Gluon Structure of Hadrons and Nuclei

Phiala Shanahan

William and Mary Thomas Jefferson National Accelerator Facility

Gluon Structure

- Past 60+ years: detailed view of quark structure of nucleons
- Gluonic structure (beyond gluon density) relatively unexplored
- Electron-Ion Collider
- Priority in 2015 nuclear physics long range plan
- "Understanding the glue that binds us all"
- Insights from Lattice QCD?

Cover image from EIC whitepaper arXiv::1212.1701

Gluon Structure from LQCD

How is the gluon structure of a proton modified in a nucleus

Gluonic 'EMC' effect e 'Exotic' glue

Nucleon momentum decomposition ²⌃ *J L* h*x*i *Acknowledgments:* We thank all members of ETMC ntum decomposition and in Ste \sim fruitful discussions. We acknowledge funding funding

Gluon Momentum fraction $\overline{0.183}$ s -0.001110 UNION Promentum Traction

 $u_{\rm 15}(3)$ $u_{\rm 20}(3)$ $u_{\rm 30}(3)$ $u_{\rm 20}(3)$ $u_{\rm 30}(3)$ $u_{\rm 40}(3)$

• Two direct calculations at the physical point since last year \bullet Tot. 0.2010 0.541 1.07(17) 0.341

C. Alexandrou et al., arXiv:1706.02973 Y.-B.Yang et al., χ QCD, in preparation

from the European Union's Horizon 2020 research and

Nucleon spin decomposition

Two decompositions of the proton spin:

Interpolation between decompositions: M. Engelhardt, PRD 95 094505 (2017)

Ji spin decomposition show schematically the various contributions to the various contributions to the spinner.
The spinner of the s

C. Alexandrou et al., arXiv: 1706.02973

- Physical pion mass cal point for the strange quark and the strange quark and the first to include α Physical pion mass at the physical point \mathbb{R} \mathcal{U} and down quarks. We also note that the charm axial t
- All terms calculated directly consistent with \sim

and momentum fraction. MS-scheme at 2 GeV

J-M spin decomposition

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

Gluon Helicity

- Can't be calculated directly \bigcirc
- Match to calculable ME in infinite \bigcirc momentum frame limit using large momentum effective theory LaMET: X. Ji et al., PRL 111 112002 (2013)

de Florian et. al, Phys.Rev.Lett. 113, 012001 (2014)

Gluon Structure from LQCD

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Gluonic 'EMC' effect ^o 'Exotic' glue

Gluonic Transversity

Targets with J≥1 have leading twist gluon parton distribution $\Delta(x,Q^2)$: double helicity flip [Jaffe & Manohar 1989]

- Unambiguously gluonic: no analogous quark PDF at twist-2
- Non-vanishing in forward limit for targets with spin≥1
- Experimentally measurable in unpolarised electron DIS on polarised target
	- Nitrogen target: JLab Lol 2015
	- Polarised nuclei at EIC
- Moments calculable in LQCD

Gluonic Transversity

Double helicity flip structure function $\Delta(x,Q^2)$ Double helicity flip structure function $\Delta(X,Q^2)$

Changes both photon an Changes both photon and target helicity by 2 units Photon helicity Target helicity $\Delta(x,Q^2) = A \Box \Box = A \Box$

Double Helicity Flip Gluon Structure Function: (*x, Q*²) Gluonic Transversity *^Mn*(*Q*²) = ^Z ¹ *dxxⁿ*¹(*x, Q*²) (12) $r_{\rm{max}}$ is 1040(3) MeV.

Pauble helicity form Double helicity flip structure function Δ(x, Q²). \sum , \sum \sum In this work we consider the lowest dimension (*n* = 2)

0

Hadrons: Gluonic Transversity (parton model interpretation) **11 0113.** Clubine mansversity (parton moderniterpretation)

$$
\Delta(x, Q^2) = -\frac{\alpha_s(Q^2)}{2\pi} \text{Tr} Q^2 x^2 \int_x^1 \frac{dy}{y^3} \left[g_{\hat{x}}(y, Q^2) - g_{\hat{y}}(x, Q^2) \right]
$$

 $g_{\hat{x},\hat{y}}(y,Q^2)$: probability of finding a gluon with momentum fraction y linearly **linearly polarised in** \hat{x} , \hat{y} direction $G_{\mu}(\Omega^2)$: probability of finding a gluon with momen \mathcal{Y} dimension under renormalization (this operator mixes n traction y linearly $\hspace{0.1mm}$

 \mathbf{g} aligned rather than perpendicular than perpendicular to it in the transverse plane \mathbf{g} gluons aligned rather than perpendicular than perpendicular to it in the transverse plane \mathcal{L} Nuclei: Exotic Glue

Phiala Shanahan (MIT) Exotic Glue in the Nucleus July 8, 2016 8 / 23 with individual nucleons $\langle N, Z | \mathcal{O} | N, Z \rangle \neq 0$ gluons not associated in nucleus

$$
\langle p|O|p\rangle = 0
$$
\nAns not associated

\n
$$
\langle N, Z|O|N, Z\rangle \neq 0
$$
\nindividual nucleons

B. Lattice Operator Construction

Double Helicity Flip Gluon Structure Function: (*x, Q*²) Gluonic Transversity *^Mn*(*Q*²) = ^Z ¹ *dxxⁿ*¹(*x, Q*²) (12) $r_{\rm{max}}$ is 1040(3) MeV.

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$$

B. Lattice Operator Construction

Gluonic Transversity

Moments of $\Delta(x,Q^2)$ are calculable in LQCD Extraction of *A*²

Determined by matrix elements of local gluonic operators annie op maark eieme $\frac{1}{2}$ where Double Helicity Flip Gluon Structure Function: (*x, Q*²)

$$
\langle pE' | \underline{S} \left[G_{\mu\mu_1} \overleftrightarrow{D}_{\mu_3} \dots \overleftrightarrow{D}_{\mu_n} G_{\nu\mu_2} \right] | pE \rangle \text{ symmetric in } \mu_1, \dots, \mu_n \text{, trace subtract in all free indices} \\ = (-2i)^{n-2} \underline{S} \left[(p_\mu E'^*_{\mu_1} - p_{\mu_1} E'^*_{\mu}) (p_\nu E_{\mu_2} - p_{\mu_2} E_{\nu}) \right. \\ \left. + (\mu \leftrightarrow \nu) \right] p_{\mu_3} \dots p_{\mu_n} A_n (Q^2) \dots,
$$

