Spin Structure of the Nucleon from GPDs

"Detecting the missing pieces"

Kyle Shiells, March 18, 2021

CENTER for NUCLEAR FEMTOGRAPHY

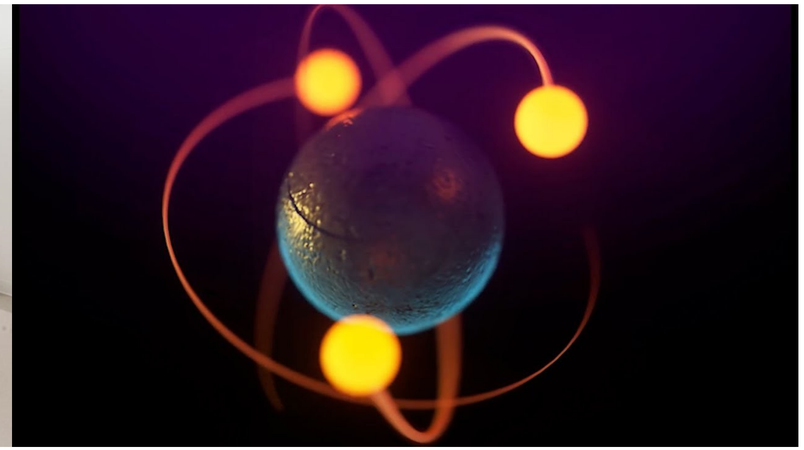
Outline

- Motivation
- Theory
- Experimental Testing
- Conclusion

The Motivation

- Protons and neutrons are among the most important particles in the universe
- The spin degree of freedom is key to explaining many phenomena and drives modern technology (Pauli exclusion, Condensates, MRI's, properties of materials, etc.)



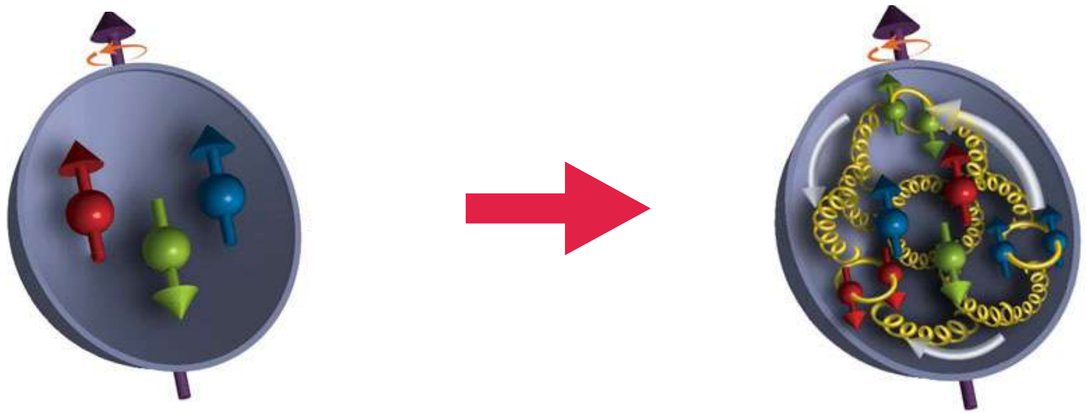


⇒ Proton and neutron spin should be very high on the priority list!

- The spin puzzle was raised in 1989 (EMC data)

$$\Delta\Sigma(Q^2 = 10.7\ \mathrm{GeV}^2) = .060 \pm .047 \pm .069$$

- Quark spin alone cannot account for all of a proton's spin



- QCD has a much more complex way of generating proton's spin
- Theory is nonperturbative

Theory

$$\langle P,S|J^i|P,S\rangle = \frac{\hbar}{2}$$ → **SPIN SUM RULE**

Jaffe & Manohar 1990:

$$\vec{J}_{QCD} = \int d^3x \left[\psi_f^\dagger \frac{\vec{\sigma}}{2}\psi_f + \psi_f^\dagger \vec{x}\times(-i\vec{\partial})\psi_f + \vec{E}_a \times \vec{A}_a + E_a^i(\vec{x}\times\vec{\partial})A_a^i\right]$$

