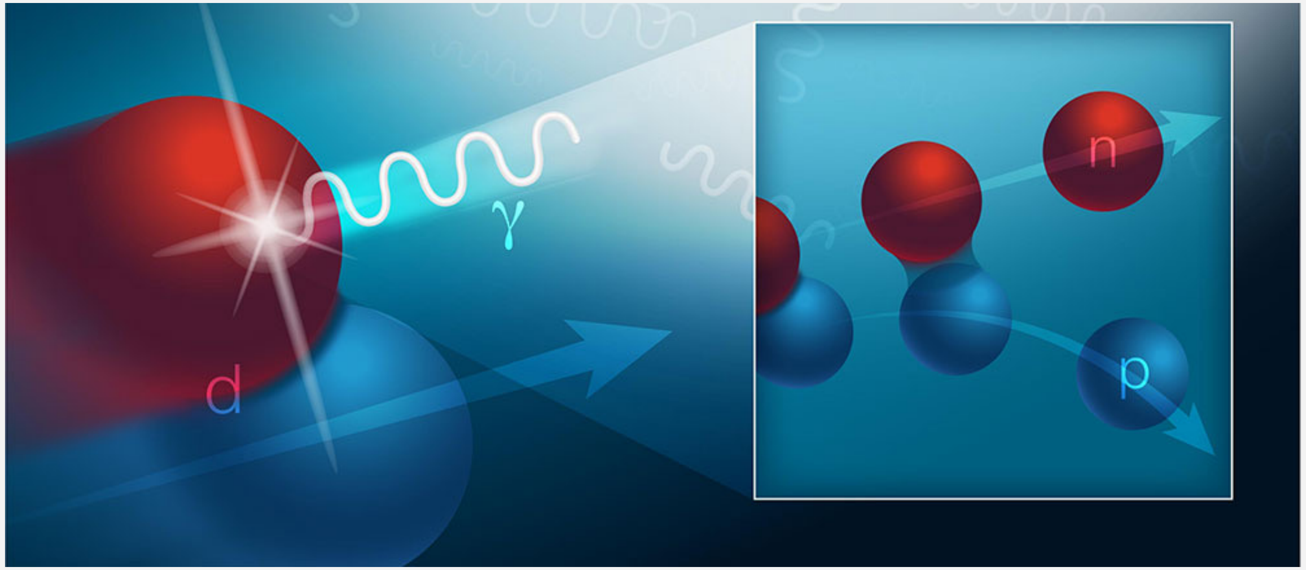
Tagged nucleon at the EIC

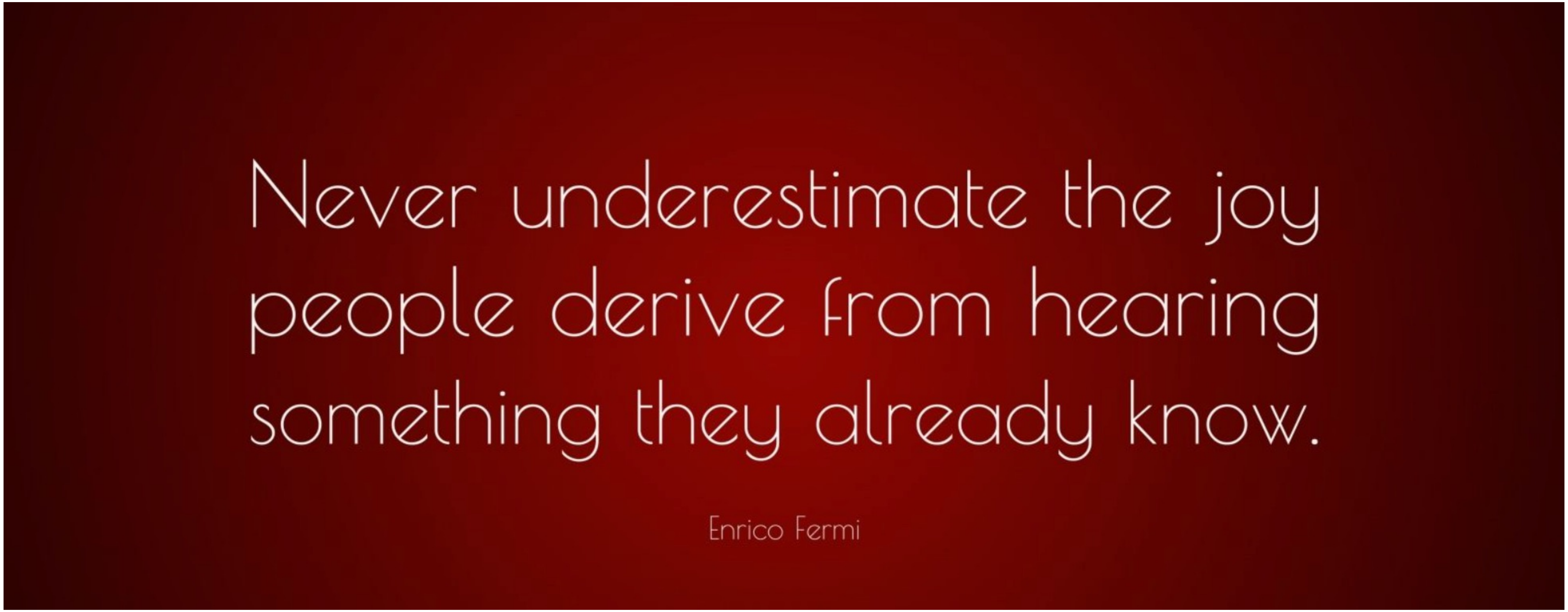


(Image made by BNL on d+Au ultra-peripheral collisions with neutron tagging)

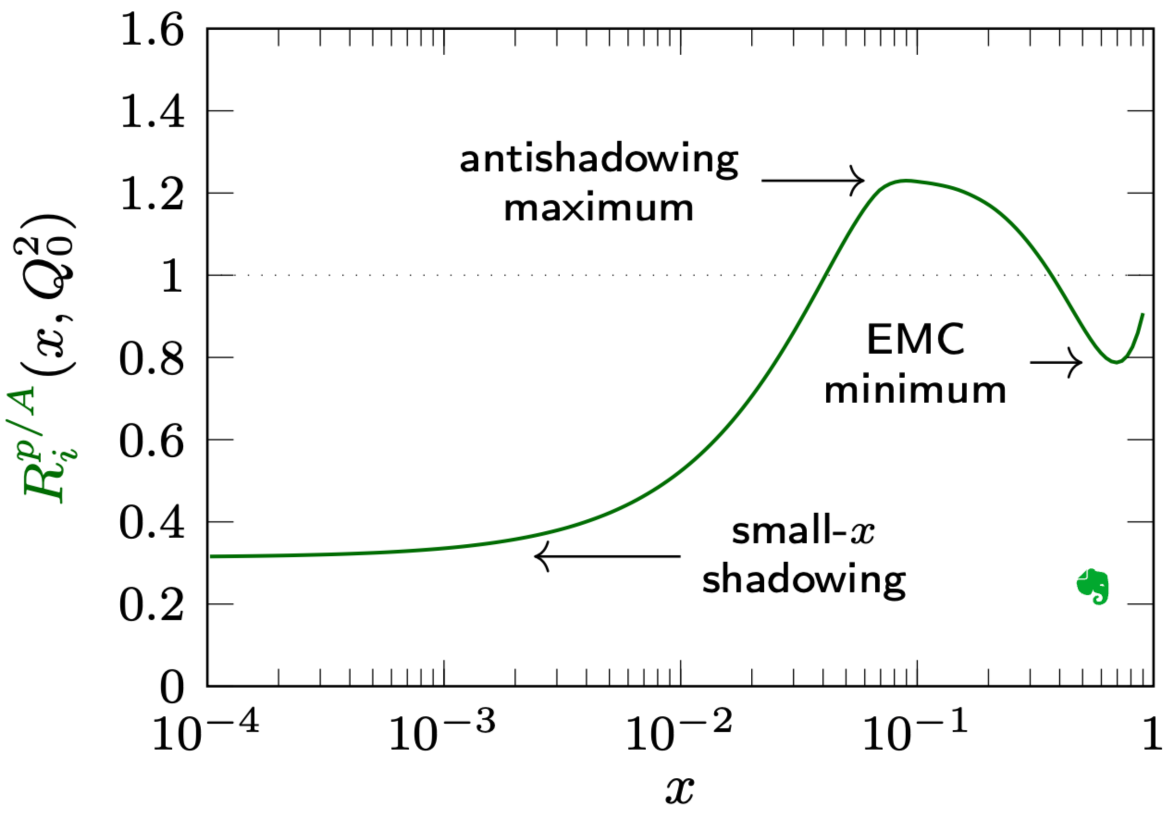
Kong Tu, BNL*

*In collaboration with A. Jentsch, C. Weiss, and others.

Last talk of a 5-day workshop…



Motivation



This workshop focus on the EMC effect/region.

In this talk, I will provide a few studies that range from high-x to low-x physics with a totally different machine and capability – the **Electron-Ion Collider (EIC)**

Nuclear effects span over a wide range of phase space

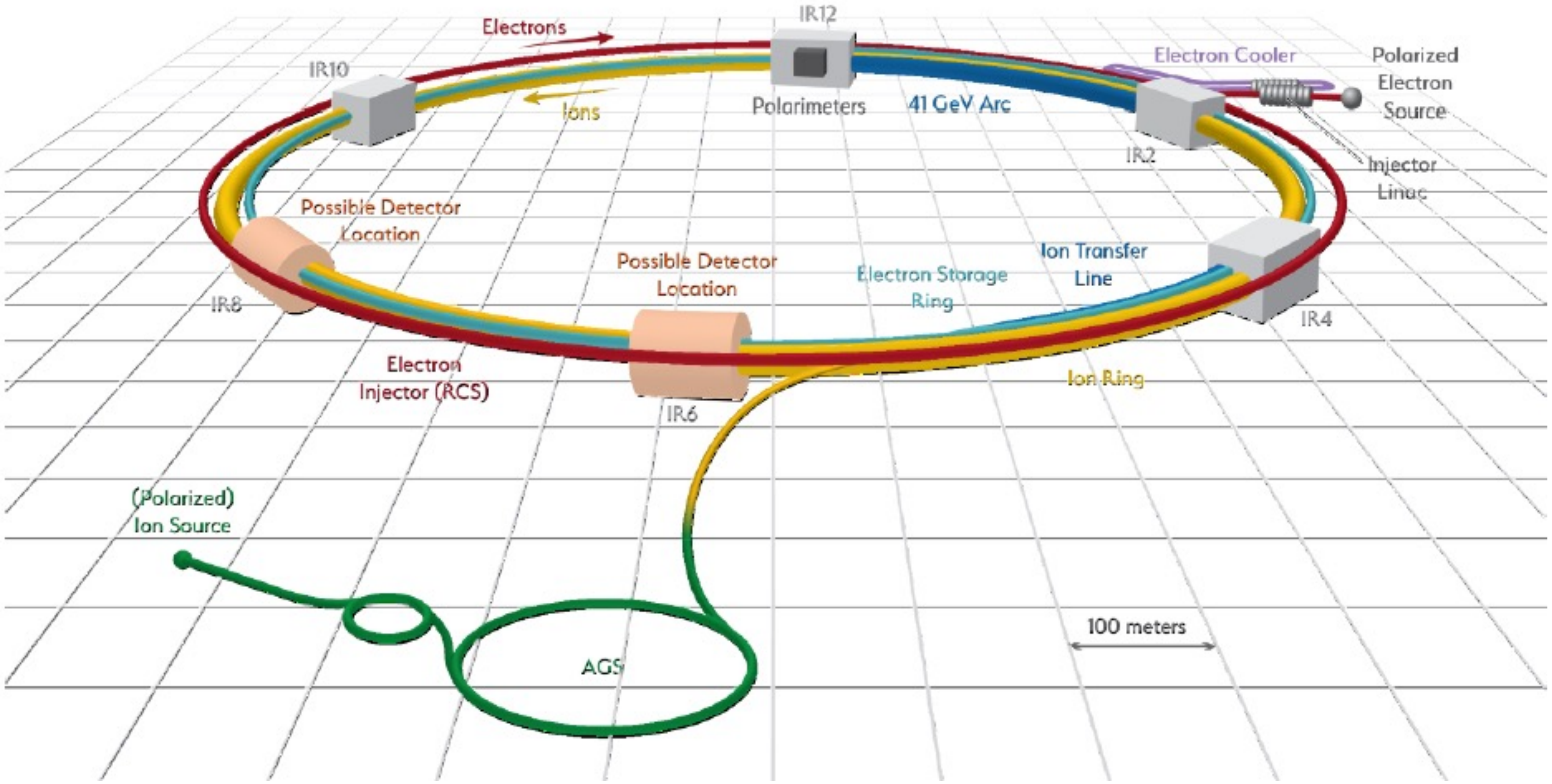
Climbing the `mountain` from a different route

- Short-distance dynamics and tagged DIS has been and will be extensively studied at Jefferson lab.

