Tagging with polarized deuteron

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in collaboration with Ch. Weiss
1906.11119,2006.03033
JLab LDRD project on spectator tagging
1409.5768,1601.06665

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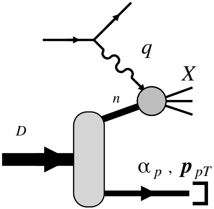
Intro

- Deuteron
  - Lightest nuclear system (loosely bound)
  - Effective neutron target
  - Short-range NN force → Talk W. Boeglin
  - First principle calculations
  - Spin 1
- Spectator tagging
  - Additional control over initial nuclear configuration
  - Pole extrapolation at low momenta → free neutron structure [talk S. Kuhn]
  - Medium modifications at high momenta [talk Kutz], **but** final-state interactions
  - Deuteron reaction model calculable
  - Especially suited for colliders with far-forward detectors → talks Friday PM



Polarized spin 1 particle

- polarization states $m = \pm 1, \mathbf{0}$
- 3 by 3 density matrix in a basis of spin 1 states polarized along the collinear virtual photon-target axis

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

- **Vector** (3) and **tensor** (5) polarization parameters

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

- Can be formulated in **covariant** manner
$\rightarrow \rho^{\mu\nu} = \sum_{\lambda\lambda'} \rho_{\lambda\lambda'}\epsilon^{\mu}(p,\lambda)\epsilon^{*\nu}(p,\lambda') = \frac{1}{3}\left(-g^{\mu\nu} + \frac{p^\mu p^\nu}{p^2}\right) + \frac{i}{2M}\epsilon^{\mu\nu\rho\sigma}p_\rho s_\sigma - t^{\mu\nu}$
Cfr. Spin 1/2
$\rightarrow \rho = \sum_{\lambda\lambda'} \rho_{\lambda\lambda'} u(p,\lambda)\bar{u}(p,\lambda') = \frac{1}{2}(\not{p} + m)(1+\gamma_5 \not{s})$

Tensor polarization: physics interest

- Tensor polarized observables are proportional to deuteron D-wave [**Frankfurt, Strikman 80s**]
  - short-range nature of the NN force
  - universality of short-range correlations for medium and heavy nuclei
- Admits gluon transversity in DIS [**Jaffe, Manohar '89**] → talk Shanahan
  - arises from nuclear interactions
  - $\Delta L = 2$ to compensate gluon helicity flip, not possible for nucleon
- Spin-orbit phenomena beyond the nucleon
- Exotic effects (hidden color etc.) [**Miller, CR Ji, Brodsky**]
- Tensor polarization of the quark sea [**Kumano**]
- Deuteron polarimetry

Theoretical Formalism

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

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

- 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 (unpolarized [Strikman, Weiss PRC '18], $\longrightarrow$ talk Weiss)

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)]

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

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

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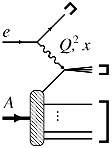
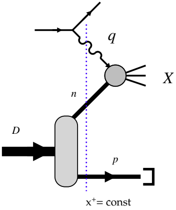
  - 23 SF unique to the spin 1 case (tensor pol.), 4 survive in inclusive (b_{1-4}) [Hoodbhoy, Jaffe, Manohar PLB'88]

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

Theory: high-energy scattering with nuclei

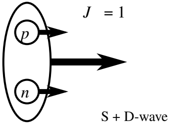




→ talks Strikman, Weiss

- 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

Deuteron light-front wave function



- 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 → talk Strikman

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

- 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

Effective neutron spin density matrix

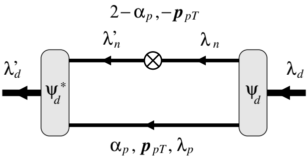
- Deuteron LF wavefunction:

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

- 4D covariant formulation: [Kondryatchuk, Strikman '83]

$$\Psi_{\lambda_d}(\alpha_p,\boldsymbol{p}_{pT},\lambda_p,\lambda_n) = \bar{u}_{\rm LF}(p_n\lambda_n)\Gamma_\alpha(p_p,p_n)v_{\rm LF}(p_p,\lambda_p)\epsilon^\alpha_{pn}(p_{pn},\lambda_d)$$

- Matrix elements of nucleon operators



$$\langle\hat{O}_n\rangle = \int\frac{d\alpha_p}{\alpha_p}d^2p_{pT}\frac{2\mathrm{tr}[\Pi_n\Gamma_n]}{(2-\alpha_p)} \qquad \alpha_p = 2p_p^+/p_d^+$$

- Effective neutron spin density matrix (cfr. parton correlators in QCD)

$$\Pi_n = (\rho_{pn})^{\alpha\beta}(\not{p}_n+m)\Gamma_\alpha(\not{p}_p-m)\Gamma_\beta(\not{p}_n+m)$$

