Physics opportunities with light ions at the EIC

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POETIC 23, Sao Paulo

Why are light ions interesting?

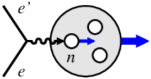
- Measurements with light ions address essential parts of the EIC physics program
  - neutron structure
  - nucleon interactions
  - nuclear tomography
  - coherent phenomena

- Light ions have unique features
  - polarized beams, different spins
  - breakup measurements & tagging
  - first principle theoretical calculations of initial state

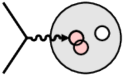
- Intersection of two communities
  - high-energy scattering
  - low-energy nuclear structure

Use of light ions for high-energy scattering and QCD studies remains largely underexplored

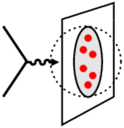
Light ions at EIC: physics objectives



- **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

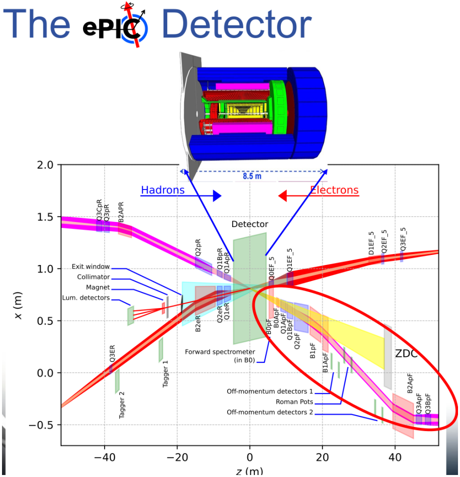


- Nucleon **interactions** in QCD
  - medium modification of quark/gluon structure
  - QCD origin of short-range nuclear force
  - nuclear gluons
  - coherence and saturation



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

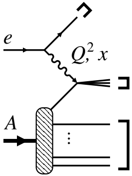
Need to control nuclear configurations that play a role in these processes

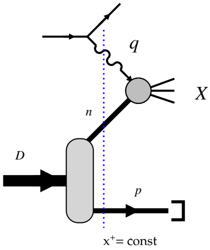


A. Jentsch, ePIC collab. meeting

- Set of far-forward detectors
- Design and engineering challenge
- Useful across EIC physics program
  - exclusive coherent/incoherent diffraction
  - inclusive diffraction
  - *ep* target fragmentation
  - pion and kaon structure
- Light ions: measure breakup, “tag” particles
- Complementarity with second IR

Theory: high-energy scattering with nuclei

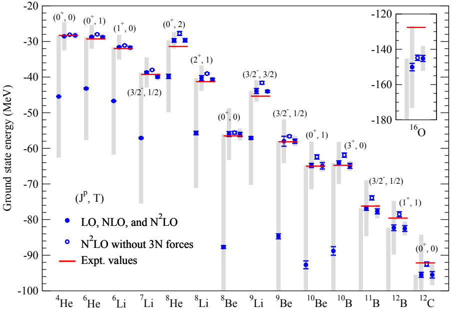




- Interplay of two scales: high-energy scattering and low-energy nuclear structure. Virtual photon probes nucleus at fixed lightcone time $x^+ = x^0 + x^3$
- Scales can be separated using methods of light-front quantization and QCD factorization
- Tools for high-energy scattering known from ep
- Nuclear input: light-front momentum densities, spectral functions, overlaps with specific final states in breakup/tagging reactions
  - framework known for deuteron
  - technical for $A > 3$ (Sokolov packing operators)
- Structure functions (IA) $F_A \propto F_N(\tilde{x}, Q^2)S(\alpha_p, p_{pT})$

Theory: nuclear structure calculations

- First principle NR calculations available for light ions



LENPIC collab, arXiv:1807.02848

- Controlled expansion and hierarchy using χEFT for two- and three- body forces
- Variety of methods: finite-basis, no-core SM, GFMC, lattice EFT
- Fadeev methods for ^{3}He reactions

- These tools need to be extended for applications in high-energy scattering
  - Light-front formulation of nuclear EFT techniques

Neutron structure measurements

Needed for flavor separation, singlet vs non-singlet evolution etc.

