Spectator tagging with polarized deuteron

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JLab tensor SIDIS workshop

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JLab LDRD project on EIC spectator tagging
1409.5768,1601.06665

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Deuteron tensor polarized observables

- Many structures appear in cross section etc.
  $\rightarrow$ Challenging to disentangle
- Direction of polarization relative to scattering plays a role

$$\sigma = \sigma_U(1 + P\, A^V(N_{\mathrm{pol}}) + Q\, A^T(N_{\mathrm{pol}}))$$

  $\rightarrow$ Effective polarizations

  [See also `2410.12764`]

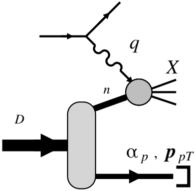
- Tensor polarization needs deuteron D-wave ($L = 2$)

$$\sim \left(2f_0(k) + \frac{f_2(k)}{\sqrt{2}}\right) \frac{f_2(k)}{\sqrt{2}}$$

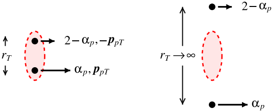
  $\rightarrow$ **Small** when averaged over all internal momenta

- In inclusive measurement nuclear correction is an important systematic uncertainty

Deuteron Spectator tagging



$\alpha_p = 2\frac{p_p^+}{p_d^+} = 2\frac{E_p+p_p^z}{E_d+p_d^z}$



$p_{pT}^2 > 0$
physical region

$p_{pT}^2 \to -a_T^2$
on-shell extrapolation

- Detection of nucleon in target fragmentation region: **"spectator"**
- Interaction w photon can be elastic, DIS, hard exclusive, SIDIS, etc.
- **Control** over your initial nuclear state
  → Active nucleon identified, create effective targets
- Spectator can **reinteract** with other final-state hadrons
  → "Simple" for deuteron
- Spectator kinematics gives handle on initial state
  → **On-shell extrapolation** for free nucleon
  [Sargsian, Strikman, PLB05]
  → Larger momenta for medium modifications
- Measurements with fixed target [BONuS, Deeps, LAD, BAND, Alert,..] and collider [EIC] with large acceptance far forward detectors

Tagged DIS: Theoretical Formalism

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

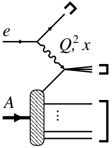
$$\vec{e} + \vec{T} \to e' + X + h$$

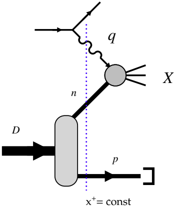
  - 41 $(18 + 23)$ structure functions

- 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 all SF: deuteron LF distributions $\times$ nucleon collinear pdfs
  - FSI corrections

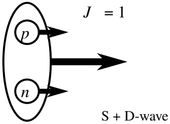
High-energy scattering with nuclei [Frankfurt,Strikman 80s+]





- 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 but challenges
  - still **low-energy** nuclear physics, just formulated differently

Deuteron light-front wave function

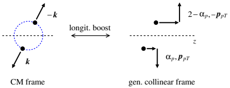


- Up to momenta of a few 100 MeV: dominated by ***NN***
- Can be evaluated in LFQM [Berestetsky, Frankfurt, Strikman, Terentev]
- Overlap with **on-shell** free two-nucleon state

- 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:
  - **Melosh rotations** to account for light-front spin
  - $\boldsymbol{k}$ is the rel. 3-momentum in the rest frame of the on-shell NN state



- Allows for the definition of nucleon LF momentum distributions ∼ nucleon TMDs in deuteron

Unpolarized	$P_{[U]}(\alpha_p,\boldsymbol{p}_{pT}\|U,S_d,T_d)$	γ^+	deut: unpol, tensor
L polarized	$P_{[S_L]}(\alpha_p,\boldsymbol{p}_{pT}\|(U,S_d,T_d)$	$\gamma^+\gamma_5$	deut: vector
T polarized	$P_{[S_T]}(\alpha_p,\boldsymbol{p}_{pT}\|U,S_d,T_d)$	$i\sigma^{i+}\gamma_5$	deut: vector

