Deuteron spin structure in inclusive and tagged spectator processes in the virtual nucleon approximation

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Outline

- Inclusive DIS from polarized deuteron

  W.C., Yu-Bing Dong, S. Kumano, M. Sargsian,
  arXiv:1702.05337 [PRD accepted], arXiv:1702.07594

- Tagged spectator DIS from polarized deuteron

  W.C., M. Sargsian, Ch. Weiss, in preparation.

  JLab LDRD project https://www.jlab.org/theory/tag/
  arXiv:1407.3236, arXiv:1409.5768v1, arXiv:1601.066665

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

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

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
  $b_1 = \frac{1}{2}\sum_q e_q^2(q^0 - q^1)$
- Obeys Callan-Gross like relation in the scaling limit $2xb_1(x) = b_2(x)$
- Obeys Kumano-Close sum rule $\int dx b_1(x) = 0$ [PRD42, 2377]

b_1 for the deuteron

- np-component: b_1 is only non-zero due to the D-wave admixture in the deuteron, small.
- Interplay of nuclear and quark degrees of freedom.
- 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`]
- Also possible @ Fermilab in DY [`Kumano, Song, PRD94, 054022`], EIC with polarized deuteron beam and ILC with a fixed target experiment

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 $\otimes$ pol. deuteron momentum distribution]
- Only one (?) published Khan, Hoodbhoy [PRC44, 1219]

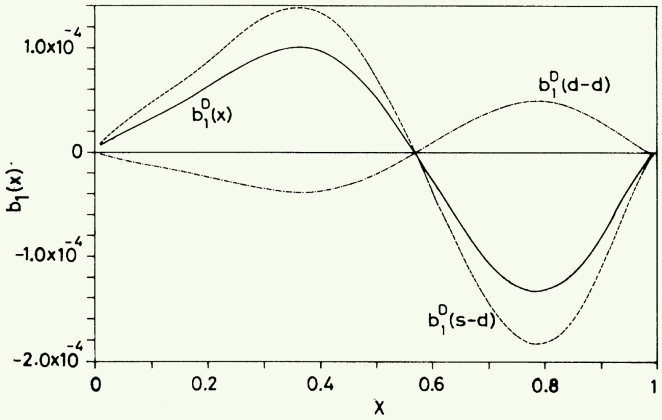
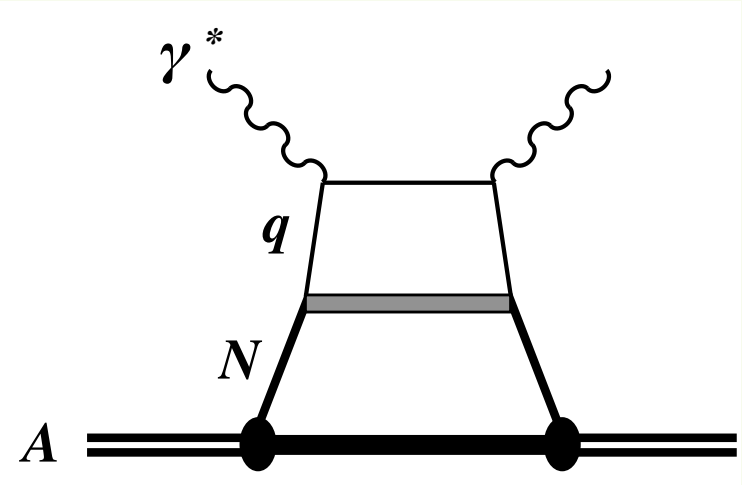


FIG. 2. $b_1^D(x)$ (solid curve), the *s-d* contribution to $b_1^D(x)$ (dashed curve), and the *d-d* contribution to $b_1^D(x)$ (dot-dashed curve).

