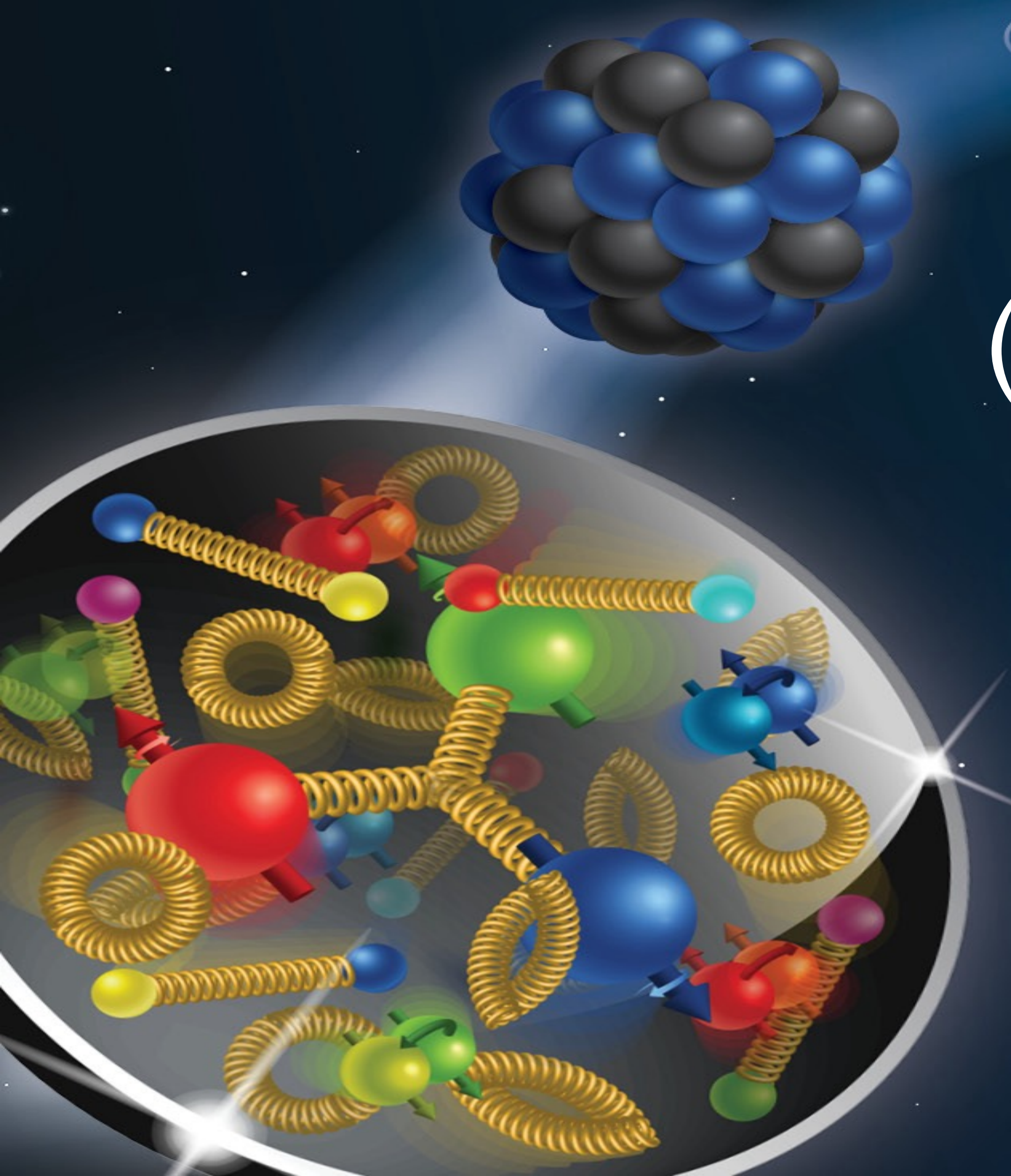


# (some) Far-Forward Physics Opportunities at the EIC

Alex Jentsch, *Brookhaven National Lab*

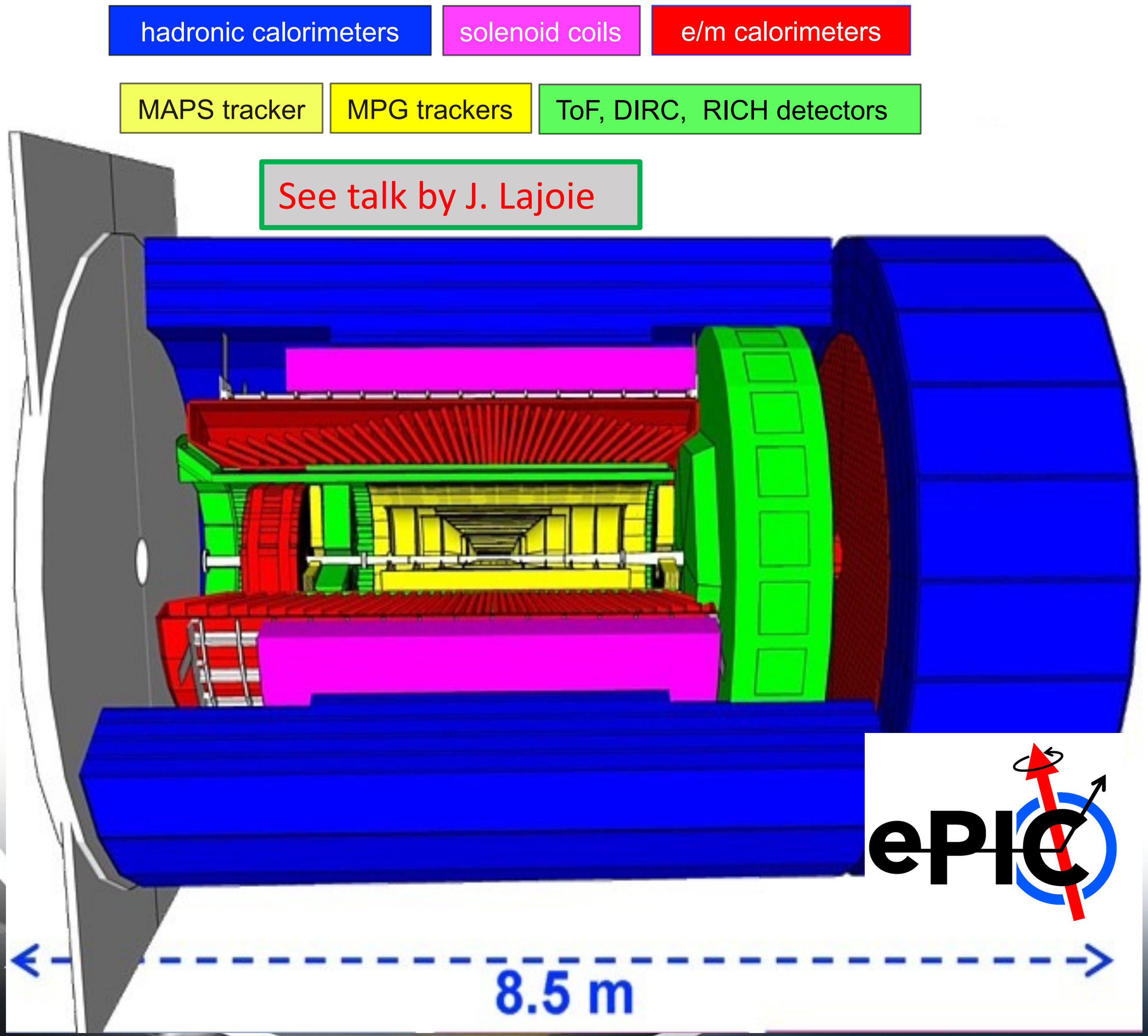
*ajentsch@bnl.gov*

XXIX The Cracow Epiphany Conference

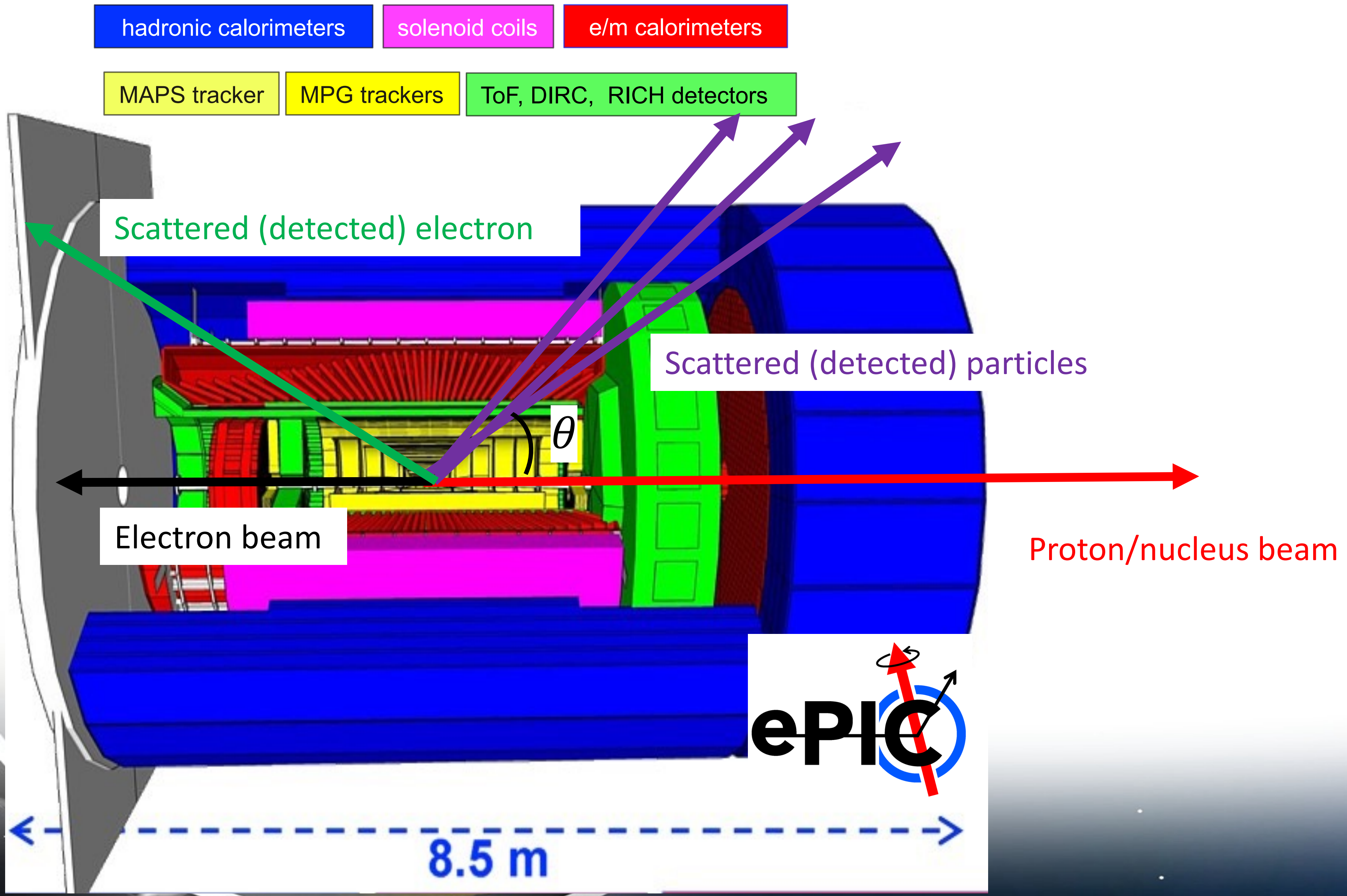
*January 16-19, 2022*

*Cracow, Poland*

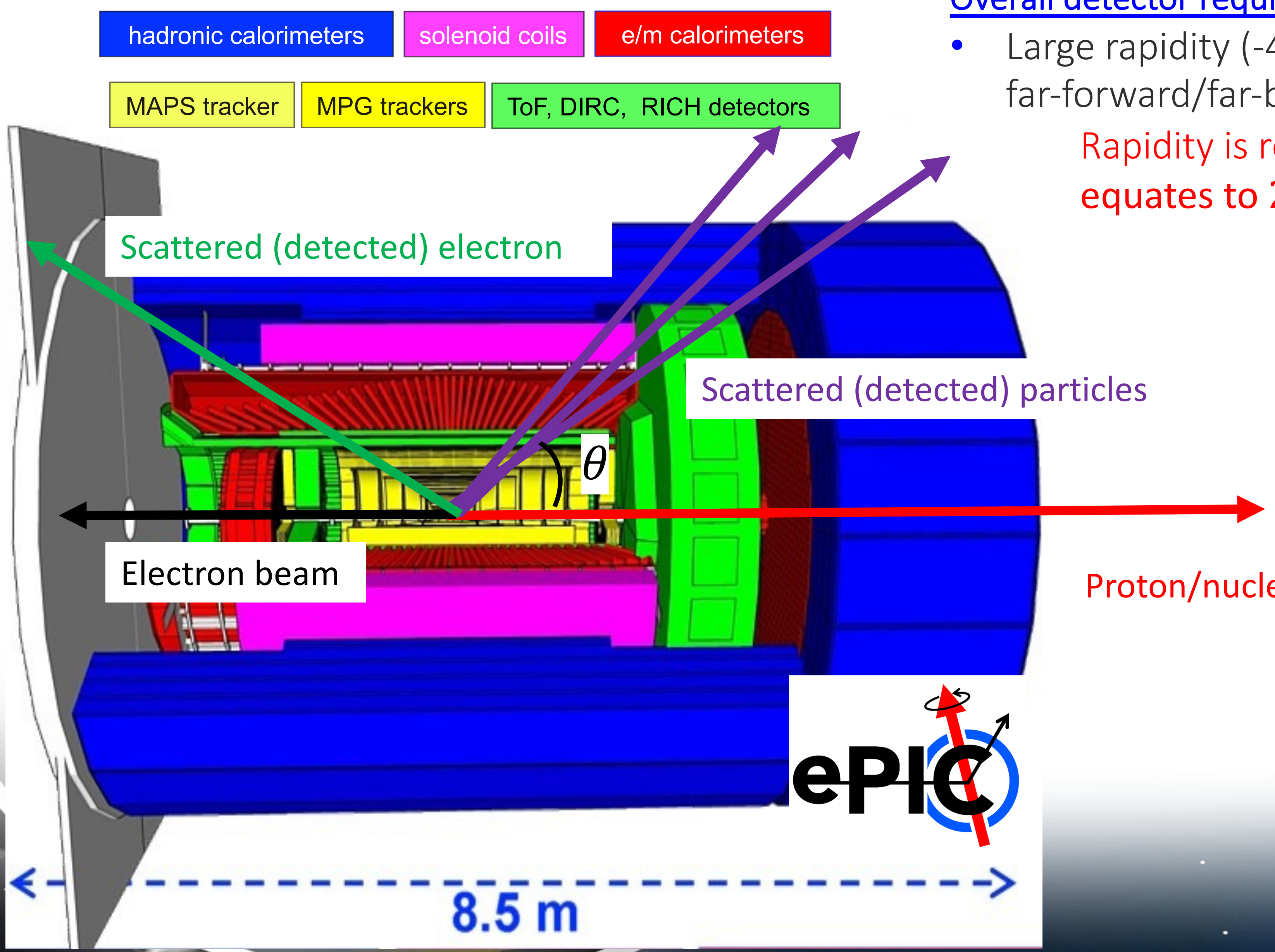
# What is meant by Far-Forward?



# What is meant by Far-Forward?



# What is meant by Far-Forward?




Overall detector requirements:

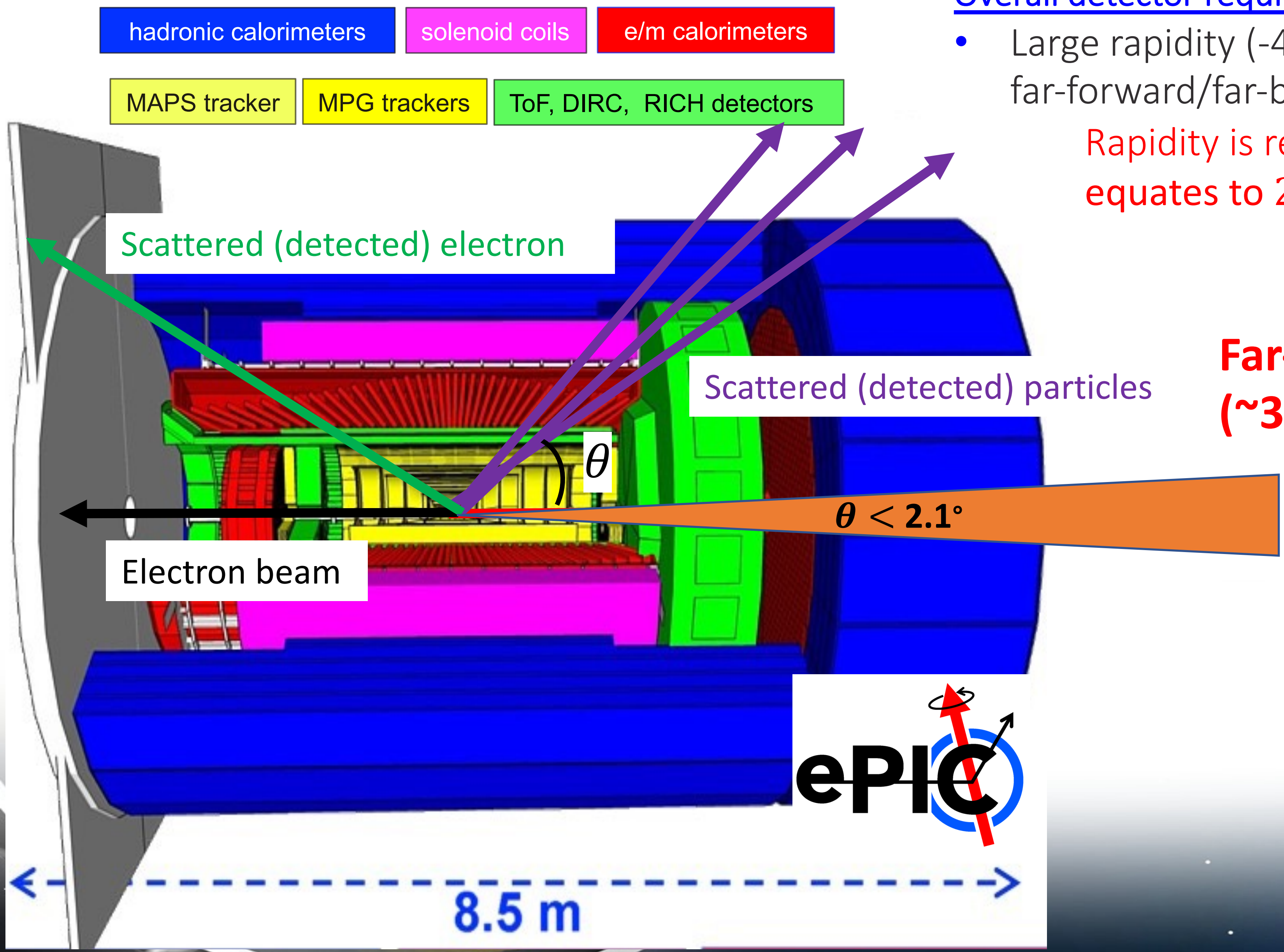
- Large rapidity (-4 < η < 4) coverage; and far beyond in far-forward/far-backward detector regions

Rapidity is related to the polar angle → 0 < η < 4 equates to $2.1^{\circ} < \theta < 90^{\circ}$

$$\eta = -ln(tan(\theta/2))$$

pseudorapidity

# What is meant by Far-Forward?




Overall detector requirements:

- Large rapidity (-4 < η < 4) coverage; and far beyond in far-forward/far-backward detector regions

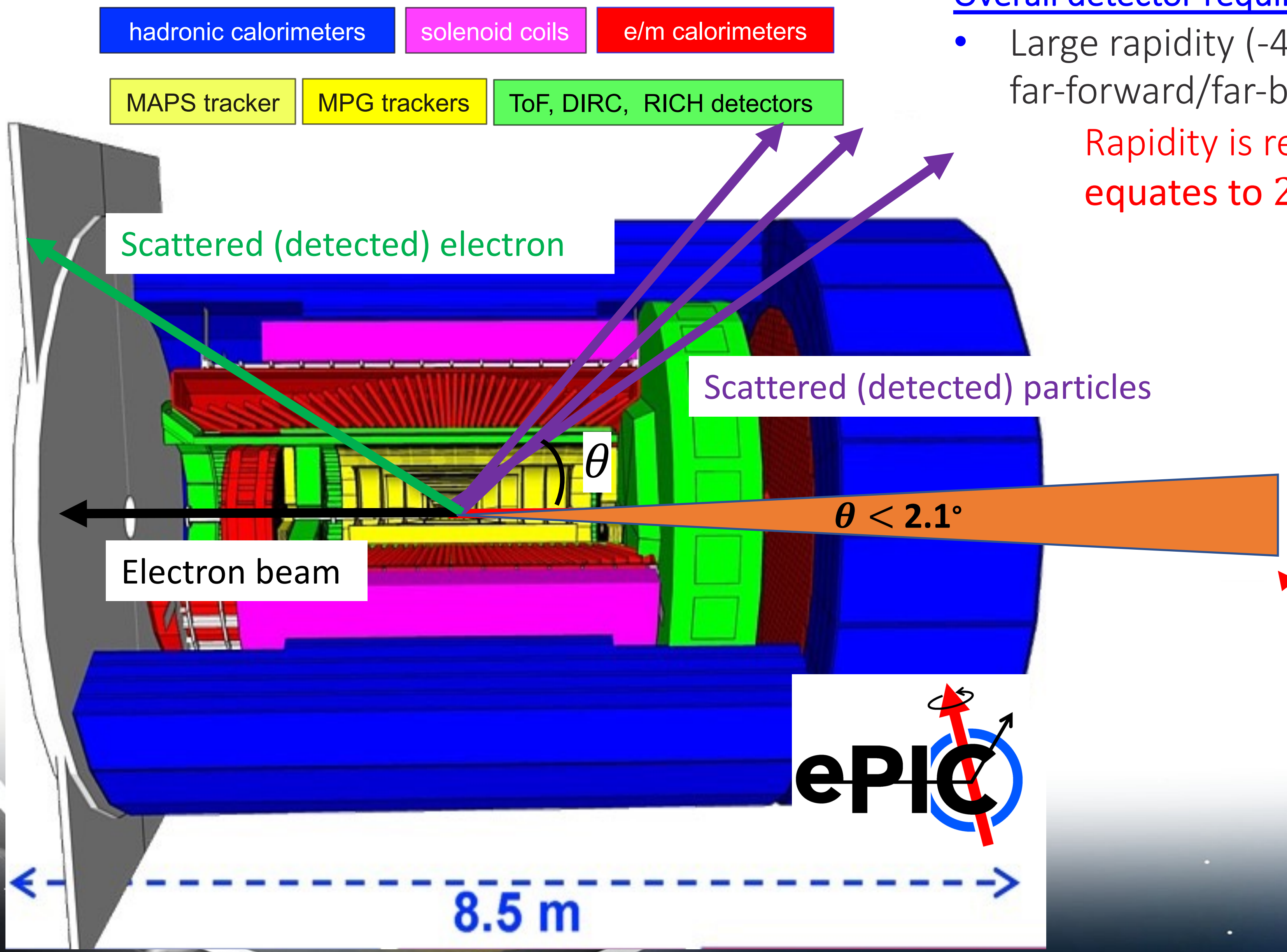
Rapidity is related to the polar angle → 0 < η < 4 equates to $2.1^{\circ} < \theta < 90^{\circ}$

$\eta = -ln(tan(\theta/2))$

pseudorapidity

**Far-forward here means $\theta < 2.1°$ (~37 mrad)**

# What is meant by Far-Forward?



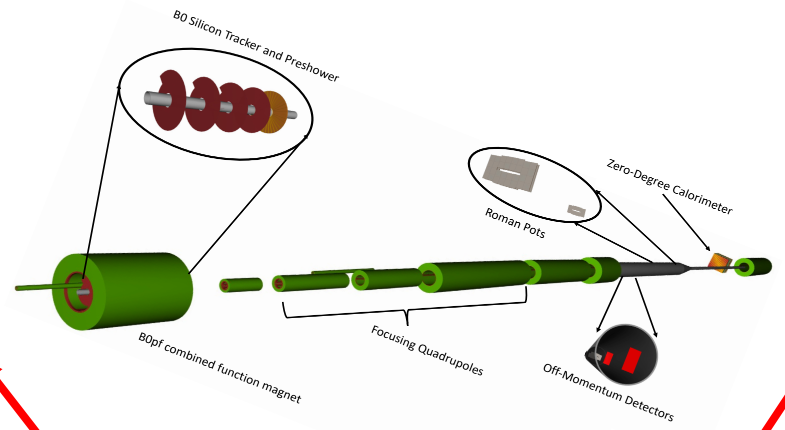

<u>Overall detector requirements:</u>

- 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 $2.1^{\circ} < \theta < 90^{\circ}$