Reduced Matrix Element

LQCD Calculation

Gluon transversity of the φ meson

- First moment in φ meson (simplest spin-1 system \longrightarrow nuclei) . moment in $\bm{\phi}$
- Lattice details: clover fermions, Lüscher-Weisz gauge action

- Many systematics not addressed (yet)
	- Quark mass effects I RUSS CITCLE
	- Volume effects
- **Discretisation**
- Momenta up to the contract up to the contract up to α or α . Die rent in die rent die rent die rent die rent
Die rent in die rent die rent
 Renormalisation Alexandrou et al. arXiv:1611.06901

W. Detmold, PES, PRD 94 (2016), 014507 + W. Detmold, D. Pefkou, PES PRD 95 (2017), 114515

Doing lattice QCD

Correlation decays exponentially with distance in time:

$$
C(t) = \sum_{n} Z_n \exp(-E_n t)
$$

At late times:

 $\rightarrow Z_0 \exp(-E_0 t)$

Ground state mass revealed through "effective mass plot"

$$
M(t) = \ln \left[\frac{C(t)}{C(t+1)} \right] \stackrel{t \to \infty}{\longrightarrow} E_0
$$

LQCD matrix elements

How do we calculate matrix elements?

- Create three quarks (correct quantum numbers) at a source and annihilate the three quarks at sink far from source
- Insert operator at intermediate timeslice

Remove time-dependence by dividing out with two-point correlators: $C_3(t, \tau, \vec{p'}, \vec{q})$ $C_2(t-\tau, p')C_2(\tau, p)$ $\stackrel{t\rightarrow\infty}{\longrightarrow}\langle N(p')|\mathcal{O}(q)|N(p)\rangle$

LQCD Calculation **1 OCD Calculati** 2 , 2 , 2 , 2 4 , 201 ¹ , ⌧ (2) 2 , 2 , 3 2×10^{10} 3 , 3 , 3 , 3 , 3 $1/2$ 2 , 2 , 2 , 2 1 , 3 , 3 , 3 , 3

3

Calculate lowest moment of $\Delta(x,Q^2)$: T is a percentation of the first time at each rank $\left(\frac{1}{2}, \frac{1}{2}\right)$.

 $\frac{4}{3}$ (1) $\frac{4}{3}$ (1) $\frac{4}{3}$

Ratio of LQCD correlators $R_{jk}(t, \tau, \vec{p})$ $R_{jk}(t,\tau,\vec{p})$

TABLE II. Dimension indicates that the operator transforms as a subset of the symmetry group shown. ~*e[±]* = ⌥ energy of the state, and *m* p2 (0*,* 1*, ±i*)*,* (23) of gauge-invariant \mathcal{L} in the spatial smearing \mathcal{L} directions at both source and sink. Measurements were performed for 96 di↵erent source locations on each of 1042 configurations, resulting in 100032 measurements. is die oordeeling of the values physical simulation. For example, statistical agreement ing vectors in the direction of \mathcal{U} \sim which the operator under consideration subduces at \sim $\mathcal{H}(\mathcal{A})$ is the explicit forms of the Euclidean basis \blacksquare Idli \mathcal{L} . The operator defined in the operator defined in \mathcal{L} \blacksquare . It is significant that we find a statistical vector \blacksquare and theoretically consistent and robust signal in this unphysical simulation. For example, statistical agreement is seen between the values of this observable obtained us-Appendix A: Explicit Lattice Basis Vectors Gancanach en list the experience of the Euclidean basis of the Euclidean basis of the Euclidean Basis of the E

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masses used in this work and subject to caveats regarding to caveats regarding to caveat subject to caveat subj

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Section III.

• Discrete lattice: rotational symmetry • hypercubic symmetry Take linear combinations of operators that transform irreducibly under hypercubic group: safe from mixing e.g., for $\mathcal{O}^{(E)}_{\mu\nu\mu_1\mu_2} = G^{(E)}_{\mu\mu_1} G^{(E)}_{\nu\mu_2}$ use 2 Z 3 ⌧ (4) Take linear combinations of operate hypercubic group safe from mixing $\alpha(E) = \alpha(E) \alpha(E)$, $\alpha(E) = \alpha(E) - \alpha(E) = \alpha(E) + \alpha(E) + \alpha(E) + \alpha(E) = 3\alpha(E)$ are ✏ (*E*) *ⁱ* (*p,* ~) = ✏ *i* (*p,* ~)*.* (25) Tractulation three-point correlations constructions correlations constructions correlations $c=\frac{1}{2\sqrt{2}}\left(-2\mathcal{O}_{1122}^{(E)}+\mathcal{O}_{1133}^{(E)}+\mathcal{O}_{1144}^{(E)}+\mathcal{O}_{2233}+O_{2244}^{2}+2\mathcal{O}_{334}\right)$ \bullet Discrete lattice: rotational symmetry on each configuration were averaged and bootstrap states \mathcal{E} \bullet Take linear combinations of operators nypercubic group: sate trom mixing $\Omega \subset \text{for} \quad \mathcal{O}(E) \quad -\mathcal{O}(E) \quad \mathcal{O}(E)$, where $\mathcal{O}(E)$ e.g., for $\mathcal{O}^{(E)}_{\mu\nu\mu_1\mu_2} = G^{(E)}_{\mu\mu_1} G^{(E)}_{\nu\mu_2}$ use $\mathcal{O}^{(E)}_{1,1} = \frac{1}{8\sqrt{2}}$ $\mathbf{H} = \mathbf{H} \cdot \mathbf{H} \cdot \mathbf{H}$ is the explicit forms of the Euclidean basis of the Euclidean basis $\mathbf{H} = \mathbf{H} \cdot \mathbf{H}$ **v** Discrete lattice: rotational symmetry \blacksquare \mathbb{R} T₁ **Fields** lake linear combinations of operators that tra Interpretation in the property for discretisation artefacts, suggesting that such e↵ects are **Of Discrete lattice: rotational symmetry** \rightarrow **hypercubic symmetry** with di \mathcal{P}_{max} and with \mathcal{P}_{max} smearing and with Wilson- \mathcal{L} renormalization. In addition, we have explored the set of \mathcal{L} ubic group: safe trom mixing analogue $\mathcal{O}(E)$ for $\mathcal{O}(E)$ $\mathcal{O}(E)$ for $\mathcal{O}(E)$ for $\mathcal{O}(E)$ for $\mathcal{O}(E)$ for $\mathcal{O}(E)$ $\mathcal{C}(\mathcal{E})$, for $\mathcal{O}^{(E)}_{\mu\nu\mu_1\mu_2} = G^{(E)}_{\mu\mu_1} G^{(E)}_{\nu\mu_2}$ use $\mathcal{O}^{(E)}_{1,1} = \frac{1}{8\sqrt{3}} \left(-2\mathcal{O}^{(E)}_{1122} + \mathcal{O}^{(E)}_{1133} + \mathcal{O}^{(E)}_{1144} + \mathcal{O}^{(E)}_{2233} + \mathcal{O}^{(E)}_{2244} - 2\mathcal{O}^{(E)}_{3344} \right)$ tations. For a stations. For a stations are for 1 *m* i caa 2*O*(*E*) *w* Discrete faction. Totational symmetry **and the properties** symmetry Γ discretise that suggesting that suggesting that suggesting that such e Γ ects are ake linear combinations of operators that transform irreducibly under the lake linear combinations of operators that transform irreducibly unde h h h h h flowed group, sale fight $\epsilon_{\mathbf{i}}$ $\sin \sigma$ $\mathcal{O}_{1,1}^{(E)} = \frac{1}{8\sqrt{2}}$ $\overline{8\sqrt{3}}$ $\left(-2 \mathcal{O}_{1122}^{(E)} + \mathcal{O}_{1133}^{(E)} + \mathcal{O}_{1144}^{(E)}\right)$

