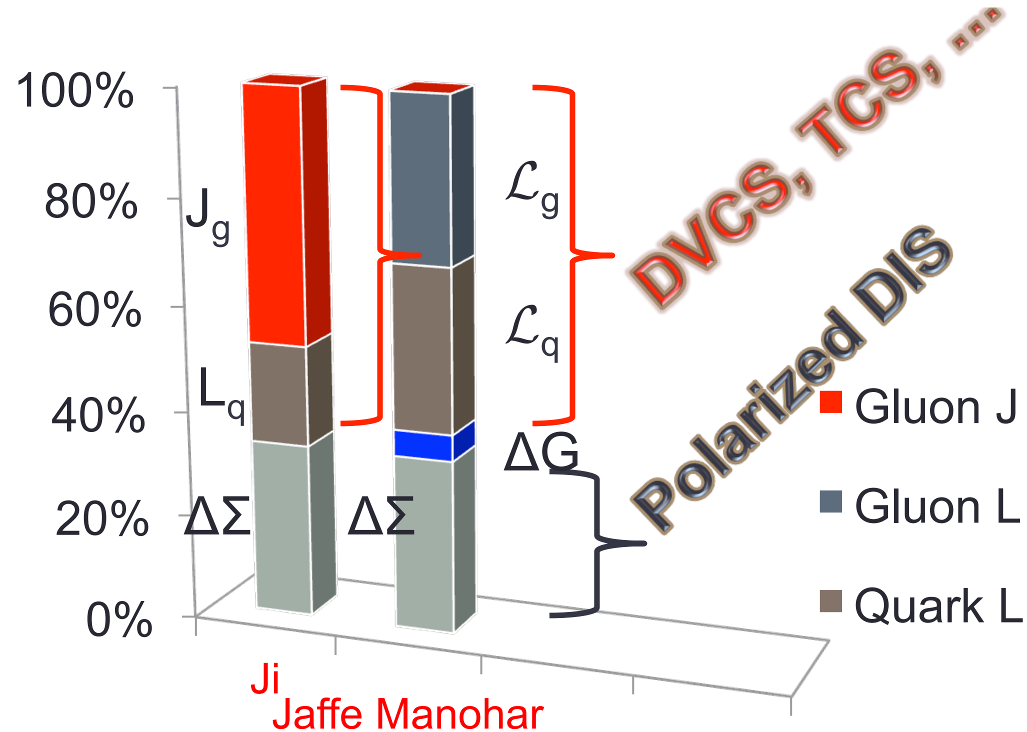
1. Introduction: aim of deeply virtual exclusive experiments
2. Overview of results on OAM
3. New OAM sum rules ➔ twist three GPD $\tilde{E}_{2T}$, role of gauge links
4. Extraction from experiment: new DVCS/TCS formalism and UVa Multivariate Analysis
5. Nuclei

Proton imaging

Why do we study GPDs?



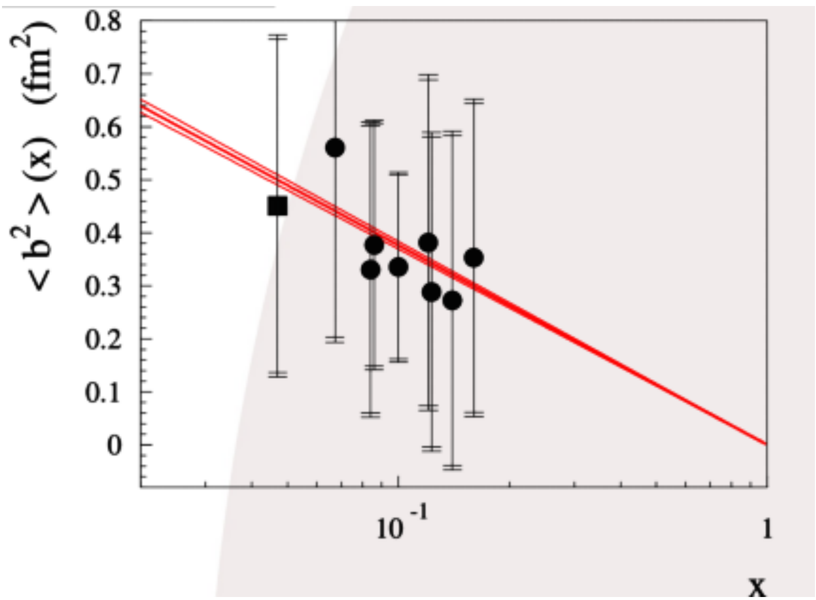




Angular Momentum

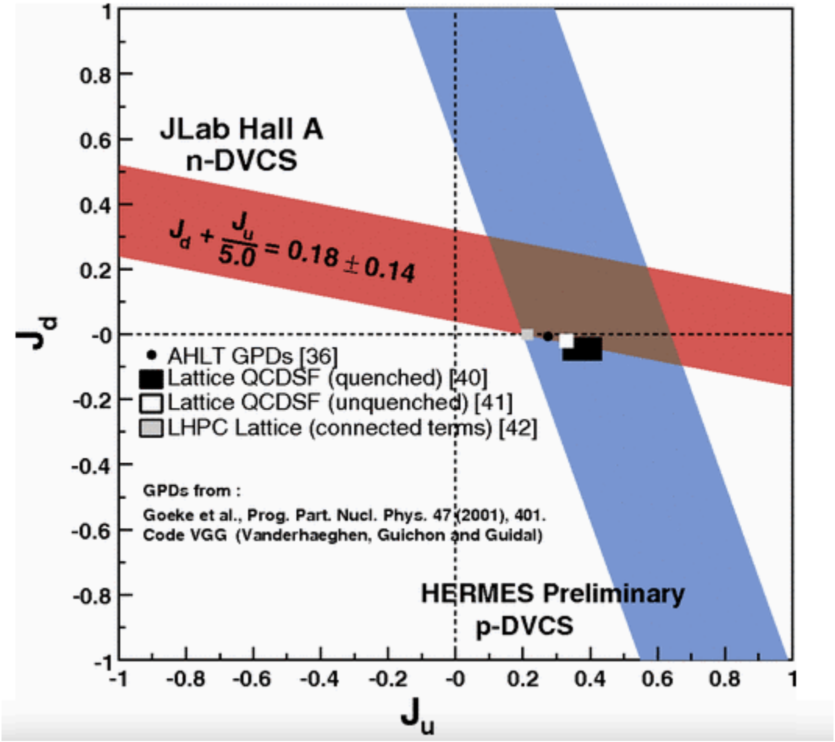
Proofs of concept

Proton Imaging



R. Duprè, M.Guidal (2016)

Angular Momentum



E.Mazouz et al., PRL(2007)

How do we move beyond the proof of concept?

