# Overview and perspective: theory

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Tensor Polarized observables
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# Tensor polarization

- Present for particles with spin $\geq 1$
- Not present for the nucleon
- Additional spin degrees of freedom that can be exploited in polarized measurements
  → more ways of looking at a system
- Focus is on spin 1 (massive)
  - Deuteron
  - Vector mesons
- Link between spin-1 and partonic properties
- Studies of NN-force

# Deuteron

- Only stable 2 nucleon system (pn)
- Small binding energy ~2 MeV
- $J^{\pi} = 1^{+}$, isospin 0 $\rightarrow$ L = 0,2
- $\frac{\mu_d - \mu_p - \mu_n}{\mu_d} = -0.026$
  $\rightarrow$ S-wave (L=0) dominates
- Quadrupole moment 0.282 $fm^2$
  $\rightarrow$ needs D-wave (L=2)
  $\rightarrow$ non-central (tensor) NN-force

**An Electrical Quadrupole Moment of the Deuteron***

Columbia University,
Hunter College (JRZ),
New York, New York,
January 15, 1939.

J. M. B. KELLOGG
I. I. RABI
N. F. RAMSEY, JR.
J. R. ZACHARIAS

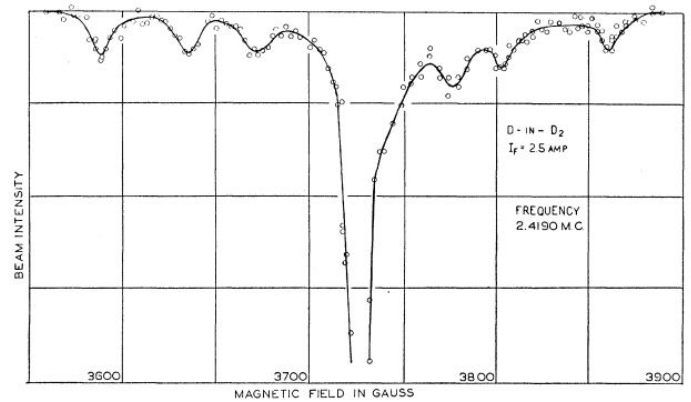



FIG. 2. Resonance minima for D in $D_2$.

# Density matrix

- Characterizes statistical ensemble of quantum system
- 3 by 3 matrix for spin-1 system
- Multipole decomposition: 5 tensor

$$\rightarrow 1 \otimes 1 = 0 \oplus 1 \oplus 2$$

- Expectation values

$$\langle O \rangle = \sum_{\lambda\lambda'} \rho_{\lambda\lambda'} \langle \lambda' | O | \lambda \rangle$$

$$\rho(\lambda,\lambda') = \begin{bmatrix} \frac{1}{3} + \frac{1}{2}S_L + \frac{1}{2}T_{LL} & \frac{1}{2\sqrt{2}}S_T e^{-i(\phi_h-\phi_S)} + \frac{1}{\sqrt{2}}T_{LT}e^{-i(\phi_h-\phi_{T_L})} & \frac{1}{2}T_{TT}e^{-i(2\phi_h-2\phi_{T_T})} \\ \frac{1}{2\sqrt{2}}S_T e^{i(\phi_h-\phi_S)} + \frac{1}{\sqrt{2}}T_{LT}e^{i(\phi_h-\phi_{T_L})} & \frac{1}{3} - T_{LL} & \frac{1}{2\sqrt{2}}S_T e^{-i(\phi_h-\phi_S)} - \frac{1}{\sqrt{2}}T_{LT}e^{-i(\phi_h-\phi_{T_L})} \\ \frac{1}{2}T_{TT}e^{i(2\phi_h-2\phi_{T_T})} & \frac{1}{2\sqrt{2}}S_T e^{i(\phi_h-\phi_S)} - \frac{1}{\sqrt{2}}T_{LT}e^{i(\phi_h-\phi_{T_L})} & \frac{1}{3} - \frac{1}{2}S_L + \frac{1}{2}T_{LL} \end{bmatrix}.$$

- Polarization measurements
- All pure states have tensor polarization
- λ = 0 has no vector polarization

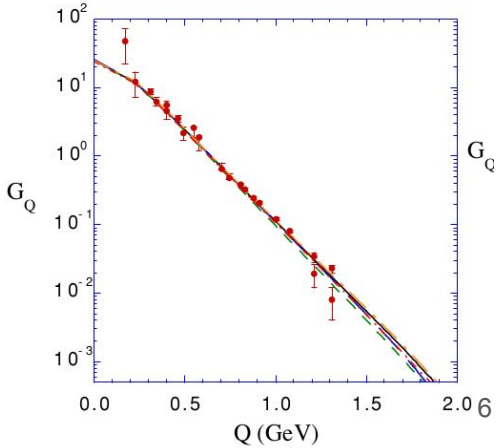
# Tensor asymmetries

- Density matrix parameters appear in cross section decomposition
  → multiply independent structure functions
  → much richer structure for spin 1 compared to nucleon
  → harder to disentangle experimentally
- $d\sigma^+ + d\sigma^- - 2d\sigma^0$ will select tensor polarized contributions
  → no electron polarization needed
  → normalized to unpolarized cross section: $A_{zz}$, $T_{20}$
- Polarized along a certain direction
  → different directions will select different $T_{LL}$, $T_{LT}$, $T_{TT}$ etc.