- EIC will measure **inclusive** DIS on light nuclei [d,^{3}He, ^{3}H(?)]
  - Simple, no FSI effects
  - Compare n from ^{3}He $\leftrightarrow$ p from ^{3}H
  - Comparison n from ^{3}He, d

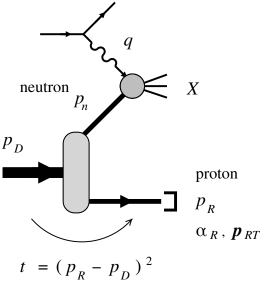
- **Uncertainties** limited by nuclear structure effects (binding, Fermi motion, non-nucleonic dof)

- ^{3}He is in particular affected because of intrinsic Δs

If we want to aim for precision, use tools that avoid these complications

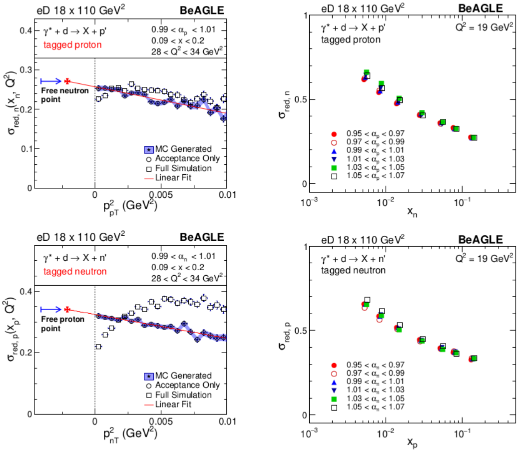
Neutron structure with tagging

- Nucleon tagging offers a way of controlling the nuclear configuration



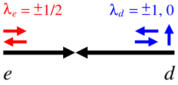
- Advantages for the deuteron
  - active nucleon identified
  - recoil momentum selects nuclear configuration (medium modifications)
  - limited possibilities for nuclear FSI, calculable
- Allows to extract **free** neutron structure with on-shell extrapolation [Sargsian, Strikman PLB'05]
- ^{3}He theoretically more complicated
- Suited for colliders: no target material ($p_p \to 0$), forward detection, polarization.
  fixed target CLAS BONuS limited to recoil momenta ~ 70 MeV
- BUT needs much more theory input
- Measurements of neutron structure at an EIC over a wide kinematic range at few percent-level accuracy

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



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

Polarized structure function g_{1n}: longitudinal asymmetry

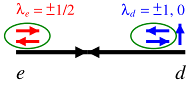


- Pole extrapolation of double spin asymmetry
  - Nominator
    $d\sigma_{||} \equiv \frac{1}{4}\left[\mathrm{d}\sigma(+\frac{1}{2},+1) - \mathrm{d}\sigma(-\frac{1}{2},+1) - \mathrm{d}\sigma(+\frac{1}{2},-1) + \mathrm{d}\sigma(-\frac{1}{2},-1)\right]$
  - Denominators: 2-state

$$d\sigma_2 \equiv \frac{1}{4}\sum_{\Lambda_e}\left[\mathrm{d}\sigma(\Lambda_e,+1) + \mathrm{d}\sigma(\Lambda_e,-1)\right]$$

  - $\lambda_d = 0$ state **not needed**!
- Impulse approximation yields in the Bjorken limit $[\alpha_p = \frac{2p_p^+}{p_d^+}]$

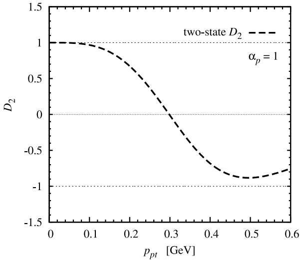
$$A_{||,2} = \frac{d\sigma_{||}}{d\sigma_2}[\phi_h \,\mathrm{avg}] \approx \mathcal{D}_i(\alpha_p, |p_{pT}|)A_{||n} = \mathcal{D}_2(\alpha_p, |p_{pT}|)\frac{D_{||}g_{1n}(\tilde{x}, Q^2)}{2(1+\epsilon R_n)F_{1n}(\tilde{x}, Q^2)}$$