$$
C_{jk}^{\text{2pt}}(t,\vec{p}) = \sum_{\vec{x}} e^{i\vec{p}\cdot\vec{x}} \langle \eta_j(t,\vec{x})\eta_k^{\dagger}(0,\vec{0}) \rangle
$$

\n
$$
= Z_{\phi} \left(e^{-Et} + e^{-E(T-t)} \right) \sum_{\lambda} \epsilon_j^{(E)}(\vec{p},\lambda) \epsilon_k^{(E)*}(\vec{p},\lambda)
$$

\n
$$
= Z_{\phi} e^{-Et} \sum_{\lambda\lambda'} \epsilon_j^{(E)}(\vec{p},\lambda) \epsilon_k^{(E)*}(\vec{p},\lambda)
$$

\n
$$
= Z_{\phi} e^{-Et} \sum_{\lambda\lambda'} \epsilon_j^{(E)}(\vec{p},\lambda) \epsilon_k^{(E)*}(\vec{p},\lambda)
$$

$$
R_{jk}(t,\tau,\vec{p}) = \frac{C_{jk}^{\rm 3pt}(t,\tau,\vec{p}) + C_{jk}^{\rm 3pt}(T-t,T-\tau,\vec{p})}{C_{jk}^{\rm 2pt}(t,\vec{p})}
$$

- All polarisation combinations (j,k) To construct the three-point correlators correspond- $\mathcal{O}(\mathcal{C})$ *O*(*E*) ²*,*¹ = risation combinations (j,k) m s been considerable (n, y) **Conservations in a non-individual non-individual nucleons** in a number of α clear polarization considerable
- Boost momenta up to (I, I, I) \overline{C} 1 \overline{C} α up to (l,l,l) lattice studies of the spectroscopy $\{1,1,1\}$ \sum \bullet Roost momenta un to $(1 \mid \cdot)$ \sim beese momenta ap to $(1,1)$

 \overline{a}

sider lattice operators transforming under these three ir-

 $\mathbb{E}_{\mathbf{r}}$

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14 de janvier de la component de la component

ing vectors in the extension of the

These propagators were contracted to form two-point and σ

 $A \in \mathbb{R}$, and the set of $A \in \mathbb{R}$, and the set of $A \in \mathbb{R}$, and the set of $A \in \mathbb{R}$

Examine all elements of each hypercubic irrep. point functions above were configurated configurations and configurations above were configurated configuration \blacksquare confirmed and source-location and a due to contributions from the top contributions in the state of conclusions in the top of contributions o in the derivation of Eq. (26). Note that the two point correction of the two points of the two points of the t Minkowski space the expansion of a deles in the let e $\overline{ }$ nents of each hypercubic i p all olements of each bypersubic inner c all citations of cathing per cubit in the lattice studies in the spectroscopy in the spectroscopy Γ **EXAMINIUM AND CICITIONES** OF CACH Arcubic irran

for *{t,* ⌧*} < T/*2. Other choices for the ratio, with difof (1)*ⁿ*⁴ where *ⁿ*⁴ is the number of temporal indices in the operator *^O*. In constructing *^C*3pt, various levels ratio depends on ²*,*⁶ ⁼¹ ⇣ *O*(*E*) ¹²³³ *^O*(*E*) 1244⌘ *.* (A9) *,* (A8) of Wilson flow and Polarisations, momentum, α *Operator* $\overline{4}$ Finally, we consider the ⌧ (2) ² basis vectors: *.* (A9)

 σ the gluonic operator. The three-point correlators operators of the three-point correlators o

¹¹⁴⁴ ⁺ *^O*(*E*)

3344⌘

 $\mathbf{E}(\mathbf{r}) = \mathbf{E}(\mathbf{r})$ is built from the point from

LQCD Calculation

operator insertion time τ

LQCD Calculation

Detmold PFS PRD 94 (2016) 014507 W. Detmold, PES, PRD 94 (2016), 014507

Soffer-type Bounds

Constraint relating transversity, spin-indep. and spin-dep. distributions

For quark distributions in spin 1/7 state: For quark distributions in spin 1/2 state:

$$
|\delta q(x)| \leq \frac{1}{2} \left(q(x) + \Delta q(x) \right)
$$

Spin-dependent

Analogue for first moments of gluon distributions?