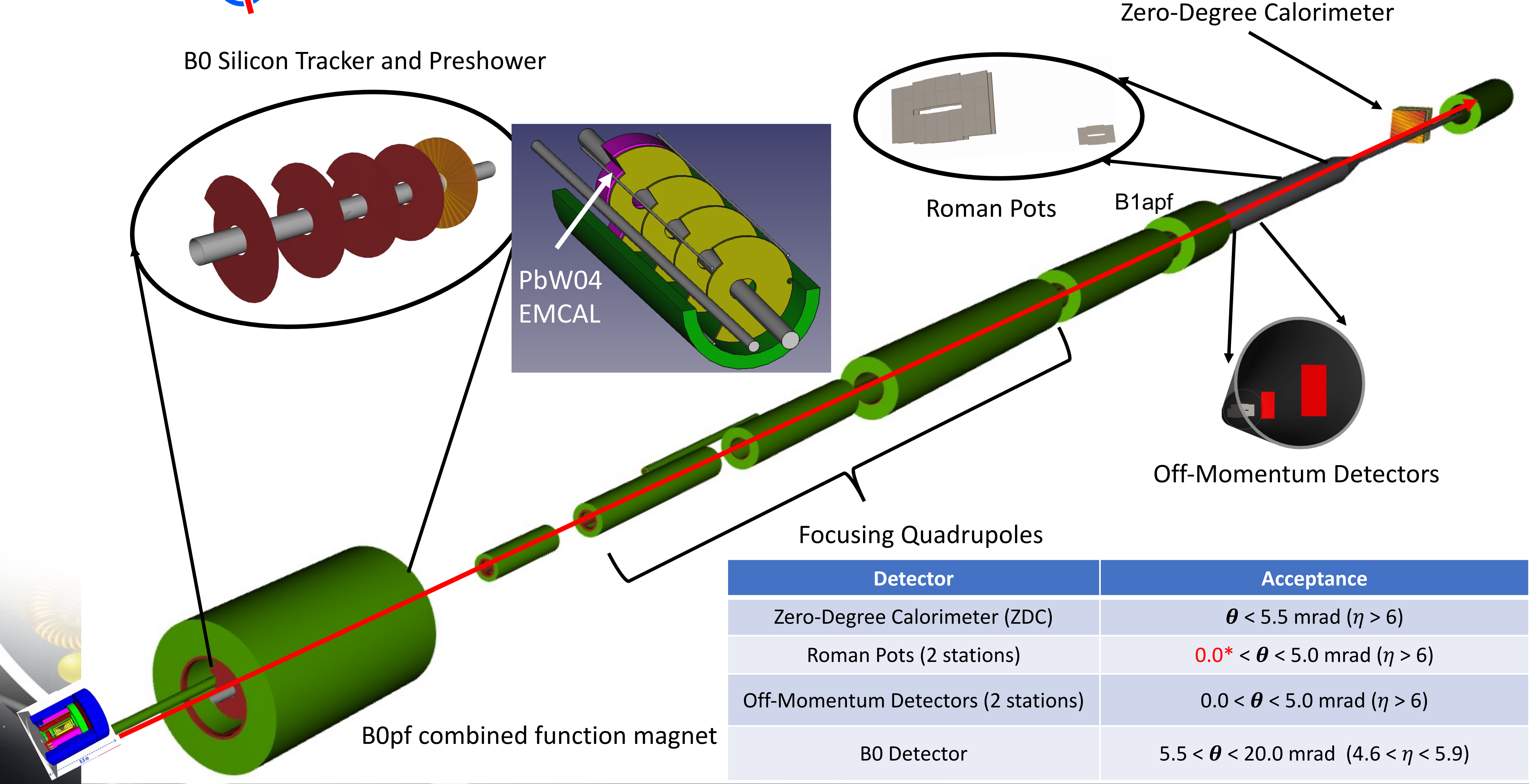
$$\eta = -ln(tan(\theta/2))$$

pseudorapidity



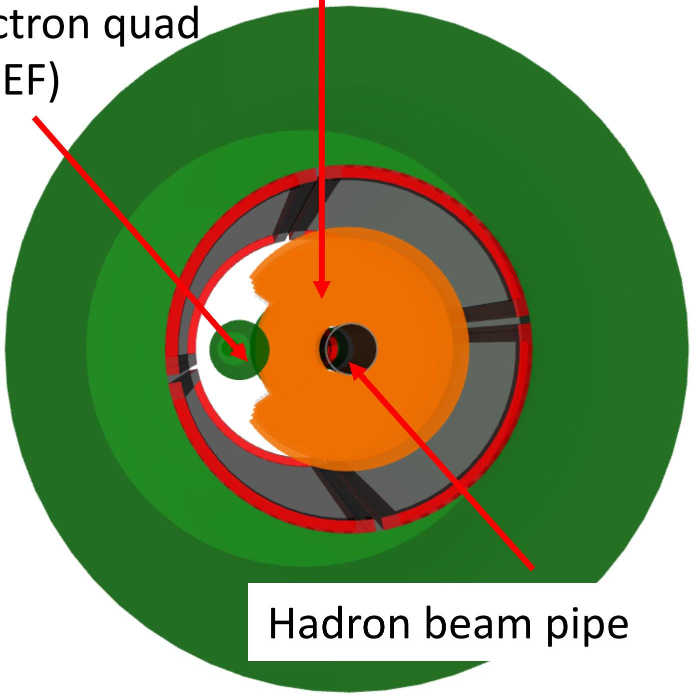

**Need detectors here!!**

# The ePIC Far-Forward Detectors

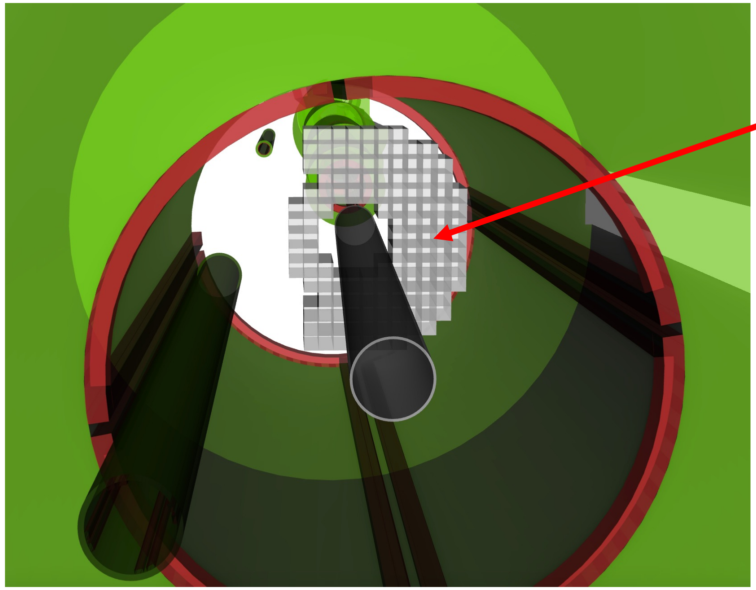



| Detector | Acceptance |
|---|---|
| Zero-Degree Calorimeter (ZDC) | $\boldsymbol{\theta} < 5.5$ mrad ($\eta > 6$) |
| Roman Pots (2 stations) | 0.0* $< \boldsymbol{\theta} < 5.0$ mrad ($\eta > 6$) |
| Off-Momentum Detectors (2 stations) | $0.0 < \boldsymbol{\theta} < 5.0$ mrad ($\eta > 6$) |
| B0 Detector | $5.5 < \boldsymbol{\theta} < 20.0$ mrad ($4.6 < \eta < 5.9$) |

# B0 Tracking and EMCAL Detectors



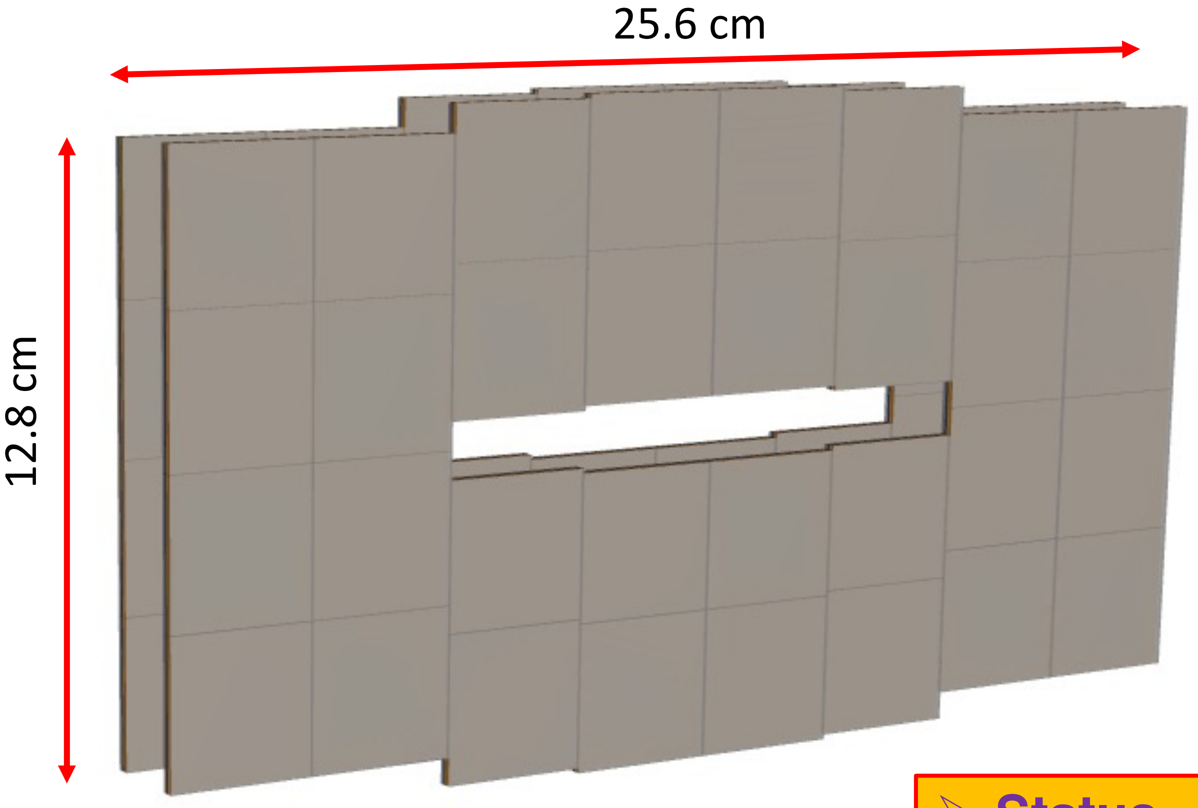

ePIC DD4HEP Simulation



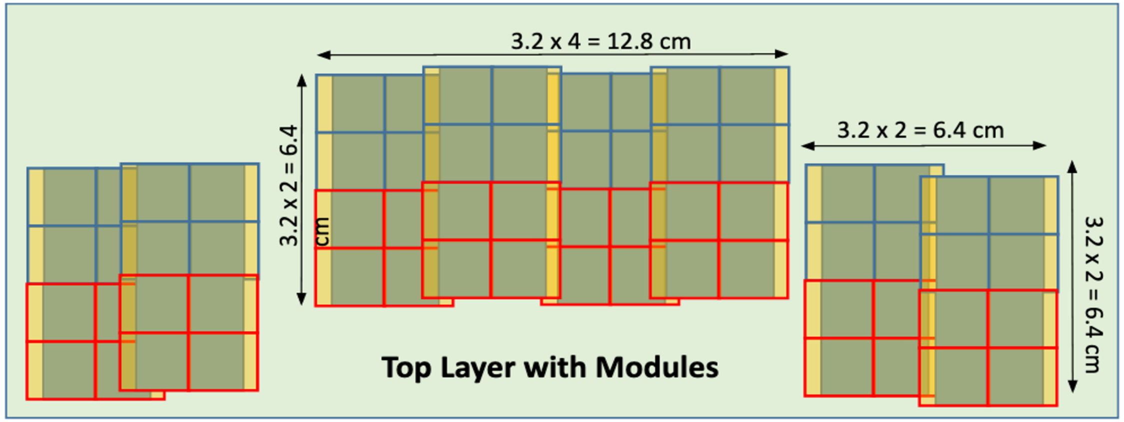

- **Technology choices:**
  - **Tracking: IT3 or ITS2 MAPS (3 layers) + AC-LGADs (1 layer; in middle)**
  - **PbWO4 EMCAL or silicon preshower, depending on available space in final B0pf magnet design (pending).**

- **Status**
  - ✓ **Used to reconstruct charged particles and photons.**
    - ✓ **Acceptance: 5.5 < $\theta$ < 20.0 mrad**
    - ✓ **Focus now is on readout, new tracking software, and engineering support structure.**
  - ✓ **Stand-alone simulations have demonstrated tracking resolution.**
    - https://indico.bnl.gov/event/17905/
    - https://indico.bnl.gov/event/17622/

# Roman "Pots" @ the EIC




DD4HEP Simulation

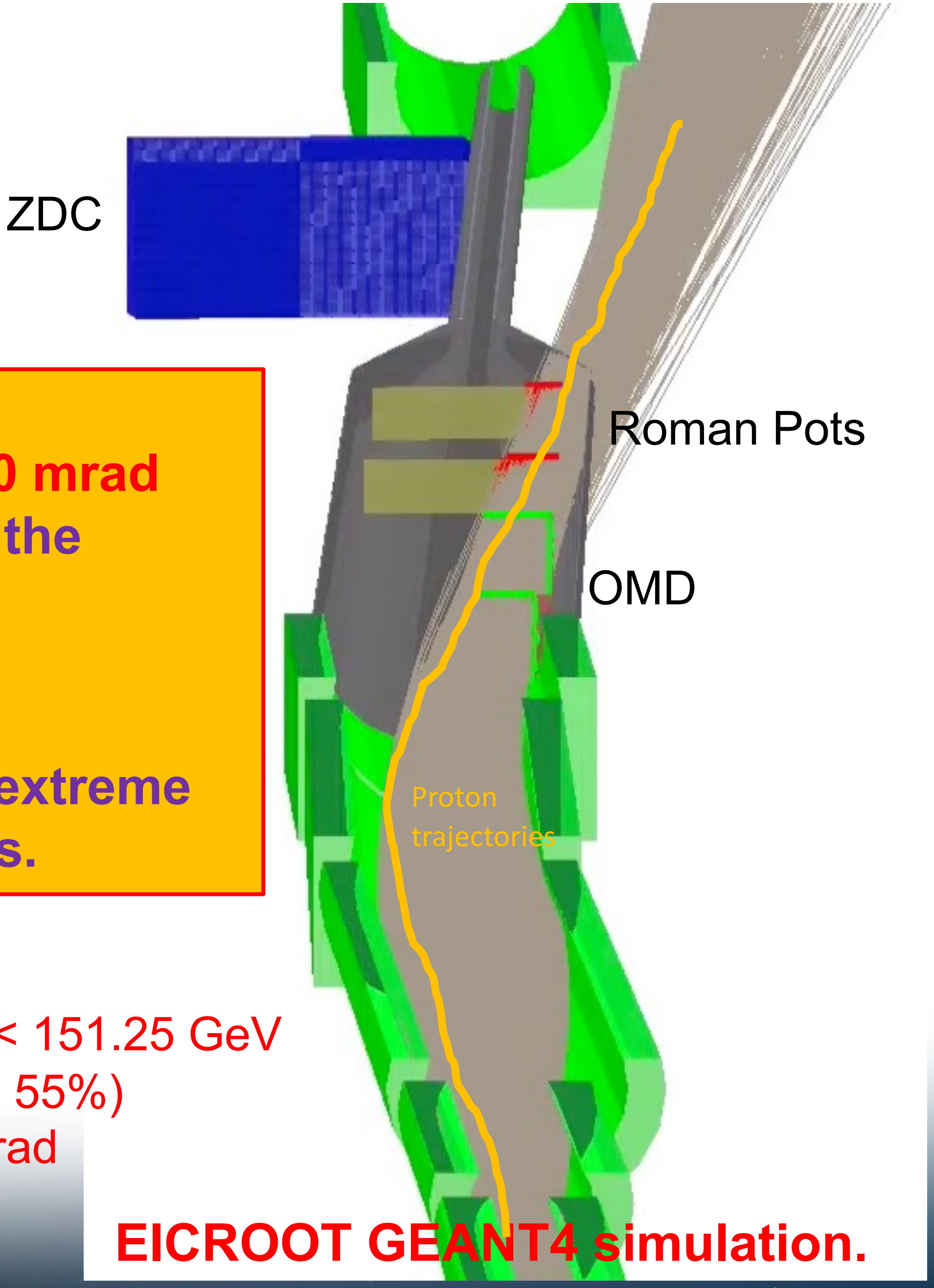



- **Technology**
  - 500um, pixilated AC-LGAD sensor provides both fine pixilation.
  - "Potless" design concept with thin RF foils surrounding detector components.

- **Status**
  - ✓ **Acceptance: 0.0* < $\theta$ < 5.0 mrad (lower bound depends on optics).**
  - ✓ **Detector directly in-vacuum a challenge for both detector and beam → impedance studies underway.**
  - ✓ **Approved generic R&D to develop more-adaptive reconstruction code!**

# Off-Momentum Detectors

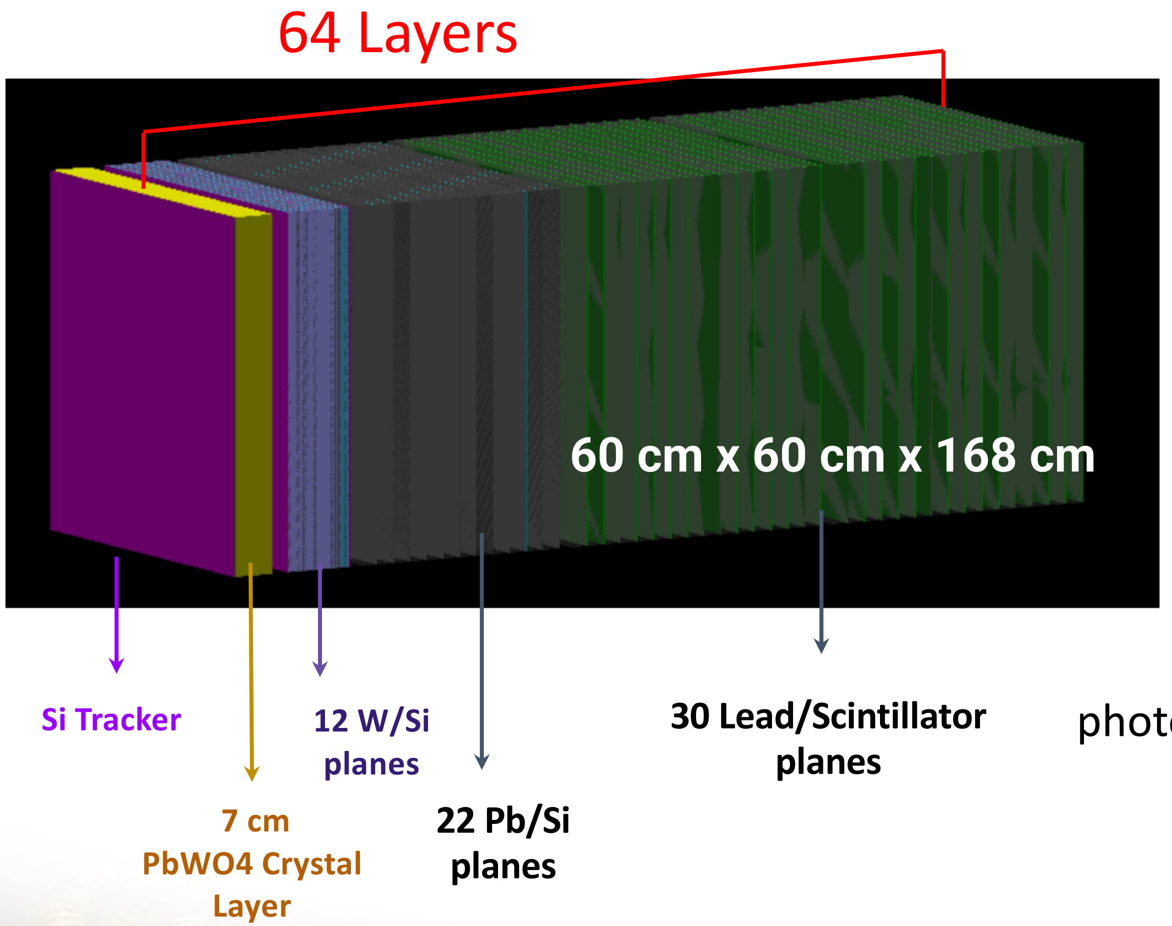

- **Status**
  - ✓ **Acceptance: 0.0 < $\theta$ < 5.0 mrad**
  - ✓ **Same technology as for the Roman Pots.**
  - ✓ **Even more-challenging reconstruction with off-momentum particles → extreme orbit path in the magnets.**



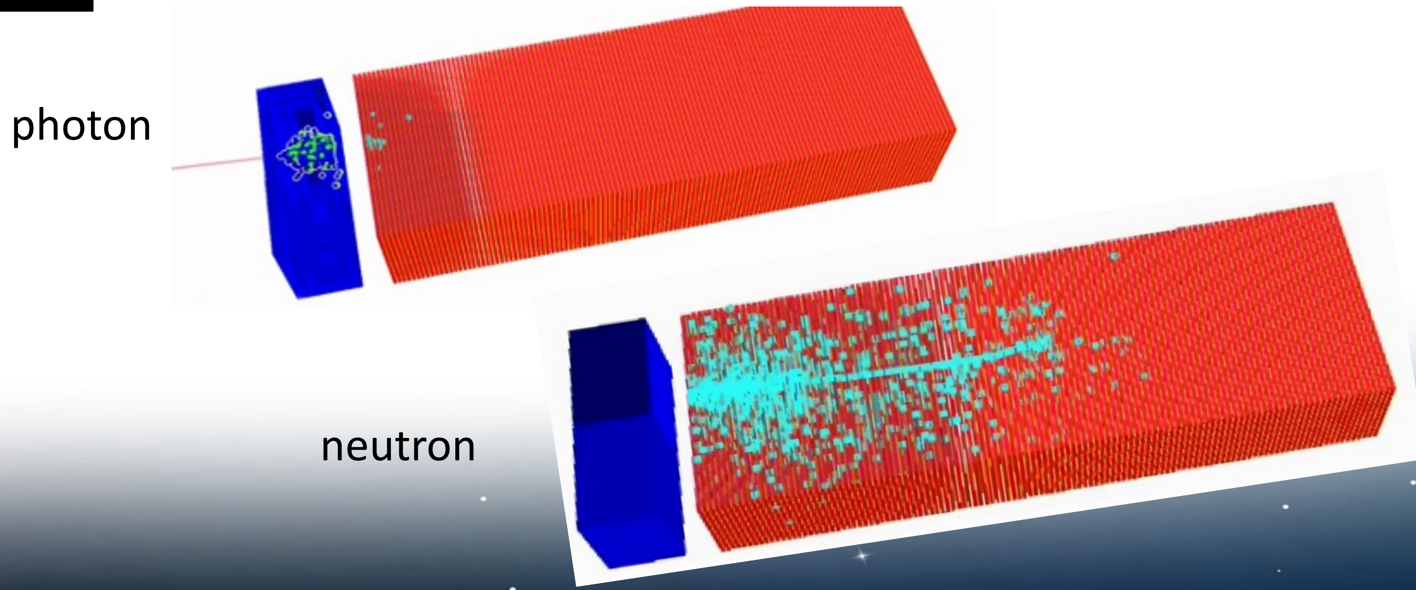

Off-momentum detectors implemented as horizontal "Roman Pots" style sensors.

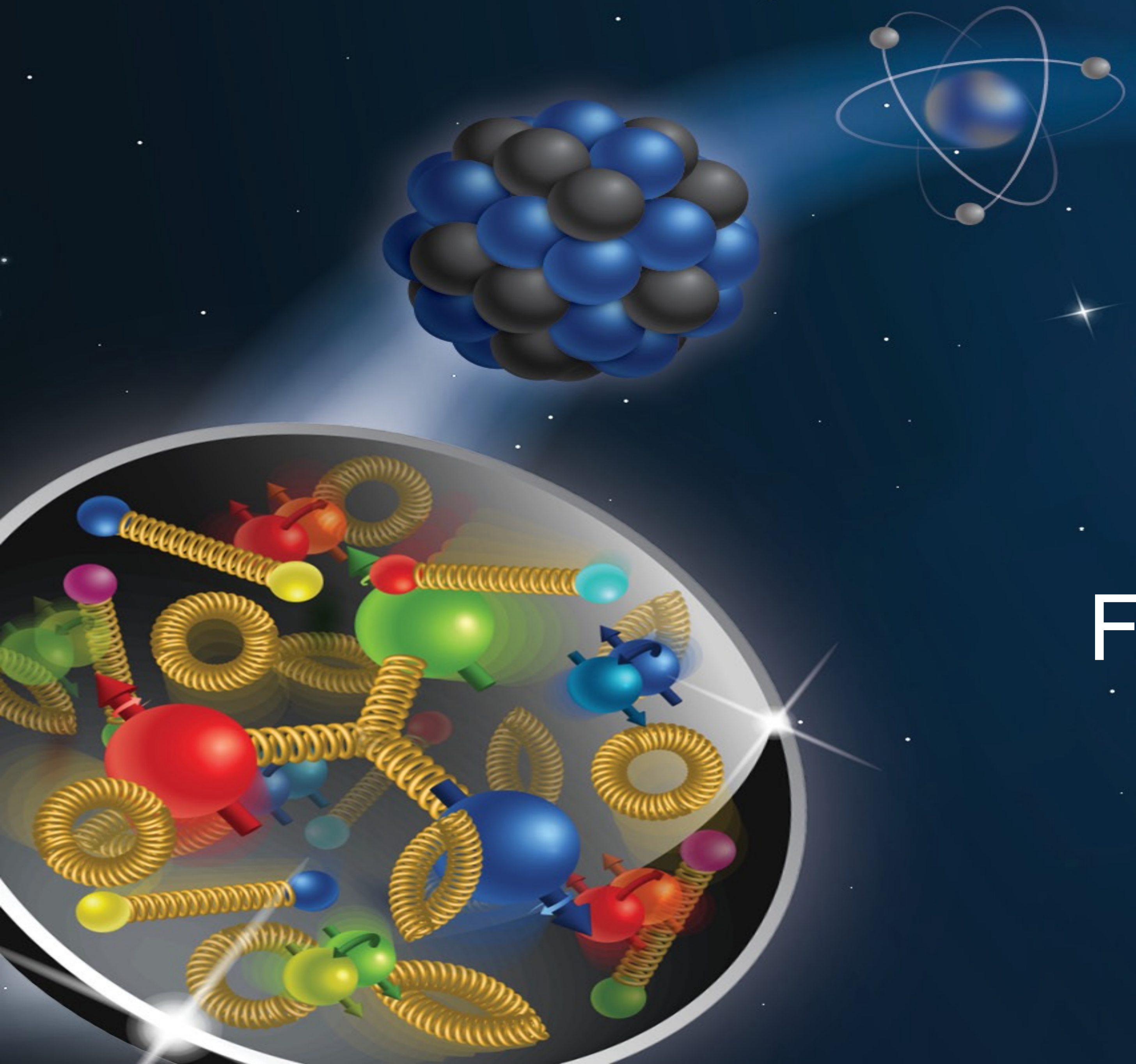
Protons
123.75 < E < 151.25 GeV
(45% < xL < 55%)
0 < $\theta$ < 5 mrad

# Zero-Degree Calorimeter




- **Status**
  - ✓ 30 m from IR
  - ✓ Detect spectator neutrons (HCAL) & photons (EMCAL)
  - ✓ Acceptance: +4.5 mrad, -5.5mrad (aperture limits)
  - ✓ Position resolution ~1.3mm at 40 GeV
  - ✓ Meets requirements from Yellow Report.
  - ✓ Lots of work to do on shower reconstruction with imaging layers.

