Nuclear structure at EIC

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Theory for EIC in the next decade
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Thanks to colleagues for input

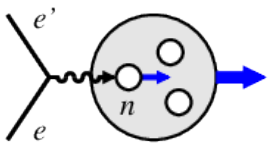
Supported by

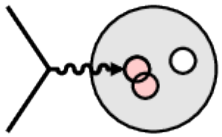
A tale with two sides

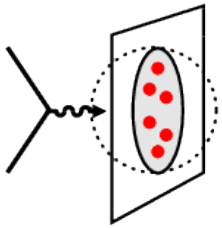
- Low-energy nuclear structure enters as **input** in a whole range of calculations for EIC
  - But high-energy nuclear scattering
    → light-front quantization

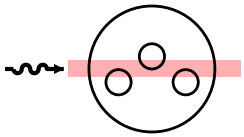
- **Novel studies** of nuclear structure at EIC
  - Short-range correlations
    → Theoretical interpretation (ab initio, pheno, contacts, . . .)
  - Non-nucleonic components
  - Final-state interactions

Ions: physics objectives







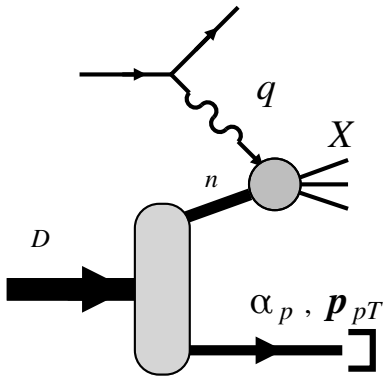


- **Neutron** structure
  - flavor decomposition of quark PDFs/GPDs/TMDs
  - flavor structure of the nucleon sea
  - singlet vs non-singlet QCD evolution, leading/higher-twist effects
- Nucleon **interactions** in QCD
  - medium modification of quark/gluon structure
  - QCD origin of short-range nuclear force
  - nuclear gluons
- **Imaging** nuclear bound states
  - imaging of quark-gluon degrees of freedom in nuclei through GPDs
  - clustering in nuclei
- **Coherence** and saturation
  - interaction of high-energy probe with coherent quark-gluon fields

    → Next talk (R. Venugopalan)

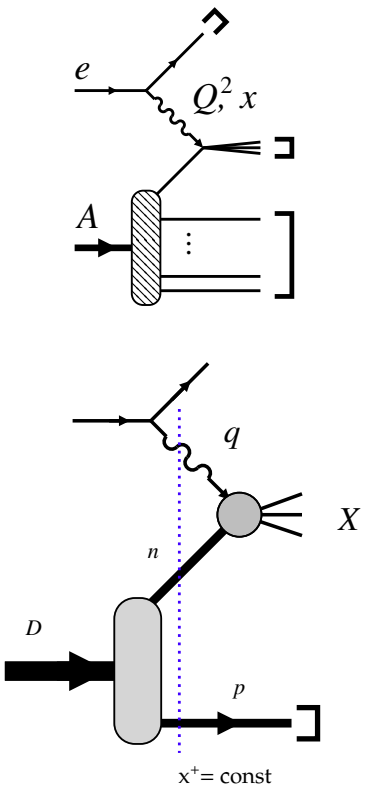
EIC: detection of nuclear breakup / coherent scattering

- Enabled by the EIC far-forward detectors
- Detection of spectator fragments
- Additional **control** over initial configuration
  - $\leftrightarrow$ averaging over all configs in inclusive scattering
  - $\rightarrow$ on-shell extrapolation
    [Sargsian, Strikman '05; WC, Weiss 19+]
  - $\rightarrow$ differential study of medium modifications
  - $\rightarrow$ needs modelling of **final-state interactions**



- Light ions
  - $\rightarrow$ polarization; different spins
  - $\rightarrow$ precision predictions with ab initio wave functions
- Lots of potential for **novel measurements**
  - $\leftrightarrow$ more difficult in fixed target
- But needs **much more theory input**!

