Far-Forward Physics @ the EIC

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Electron Ion Collider
What is meant by Far-Forward?

Overall detector requirements:
- Large rapidity \((-4 < \eta < 4)\) coverage; and far beyond in far-forward/far-backward detector regions

Rapidity is related to the polar angle \(0 < \eta < 4\) equates to \(2.1^\circ < \theta < 90^\circ\) \(\eta = -\ln(\tan(\theta/2))\) pseudorapidity

Far-forward here means \(\theta < 2.1^\circ\) (~37 mrad)

When we say “far-forward” physics, we really just mean interactions with some final state particles at very high pseudorapidity (or small angle with respect to the beam).
Diffractive + Exclusive Final States

- Diffractive events characterized by an “$\eta$-gap” between jet and scattered proton $\rightarrow$ proton scattered at high pseudorapidity!

\[ t = -(p - p')^2 \approx -p_{t,p'}^2 \]

Mandelstam $t$
Diffractive + Exclusive Final States

• Diffractive events characterized by an “$\eta$-gap” between jet and scattered proton $\rightarrow$ proton scattered at high pseudorapidity!
  • Can be described by color-singlet “pomeron” exchange in Regge theory.
    • Accounts for $\sim 15\%$ of the total $e + p$ cross section at HERA and non-perturbative!
    • HERA: the rest-frame proton was seeing a $50$ TeV electron – and $15\%$ of the time the proton didn’t break up!

\[ t = - (p - p')^2 \approx -p_{t,p}^2, \]

\[ \eta\text{-gap} \quad \text{Mandelstam } t \]
Far-Forward Processes at the EIC

e+p DVCS

e+d exclusive J/Psi with p/n tagging

e+He3 spectator tagging

cohherent/incoherent J/ψ production in e+A

Meson structure:

\( e p \rightarrow (π) \rightarrow e' n X \)

\( Λ \rightarrow pπ^0 \) and \( Λ \rightarrow nπ^0 \)

Quasi-elastic electron scattering

u-channel backward exclusive electroproduction

...and MANY more!
Far-Forward **Physics at the EIC**

- **e+p DVCS**
- **e+d exclusive J/Psi with p/n tagging**
- **e+He3 spectator tagging**
- **coherent/incoherent J/ψ production in e+A**

### Meson structure:
- $\pi^+ \pi^-$
- $K^0, K^+, B^0$
- $n, n', N, N', Δ^+, Δ^+_b$

### Proton spin: orbital angular momentum

### Free Neutron Structure Functions & EMC Effect

### Quasi-elastic electron scattering

### Neutron Spin Structure

### Short-Range Correlations

### Saturation

### Short-Range Correlations

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**References:**


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...and MANY more!
Protons: Partonic Imaging
Partonic Imaging of Nucleons

Fig. 2.2 from the EIC White Paper
Partonic Imaging of Nucleons

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Spin-dependent 3D momentum space images from semi-inclusive scattering

Spin-dependent 2+1D coordinate space images from exclusive scattering
Deeply Virtual Compton Scattering

**DVCS (γ)**

- Exclusive process with all final state particles detected in the event.
- Sensitive to the proton GPD.

\[ t = -(p - p')^2 \approx -p'^2 \]

\( p_t \) and \( b_t \) are conjugate variables!

**Plot from EIC White Paper:**

\[ d^2 \sigma/dt dB = F (x, b) \]
Exclusive Vector Meson and Real Photon Production

DVCS:  
• Very clean experimental signature  
• No VM wave-function uncertainty  
• Hard scale provided by $Q^2$  
• Sensitive to both quarks and gluons $Q^2$ dependence of cross section

VMP:  
• Uncertainty of wave function  
• J/Psi $\rightarrow$ direct access to gluons, c+cbar pair production  
• Light VMs $\rightarrow$ quark-flavor separation
Small GPD Primer

\[ \frac{d\sigma}{dt} \sim A_0 \left[ |H|^2 (x,t,Q^2) - \frac{t}{4M_p^2} |E|^2 (x,t,Q^2) \right] \]