Questions:
- Will the EMC be solved by then?
- How to further understand the origin of nuclear effects, from light to heavy nuclei, from high to low-x?

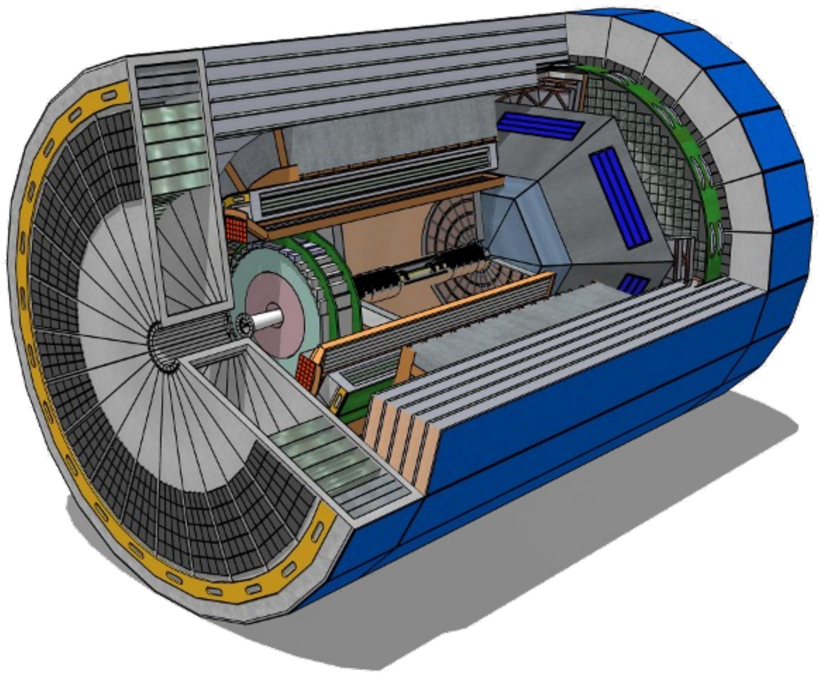
- What would be left for the EIC?

Electron-Ion Collider



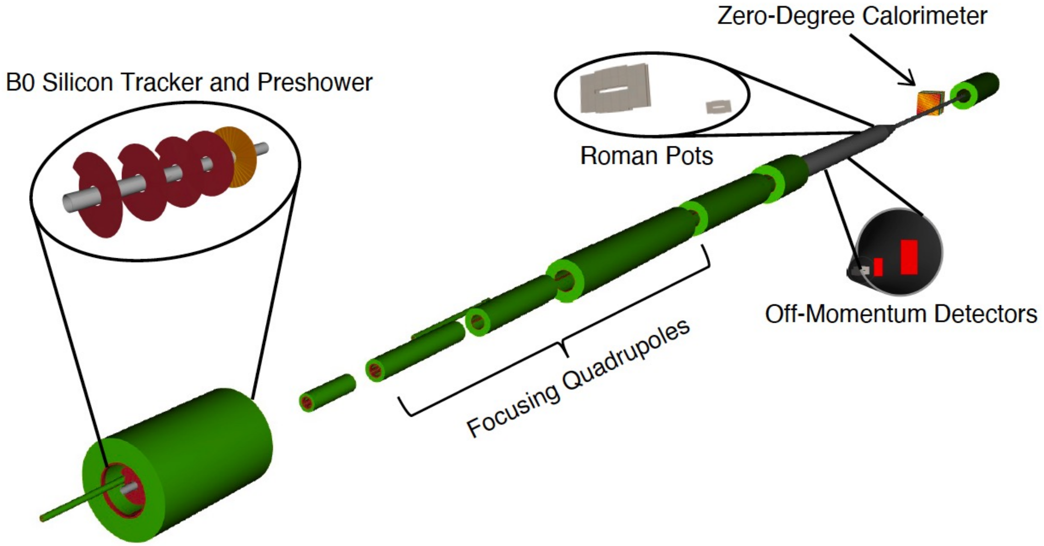
EIC can deliver deuterium to Uranium, p/d(?)/He3 polarization, wide acceptances, and energy up to 140 GeV

Electron-Ion Collider and ePIC



EIC - ePIC

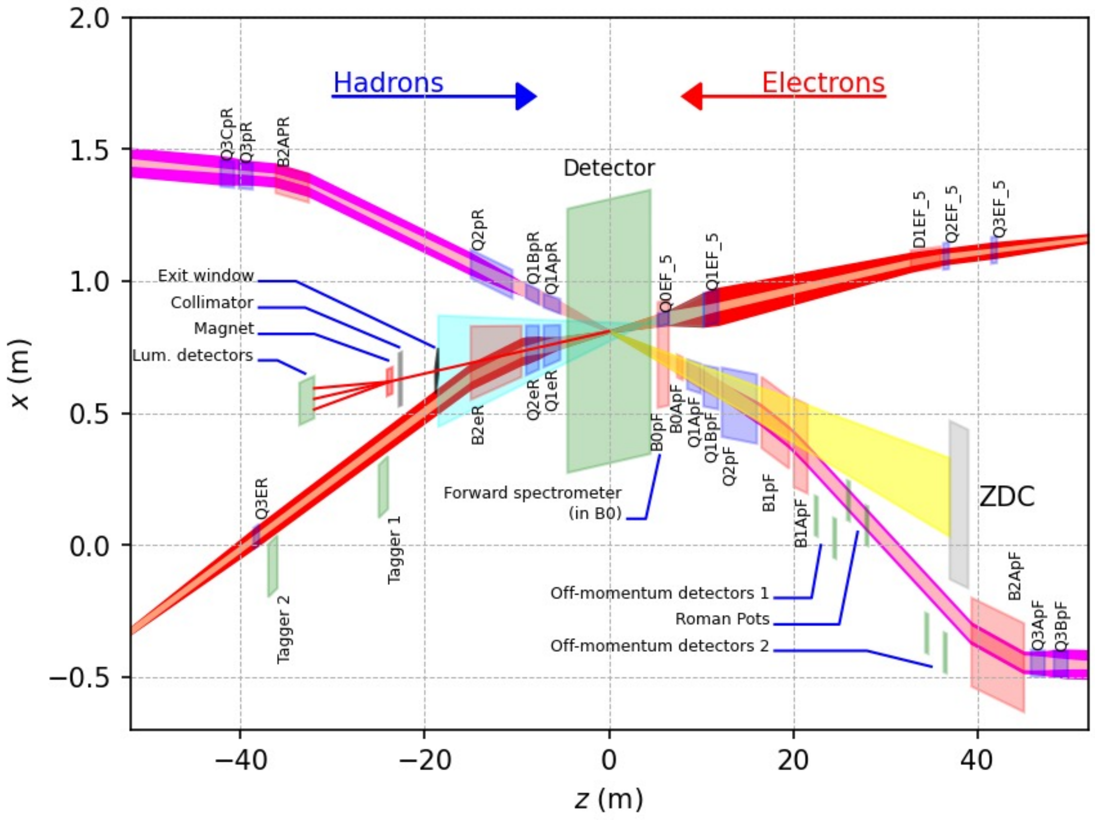
Far-forward detectors



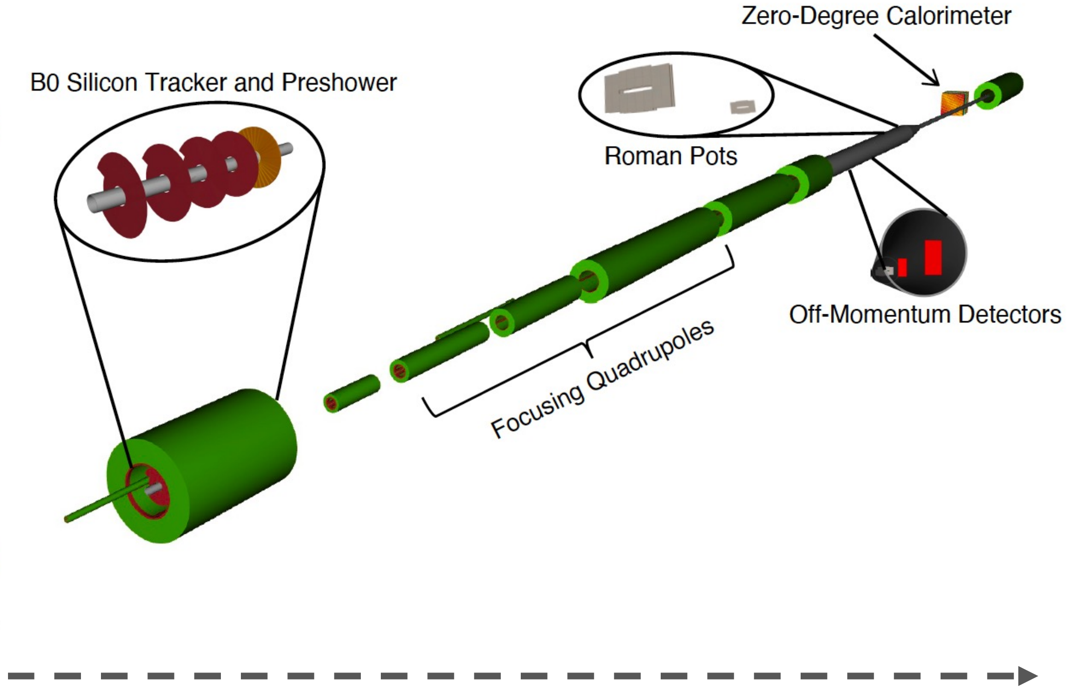
~ 38 m to ZDC

EIC can deliver deuterium to Uranium, p/d(?)/He3 polarization, wide acceptances, and energy up to 140 GeV

