Tagged DIS and the EMC Effect at the EIC

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Electron-Nuclei Interactions at the EIC

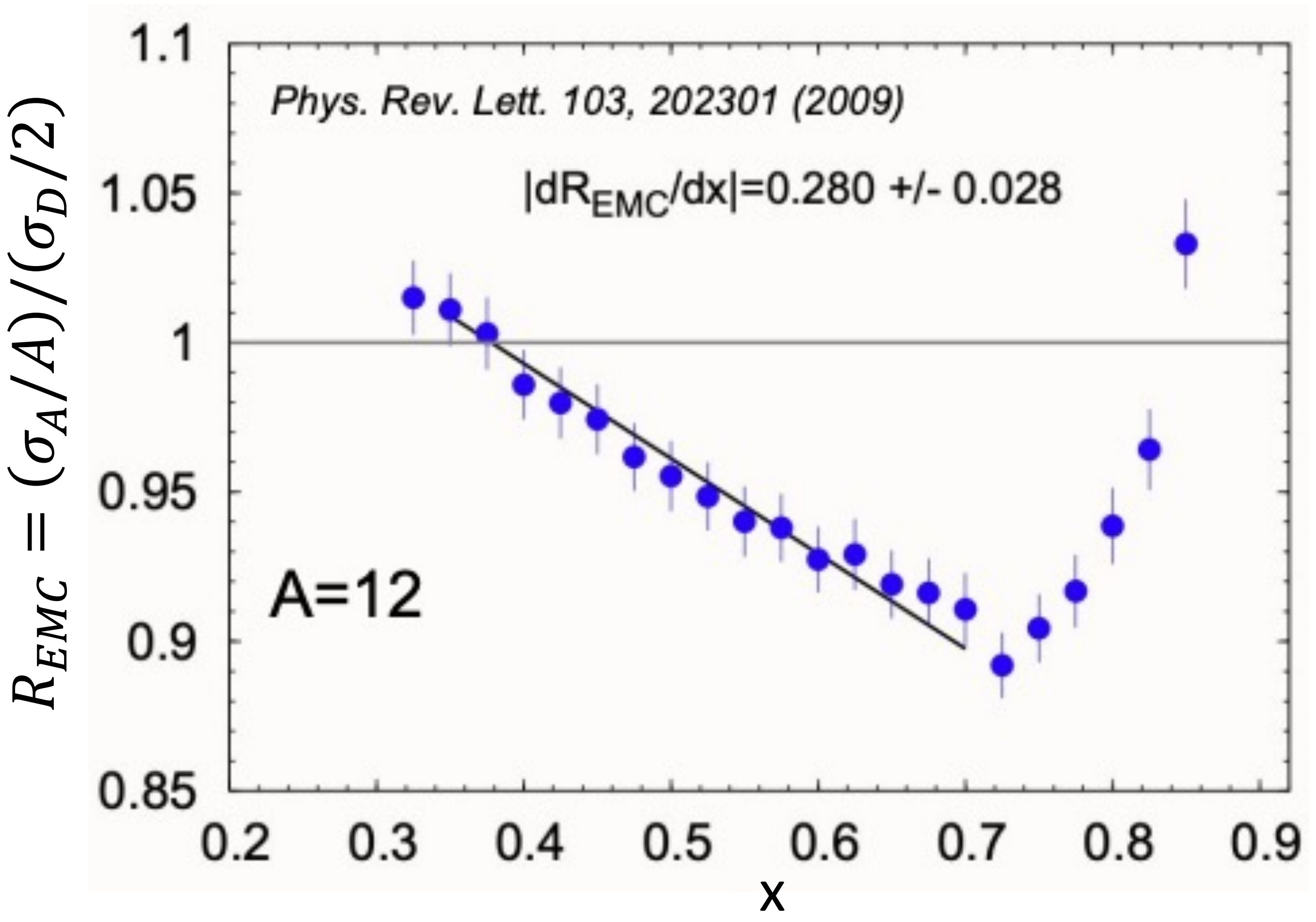
July 6th-7th, 2023

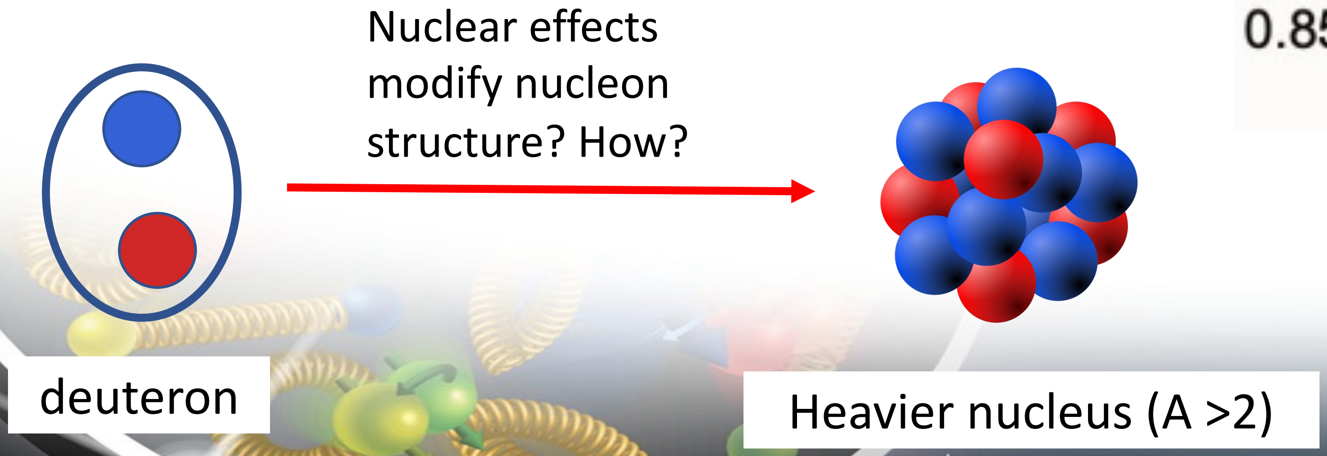
Stony Brook University

BROOKHAVEN NATIONAL LABORATORY
Jefferson Lab
U.S. DEPARTMENT OF ENERGY | Office of Science

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.
- Established via measurements with **different nuclear targets**!

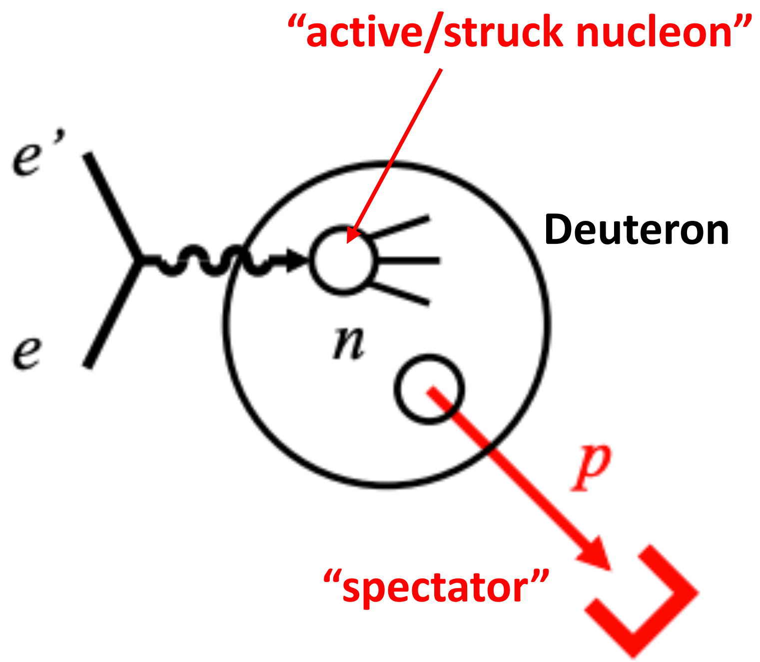




Understanding the origin of the EMC effect and nuclear modifications of prime interest in nuclear physics!