- 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 [`arXiv:1702.05337`]

Model 1: standard convolution picture



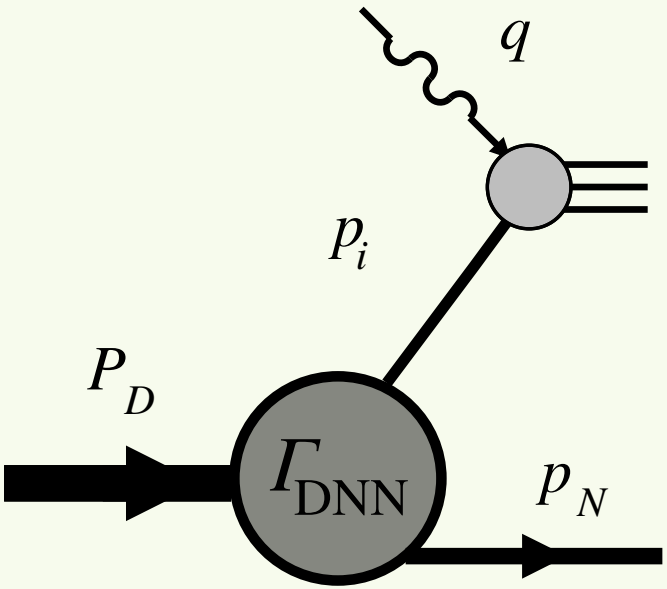
- $W^A_{\mu\nu}(P_A, q) = \int d^4p\, S(p)\, W^N_{\mu\nu}(p, q)$
- Relation between b_1 and helicity amplitudes in **scaling limit**
  $b_1 = A_{+0,+0} - \frac{A_{++,++} + A_{+-,+-}}{2}$

$$b_1(x, Q^2) = \int \frac{dy}{y}\, \delta_T f(y)\, F_1^N(x/y, Q^2)$$

$$\delta_T f(y) = \int d^3p\, y \left[-\frac{3}{4\sqrt{2}\pi} \phi_0(p)\phi_2(p) + \frac{3}{16\pi} |\phi_2(p)|^2 \right] \times (3\cos^2\theta - 1)\, \delta\left(y - \frac{p \cdot q}{M_N \nu} \right)$$

- Deuteron wave function obeys baryon number conservation
- Nucleon structure functions include HT contributions, nuclear part does not

Model 2: virtual nucleon approximation

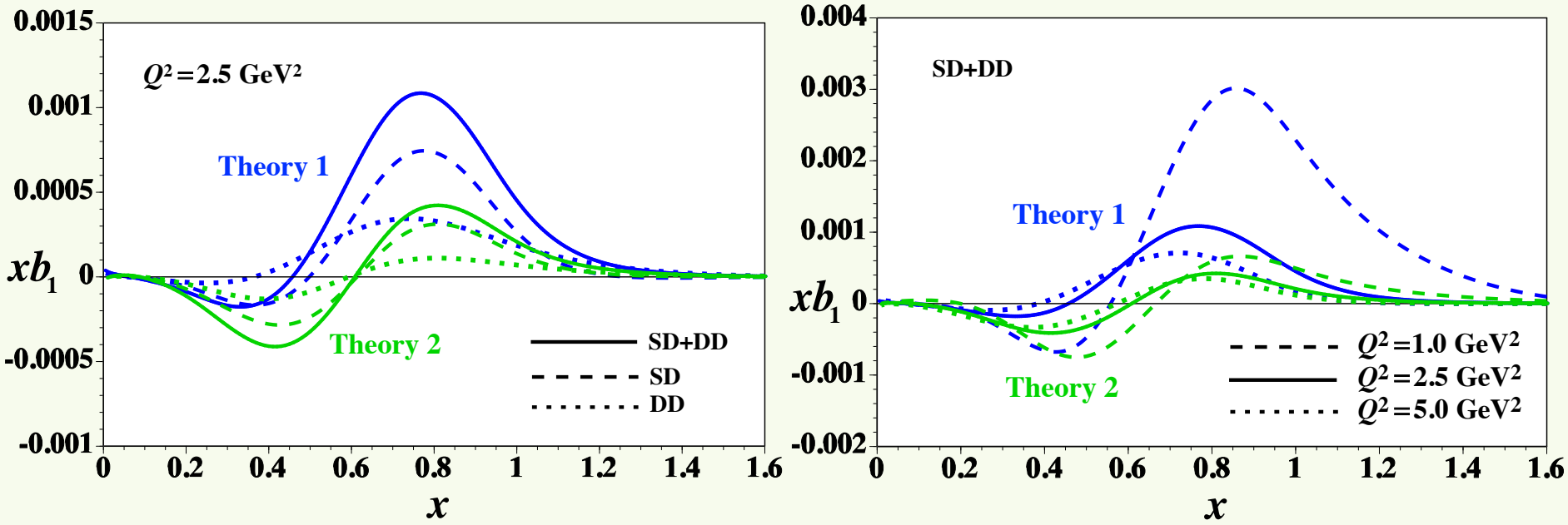


- Non-interacting "spectator" on-shell, photon interacts with off-shell nucleon
- $b_1 = -\frac{1}{1+\gamma^2}\sqrt{\frac{3}{8}}\left[F_{UT_{LL},T} + F_{UT_{TT}}^{\cos(2\phi_{T_\perp})}\right]$.
- Structure functions computed in the IA, no scaling limit applied, HT nuclear effects included.
- Deuteron light-front wave function, obeys baryon and momentum sum rules.

