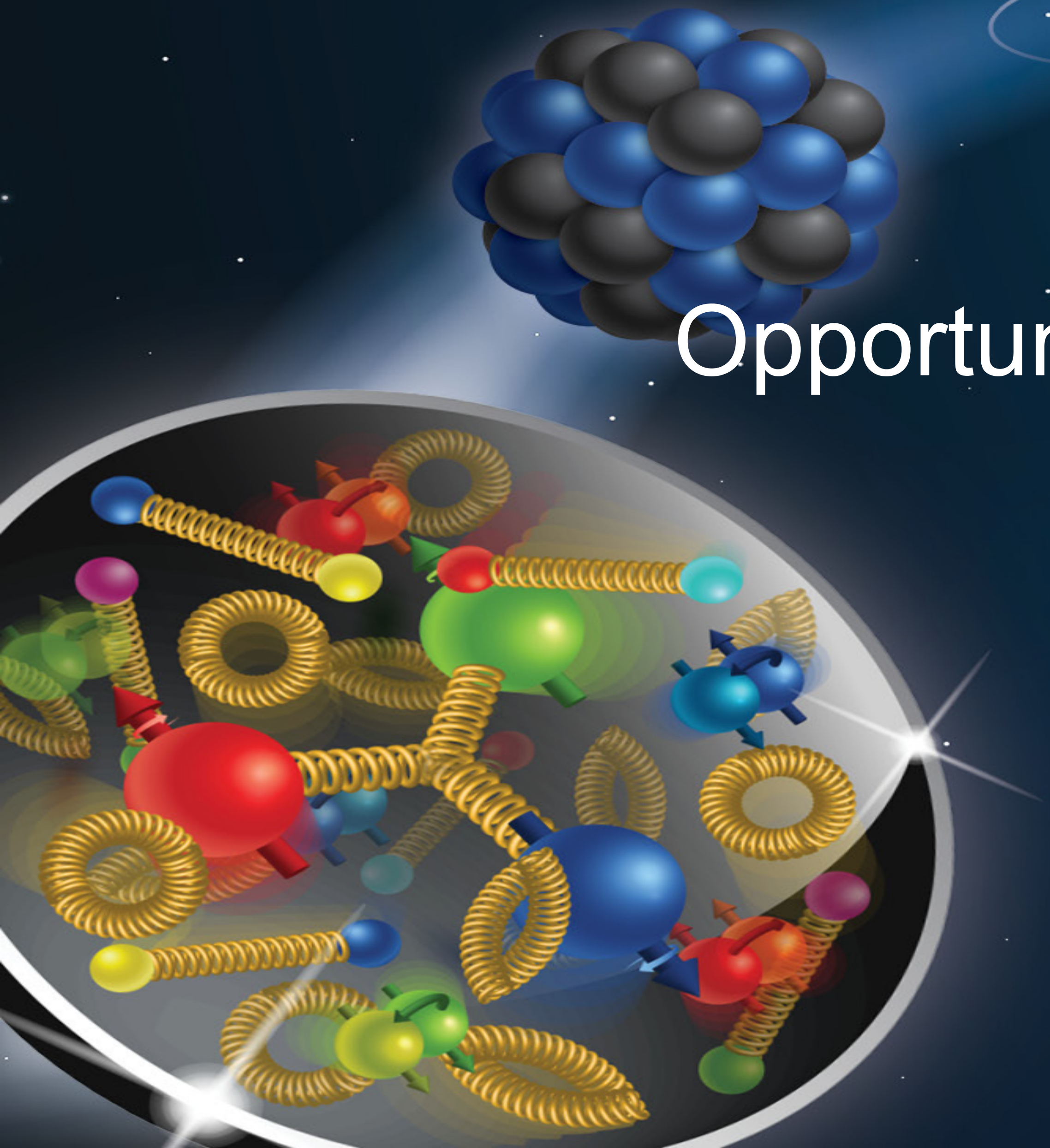


(some) Exclusive Physics Opportunities at the EIC and the Tools Needed to Study Them

Alex Jentsch, *Brookhaven National Lab*

ajentsch@bnl.gov

RBRC Workshop: Workshop on Generalized Parton Distributions for Nucleon Tomography in the EIC Era

January 17th – 19th, 2024

Brookhaven National Laboratory, Upton, NY

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

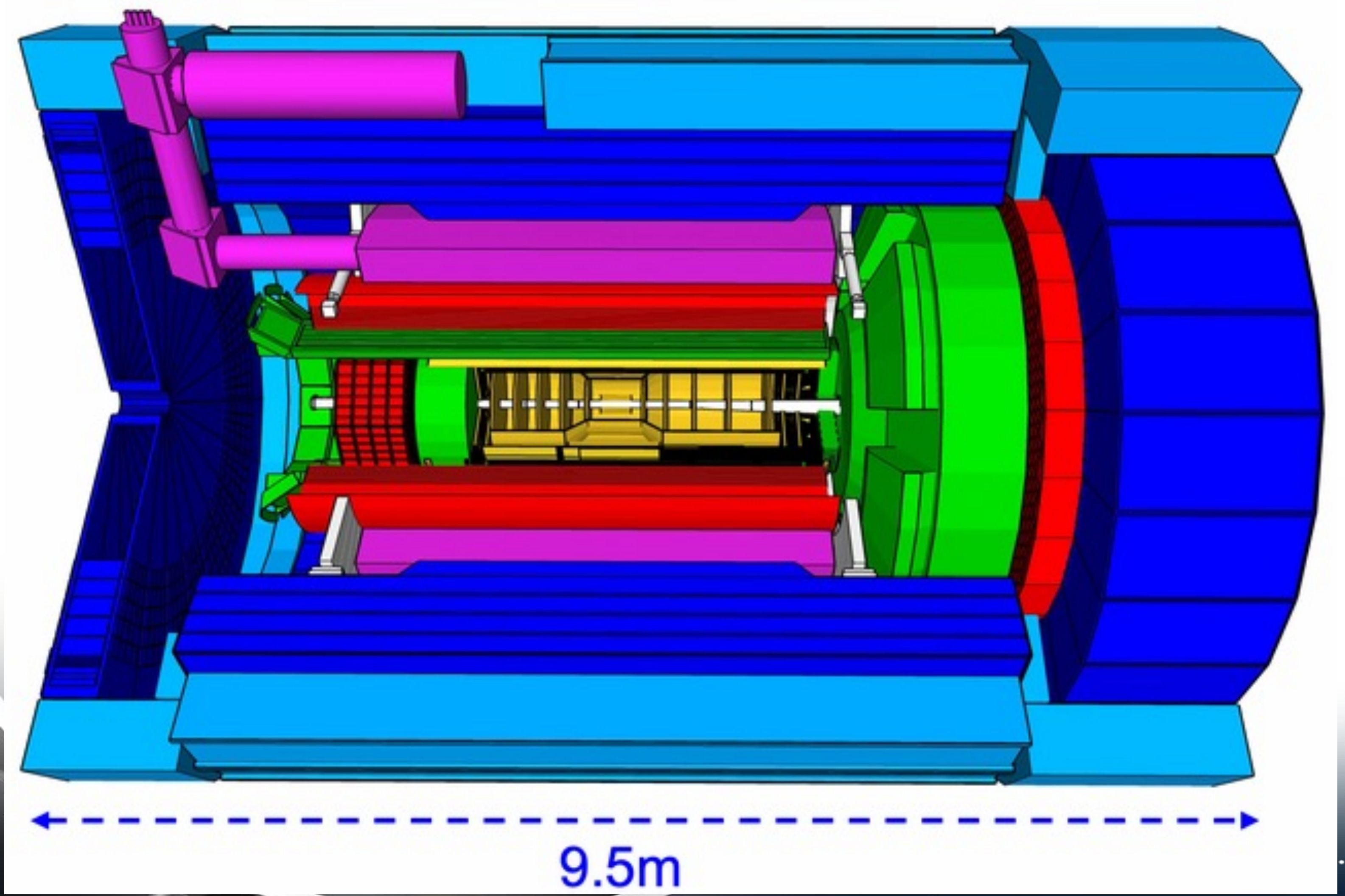
Accessing Exclusive Reactions at the EIC

hadronic calorimeters | solenoid coils | e/m calorimeters

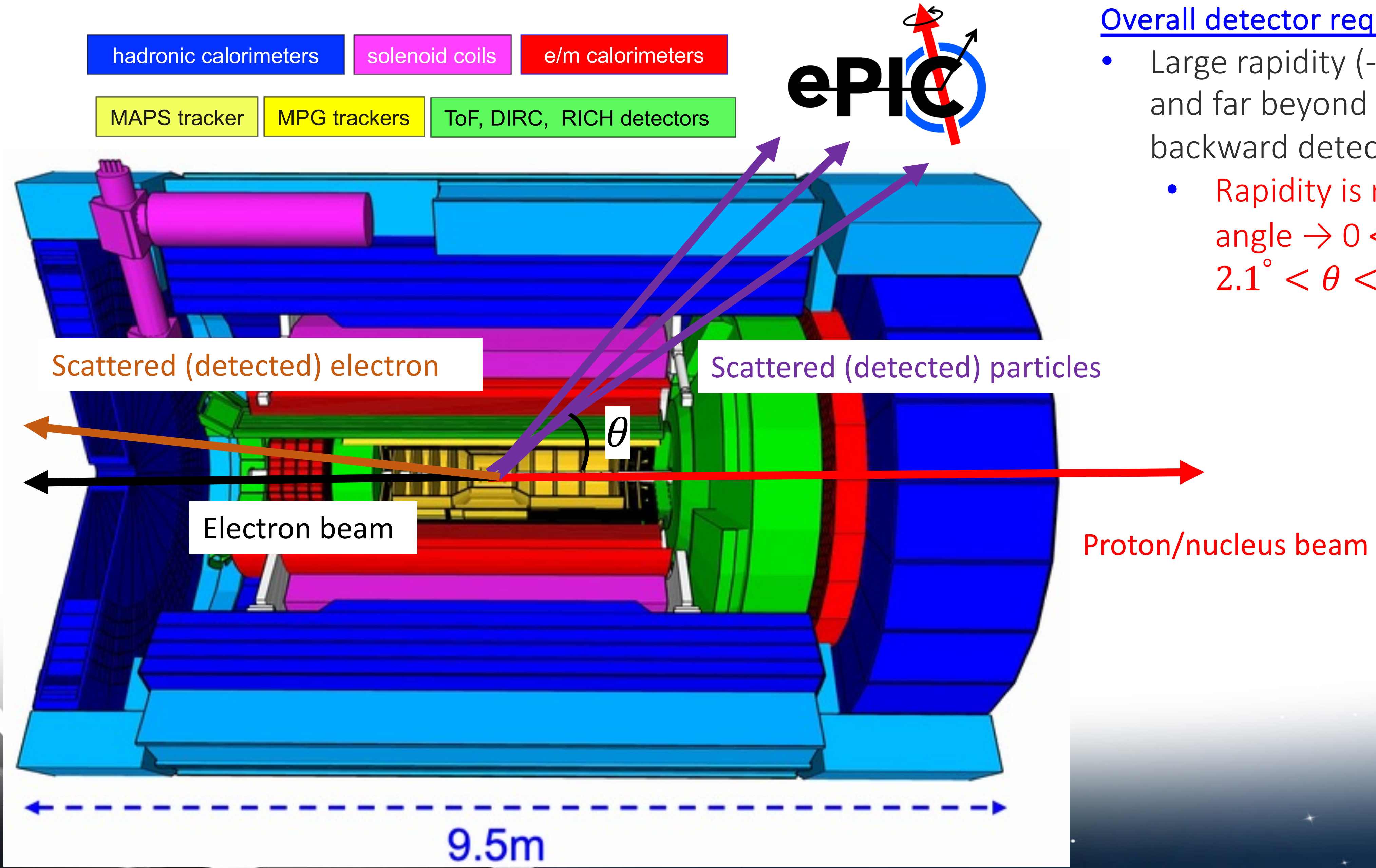
MAPS tracker | MPG trackers | ToF, DIRC, RICH detectors

ePIC

See Silvia's talk from Monday!



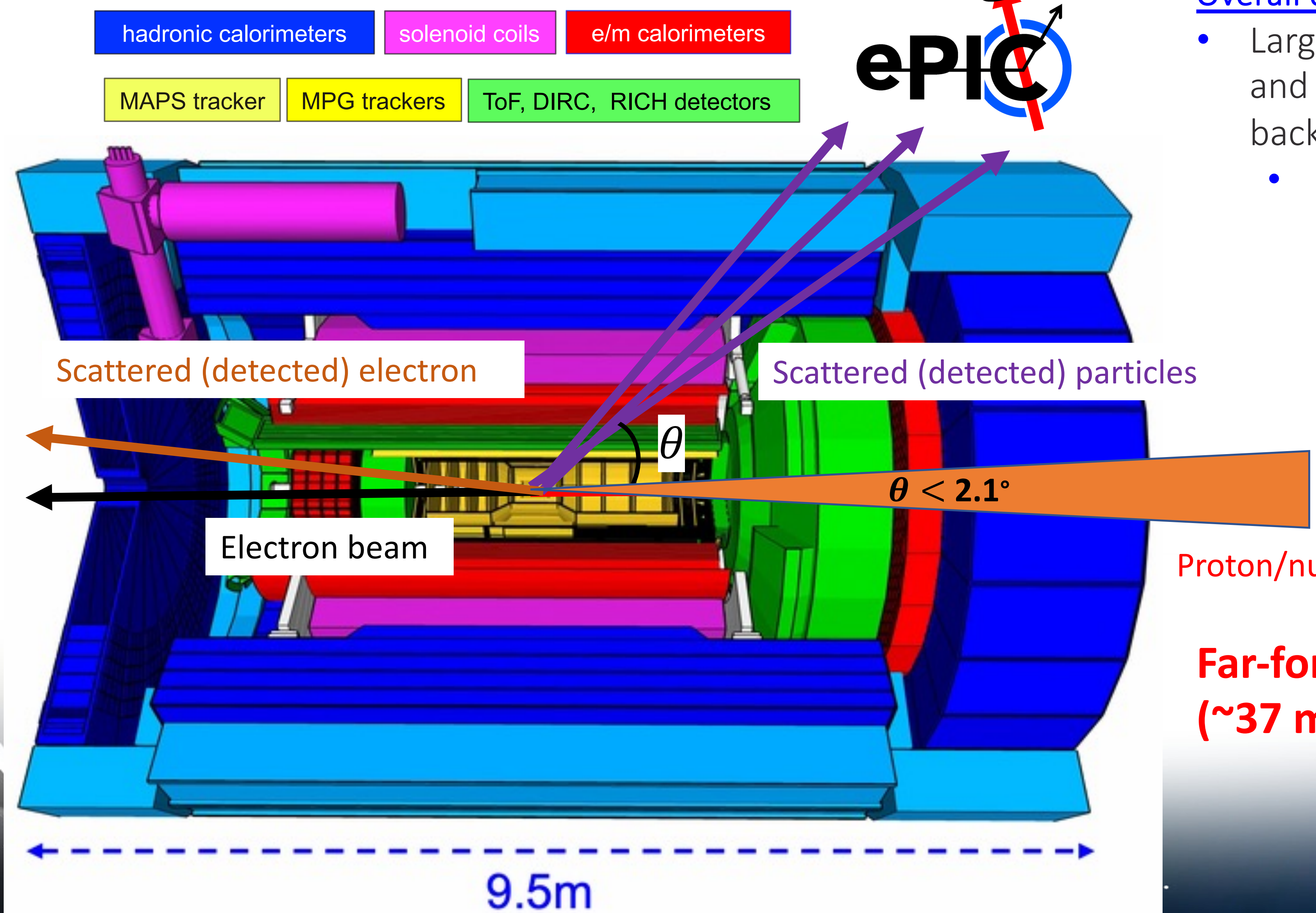
Accessing Exclusive Reactions at the EIC



<u>Overall detector requirements:</u>

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

Accessing Exclusive Reactions at the EIC



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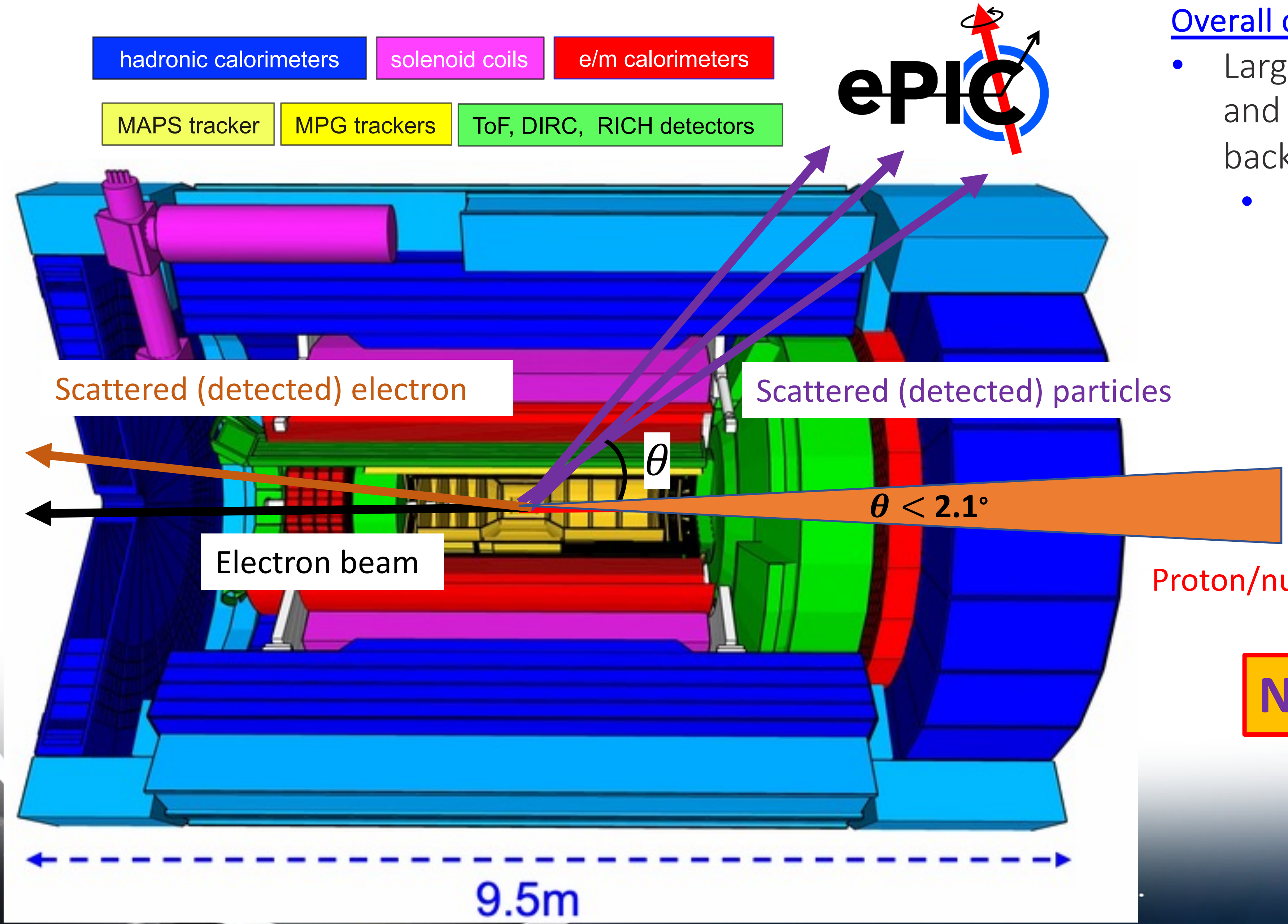
- Large rapidity (-4 < η < 4) coverage; and far beyond in far-forward/far-backward detector regions
  - Rapidity is related to the polar angle → 0 < η < 4 equates to $2.1^{\circ} < \theta < 90^{\circ}$

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

Accessing Exclusive Reactions at the EIC



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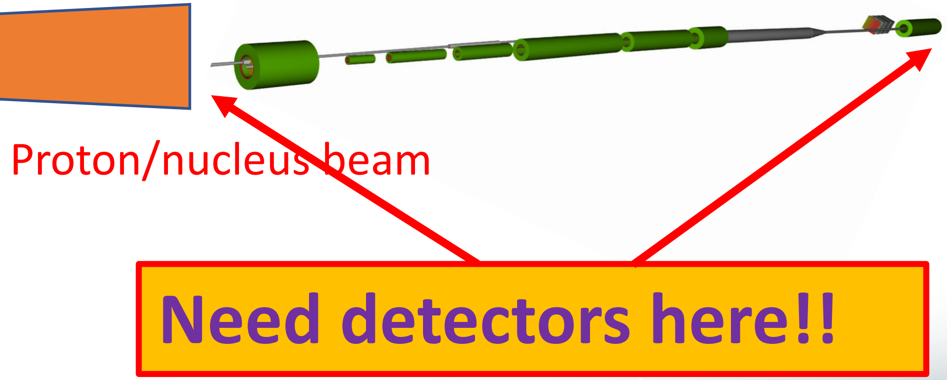
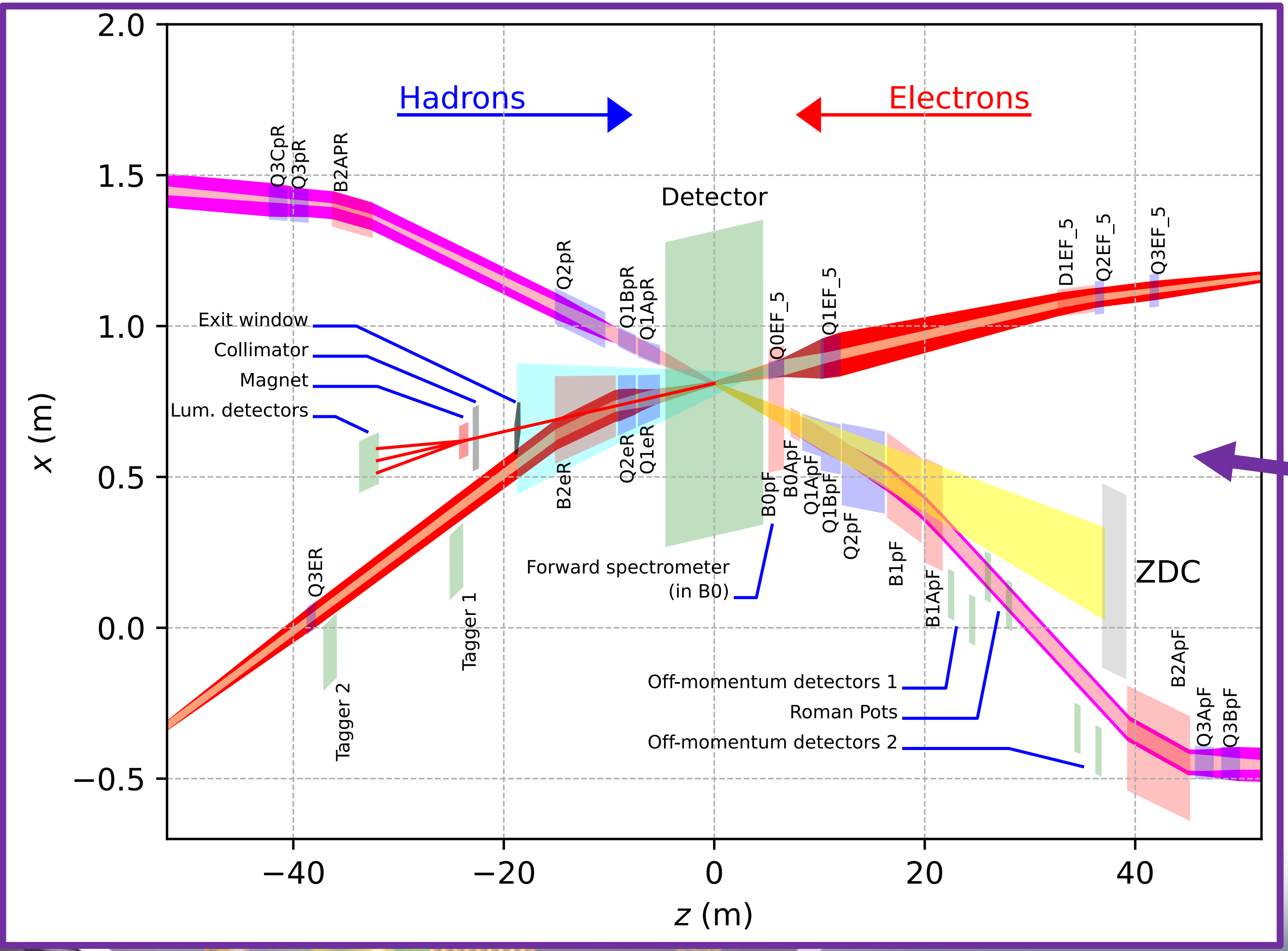
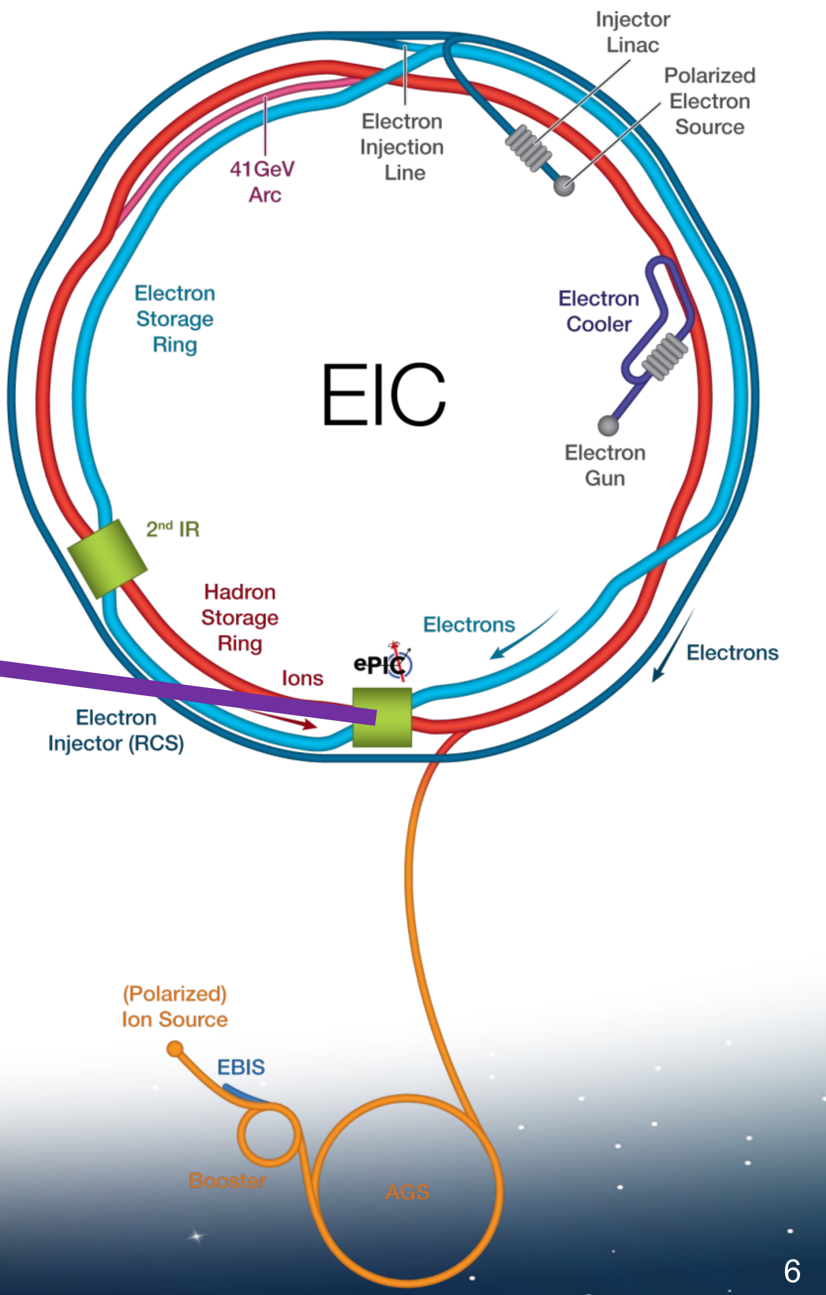


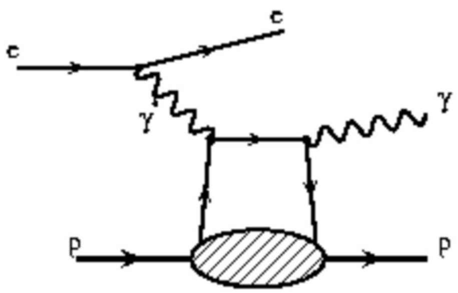
and the full interaction region!



