Spin physics with a polarized deuteron

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Exposing Novel Quark and Gluon Effects in Nuclei
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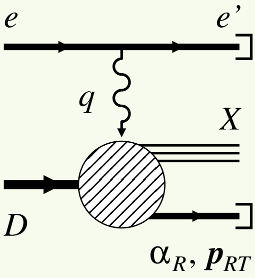
Outline

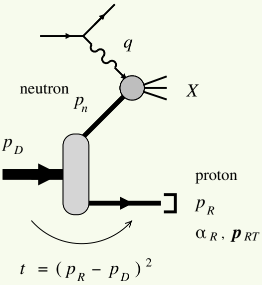
- Tagged spectator DIS with a polarized deuteron
  `WC, M. Sargsian, Ch. Weiss, in preparation`
- Inclusive DIS with tensor polarized deuteron
  `WC, Y. Dong, S. Kumano, M. Sargsian, PRD95 074036 ('17)`
- Transversity GPDs for the deuteron
  `WC, B. Pire, in preparation`

Tagged spectator DIS process with deuteron



- DIS off a nucleus target with a slow (relative to nucleus c.m.) nucleon detected in the final state
- Control nuclear configuration
- Advantages for the deuteron
  - simple *NN* system, non-nucleonic ($\Delta\Delta$) dof suppressed
  - active nucleon identified
  - recoil momentum selects nuclear configuration (medium modifications)
  - limited possibilities for nuclear FSI, calculable
- Wealth of possibilities to study (nuclear) QCD dynamics
- Will be possible in a wide kinematic range @ EIC (**polarized**)
- Suited for colliders: no target material, forward detection, transverse pol.
  fixed target CLAS BONuS limited to recoil momenta $\sim$ 70 MeV

Pole extrapolation for on-shell nucleon structure



- Allows to extract free neutron structure in a **model independent** way
  - Recoil momentum p_R controls off-shellness of neutron $t' \equiv t - m_N^2$
  - Free neutron at pole $t - m_N^2 \to 0$: "on-shell extrapolation"
  - Small deuteron binding energy results in small extrapolation length
  - Eliminates nuclear binding and FSI effects `[Sargsian,Strikman PLB '05]`
- D-wave suppressed at on-shell point → neutron ∼ 100% polarized
- Precise measurements of neutron (spin) structure at an EIC

What is needed?

- Theoretical Formalism
  - General expression of SIDIS for a polarized spin 1 target
    - Tagged spectator DIS is SIDIS in the target fragmentation region

$$\vec{e} + \vec{\vec{T}} \rightarrow e' + X + h$$

  - Dynamical model to express structure functions of the reaction
    - First step: impulse approximation (IA) model
    - FSI corrections (unpolarized)
  - Light-front structure of the deuteron
    - Natural for high-energy reactions as **off-shellness of nucleons** in LF quantization remains **finite**

Polarized spin 1 particle

- Spin state described by a 3*3 density matrix in a basis of spin 1 states polarized along the collinear virtual photon–target axis

$$W_D^{\mu\nu} = Tr[\rho_{\lambda\lambda'} W^{\mu\nu}(\lambda'\lambda)]$$

- Characterized by 3 **vector** and 5 **tensor** parameters

$$S^\mu = \langle \hat{W}^\mu \rangle , \qquad T^{\mu\nu} = \frac{1}{2}\sqrt{\frac{2}{3}}\langle \hat{W}^\mu \hat{W}^\nu + \hat{W}^\nu \hat{W}^\mu + \frac{4}{3}\left(g^{\mu\nu} - \frac{\hat{P}^\mu \hat{P}^\nu}{M^2} \right) \rangle$$

- Split in longitudinal and transverse components

$$\rho_{\lambda\lambda'} = \frac{1}{3}\begin{bmatrix} 1 + \frac{3}{2}S_L + \sqrt{\frac{3}{2}}T_{LL} & \frac{3}{2\sqrt{2}}S_T e^{-i(\phi_h-\phi_S)} + \sqrt{3}T_{LT}e^{-i(\phi_h-\phi_{T_L})} & \sqrt{\frac{3}{2}}T_{TT}e^{-i(2\phi_h-2\phi_{T_T})} \\ \frac{3}{2\sqrt{2}}S_T e^{i(\phi_h-\phi_S)} + \sqrt{3}T_{LT}e^{i(\phi_h-\phi_{T_L})} & 1-\sqrt{6}T_{LL} & \frac{3}{2\sqrt{2}}S_T e^{-i(\phi_h-\phi_S)} - \sqrt{3}T_{LT}e^{-i(\phi_h-\phi_{T_L})} \\ \sqrt{\frac{3}{2}}T_{TT}e^{i(2\phi_h-2\phi_{T_T})} & \frac{3}{2\sqrt{2}}S_T e^{i(\phi_h-\phi_S)} - \sqrt{3}T_{LT}e^{i(\phi_h-\phi_{T_L})} & 1 - \frac{3}{2}S_L + \sqrt{\frac{3}{2}}T_{LL} \end{bmatrix}.$$

Spin 1 SIDIS: General structure of cross section

- To obtain structure functions, enumerate all possible tensor structures that obey hermiticity and transversality condition ($qW = Wq = 0$)
- Cross section has 41 structure functions,

$$\frac{d\sigma}{dx dQ^2 d\phi_{l'}} = \frac{y^2 \alpha^2}{Q^4(1-\epsilon)} (F_U + F_S + F_T)\, d\Gamma_{P_h},$$