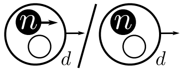
- On-shell extrapolation of double spin asymmetry

$$A_{||} \approx \mathcal{D}_2(\alpha_p, |p_{pT}|) A_{||n} = \mathcal{D}_2(\alpha_p, |p_{pT}|) \frac{D_{||} g_{1n}(\tilde{x}, Q^2)}{2(1 + \epsilon R_n) F_{1n}(\tilde{x}, Q^2)}$$

- $\mathcal{D}_2$ 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)

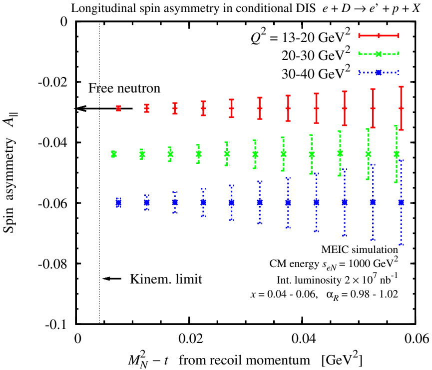


- Bounds: $-1 \leq \mathcal{D}_2 \leq 1$
- Due to lack of OAM $\mathcal{D}_2 \equiv 1$ for $p_T = 0$
- Clear contribution from D-wave at finite recoil momenta
- $\mathcal{D}_2$ close to unity at small recoil momenta

Tagging: polarized neutron structure

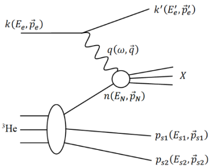
- **On-shell extrapolation** of double spin asymm.

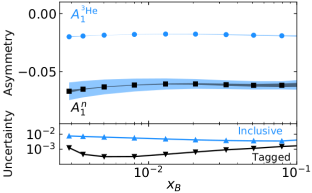
$$A_{||} = \mathcal{D}_2(\alpha_p, |p_{pT}|) \frac{D_{||} g_{1n}(\tilde{x}, Q^2)}{2(1+\epsilon R_n) F_{1n}(\tilde{x}, Q^2)}$$

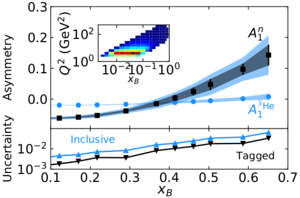


JLab LDRD arXiv:1407.3236, arXiv:1409.5768
https://www.jlab.org/theory/tag/

- D-wave suppr. at on-shell point → neutron ∼ 100% polarized
- 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 $\sim 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$



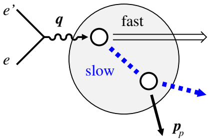


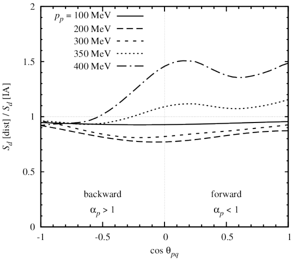


I. Friscic et al., PLB'21

- Double spectator nucleon tagging (p, n) with ^{3}He
- Reduced uncertainties for tagged A_1
- Simplified treatment of nuclear corrections (no FSI between $n - p$; Δ-components in ^{3}He)

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
  → *ep* target framentation measurements
- 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
  → on-shell extrapolation **still feasible**

Nucleon interactions

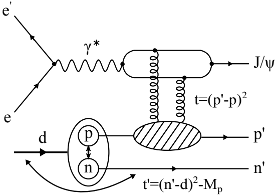
How do nucleon interactions emerge from QCD?

- **Short-range structure** of nuclei, NN force at very short distances
  - Quasi-elastic d breakup
  - Short-range correlation studies: (multi-)nucleon knockout w high ($>k_F$) initial momenta, 3N correlations?