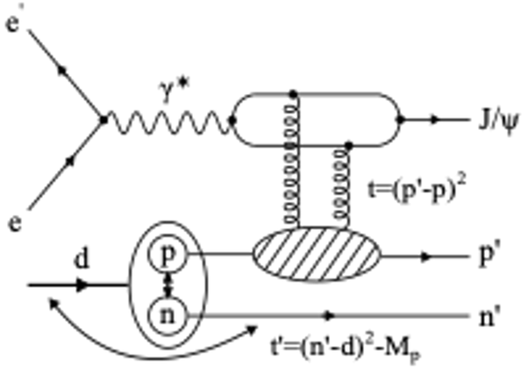


(some) Exclusive Processes at the EIC

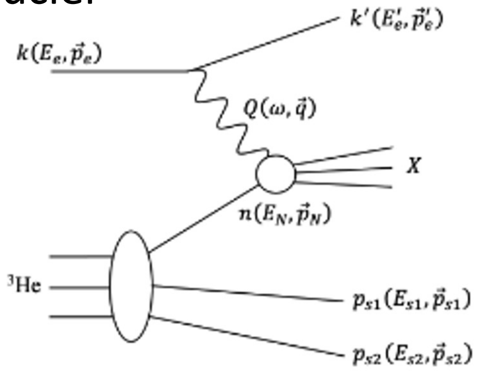
e+p DVCS



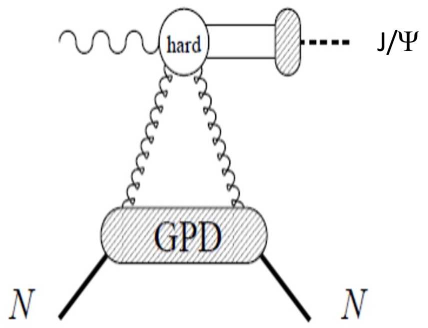
e+d exclusive J/Psi with p/n tagging



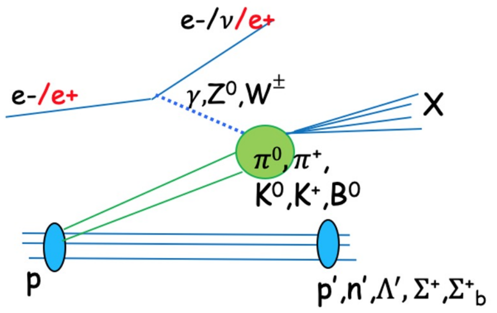
spectator tagging in light nuclei



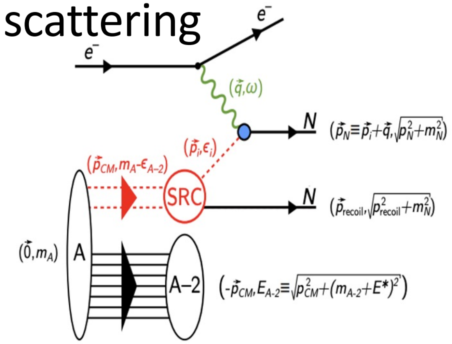
coherent/incoherent J/ψ production in e+A



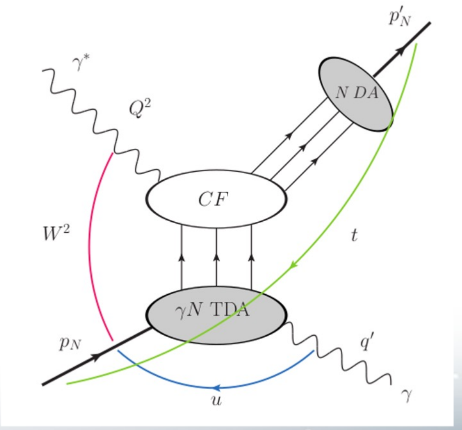
Sullivan process



Quasi-elastic electron scattering



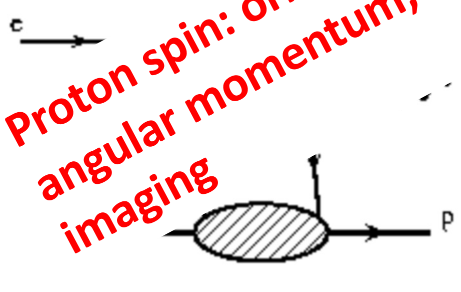
u-channel backward exclusive electroproduction



...and MANY more!

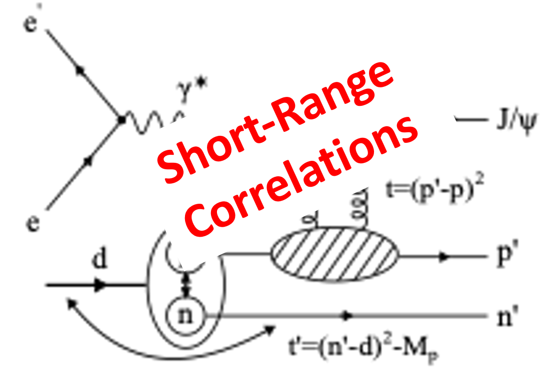
(some) Exclusive **Physics** at the EIC

e+p DVCS



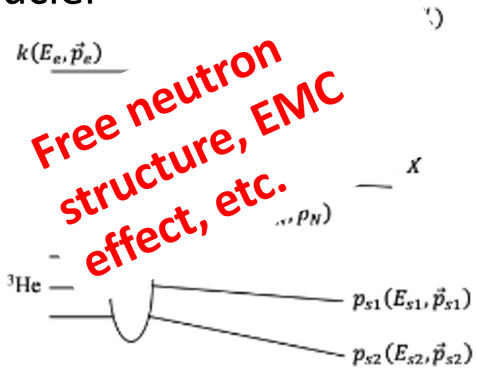
Proton spin: orbital angular momentum; imaging

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



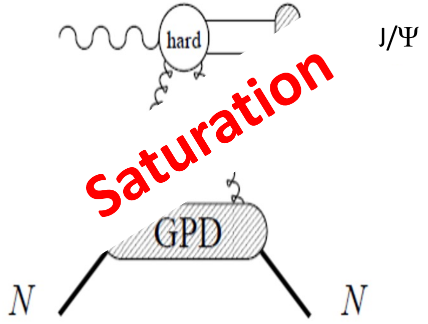
Short-Range Correlations

spectator tagging in light nuclei



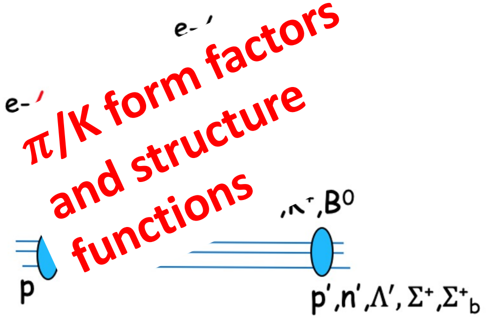
Free neutron structure, EMC effect, etc.

coherent/incoherent J/ψ production in e+A



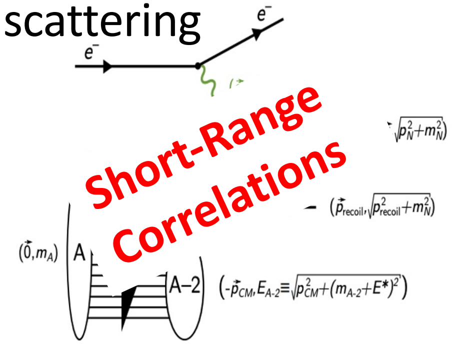
Saturation

Sullivan process



π/K form factors and structure functions

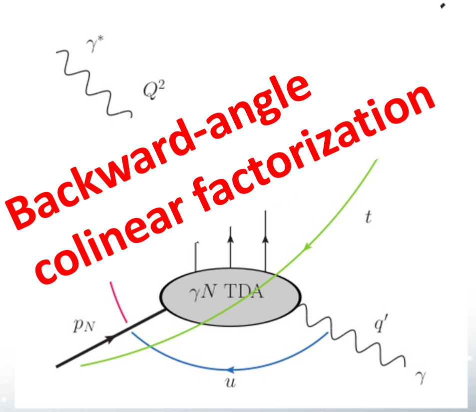
Quasi-elastic electron scattering



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



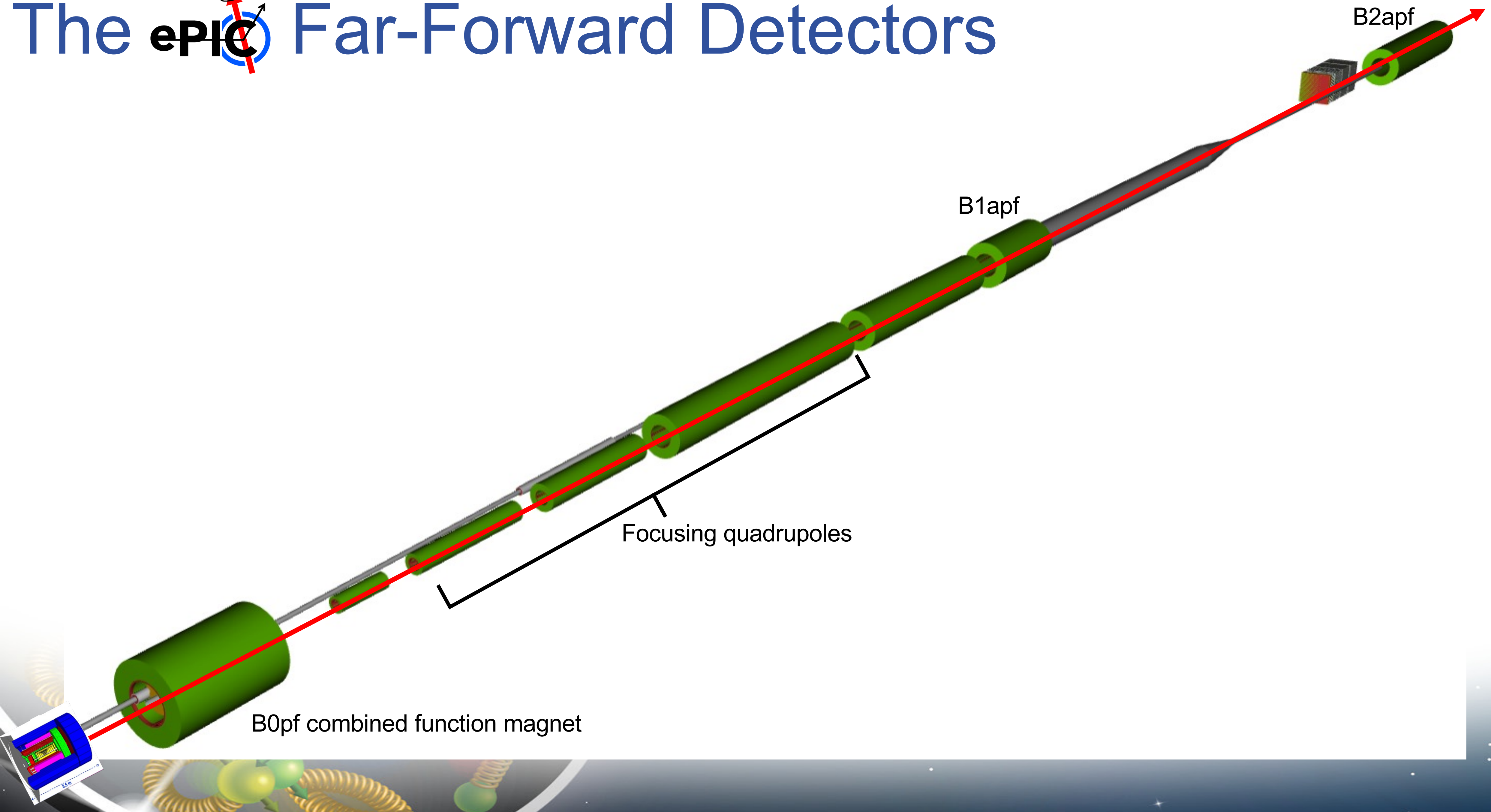
Backward-angle colinear factorization

…and MANY more!

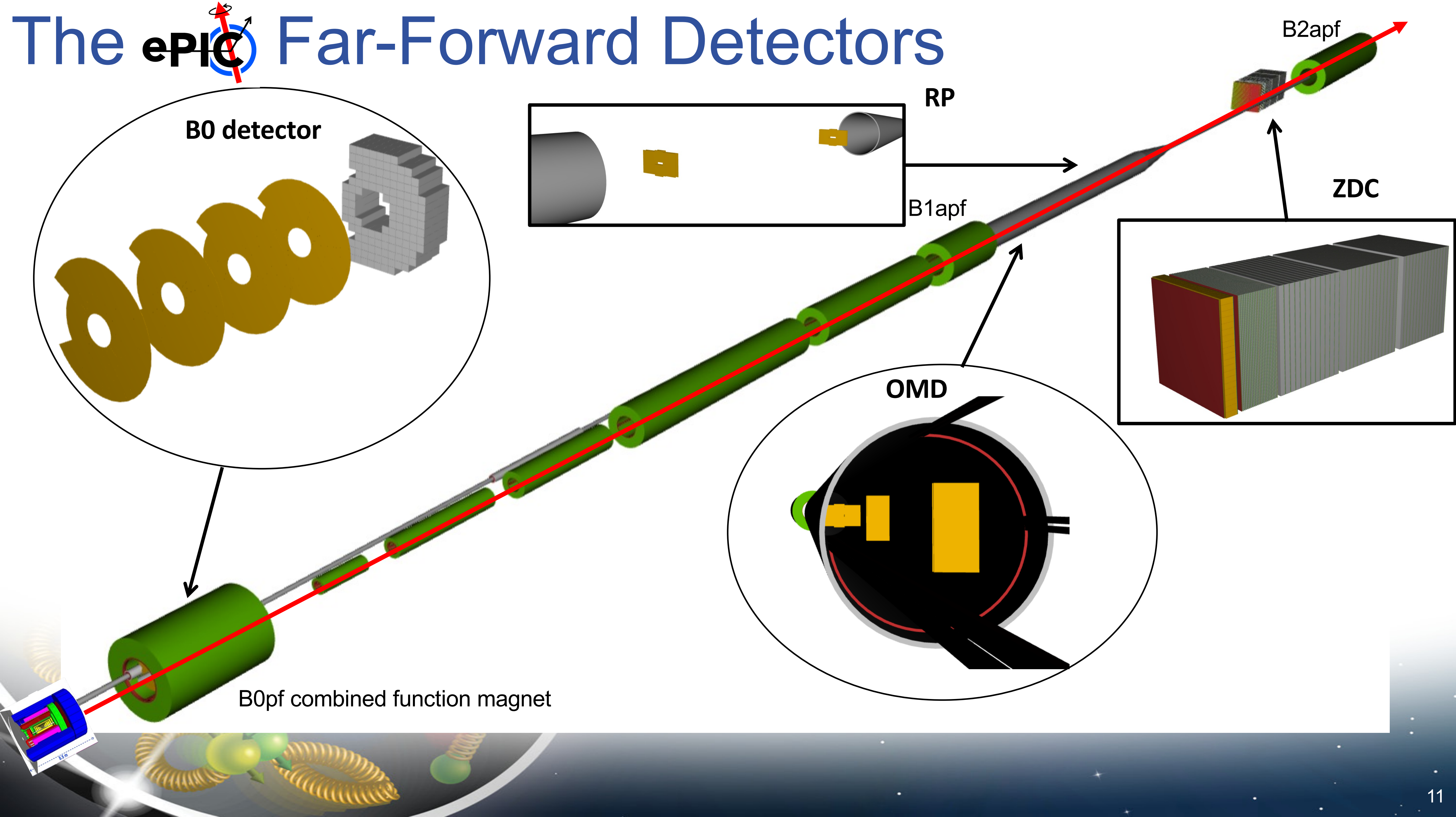
(some) Exclusive **Physics** at the EIC

- Physics channels require tagging of **charged hadrons** (protons, pions) or **neutral particles** (neutrons, photons) at **very-forward rapidities ($\eta > 4.5$).**
- Different final states $\longrightarrow$ tailored detector subsystems.
- Various beams and energies (h: 41, 100-275 GeV, e: 5-18 GeV; e+p, e+d, e+Au, etc.).
- Placing and operation of far-forward detectors challenging due to integration with accelerator.

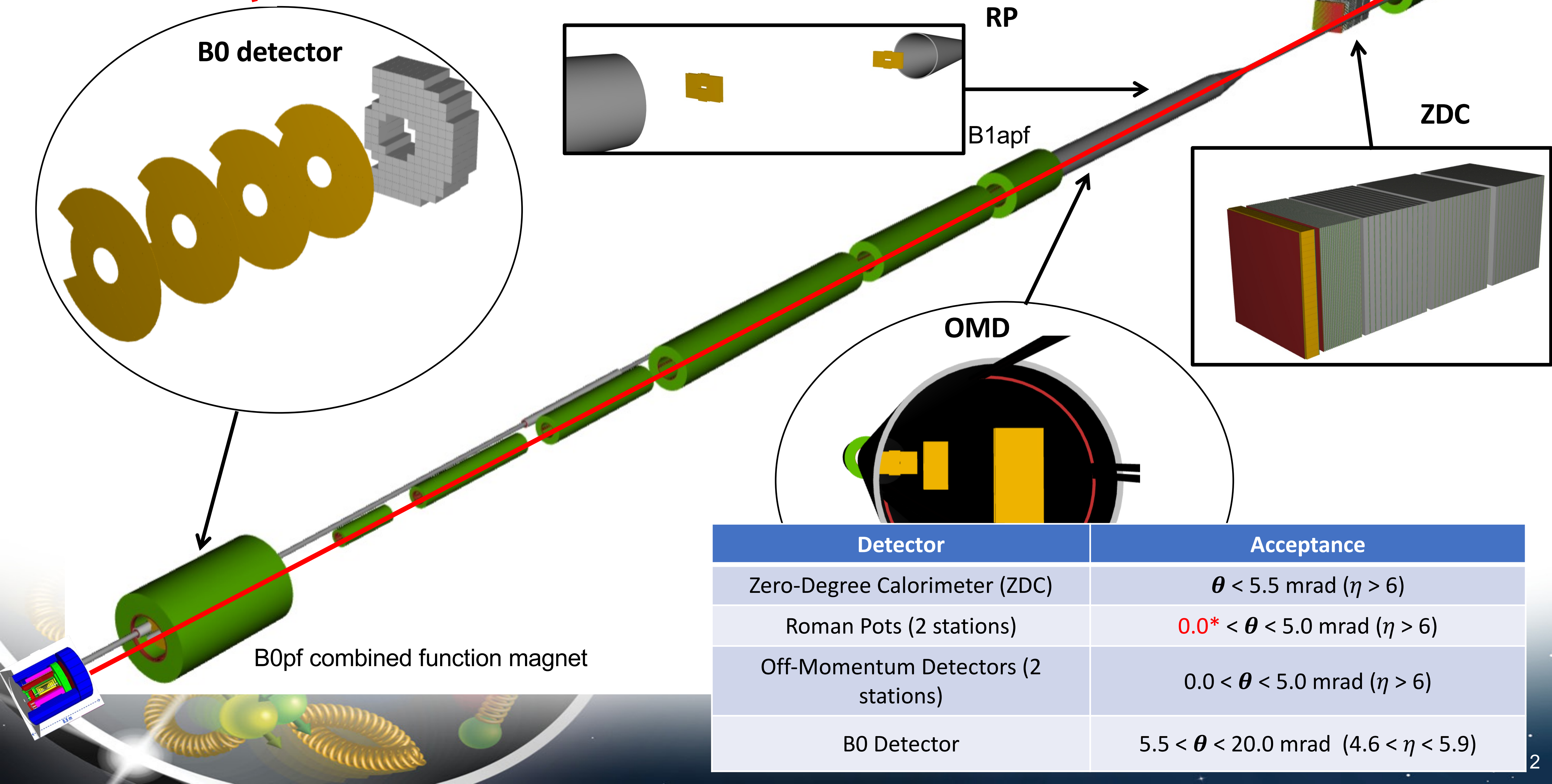
The ePIC Far-Forward Detectors



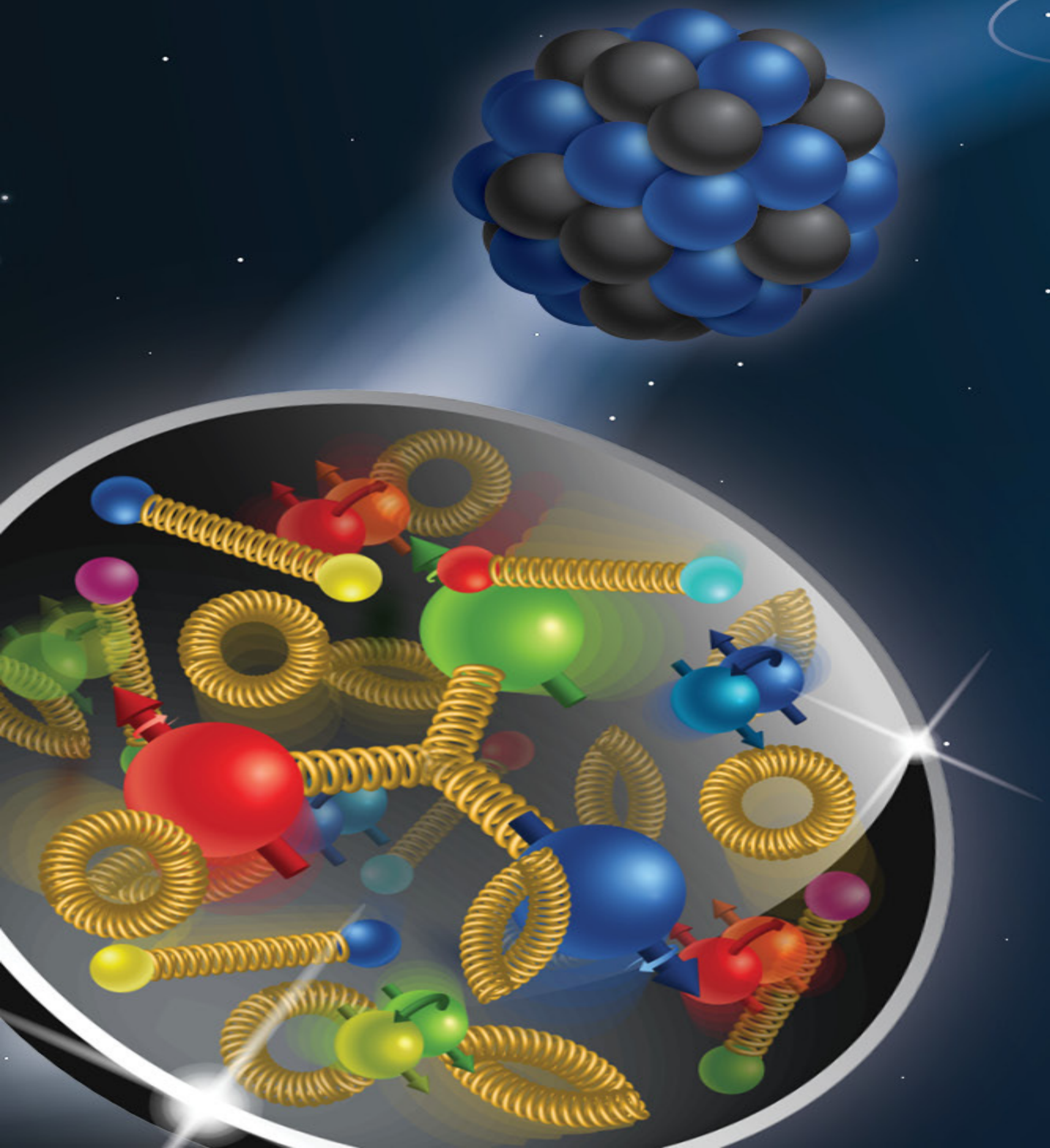
The ePIC Far-Forward Detectors

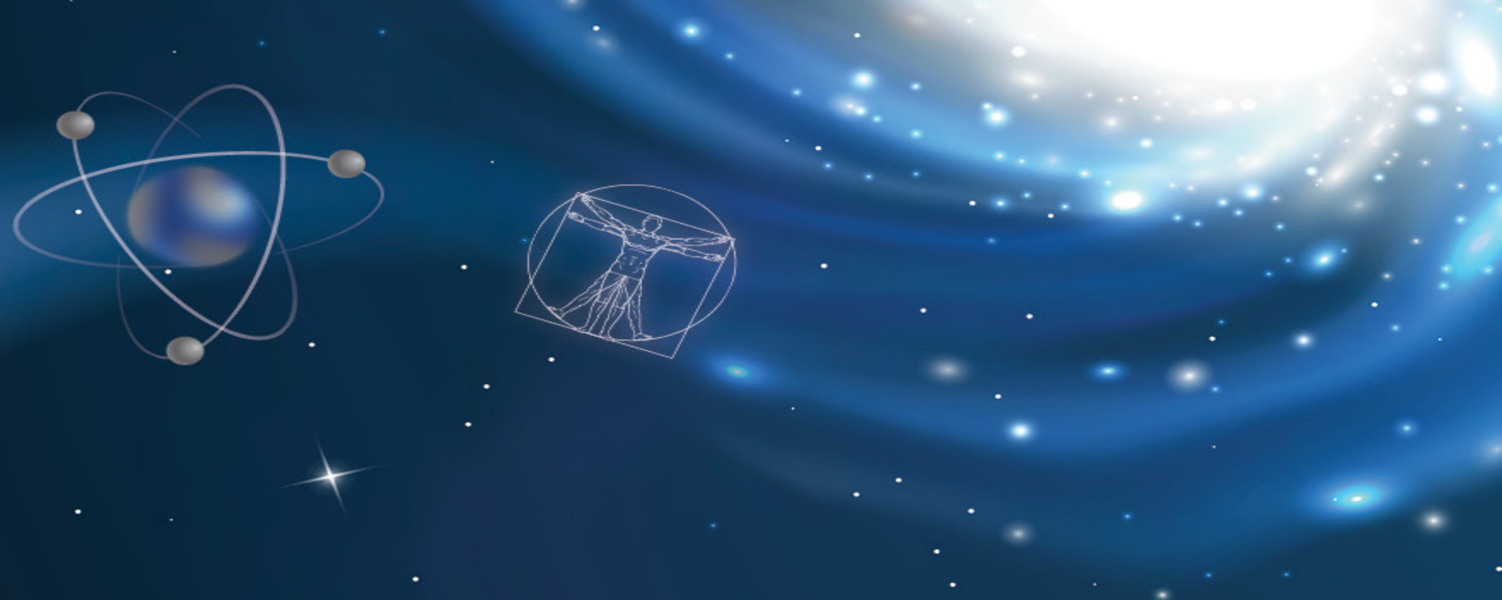


The ePIC Far-Forward Detectors



Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	θ < 5.5 mrad (η > 6)
Roman Pots (2 stations)	0.0* < θ < 5.0 mrad (η > 6)
Off-Momentum Detectors (2 stations)	0.0 < θ < 5.0 mrad (η > 6)
B0 Detector	5.5 < θ < 20.0 mrad (4.6 < η < 5.9)

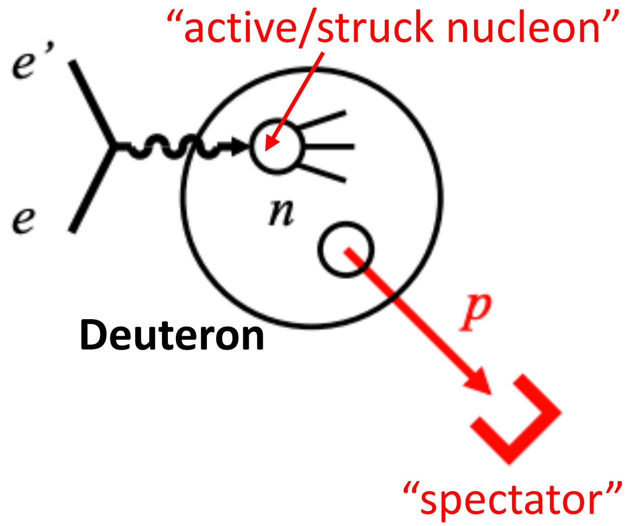


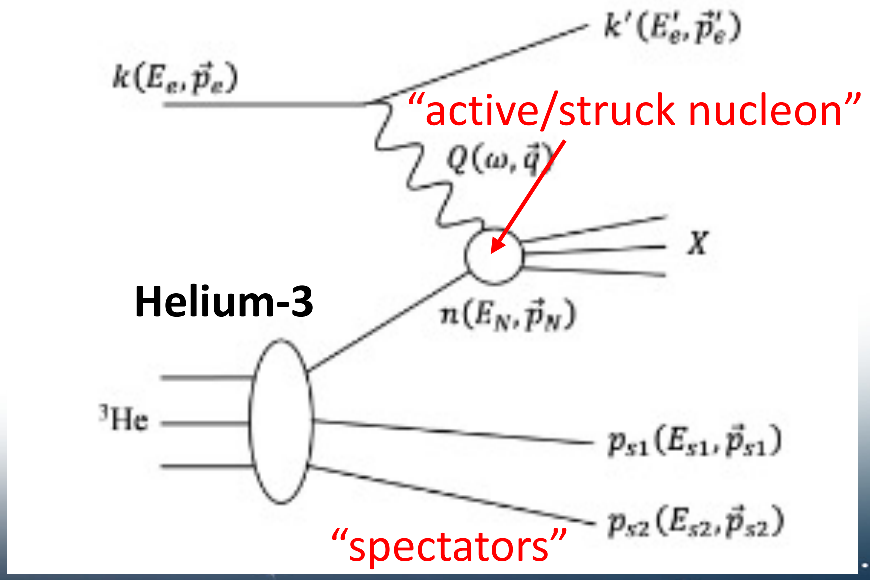


Physics focus: Deuterons and Tagged DIS

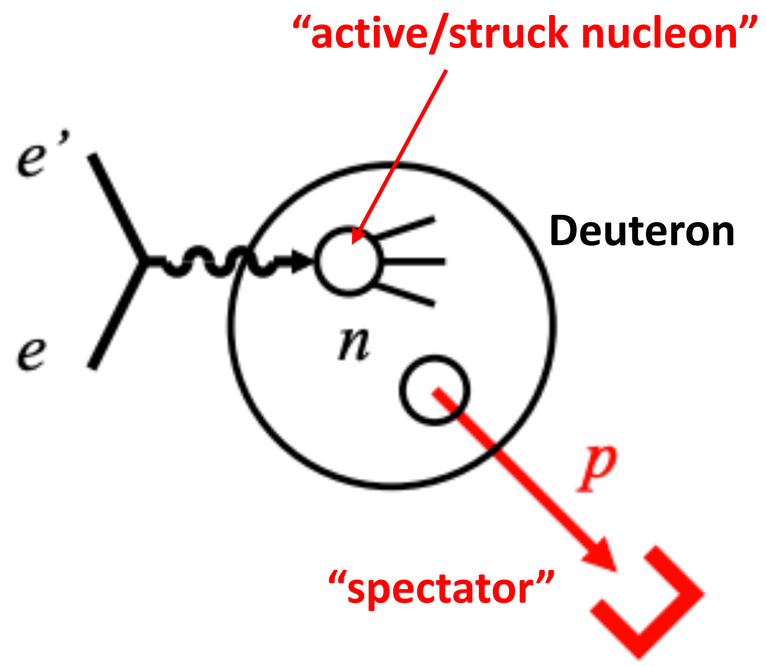
Deuteron tagged DIS as a tool at the EIC

- **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.