  - U + S part identical to spin 1/2 case [Bacchetta et al. JHEP ('07)]

$$F_U = F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} + \epsilon \cos 2\phi_h F_{UU}^{\cos 2\phi_h} + h\sqrt{2\epsilon(1-\epsilon)} \sin\phi_h F_{LU}^{\sin\phi_h}$$

$$\begin{aligned} F_S = {} & S_L \left[\sqrt{2\epsilon(1+\epsilon)} \sin\phi_h F_{US_L}^{\sin\phi_h} + \epsilon \sin 2\phi_h F_{US_L}^{\sin 2\phi_h}\right] \\ & + S_L h \left[\sqrt{1-\epsilon^2} F_{LS_L} + \sqrt{2\epsilon(1-\epsilon)} \cos\phi_h F_{LS_L}^{\cos\phi_h}\right] \\ & + S_\perp \Big[\sin(\phi_h - \phi_S)\left(F_{US_T,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{US_T,L}^{\sin(\phi_h-\phi_S)}\right) + \epsilon \sin(\phi_h+\phi_S) F_{US_T}^{\sin(\phi_h+\phi_S)} \\ & + \epsilon \sin(3\phi_h - \phi_S) F_{US_T}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)} \left(\sin\phi_S F_{US_T}^{\sin\phi_S} + \sin(2\phi_h - \phi_S) F_{US_T}^{\sin(2\phi_h-\phi_S)}\right)\Big] \\ & + S_\perp h \Big[\sqrt{1-\epsilon^2} \cos(\phi_h - \phi_S) F_{LS_T}^{\cos(\phi_h-\phi_S)} + \\ & \sqrt{2\epsilon(1-\epsilon)} \left(\cos\phi_S F_{LS_T}^{\cos\phi_S} + \cos(2\phi_h - \phi_S) F_{LS_T}^{\cos(2\phi_h-\phi_S)}\right)\Big], \end{aligned}$$

Spin 1 SIDIS: General structure of cross section

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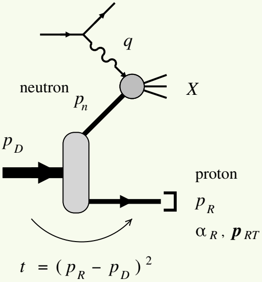
- Cross section has 41 structure functions,

$$\frac{d\sigma}{dxdQ^2 d\phi_{l'}} = \frac{y^2 \alpha^2}{Q^4(1-\epsilon)} (F_U + F_S + F_T)\, d\Gamma_{P_h}\,,$$

  - 23 SF unique to the spin 1 case (tensor pol.), 4 survive in inclusive (b_{1-4}) [Hoodbhoy, Jaffe, Manohar PLB'88]

$$\begin{aligned}
F_T = T_{LL} \Big[& F_{UT_{LL},T} + \epsilon F_{UT_{LL},L} + \sqrt{2\epsilon(1+\epsilon)} \cos\phi_h F_{UT_{LL}}^{\cos\phi_h} + \epsilon \cos 2\phi_h F_{UT_{LL}}^{\cos 2\phi_h} \Big] \\
& + T_{LL} h \sqrt{2\epsilon(1-\epsilon)} \sin\phi_h F_{LT_{LL}}^{\sin\phi_h} \\
& + T_{L\perp}[\cdots] + T_{L\perp} h [\cdots] \\
& + T_{\perp\perp} \Big[\cos(2\phi_h - 2\phi_{T_\perp}) \Big(F_{UT_{TT},T}^{\cos(2\phi_h - 2\phi_{T_\perp})} + \epsilon F_{UT_{TT},L}^{\cos(2\phi_h - 2\phi_{T_\perp})} \Big) \\
& + \epsilon \cos 2\phi_{T_\perp} F_{UT_{TT}}^{\cos 2\phi_{T_\perp}} + \epsilon \cos(4\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(4\phi_h - 2\phi_{T_\perp})} \\
& + \sqrt{2\epsilon(1+\epsilon)} \Big(\cos(\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(\phi_h - 2\phi_{T_\perp})} + \cos(3\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(3\phi_h - 2\phi_{T_\perp})} \Big) \Big] \\
& + T_{\perp\perp} h [\cdots]
\end{aligned}$$

Tagged DIS with deuteron: model for the IA



- Hadronic tensor can be written as a product of nucleon hadronic tensor with deuteron light-front densities

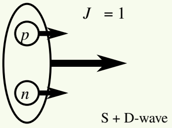
$$W_D^{\mu\nu}(\lambda', \lambda) = 4(2\pi)^3 \frac{\alpha_R}{2 - \alpha_R} \sum_{i=U,z,x,y} W_{N,i}^{\mu\nu} \rho_D^i(\lambda', \lambda)\,,$$

All SF can be written as

$F_{ij}^k = \{\text{kin. factors}\} \times \{F_{1,2}(\tilde{x}, Q^2) \text{or}\, g_{1,2}(\tilde{x}, Q^2)\} \times \{$bilinear forms in deuteron radial wave function $U(k), W(k)\}$

- In the IA the following structure functions are **zero** → sensitive to FSI
  - beam spin asymmetry [$F_{LU}^{\sin\phi_h}$]
  - target vector polarized single-spin asymmetry [8 SFs]
  - target tensor polarized double-spin asymmetry [7 SFs]

Deuteron light-front wave function



- Up to momenta of a few 100 MeV dominated by ***NN*** component
- Can be evaluated in LFQM [Coester,Keister,Polyzou et al.] or covariant Feynman diagrammatic way [Frankfurt,Sargsian,Strikman]

