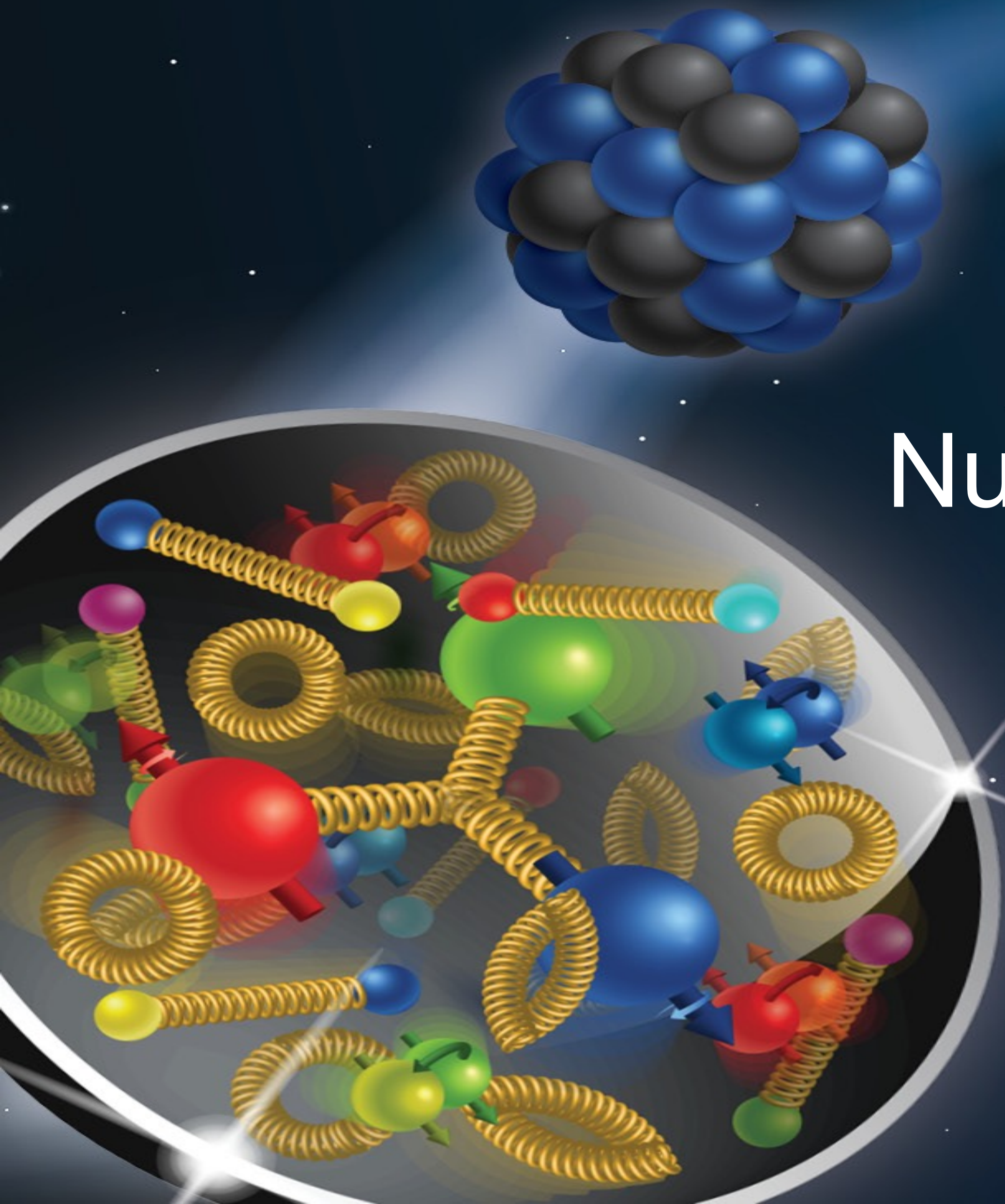

Exploring Free and Bound Nucleon Structure Using Deuteron Tagged DIS at the EIC

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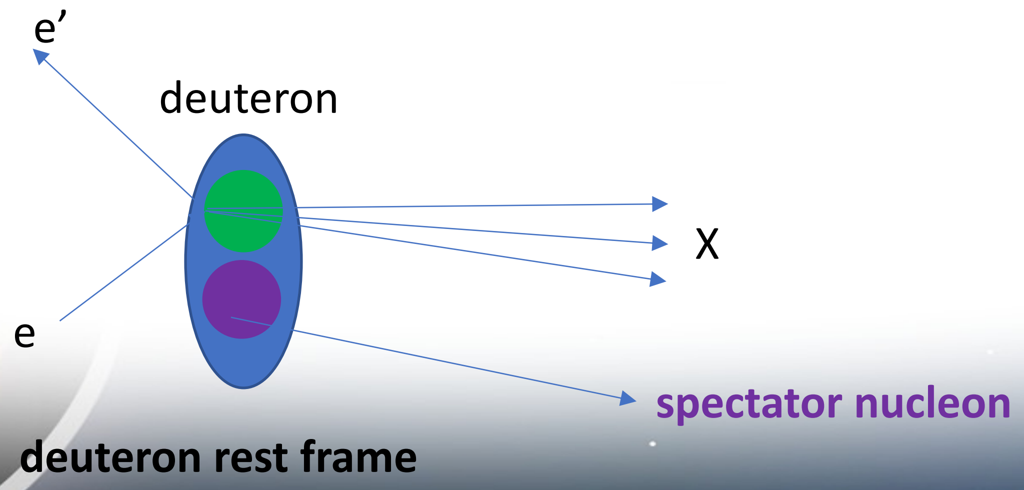
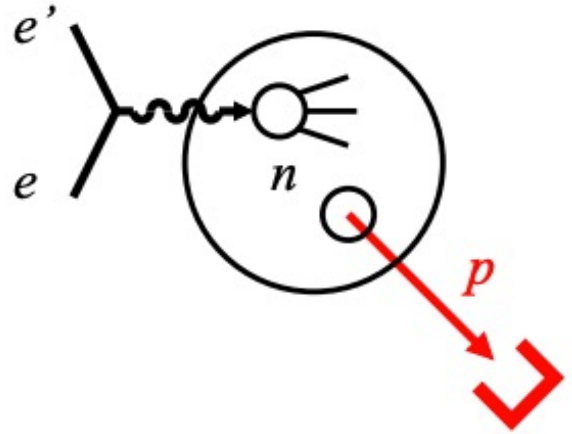
Tagged DIS at the EIC

- Explore potential of tagged DIS measurements on unpolarized deuterons at the EIC.
  - Extract free neutron structure function (this study).
  - Study nuclear modifications of both nucleons in the deuteron (future study).
    - EMC effect, anti-shadowing, etc.
- Tagged spectator nucleon momentum provides experimental variable for selecting nuclear configurations with free and modified nucleons.



Neutron F_2



- 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.
- <u>Two options:</u>
  1. Inclusive measurements → Average over all nuclear configurations, use theory input.
  2. Tagged measurements → 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 → SRC physics; very low p_T ~ 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)

Neutron F_2