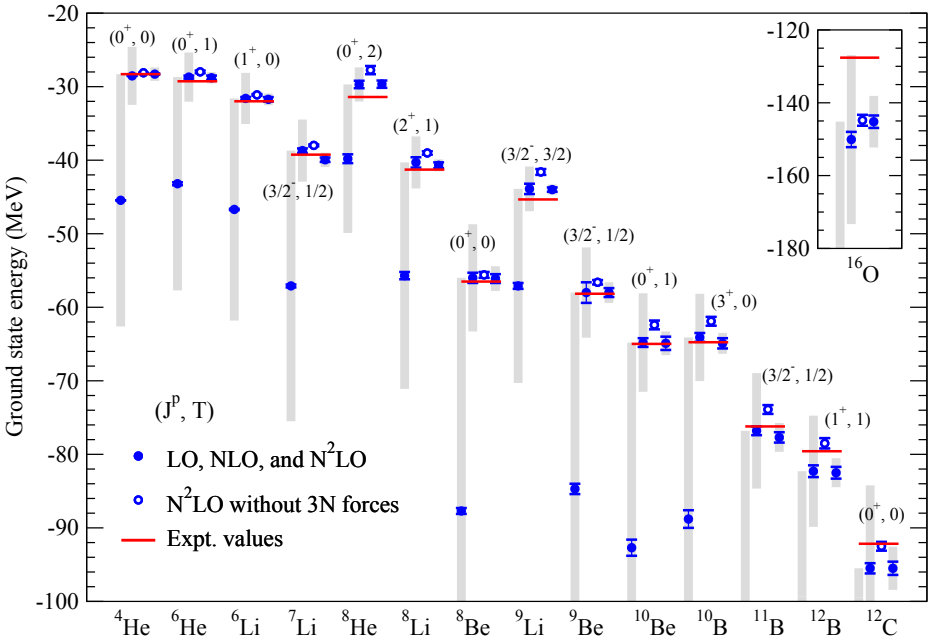
High-energy scattering with nuclei [Frankfurt,Strikman 80s+]



- 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 few-body $A > 2$ but challenges
  - still **low-energy** nuclear physics, just formulated differently
- 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 2b and 3b forces
- Variety of methods: finite-basis, no-core SM, GFMC, lattice EFT
- Fadeev methods for ^{3}He reactions

- We currently **match** LF nuclear wf to NR ones at low momenta

These tools need to be extended for applications in high-energy scattering

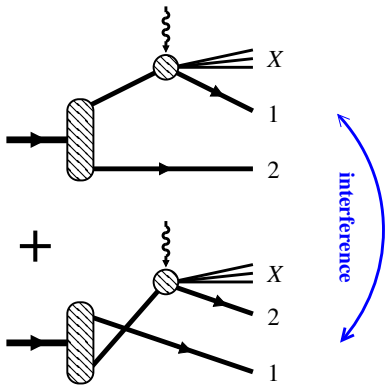
Light-front nuclear structure

- Relativistic spin effects
- Dynamical variables in LF boosted rest frame of on-shell A-nucleon state
- Ab initio / EFT based methods can be extended to light-front quantization
  - Calculation of 2b NN at LO/NLO in χEFT can be a start
- Mean-field formulation for medium/heavy nuclei?
- Opportunity to involve the **low-energy community** in EIC physics
- For $A > 2$ Poincaré invariance and cluster separability imposes non-trivial constraints [Sokolov 70s, Lev et al 90s]
  - Formalism is known [Sokolov Packing operators], but technical
  - Trivial for deuteron
  - Applications to ^{3}He [Rinaldi,Pace,Salme,Scopetta et al]

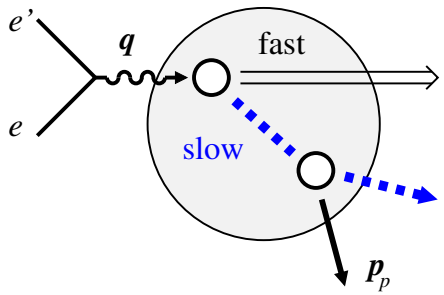
Reaction Frameworks

- Tagged reactions beyond DIS
  $\rightarrow$ tagged exclusive reactions, tagged SIDIS
- Higher spin (polarized deuteron)
- Consistent treatment of medium modifications and FSI [2N operators]
- Polarized FSI