Electron-Ion Collider and ePIC

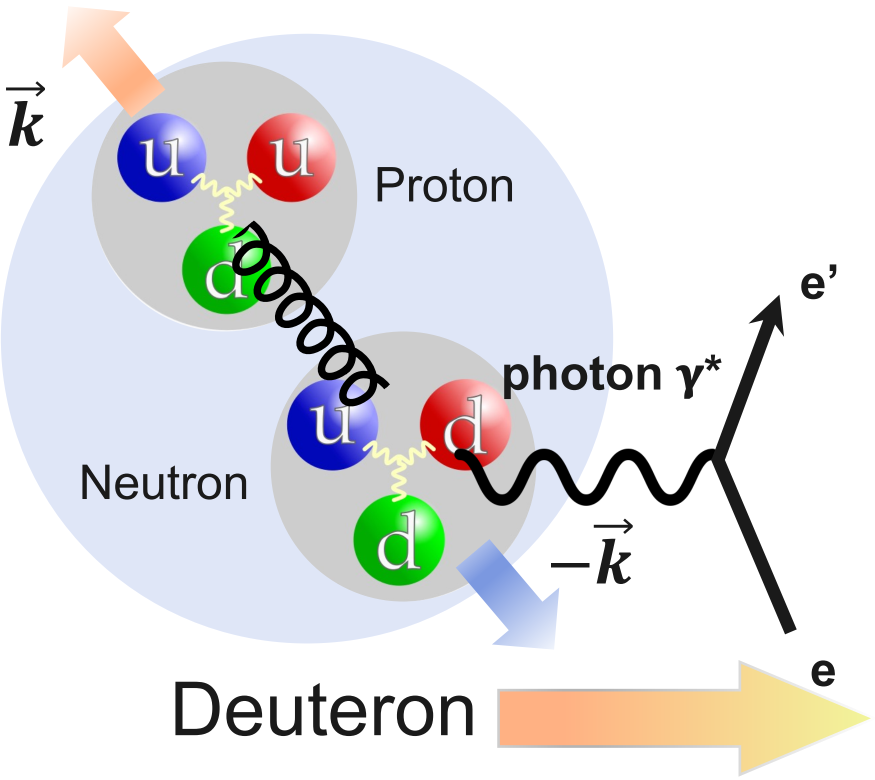


Far-forward detectors



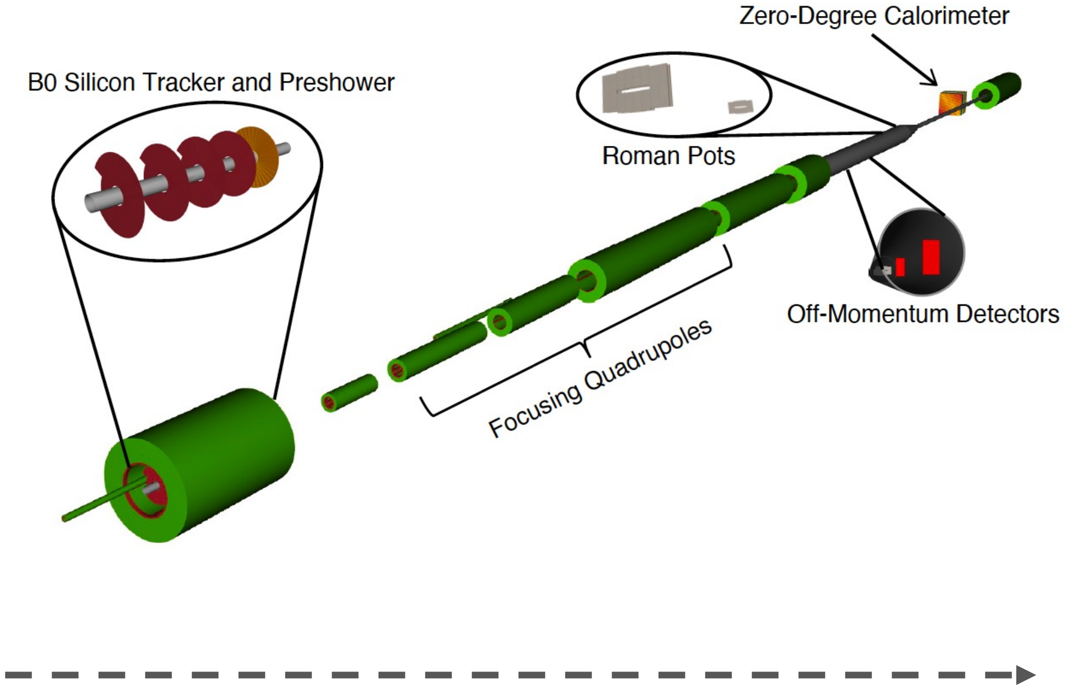
EIC can deliver deuterium to Uranium, p/d(?)/He3 polarization, wide acceptances, and energy up to 140 GeV

Free neutron (nucleon) structures from tagging



(110 GeV/c beam momentum)

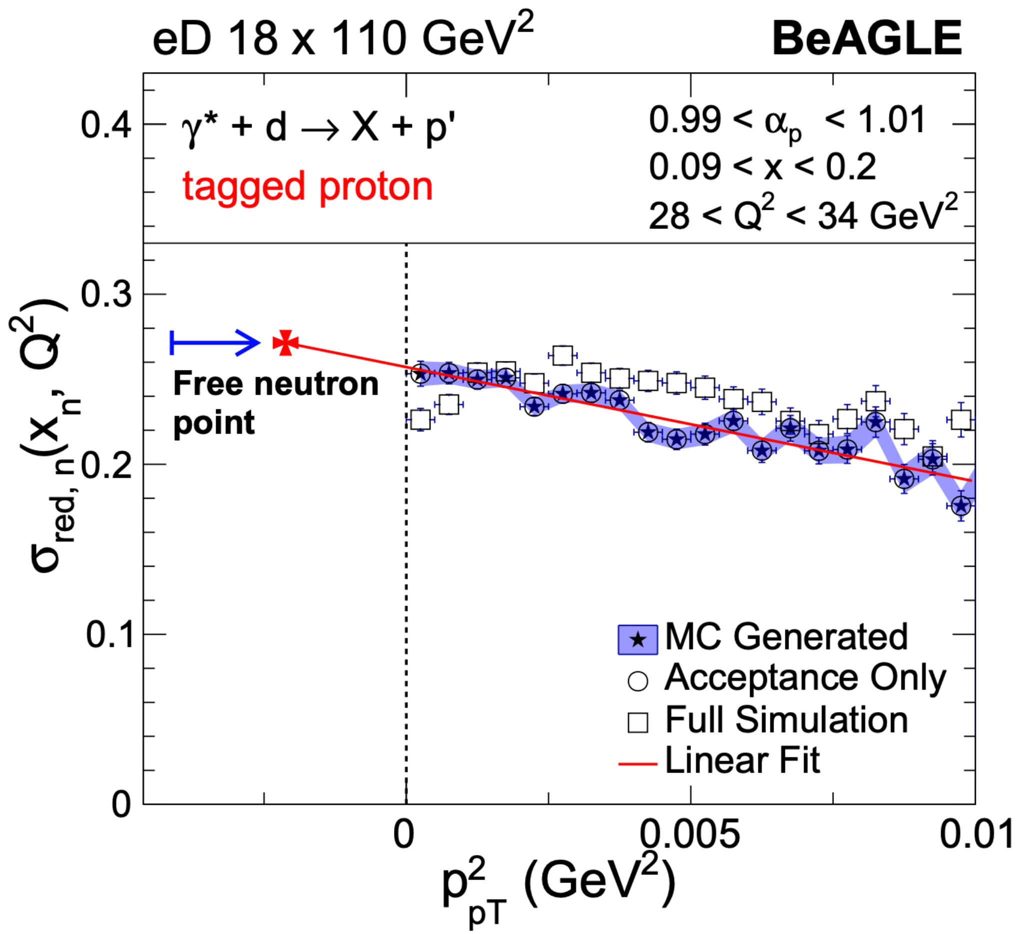
Far-forward detectors



~ 38 m to ZDC

Easily reach zero momentum in the ion rest frame at the EIC via tagging.

Tagged protons to probe free neutrons

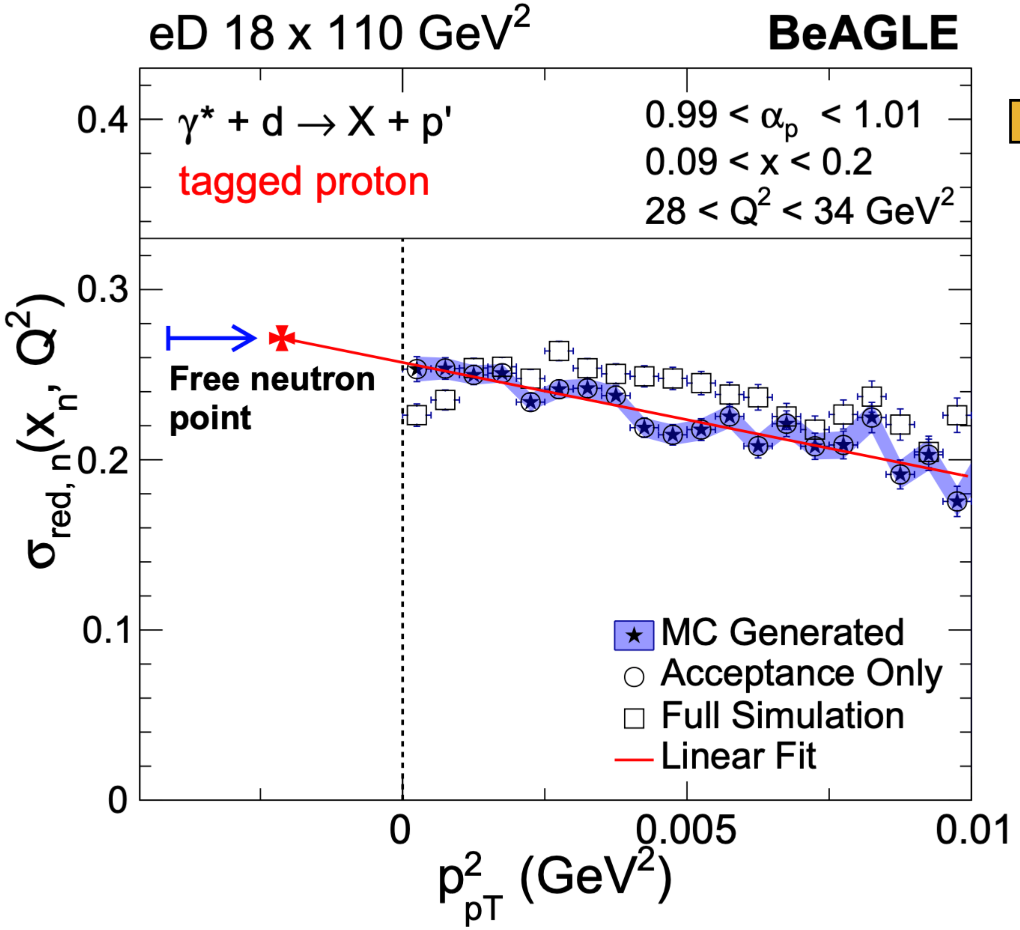


Detector	Used for	θ accep. [mrad]	ζ accep.
B0 tracker	p	5.5–20.0	N/A
Off-Momentum	p	0.0–5.0	0.45–0.65
Roman Pots	p	0.0–5.0	0.6–0.95*
Zero-Degree Calorim.	n	0.0–4.0	N/A

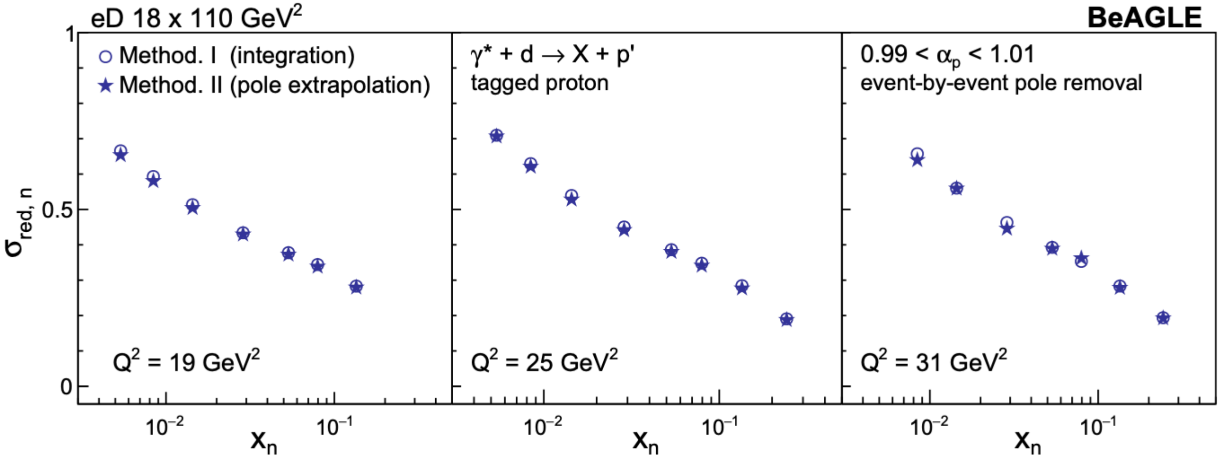
BeAGLE - general purpose eA MC, *Phys.Rev.D* 106 (2022) 1, 012007