Nucleon LF momentum distributions

- Unpolarized, helicity independent

$$P_{[U,U]} = \frac{f_0^2(k) + f_2^2(k)}{2+\alpha_p}$$

- Tensor polarized, helicity independent: needs D-wave, $\sim Y_{2m}(\theta, 0)$

$$P_{[T_{LL},U]}(\alpha_p, \boldsymbol{p}_{pT}) = -\frac{1}{2+\alpha_p}\left(2f_0 + \frac{f_2}{\sqrt{2}}\right)\frac{f_2}{\sqrt{2}}\,\frac{3}{2}(3\cos^2\theta_k - 1),$$

$$P_{[T_{LT},U]}(\alpha_p, \boldsymbol{p}_{pT}) = -\frac{1}{2+\alpha_p}\left(2f_0 + \frac{f_2}{\sqrt{2}}\right)\frac{f_2}{\sqrt{2}}\,6\cos\theta_k\sin\theta_k,$$

$$P_{[T_{TT},U]}(\alpha_p, \boldsymbol{p}_{pT}) = -\frac{1}{2+\alpha_p}\left(2f_0 + \frac{f_2}{\sqrt{2}}\right)\frac{f_2}{\sqrt{2}}\,3\sin^2\theta_k,$$

- L/T nucleon polarized

$$P_{[S_L,S_L]}(\alpha_p, \boldsymbol{p}_{pT}) = \frac{1}{2+\alpha_p}\left(f_0 - \frac{f_2}{\sqrt{2}}\right)\left[A_{[=]}(\boldsymbol{k})\left(f_0 - \frac{f_2}{\sqrt{2}}\right) + B_{[=]}(\boldsymbol{k})\left(f_0 + \sqrt{2}f_2\right)\right]$$

$$P_{[S_T,S_L]}(\alpha_p, \boldsymbol{p}_{pT}) = \frac{1}{2+\alpha_p}\left(f_0 - \frac{f_2}{\sqrt{2}}\right)\left[A_{[\neq]}(\boldsymbol{k})\left(f_0 - \frac{f_2}{\sqrt{2}}\right) - B_{[\neq]}(\boldsymbol{k})\left(f_0 + \sqrt{2}f_2\right)\right]$$

$$P_{[S_L,S_T]}(\alpha_p, \boldsymbol{p}_{pT}) = \frac{1}{2+\alpha_p}\left(f_0 - \frac{f_2}{\sqrt{2}}\right)\left[B_{[\neq]}(\boldsymbol{k})\left(f_0 - \frac{f_2}{\sqrt{2}}\right) - A_{[\neq]}(\boldsymbol{k})\left(f_0 + \sqrt{2}f_2\right)\right]$$

$$P^{||}_{[S_T,S_T]}(\alpha_p, \boldsymbol{p}_{pT}) = \frac{1}{2+\alpha_p}\left(f_0 - \frac{f_2}{\sqrt{2}}\right)\left[B_{[=]}(\boldsymbol{k})\left(f_0 - \frac{f_2}{\sqrt{2}}\right) + A_{[=]}(\boldsymbol{k})\left(f_0 + \sqrt{2}f_2\right)\right]$$

- Remarkable symmetry between helicity and transversity
  - $\rightarrow$ Rotational invariance + relativistic spin effects

Nucleon LF momentum distributions: Sum Rules

- baryon

$$\int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} P_{[U,U]}(\alpha_p, \boldsymbol{p}_{pT}) = 1\,,$$
$$\int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} P_{[T,U]}(\alpha_p, \boldsymbol{p}_{pT}) = 0\,,$$

