Far-Forward Physics @ the EIC

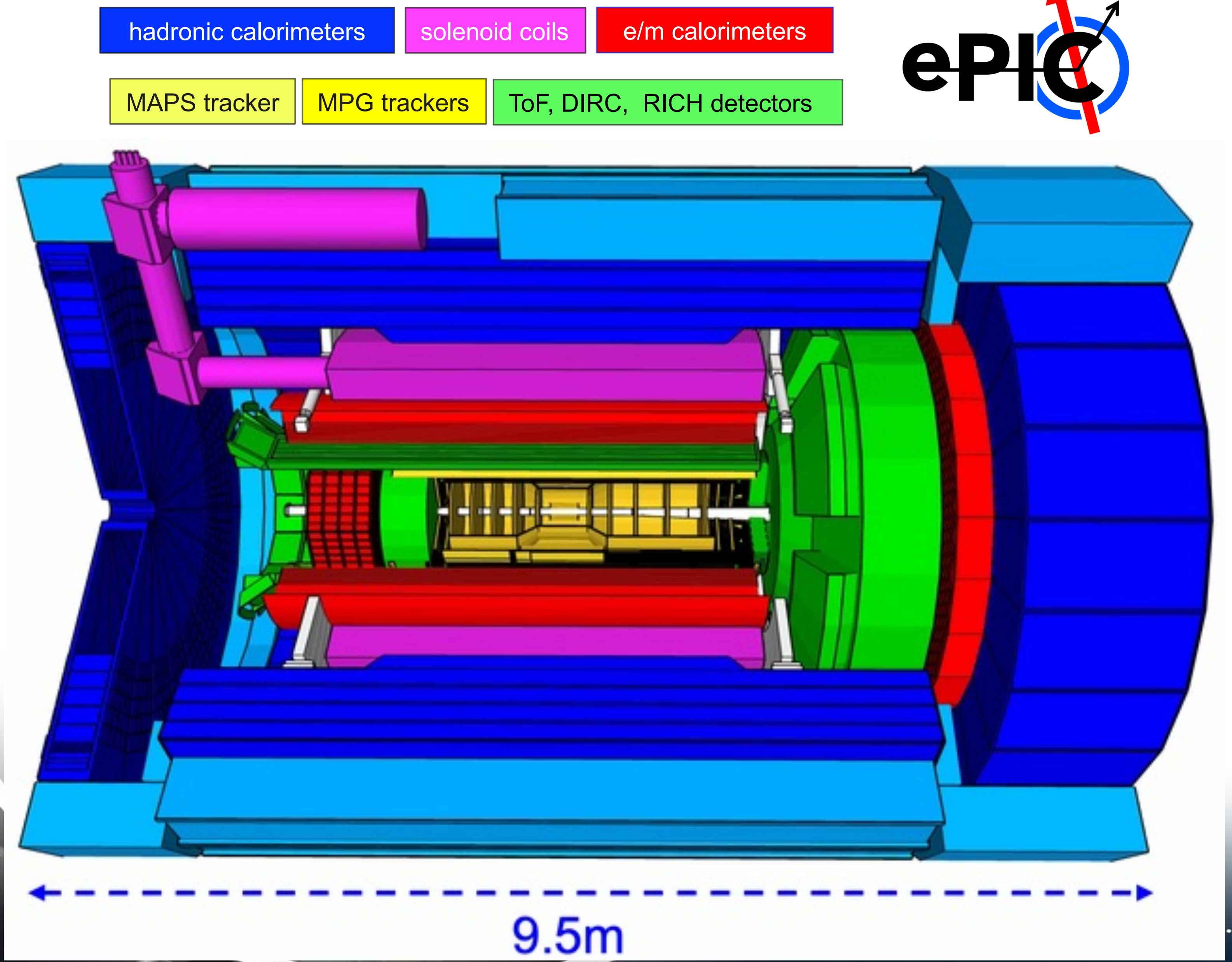
Alex Jentsch, *Brookhaven National Lab*
ajentsch@bnl.gov

NuSTEAM/NuPUMAS @ BNL
July 10th, 2024

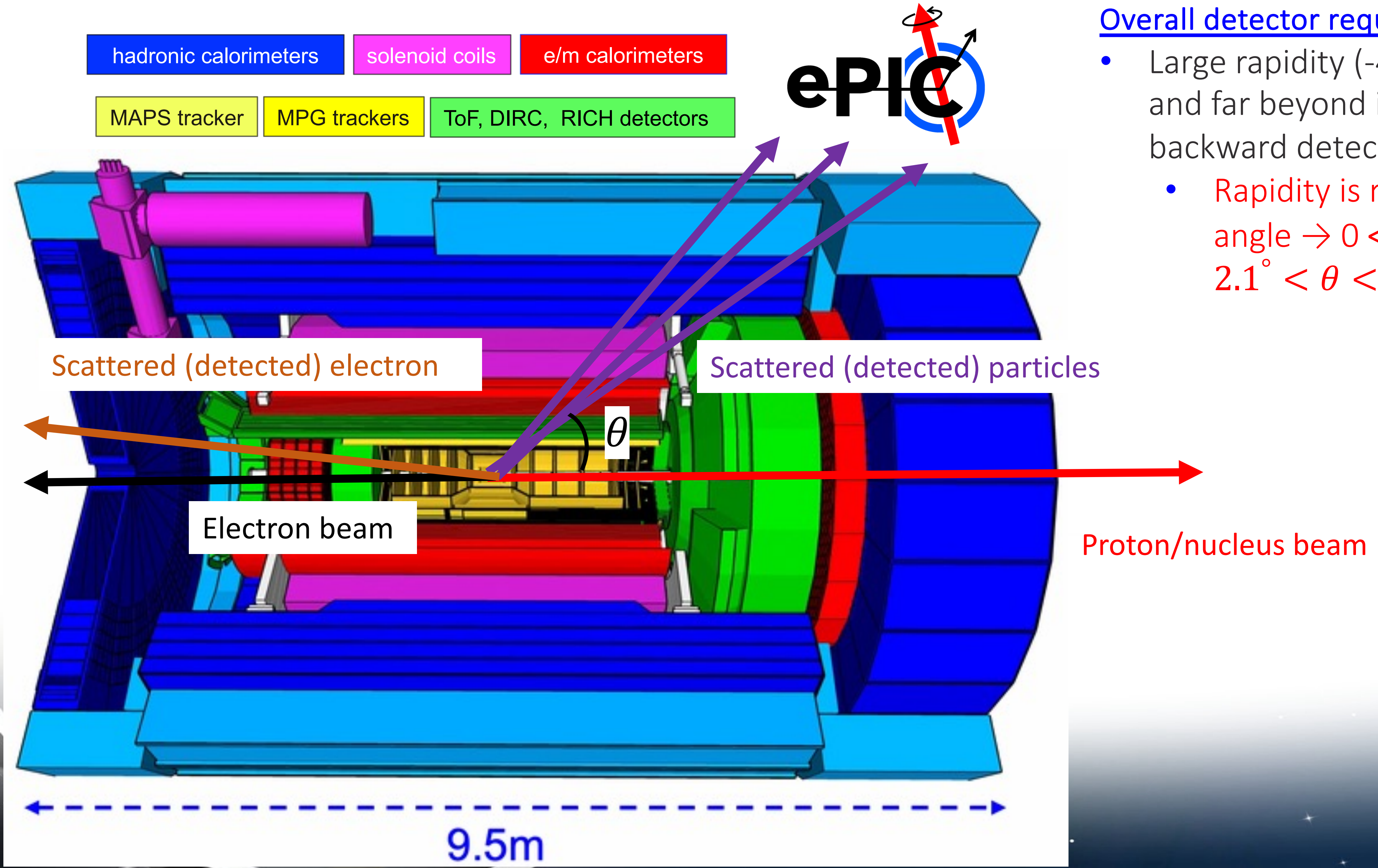
Electron Ion Collider

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

Accessing Far-Forward Physics at the EIC



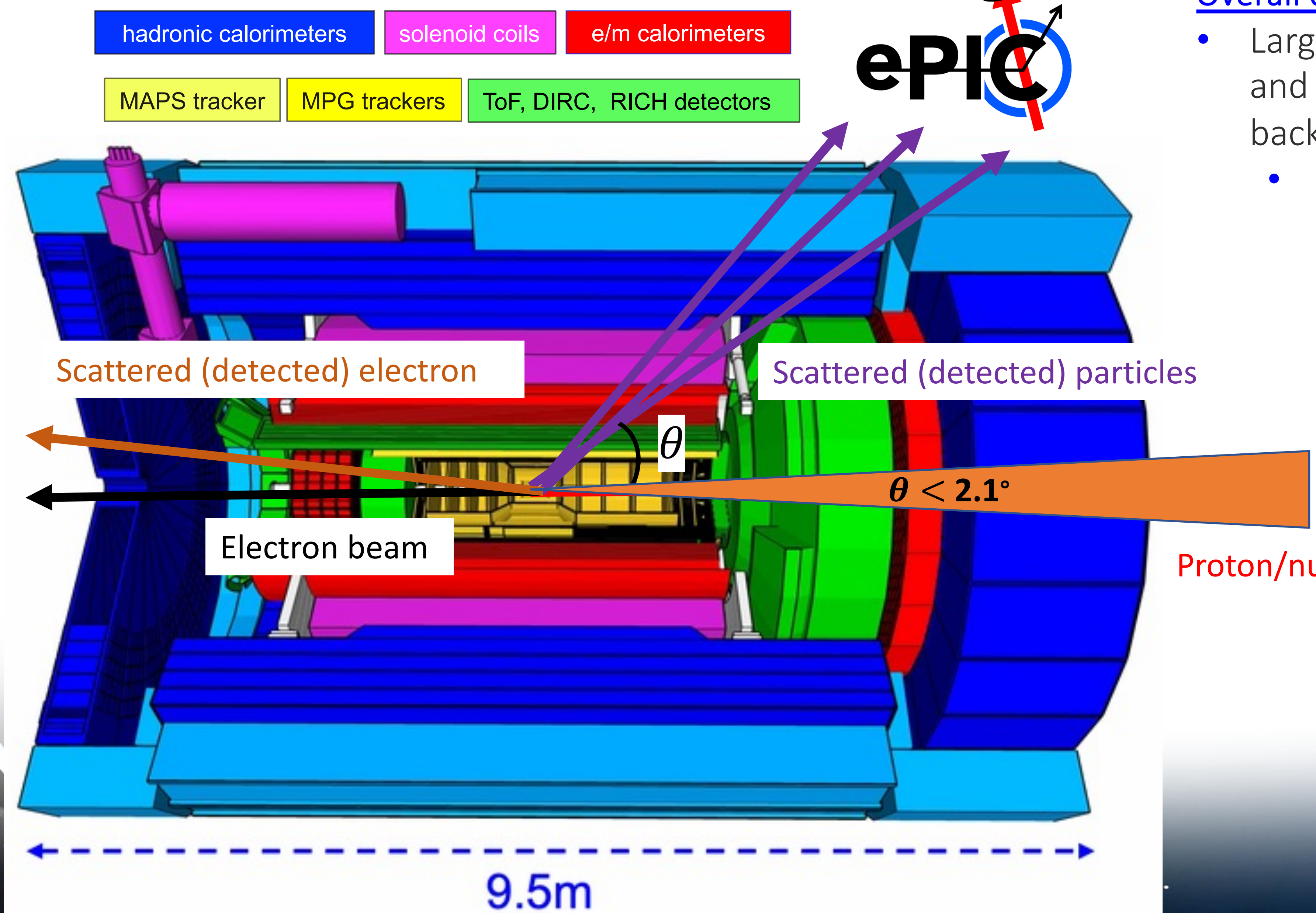
Accessing Far-Forward Physics at the EIC



Overall detector requirements:

- Large rapidity (-4 < η < 4) coverage; and far beyond in far-forward/far-backward detector regions
  - Rapidity is related to the polar angle → 0 < η < 4 equates to $2.1^\circ < \theta < 90^\circ$

Accessing Far-Forward Physics at the EIC

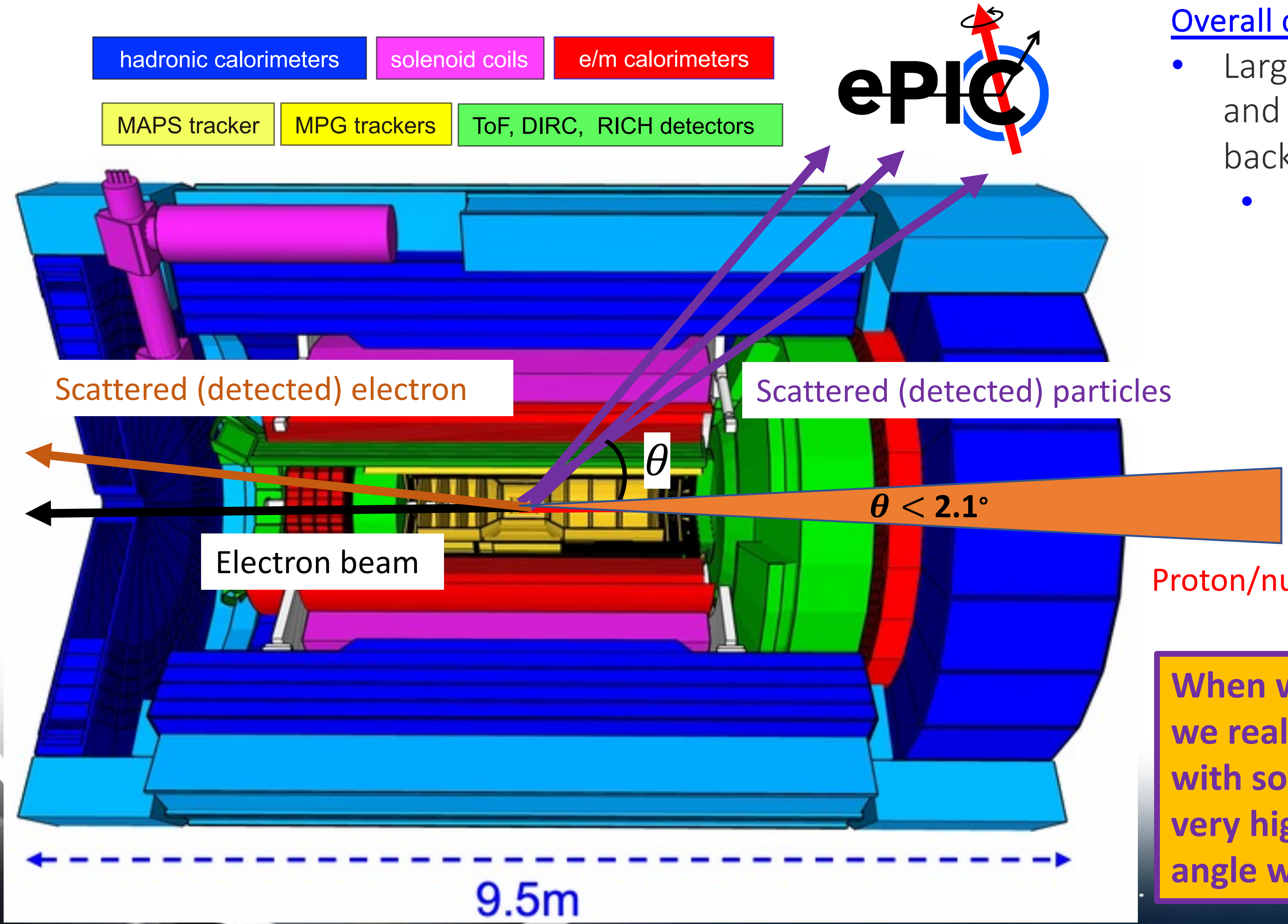


Overall detector requirements:

- Large rapidity (-4 < η < 4) coverage; and far beyond in far-forward/far-backward detector regions
  - Rapidity is related to the polar angle → 0 < η < 4 equates to $2.1^{\circ} < \theta < 90^{\circ}$

Far-forward here means $\boldsymbol{\theta} < \mathbf{2.1^{\circ}}$ (~37 mrad)

Accessing Far-Forward Physics at the EIC



Proton/nucleus beam

<u>Overall detector requirements:</u>

- Large rapidity (-4 < η < 4) coverage; and far beyond in far-forward/far-backward detector regions
  - Rapidity is related to the polar angle → 0 < η < 4 equates to $2.1^{\circ} < \theta < 90^{\circ}$

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).

