Light-front distributions of the polarized deuteron

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in collaboration with Ch. Weiss
1906.11119,2006.03033, in preparation
JLab LDRD project on EIC spectator tagging
1409.5768,1601.06665
Builds on
Frankfurt, Kondratyuk, Strikman,...80s+

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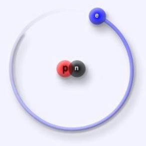
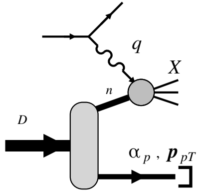
Deuteron

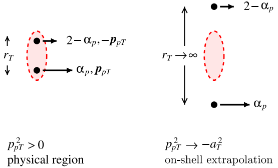


- Simplest non-trivial nucleus: bound *pn* system
  → loosely bound, 2.2 MeV binding energy
- Spin 1
  → 5 additional tensor polarizations
- Ab initio wave functions available
  → radial S and D wave
- Physics interest
  - Neutron structure, flavor decomposition
    → free neutron?
  - Short-range *NN* interaction
  - Influence of nuclear interactions on partonic properties
    → which nuclear configurations
  - Tomography of bound nuclear states, bound nucleon
    → coherent, incoherent exclusive reactions
  - Non-nucleonic configurations
    → $\Delta\Delta$ components

Deuteron Spectator tagging



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



- 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
  → 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

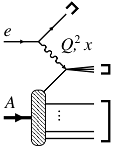
$$\vec{e} + \vec{T} \to e' + X + h$$

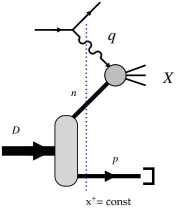
  - 41 $(18 + 23)$ structure functions

- 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

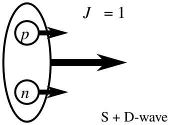
High-energy scattering with nuclei [Frankfurt,Strikman 80s+]





- 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

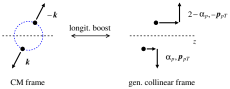
Deuteron light-front wave function



- 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

Helicity independent	$P_{[U]}(\alpha_p, \boldsymbol{p}_{pT}\vert U, S_d, T_d)$	γ^+	deut: unpol, tensor
Helicity dependent	$P_{[S_L]}(\alpha_p, \boldsymbol{p}_{pT}\vert(U, S_d, T_d)$	$\gamma^+\gamma_5$	deut: vector
Transversity	$P_{[S_T]}(\alpha_p, \boldsymbol{p}_{pT}\vert U, S_d, T_d)$	$i\sigma^{i+}\gamma_5$	deut: vector

Nucleon LF momentum distributions

- Unpolarized, helicity independent

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

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

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

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

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

- Vector polarized, helicity and transversity

$$P_{[S_L,S_L]}(\alpha_p, \boldsymbol{p}_{pT}) = \left(f_0 - \frac{f_2}{\sqrt{2}}\right)\left[F_1(\boldsymbol{k})\left(f_0 - \frac{f_2}{\sqrt{2}}\right) + F_2(\boldsymbol{k})\left(f_0 + \sqrt{2}f_2\right)\right]$$

$$P_{[S_T,S_L]}(\alpha_p, \boldsymbol{p}_{pT}) = \left(f_0 - \frac{f_2}{\sqrt{2}}\right)\left[U_1(\boldsymbol{k})\left(f_0 - \frac{f_2}{\sqrt{2}}\right) - U_2(\boldsymbol{k})\left(f_0 + \sqrt{2}f_2\right)\right]$$

$$P_{[S_L,S_T]}(\alpha_p, \boldsymbol{p}_{pT}) = \left(f_0 - \frac{f_2}{\sqrt{2}}\right)\left[-U_1(\boldsymbol{k})\left(f_0 - \frac{f_2}{\sqrt{2}}\right) + U_2(\boldsymbol{k})\left(f_0 + \sqrt{2}f_2\right)\right]$$

$$P^{||}_{[S_T,S_T]}(\alpha_p, \boldsymbol{p}_{pT}) = \left(f_0 - \frac{f_2}{\sqrt{2}}\right)\left[F_1(\boldsymbol{k})\left(f_0 - \frac{f_2}{\sqrt{2}}\right) + F_2(\boldsymbol{k})\left(f_0 + \sqrt{2}f_2\right)\right]$$