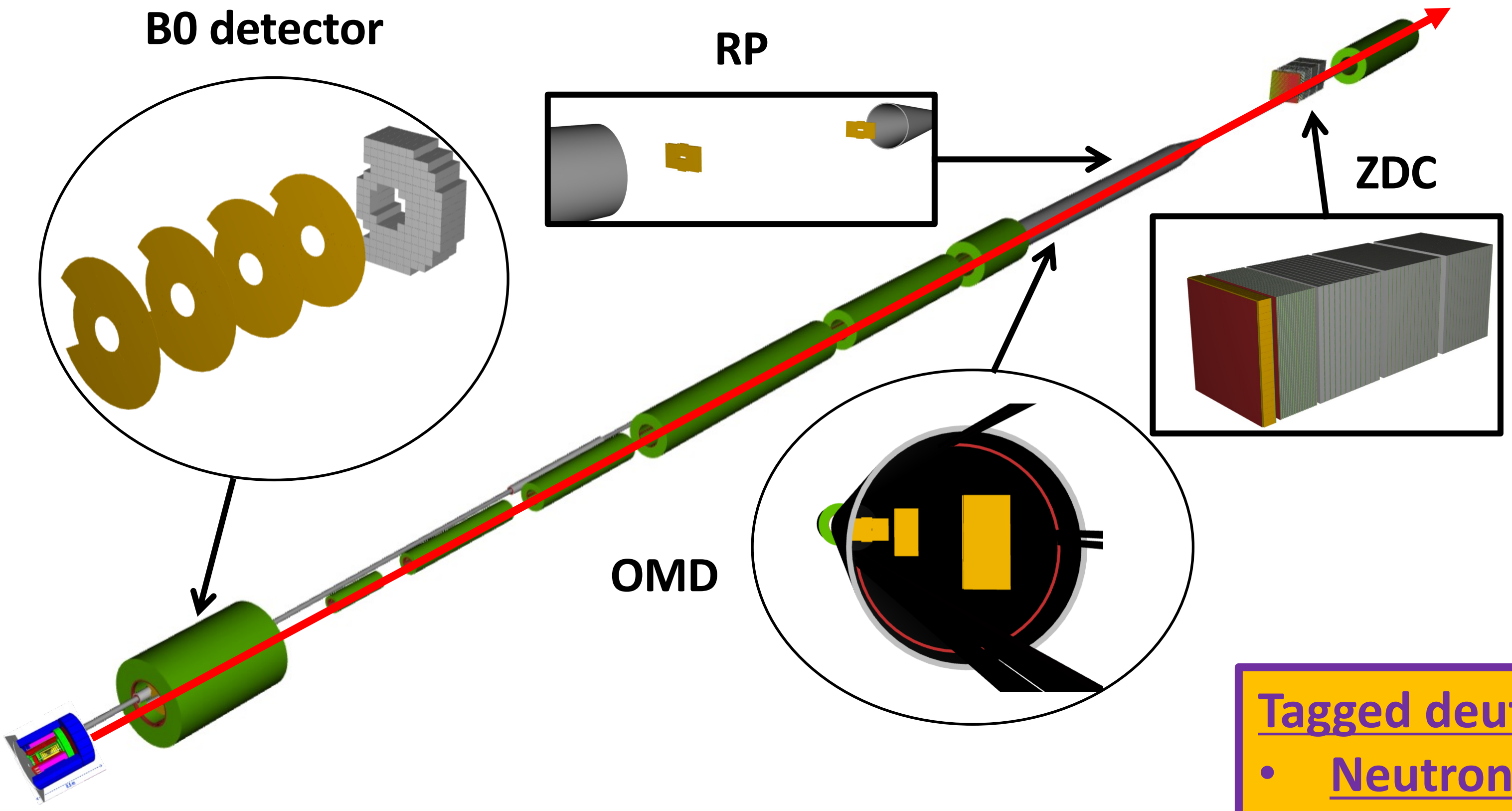
Tagged DIS with deuterons



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

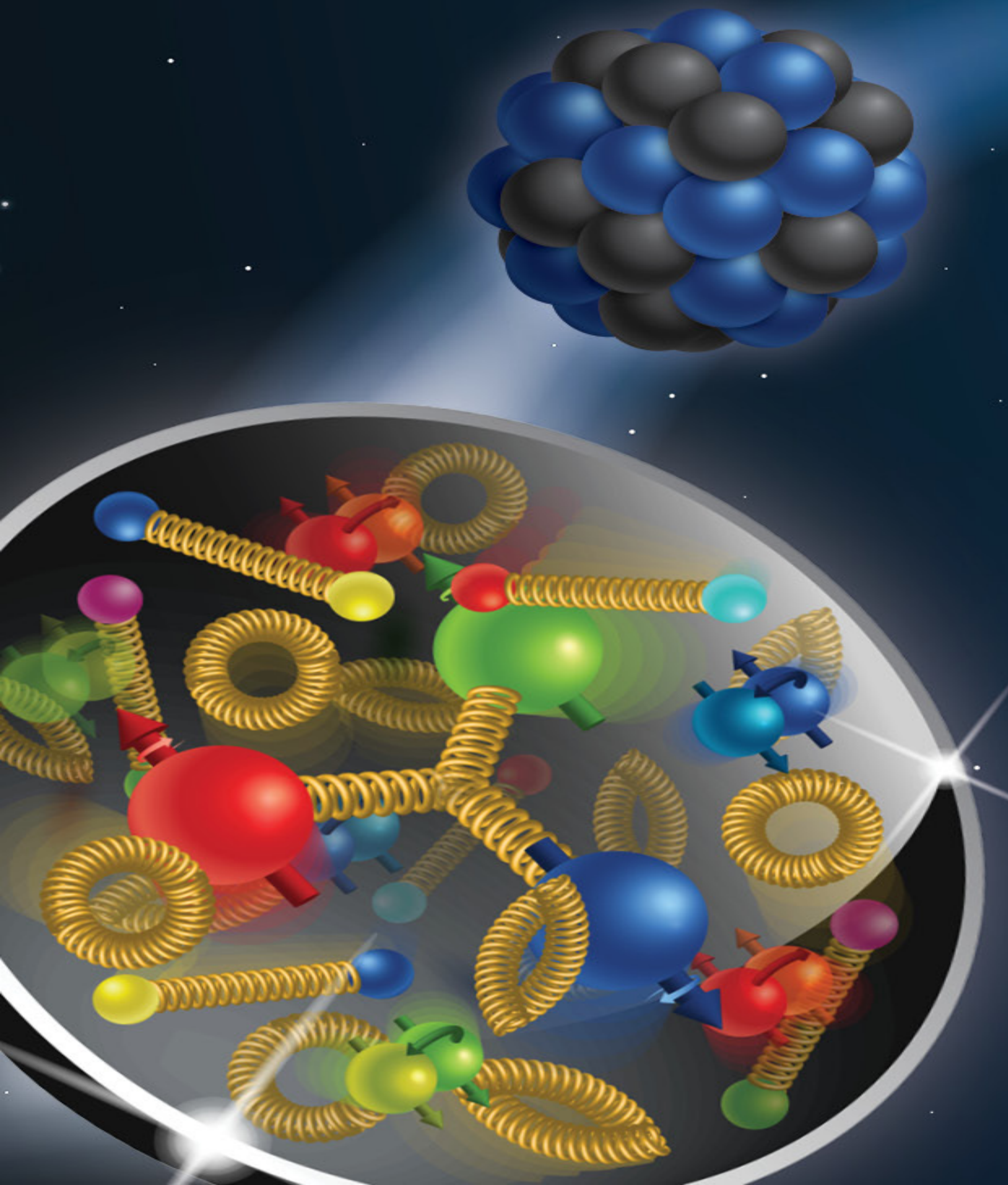
Tagged DIS on the deuteron enables study of free and modified nuclear structure in a single nucleus!

Full Detector Simulations – Tagged Spectators



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).

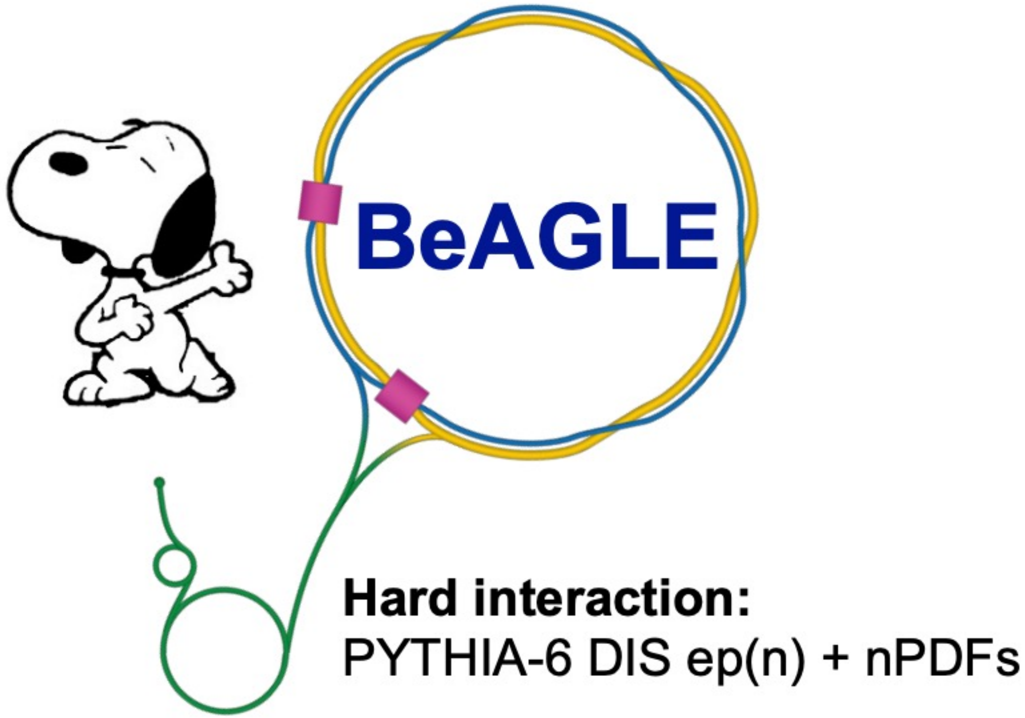


Deuterons: Gluons and Short-Range Correlations

Monte Carlo for all e+d studies presented here

General-purpose eA DIS MC generator

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



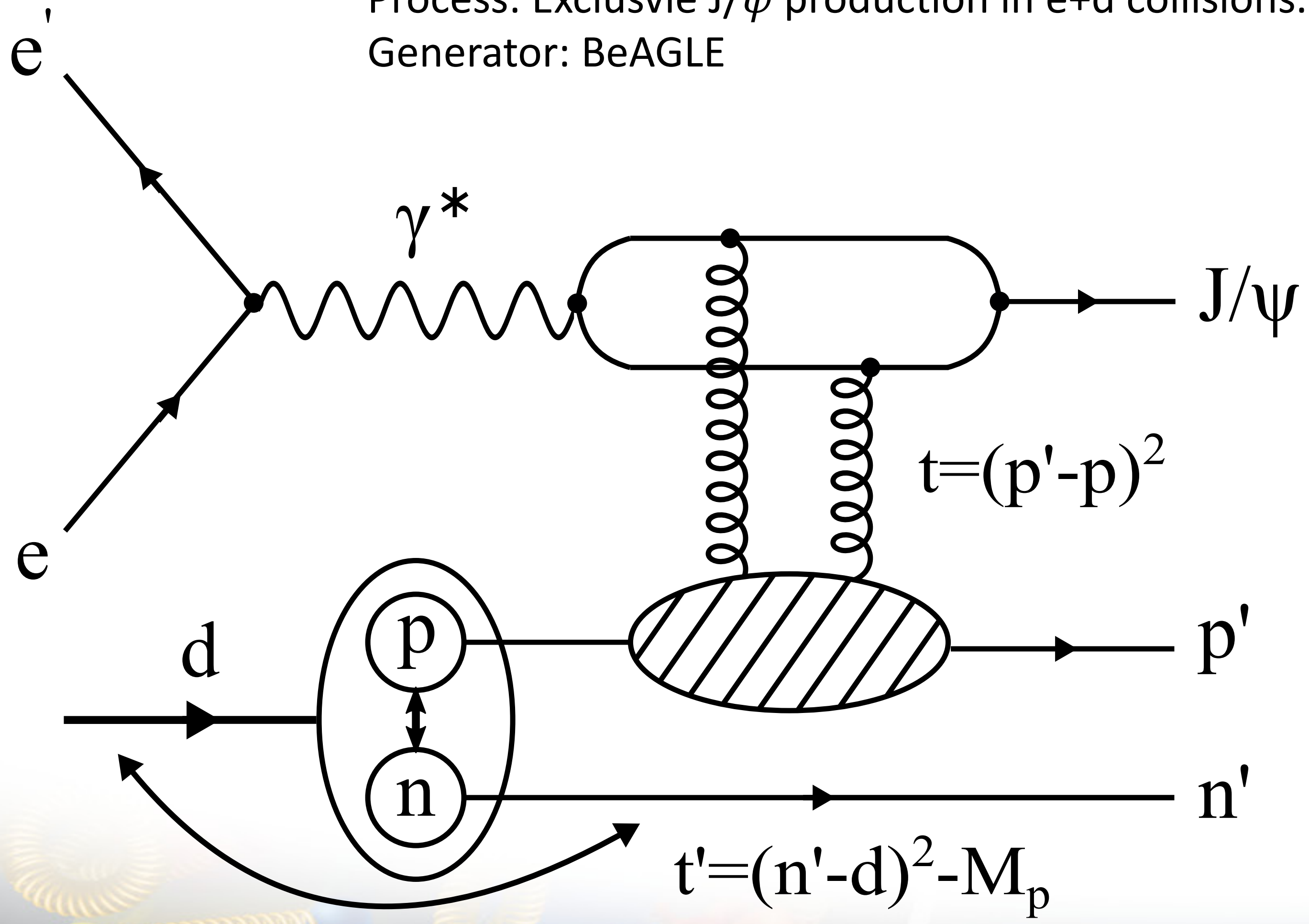
Wan Chang, Elke-Caroline Aschenauer, Mark D. Baker, Alexander Jentsch, Jeong-Hun Lee, Zhoudunming Tu, Zhongbao Yin, and Liang Zheng
Phys. Rev. D **106**, 012007 (2022)

- Use BeAGLE to simulate the hard e + (active) nucleon scattering and primary process (e.g. J/ψ production, DIS, etc.)
  - **For heavy A:** DPMJET and FLUKA
  - **For deuteron:** 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!

Short-Range Correlations in Deuterons

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

Process: Exclusvie J/ψ production in e+d collisions.
Generator: BeAGLE

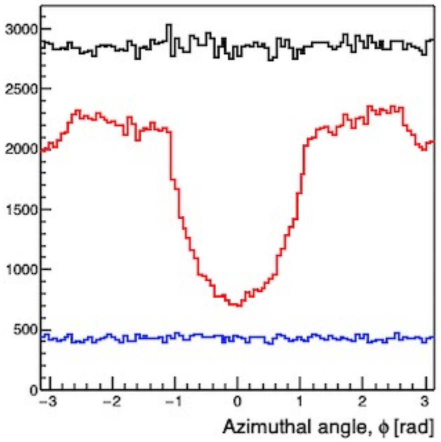


- J/ψ produced at mid-rapidity.
  - **Sensitive to gluons!**
- Tagging active and spectator nucleons allow for experimental control of nuclear configuration → study transition into SRC region (e.g. where nuclear effects become larger).
- Tagging **both** nucleons allows for full reconstruction of momentum transfer!

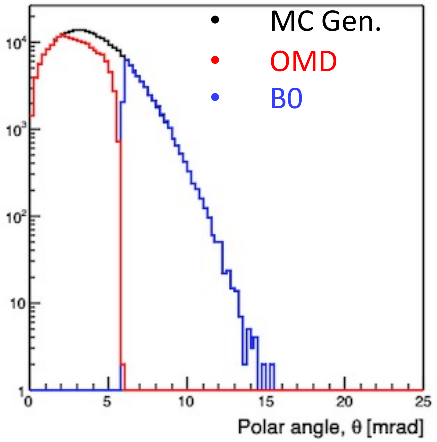
Short-Range Correlations in Deuterons

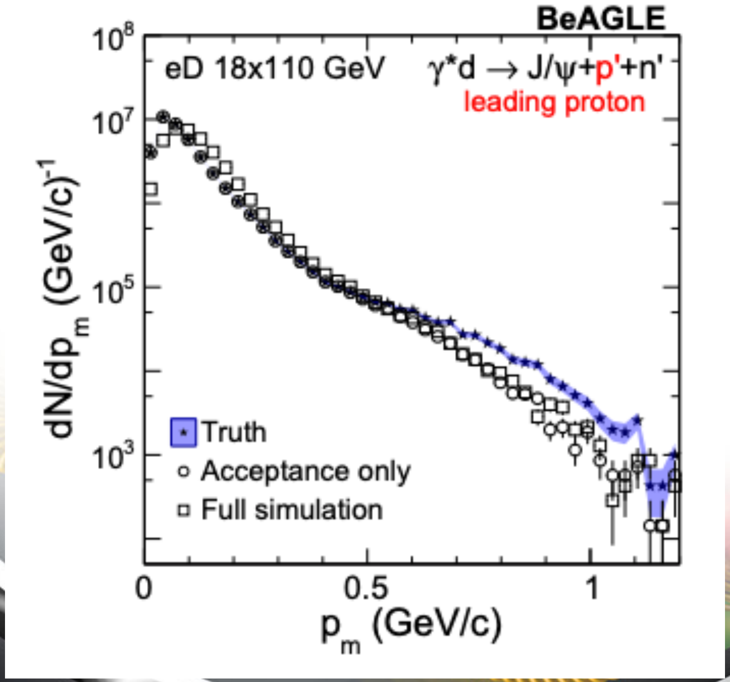
Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)

"active" protons



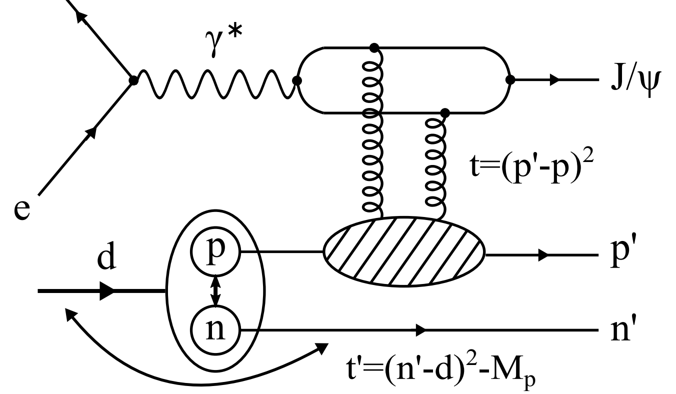
"active" protons





<u>Neutron</u> "spectator" case.

18x110GeV



Short-Range Correlations in Deuterons

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

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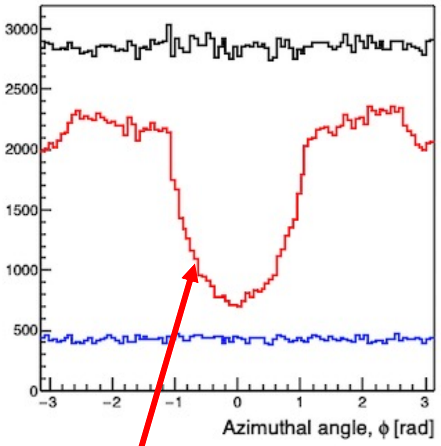
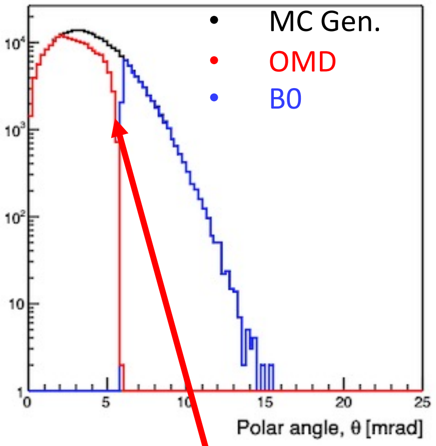


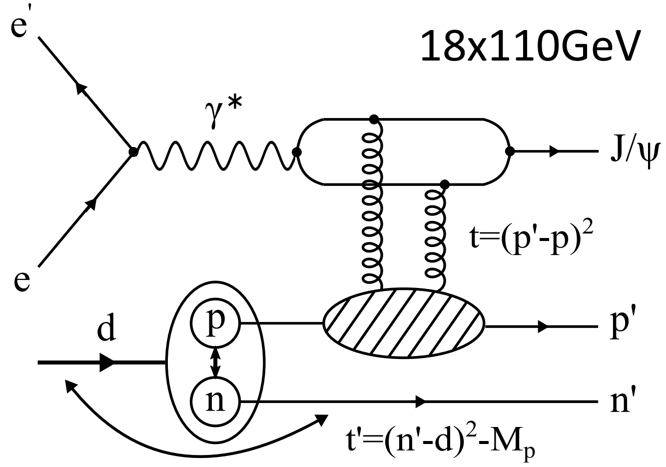
"active" protons

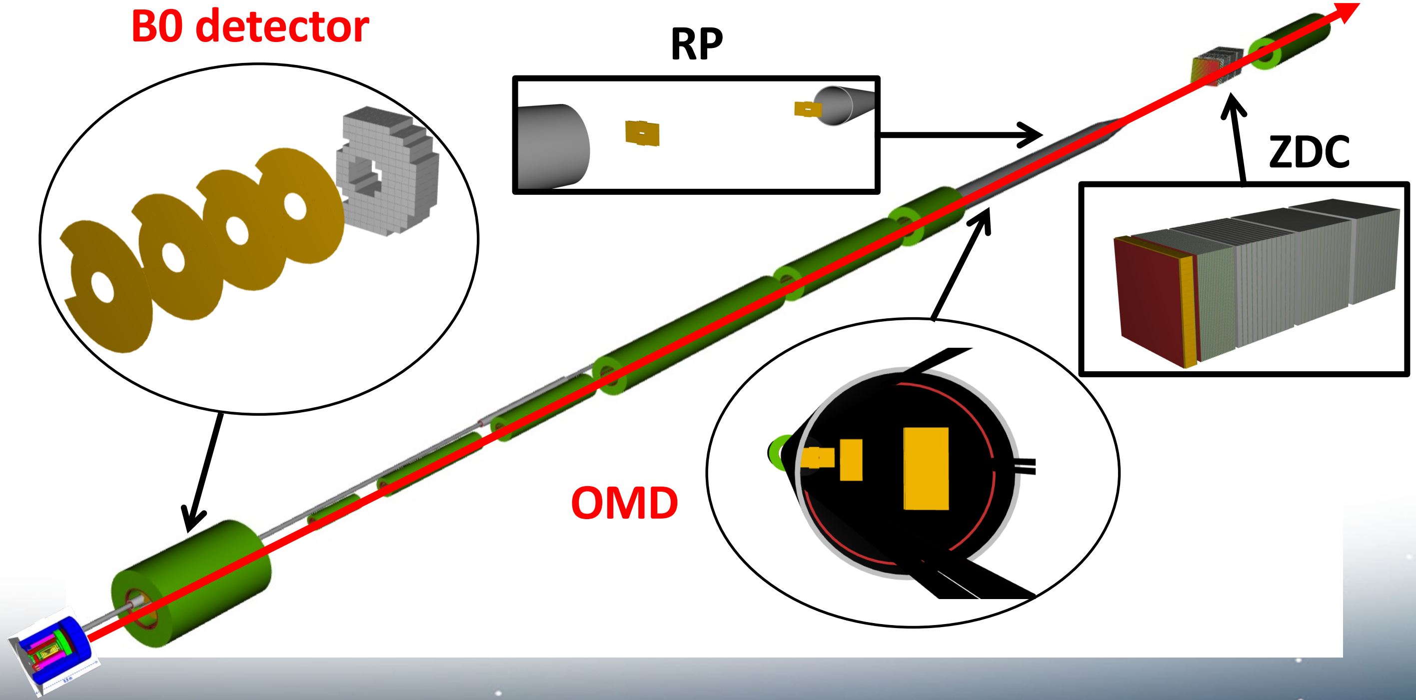


Off-momentum protons lost in quadrupole magnets.

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

Neutron "spectator" case.





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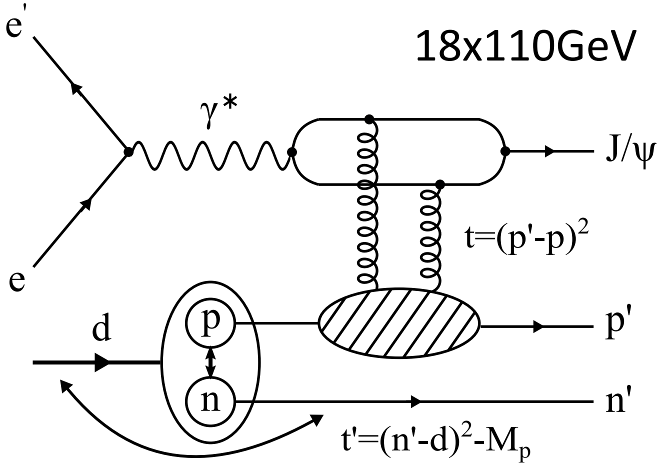
Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)



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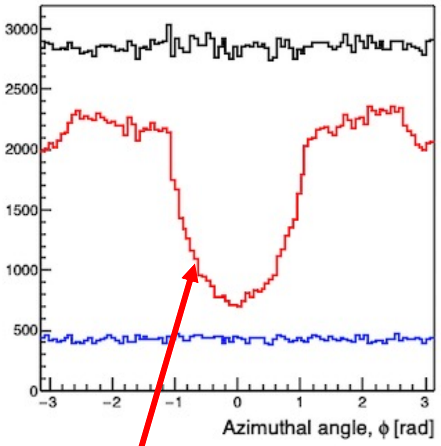

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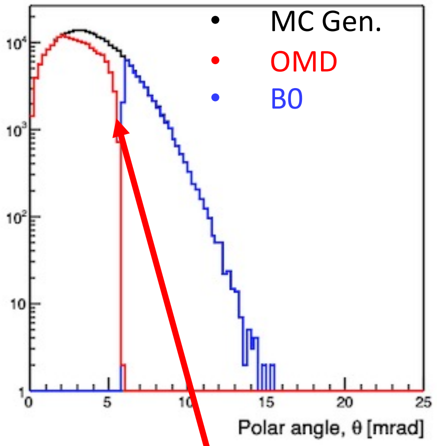

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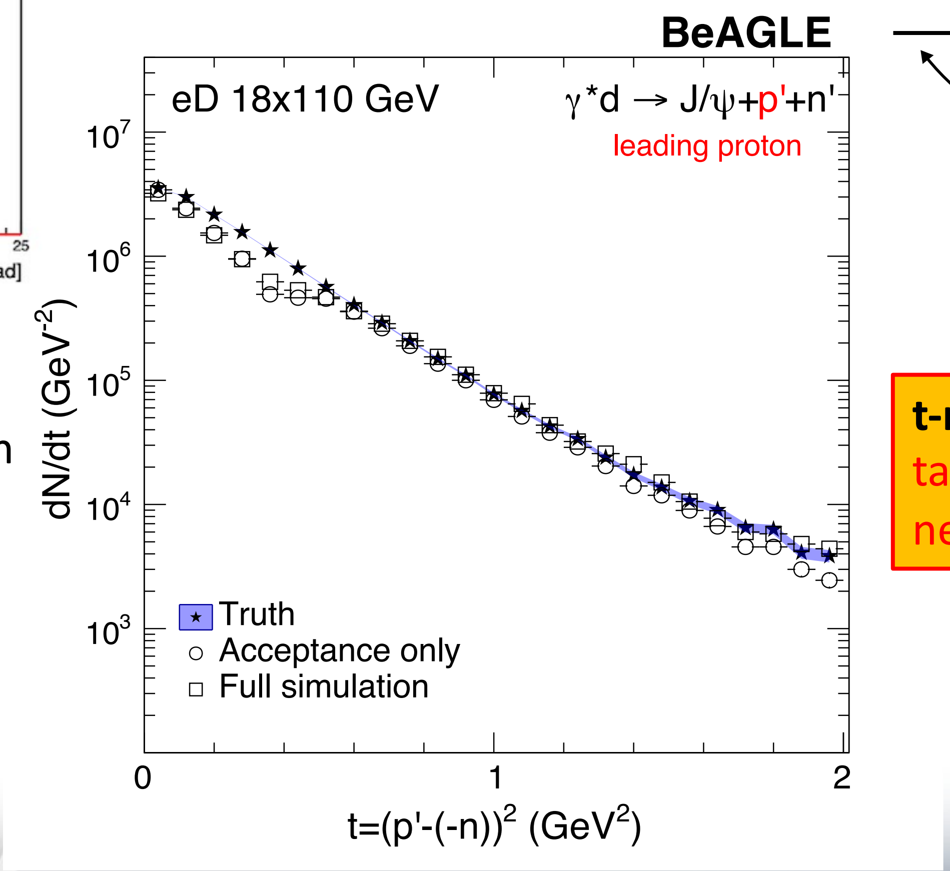
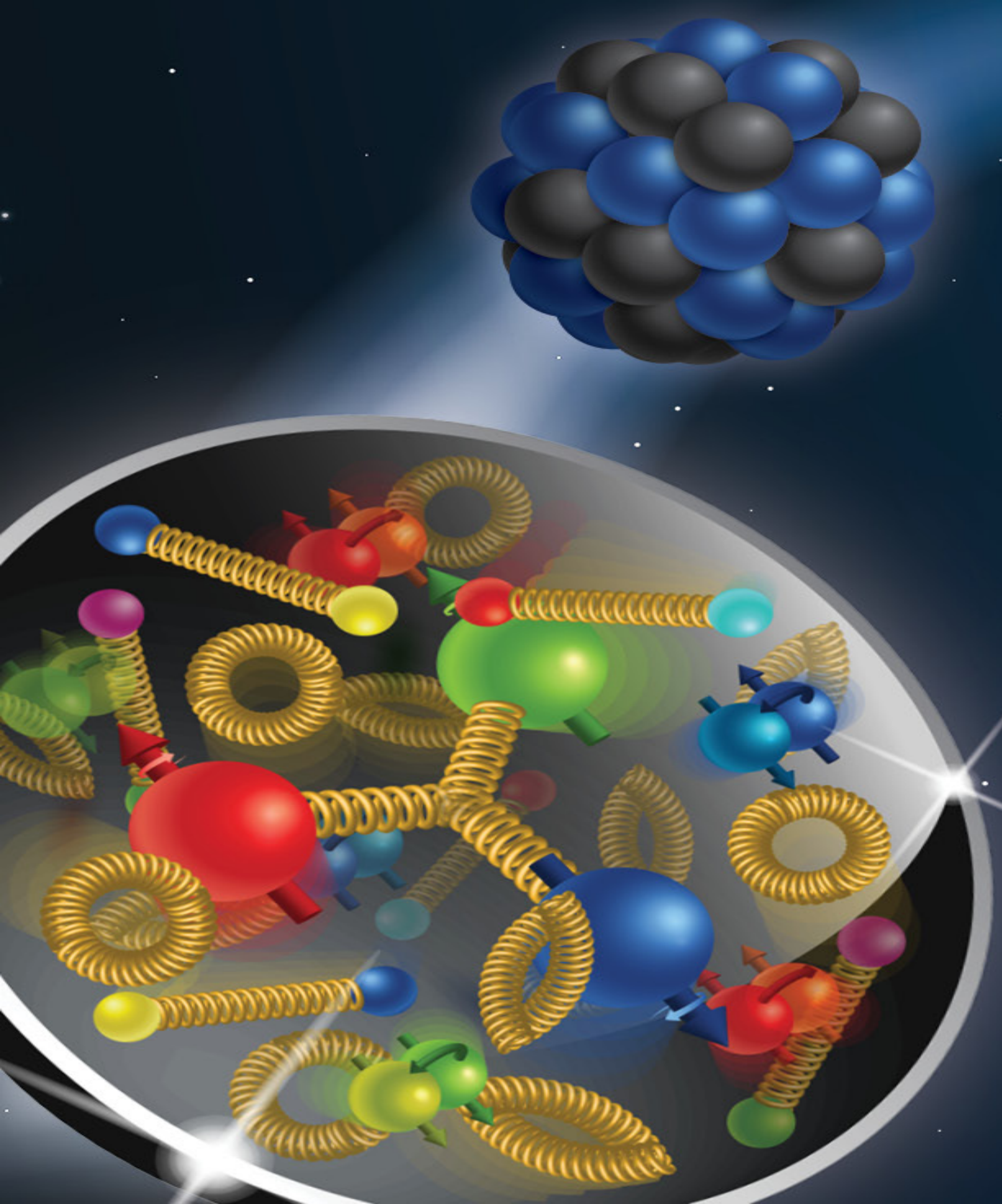


t-reconstruction using double-tagging (both proton and neutron reconstructed).