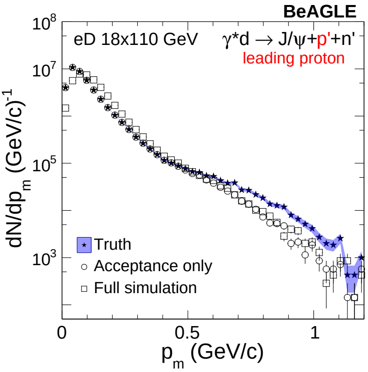
- **Medium modification** of nucleon properties embedded in nucleus: EMC effect, other quantities
  - Q^2, isospin ($N \neq Z$) dependence
  - gluon EMC effect
  - spin-dependent EMC effect on polarized light ions
  - tagging: what intra-nucleon distances play a role?

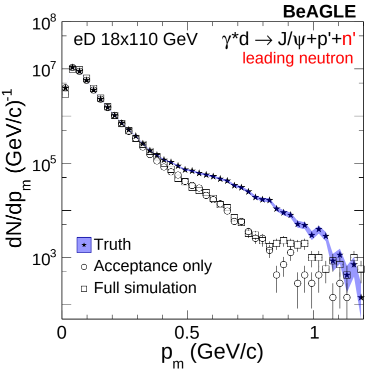
JLab12 will measure some of these processes,
but open questions will remain that can be addressed at EIC

Diffractive deuteron break up: gluon density modification



- Double spectator tagging in forward detectors
- Study gluon densities as a function of initial nucleon momenta
- FSI treatment not included





Z. Tu et al, PLB'21

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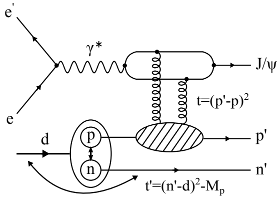

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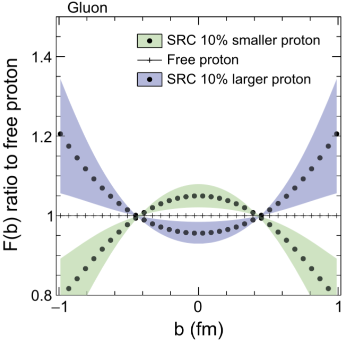
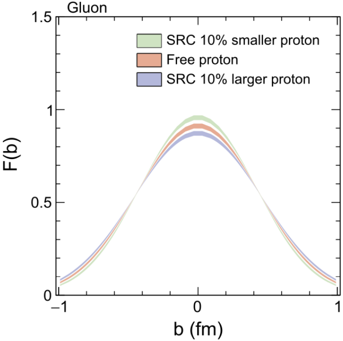
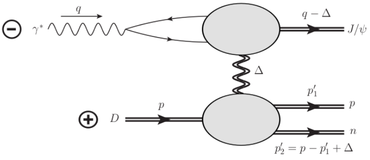


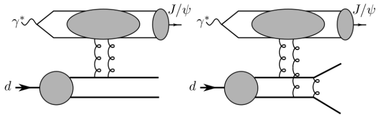


Z. Tu et al, PLB'21

Diffractive deuteron break up at large p_T: theory study



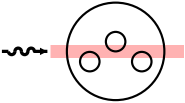
Miller, Sievert, Venugopalan, PRC '16



EIC YR

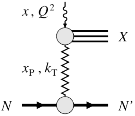
- Large p_T between nucleons in final state $\rightarrow$ FSI
- LO calculation, gluon singlet and octet contributions
- Distinguish between different SRC dynamics

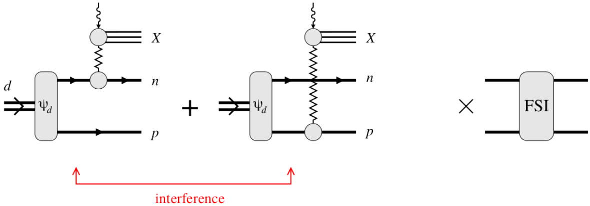
Nuclear interactions: Coherence



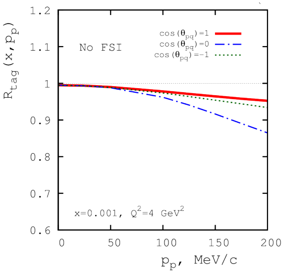
- interaction of high-energy probe with coherent quark-gluon fields