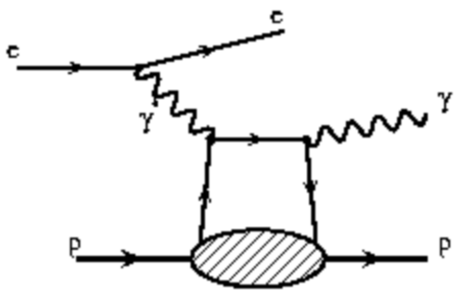




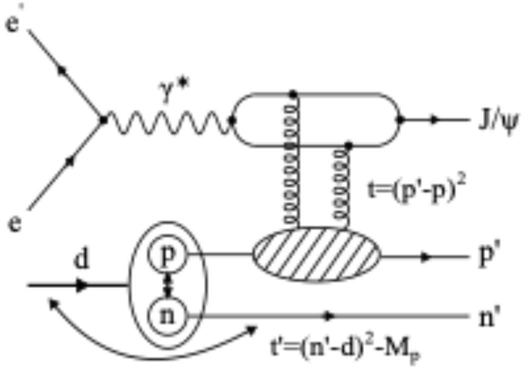
# EIC Physics in the Far-Forward Region

# (some) Far-Forward Processes at the EIC

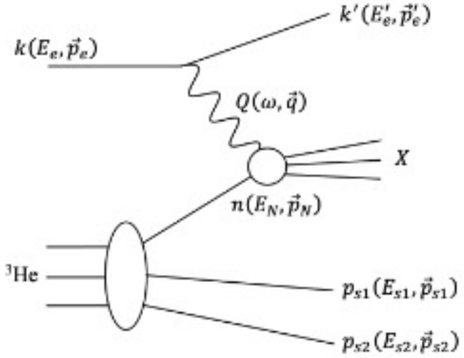
e+p DVCS



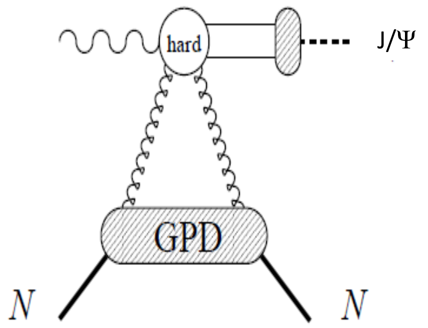

e+d exclusive J/Psi with p/n tagging




e+He3 spectator tagging

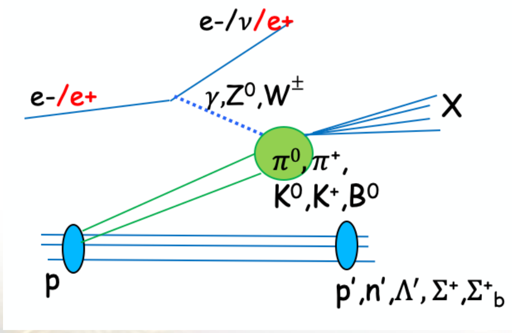



coherent/incoherent $J/\psi$ production in e+A

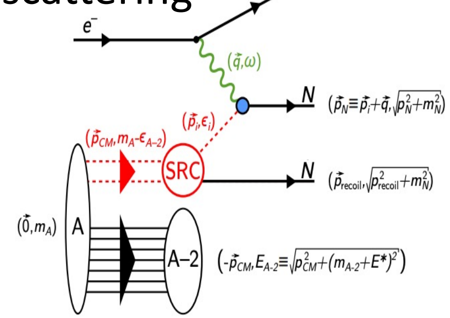



Meson structure:

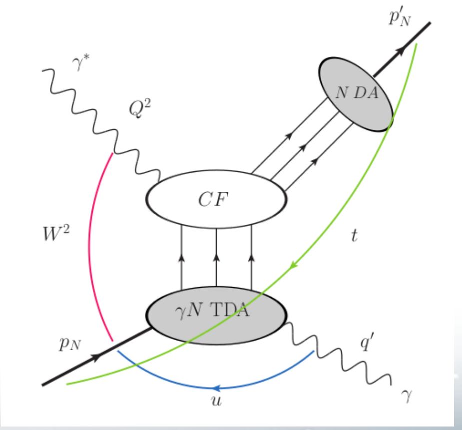
- ep→ ($\pi$) →e' n X
- $\Lambda$ →p$\pi^-$ and $\Lambda \rightarrow n\pi^0$




Quasi-elastic electron scattering




u-channel backward exclusive electroproduction




**…and MANY more!**

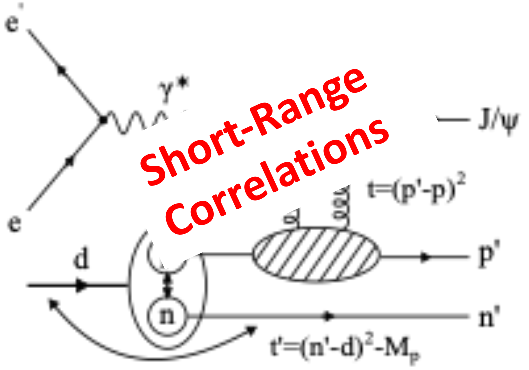
# (some) Far-Forward **Physics** at the EIC

e+p DVCS

Proton spin: orbital angular momentum; imaging

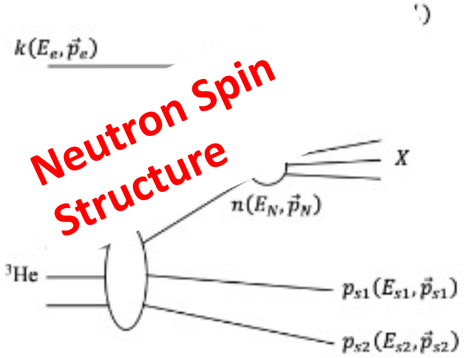
See talk by S. Fazio

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



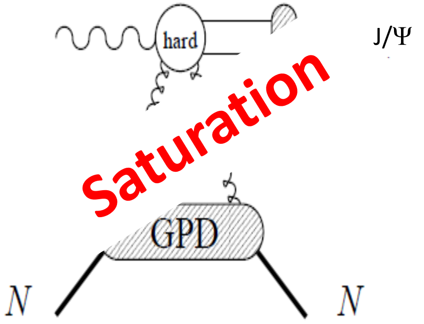

Short-Range Correlations

e+He3 spectator tagging




Neutron Spin Structure

coherent/incoherent $J/\psi$ production in e+A

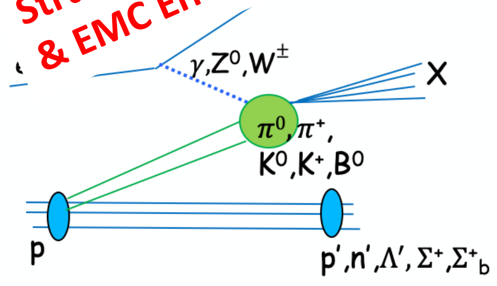



Saturation

Meson structure

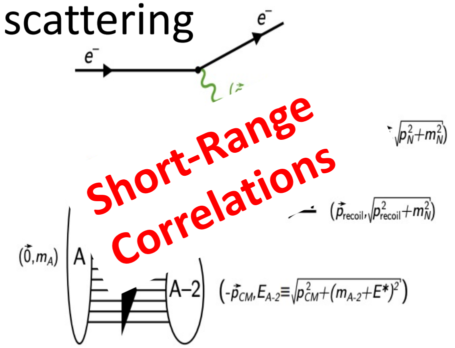
- ep→
-

$n\pi^0$




Free Neutron Structure Functions & EMC Effect

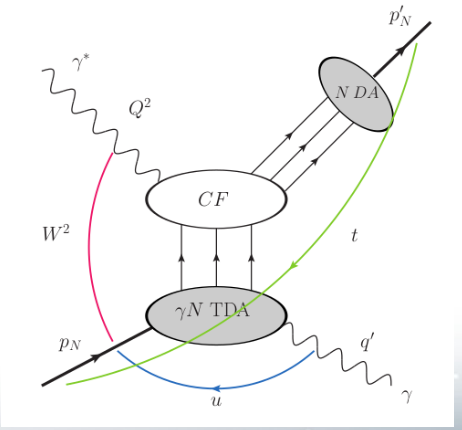
Quasi-elastic electron scattering




Short-Range Correlations


[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

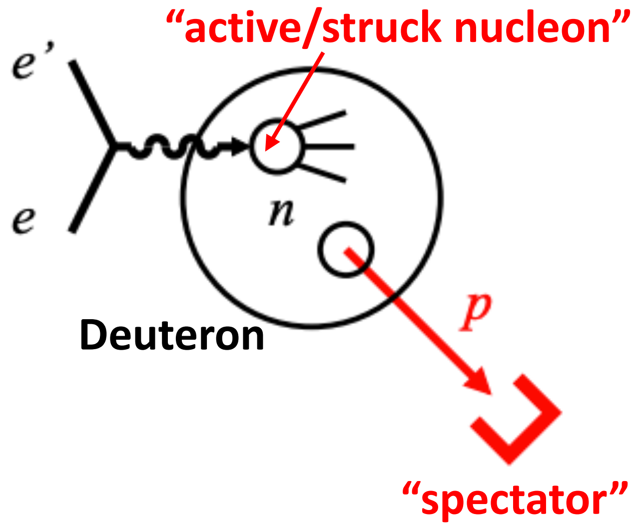


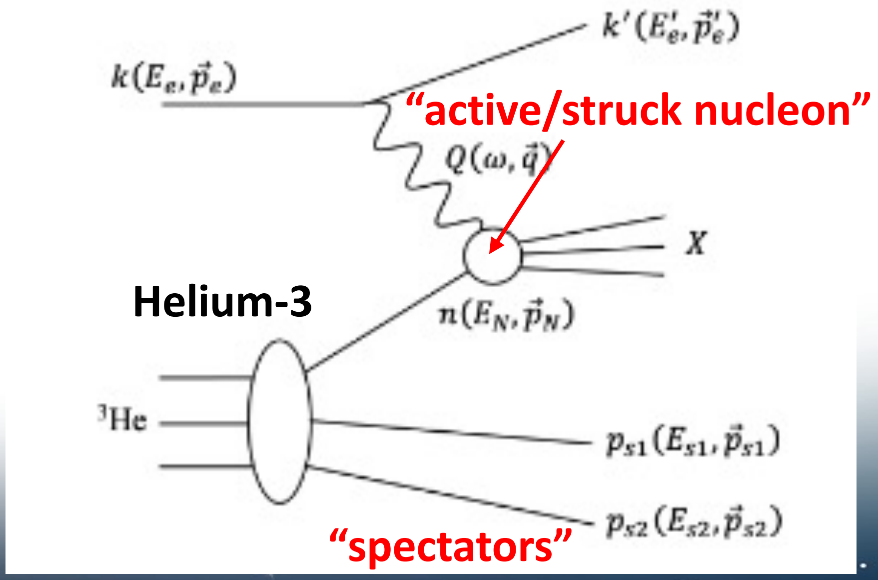

**…and MANY more!**

# Focus: Deuterons as an unexpected QCD laboratory at the EIC.

# Deuteron tagged DIS as a tool 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.



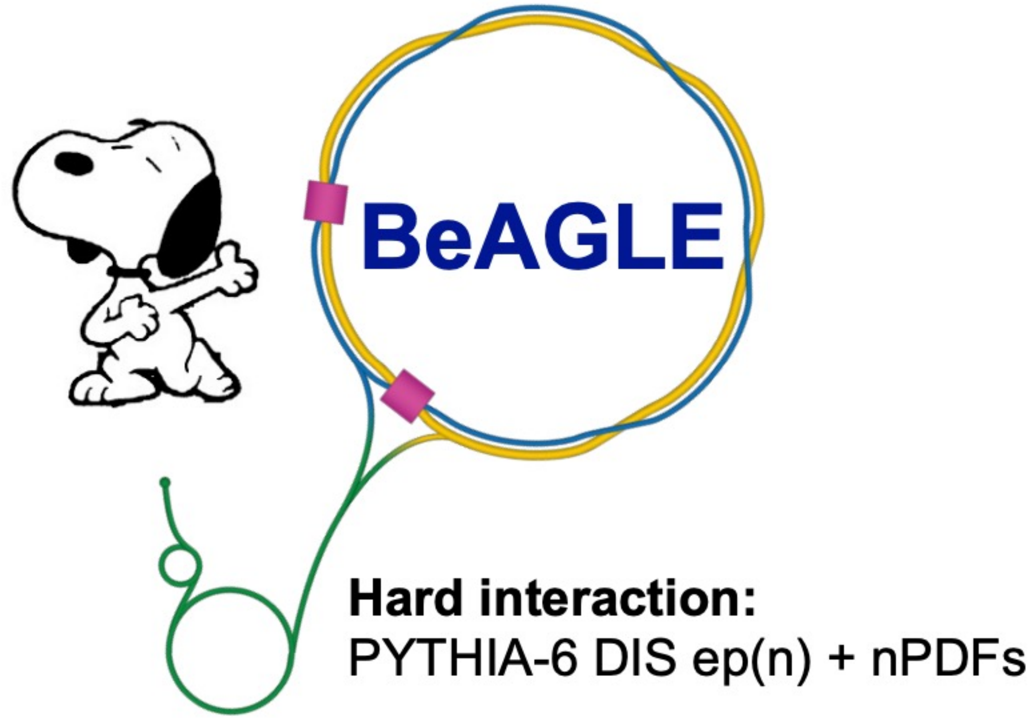




**Tagged spectator nucleon momentum → experimental handle on nuclear configurations with free and modified nucleons.**

# Monte Carlo for all e+d studies presented here

General-purpose eA DIS MC generator

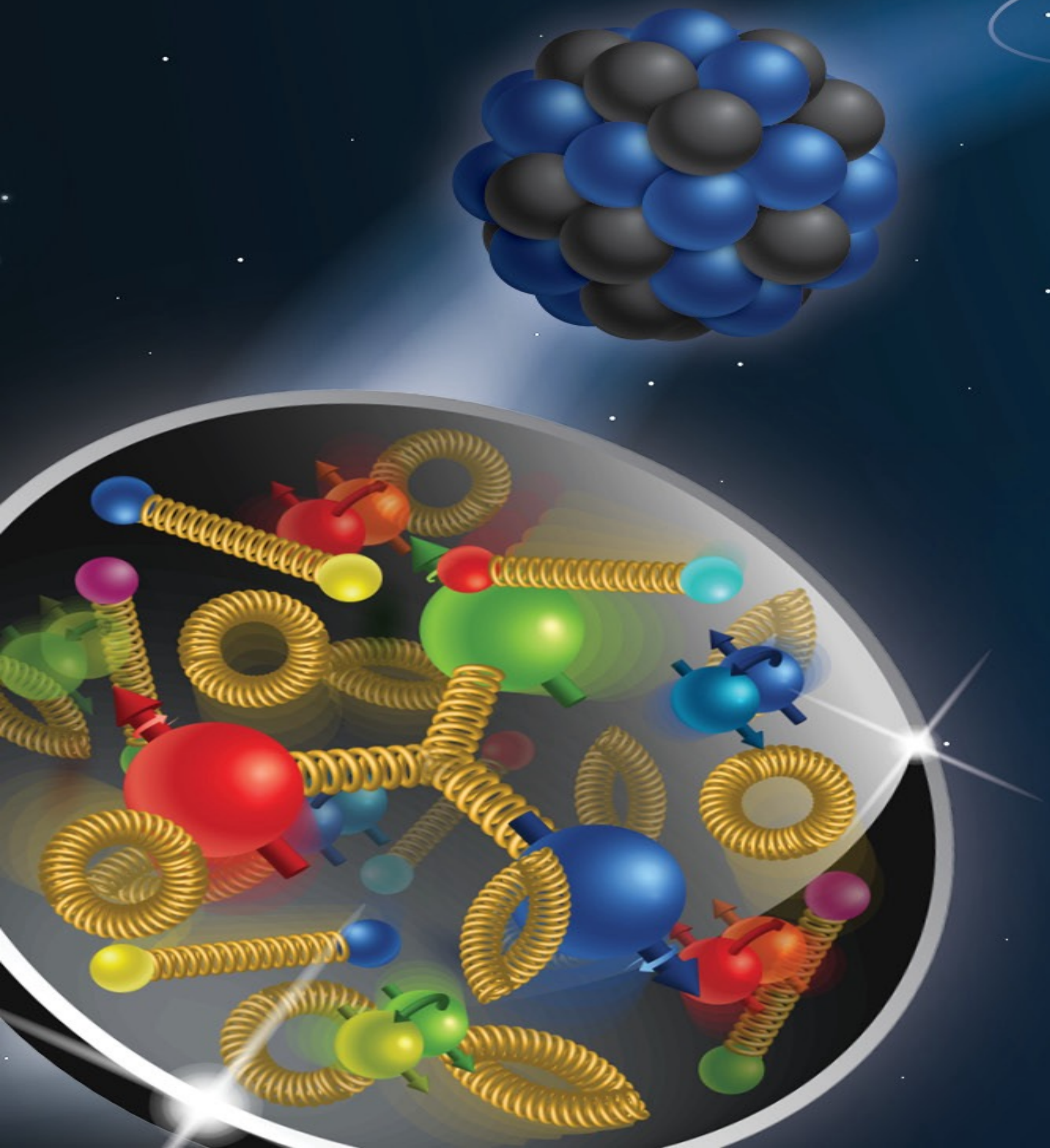
https://eic.github.io/software/beagle.html




Wan Chang, Elke-Caroline Aschenauer, Mark D. Baker, Alexander Jentsch, Jeong-Hun Lee, Zhoudunming Tu, Zhongbao Yin, and Liang Zheng
Phys. Rev. D **106**, 012007 (2022)

➢ **For e+d collisions:**

- ✓Use BeAGLE to simulate the hard e + (active) nucleon scattering and primary process (e.g. J/$\psi$ production, DIS, etc.)
- ✓Spectator momentum spectra calculated via deuteron spectral function, using parametrization of Ciofi and Simula.
  - ✓C. Ciofi degli Atti and S. Simula, Phys. Rev. C 53, 1689 (1996)
- ✓BeAGLE MC samples passed through full detector simulations, including beam effects to study prospects for future analysis!

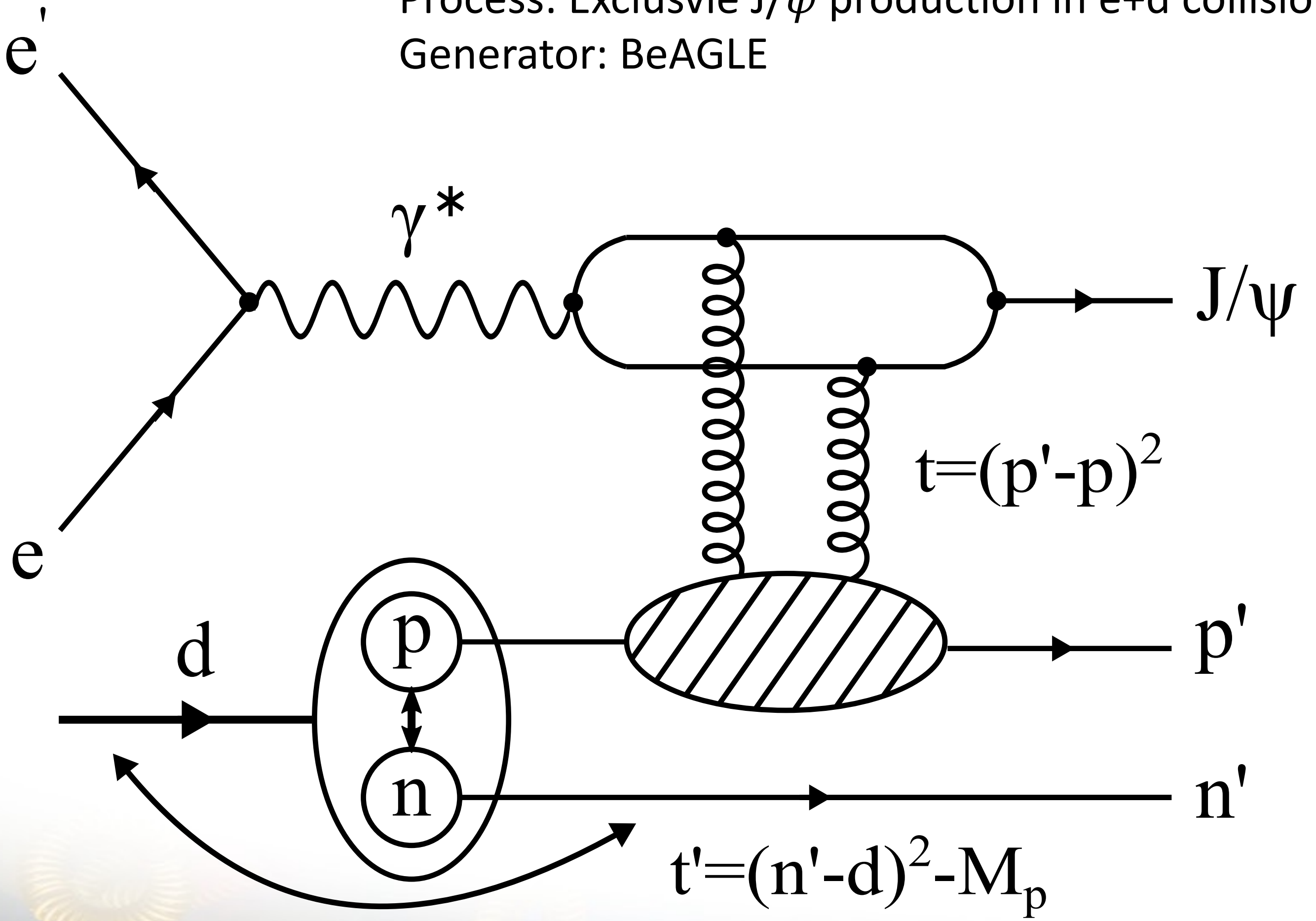


# Deuterons: Gluons and Short-Range Correlations

# Short-Range Correlations in Deuterons

Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)

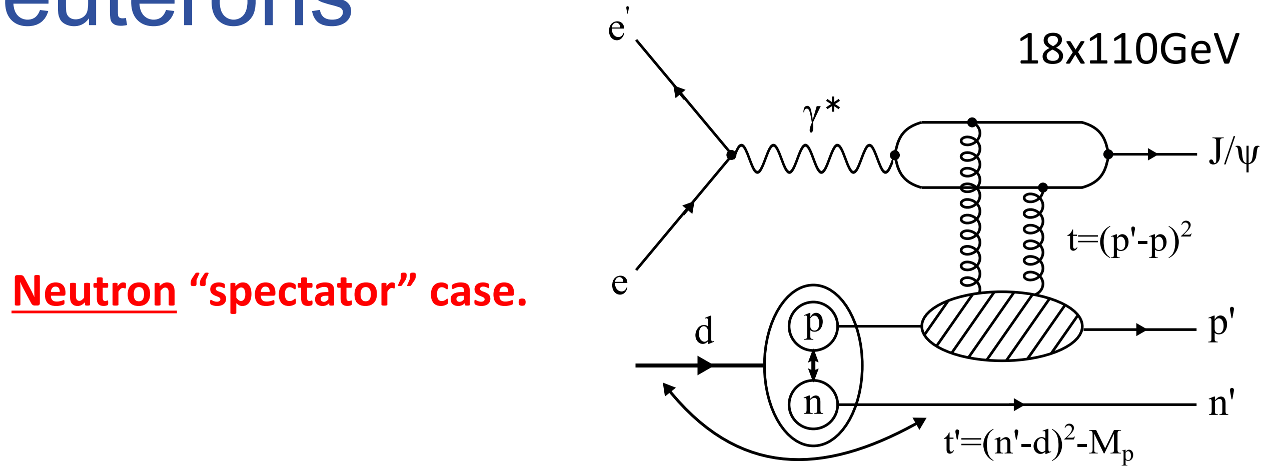
Process: Exclusvie J/$\psi$ production in e+d collisions.
Generator: BeAGLE



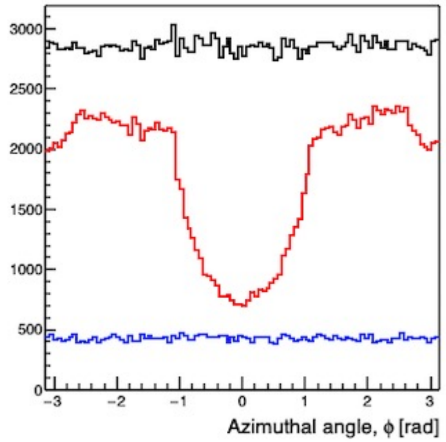

- J/$\psi$ produced at mid-rapidity.
  - **Sensitive to gluons!**
- Tagging active and spectator nucleons allow for experimental control of nuclear configuration → control nuclear effects!
- Tagging **both** nucleons allows for full reconstruction of momentum transfer!

