Next-generation neutron structure measurements with spectator tagging at EIC

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Collider Kinematics

• Natural light-cone direction is event-by-event frame with $q$ and $P_D$ anti-collinear.
  • Spectator proton (or neutron) emitted in forward direction with $\sim 50\%$ of beam momentum

• Beam emittance envelope is comparable to Far-Forward tracking resolution of spectator proton

• Both effects (and crossing angle) included in $eD \rightarrow e'pX$ Monte-Carlo
  • Jlab LDRD 2014-2015
    [link](www.jlab.org/theory/tag/)
    Codes, references...
Light-Cone Variables: 
\((\alpha, p_\perp)\)

\[
P_D^{[+,-,\perp]} = \left[ P_D^+, \frac{M_D^2}{2P_D^+}, 0_\perp \right], \quad P_D^+ \gg M_D = 2M_N - B;
\]

\[
p_S = p_p^{[+,-,\perp]} = \left[ \frac{\alpha}{A} P_D^+, \frac{M_N^2 + p_\perp^2}{2\alpha P_D^+ / A}, p_\perp \right], \quad 0 < \alpha < A = 2;
\]

\[
p_n^2 = (P_D - p_p)^2 \equiv t
\]

\[
M_N^2 - t \approx 2M_NB + 2p_{\text{Rest}}^2
\]

\[
\alpha \approx 1 + \frac{p_{\text{Rest-frame}}}{M}
\]

\[
|\alpha - 1| \lesssim p_F
\]
Detector implementation

- JLEIC example

GEMC:
- $e^-$
- $D$
- $p$

D(e,e'p)X

DEUTERON MOMENTUM DISTRIBUTION
From D(e,e'p)n at 500 MeV

- $q = 450$ MeV/c ($\times 141$)
- $q = 350$ MeV/c ($\times 141$)

$\alpha \approx k/M$
Beam Emittance & Detector Resolution

• Beam emittance envelope (JLEIC)
  • $\sigma(P_D)/P_D \approx 3 \times 10^{-4}$, $\sigma(P_{\perp})/P_D \approx 2 \times 10^{-4}$

• Spectator tracking resolution
  • $\sigma(x) \approx 100\mu m$, Dispersion $\approx 1m$
  • $\sigma(P_{||}, P_{\perp})/P_p \leq 2 \times 10^{-4}$
  • Requires relative stability/position measurement of transverse beam crossing to $\sim 100\mu m$

• On-shell extrapolation is smooth in $(t')^2 d\sigma$
  • Sensitive to resolution of $t'$: Simulation results assume emittance is known/stable to $\pm 10\%$

• $P_D = 100\,\text{GeV/c}$
  • $\sigma(p_{\perp}) \approx 15\,\text{MeV/c}$
  • $\sigma(\alpha) \approx 0.0002$
Neutron $F_2$

- On-shell extrapolation

![Graph of $F_2$ vs. $-t'$](image)

- Cross section multiplied by $(t')^2$

18 April 2018  C. Hyde, DIS2018-WG7
**D(e,ep_S)X: p_S+X FSI**

- Final State Interactions alter the shape of the On-Shell extrapolation, not the residue $F_{2n}$ at the pole $1/(t')^2$
- M.Strikman, C.Weiss, PRC 97 (2018)

![Graphs showing FSI effects](image1)

![Graphs showing FSI effects](image2)
The EMC Effect in the Deuteron

- **Concept:** EMC effect arises from short range fluctuations in D wave-function
- **Extract on-shell point** for $|\alpha - 1| < 0.02$
- **Dashed line is IA for $\alpha = 0.9$**
- **Pseudo-data shows possible magnitude of EMC effect**
- **“Model-Independent” extraction**

![Graph showing EMC effect in tagged DIS $e + D \rightarrow e' + p + X$, backward kinematics](image_url)

- Parameters:
  - $x = 0.3-0.4$, $Q^2 = 20-30$ GeV$^2$
  - $\alpha_R = 0.89-0.91$ (backward)
  - $L_{\text{int}} = 10^7$ nb$^{-1}$, $s_{eN} = 1000$ GeV$^2$
Polarization: On-Shell Extrapolation

- Simulation with S-state only
  - Asymmetry independent of $t'$

\[
\text{Longitudinal spin asymmetry in tagged DIS } e + D \rightarrow e' + p + X
\]

- S+D state:
  - Sargsian, Cosyn, Weiss 2017
  - Extrapolation smooth for $t' < 0.08 \text{ GeV}^2$
Polarization

• 1 year @ 10^{34}/cm^2/s

• Depolarization favors lower energy: 
  \( D = y(2-y)/(2-2y+y^2) \)

• \( p \pm n \)
  • flavor
  • Bjorken Sum Rule
  • \( \alpha_S(Q^2) \)

Neutron spin structure with tagged DIS \( \overline{c} + \overline{D} \rightarrow e^+ + p(\text{recoil}) + X \)
EIC simulation, \( s_{eN} = 2000 \text{ GeV}^2 \), \( L_{\text{int}} = 100 \text{ fb}^{-1} \)
Nuclear binding eliminated through on-shell extrapolation in recoil proton momentum

Error estimates include extrapolation uncertainty
DIS from Bound Proton

- Tag spectator neutron
  - \( D(e,e'\alpha) X \)
  - State-of-the-art HCal
    \( \sigma(E)/E \gtrsim 30\%/VE \)
    NIM A 866 (2017) 76.

- 3 contours/decade in D momentum distribution.

- Ovals are 1-\( \sigma \) envelope of tagged neutron resolution.
Diffraction, (Anti-) Shadowing and the NN interaction

- $D(\text{e,e'}\text{pn})X$
- Small sized color neutral “$X$”
  - Only FSI are ordinary $pn$ interactions
- $D(\text{e,e'}\text{Vpn})$
  - Transition GPD of $D \rightarrow pn$ continuum
  - G. Miller, M. Sievert, R. Venugopalan, PRC 93 (2016)
    - Final state $np$ relative momentum Fourier Conjugate to initial state $np$ spatial separation.
  - Study the quark-gluon structure of interacting $np$ pair
    - Or Hen, Alterelli Prize lecture on dynamics of EMC effect
Conclusions

• Unprecedented precision study of neutron, and NN, NNN quark-gluon structure possible with spectator tagging at an Electron Ion Collider
  • Boost enables tagging to $p_s \approx 0$
  • Transverse, Longitudinal, Tensor Polarization without dilution

• $^3$He (polarized) is essential too, but not a substitute for the deuteron (polarized or unpolarized)