Jentsch, Tu, Weiss, Phys. Rev. C 104 (2021) 6, 065205

Tagged protons to probe free neutrons



Every x_n bin will need an extrapolation

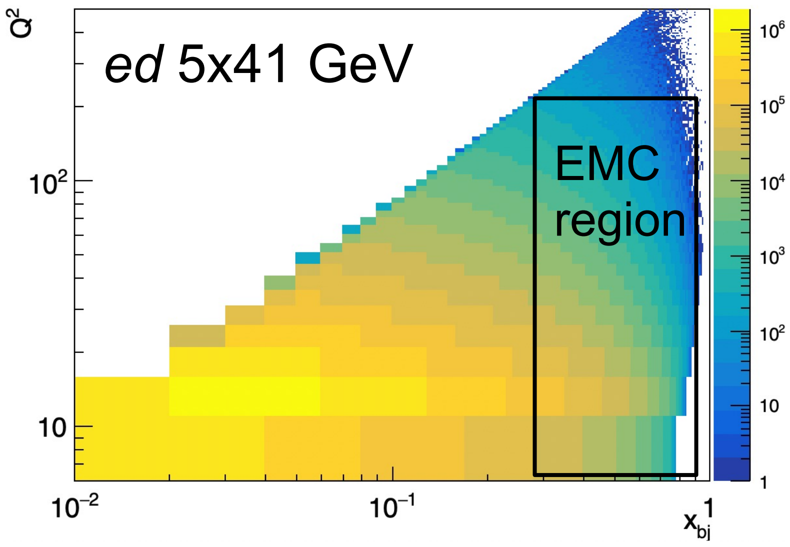


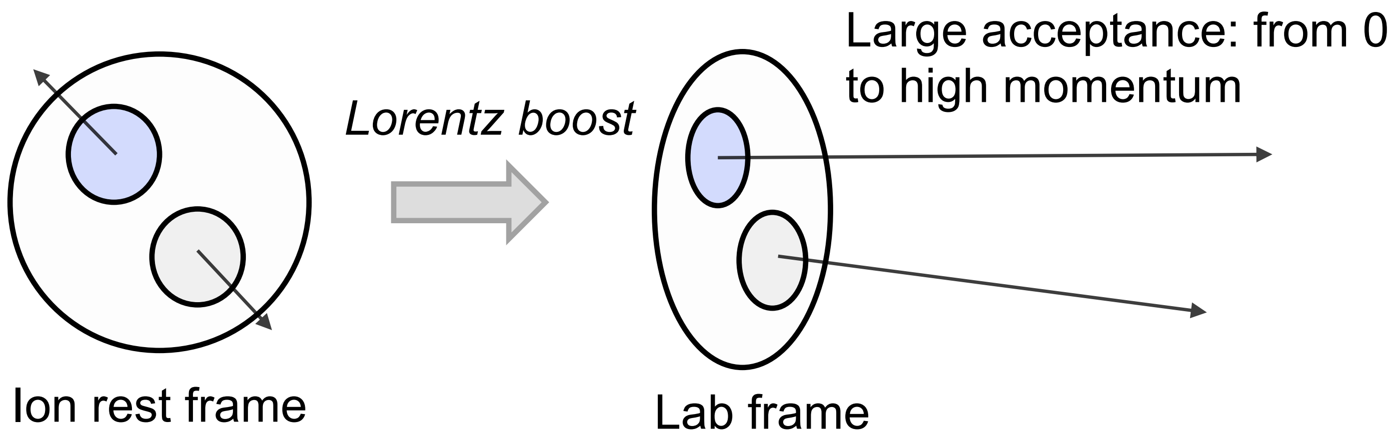
Model independent extraction of free neutron structures

Jentsch, Tu, Weiss, Phys. Rev. C 104 (2021) 6, 065205

Free vs Bound nucleons

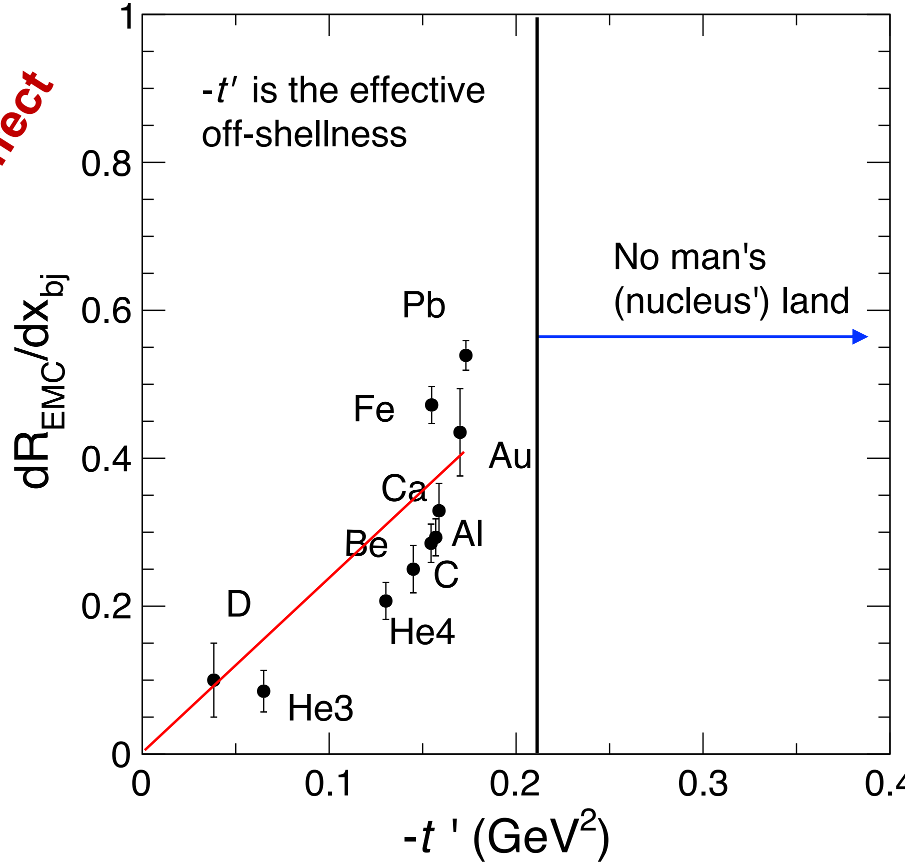
- **Advantages** of studying the EMC effect at the EIC:
  - Lepton side - Wide kinematic range in Q^2 (e.g., test high Q^2 , higher twists).
  - Deuteron side - Lorentz boost provides wide range in spectator kinematics, in terms of spectator p_T and light-cone momentum fraction α .
    - ***Driving virtuality from both directions.***





Tagged EMC effect

EMC effect



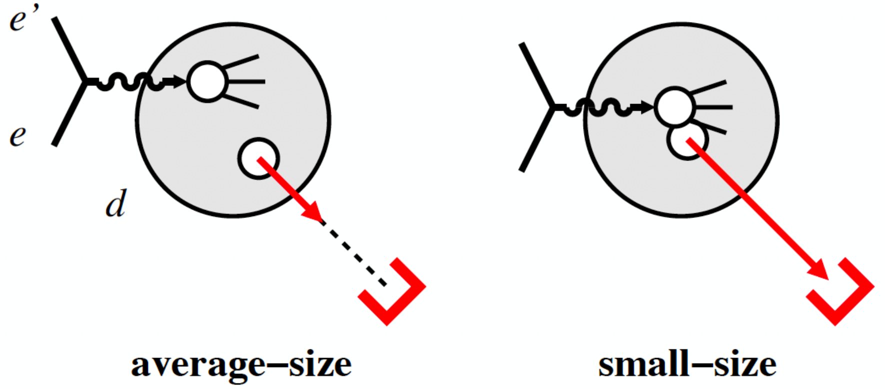
virtuality

Ciofi et al. https://arxiv.org/abs/0706.2937

(see C. Weiss's talk)

Low off-shellness

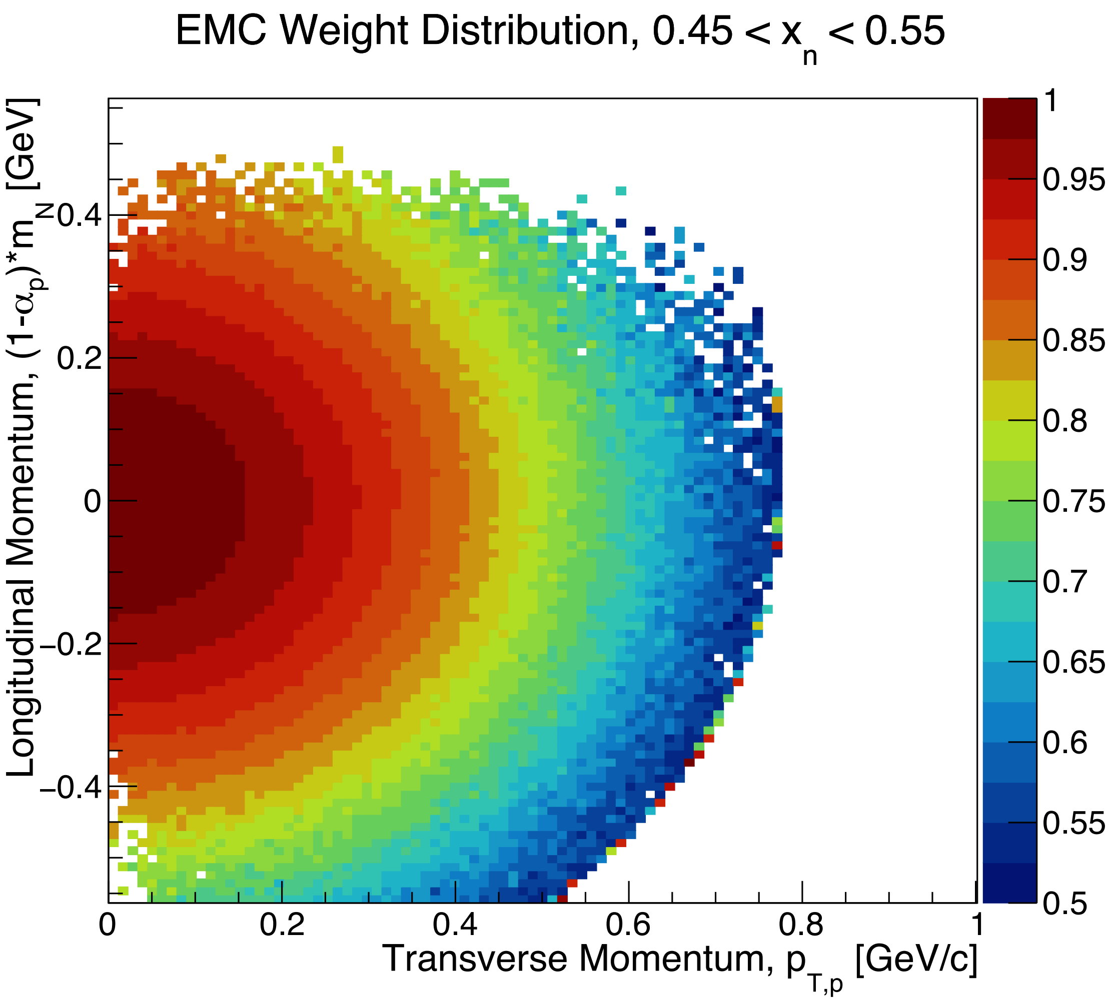
High off-shellness



Tagged DIS Process: e + d → e' + X + p' or n'