# Hadronic matrix elements

$$\langle d'|J^\mu|d\rangle = -\left(\left\{G_1(Q^2)[\xi'^* \cdot \xi] - G_3(Q^2)\frac{(\xi'^* \cdot q)(\xi \cdot q)}{2m_d^2}\right\}(d^\mu + d'^\mu) + G_M(Q^2)[\xi^\mu(\xi'^* \cdot q) - \xi'^{*\mu}(\xi \cdot q)]\right)$$

- quark/gluon currents & correlators → form factors & parton distribution functions
- Operators still the same → same QCD evolution etc.
- Tensor polarization → richer structure of independent structures
- Quadrupole formfactor from elastic ed
- Probed in (semi)inclusive DIS, exclusive reactions with polarized deuteron
  - → global fits
  - → model calculations



# Inclusive DIS: b1 [See talk Kumano]

**NOVEL EFFECTS IN DEEP INELASTIC SCATTERING FROM SPIN-ONE HADRONS[1]**

Pervez HOODBHOY[2], R.L. JAFFE and Aneesh MANOHAR[3]

$$W_{\mu\nu} = -F_1 g_{\mu\nu} + F_2 \frac{p_\mu p_\nu}{\nu} - b_1 r_{\mu\nu} + \tfrac{1}{6} b_2 (s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu}) + \tfrac{1}{2} b_3 (s_{\mu\nu} - u_{\mu\nu})$$

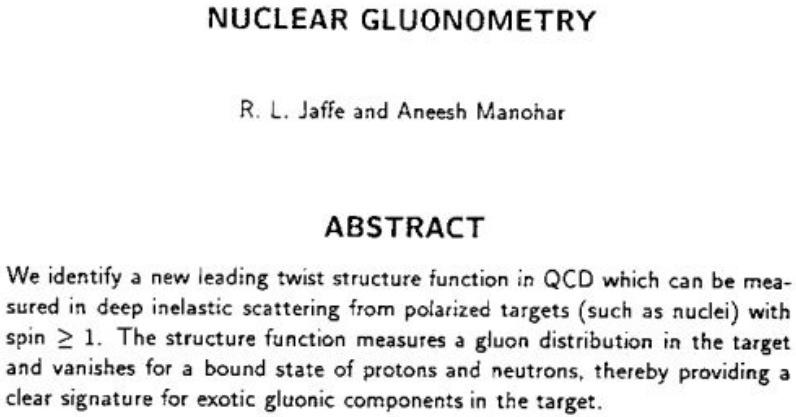
$$+ \tfrac{1}{2} b_4 (s_{\mu\nu} - t_{\mu\nu}) + i \frac{g_1}{\nu} \epsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + i \frac{g_2}{\nu^2} \epsilon_{\mu\nu\lambda\sigma} q^\lambda (p \cdot q s^\sigma - s \cdot q p^\sigma),$$

- b1 is a **structure function**
- at LO charge weighted tensor polarized pdf
  → difference of unpolarized quark distribution between $\lambda = \mp 1$ and $\lambda = 0$
- Kumano-Close sum rule
- Hermes data (puzzle?), upcoming JLab
- Tensor asymmetry still measures combination of 4 SF [See talk Zec]

$$A_{zz} = 2 \frac{[T_{LL}](\Lambda_d = +1)(F_{UT_{LL},T} + \epsilon F_{UT_{LL},L} + [T_{LT} \cos\phi_{T_L}](\Lambda_d = +1)\sqrt{2\epsilon(1+\epsilon)} F_{UT_{LT}}^{\cos\phi_{T_L}} + [T_{TT} \cos 2\phi_{T_T}](\Lambda_d = +1)\epsilon F_{UT_{TT}}^{\cos 2\phi_{T_T}}}{F_{UU,T} + \epsilon F_{UU,L}}$$

# Gluon transversity pdf [See talk Maxwell]

- Gluon helicity flip → impossible in nucleon
- Has to probe gluons beyond single-nucleon level
- But resides in twist-4 SF
- Lattice study for $\phi$ meson (moment)
  [Detmold, Shanahan PRD'16]
- Recent work on DY
  [Kumano, QT Song PRD'20 ]