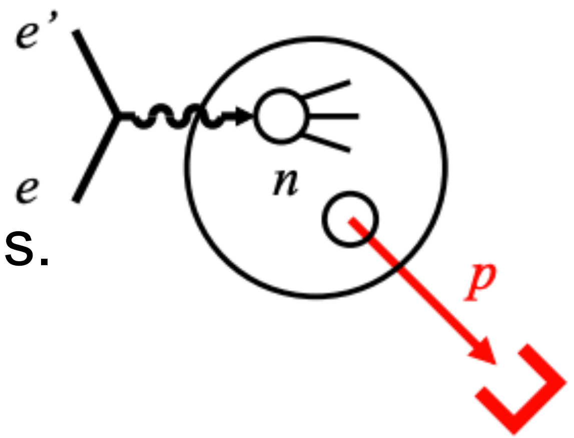
➢ **Spectator information is the "dial" for the SRC region.**



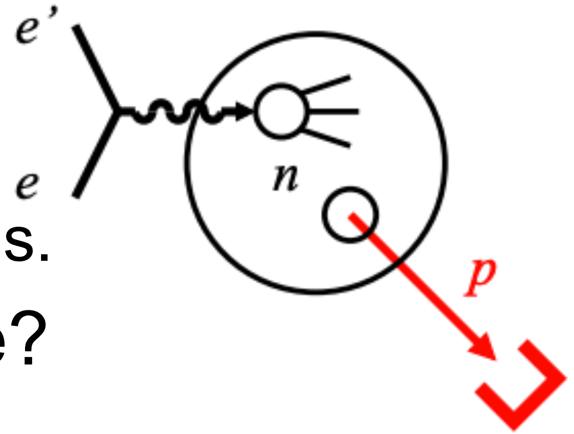
Deuterons: Free Neutron Structure

Neutron Structure

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



Neutron Structure



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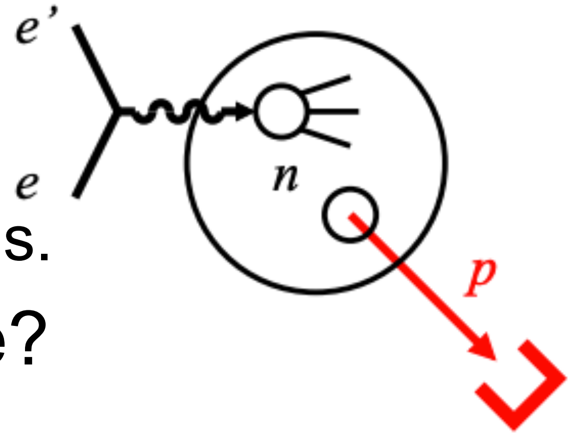
- What makes the free neutron structure hard to measure?
  - Can only access neutrons *in a nucleus.*
  - Includes nuclear binding effects, Fermi motion, etc.

Neutron Structure



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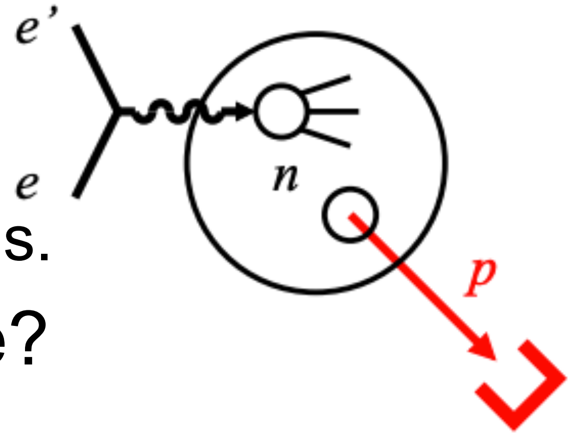
- <u>Two options:</u>
  1. Inclusive measurements → Average over all nuclear configurations, use theory input to correct for nuclear binding effects.

Neutron Structure



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  - 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 provide a knob to dial in different regions of interest for study (i.e. high p_T → SRC physics; very low p_T ~ 0 GeV/c yields access to on-shell extrapolation).
     - On-shell extrapolation enables access to **free** nucleon structure.
       - M. Sargsian, M. Strikman PLB **639** (iss. 3-4) 223231 (2006)

Neutron Structure

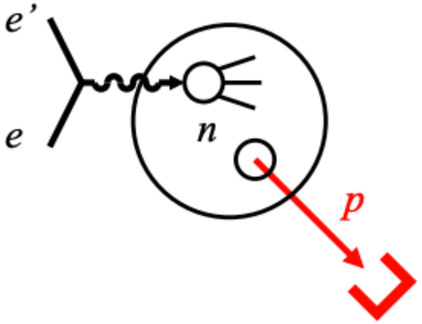
- Previous fixed target experiments with tagging have measured the neutron F_2 at high-x.
  - CLAS - Phys. Rev. Lett. **108**, 199902 (2012)
  - CLAS + BONUS - Phys. Rev. C 89, 045206 (2014)
    - measurement had a lower p_T cutoff ~ 70 MeV/c.
- Future JLAB 12 GeV studies planned.
  - ALERT - https://arxiv.org/abs/1708.00891
  - 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

α_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}, α_p)

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

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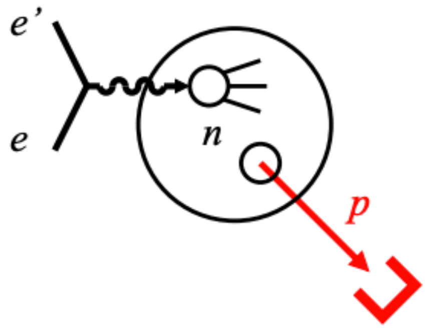

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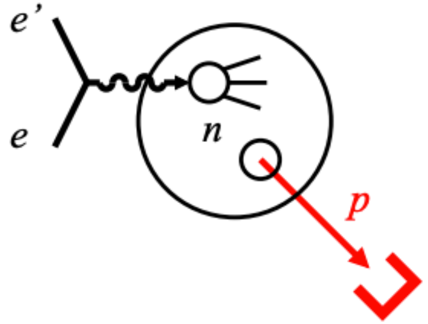
- Measure the cross-section differential on the spectator kinematics.
  - Spectator kinematics provide control knob on the nuclear configuration.
- Solve for the deuteron reduced cross section.

Tagged Deuteron Cross Section



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Total cross section
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- 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.

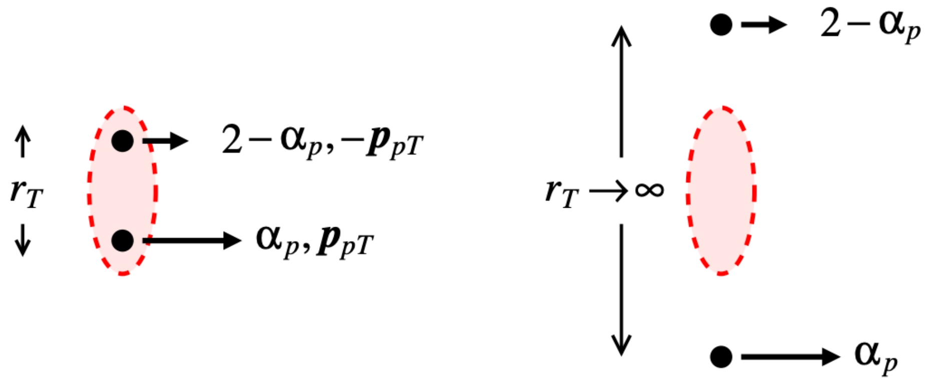
$$\sigma_{red,d}\left(x, Q^2; p_{pT}, \alpha_p\right) = [2(2\pi)^3] \times S_d(p_{pT}, \alpha_p)[pole] \times \sigma_{red,n}(x, Q^2)$$

Measurement of the deuteron reduced cross section yields access to the struck nucleon structure via the tagged spectator!

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

$p_{pT}^2 \rightarrow -a_T^2$
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

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

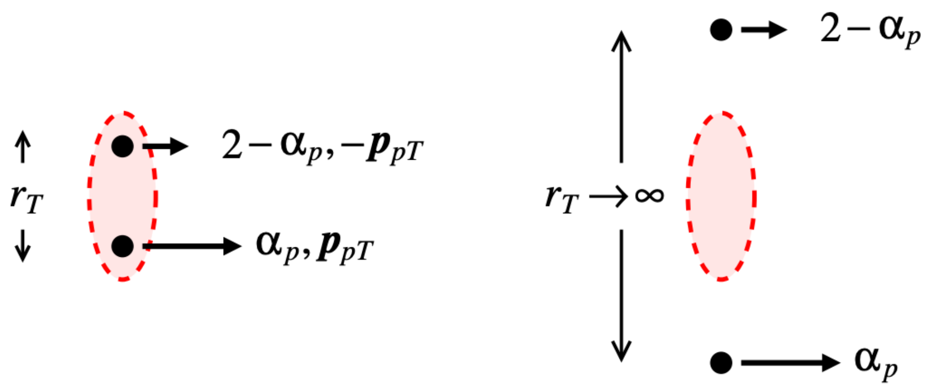
$$a_T^2 = m_N^2 - \alpha_p(2 - \alpha_p)\frac{M_d^2}{4}$$

$R = residue\ of\ spectral\ function$

$a_T^2 = position\ of\ pole$

Pole Extrapolation

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



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

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

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

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

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

$R = residue\ of\ spectral\ function$

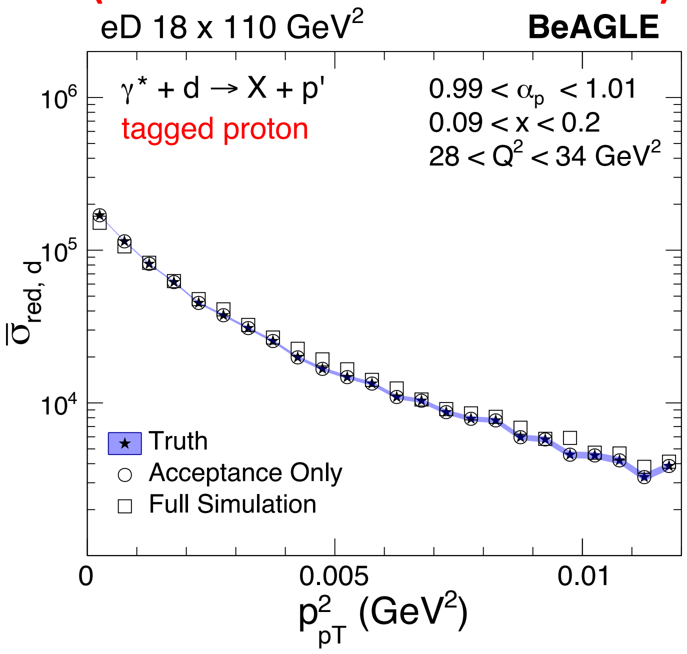
$a_T^2 = position\ of\ pole$

- Extrapolate to $p_{pT}^2 \to -a_T^2$ to extract F_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)

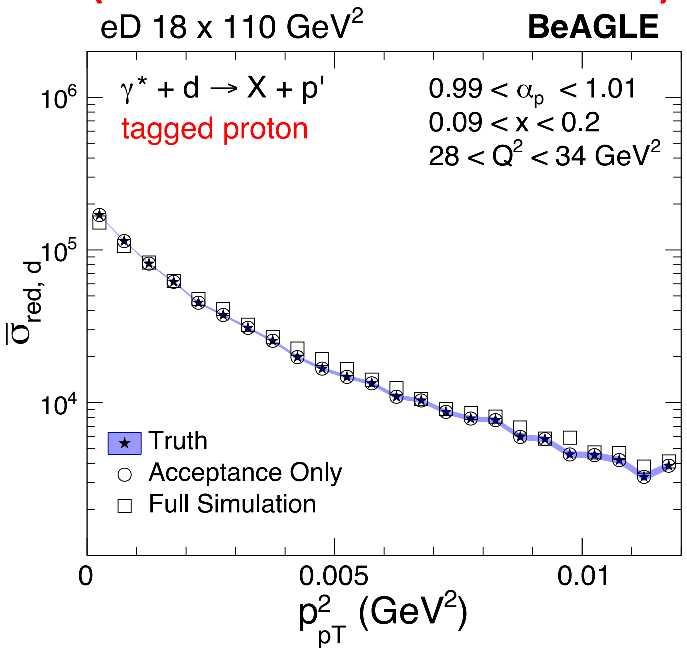


- Start with the deuteron reduced cross section → **direct measurement!**

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.

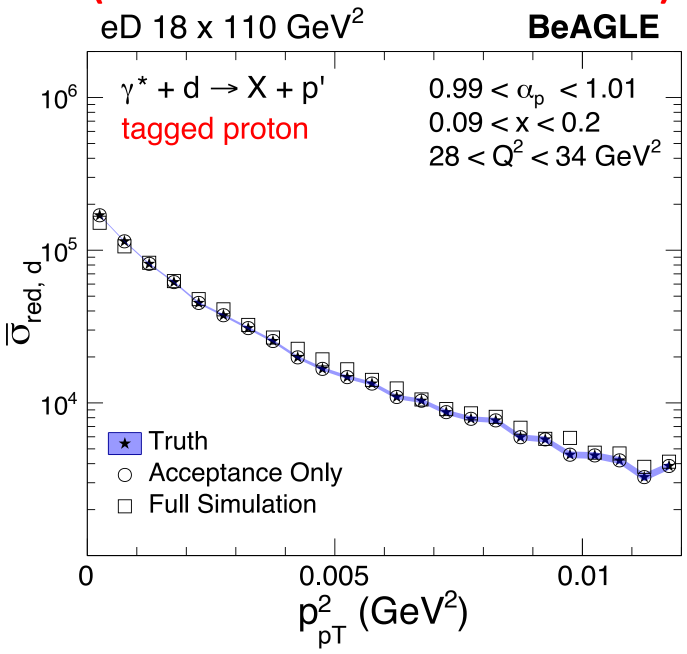
$$\frac{1}{S_d(p_{pT}, \alpha_p)[pole]}$$

(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)**

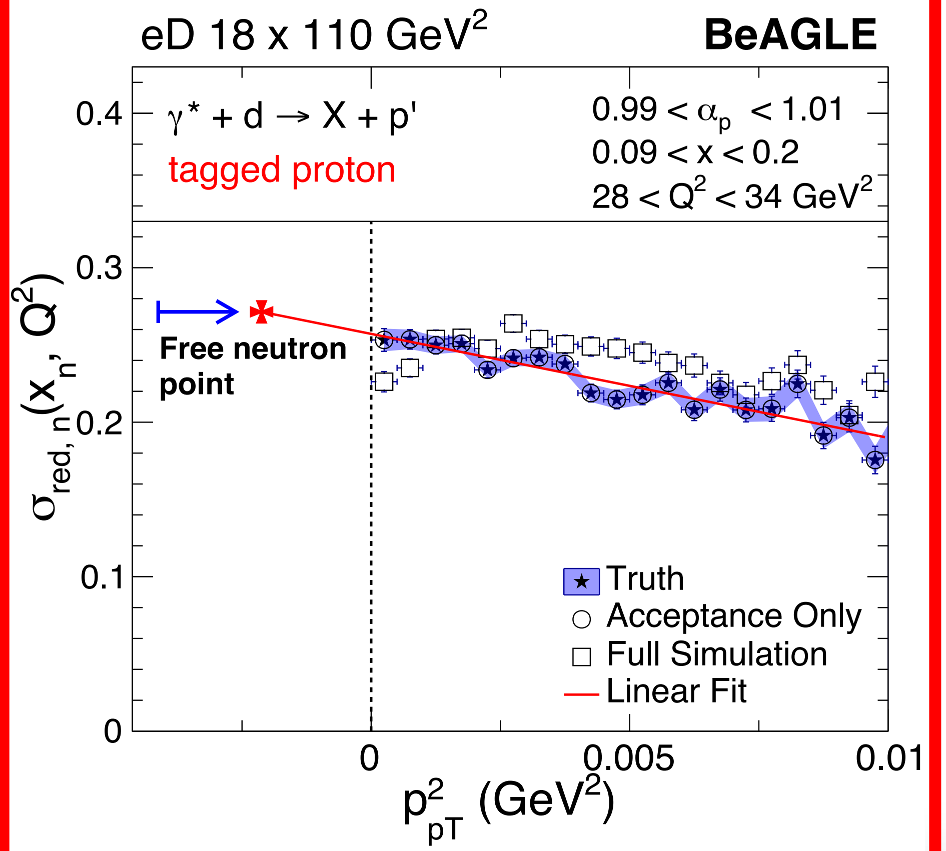
(deuteron reduced cross section)



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

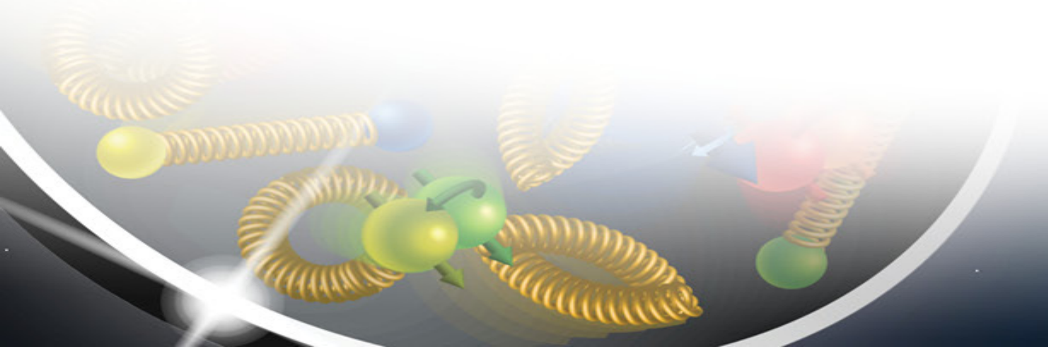
$$\times \quad \frac{1}{S_d(p_{pT},\alpha_p)[pole]}$$

(inverse pole of deuteron spectral function)



(Active nucleon reduced cross section)

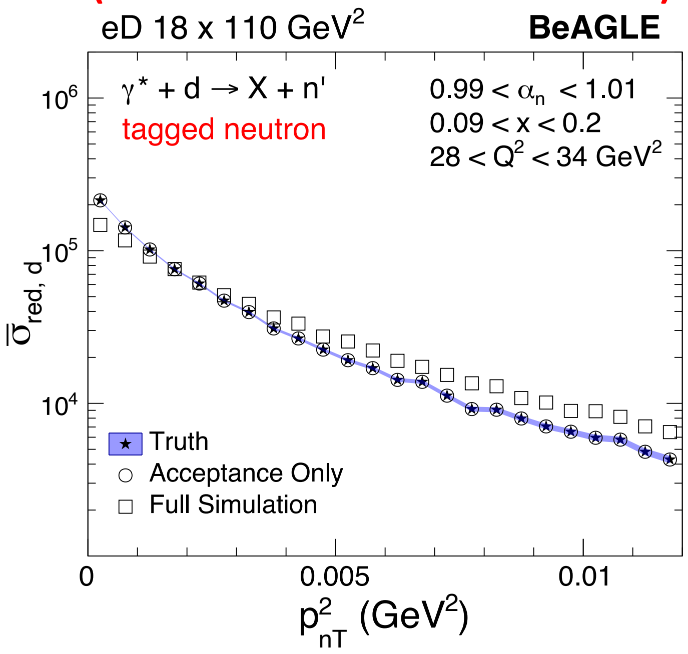
$$\sigma_{red,n}(x,Q^2) = \frac{\sigma_{red,d}}{[2(2\pi)^3]S_d(p_{pT},\alpha_p)}$$



Free Proton F_2 Extraction

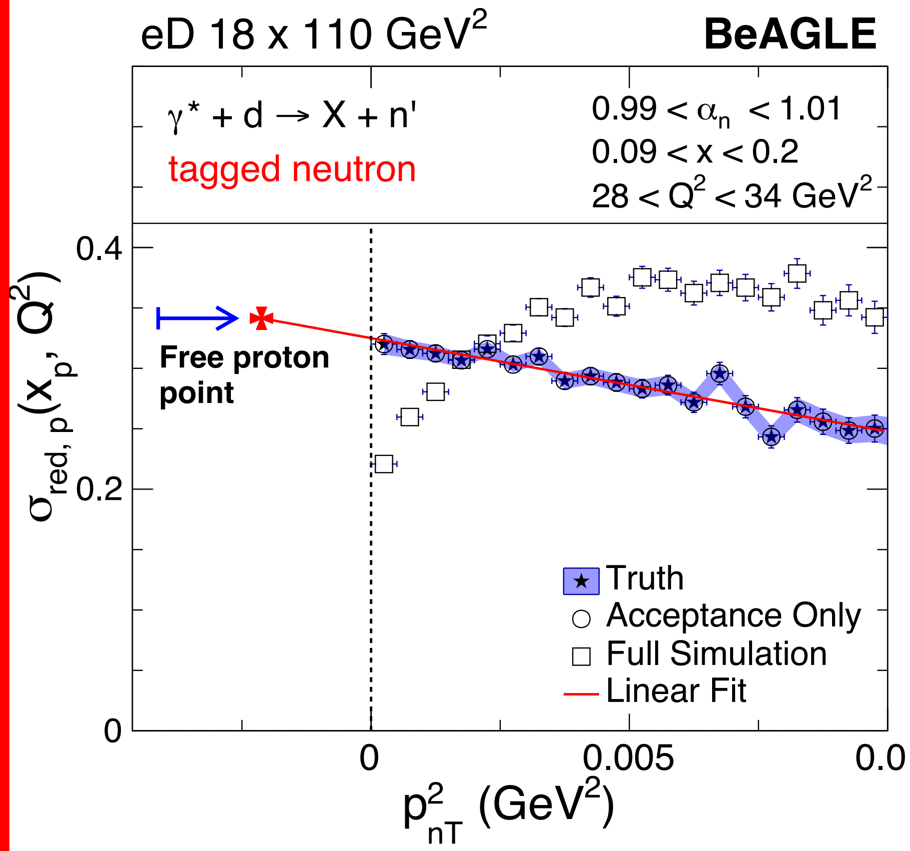
A. Jentsch, Z. Tu, and C. Weiss, Phys. Rev. C **104,** 065205, (2021) **(Editor's Suggestion)**

(deuteron reduced cross section)



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

(inverse pole of deuteron spectral function)

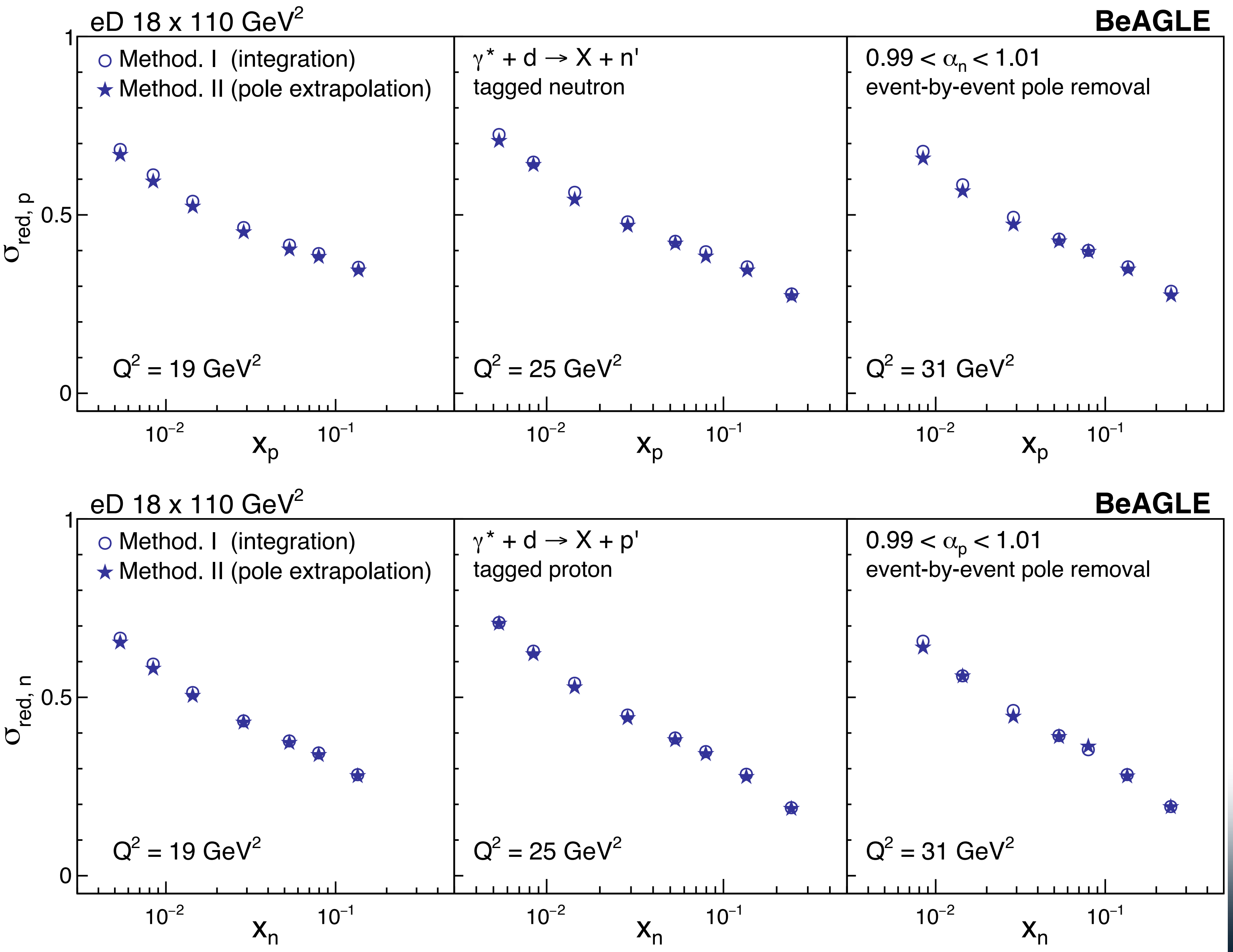


(Active nucleon reduced cross section)