$-t^2 = M_N^2 - (p_d - p_p)^2$ virtuality/off-shellness in deuteron

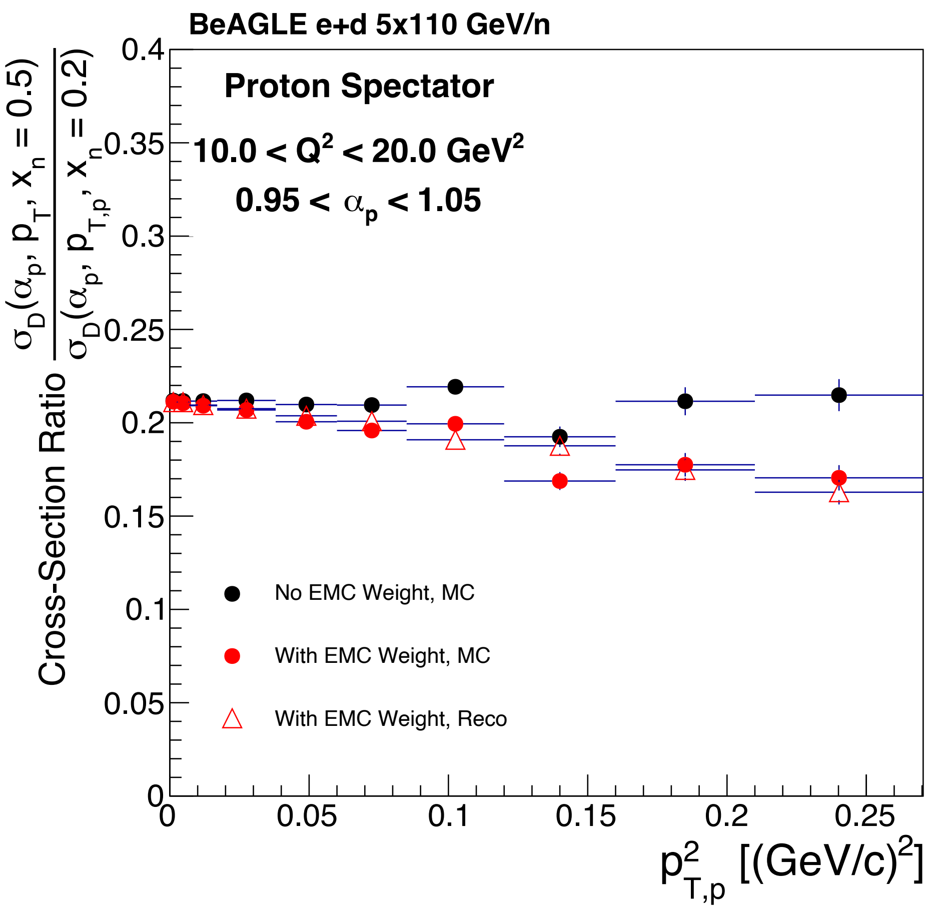
Two ways to drive virtuality



One experimental test is to see if the EMC effect (modification) is the same:

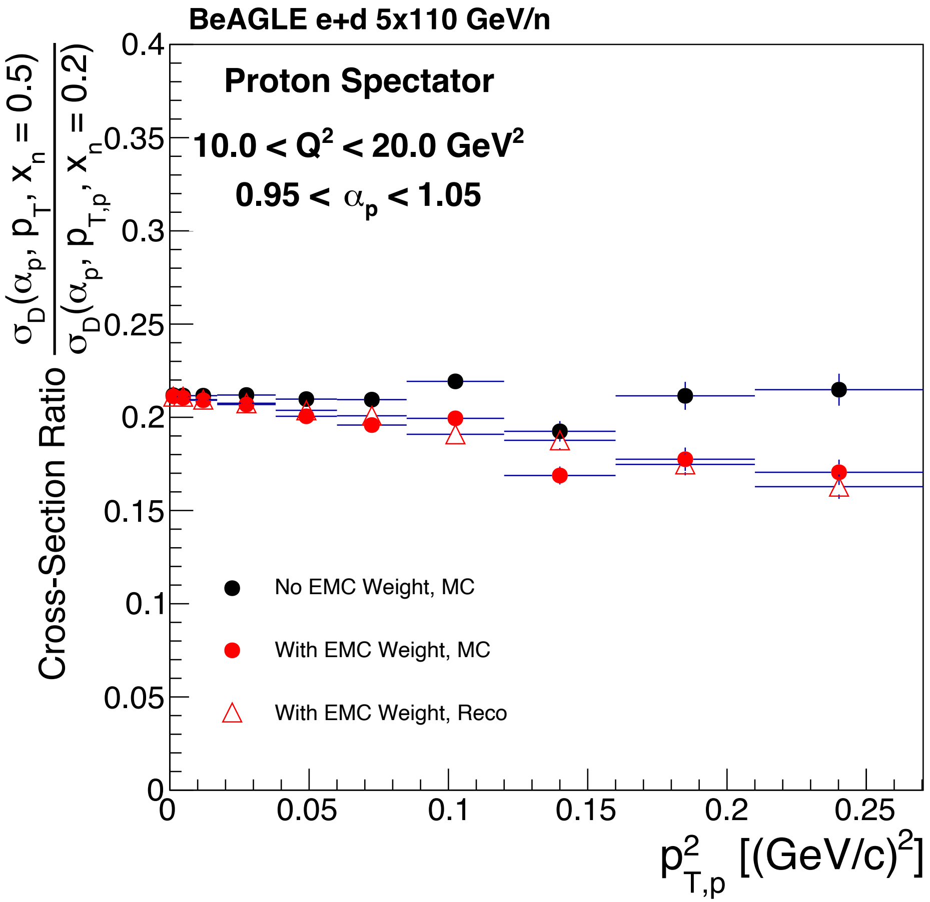
(1-alpha)*m_N ~ p_T ~ @ constant contour

1- Reaching high virtuality from p_T



- Reduced cross section ratio between $x_{bj} = 0.2$ and $x_{bj} = 0.5$
- Detector effects are very small, driven by beam effects
- Luminosity requirement ~ 10 fb^{-1} ,which is challenging

1- Reaching high virtuality from p_T

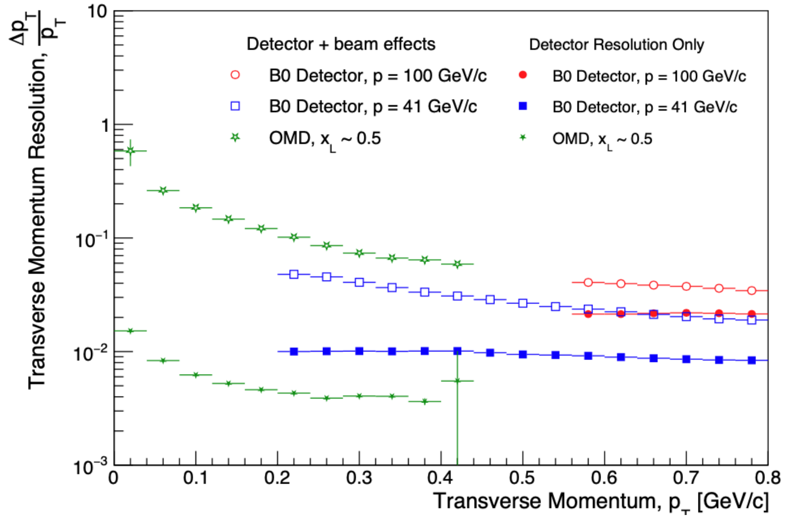


At the RECO level:

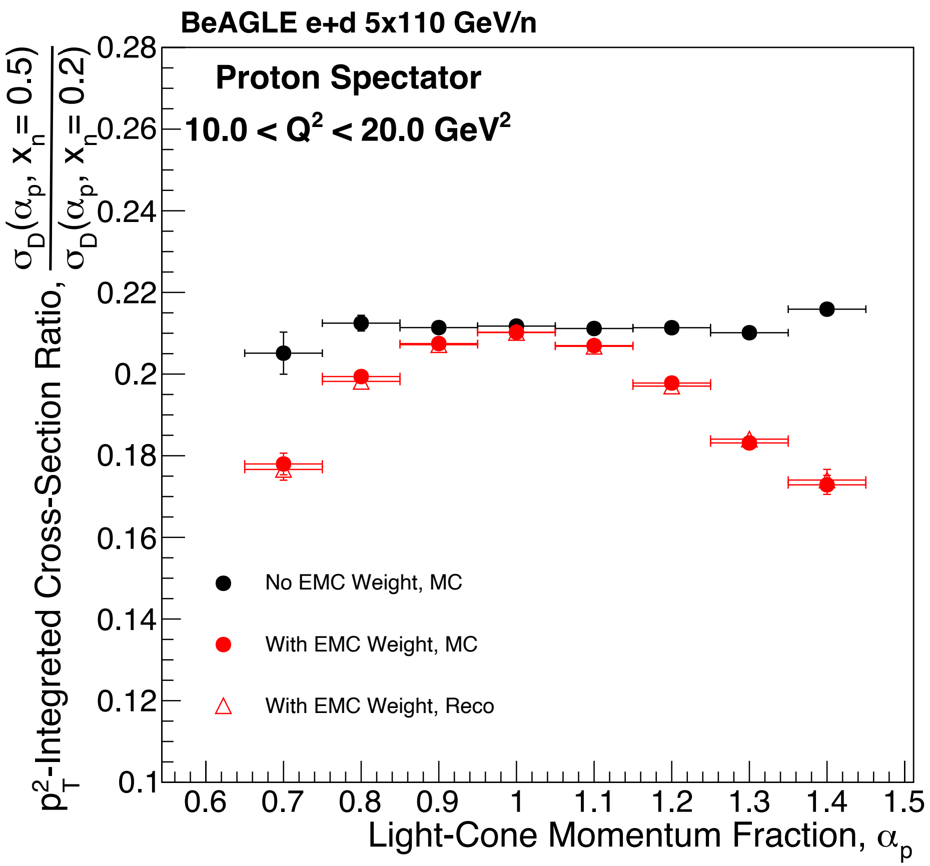
- Very well reconstructed with good acceptance and momentum resolution.
- $p_T^2 < \sim 0.04$ GeV² (Off Momentum Detector)
- $p_T^2 > \sim 0.04$ GeV² (**B0 tracker**) dominated

p_T resolution ~ 25 MeV/c

Dominated by beam effects not detectors!



2 - Reaching high virtuality from alpha



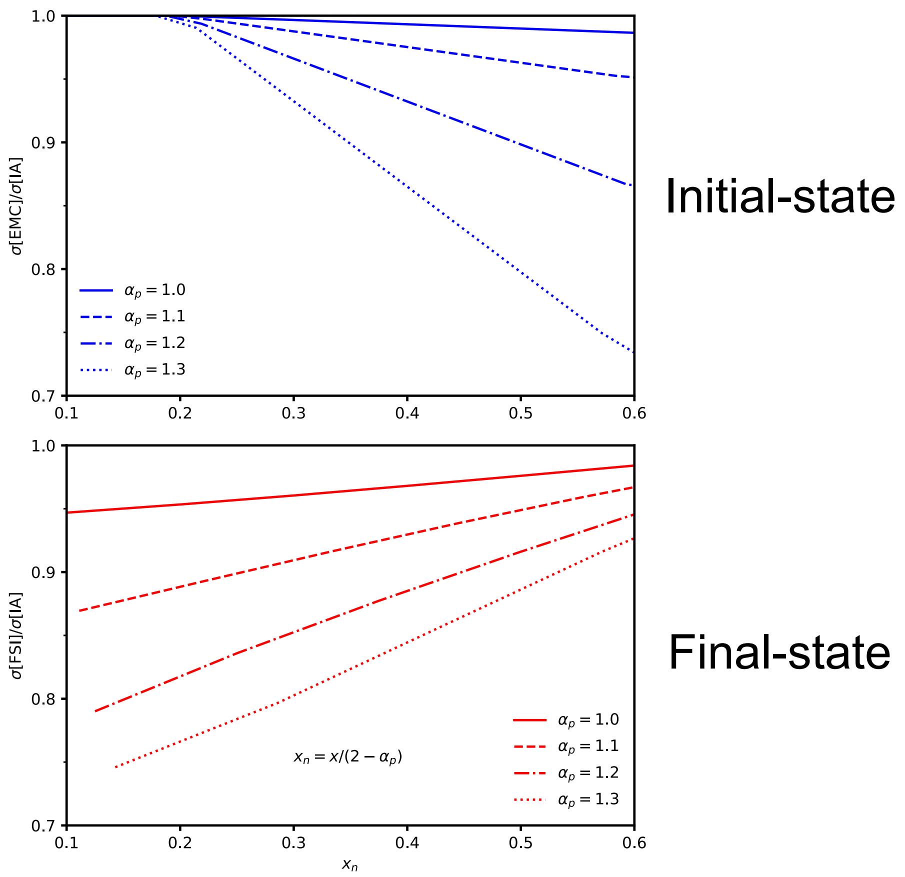
- Reduced cross section ratio between $x_{bj} = 0.2$ and $x_{bj} = 0.5$
- Detector effects are very small, driven by beam effects
- Luminosity requirement ~ 10 fb^{-1} ,which is challenging

Where's the best place to look?