NUCLEAR GLUONOMETRY

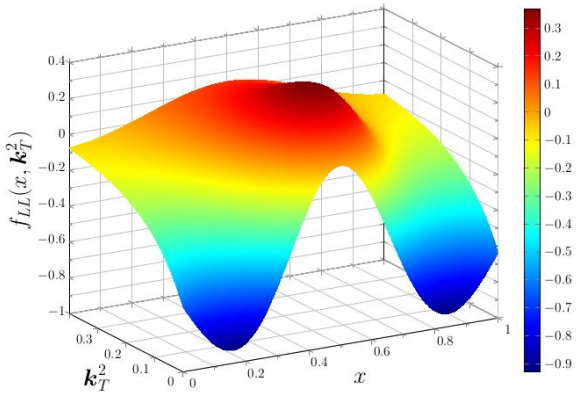
R. L. Jaffe and Aneesh Manohar

ABSTRACT

We identify a new leading twist structure function in QCD which can be measured in deep inelastic scattering from polarized targets (such as nuclei) with spin $\geq 1$. The structure function measures a gluon distribution in the target and vanishes for a bound state of protons and neutrons, thereby providing a clear signature for exotic gluonic components in the target.

# Spin-1 Transverse momentum distributions

- First discussed for quarks at leading twist by Bacchetta & Mulders (2000)
  → gluons D. Boer et al. JHEP 2016
- Recently extended to twist 4 [Kumano & Q.T. Song JHEP 2021]
- SIDIS and Drell-Yann (NICA, Spinquest) measurements
- Several model calculations for rho meson
  - NJL [Ninoyima, Bentz, Cloet PRC '17]
  - LF holographic [C. Mondal et al]



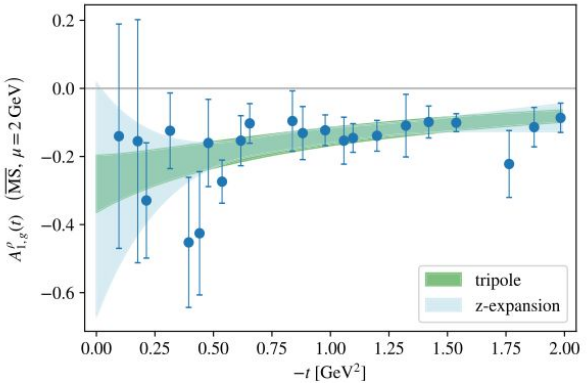
# Generalized Parton Distributions

- Leading twist [Berger et al PRL'04; Cosyn, Pire PRD'18]

- Spin sum rule [Abidin, Carlson PRD'08; Taneja, Liuti et al. PRD'12]
  and Energy-Momentum tensor [+ Holstein PRD'06, Cotogno et al EPJC '19]

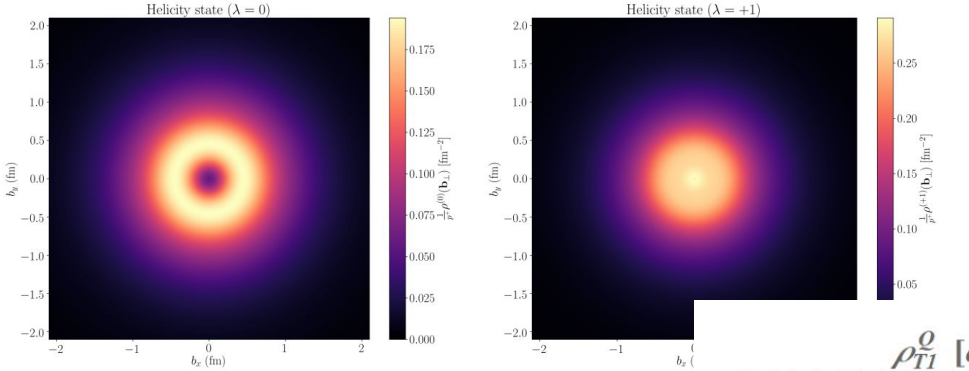
- Extract from coherent exclusive reactions
  → few Hermes data, JLab possibilities

- Lattice study of gluon GravFF in ϕ-meson
  [Detmold, Pefkou, Shanahan, Hackett 17+]
  NJL calculations for rho-meson GravFF
  [Freese, Cloet, PRC'19]

