NUCLEON FEMTOGRAPHY FROM EXCLUSIVE REACTIONS

SPIN 2018

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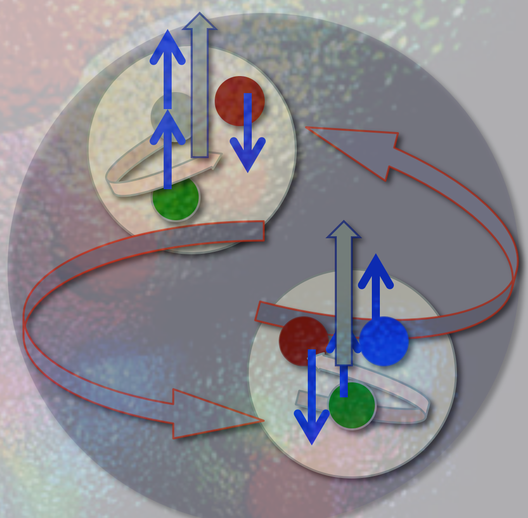


Outline

- **Physics goals**

quarks and gluons imaging, origin of mass, spin, nuclear structure

- **Theory**

Energy Momentum Tensor (EMT) and Generalized Parton Distributions (GPDs): probing the mechanical properties of the proton

- **Method**

Femtography. Fourier transforms, merging information from lattice, models/ parametrizations

- **Disentangling quark and gluon OAM**

twist-3 GPDs, k_T dependence (GTMDs) from lattice

- **A concerted effort**

  Center for Nuclear Femtography
  - organizing a variety of approaches /setting benchmarks
  - extraction from experiments at EIC ➔ ***beyond standard analyses/ computational methods/phen. approaches***

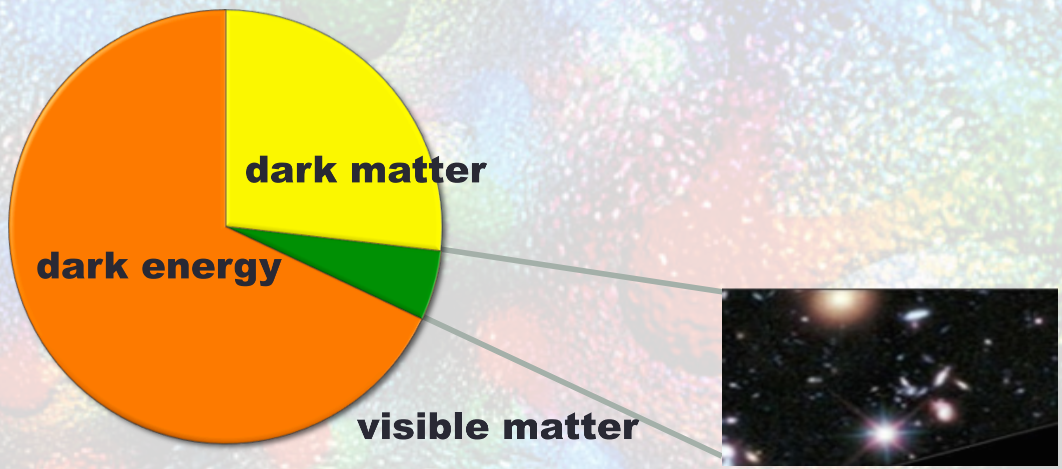
- **Conclusions and Outlook**

1. PHYSICS GOALS

GPDs and Deeply Virtual Exclusive Experiments

A new paradigm that will allow us to both penetrate and visualize the deep structure of visible matter … to answer questions that we couldn't even afford asking before

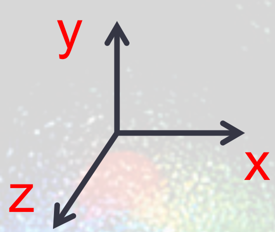
what is the origin of mass and spin?

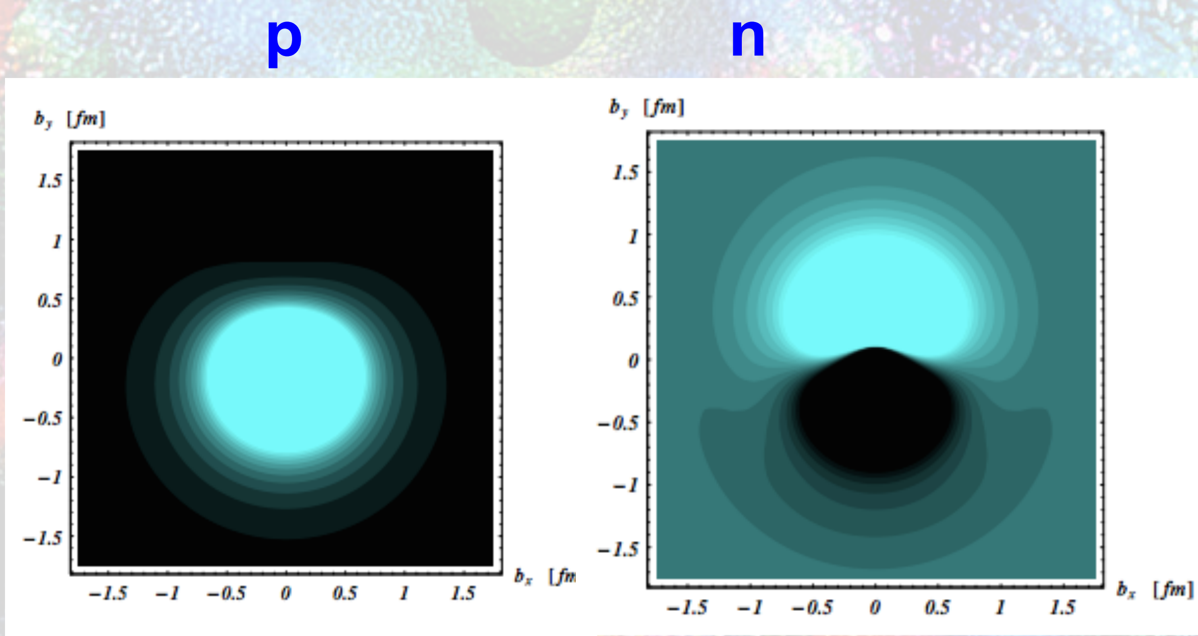


… a new way of thinking strongly interacting systems

… a link to phenomenology that allows us to measure what could only be conceivably explored through "thought" experiments in Lattice QCD

what is the spatial structure of hadrons?





NA Press, 2013

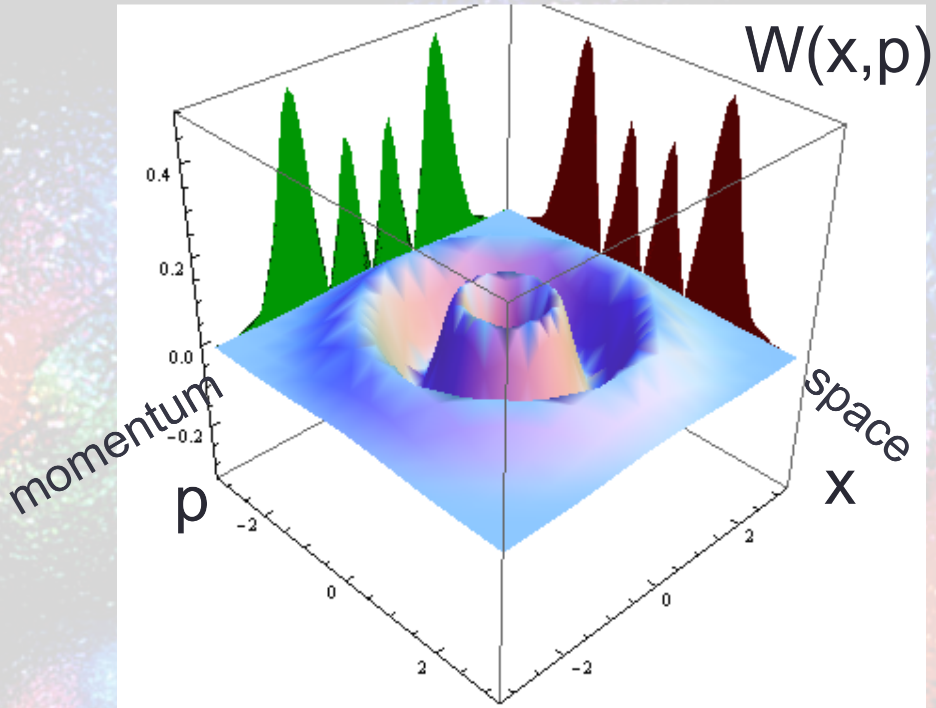
M. Burkardt

Ph. Haegler, M. Diehl

C.Carlson,

M.Vanderheaghen

GPDs connect to complex phase space distributions (Wigner)



…To observe, evaluate and interpret Wigner distributions requires stepping up data analyses from the standard methods ➔ developing new numerical/analytic/quantum computing methods

2. THEORY: EMT AND GPDS

How does the proton get its mass and spin?

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

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

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

Energy Momentum Tensor

from **translation** inv. ➡

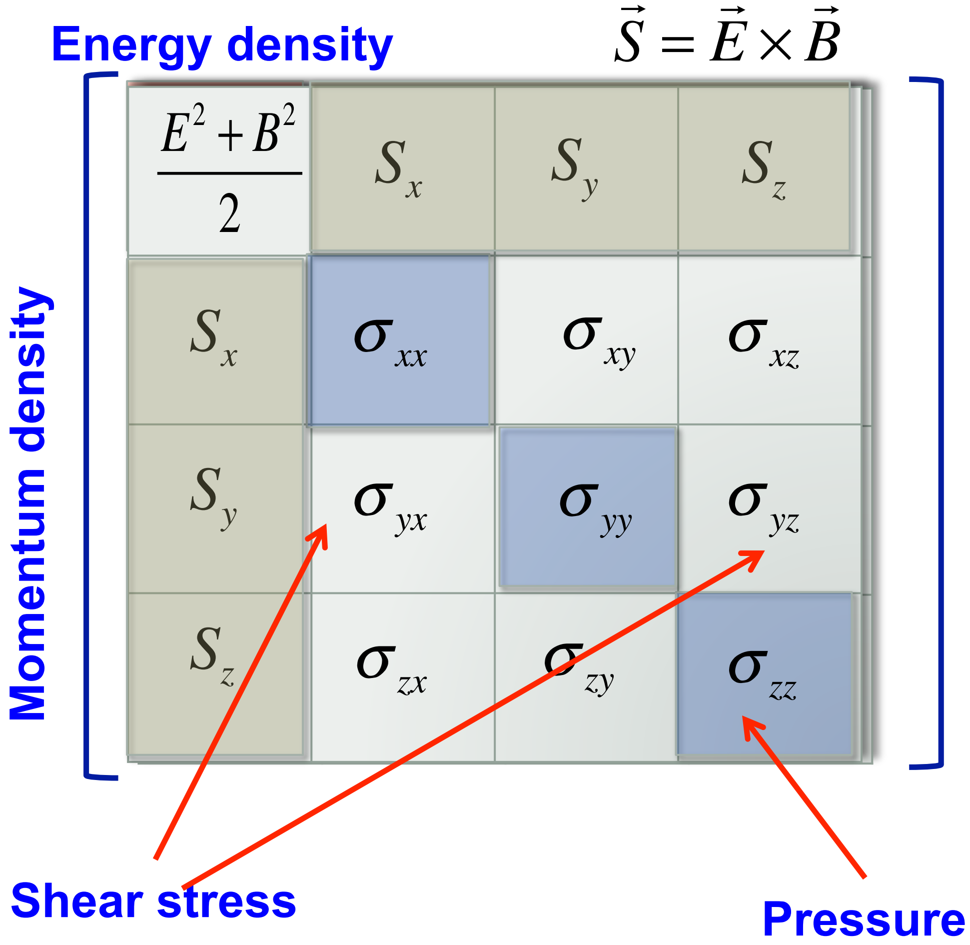
$$T^{\mu\nu}_{QCD} = \frac{1}{4}\,\overline{\psi}\,\gamma^{(\mu}D^{\nu)}\psi + Tr\left\{F^{\mu\alpha}F^{\nu}_{\alpha} - \frac{1}{2}g^{\mu\nu}F^2\right\}$$

Angular Momentum Tensor

from **rotation** inv. ➡

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

QCD Energy Momentum Tensor and Angular Momentum



Conserved quantities

Momentum

$$P^\mu = \int d^3\mathbf{x}\, T^{o\mu}$$

Angular Momentum

$$M^{\mu\nu} = \int d^3\mathbf{x}\, M^{o\mu\nu}$$
$$= \int d^3\mathbf{x}\, [x^\mu T^{o\nu} - x^\nu T^{o\mu}]$$

Angular Momentum density

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

EMT matrix elements

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

S=0

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

S=1/2

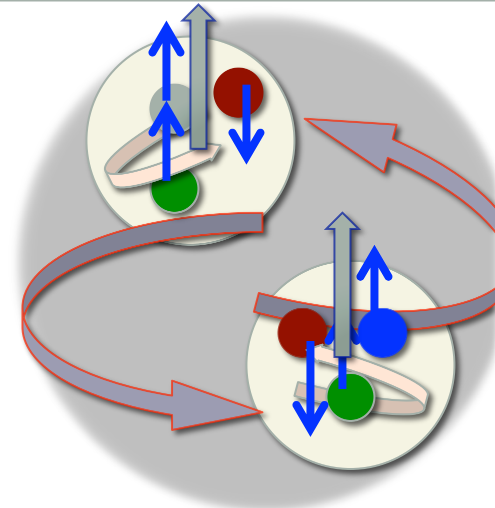
$$\langle p', \Lambda \mid T^{\mu\nu} \mid p, \Lambda \rangle = A(t)\bar{U}(p', \Lambda')[\gamma^\mu P^\nu + \gamma^\nu P^\mu]U(p, \Lambda) + B(t)\bar{U}(p', \Lambda')i\,\frac{\sigma^{\mu(\nu}\Delta^{\nu)}}{2M}U(p, \Lambda)$$
$$+C(t)[\Delta^2 g^{\mu\nu} - \Delta^{\mu\nu}]\bar{U}(p', \Lambda')U(p, \Lambda)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

forward

off-forward

q and g not separately conserved

Energy Momentum Tensor in a spin 1 system

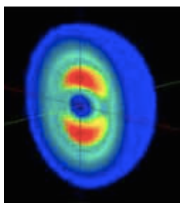


Angular momentum sum rule for spin one hadronic systems

Swadhin K. Taneja,[1,*] Kunal Kathuria,[2,†] Simonetta Liuti,[2,‡] and Gary R. Goldstein[3,§]