Initial-state modification vs **Final-state Interaction**
(see C. Weiss' talk)

Figure: p_T integrated cross section up to 0.4 GeV.

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

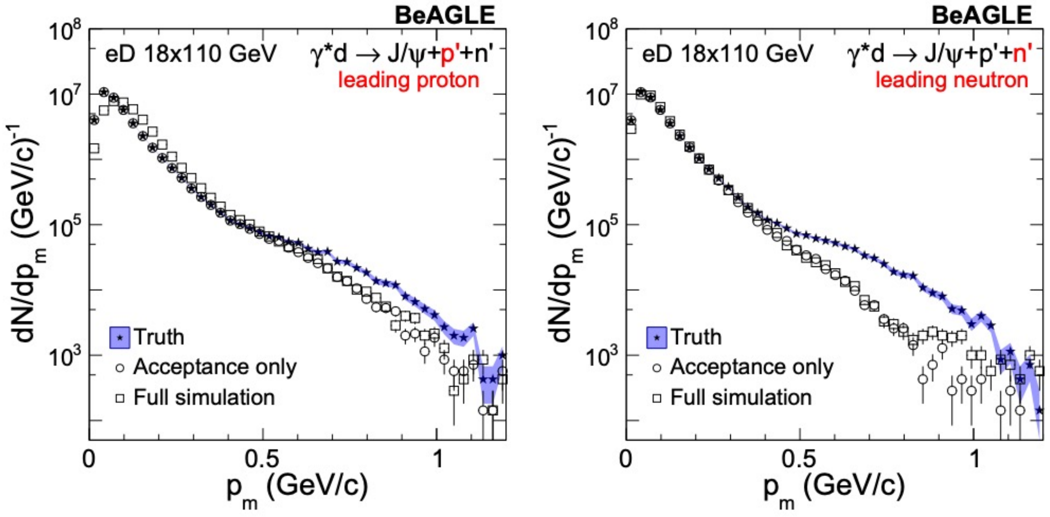


High x & alpha region has the best shot to separate EMC and FSI!

Tagging at low-x

Exclusive observables, e.g., Vector Meson, electroproduction off deuteron with spectator tagging.

- Shadowing effect (M. Strikman, V. Guzey, C. Weiss….)
- Incoherent production – sensitive to fluctuations. (H. Mäntysaari, B. Schenke)
- Gluonic radius of bound nucleon (ZT, A. Jentsch, M. Baker et al)
- Tagging in heavy nuclei (eA program in ePIC)



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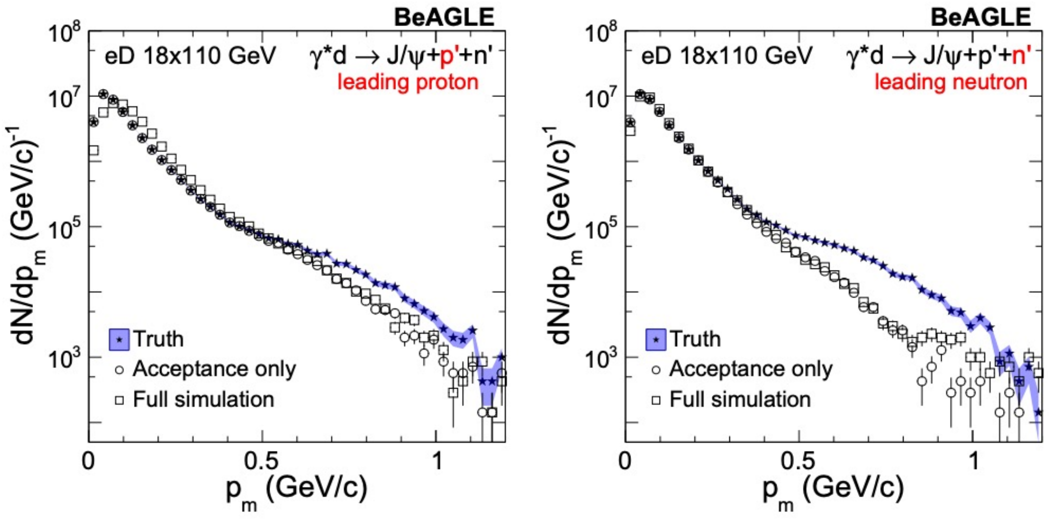


Ultra-Peripheral Collisions can be a complementary probe

Incoherent VM production

(from B. Schenke's talk)

Incoherent diffraction:

Initial state: $|i\rangle$; Final state: $|f\rangle$; Amplitude for diffractive scattering: $\mathscr{A}$

Squared transition amplitude, which enters in the cross section:

H. I. Miettinen and J. Pumplin, Phys. Rev. D18 (1978) 1696

$$\sum_{f\neq i} |\langle f|\mathscr{A}|i\rangle|^2 = \sum_f \langle i|\mathscr{A}^*|f\rangle\langle f|\mathscr{A}|i\rangle - \langle i|\mathscr{A}|i\rangle\langle i|\mathscr{A}^*|i\rangle$$
$$= \langle i|\mathscr{A}^*\mathscr{A}|i\rangle - |\langle i|\mathscr{A}|i\rangle|^2$$

Sum over final states includes all possible states for the final state target

Average over all possible initial states → cross section

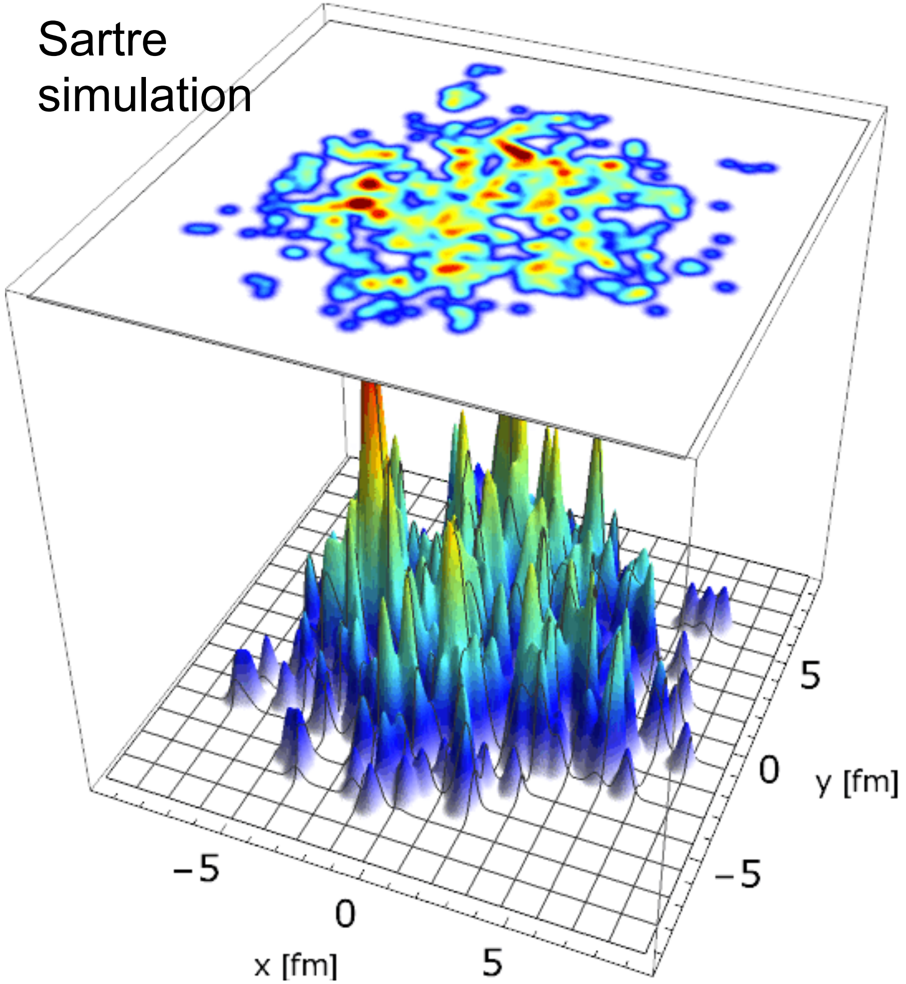
$$\frac{d\sigma^{\gamma^* A\to VA}}{dt} = \frac{1}{16\pi}\left(\left\langle\left|\mathscr{A}^{\gamma^* A\to VA}\right|^2\right\rangle - \left|\left\langle\mathscr{A}^{\gamma^* A\to VA}\right\rangle\right|^2\right)$$

4

Björn Schenke, BNL

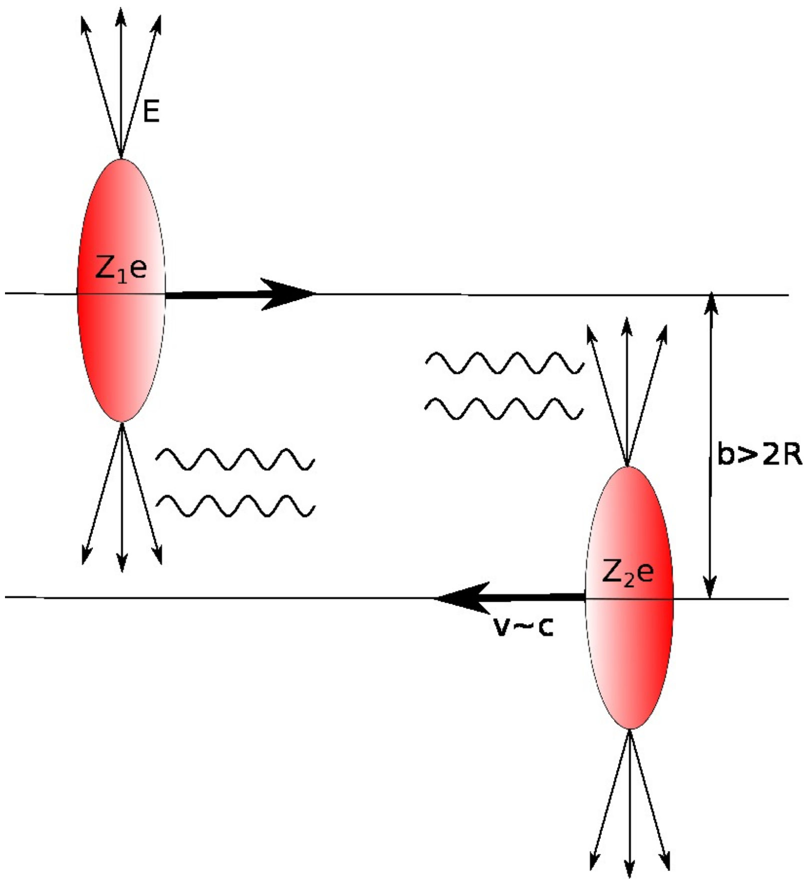
(known as the Good-Walker picture)

Sartre simulation



[made by A. Kumar (IIT, Delhi)]