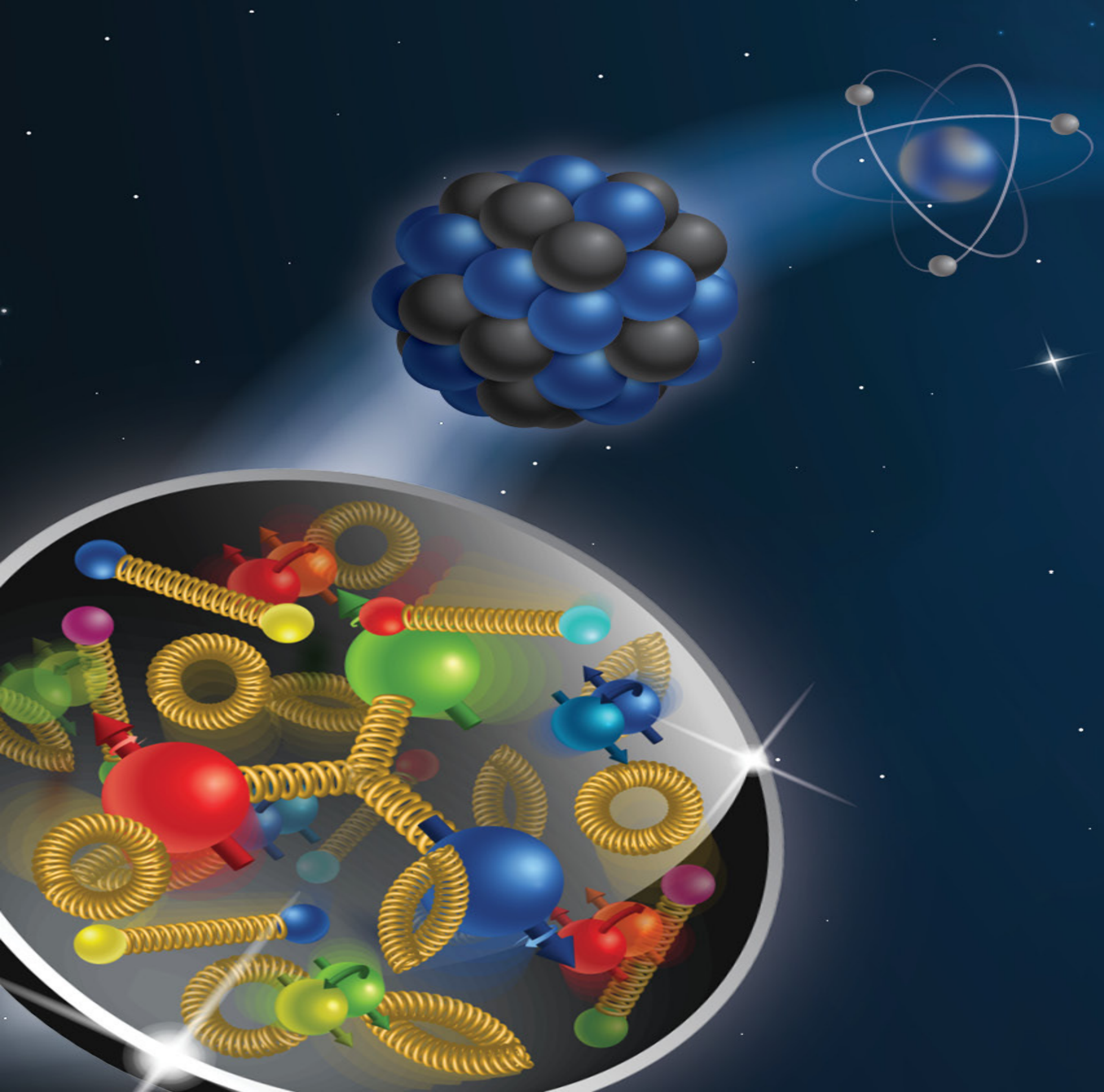
$$\sigma_{red,p}(x, Q^2) = \frac{\sigma_{red,d}}{[2(2\pi)^3]S_d(p_{nT}, \alpha_n)}$$

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

Closure Test – Pole Extrapolation vs. Integration (generator level)



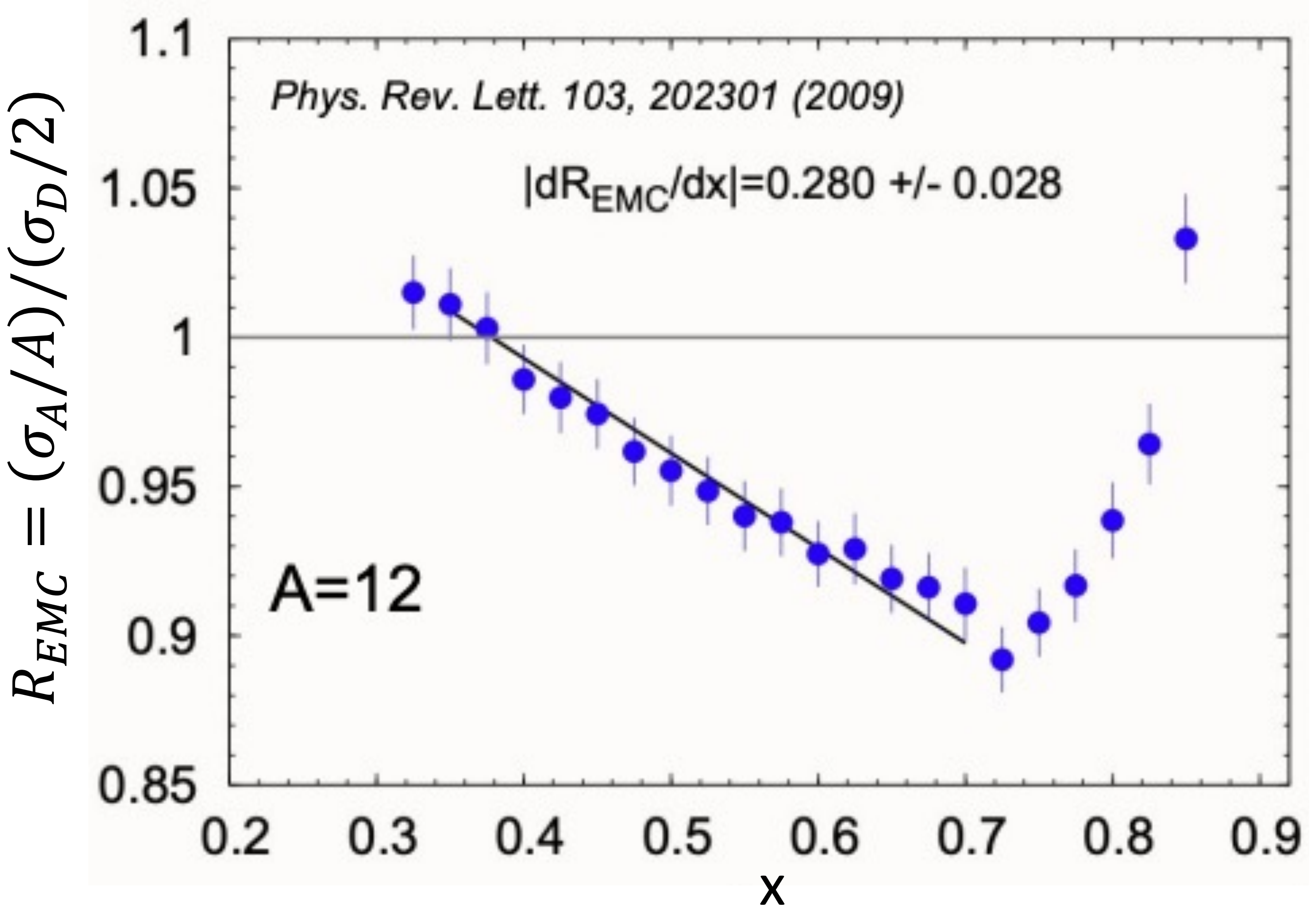
- Pole factor removed using "event by event (EbE)" (**method II**) approach.
  - Pole factor calculated and applied for each event (i.e. pole factor calculated for each exact nuclear configuration).
- Result compared to integration (**method I**) over the spectator kinematics to recover the original input.
- Remaining differences due to fitting and statistics.

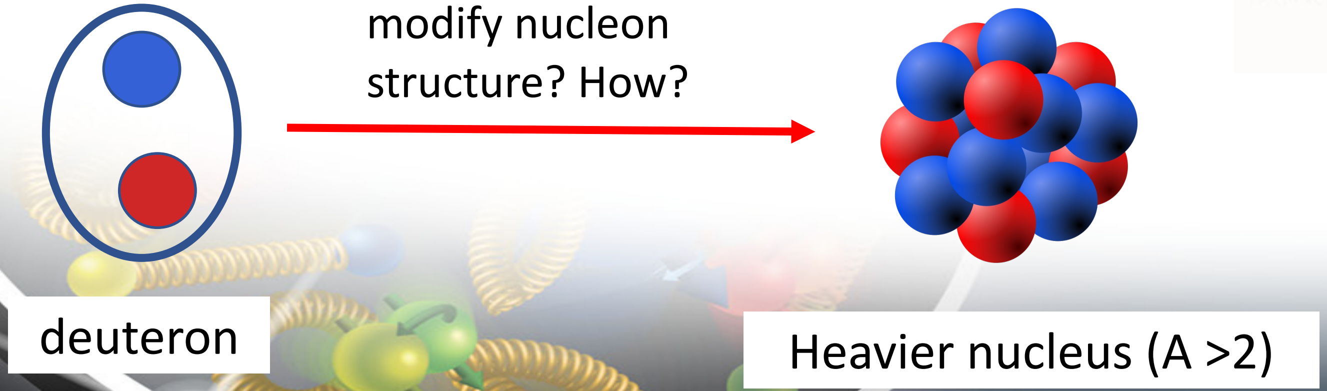


Deuterons:
The EMC Effect
(on-going study)

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**!



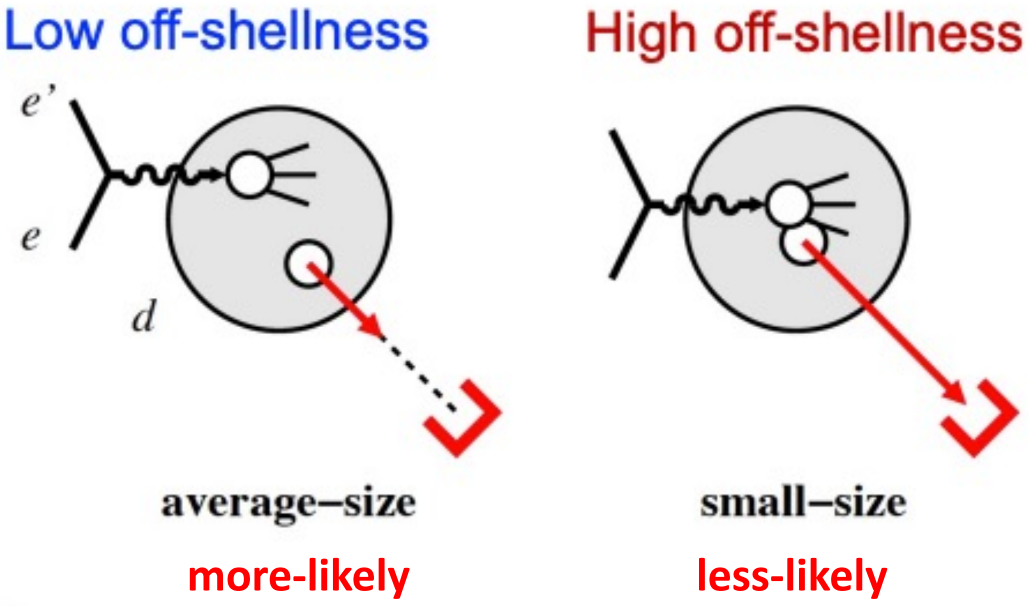


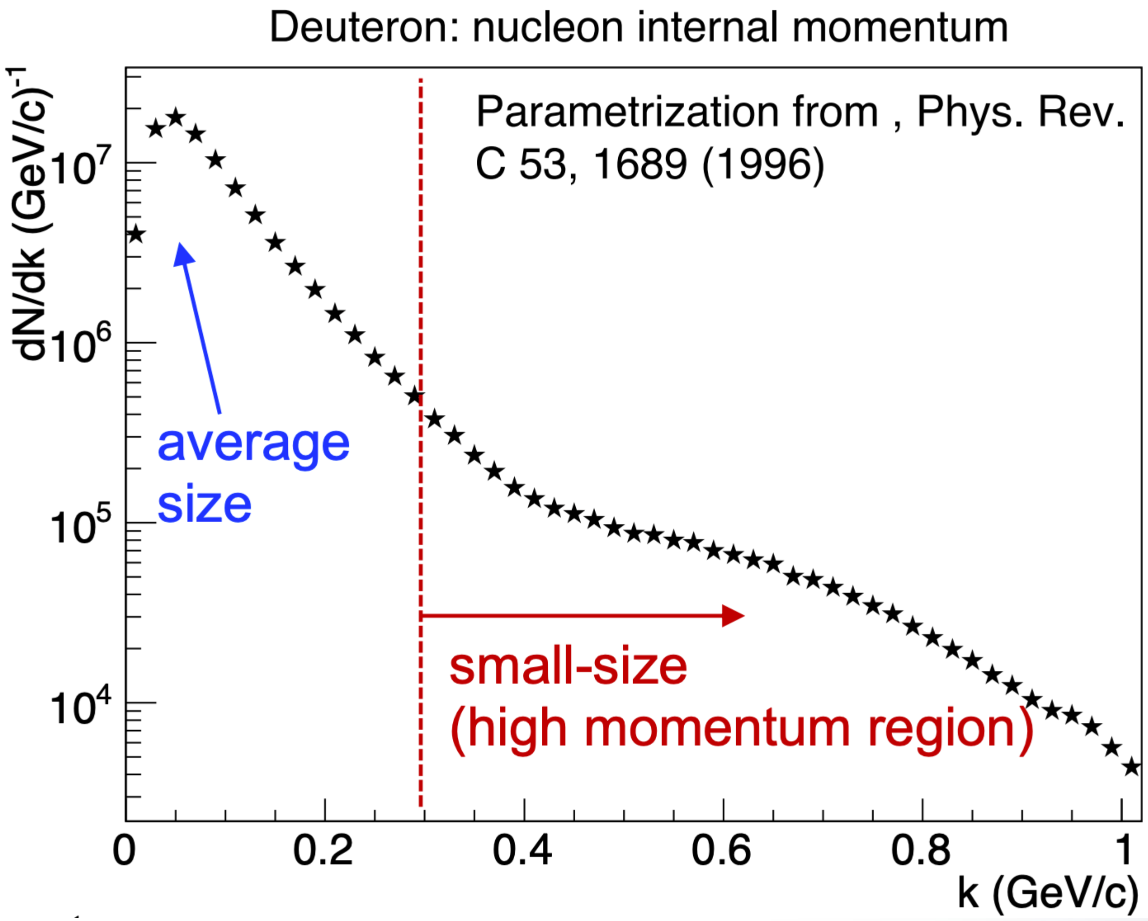
Understanding the origin of the EMC effect and nuclear modifications of prime interest in nuclear physics!

The Deuteron – a stand-alone lab for nuclear physics

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

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



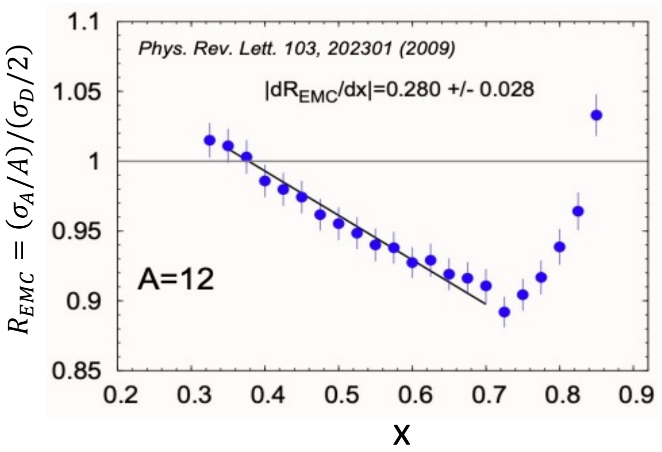


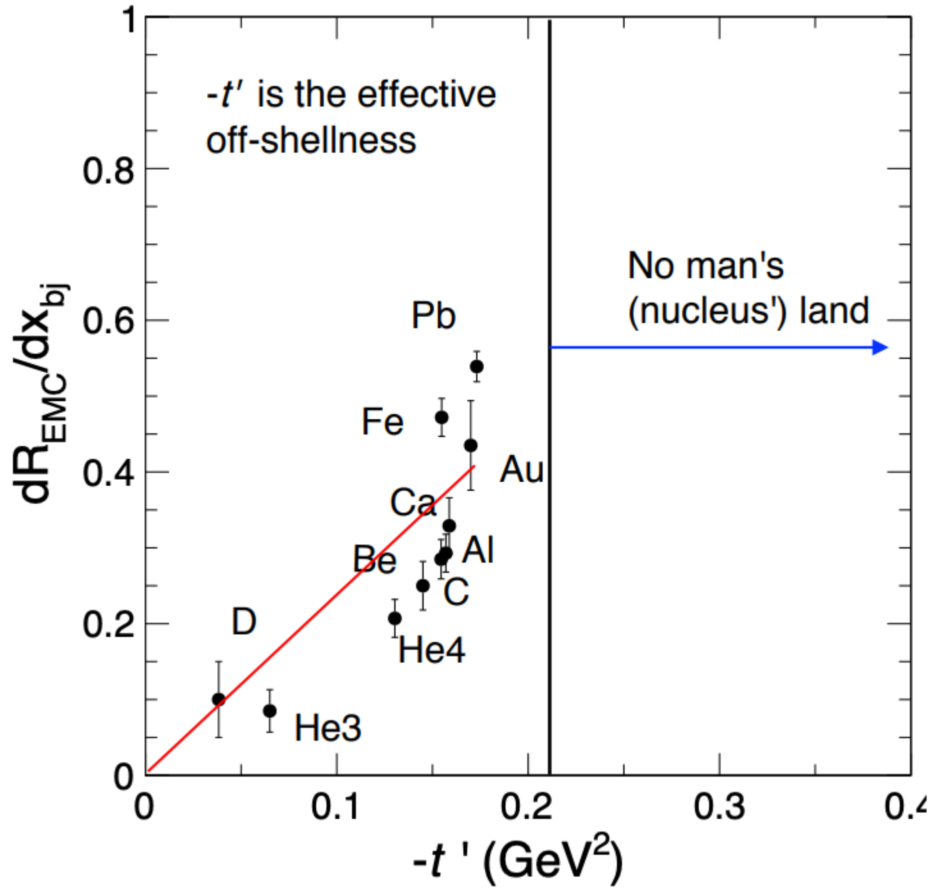
$$-t'^2 = M_N^2 - (p_d - p_p)^2$$

Virtuality/off-shellness in the deuteron

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

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)

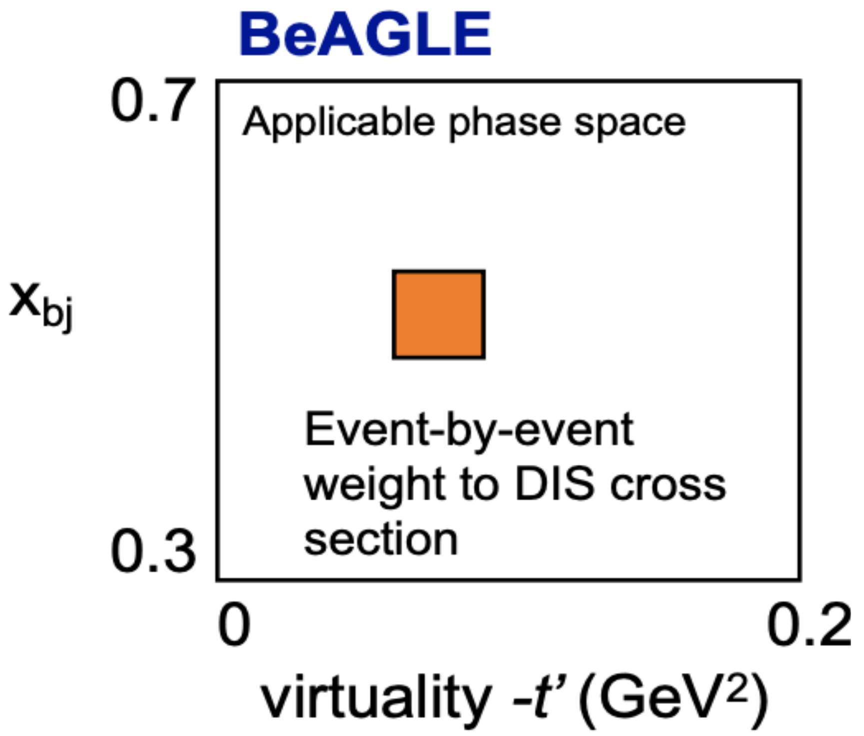
Linear fit to virtuality dependence → Minimal parametrization:

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

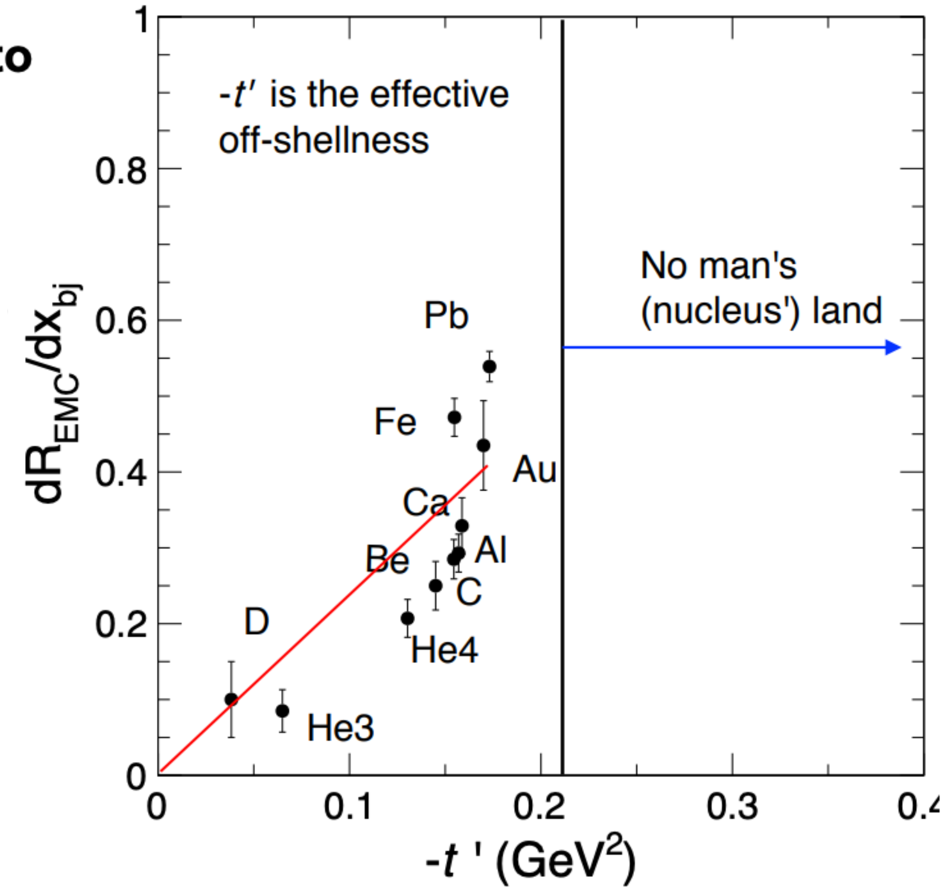
C. Ciofi *et al.,* Phys. Rev. C **76**, 055206 (2007)

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)

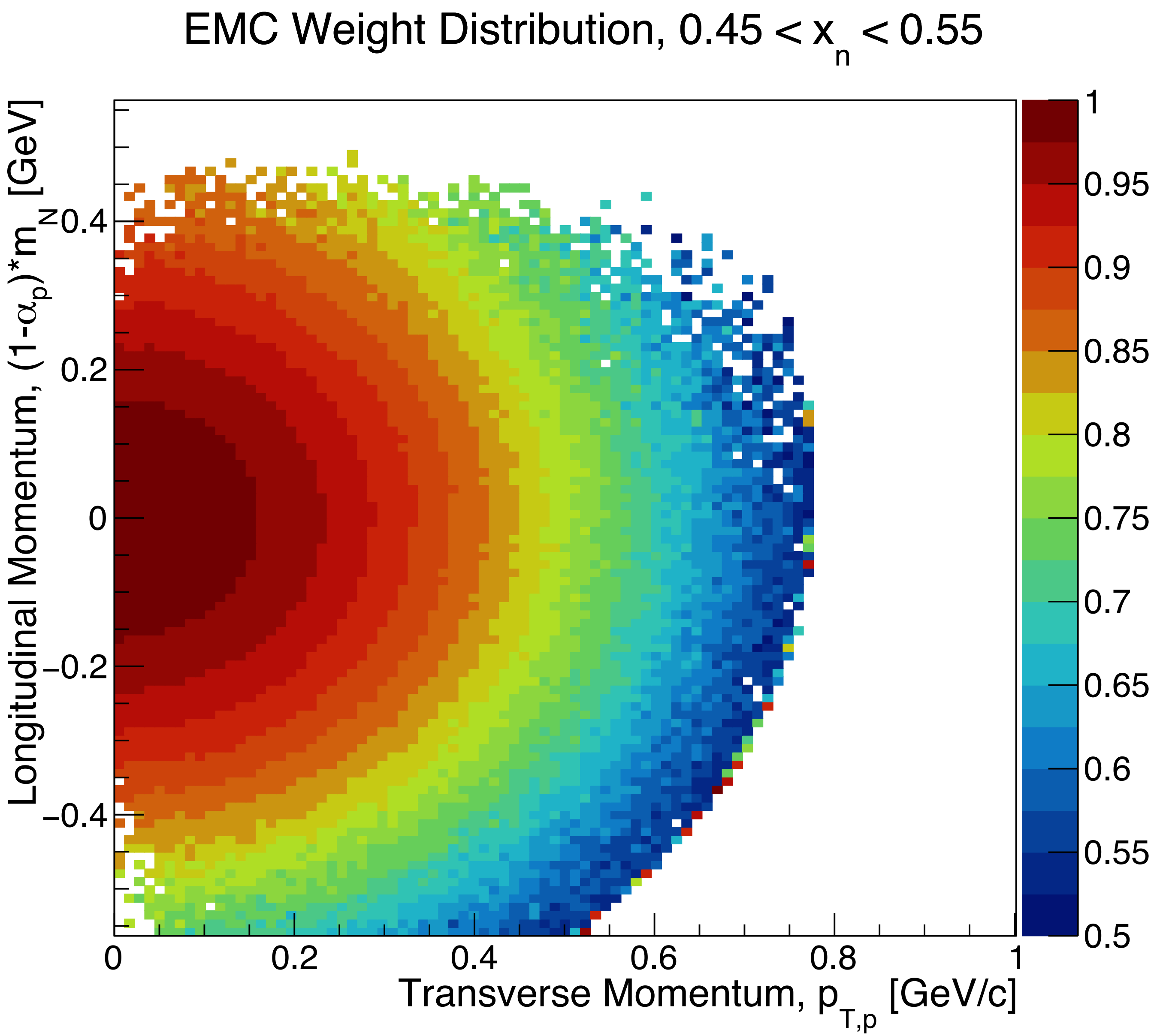
Linear fit to virtuality dependence → Minimal parametrization:

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



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.

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)

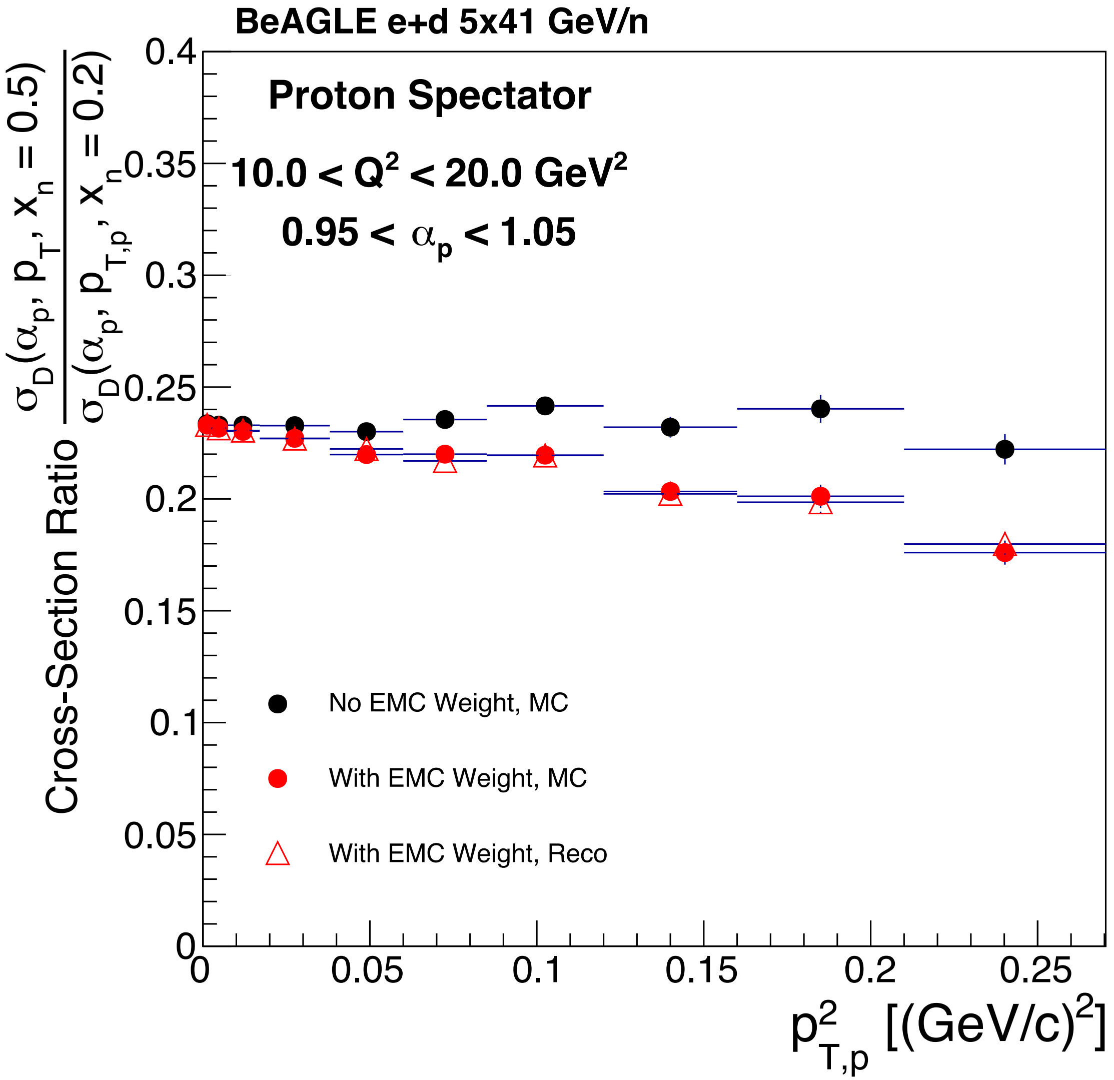
➢ Quantity allows direct comparison of cross section with and without EMC weight (x ~ 0.2 chosen to avoid anti-shadowing region).