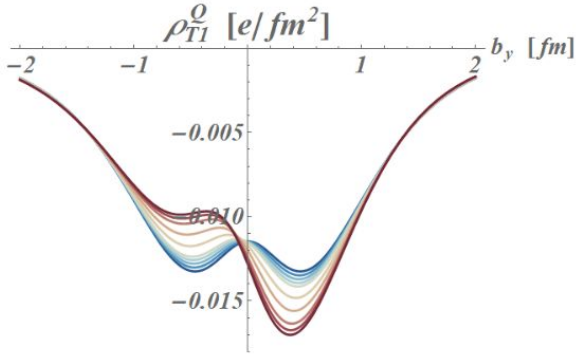


# Transverse densities

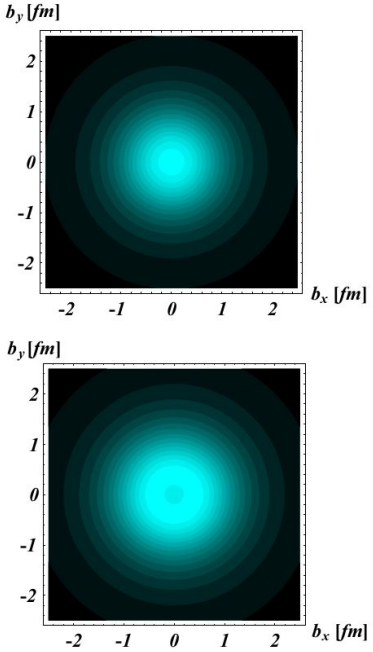
- Obtained from FT of form factors (EM, gravitational)




[Freese, Cosyn PRD'22]




[Lorce, Wang, '23]




[Carlson, VdHaeghen EPJA'08]

# Model calculations

- EM form factors [See reviews Garcon, Van Orden ‘01; Gilman, Gross ‘02]
- Only spin-1 precision data set that has tensor pol. data
- Many models, with different approaches, challenging calculations
  - Need for relativistic treatment
  - Substantial differences from how relativistic effects are included or mesonic contributions
  - Light-front treatments need to impose angular conditions
- How to reach same level / avoid pitfalls for other observables

# NN-force [Frankfurt, Strikman NPA'83]

- Tensor/unpol: currents couple similarly to nucleon
- Tensor asymmetry mainly sensitive to deuteron structure
- Probes wf bilinear proportional to D-wave
- Test different deuteron wf, dynamics
  → short-range NN force
  → non-nucleonic dof?

⇒ Talks Strikman, Sargsian

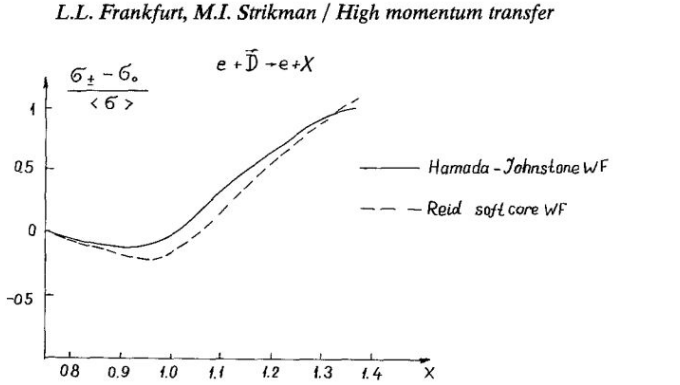
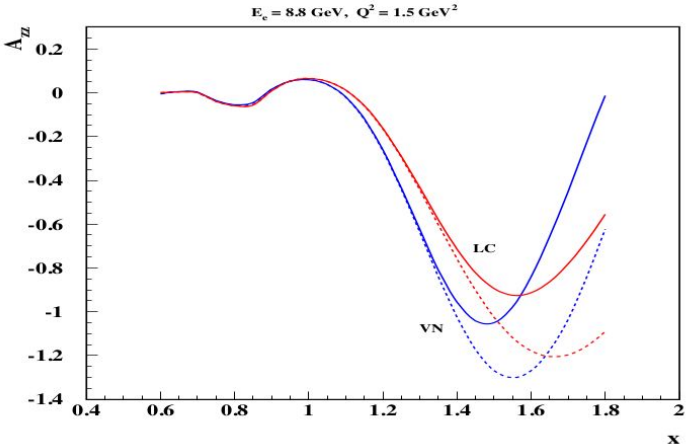



Fig. 3. The dependence of $F^{\xi}_{2D}(x, q^2)$ on the deuteron polarization.




[Sargsian, Strikman '14]

# Beyond Inclusive observables

- Spectator tagged DIS
  - Restriction on initial state, no averaging over all configurations

    → sizeable tensor asymmetry in tagged DIS [talk Weiss]

- Quasi-elastic D(e,e'N) : many reaction frameworks
  - Polarization observables very sensitive to model inputs

    ⇒ Talks Yero, Jeschonnek; see also recent Flores, Chabysheva, Hiller PRC23
    Grassi, Golak et al. PRC22

- Need to include (spin-dependent) FSI

# Conclusions

- Tensor polarized observables give access to properties of hadrons beyond beyond spin ½ case

- Proliferation of observables / distribution
  → Important for theory to identify connection between the two
  → Corrections from theory

- Beyond EM FF: few data, some calculations
  → new data can lead to renewed interest

- Deuteron especially interesting as system to study NN interaction