- Previous fixed target experiments with tagging have measured the neutron F_2 at high-x.
  - (CLAS, Phys. Rev. Lett. **108**, 199902 (2012))
  - BONUS measurement had a lower p_T cutoff ~ 70 MeV/c.
- Tagged DIS @ the EIC:
  - In a collider, can tag spectators down to p_T ~ 0 MeV/c → Enables extraction of free neutron structure function via pole extrapolation.
  - Can extend tagged DIS measurement to $x \lesssim 0.1$.

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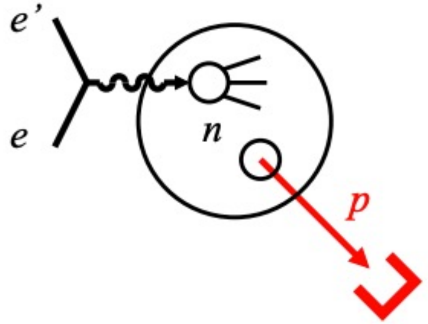
  - Can extend tagged DIS measurement to $x \lesssim 0.1$.
- BeAGLE used to generate e+d DIS events @ 18x110 GeV/n.
  - Implements the light-front wavefunction of the deuteron.
  - Same setup was used for the BeAGLE paper (PLB 811, 135877 (2020)), just the DIS process.
- Full detector simulations carried out with EICRoot + reference detector far-forward region detailed in the EIC YR and CDR (https://arxiv.org/abs/2103.05419).
  - Most spectators are at very high η (> 4.5) necessitating dedicated detector system.

