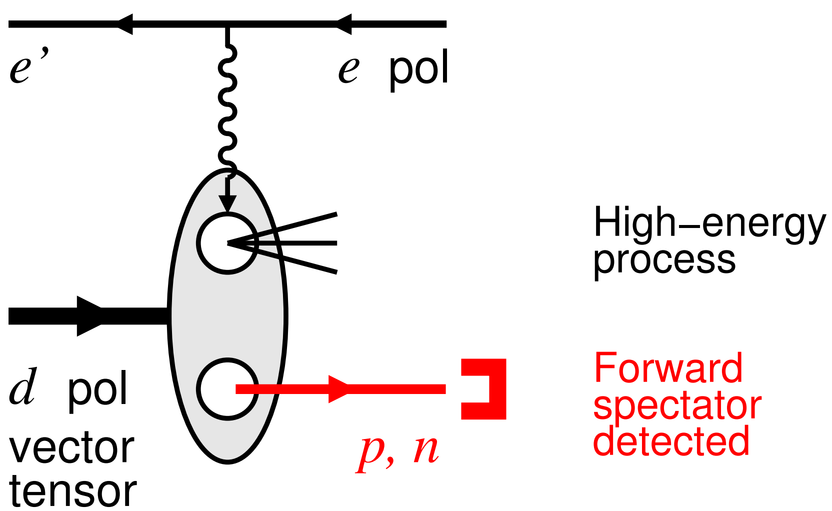
Polarized deuteron physics at EIC

C. Weiss, Tensor spin observables, ECT* Trento, 10-14 July 2023



Purpose: Discuss what physics topics could be studied with polarized deuteron beams at EIC

Use far-forward ion detection: Spectator tagging, coherent scattering

Focus on EIC energy and luminosity range: Complementary to JLab 12 GeV, connections

Style: High-level overview; concepts and theory can be elaborated in discussion

Light ion physics

- Objectives and challenges
- Deuteron and spectator tagging

Inclusive polarized $e + d \to e' + X$

- Vector pol: Neutron spin structure
- Tensor pol: Shadowing at small x

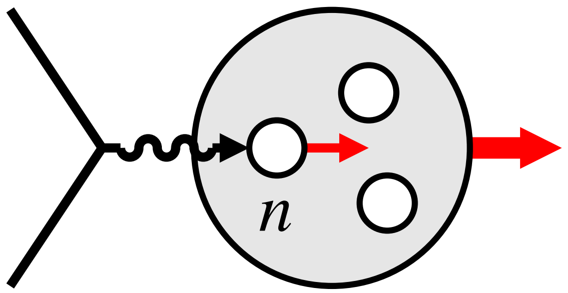
Tagged polarized $e + d \to e' + X' + p(n)$

- Theoretical framework and observables
- Vector pol: Control neutron polarization
- Tensor pol: Maximize tensor polarization

[Coherent processes $e + d \to e' + M + d'$ **]**

EIC far-forward detectors

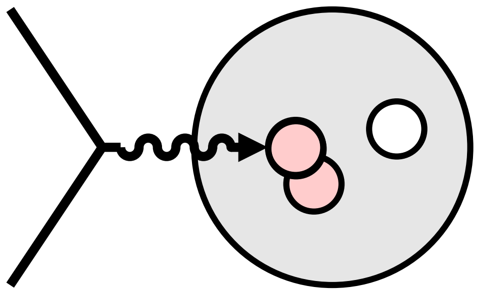
Light ions: Physics objectives



Neutron spin structure

Flavor decomposition of quark PDFs/spin, GPDs, TMDs

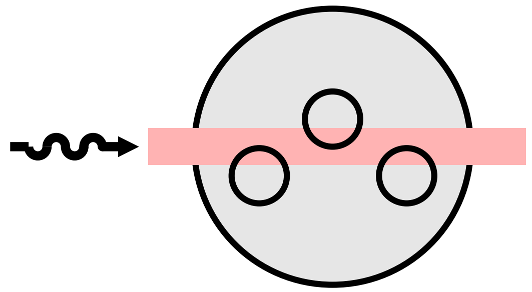
Singlet-nonsinglet separation in QCD evolution for ΔG



Nuclear interactions

Hadronic: Short-range correlations, NN core, non-nucleonic DoF

Partonic: Nuclear modification of partonic structure
EMC effect $x > 0.3$, antishadowing $x \sim 0.1$
Quarks/antiquarks/gluons? Spin, flavor? Dynamical mechanism?



Coherent phenomena

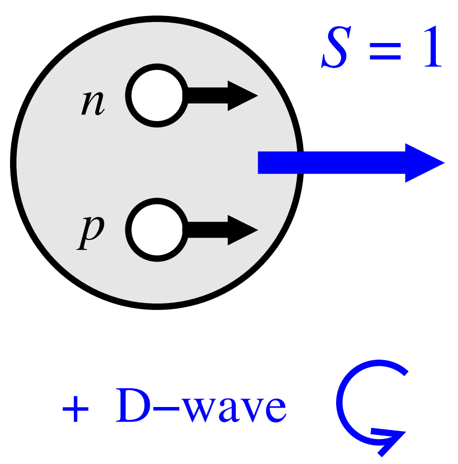
Nuclear shadowing $x \ll 0.1$

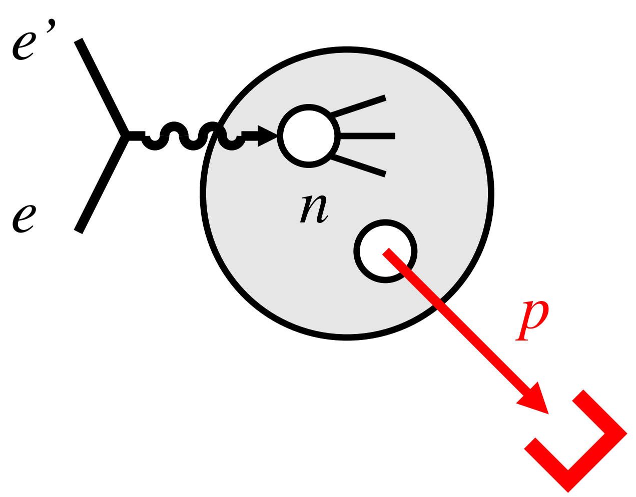
Buildup of coherence, interaction with 2, 3, 4… nucleons?
$\leftrightarrow$ Shadowing and saturation in heavy nuclei

[Nucleus rest frame view]

Common challenge: Effects depend on nuclear configuration during high-energy process. Main limiting factor.

Light ions: Deuteron and spectator tagging





[Nucleus rest frame view]

Deuteron as simplest system

Nucleonic wave function simple, well known (p ~< 400 MeV)

Nucleons spin-polarized, some D-wave depolarization

Non-nucleonic DoF suppressed: Δ isobars, π

Frankfurt, Strikman 81. Large Δ component in 3He → see below

Spectator nucleon tagging

Identifies active nucleon

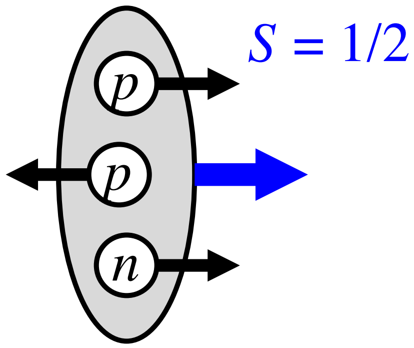
Controls configuration through recoil momentum:
spatial size → interactions, S/D wave → polarization

Average configurations ~ few 10 — 100 MeV
Small-size configurations ~ 200-500 MeV

Fixed-target experiments: JLab BONuS 6/12 GeV,
ALERT (protons), BAND (neutrons)