Need to calculate moments of spin independent gluon distribution (first moment of spin-dependent gluon distribution vanishes by operator symmetries)

Spin-indep. gluon structure distributions in the control of the $\mathcal{A}=\mathcal{A}$ Eq. (34) for *n* = 2 is

W. Detmold, PES, PRD 94 (2016), 014507 :S, PRD reduced matrix elements of local operators:

Spin-independent gluon operator: =*S f*₂ *gluon* operator:

$$
\overline{\mathcal{O}}_{\mu_1...\mu_n}=S\left[G_{\mu_1\alpha}\overleftrightarrow{D}_{\mu_3}\dots \overleftrightarrow{D}_{\mu_n}G_{\mu_2}^{\quad \alpha}\right] \qquad \qquad \overset{\text{\tiny -0.2}}{\underset{\bar{\mathfrak{m}}}{\prod}} \qquad \qquad
$$

Matrix elements at $n=2$ define lowest moment of structure functions for the transversity, spin-independent and spin-

$$
\langle pE'|\overline{O}_{\mu_1\mu_2}|pE\rangle
$$

= $S[M^2E_{\mu_1}^{'*}E_{\mu_2}]B_{2,1}(\mu^2)$
+ $S[(E \cdot E'^*)p_{\mu_1}p_{\mu_2}]B_{2,2}(\mu^2)$

Two reduced matrix elements $\begin{bmatrix} 1 \\ 2 \end{bmatrix}$ for the main paper. The main replaces Equation replaces Eq. (37) from the main paper. The main paper of the main paper. The main paper of the main paper. The main paper of the main paper of the main paper. The main paper of the main paper. Th **Parity is analogue of the Souer bound for the Souer bound for the So** $\frac{1}{2}$

- Analysis as in transversity case
- Mixing with quark ops. neglected, pQCD calcs. shown that it is small: Alexandrou 1611.06901 below replace for the main paper. The main pap \sim 1 manng verter quank ups. increased the pure calls. \sim \sim \sim SHOWIT that it is sitiall. Alexandrous for 1.00701 Conclusions of the analysis, increased that the analysis of the social soft- Ω ops. neg 1all ۔
ماد \mathbf{a} $PQCD$ calls.

*O^µ*1*µ*²

= *G*(*E*)

So↵er bound analogue Sofferty So↵er bound analogue So↵er bound analogue Explore gluon structure of meson more generally Explore gluon structure of meson more generally shnu e Bo quark
Mark Barat
Mark Barat Soffer-type Bounds *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, U.S.A.*

 $\langle 3\rangle$ $\langle 11\rangle$ and $\langle 3\rangle$ So↵er bound for transversity quark distributions: (spin-1 state): ibutions
ibutions distribution
 bound soiler-type bound for leading moments of giuon dis
(spin-1 state): Soffer-type bound for leading moments of gluon distributions (spin-1 state):

Explore gluon structure of meson more generally

Direct

$$
|A_2| \leq \frac{1}{24}(5B_{2,1} - 6B_{2,2})
$$

Spin-dependent
spin-dependent

$$
|0.24| \le \frac{1}{24} [5(-0.5) - 6(-1.4)] = 0.24
$$

 \overline{C} Nucleus Soffer-like bound approximately saturated

Gluon Radii

How does the gluon radius of a proton compare to the quark/charge radius?

Or is the picture more complicated?

Gluon Generalised FFs particles, there are 7(b*n/*2c + 1) spin-independent gluon ~*e*⁰ = (1*,* 0*,* 0)*,* (6)

Matrix elements of the spin-independent gluon structure function

Off-forward matrix elements are complicated:

$$
\left\langle p'E'\left|S\left[G_{\mu\alpha}i\overleftrightarrow{D}_{\mu_1}\dots i\overleftrightarrow{D}_{\mu_n}G_{\nu}^{\alpha}\right]\right|pE\right\rangle
$$

\n
$$
=\sum_{\substack{m \text{ even} \\ m=0}}^{n} \left\{B_{1,m}^{(n+2)}(\Delta^2)M^2S\left[E_{\mu}E_{\nu}^{\prime*}\Delta_{\mu_1}\dots\Delta_{\mu_m}P_{\mu_{m+1}}\dots P_{\mu_n}\right]\right.\n+ B_{2,m}^{(n+2)}(\Delta^2)S\left[(E\cdot E^{\prime*})P_{\mu}P_{\nu}\Delta_{\mu_1}\dots\Delta_{\mu_m}P_{\mu_{m+1}}\dots P_{\mu_n}\right]\n+ B_{3,m}^{(n+2)}(\Delta^2)S\left[(E\cdot E^{\prime*})\Delta_{\mu}\Delta_{\nu}\Delta_{\mu_1}\dots\Delta_{\mu_m}P_{\mu_{m+1}}\dots P_{\mu_n}\right]\n+ B_{4,m}^{(n+2)}(\Delta^2)S\left[\left((E^{\prime*}\cdot P)E_{\mu}P_{\nu} + (E\cdot P)E_{\mu}^{\prime*}P_{\nu}\right)\Delta_{\mu_1}\dots\Delta_{\mu_m}P_{\mu_{m+1}}\dots P_{\mu_n}\right]\n+ B_{5,m}^{(n+2)}(\Delta^2)S\left[\left((E^{\prime*}\cdot P)E_{\mu}\Delta_{\nu} - (E\cdot P)E_{\mu}^{\prime*}\Delta_{\nu}\right)\Delta_{\mu_1}\dots\Delta_{\mu_m}P_{\mu_{m+1}}\dots P_{\mu_n}\right]\n+ \frac{B_{6,m}^{(n+2)}(\Delta^2)}{M^2}S\left[(E\cdot P)(E^{\prime*}\cdot P)P_{\mu}P_{\nu}\Delta_{\mu_1}\dots\Delta_{\mu_m}P_{\mu_{m+1}}\dots P_{\mu_n}\right]\n+ \frac{B_{7,m}^{(n+2)}(\Delta^2)}{M^2}S\left[(E\cdot P)(E^{\prime*}\cdot P)\Delta_{\mu}\Delta_{\nu}\Delta_{\mu_1}\dots\Delta_{\mu_m}P_{\mu_{m+1}}\dots P_{\mu_n}\right].
$$

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$$
\n
$$
=\sum_{\substack{m \text{ even} \\ m=0}}^{n} \left\{\frac{B_{1,m}^{(n+2)}(\Delta^2)M^2S\left[E_{\mu}E'_{\nu}\Delta_{\mu_1}...\Delta_{\mu_m}P_{\mu_{m+1}}...P_{\mu_n}\right]}{+\frac{B_{2,m}^{(n+2)}(\Delta^2)S\left[(E\cdot E'_{\nu}]\right]}{B_{3,m}^{(n+2)}(\Delta^2)S\left[(E\cdot E'_{\nu}]\right]} \right\}
$$
\nMany gluonic radii:

\n
$$
+\frac{B_{3,m}^{(n+2)}(\Delta^2)}{B_{3,m}^{(n+2)}(\Delta^2)}S\left[(E\cdot E)(E'^*\cdot P)P_{\mu}P_{\nu}\Delta_{\mu_1}...\Delta_{\mu_m}P_{\mu_{m+1}}...P_{\mu_n}\right]}{[\frac{B_{1,m}^{(n+2)}(\Delta^2)}{M^2}S\left[(E\cdot P)(E'^*\cdot P)\Delta_{\mu}\Delta_{\nu}\Delta_{\mu_1}...\Delta_{\mu_m}P_{\mu_{m+1}}...P_{\mu_n}\right]}\right\}.
$$