Far-forward → "Exclusive"

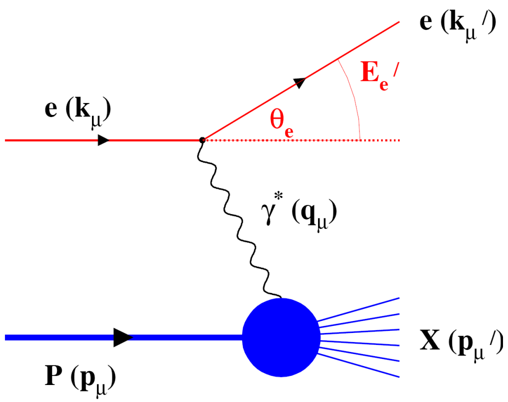
experimental measurements categories to address EIC physics:

Parton Distributions in nucleons and nuclei

QCD at Extreme Parton Densities - Saturation

Spin and Flavor structure of nucleons and nuclei

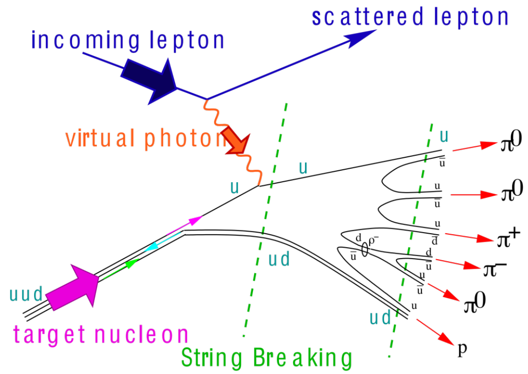
Tomography Transverse Momentum Dist.



inclusive DIS

- measure scattered lepton
- multi-dimensional binning: x, Q^2

→ reach to lowest x, Q^2 impacts Interaction Region design



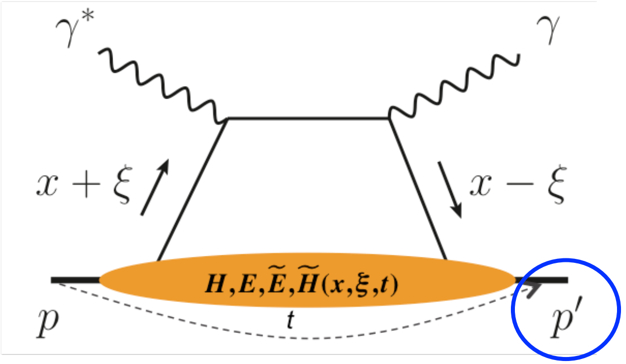
semi-inclusive DIS

- measure scattered lepton and hadrons in coincidence
- multi-dimensional binning: x, Q^2, z, p_T, Θ

→ particle identification over entire region is critical

QCD at Extreme Parton Densities - Saturation

Tomography Spatial Imaging



exclusive processes

- measure all particles in event
- multi-dimensional binning: x, Q^2, t, Θ
- proton p_t: 0.2 - 1.3 GeV

→ cannot be detected in main detector

→ strong impact **on Interaction Region design**

∫Ldt: 1 fb^{-1}

10 fb^{-1}

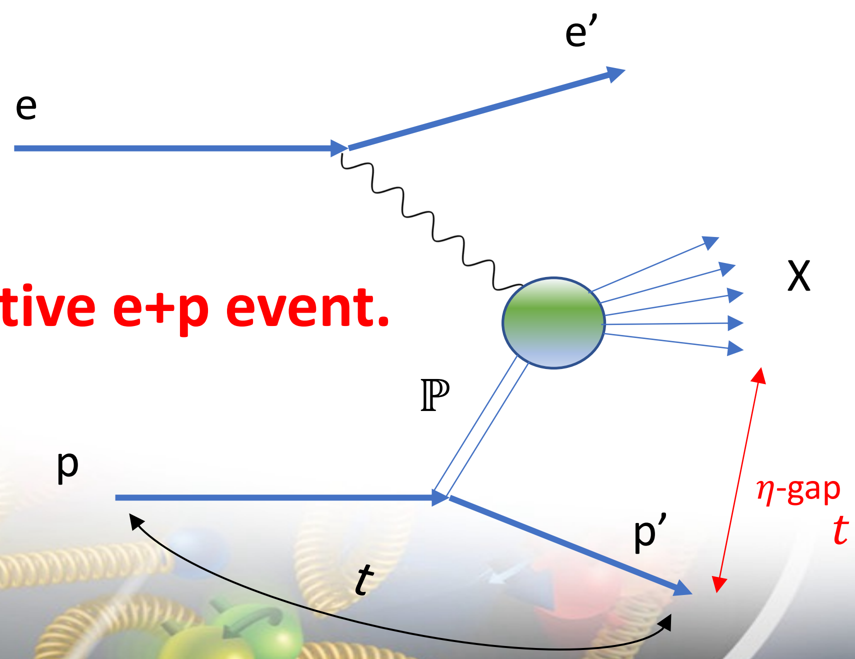
10 - 100 fb^{-1}

machine & detector requirements

Diffractive + Exclusive Final States

- Diffractive events characterized by an "η-gap" between jet and scattered proton → proton scattered at high pseudorapidity!

Diffractive e+p event.



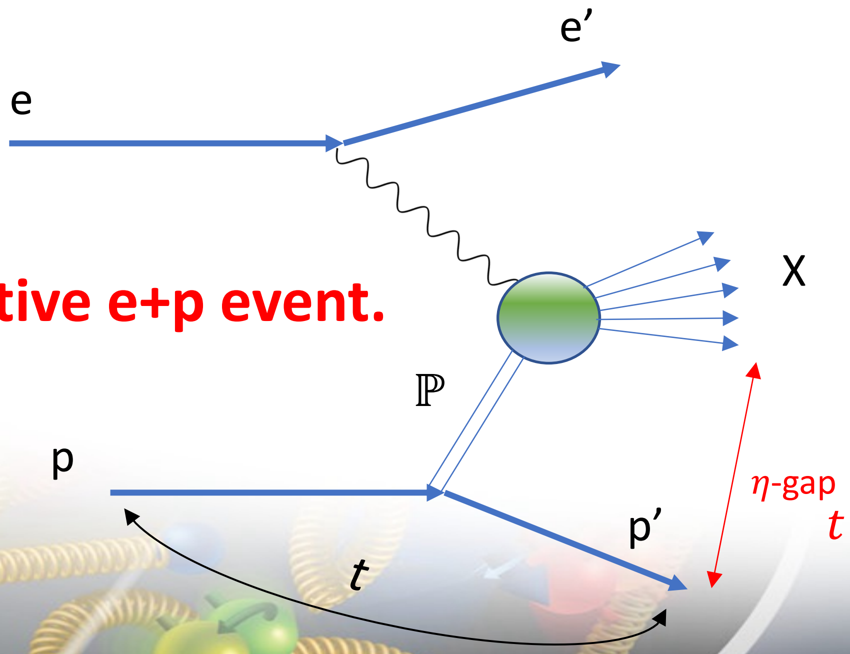
$t = -(p - p')^2 \approx -p_{t,p'}^2$

Mandelstam t

Diffractive + Exclusive Final States

- Diffractive events characterized by an "η-gap" between jet and scattered proton → proton scattered at high pseudorapidity!
- Can be described by color-singlet "pomeron" exchange in Regge theory.
  - Accounts for ~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!

Diffractive e+p event.

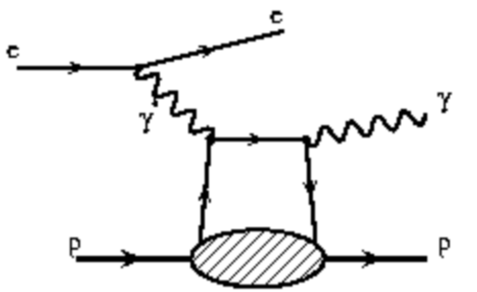


$$t = -(p - p')^2 \approx -p_{t,p'}^2$$

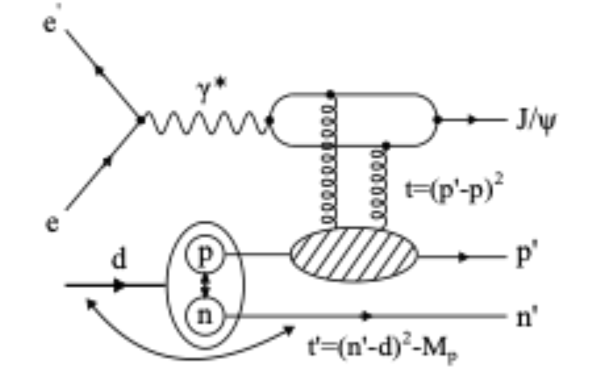
Mandelstam t

Far-Forward Processes at the EIC

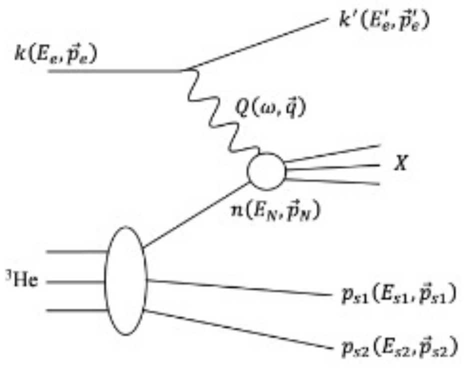
e+p DVCS



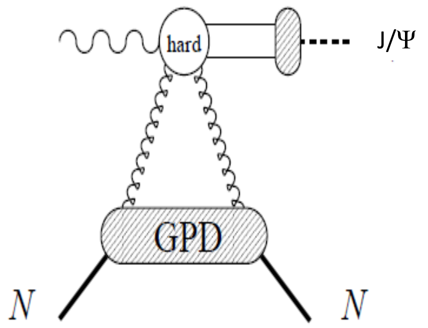
e+d exclusive J/Psi with p/n tagging



e+He3 spectator tagging

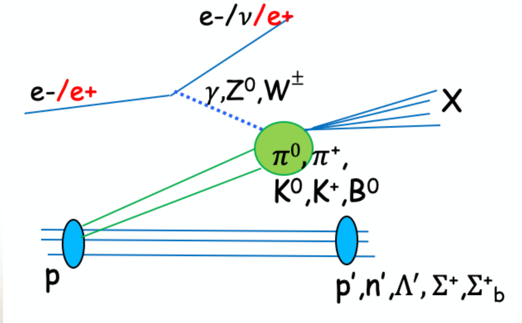


coherent/incoherent J/ψ production in e+A

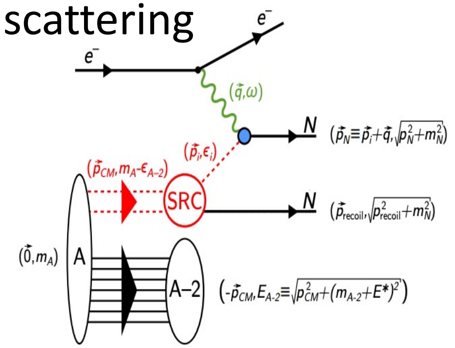


Meson structure:

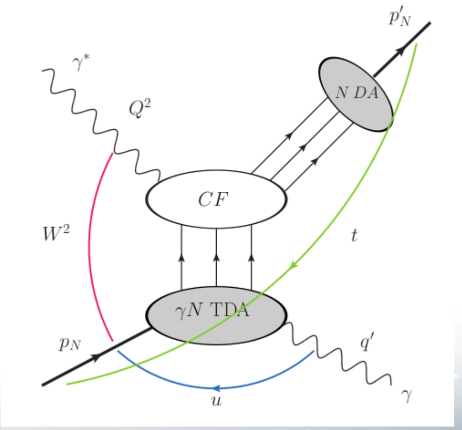
- ep→ (π) →e' n X
- Λ →pπ^- and $\Lambda \rightarrow n\pi^0$



Quasi-elastic electron scattering



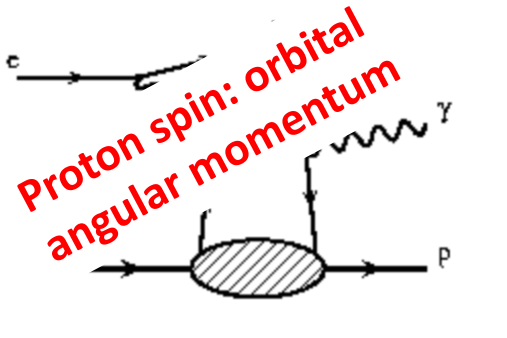
u-channel backward exclusive electroproduction



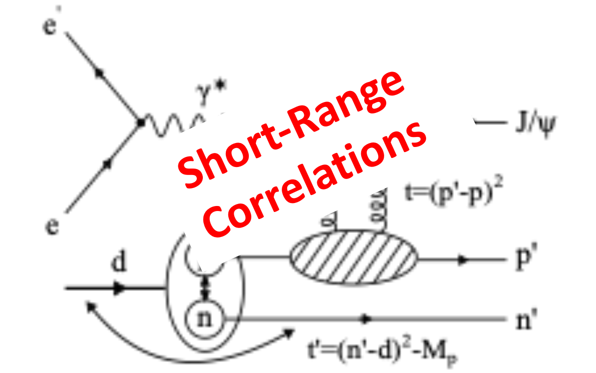
…and MANY more!