EIC: Far-forward detection

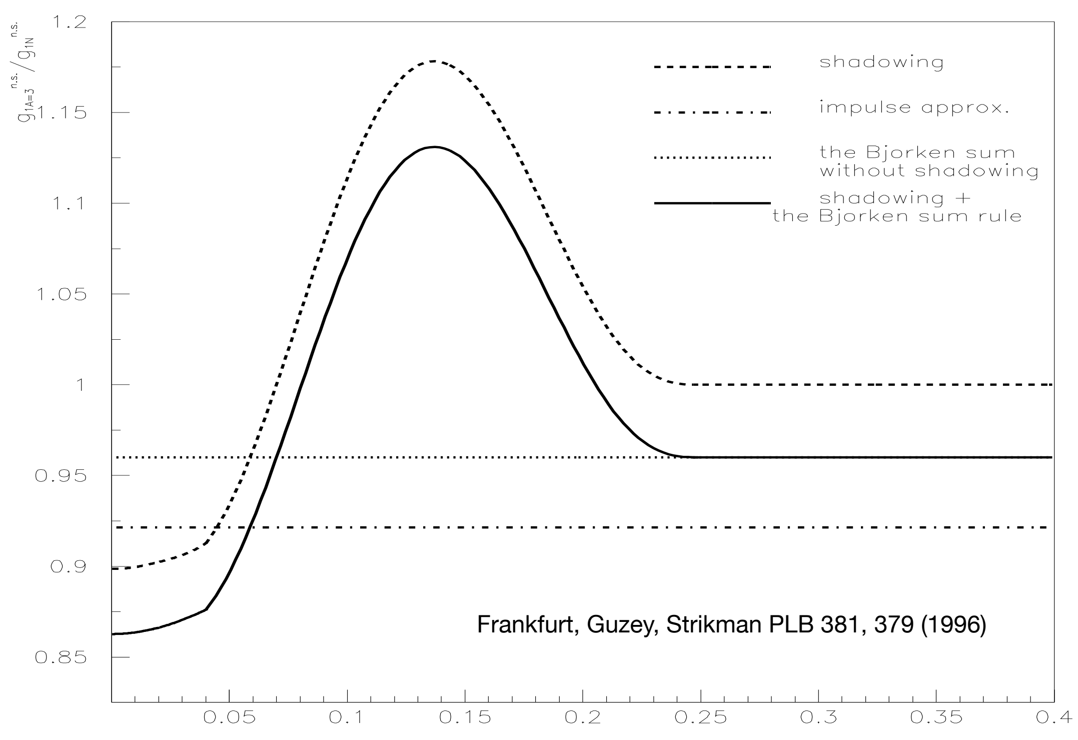
Inclusive: Neutron spin structure



$|3\text{He}\rangle \rightarrow |ppn\rangle, |NN\Delta\rangle$

$|\text{d}\rangle \rightarrow |pn\rangle$, ~~$|N\Delta\rangle$~~, only $|\Delta\Delta\rangle$

isospin $I = 0$



Neutron spin structure from polarized 3He

Nonrelativistic theory: Effective neutron polarization ~80%, calculated precisely

Relativistic formulation for high-energy scattering:
Large corrections from Δ isobars and shadowing ~15-20%
Frankfurt, Guzey, Strikman 1996. Constrained by Bjorken sum rule for nucleus

Results limited by theoretical uncertainty!

Neutron spin structure from polarized deuteron

Δ isobars suppressed by isospin $I = 0$

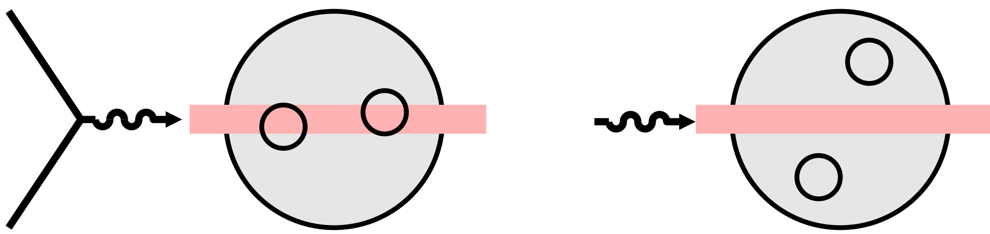
Polarized shadowing effect small, ~few%

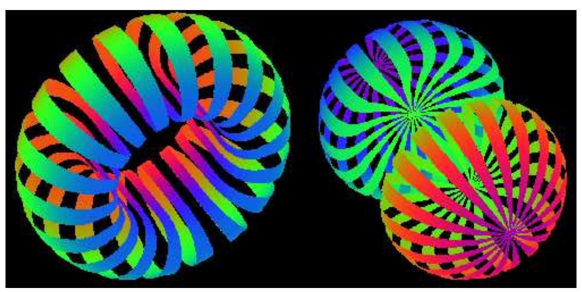
Deuteron can achieve much better theoretical precision
→ overall precision!

Measurement

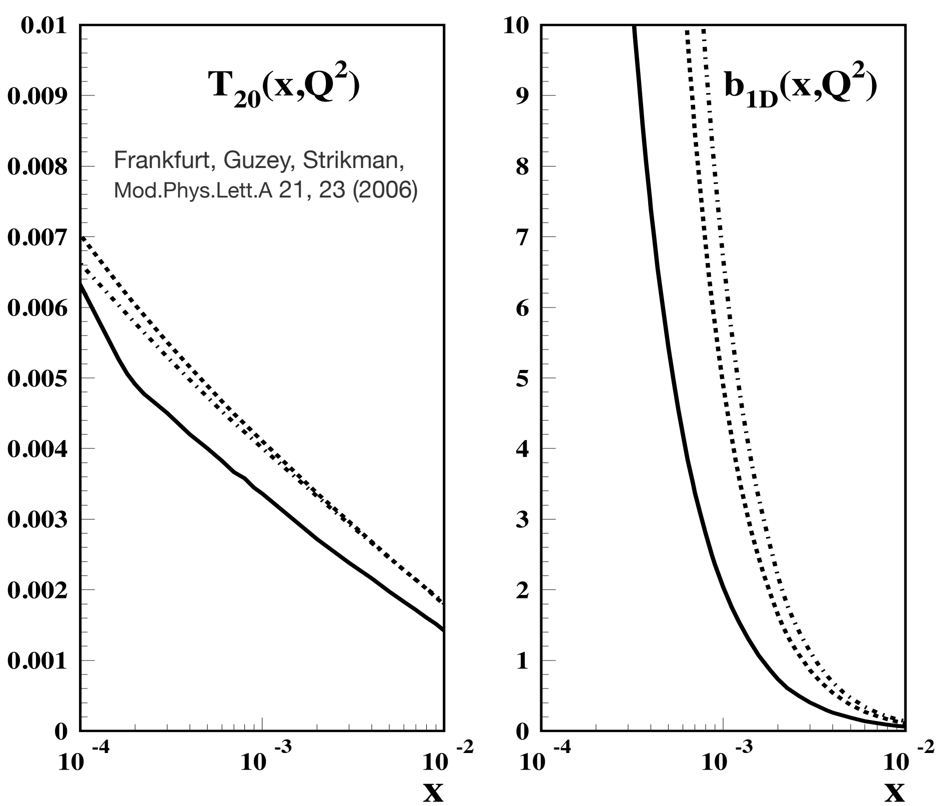
$A_{\|d} = [\text{theory}] \times A_{\|n}$ Longitudinal vector pol.