Tagged DIS as a tool at the EIC

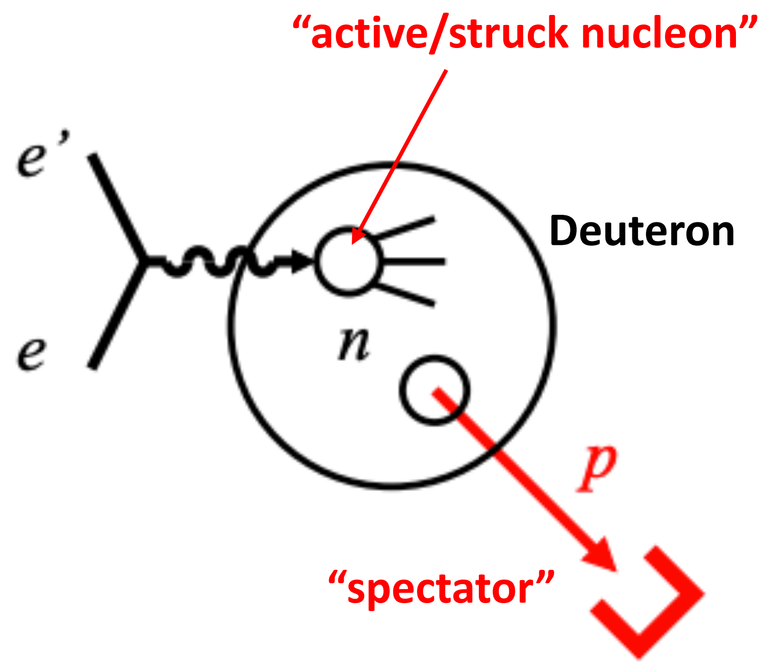
- **Tagged DIS** measurements → "tag" (generally) far-forward **spectators** in final state.
  - Provides more information than inclusive cross sections → information on nucleon configuration.
- **Lots of topics!**
  - Short-range correlations[1].
  - Gluon distributions in nuclei.
  - Free nucleon structure functions.
  - Nuclear modifications of nucleons in light nuclei.
    - EMC effect, anti-shadowing, etc.



Tagged spectator nucleon momentum → experimental handle on nuclear configurations with free and modified nucleons.

[1] Z. Tu, A. Jentsch, M. Baker, *et al.,* Phys. Lett. B **811,** 135877 (2020)

Tagged DIS with deuterons



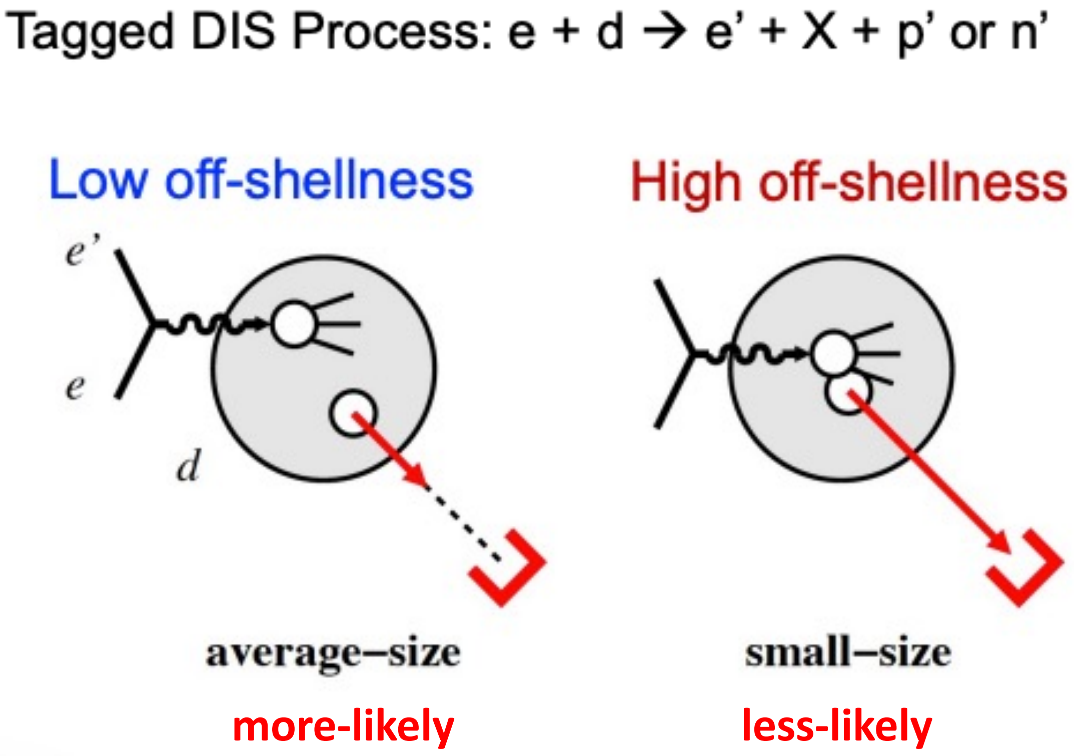
- Spectator kinematics → determines nuclear configuration.
  - **Loosely bound configuration** – enables extraction of free nucleon structure via pole extrapolation (previous study[2]).
  - **Configuration with strongly-interacting nucleons** – opens up study of nuclear modifications.
    - Differential study of transition region where nuclear effects manifest!

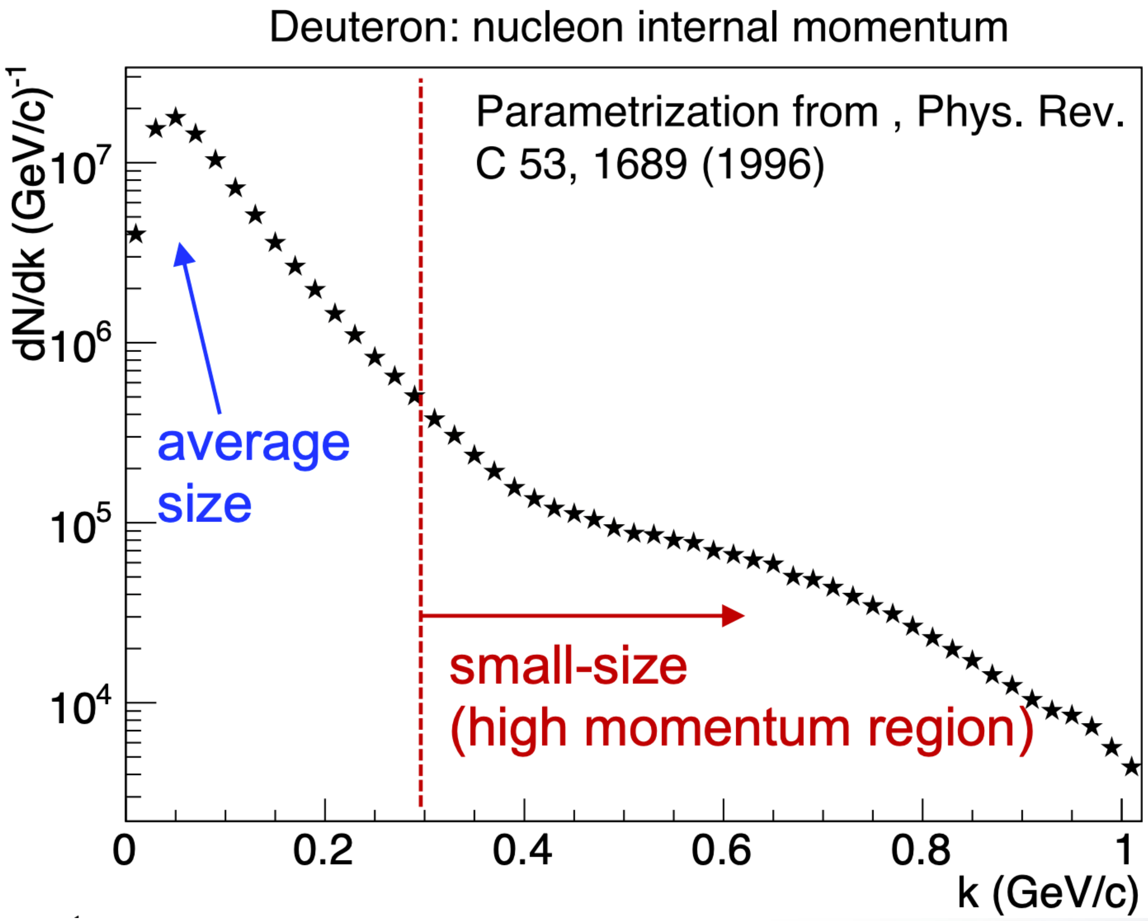
Tagged DIS on the deuteron enables study of free and modified nuclear structure in a single nucleus!