Far-Forward Physics at the EIC

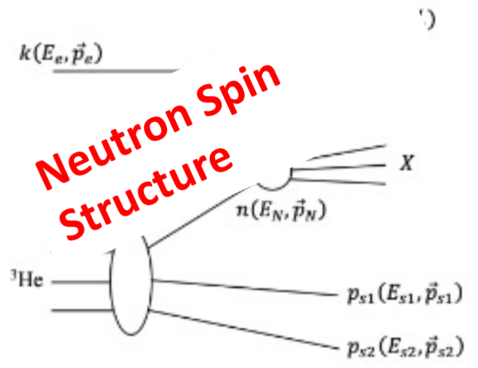
e+p DVCS



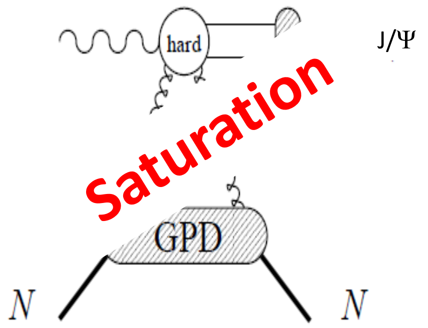
e+d exclusive J/Psi with p/n tagging



e+He3 spectator tagging

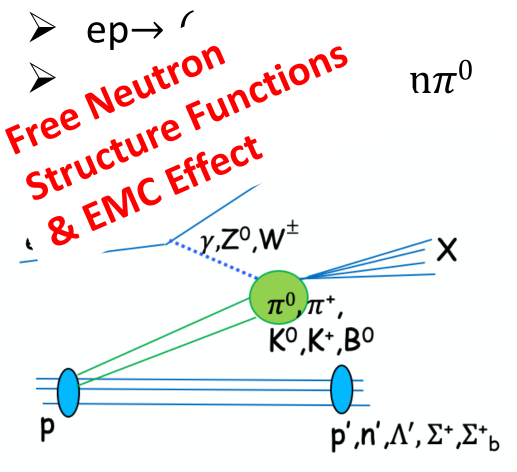


coherent/incoherent J/ψ production in e+A

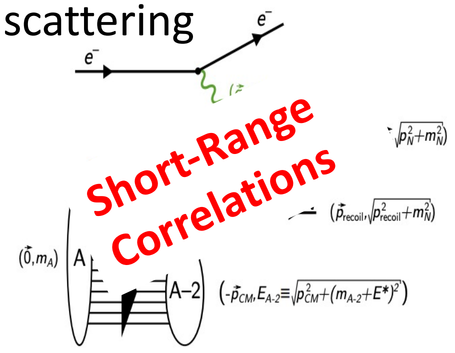


Meson structu

- ep→

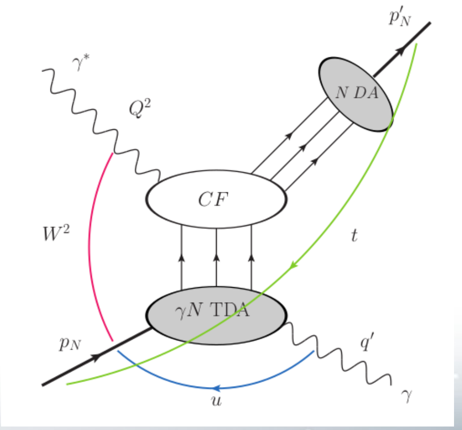


Quasi-elastic electron scattering

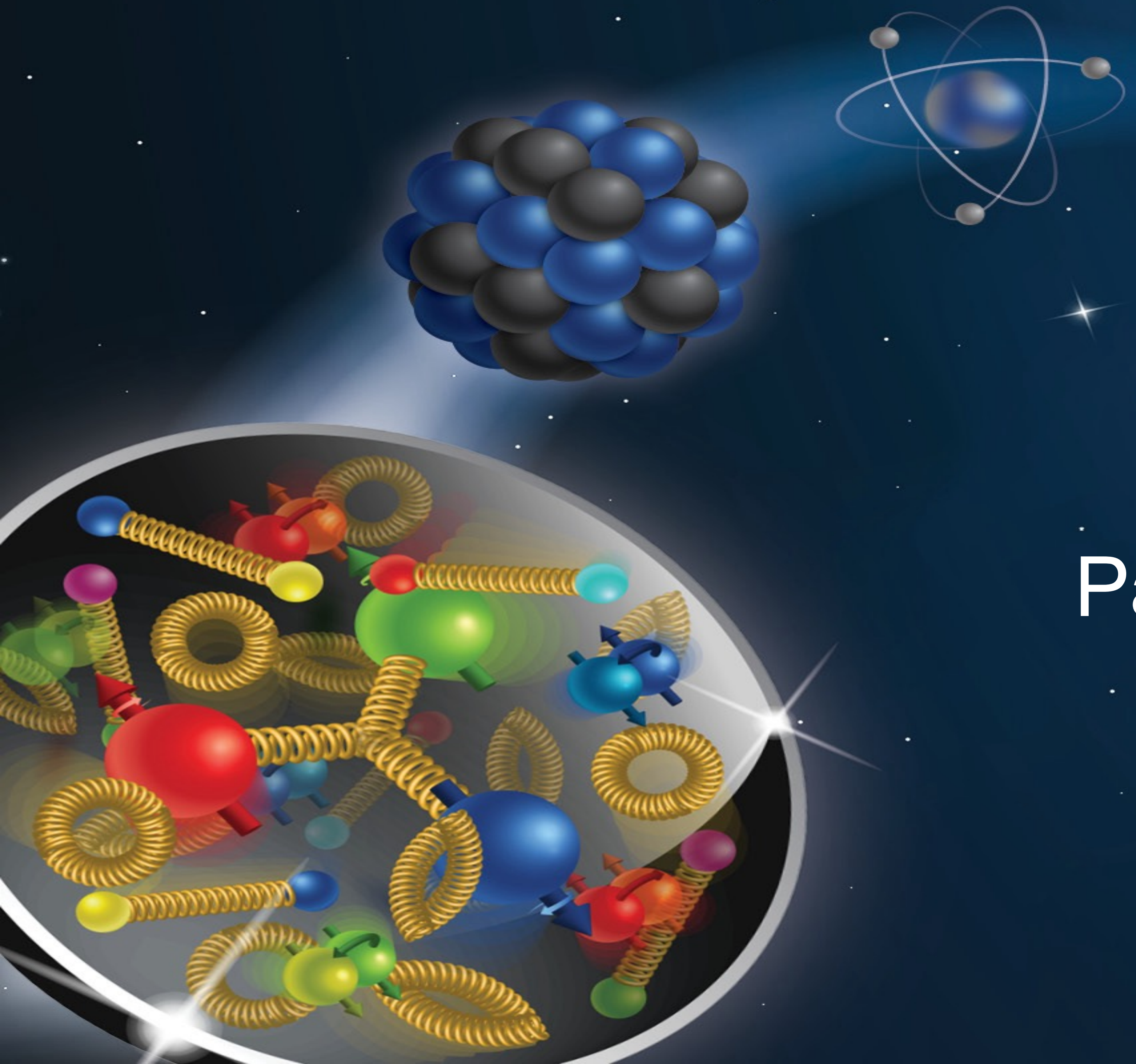


[1] Z. Tu, A. Jentsch, et al., Physics Letters B, (2020)
[2] I. Friscic, D. Nguyen, J. R. Pybus, A. Jentsch, *et al.*, Phys. Lett. B, **Volume 823**, 136726 (2021)
[3] W. Chang, E.C. Aschenauer, M. D. Baker, A. Jentsch, J.H. Lee, Z. Tu, Z. Yin, and L.Zheng, Phys. Rev. D **104**, 114030 (2021)
[4] A. Jentsch, Z. Tu, and C. Weiss, Phys. Rev. C **104,** 065205, (2021) **(Editor's Suggestion)**

u-channel backward exclusive electroproduction

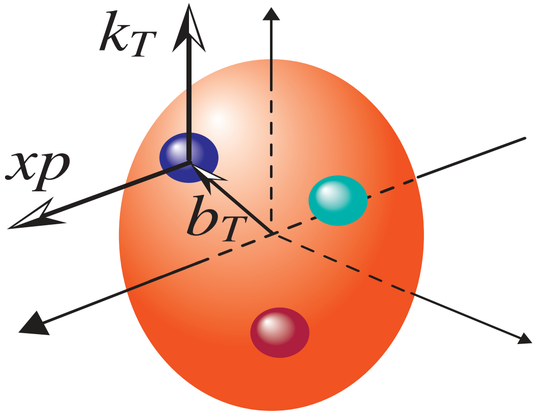


…and MANY more!



Protons:
Partonic Imaging

Partonic Imaging of Nucleons



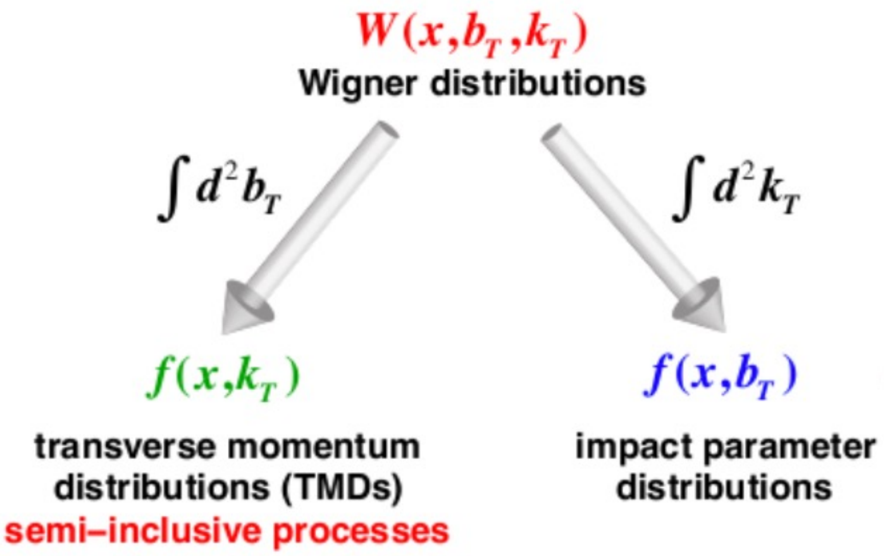
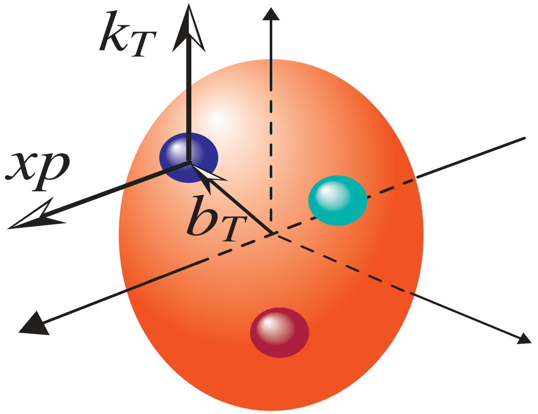


Fig. 2.2 from the EIC White Paper

Partonic Imaging of Nucleons



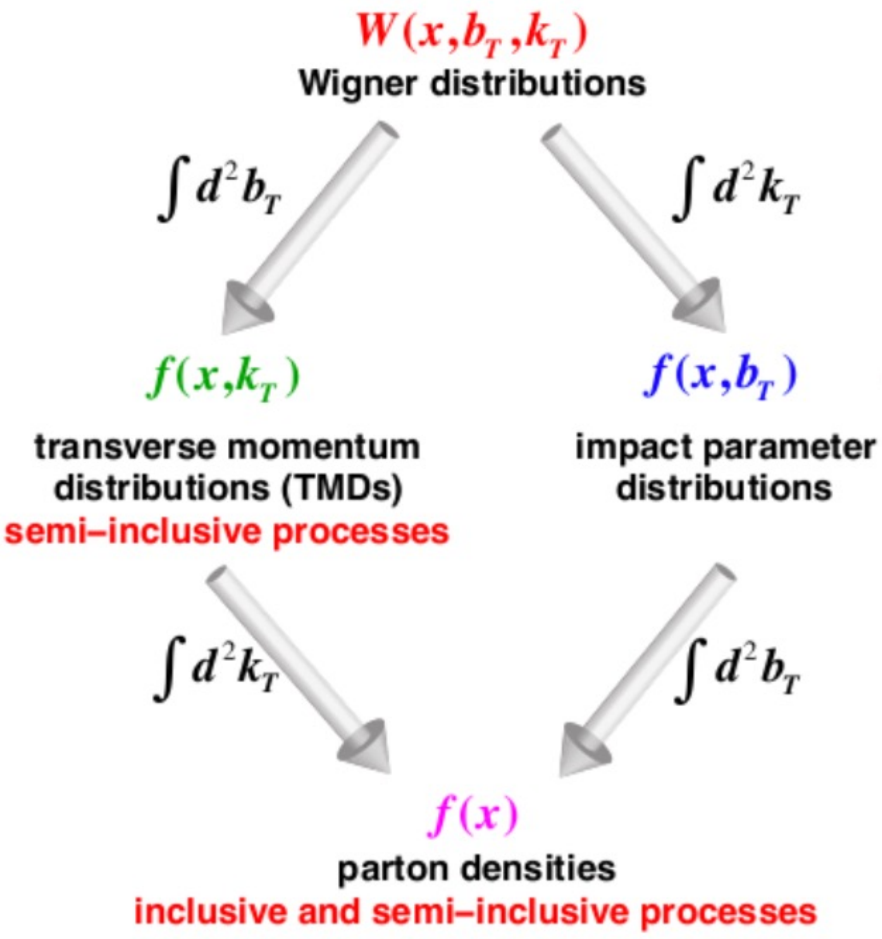
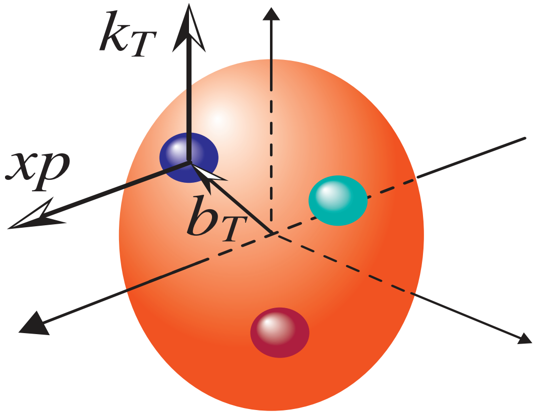