Basic Method - Tagging



spectator nucleon $(p_{T,spect}, \alpha_{spect})$

α_{spect}: light-cone momentum fraction

$$\alpha_{spect} \equiv \frac{2p^{+}_{nucleon}}{p^{+}_{nucleus}} = \frac{2(E_{spect} + p_{z,spect})}{M_d}$$

S_d: deuteron spectral function pole

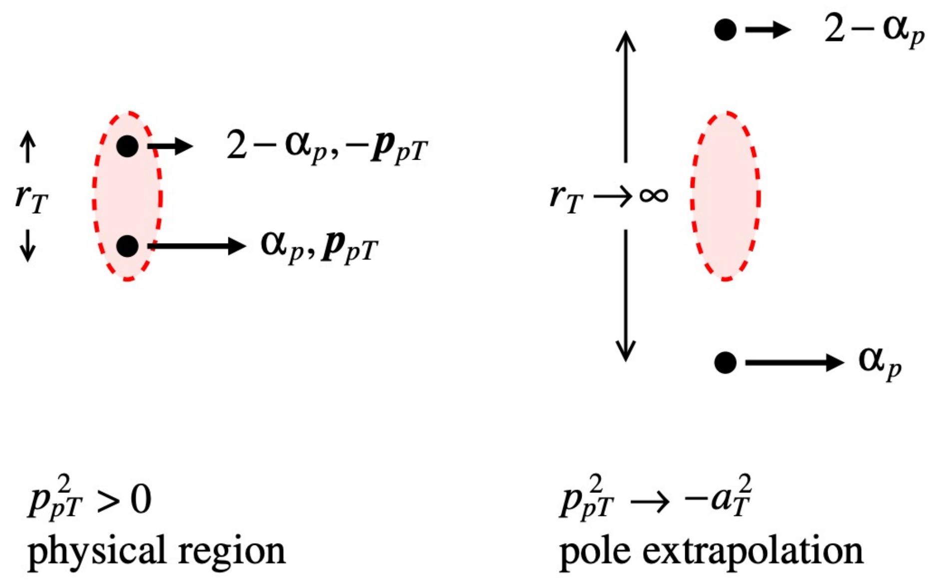
$$d\sigma = Flux(x, Q^2) \times \sigma_{red,d} \times \frac{dx}{2} dQ^2 \frac{d\phi_{e'}}{2\pi} [2(2\pi)^3]^{-1} \frac{d\alpha_{spect}}{\alpha_{spect}} \frac{dp^2_{T,spect}}{2} d\phi_{spect}$$

- Measure the cross-section differential on the spectator kinematics.
- Solve for the deuteron reduced cross section. arxiv:2006.03033

$$\sigma_{red,d}(x, Q^2;\ p_{T,spect}, \alpha_{spect}) \sim F_{2,d} = [2(2\pi)^3] \times S_d(p_{T,spect}, \alpha_{spect}) \times F_{2,n}(x, Q^2)$$

Measurement of the deuteron reduced cross-section yields access to F_2 of active *nucleon* via the spectral function pole of the deuteron!

Basic Method - pole extrapolation (arxiv:2006.03033)



- The resulting distribution is F_2 as a function of $p^2_{T,spect}$.

$$F_{2,n}(x, Q^2) = \frac{F_{2,d}}{[2(2\pi)^3] S_d(p_{T,spect}, \alpha_{spect})}$$

- Extrapolate to $p^2_{T,spect} \to -a_T^2$ to extract F_2 to extract free nucleon F_2.
  - Method eliminates nuclear binding effects.