- One obtains a Schrödinger (non-rel) like eq. for the wave function components, rotational invariance recovered
- Light-front WF obeys baryon and momentum sum rule

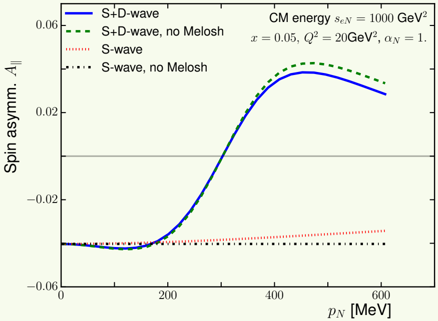
$$\Psi^D_\lambda(\boldsymbol{k}_f,\lambda_1,\lambda_2) = \sqrt{E_{k_f}} \sum_{\lambda'_1\lambda'_2} \mathcal{D}^{\frac{1}{2}}_{\lambda_1\lambda'_1}[R_{fc}(k^\mu_{1f}/m_N)]\mathcal{D}^{\frac{1}{2}}_{\lambda_2\lambda'_2}[R_{fc}(k^\mu_{2f}/m_N)]\Phi^D_\lambda(\boldsymbol{k}_f,\lambda'_1,\lambda'_2)$$

- Differences with non-rel wave function:
  - appearance of the **Melosh rotations** to account for light-front quantized nucleon states
  - $\boldsymbol{k}_f$ is the relative 3-momentum of the nucleons in the light-front boosted rest frame of the free 2-nucleon state (so not a "true" kinematical variable)

Polarized structure function

On-shell extrapolation of double spin asymm.

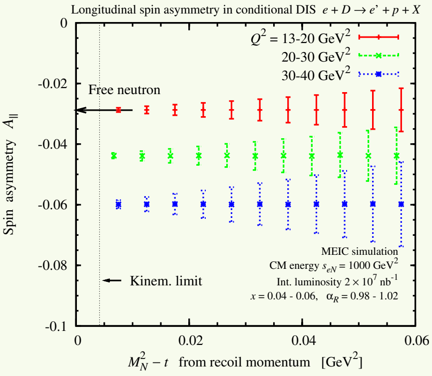
$$A_{||} = \frac{\sigma(++)-\sigma(-+)-\sigma(+-)+\sigma(--)}{\sigma(++)+\sigma(-+)+\sigma(+-)+\sigma(--)}[\phi_h \text{avg}] = \frac{F_{LS_L}}{F_T+\epsilon F_L} = D\frac{g_{1n}}{F_{1n}} + \cdots$$



- Clear contribution from D-wave at finite recoil momenta
- Relativistic nuclear effects through Melosh rotations, grow with recoil momenta
- Both effects drop out near the on-shell extrapolation point

On-shell extrapolation of double spin asymm.

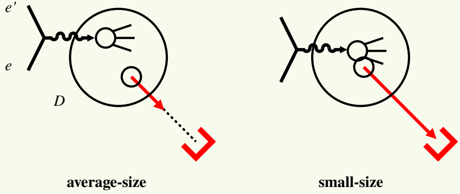
$$A_{||} = \frac{\sigma(++)-\sigma(-+)-\sigma(+-)+\sigma(--)}{\sigma(++)+\sigma(-+)+\sigma(+-)+\sigma(--)}[\phi_h \text{avg}] = \frac{F_{LS_L}}{F_T+\epsilon F_L} = D\frac{g_{1n}}{F_{1n}} + \cdots$$

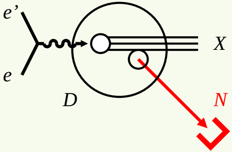


`JLab LDRD arXiv:1407.3236, arXiv:1409.5768`

- Systematic uncertainties cancel in ratio (momentum smearing, resolution effects)
- Statistics requirements
  - Physical asymmetries $\sim 0.05 - 0.1$
  - Effective polarization $P_e P_D \sim 0.5$
  - Luminosity required $\sim 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$
- Precise measurement of neutron spin structure
  - non-singlet/singlet QCD evolution
  - pdf flavor separation $\Delta u, \Delta d$. ΔG through singlet evolution

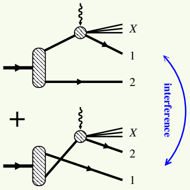
Tagging: EMC effect



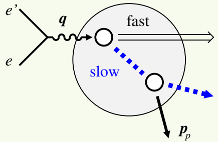


Final−state interactions

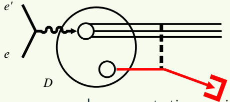
- Medium modification of nucleon structure embedded in nucleus (EMC effect)
  - dynamical origin?
  - caused by which momenta/distances in nuclear WF
  - spin-isospin dependence?
- tagged EMC effect
  - recoil momentum as extra handle on medium modification (off-shellness, size of nuclear configuration) away from the on-shell pole
  - EIC: Q^2 evolution, gluons, spin dependence!
- Interplay with final-state interactions!
  - use $\tilde{x} = 0.2$ to constrain FSI
  - constrain medium modification at higher $\tilde{x}$



shadowing, low x



DIS regime, intermediate x



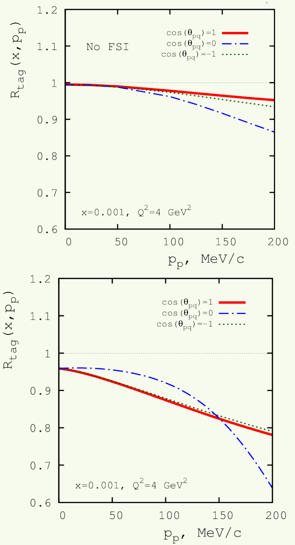
subasymptotic regime:
low Q^2, high x

- Shadowing in inclusive DIS $x \ll 10^{-1}$
  - Diffractive DIS on single nucleon (leading twist, HERA)
  - Interference of DIS on nucleon 1 and 2
  - Calculable in terms of nucleon diffractive structure functions [Gribov 70s, Frankfurt,Guzey,Strikman '02+]
- FSI between slow hadrons from the DIS products and spectator nucleon, fast hadrons hadronize after leaving the nucleus.
  - Data show slow hadrons in the target fragmentation region are mainly nucleons.
  - Input needed from nucleon target fragmentation data → also possible at EIC