- momentum

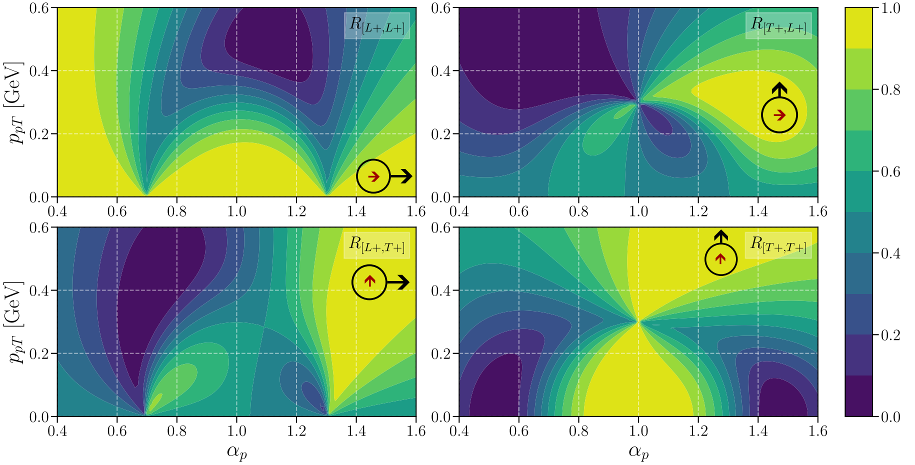
$$\int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} (2-\alpha_p) P_{[U,U]}(\alpha_p, \boldsymbol{p}_{pT}) = 1\,,$$
$$\int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} (2-\alpha_p) P_{[T,U]}(\alpha_p, \boldsymbol{p}_{pT}) = 0$$

- axial

$$\int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} P_{[S_L,S_L]}(\alpha_p, \boldsymbol{p}_{pT}) = S_d^z \frac{g_{Ad}}{2g_A}\,, \qquad \int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} P_{[S_L,S_T]}(\alpha_p, \boldsymbol{p}_{pT}) = \epsilon_{S_L}\,,$$
$$\int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} P^{||}_{[S_T,S_L]}(\alpha_p, \boldsymbol{p}_{pT}) = \epsilon_{S_T} \approx -\epsilon_{S_L}\,, \qquad \int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} P_{[S_T,S_T]}(\alpha_p, \boldsymbol{p}_{pT}) = S_d^T \frac{g_{Ad}}{2g_A}\,,$$
$$1 - \frac{3}{2}\omega_2 = \frac{g_{Ad}}{2g_A}\,.$$

$\rightarrow$ cfr correction in inclusive polarized ed DIS

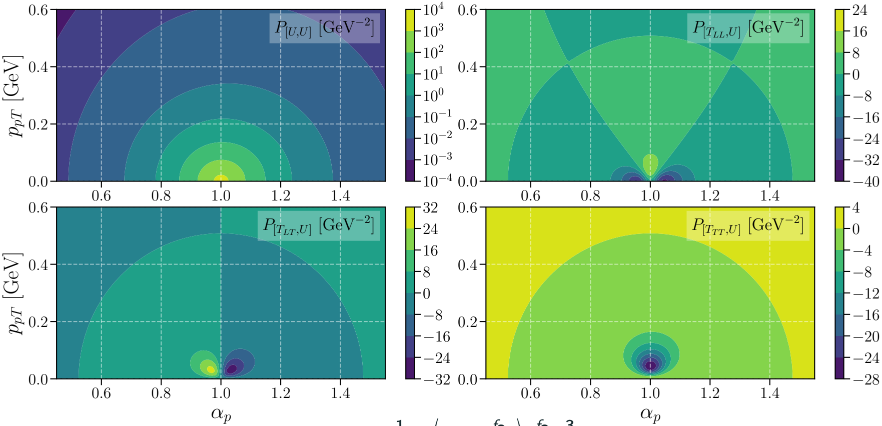
Probabilistic Distributions for pure states



Probabilistic Distributions for pure states

- At small momenta S-wave dominates
  $\rightarrow$ polarization of nucleon is transferred from deuteron one
- Depolarization at larger momenta
  $\rightarrow$ D-wave
- Limits at $p_{dT} = 0$
  $\rightarrow$ on-shell extrapolation
- Relativistic spin effects
  $\rightarrow$ sideways polarization
- Positivity remains for any **mixed deuteron state**