PRD86(2012)

S=1



$$\langle p',\Lambda'|T^{\mu\nu}|p,\Lambda\rangle = -\frac{1}{2}P^\mu P^\nu(\epsilon'^*\epsilon)\mathcal{G}_1(t) - \frac{1}{4}P^\mu P^\nu\frac{(\epsilon P)(\epsilon'^* P)}{M^2}\mathcal{G}_2(t)$$
$$-\frac{1}{2}\left[\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2\right](\epsilon'^*\epsilon)\mathcal{G}_3(t) - \frac{1}{4}\left[\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2\right]\frac{(\epsilon P)(\epsilon'^* P)}{M^2}\mathcal{G}_4(t)$$
$$+\frac{1}{4}\left[\left(\epsilon'^{*\mu}(\epsilon P) + \epsilon^\mu(\epsilon'^* P)\right)P^\nu + \mu\leftrightarrow\nu\right]\mathcal{G}_5(t)$$
$$+\frac{1}{4}\left[\left(\epsilon'^{*\mu}(\epsilon P) - \epsilon^\mu(\epsilon'^* P)\right)\Delta^\nu + \mu\leftrightarrow\nu + 2g_{\mu\nu}(\epsilon P)(\epsilon'^* P) - (\epsilon'^{*\mu}\epsilon^\nu + \epsilon'^{*\nu}\epsilon^\mu)\Delta^2\right]\mathcal{G}_6(t)$$
$$+\frac{1}{2}\left[\epsilon^{*\prime\mu}\epsilon^\nu + \epsilon'^{*\nu}\epsilon^\mu\right]\mathcal{G}_7(t) + g^{\mu\nu}(\epsilon'^*\epsilon)M^2\mathcal{G}_8(t)$$

QCD Energy Momentum Tensor relations (spin ½)

Momentum

$$\langle p'|\int d^3x\, T^{0i}_{q,g}\,|p\rangle = p^i\langle p'|p\rangle = A^{q,g} p^i \int d^3x\, 2p^0 \quad\Rightarrow\quad A^q + A^g = 1$$

Angular Momentum

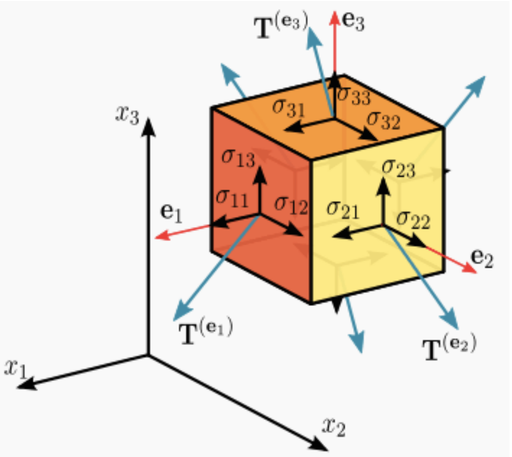
$$\langle p'|\int d^3x\left(x_1 T^{02}_{q,g} - x_2 T^{01}_{q,g}\right)|p\rangle = (A+B)^{q,g}\int d^3x\, p^0 \quad\Rightarrow\quad \frac{1}{2}\left(A^{q,g} + B^{q,g}\right) = J^{q,g}_z$$

Stress Tensor

(Donoghue et al., PLB 2001, Polyakov Shuvaev (2002) 0207153)

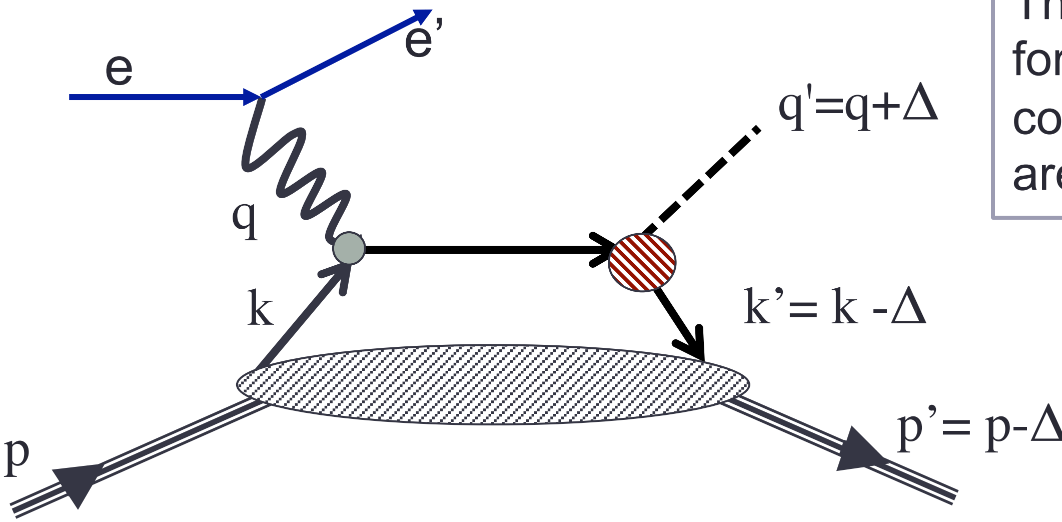
$$T_{ij}(\vec{r}) = \frac{1}{M}\int \frac{d^3\Delta}{(2\pi)^3}\, e^{i\vec{q}\cdot\vec{r}}\left(\Delta_i\Delta_j - \Delta^2\delta_{ij}\right) C(t)$$

C defines the stress at a given point inside the nucleon



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

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

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

MOMENTS

The EMT off-forward matrix elements coincide with the ones for a specific correlation function at $z^{-}=0$

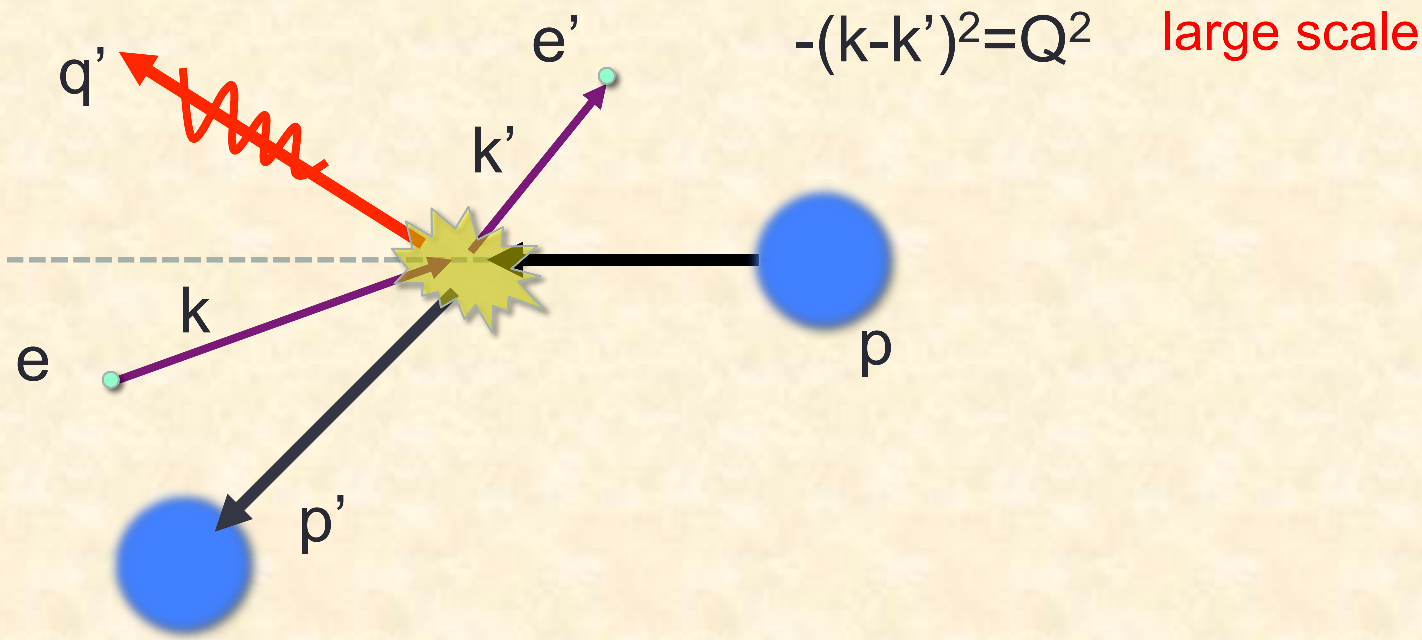
$$M^{+12} = \psi^{\dagger}\sigma^{12}\psi + \psi^{\dagger}\left[\vec{x}\times(-i\vec{D})\right]^{3}\psi + \left[\vec{x}\times(\vec{E}\times\vec{B})\right]^{3}$$

quark field

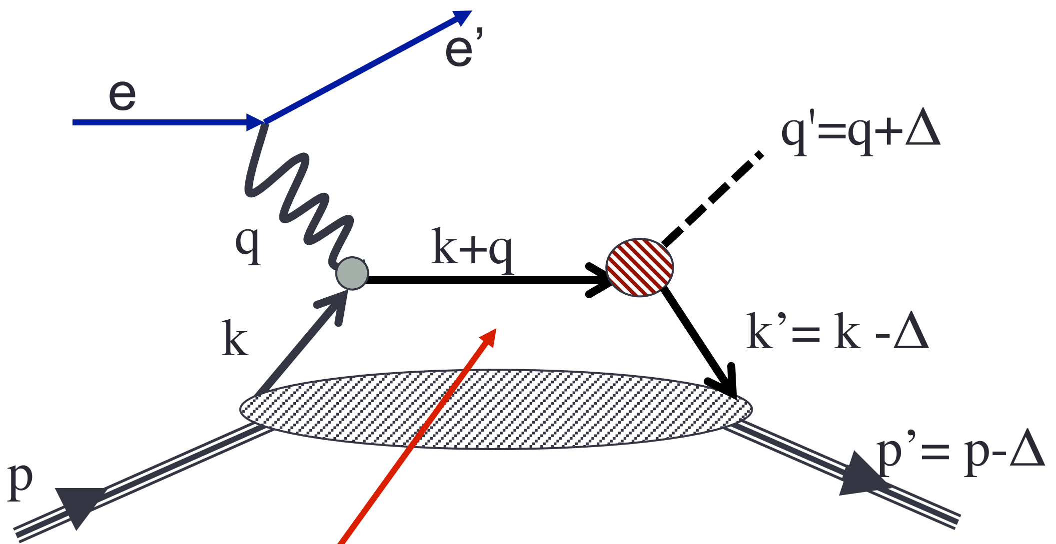
gluon field

DVCS

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



Deeply virtual photon/meson production



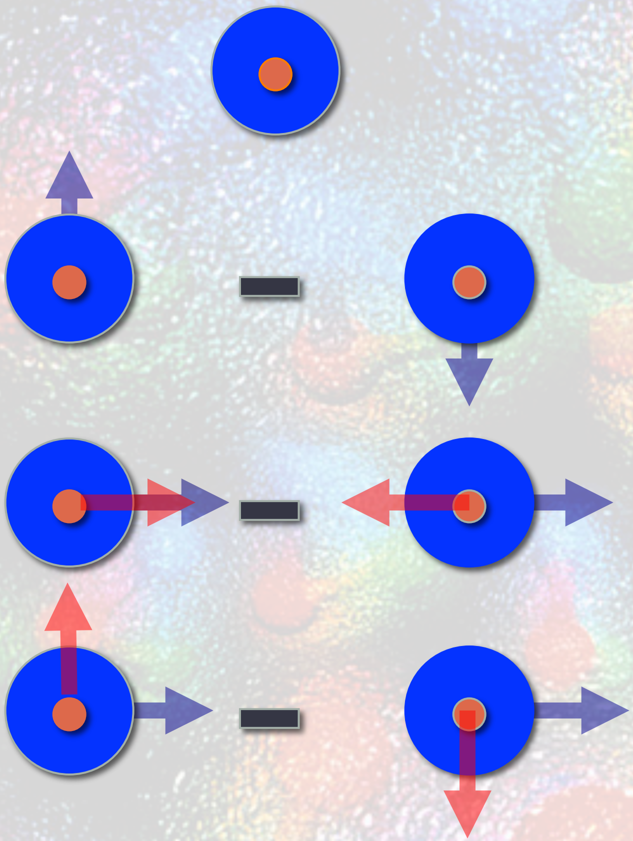
Loop directly in LO amplitude

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

Both Re and Im parts are present

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

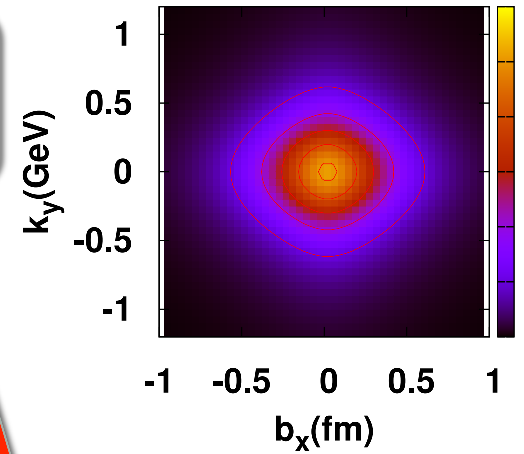
Physical meaning from helicity structure