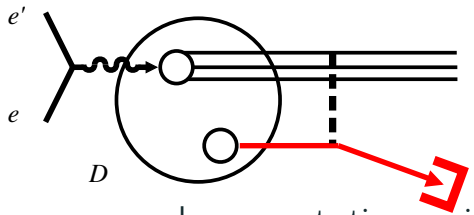
Tagging final-state interactions: three physical pictures



shadowing, low x



DIS regime, intermediate x

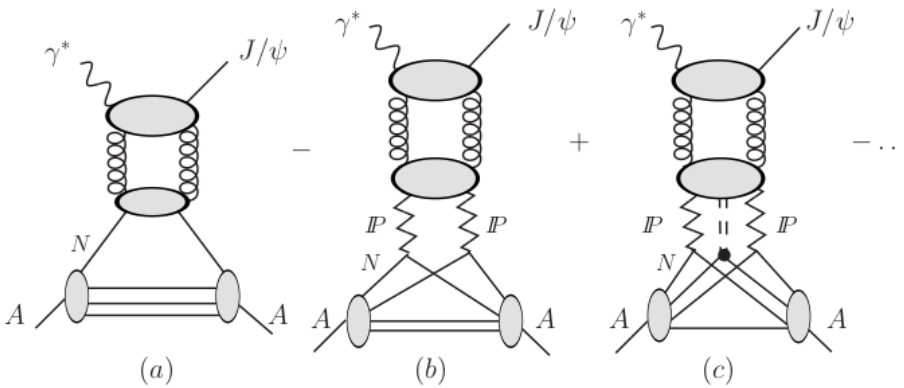


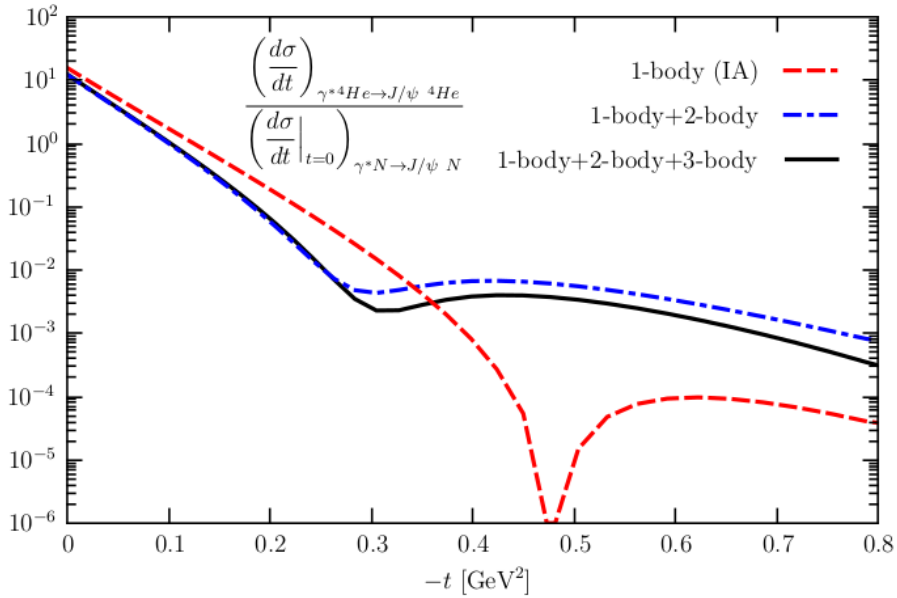
subasymptotic regime:
low Q^2, high x

- 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 is low energy NN scattering
- 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**
    `[Strikman, Weiss PRC'18]`
- Rescattering of resonance-like structure in eikonal approximation [Deeps,BONuS].