Tensor polarized distributions



$$P_{[T_{LL},U]}(\alpha_p, \boldsymbol{p}_{pT}) = -\frac{1}{2+\alpha_p}\left(2f_0 + \frac{f_2}{\sqrt{2}}\right)\frac{f_2}{\sqrt{2}}\,\frac{3}{2}(3\cos^2\theta_k - 1),$$

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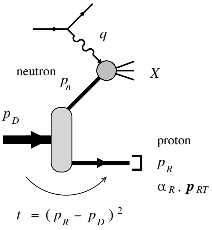
Tagged DIS with deuteron: model for the IA

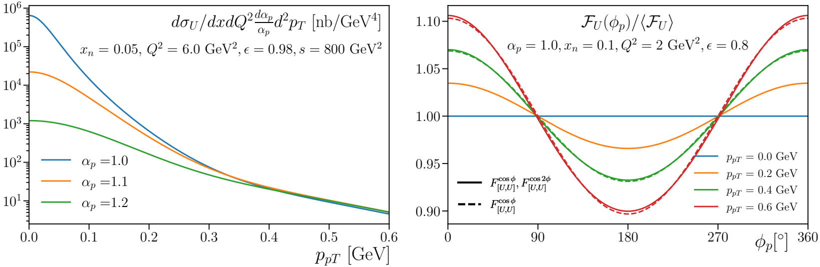


- Hadronic tensor can be written as a product of nucleon hadronic tensor with deuteron light-front densities

All SF can be written as

$$F^k_{ij} = \{\text{kin. factors}\} \times \{F_{1,2}(\tilde{x}, Q^2) \text{ or } g_{1,2}(\tilde{x}, Q^2)\} \times \{P_{[U,U]}, P_{[T,U]} \text{ or } P_{[S,S]}\}$$

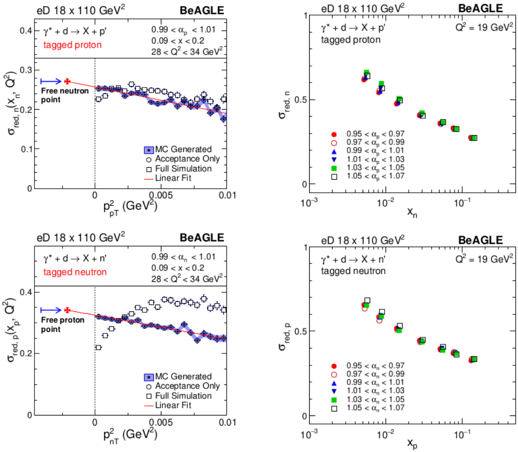
- In the IA the following structure functions are **zero** → sensitive to FSI
  - beam spin asymmetry $[F_{LU}^{\sin\phi_h}]$
  - target vector polarized single-spin asymmetry [8 SFs]
  - target tensor polarized double-spin asymmetry [7 SFs]
- Applied in studies of F_2 and tensor and vector polarized asymmetries `[1906.11119,2006.03033,2108.08314, 2603.23699, 2603.23700, etc.]`



- Sizable rates
- Drops fast with α_p, p_{pT}
- ϕ-modulations are power suppressed (p_{pT}/Q)
- Verification of reaction dynamics
- Pole extrapolation: unpolarized neutron structure

On-shell extrapolation of F_{2N}

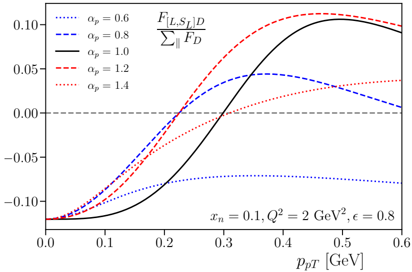
$$F_{2d} = [2(2\pi)^3]\, S_d(\alpha_p, \boldsymbol{p}_{pT})[\text{unpol}]\, F_{2n}(\tilde{x}, Q^2)$$