	GPD	Form F.	TMD	Phase
H		F_1	f_1	1
E		F_2	$f_{1T}^{\perp}$	$\sqrt{-t}\, e^{i\varphi}$
$\tilde{H}$		g_A	g_1	1
$\tilde{E}$		g_P	g_{1T}	$\sqrt{-t}\, e^{i\varphi}$

GTMDs
doubly exclusive

$$F_{12}\left(x,\xi,\Delta_T^2,k_T^2,k_T\cdot\Delta_T\right)=F_{12}^{even}+iF_{12}^{odd}$$



$$\int d^2k_T$$

GPDs
exclusive

$$E$$

$$\int d^2b$$

TMDs
(semi) inclusive

$$f_{1T}^{\perp}$$

Local operators: OPE&Mellin Moments (X. Ji, 1998)

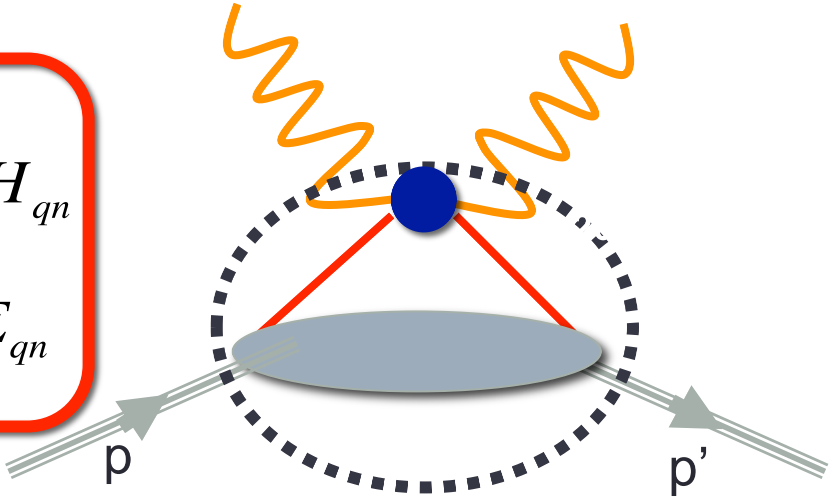
$$n_{\mu_1}\ldots n_{\mu_n}\langle P'|O_q^{\mu_1\ldots\mu_n}|P\rangle = \overline{U}(P')\,\not{n}U(P)H_{qn}(\xi,t) + \overline{U}(P')\frac{\sigma^{\mu\alpha}n_\mu i\Delta_\alpha}{2M}U(P)E_{qn}(\xi,t)$$

helicity conserving   helicity flip

Mellin Moments

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

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



2^{nd} Mellin moments

Nucleon

From OPE ⟷ From EMT

$$\int dx\, x H(x,\xi,t) = A_{20}(t) + \xi^2 C_{20}(t) \equiv A(t) + \xi^2 C(t)$$

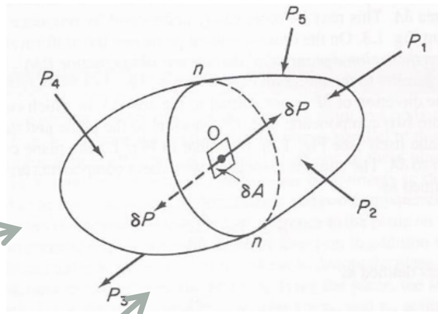
$$\int dx\, x E(x,\xi,t) = B_{20}(t) - \xi^2 C_{20}(t) \equiv B(t) - \xi^2 C(t)$$

← D-term

GPDs are the key to interpret the mechanical properties of the proton

Deuteron

From OPE ⟷ From EMT



$$2\int dx\, x[H_1(x,\xi,t) - \frac{1}{3}H_5(x,\xi,t)] = \mathcal{G}_1(t) + \xi^2\mathcal{G}_3(t)$$ Momentum

$$2\int dx\, x H_2(x,\xi,t) = \mathcal{G}_5(t)$$ Angular Momentum

$$2\int dx\, x H_3(x,\xi,t) = \mathcal{G}_2(t) + \xi^2\mathcal{G}_4(t)$$ Quadrupole

$$-4\int dx\, x H_4(x,\xi,t) = \xi\mathcal{G}_6(t)$$ T-odd

$$\int dx\, x H_5(x,\xi,t) = -\frac{t}{8M_D^2}\mathcal{G}_6(t) + \frac{1}{2}\mathcal{G}_7(t)$$ Connected to b_1 SR

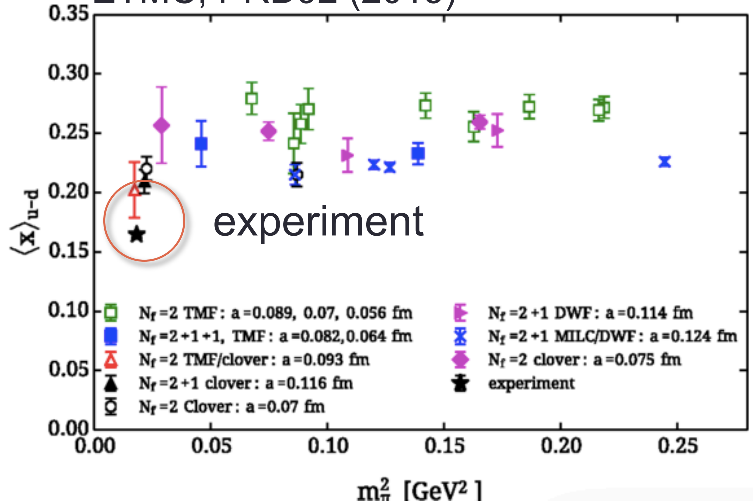
Double flip D-term dependent on polarization

Connecting with observables: work in progress with W. Cosyn and A. Freese

Let's summarize what we know so far…

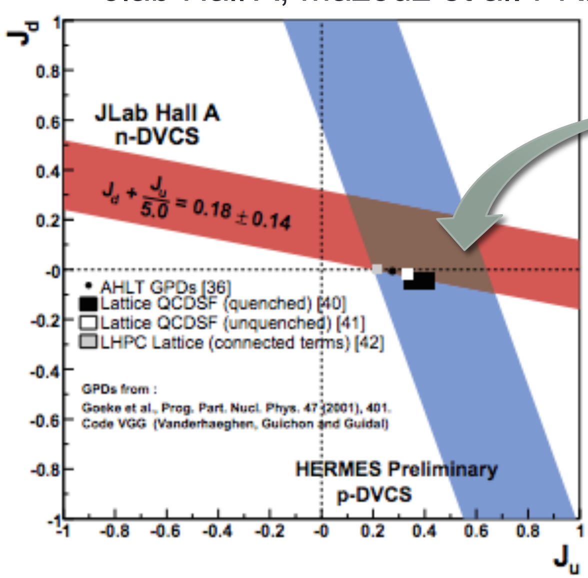
A^{u-d}_{20}

ETMC, PRD92 (2015)

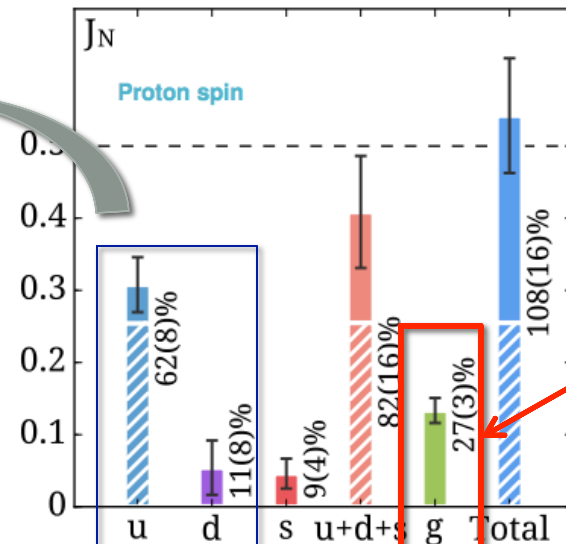


$A_{20}+B_{20}$

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



C. Alexandrou et al., PRL119(2017)

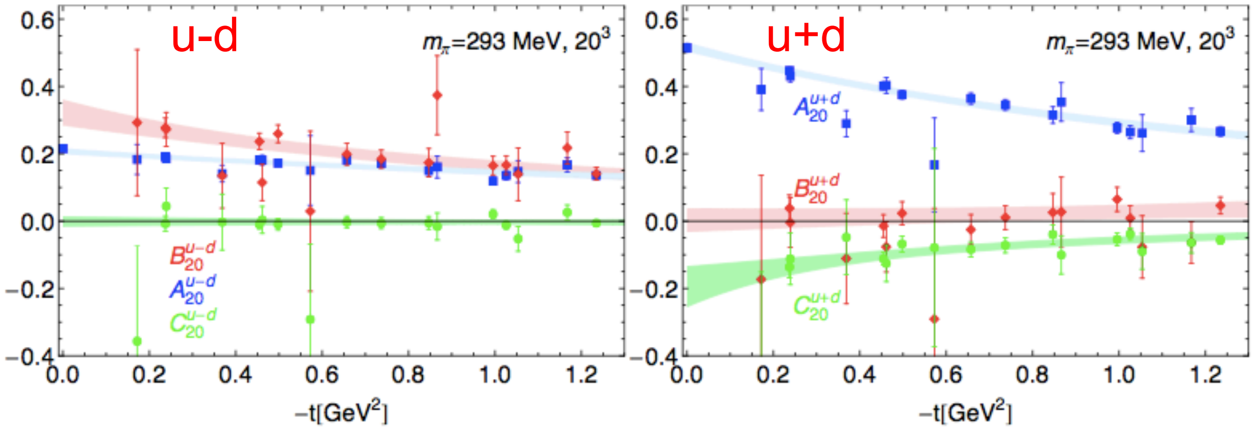


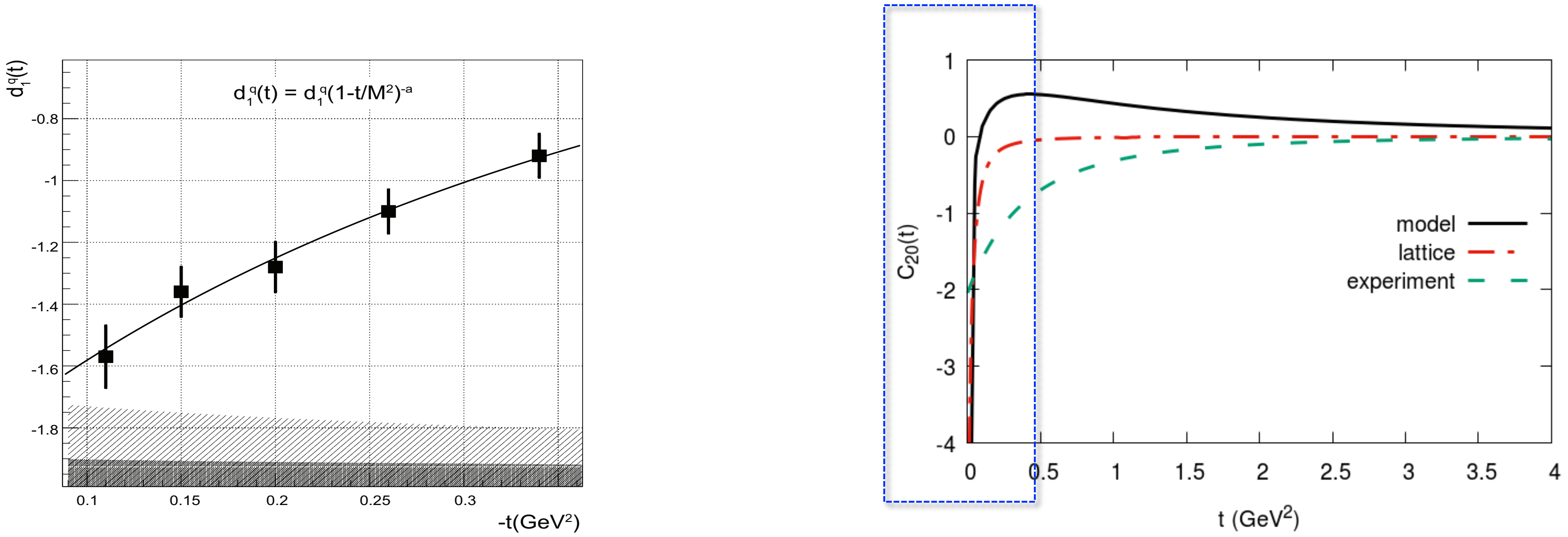
J_g

consistent with χQCD Coll., Deka et al. PRD(2015)

