

Next-generation nuclear DIS with spectator tagging at EIC

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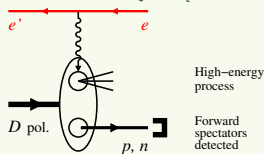
Ghent University, Belgium

DIS 2016
DESY Hamburg



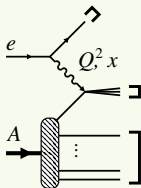
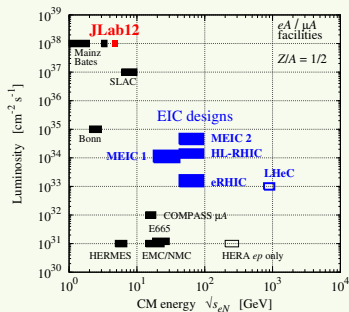
- ▶ Light ion physics program @ EIC
- ▶ Deuteron DIS with spectator tagging

- JLAB '14/'15 LDRD Project [Ch. Weiss]



- ▶ Experimental apparatus

Light ions at an EIC



- ▶ Wide kinematic range: CM energy $\sqrt{s_{eN}} = 20 - 100 \text{ GeV}$
 - $Q^2 \sim \text{few } 10 \text{ GeV}^2$ for DIS
 - $x \sim 10^{-1} - 10^{-3}$ for sea quarks & gluons

- ▶ High luminosity $\sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
 - detection of exception nuclear configurations feasible
 - multi-variable final states
 - polarization observables

- ▶ **Polarized** light ions
 - eRHIC: unpolarized D, polarized ^3He
 - JLEIC: polarized **D** and ^3He figure-8 ring layout

Light 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

How to account for nuclear binding and non-nucl. dof?

▶ Bound nucleons in QCD

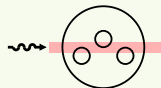
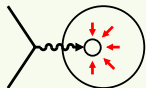
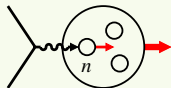
- medium modification of quark/gluon structure
- QCD origin of short-range nuclear force

How to control nuclear environment?

▶ Coherence and saturation

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

How to verify onset of coherence?



Challenges to be addressed by theory and new experimental techniques

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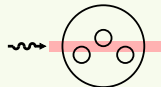
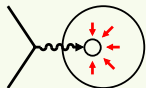
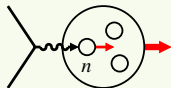
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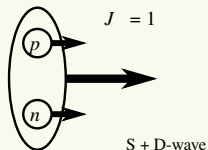
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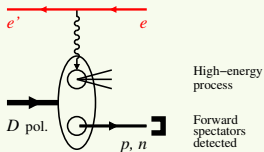
Challenges to be addressed by theory and new experimental techniques

Deuteron spectator tagging



► Polarized deuteron

- NN Wave function known (light-front)
- neutron spin-polarized
- non-nucleonic dof suppressed
- $|D\rangle = |pn\rangle + \epsilon|\Delta\Delta\rangle$
- limited possibilities for nuclear final-state interactions



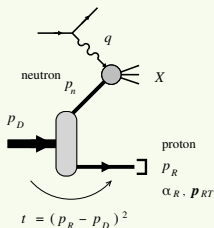
► Spectator nucleon tagging

- detection of forward nucleon
 - NN component, identifies active nucleon, controls deuteron configuration
 - suited for colliders: no target material, forward detection, transverse pol.
- fixed target CLAS BONuS limited to recoil momenta ~ 70 MeV

Tagged deuteron DIS: observables and structures

[talk yesterday in WG6]

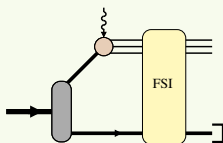
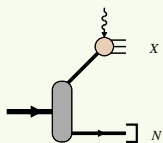
- ▶ Conditional cross section $\vec{e} + \vec{D} \rightarrow e' + N + X$



$$\frac{d\sigma}{dx dQ^2 d\phi_Y} = \frac{y^2 \alpha^2}{Q^4 (1 - \epsilon)} (F_U + F_S + F_T) d\Gamma_{P_N},$$

$$F_U = F_{UU,T}(x, Q^2, \alpha_R, \mathbf{p}_{R\perp}) + \epsilon F_{UU,L}(\dots) + \sqrt{2\epsilon(1+\epsilon)} \cos \phi_R F_{UU}^{\cos \phi_R}(\dots) \\ + \epsilon \cos 2\phi_R F_{UU}^{\cos 2\phi_R}(\dots) + h\sqrt{2\epsilon(1-\epsilon)} \sin \phi_R F_{LU}^{\sin \phi_R}(\dots)$$