$$R = 2\alpha^2_{spect} m_N \Gamma^2 (2 - \alpha_{spect})$$

$$a_T^2 = m_N^2 - \alpha_{spect}(2 - \alpha_{spect}) \frac{M_d^2}{4}$$

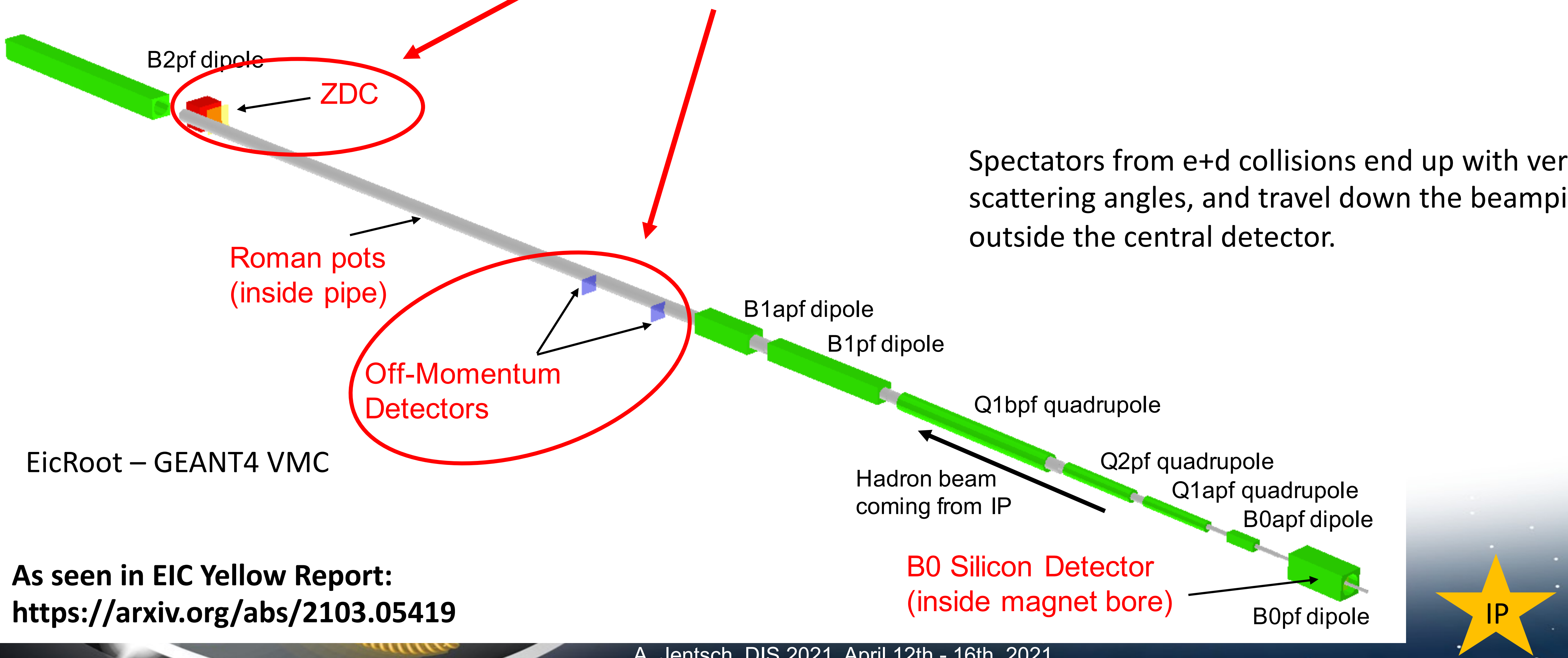
$R = residue\ of\ spectral\ function$

$a_T^2 = position\ of\ pole$

$$S_d(p_{T,spect}, \alpha_{spect}) = \frac{R}{\left(p^2_{T,spect} + a_T^2\right)^2}$$

Full Detector Simulations

Detector	Acceptance	Notes
Zero-Degree Calorimeter (ZDC)	$\theta < 5.5$ mrad ($\eta > 6$)	Neutron Tagging
Off-Momentum Detectors (OMD)	$0.0 < \theta < 5.0$ mrad ($\eta > 6$)	Proton Tagging