C_{20}

Ph. Haegler, JoP: **295** (2011) 012009



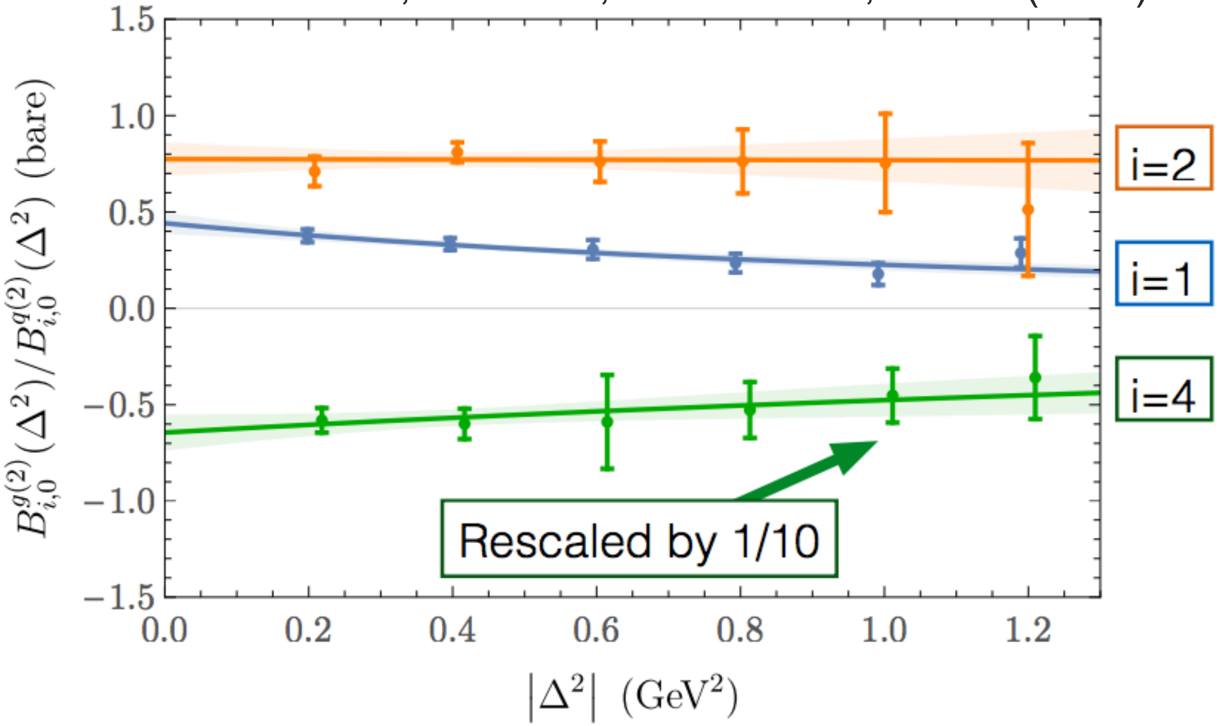


Jlab Hall B, Burkert Elouadrhiri, Girod, Nature (2018)

Deuteron

Ratio of Gluons/Quarks

W. Detmold, D.Pefkou, P. Shanahan, PRD95(2017)



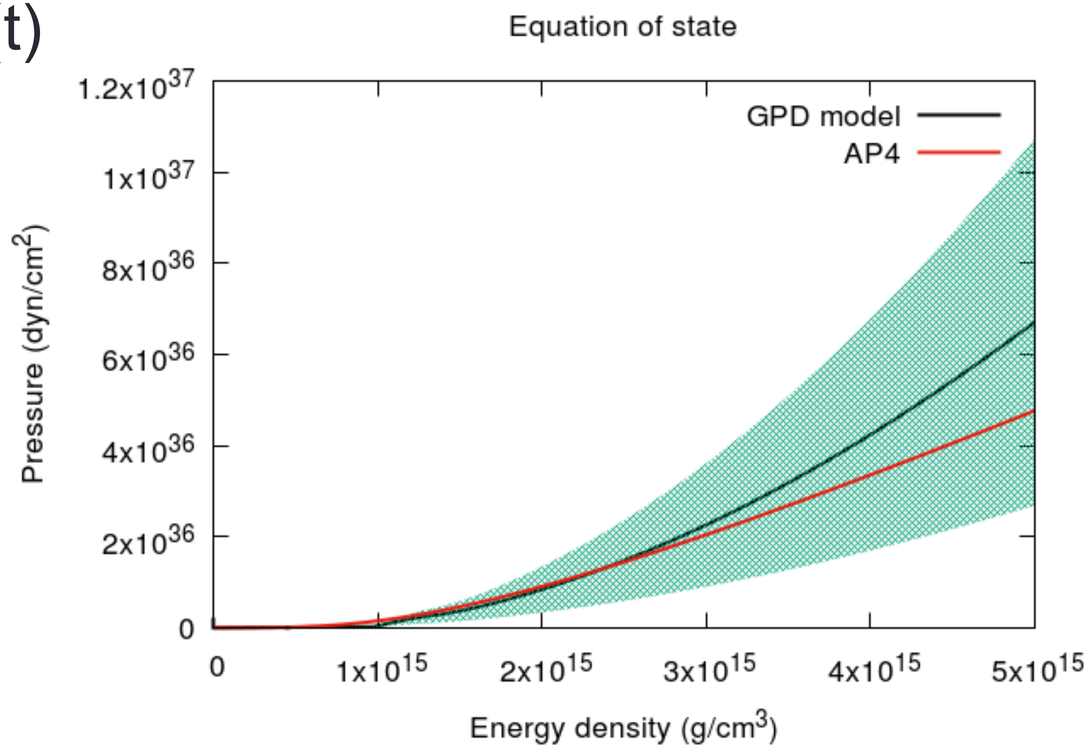
$$\frac{B_1^{g(2)}}{B_1^{q(2)}}, \frac{B_2^{g(2)}}{B_2^{q(2)}}, \frac{B_4^{g(2)}}{B_4^{q(2)}}$$

experimentally… an open field…

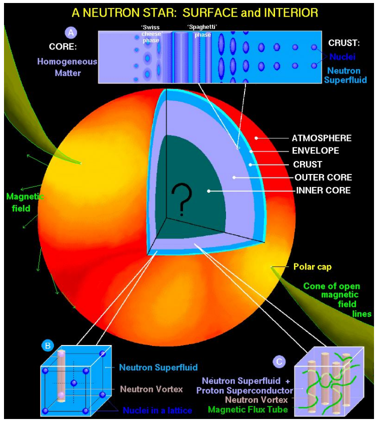
Neutron stars

Comparing the QCD EMT with the Equation of State of neutron stars, after event GW178017 (see W. Van de Brandt's talk)

C(t)



A(t)



SL, A. Rajan, K. Yagi, in preparation

3. FEMTOGRAPHY

To understand mass and spin we need to describe and measure the joint space and momentum distributions of quarks and gluons inside the nucleon

mass

Color charge flux tube

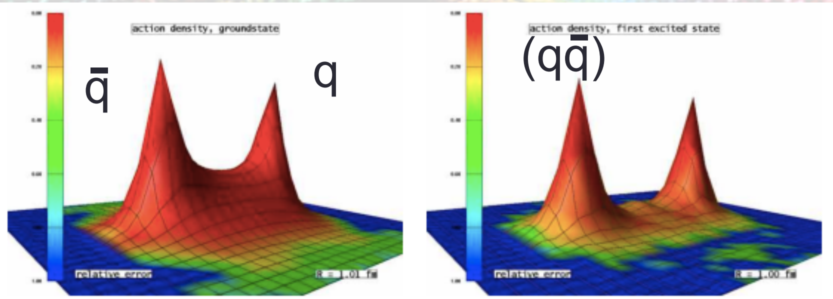


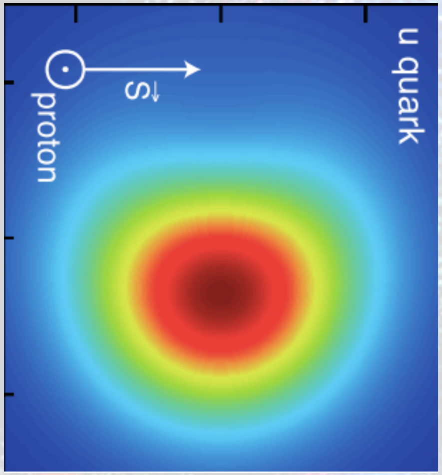
Figure 3: Action density distribution for the ground state and the first excitation.

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

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

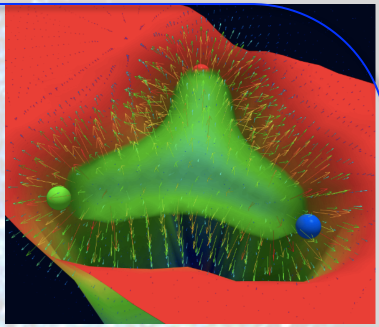
Spin

Quarks



u quark density distribution in transv. polarized proton

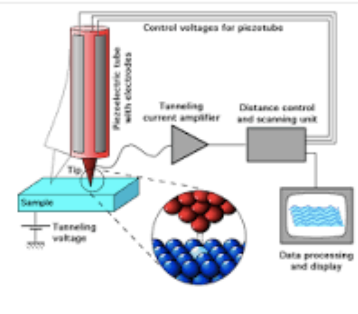
Gluons



- ✓ Are gluons concentrated in the interior of the proton
- ✓ … or are they occupying the whole volume beyond the quark radius
- ✓ Do they cluster around the quarks
- ✓ …or do they form their own "hot spots"

Images of Atoms

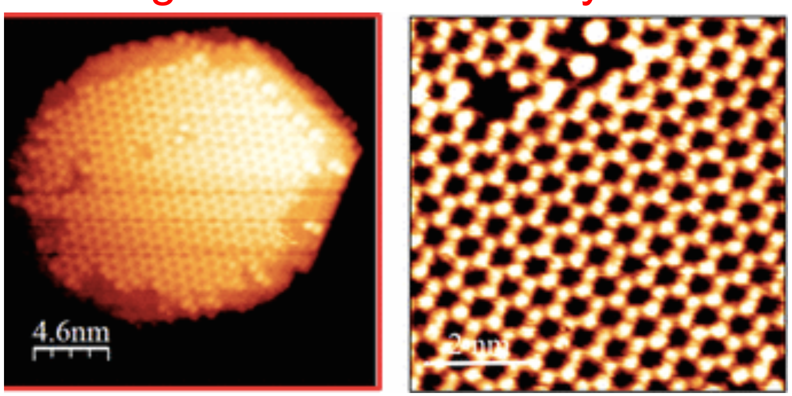
- Transmission Electron Microscope: by scattering electrons -- with a much smaller wavelength --allows us to reconstruct pictures of microscopic particles
- Scanning Probe Microscope: we monitor the tunneling current between the probe and the surface of a sample, as the tip scans the surface



- We can now image the structure of matter in 3D at the atomic level

(1 Å=10^{-10} m= 0.1 nm)

Hexagonal-MoSi2 nanocrystallites

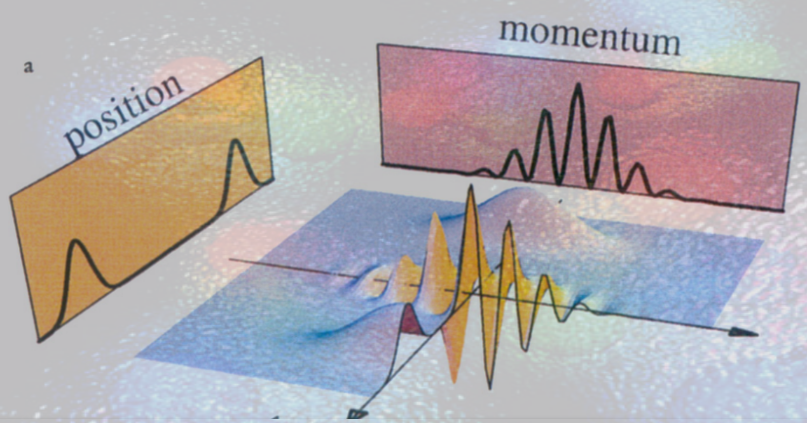


courtesy Petra Reinke et al. (Material Science Dept. UVa , Nanoletters (2017)

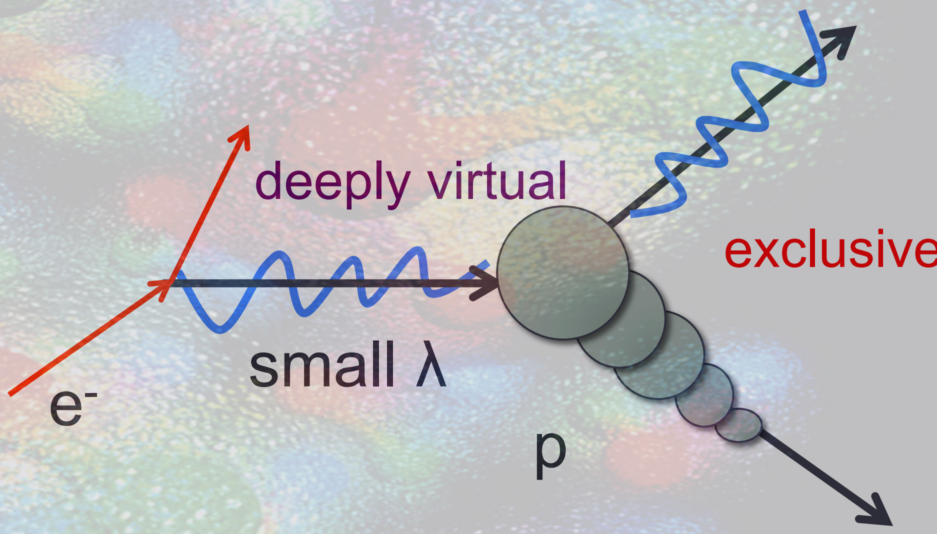
Facing the next challenge….images at the femtoscale

five orders of magnitude below

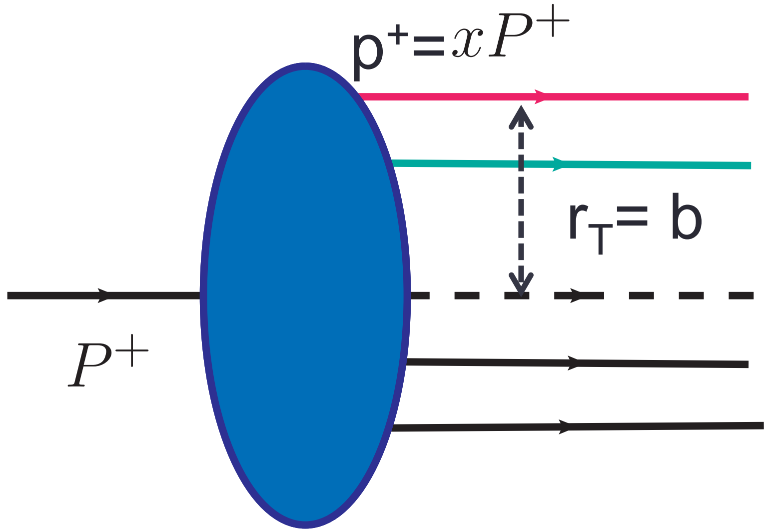
Key Theory Development:
Wigner/phase space distributions at the femtoscale