Quark canonical OAM — Gluon spin — Gluon canonical OAM

$$\frac{1}{2}\Delta q + l_q^z + \Delta G + l_g^z = \frac{\hbar}{2}$$

- Last 3 terms are gauge-dependent
- Used in infinite momentum frame (IMF) in light cone gauge ⇒ measurable
- All terms possess a partonic density
- Only applied to longitudinally polarized proton until RECENTLY

Ji 1995:

$$= \int d^3x \left[\psi_f^\dagger \frac{\vec{\sigma}}{2}\psi_f + \psi_f^\dagger \vec{x}\times(-i\vec{\nabla} - g\vec{A})\psi_f + \vec{x}\times(\vec{E}\times\vec{B})\right]$$

Quark spin — Quark kinetic OAM — Gluon total AM

$$\frac{1}{2}\Delta q + L_q^z + J_g^z = \frac{\hbar}{2}$$

- Each term is gauge-independent
- Frame-independent
- Not all terms have partonic density
- Applicable to both longitudinally- and transversely-polarized nucleon

Twist:

- Accounts for both the kinematical suppression/enhancement effect of the hard scale in high energy scattering as well as the boost properties of operators
- Works in tandem with light cone coordinates

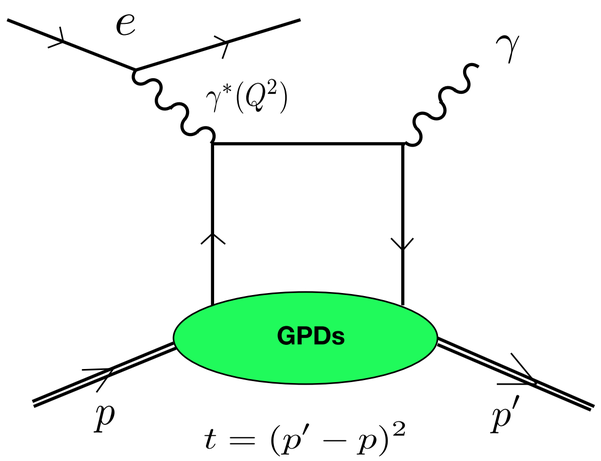
Main idea: it's a meaningful number to gauge what's large and what's small

At high Q^2 :

$$F_i^{(2)} > \frac{F_i^{(3)}}{Q} > \frac{F_i^{(4)}}{Q^2} \to 0$$

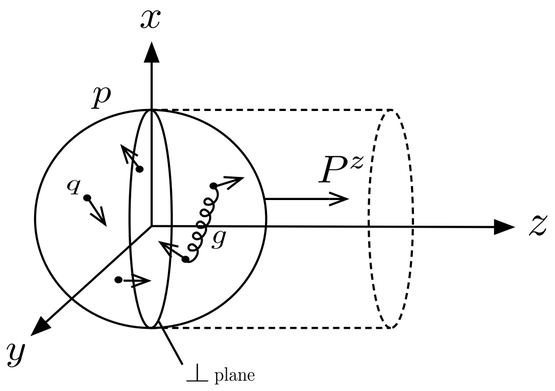
$$\text{Twist-2} > \text{Twist-3} > \text{Twist-4} \cdots$$

Must be disentangled!

