Study of Neutron Structure via Far-Forward Tagging of $eD \rightarrow e'NX$ in EIC

Kijun Park

$^{1}$Old Dominion University/Jefferson Lab

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No Free Neutron Target
- Neutron Structure (flavor decomposition of quark-spin, sea quarks, gluon pol.)
- Spectator Nucleon Tagging (forward detection/unique for collider)
- $\vec{D}$ (a well understood wave function/pol. neutron spin/limited FSI/coherence $N = 2,\ldots$)

Neutron structure function
- Gluon and sea quark (transverse) imaging of the nucleon
- Nucleon Spin ($\Delta G$ vs. $\log Q^2$, transverse momentum)
- Nucleon QCD (gluons in nuclei, quark/gluon energy loss)
- QCD vacuum and Hadron Structure and formation
Spectator Tagging $\rightarrow$ Extrapolating Neutron Structure

- Light-Cone parallel to $\bar{q} + \vec{P}_D$
- Light-Cone momentum fraction, Transverse momentum of recoil proton:
  $$\alpha_R = 2 \frac{E_R + p_R^2}{M_D}, \quad \vec{p}_{RT}$$

- Cross-section in the IA
  $$\frac{d\sigma}{dx dQ^2 d\alpha_R d^3 p_R/E_R} = f_{\text{Flux}} \times S_D(\alpha_R, p_{RT}) \times F_{2n} \left( \frac{x}{2 - \alpha_R}, Q^2 \right)$$

- On-shell extrapolation: $t \rightarrow M_N^2$ or $(t - M_N^2) \equiv t' \rightarrow 0$
  - Free neutron structure at pole
  - Model-independent method

[by courtesy of C. Weiss]
E_e = 5 GeV, E_D = 100 GeV, cross-angle: 50 mrad, p_R (rest frame) = 300 MeV
Normal. Emittances: \(dp/p = 3 \times 10^{-4}\), \(d\theta = 2 \times 10^{-4}\),
Luminosity = \(10^{33} \text{cm}^{-2}\text{sec}^{-1}\), Time = \(10^6\)(sec)

Cross-section Comparison between MC and Analytic calculation (±5% bin-center)
MEIC Beam Emittance effect << ±1%, even with fine binning
Sufficient \(t'\) resolution for the extrapolation
\(F_{2D}\) structure function on-shell extrapolation with experimental uncertainty estimation

\[
\frac{d\sigma}{dxdQ^2d\alpha_Rd^3p_R/E_R} = f_{\text{Flux}} \times F^n_{2D}(x_{Bj}, \alpha_R, p_{RT}) = f_{\text{Flux}} \times S_D(\alpha_R, p_{RT}) \times F_{2n} \left(\frac{x}{2 - \alpha_R}, Q^2\right)
\]

\[
\Delta \sigma_{MC} = \sum N_i \Delta t' \frac{d\sigma}{dxdQ^2dt'} \Gamma \cdot J/N_0 \ , \ \text{count} = L \cdot T \cdot \Delta \sigma_{MC} \ , \ \sigma(\Delta \sigma_{MC}) = \frac{\Delta \sigma_{MC}}{\sqrt{\text{count}}} = \sqrt{\frac{\Delta \sigma_{MC}}{L \cdot T}}
\]

[See Backup Slide]
MC Simulation \rightarrow F_{2D}(x, Q^2, \alpha_R, t')

- $t' = (p_S - p_D)^2 - M_N^2$
- Intrinsic momentum spread in ion beam smears recoil momentum
- Dominant uncertainty for MEIC
- Effect on $t'$ (angular spread)
- Smearing $< t'$ bin-size

- $F_{2D}$ vs. $t'$: take out $f_{\text{flux}}$
- $\alpha_R$: cut around $1 \pm 0.02$
- Excellent resolution allows to reach smaller $t'$
- Feasible on-shell extrapolation
- Blue vertical dash line $= t'_{\text{min}} = 0.00416$ GeV$^2 \approx 2M_N B_D$
- High resolution in $p_R$ permits fine binning in $t'$
\( F_{2D} \rightarrow F_{2n}/S_D(\alpha_R, p_{RT}) \)

- \( F_{2D} \times (t')^2 \) vs. \( t' \): take out a pole term contribution in spectral function; \( S_D(\alpha_R, p_{RT}) \)
- \( RES = \text{Res}(\psi_d(T_{pol})) = \frac{C}{2\sqrt{2 \pi} M_N} \text{GeV}^{-1/2} \)
- Extrapolation with Error evaluation from "quadratic fit": 0.3902 ± 0.0048
Far-Forward Detection in EIC

- Good acceptance for all ion fragments - rigidity different from beam
  - Large magnet apertures (small gradients a fixed maximum peak field)
- Good acceptance for low-$p_T$ recoils - rigidity similar to beam
  - Small beam size detection point (downstream focus, efficient cooling)
  - Large dispersion (generated after the IP, $D=D'=0$ the IP)
- Good momentum and angular resolution
  - Longitudinal $dp/p \approx 4 \cdot 10^{-4}$
  - Angular in $\theta$, for all $\phi$: $\approx 0.2\text{mrad}$
  - $p_{RT} \approx 15\text{MeV/c}$ resolution for tagged nucleon in 100GeV deuterium beam
  - Long, instrumented drift space (no apertures, magnet, ...)
- Sufficient beam line separation ($\approx 1\text{m}$)

[Talk: P. Nadel-Turonski]
Sample Tracks in Detector Simulation [GEMC]

10 events from \( eD \rightarrow e'p_sX \)

**Figure:** Examples of physics event \( eD \rightarrow e'p_sX \), red color rays: spectator protons, light-blue rays: scattered electrons
Figure: $p_R$ (GeV) vs. $\alpha_R$: (left: Generated, middle: Accepted, right Cross section weighted) on the 2nd Dipole Exit Window
The MEIC will be an excellent tool to provide unique and precise nuclear physics measurements.

- Kinematics / Polarized $D$ & $^3He$ / Forward nucleon tagging

Nucleon tagging is an excellent tool to study parton structure

- Free neutron structure function ($F_2$) from on-shell extrapolation

Optimize energy, luminosity, and detector/IR in MC for deep exclusive and SIDIS processes

- MC simulation will provide more realistic requirement of experimental detectors

R&D in progress to establish methods

- Theoretical : Polarization($\vec{e}$, $\vec{D}$), FSI, Shadowing,...
- Experimental : MC simulation, Particle Tracking, Systematics, ...
**Left**  Comparison between MC and Analytic calculation (±5% bin-centering effect)

**Middle**  Initial State Smearing (ISS) is << ±1%

**Right**  Intrinsic MC Statistical Uncertainty is ~ 0.3%
Spectator Tagging: Coherent Effects

- Shadowing effect important in inclusive DIS $x \ll 0.1$
- Diffractive scattering on single nucleon
- Interference between scattered $p$ and $n$

- Shadowing in Tagged DIS
- Coherent effect is clean ($N = 2$)
- Systematics is important (unpol./pol.) in $p$-$n$
- FSI between $p$ and $n \rightarrow$ distortion of $p_T$, spin