$$W_{\mu\nu}^{\lambda'\lambda}(P,q) = 4(2\pi)^3 \int \frac{\alpha_i d^3\vec{k}}{2E_k(2\pi)^3}\frac{\alpha_N}{\alpha_i} W_{\mu\nu}^N(p_i,q)\rho_D(\lambda',\lambda)$$

$$b_1(x,Q^2) = \frac{3}{4(1+\gamma^2)}\int \frac{k^2}{\alpha_i} dk\, d(\cos\theta_k)\left[F_1^N(x_i,Q^2)\left(6\cos^2\theta_k - 2\right) - \frac{T^2}{2\,p_i\cdot q}F_2^N(x_i,Q^2)\left(5\cos^2\theta_k - 1\right)\right]\left[\frac{U(k)W(k)}{\sqrt{2}} + \frac{W(k)^2}{4}\right]$$

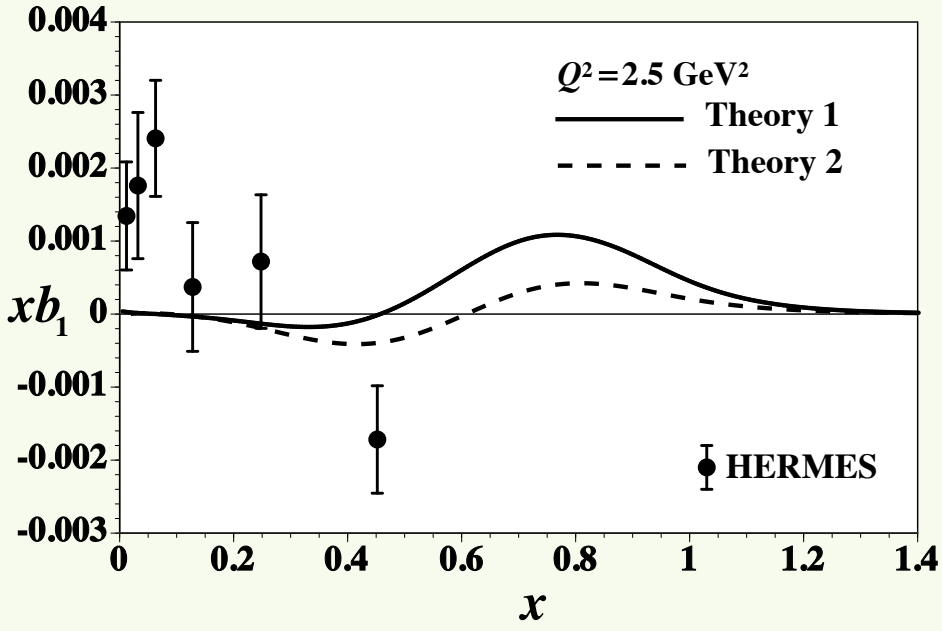
Comparison between two models



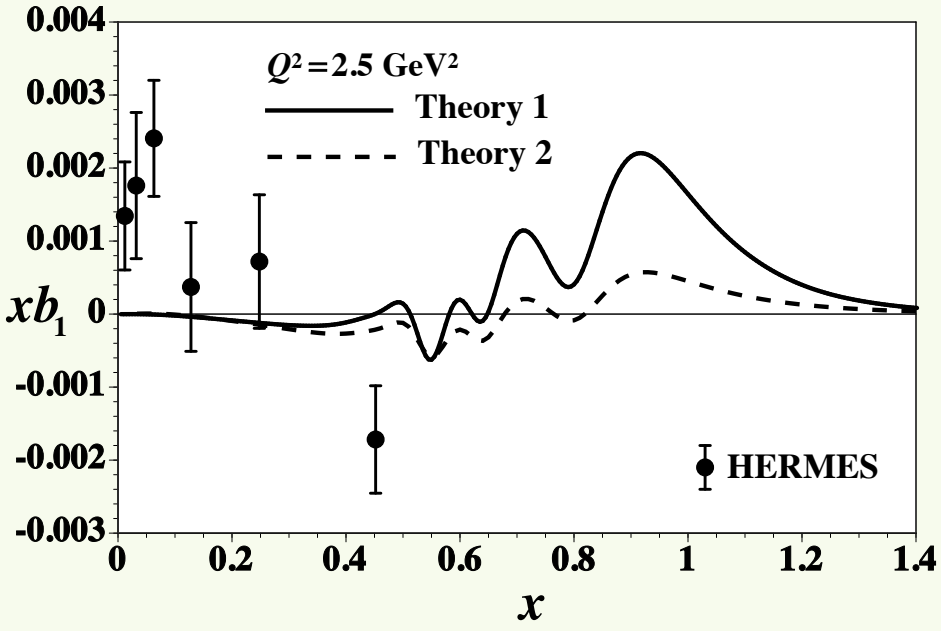
MSTW08 nucleon pdfs, CDBonn deuteron wf, SLAC $R = F_L/F_T$