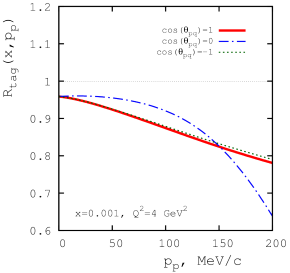
- **Shadowing** is manifestation of coherence
  - **Diffractive** DIS at $x \ll 0.1$: 10-15% of events at HERA
  - **Interference** between diffractive amplitudes $\rightarrow$ reduction of cross section, leading twist
  - Extensively studied in heavy nuclei
  - Is especially clean in the **deuteron**, effects can be calculated
  - **Dynamics** of shadowing can be explored in tagging: **single** and **double**
  - Tagging also results in **FSI** between the slow n and p





Shadowing: tagged DIS

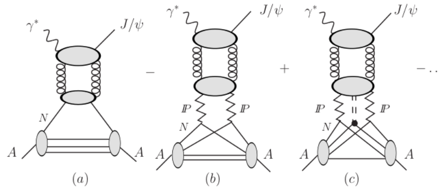




[Guzey,Strikman,Weiss; in preparation]

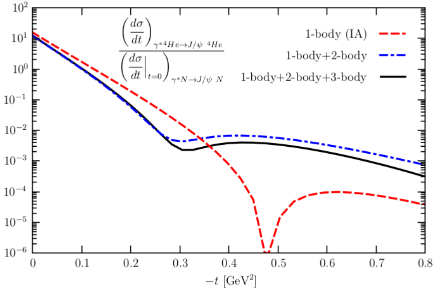
- Explore shadowing through recoil momentum dependence
- Shadowing **enhanced** in tagged DIS compared to inclusive
  - enhancement factor from AGK rules
  - shadowing term drops slower with p_R than IA
- Large FSI effects in diffractive amplitudes ($\sim 40\%$), also at zero spectator momenta due to orthogonality of *np* state to deuteron

Nuclear shadowing in exclusive processes



Guzey, Rinaldi et al. 2202.12200

^{4}He coherent J/Ψ production

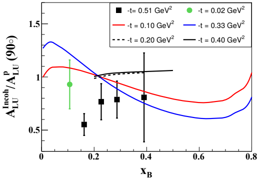


- Can be studied on heavy and light nuclei, large effect
- Gluonic imaging of nuclei $g_A(x, Q^2)$
- Likely gluons belong to more than 1 nucleon
- Shadowing one nucleon at a time in diffractive J/ψ production on light nuclei
- k-body FF enter in amplitude $\rightarrow$ nuclear wf

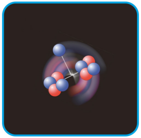
Nuclear imaging

Images of nuclei in terms of quark and gluon dof

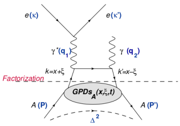
- Deeply virtual Compton scattering → **GPDs**
  - coherent: transverse imaging of nuclei
  - incoherent: medium modification of transverse nucleon densities
- **Tagged** DVCS provides additional control over initial configuration
- Transverse **gluon** structure of light ions (d, ^{4}He, ^{3}He) with exclusive coherent J/ψ production
- Clustering & spin-orbit phenomena in nuclear structure of light nuclei



^{4}He DVCS
M. Hattawy et al. [CLAS PRL]



^{9}Be Clustering



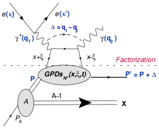
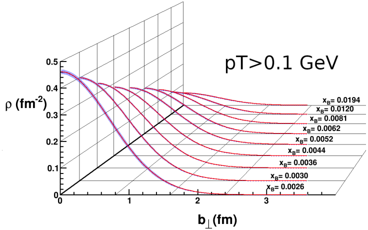
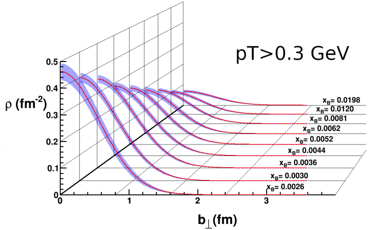