Inclusive: Nuclear shadowing with tensor polarization





[E12-13-011 PAC Proposal]



Nuclear shadowing

Small-x probe has coherence length $\gg R_{NN}$

Interference of amplitudes scattering on nucleon 1 and 2:
QM phenomenon, enabled by diffractive final states
Gribov 70s

Leading-twist phenomenon, calculable in QCD factorization, extensive studies at LHC, EIC
Review: Frankfurt, Guzey, Strikman 2012

Depends on nuclear configuration: Requires alignment of nucleons along reaction axis

Tensor-polarized deuteron

D-wave: Deuteron polarization controls spatial distribution of nucleons, different for $I_z = 0$ and ± 1 states

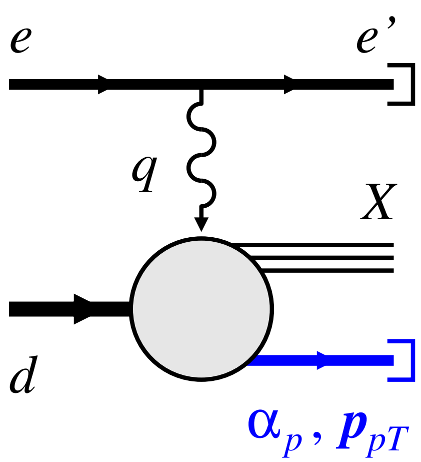
Tensor-polarized asymmetry from shadowing

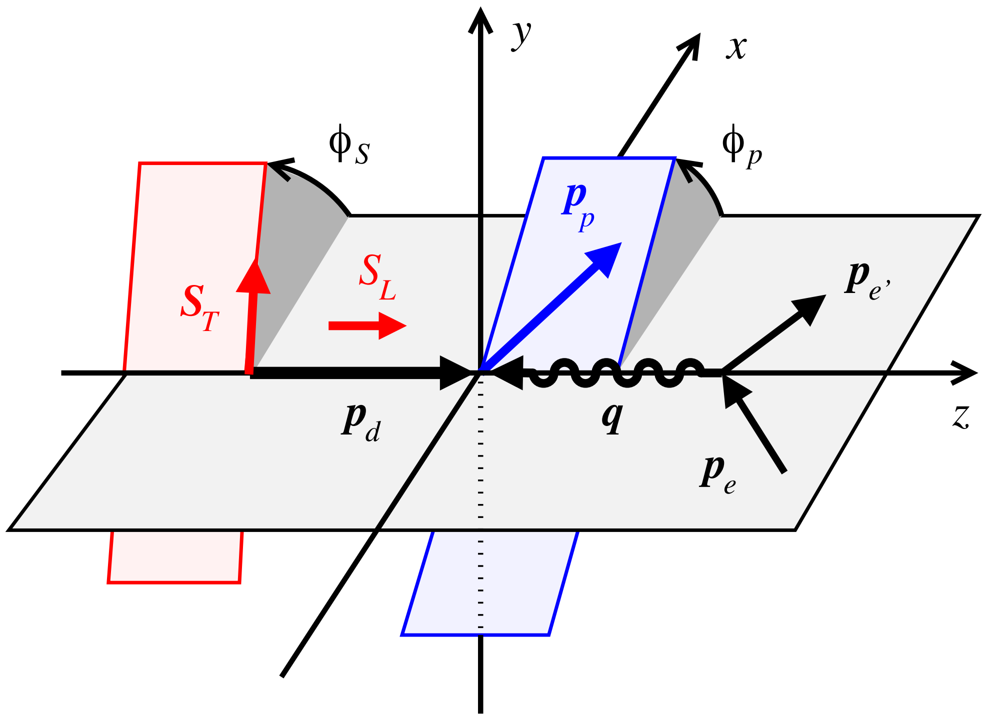
Measurement

$$b_{1d} = \frac{F_{2d}}{2x} T_{20} \qquad T_{20} = \frac{\sigma(+1) + \sigma(-1) - 2\sigma(0)}{\sigma(+1) + \sigma(-1) + \sigma(0)}$$

EIC: Asymmetry ~ 0.5%, large cross section

Tagging: Cross section





$$\frac{d\sigma}{dx dQ^2 \, (d^3p_p/E_p)} = \text{Flux} \times \sum \text{Kin}(y) \times F_d(x, Q^2; \alpha_p, p_{pT}) \times \text{Harmonic}(\phi_p)$$

+ spin dependence

Semi-inclusive cross section $e + d \rightarrow e' + X + p$ (or n)

Collinear frame: Virtual photon and deuteron momenta collinear $\mathbf{q} \parallel \mathbf{p}_d$, along z-axis

Proton recoil momentum described by light-cone components: $p_p^+ = \alpha_p p_d^+/2, \quad \mathbf{p}_{pT}$
Related in simple way to rest-frame 3-momentum

Here: No assumption re composite nuclear structure, $A = \sum N$, or similar!

Tagging: Cross section spin dependence

$$\sigma = \sum_{\lambda,\lambda'} \rho_{\lambda\lambda'} \langle d, \lambda' | \dots | d, \lambda \rangle$$

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

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

Here $\phi_h \equiv \phi_p$

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

Cosyn, Weiss, PRC102 (2020) 065204 + in preparation (2023)

Invariant formulation, suitable for collider and fixed-target

General result, valid for any spin-1 target

Deuteron polarization

Spin-1 density matrix $\rho_{\lambda'\lambda}(S, T)$

3 vector, 5 tensor parameters

Fixed by beam polarization measurements

Polarized cross section

Average with deuteron spin density matrix

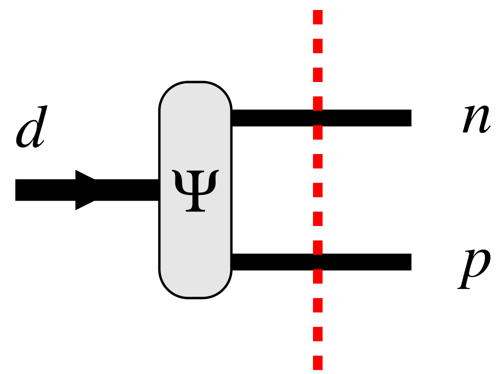
U + S + T structures

U + S cross section has same form and ϕ_p-dep as for spin-1/2 target
Bacchetta et al 2007

T cross section has 23 new structures, some with ϕ_p-dep unique to T polarization

Integration over tagged proton momentum: Recover inclusive tensor-polarized structures $b_1 \dots b_4$

Tagging: Deuteron structure



$x^+ = x^0 + x^3 = \text{const.}$

Deuteron light-front structure

pn wave function at fixed light-front time $x^+ = x^0 + x^3$

Permits matching with high-energy/DIS processes on nucleon
[Frankfurt, Strikman 80s]

Contains low-energy nuclear structure ← NN interactions

Polarized deuteron light-front wave function

$\Psi_d(\alpha_p, \mathbf{p}_{pT}; \lambda_p, \lambda_n \,|\, \lambda_d)$

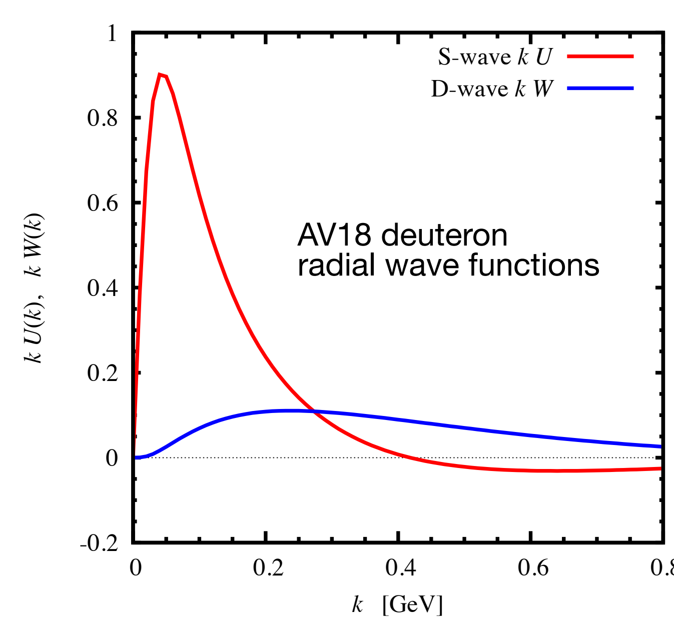
↑ light-front helicity

$\Psi_d(\mathbf{k}; \sigma_p, \sigma_n \,|\, \sigma_d)$

canonical spin

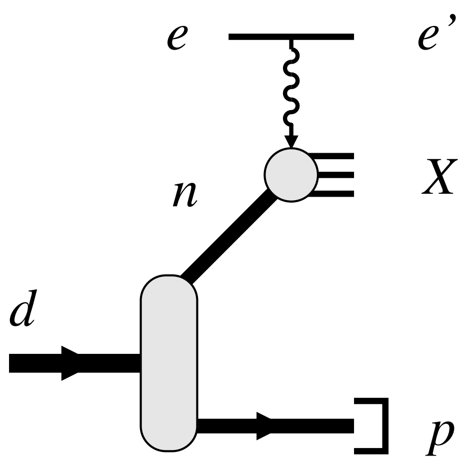
Spins described by light-front helicity states