Key Experimental Probe:
Deeply virtual exclusive scattering experiments



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^+=const invariant, is isomorphic to the Galilean group in 2D"
- We can disentangle the transverse components from the longitudinal components in boosts

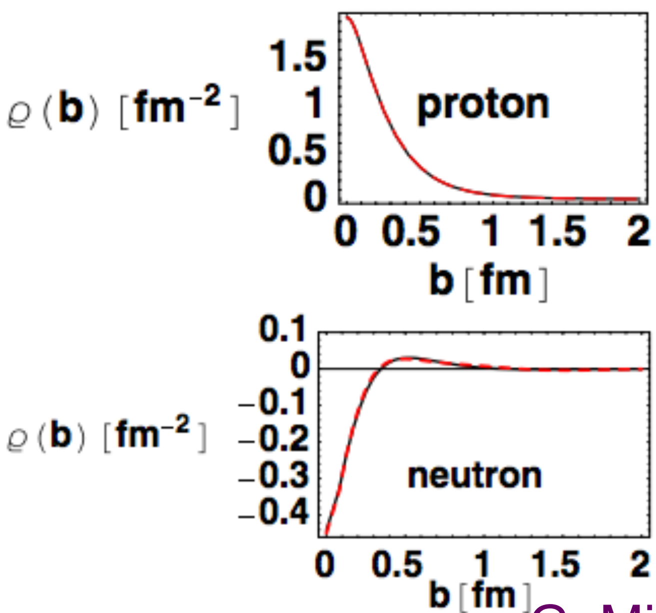
Implication

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

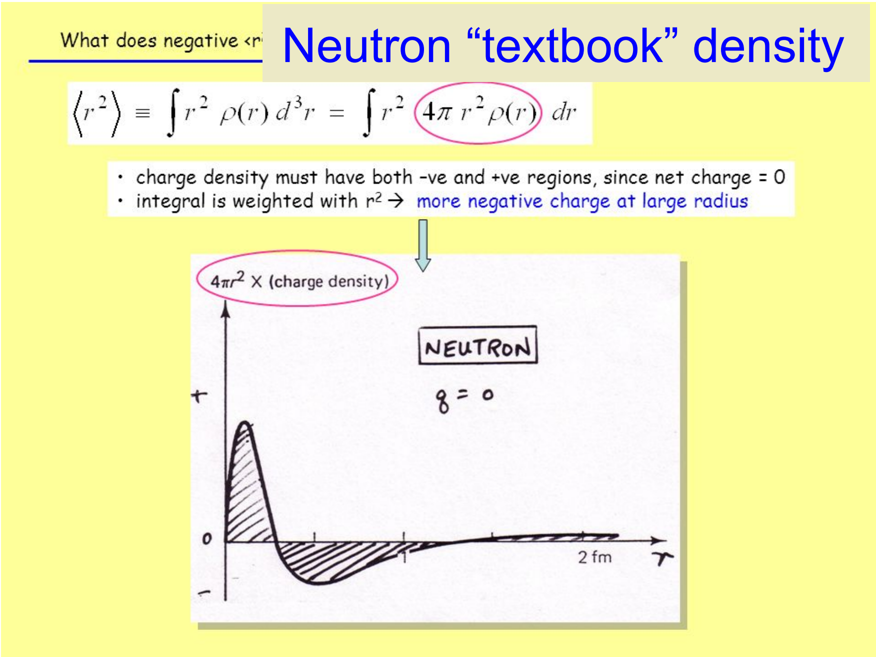
$$q(x,\vec{b}) = \frac{dn}{dx\,d^2\vec{b}}$$

Soper (1977), Burkardt (2001)

Already a surprise: re-evaluation of nucleon charge distribution

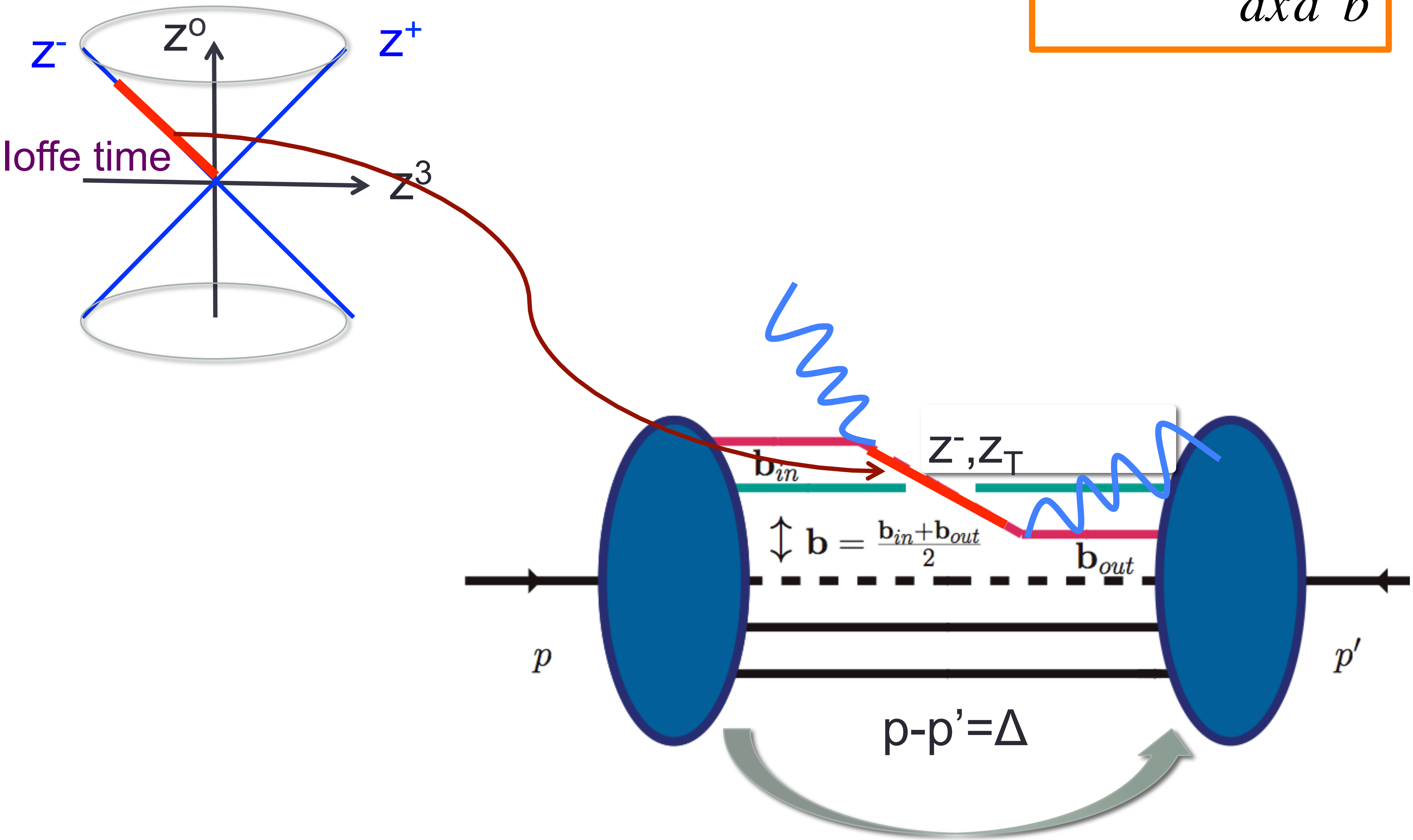


G. Miller(2007)



Two distinct distance scales

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



GPDs involve two types of distance

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

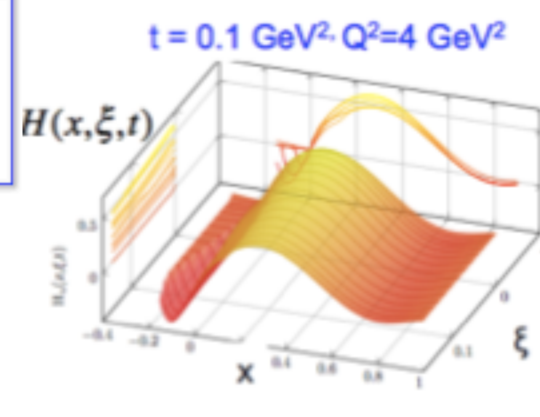
x distribution ➔ **Fourier transform** of **non-diagonal** density distribution in **z^-**

Δ distribution ➔ **Fourier transform** of **diagonal** density distribution in **b**

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

Ioffe time reconstruction

A. Rajan, SL (LC Meeting, 2018)



Reconstructed

In summary…imaging nucleons at the femtoscale

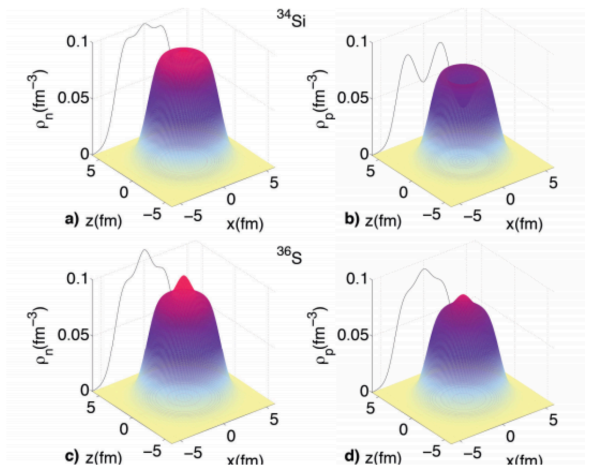
- Knowing the longitudinal (LC) momentum dependence allows us to separate out the transverse plane where Poincarè invariance applies

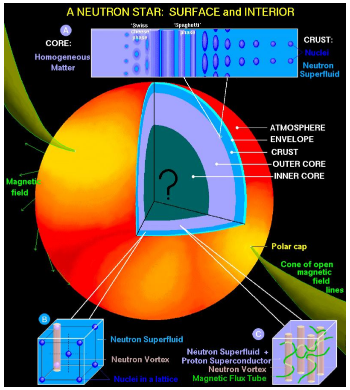
- We can then scan the transverse plane by measuring the scattered photon and proton with momentum transfer Δ

- Impact on nucleon and nuclear density distributions

- Impact on equation of state of neutron stars as we explore the core of the neutron with new GW data

A. Mutschler et al., Nature (2017





3. OAM AND OTHER GENERALIZED WANDZURA WILCZEK RELATIONS

Based on

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

Parton transverse momentum and orbital angular momentum distributions

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[4]Physics Depa...

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

DOI: 10.110...

PRD2018

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

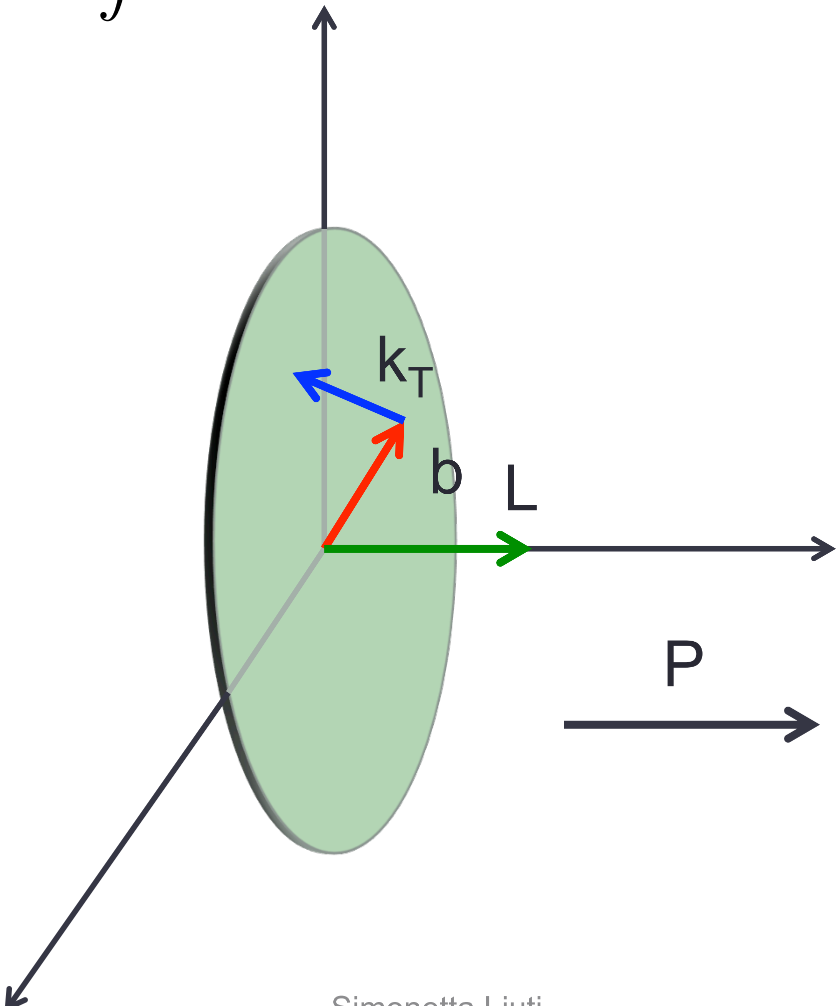
We derive new Lorentz Invariance and Equation of Motion Relations between twist-three Generalized Parton Distributions (GPDs) and moments in the parton transverse momentum, k_T, of twist-two Generalized Transverse Momentum-Dependent Distributions (GTMDs), as a function of the parton longitudinal momentum 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

Definition: 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,
Courtoy,
Engelhardt, Rajan,
SL



Possible Observable for L_q

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

$L_q(x)$

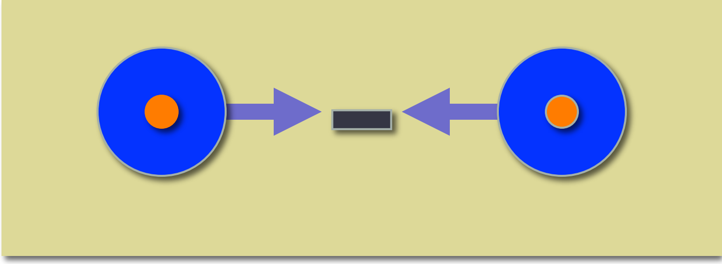
k_T moment of a GTMD
(Lorce and Pasquini)

$\xi=0$
$k_T \bullet \Delta_T=0$
$\Delta_T^{\,2}=0$

CAN IT BE MEASURED?