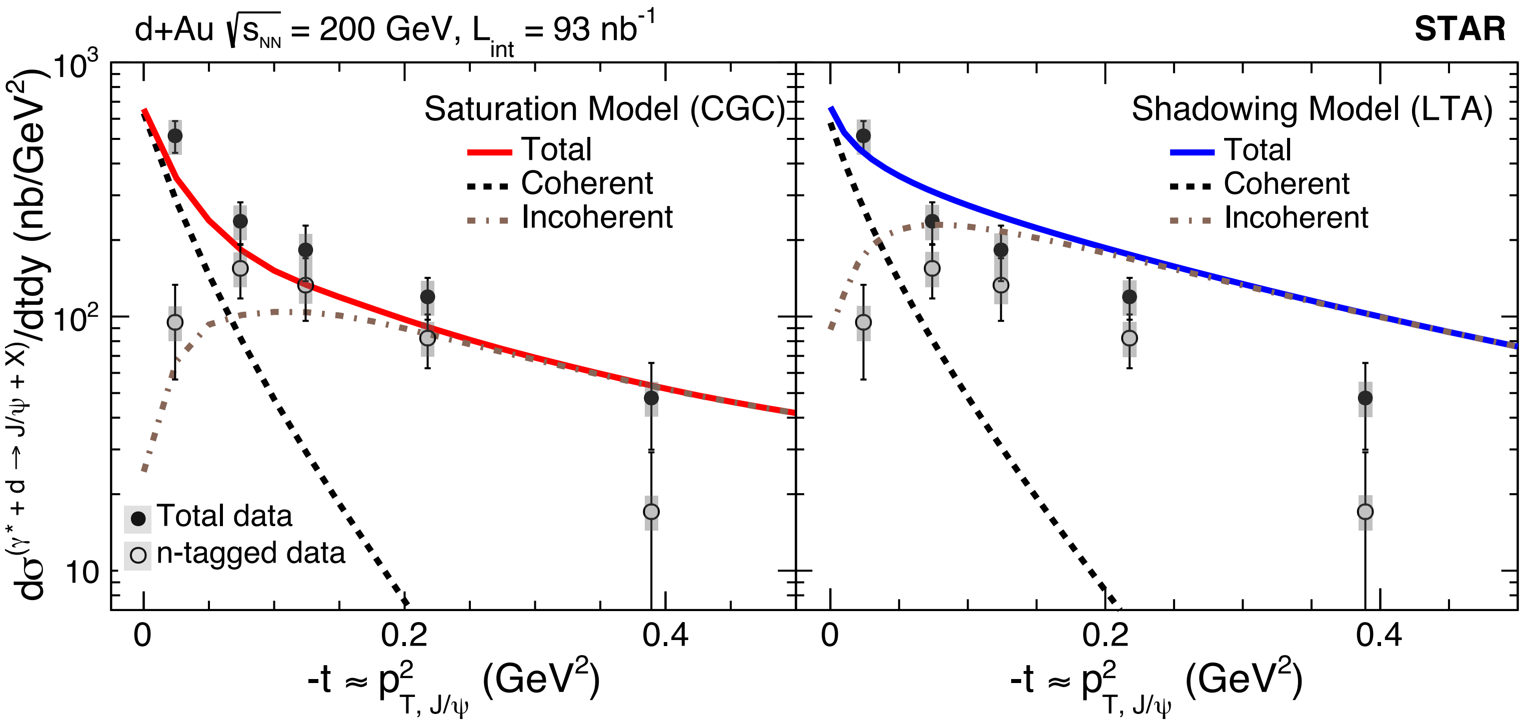
Ultra-Peripheral Collisions

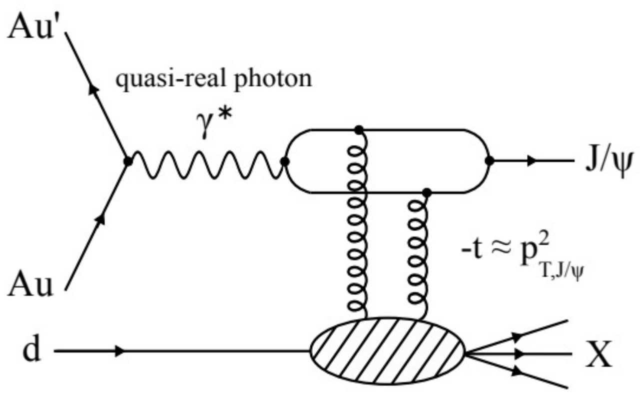


Collisions that don't "collide":

- Strong EM field ~ quasi-real photons;
- $Z\alpha_{EM} \sim \mathcal{O}(1)$, overcomes the weak coupling by large photon flux;
- Impact parameter $b > 2R_A$, but cannot be controlled event-by-event;
- Photon energy is unknown, unless inferred by the final-states

Fluctuation of parton density?

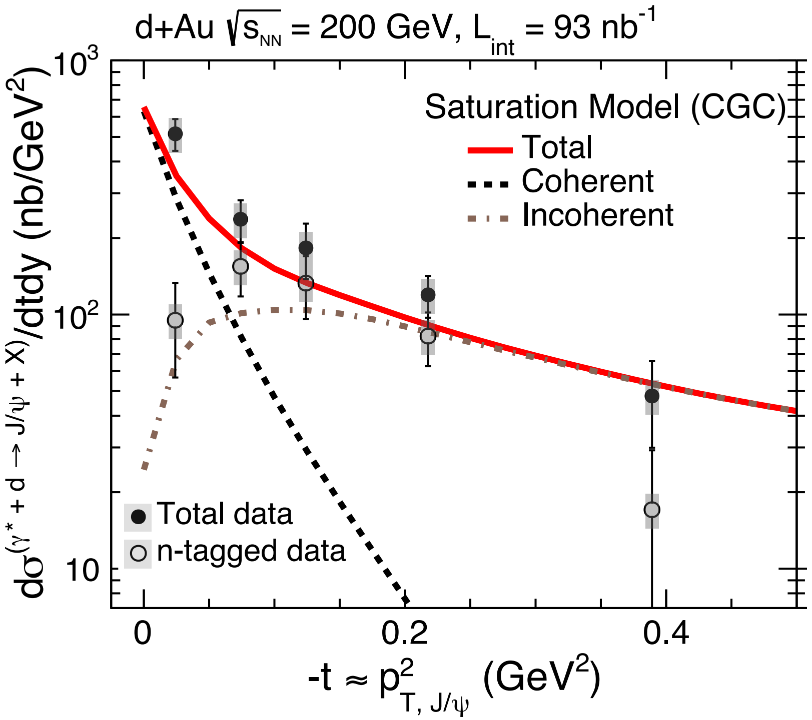


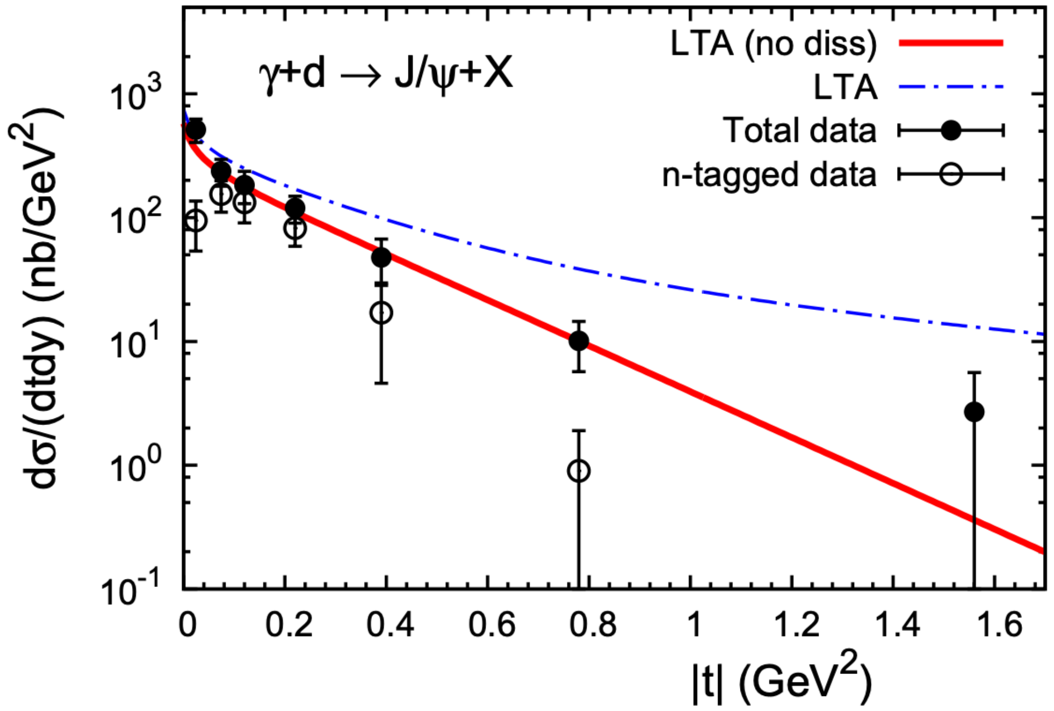


UPC d+Au data,
PRL 128 (2022) 12, 122303

First spectator tagging of deuteron in high energy experiment.

Fluctuation of parton density?



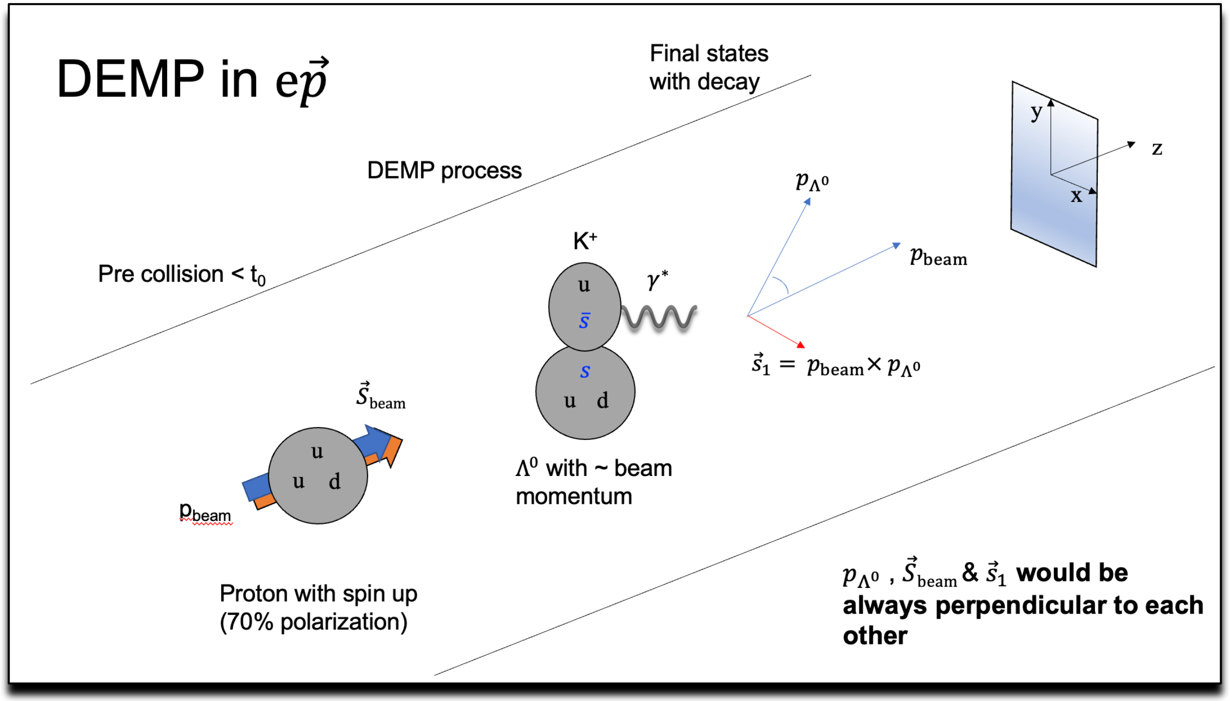


UPC d+Au data,
PRL 128 (2022) 12, 122303

Guzey et al. 2022

EIC with wide tagging capabilities can provide further insights to fluctuation.

Triple Tagging:
DEMP as a probe of spin polarization of Λ hyperon



e+p → e' + K⁺ + Λ^0 with beam polarization.