Nucleon LF momentum distributions

- Can be split into unpolarized, vector and tensor polarization terms:

$$\Pi_n[\text{unpol}] = \frac{1}{2}(\not{p}_n + m)(f_0^2 + f_2^2)\,,$$
$$\Pi_n[\text{vector}] = \frac{1}{2}(\not{p}_n + m)\not{s}_n(\boldsymbol{S}_d, \boldsymbol{k})\gamma_5\,,$$
$$\Pi_n[\text{tensor}] = -\frac{1}{2}(\not{p}_n + m)(\boldsymbol{k}\,T_d\,\boldsymbol{k})\frac{3}{k^2}\left(2f_0 + \frac{f_2}{\sqrt{2}}\right)\frac{f_2}{\sqrt{2}}\,.$$

- Allows for the definition of **nucleon** light-front momentum distributions

Helicity independent	$S_d(\alpha_p, \boldsymbol{p}_{pT}) = \frac{\text{tr}[\Pi_n \gamma^+]}{(2-\alpha_p)^2 p_d^+}\,,$
Helicity dependent	$\Delta S_d(\alpha_p, \boldsymbol{p}_{pT}) = \frac{\text{tr}[\Pi_n(-\gamma^+\gamma_5)]}{(2-\alpha_p)^2 p_d^+}\,,$
Transversity	$\Delta_T S_d(\alpha_p, \boldsymbol{p}_{pT}) = \frac{\text{tr}[\Pi_n(i\sigma^{i+}\gamma_5)]}{(2-\alpha_p)^2 p_d^+}\,,$

- S_d receives contributions from Π_n[unpol] and Π_n[tensor]
  $\Delta S_d, \Delta_T S_d$ receives contributions from Π_n[vector]
- Tensor polarization does not induce nucleon helicity dependence

Nucleon LF momentum distributions (II)

- LF momentum distributions obey sum rules
  - baryon

$$\int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} S_d(\alpha_p, \boldsymbol{p}_{pT})[\text{unpol}] = 1\,,$$

$$\int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} S_d(\alpha_p, \boldsymbol{p}_{pT})[\text{tensor}] = 0\,,$$

  - momentum

$$\int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} (2-\alpha_p) S_d(\alpha_p, \boldsymbol{p}_{pT})[\text{unpol}] = 1\,,$$

$$\int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} (2-\alpha_p) S_d(\alpha_p, \boldsymbol{p}_{pT})[\text{tensor}] = 0$$

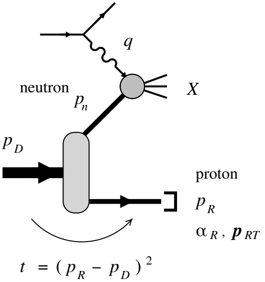
  - axial

$$\int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} \Delta S_d(\alpha_p, \boldsymbol{p}_{pT})[\text{vector}] = S_d^z \frac{g_{Ad}}{2g_A}\,,$$

$$1 - \frac{3}{2}\omega_2 = \frac{g_{Ad}}{2g_A}\,.$$

$\rightarrow$ cfr correction in inclusive polarized ***ed*** DIS

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

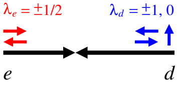
$$\sum_{\lambda,\lambda'} \rho_{\lambda\lambda'} W_D^{\mu\nu}(\lambda', \lambda) = 4(2\pi)^3 \frac{\alpha_R}{2-\alpha_R} \sum_i W_{N,i}^{\mu\nu} S_{d,i} \,,$$

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]

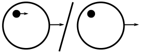
Polarized structure function: longitudinal asymmetry

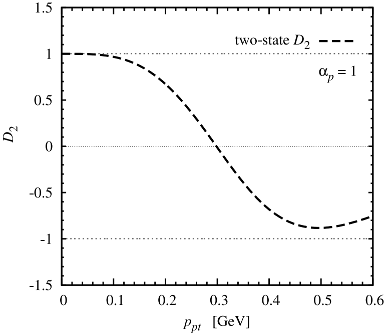


- Pole extrapolation of double spin asymmetry
  - Nominator
    $d\sigma_{||} \equiv \frac{1}{4}\left[\mathrm{d}\sigma(+\tfrac{1}{2},+1) - \mathrm{d}\sigma(-\tfrac{1}{2},+1) - \mathrm{d}\sigma(+\tfrac{1}{2},-1) + \mathrm{d}\sigma(-\tfrac{1}{2},-1)\right]$
  - Denominators: 2-state
    $$d\sigma_2 \equiv \frac{1}{4}\sum_{\Lambda_e}\left[\mathrm{d}\sigma(\Lambda_e,+1) + \mathrm{d}\sigma(\Lambda_e,-1)\right]$$
  - Asymmetries: **tensor polarization** enters in 2-state one
    $$A_{||,2} = \frac{d\sigma_{||}}{d\sigma_2}[\phi_h \,\text{avg}] = \frac{F_{LS_L}}{F_T + \epsilon F_L + \frac{1}{\sqrt{6}}(F_{T_{LL}T} + \epsilon F_{T_{LL}L})}$$
- 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**