… a closer look at angular momentum

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

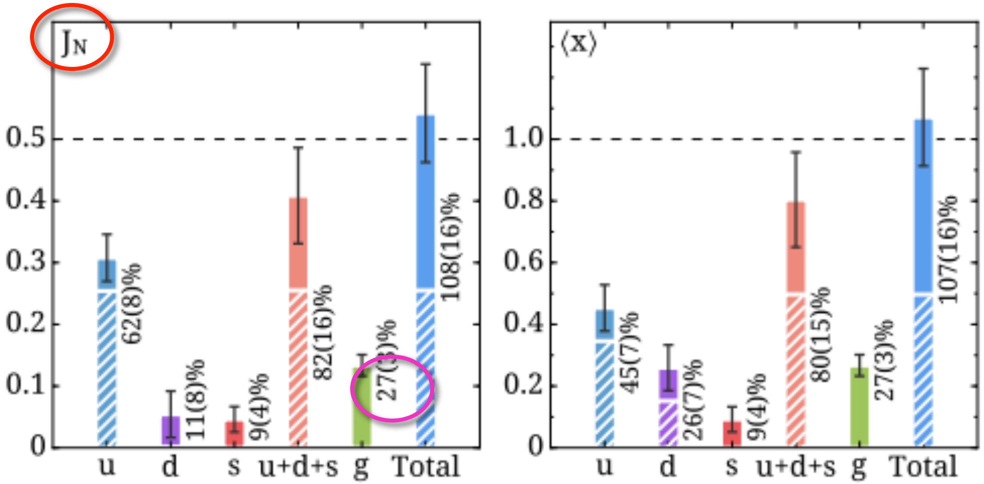
quark spin

quark orbital angular momentum

gluon angular momentum

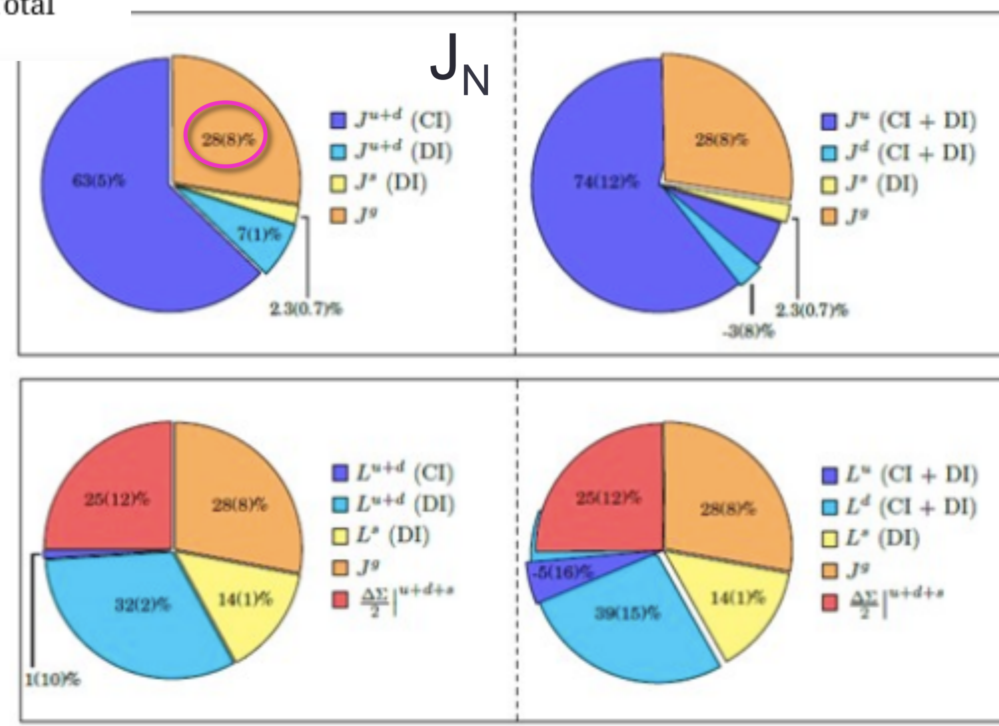
…what do we know so far?

The nucleon spin in Lattice QCD

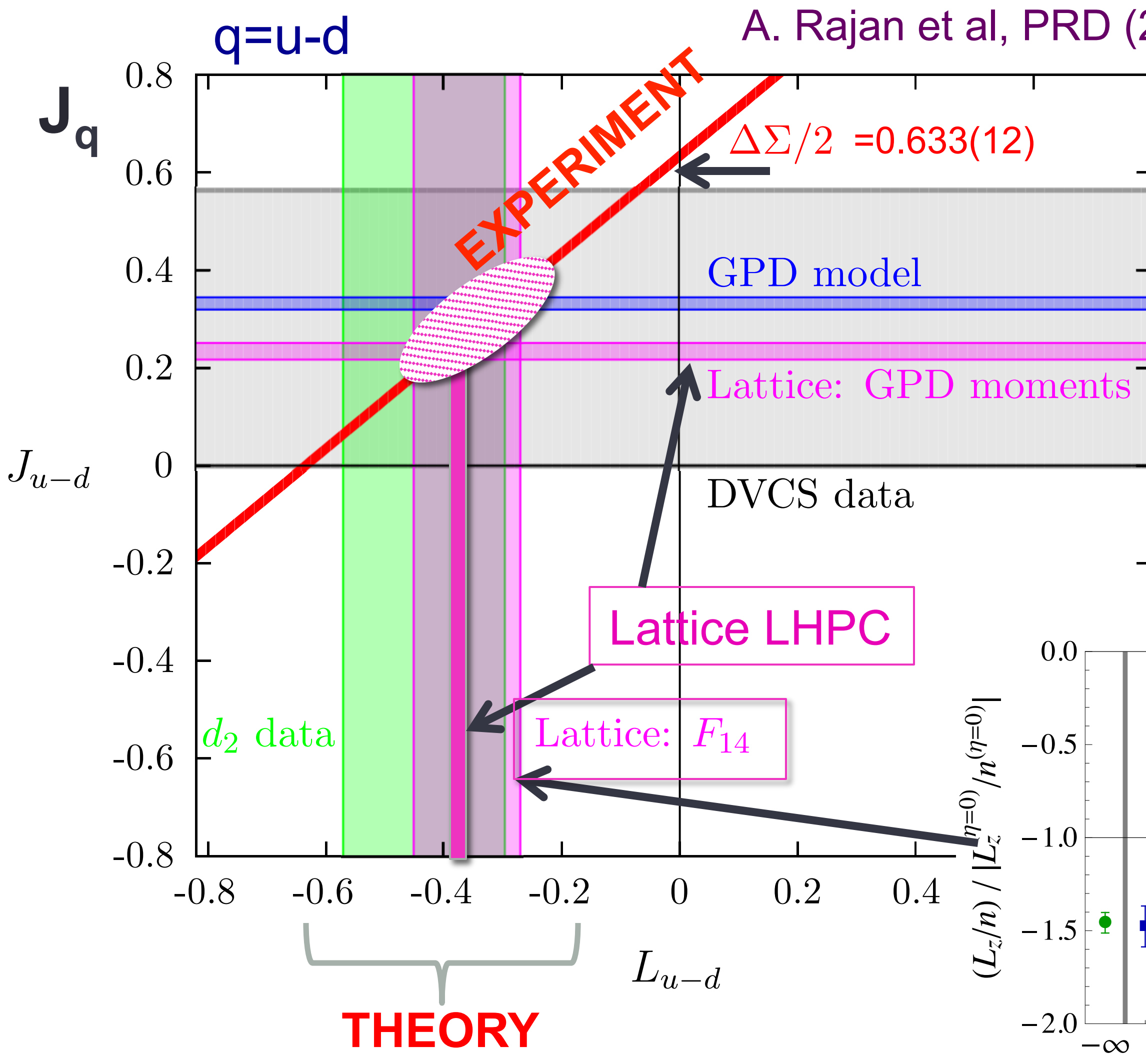


C. Alexandrou et al., PRL (2017)

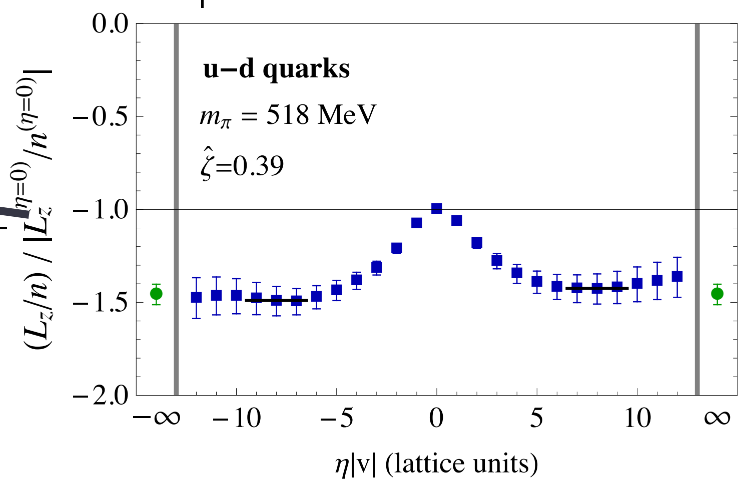
χQCD Coll., Deka et al. PRD (2015)