Matrix elements of the gluon transversity structure function

$$
\begin{split}\n\text{Similarly complicated:} \\
\langle p'E'|&S\left[\frac{G_{\mu\mu_{1}}\tilde{D}_{\mu_{3}}\dots\tilde{D}_{\mu_{n}}G_{\nu\mu_{2}}}{\frac{M_{1,m=3}^{(n)}(k,\mu^{2})}{M^{2}}\right]pE}\rangle \\
&= \sum_{\substack{m \text{ odd} \\ m=3}}^{n} \frac{\left\{\frac{A_{1,m=3}^{(n)}(k,\mu^{2})}{\left[\left(\Delta_{\mu}E_{\mu_{1}}-E_{\mu}P_{\mu_{1}}\right)\left(P_{\nu}E'^{*}_{\mu_{2}}-E'^{*}_{\nu}P_{\mu_{2}}\right)\Delta_{\mu_{3}}\dots\Delta_{\mu_{m-1}}P_{\mu_{m}}\dots P_{\mu_{n}}\right]\right.}{\left.+\frac{A_{2,m=3}^{(n)}(k,\mu^{2})}{A_{3,m=3}^{(n)}(k,\mu^{2})}\right]S\left[\left((\Delta_{\mu}E_{\mu_{1}}-E_{\mu}\Delta_{\mu_{1}})\left(\Delta_{\nu}E'^{*}_{\mu_{2}}-E'^{*}_{\nu}P_{\mu_{2}}\right)\Delta_{\mu_{3}}\dots\Delta_{\mu_{m-1}}P_{\mu_{m}}\dots P_{\mu_{n}}\right] \\
&\quad + \frac{A_{3,m=3}^{(n)}(k,\mu^{2})}{A_{3,m=3}^{(n)}(k,\mu^{2})}\right]S\left[\left((E_{\mu}E'^{*}_{\mu_{1}}-E_{\mu}\Delta_{\mu_{1}})\left(P_{\nu}E'^{*}_{\mu_{2}}-P_{\nu}^{*}P_{\mu_{2}}\right)-(\Delta_{\mu}E'^{*}_{\mu_{1}}-E'^{*}_{\mu}\Delta_{\mu_{1}})\left(P_{\nu}E_{\mu_{2}}-E_{\nu}P_{\mu_{2}}\right)\right) \\
&\quad + \frac{A_{3,m=3}^{(n)}(k,\mu^{2})}{M^{2}}S\left[\left((E_{\mu}E'^{*}_{\mu_{1}}-E_{\mu_{1}}E'^{*}_{\mu})(P_{\nu}\Delta_{\mu_{2}}-P_{\mu_{2}}\Delta_{\nu})\Delta_{\mu_{3}}\dots\Delta_{\mu_{m-1}}P_{\mu_{m}}\dots P_{\mu_{n}}\right] \\
&\quad + \frac{A_{3,m=3}^{(n)}(k,\mu^{2})}{M^{
$$

- Complicated over and under-determined systems of equations (different choices of polarisation and boost at same momentum transfer)
- Some GFFs suppressed by orders of magnitude
- Some GFFs related by symmetries at some momenta