Fig. 2.2 from the EIC White Paper

Partonic Imaging of Nucleons



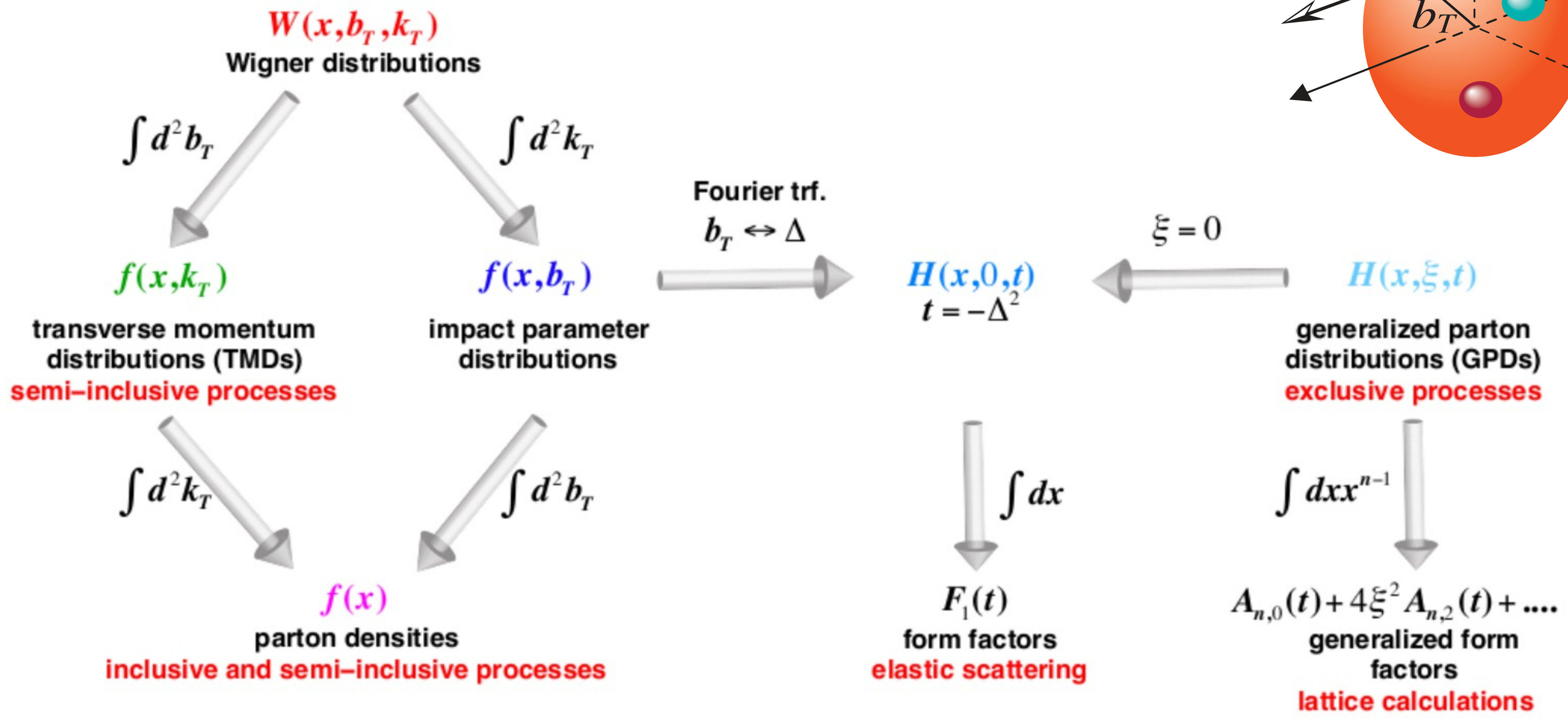


Fig. 2.2 from the EIC White Paper

Partonic Imaging of Nucleons

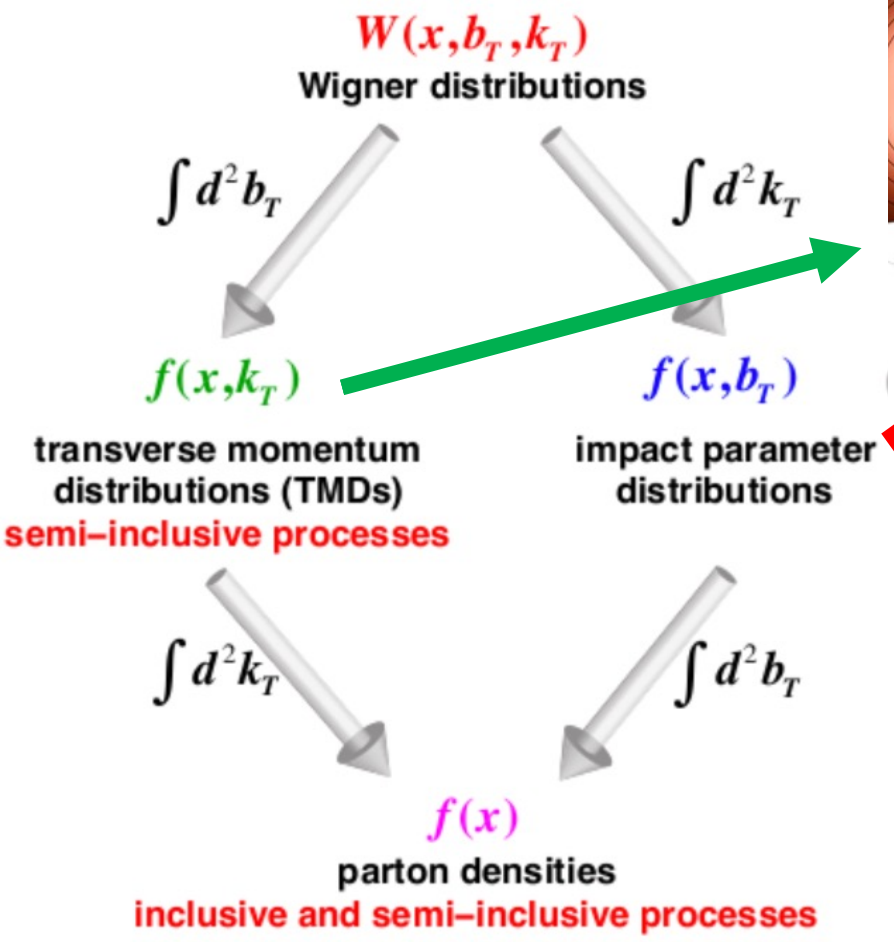
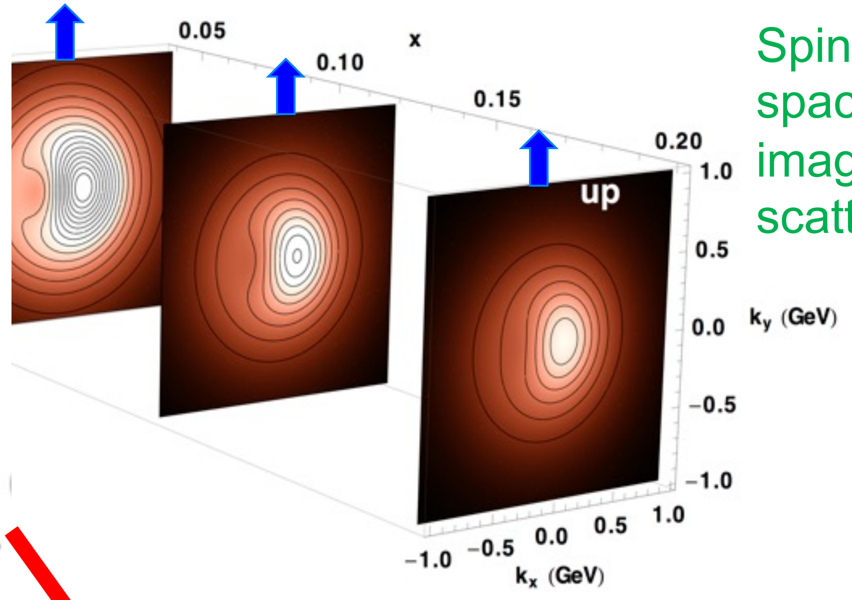
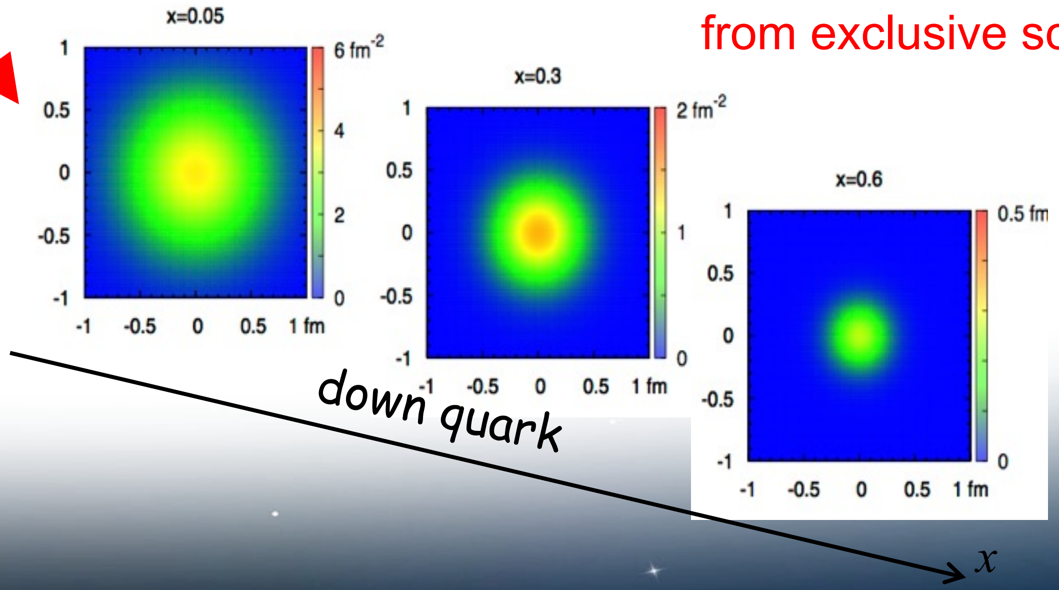


Fig. 2.2 from the EIC White Paper

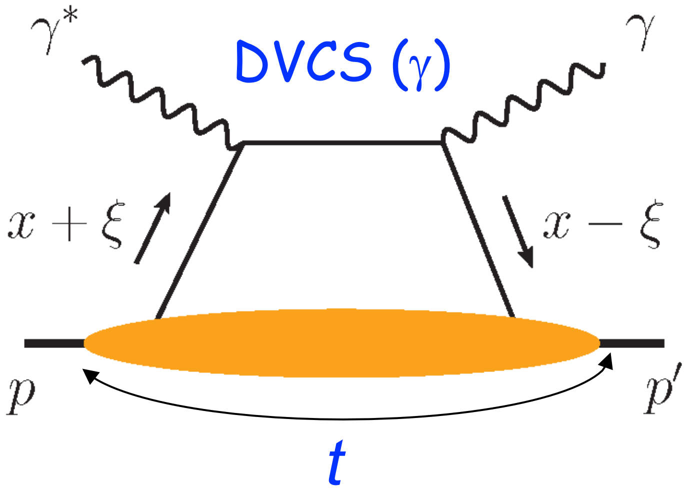


Spin-dependent 3D momentum space
images from semi-inclusive scattering

Spin-dependent 2+1D coordinate space images from exclusive scattering



Deeply Virtual Compton Scattering

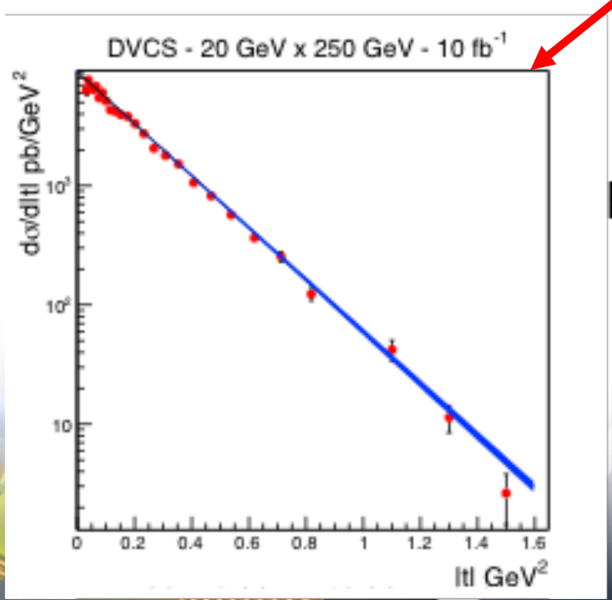


- Exclusive process with all final state particles detected in the event.
- Sensitive to the proton GPD.

$$t = -(p - p')^2 \approx -p'^2_t$$

p_t and b_t are conjugate variables!

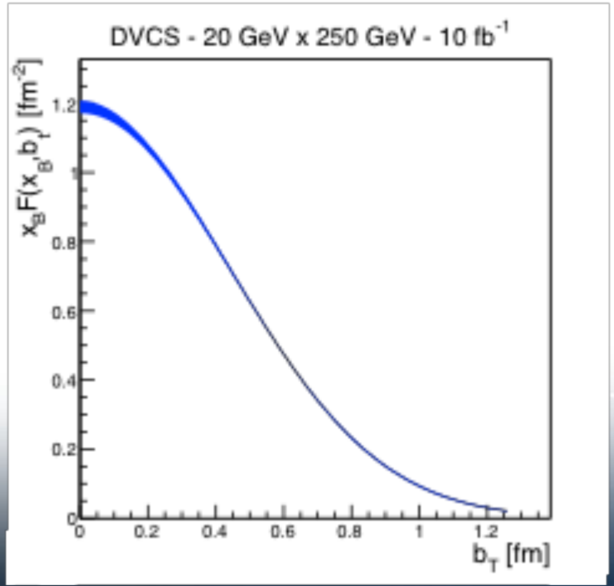
Measurement



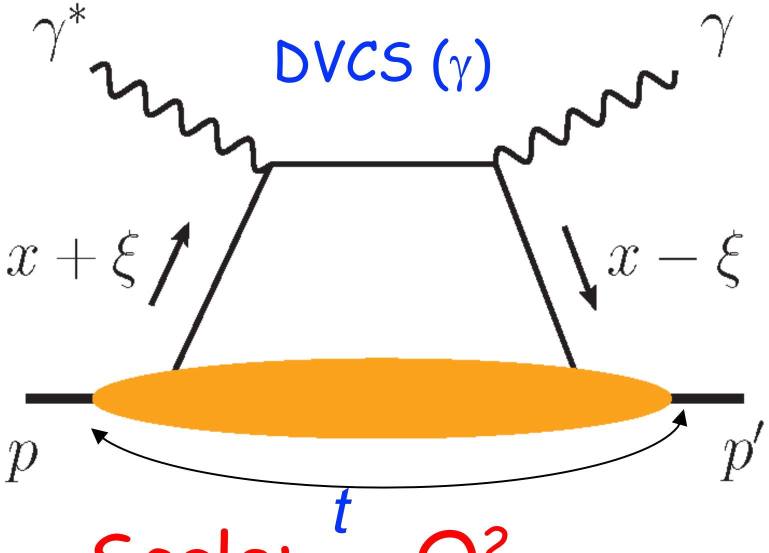
Plots from EIC White Paper:

Fourier transform

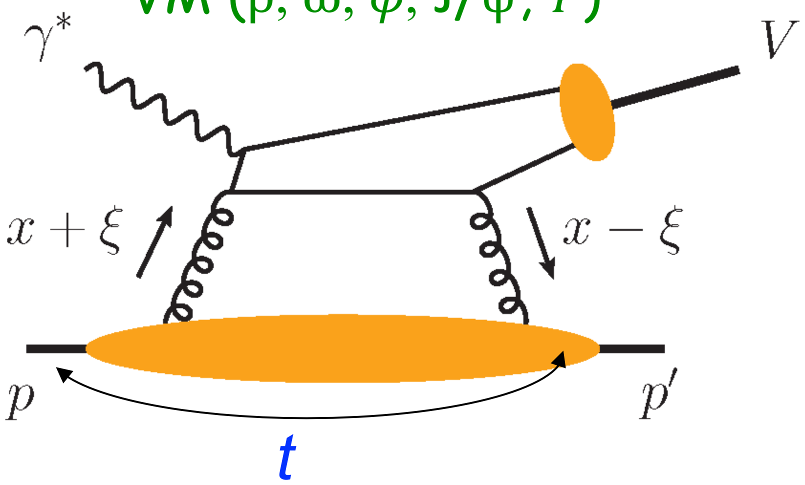
Physics observable (Impact parameter distribution)



Exclusive Vector Meson and Real Photon Production



square 4-momentum at *p*-vertex: $t=(p'-p)^2$



Scale: Q^2 ⟷ $Q^2 + M^2$

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 → direct access to gluons, c+cbar pair production
- Light VMs → quark-flavor separation

Small GPD Primer

$H^{q,g}(x,\xi,t)$	$E^{q,g}(x,\xi,t)$	*for sum over parton helicities*
$\widetilde{H}^{q,g}(x,\xi,t)$	$\widetilde{E}^{q,g}(x,\xi,t)$	*for difference over parton helicities*
nucleon helicity conserved	*nucleon helicity changed*	

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

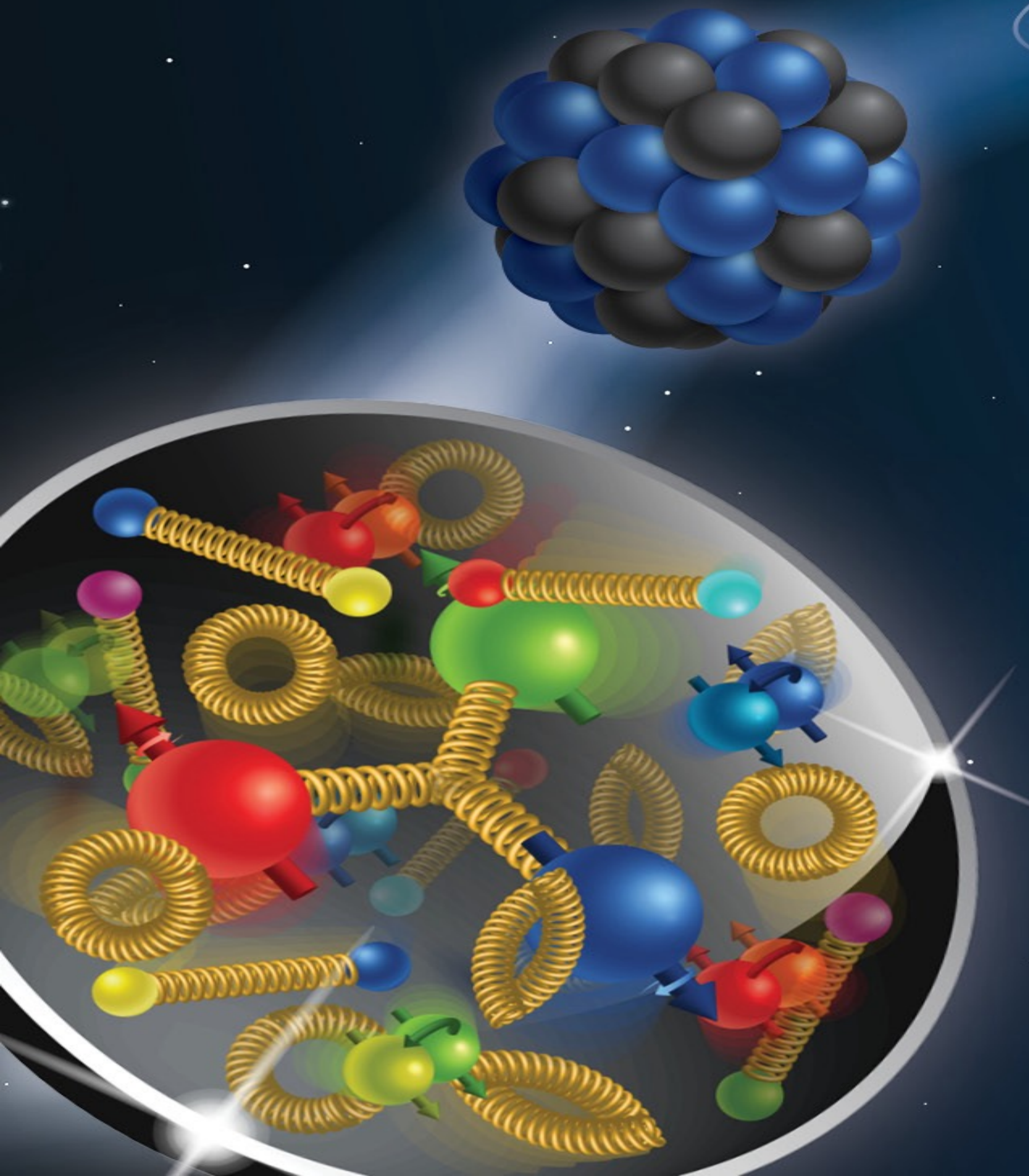
Dominated by H
slightly dependent on E

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

→ ***sin(Φ$_T$–ϕ$_N$)***
governed by E and H

Requires a polarized proton-target

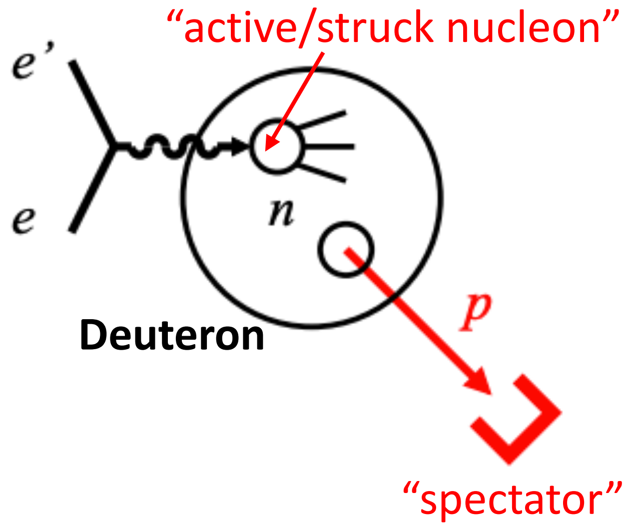
responsible for total orbital angular momentum through Ji sum rule
a window to the SPIN physics

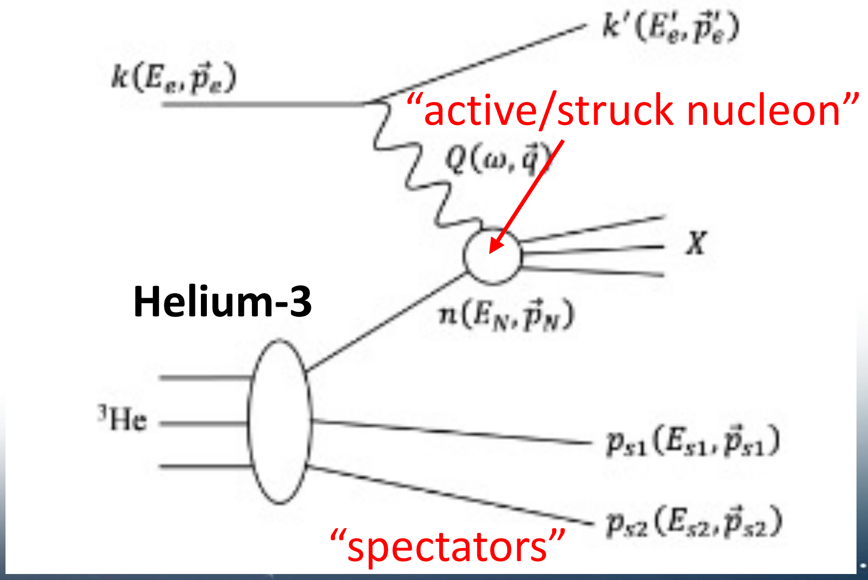


What about (light) nuclei?

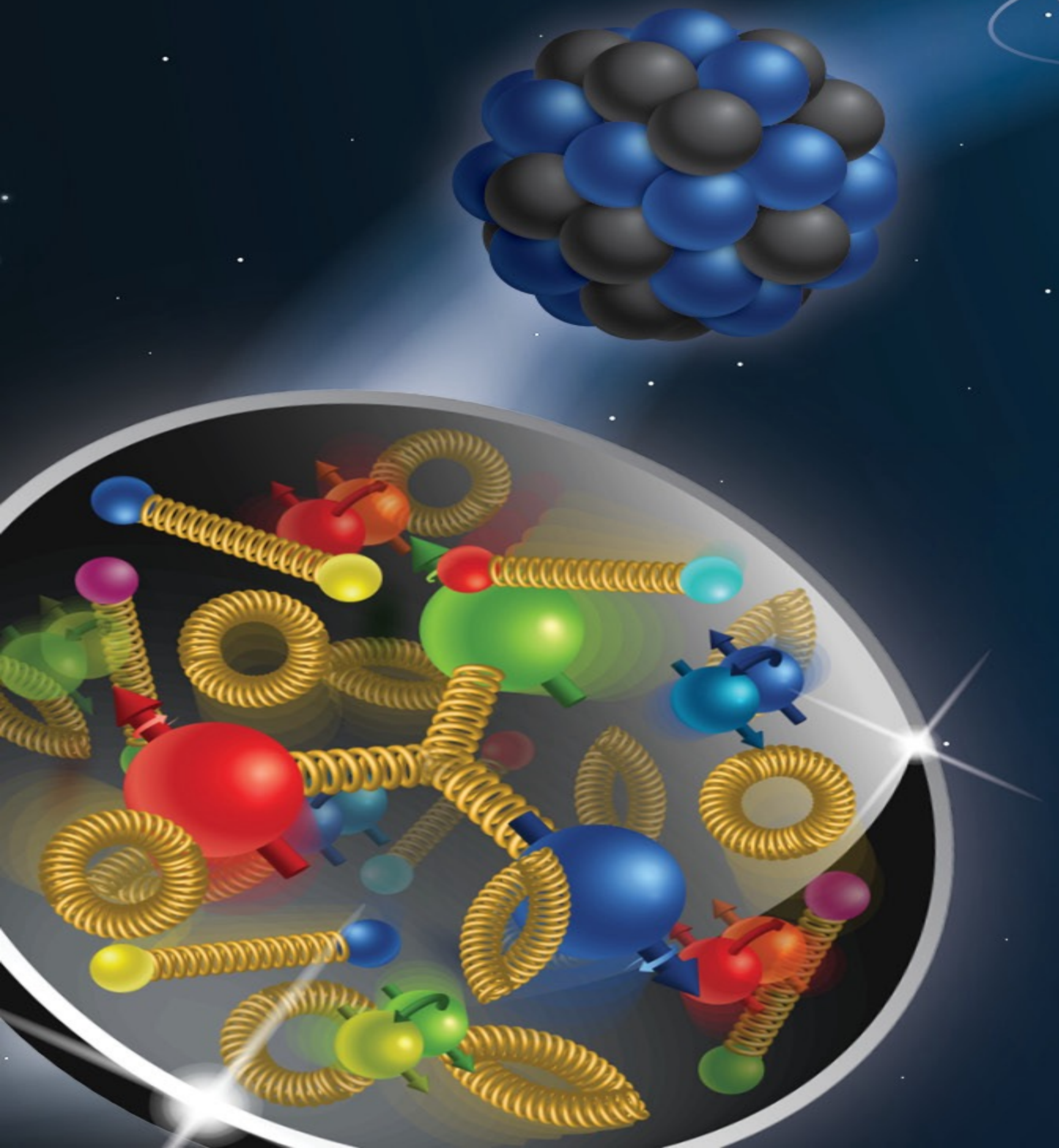
Tagged DIS at the EIC

- **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.





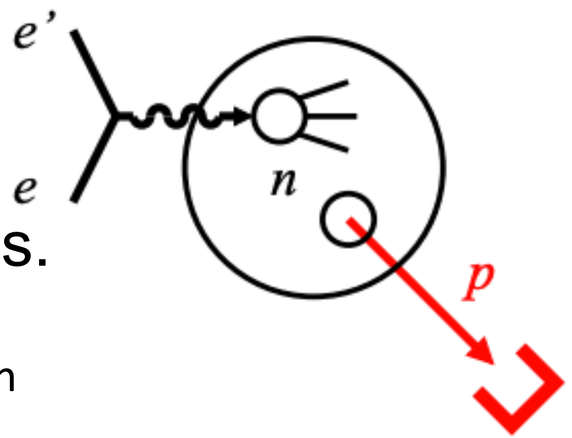
Tagged spectator nucleon momentum → experimental variable for selecting nuclear configurations with free and modified nucleons.