`[W.C.M. Sargsian arXiv:1704.06117]`

Leading twist nuclear shadowing



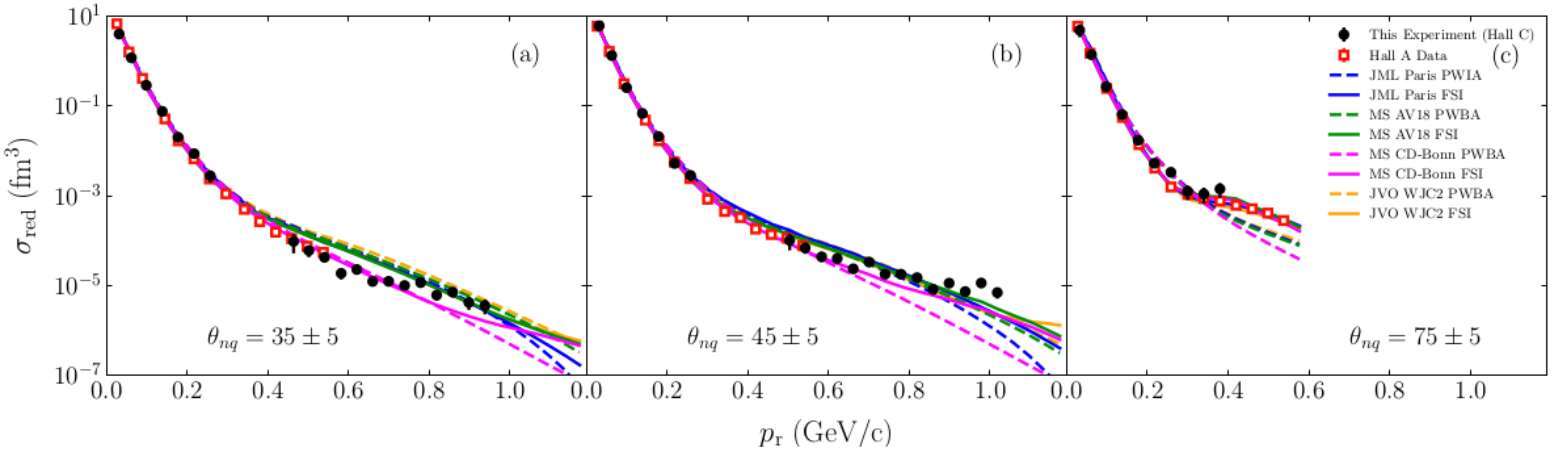


Guzey, Rinaldi et al. 2202.12200

- 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

Target fragmentation physics

- In general not too much understood/known about the dynamics
- In *ep* → input for FSI in tagged processes
- In eA → tagging non-nucleonic components (Δ etc.)
- Theory guidance?
  → '20 '22 CNFS ad-hoc workshops



C. Yero et al (Hall C) PRL '20

Coherent exclusive reactions

- 3D imaging of bound nuclear states, nuclear GPDs
- Work by several groups [Perugia; Guzey et al; Freese, Cloët; WC, Cano, Pire;...]
- A lot of it is based on a convolution picture
  $\leftrightarrow$ breaks Lorentz covariance, GPD polynomiality
  $\leftrightarrow$ no multinucleon contributions
- Reaction frameworks for higher spin
- Inverse problem: extraction of CFFs, GPDs, GFFs
  $\rightarrow$ dedicated studies needed

Incoherent diffractive

- In *eA* (heavy) photon emission detection is one possible channel to veto incoherent channel
  → detection is not easy
- Nuclear energy spectrum plays a role (keV vs MeV, lifetime)