[2] A. Jentsch, Z. Tu, and C. Weiss, Phys. Rev. C **104,** 065205, (2021) **(Editor's Suggestion)**

The Deuteron – a stand-alone lab for nuclear physics

- **Off-shellness in deuterons as a probe of nuclear effects.**





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

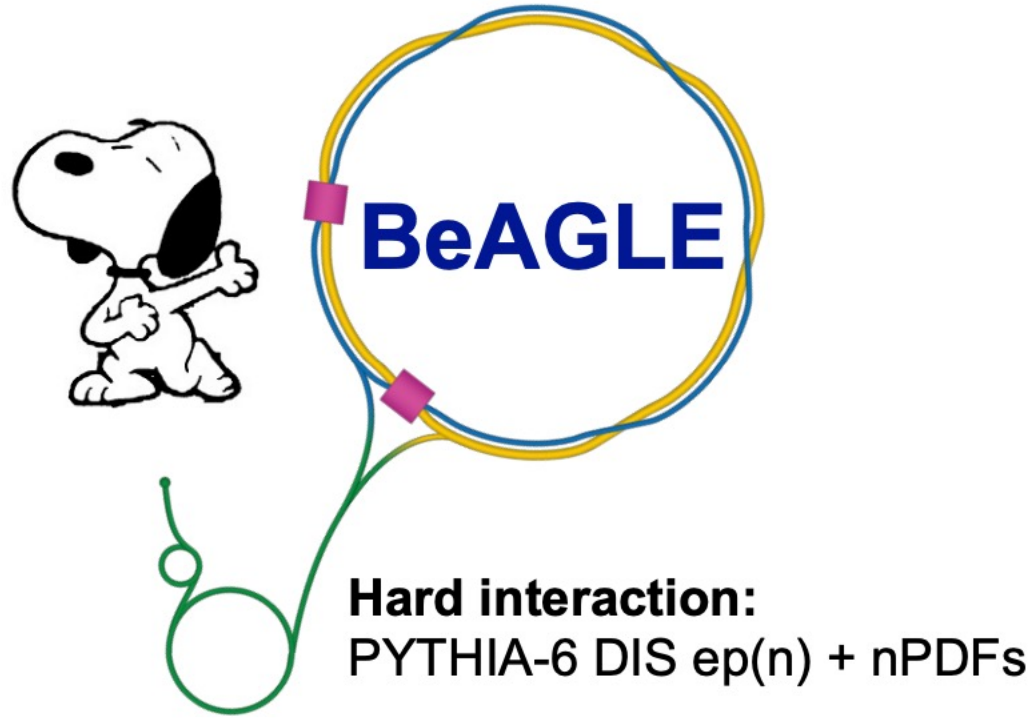
Virtuality/off-shellness in the deuteron

Question: can the EMC effect be controlled via the off-shellness **without altering the nuclear species?**

Monte Carlo sample for study

General-purpose eA DIS MC generator

https://eic.github.io/software/beagle.html

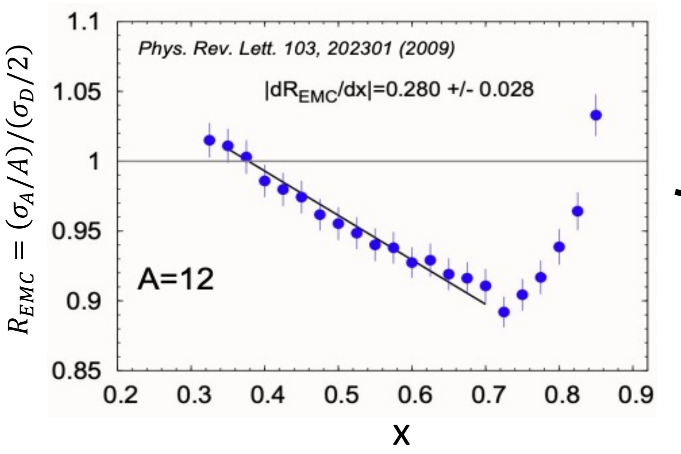


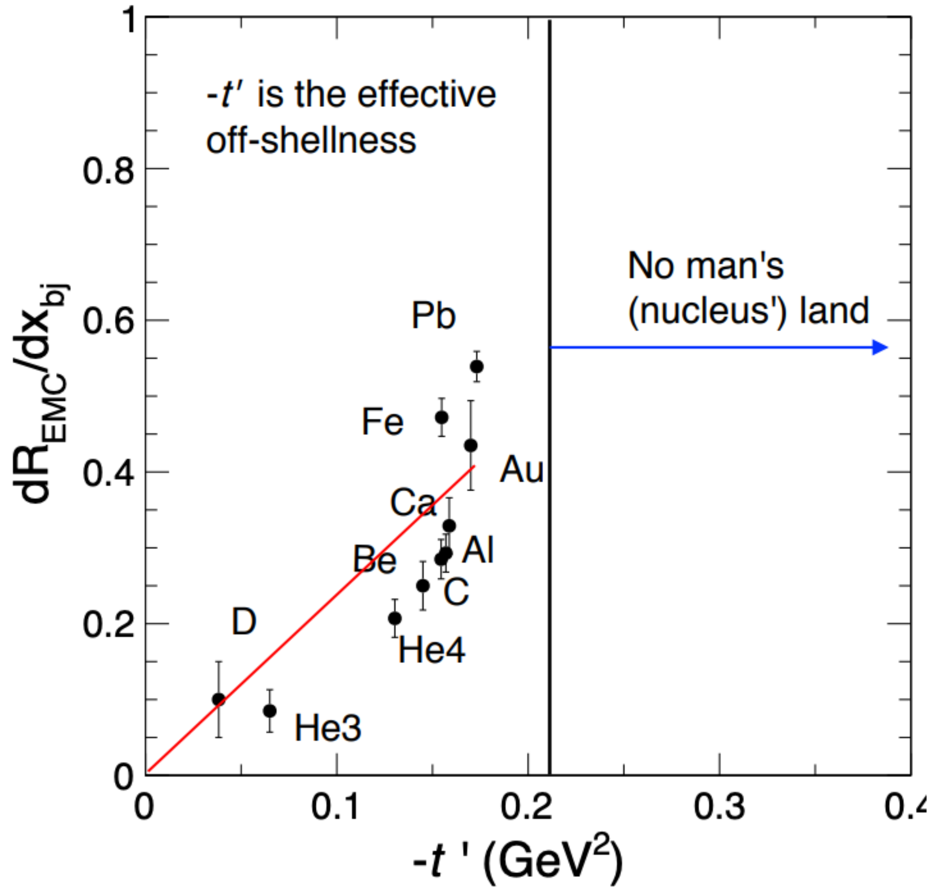
For e+d collisions:

- BeAGLE[3] → hard nucleon scattering (DIS process)
- Spectator momentum calculated via deuteron spectral function, using parametrization of Ciofi and Simula.
  - ✓C. Ciofi degli Atti and S. Simula, Phys. Rev. C 53, 1689 (1996)
  - ✓Same process as in [1].
- BeAGLE MC samples passed through **full detector simulations**, including beam effects!

[3] W. Chang, E. C. Aschenauer, M. D. Baker, A. Jentsch, Jeong-Hun Lee, Z. Tu, Z. Yin, and L. Zheng, Phys. Rev. D **106**, 012007 (2022)

Simulating the EMC Effect in BeAGLE





Use EMC effect slope measurements from data with different nuclear targets.