Light-front WF constructed from 3D WF in pn CM frame, including transformation of spin states (Melosh rotation)



Contains S and D waves

Tagging: DIS process

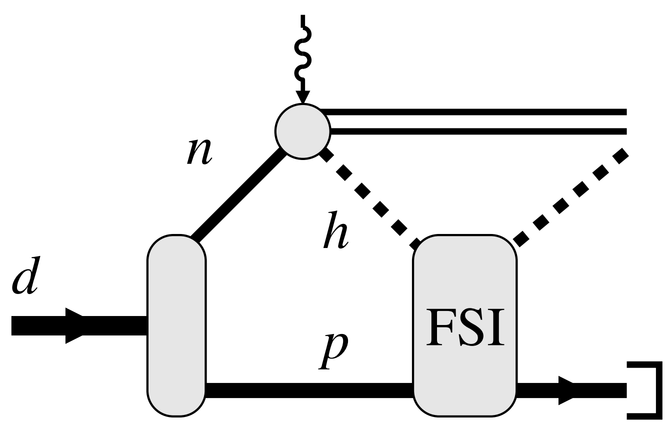


Impulse approximation

Spectator and DIS final state evolve independently

$$d\sigma[ed \to e'Xp] \;=\; S_d(\alpha_p, p_{pT})\, d\Gamma_p \times d\sigma[en \to e'X]$$

$S_d(\alpha_p, p_{pT}) \;=\; \text{Flux}(\alpha_p) \;\times\; |\Psi_d(\alpha_p, p_{pT})|^2$ spectral function



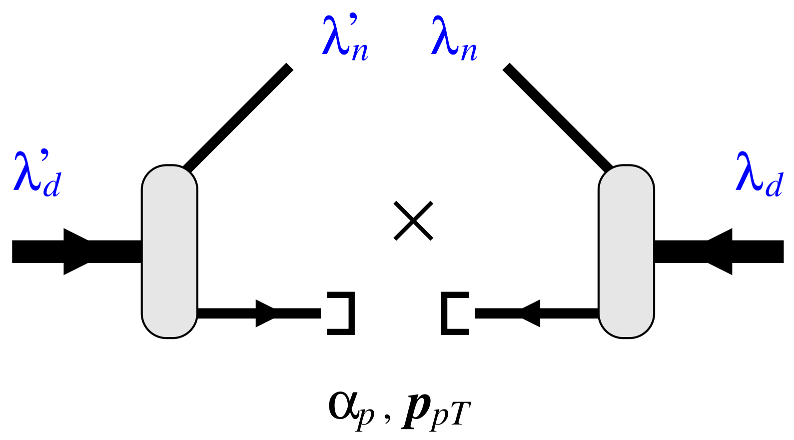
Final-state interactions

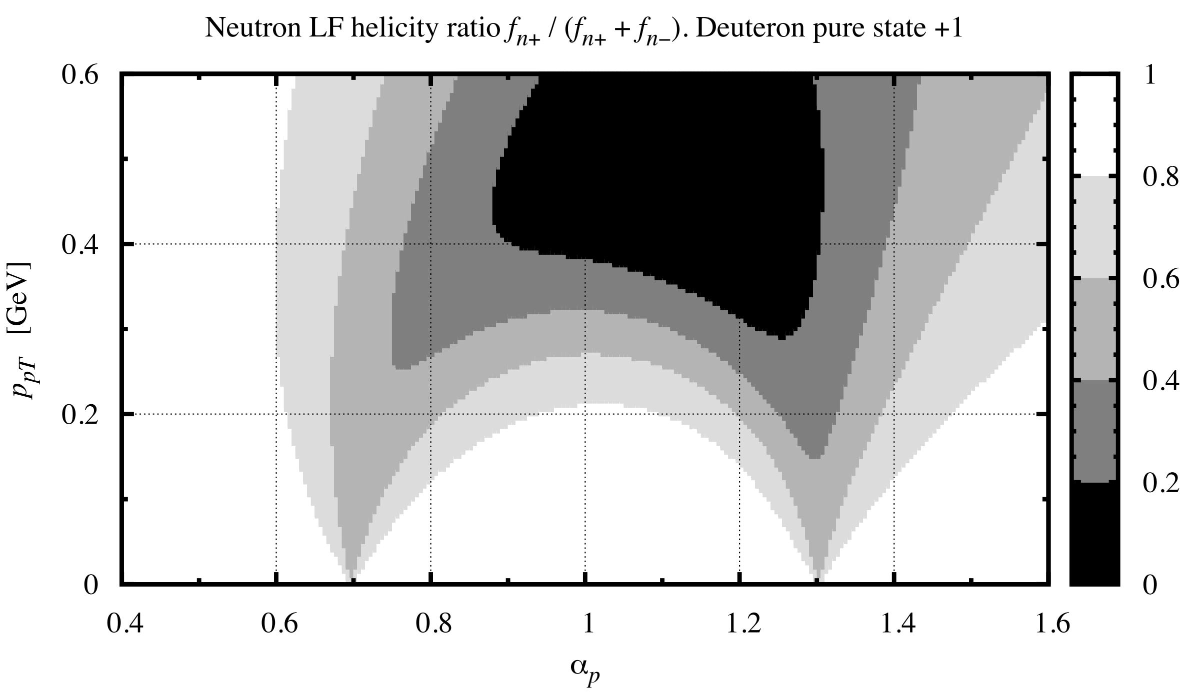
Part of DIS final state interacts with spectator, transfers momentum

Requires theoretical modeling → later

For DIS in scaling regime $\nu, Q^2 \to \infty$: These approximations are consistent with leading twist factorization of $\sigma[eN]$, partonic sum rules, etc.

Tagging: Deuteron spectral function





Cosyn, Weiss PLB799 (2019) 135035; PRC102 (2020) 065204

Deuteron spectral function

Describes distribution of neutrons depending on tagged proton momentum α_p, p_{pT}

Depends on deuteron and neutron spin

Satisfies momentum and spin sum rules

Neutron polarization in deuteron

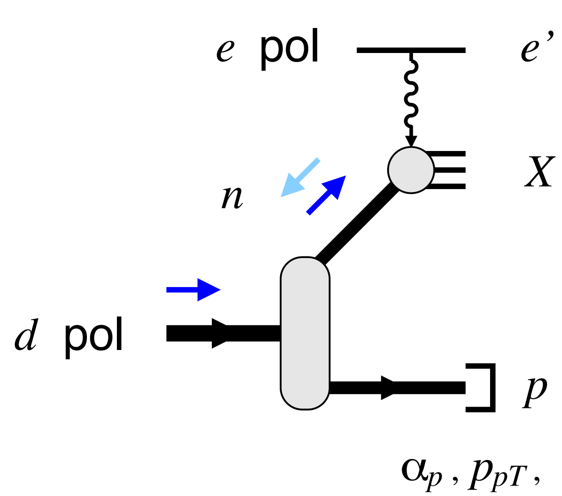
Effective neutron polarization depends on tagged proton momentum: S vs D wave

Example: Deuteron in pure spin state +1.

Plot shows probability that neutron has helicity +1/2 i.e. is polarized along deuteron spin direction

Tagged proton momentum controls effective neutron polarization!