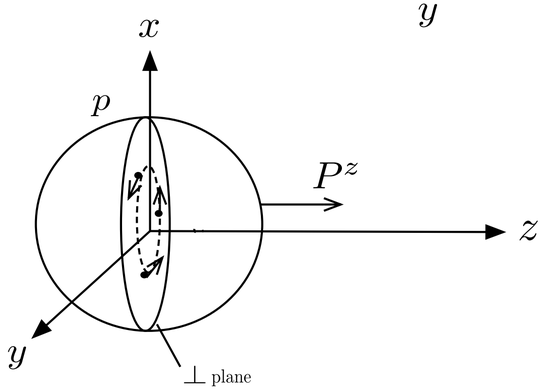


- Word of caution: the twist counting of a correlator on the light cone interferes with the kinematical factors outside of the nucleon matrix element in an amplitude

Twist of AM:



- Longitudinal:



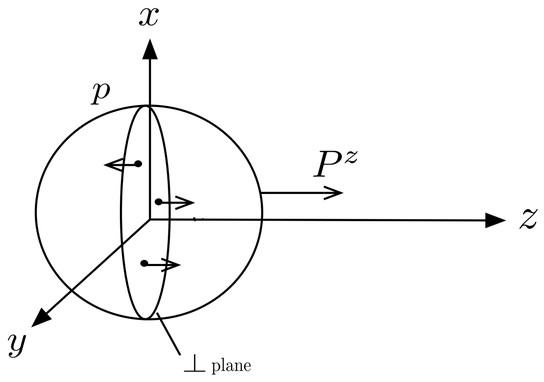
$$\langle J_q^z \rangle = \frac{i}{2E_p} \lim_{\Delta \to 0} \left(\frac{\partial}{\partial \Delta_x} \langle P + \Delta, S' | T^{0y}_{q,\mathrm{Bel}}(0) | P, S \rangle - (y \leftrightarrow x) \right)$$

$$T^{0y}_{q,\mathrm{Bel}} = \bar{\psi} \gamma^{(0} i \overleftrightarrow{D}^{y)} \psi$$

Leading twist: $\bar{\psi} \gamma^{(+} i \overleftrightarrow{D}^{y)} \psi$

Twist-3

- Transverse:



$$\langle J_q^x \rangle = \frac{i}{2E_p} \lim_{\Delta \to 0} \left(\frac{\partial}{\partial \Delta_y} \langle P + \Delta, S' | T^{0z}_{q,\mathrm{Bel}}(0) | P, S \rangle - (y \leftrightarrow z) \right)$$

Leading twist: $T^{++}_{q,\mathrm{Bel}}$ $T^{+y}_{q,\mathrm{Bel}}$

Twist-2 + Twist-3

Experimental testing:

	Longitudinal	Transverse
Frame-independent sum rule:	$\frac{1}{2}\Delta q + L_q^i + J_g^i = \frac{\hbar}{2}$	$\rightarrow J_q^x + J_g^x = \frac{\hbar}{2}$
		$\sim \int dx x$ moments of: $H_{q,g}(x), E_{q,g}(x)$ — 4 twist-2 GPDs extractable from DVCS & DVMP!
IMF sum rule:	$\frac{1}{2}\Delta q + l_q^z + \Delta G + l_g^z = \frac{\hbar}{2}$	$\frac{1}{2}\Delta q_T + l_q^x + \Delta G_T + l_g^x = \frac{\hbar}{2}$

Guo-Ji-Shiells '21

$\int dx g_1(x)$

Quark helicity distributions probed in SIDIS

$\int dx \Delta G(x)$

Gluon helicity distribution probed in p-p collisions at RHIC

$\int dx dy \mathcal{F}^{(3)}_{\mathrm{GPD}}(x,y)$

Twist-3 OAM quark and Gluon GPDs extractable From DVCS & DVMP

Less experimental constraints

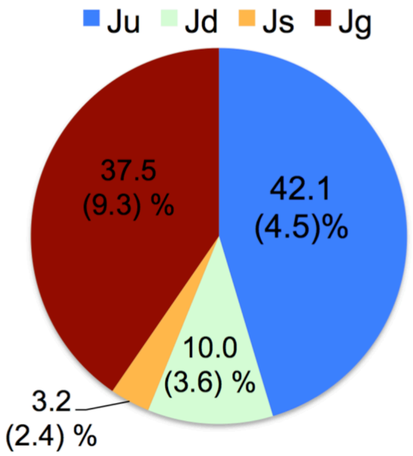
Lattice Progress:

$$J_q^x + J_g^x = \frac{\hbar}{2}$$

$$\frac{1}{2}\Delta q + l_q^z + \Delta G + l_g^z = \frac{\hbar}{2}$$

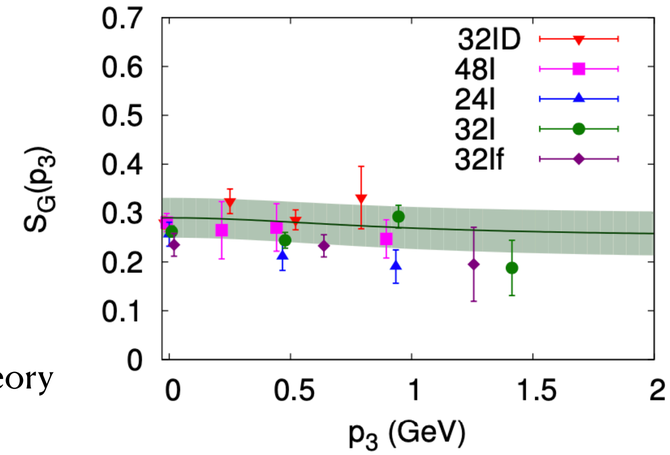
ETMC collab:

Alexandrou, C. *et al.* , *PRD*101, 094513, (2020)



χQCD collab:

Yang, Y.-B. *et al.* , PRL 118, 102001, (2017)



LaMET: large momentum effective field theory

- Total AM ✓
- Spin ✓
- Canonical OAM ✗ → Possibly can be with LaMET!

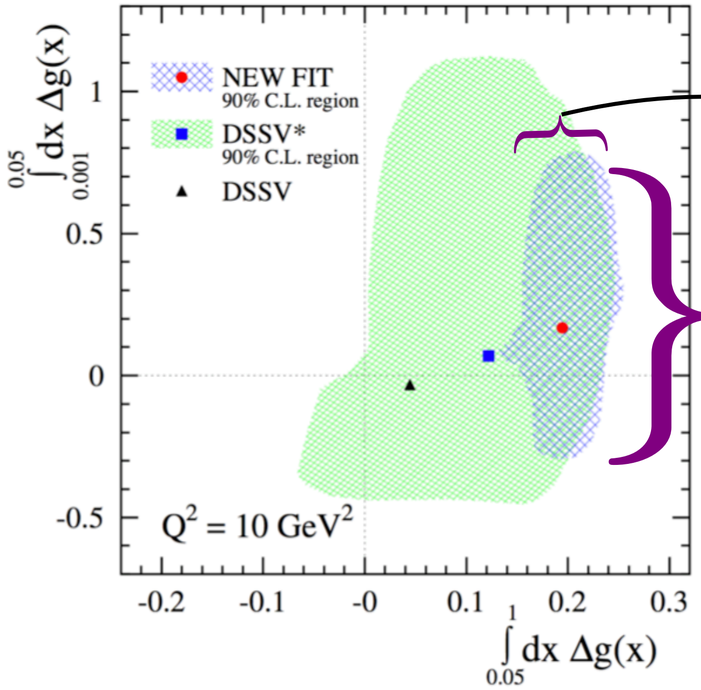
$$\frac{1}{2}\Delta q_T + l_q^x + \Delta G_T + l_g^x = \frac{\hbar}{2}$$

In the works!