Fig. credit S. Fucini

^{4}He cohererent DVCS





TOPEG generator: R. Dupré, S. Fucini, S. Scopetta YR 2103.05419 + in preparation

- Quark density profiles extracted from ^{4}He DVCS pseudodata
- Roman pot acceptance has clear influence on errors bars
- Angular acceptance much more demanding than for *ep*

Nuclear imaging: deuteron tensor polarization

- Tensor polarization in d probes **nuclear effects**
- Little explored in high-energy scattering
- Possible at design EIC (magic energies)
- Inclusive b_1 result from HERMES: no conventional nuclear calculation reproduces data
- Unique features: eg access **gluon transversity**, new TMDs & GPDs
- Tagged cross section yields 23 additional structure functions with specific azimuthal dependences [Cosyn, Weiss, in prep.]

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

- T-odd SF [DSA] are zero in impulse approximation → sensitive to FSI

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

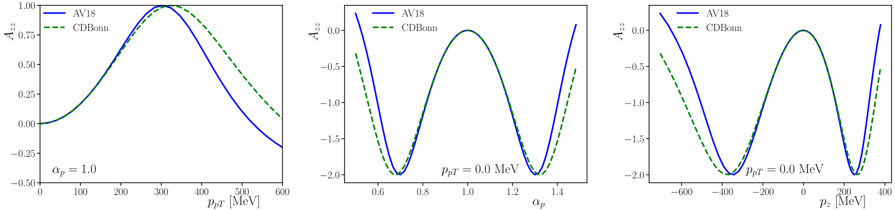
- Tensor analogue of $A_{LL} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$ is tensor asymmetry $A_{zz} = \frac{\sigma^+ + \sigma^- - 2\sigma^0}{\sigma^+ + \sigma^- + \sigma^0}$

  $\rightarrow$ **no** electron polarization required, **all 3** deuteron states $(\pm, 0)$

- Tensor polarization is sensitive to unpolarized quark distributions
  $\rightarrow$ ratio of LF densities remains

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

  $\rightarrow$ **Constraints on deuteron D-wave**



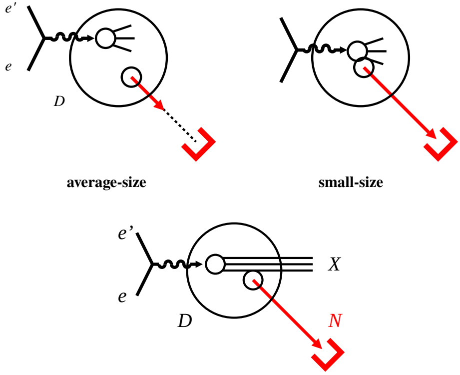
WC, C. Weiss, in preparation

- **Maximal** asymmetries (1,-2) for tagged, tiny in inclusive

Conclusions

- Light ions address important parts of the EIC physics program
- Tagging and nuclear breakup measurements overcome limitations due to nuclear uncertainties in inclusive DIS → **precision machine**
- Coherent phenomena can be explored in light nuclei both in tagged DIS and exclusive measurement
- Quantification of nuclear interaction effects
- Tomography of light nuclei
- Unique observables with **polarized deuteron**: free neutron spin structure, tensor polarization
- All this requires excellent detection capabilities in far forward region

Tagging: EMC effect



Final−state interactions

- Medium modification of nucleon structure embedded in nucleus (EMC effect)
  - dynamical origin?
  - caused by which momenta/distances in nuclear WF
  - spin-isospin dependence?
- tagged EMC effect
  - recoil momentum as extra handle on medium modification (off-shellness, size of nuclear configuration) away from the on-shell pole
  - EIC: Q^2 evolution, gluons, spin dependence!
- Interplay with final-state interactions!
  - use $\tilde{x} = 0.2$ to constrain FSI
  - constrain medium modification at higher $\tilde{x}$