*Data from J. Seely *et al.* Phys. Rev. Lett. **103**, 202301 (2009)

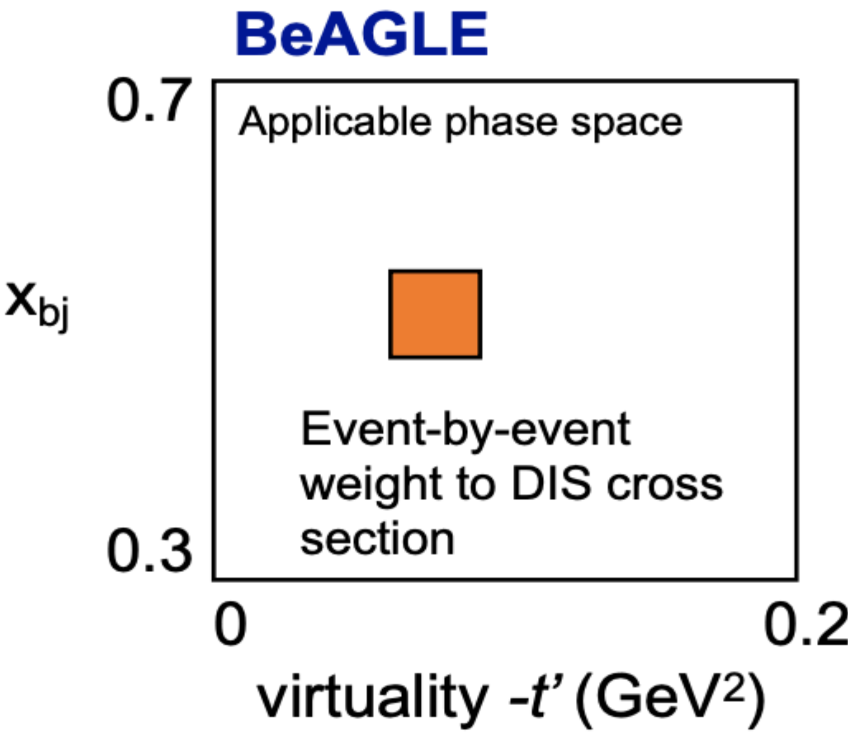
Linear fit to virtuality dependence → Minimal parametrization:

Frankfurt and Strikman, Nuc. Phys. B **250** (1985)

C. Ciofi *et al.,* Phys. Rev. C **76**, 055206 (2007)

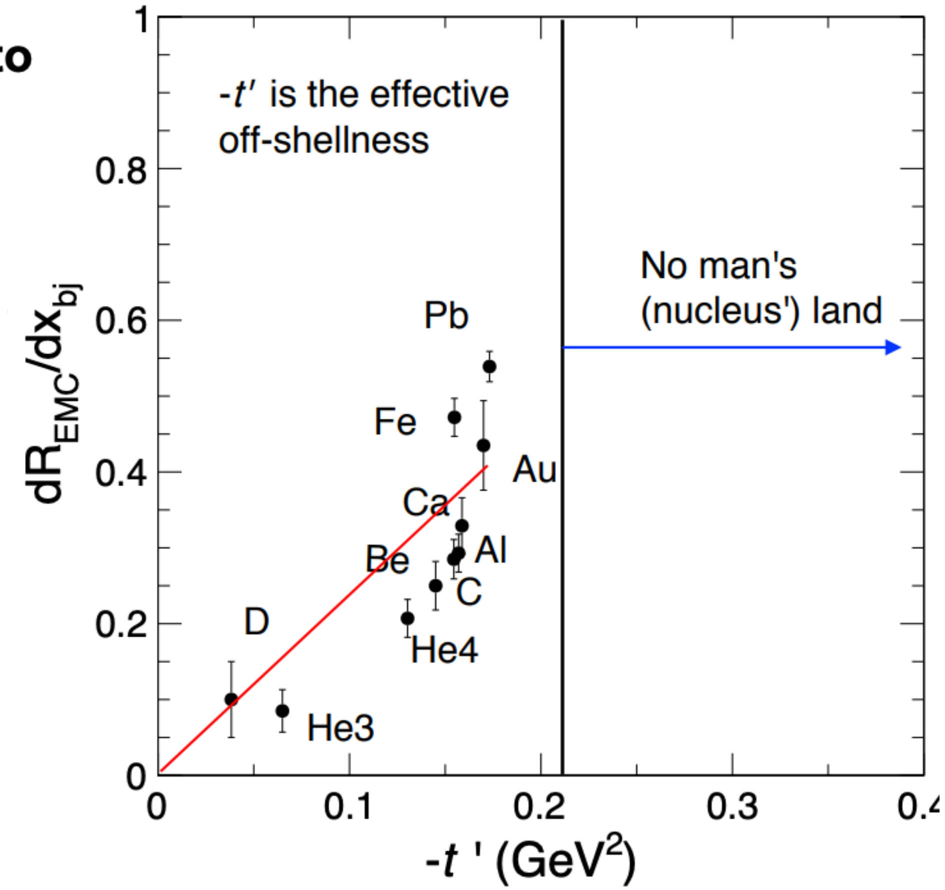
And others…

Simulating the EMC Effect in BeAGLE



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)



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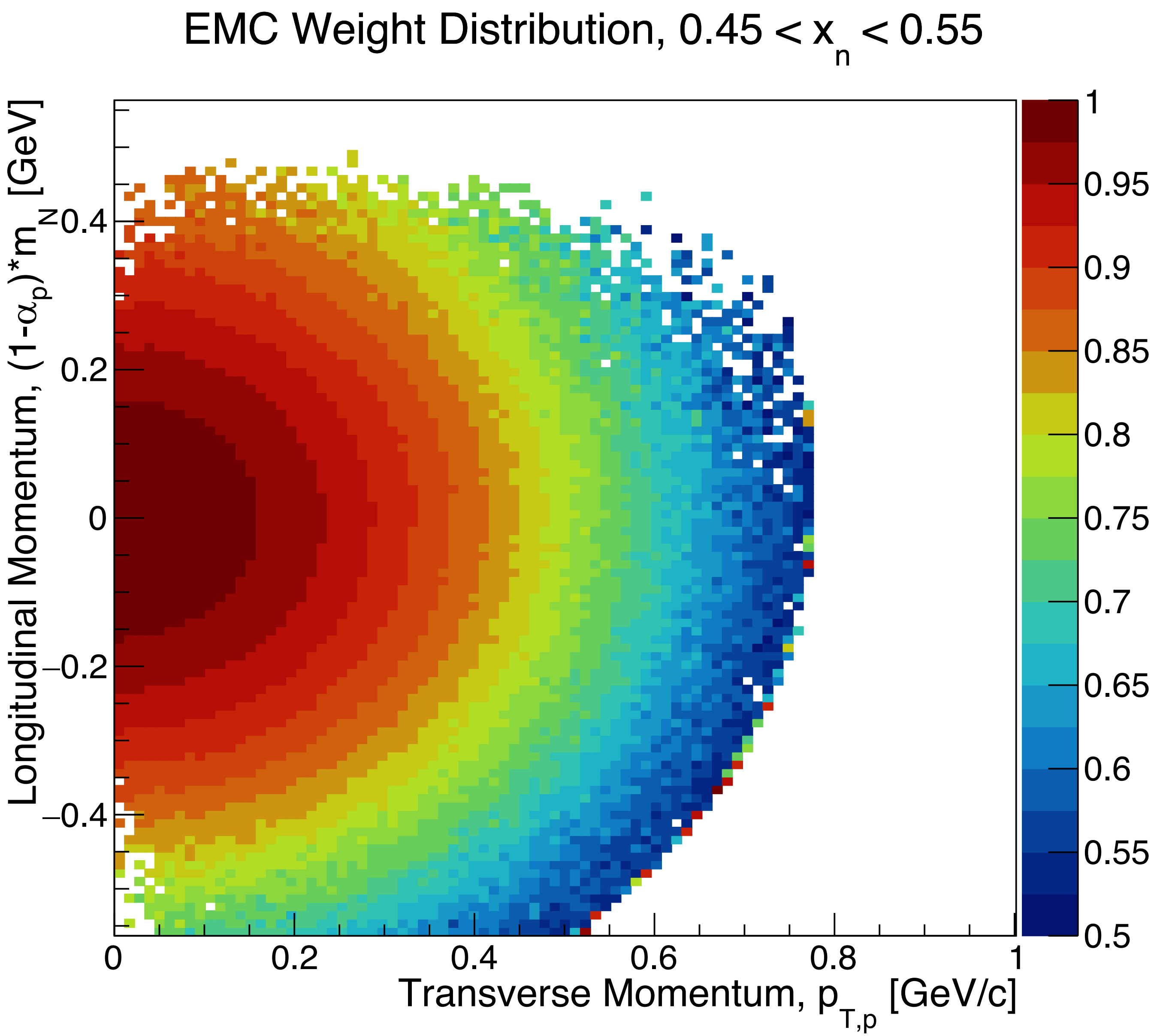
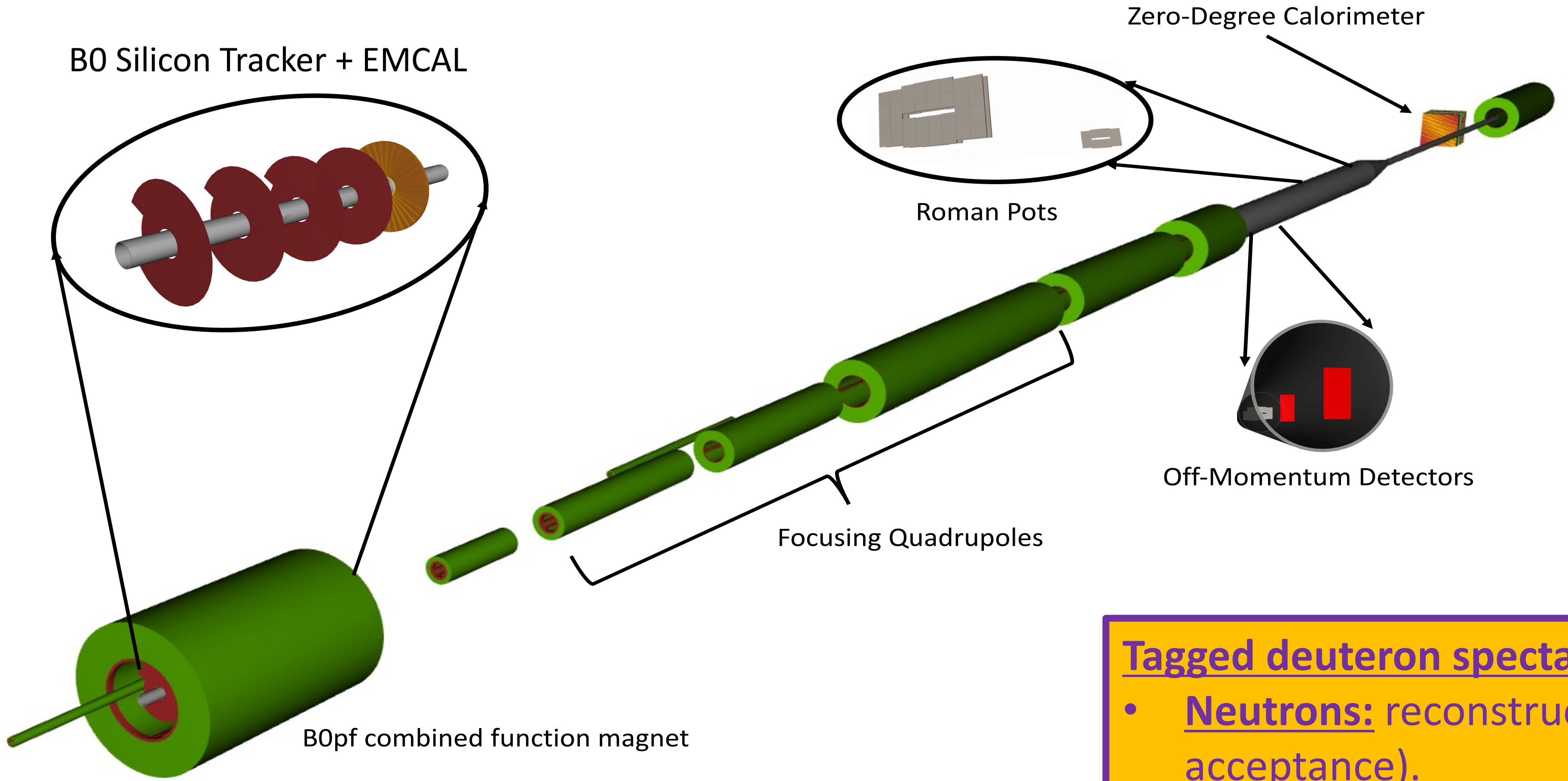