Tagging: Longitudinal double spin asymmetry

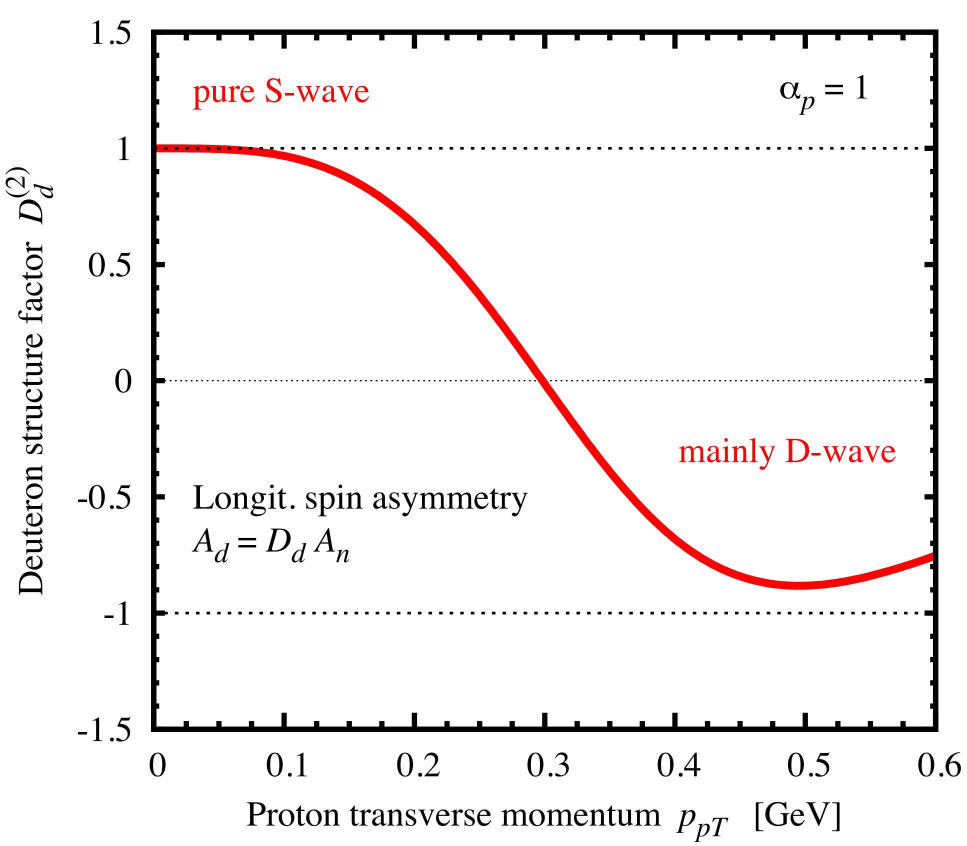


$A_{\parallel,d}(x_n, Q^2; \alpha_p, p_{pt})$ tagged longitud double spin asymmetry

$$= \frac{d\sigma_\parallel(+\tfrac{1}{2}, +1) - d\sigma_\parallel(-\tfrac{1}{2}, +1) - d\sigma_\parallel(+\tfrac{1}{2}, -1) + d\sigma_\parallel(-\tfrac{1}{2}, -1)}{d\sigma_\parallel(+\tfrac{1}{2}, +1) + d\sigma_\parallel(-\tfrac{1}{2}, +1) + d\sigma_\parallel(+\tfrac{1}{2}, -1) + d\sigma_\parallel(-\tfrac{1}{2}, -1)}$$

$$= \underbrace{\frac{S_d(\alpha_p, p_{pT})[S]}{S_d(\alpha_p, p_{pT})[U+T]}}_{D_d(\alpha_p, p_{pT})} A_{\parallel,n}(x_n, Q^2)$$

$D_d(\alpha_p, p_{pT})$ effective neutron polarization, depends on tagged proton momentum



D wave drops out at $\mathbf{p}_{pT} = 0$:
Pure S-wave, neutron 100% polarized

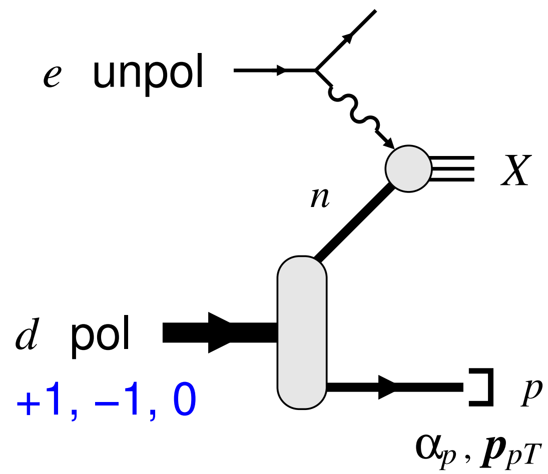
D wave dominates at $\mathbf{p}_{pT} \sim$ 400 MeV:
Neutron polarized opposite to deuteron spin!

Tagged proton momentum controls effective neutron polarization in deuteron

Frankfurt, Strikman 1983

Cosyn, Weiss PLB799 (2019) 135035; PRC102 (2020) 065204

Tagging: Tensor polarized asymmetry



$A_{zz,\,d}(x, Q^2; \alpha_p, \mathbf{p}_{pt})$ tagged tensor polarized asymmetry

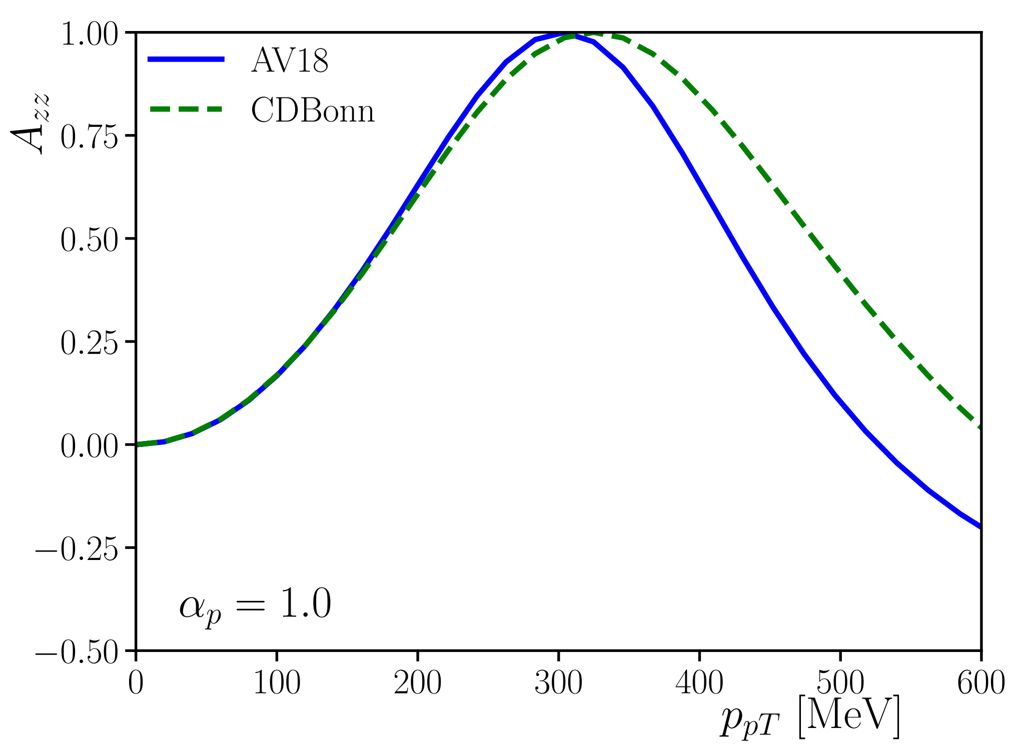
$$= \frac{d\sigma(+1) + d\sigma(-1) - 2d\sigma(0)}{d\sigma(+1) + d\sigma(-1) + d\sigma(0)} \qquad -2 < A_{zz,\,d} < 1$$