# Short-Range Correlations in Deuterons

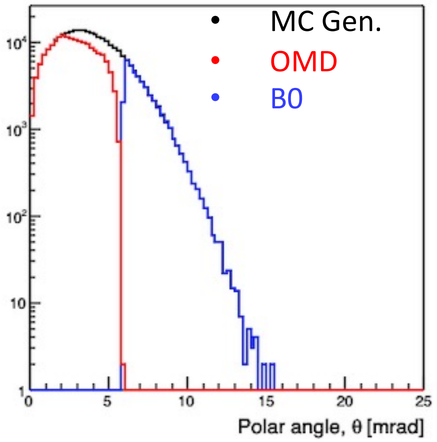
Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)

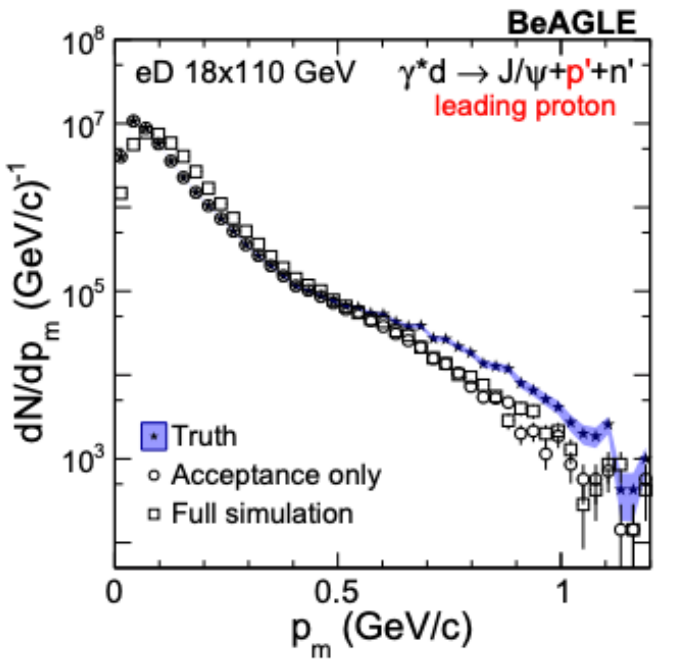



"active" protons

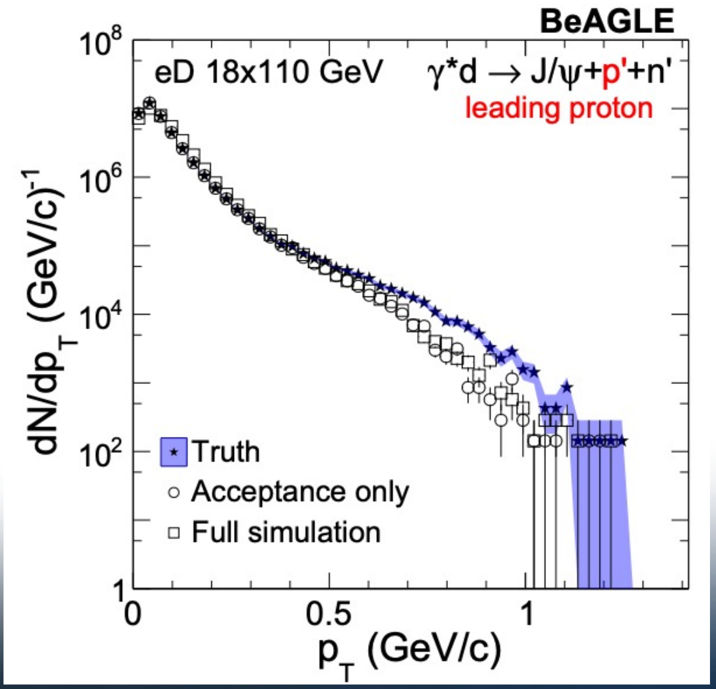



"active" protons




Missing 3-momentum from neutron spectator



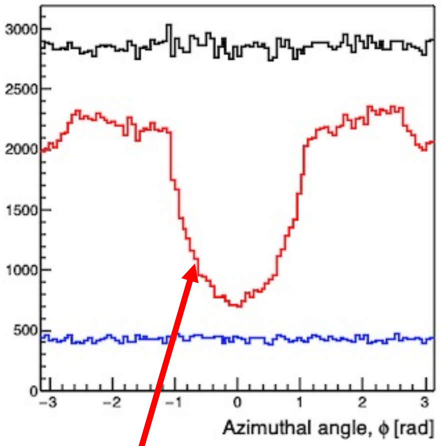

Transverse momentum from neutron spectator

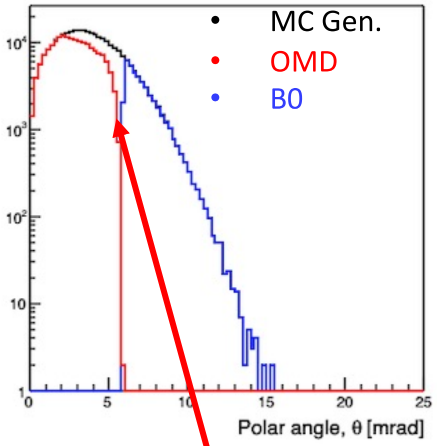
# Short-Range Correlations in Deuterons

Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)

18x110GeV

**"active" protons** **"active" protons**

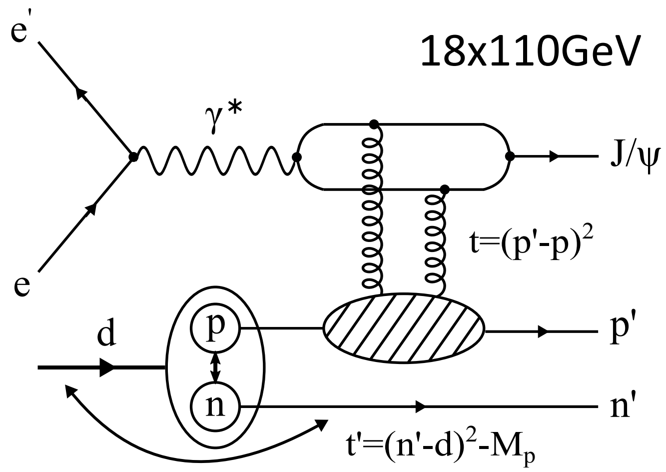



Off-momentum protons lost in quadrupole magnets.

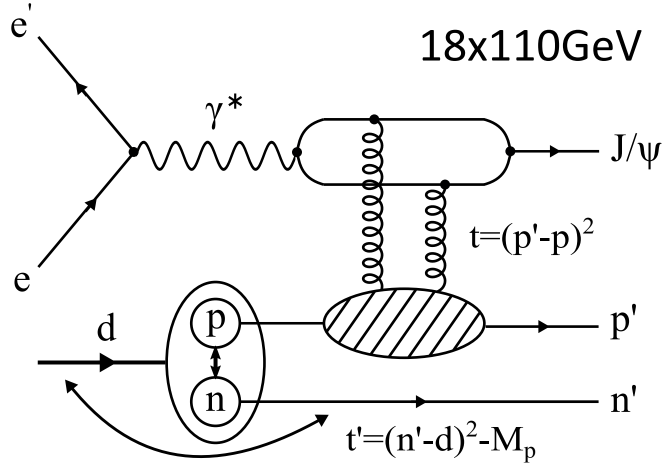
Protons lost in transition between very far-forward detectors and B0 spectrometer.

**Neutron "spectator" case.**

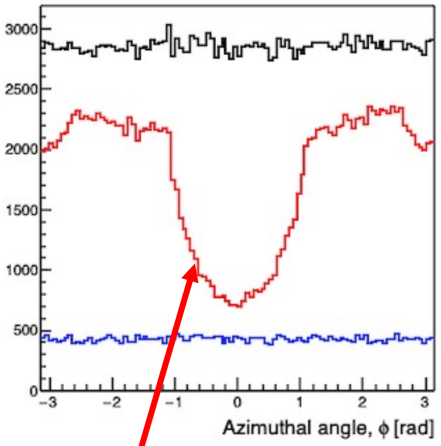


# Short-Range Correlations in Deuterons

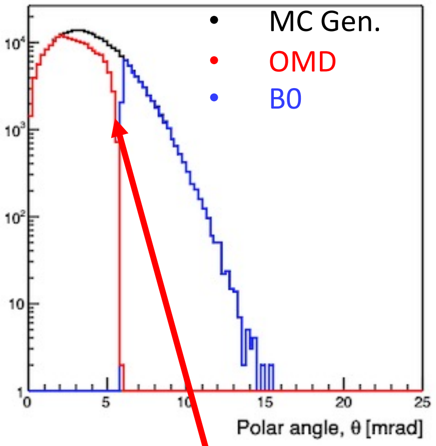
Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)




**"active" protons**



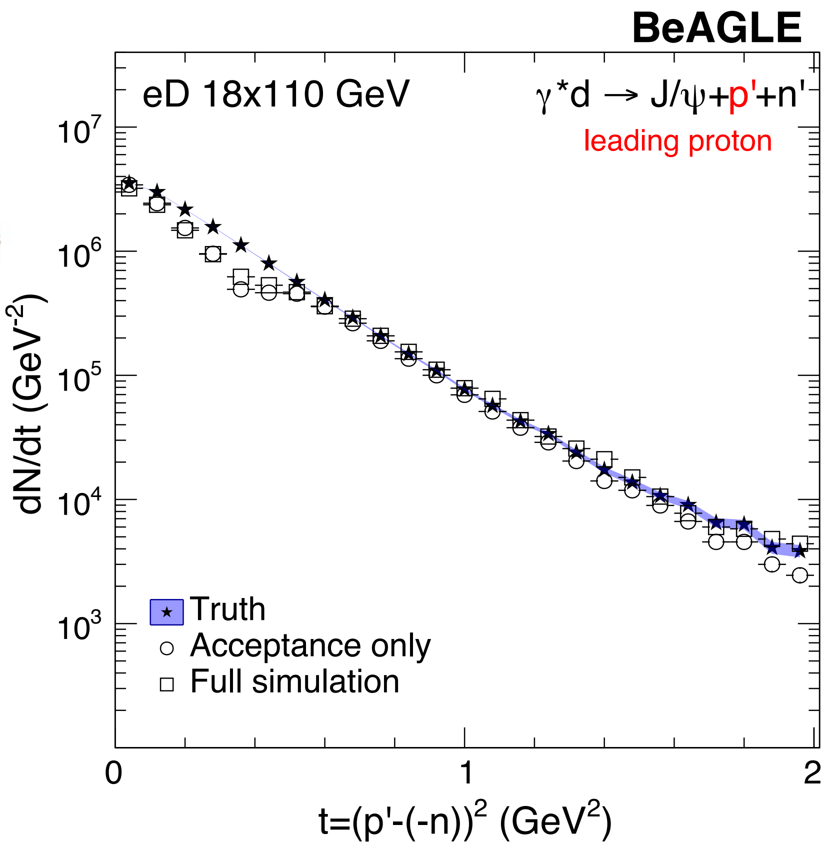

**"active" protons**




Off-momentum protons lost in quadrupole magnets.

Protons lost in transition between very far-forward detectors and B0 spectrometer.

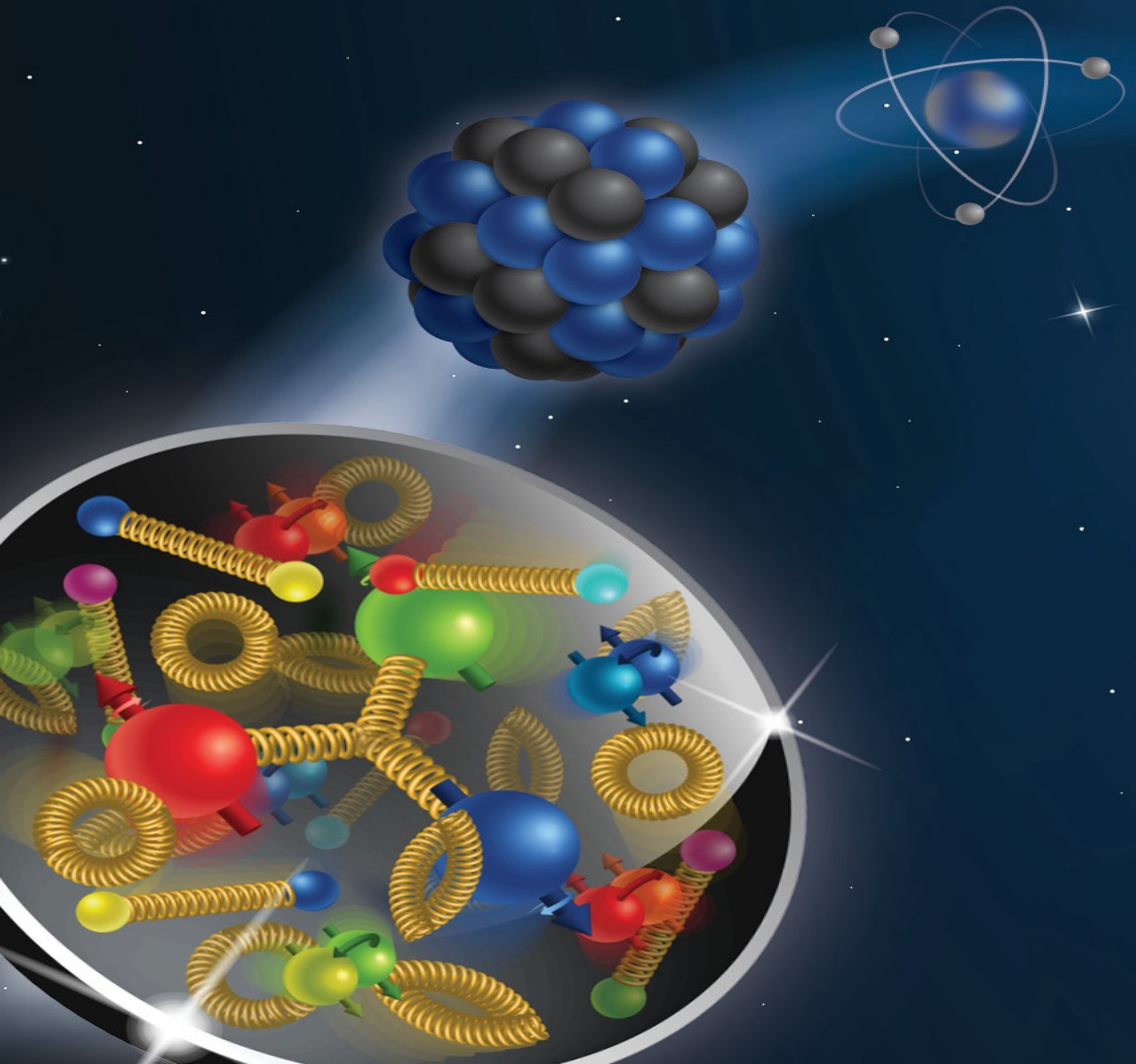
**Neutron "spectator" case.**




**t-reconstruction** using double-tagging (both proton and neutron reconstructed).

➢ **Spectator information is the "dial" for the SRC region.**

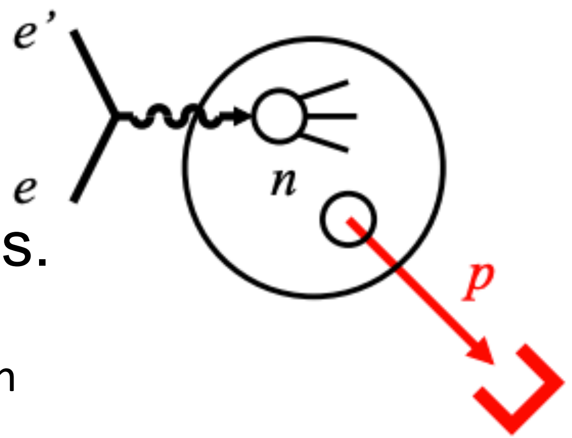
# Deutrerons: Free Neutron Structure



# Neutron Structure

See talk by K. Wichmann

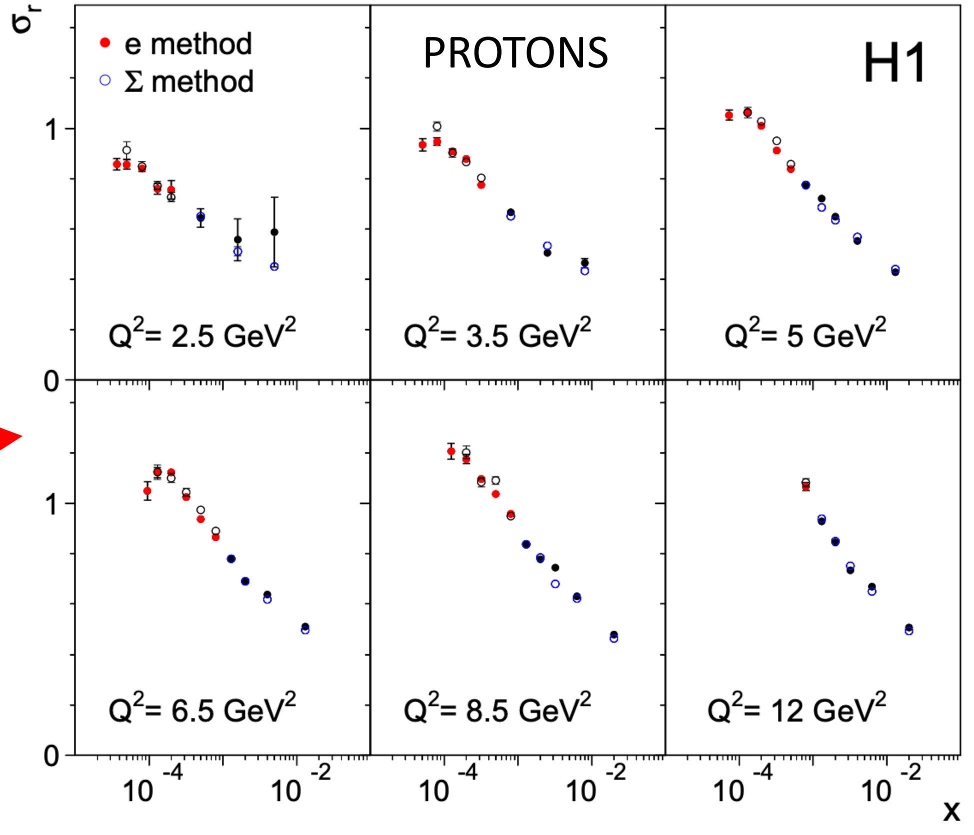
- Protons well-studied at HERA -> So…why the neutron?
  - Flavor separation, baseline for studies of nuclear modifications.




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

Reduced cross section

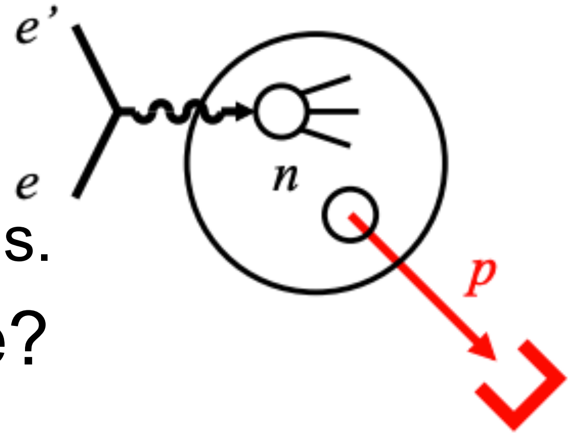
"Flux factor" — Differential cross section — Structure functions




Some useful HERA references for measurements on proton

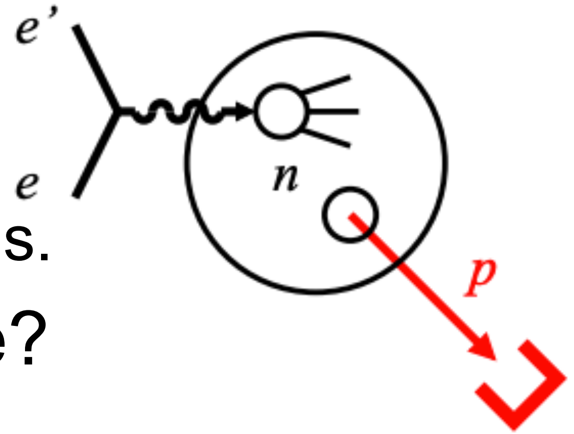
- F. Aaron *et al.* (H1 Collaboration), The European Physical Journal C volume 63, Article number: 625 (2009)
- V. Andreev *et al.* (H1 Collaboration), *Eur.Phys.J.C* 74 (2014) 4, 2814
- H. Abramowicz *et al.* (H1 and ZEUS Collaborations) *The European Physical Journal C* **volume 75**, Article number: 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.

- **Two options:**
  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 control configuration of nucleons (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 Structure

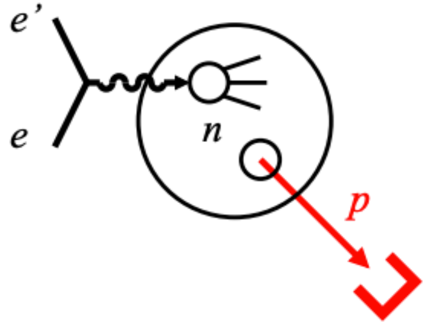
- Previous fixed target experiments with tagging have measured the neutron $F_2$ at high-x.
  - CLAS - Phys. Rev. Lett. **108**, 199902 (2012)
  - CLAS + BONUS - Phys. Rev. C 89, 045206 (2014)
    - **measurement had a lower $p_T$ cutoff ~ 70 MeV/c (fixed target limitations).**
- Future JLAB 12 GeV studies planned.
  - ALERT - https://arxiv.org/abs/1708.00891
  - CLAS - https://www.jlab.org/exp_prog/proposals/10/PR12-06-113-pac36.pdf
- **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 $x \lesssim 0.1$.

# Tagged Deuteron Cross Section

$\alpha_p$: light-cone momentum fraction

$$\alpha_p \equiv \frac{2p_p^+}{p_d^+} = \frac{2(E_p + p_{z,p})}{M_d}$$

$S_d$: deuteron spectral function pole




spectator nucleon $(p_{pT}, \alpha_p)$

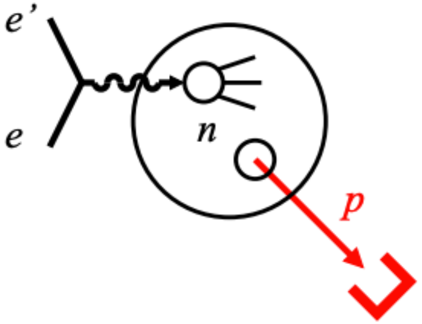
Total cross section $d\sigma = Flux(x, Q^2) \times \sigma_{red,d} \times \frac{dx}{2} dQ^2 \frac{d\phi_{e\prime}}{2\pi} [2(2\pi)^3]^{-1} \frac{d\alpha_p}{\alpha_p} \frac{dp_{pT}^2}{2} d\phi_p$

# Tagged Deuteron Cross Section

$\alpha_p$: light-cone momentum fraction

$$\alpha_p \equiv \frac{2p_p^+}{p_d^+} = \frac{2(E_p + p_{z,p})}{M_d}$$

$S_d$: deuteron spectral function pole




spectator nucleon $(p_{pT}, \alpha_p)$

Total cross section $$d\sigma = Flux(x,Q^2)\times \sigma_{red,d}\times \frac{dx}{2}dQ^2\frac{d\phi_{e'}}{2\pi}[2(2\pi)^3]^{-1}\frac{d\alpha_p}{\alpha_p}\frac{dp_{pT}^2}{2}d\phi_p$$

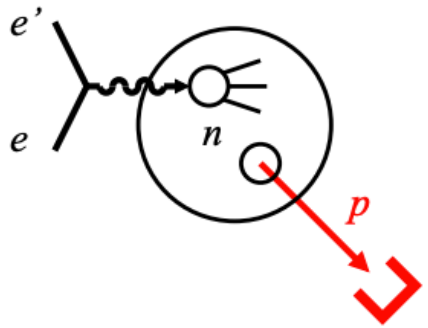
- Measure the cross-section differential on the spectator kinematics.
  - Spectator kinematics provide control knob on the nuclear configuration.
- Solve for the deuteron reduced cross section.

# Tagged Deuteron Cross Section

$\alpha_p$: light-cone momentum fraction

$$\alpha_p \equiv \frac{2p_p^+}{p_d^+} = \frac{2(E_p + p_{z,p})}{M_d}$$

$S_d$: deuteron spectral function pole




spectator nucleon $(p_{pT}, \alpha_p)$

Total cross section $$d\sigma = Flux(x,Q^2)\times \sigma_{red,d} \times \frac{dx}{2} dQ^2 \frac{d\phi_{e'}}{2\pi} [2(2\pi)^3]^{-1} \frac{d\alpha_p}{\alpha_p} \frac{dp_{pT}^2}{2} d\phi_p$$

- Measure the cross-section differential on the spectator kinematics.
  - Spectator kinematics provide control knob on the nuclear configuration.
- Solve for the deuteron reduced cross section.
- Deuteron reduced cross section related to the struck nucleon reduced cross section via the deuteron spectral function.

$$\sigma_{red,d}(x,Q^2;\, p_{pT},\alpha_p) = [2(2\pi)^3] \times S_d(p_{pT},\alpha_p)[pole] \times \sigma_{red,n}(x,Q^2)$$

What we measure directly.

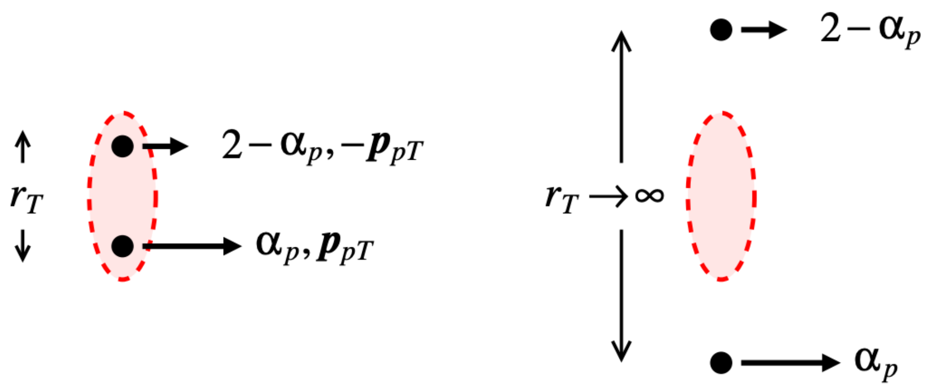
Theory assumption (e.g. wave function parametrization).

The thing we actually want!