Result → EMC Weight in BeaGLE

- Weight factor simulates the EMC effect from the *virtuality* in the deuteron.
- Applied event-by-event to compare **with and without weight →** enables study of sensitivity to EMC effect in various observables.

Full Detector Simulations – Tagged Spectators



Sample of MC events run through GEANT4 to extract acceptances + momentum smearing.

Tagged deuteron spectators

- **Neutrons:** reconstructed in ZDC ($\theta < 5$ mrad acceptance).
- **Protons:** reconstructed in B0 tracker ($6 < \theta < 20$ mrad) and off-momentum detectors ($\theta < 5$ mrad).

The EMC Effect @ the EIC

- <u>Approach:</u>
  - Measure deuteron reduced cross-section σ_D, with and without the off-shell effects included.
    - No FSI included.
  - Ratio of σ_D **inside and outside the EMC region** (e.g. x ~ 0.5 and x ~ 0.2)

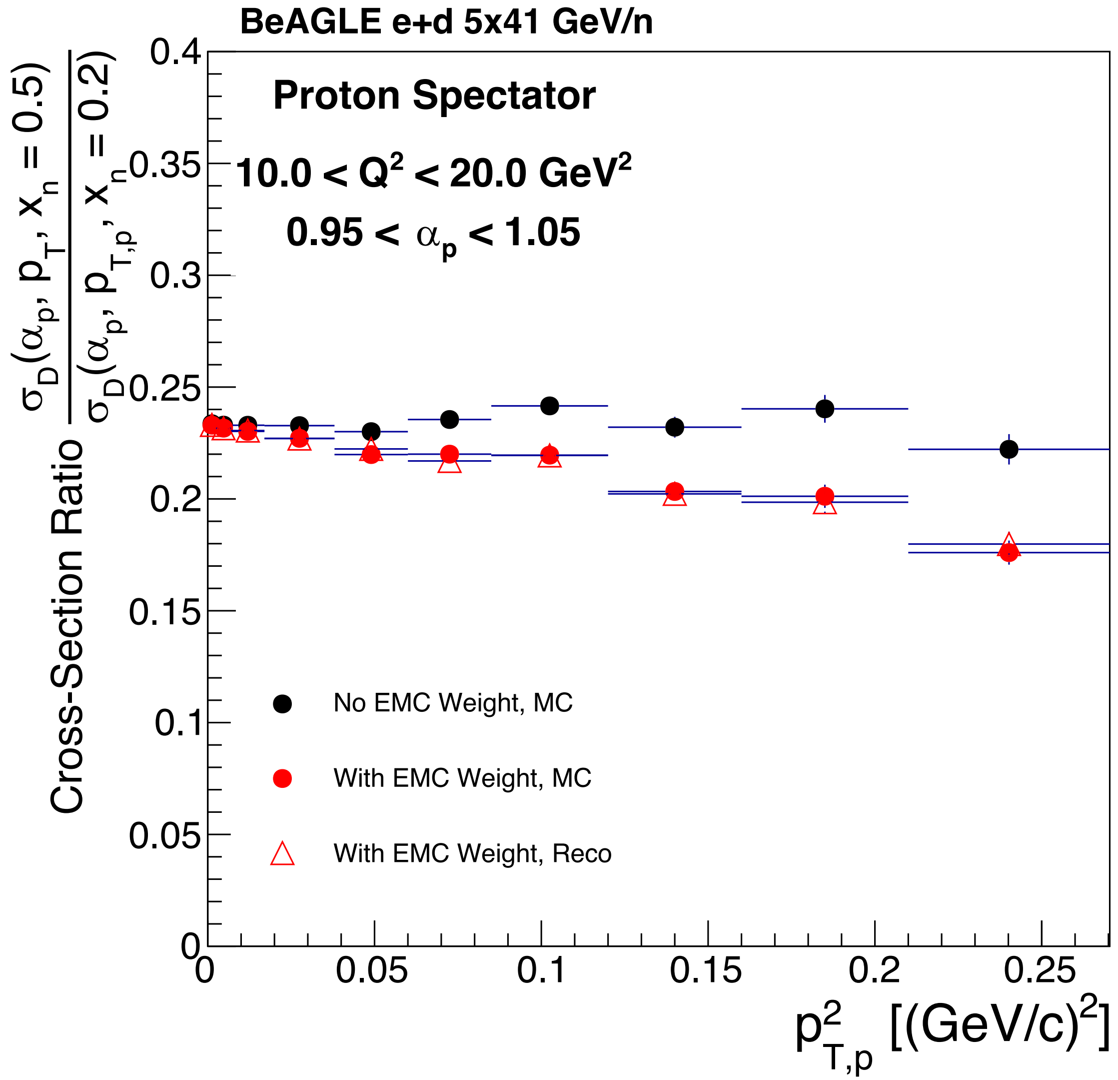
➢ Quantity allows direct comparison of cross section with and without EMC weight (x ~ 0.2 chosen to avoid anti-shadowing region).

$$\frac{\sigma_D(\alpha_p, p_{T,p}, x_n = 0.5)}{\sigma_D(\alpha_p, p_{T,p}, x_n = 0.2)}$$