    M. Strikman,Ch. Weiss arXiv:1706.02244
- rescattering of resonance-like structure with spectator nucleon in eikonal approximation [Deeps,BONuS].

  WC,M. Sargsian arXiv:1704.06117

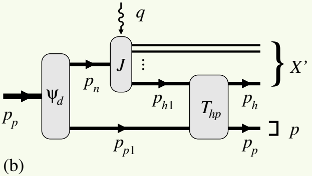
FSI 1: Shadowing at small x in tagged DIS

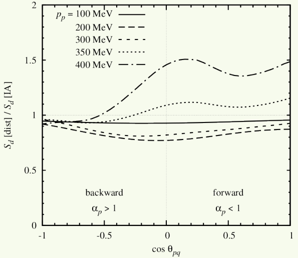


[Guzey,Strikman,Weiss; in preparation]

- Explore shadowing through recoil momentum dependence
- Shadowing enhanced in tagged DIS compared to inclusive
  - enhancement factor from AGK rules
  - shadowing term drops slower with p_R than IA
- FSI contributions between slow p and n in diffractive events
- Large FSI effects in diffractive amplitudes ($\sim 40\%$), also at zero spectator momenta due to orthogonality of np state to deuteron
- Effects smaller in tagged as diffractive are $\sim 10\%$ of total events
- Possibilities to study diffractive events by double tagging

FSI 2: intermediate x model





Strikman, Weiss, arXiv:1706.02244, PRC7 035209 ('18)

- Features of the FSI of slow hadrons with spectator nucleon are similar to what is seen in quasi-elastic deuteron breakup.
- Inclusion FSI diagram adds two contributions: FSI term ($\sim$ absorption, negative) and FSI^2 term ($\sim$ refraction, postive)
- At low momenta ($p_r < 200$ MeV) FSI term dominates, at larger momenta FSI^2 dominates.
- Both contributions vanish at the pole $\rightarrow$ pole extrapolation **still feasible**
- Calculation with realistic deuteron wf (AV18)

Tagging: developments and extensions

- Final-state interactions
  - in tagged $\vec{e} + \vec{D}$
  - maximized/minimized by choice of kinematics. Constrain FSI models.
  - azimuthal and spin observables non-zero through FSI
- Tagging with complex nuclei $A > 2$
  - isospin dependence, universality of bound nucleon structure
  - $A - 1$ ground state recoil
- Resolved final states: SIDIS on neutron, hard exclusive channels

R&D project at JLAB

- Develop simulation tools (physics models, event generators, analysis tools) for DIS on light ions with spectator tagging at MEIC and study physics impact.
- ran FY14-15
  D. Higinbotham, W. Melnitchouk, P. Nadel-Turonski, K. Park, C. Weiss (JLab), Ch. Hyde (ODU), M. Sargsian (FIU), V. Guzey (PNPI), with collaborators W. Cosyn (Ghent), S. Kuhn (ODU), M. Strikman (PSU), Zh. Zhao (JLab)
- **Tools, documentation, results publicly available. Open for collaboration!**
- More info:
  `https://www.jlab.org/theory/tag/`
  `arXiv:1407.3236, arXiv:1409.5768v1, arXiv:1601.066665, arXiv:1609.01970`

Inclusive DIS Xsection on pol. spin 1 with unpol. beam

$$\frac{d\sigma}{dx\,dQ^2} = \frac{\pi y^2 \alpha^2}{Q^4(1-\epsilon)}\Big[F_{UU,T} + \epsilon F_{UU,L} + T_{LL}\left(F_{UT_{LL},T} + \epsilon F_{UT_{LL},L}\right)$$
$$+ T_{L\perp}\cos\phi_{T_L}\sqrt{2\epsilon(1+\epsilon)}\,F_{UT_{LT}}^{\cos\phi_{T_L}} + T_{\perp\perp}\cos(2\phi_{T_\perp})\,\epsilon\,F_{UT_{TT}}^{\cos(2\phi_{T_\perp})}\Big],$$

- 4 tensor polarized structures can be related to the b_{1-4} introduced by Hoodbhoy, Jaffe, Manohar [Nucl. Phys. B 312]
  $F_{UT_{LL},T} = -\frac{1}{x}\sqrt{\frac{2}{3}}\left[2(1+\gamma^2)xb_1 - \gamma^2\left(\frac{1}{6}b_2 - \frac{1}{2}b_3\right)\right]$
- Alternative set of b_{1-3}, Δ by Edelmann Piller Weise [Z. Phys. A 357]. Two sets are **equal only in the scaling limit**!
- In the parton model: distribution of unpol. quarks in pol. hadron $b_1 = \frac{1}{2}\sum_q e_q^2(q^0 - q^1)$
- Obey Callan-Gross like relation in the scaling limit $2xb_1(x) = b_2(x)$
- Obeys Kumano-Close sum rule for valence quarks $\int dx b_1(x) = 0$ [PRD42, 2377]

b_1 for the deuteron

- Interplay of nuclear and quark degrees of freedom.
  $b_1 = \frac{1}{2}\sum_q e_q^2 (q^0 - q^1)$

Fig. from K. Slifer

- *np*-component: b_1 is only non-zero due to the *D*-wave admixture in the deuteron, small.