M. Strikman and C. Weiss, Phys. Rev. C 97, 035209 (2018)

# 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

- Divide by deuteron spectral function (nucleon pole).
  - The resulting distribution is the active nucleon reduced cross section as a function of $p_{pT}^2$.

$$\sigma_{red,n}(x, Q^2) = \frac{\sigma_{red,d}(x, Q^2;\, p_{pT}, \alpha_p)}{[2(2\pi)^3] S_d(p_{pT}, \alpha_p)[pole]}$$

$$S_d(p_{pT}, \alpha_p)[pole] = \frac{R}{\left(p_{pT}^2 + a_T^2\right)^2}$$

Deuteron spectral function

$$R = 2\alpha_p^2 m_N \Gamma^2(2-\alpha_p)$$

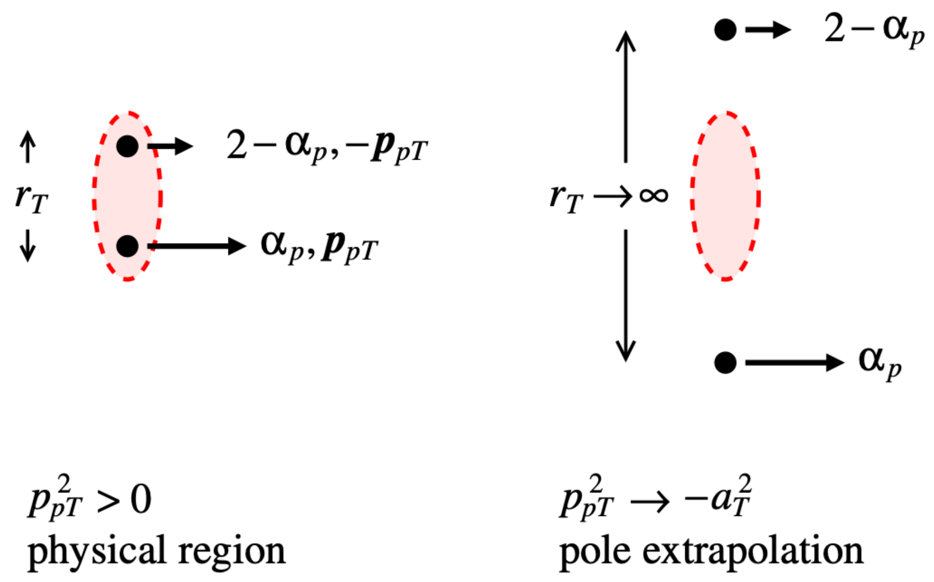
$$a_T^2 = m_N^2 - \alpha_p(2-\alpha_p)\frac{M_d^2}{4}$$

$R = residue\ of\ spectral\ function$

$a_T^2 = position\ of\ pole$

# Pole Extrapolation

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




- Divide by deuteron spectral function (nucleon pole).
  - The resulting distribution is the active nucleon reduced cross section as a function of $p_{pT}^2$.

$$\sigma_{red,n}(x, Q^2) = \frac{\sigma_{red,d}(x, Q^2;\ p_{pT}, \alpha_p)}{[2(2\pi)^3] S_d(p_{pT}, \alpha_p)[pole]}$$

$$S_d(p_{pT}, \alpha_p)[pole] = \frac{R}{(p_{pT}^2 + a_T^2)^2}$$ Deuteron spectral function

$$R = 2\alpha_p^2 m_N \Gamma^2 (2-\alpha_p)$$

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

$R = residue\ of\ spectral\ function$

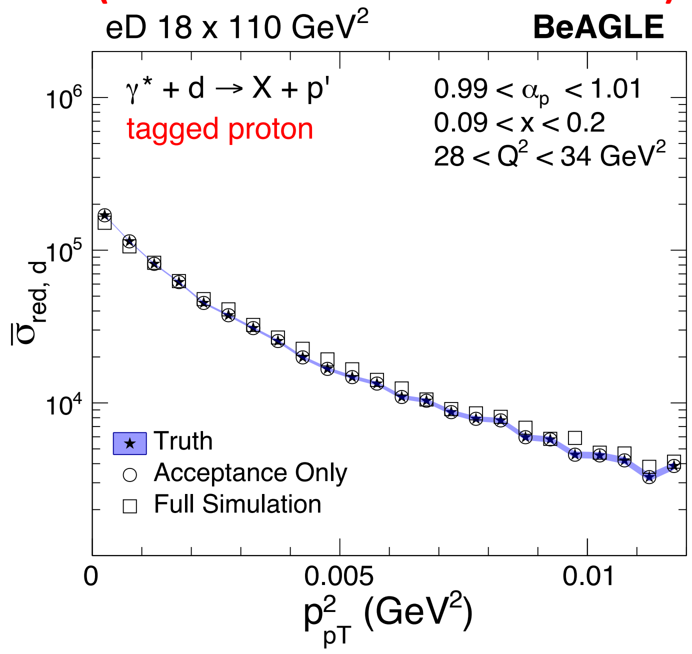
$a_T^2 = position\ of\ pole$

- Extrapolate $p_{pT}^2 \to -a_T^2$ to extract free nucleon $F_2$.
  - Pole extrapolation selects large-size pn configurations where nuclear binding and FSI are absent.

# 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)**

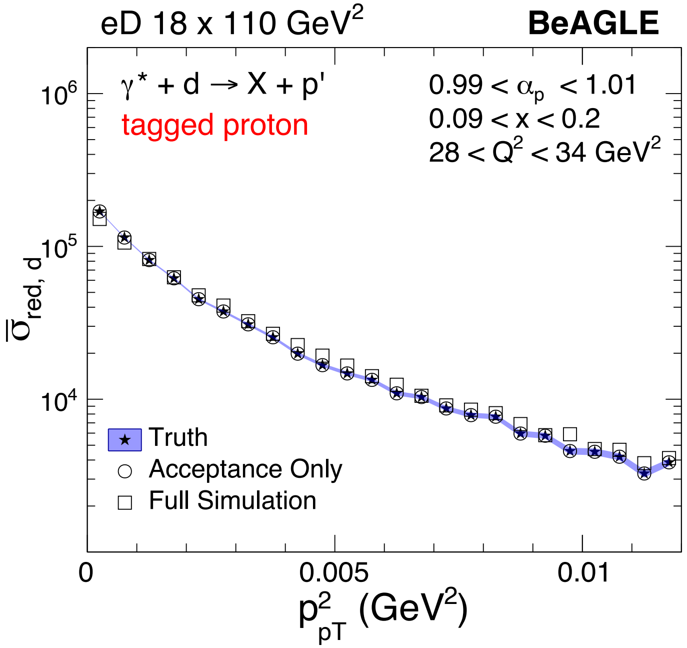



- Start with the deuteron reduced cross section → **direct measurement!**

# 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)**




- Start with the deuteron reduced cross section → direct measurement!
- Multiply by the inverse of the deuteron spectral function pole.

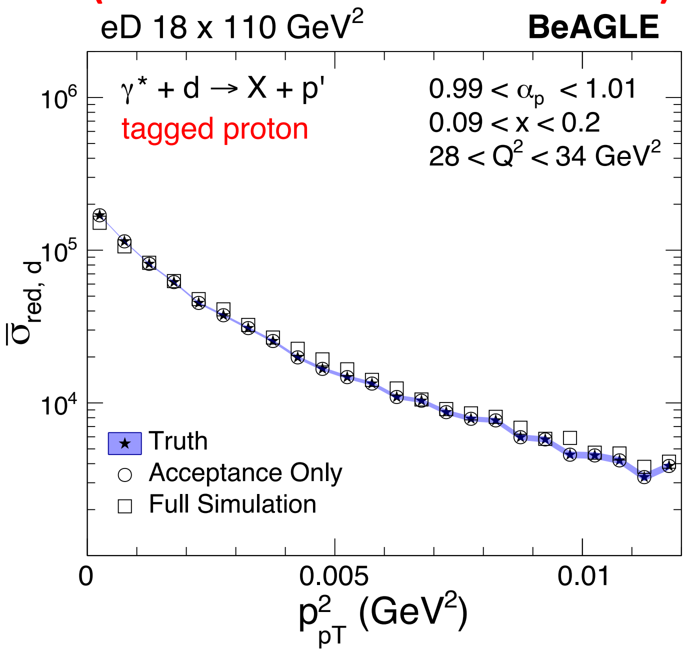
$$\times \quad \frac{1}{S_d(p_{pT}, \alpha_p)[pole]}$$

**(inverse pole of deuteron spectral function)**

# Free Neutron $F_2$ Extraction

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

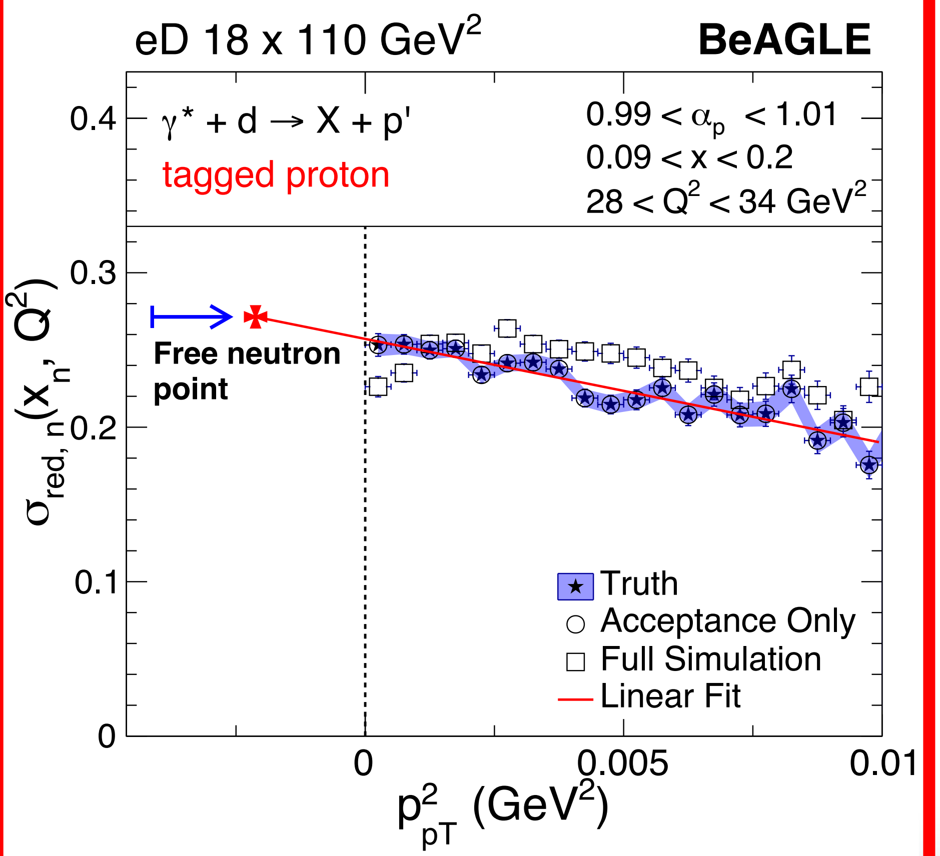
**(deuteron reduced cross section)**




**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)**

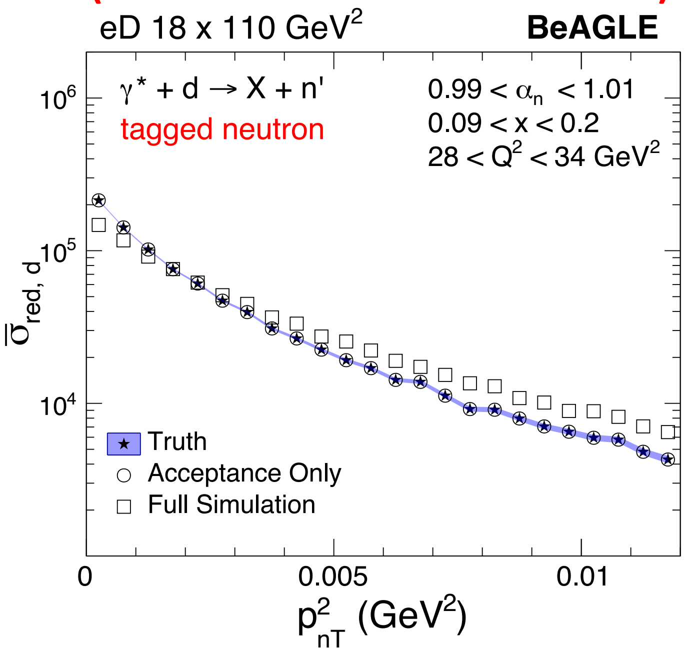
$$\sigma_{red,n}(x, Q^2) = \frac{\sigma_{red,d}}{[2(2\pi)^3]S_d(p_{pT}, \alpha_p)}$$

- Generator-level (purple) enables direct comparison to input inclusive cross-section for validation of procedure.

# Free Proton $F_2$ Extraction

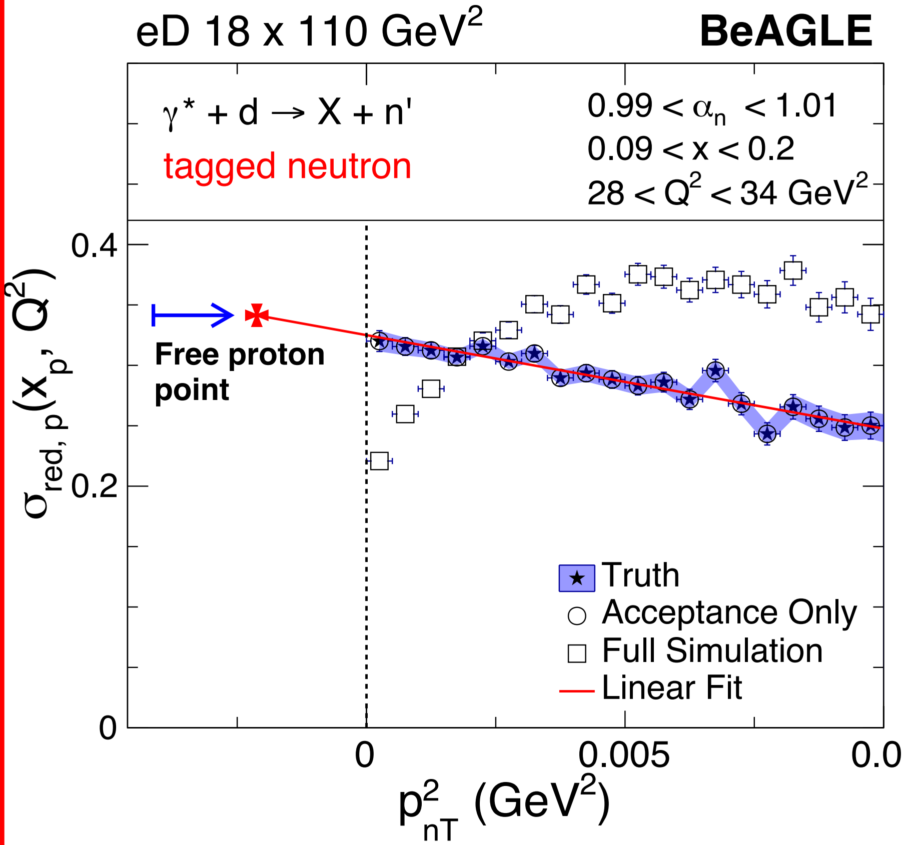
A. Jentsch, Z. Tu, and C. Weiss, Phys. Rev. C **104,** 065205, (2021) **(Editor's Suggestion)**

**(deuteron reduced cross section)**




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

**(inverse pole of deuteron spectral function)**



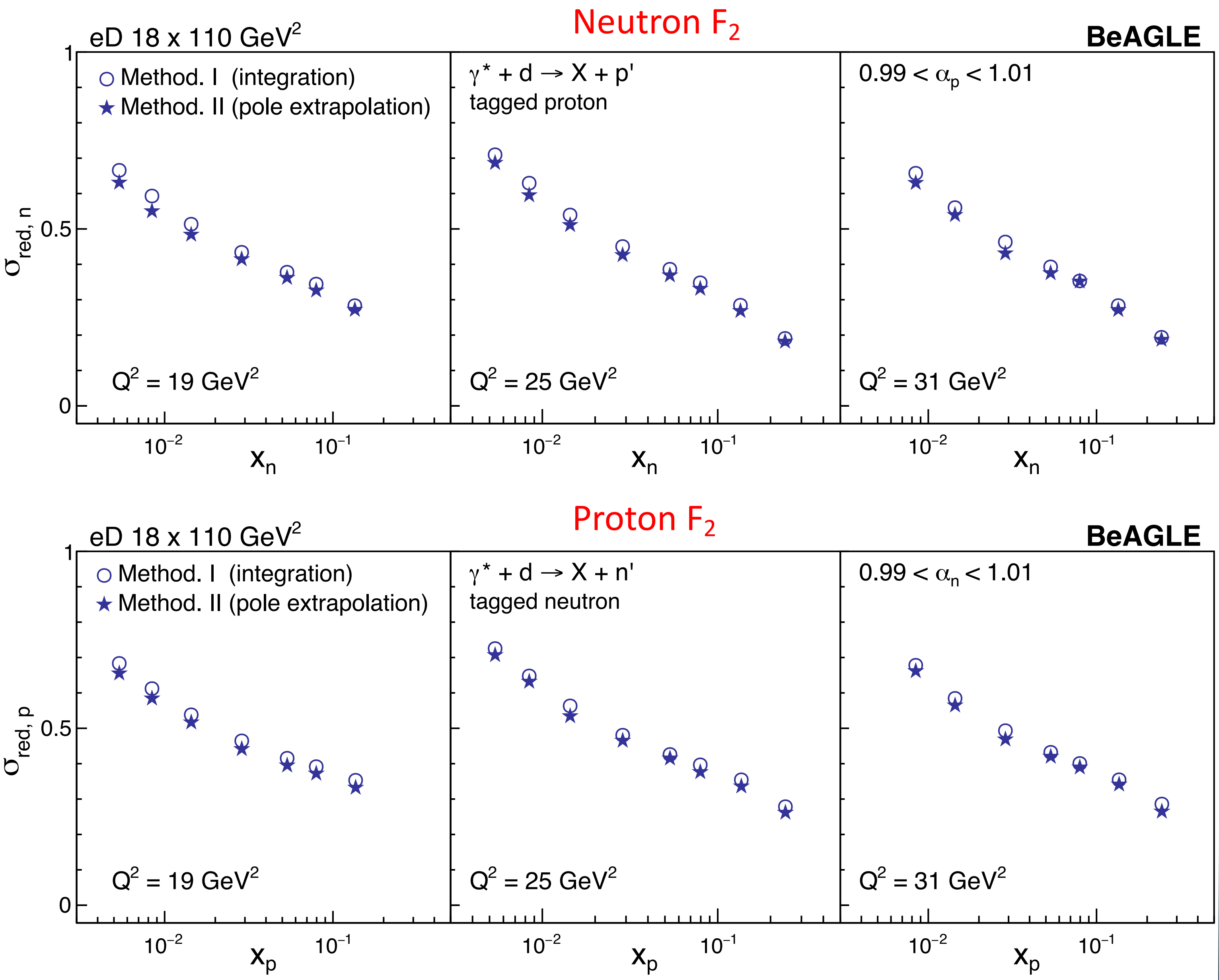

**(Active nucleon reduced cross section)**

$$\sigma_{red,p}(x, Q^2) = \frac{\sigma_{red,d}}{[2(2\pi)^3]S_d(p_{nT}, \alpha_n)}$$

- Measurement of ***proton*** $\mathbf{F_2}$ using this method provides ability to directly estimate systematics for extrapolation procedure, since proton $F_2$ directly measurable in e+p scattering!

# Free Nucleon Structure

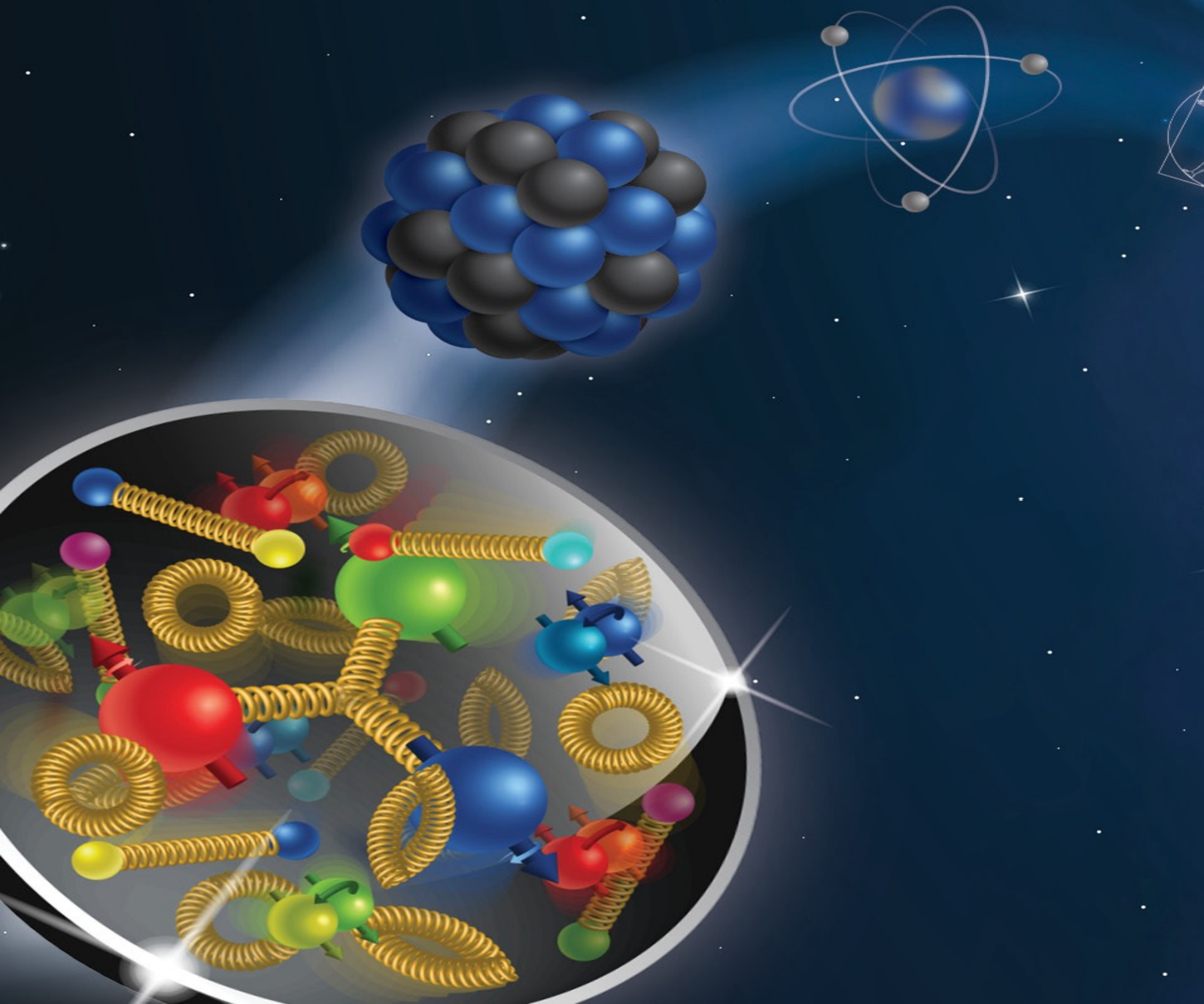
A. Jentsch, Z. Tu, and C. Weiss, Phys. Rev. C **104,** 065205, (2021) **(Editor's Suggestion)**




<u>**Open circles:**</u> "inclusive" measurement.
<u>**Stars:**</u> pole extrapolation procedure.

**Differences driven by evaluation of pole fucntion (average in bin, vs. event-by-event).**

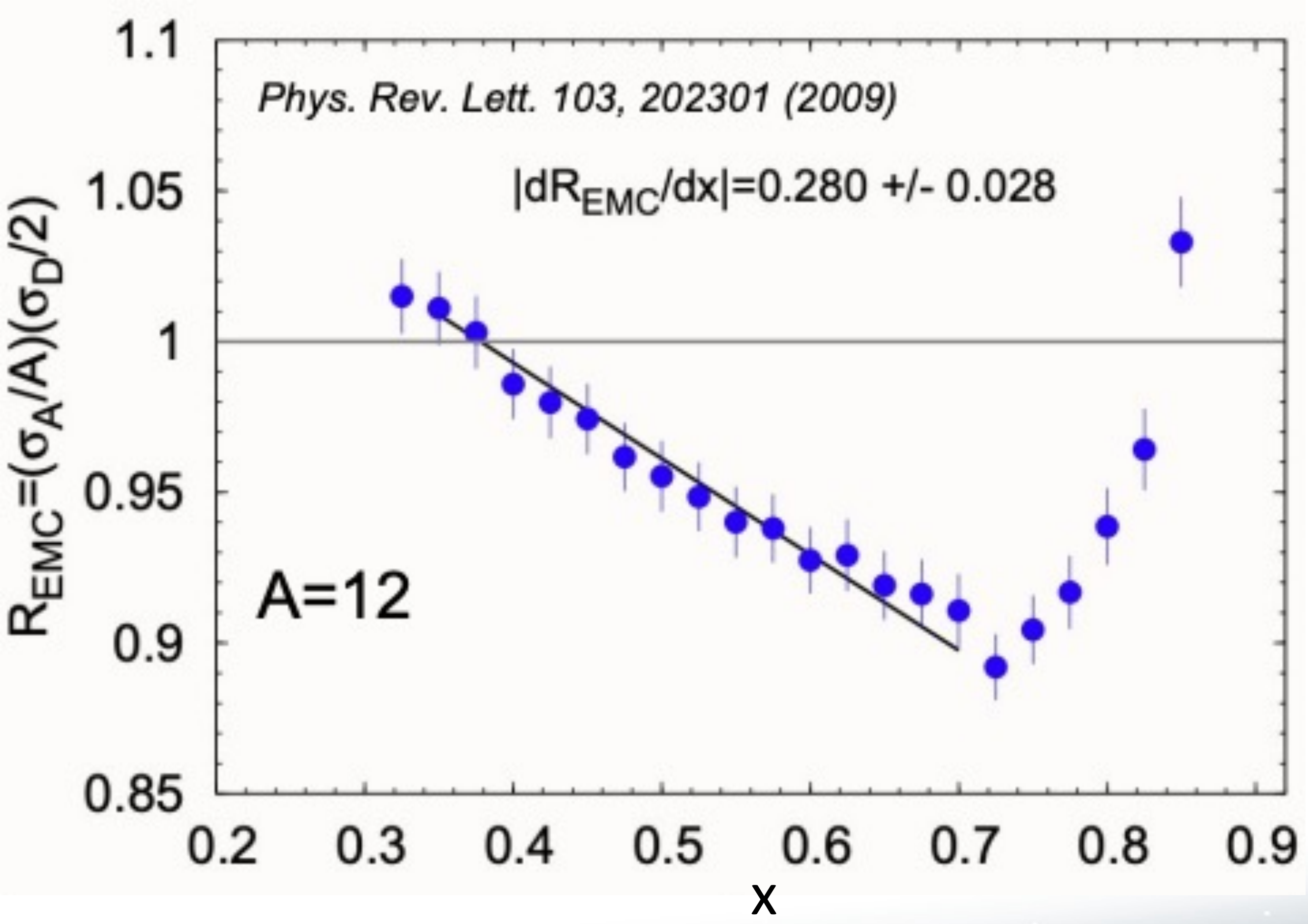
- Similar kinds of high-precision results achievable as was done for proton $F_2$ at HERA!
- Only ~ 1 $fb^{-1}$ of integrated luminosity needed!