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



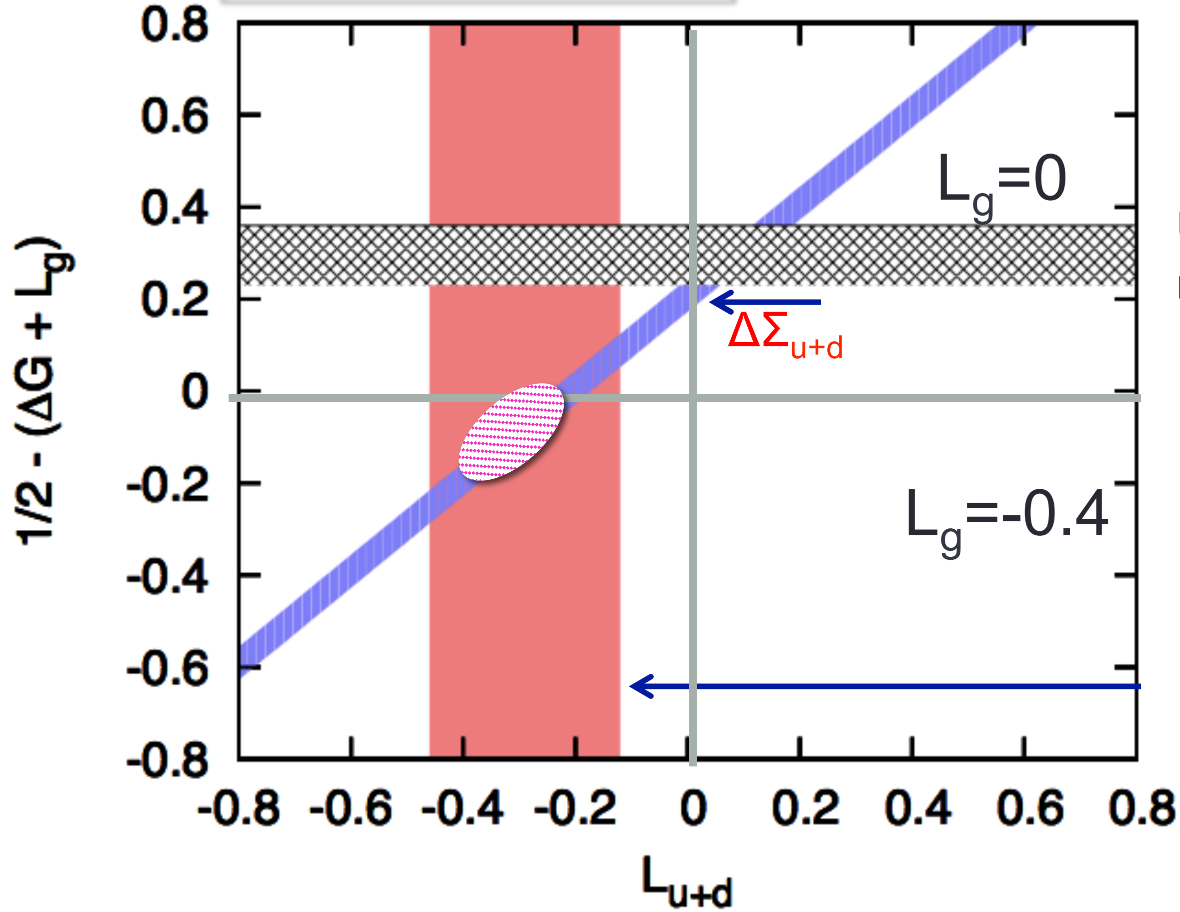
M. Engelhardt (PRD, 2017)



EIC ➔ Adding gluons: Jaffe Manohar Sum Rule

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

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



Using the “estimated” measured value of ΔG

M. Engelhardt, preliminary

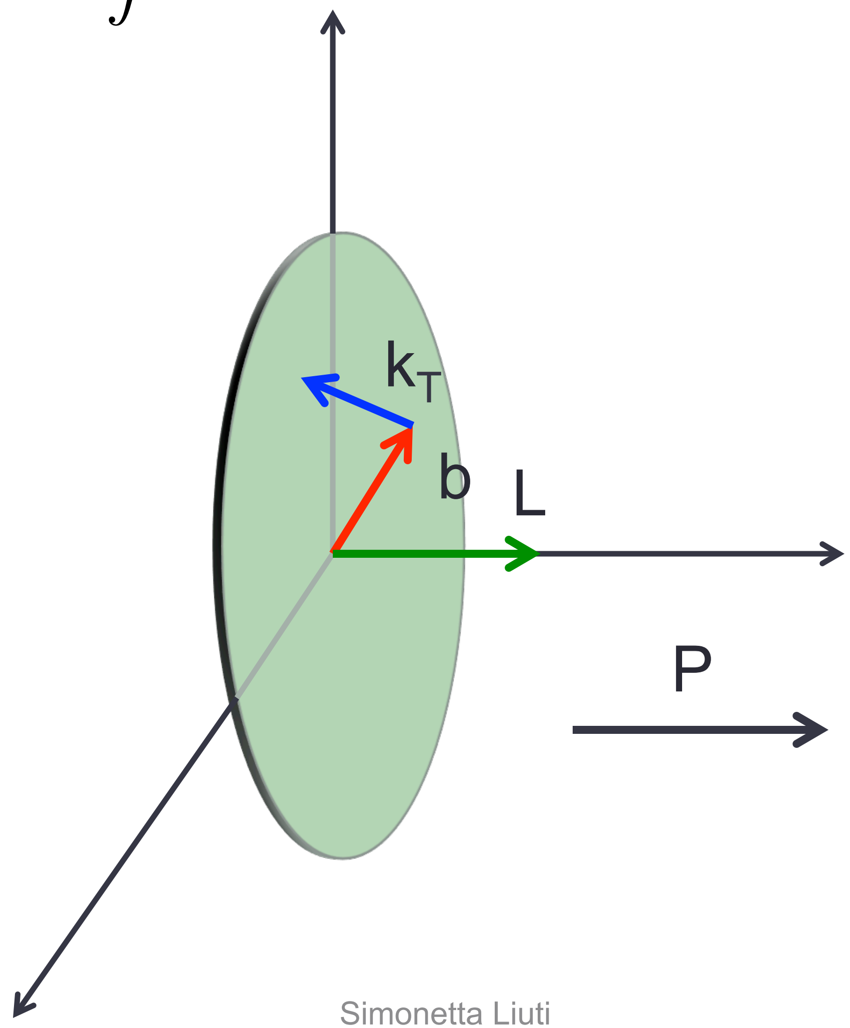
Lattice QCD evaluation of GTMD F_{14}+ gauge link

2. OAM FROM WIGNER DISTRIBUTIONS AND TWIST THREE GPDS

Partonic OAM: 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
Lorce, Pasquini,
Xiong, Yuan
Mukherjee



