Theoretical overview of spectator tagging in DIS measurements

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in collaboration with Ch. Weiss
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JLab LDRD project on spectator tagging
1409.5768,1601.06665

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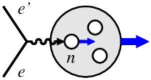
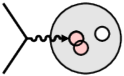
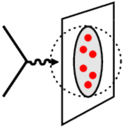
Light ions: physics objectives



- **Neutron** structure
  - flavor decomposition of quark PDFs/GPDs/TMDs
  - flavor structure of the nucleon sea
  - singlet vs non-singlet QCD evolution, leading/higher-twist effects



- Nucleon **interactions** in QCD
  - medium modification of quark/gluon structure
  - QCD origin of short-range nuclear force
  - nuclear gluons
  - coherence and saturation

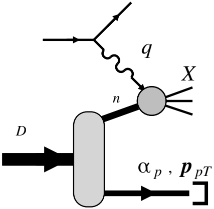


- **Imaging** nuclear bound states
  - imaging of quark-gluon degrees of freedom in nuclei through GPDs
  - clustering in nuclei

Need to control nuclear configurations that play a role in these processes

Tagging and deuteron

- Spectator tagging
  - Additional control over initial nuclear configuration
  - Pole extrapolation at low momenta
    $\rightarrow$ free neutron structure
  - Medium modifications at high momenta,
    but final-state interactions
  - Tagging non-nucleonic components (Δ isobars)
  - Especially suited for colliders with far-forward detectors [EIC $\rightarrow$ talk A. Jentsch 590. Thu 8AM]



- Deuteron
  - Lightest nuclear system (loosely bound)
  - Effective neutron target $\rightarrow$ **tagged A_{LL}**
  - Short-range NN force $\rightarrow$ **tagged A_{zz}**
  - First principle calculations of wf
  - Spin 1 (5 tensor polarization parameters), radial S- and D-wave.

Theoretical Formalism

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

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

  - Fracture functions, factorization theorems [Trentadue, Veneziano 93; Collins 97]

- Light-front structure of the deuteron
  - Natural for high-energy reactions as **off-shellness of nucleons** in LF quantization remains **finite**

- Dynamical model to express structure functions of the reaction
  - First step: impulse approximation (IA) model
  - Results for longitudinal, tensor spin asymmetries A_{LL}, A_{zz}
  - FSI corrections

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,

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

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

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

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

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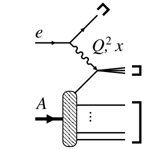
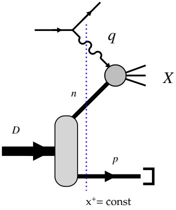
  - 23 SF unique to the spin 1 case (tensor pol.), 4 survive in inclusive (b_{1-4}) [Hoodbhoy, Jaffe, Manohar PLB'88]

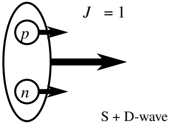
$$\begin{aligned}
F_T = T_{LL}\Big[& F_{UT_{LL},T} + \epsilon F_{UT_{LL},L} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_h F_{UT_{LL}}^{\cos\phi_h} + \epsilon\cos 2\phi_h F_{UT_{LL}}^{\cos 2\phi_h}\Big] \\
& + T_{LL} h \sqrt{2\epsilon(1-\epsilon)}\sin\phi_h F_{LT_{LL}}^{\sin\phi_h} \\
& + T_{L\perp}[\cdots]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

Theory: high-energy scattering with nuclei





- Interplay of two scales: high-energy scattering and low-energy nuclear structure. Virtual photon probes nucleus at fixed lightcone time $x^+ = x^0 + x^3$
- Scales can be separated using methods of light-front quantization and QCD factorization
- Tools for high-energy scattering known from ep
- Nuclear input: light-front momentum densities, spectral functions, overlaps with specific final states in breakup/tagging reactions
  - framework known for deuteron, can be extended to ^{3}He
  - still **low-energy** nuclear physics, just formulated differently



- Up to momenta of a few 100 MeV: dominated by ***NN***
- Can be evaluated in LFQM

  [Berestetsky, Frankfurt, Strikman, Terentev]
- Overlap with **on-shell** free two-nucleon state

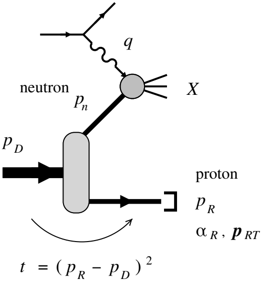
  $$p^i_{NN} = p^i_D \quad i = +, T; \quad p^-_{NN} \neq p^-_D$$

- Schrödinger (non-rel) like eq. for the wf components, rotational invariance recovered

$$\Psi_\lambda(\boldsymbol{k}, \lambda_p, \lambda_n) = \sqrt{E_k} \sum_{\lambda'_p \lambda'_n} \mathcal{D}^{\frac{1}{2}}_{\lambda_p \lambda'_p}[R_{fc}(k_1^\mu/m)] \mathcal{D}^{\frac{1}{2}}_{\lambda_n \lambda'_n}[R_{fc}(k_2^\mu/m)] \Phi_\lambda(\boldsymbol{k}, \lambda'_p, \lambda'_n)$$