Light nuclei - deutrerons: Free Neutron Structure

Neutron Structure

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



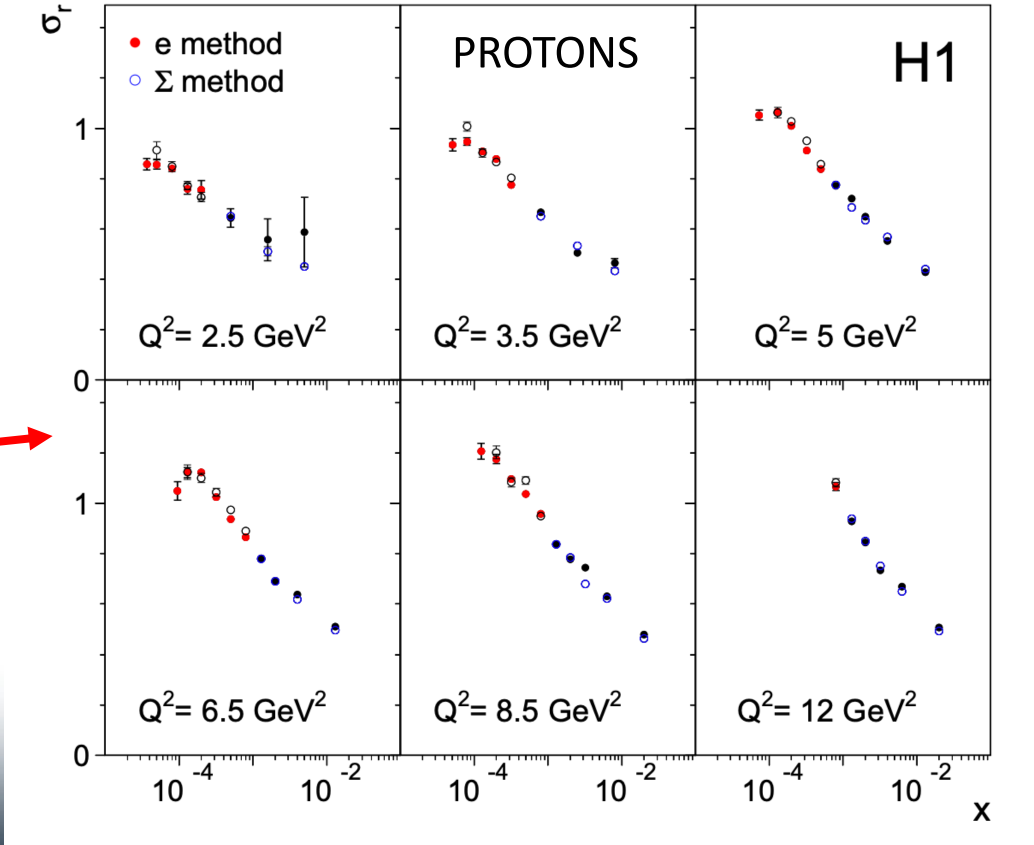
$$\sigma_r = \frac{Q^4 x}{2\pi\alpha^2[1+(1-y)^2]} \cdot \frac{d^2\sigma}{dx\,dQ^2} = F_2(x,Q^2) - f(y)\cdot F_L(x,Q^2)$$

Reduced cross section

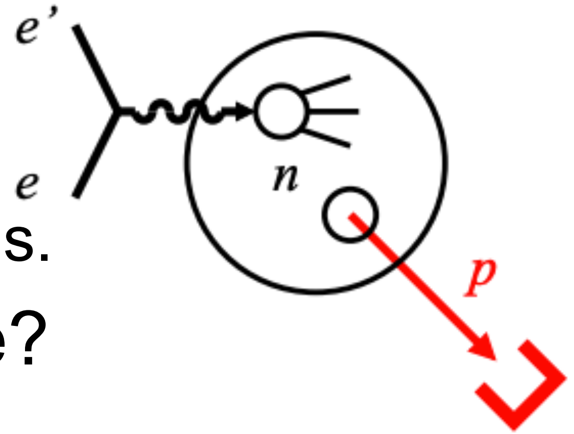
"Flux factor" — Differential cross section — Structure functions

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)
- V. Andreev *et al.* (H1 Collaboration), *Eur.Phys.J.C* 74 (2014) 4, 2814
- H. Abramowicz *et al.* (H1 and ZEUS Collaborations) *The European Physical Journal C* **volume 75**, Article number: 580 (2015)

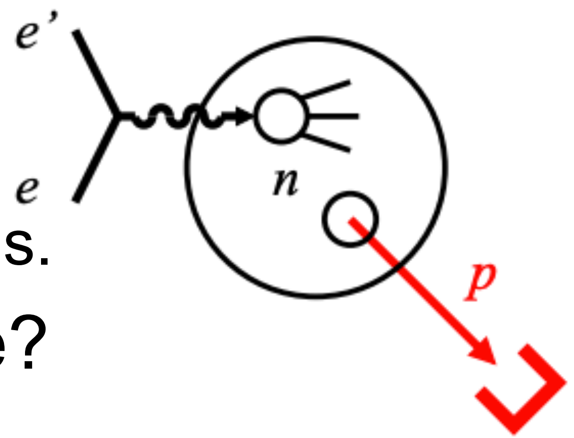


Neutron Structure



- 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

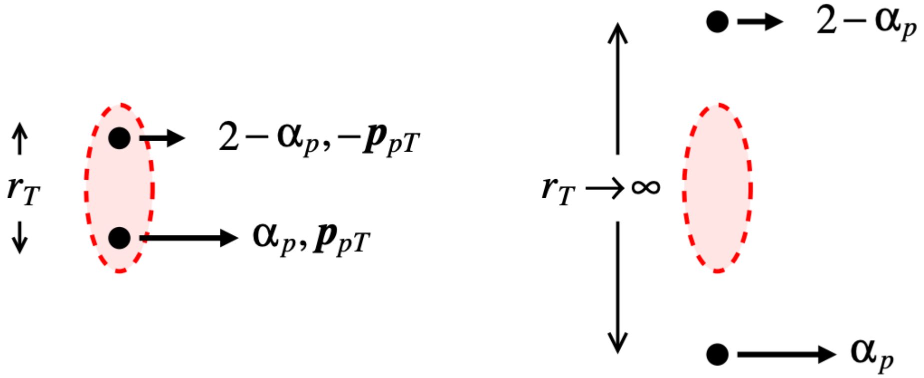


- Protons well-studied at HERA -> So…why the neutron?
  - Flavor separation, baseline for studies of nuclear modifications.
- What makes the free neutron structure hard to measure?
  - Can only access neutrons *in a nucleus.*
  - Includes nuclear binding effects, Fermi motion, etc.

- <u>Two options:</u>
  1. Inclusive measurements → Average over all nuclear configurations, use theory input to correct for nuclear binding effects.
  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)

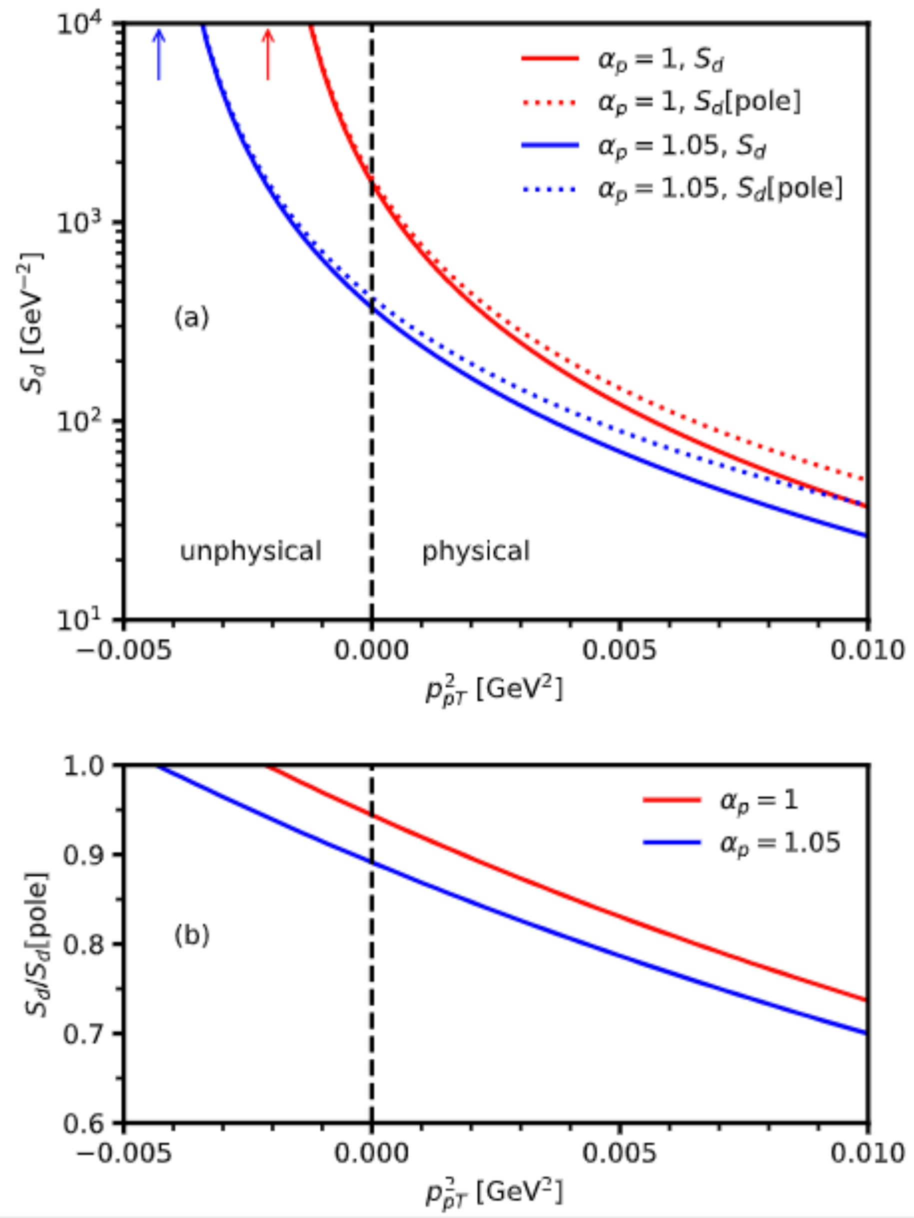
Basic Method - Pole Extrapolation

C. Weiss and W. Cosyn
Phys. Rev. C **102**, 065204 (2020)



$p_{pT}^2 > 0$
physical region

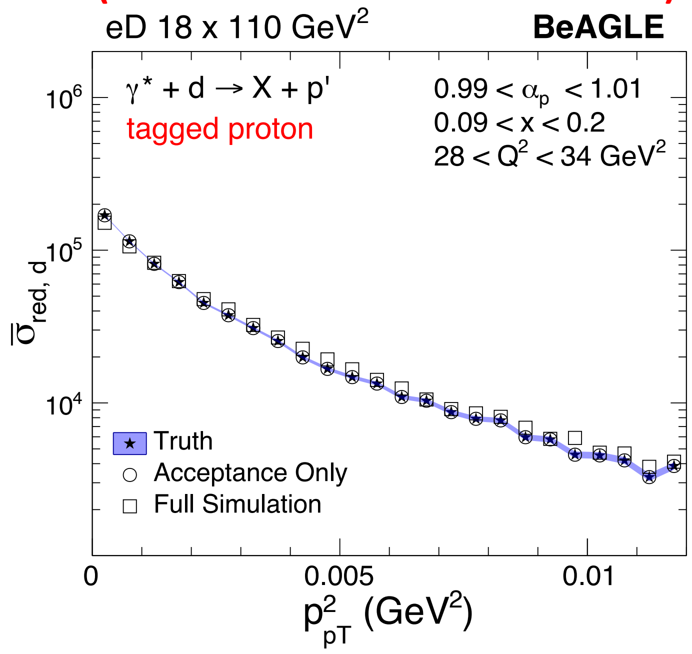
$p_{pT}^2 \to -a_T^2$
pole extrapolation



Free Neutron F_2 Extraction

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

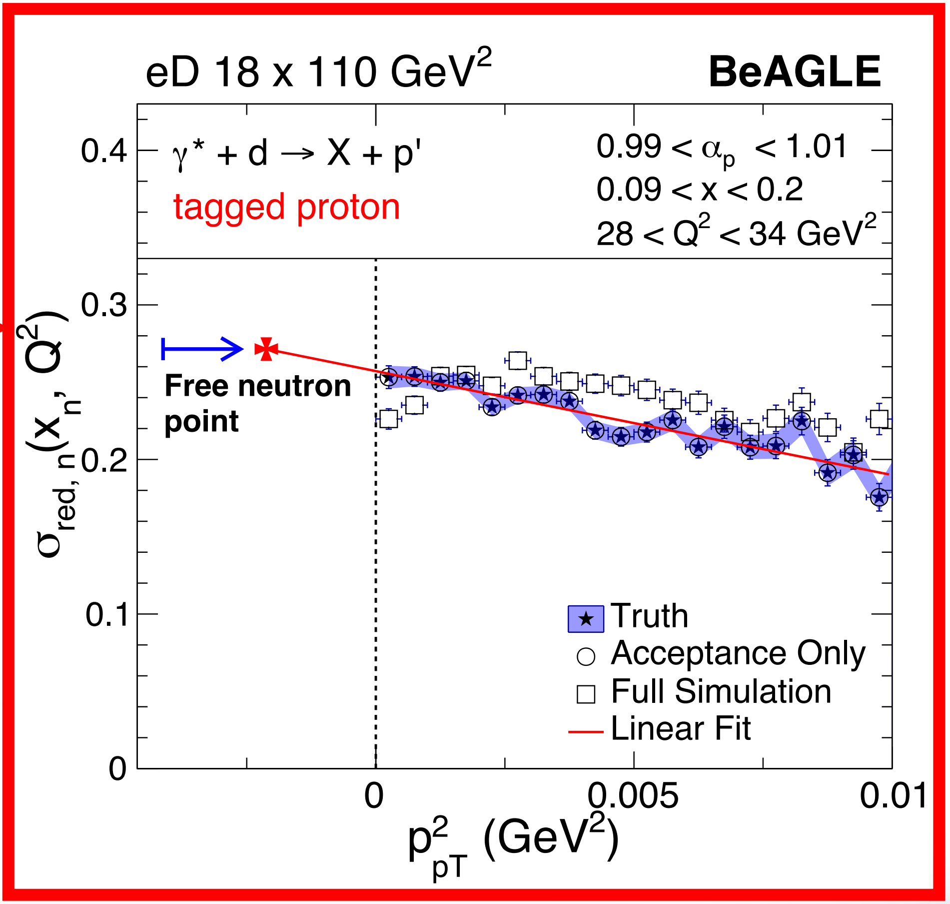
(deuteron reduced cross section)



RESULT: Reduced cross section on the **active nucleon.**

$$\times \quad \frac{1}{S_d(p_{pT}, \alpha_p)[pole]}$$

(inverse pole of deuteron spectral function)

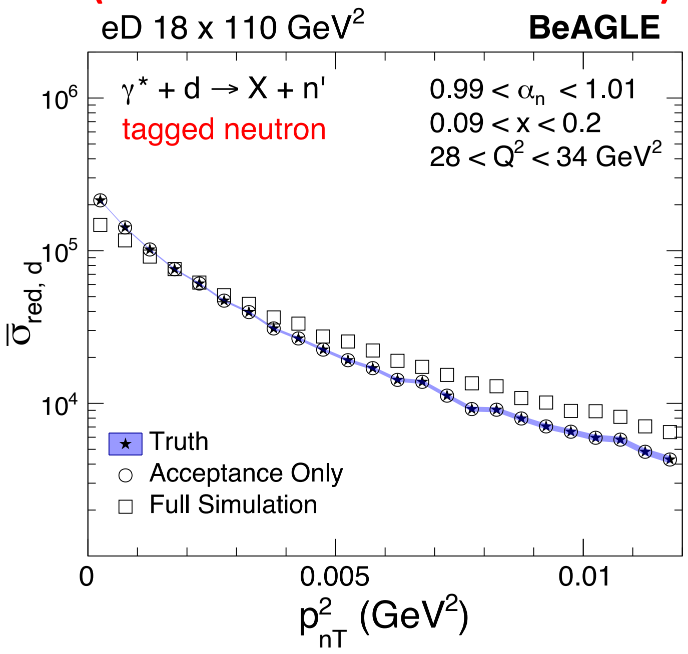


(Active nucleon reduced cross section)