- 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?

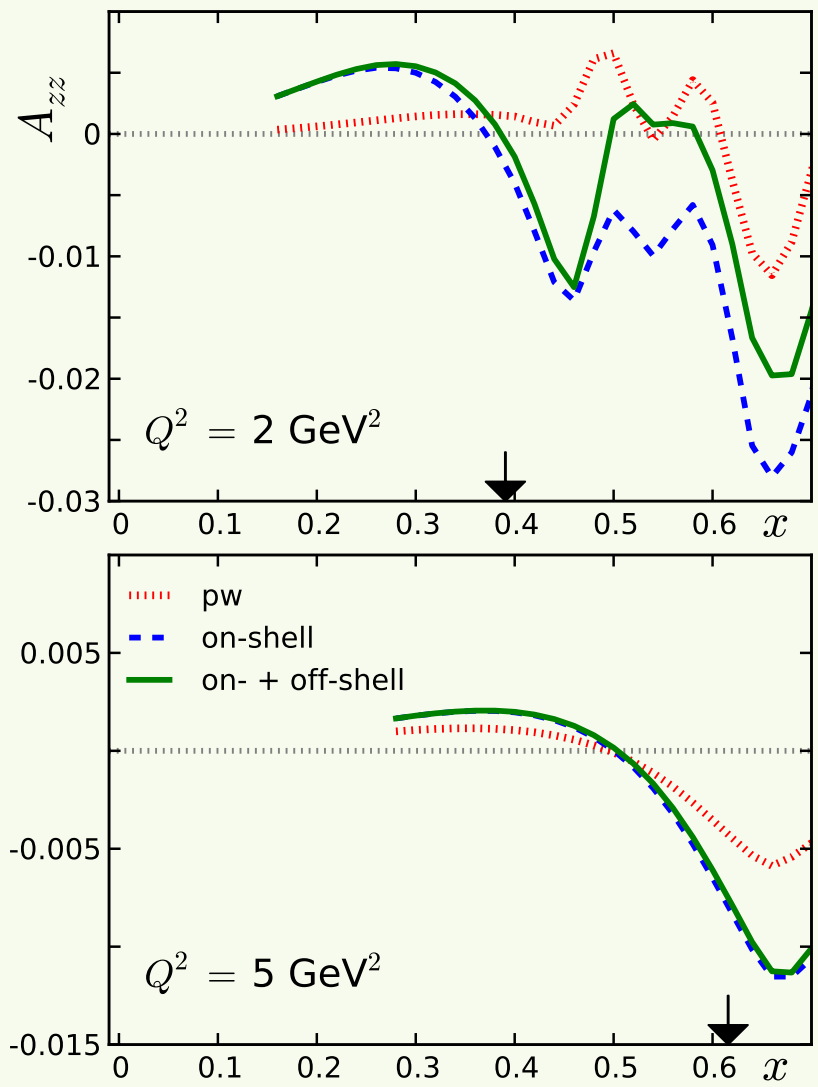
- Experimental measured asymmetry [θ_q is angle between momentum transfer and polarization axis]
  $A_{zz} = \frac{2\sigma^+ - 2\sigma^0}{2\sigma^+ + \sigma^0} = \frac{\sqrt{2}}{4\sqrt{3}\left(F_{UU,T} + \epsilon F_{UU,L}\right)} \Big\{ [1 + 3\cos 2\theta_q] \left(F_{UT_{LL},T} + \epsilon F_{UT_{LL},L}\right) +$
  $3\sin 2\theta_q \sqrt{2\epsilon(1+\epsilon)} F_{UT_{LT}}^{\cos\phi_T} + 3[1 - \cos 2\theta_q]\epsilon F_{UT_{TT}}^{\cos 2\phi_{T_\perp}} \Big\},$
- **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