- Differences with non-rel wave function:
  - appearance of the **Melosh rotations** to account for light-front quantized nucleon states
  - $\boldsymbol{k}$ is the rel. 3-momentum in the rest frame of the on-shell NN state

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

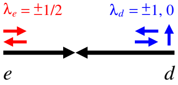
$$\sum_{\lambda,\lambda'} \rho_{\lambda\lambda'} W_D^{\mu\nu}(\lambda',\lambda) = 4(2\pi)^3 \frac{\alpha_R}{2-\alpha_R} \sum_i W_{N,i}^{\mu\nu} S_{d,i}\,,$$

All SF can be written as

$$F_{ij}^k = \{\text{kin. factors}\} \times \{F_{1,2}(\tilde{x},Q^2) \text{ or } g_{1,2}(\tilde{x},Q^2)\}$$
$$\times \{\text{bilinear in deuteron radial } f_0(k)\ [\text{S-wave}],\ f_2(k)\ [\text{D-wave}]\}$$

- In the IA the following structure functions are **zero** $\rightarrow$ 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]

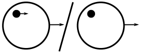
Polarized structure function: longitudinal asymmetry

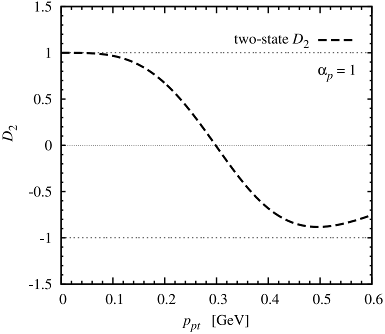


- Pole extrapolation of double spin asymmetry
  - Nominator
    $$d\sigma_{||} \equiv \frac{1}{4}\left[\mathrm{d}\sigma(+\tfrac{1}{2},+1) - \mathrm{d}\sigma(-\tfrac{1}{2},+1) - \mathrm{d}\sigma(+\tfrac{1}{2},-1) + \mathrm{d}\sigma(-\tfrac{1}{2},-1)\right]$$
  - Denominators: 2-state
    $$d\sigma_2 \equiv \frac{1}{4}\sum_{\Lambda_e}\left[\mathrm{d}\sigma(\Lambda_e,+1) + \mathrm{d}\sigma(\Lambda_e,-1)\right]$$
  - Asymmetries: **tensor polarization** enters in 2-state one
    $$A_{||,2} = \frac{d\sigma_{||}}{d\sigma_2}[\phi_h\,\mathrm{avg}] = \frac{F_{LS_L}}{F_T + \epsilon F_L + \frac{1}{\sqrt{6}}(F_{T_{LL}T} + \epsilon F_{T_{LL}L})}$$
- Impulse approximation yields in the Bjorken limit $\left[\alpha_p = \frac{2p_p^+}{p_D^+}\right]$
  $$A_{||,i} \approx \mathcal{D}_i(\alpha_p, |p_{pT}|)A_{||n} = \mathcal{D}_i(\alpha_p, |p_{pT}|)\frac{D_{||}g_{1n}(\tilde{x}, Q^2)}{2(1+\epsilon R_n)F_{1n}(\tilde{x}, Q^2)}$$

Nuclear structure factor $\mathcal{D}_2$

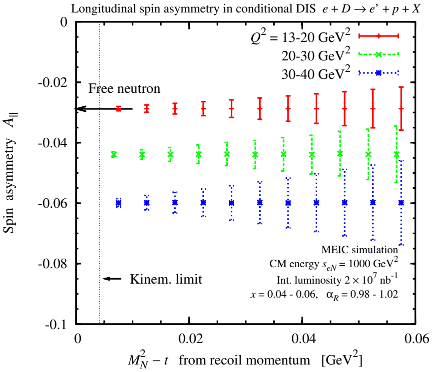
- Quantifies neutron depolarization due to nuclear structure
- Depends on spectator kinematics α_p, p_{pT}
- $\mathcal{D}_2 = \Delta S_d[\text{pure } +1]/S_d[\text{pure } +1]$ has **probabilistic interpretation**





WC, C. Weiss, PLB ('19); PRC ('20)

- Bounds: $-1 \leq \mathcal{D}_2 \leq 1$
- Due to lack of OAM $\mathcal{D}_2 \equiv 1$ for $p_T = 0$
- Clear contribution from D-wave at finite recoil momenta
- $\mathcal{D}_2$ close to unity at small recoil momenta
- 3-state (unpol) denominator less "nice"
- 2-state asymmetry is also easier experimentally!!