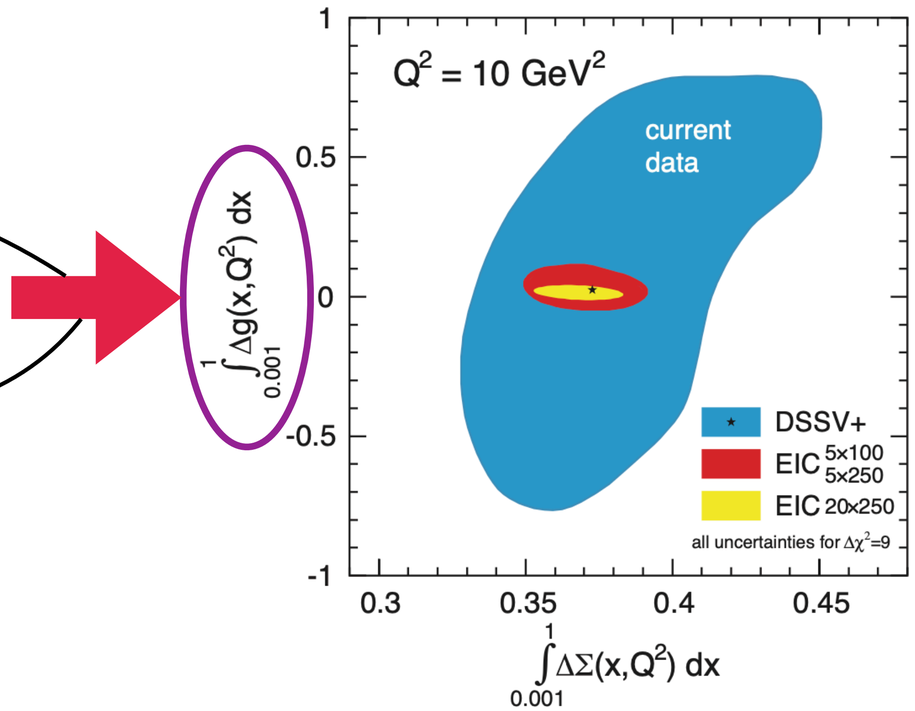
S. Bhattacharya *et al.* PRD 102, 034005 (2020)

Gluon Helicity: ΔG

- Measured via double-spin asymmetry in p-p collision jet production at RHIC
- Largely unconstrained for $x \leq 0.05$



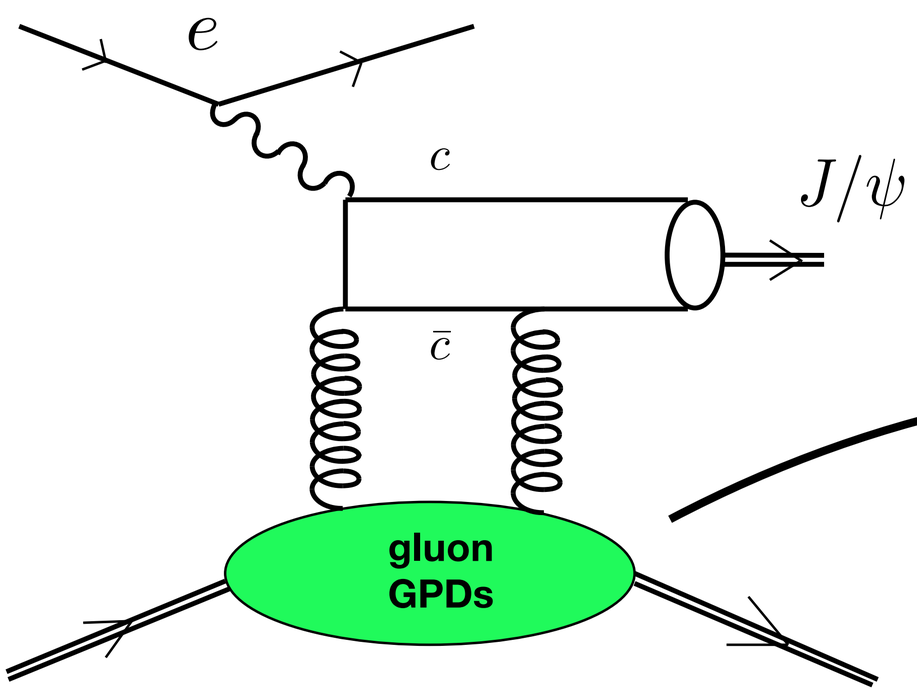
D. de Florian *et al.* PRL (2014)