 $\sqrt{ }$ BB@ 0*.*604 0*.*0424 0 0 0 0 0*.*0588 0 0.592 -2.45×10^{-3} 0.0785 -0.0785 6.58×10^{-3} -0.0992 -0.103 -4.15×10^{-3} 0*.*485 0*.*0429 0 0 0 0 0*.*0379 0 0.481 0.0431 -3.02×10^{-5} 3.02×10^{-5} -2.53×10^{-6} -4.03×10^{-7} 0.0374 -1.69×10^{-8} 0.475 -3.29×10^{-3} 0.0791 -0.0791 6.59×10^{-3} -0.0791 -0.0824 -3.29×10^{-3} 0.353 -7.97×10^{-4} 0.0385 -0.0385 3.28×10^{-3} -0.0598 -0.0631 -2.54×10^{-3} 0*.*347 0*.*0382 0 0 0 0 0*.*0962 0 0*.*258 0*.*0806 0 0 0 0 0*.*0374 0 0*.*258 0*.*0808 0 0 0 0 0*.*0379 0 0.253 0.101 -8.60×10^{-4} 8.60×10^{-4} -7.20×10^{-5} 6.32×10^{-7} -0.0588 2.65×10^{-8} 0.253 0.101 -8.60×10^{-4} 8.60×10^{-4} -7.20×10^{-5} 6.32×10^{-7} -0.0588 2.65×10^{-8}
 0.239 -1.66×10^{-3} 0.0401 -0.0401 3.29×10^{-3} -0.0393 -0.0402 -1.61×10^{-3}
 0.238 -1.65×10^{-3} 0.238 -1.65×10^{-3} 0.0396 -0.0396 3.29×10^{-3} -0.0396 -0.0412 -1.65×10^{-3} 0.228 -0.0581 8.30×10^{-4} -8.30×10^{-4} 6.94×10^{-5} -1.04×10^{-6} 0.0962 -4.33×10^{-8} 0*.*228 0*.*0379 0 0 0 0 0*.*0758 0 0.0590 -0.0109 0.139 -0.139 0.0112 -4.97×10^{-3} -3.94×10^{-4} -8.24×10^{-6} 0.0578 -2.56×10^{-4} 9.42×10^{-3} -9.42×10^{-3} 3.89×10^{-4} -4.65×10^{-3} 2.51×10^{-4} 5.25×10^{-6} 0.0338 1.59×10^{-3} -0.128 0.128 -0.0107 3.18×10^{-4} 0.0154 1.33×10^{-5} 0.0183 6.36×10^{-3} -1.29×10^{-4} 1.29×10^{-4} 3.84×10^{-4} 4.84×10^{-3} 5.99×10^{-3} 5.18×10^{-6} $\begin{array}{cccccccc} 0.0155 & -4.78 \times 10^{-3} & -0.128 & 0.128 & -0.0111 & -4.52 \times 10^{-3} & 9.41 \times 10^{-3} & 8.14 \times 10^{-6} \\ 1.19 \times 10^{-3} & -0.0106 & 0.129 & -0.129 & 0.0108 & -3.22 \times 10^{-4} & -6.45 \times 10^{-4} & -1.35 \times 10^{-5} \end{array}$ 1.19×10^{-3} -0.0106 0.129 -0.129 0.0108 -3.22×10^{-4} -6.45×10^{-4} -1.35×10^{-5} 0.549 2.44×10^{-3} 0 0 0 0 0.0895 0 $\begin{array}{cccccccc} 0.549 & & 2.44 \times 10^{-3} & & 0 & & 0 & & 0 & & 0.0895 & & 0 \\ 0.546 & & -1.88 \times 10^{-3} & & 0.0676 & & -0.0676 & & 5.69 \times 10^{-3} & & -0.0918 & & -0.0960 & & -3.86 \times 10^{-3} \\ 0.498 & & 0.0710 & & 0 & & 0 & & 0 & & 0.0123 & & 0 \end{array}$ 0*.*498 0*.*0710 0 0 0 0 0*.*0123 0 0.480 -2.37×10^{-3} 0.0685 -0.0685 5.70×10^{-3} -0.0799 -0.0828 -3.33×10^{-3}
 0.429 0.0714 0 0 0 0*.*429 0*.*0714 0 0 0 0 0 0 0.424 0.0834 -5.14×10^{-4} 5.14×10^{-4} -4.30×10^{-5} 1.33×10^{-7} -0.0123 5.55×10^{-9} 0.412 2.85×10^{-3} 0 0 0 0 0 0.0657 0 0.412 -2.85×10^{-3} 0.0685 -0.0685 5.70×10^{-3} -0.0685 -0.0714 -2.85×10^{-3} 0.409 -8.65×10^{-3} 4.61×10^{-4} -4.61×10^{-4} 3.86×10^{-5} -8.30×10^{-7} 0.0771 -3.47×10^{-8} 0.0674 -6.43×10^{-3} 0.0856 -0.0856 6.70×10^{-3} -5.55×10^{-3} -8.26×10^{-5} -1.73×10^{-6} 0.0656 4.96×10^{-4} -9.21×10^{-4} 9.21×10^{-4} -6.37×10^{-6} -0.0119 -0.0132 -5.32×10^{-4} 0*.*0514 0*.*0685 0 0 0 0 0*.*0771 0 0.0347 -0.0124 0.155 -0.155 0.0127 -3.05×10^{-3} -6.00×10^{-4} -1.26×10^{-5} 0.0327 5.99×10^{-3} -0.0692 0.0692 -6.03×10^{-3} -2.50×10^{-3} 5.17×10^{-4} 1.08×10^{-5} 0.0301 4.59×10^{-3} -0.0738 0.0738 -5.95×10^{-3} 2.98×10^{-3} 0.0123 1.07×10^{-5} 0.0285 -1.84×10^{-3} -0.147 0.147 -0.0126 -2.43×10^{-3} 0.0143 1.24×10^{-5} 0*.*0171 0*.*0685 0 0 0 0 0*.*0657 0 0.0146 0.0920 -9.75×10^{-4} 9.75×10^{-4} -8.17×10^{-5} 9.63×10^{-7} -0.0895 4.03×10^{-8} $\frac{1.59 \times 10^{-3}}{6.43 \times 10^{-3}}$ $\frac{-9.75 \times 10^{-4}}{0.0736}$ $\frac{9.75 \times 10^{-4}}{0.0736}$ $\frac{-8.17 \times 10^{-5}}{6.61 \times 10^{-3}}$ $\frac{9.63 \times 10^{-7}}{5.40 \times 10^{-3}}$ $\frac{-0.0895}{-1.97 \times 10^{-3}}$ $\frac{4.03 \times 10^{-8}}{1.71 \times 10^{-6}}$ \setminus CCA $A^{(2)}_{1,0}(1)$ BBBBBBBBBBBBBBBBBBBBB@ $A_{2,0}^{(2)}(1)$ $A_{3,0}^{(2)}(1)$ $A_{4,0}^{(2)}(1)$ $A_{5,0}^{(2)}(1)$ $A_{6,0}^{(2)}(1)$ $A_{7,0}^{(2)}(1)$ $A_{8,0}^{(2)}(1)$ CCCCCCCCCCCCCCCCCCCCCA = $\sqrt{ }$ BBB@ 0*.*179(36) 0*.*150(38) 0*.*152(30) 0*.*154(37) 0*.*129(32) 0*.*056(31) 0*.*067(41) 0*.*056(35) 0*.*069(21) 0*.*093(36) 0*.*028(32) 0*.*041(27) 0*.*012(33) 0*.*029(30) $0.024(11)$ $-0.005(21)$ $-0.0056(96)$ $-0.002(11)$ $0.009(16)$ 0*.*0162(91) 0*.*086(26) 0*.*131(31) 0*.*155(33) 0*.*086(33) 0*.*098(16) 0*.*094(17) 0*.*088(27) 0*.*114(25) 0*.*075(27) 0*.*034(25) $-0.006(22)$ $-0.001(31)$ $0.022(11)$ 0*.*014(16) 0*.*0010(16) 0*.*0008(85) 0*.*018(23) 0*.*001(29) $0.005(18)$

 $\frac{1}{4}$ Simplest example: Transversity GFFs One basis (2 vectors) Mtm I (lattice units)

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CCCA

- Complicated over and under-determined systems of equations (different choices of polarisation and boost at same momentum transfer)
- Some GFFs suppressed by orders of magnitude
- Some GFFs related by symmetries at some momenta