- ▶ Conditional structure functions

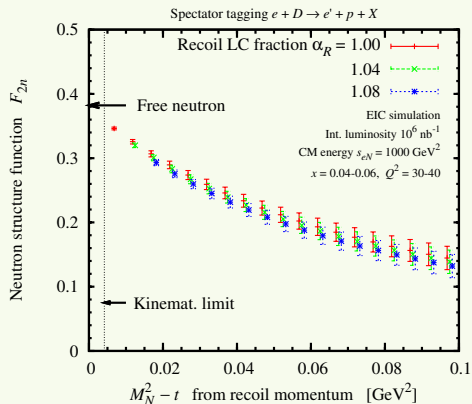


- impulse approximation:
 $F_x = \mathcal{F}(F_{1n}, F_{2n}, g_{1n}, g_{2n}) \times S_{LF}^D(\alpha_R, \mathbf{p}_{R\perp})$
- deuteron light-front spectral functions
- final-state interaction calculable (work in progress)

- ▶ Use recoil momentum as control variable: binding, fsi

Tagging: free neutron structure

Precise measurements of F_{2n}

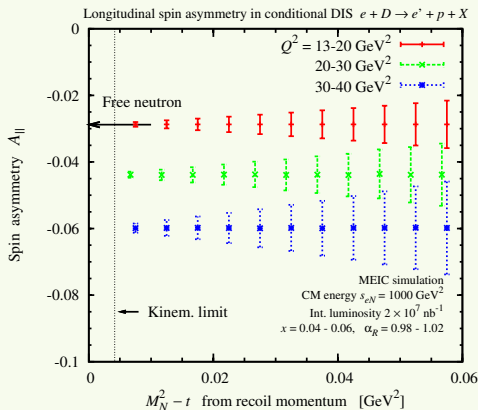


- ▶ F_{2n} extracted with percent-level accuracy at $x < 0.1$
- ▶ Uncertainty mainly systematic (JLab LDRD project: detailed estimates)
- ▶ In combination with proton data non-singlet $F_{2p} - F_{2n}$, sea quark flavor asymmetry $\bar{d} - \bar{u}$

Tagging: polarized neutron structure

On-shell extrapolation of double spin asymmm.

$$A_{||} = \frac{\sigma(++) - \sigma(--)}{\sigma(++) + \sigma(--)} = \frac{F_{LSL}}{F_T + \epsilon F_L} = D \frac{g_{1n}^n}{F_{1n}} + \dots$$



► Systematic uncertainties cancel in ratio (momentum smearing, resolution effects)

► Statistics requirements

■ Physical asymmetries

$\sim 0.05 - 0.1$

■ Effective polarization

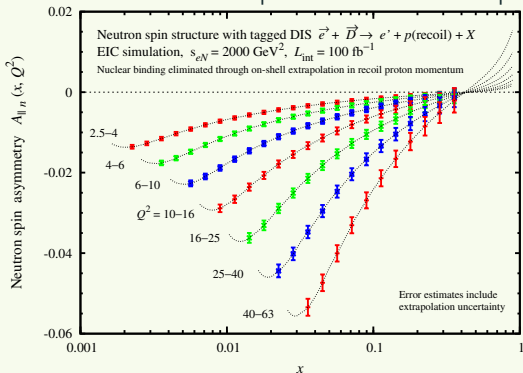
$P_e P_D \sim 0.5$

■ Luminosity required

$\sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

Tagging: polarized neutron structure II

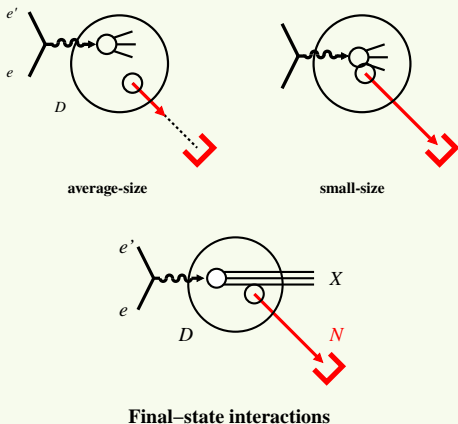
On-shell extrapolation of double spin asym. $A_{||n} = D \frac{g_{1n}}{F_{1n}} + \dots$



- ▶ As depolarization factor $D = \frac{y(2-y)}{2-2y+y^2}$ and $y \approx \frac{Q^2}{xs_{eN}}$, wide range of s_{eN} required!

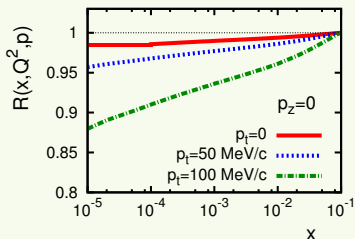
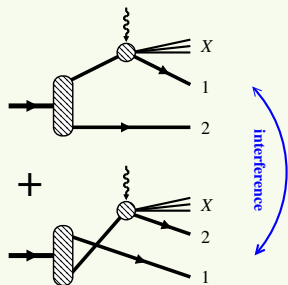
- ▶ Precise measurement of neutron spin structure
 - separate leading- /higher-twist
 - non-singlet/singlet QCD evolution
 - pdf flavor separation $\Delta u, \Delta d, \Delta G$ through singlet evolution
 - non-singlet $g_{1p} - g_{1n}$ and Bjorken sum rule