The EMC Effect @ the EIC

5x41 GeV/n Integrated Luminosity ~25 fb^{-1}

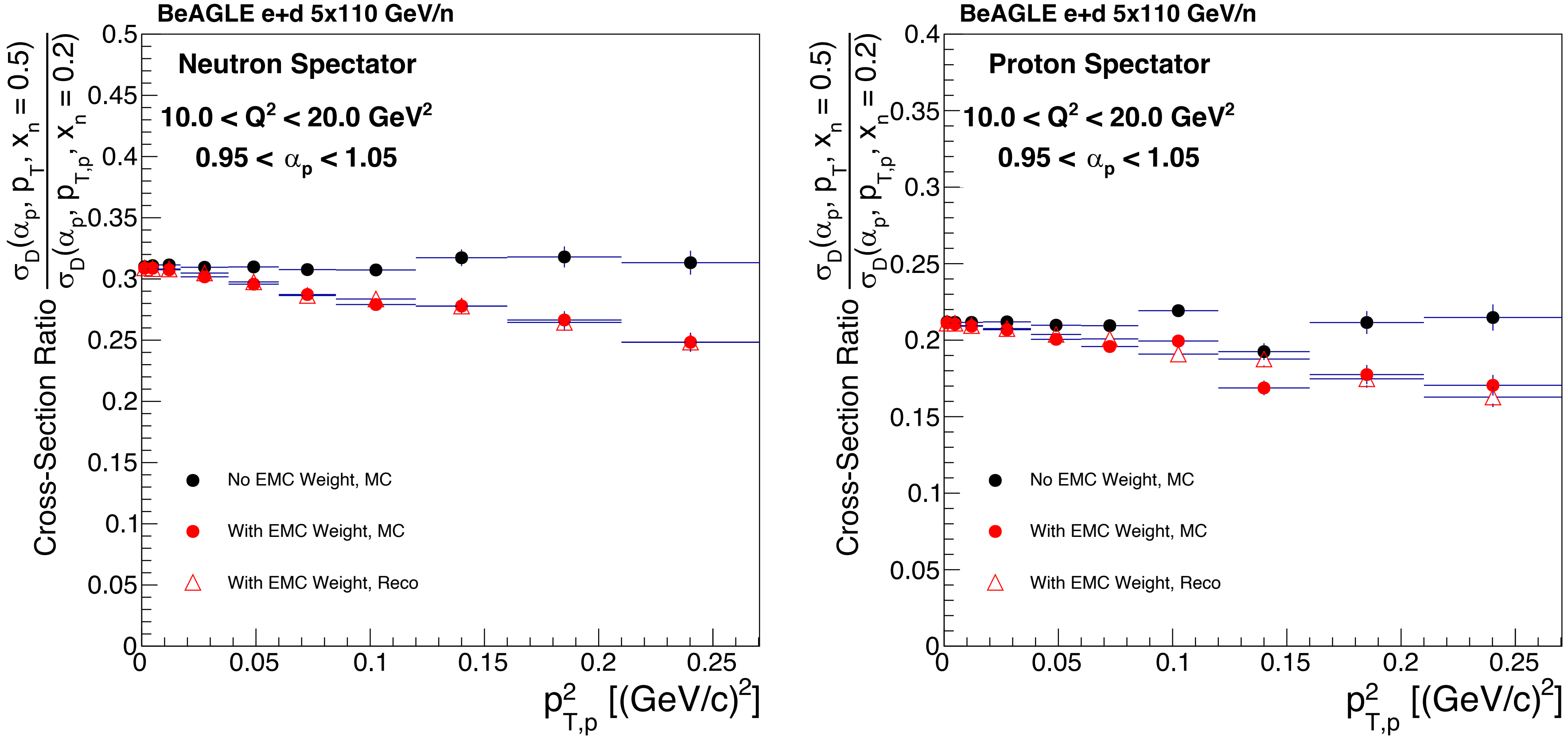
- <u>Approach:</u>
  - Measure deuteron reduced cross-section σ_D, with and without the off-shell effects included.
    - No FSI included.
  - Ratio of σ_D **inside and outside the EMC region** (e.g. x ~ 0.5 and x ~ 0.2)
  - Establish required integrated luminosity.
    - **Challenging measurement →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



5x110 GeV/n Integrated Luminosity ~16 fb^{-1}

The EMC Effect @ the EIC

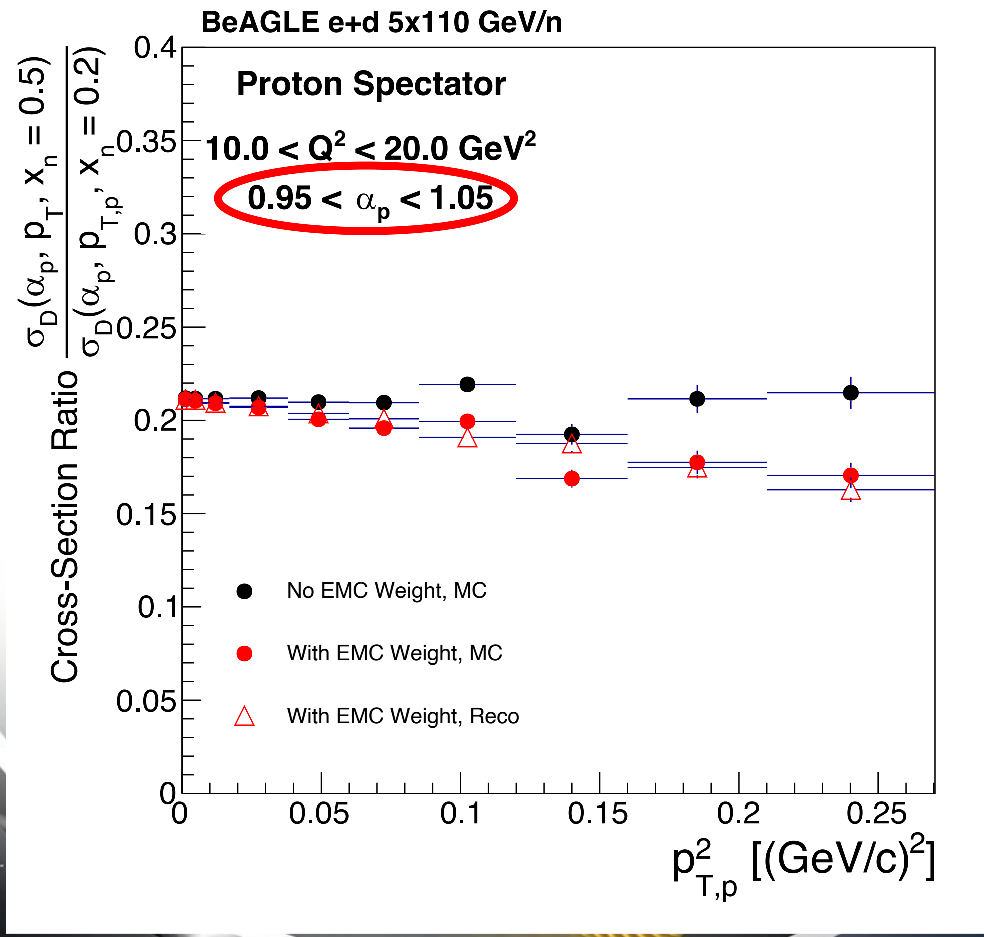
- <u>EIC versatility → different beam energy configurations!</u>