Free Proton F_2 Extraction

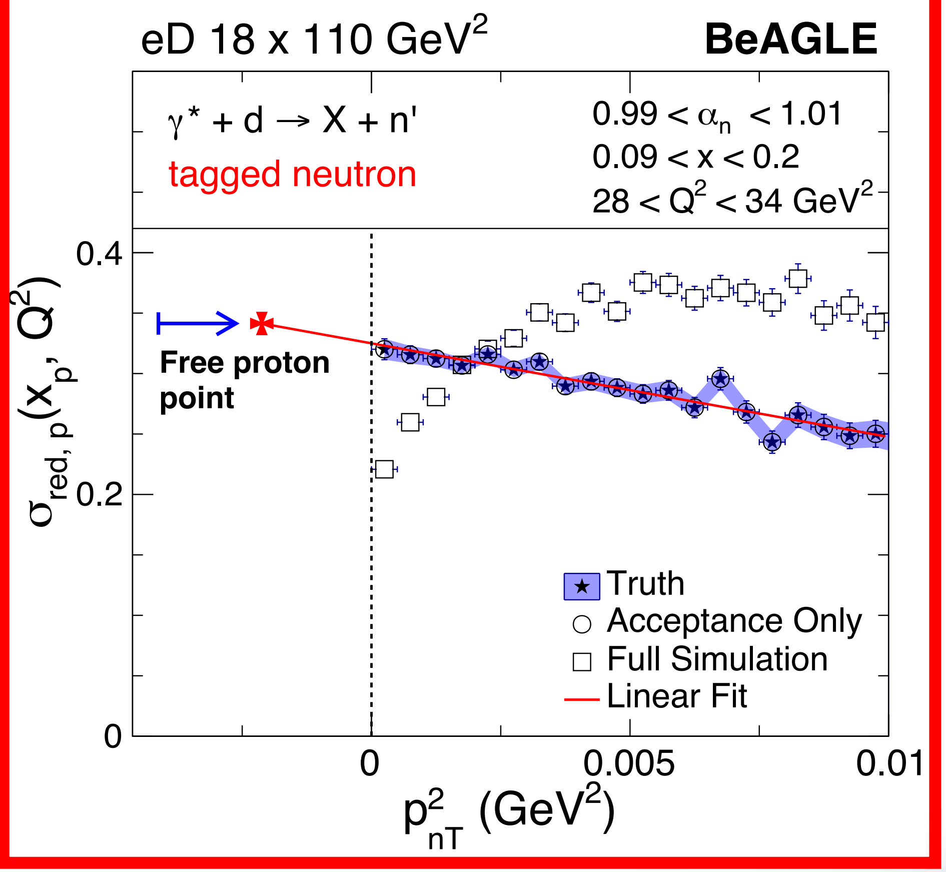
A. Jentsch, Z. Tu, and C. Weiss, Phys. Rev. C **104,** 065205, (2021) **(Editor's Suggestion)**

(deuteron reduced cross section)

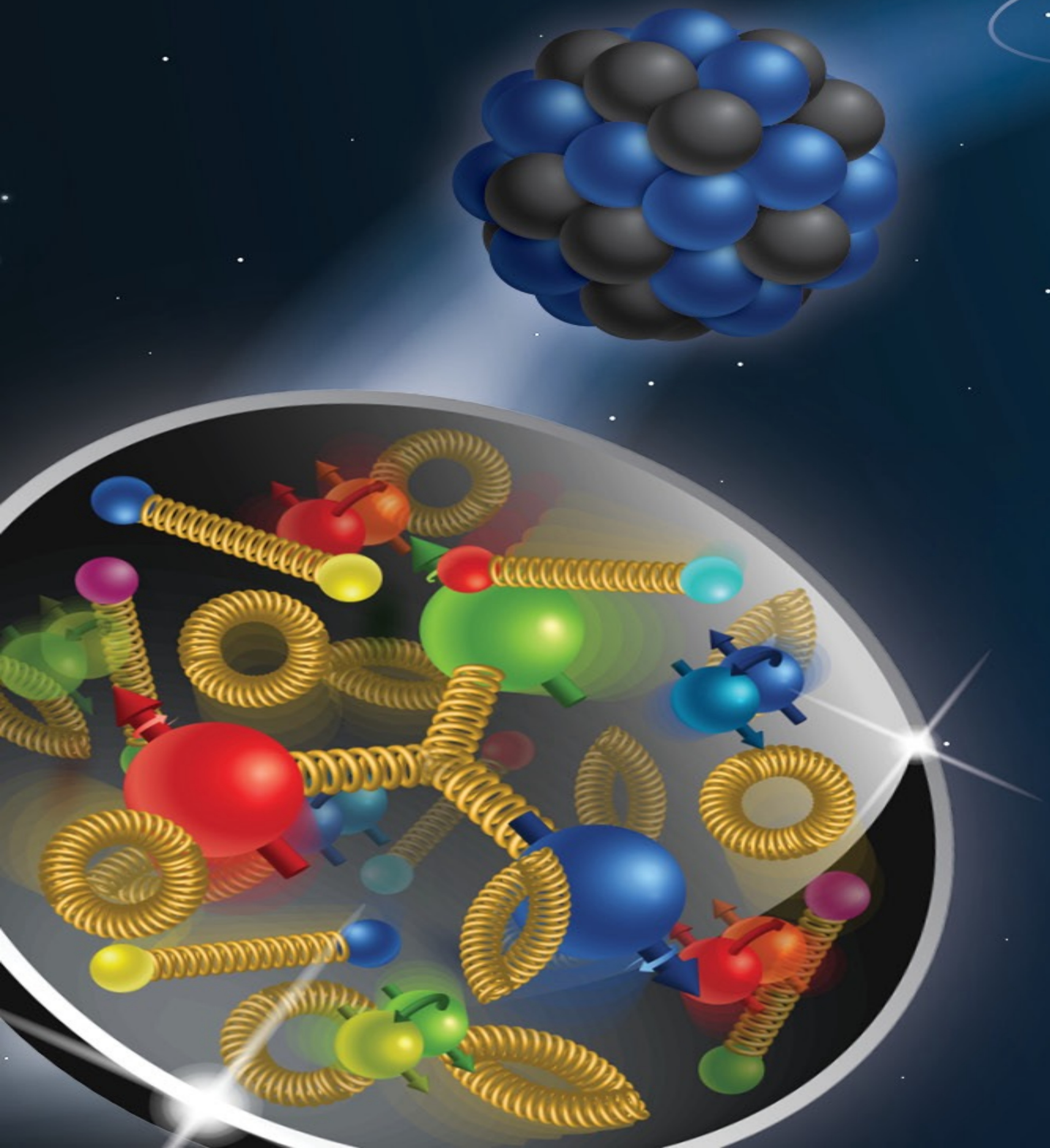


$$\frac{1}{S_d(p_{pT}, \alpha_p)[pole]}$$

(inverse pole of deuteron spectral function)



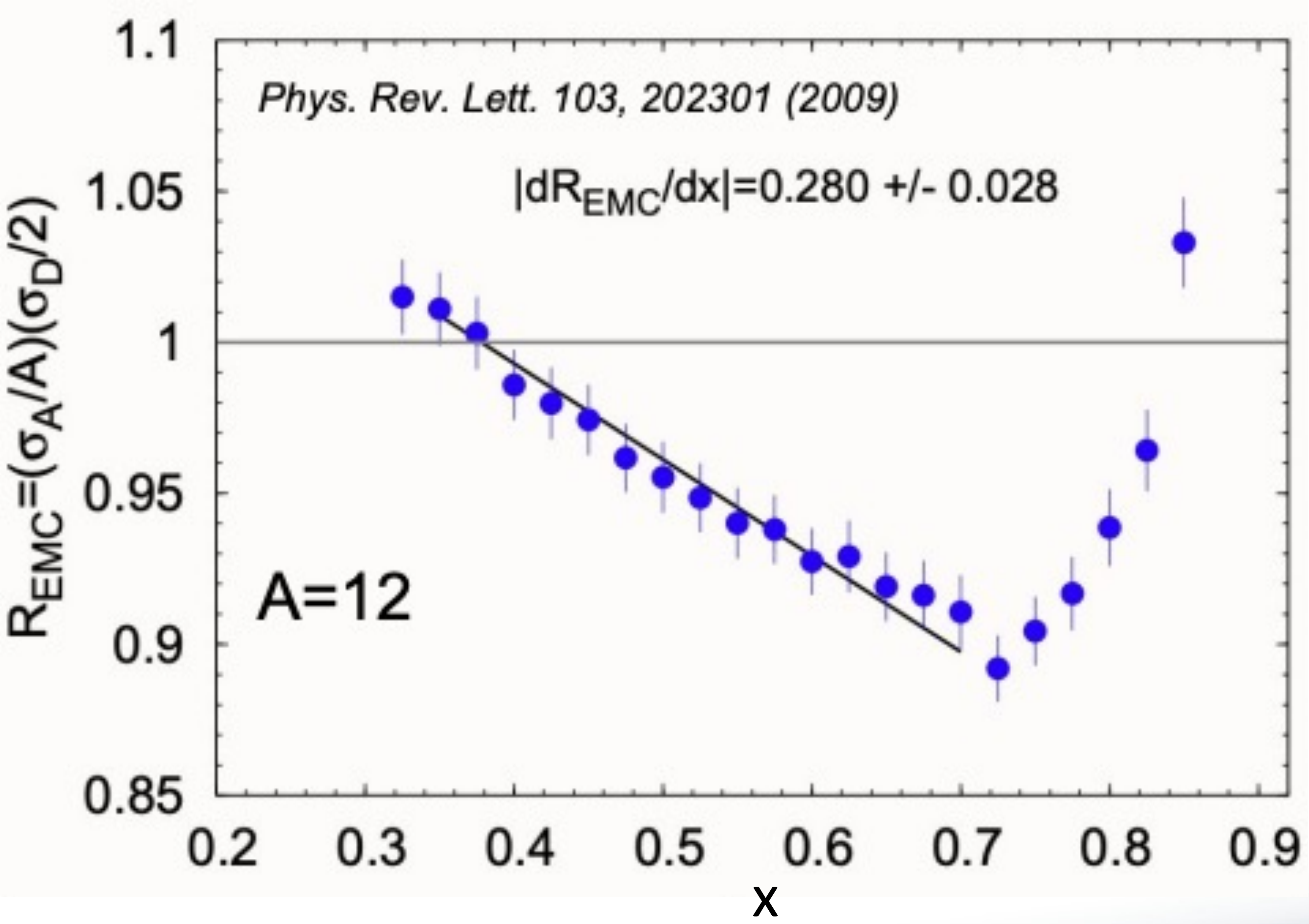
(Active nucleon reduced cross section)



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

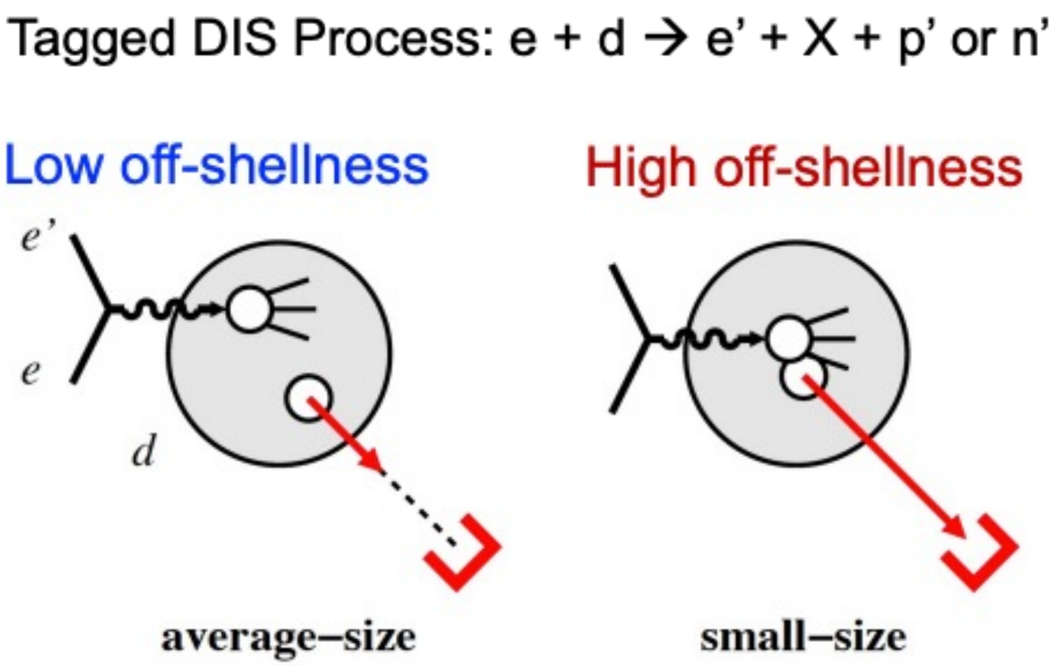
The EMC Effect

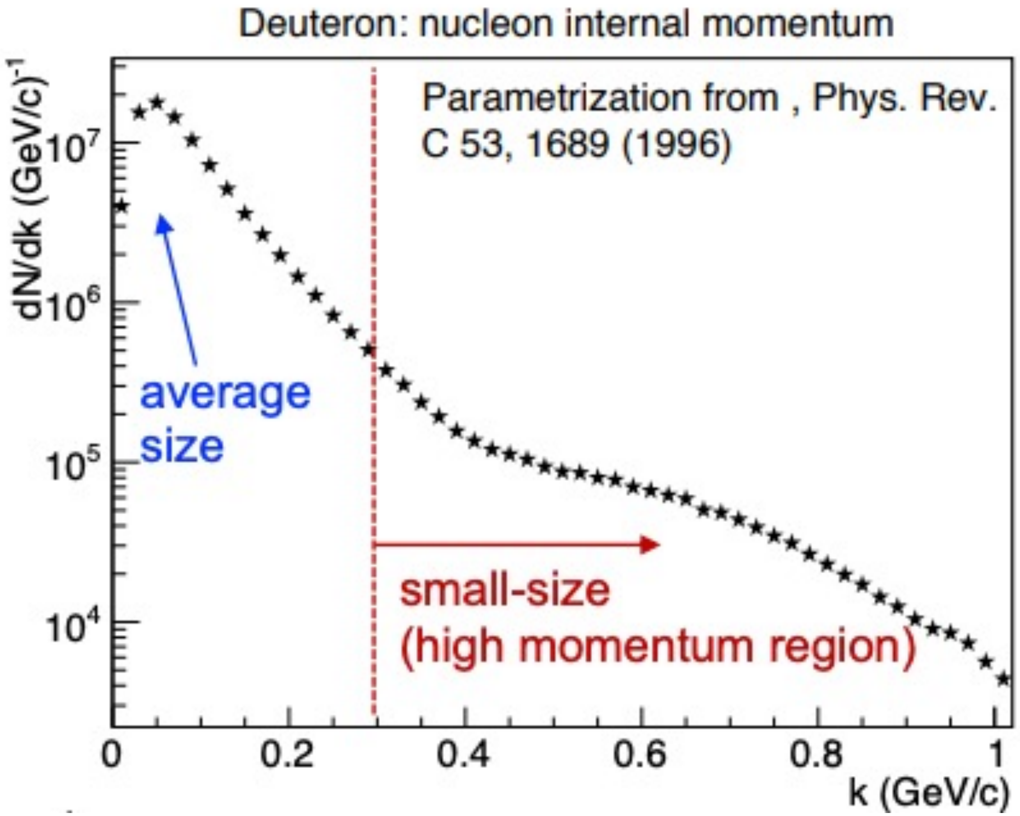
- Discovered by the European Muon Collaboration ~40 years ago.
  - Puzzle: why the dip?
- Still an unanswered question, and one we hope the EIC can aid in answering.