- Measured @ Hermes [PRL95, 242001], not small + sign change. No agreement with conventional deuteron models.

- Upcoming measurements at JLab12 for $x < 1$ (DIS) and $x > 1$ (QE) [arXiv:1311.4835]

Conventional calculations for deuteron b_1

- Important to provide an accurate calculation of deuteron b_1 in a conventional nuclear model to constrain possible exotic mechanisms
- Consider *np* component, convolution approach [unpol. nucleon structure $\otimes$ tensor pol. deuteron momentum distribution]
- Only one (?) published Khan, Hoodbhoy [PRC44, 1219]

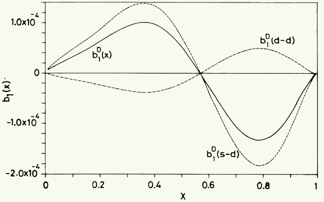
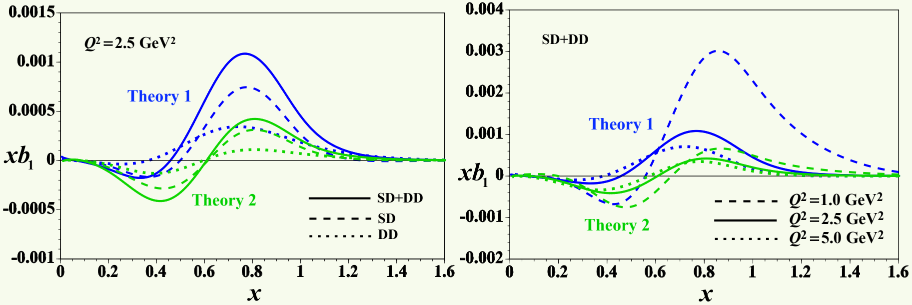


FIG. 2. $b_1^D(x)$ (solid curve), the *s-d* contribution to $b_1^D(x)$ (dashed curve), and the *d-d* contribution to $b_1^D(x)$ (dot-dashed curve).

- Updated check in two similar models: one standard convolution model with instant form deuteron wave function, one in the virtual nucleon approximation with light-front deuteron wf [`W.C., Y. Dong, S. Kumano, M. Sargsian, PRD95(074036) '17`]

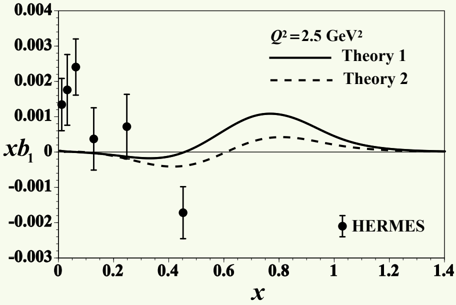
Comparison between two models



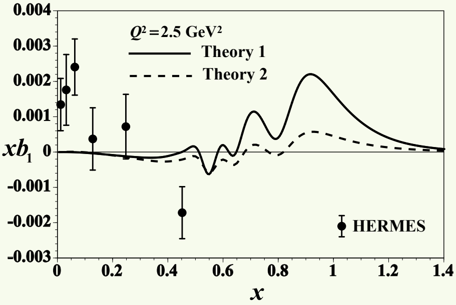
MSTW08 nucleon pdfs, CDBonn deuteron wf, SLAC $R = F_L/F_T$

- Differences with Khan, Hoodbhoy calculation
  - different sign SD term
  - non-zero distribution at $x > 1$
- Significant nuclear higher-twist effects at low Q^2
- DD-term is not small (given $\sim 5\%$ D-wave admixture)

Comparison with Hermes data



MSTW08



SLAC (Bodek, Ricci)

- Clear mismatch between data and calculations in size
- Future JLab12 data should shed more light
- Possible contribution from exotic mechanism → Miller [PRC89,045203] hidden color + pions
- Higher twist effects?

How was b_1 extracted?

- Experimental measured asymmetry [θ_q is angle between momentum transfer and polarization axis]

  $A_{zz} = \frac{2\sigma^+ - 2\sigma^0}{2\sigma^+ + \sigma^0} = \frac{\sqrt{2}}{4\sqrt{3}\left(F_{UU,T} + \epsilon F_{UU,L}\right)} \Bigg\{ [1 + 3\cos 2\theta_q] \left(F_{UT_{LL},T} + \epsilon F_{UT_{LL},L}\right) +$
  $3 \sin 2\theta_q \sqrt{2\epsilon(1+\epsilon)} F_{UT_{LT}}^{\cos\phi_T} + 3[1 - \cos 2\theta_q]\epsilon F_{UT_{TT}}^{\cos 2\phi_{T_\perp}} \Bigg\},$
- **Only** when $\theta_q = 0$ and scaling relations applied, higher twist $b_{3,4}$ neglected, we have

  $A_{zz} \to \sqrt{\frac{2}{3}} \frac{F_{UT_{LL},T}}{F_{UU,T}} \to -\frac{2}{3}\frac{b_1}{F_1}$
- Q^2-range of Hermes experiment quite low values: 0.5–5 GeV^2
- We can directly compute A_{zz}: still way smaller than the Hermes data