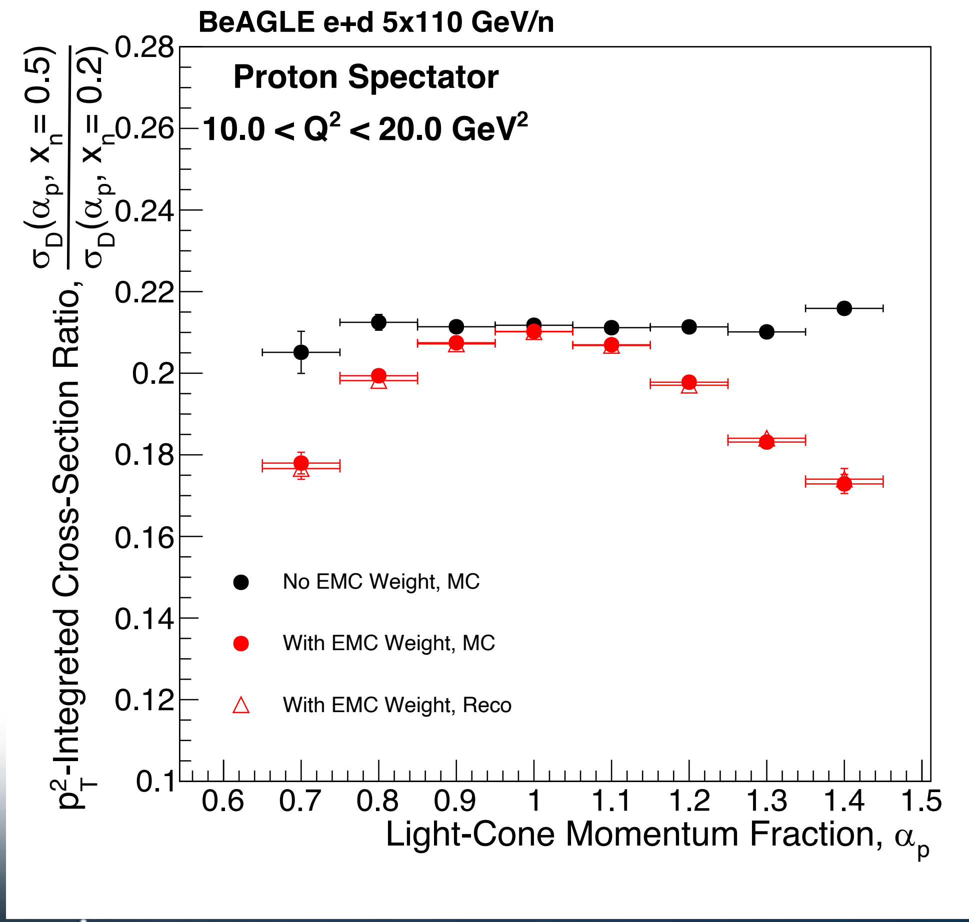
- Higher energy configuration (5x110 GeV/n).
- **More favorable detector acceptance → study of proton *and* neutron spectators with same beam configuration.**
- Measurement of same observable with different beam energies/spectator reconstruction enables better understanding of experimental systematics.

Different nuclear configurations

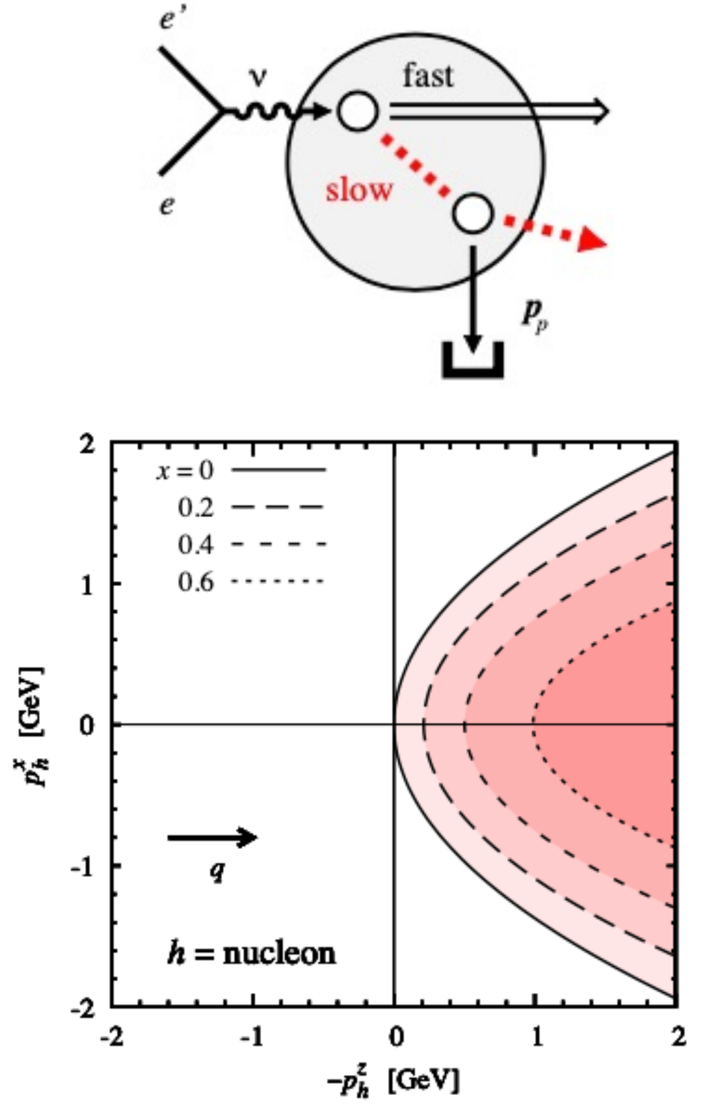
- EIC kinematic coverage enables broad, differential study of effects.
  - Spectator kinematic coverage → varied deuteron nuclear configurations.



Integrate cross section over $p_{T,p}^2$ in each α bin.



Final-State Interaction: Physical Picture



Momentum distribution of slow hadrons in nucleon rest frame: Cone in virtual photon direction.

Space-time picture in deuteron rest-frame

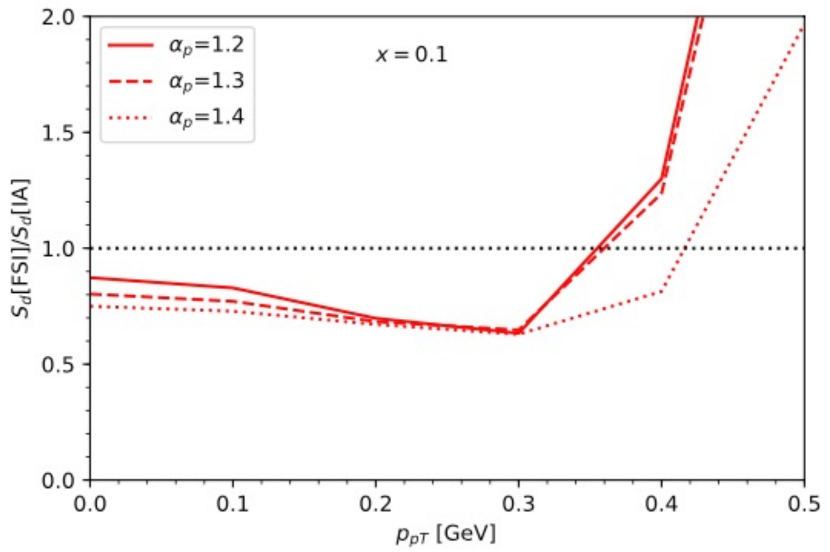
- $\nu \gg$ hadronic scale: large phase space for hadron production.
- "Fast" hadrons $E_h = \mathcal{O}(\nu)$ → current fragmentation region: Formed outside the nucleus, interaction with the spectator suppressed.
- "Slow" hadrons $E_h = \mathcal{O}(1\ GeV)$ → target fragmentation region: Formed inside the nucleus, interact with hadronic cross sections.
  - ➢ Source of FSI in tagged DIS!

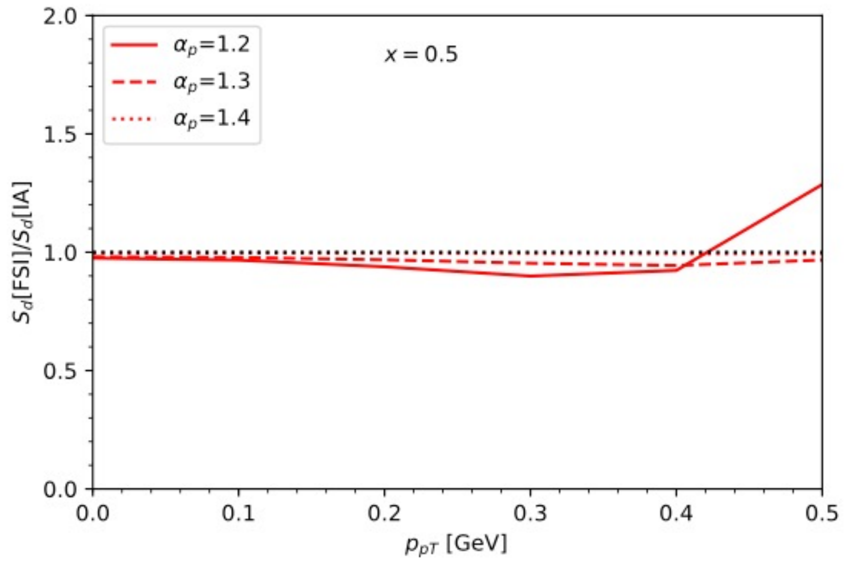
Implementation

- Distributions of slow hadrons in DIS on nucleon: kinematic dependence, empirical distributions
- Hadron-nucleon scattering amplitudes: Re/Im
- Calculation of rescattering process: phase space integral
- Study kinematic dependences: x, α_p, p_{pT}