Calculation of $b_{1,4}$ in VNA model

x	Q^2 (GeV^2)	$b_1(10^{-4})$	$b_2(10^{-5})$	$b_3(10^{-3})$	$b_4(10^{-3})$	$b_2/(2xb_1)$	$\gamma = 2Mx/Q$
0.012	0.51	2.81	0.264	-1.34	5.06	0.783	0.0315
0.032	1.06	6.92	1.97	-1.87	7.51	0.890	0.0583
0.063	1.65	3.50	0.265	-2.02	7.96	0.120	0.0920
0.128	2.33	-1.80	-7.38	-2.13	7.49	3.20	0.157
0.248	3.11	-8.39	-28.1	-2.09	4.58	1.35	0.264
0.452	4.69	-6.18	-21.7	-1.11	-0.58	0.777	0.392

- VNA calculation only including *pn* IA contribution
- Higher twist b_3, b_4 not small compared to b_1, b_2
- Callan-Gross relation not satisfied
- "Improved" extraction feasible?
- Direct comparison of VNA calculations of A_{zz} at largest x value is still two orders of magnitude too small!

Final-state interactions in A_{zz}

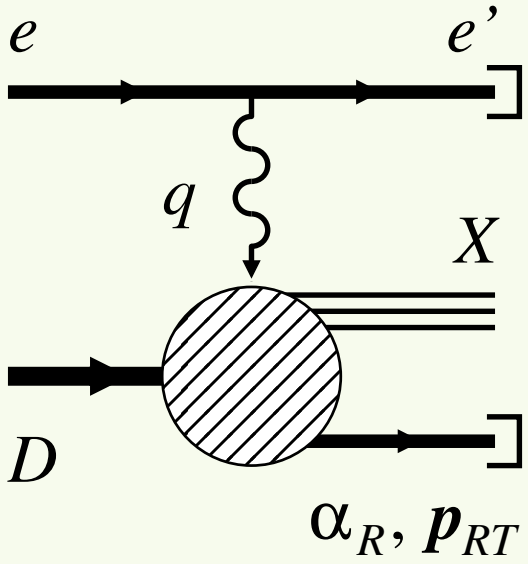


WC, M. Sargsian, arXiv:1407.1653

WC,W. Melnitchouk, MS, PRC89 ('14)

- Only resonance contributions considered in the FSI, eikonal rescattering of produced X with spectator nucleon
- JLab 12 GeV kinematics considered
- Only spin independent FSI included
- Non-negligable contribution from FSI even at low x, but not enough to match Hermes data
- Convolution (D-wave dominance $\rightarrow$ high spectator momenta) can pick up resonance contributions through the convolution
- Size of FSI effects decreases at higher Q^2 (phase-space effect)

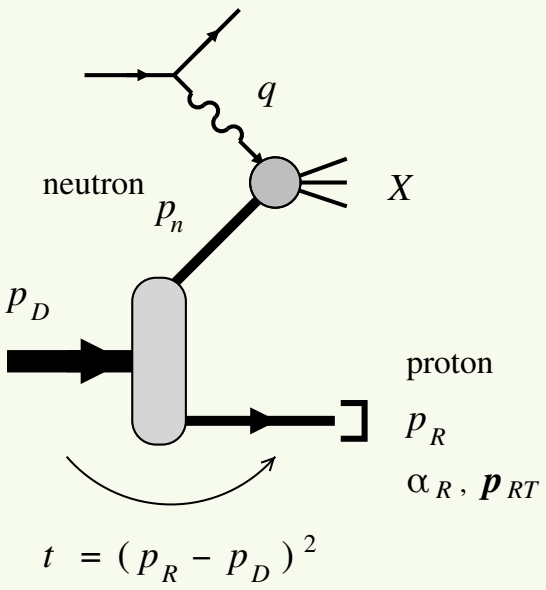
Tagged spectator DIS process with deuteron