 $\sqrt{ }$ BB@ 0*.*604 0*.*0424 0 0 0 0 0*.*0588 0 0.592 -2.45×10^{-3} 0.0785 -0.0785 6.58×10^{-3} -0.0992 -0.103 -4.15×10^{-3} 0*.*485 0*.*0429 0 0 0 0 0*.*0379 0 0.481 0.0431 -3.02×10^{-5} 3.02×10^{-5} -2.53×10^{-6} -4.03×10^{-7} 0.0374 -1.69×10^{-8} 0.475 -3.29×10^{-3} 0.0791 -0.0791 6.59×10^{-3} -0.0791 -0.0824 -3.29×10^{-3} 0.353 -7.97×10^{-4} 0.0385 -0.0385 3.28×10^{-3} -0.0598 -0.0631 -2.54×10^{-3} 0*.*347 0*.*0382 0 0 0 0 0*.*0962 0 0*.*258 0*.*0806 0 0 0 0 0*.*0374 0 0*.*258 0*.*0808 0 0 0 0 0*.*0379 0 0.253 0.101 -8.60×10^{-4} 8.60×10^{-4} -7.20×10^{-5} 6.32×10^{-7} -0.0588 2.65×10^{-8} $\begin{array}{ccccccccc} 0.253 & 0.101 & -8.60 \times 10^{-4} & 8.60 \times 10^{-4} & -7.20 \times 10^{-5} & 6.32 \times 10^{-7} & -0.0588 & 2.65 \times 10^{-8} \ 0.239 & -1.66 \times 10^{-3} & 0.0401 & -0.0401 & 3.29 \times 10^{-3} & -0.0393 & -0.0402 & -1.61 \times 10^{-3} \ 0.238 & -1.65 \times 10^{-3} & 0.0396 & -0.0396 &$ 0.238 -1.65×10^{-3} 0.0396 -0.0396 3.29×10^{-3} -0.0396 -0.0412 -1.65×10^{-3}
 0.228 -0.0581 8.30×10^{-4} -8.30×10^{-4} 6.94×10^{-5} -1.04×10^{-6} 0.0962 -4.33×10^{-8} 0.228 -0.0581 8.30×10^{-4} -8.30×10^{-4} 6.94×10^{-5} -1.04×10^{-6} 0.0962 -4.33×10^{-8} 0*.*228 0*.*0379 0 0 0 0 0*.*0758 0 0.0590 -0.0109 0.139 0.0139 **0** 0.0119 0.07×10^{-3} 2.04×10^{-4} 8.94×10^{-6} ⁰*.*⁰⁵⁷⁸ 2*.*⁵⁶ ⇥ ¹⁰⁴ ⁹*.*⁴² ⇥ ¹⁰³ 9*.*⁴² ⇥ ¹⁰³ ³*.*⁸⁹ ⇥ ¹⁰⁴ 4*.*⁶⁵ ⇥ ¹⁰³ ²*.*⁵¹ ⇥ ¹⁰⁴ ⁵*.*²⁵ ⇥ ¹⁰⁶ 0.0338 1.59 103 0.0128 1.59 103 103 104 128 104 104 104 105 104 105 11.012 0.0183 6.36 **A.29 A.29 A.29 T.1 T.1 104 261 d. SUDS61 OI**. UOIT $0.0155 \t -4.78 \times 10^{-3} \t 0.128$ 0.128 1.19×10^{-3} -0.0106 0.129 **0.129** 0.549 2.44×10^{-3} 0 0 0 0 0.0895 0 $\begin{array}{cccccccc} 0.549 & & 2.44 \times 10^{-3} & & 0 & & 0 & & 0 & & 0.0895 & & 0 \\ 0.546 & & -1.88 \times 10^{-3} & & 0.0676 & & -0.0676 & & 5.69 \times 10^{-3} & & -0.0918 & & -0.0960 & & -3.86 \times 10^{-3} \\ 0.498 & & 0.0710 & & 0 & & 0 & & 0 & & 0.0123 & & 0 \end{array}$ 0*.*498 0*.*0710 0 0 0 0 0*.*0123 0 0.480 -2.37×10^{-3} 0.0685 -0.0685 5.70×10^{-3} -0.0799 -0.0828 -3.33×10^{-3}
 0.429 0.0714 0 0 0 0*.*429 0*.*0714 0 0 0 0 0 0 0.424 0.0834 -5.14×10^{-4} 5.14×10^{-4} -4.30×10^{-5} 1.33×10^{-7} -0.0123 5.55×10^{-9} 0.412 2.85×10^{-3} 0 0 0 0 0 0.0657 0 0.412 -2.85×10^{-3} 0.0685 -0.0685 5.70×10^{-3} -0.0685 -0.0714 -2.85×10^{-3} 0.409 -8.65×10^{-3} 4.61×10^{-4} -4.61×10^{-4} 3.86×10^{-5} -8.30×10^{-7} 0.0771 -3.47×10^{-8} 0.0674 -6.43×10^{-3} 0.0856 -0.0856 6.70×10^{-3} -5.55×10^{-3} -8.26×10^{-5} -1.73×10^{-6} 0.0656 4.96×10^{-4} -9.21×10^{-4} 9.21×10^{-4} -6.37×10^{-6} -0.0119 -0.0132 -5.32×10^{-4} 0*.*0514 0*.*0685 0 0 0 0 0*.*0771 0 0.0347 -0.0124 0.155 -0.155 0.0127 -3.05×10^{-3} -6.00×10^{-4} -1.26×10^{-5} 0.0327 5.99×10^{-3} -0.0692 0.0692 -6.03×10^{-3} -2.50×10^{-3} 5.17×10^{-4} 1.08×10^{-5} 0.0301 4.59×10^{-3} -0.0738 0.0738 -5.95×10^{-3} 2.98×10^{-3} 0.0123 1.07×10^{-5} 0.0285 -1.84×10^{-3} -0.147 0.147 -0.0126 -2.43×10^{-3} 0.0143 1.24×10^{-5} 0*.*0171 0*.*0685 0 0 0 0 0*.*0657 0 0.0146 0.0920 -9.75×10^{-4} 9.75×10^{-4} -8.17×10^{-5} 9.63×10^{-7} -0.0895 4.03×10^{-8} $\frac{1.59 \times 10^{-3}}{6.43 \times 10^{-3}}$ $\frac{-9.75 \times 10^{-4}}{0.0736}$ $\frac{9.75 \times 10^{-4}}{0.0736}$ $\frac{-8.17 \times 10^{-5}}{6.61 \times 10^{-3}}$ $\frac{9.63 \times 10^{-7}}{5.40 \times 10^{-3}}$ $\frac{-0.0895}{-1.97 \times 10^{-3}}$ $\frac{4.03 \times 10^{-8}}{1.71 \times 10^{-6}}$ \setminus CCA $\sqrt{ }$ $\begin{bmatrix} 1 \\ 2 \end{bmatrix}$ $A^{(2)}(1)$ *^A*(2) ²*,*0(1) *^A*(2) ³*,*0(1) ⁴*,*0(1) $A_{5,0}^{(2)}(1)$ $A_{6,0}^{(2)}(1)$ $A_{7,0}^{(2)}(1)$ $A_{8,0}^{(2)}(1)$ $\overline{}$ \mathcal{L} \mathbb{R}^2 $\sqrt{ }$ |
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|
| 0*.*179(36) 0*.*150(38) 0*.*152(30) 0*.*154(37) 0*.*129(32) 0*.*056(31) 0*.*067(41) 0*.*056(35) 0*.*069(21) 0*.*093(36) 0*.*028(32) 0*.*041(27) 0*.*012(33) 0*.*029(30) \cap Γ \subset 0*.*0056(96) Target a subset of "dominant GFFs" 0*.*0162(91) 0*.*086(26) 0*.*131(31) 0*.*155(33) 0*.*086(33) 0*.*098(16) 0*.*094(17) 0*.*088(27) 0*.*114(25) 0*.*075(27) 0*.*034(25) $-0.006(22)$ $-0.001(31)$ $0.022(11)$ 0*.*014(16) 0*.*0010(16) 0*.*0008(85) 0*.*018(23) 0*.*001(29) $0.005(18)$ \setminus CCCA

 $\frac{1}{4}$ Simplest example: Transversity GFFs One basis (2 vectors) Mtm I (lattice units)

Example:

Spin-indep GFFs, lowest non-zero momentum transfer

- Projection into planes of dominant GFFs
- Others set to 0 ± 10
- Only tightly-constrained bands shown in each projection.