Self-analyzing weak decay of $\mathbf{\Lambda^0}$ can measure spin polarization.

$$\frac{dN}{d\cos(\theta^\star)} = 1 + \alpha P_\Lambda \cos(\theta^\star)$$

θ^* is the angle btw the proton daughter and spin axis in $\mathbf{\Lambda^0}$ rest frame

Triple Tagging:
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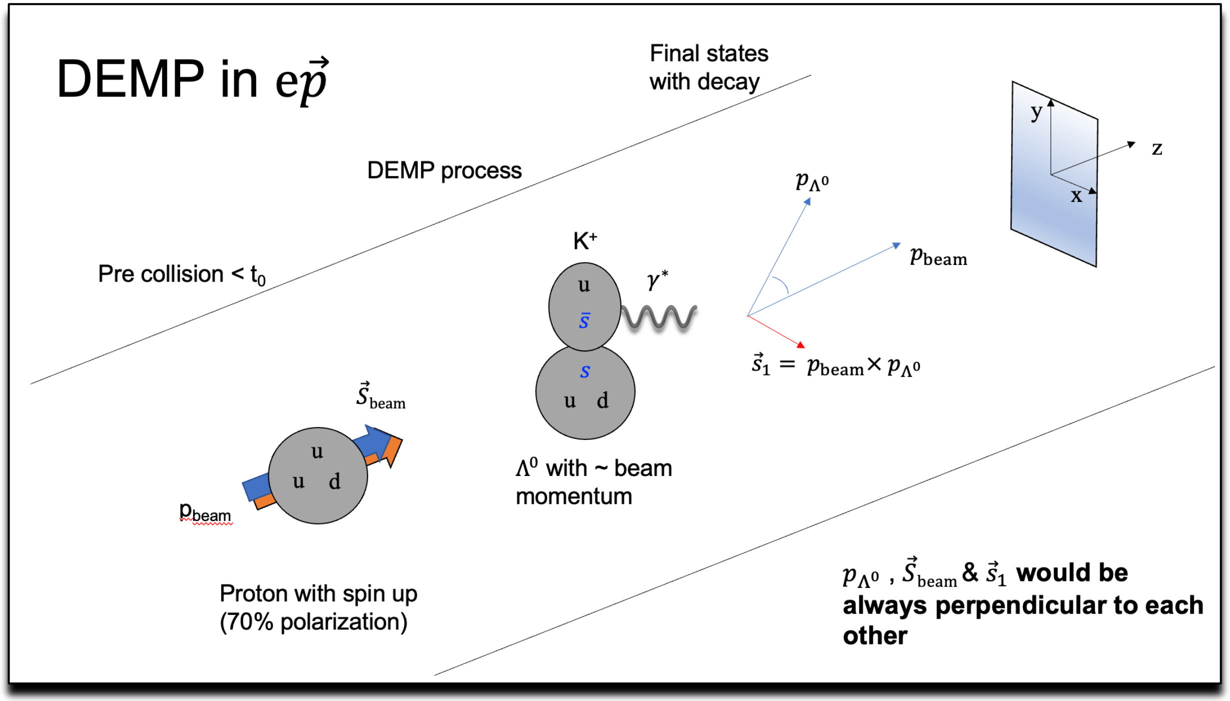

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Tagging Pion, Kaon, Proton in the same event - t
- Which direction Λ hyperon will be polarized?
- What about polarized deuteron?

See more next week at the Warsaw Meeting for EIC Det 2

Overview: what can be tagged down to $p_T = 0$

Light nuclei & protons

EIC ePIC detector:
Protons (coherent)
Breakup protons (incoherent)
Breakup neutrons (incoherent)

EIC Detector 2 with secondary focus:
Protons (coherent)
D^2 (coherent)
He^3 (coherent)
He^4 (coherent)
..
(x > 0.01A)

Heavy nuclei

EIC ePIC detector:
Heavy nuclei (via vetos)
Breakup protons (incoherent)
Breakup neutrons (incoherent)

EIC Detector 2 with secondary focus:
Heavy nuclei (via vetos)
Tagging A-1 is possible up to Zr^{90}

For higher p_T, the capabilities will change as expected and tagging will be easier.

Summary

EIC will expand to higher energy (lower-x), higher Q^2, and with wide acceptances and beam polarizations.
– complementary to **Jlab** experiments and the **heavy-ion** experiments.

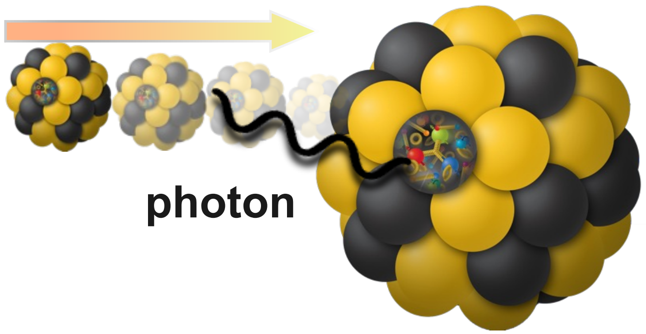
Tagged nucleon program will be a new experimental tool to understand nuclear effects and **short-distance dynamics**, from light to heavy nuclei, and from high to low x.

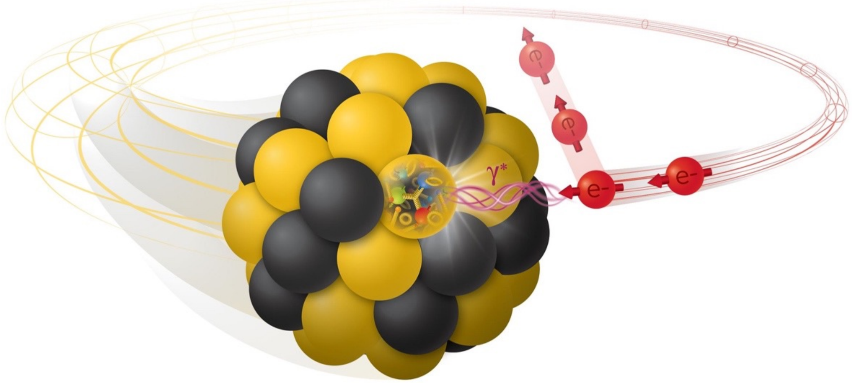
EIC second detector may have even better capability for tagging physics!


Thank you!

Backup

Complementarity: UPC and EIC

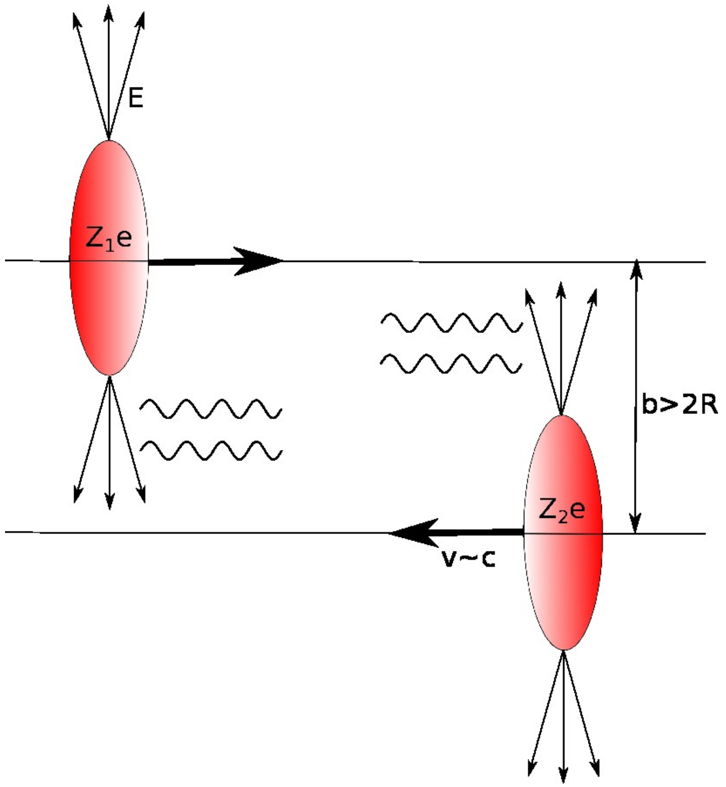




UPC RHIC & LHC	EIC
Photoproduction only (real photons)	Electroproduction (virtual photons)
Mass or p_T – hard scales	Q^2 – an independent hard scale
CM energy, W ~ [4, 400-1000] GeV, x ~ 10^{-5} - 10^{-1}	CM energy, W ~ [9, 86] GeV, x ~ 10^{-4} - 10^{-2}
mostly Pb^{208}, Au^{197}.	Deuterium to Uranium
Limited far-forward coverage for breakup products	Large far-forward coverage, esp. for nuclear breakup.

Naively, UPCs is an “easier” option to probe saturation.

UPCs kinematics & challenges



- $Z\alpha_{EM}$ ~ $\mathcal{O}(1)$, overcomes the weak coupling by **large photon flux**;

Three challenges:

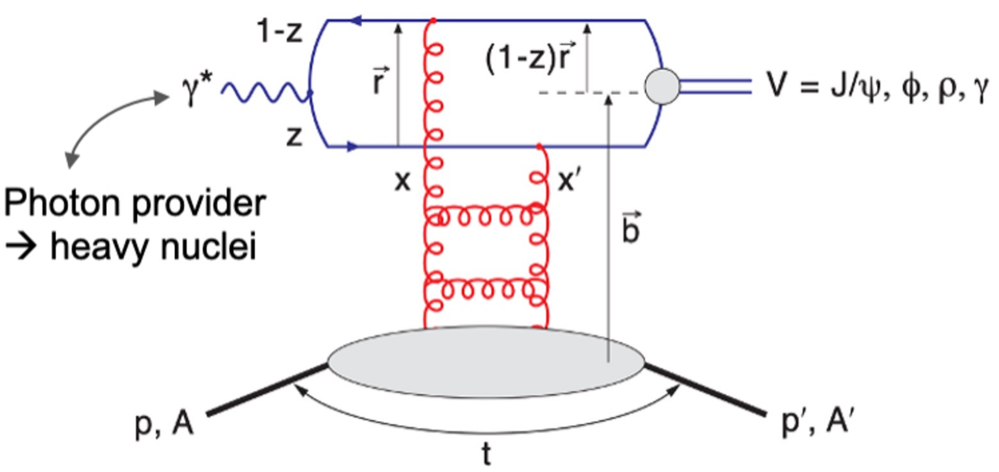
a) Impact parameter b > $2R_A$, but cannot be controlled event-by-event;
How to know its photon-induced interactions?

b) Kinematics is unknown, unless inferred by the final-states:
what is the C.o.M energy (e.g., W)?

c) Photon energy is ambiguous in AA UPCs:
who is the photon emitter?

Vector Meson photoproduction sensitive to $xG(x,Q^2)$

- One that ticks all the boxes…



Coherent (target stays intact)	**Incoherent (target breaks up)**
Average gluon density*	Event-by-event gluon density fluctuations*
Momentum transfer (*t*) and transverse spatial position (*b*) are Fourier transforms of each other;	

* known as the Good-Walker Paradigm

UPC VMs measurement:

- Large rapidity gap and only 1 VM in central rapidity.
- *t* is approximated by: $t \sim (\mathbf{k}_{T,photon} + \mathbf{p}_{T,VM})^2 \sim (\mathbf{p}_{T,VM})^2$, photon $\langle k_T \rangle$ is 30-40 MeV
- W is determined by exclusivity: $W^2 = 2E_N M_{VM} Exp(-y)$

Incoherent J/ψ cross section vs p_T^2

New

- Compared to the H1 data with free proton. **The suppression factor ~ is 40%.** Stronger than that for coherent production.
- Models have found that the H1 data supports **sub-nucleonic fluctuation**. *[Phys. Rev. Lett. 117 (2016) 5, 052301]*
- STAR data shows the bound nucleon has a similar shape in p_T^2 as the free proton, indicating **similar sub-nucleonic fluctuation in heavy nuclei.** *[Phys. Rev. D 106 (2022) 7, 074019]*