- DIS off a nuclear 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** for JLEIC)
- suited for colliders: no target material, forward detection, transverse pol. $\rightarrow$ R. Ent's talk on Wed
  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 $t - m_N^2$
  - 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 $\to$ neutron $\sim 100\%$ polarized
- Precise measurements of neutron structure at an EIC

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)]

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

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

Spin 1 SIDIS: General structure of cross section

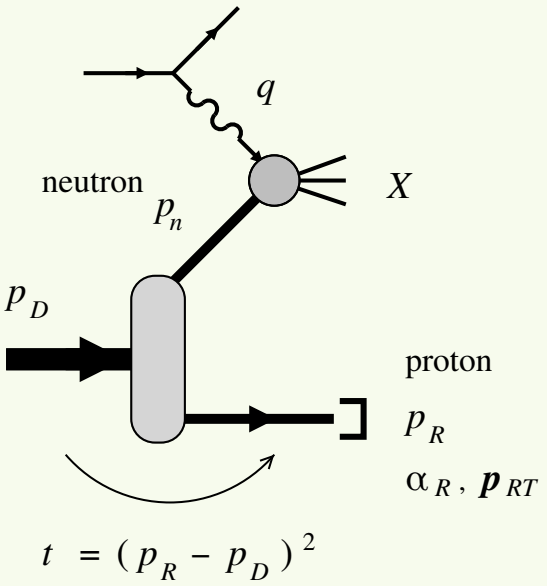
- To obtain structure functions, enumerate all possible tensor structures that obey hermiticity and transversality condition ($qW = Wq = 0$)
- Cross section has 41 structure functions,

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

  - 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

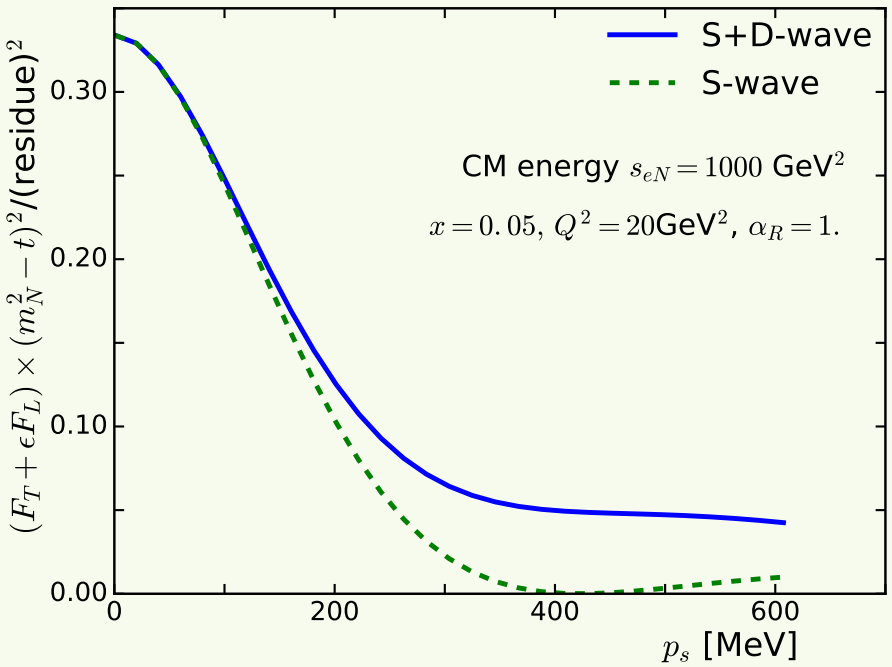
$$W_D^{\mu\nu}(\lambda', \lambda) = 4(2\pi)^3 \frac{\alpha_R}{2 - \alpha_R} \sum_{i=U,z,x,y} W_{N,i}^{\mu\nu} \rho_D^i(\lambda', \lambda)\,,$$