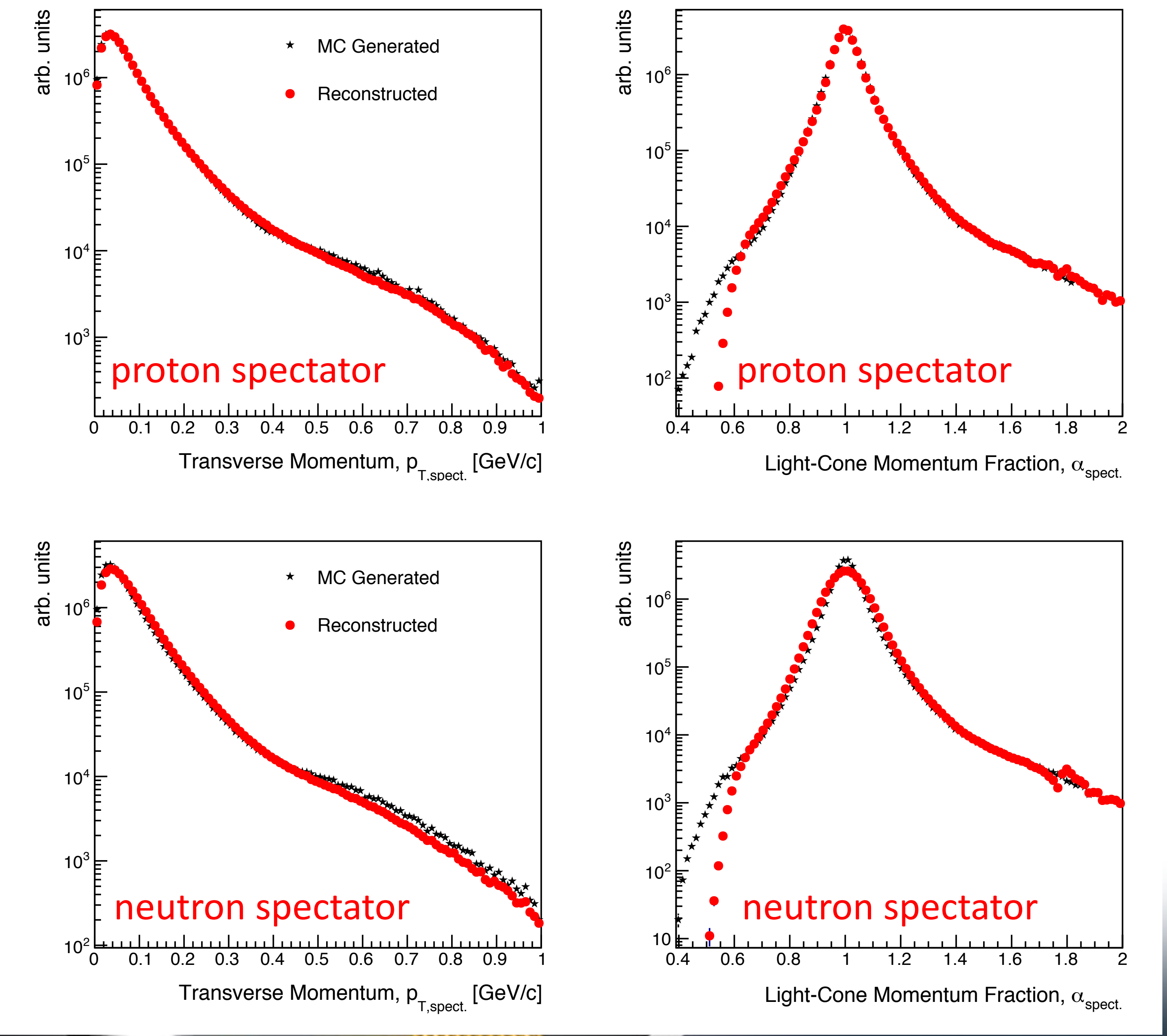


Spectators from e+d collisions end up with very small scattering angles, and travel down the beampipe far outside the central detector.

EicRoot – GEANT4 VMC

As seen in EIC Yellow Report:
https://arxiv.org/abs/2103.05419

Kinematic Distributions and Smearing



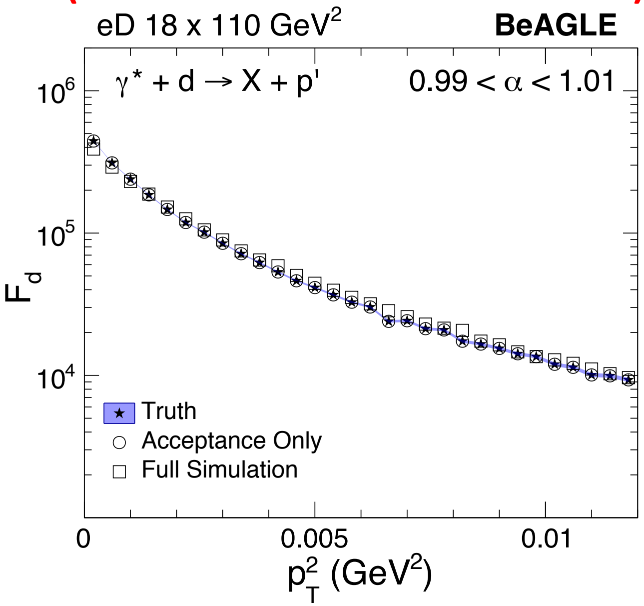
- Event sub-sample passed through full GEANT4 simulations.
  - Smearing parametrizations extracted for (p_x, p_y, p_z, E).
- Larger smearing observed for neutrons, consistent with previous study.
  - Neutrons reconstructed with ZDC/HCAL, protons with silicon tracking/transfer matrix.