Dominated by H
slightly dependent on E

\[ A_{UT} \propto \sqrt{-\frac{t}{4M^2}} \left[ F_2(t) H(\xi,\xi,t,Q^2) - F_1(t) E(\xi,\xi,t,Q^2) + \ldots \right] \]

\[ \sin(\Phi_T - \Phi_N) \]

governed by E and H

Requires a polarized proton-target

responsible for total orbital angular momentum through Ji sum rule
a window to the SPIN physics
What about (light) nuclei?
Tagged DIS at the EIC

- Tagged DIS measurements on light nuclei → "tag" (generally) far-forward particles in final state for useful kinematic information!
  - Provides more information than inclusive cross sections!
- Lots of topics!
  - Short-range correlations.
  - Gluon distributions in nuclei.
  - Free neutron structure functions.
  - Nuclear modifications of nucleons in light nuclei.
    - EMC effect, anti-shadowing, etc.

Tagged spectator nucleon momentum → experimental variable for selecting nuclear configurations with free and modified nucleons.
Light nuclei - deuterons: Free Neutron Structure
Neutron Structure

- Protons well-studied at HERA -> So…why the neutron?
  - Flavor separation, baseline for studies of nuclear modifications.

\[ \sigma_r = \frac{Q^4 x}{2\pi\alpha^2[1 + (1 - y)^2]} \cdot \frac{d^2\sigma}{dx\,dQ^2} = F_2(x, Q^2) - f(y) \cdot F_L(x, Q^2) \]

“Flux factor”

Differential cross section

Structure functions

Reduced cross section

Some useful HERA references for measurements on proton

- F. Aaron et al. (H1 Collaboration), The European Physical Journal C volume 63, Article number: 625 (2009)
Neutron Structure

• Protons well-studied at HERA - So…why the neutron?
  • Flavor separation, baseline for studies of nuclear modifications.

• What makes the free neutron structure hard to measure?
  • Can only access neutrons in a nucleus.
  • Includes nuclear binding effects, Fermi motion, etc.
Neutron Structure

• Protons well-studied at HERA -> So…why the neutron?
  • Flavor separation, baseline for studies of nuclear modifications.

• What makes the free neutron structure hard to measure?
  • Can only access neutrons *in a nucleus*.
  • Includes nuclear binding effects, Fermi motion, etc.

• **Two options:**
  1. Inclusive measurements \(\rightarrow\) Average over all nuclear configurations, use theory input to correct for nuclear binding effects.
  2. Tagged measurements \(\rightarrow\) Select nuclear configuration via spectator kinematics, allows for differential study.
    • Spectator kinematics provide a knob to dial in different regions of interest for study (i.e. high \(p_T\) \(\rightarrow\) SRC physics; very low \(p_T \approx 0\) GeV/c yields access to on-shell extrapolation).
    • On-shell extrapolation enables access to **free** nucleon structure.
      • M. Sargsian, M. Strikman PLB 639 (iss. 3-4) 223231 (2006)
Basic Method - Pole Extrapolation

\[ p_{\rho T}^2 > 0 \quad \text{physical region} \]

\[ p_{\rho T}^2 \rightarrow -a_f^2 \quad \text{pole extrapolation} \]

\[ \alpha_p, p_{\rho T} \]

\[ 2 - \alpha_p \]

\[ r_T \rightarrow \infty \]

\[ \alpha_p \]

\[ \uparrow \quad r_T \quad \downarrow \]

\[ 2 - \alpha_p, -p_{\rho T} \]

\[ \alpha_p, p_{\rho T} \]

\[ \alpha_p \]

\[ \alpha_p = 1, S_d \]

\[ \alpha_p = 1, S_d \text{[pole]} \]

\[ \alpha_p = 1.05, S_d \]

\[ \alpha_p = 1.05, S_d \text{[pole]} \]
Free Neutron $F_2$ Extraction

\[ \frac{1}{S_d(p_{pT}, \alpha_p)[\text{pole}]} \]

Result: Reduced cross section on the active nucleon.