Is there any observable that we can identify OAM with?

A New Relation



A. Rajan, A. Courtoy, M. Engelhardt, S.L., PRD (2016) arXiv:1601.06117
A. Rajan, M. Engelhardt, S.L., PRD (2018) arXiv:1709.05770

$$\frac{1}{M}\underbrace{\int d^2k_T\, k_T^2\, F_{14}(x,0,k_T^2,0,0)}_{\text{OAM: twist 2 GTMD}} = -\int_x^1 dy \underbrace{\left[\widetilde{E}_{2T} + H + E\right]}_{\text{twist-3 GPD}}$$

Generalized Lorentz Invariance Relation (LIR)

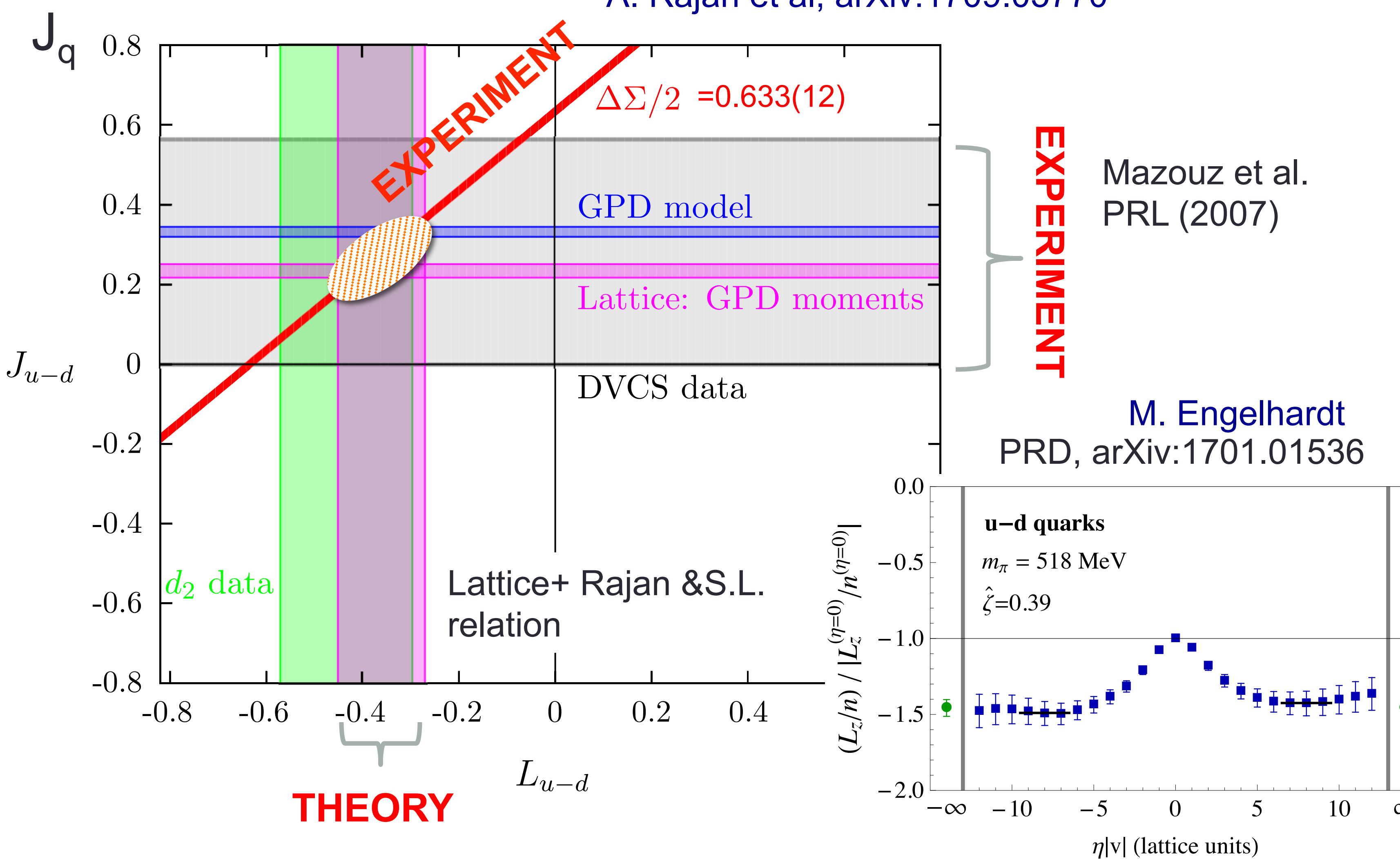
*Different notation! $G_2 \rightarrow \tilde{E}_{2T} + H + E$

Polyakov et al. Meissner, Metz and Schlegel, JHEP(2009)

Quark sector :

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

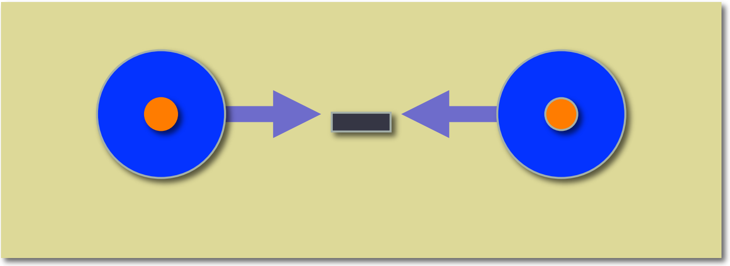
A. Rajan et al, PRD (2016) arXiv:1601.06117
A. Rajan et al, arXiv:1709.05770



Angular Momentum Sum Rule

A. Rajan et al, arXiv:1709.05770

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



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

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

New! From DVCS

DVCS (Ji,'97)

Polarized ep

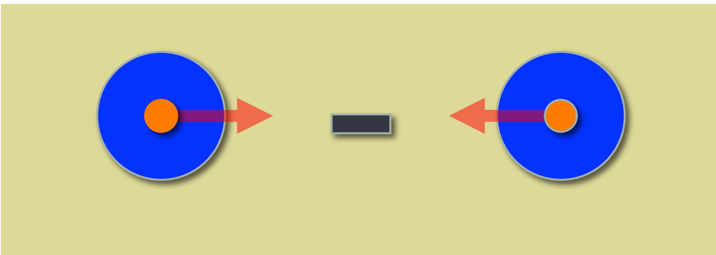
$g_1(x)$

Color force/gauge link

L = J - S + 0

Other correlations: quark and gluon spin-orbit

A. Rajan et al, arXiv:1709.05770, PRD



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

chiral odd magnetic moment

Chiral symmetry breaking test!

$$\frac{1}{2}\int dx\, x\widetilde{H} + \frac{m_q}{2M}\kappa_T^q = \int dx\, x(2\widetilde{H}'_{2T} + E'_{2T} + \widetilde{H}) + \frac{1}{2}e_q$$

$(J \cdot S)$ $\quad -J_T \cdot S_T$ $\quad L_z S_z$ $\quad S_z S_z$

$J_z S_z$

Interpretation of gauge link

$M_2(v^-)$

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

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

Force acting on quark

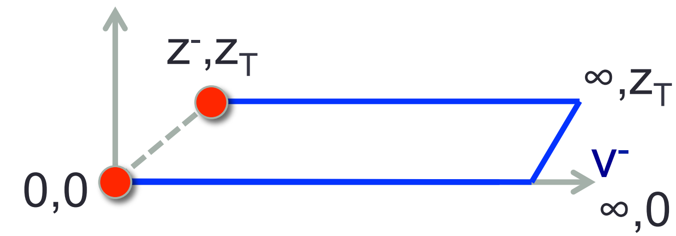
Non zero only for staple link

$M_3(v^-=0)$

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

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

A more profound understanding of quark-gluon-quark correlations



Two types

- Difference between JM and Ji (LIR violating term)

$$L^{JM}(x) - L^{Ji}(x) = \mathcal{M}_{F_{14}} - \mathcal{M}_{F_{14}}|_{v=0} = -\int_x^1 dy\, \mathcal{A}_{F_{14}}(y).$$

- Genuine twist 3 term (Generalized Qiu Sterman)

$$\int d^2k_T \, \frac{k_T^2}{M^2} \, F_{14}^{JM} - \int d^2k_T \, \frac{k_T^2}{M^2} \, F_{14}^{Ji} = T_F(x, x, \Delta)$$

An experimental measurement of twist 3 GPDs is sensitive to OAM but it cannot disentangle the difference between JM and Ji decompositions

Relations between gauge links derivatives

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

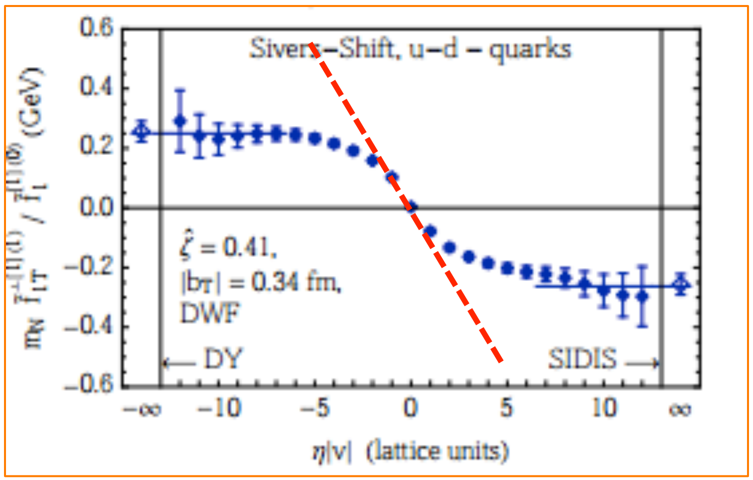
$$\frac{d}{dv^-}\mathcal{M}^{i,A(n=2)}_{\Lambda\Lambda'}\bigg|_{v^-=0} = -i(2P^+)\mathcal{M}^{i,S(n=3)}_{\Lambda}$$