Free Neutron F_2 Extraction

$$F_{2,n}(x, Q^2) = \frac{F_{2,d}}{[2(2\pi)^3] S_d(p_{T,spect}, \alpha_{spect})}$$

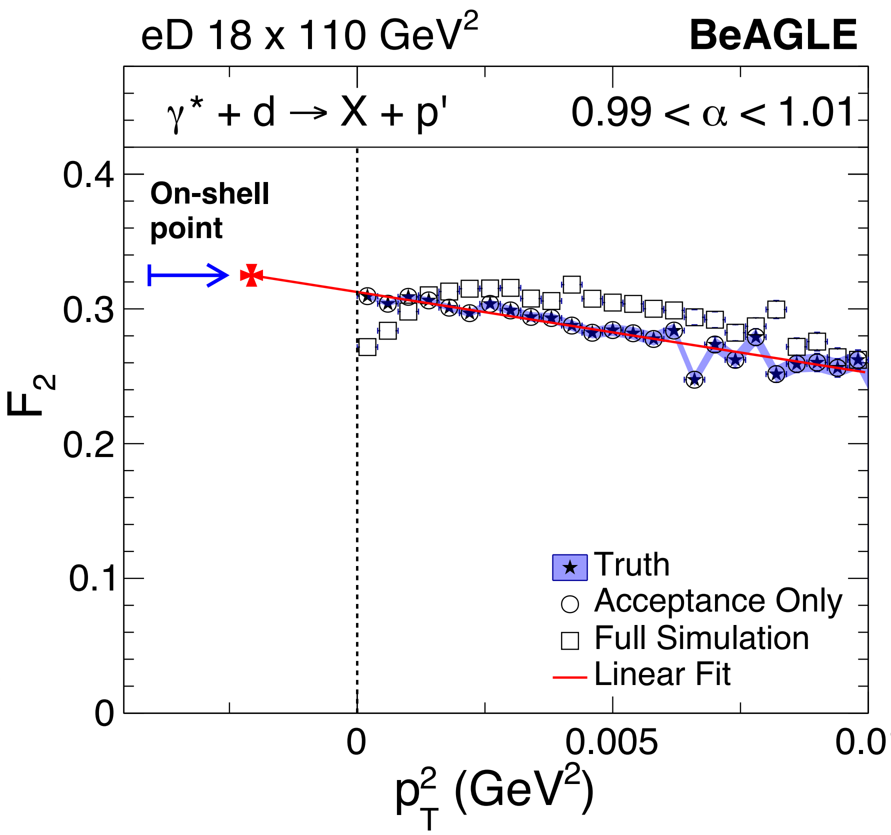
1.0 < Q^2 < 2.0 GeV^2
0.0002 < x < 0.0004

(deuteron reduced cross section)



$$\frac{1}{S_d(p_{T,spect}, \alpha_{spect})} = \frac{\left(p_{T,spect}^2 + a_T^2\right)^2}{R}$$

(inverse pole of deuteron spectral function)



(Active nucleon F_2)

- Resulting dependence on $p_{T,spect}^2$ is very weak and the extrapolation can be performed with a 1st-degree polynomial fit.
- Extrapolation only performed for the generator-level distribution.