# Deuterons:
# The EMC Effect
# (on-going study)

# The EMC Effect

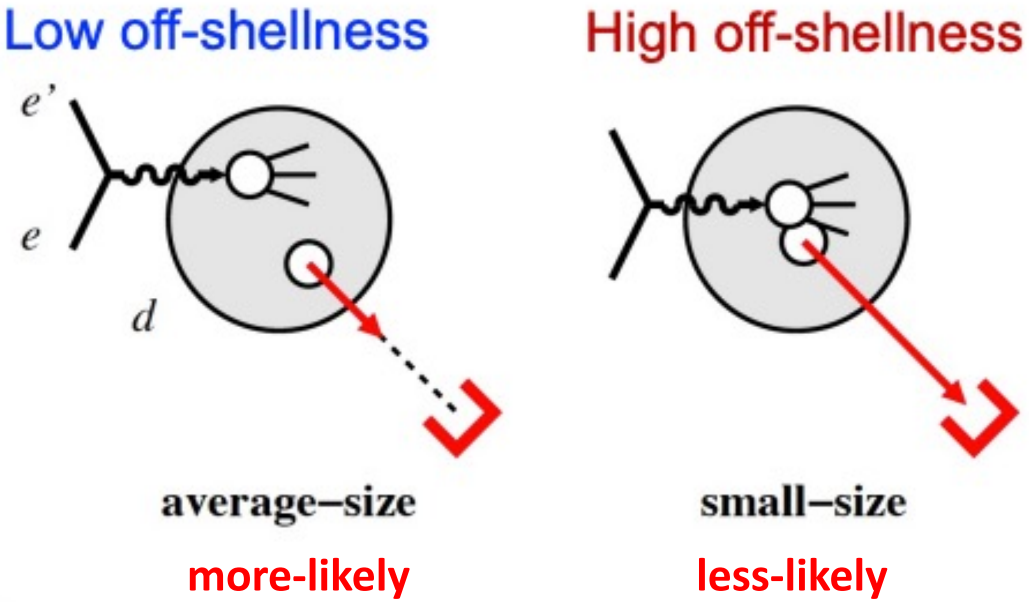
- Discovered by the European Muon Collaboration ~40 years ago.
  - Puzzle: why the dip?
- Still an unanswered question, and one we hope the EIC can aid in answering.
- Established via measurements with different nuclear targets!

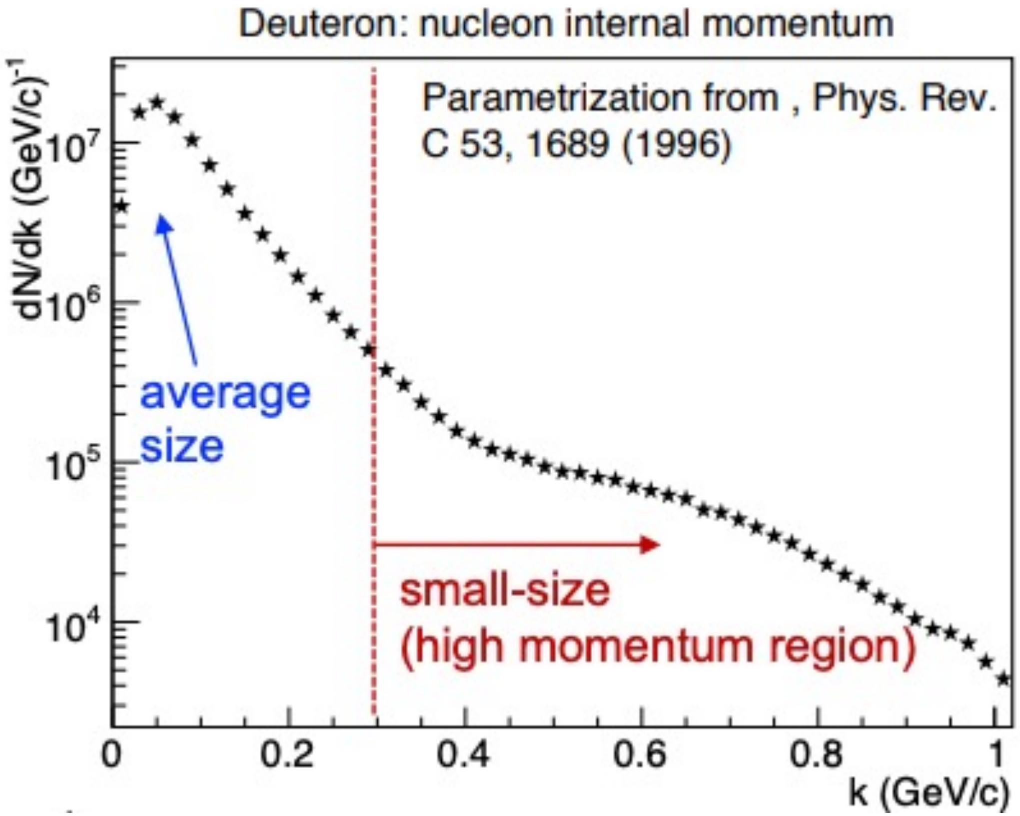


# The EMC Effect

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

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



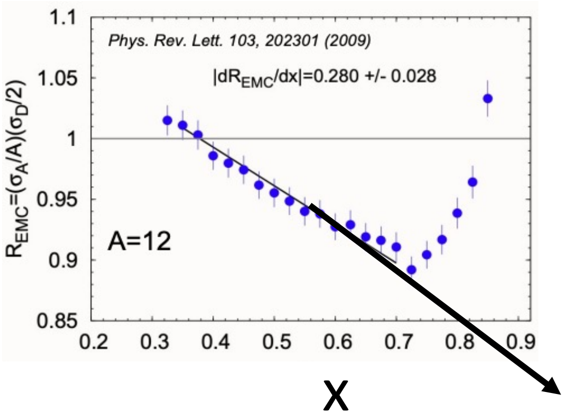

$$-t'^2 = M_N^2 - (p_d - p_p)^2$$

Virtuality/off-shellness in the deuteron

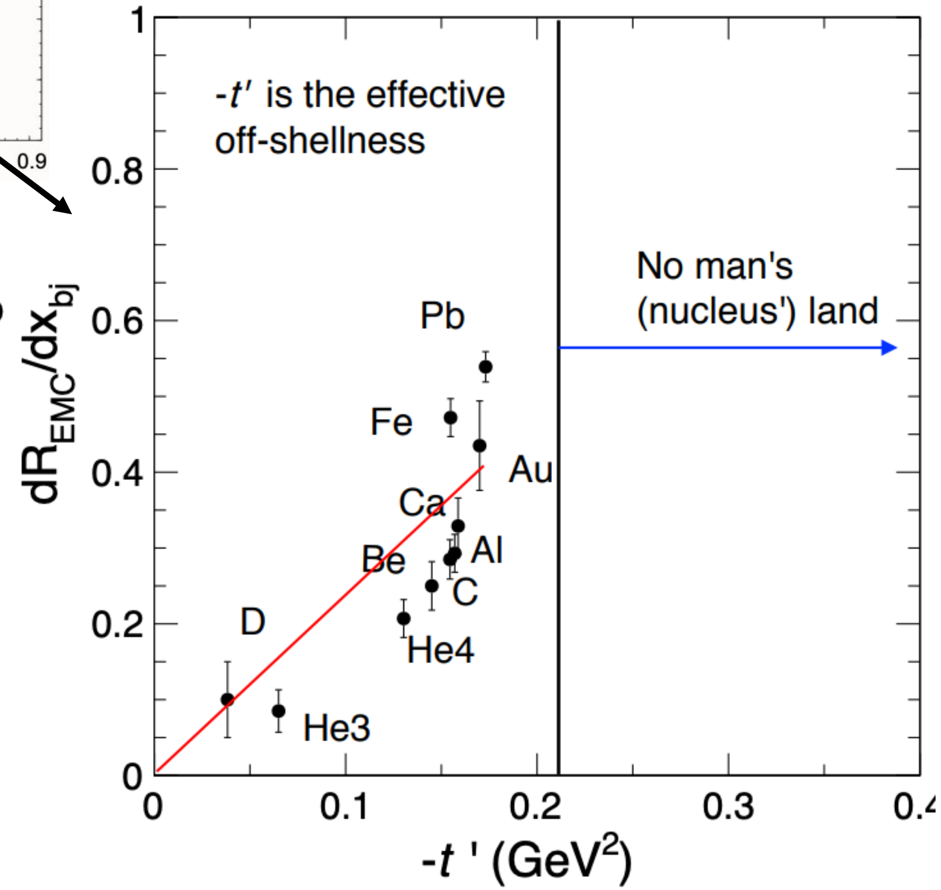
**Question:** can the EMC effect be controlled via the off-shellness **without altering the nuclear species?**

**Our goal:** establish experimental prospects for this approach!

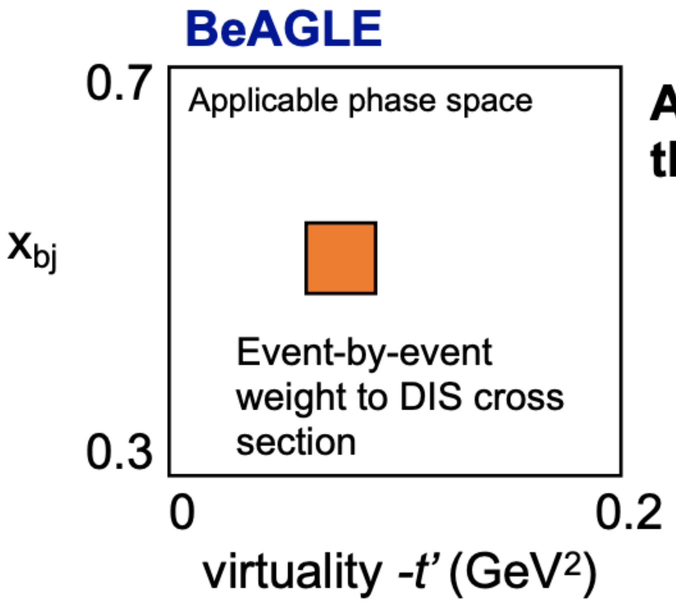
# The EMC Effect




Use EMC effect measurements from data with different nuclear targets.




**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)

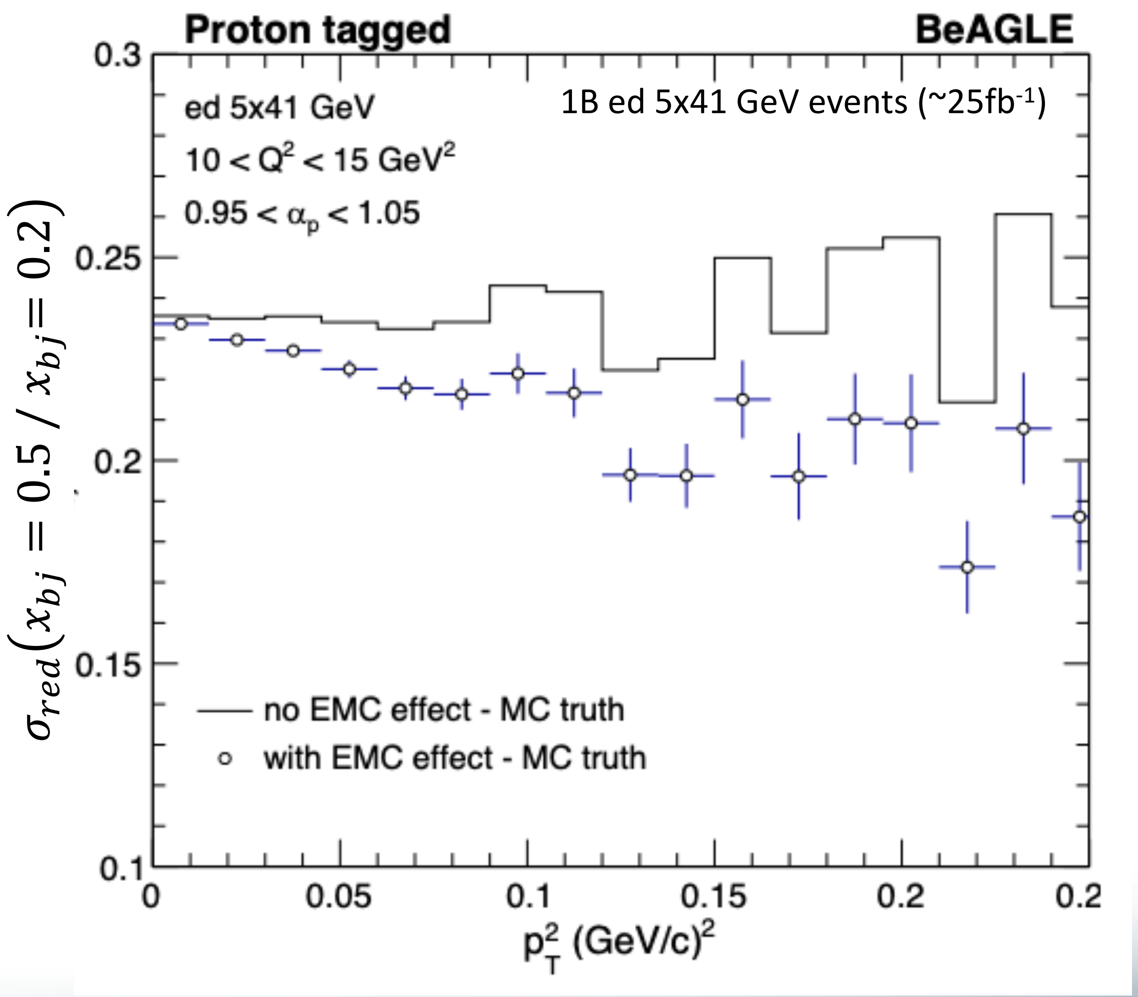
**Minimal parametrization (linear)**

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

# The EMC Effect

- <u>Current study:</u>
  - Measure reduced cross-section as in the free neutron study, with and without the off-shell effects included.
  - Take ratio of reduced cross sections in both cases of x-bins **inside and outside the EMC region** (e.g. x ~ 0.5 and x ~ 0.2)
  - Establish required integrated luminosity to provide needed sensitivity to off-shell effects.
    - **<u>Spoiler</u> – this will be a challenging measurement → high-x + low probability nuclear configuration + lower beam energies.**

Reduced cross section ratio $\frac{\sigma_{red}^{x=0.5}}{\sigma_{red}^{x=0.2}}$



# Summary and Takeaways

- 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!!

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

**Want to get involved?? Join our meetings and learn how!**

Meeting time: Tuesdays @ 9am EDT (bi-weekly, or weekly, as needed)

Indico: https://indico.bnl.gov/category/407/

Wiki: https://wiki.bnl.gov/eic-project-detector/index.php?title=Collaboration

Email-list: eic-projdet-FarForw-l@lists.bnl.gov

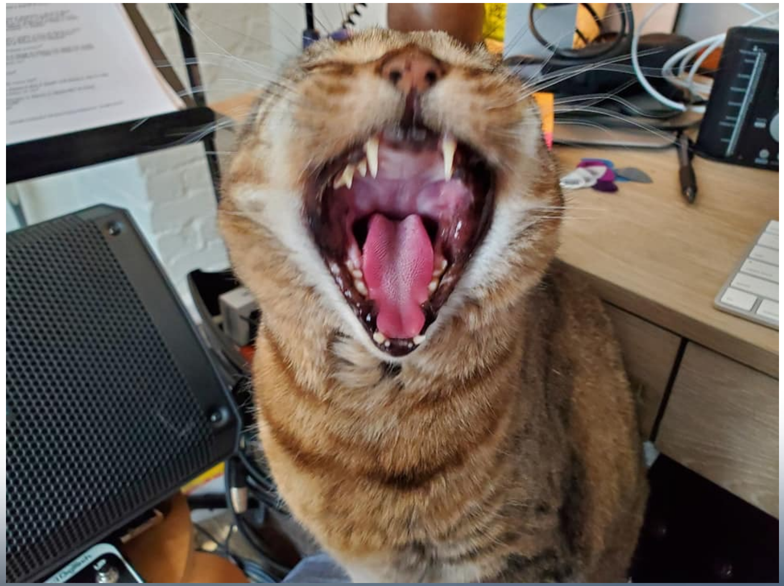
Subscribe to mailing list through: https://lists.bnl.gov/mailman/listinfo/eic-projdet-farforw-l

# Thank you!

**Julep**

They (mostly) get along.

**Lilu**

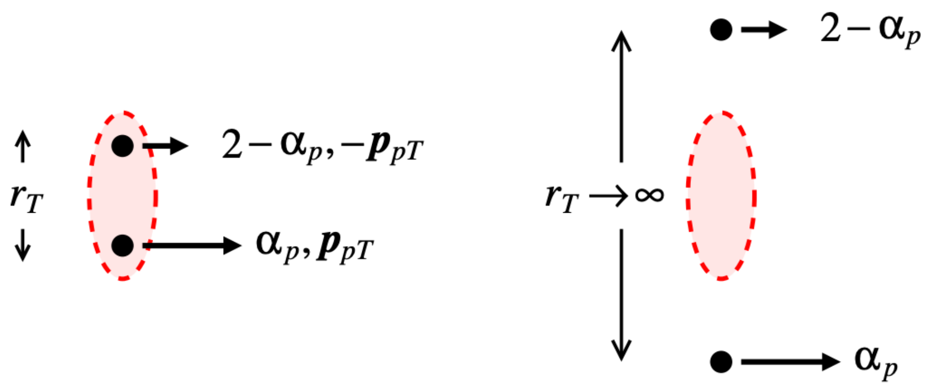


She’s in a death metal band.

# Backup

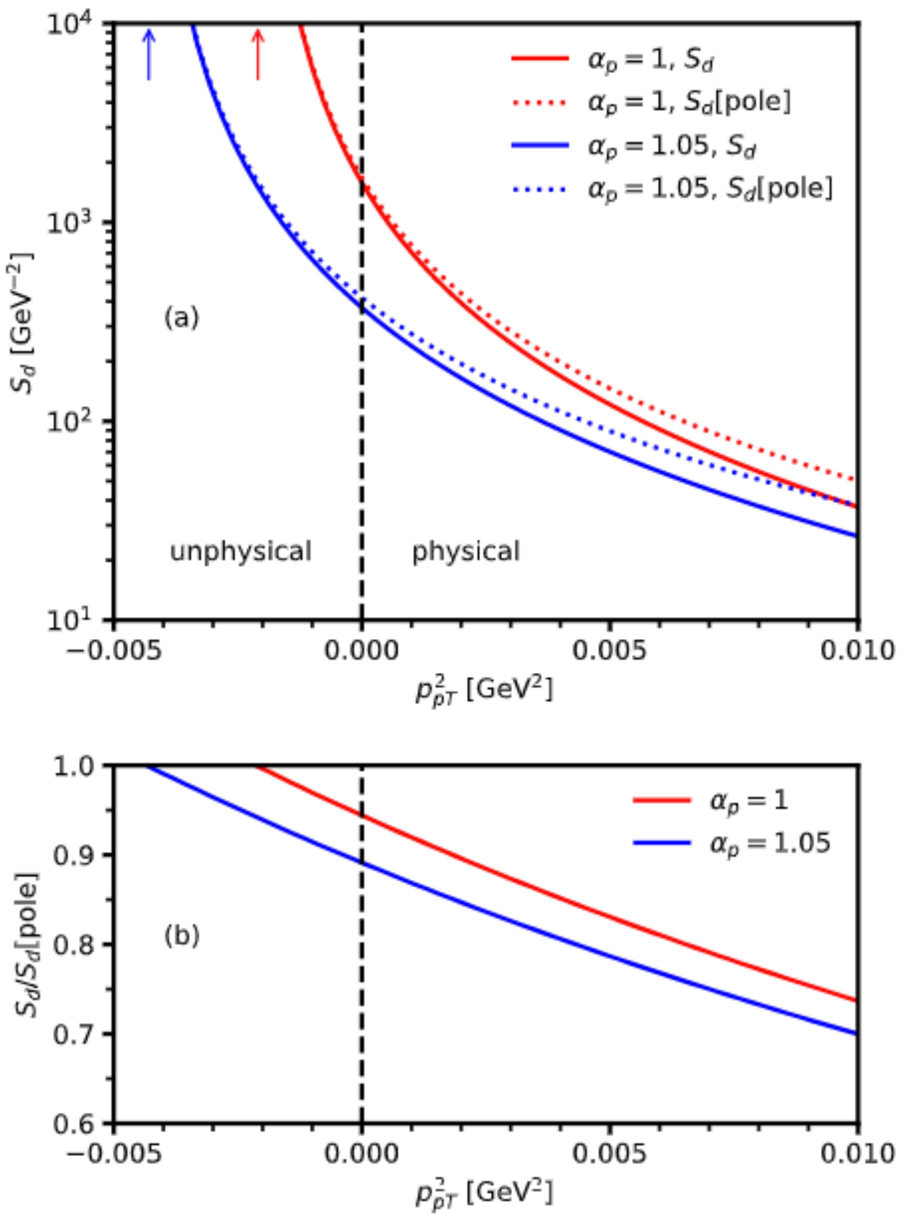
# Pole Extrapolation

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

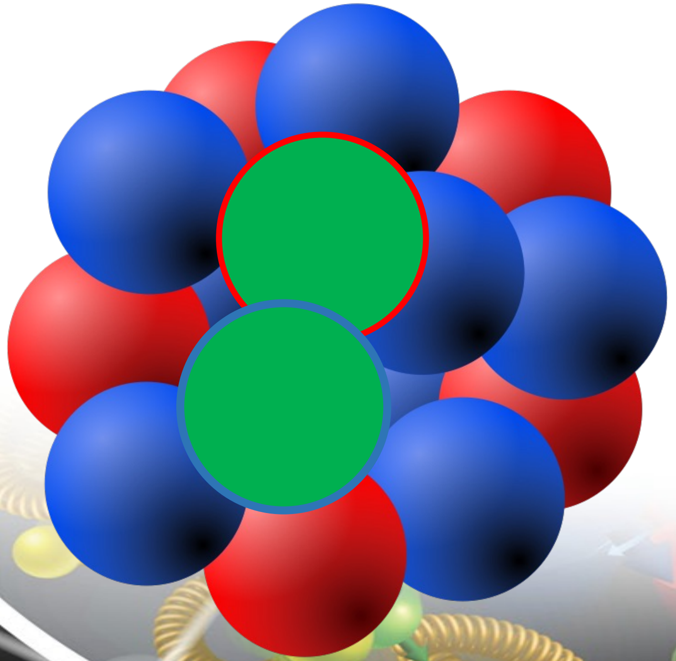


# Short-Range Correlations

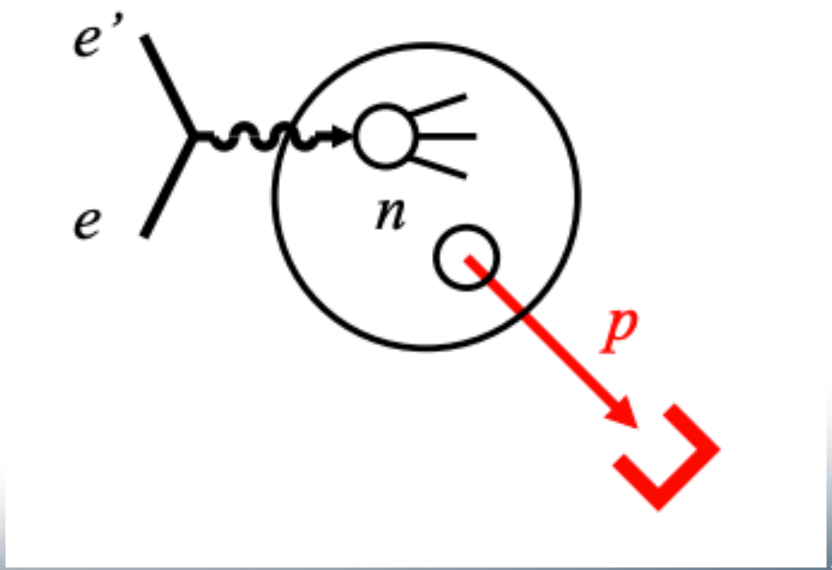
"The nucleus can often be approximated as an independent collection of protons and neutrons confined in a volume, but for short periods of time, the nucleons in the nucleus can strongly overlap. This quantum mechanical overlapping, known as a nucleon-nucleon short-range correlation, is a manifestation of the nuclear strong force, which produces not only the long-range attraction that holds matter together, but also the short-range repulsion that keeps it from collapsing."

Excerpt from: https://www.jlab.org/research/nucleon_nucleon

Lots of SRC pairs!!! -> Really tough!