Possible Observable for L_q

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

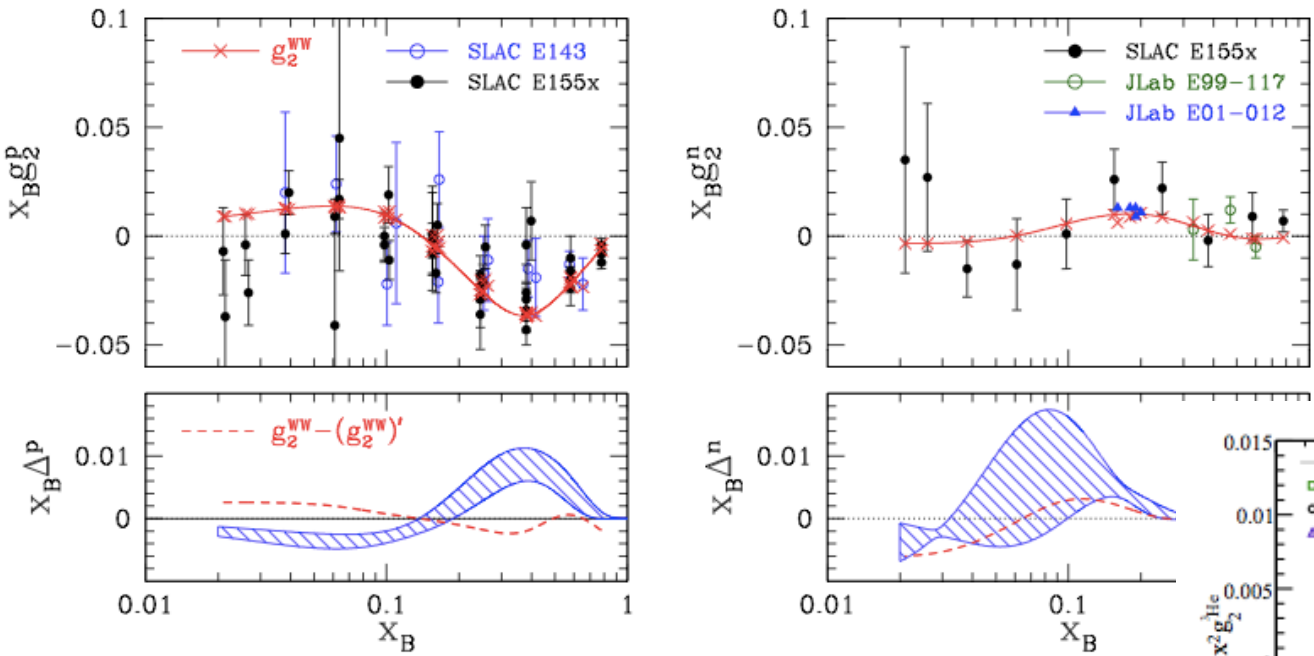
k_T moment of a GTMD
(Lorce and Pasquini)

$\xi=0$
$k_T \bullet \Delta_T=0$
$\Delta_T^2=0$

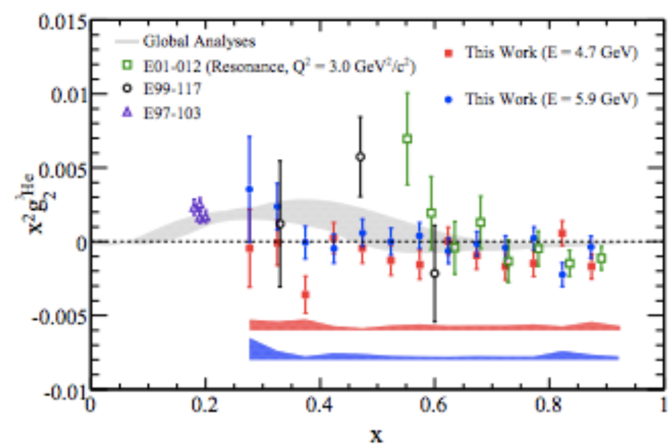
CAN IT BE MEASURED?

Analogously to studies of g_2 where…

$$\int d^2k_T \, \frac{k_T^2}{M^2} \, g_{1T}(x, k_T^2) = -\int_x^1 g_2(y)dy + \widehat{g}_T$$



Accardi, Bacchetta, Melnitchouk, Schlegel JHEP (2009)



The effect of the two twist-three terms combined might be small but each individual contribution can be large

D. Flay et al, PRC 2016

…F_{14} is connected to twist three GPDs through a generalized Lorentz Invariance Relation

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

A. Rajan, A. Courtoy, M. Engelhardt, S.L., PRD (2016), arXiv:1601.06117
A. Rajan, M. Engelhardt, S.L., submitted to PRD arXiv:1709.xxxxx

Using the QCD EoM we find that the integrated OAM obtained by subtraction from Ji Sum Rule

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

genuine twist three term

L = J - S + 0

x-Moments

M_0

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

M_1 OAM Sum Rule

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

M_2

$$\int dx x^2 \tilde{E}_{2T} = -\frac{1}{3}\int dx x^2 (H+E) - \frac{2}{3}\int dx x \tilde{H} - \frac{2}{3}\int dx x \mathcal{M}_{F_{14}}$$

Measuring twist three GPDs gives us the same information on OAM as measuring k_T integrals GTMDs, but….

….we have referred so far only to Ji's OAM

Genuine “intrinsic” twist three terms

$$\mathcal{M}^{i}_{\Lambda\Lambda'} = \frac{1}{4}\int \frac{dz^- d^2 z_T}{(2\pi)^3} e^{ixP^+ z^- - ik_T\cdot z_T}$$

$$\langle p', \Lambda' \mid \overline{\psi}(-z/2) \left[(\overrightarrow{\partial\!\!\!/} - igA\!\!\!/)\mathcal{U}\Gamma\Big|_{-z/2} + \Gamma\mathcal{U}(\overleftarrow{\partial\!\!\!/} + igA\!\!\!/)\Big|_{z/2} \right] \psi(z/2) \mid p, \Lambda\rangle_{z^+=0}$$

EoM

$$-x\tilde{E}_{2T} = \tilde{H} - \int d^2 k_T \frac{k_T^2}{M^2} F_{14}^{\rm staple} + \mathcal{M}_{F_{14}}^{\rm staple}$$

Jaffe Manohar

$$-x\tilde{E}_{2T} = \tilde{H} - \int d^2 k_T \frac{k_T^2}{M^2} F_{14}^{\rm straight} + \mathcal{M}_{F_{14}}^{\rm straight}$$

Ji

By subtracting the two expressions

$$F_{14}^{(1)}\Big|_{\text{staple}} - F_{14}^{(1)}\Big|_{\text{staple}} = \mathcal{M}_{F_{14}}|_{\text{staple}} - \mathcal{M}_{F_{14}}|_{\text{straight}}$$

integrating

$$-\int dx\ F_{14}^{(1)}\Big|_{\text{diff}}\Big|_{\Delta_T=0} = -\frac{\partial}{\partial\Delta_i} i\epsilon^{ij} g v^- \frac{1}{2P^+}\int_0^1 ds\,\langle p',+|\bar{\psi}(0)\gamma^+ U(0,sv)F^{+j}(sv)U(sv,0)\psi(0)|p,+\rangle\Big|_{\Delta_T=0}$$

Difference between Jaffe-Manohar and Ji
(Hatta, Burkardt, 2013)

$$\mathcal{A} = \frac{d}{dx}\left(\mathcal{M}^{\text{staple}} - \mathcal{M}^{\text{straight}}\right)$$