Tagging: EMC effect



- ▶ 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}

Tagging: Coherence and shadowing at small x

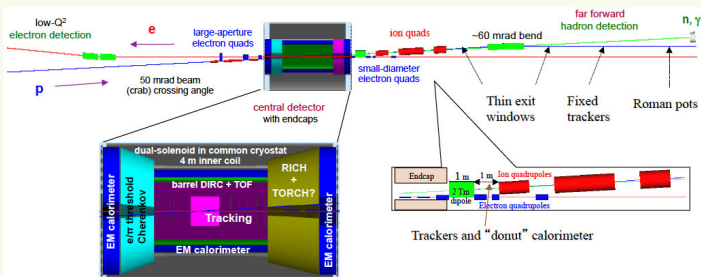


- ▶ Shadowing in inclusive DIS $x \ll 10^{-1}$
 - Diffractive DIS on single nucleon (leading twist, HERA)
 - Interference of DIS on nucleon 1 and 2
 - Calculable in terms of nucleon diffractive structure functions [Gribov 70s, Frankfurt, Guzey, Strikman '02+]
- ▶ Shadowing in tagged DIS
 - Explore shadowing through recoil momentum dependence [Guzey, Strikman, Weiss; in progress]
 - Reveal nuclear momentum components building up coherent fields at small x
 - Study coherence in $A = 2$, complementary to $A \gg 1$
 - Quantify approach to saturation at small x
- ▶ Coherent scattering $e + D \rightarrow e + M + D$
Exclusive meson production, DVCS, nuclear GPDs

Tagging: developments and extensions

- ▶ Final-state interactions in tagged $e + D$
 - distorts recoil momentum dependence away from the on-shell pole $t \neq m_N^2$
 - broad momentum distribution, interactions of spectator with slow debris [Cosyn, Sargsian, Strikman, Weiss; in progress. Ciofi, Kopeliovich 02]
 - maximized/minimized by choice of kinematics. Constrain FSI models.
 - azimuthal and spin observables non-zero through FSI
- ▶ Tagging with complex nuclei $A > 2$
 - isospin dependence, universality of bound nucleon structure
 - $A - 1$ ground state recoil
- ▶ Resolved final states: SIDIS on neutron, hard exclusive channels

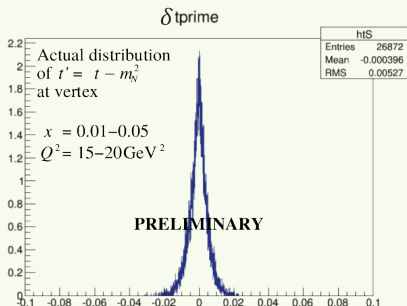
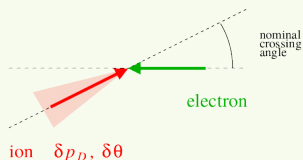
MEIC full-acceptance detector



P. Nadel-Turonski et al.

- ▶ Forward detector integrated in interaction region & beam optics
- ▶ Good acceptance for spectators and ion fragments
Rigidity different from beam. Large magnet apertures, small gradients
- ▶ Good acceptance for elastic recoil
Rigidity same as beam. Large dispersion generated *after* IP
Longitudinal momentum up to 99.5% of beam, angles down to 2 mrad (10σ)
- ▶ Good momentum and angular resolution
Longitudinal $dp/p \sim 4 \times 10^{-4}$, angular $\delta\theta \sim 0.2$ mrad
 $p_{TR} \sim 15$ MeV/c resolution for tagged 50 GeV/A deuterium beam

MEIC: Momentum spread in beam



- ▶ Intrinsic beam spread in ion beam “smears” recoil momentum
 - $p_R(\text{measured}) \neq p_R(\text{vertex})$
 - **Dominant** uncertainty for MEIC (diff. for eRHIC)
 - At nominal MEIC emittance
$$\frac{\delta p_D}{p_D} = 3 \times 10^{-4}$$
$$\delta \theta = 2 \times 10^{-4}$$
- ▶ Effect on extrapolation variable $t' = t - m_N^2$
 - Dominant effect from ion $\delta \theta$
 - Smearing width *leq* bin size
- ▶ On-shell extrapolation feasible!!

- ▶ Develop simulation tools (physics models, event generators, analysis tools) for DIS on light ions with spectator tagging at MEIC and study physics impact.
- ▶ ran FY14-15
D. Higinbotham, W. Melnitchouk, P. Nadel-Turonski, K. Park, C. Weiss (JLab), Ch. Hyde (ODU), M. Sargsian (FIU), V. Guzey (PNPI), with collaborators W. Cosyn (Ghent), S. Kuhn (ODU), M. Strikman (PSU), Zh. Zhao (JLab)
- ▶ Tools, documentation, results publicly available. Open for collaboration!
- ▶ More info:
<https://www.jlab.org/theory/tag/>
arXiv:1407.3236, arXiv:1409.5768v1, arXiv:1601.066665

Summary

- ▶ Spectator tagging in eD scattering with EIC enables next-generation measurements with maximal control and unprecedented accuracy
 - Neutron structure functions, including spin
 - Nuclear modifications of quark/gluon structure
 - Coherence and shadowing
- ▶ Recoil momentum dependence permits separation of nuclear and nucleon structure
 - On-shell extrapolation, controlled size of NN configuration, FSI
- ▶ Great opportunities, new physics applications