Proton transverse spin configuration

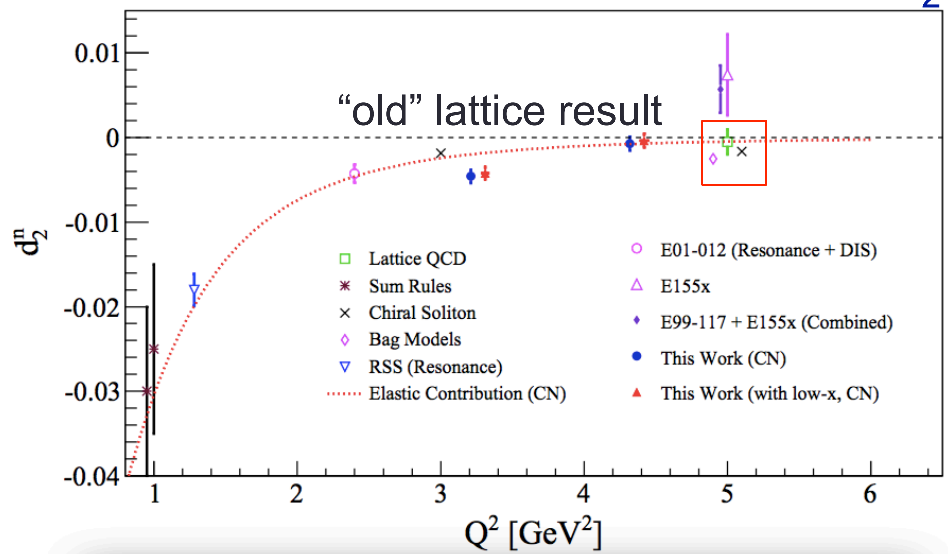
n=2

n=3

Slope of Sivers function in staple length



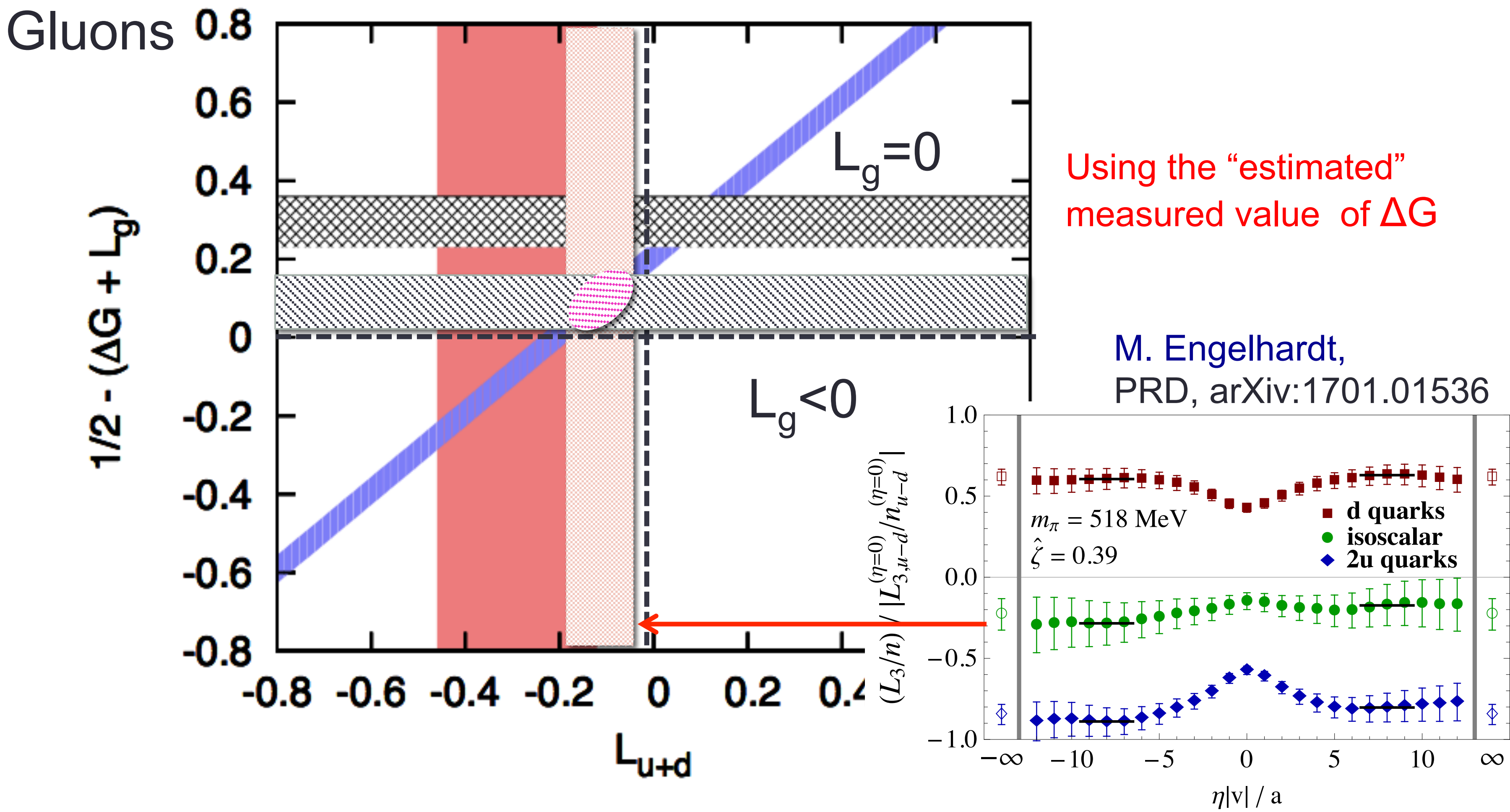
Genuine twist three d_2



Work in progress: W. Armstrong, F. Aslan, M. Burkardt, M. Engelhardt, SL

EIC ➔ Adding gluons: Present data consistent with $L_g<0$

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



Using the “estimated” measured value of ΔG

M. Engelhardt,
PRD, arXiv:1701.01536

4. A NEW EFFORT

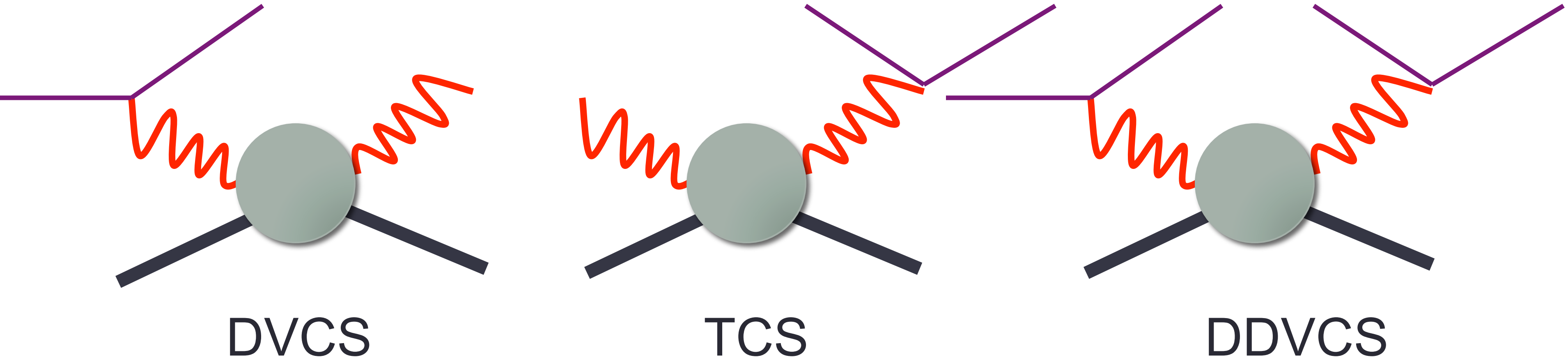
Multi-process, multi-variable analysis

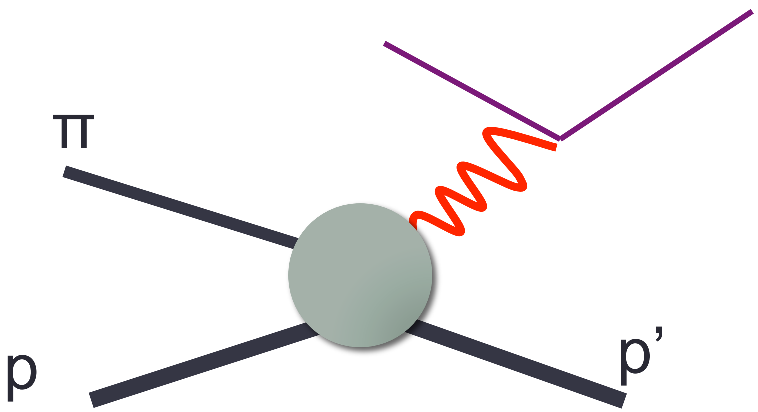
- ✓ Deeply Virtual Compton Scattering
- ✓ Deeply Virtual Meson Production
- ✓ Timelike Compton Scattering
- ✓ Double DVCS
- ✓ DVCS, TCS with Recoil Polarization
- ✓ Exclusive DY

Universality

(BTW…NEED EIC TO CARRY OUT THIS PROGRAM)

All the channels

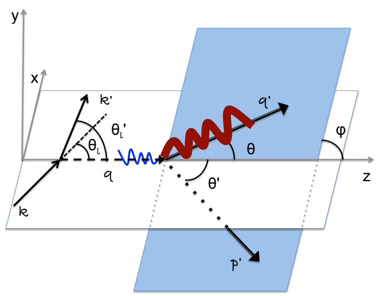


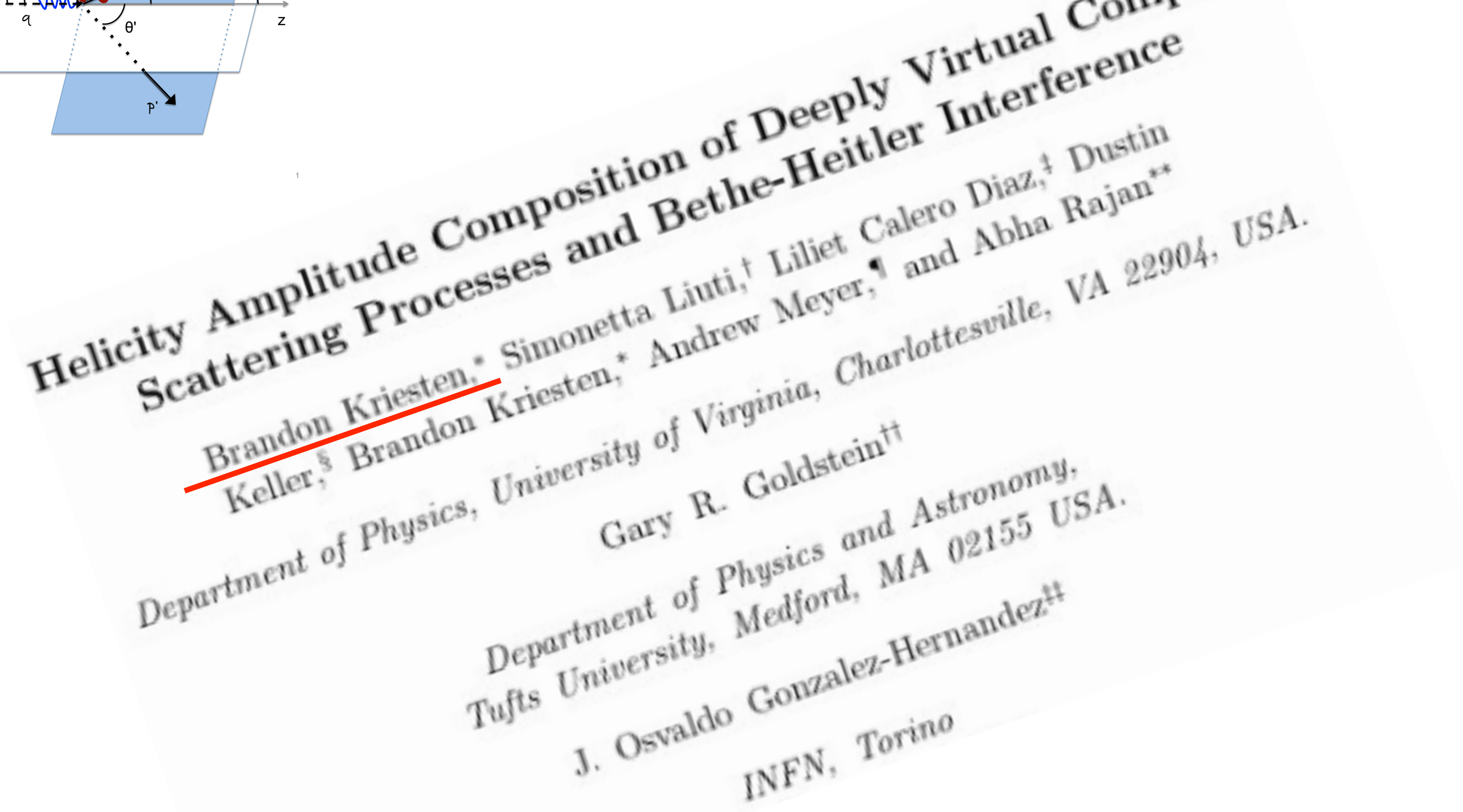


. . .

Exclusive pion induced DY **(EDY)**, T. Sawada et al., PRD93 (2016)
accessible at LHC SPIN ➔ **P. Di Nezza's talk**

DVCS



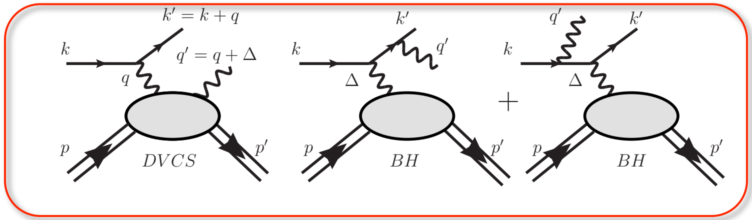


Helicity Amplitude Composition of Deeply Virtual Compton Scattering Processes and Bethe-Heitler Interference

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



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

twist two GPDs

twist three GPDs

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

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

$$+ \lambda_e \sqrt{2\epsilon(1-\epsilon)} \sin\phi F_{LU}^{\sin\phi} \Big]$$

$$+ S_L \Big[F_{UL} + \sqrt{\epsilon(\epsilon+1)} \sin\phi F_{UL}^{\sin\phi} + \epsilon \sin 2\phi F_{UL}^{\sin 2\phi}$$

$$+ \lambda_e \sqrt{1-\epsilon^2} F_{LL} + 2 \lambda_e \sqrt{\epsilon(1-\epsilon)} \cos\phi F_{LL}^{\cos\phi} \Big]$$

$$+ |S_T| \Big[\sin(\phi-\phi_S) \Big(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)} \Big)$$

$$\epsilon \sin(\phi+\phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \epsilon \sin(3\phi-\phi_S) F_{UT}^{\sin(3\phi-\phi_S)}$$

$$+ \sqrt{2\epsilon(1+\epsilon)} \Big(\sin\phi_S F_{UT}^{\sin\phi_S} + \sin(2\phi-\phi_S) F_{UT}^{\sin(2\phi-\phi_S)} \Big) \Big]$$

$$+ \lambda_e |S_L| \Big[\sqrt{1-\epsilon^2} \cos(\phi-\phi_S) F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)} \cos\phi_S F_{LT}^{\cos\phi_S}$$

$$+ \sqrt{2\epsilon(1-\epsilon)} \cos(2\phi-\phi_S) F_{LT}^{\cos(2\phi-\phi_S)} \Big] \Big\}$$