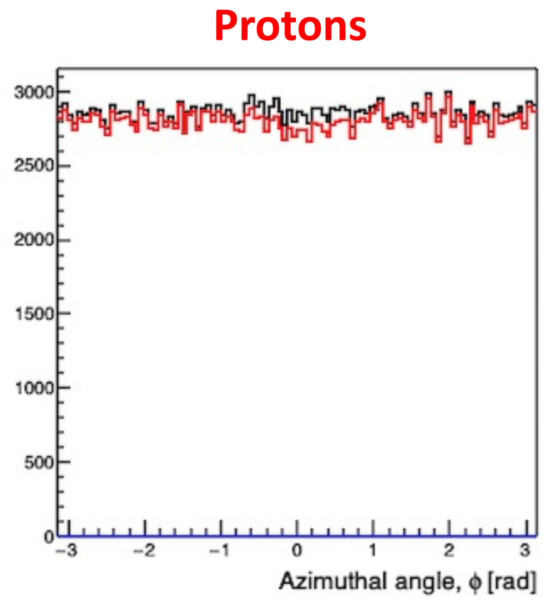


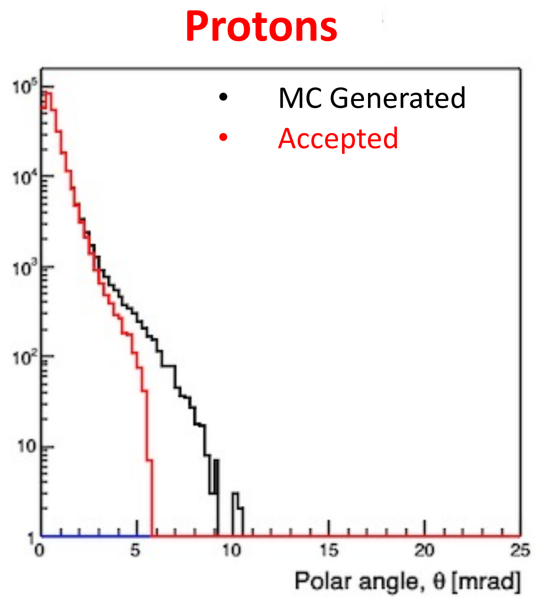
Use deuteron as "SRC laboratory", where nucleon kinematics are readily accessible.



# Short-Range Correlations in Deuterons

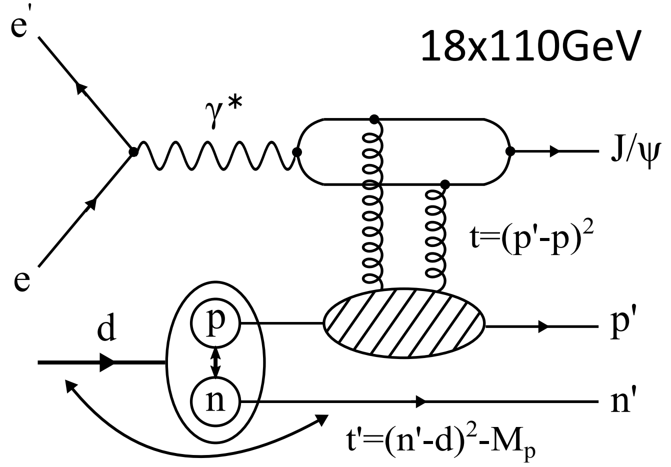
Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)




**Proton "spectator" case.**

Particular process in BeAGLE: incoherent diffractive J/$\psi$ production off bounded nucleons.

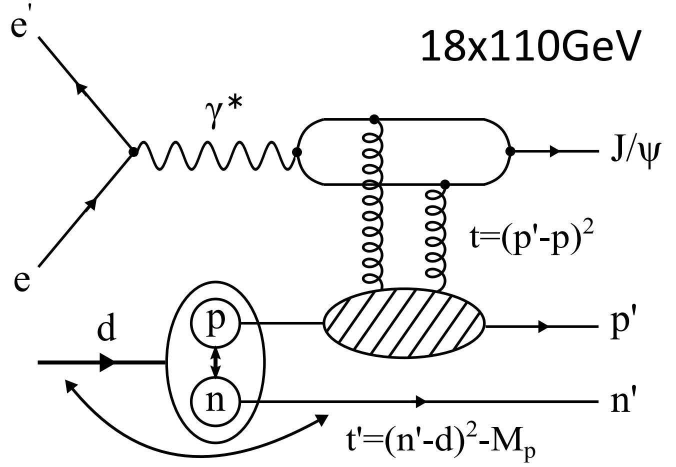



MC generated events shown in black – "accepted" protons in red.

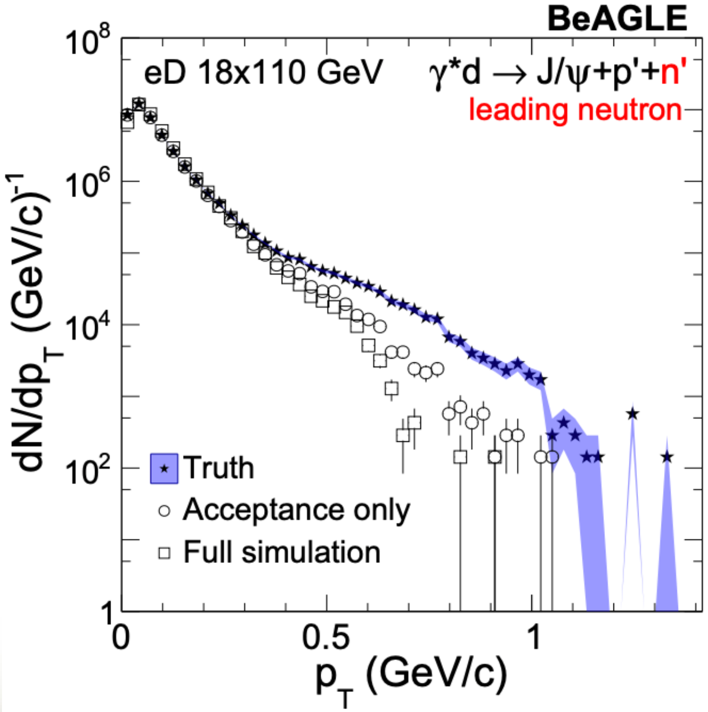
Acceptance refers to particles which are actually captured by the detector.

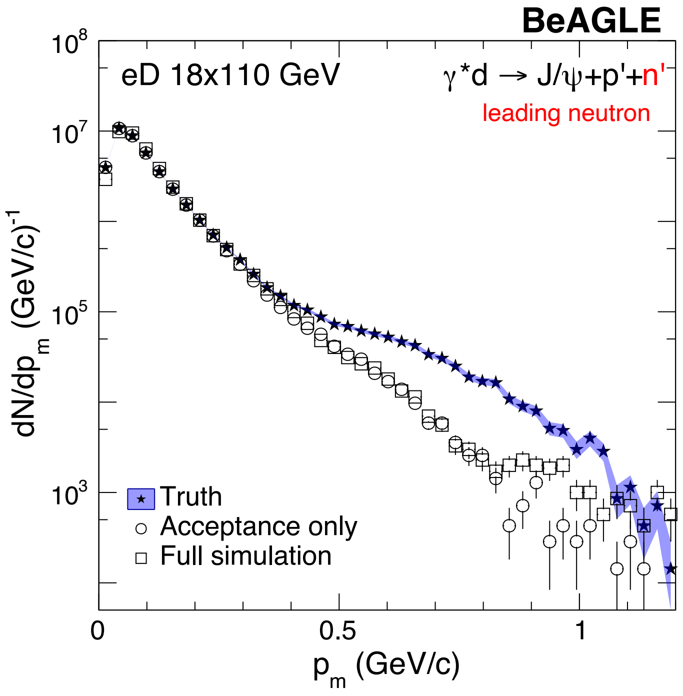
# Short-Range Correlations in Deuterons

Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)




**Proton "spectator" case.**




- Spectator kinematic variables reconstructed over a broad range.
- **All detector and beam effects included in the full GEANT simulations!**
  - Bin migration is observed due to smearing in the reconstruction.

- **In the proton spectator case, essentially all spectators tagged up to pT ~ 600 MeV/c.**
- **Active neutrons only tagged up to 4.5 mrad → double-tagging efficiency very low.**

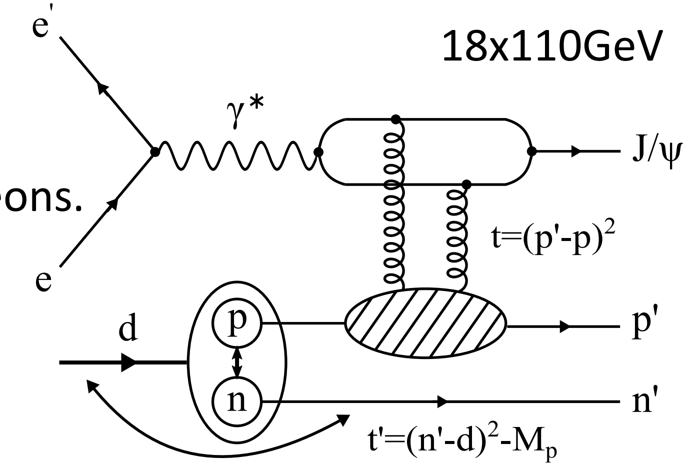
# e+d Spectator Tagging

Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)

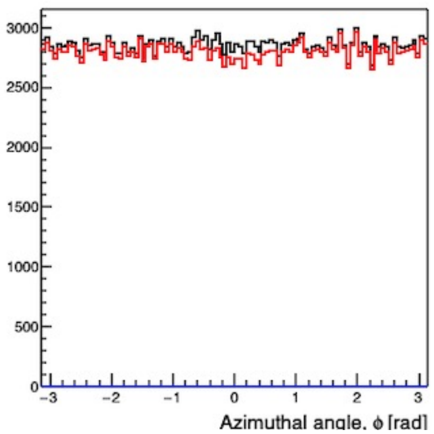
**Proton spectator case.**

Particular process in BeAGLE: incoherent diffractive J/psi production off bounded nucleons.

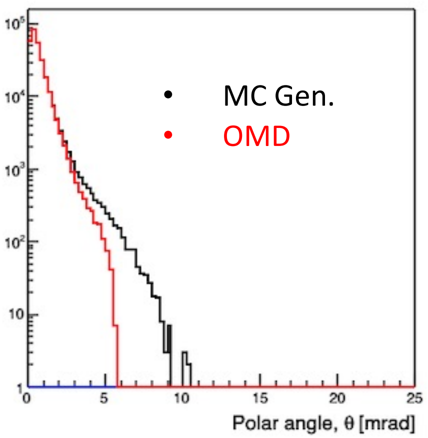
18x110GeV

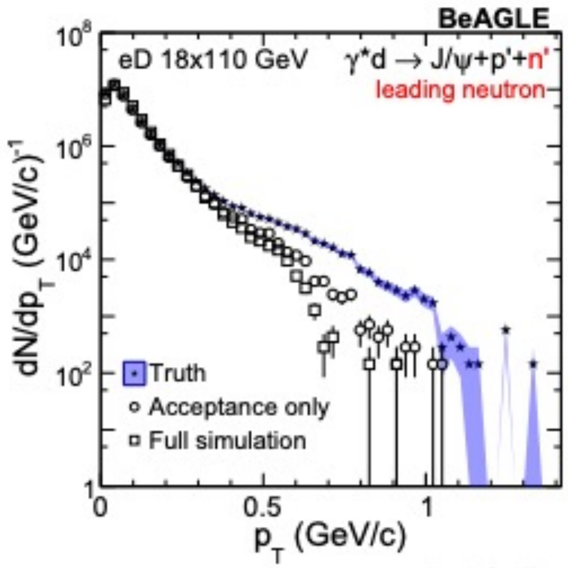


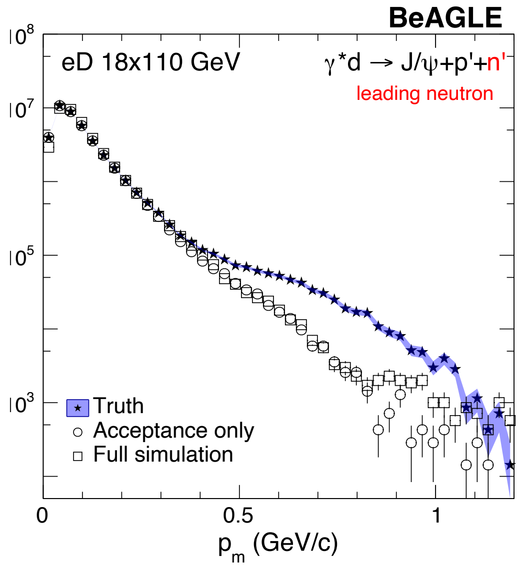

**Protons**

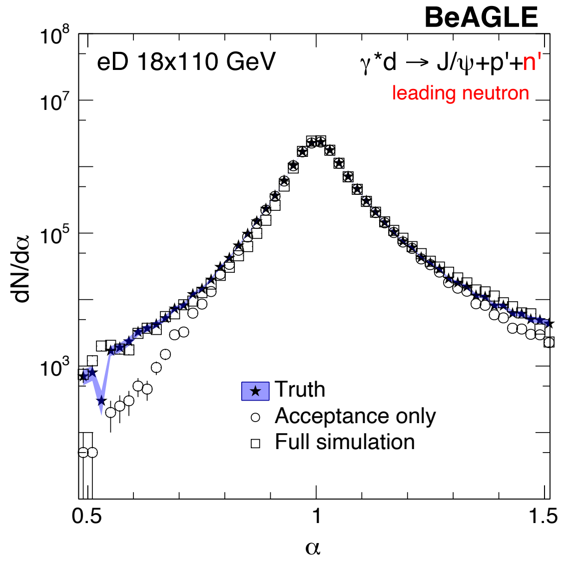



**Protons**



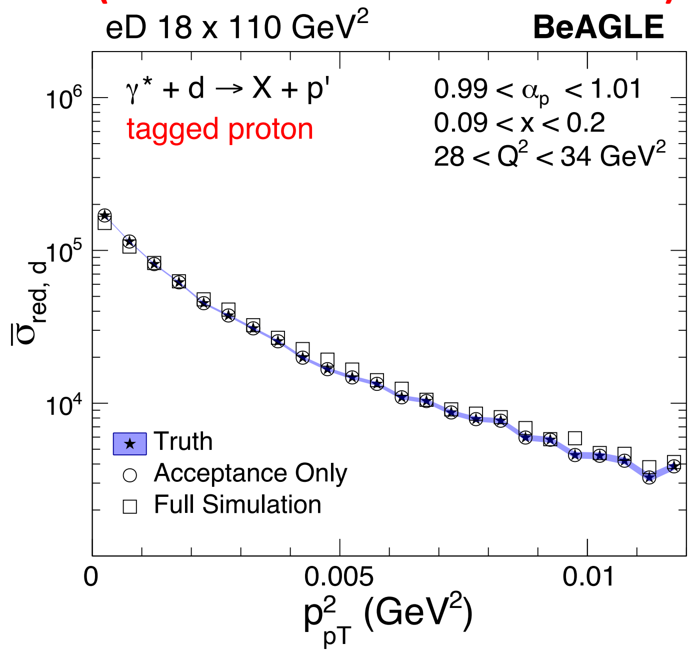

Spectator kinematic variables reconstructed over a broad range. Bin migration is observed due to smearing in the reconstruction. Each plot shows the MC (closed circles), acceptance effects only (open circles), and full reconstruction (open squares).

- **In the proton spectator case, essentially all spectators tagged.**
- **Active neutrons only tagged up to 4.5 mrad.**

# Free Neutron $F_2$ Extraction

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

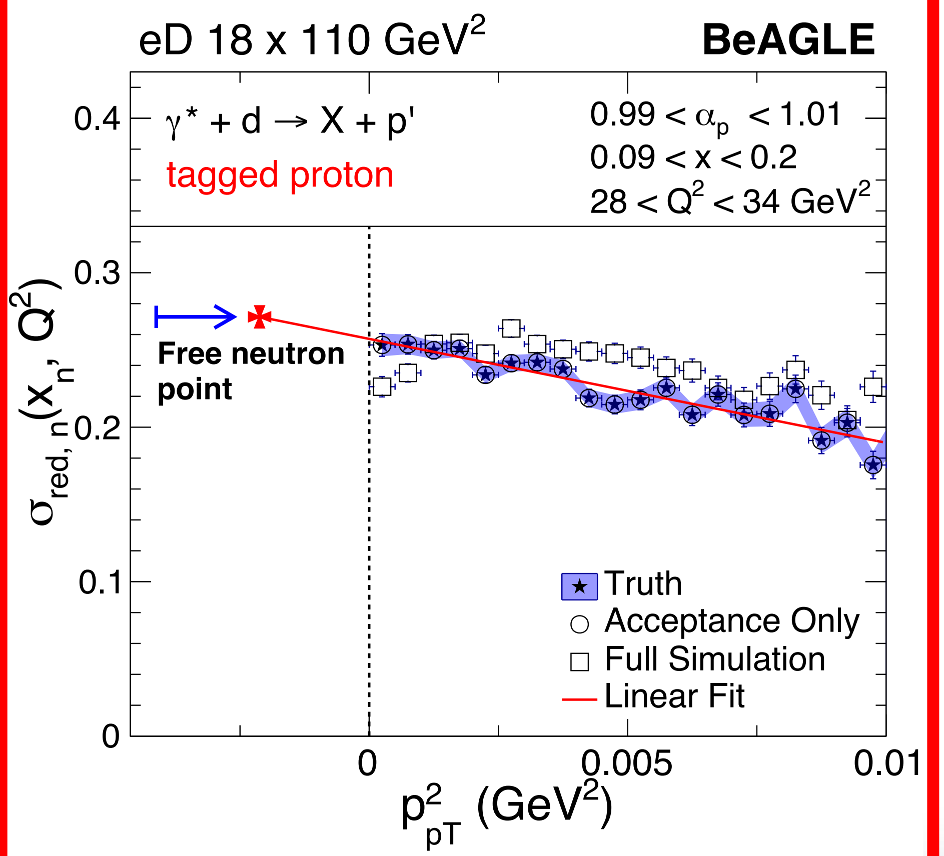
**(deuteron reduced cross section)**




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

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

**(inverse pole of deuteron spectral function)**




**(Active nucleon reduced cross section)**

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

$$R = 2\alpha_p^2 m_N \Gamma^2 (2-\alpha_p)$$

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

$R = residue\ of\ spectral\ function$

$a_T^2 = position\ of\ pole$

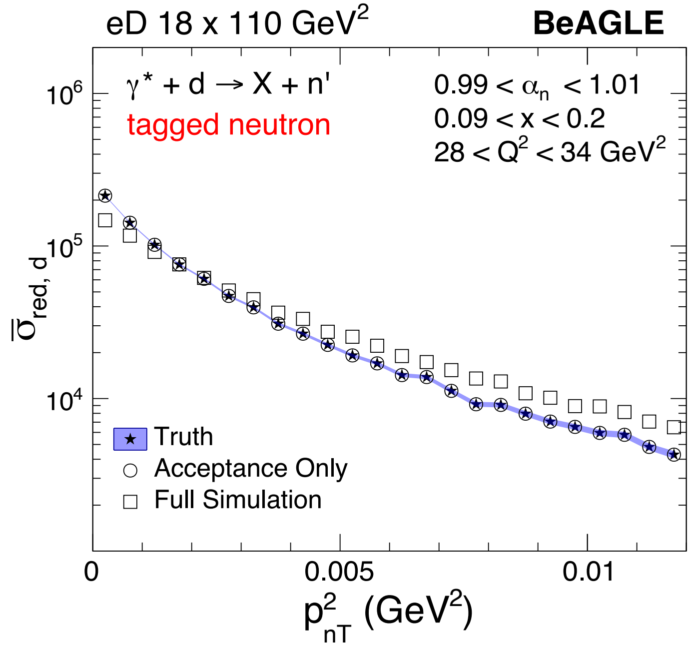
$$S_d(p_{pT},\alpha_p)[pole] = \frac{R}{\left(p_{pT}^2 + a_T^2\right)^2}$$

$$\sigma_{red,n}(x,Q^2) = \frac{\sigma_{red,d}}{[2(2\pi)^3]S_d(p_{pT},\alpha_p)}$$

# Free Proton $F_2$ Extraction

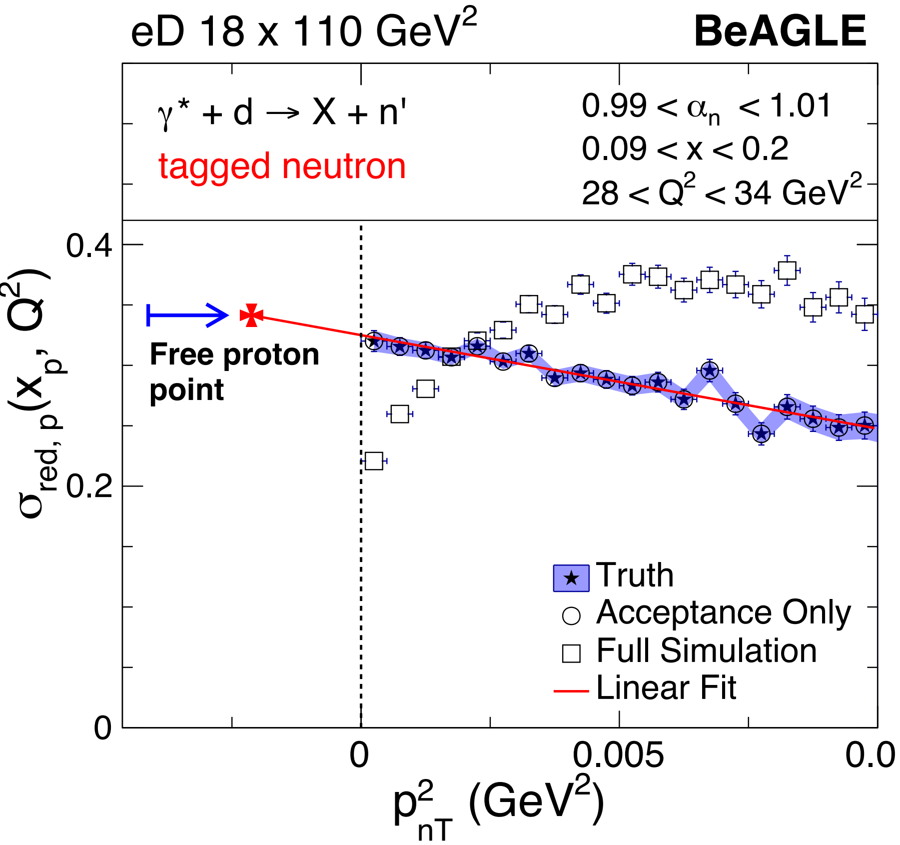
A. Jentsch, Z. Tu, and C. Weiss, Phys. Rev. C **104**, 065205, (2021) **(Editor's Suggestion)**

**(deuteron reduced cross section)**




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

**(inverse pole of deuteron spectral function)**




**(Active nucleon reduced cross section)**

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

$$R = 2\alpha_p^2 m_N \Gamma^2 (2 - \alpha_p)$$

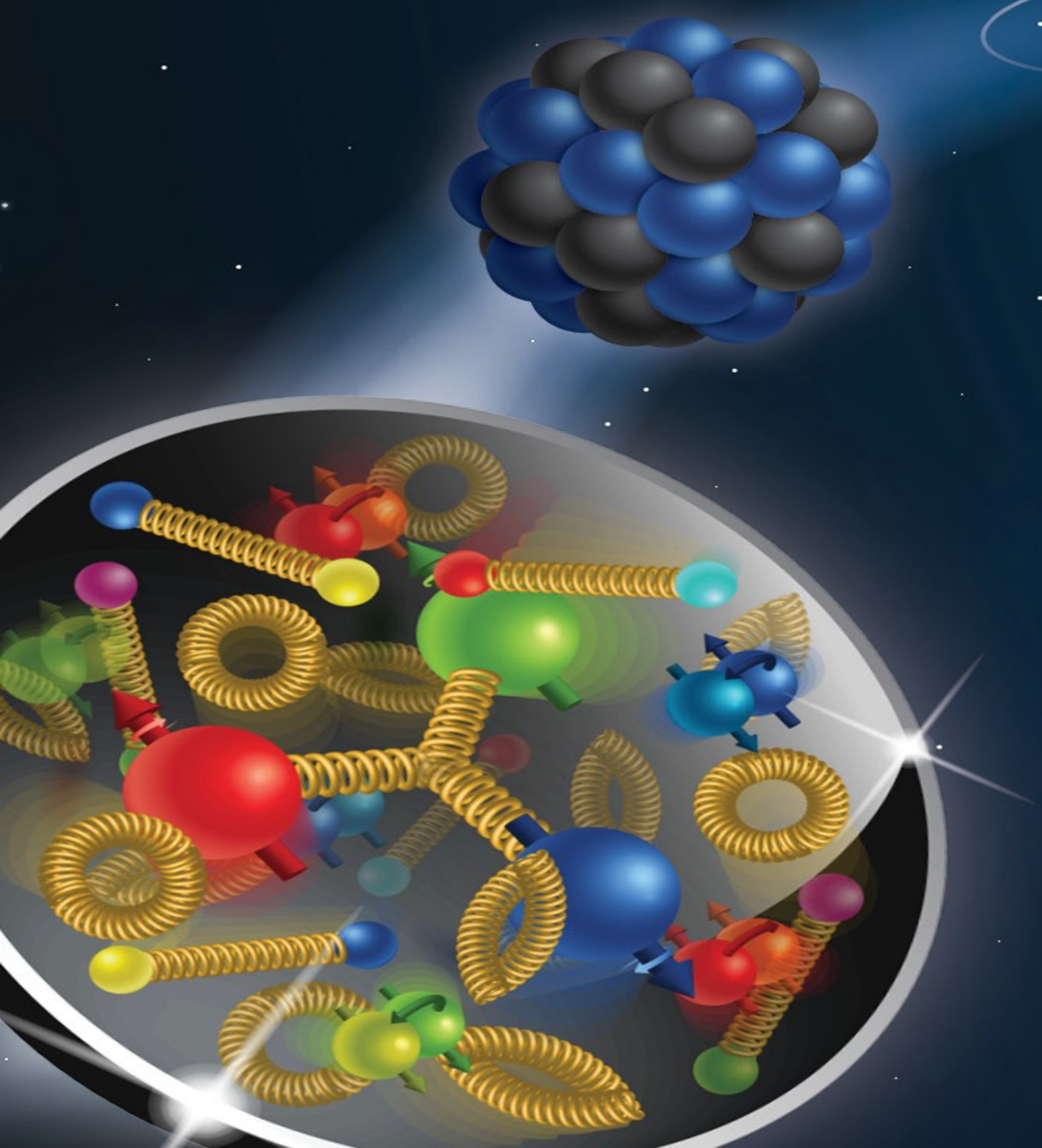
$$a_T^2 = m_N^2 - \alpha_p(2 - \alpha_p)\frac{M_d^2}{4}$$