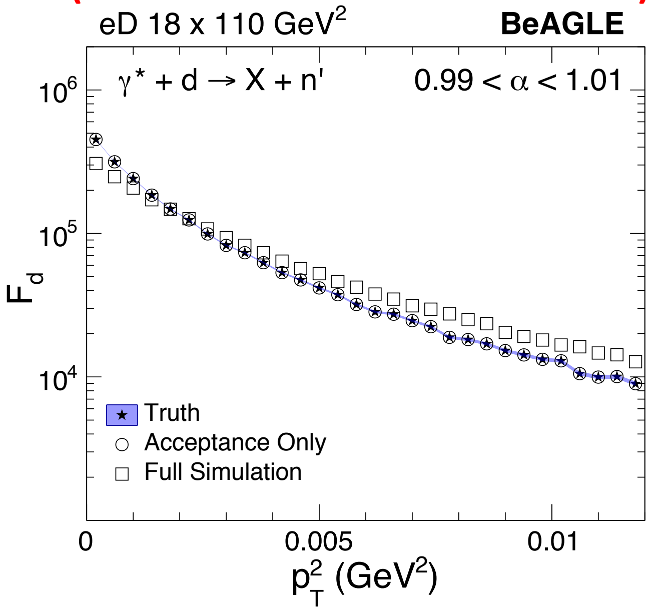
Free Proton F_2 Extraction

$$F_{2,n}(x, Q^2) = \frac{F_{2,d}}{[2(2\pi)^3]S_d(p_{T,spect}, \alpha_{spect})}$$

$1.0 < Q^2 < 2.0$ GeV^2

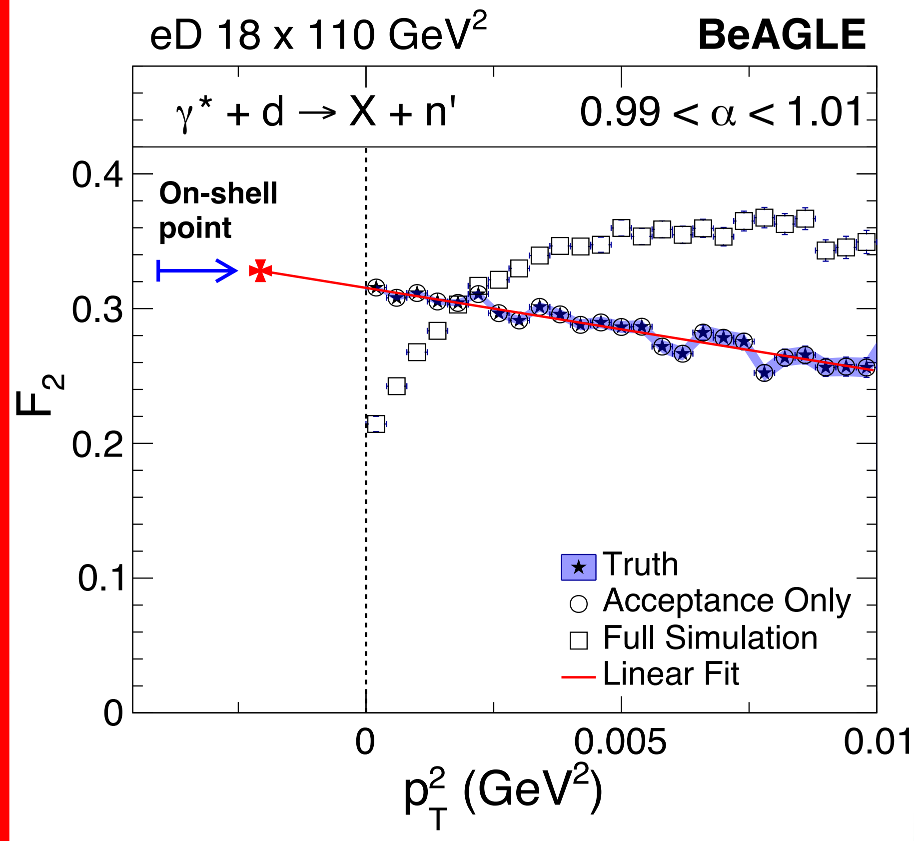
$0.0002 < x < 0.0004$

(deuteron reduced cross section)



$$\times \quad \frac{1}{S_d(p_{T,spect}, \alpha_{spect})} = \frac{(p^2_{T,spect} + a^2_T)^2}{R}$$

(inverse pole of deuteron spectral function)



(Active nucleon F_2)