$$= \frac{S_d(\alpha_p, p_{pT})[T_{LL}]}{S_d(\alpha_p, p_{pT})[U]}$$

effective tensor polarization,
depends on tagged momentum

$$= \frac{\frac{1}{\sqrt{2}}UW + \frac{1}{4}W^2}{U^2 + W^2} \times \text{Angular}$$

requires D-wave



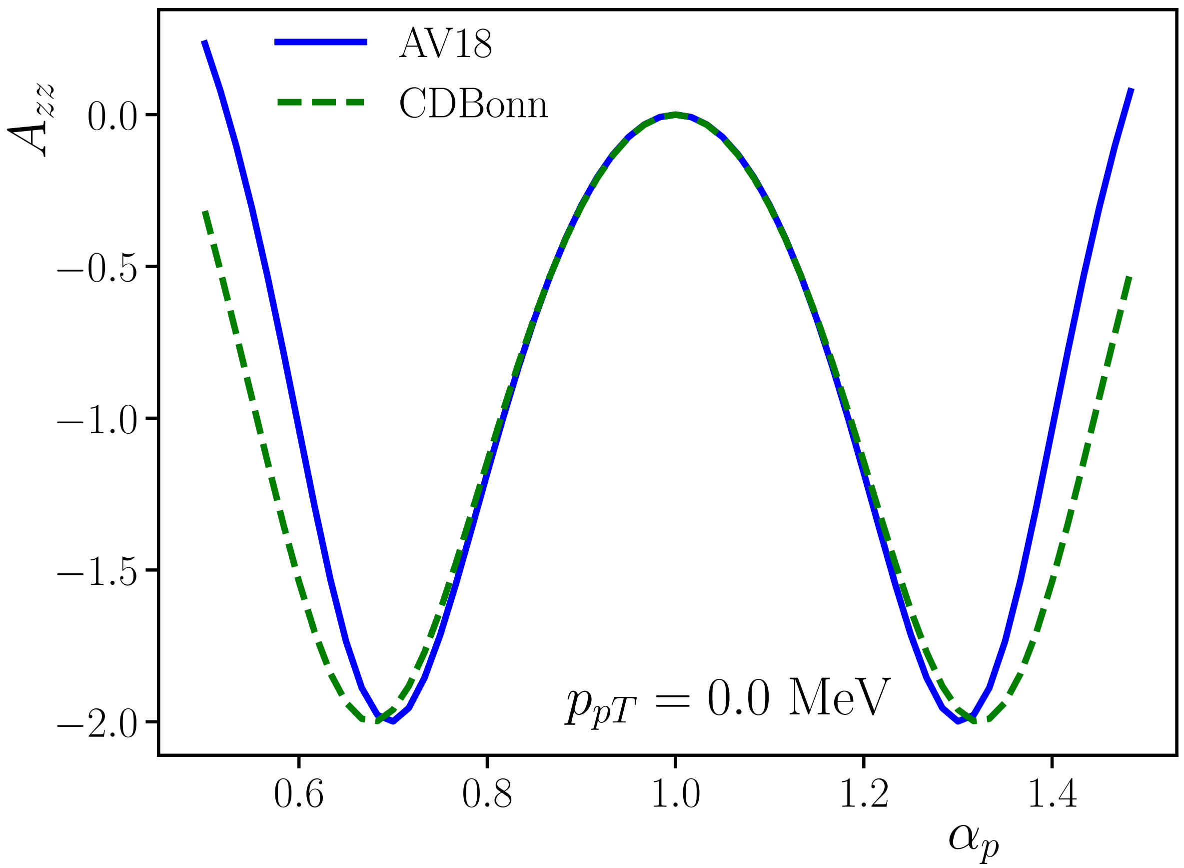
Maximal tensor polarization $A_{zz} = 1$
can be achieved at $p_{pT} \approx$ 300 MeV and $\alpha_p = 1$

Much larger tensor asymmetry than in untagged scattering where most events come from nucleon momenta ~ few 10 MeV and D-wave is small

Frankfurt, Strikman 1983

Cosyn, Weiss, in progress

Tagging: Tensor polarized asymmetry



Tensor polarization $A_{zz} = -2$
achieved at $p_{pT} = 0$ and $\alpha_p - 1 \approx \pm 0.3$

Spectator tagging can realize tensor asymmetries O(1) through control of S/D wave ratio

Frankfurt, Strikman 1983

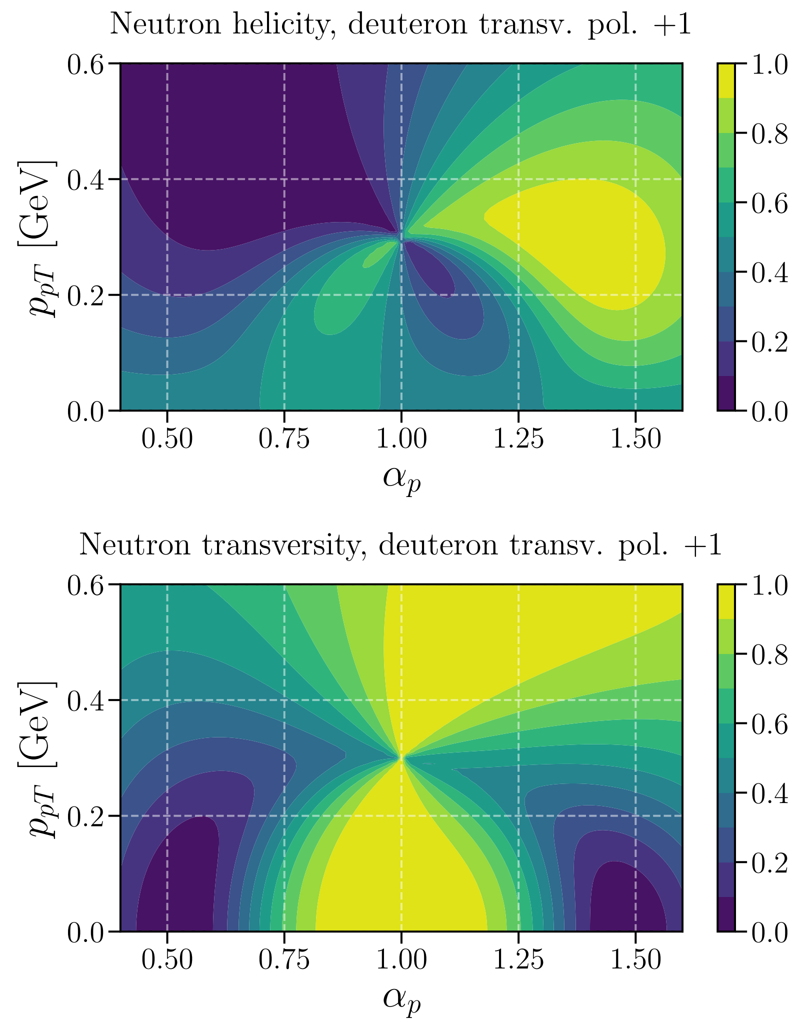
Cosyn, Weiss, in progress

Tagging: More polarization observables

Transverse vector polarization of deuteron

Induces transverse nucleon polarization (transversity)
deforms longitudinal nucleon polarization (spin-orbit)

Tagged measurements of g_{2n} neutron spin structure function?
Challenge for light-front method. Involves “bad components” of EM current