A. Accardi *et al.* Eur.Phys. J (2016)

Ideal EIC processes involved:
- DVCS
- J/ψ production

J/ψ production:



- Resolution scale: $M^2_{J/\psi} + Q^2$ allows unprecedented access to small-x gluons

$H_g(x), E_g(x)$ Gluon twist-2 GPDs

Possibility: $L_g = J_g - \Delta G$

- Theory description more challenging than DVCS, multiple approaches proposed

e.g. 2 Gluon form factors: Frankfurt, Strikman (2002)

EIC:

High CM energy $\sqrt{s} \sim 173$ GeV allows much broader (x, Q^2) coverage, especially low x

Quark total AM: "Pioneer work"

$$\boxed{\int dx[J_q^{x(2)}(x) + J_g^{x(2)}(x)] = \frac{\hbar}{2}}$$

Quark AM density: $J_q^{x(2)}(x) = \frac{x}{2}[H_q(x) + E_q(x)]$

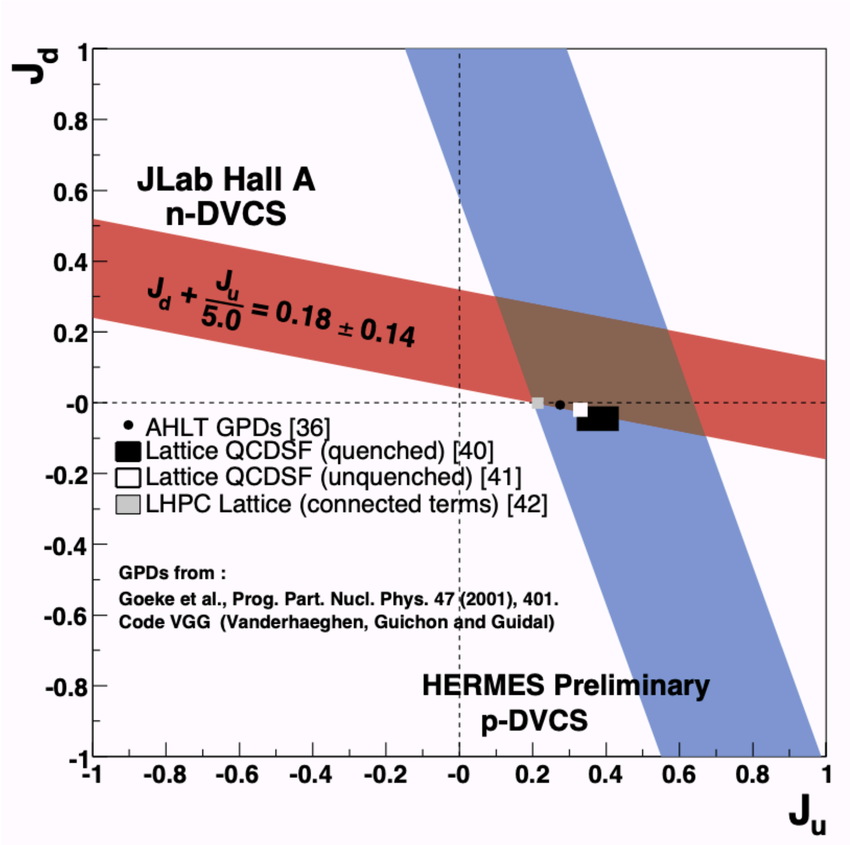
$$H_{q,g}(x) = H_{q,g}(x, \xi = 0, t = 0)$$