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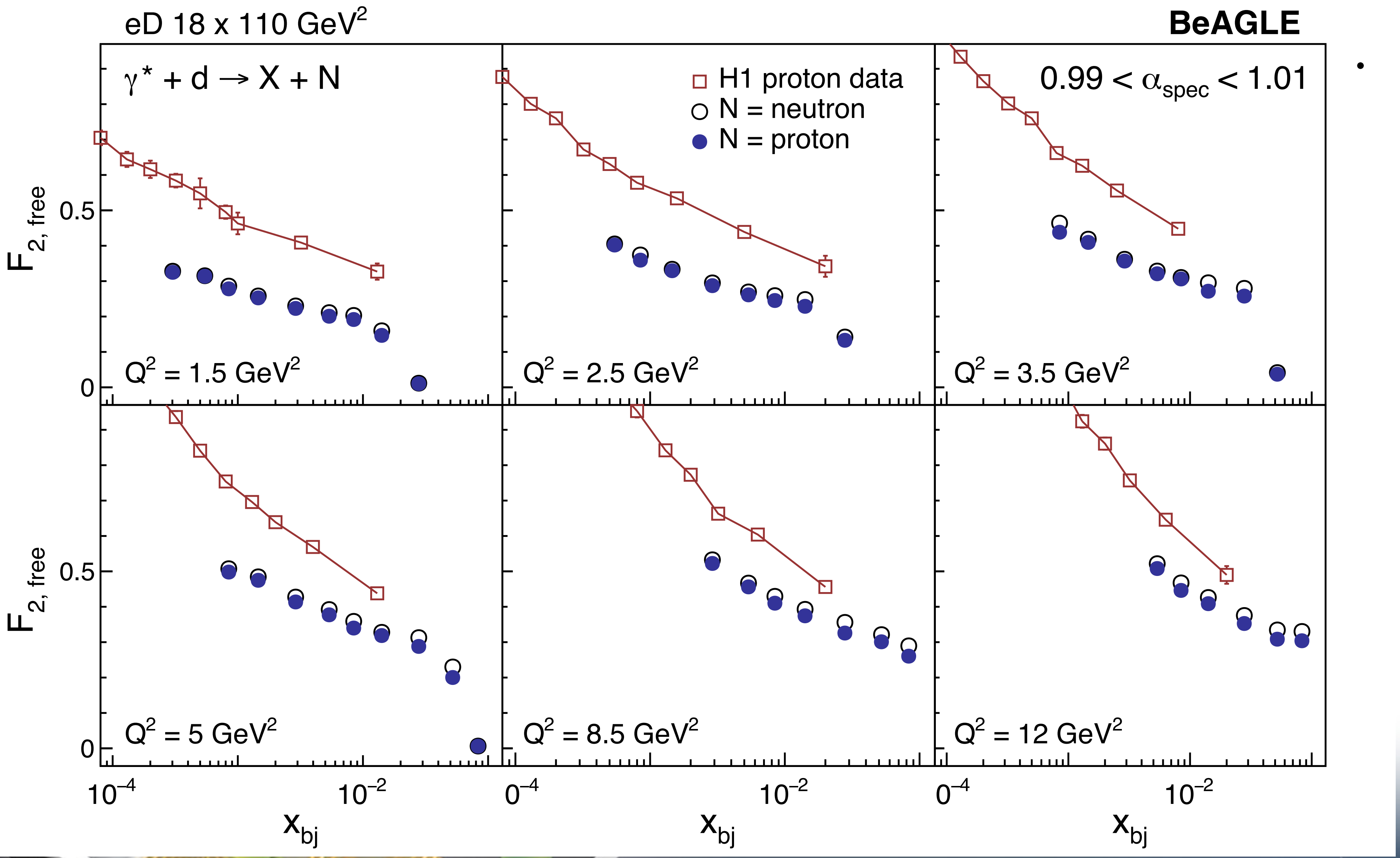
- Extrapolation only performed for the generator-level distribution.

Summary

- Measurement of free neutron F_2 using method of on-shell extrapolation demonstrated.
  - Method removes nuclear binding effects and FSI to yield access to free nucleon structure.
- Free nucleon structure functions extracted with tagging reproduce free nucleon input.
- With detector effects added, distortions in F_2 distributions will alter extrapolation/fitting outcome.
  - Will benefit from careful unfolding method in real EIC experiment.
- Results show what can be possible for tagged measurements at the EIC and lay groundwork for further study!
- Nuclear modifications next to be studied - stay tuned!

Backup

Comparison with HERA (H1) Results



- H1 Proton Data
  - H1 Collaboration, Euro. Phys. Jour. C **63** (2009)