LIR violating term is the difference between JM and Ji

Interpretation

M_1

Force acting on quark

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

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

Non zero only for staple link

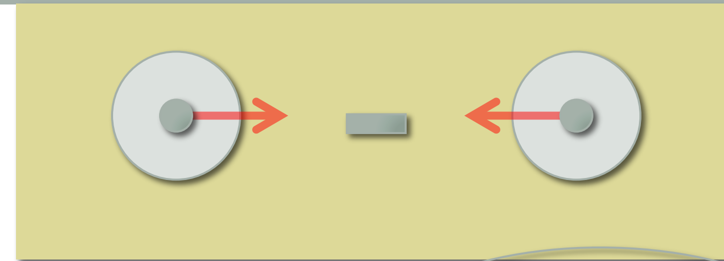
M_2

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

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

“rest frame” interaction, analogous to d_2 but different helicity configuration

Other integrated relations: SPIN ORBIT!



$$\int dx\, x \left(E'_{2T} + 2\tilde{H}'_{2T}\right) = -\frac{1}{2}\int dx\, x\tilde{H} - \frac{1}{2}\int dx H + \frac{m}{2M}\int dx (E_T + 2\tilde{H}_T)$$

$$(L_z S_z)_q = \int dx\, x \left(E'_{2T} + 2\tilde{H}'_{2T} + \tilde{H}\right), \quad \kappa_T = \int dx\, (E_T + 2\tilde{H}_T), \quad e_q = \int dx\, H$$

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

- Integral relation without connecting to spin-orbit Polyakov et al. (2000)

Chiral symmetry breaking test!

Transverse proton spin (unpolarized quark)

$$-x\left(F_{23}+\frac{k_T^2\Delta_T^2-(k_T\cdot\Delta_T)^2}{M^2\Delta_T^2}F_{24}\right)+\quad\frac{1}{2M^2}\left(\Delta_T^2G_{13}+k_T\cdot\Delta_T G_{12}\right)+\frac{k_T^2\Delta_T^2-(k_T\cdot\Delta_T)^2}{M^2\Delta_T^2}F_{12}$$

$$+\quad\frac{\Delta_T^i}{2M\Delta_T^2}\Big((\Delta_1-i\Delta_2)\mathcal{M}^{i,S}_{-+}+(\Delta_1+i\Delta_2)\mathcal{M}^{i,S}_{+-}\Big)=0.$$

⇓

$$f_{1T}^{\perp(1)}=-F_{12}^{o(1)}=\mathcal{M}_{F_{12}}|_{\Delta_T=0}$$

Sivers function

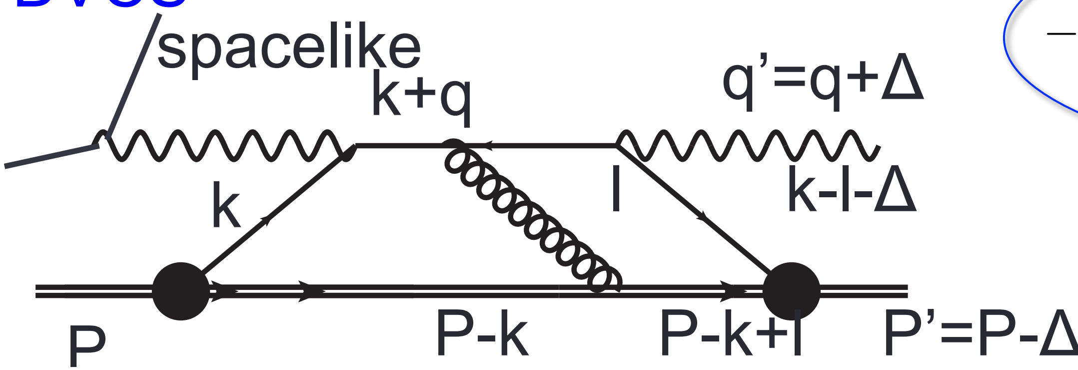
Qiu-Sterman term

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

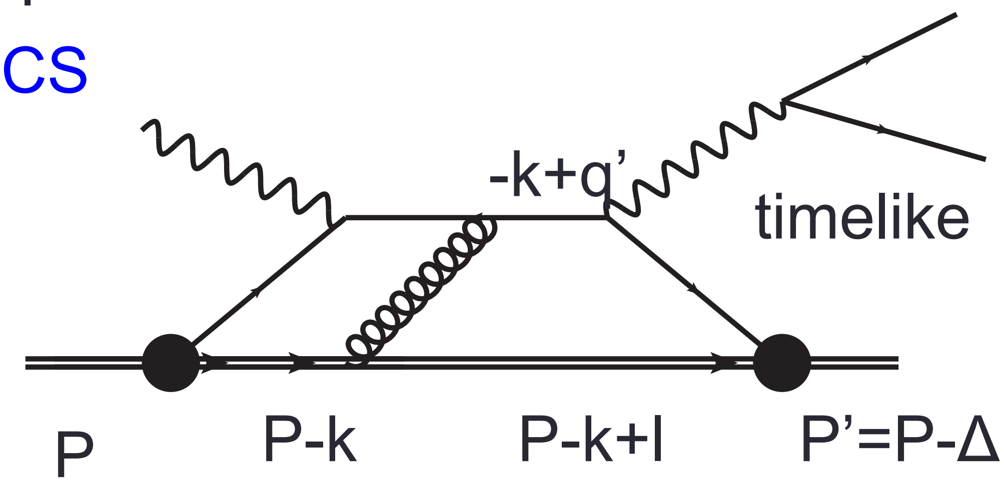
$$\tilde{E}_{2T} = \tilde{E}_{2T}^{WW} + \tilde{E}_{2T}^{(3)} + \tilde{E}_{2T}^{LIR}$$

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

DVCS



TCS

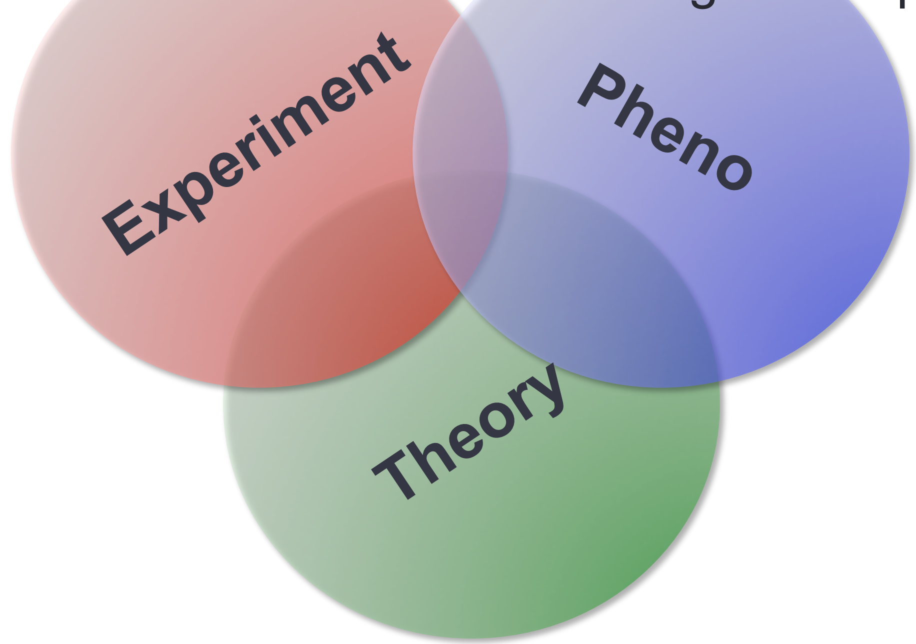


Test Universality!