Transversity GPDs for spin 1 hadrons

- GPDs: FT of off-forward matrix elements of quark or gluon correlators
  `Talk M. Hattawy`
- Transversity (chiral odd) GPDs for spin 1/2 hadron
  `M. Diehl, EPJC19, 485 (2001)`
- Chiral even GPDs for spin 1
  `Berger, Cano, Diehl, Pire, PRL87 142302 (2001)`
- Motivated by recent $ed \to ed\pi^0$ JLAB Hall A data
  `Mazouz et al, 1702.00835`
- Phenomenology linking pion deep exclusive electroproduction data on the proton with transversity GPDs $\otimes$ higher twist pion DA
  `[Goloskokov & Kroll, Liuti & Goldstein]`
- First step: writing down the transversity GPDs for spin 1, determine their properties and study in **basic convolution model**

Properties of spin 1 transversity GPDs

- Both for the quark and gluon sector there are 9 transversity GPDs

$$\int \frac{d\kappa}{2\pi} e^{2ix\kappa(Pn)} \langle p'\,\lambda'|\bar{\psi}(-\kappa n)(in_\mu \sigma^{\mu i})\psi(\kappa n)|p\,\lambda\rangle = M \frac{(\epsilon'^{*} n)\epsilon^i - \epsilon'^{*i}(\epsilon n)}{2\sqrt{2}(Pn)} H_1^T(x,\xi,t)$$
$$+ M\left[\frac{2P^i(\epsilon n)(\epsilon'^{*} n)}{2\sqrt{2}(Pn)^2} - \frac{(\epsilon n)\epsilon'^{i*} + \epsilon^i(\epsilon'^{*} n)}{2\sqrt{2}(Pn)}\right] H_2^T(x,\xi,t)$$
$$+ \frac{(\Delta^i + 2\xi P^i)}{M} \frac{(\epsilon n)(\epsilon'^{*} P) - (\epsilon'^{*} n)(\epsilon P)}{(Pn)} H_3^T(x,\xi,t)$$
$$+ \frac{(\Delta^i + 2\xi P^i)}{M} \frac{(\epsilon n)(\epsilon'^{*} P) + (\epsilon'^{*} n)(\epsilon P)}{(Pn)} H_4^T(x,\xi,t) + (\Delta^i + 2\xi P^i) M \frac{(\epsilon'^{*} n)(\epsilon n)}{(Pn)^2} H_5^T(x,\xi,t)$$
$$+ \frac{(\Delta^i + 2\xi P^i)}{M} (\epsilon'^{*}\epsilon) H_6^T(x,\xi,t) + \frac{(\Delta^i + 2\xi P^i)}{M} \frac{(\epsilon'^{*} P)(\epsilon P)}{M^2} H_7^T(x,\xi,t)$$
$$+ \left[\frac{(\epsilon'^{*} n)P^i - \epsilon'^{i*}(Pn)}{M(Pn)}(\epsilon P) + \frac{(\epsilon n)P^i - \epsilon^i(Pn)}{M(Pn)}(\epsilon'^{*} P)\right] H_8^T(x,\xi,t)$$
$$+ \left[\frac{(\epsilon'^{*} n)P^i - \epsilon'^{i*}(Pn)}{M(Pn)}(\epsilon P) - \frac{(\epsilon n)P^i - \epsilon^i(Pn)}{M(Pn)}(\epsilon'^{*} P)\right] H_9^T(x,\xi,t)\,.$$

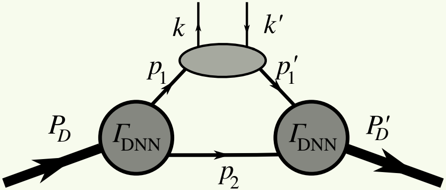
- Complex conjugation and P, T symmetries

Properties of spin 1 transversity GPDs

- Both for the quark and gluon sector there are 9 transversity GPDs
- Complex conjugation and P, T symmetries
  $\rightarrow$ all are **real**, even/oddness in ξ
- **Forward limit** gives connections with collinear pdfs
  - $H^T_{q1}(x,0,0) = h_1(x)$,
  - $H^T_{g5}(x,0,0) = x\Delta(x)$ [Talk P. Shanaghan]
- **Sum rules** for first moments, several are zero due to Lorentz invariance.
- General moments can be connected with generalized form factors [in progress]
- Can be linked to 9 **helicity amplitudes** $\mathcal{A}_{\lambda'+;\lambda-}$ through linear set of equations

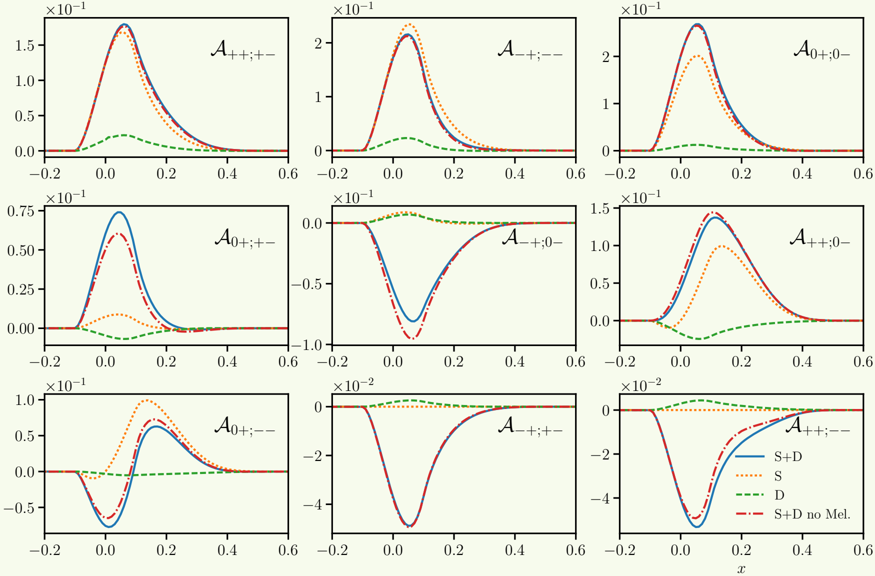
Deuteron chiral odd quark GPDs: convolution calculation