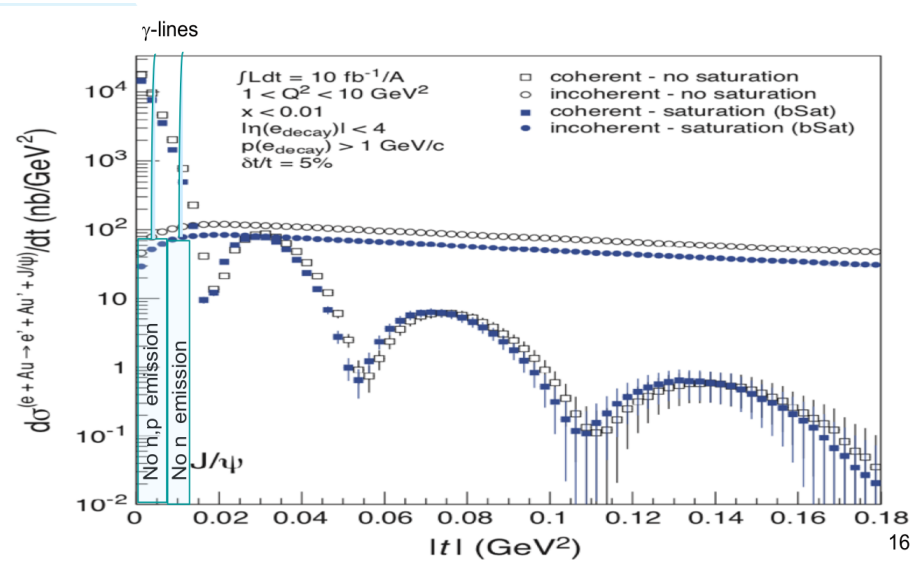


Figure: Spencer Klein (YR talk & ongoing work) based on EIC white paper

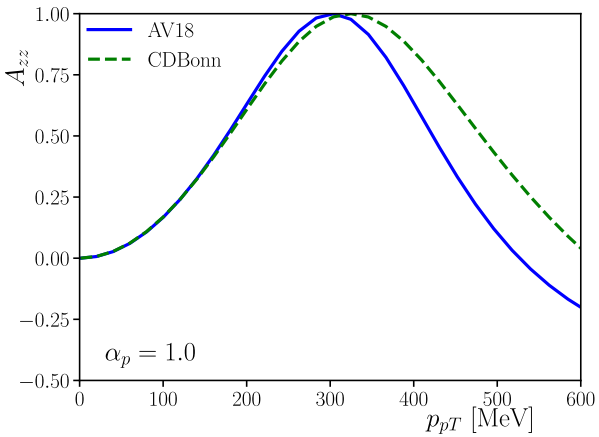
Conclusions

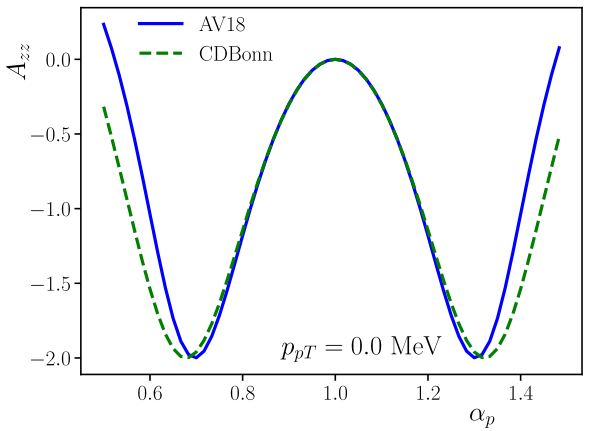
- Nuclear structure appears in many aspects of the EIC program
- Breakup and coherent measurements with EIC far forward detectors enable novel measurements for ions
- Light front nuclear structure is an avenue to involve low energy community
- Lots of work to be done to prepare reaction frameworks
  [tagged reactions, FSI, higher spin, $A > 2$]
- EIC also allows novel studies of nuclear structure
  - SRC studies
  - Deuteron short range structure through tagged tensor asymmetries

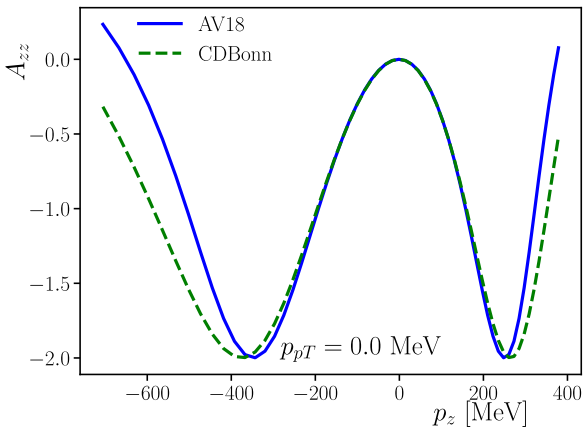
Deuteron short-range structure

- Maximize tensor asymmetry A_{zz} with tagging.
- Tensor polarization is sensitive to unpolarized quark distributions, partonic factor cancels out $\rightarrow$ **ratio of LF densities** remains

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







- Maximal A_{zz} at $f_2(k) = \sqrt{2}f_0(k)$, not the S wave node!
- Needs quantification of FSI effects

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