B. Kriesten, in progress

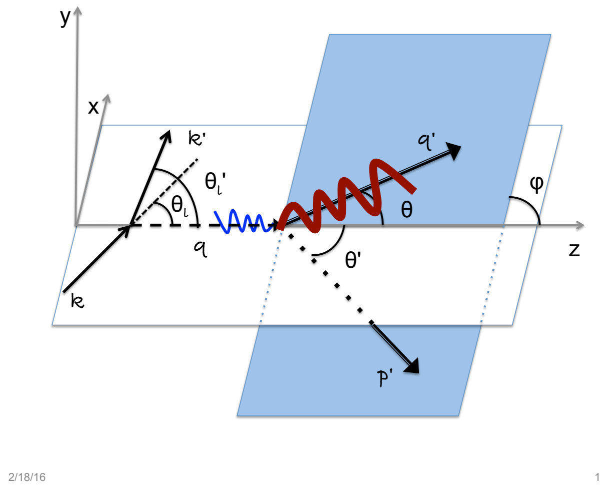
How do we detect all this?

Dustin Keller, L. Calero Diaz
& U.Va. Polarized Target Group

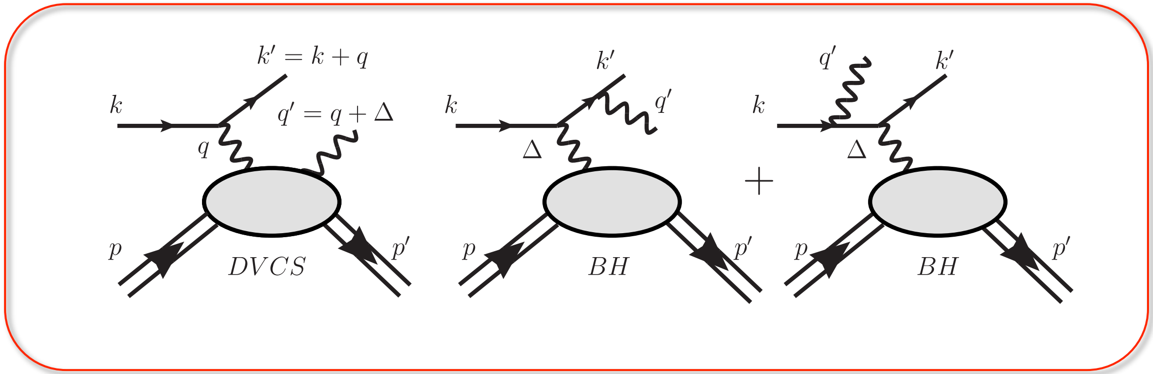


G. Goldstein, O. Gonzalez Hernandez, B. Kriesten, A. Meyer, A. Rajan,

Measuring GPDs in Deeply Virtual Exclusive Experiments



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



Demystification of "harmonics"

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

$$\begin{aligned}
= \frac{\Gamma}{Q^2(1-\epsilon)} \Big\{ \Big[& F_{UU,T} + \epsilon F_{UU,L} + \epsilon\cos 2\phi F_{UU}^{\cos 2\phi} + \sqrt{\epsilon(\epsilon+1)}\cos\phi F_{UU}^{\cos\phi} \\
& + (2h)\ \sqrt{2\epsilon(1-\epsilon)}\sin\phi F_{LU}^{\sin\phi}\Big] \\
& + (2\Lambda)\ \Big[F_{UL} + \sqrt{\epsilon(\epsilon+1)}\sin\phi F_{UL}^{\sin\phi} + \epsilon\sin 2\phi F_{UL}^{\sin 2\phi} \\
& + (2h)\ \sqrt{1-\epsilon^2}F_{LL} + 2(2h)\sqrt{\epsilon(1-\epsilon)}\cos\phi F_{LL}^{\cos\phi}\Big] \\
& + \mid \vec{S}_\perp \mid \Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) \\
& \epsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)} \\
& + \sqrt{2\epsilon(1+\epsilon)}\left(\sin\phi_S F_{UT}^{\sin\phi_S} + \sin(2\phi-\phi_S)F_{UT}^{\sin(2\phi-\phi_S)}\right)\Big] \\
+ (2h) \mid \vec{S}_\perp \mid \Big[& \sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos\phi_S F_{LT}^{\cos\phi_S} \\
& + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)F_{LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}
\end{aligned}$$

"Exact" Rosenbluth-like separation

BH unpolarized cross section

$$\sigma_{BH} = \Gamma\left[A(y,t,\gamma,Q^2,\phi)\frac{F_1+\tau F_2^2}{M^2} + B(y,t,\gamma,Q^2,\phi)\tau G_M^2(t)\right]$$

DVCS unpolarized cross section

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

$$F_{UU,T} = 2(F_{++}^{11} + F_{+-}^{11} + F_{-+}^{11} + F_{--}^{11}),$$ **Twist 2**

$$F_{UU,L} = 2F_{++}^{00}$$ **Twist 4**

$$F_{UU}^{\cos\phi} = \mathrm{Re}\left[F_{++}^{01} + F_{--}^{01}\right]$$ **Twist 3**

$$F_{UU}^{\cos 2\phi} = \mathrm{Re}\left[F_{++}^{1-1} + F_{+-}^{1-1} + F_{-+}^{1-1} + F_{--}^{1-1}\right]$$ **Photon helicity flip: transverse gluons**

$$F^{11}_{++} = (1-\xi^2) \mid \mathcal{H} + \widetilde{\mathcal{H}} \mid^2 - \xi^2 \left[(\mathcal{H}^* + \widetilde{\mathcal{H}})^* (\mathcal{E} + \widetilde{\mathcal{E}}) + (\mathcal{H} + \widetilde{\mathcal{H}})(\mathcal{E}^* + \widetilde{\mathcal{E}}^*) \right]$$

$$F^{11}_{--} = (1-\xi^2) \mid \mathcal{H} - \widetilde{\mathcal{H}} \mid^2 - \xi^2 \left[(\mathcal{H}^* - \widetilde{\mathcal{H}})^* (\mathcal{E} - \widetilde{\mathcal{E}}) + (\mathcal{H} - \widetilde{\mathcal{H}})(\mathcal{E}^* - \widetilde{\mathcal{E}}^*) \right]$$

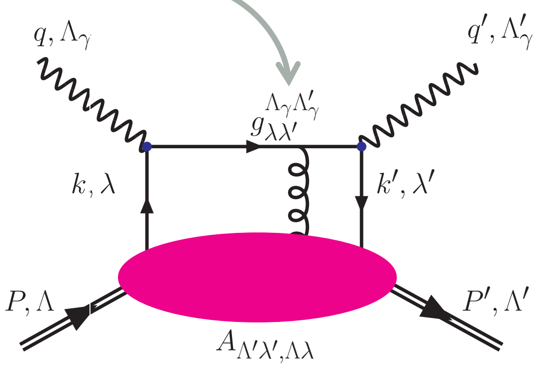
$$F^{11}_{+-} = \frac{t_0 - t}{4M^2} \mid \mathcal{E} + \xi \widetilde{\mathcal{E}} \mid^2$$

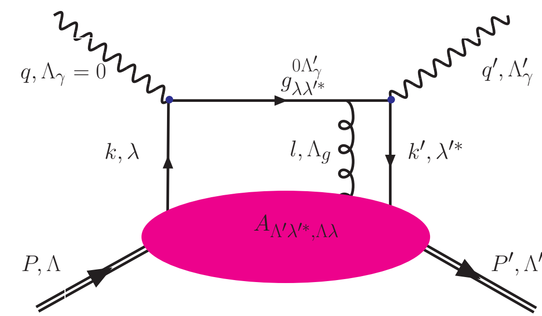
$$F^{11}_{-+} = \frac{t_0 - t}{4M^2} \mid \mathcal{E} - \xi \widetilde{\mathcal{E}} \mid^2$$