- Same approach as `Cano, Pire, EPJA19 ('04) 423-438`
  Only difference: tensor current instead of (axial) vector

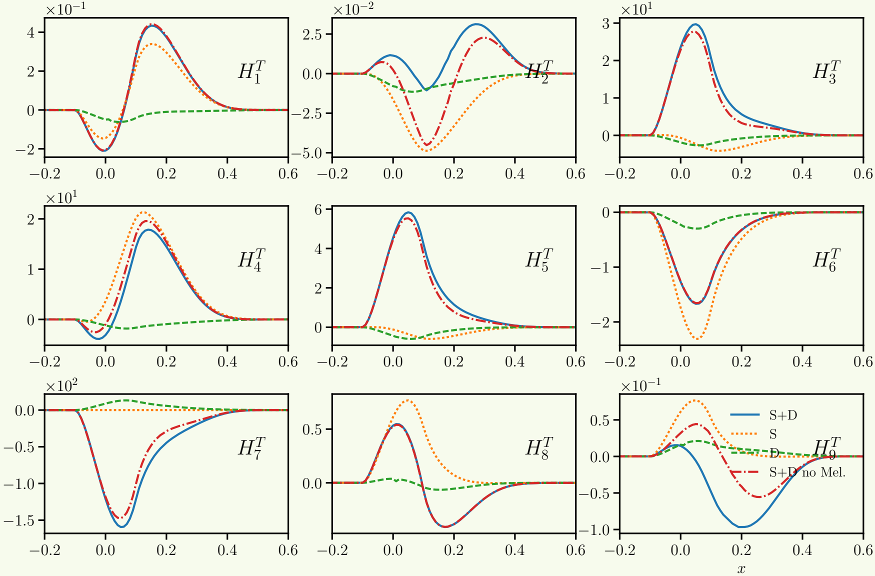


- Deuteron helicity amplitudes written as convolution of nucleon chiral odd helicity amplitudes $\otimes$ deuteron LF wave function
- Nucleon chiral odd helicity amplitudes $\rightarrow$ nucleon transversity GPDs [parametrization based on `Goloskokov, Kroll, EPJA47 112 ('11)`]
- Deuteron helicity amplitudes $\rightarrow$ GPDs $H^T_{q1} - H^T_{q9}$

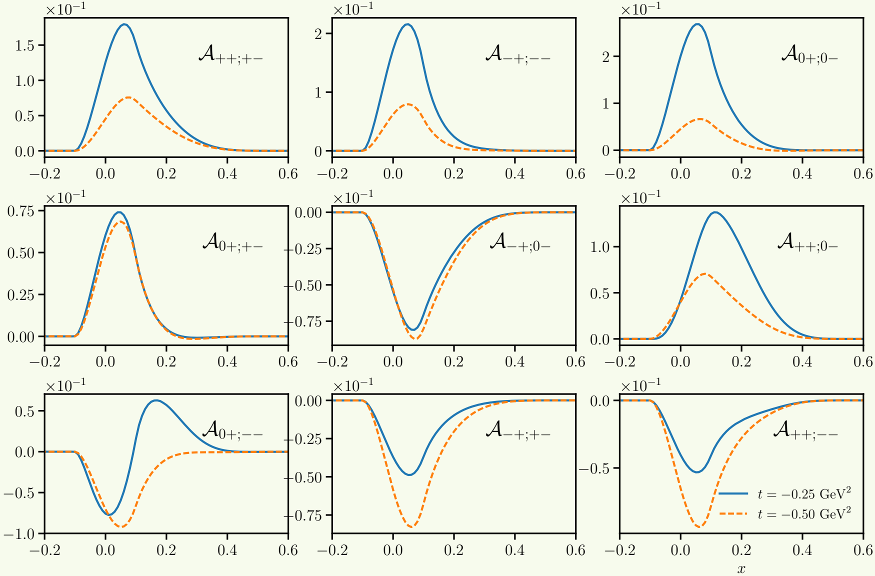
Deuteron hel. amplitudes: $\xi = 0.1, t = -0.25$ GeV^2