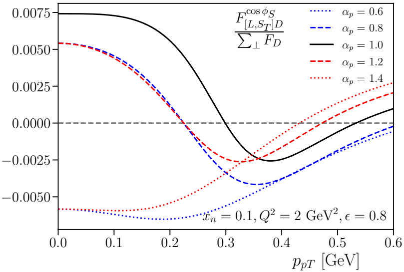


Detailed simulations for EIC [Jentsch,Tu,Weiss, PRC 21]

Vector pol double asymmetries (ϕ_p-integrated

- $A^V = D_{[S_L]} \frac{F_{[LS_L]}}{\sum F} \sim \frac{g_{1n}}{F_{1n}}$ $\qquad$ $A^V_\perp = D_{\perp[S_L]} \frac{F_{[LS_L]}}{\sum_\perp F} + D_{\perp[S_T]} \frac{F^{\cos\phi_S}_{[LS_T]}}{\sum_\perp F}$





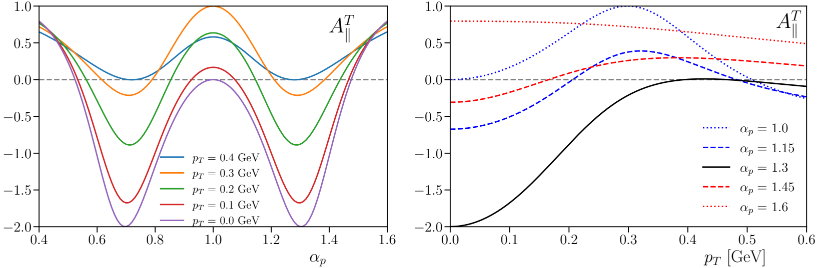
- Pole extrapolation of polarized neutron structure g_{1n}, g_{2n}
- At larger momenta: polarized (tagged) EMC effect

Tagged Tensor asymmetry

- No more averaging → nucleon (unpol.) DIS part cancels!

$$A_{\|}^{T} = -2A_{\perp}^{T} \stackrel{LP}{=} \frac{\left(2f_0 + \frac{1}{\sqrt{2}} f_2\right) \frac{1}{\sqrt{2}} f_2}{f_0^2 + f_2^2} \left(1 - 3\cos^2\theta_k\right).$$

- Maximal $A^T = \{-2, 1\}$ can be reached at D/S ratio $f_2/f_0 = \{\sqrt{2}, -\frac{1}{\sqrt{2}}\}$
- Constrains deuteron wf
- Needs FSI corrections (can be sizeable)



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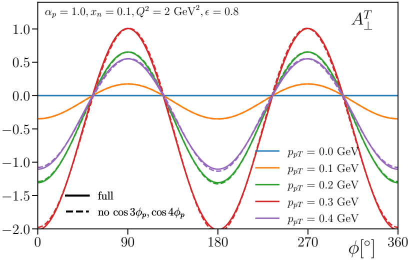

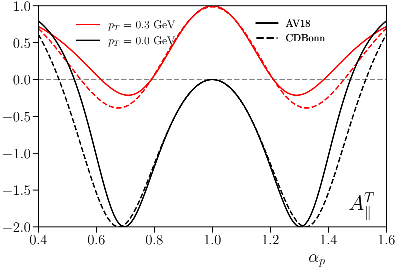

Outlook & Conclusions

- Tagged reactions on deuteron have unique capabilities
  $\rightarrow$ control over nuclear effects
- Light-front is natural picture for high-energy nuclear scattering
- Deuteron structure can be quantified using polarized LF distributions
  $\rightarrow$ "our" TMDs (of nucleons in deuteron)
- Interesting relativistic spin effects
- Creates phi-dependent structures, spin-orbit effects etc.
- In proper reaction theory FSI need to be accounted for.
  $\rightarrow$ Distorted momentum distributions
- Extensions: tagged SIDIS/exclusive, tagging beyond proton, $A > 2$ etc.
- Lots of interesting physics opportunities and work to be done...