All SF can be written as

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

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

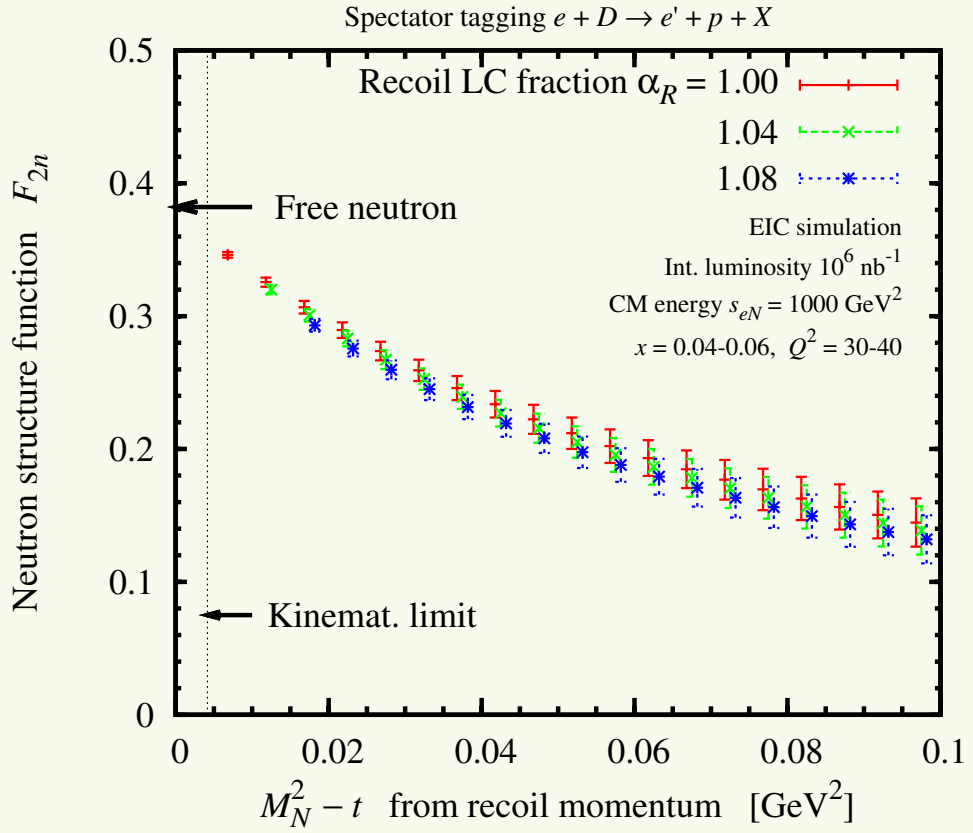
Unpolarized structure function



- Extrapolation for $(m_N^2 - t) \to 0$ corresponds to on-shell neutron $F_{2N}(x, Q^2)$
- 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