The EMC Effect

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



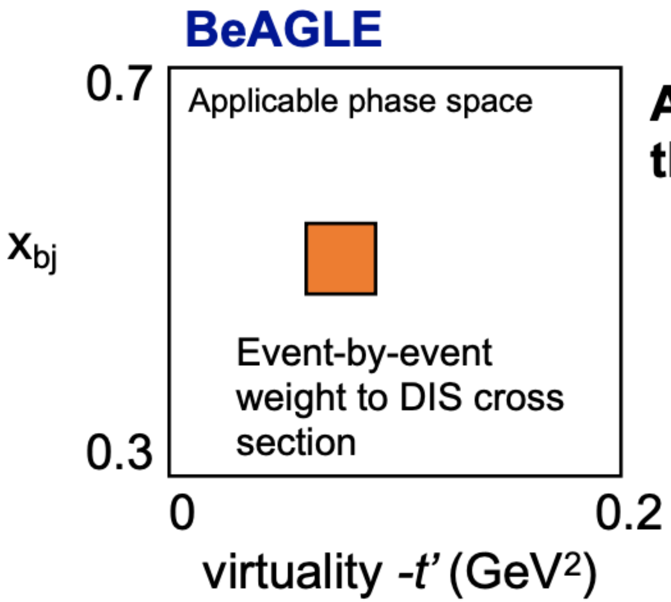


$$-t'^2 = M_N^2 - (p_d - p_p)^2$$

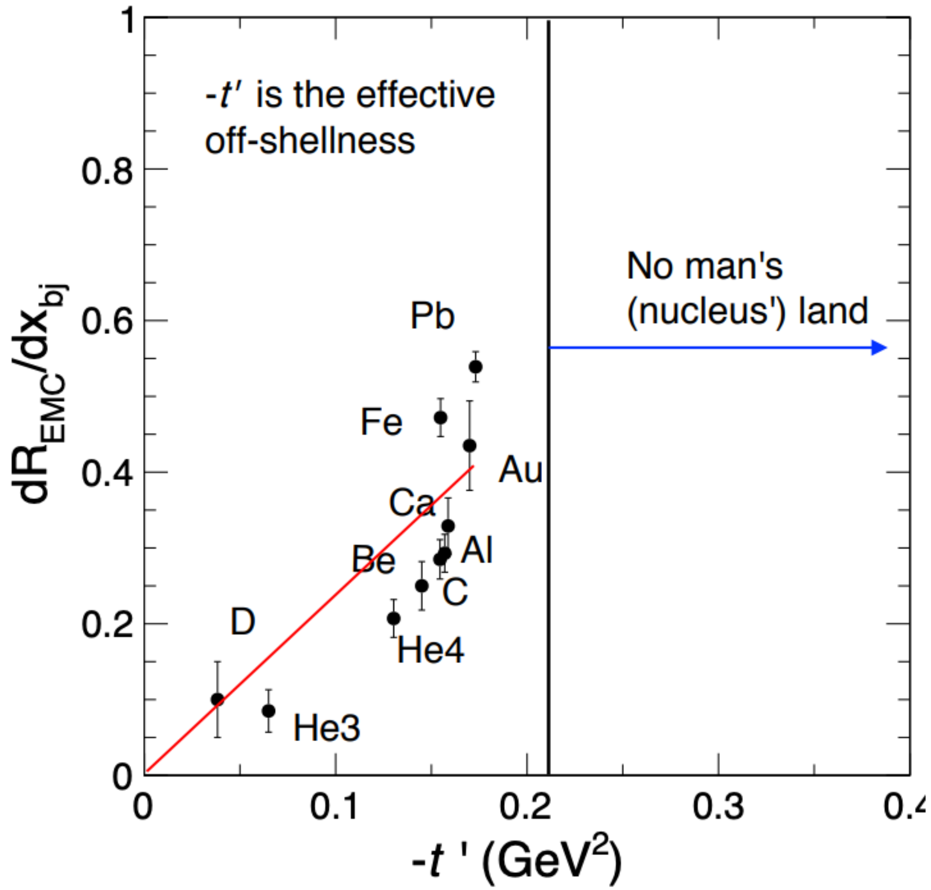
Virtuality/off-shellness in the deuteron

Question: can the EMC effect be controlled via the off-shellness without altering the colliding system?
Our goal: establish experimental prospects to see if we will be sensitive enough to study this!

The EMC Effect



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)

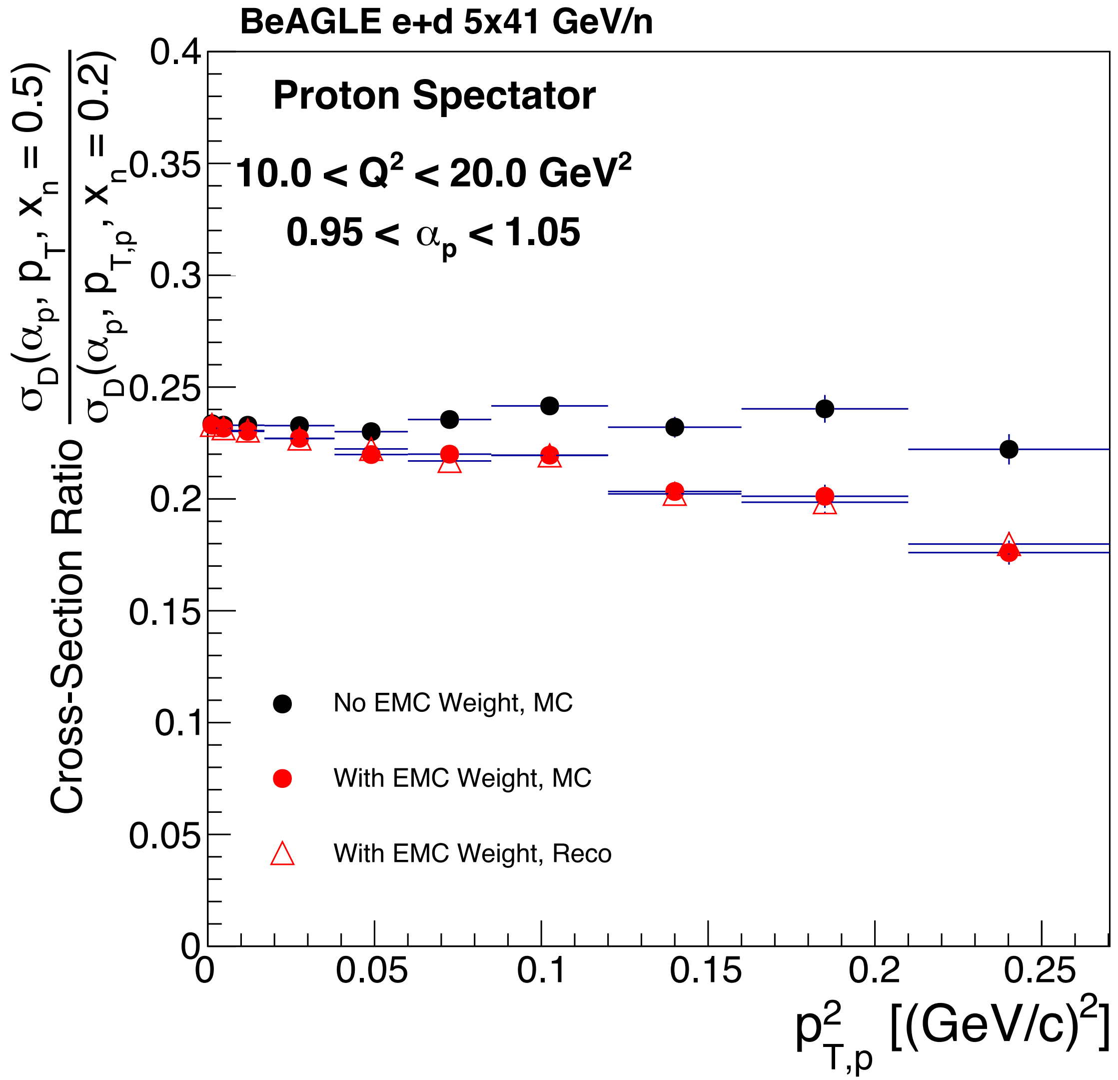
Minimal parametrization (linear)

Linear offshell dependence on the EMC effect.
(Frankfurt, Strikman 80', Weiss)

The EMC Effect @ the EIC

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

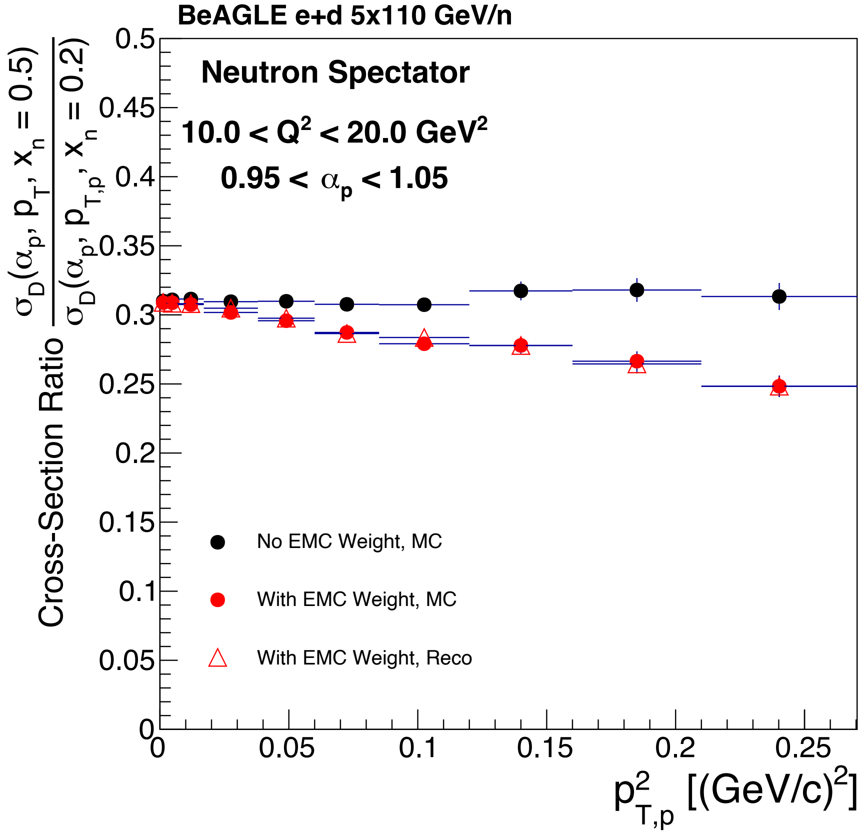
- <u>Approach:</u>
  - Measure deuteron reduced cross-section σ_D, with and without the off-shell effects included.
    - No FSI included.
  - Ratio of σ_D **inside and outside the EMC region** (e.g. x ~ 0.5 and x ~ 0.2)
  - Establish required integrated luminosity.
    - **Challenging measurement →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

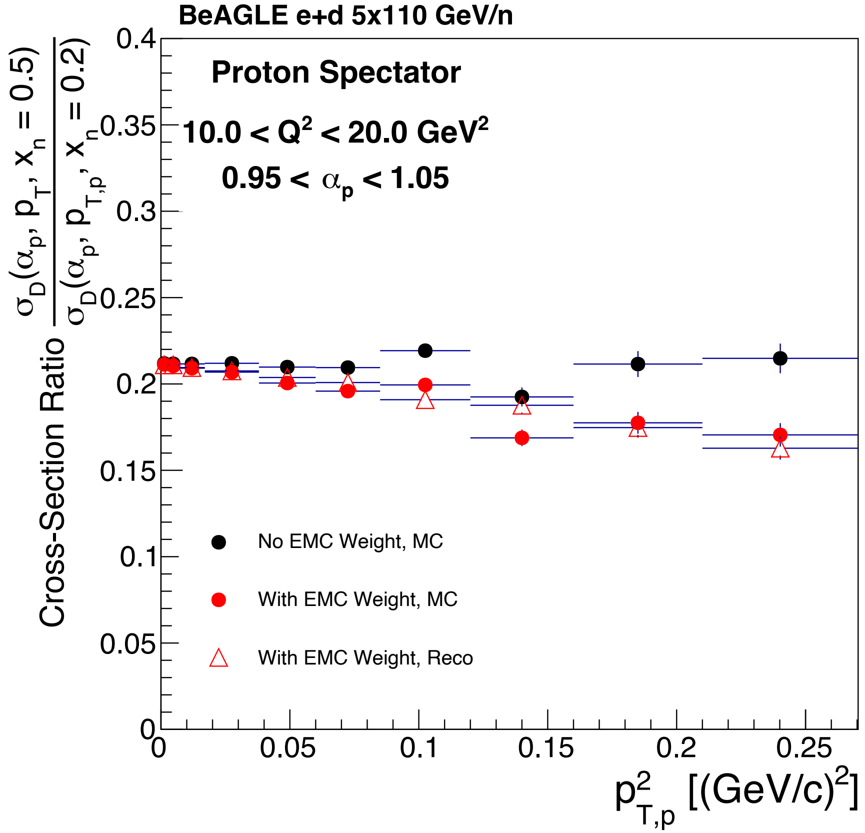


The EMC Effect @ the EIC

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

- EIC versatility → different beam energy configurations!





- 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?