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

The EMC Effect @ the EIC

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

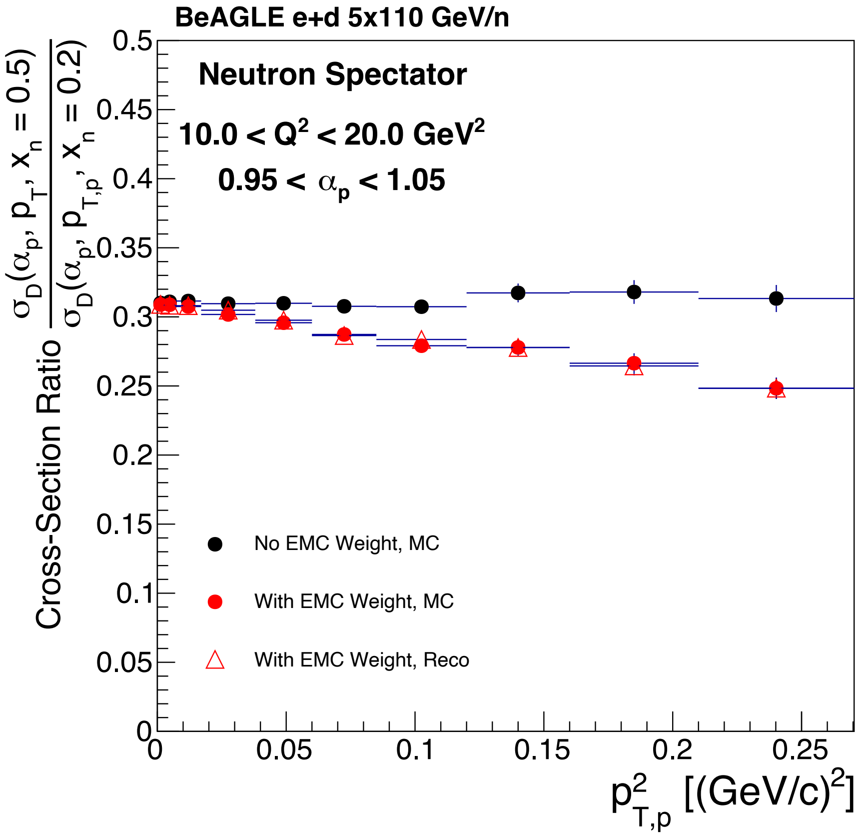
- <u>Approach:</u>
  - Measure deuteron reduced cross-section σ_D, with and without the off-shell effects included.
    - No FSI included.
  - Ratio of σ_D **inside and outside the EMC region** (e.g. x ~ 0.5 and x ~ 0.2)
  - Establish required integrated luminosity.
    - **Challenging measurement →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

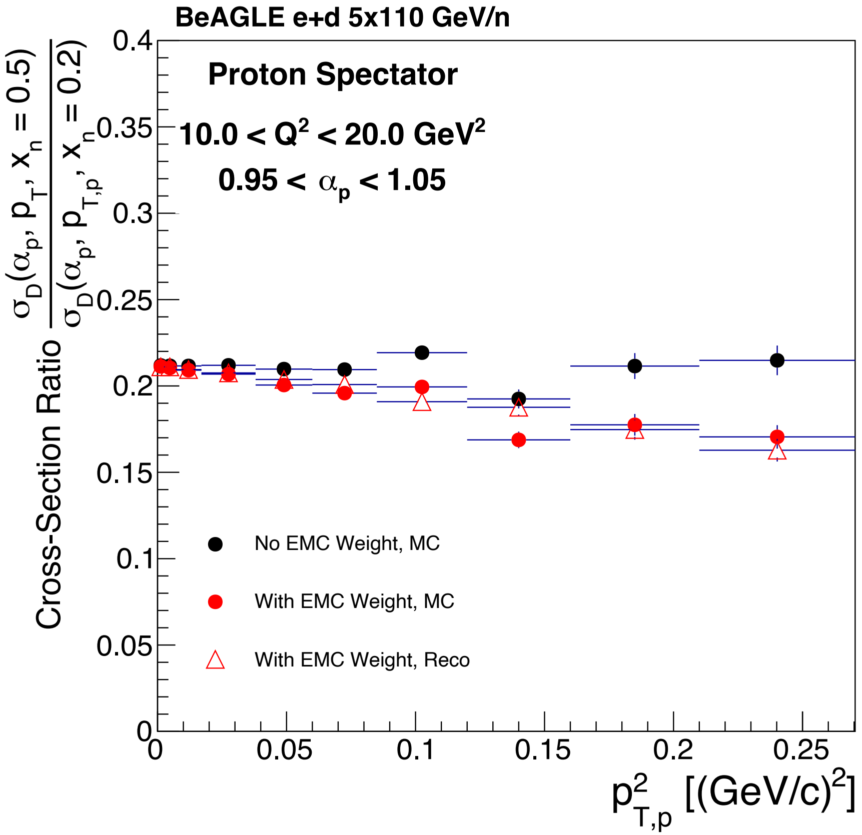


The EMC Effect @ the EIC

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

- EIC versatility → different beam energy configurations!

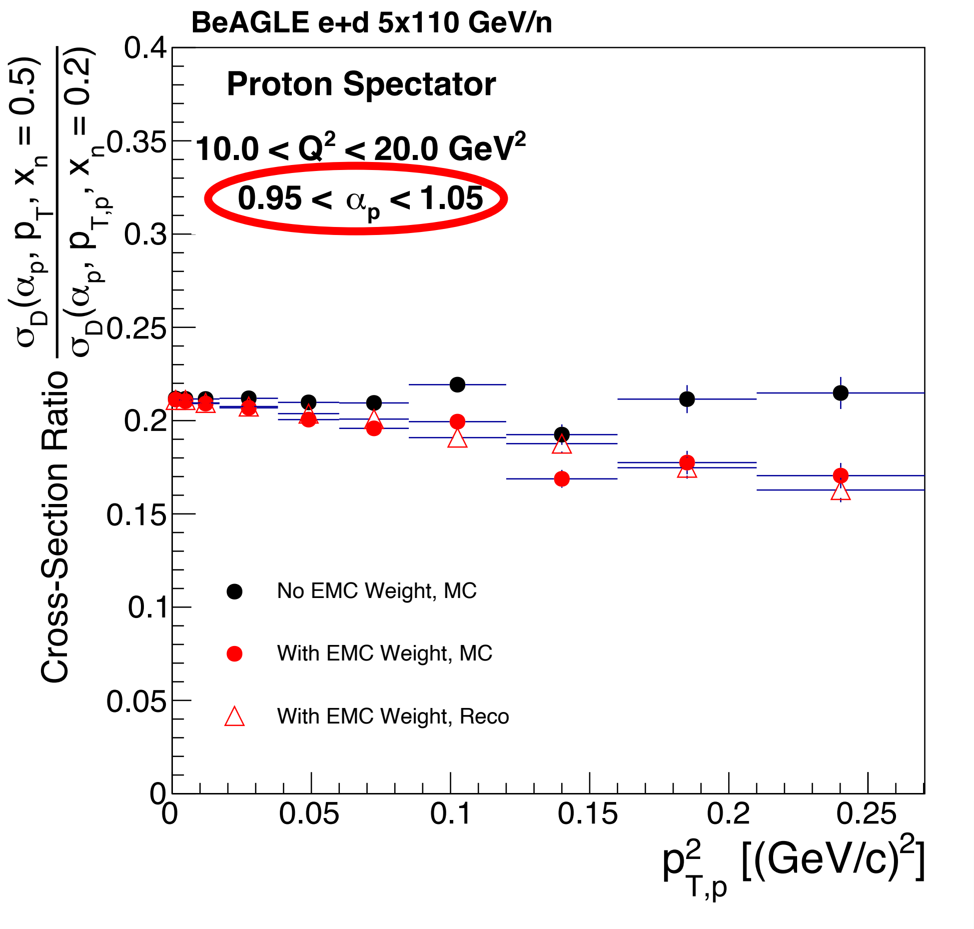




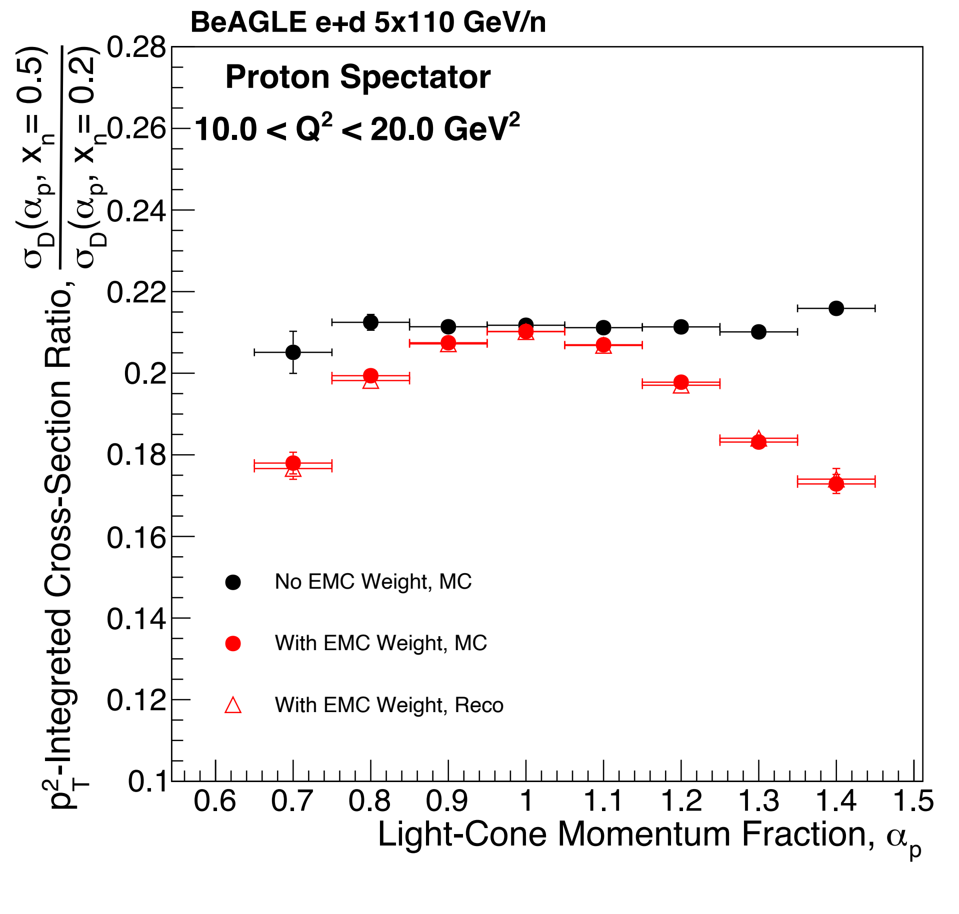
- Higher energy configuration (5x110 GeV/n).
- **More favorable detector acceptance → study of proton *and* neutron spectators with same beam configuration.**
- Measurement of same observable with different beam energies/spectator reconstruction enables better understanding of experimental systematics.

Different nuclear configurations

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

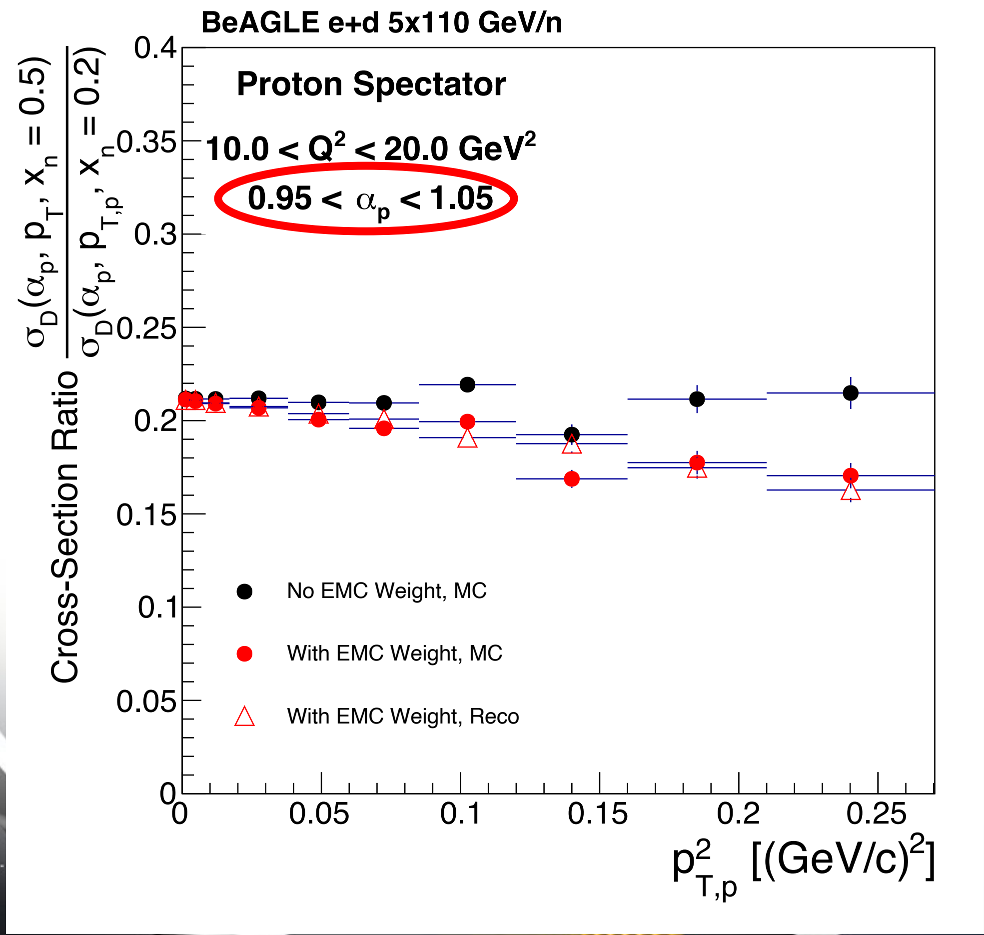


Integrate cross section over $p_{T,p}^2$ in each α bin.

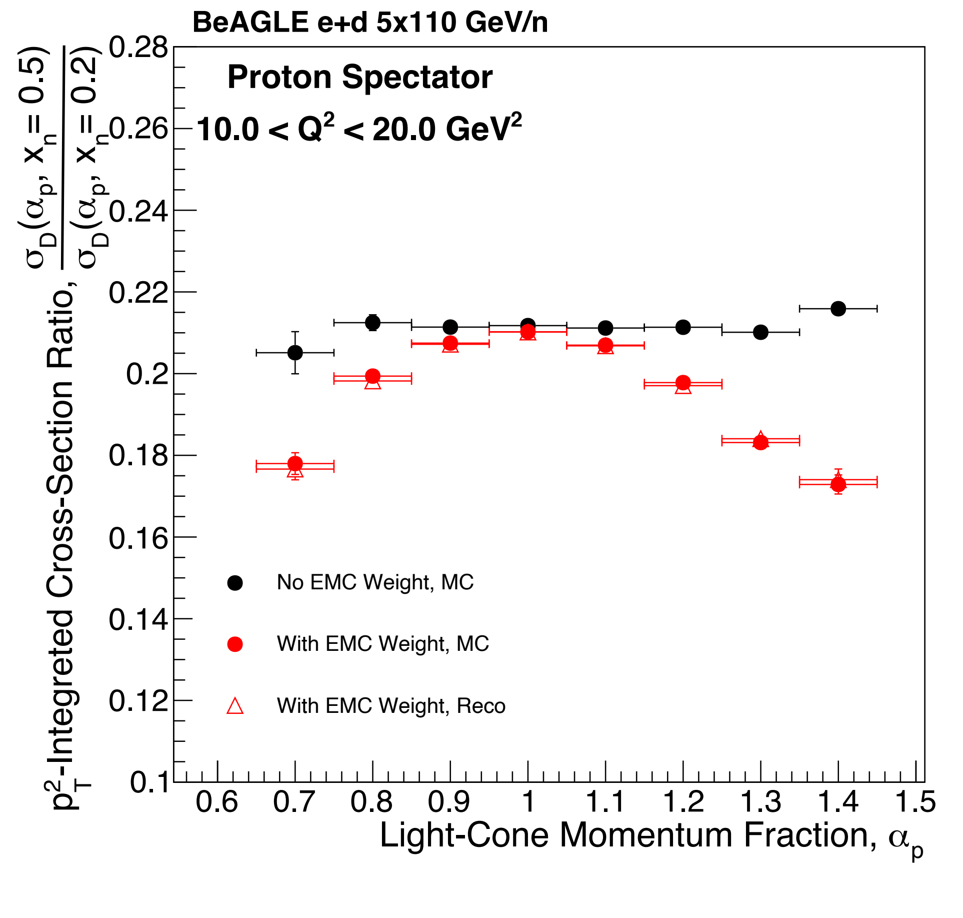


Different nuclear configurations

Study of FSI and comparisons in-progress (see backup).



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



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 for exclusive physics → I have only shown a few studies here.
  - Exciting time to get involved!!

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

Interested the EIC far-forward physics?? Join the ePIC Collaboration and get involved!

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

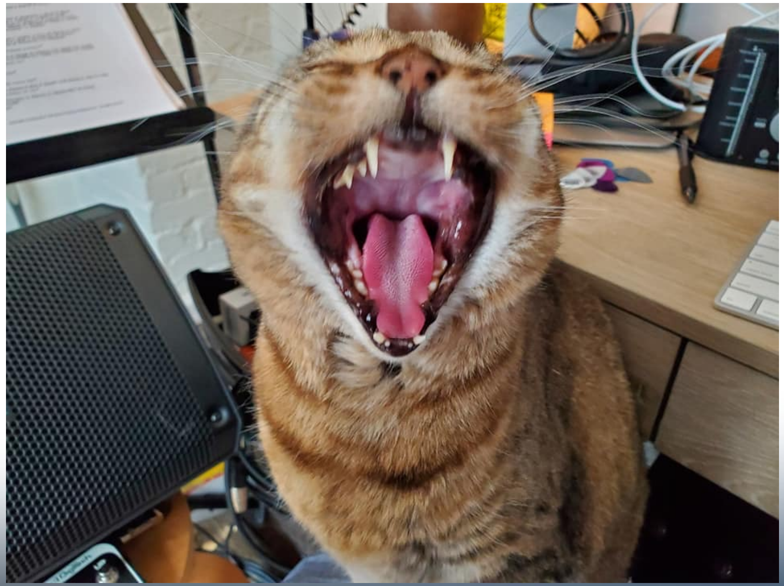
ePIC

Thank you!

Julep

They (mostly) get along.

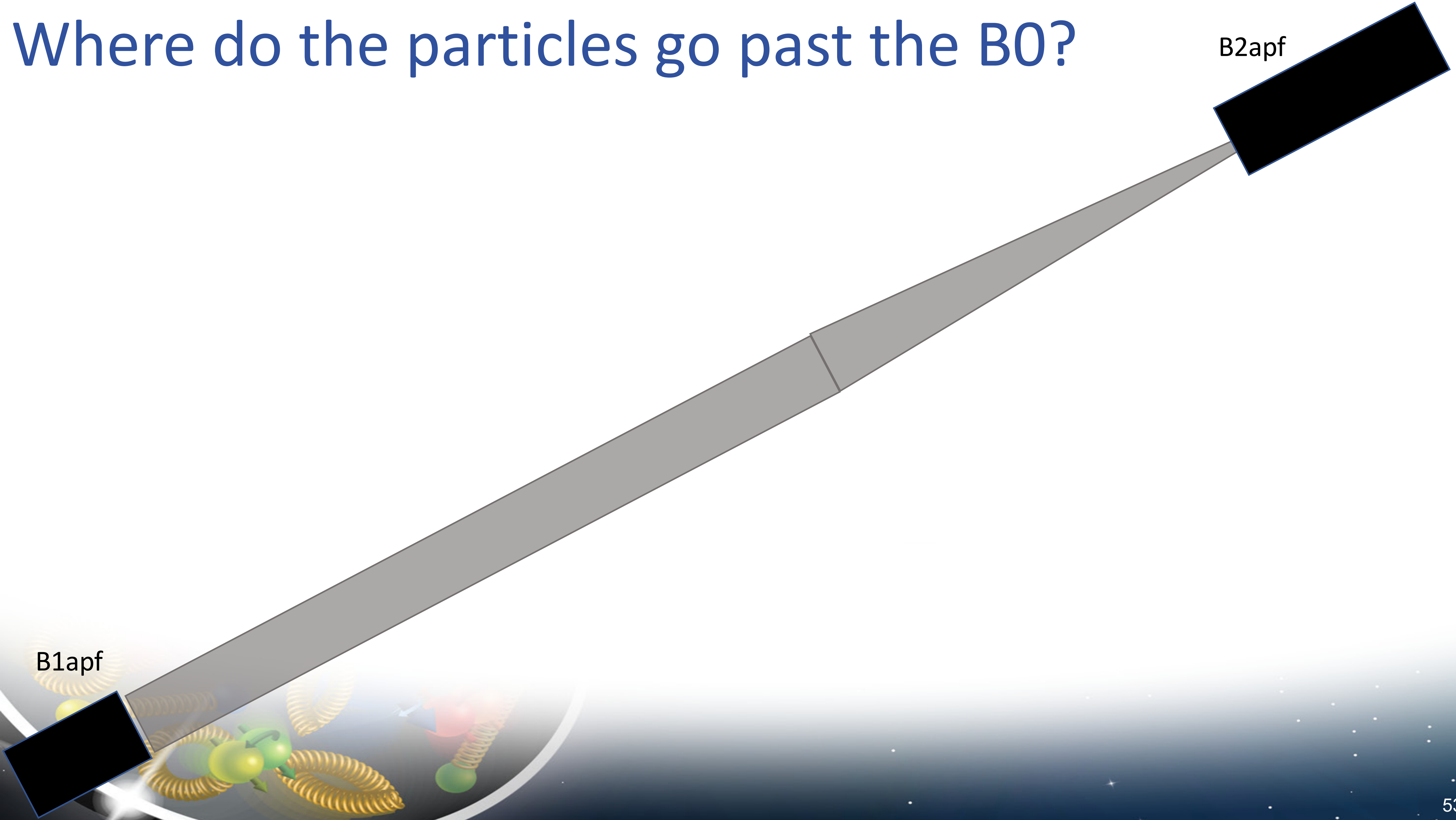
Lilu



She’s in a death metal band.

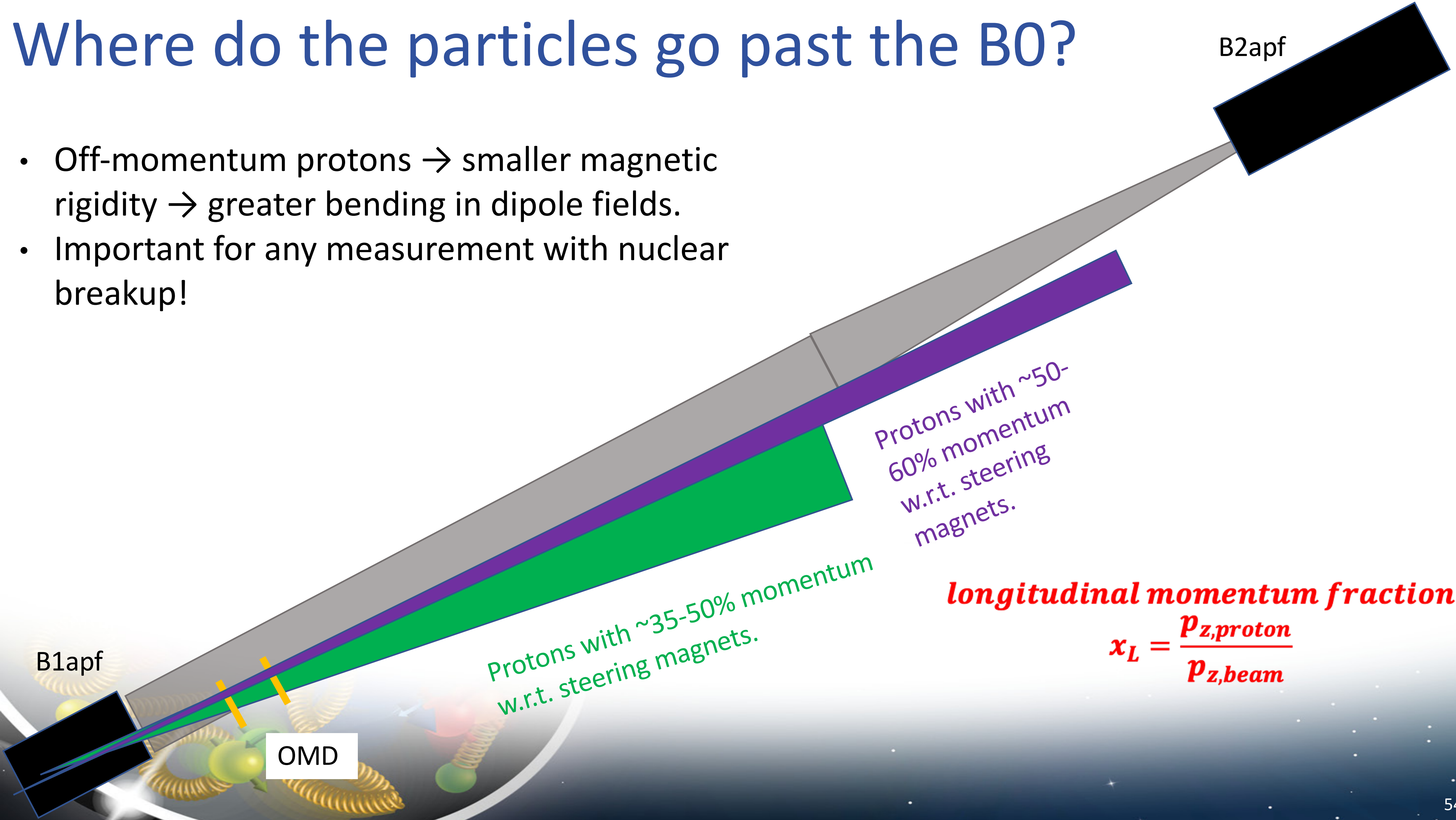
Backup

Where do the particles go past the B0?



Where do the particles go past the B0?

- Off-momentum protons → smaller magnetic rigidity → greater bending in dipole fields.
- Important for any measurement with nuclear breakup!

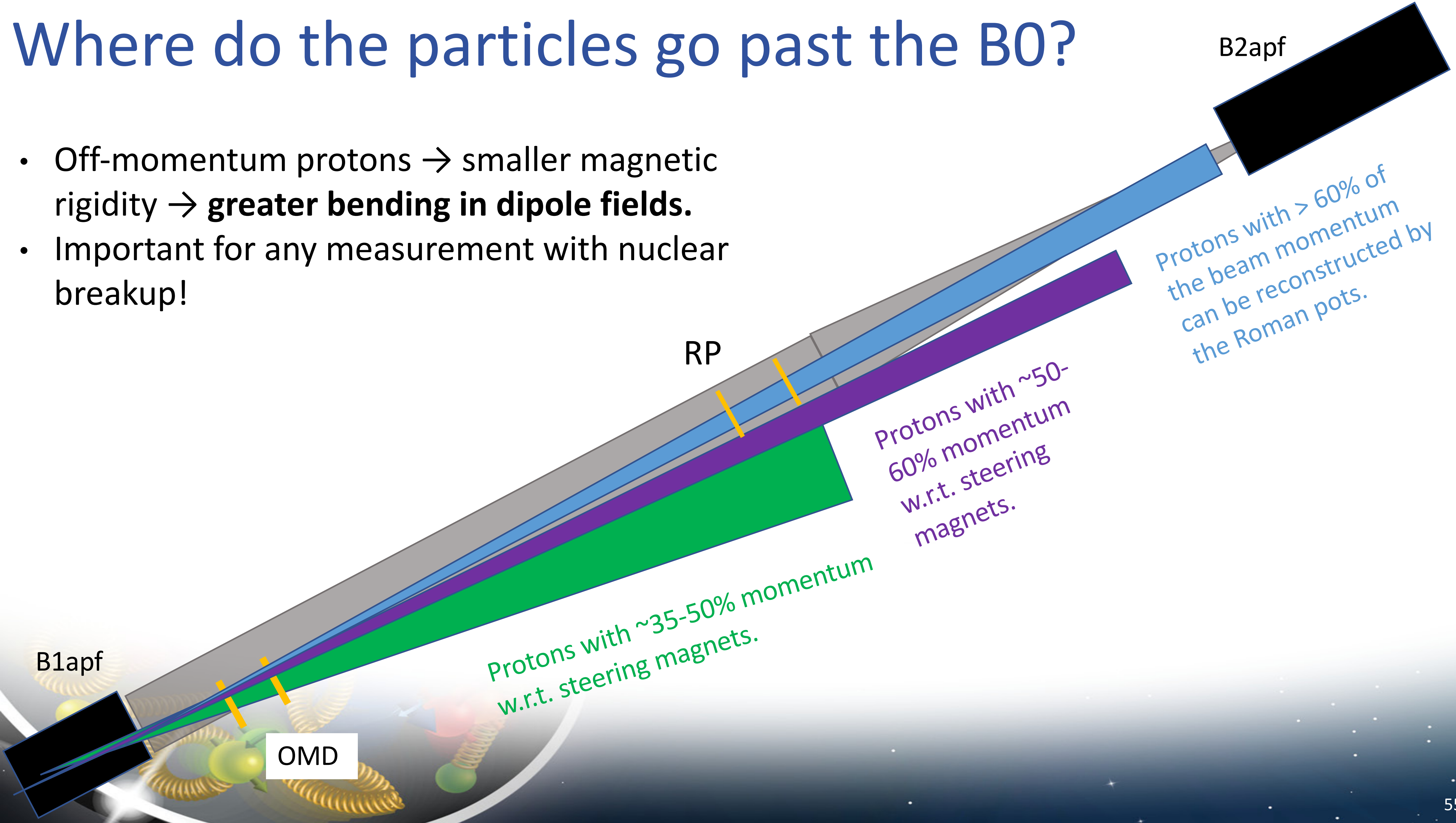


longitudinal momentum fraction

$$x_L = \frac{p_{z,proton}}{p_{z,beam}}$$

Where do the particles go past the B0?