Twist 3

$$f^{01}_{\Lambda\Lambda'} = g^{01}_{-*+} \otimes A_{\Lambda'+,\Lambda-*} + g^{01}_{-+*} \otimes A_{\Lambda'+*,\Lambda-} + g^{01}_{+*-} \otimes A_{\Lambda'-,\Lambda+*} + g^{01}_{+-*} \otimes A_{\Lambda'-*,\Lambda+}$$

"Bad" component (exchanged gluon flips the quark chirality)





Connecting the DVCS formalism with the TMD/GPD/GTMD comprehensive parametrizations

Bacchetta et al JHEP02 (2007), Meissner Metz and Schlegel, JHEP08 (2009)

Example

$$A_{+-,++^*} = \frac{1}{2}\left(\tilde{E}_{2T} - \overline{E}_{2T} + \tilde{E}'_{2T} + \overline{E}'_{2T}\right)$$

$$A_{+-^*,++} = \frac{1}{2}\left(-\tilde{E}_{2T} + \overline{E}_{2T} + \tilde{E}'_{2T} + \overline{E}'_{2T}\right)$$

$$\vdots$$

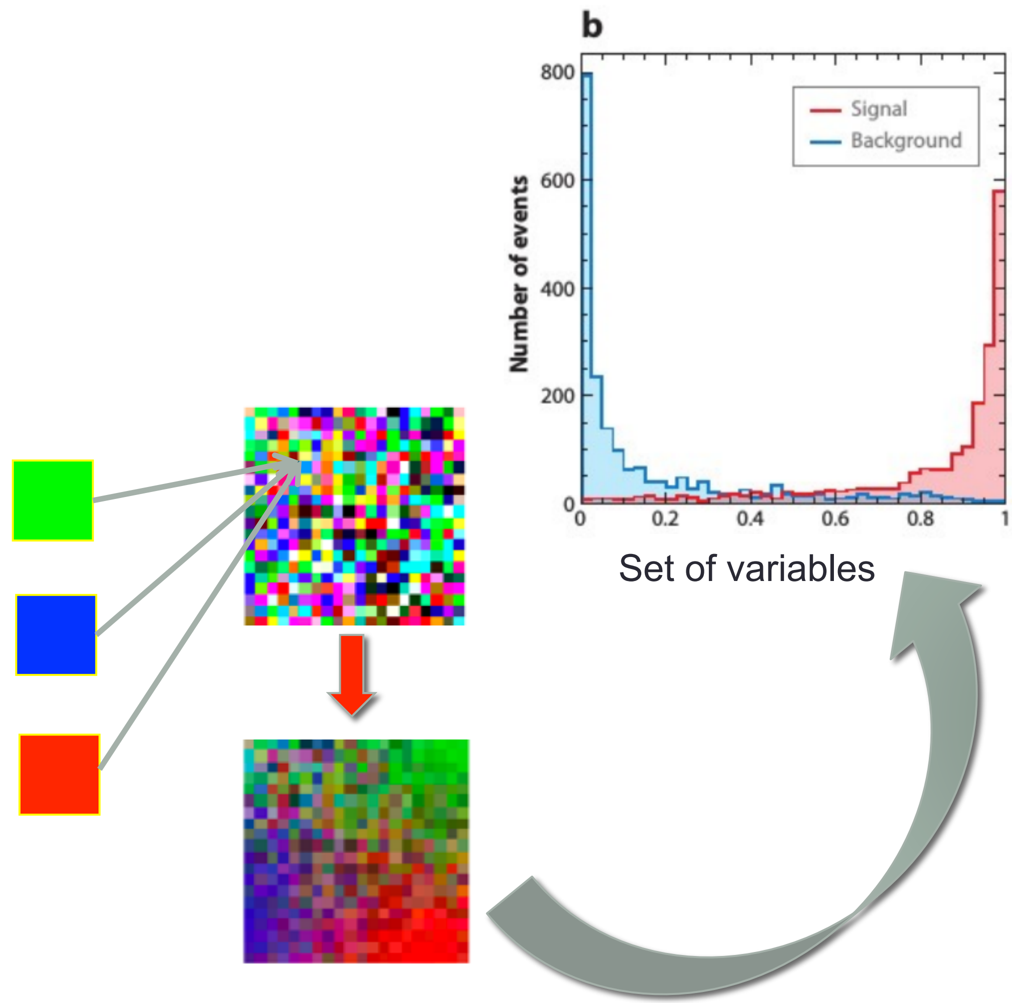
Spin Orbit interaction

Orbital angular momentum

IMPORTANT MESSAGE: Twist two and Twist three GPDs can be treated and should be treated simultaneously within "New generation" analysis with multivariate techniques

Dustin Keller, Andrew Meyer, Liliet Calero-Diaz

- Boosted Decision Trees
- Artificial Neural Networks
  - Self-Organizing Maps (E. Askanazi)



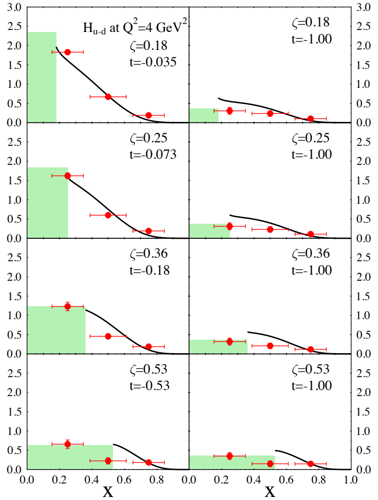
GPD Model: Flexible parametrization

PRD75(2007) AHMAD HONKANEN S.L. TANEJA
EPJC63(2009) AHMAD HONKANEN, S.L. TANEJA

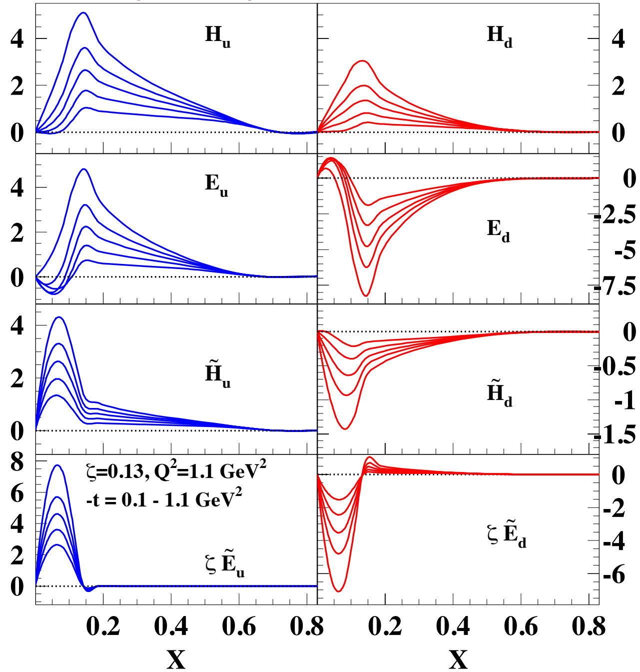
PRD84(2011)GOLDSTEIN GONZALEZ S.L.
PRC88(2013)GONZALEZ GOLDSTEIN S.L. KATHURIA

PRD91(2015) GOLDSTEIN GONZALEZ S,.L

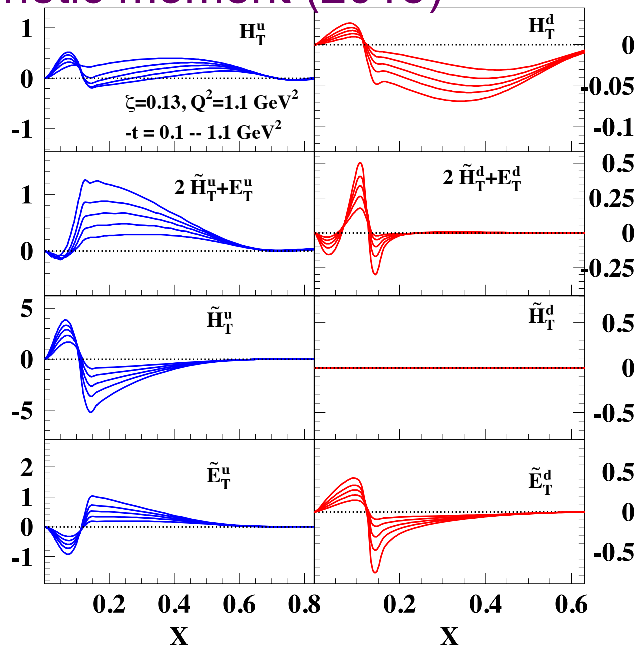
Ahmad et al., using lattice moments



Chiral Even (2011)