(inverse pole of deuteron spectral function)
Free Proton $F_2$ Extraction

Light nuclei – deuterons: The EMC Effect (on-going study)
The EMC Effect

• Discovered by the European Muon Collaboration ~40 years ago.
  • Puzzle: why the dip?
• Still an unanswered question, and one we hope the EIC can aid in answering.
The EMC Effect

• Potential pathway forward – study off-shell effect in deuterons.

Tagged DIS Process: $e + d \rightarrow e' + X + p'$ or $n'$

Low off-shellness

High off-shellness

$-t' = M_N^2 - (p_d - p_p)^2$

Virtuality/off-shellness in the deuteron

Question: can the EMC effect be controlled via the off-shellness without altering the colliding system?

Our goal: establish experimental prospects to see if we will be sensitive enough to study this!
The EMC Effect

BeAGLE
Applicable phase space

Add EMC effect according to the linear parametrization

- Only apply to $0.3 < x_{bj} < 0.7$
- $Q^2$ independent
- Weight = $F_2$ (bound)/ $F_2$ (free)

Minimal parametrization (linear)
Linear offshell dependence on the EMC effect.
(Frankfurt, Strikman 80’, Weiss)
The EMC Effect @ the EIC

- **Approach:**
  - Measure deuteron reduced cross-section $\sigma_D$, with and without the off-shell effects included.
    - No FSI included.
  - Ratio of $\sigma_D$ inside and outside the EMC region (e.g. $x \sim 0.5$ and $x \sim 0.2$)
  - Establish required integrated luminosity.
    - Challenging measurement $\rightarrow$ high-$x$ + low probability nuclear configuration + lower beam energies.
  - Neutron spectator not possible in 5x41 GeV/n due to detector acceptance.

BeAGLE e+d 5x41 GeV/n

- 5x41 GeV/n Integrated Luminosity $\sim 25$ fb$^{-1}$

- Proton Spectator
  - $10.0 < Q^2 < 20.0$ GeV$^2$
  - $0.95 < \alpha_p < 1.05$

- **Cross-Section Ratio**

- **Graph**
  - $p^2_{T,p}$ vs. $x$
  - No EMC Weight, MC
  - With EMC Weight, MC
  - With EMC Weight, Reco
The EMC Effect @ the EIC

- EIC versatility → different beam energy configurations!

BeAGLE e+d 5x110 GeV/n

Neutron Spectator

10.0 < Q^2 < 20.0 GeV^2
0.95 < \alpha_p < 1.05

Cross-Section Ratio

\sigma_D(\alpha_p, p^2_{T,p}, x_n = 0.5) / \sigma_D(\alpha_p, p^2_{T,p}, x_n = 0.2)

- No EMC Weight, MC
- With EMC Weight, MC
- With EMC Weight, Reco

Proton Spectator

10.0 < Q^2 < 20.0 GeV^2
0.95 < \alpha_p < 1.05

Cross-Section Ratio

\sigma_D(\alpha_p, p^2_{T,p}, x_n = 0.5) / \sigma_D(\alpha_p, p^2_{T,p}, x_n = 0.2)

- No EMC Weight, MC
- With EMC Weight, MC
- With EMC Weight, Reco

• Higher energy configuration (5x110 GeV/n).
• More favorable detector acceptance → study of proton and neutron spectators with same beam configuration.
• Measurement of same observable with different beam energies/spectator reconstruction enables better understanding of experimental systematics.
Summary

• Far-forward physics characterized by exclusive+diffractive final states.
  • Lots to unpack! – proton spin, neutron structure, saturation, partonic imaging, meson structure, etc.
• There is lots of interest in the EIC community in studying this physics via these final states!
  • Exciting time to get involved!!
• Special thanks to Elke Aschenauer, Salvatore Fazio, and Kong Tu for some slides!!

Email me if you have any questions: ajentsch@bnl.gov

Now...*how do we do this physics program?*