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

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Electron Ion Collider → Spectator Tagging

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 $\bar{q} + \bar{P}_D$

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

$$\frac{d\sigma}{dxdQ^2d\alpha_Rd^3p_R/E_R} = f_{Flux} \times S_D(\alpha_R, p_{RT}) \times F_{2n} \left(\frac{x}{2 - \alpha_R}, Q^2\right)$$

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}$ cm$^{-2}$sec$^{-1}$, Time$ = 10^6$ (sec)

Cross-section Comparison between MC and Analytic calculation ($\pm 5\%$ bin-center)

MEIC Beam Emittance effect $<< \pm 1\%$, even with fine binning

Sufficient $t'$ resolution for the extrapolation

$F_{2D}$ structure function on-shell extrapolation with experimental uncertainty estimation

$$\frac{d\sigma}{dxdQ^2d\alpha_R d^3p_R/E_R} = f_{Flux} \times F^{n}_{2D}(x_B, \alpha_R, p_{RT}) = f_{Flux} \times S_D(\alpha_R, p_{RT}) \times F_{2n}\left(\frac{x}{2 - \alpha_R}, Q^2\right)$$

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

[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 $= t'_{\text{min}} = 0.00416 \text{ GeV}^2 \approx 2M_NB_D$
- 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 $\phi$: $\approx 0.2$ 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 ($\approx 1$ 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

[Talk: M. Ungaro]
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, ...

[JLab LDRD project]
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 $x << 0.1$
- 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