Gluon Transversity GFFs

W. Detmold, PES, PRD 94 (2016), 014507 + W. Detmold, D. Pefkou, PES PRD 95 (2017), 114515

One GFF can be resolved for all momenta

Spin-Indep. Gluon GFFs

W. Detmold, PES, PRD 94 (2016), 014507 + W. Detmold, D. Pefkou, PES PRD 95 (2017), 114515

Three GFFs can be resolved for all momenta

Spin-Indep. Quark GFFs

W. Detmold, PES, PRD 94 (2016), 014507 + W. Detmold, D. Pefkou, PES PRD 95 (2017), 114515

Three GFFs can be resolved for all momenta

GFF decomposition has precisely the same structure as in the spinindependent gluon case

Quark and Gluon GFFs

Ratio of gluon to quark unpolarised GFFs

Gluon vs quark radius is a non-trivial question Much more complicated than intuitive pictures

Gluon Structure from LQCD

How is the gluon structure of a proton modified in a nucleus

Gluonic 'EMC' effect ^o 'Exotic' glue

Glue structure of nuclei

First investigations:

ϕ meson simplest spin-1 system (has fwd limit gluon transversity)

Phenomenologically relevant: nucleon, nuclei

teraction with coupling strength a and α = Q^2 α = Q^2 longitudinal nucleon momentum carried by the struck quark, in a frame where the nucleon moves with infinite momentum in the direction opposite to the virtual photon. The virtual photon of the virtual photon Gluon structure - nuclei

x and z² Collaboration (1983):

cross section of nucleons Modification of per-nucleon bound in nuclei

Precise understanding of nuclear extraction of neutrino mass hierarchy, mixing parameters

At leading order in QCD the structure function F² is defined as the sum of the momentum and and and and and and and and and R atio of structure function F₂ per q, where an is the mucleon for iron and deuterium European Muon

nucleon for iron and deuterium

approximate and approximate the EMC effect? ic giubine analogue di uie en le eneed. What is the gluonic analogue of the EMC effect?

Nuclear glue, m_{π} ~450 MeV

NPLQCD Collaboration, arXiv:1709.00395

Signals for spin-independent gluon operator in deuteron

Gluon momentum fraction

NPLQCD Collaboration, arXiv:1709.00395

- Matrix elements of the Spin-independent gluon operator in nucleon and light nuclei
- Present statistics: can't distinguish from no-EMC effect scenario
- Small additional uncertainty from mixing with quark operators

Double Helicity Flip Gluon Structure Function: (*x, Q*²) Gluonic Transversity ² *, n* = 2*,* ⁴*,* ⁶ *...,* (11) where *Aⁿ* is renormalized at the scale *µ*² = *Q*², and \mathbf{r} 450 meV and the strange quark mass is such that the strange quark mass is such that the strange \sim resulting mass of the is 1040(3) MeV.

Parto and Manohar "N e and Manohar, "Nuclear Double helicity flip structure function $\Delta(x,Q^2)$ *^Mn*(*Q*²) = ^Z ¹ r *dxxⁿ*¹(*x, Q*²) (12) ad Manobar "Nuclear Gluonom" Jaffe and Manohar,"Nuclear Gluonometry" Phys. Lett. B223 (1989) 218

Double Helicity Flip Gluon Structure Function: (*x, Q*²)

• Hadrons: Gluonic Transversity (parton model interpretation) For a target in the infinite momentum frame polarized in the *x*ˆ direction **o**¹**11**</sup> momentum (defined to be interesting to be in the second of θ

$$
\Delta(x, Q^2) = -\frac{\alpha_s(Q^2)}{2\pi} \text{Tr} Q^2 x^2 \int_x^1 \frac{dy}{y^3} \left[g_{\hat{x}}(y, Q^2) - g_{\hat{y}}(x, Q^2) \right]
$$

'Exotic' Glue in the Nucleus in the Nucleu $g_{\hat{x},\hat{y}}(y,Q^2)$: probability of finding a gluon with momentum fraction y linearly **linearly polarised in** \hat{x} , \hat{y} direction $\frac{1}{2}$ α dimension under renormalization (this operator mixes α intraction y linearly four-

O Nuclei: Exotic Glue (plane) per a **l** a b y c b c d u

Phiala Shanahan (MIT) Exotic Glue in the Nucleus July 8, 2016 8 / 23 in nucleus \mathcal{P}_max . The Nucleus Shanahan (MIT) Exotic Glue in the Nucleus July 8, 2016 8 \mathcal{P}_max gluons not associated with individual nucleons transversels polarized target.
Transverselselsel

CICI: EXOTIC GJUE

\n
$$
\langle p|O|p\rangle = 0
$$
\nAns not associated

\n
$$
\langle N, Z|O|N, Z\rangle \neq 0
$$
\nindividual nuclears

Non-nucleonic Glue in Deuteron

NPLQCD Collaboration, arXiv:1709.00395 Ratio of 3pt and 2pt functions

First moment of gluon transversity distribution in the deuteron, m_" ~800 MeV

- First evidence for non-nucleonic gluon contributions to nuclear structure
- Magnitude relative to momentum fraction as expected from large-Nc

Gluon structure circa 2025

- Electron-Ion collider will dramatically alter our knowledge of the gluonic structure of hadrons and nuclei
	- Work towards a complete 3D picture of parton structure (moments, x-dependence of PDFs, GPDs, TMDs)
	- $\Delta(\!\times\! ,\!Q^2)$ has an interesting role

Purely gluonic

Non-nucleonic: directly probe nuclear effects

- Compare quark and gluon distributions in hadrons and nuclei
- Lattice QCD calculations in hadrons and light nuclei will complement and extend understanding of fundamental structure of nature