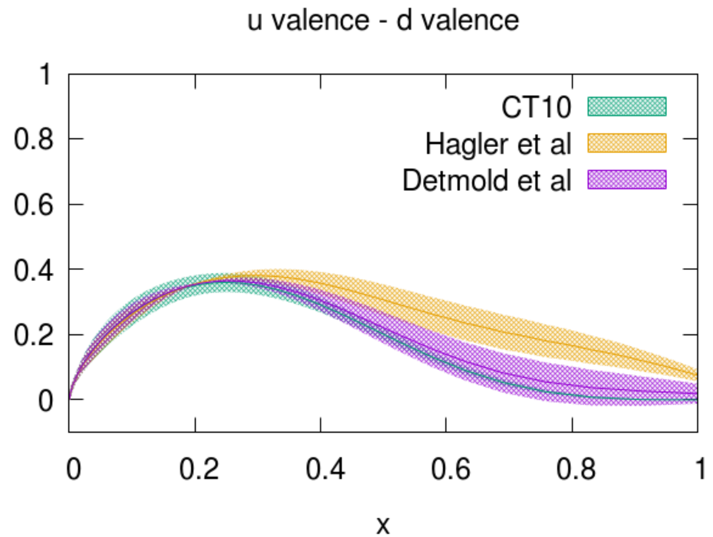


Chiral Odd --tensor charge and magnetic moment (2015)



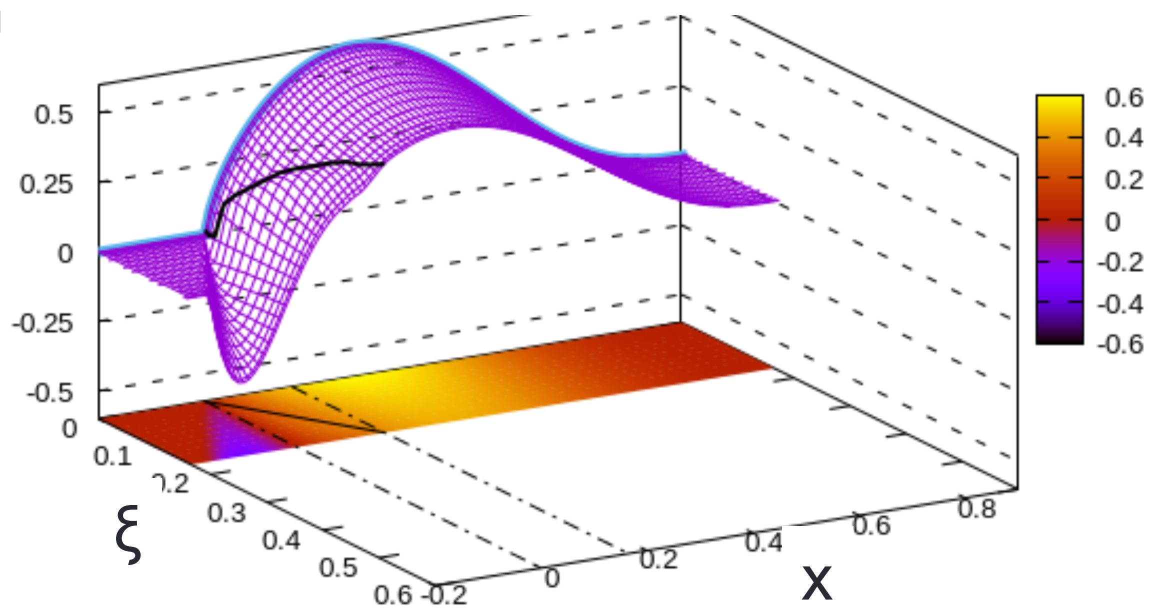
Reconstructing PDFs/GPDs from a finite number of Mellin moments from Lattiec QCD and Ioffe time behavior

A. Rajan, S.L.



PDF, $Q^2 = 4\ GeV^2$

GPD H $t=-0.1\ GeV^2$



Finally, nuclei

First Exclusive Measurement of Deeply Virtual Compton Scattering off ^{4}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)

Physics of the D-term

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

d represents the spatial distribution of the shears forces (Polyakov Shuvaev)

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

From S.L. and S.K. Taneja, PRC72(2005)

$$F^A(t) = F^{A,point}(t)F^N(t) \quad (54)$$

$$M_2^A(\xi,t) = M_2^{A,point}(t)M_2^N(t) + M_0^{A,point}(t)\frac{4}{5}d_1^N(t)\xi^2, \quad (55)$$

with $M_n^{A,point}(t) = \int dy y^{n-1} f_A(y,t)$, the nuclear moment obtained by considering "point-like" nucleons. At $\xi = 0$ one has:

$$M_2^A(t) = M_2^{A,point}(t)M_2^N(t), \quad (56)$$

related to the average value of the longitudinal momentum carried by the quarks in a nucleus:

$$\langle x(t)\rangle_A = \frac{M_2^A(t)}{F^A(t)} = \frac{M_2^{A,point}(t)}{F^{A,point}(t)}\frac{M_2^N(t)}{F^N(t)} = \langle y(t)\rangle_A \langle x(t)\rangle_N, \quad (57)$$

The D-term in a nucleus reads:

$$d_1^A(t) = M_0^{A,point}(t)d_1^N(t). \quad (58)$$

Is this factorization broken? First signature of non-nucleonic effects

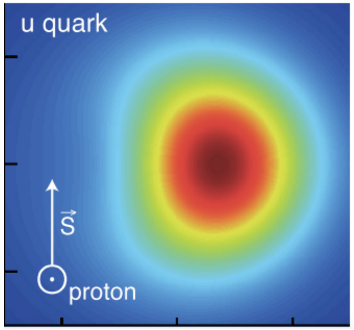
In liquid drop model

$$d_1^A(0) \propto \boxed{A^{7/3}}$$

$$d_1^A(0) \approx \frac{1}{1 - \frac{\langle E \rangle_A}{M} + \frac{2}{3}\frac{\langle p_\mu^2 \rangle_A}{M^2}} \propto \boxed{A \ln A}$$

Nuclear model taking into account virtuality

➢ Spin and 3D structure of Deuteron



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

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)

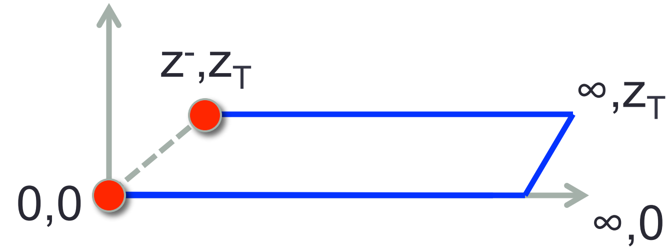
Spin 1 nucleus GPD related to deuteron form factor, G_M:
measurable with transverse polarized target
(Crabb, Day, Keller)

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)

Back Up

Generalized LIR for a staple link



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

LIR violating term

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