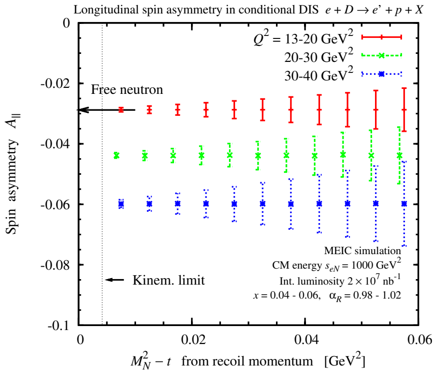




WC, C. Weiss, PLB ('19); PRC ('20)

- 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!!

Tagging: simulations of $A_{||}$



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

- 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

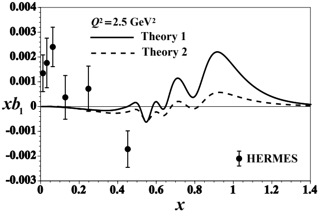
$$A_{zz} = \frac{\sigma^+ + \sigma^- - 2\sigma^0}{\sigma^+ + \sigma^- + \sigma^0}$$

$\rightarrow$ **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 $x = 2\,\frac{Q^2}{2(p_d q)}$, $\quad x \in [0, 2]$:
  - 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 $\rightarrow$ "donut" vs "dumbbell"



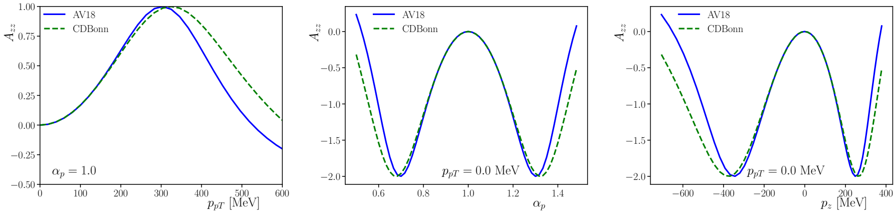
Cosyn, Dong, Kumano, Sargsian PRD'17

- Small A_{zz} values $\rightarrow$ averaging over initial nuclear confs.
- Mismatch theory / data $\rightarrow$ 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

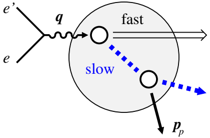
$$A_{zz}(\alpha_p, \boldsymbol{p}_T) = -\frac{\frac{f_0(k) f_2(k)}{\sqrt{2}} + \frac{f_2^2(k)}{4}}{f_0^2(k) + f_2^2(k)} (3\cos 2\theta_k + 1) \qquad \alpha_p = \left(1 + \frac{k^3}{\sqrt{m^2 + k^2}}\right); \quad \boldsymbol{p}_{pT} = \boldsymbol{k}_T$$

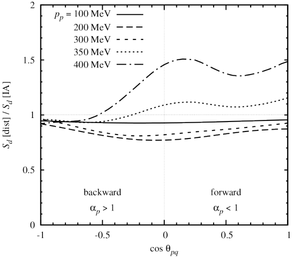


- Maximal A_{zz} at $f_2(k) = \sqrt{2} f_0(k)$, not the S wave node!
- $A_{zz} = 1$ at $\alpha_p = 1$ ($\theta_k = \pi/2$) → pure $m = \pm 1$)
  $A_{zz} = -2$ at $p_{pT} = 0$ ($\theta_k = 0, \pi$) → pure $m = 0$
- Needs quantification of FSI effects

→ Constraints on deuteron D-wave

Final-state interactions in tagging





Strikman, Weiss, PRC7 035209 ('18)

- **Issue** in tagging: DIS products can interact with spectator → rescattering, absorption
- Dominant contribution at intermediate $x \sim 0.1 - 0.5$ from "**slow**" hadrons that hadronize inside nucleus
- Measure nucleon fracture functions [EIC]
- Features of the FSI of slow hadrons with spectator nucleon are similar to what is seen in quasi-elastic deuteron breakup.
- FSI vanish at the pole → pole extrapolation **still feasible**

Conclusions

- Unique observables with **polarized deuteron**: free neutron spin structure, tensor polarization
- Natural and intuitive interpretation through effective neutron spin density matrix [deuteron polarization, nuclear structure]
- 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 (but drop out for pole extrapolation)
- Lots of extensions to be explored...