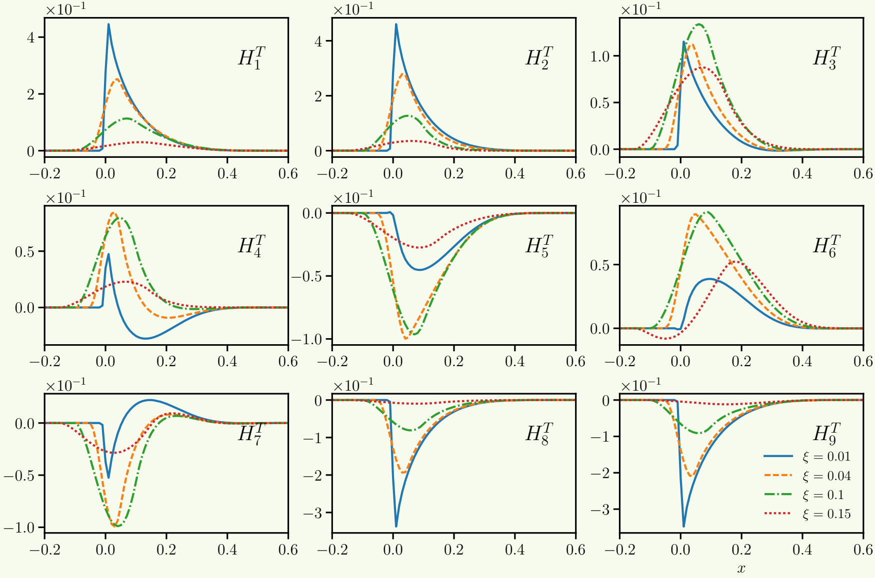
Deuteron transv. quark GPDs: $\xi = 0.1, t = -0.25$ GeV^2



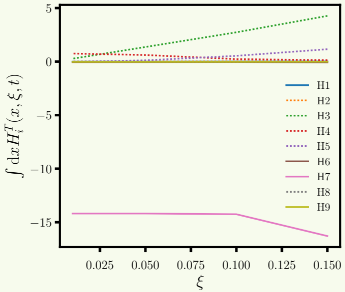
Deuteron hel. amplitudes: t–dep, $\xi = 0.1$



Deuteron transv. quark GPDs: ξ–dep, $t = -0.4$ GeV^2



Sum rules: first moments



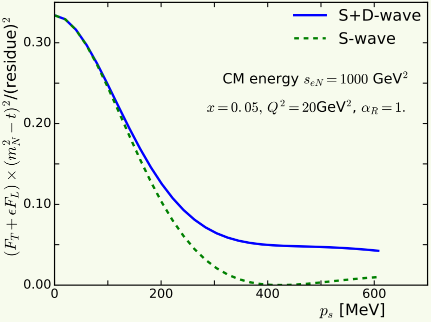
- First moments should be independent of ξ
- Dashed curves should have zero sum rules
- Limitations of convolution picture?
- strong ξ dependence of H_3^T, H_4^T, H_5^T
- understood in minimal convolution model (no D-wave, no coordinate wf), ξ terms come with $M^2/(t-t_0)$ enhancement

Conclusions

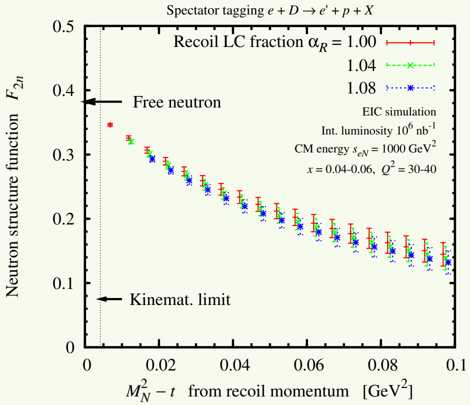
- General form of SIDIS with a spin 1 target, 23 tensor polarized structure functions unique to spin 1
- Results for the impulse approximation using deuteron light-front structure, relativistic nuclear spin effects contribute.
- FSI/shadowing effects calculable
- Spectator tagging in eD scattering with EIC enables next-generation measurements with maximal control and unprecedented accuracy
  - Neutron structure functions, including spin
  - Nuclear modifications of quark/gluon structure
- Update of convolution calculation for deuteron b_1
  Does not match Hermes data
- Deuteron chiral odd quark GPDs in convolution picture

Backup Slides

Unpolarized structure function



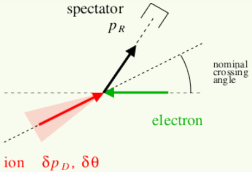
- Extrapolation for $(m_N^2 - t) \to 0$ corresponds to on-shell neutron $F_{2N}(x, Q^2)$, here equivalent to imaginary p_s
- Clear effect of deuteron D-wave, largest in the region dominated by the tensor part of the NN-interaction
- D-wave drops out at the on-shell point

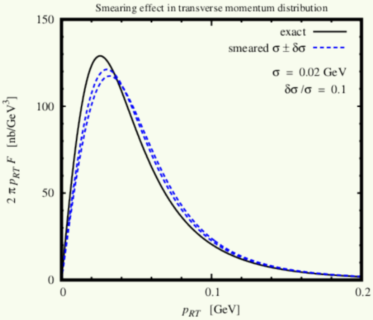


JLab LDRD arXiv:1407.3236, arXiv:1409.5768,
C. Hyde talk

- F_{2n} extracted with percent-level accuracy at $x < 0.1$
- Uncertainty mainly systematic due to intrinsic momentum spread in beam (JLab LDRD project: detailed estimates)
- In combination with proton data non-singlet $F_{2p} - F_{2n}$, sea quark flavor asymmetry $\bar{d} - \bar{u}$

JLEIC: Momentum spread in beam





[Ch. Hyde, K. Park et al.]

- Intrinsic beam spread in ion beam "smears" recoil momentum
  - transverse momentum spread of $\sigma \approx 20$ MeV ($\delta\sigma/\sigma \sim 10\%$)
  - p_R(measured) $\neq p_R$(vertex)
  - Systematic correlated uncertainty, x, Q^2 independent
- Dominant syst. uncertainty at JLEIC, detector resolution much higher than beam momentum spread (diff for eRHIC)
- On-shell extrapolation feasible!!