Cosyn, Weiss, in progress

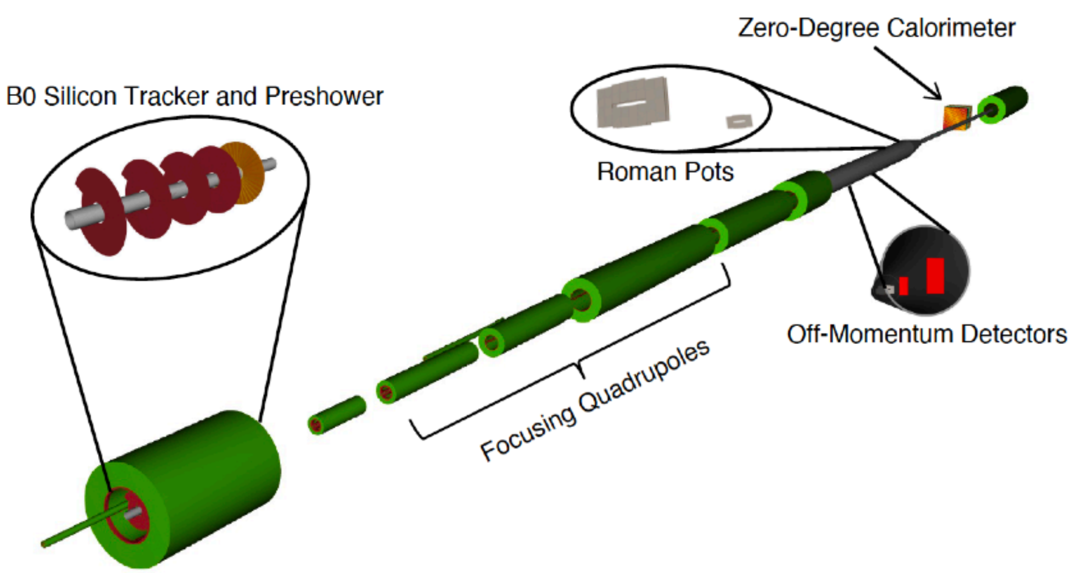
Final-state interactions

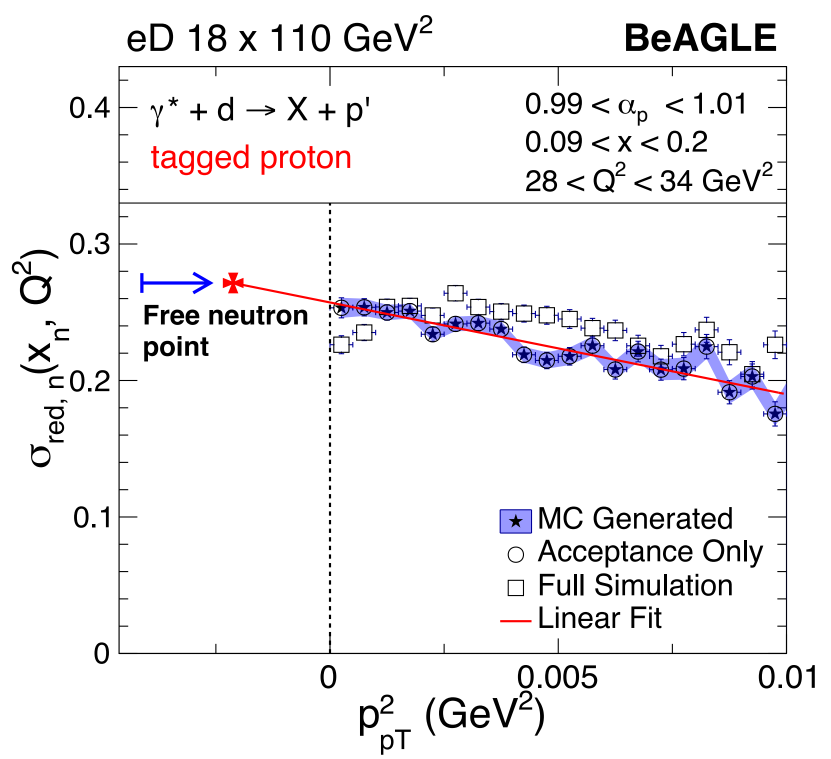
Large effects at $p_{pT} > 300$ MeV, should be included in calculations of tagged spin observables

Description based on space-time picture in deuteron rest frame: Fast and slow hadrons
Strikman, Weiss PRC97 (2018) 035209

ϕ_p dependent tagged cross section includes T-odd structures: Zero in impulse approximation, require final state interactions, can provide sensitive tests (→ Sivers effect in SIDIS)

EIC far-forward detectors





Far-forward detectors

Magnetic spectrometer for protons, several subsystems: good acceptance and resolution

Zero-Degree Calorimeter for neutron

Advantage over fixed target: No target material, can detect spectators with rest frame momenta → zero

Physics-detector simulations

Free neutron structure from proton tagging and pole extrapolation
Jentsch, Tu, Weiss, PRC 104, 065205 (2021)

Configuration dependence of EMC effect from proton and neutron tagging
in progress

Method works… can we extend it to polarized deuteron?

Further information: EIC Yellow Report 2021 [INSPIRE]

Summary

- Polarized deuteron at EIC would enable several unique high-impact measurements:

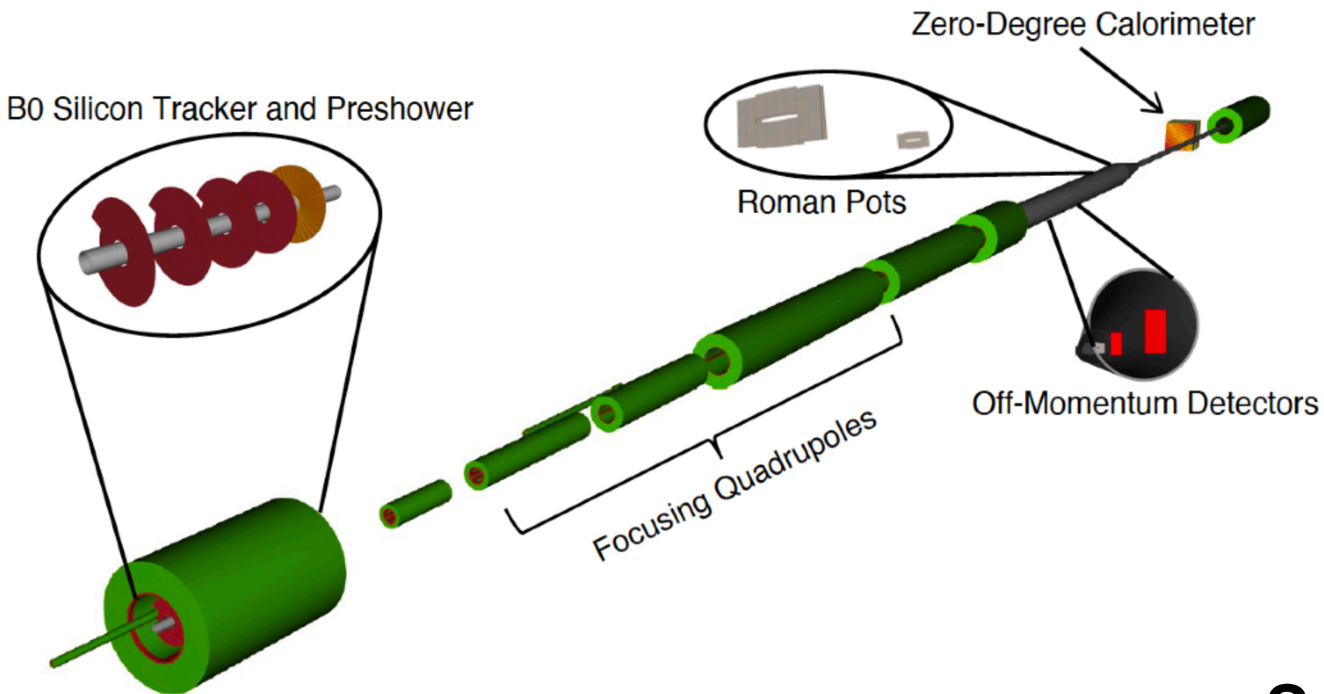
Neutron spin structure from inclusive DIS	Precision measurement neutron ~ proton Complements DIS on 3He
Shadowing from inclusive tensor-polarized T_{20}	Fundamental high-energy phenomenon in QCD Use polarization to control nucleon alignment Complements other shadowing/saturation studies
Neutron polarization in tagged DIS	Striking QM phenomenon Control nuclear configuration through tagging
Tensor-polarized tagged DIS	Achieve tensor asymmetries O(1) Control nuclear configuration through tagging Test short-distance nuclear structure
[+ coherent scattering on polarized deuteron]	