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

- Polarized deuteron and ^{3}He possible at EIC
- EIC simulations, spectator can be detected in far-forward detectors
- D-wave suppr. at on-shell point $\rightarrow$ neutron $\sim$ 100% polarized
- Precise measurements of neutron spin structure
- 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 $\sim 10^{34}\text{cm}^{-2}\text{s}^{-1}$

Tensor polarized observable A_{zz} [Frankfurt, Strikman '83]

- Analogue of $A_{LL} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$ for vector polarization ($\sim S_L$) is the tensor asymmetry

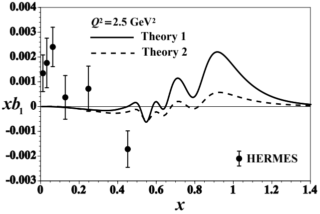
$$A_{zz} = \frac{\sigma^+ + \sigma^- - 2\sigma^0}{\sigma^+ + \sigma^- + \sigma^0}$$

$\rightarrow$ **no** electron polarization required.

- Requires all three polarization states; $A_{zz} \in [-2, 1]$ and $\sim T_{LL}$
- $e\vec{d}$: A_{zz} measured in different ranges of Bjorken $x = 2\frac{Q^2}{2(p_d q)}$, $x \in [0, 2]$:
  - elastic $x = 2$ ["T_{20}"]: NIKHEF ('98), ...
  - quasi-elastic $x > 1$: NIKHEF ('99), BLAST @ MIT-Bates ('17), future JLab12
  - DIS inclusive $x < 1$ ["b_1"]: Hermes @ DESY ('05), future JLab12

A_{zz} in inclusive DIS

- A_{zz} is proportional to tensor pol. structure function b_1 in scaling limit [Hoodbhoy, Jaffe, Manohar '89]
  - partonic density interpretation $b_1 = \frac{1}{2} \sum_q e_q^2 (q^0 - q^1)$
  - leading twist, QCD operator as in F_2, same evolution etc.
  - encodes dependence of unpol. quarks on nuclear interactions
    → "donut" vs "dumbbell"



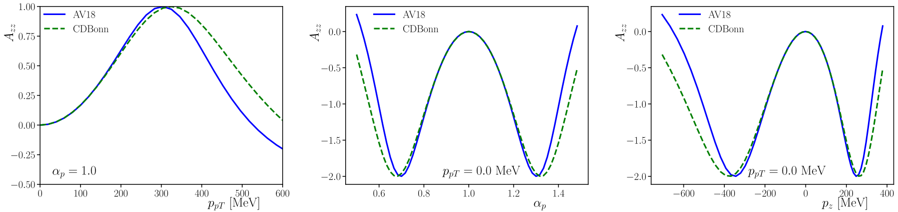
Cosyn, Dong, Kumano, Sargsian PRD'17

- Small A_{zz} values
  → averaging over initial nuclear confs.
- Mismatch theory / data → HT effects?
- Shadowing corrections at small x [Frankfurt,Strikman; Nikolaev,Schäfer '97; Edelmann,Piller,Weise '97]
- Hidden color + pions match data [Miller '16]

A_{zz} with spectator tagging

- Tensor polarization is sensitive to unpolarized quark distributions, partonic factor cancels out → ratio of LF densities remains

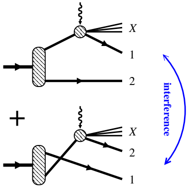
$$A_{zz}(\alpha_p, \boldsymbol{p}_T) = -\frac{\frac{f_0(k) f_2(k)}{\sqrt{2}} + \frac{f_2^2(k)}{4}}{f_0^2(k) + f_2^2(k)} (3\cos 2\theta_k + 1) \qquad \alpha_p = \left(1 + \frac{k^3}{\sqrt{m^2 + k^2}}\right); \quad \boldsymbol{p}_{pT} = \boldsymbol{k}_T$$



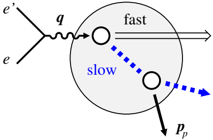
- Maximal A_{zz} at $f_2(k) = \sqrt{2} f_0(k)$, not the S wave node!
- $A_{zz} = 1$ at $\alpha_p = 1$ ($\theta_k = \pi/2$) → pure $m = \pm 1$)
  $A_{zz} = -2$ at $p_{pT} = 0$ ($\theta_k = 0, \pi$) → pure $m = 0$
- Needs quantification of FSI effects

→ Constraints on deuteron D-wave

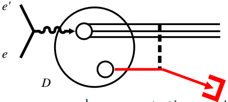
Final-state interactions: three physical pictures



shadowing, low x



DIS regime, intermediate x



subasymptotic regime:
low Q^2, high x

- Can be min/maximized depending on spectator kinematics
- 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
    → FSI like in **QE deuteron breakup**
  - Input needed from nucleon target fragmentation data
    → **possible at EIC**
    [M. Strikman, Ch. Weiss PRC'18]
- Rescattering of resonance-like structure in eikonal approximation [Deeps,BONuS].

WC,M. Sargsian arXiv:1704.06117

Conclusions

- Unique observables with **polarized deuteron**: free neutron spin structure, tensor polarization
- Extraction of **nucleon spin structure** in a wide kinematic range at EIC
- Tagged tensor asymmetry A_{zz} can be made maximal (-2,1) compared to small inclusive one
  $\rightarrow$ constraints on **D-wave**.
- **Final-state interactions** need to be further quantified for spin-dependent observables (but drop out for pole extrapolation)
- Lots of extensions to be explored: ^{3}He, exclusive channels, tagged SIDIS, ...