GPD Content

$t << Q^2$ $\xi < 1$

(with Brandon Kriesten et al., in preparation)

twist 2

$$F_{UU,T} = 4\Big[(1-\xi^2)\left(|\mathcal{H}|^2 + |\tilde{\mathcal{H}}|^2\right) + \frac{t_o - t}{2M^2}\left(|\mathcal{E}|^2 + \xi^2|\tilde{\mathcal{E}}|^2\right) - \frac{2\xi^2}{1-\xi^2}\Re\mathrm{e}\left(\mathcal{H}\mathcal{E} + \widetilde{\mathcal{H}}\widetilde{\mathcal{E}}\right)\Big]$$

$$F_{LL} = 2\Big[2(1-\xi^2)\ |\mathcal{H}\widetilde{\mathcal{H}}| + 4\xi\frac{t_o - t}{2M^2}\ |\mathcal{E}\widetilde{\mathcal{E}}| + \frac{2\xi^2}{1-\xi^2}\Re\mathrm{e}\left(\mathcal{H}\widetilde{\mathcal{E}} + \widetilde{\mathcal{H}}\mathcal{E}\right)\Big]$$

spin-orbit

twist 3

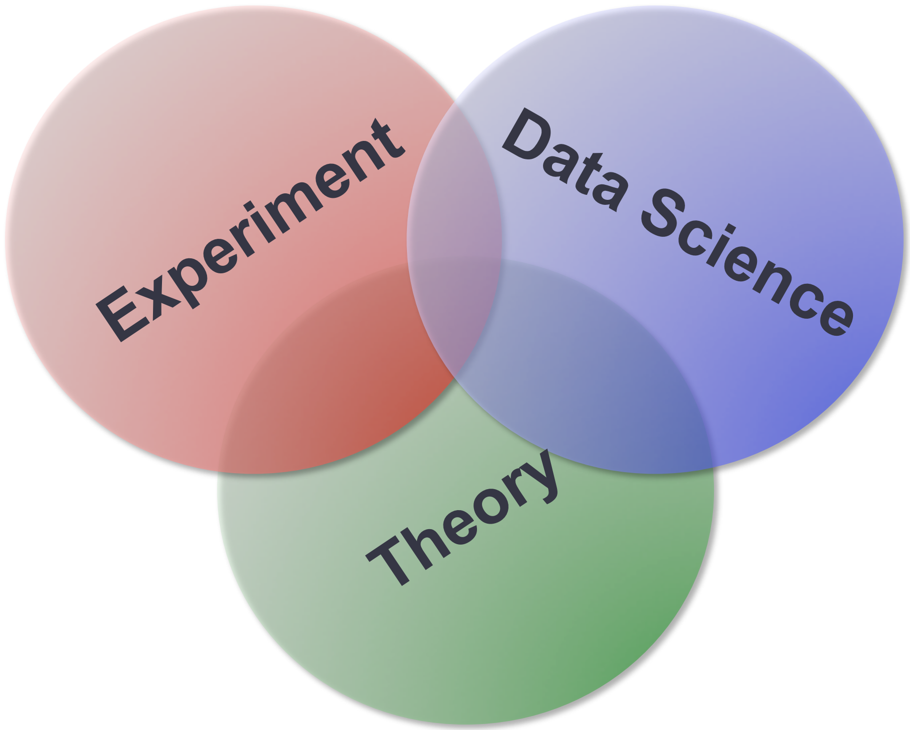
twist 2

$$F_{UU}^{\cos\phi} = -2\,(1-\xi^2)\Re\mathrm{e}\Big[\left(2\widetilde{\mathcal{H}}_{2T} + \mathcal{E}_{2T} + 2\widetilde{\mathcal{H}}'_{2T} + \mathcal{E}'_{2T}\right)\left(\mathcal{H} - \frac{\xi^2}{1-\xi^2}\mathcal{E}\right)$$

Because we are able to describe it as a GPD, OAM can be disentangled from data

A. Rajan et al, PRD (2016) arXiv:1601.06117
A. Rajan et al, arXiv:1709.05770

How do we detect all this?



New Analysis Groups

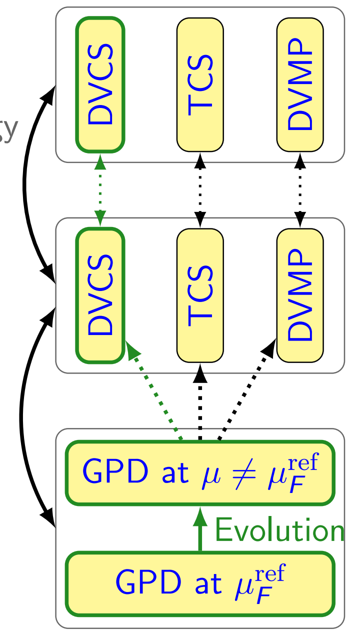
PARTONS: A GPDs dedicated Software

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

Experimental data and phenomenology

Computation of amplitudes

First principles and fundamental parameters



- DVCS chain is done and working
- Including LO evolution and NLO CFF

- TCS code exists at NLO but needs to be implemented in PARTONS
- DVMP requires more work due to meson PDAs

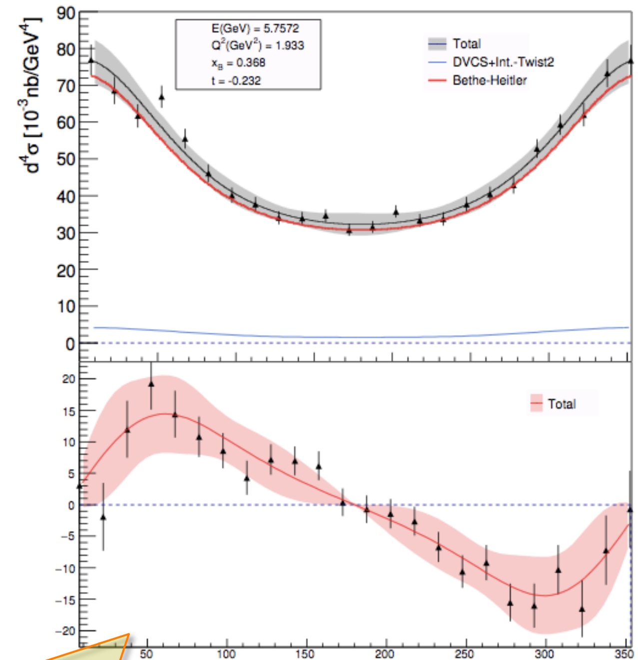
- Code and documentation available at: **http://partons.cea.fr**

Cédric Mezrag (INFN) PARTONS July 31th, 2018 2 / 0

courtesy C. Mezrag

UVa group

L. Calero Diaz, D. Keller



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 is needed!

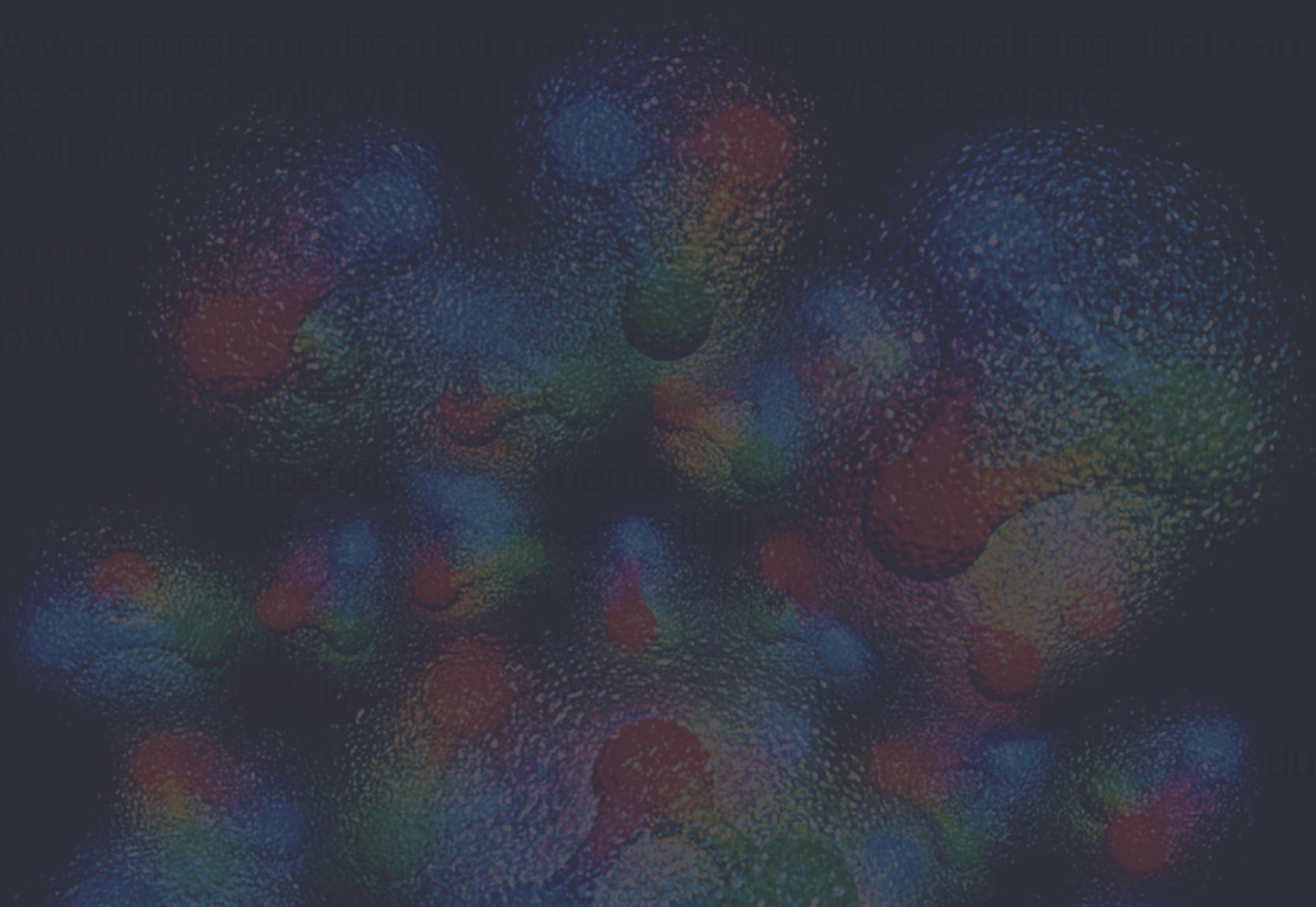
Things that I did not mention

Mass Decomposition (Z. Meziani)

Chiral Odd Sector (see recent work by W. Cosyn and B.Pire)

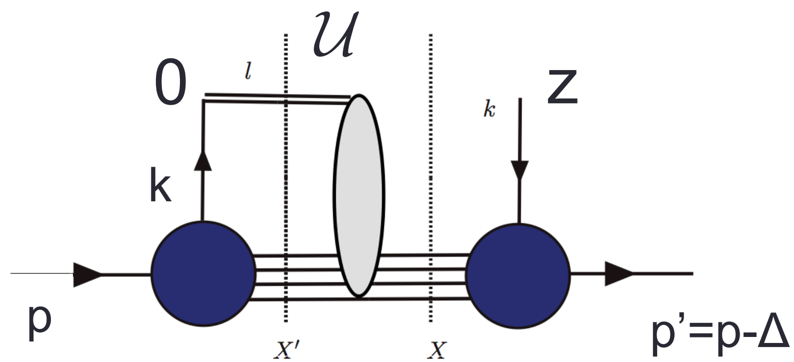
Chiral Odd and BSM searches (S. Baessler, A.Courtoy, O.Elgadawy, SL, and EIC BSM Effort: Y. Furletova)

Nuclei Jlab ALERT experiment (R. Dupre, W. Armstrong, M. Hattawy, SL…)



Back UP

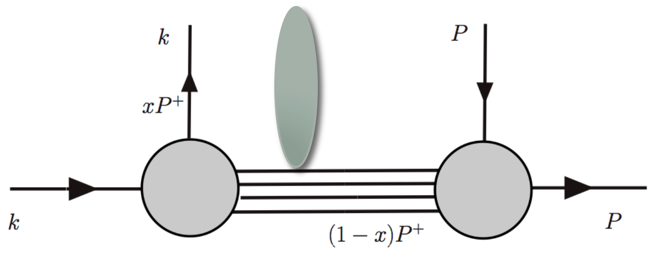
Correlation function



Unintegrated: GTMDs

$$\mathcal{W}^{[\hat{\Gamma}]} = \int dz^- d^2\mathbf{z}_T\, e^{i(xP^+z^- - \mathbf{k}_T\cdot\mathbf{z}_T)}\langle p', \Lambda' \mid \bar{\psi}(0)\hat{\Gamma}\,\mathcal{U}(0,z)\,\psi(z) \mid p, \Lambda\rangle\,|_{z^+=0}$$

Correlation function



Integrated over k_T (gauge link becomes trivial) ➔ GPDs

Parametrization of matrix element

Meissner, Metz, Schlegel, JHEP (2009)

Leading twist, chiral even

vector $$F^{[\gamma^+]}_{\Lambda\Lambda'} = \frac{1}{2P^+}\bar{U}(p,\Lambda')\left[\gamma^+ H(x,\xi,t) + \frac{i\sigma^{+j}\Delta_j}{2M}E(x,\xi,t)\right]U(p,\Lambda)$$

axial-vector $$F^{[\gamma^+\gamma_5]}_{\Lambda\Lambda'} = \frac{1}{2P^+}\bar{U}(p,\Lambda')\left[\gamma^+\gamma_5 \widetilde{H}(x,\xi,t) + \frac{\gamma_5\Delta^+}{2M}E(x,\xi,t)\right]U(p,\Lambda)$$

⋮