- These measurements are appropriate to EIC energy + luminosity and appear realistic if deuteron polarization could be achieved

- Community should formulate program and initiate technical development

Supplemental material

EIC: Far-forward detectors



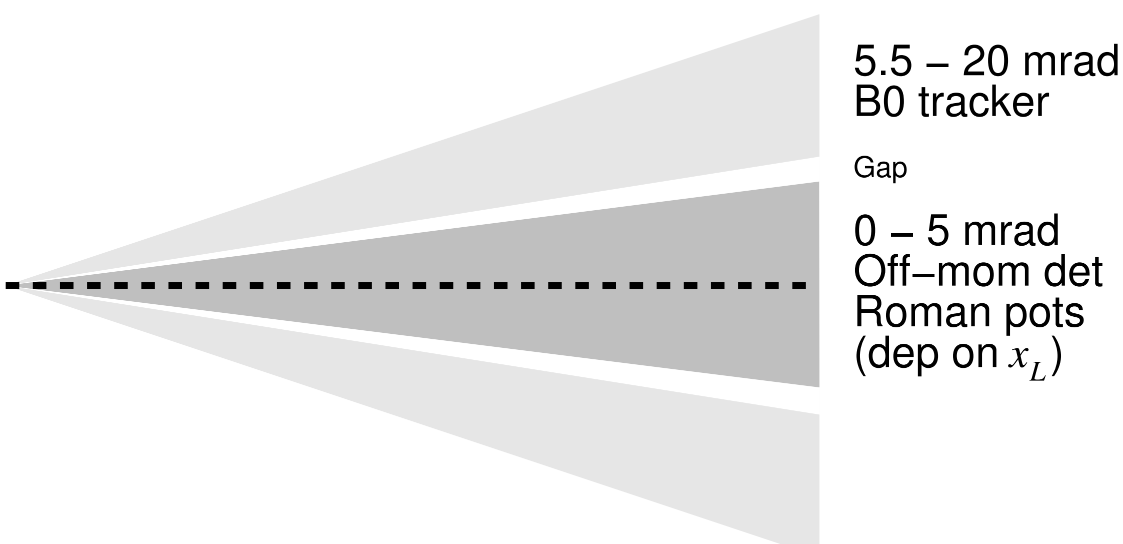
Magnetic spectrometer and detectors for charged particles, integrated in accelerator optics, several subsystems

Zero-degree calorimeter for neutrals

[This version EIC Yellow Report 2022;
fur updates see EPIC Collaboration]

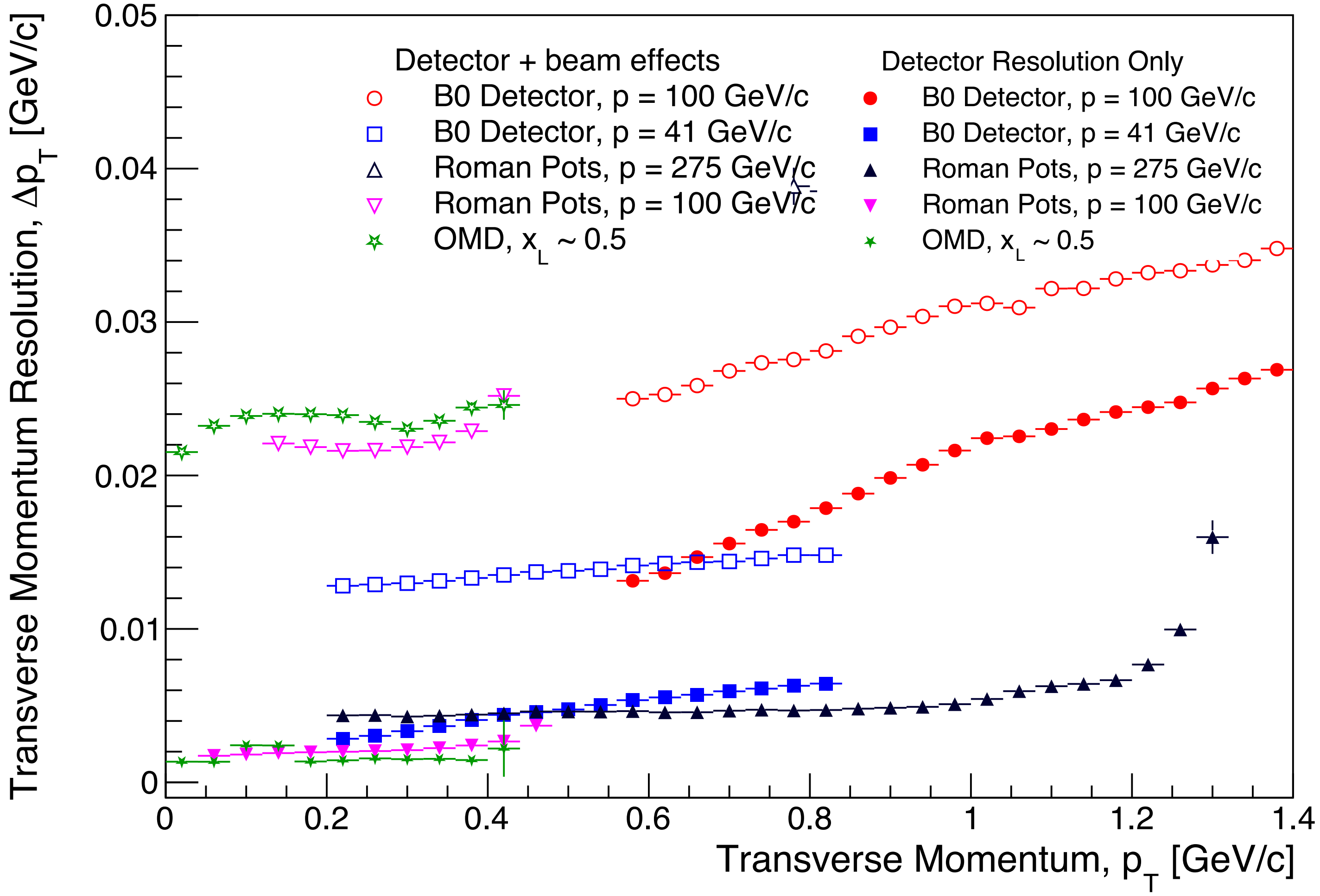
Subsystems used in spectator tagging

Protons	$\theta < 5\,\text{mrad}$ $0.2 < x_L < 0.6$	Off-mom detectors	Used in free neutron
Protons	$\theta < 5\,\text{mrad}$ $x_L > 0.6$	Roman Pots	Bound nucleon/EMC
Protons	$5.5 < \theta < 20\,\text{mrad}$	B0 tracker	Bound nucleon/EMC
Neutrons	$\theta < 4\,\text{mrad}$	ZDC	



Proton acceptance = function(θ, x_L)

EIC: Momentum resolution



Summary prepared by A. Jentsch

Proton momentum resolution

Simulations include detector resolution and beam effects: angular divergence, crabbing rotation, vertex smearing

Details depends on kinematics: Beam energy, subsystems used

Transverse momentum resolution achieved $\Delta p_T \sim$ 20 MeV at low p_T

Longitudinal momentum resolution typically $\alpha_p/\alpha_p \lesssim$ 5%, significantly better for $\alpha_p \sim 1$

Figures in supplement

Neutron momentum resolution

$$\frac{\Delta E}{E} = \frac{50\,\%}{\sqrt{E}} \oplus 5\,\% \qquad \frac{\Delta\theta}{\theta} = \frac{3\,\mathrm{mrad}}{\sqrt{E}}$$

with present ZDC design