- Difficulty: GPDs measured at fixed x, $t \neq 0$

  $\Rightarrow$ need models to predict GPD over all x

- Recoil Proton not directly detected

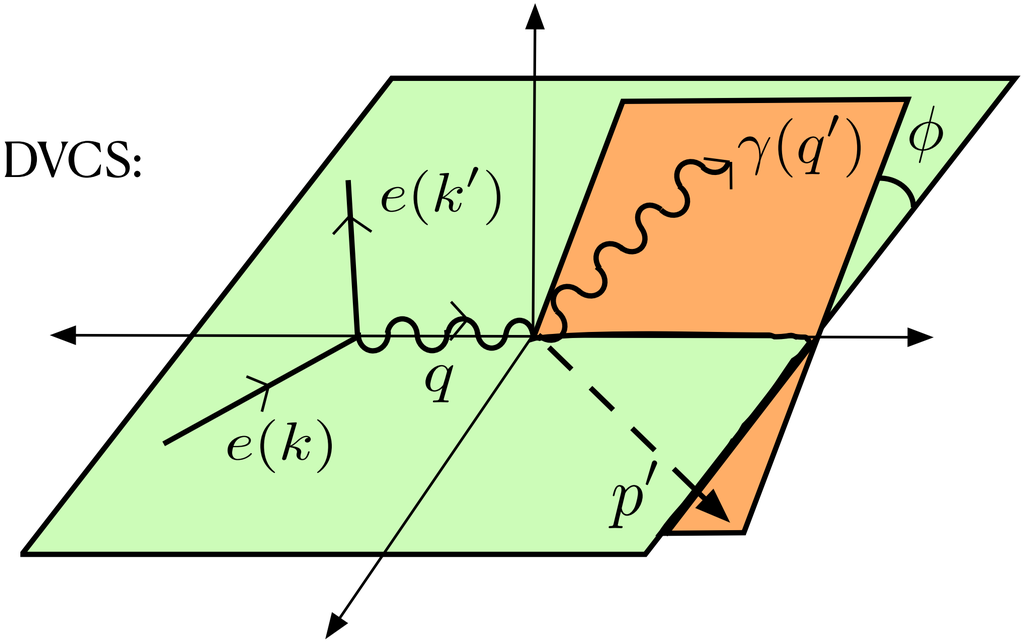
  $\Rightarrow$ missing mass techniques



Mazouz, M. *et al.*, Phys. Rev. Lett. **99**, 242501 (2007)
A. Airapetian *et al.* JHEP (2008)

- We need an extensive DVCS & DVMP observable measurement program:

DVCS:



4 twist-2 GPDs
8 twist-3 GPDs
4 twist-2 gluon transversity GPDs

16 GPDs
x 2 (Re and Im)

32 CFF's can be measured

But only small subset required for Spin sum rules!

- Includes a full set of <u>polarization combinations</u>: beam and target
- Together with angular dependence allows one to isolate different combinations of twist-2 and twist-3 CFFs

2 major cross section analyses on the market:

2002:

Theory of deeply virtual Compton scattering on the nucleon

A.V. Belitsky[a,b,c], D. Müller[c,d], A. Kirchner[d]

[a] *Department of Physics*
University of Maryland at College Park
MD 20742-4111, College Park, USA

[b] *C.N. Yang Institute for Theoretical Physics*
State University of New York at Stony Brook
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[c] *Fachbereich Physik, Universität Wuppertal*
D-42097 Wuppertal, Germany

[d] *Institut für Theoretische Physik, Universität Regensburg*
D-93040 Regensburg, Germany

- Uses finite Harmonic sums to describe angular dependence
- Twist-3 part simplified via Wandzura-Wilczek (WW) approximation

2020:

Extraction of Generalized Parton Distribution Observables from Deeply Virtual Electron Proton Scattering Experiments

Brandon Kriesten,* Andrew Meyer,† Simonetta Liuti,‡ Liliet Calero Diaz,§ and Dustin Keller¶

Department of Physics, University of Virginia, Charlottesville, VA 22904, USA.

Gary R. Goldstein**

Department of Physics and Astronomy, Tufts University, Medford, MA 02155 USA.