Strikman, Weiss PRC97 (2018) 035209

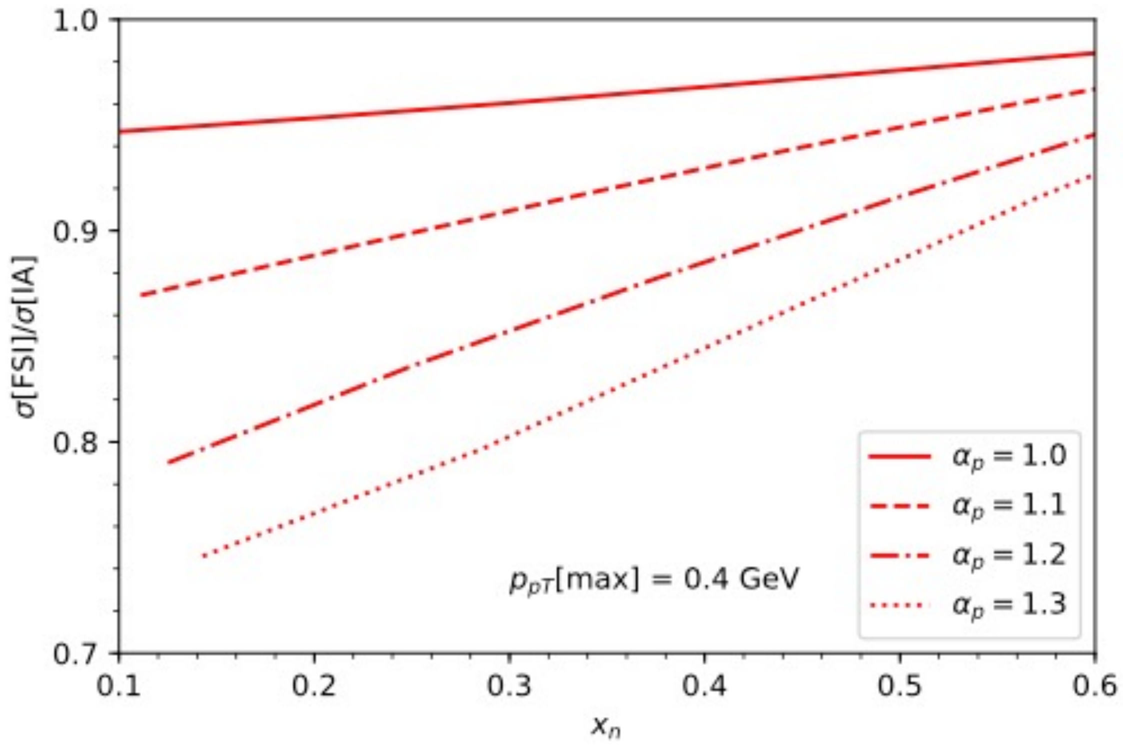
FSI: Kinematic Dependence





- FSI Ratio $S_d[\mathrm{FSI}]/S_d[\mathrm{IA}]$
- p_{pT} dependence: weak up to ~0.3 GeV, strong rise above
- α_p dependence: FSI increases with $\alpha_p - 1$ at small p_{pT}
- x dependence: FSI decreases with increasing x due to depletion of slow hadrons

FSI: pT-integrated cross-section

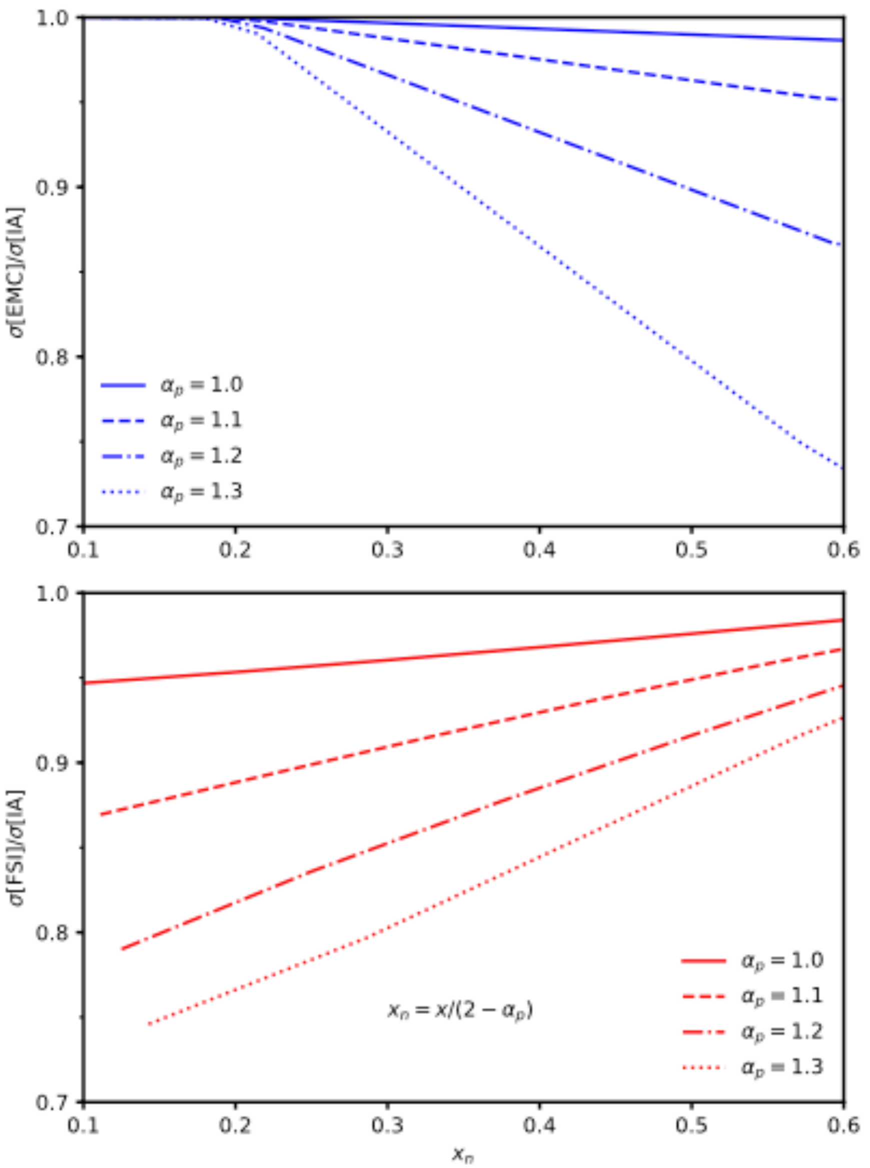


- p_{pT} - integrated cross section:

$$\sigma = \int_{p_{pT}[max]} d^2 p_{pT} S_d(\alpha_p, p_{pT}) \sigma_n(x_n)$$

- Here: Plotted as a function of $x_n = x/(2 - \alpha_p)$
- Simple dependence of α_p and x_n.
- FSI effect typically 10-20%

FSI: Initial state vs. final-state modification



- Here: p_{pT} - integrated cross section, $p_{pT}[max] = 0.4$ GeV
- EMC Effect: virtuality-dependent model

$$\frac{\sigma_n[bound]}{\sigma_n[free]} = 1 + \frac{t}{\langle t \rangle} f_{EMC}(x_n)$$

$$t = t(\alpha_p, p_{pT})$$

- Compare EMC and FSI

→ Currently in-progress!

Summary and Takeaways

- Deuteron can be used as a general tool to study nucleon structure and the onset of modifications via nuclear effects, including the EMC effect.
- EMC effect can be parametrized using the virtuality/off-shellness in lieu of using multiple nuclear species → allows EMC effect to be studied in one collision system.
- EIC far-forward detection capabilities enable broad coverage of spectator kinematics and differential study of various nuclear configurations.
- Large luminosity (~10 fb^{-1}) needed to acquire necessary statistics at high-x and $\alpha \neq 1$.
- Inclusion of FSI for comparisons to EMC effect in-progress.