$R = residue\ of\ spectral\ function$

$a_T^2 = position\ of\ pole$

$$S_d(p_{pT}, \alpha_p)[pole] = \frac{R}{(p_{pT}^2 + a_T^2)^2}$$

$$\sigma_{red,p}(x, Q^2) = \frac{\sigma_{red,d}}{[2(2\pi)^3] S_d(p_{nT}, \alpha_n)}$$

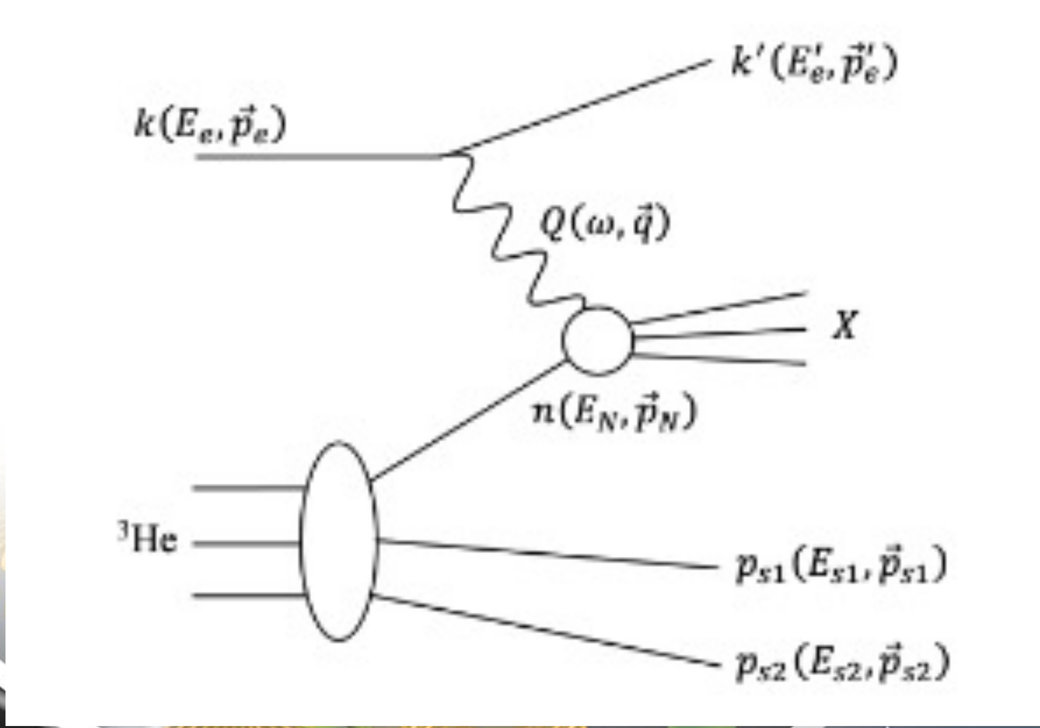


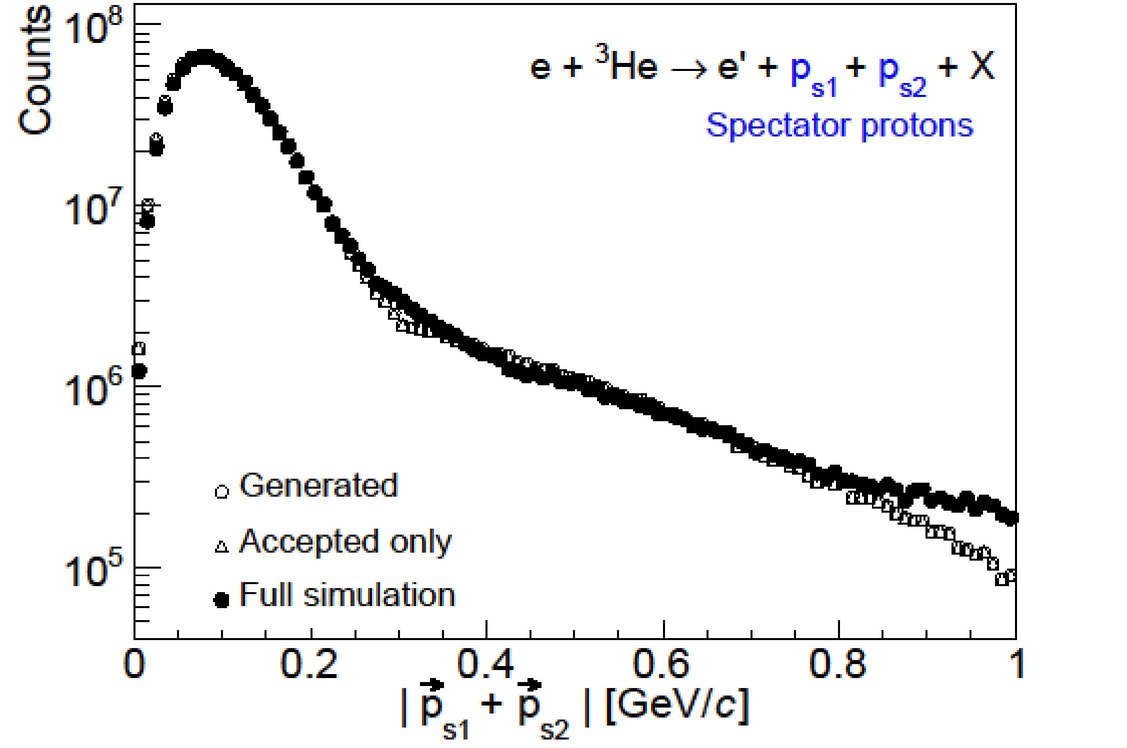
# Light nuclei – Helium-3: Neutron Spin Structure

# Neutron Spin Structure in He3

I. Friscic, D. Nguyen, J. R. Pybus, A. Jentsch, *et al.*, Phys. Lett. B, **Volume 823**, 136726 (2021)

- Studies of neutron structure with a *polarized* neutron.
- More challenging final state tagging since *both* protons must be tagged.
- MC events generated with CLASDIS in fixed-target frame, and then boosted to collider frame.



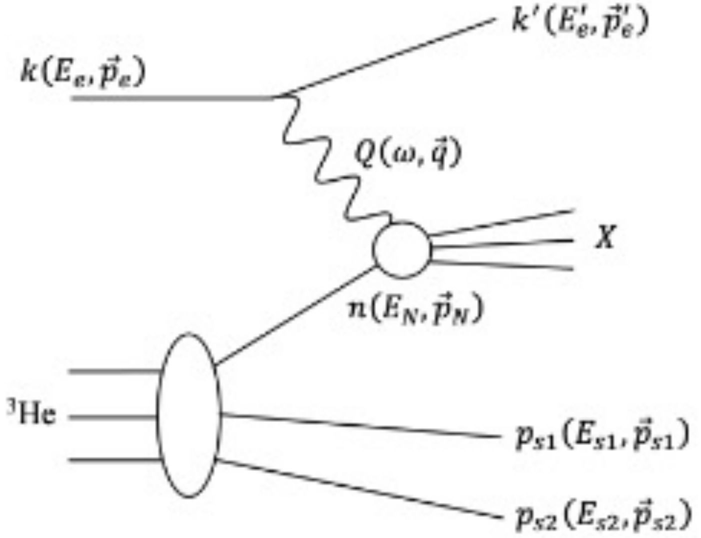



# Neutron Spin Structure in He3

I. Friscic, D. Nguyen, J. R. Pybus, A. Jentsch, *et al.*, Phys. Lett. B, **Volume 823**, 136726 (2021)

- Spin structure probed via spin asymmetries!

$$A_1^{^3\mathrm{He}} = \underbrace{P_n \frac{F_2^n}{F_2^{^3\mathrm{He}}} A_1^n}_{\text{Neutron}} + \underbrace{2P_p \frac{F_2^p}{F_2^{^3\mathrm{He}}} A_1^p}_{\text{Protons}}$$

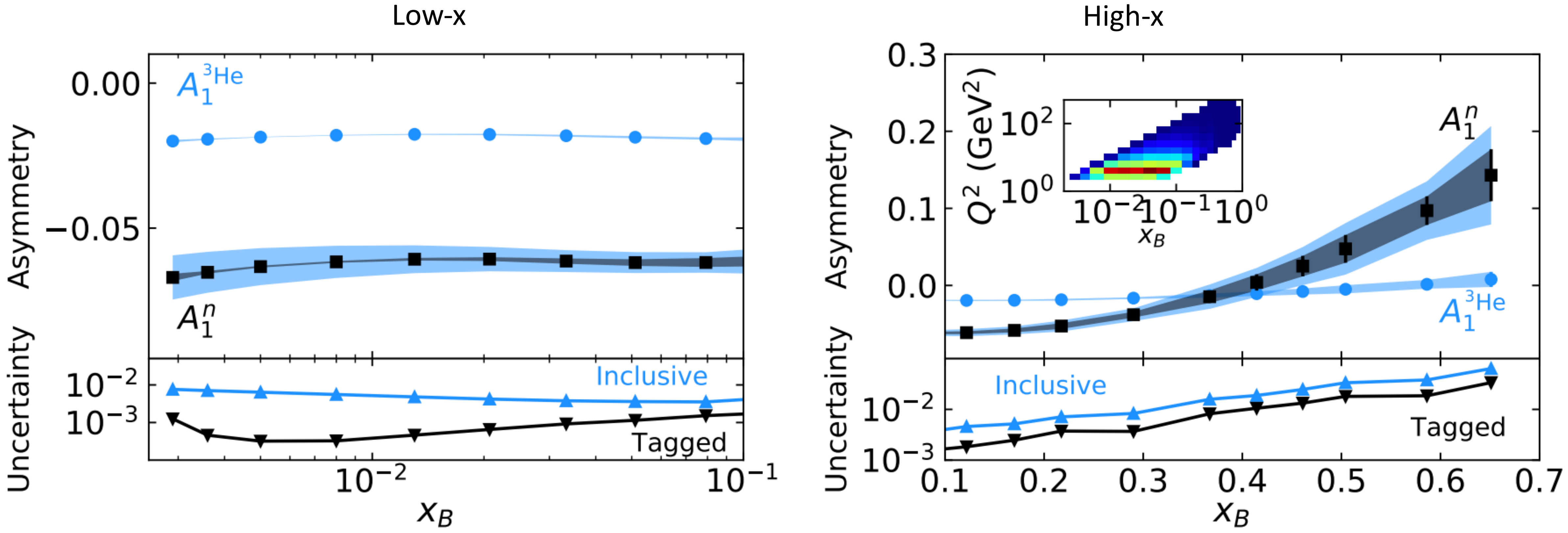



- (double) Tagged DIS measurement capable of measuring $A_1^n$ directly!
- Complementary to measurements at JLAB.

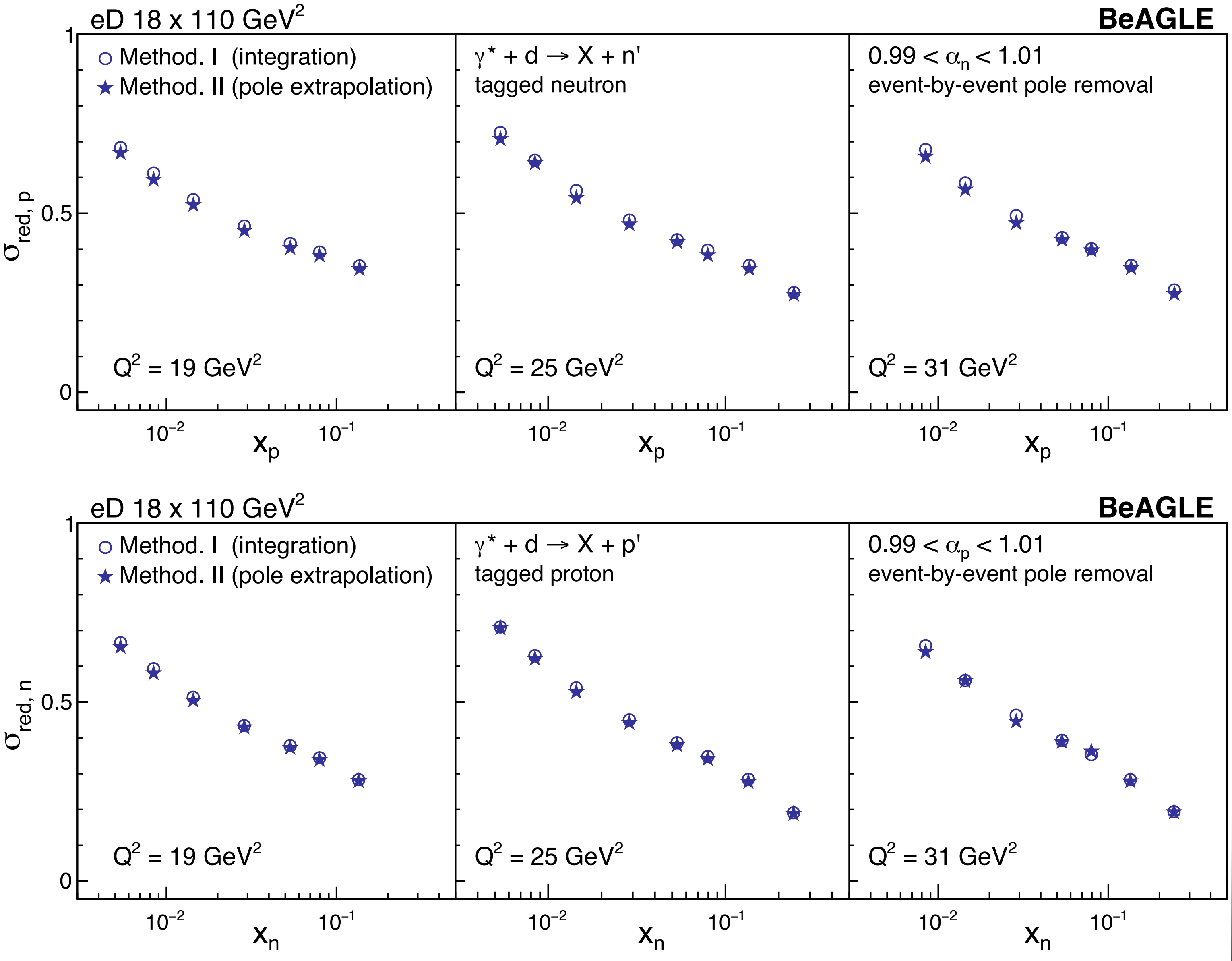
# Neutron Spin Structure in He3

I. Friscic, D. Nguyen, J. R. Pybus, A. Jentsch, *et al.*,
Phys. Lett. B, **Volume 823**, 136726 (2021)

- Neutron spin asymmetries can be measured from kinematics of the tagged protons.
- EIC can build upon measurements at JLAB by reducing polarization uncertainties, and opening a broader $Q^2$ range for study.
- Can aid in our understanding of quark orbital angular momentum in nucleons.

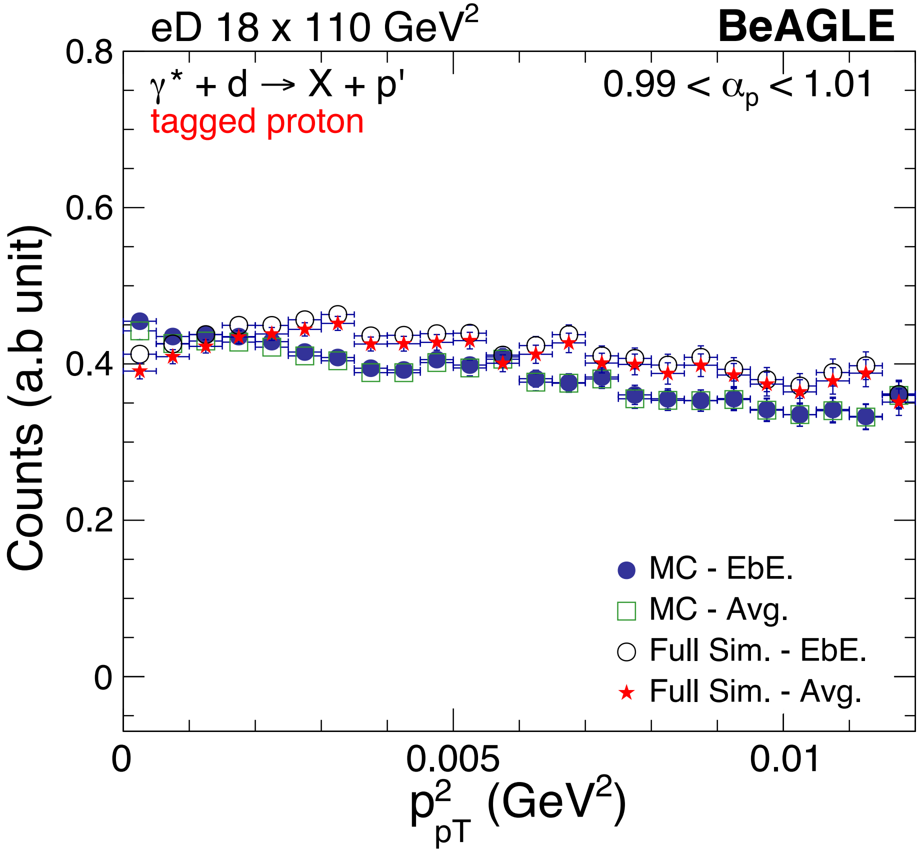


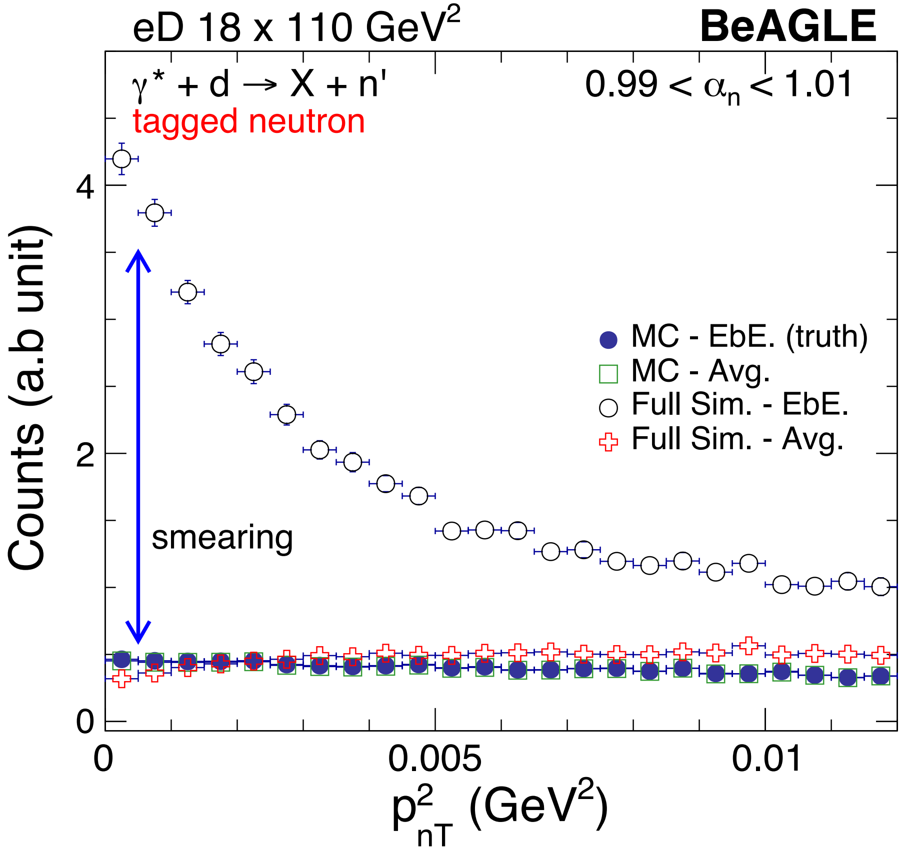
# Closure Test – Event by Event Pole Removal




- Pole factor removed using "event by event (EbE)" approach.
  - Pole factor calculated and applied for each event (i.e. pole factor calculated for each exact nuclear configuration).
  - Solved discrepancy at generator level.
    - This was also checked using an independent toy MC to confirm there was nothing related to our analysis code causing an issue.
  - Remaining differences due to fitting and statistics.

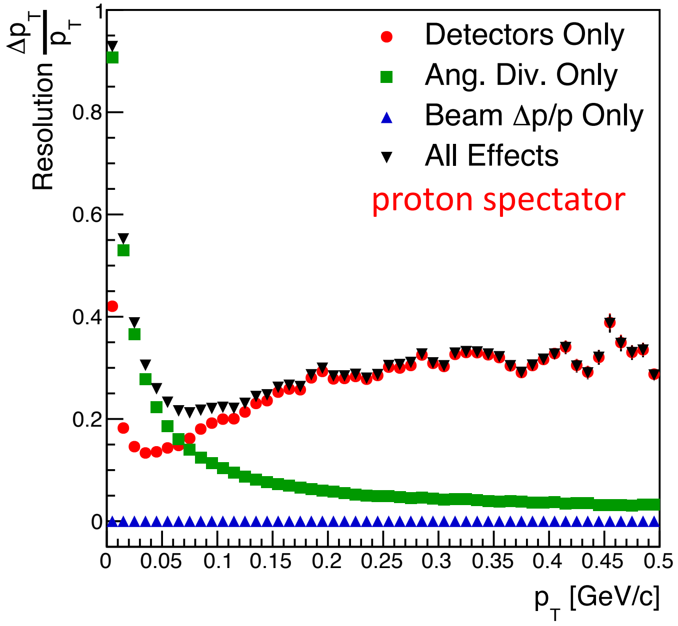
# Effects of momentum smearing on pole factor

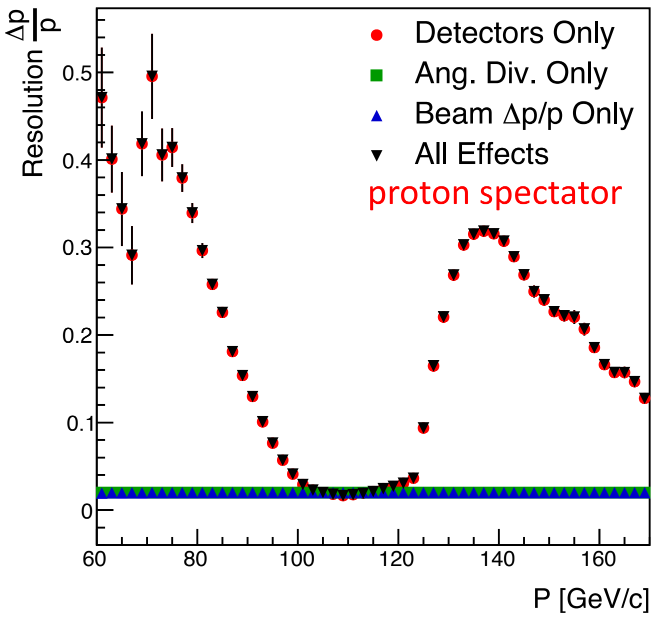


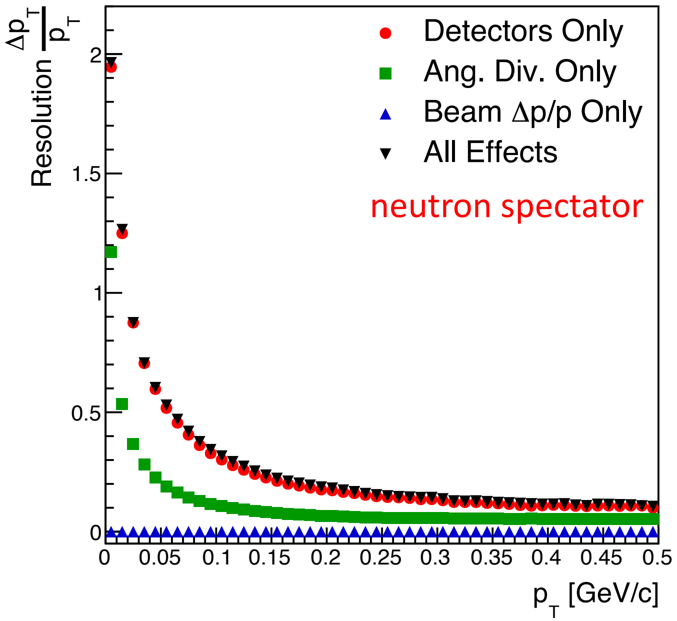



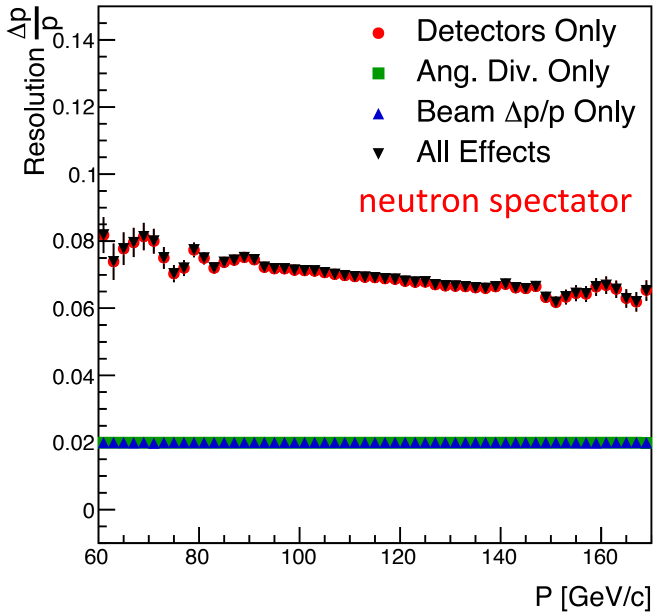

- Detector smearing has a drastic impact when the EbE method is used.
  - If you calculate the pole factor on an EbE basis with *smeared* spectator kinematic values, you now remove the pole factor for the wrong nuclear configuration!

# Kinematic Distributions and Smearing




- Event sub-sample passed through full GEANT4 simulations.
  - Smearing parametrizations extracted for ($p_x$, $p_y$, $p_z$, E).
- Larger overall smearing observed for neutrons, consistent with previous study.
- Anomalous proton smearing at high pT and p > 120 GeV/c and p < 100 GeV/c due to linear transfer matrix assumption.
  - Will be fixed in the future for TDR studies.