- Remarkable symmetry between helicity and transversity
  → 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

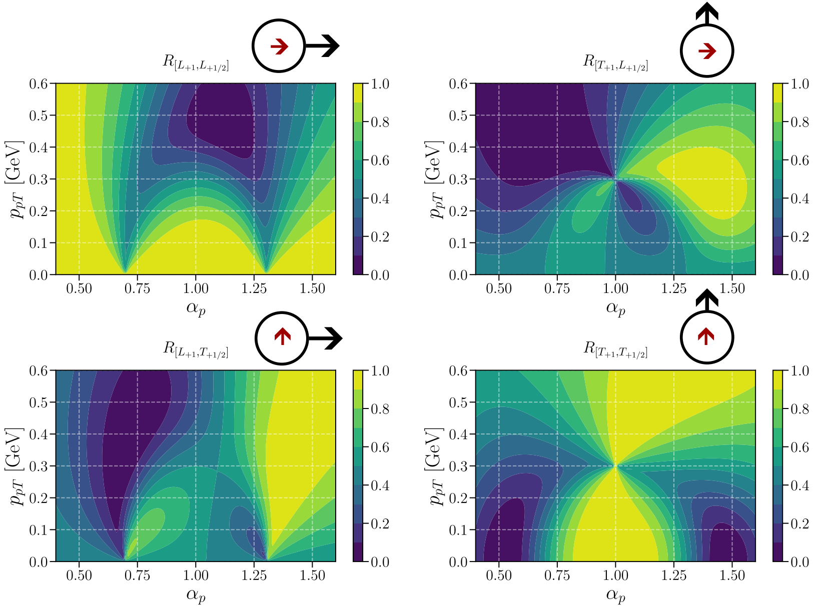
$$\int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} (2-\alpha_p) P_{[U,U]}(\alpha_p, \boldsymbol{p}_{pT}) = 1\,,$$
$$\int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} (2-\alpha_p) P_{[T,U]}(\alpha_p, \boldsymbol{p}_{pT}) = 0$$

- axial

$$\int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} P_{[S_L,S_L]}(\alpha_p, \boldsymbol{p}_{pT}) = S_d^z \frac{g_{Ad}}{2g_A}\,, \qquad \int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} P_{[S_L,S_T]}(\alpha_p, \boldsymbol{p}_{pT}) = 0,$$
$$\int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} P^{||}_{[S_T,S_L]}(\alpha_p, \boldsymbol{p}_{pT}) = 0\,, \qquad \int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} P^{||}_{[S_T,S_T]}(\alpha_p, \boldsymbol{p}_{pT}) = S_d^T \frac{g_{Ad}}{2g_A},$$
$$1 - \frac{3}{2}\omega_2 = \frac{g_{Ad}}{2g_A}\,.$$

$\rightarrow$ cfr correction in inclusive polarized ed DIS

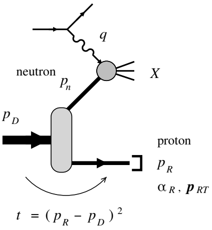
Probabilistic Distributions for pure states



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**

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

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

- 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, etc.]`

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
- Lots of interesting physics opportunities ...

Join us at POETIC next February 24–28

Physics Opportunities at an Electron-Ion Collider XI

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POETIC XI, the eleventh international conference on the 'Physics Opportunities at an Electron-Ion Collider', follows POETIC X which took place at the iICTP-SAIFR, São Paulo, Brazil in May 2023.

The primary goal of the conference is to continue the advancement of the field of the future Electron-Ion Collider (EIC) physics which was granted Critical Decision 3A (CD-3A) by the U.S. Department of Energy (DOE) and will be built at Brookhaven National Lab in New York in partnership with the Jefferson Lab (JLab). This collider will be a first-of-its-kind research machine and will push the limits of our knowledge of quantum chromo dynamics, accelerator science, particle detector design, high-performance computing and more.

Starts 24 Feb 2025, 09:00
Ends 28 Feb 2025, 18:00
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