Tagging: free neutron structure

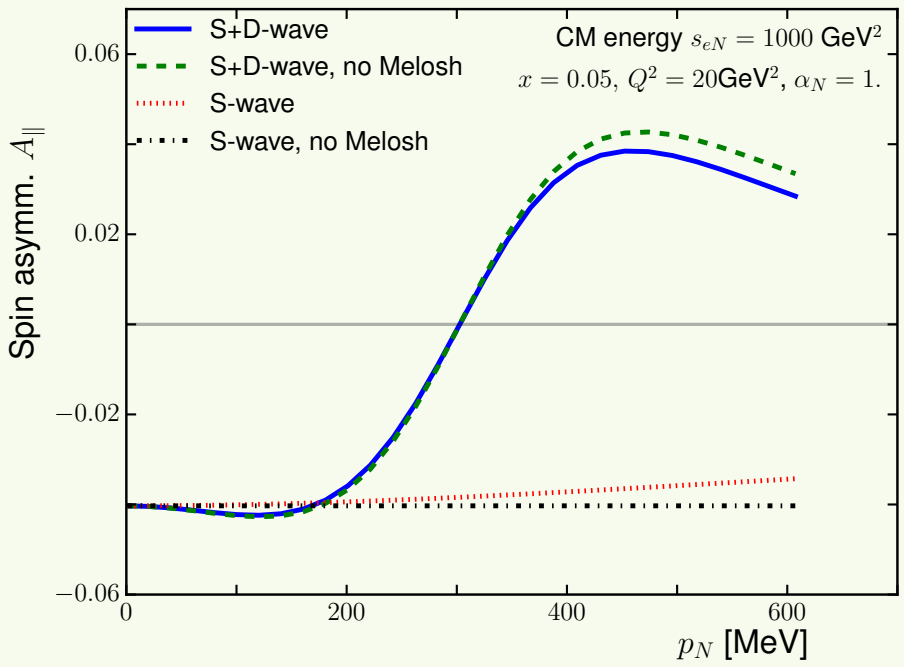
Precise measurements of F_{2n}



JLab LDRD arXiv:1407.3236, arXiv:1409.5768

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

Polarized structure function



- Spin asymmetry

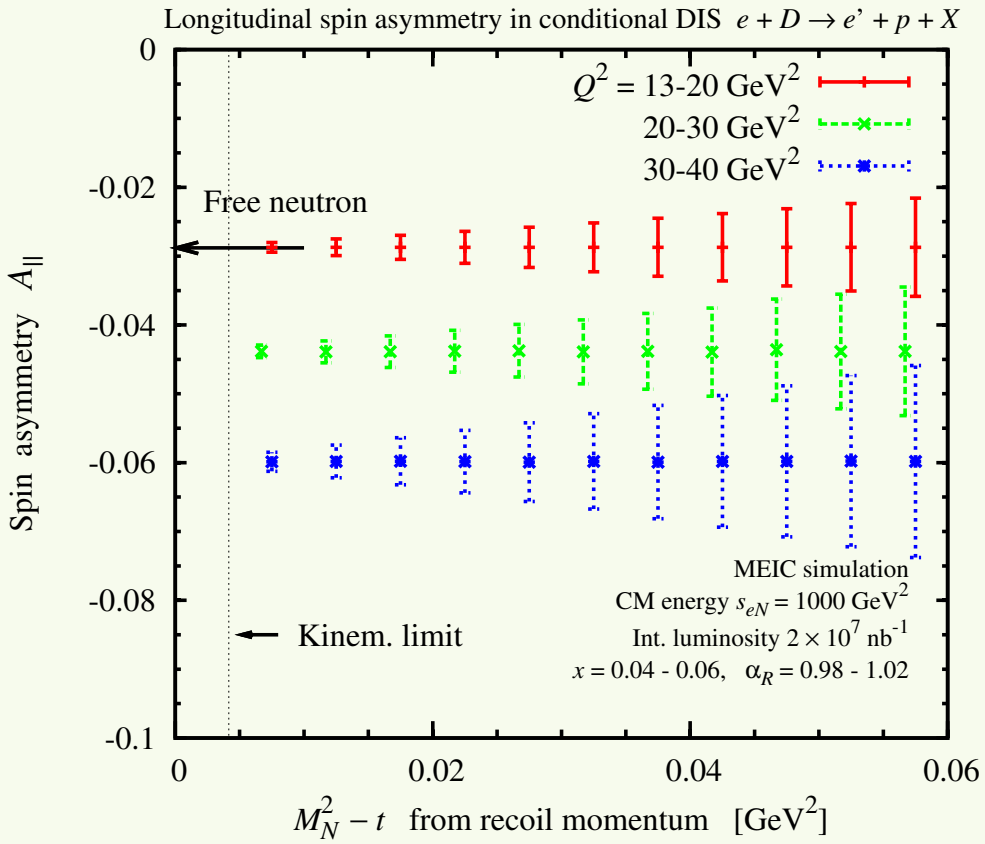
$$A_{||} = \frac{\sigma(++) - \sigma(-+) - \sigma(+-) + -\sigma(--)}{\sigma(++) + \sigma(-+) + -\sigma(+-) + -\sigma(--)}[\phi_h \text{avg}]$$
$$= \frac{F_{LS_L}}{F_T + \epsilon F_L} \propto \frac{g_{1n}}{F_{1n}}$$

- Again clear contribution from D-wave at finite recoil momenta
- Relativistic spin nuclear effects through Melosh rotations in deuteron light-front wf, grow with recoil momenta
- Both effects drop out near the on-shell extrapolation point

Tagging: polarized neutron structure

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 $\sim 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$

Conclusions

- Calculation of b_1 in standard convolution models
  - differences with older calcaultion
  - contributions from nuclear higher twist effects, account for in experimental exraction from the measured asymmetry
  - exotic mechanism contributing?
  - upcoming measurements at JLab12, possibilities at future facilities
- Tagged spectator DIS at an EIC with polarized deuteron
  - new possibilities to probe spin (41 structure functions)
  - pole extrapolation allows to extract neutron structure at the on-shell point, without nuclear effects
  - LDRD project at JLab, open to collaboration!
  - Lots of extensions possible (FSI, exclusive channels, other nuclei, EMC effect,...)