J. Osvaldo Gonzalez-Hernandez††

INFN, Torino
(Dated: March 5, 2020)

- Expresses cross sections into Rosenbluth separated form for extraction of observables
- Twist-3 GPDs kept in without approximation
- Beam and target polarization dependence is transparent

Twist-2 AM!

$$\frac{d^5\sigma^{\mathcal{I}}_{\rm unp}}{dx_{\rm Bj}dQ^2d|t|d\phi d\phi_s} = \frac{e_l\Gamma}{|t|Q^2}{\rm Re}\Big\{A_{\mathcal{I}}(F_1\mathcal{H}+\tau F_2\mathcal{E})+B_{\mathcal{I}}G_M\boxed{(\mathcal{H}+\mathcal{E})}+c_{\mathcal{I}}G_M\tilde{\mathcal{H}} + \frac{K}{\sqrt{Q^2}}\big[A^{(3)\mathcal{I}}_{UU}\big(F_1(2\tilde{\mathcal{H}}_{2T})+\mathcal{E}_{2T}+F_2(\mathcal{H}_{2T}+\tau\tilde{\mathcal{H}}_{2T})\big)+B^{(3)\mathcal{I}}_{UU}G_M\boxed{\tilde{E}_{2T}} + C^{(3)\mathcal{I}}_{UU}G_M\big(2\xi\mathcal{H}_{2T}-\tau(\tilde{\mathcal{E}}_{2T}-\xi\mathcal{E}_{2T})\big)\big]\Big\}$$

Twist-3 OAM!!

Quark and gluon OAM:

- The canonical OAM of the quark and gluon each have a partonic density
- Invariably involve twist-3 GPDs

Twist-3 GPDs extractable from DVCS & DVMP

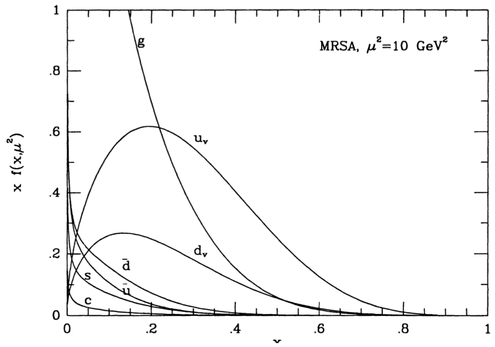
Quark: $l_q^z = \int dx l_q^z(x)$

Guo, Ji, Shiells arXiv 2101.05243:

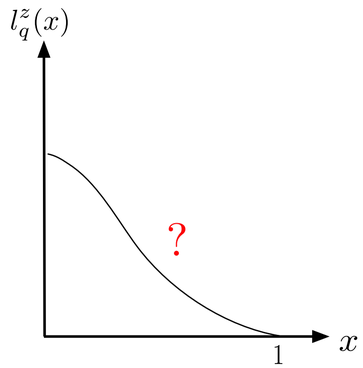
$$l_q^z(x) = \int dy \left[G_{q,D,3}(x,y) + \mathcal{P}\frac{1}{y-x} G_{q,F,3}(x,y) \right]$$

Other OAM results:

Y. Hatta PLB 708, 186 (2012)
Rajan et al. PRD 98, 074022 (2018)
M. Burkardt PRD 88, 014014 (2013)



spatial density



OAM density

Knowing this curve will be the last great challenge in fully understanding proton spin structure!

Conclusion

- 1st order: reduce uncertainty of Spin PDFs $g_1(x, Q^2)$ and $\Delta G(x, Q^2)$
- 2nd order: measure twist-2 GPDs H & E for quark and gluon $\xrightarrow{\text{Completes}}$ $J_q + J_g = \frac{\hbar}{2}$
- 3rd order: measure the twist-3 GPDs of AM $\xrightarrow{\text{Completes}}$ $\frac{1}{2}\Delta q + l_q^z + \Delta G + l_g^z = \frac{\hbar}{2}$

- EIC will be essential in solving the proton spin puzzle

High CM energy, high luminosity electron and positron beams, new detectors needed for studying exclusive processes, etc.