- Off-momentum protons → smaller magnetic rigidity → **greater bending in dipole fields.**
- Important for any measurement with nuclear breakup!



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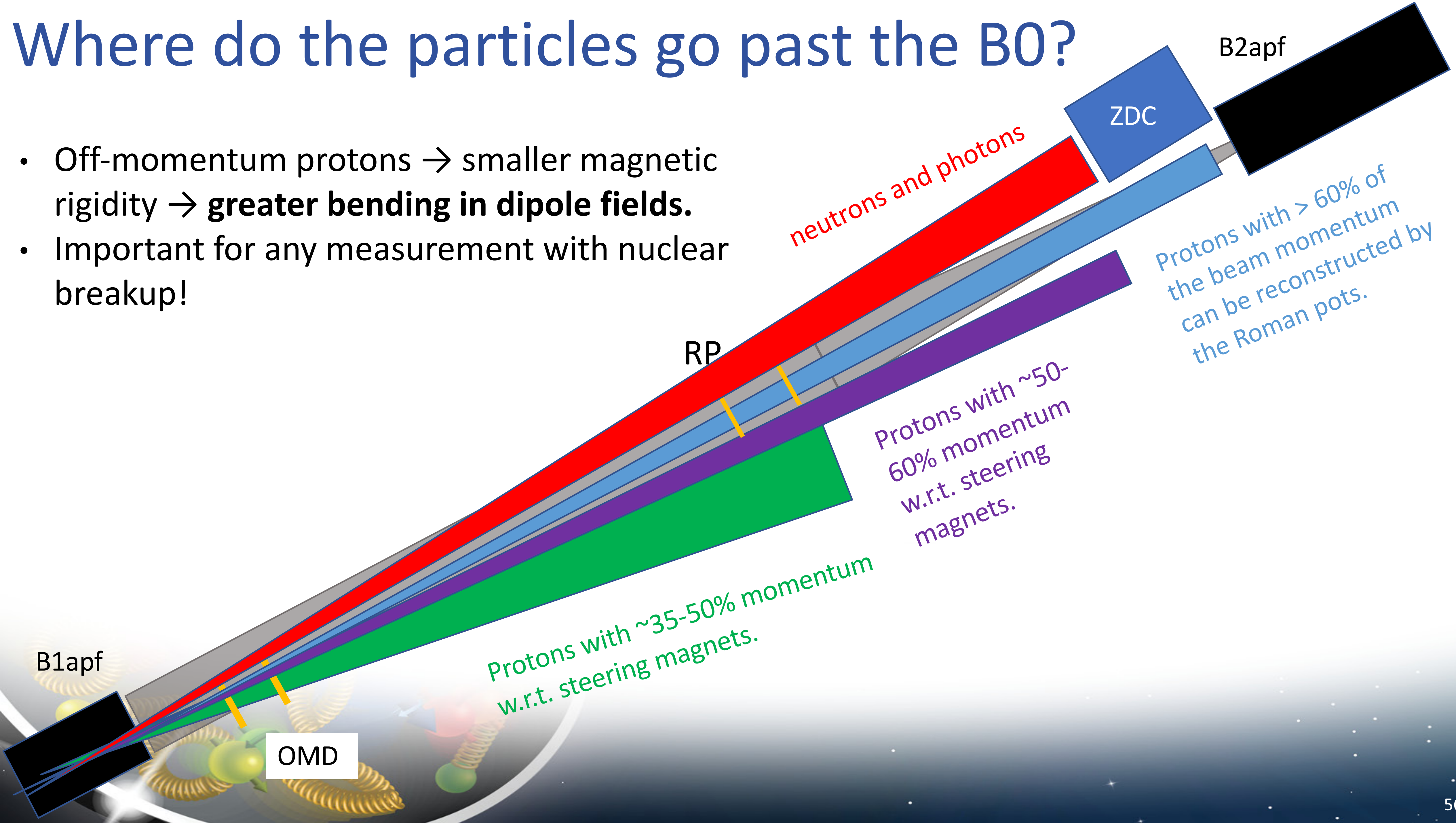
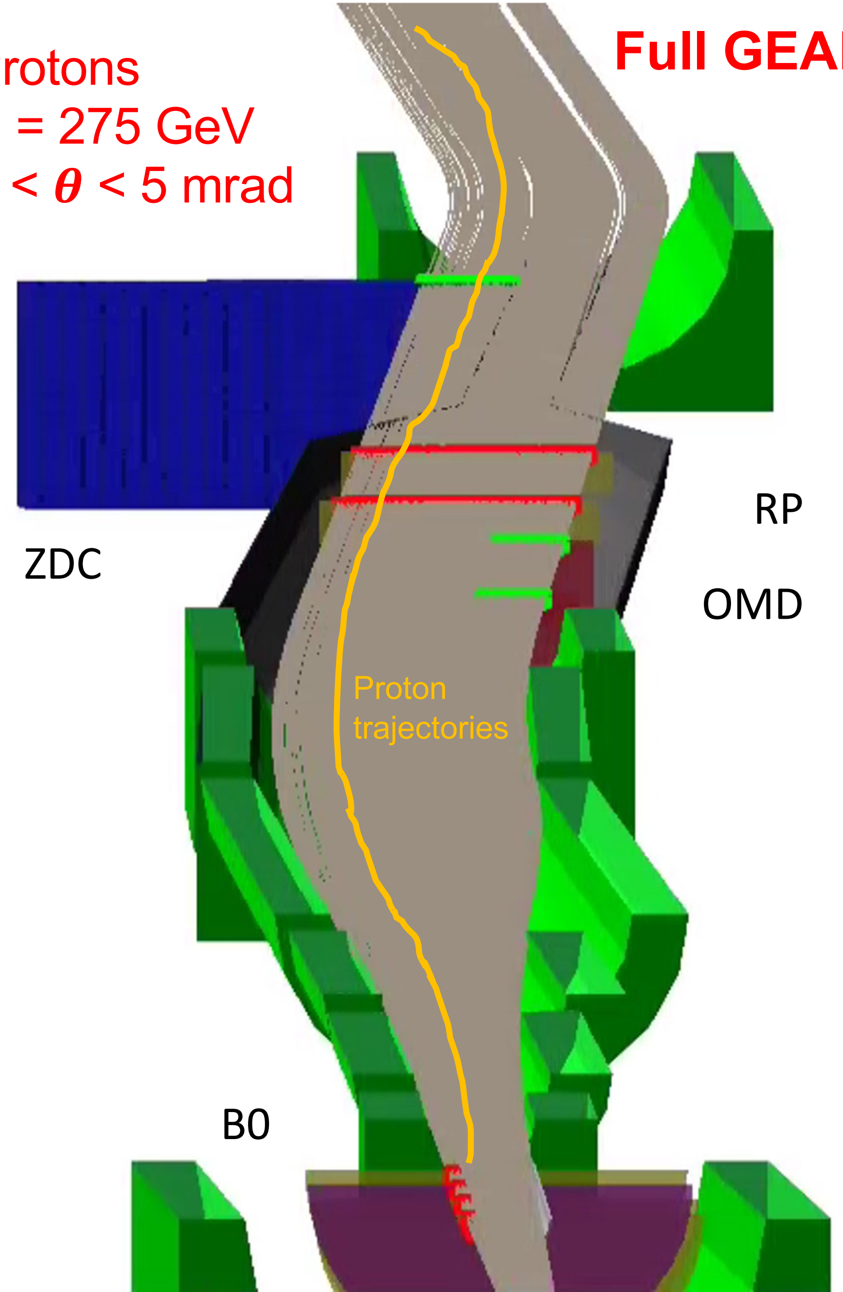


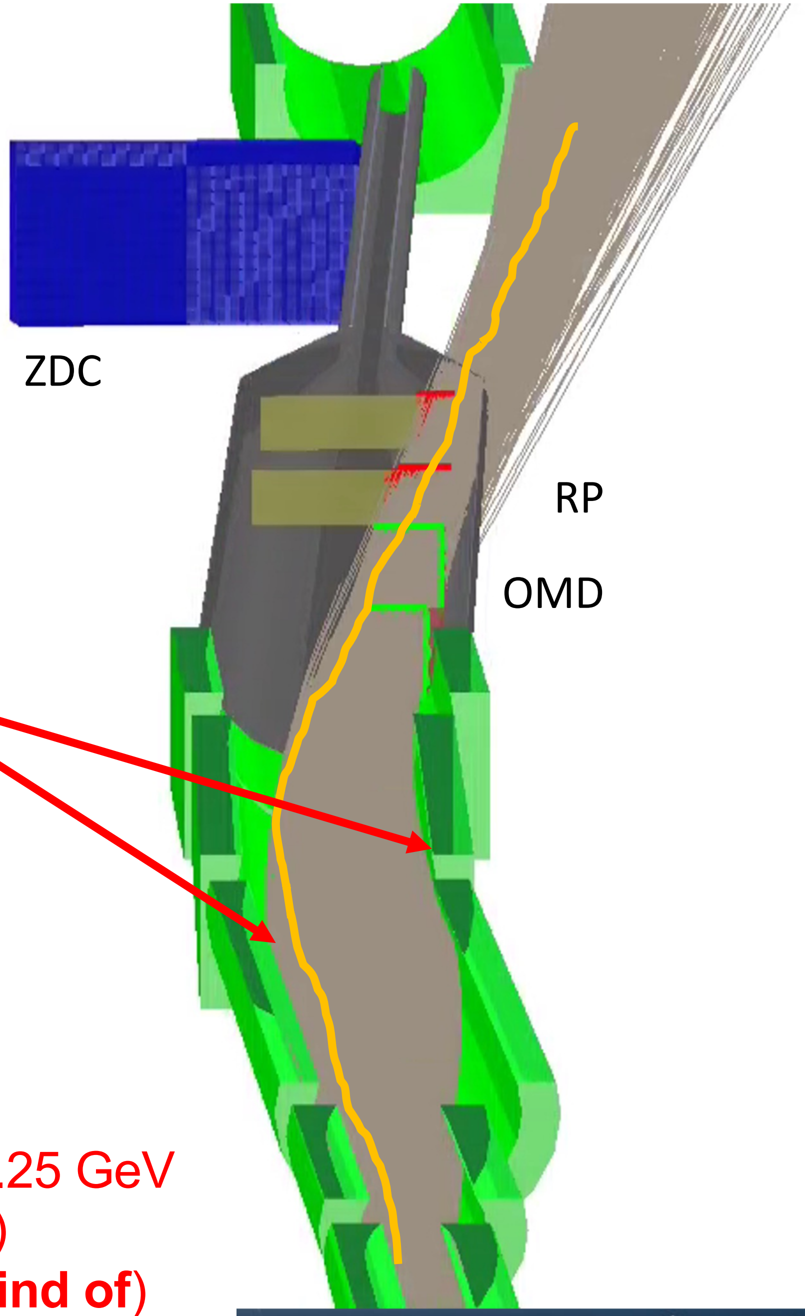
Roman Pots and OMD

Protons
E = 275 GeV
0 < θ < 5 mrad

Full GEANT4 simulation.



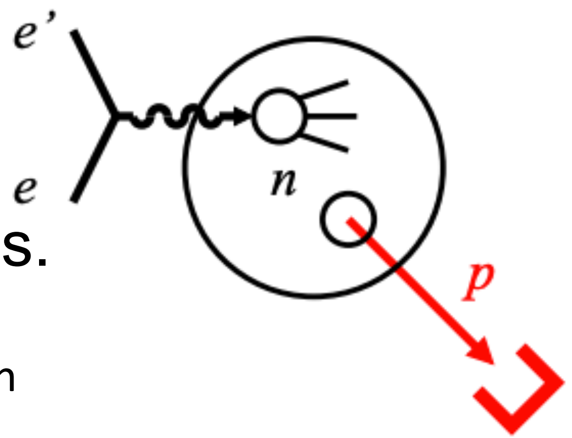
High-angle (θ > 2mrad) particles lost in aperture.



Protons
123.75 < E < 151.25 GeV
(45% < xL < 55%)
0 < θ < 5 mrad (**kind of**)

Neutron Structure

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



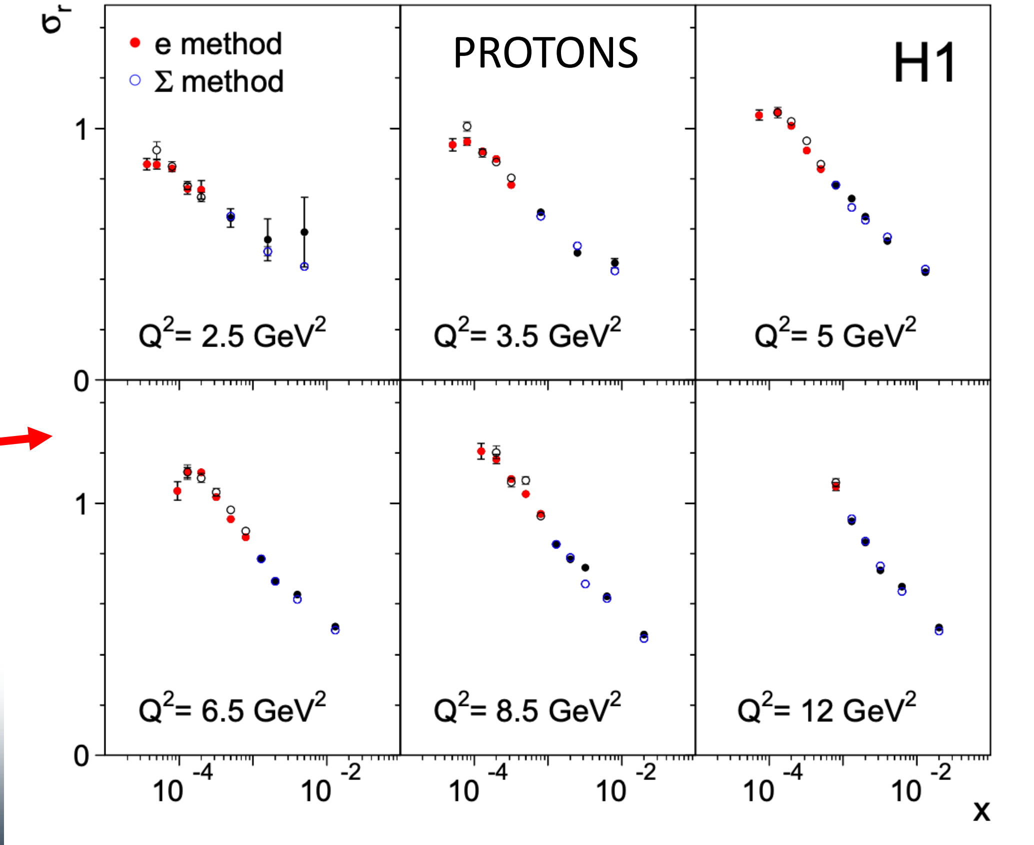
$$\sigma_r = \frac{Q^4 x}{2\pi\alpha^2[1+(1-y)^2]} \cdot \frac{d^2\sigma}{dx\,dQ^2} = F_2(x,Q^2) - f(y)\cdot F_L(x,Q^2)$$

Reduced cross section

"Flux factor"

Differential cross section

Structure functions

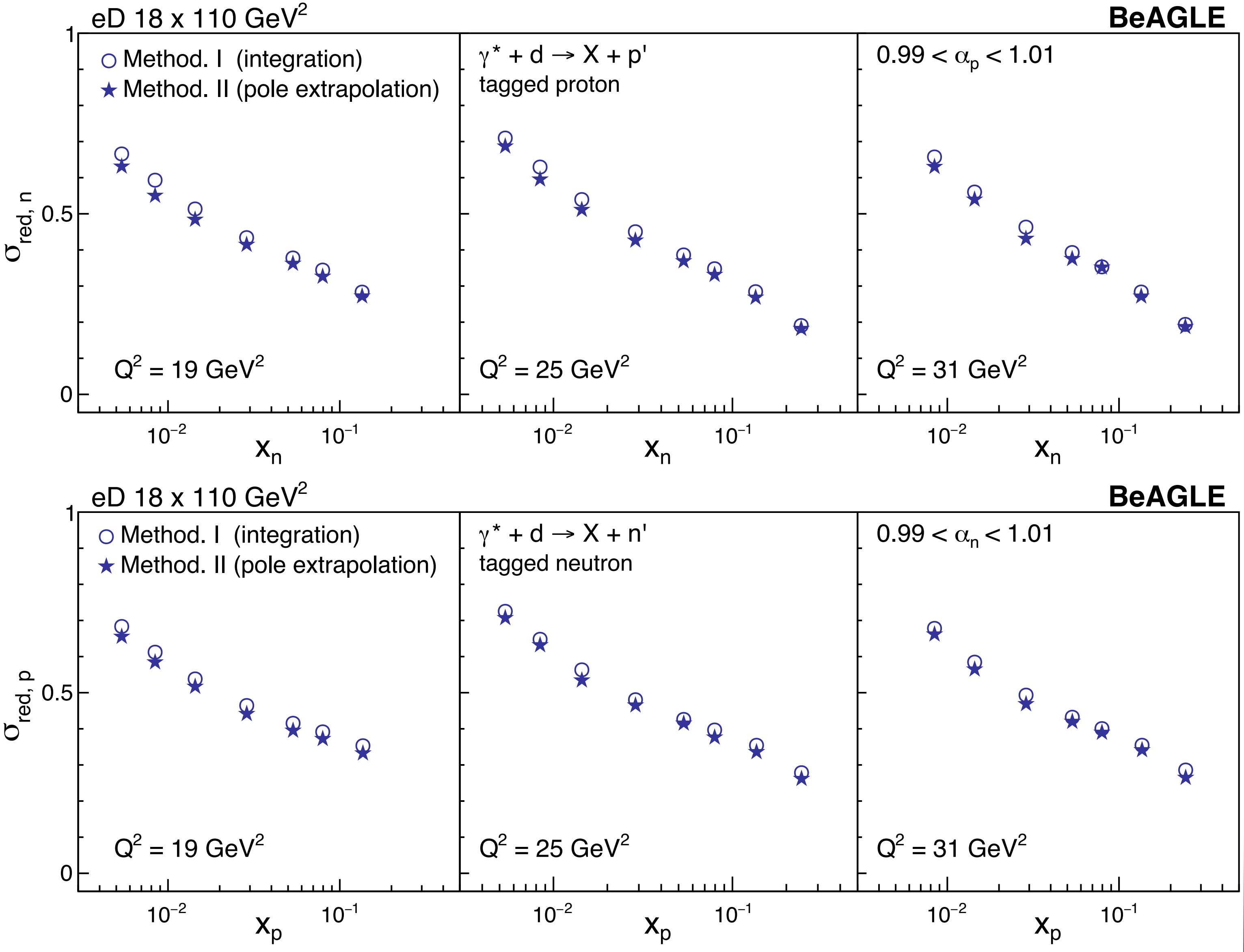


Some useful HERA references for measurements on proton

- 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)

Free Nucleon Structure

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

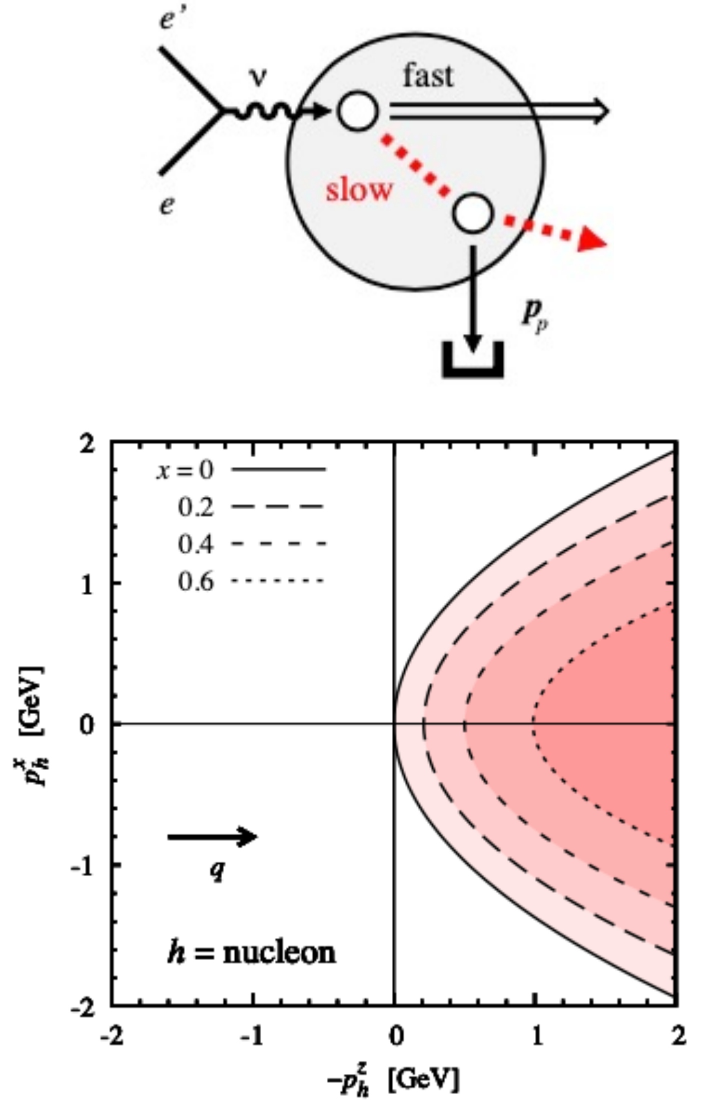


Open circles: "inclusive" measurement.
Stars: pole extrapolation procedure.

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

- Similar kinds of high-precision results achievable as was done for proton F_2 at HERA!

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

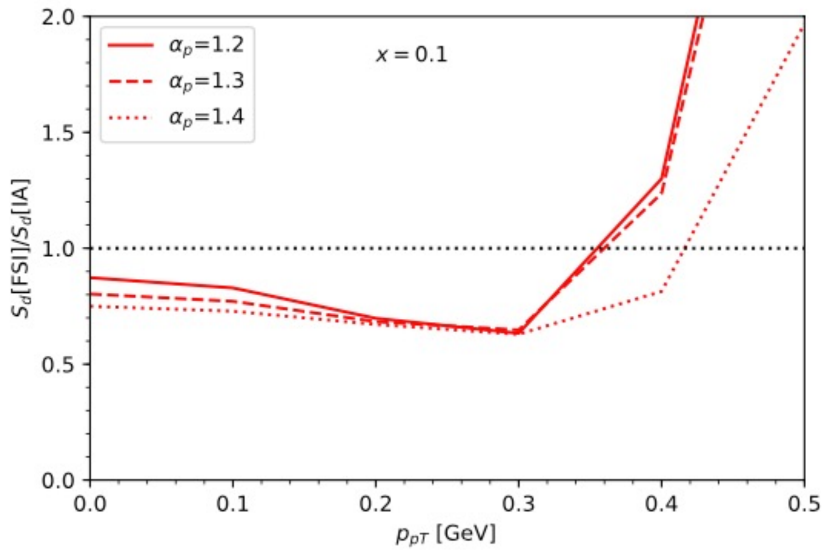
- $\nu \gg$ hadronic scale: large phase space for hadron production.
- "Fast" hadrons $E_h = \mathcal{O}(\nu)$ → current fragmentation region: Formed outside the nucleus, interaction with the spectator suppressed.
- "Slow" hadrons $E_h = \mathcal{O}(1\ GeV)$ → target fragmentation region: Formed inside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

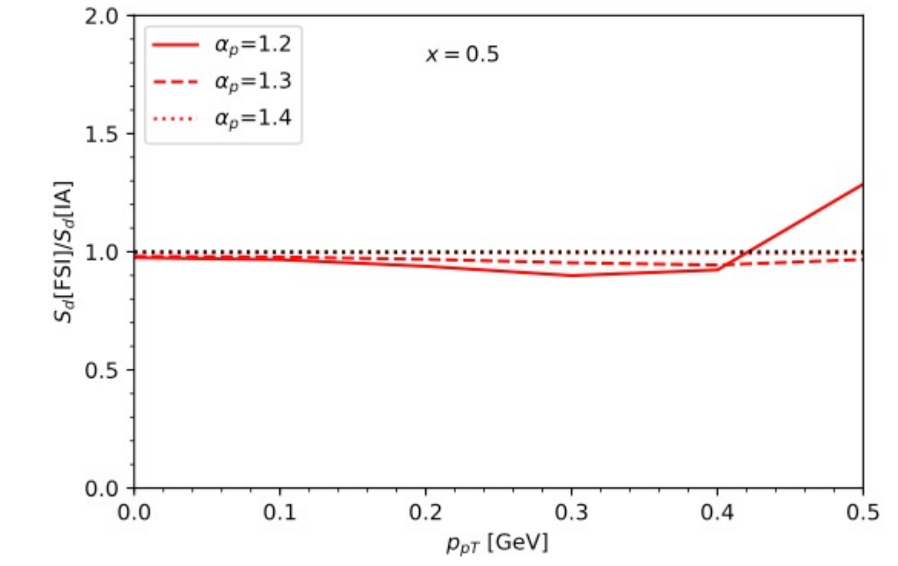
Implementation

- 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

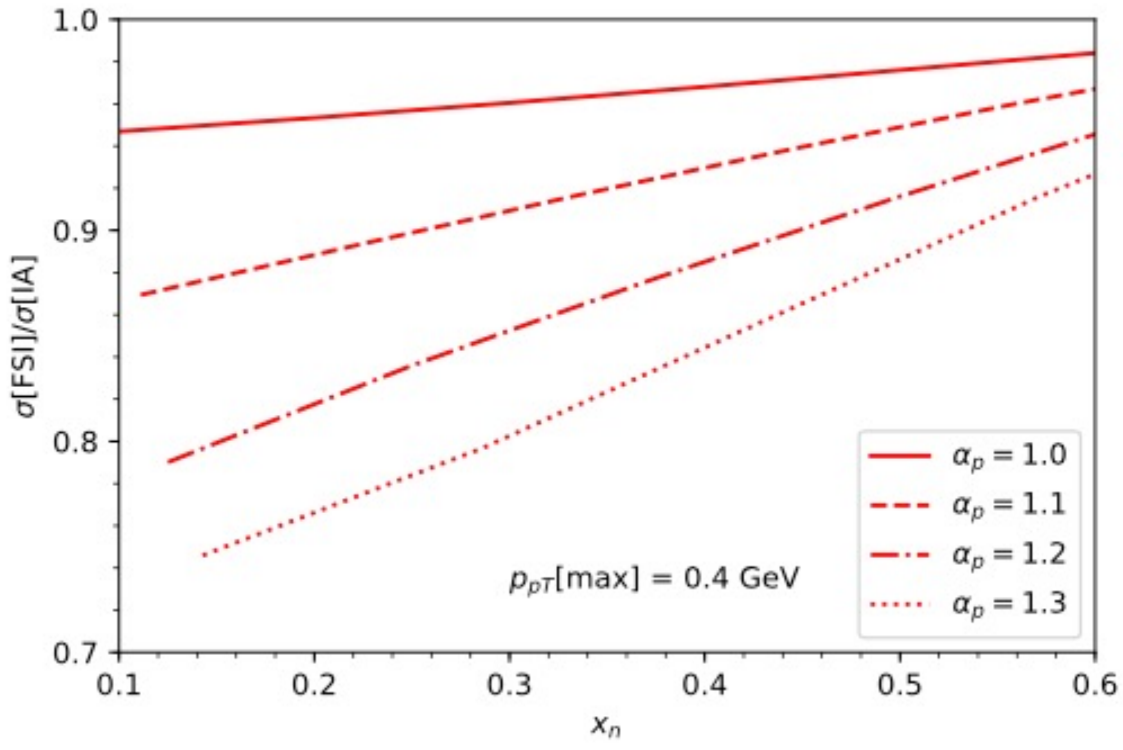
FSI: Kinematic Dependence





- 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

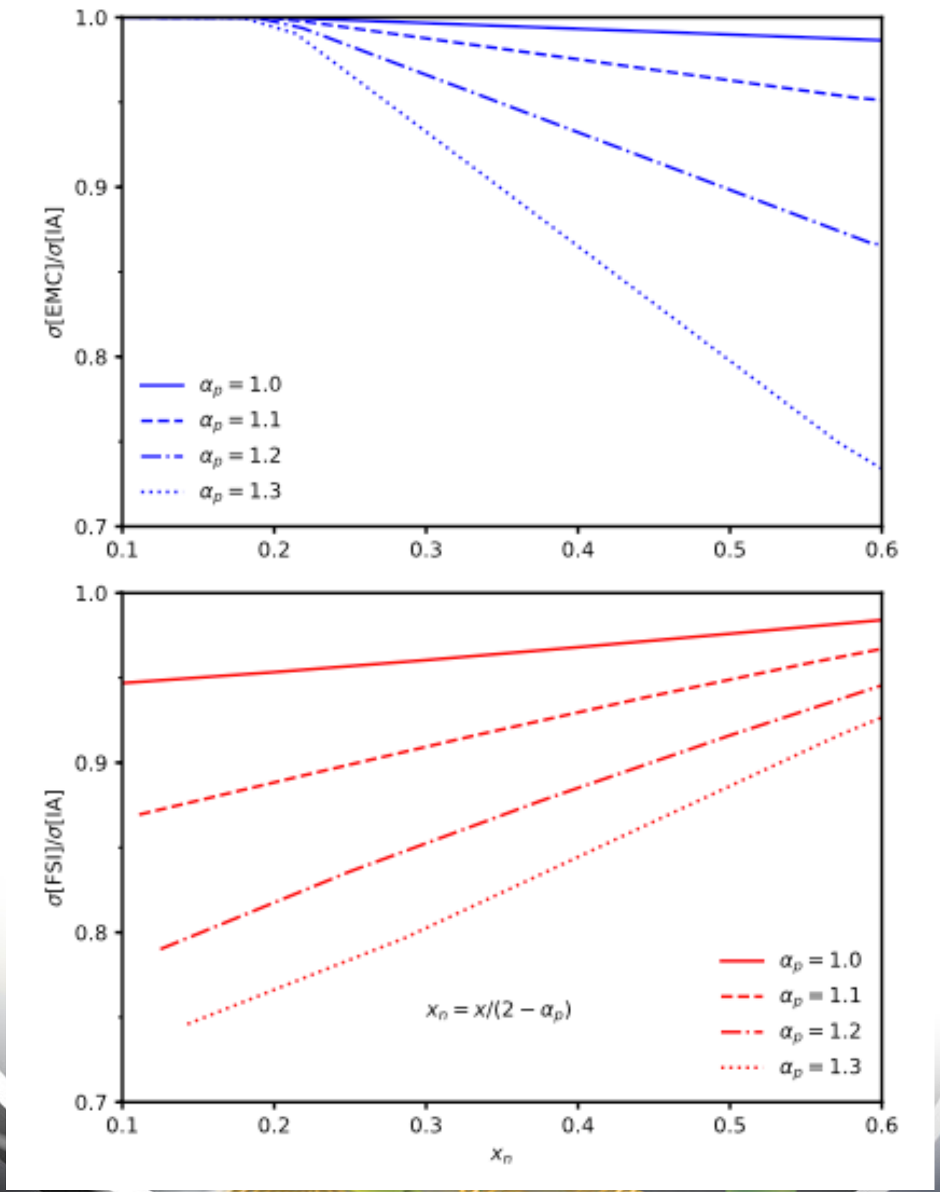


- p_{pT} - integrated cross section:

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

- 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

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

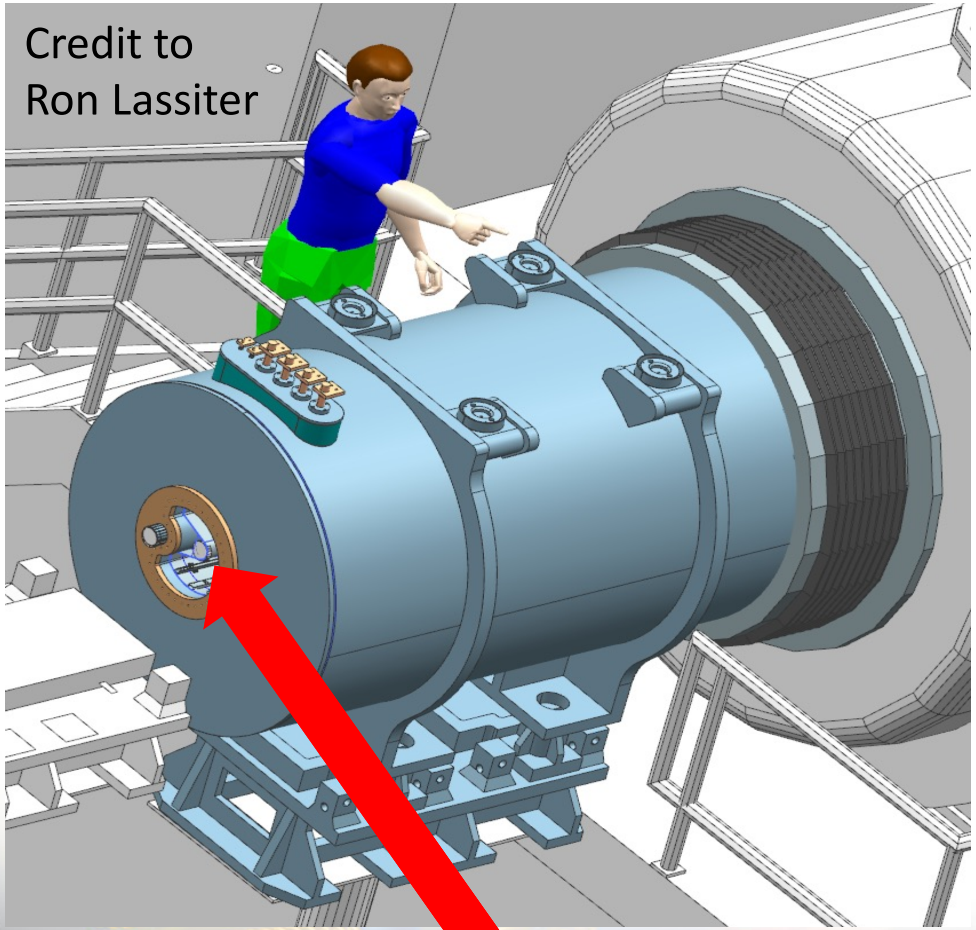
$$t = t(\alpha_p, p_{pT})$$

- Compare EMC and FSI

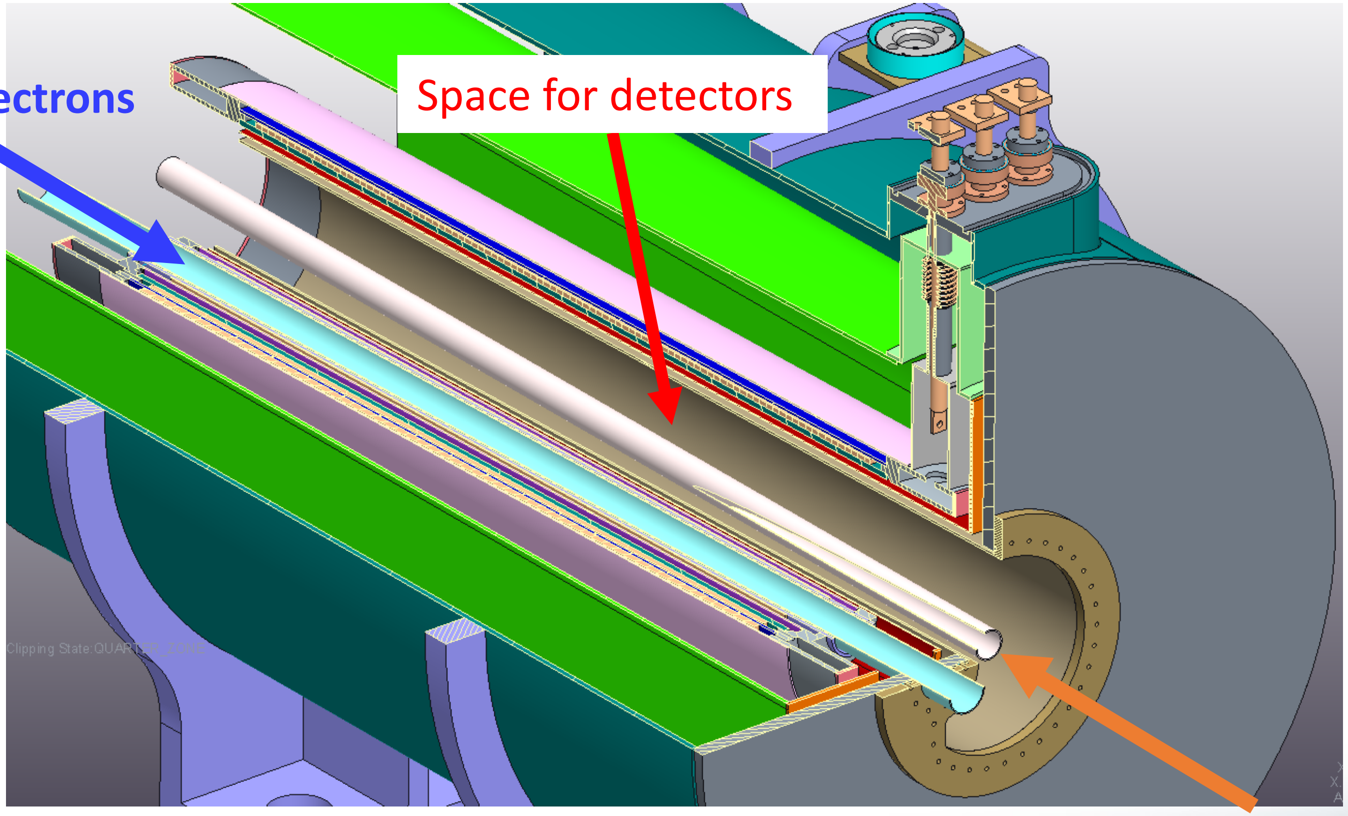
→ Currently in-progress!

B0 Detectors

- Detector subsystem embedded in an accelerator magnet.



This is the opening where the detector planes will be inserted



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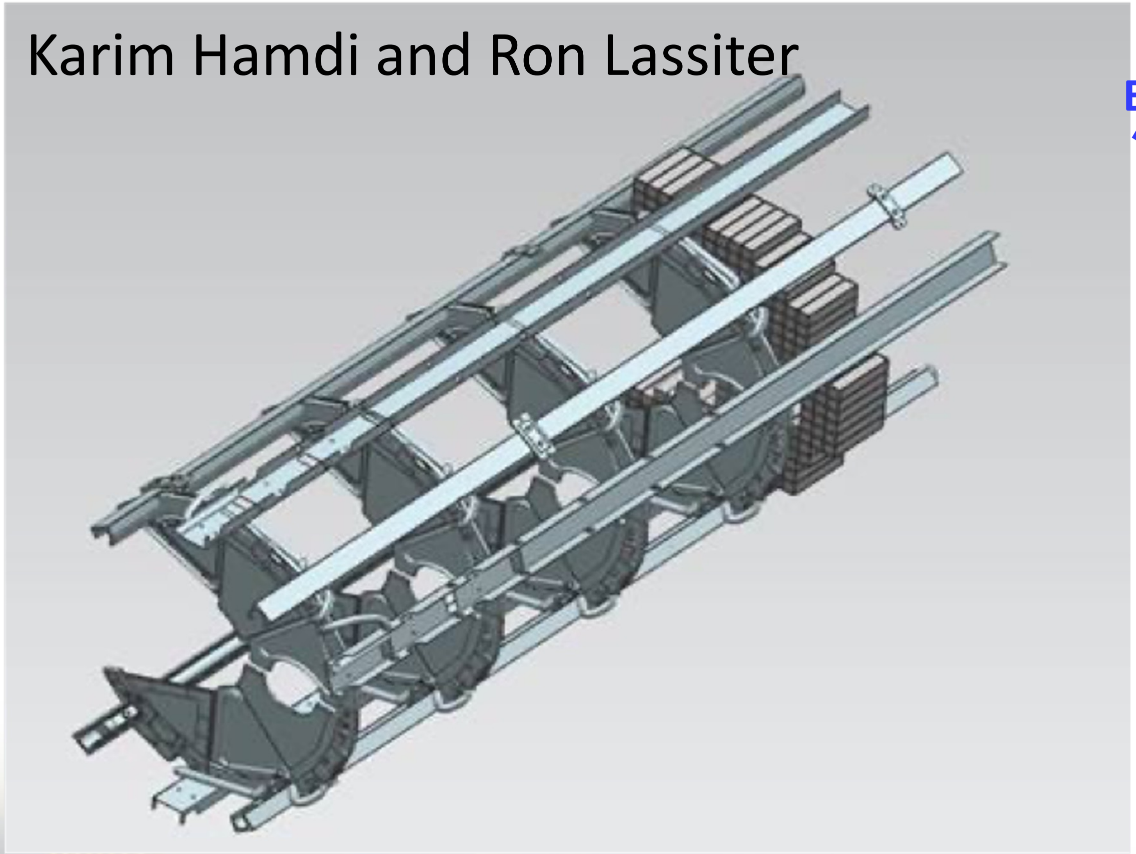
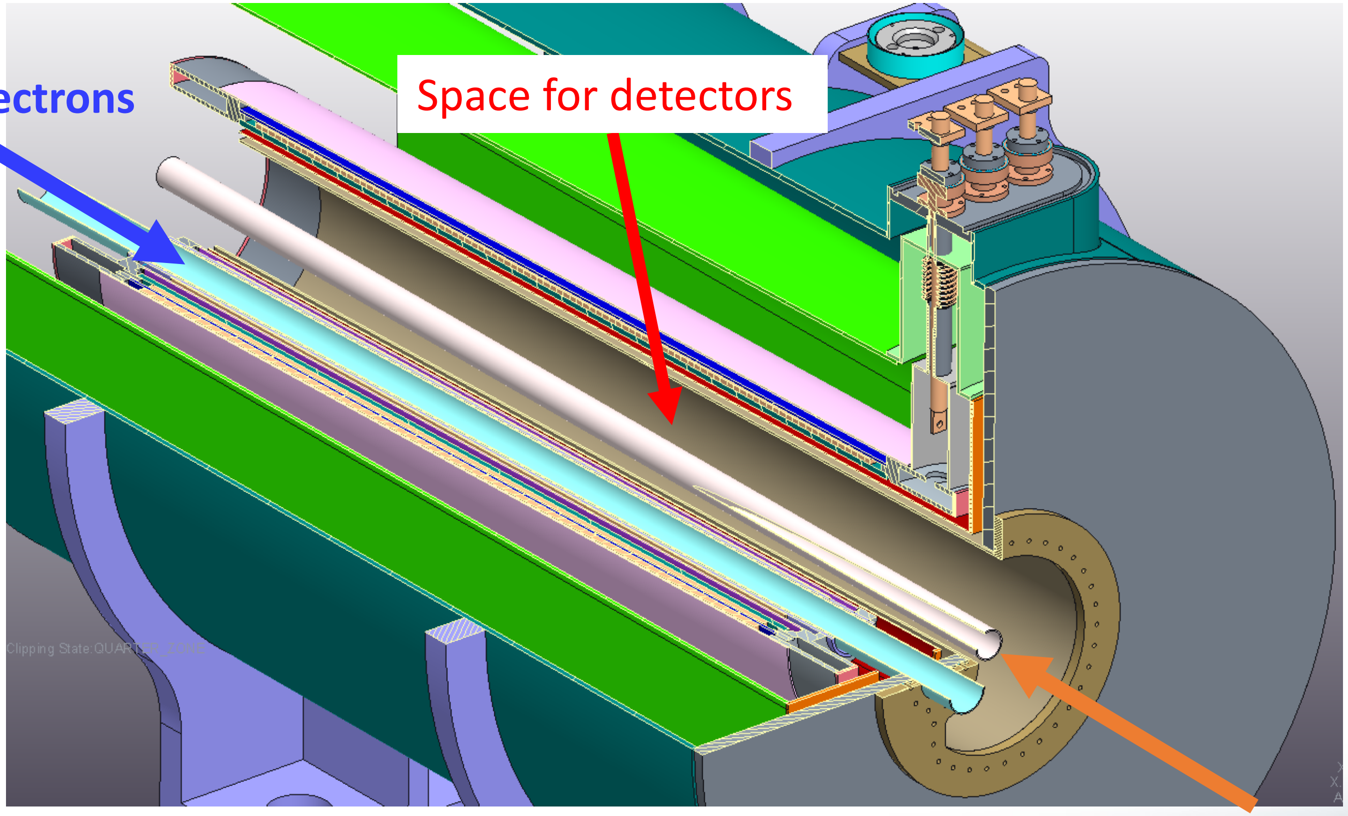
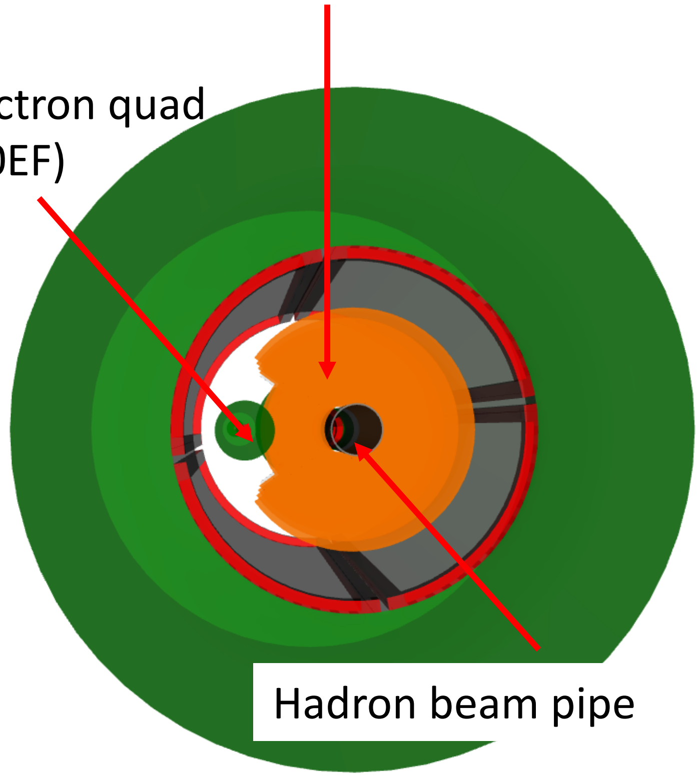
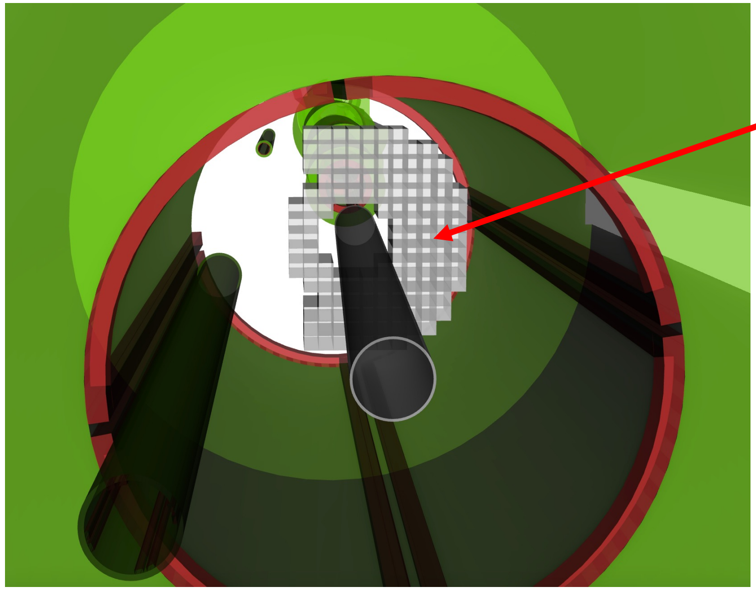




B0 Tracking and EMCAL Detectors





- **Technology choices:**
  - **Tracking: 4 layers AC-LGADs**
  - **PbWO4 or LYSO EMCAL.**

- **Status**
  - ✓ **Used to reconstruct charged particles and photons.**
    - ✓ **Acceptance: 5.5 < θ < 20.0 mrad on one side, up to 13mrad on the other.**
    - ✓ **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/

B0 Detectors

CAD Look credit: Jonathan Smith

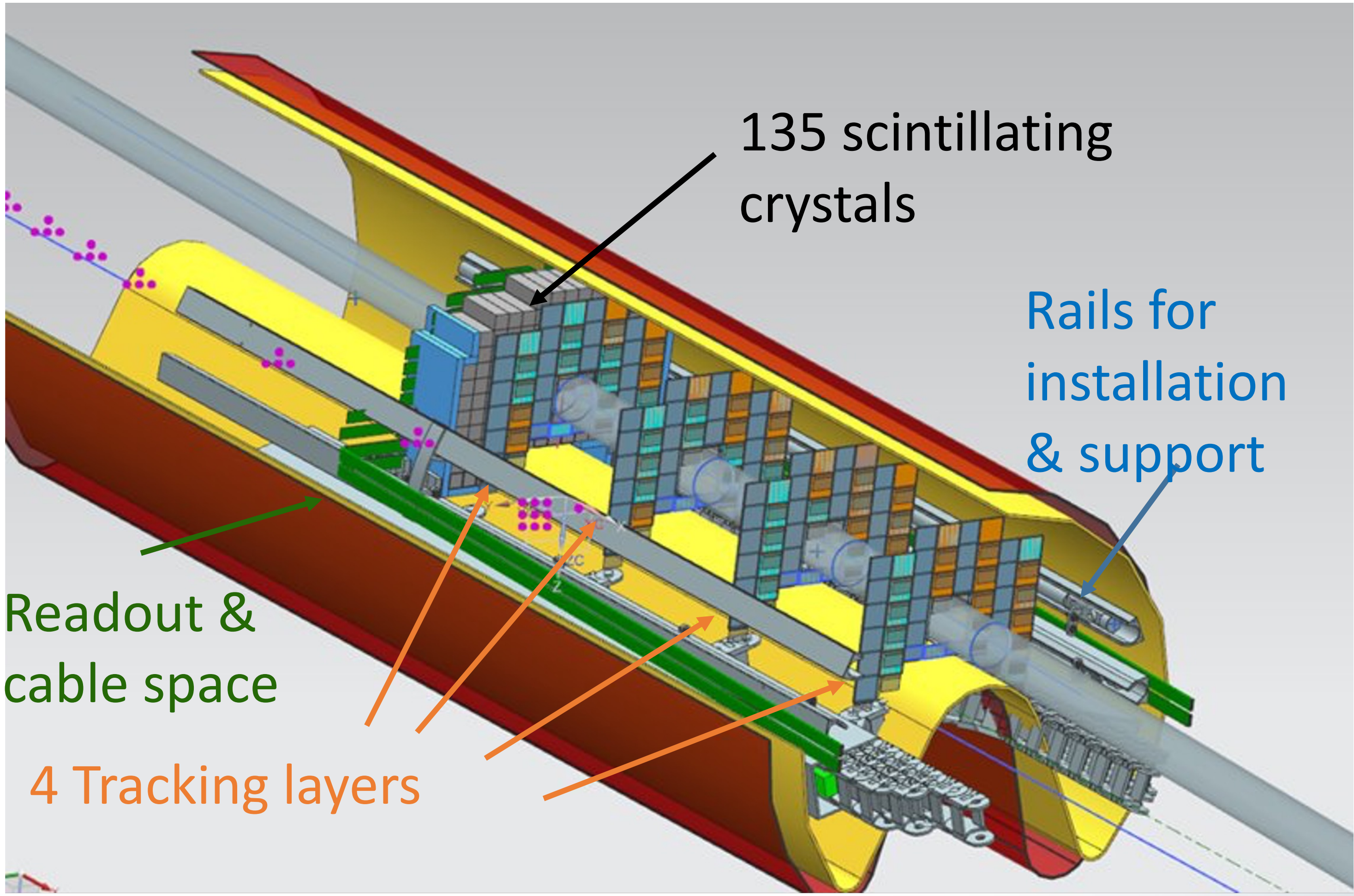
Design for two detectors is converging:

Si Tracker:

- 4 Layers of AC-LGAD → provide ~20um spatial resolution (with charge sharing) and 20-40ps timing resolution.
- Technology overlap w/ Roman pots

EM Calorimeter:

- 135 2x2x7*cm^3 LYSO crystals
- Good timing and position resolution
- Technology overlap with ZDC



* ZDC wants slightly longer crystals, ideally, we will use the same length in both detectors

B0 Detectors - Simulation Studies

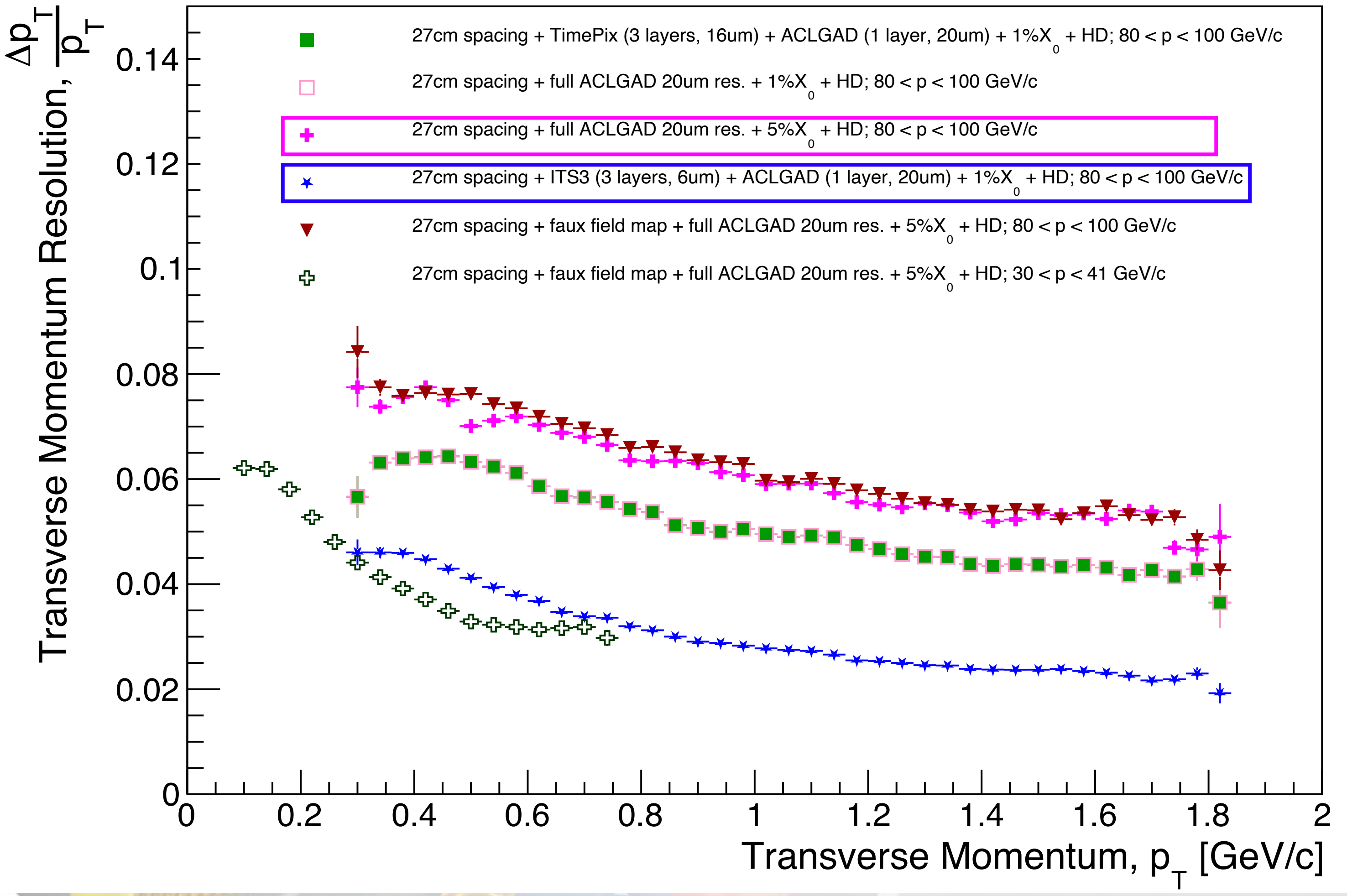
Si Tracker:

- Resolution plots made by Alex Jentsch with standalone setup (more here and here)
- ACTS Tracking (a long-standing problem) was recently solved and is implemented in the simulation (see recent Sakib R slides), we expect more results soon

EM Calorimeter:

- Caveat - studies performed with PbWO4 crystals, LYSO crystals still to be implemented in the simulation.
- General performance studies by Michael Pitt (more in FF weekly meeting)
- Sensitivity to soft photons (see Eden Mautner talk at the EICUG EC workshop early this week)

Tracking - Performance



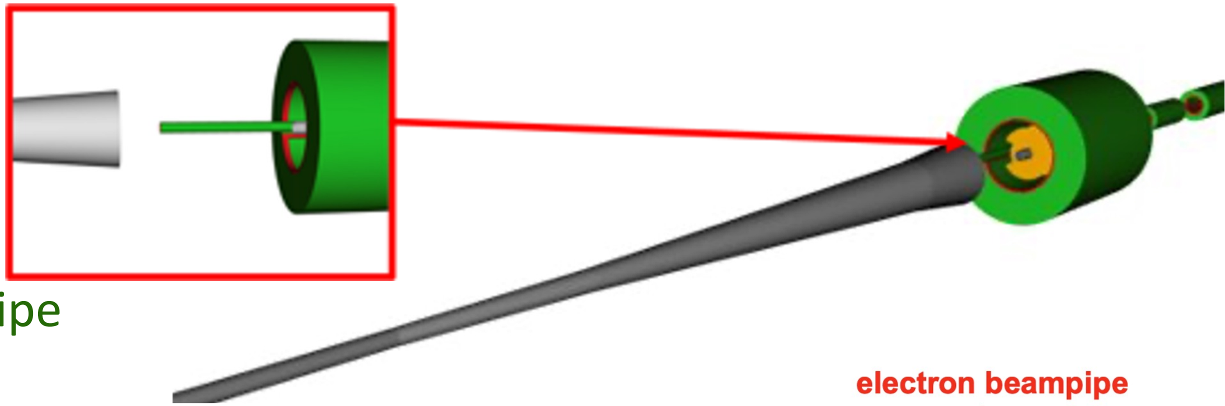
- 27cm spacing with fully AC-LGAD system and 5% radiation length may be the most-realistic option.
  - Reduced spacing (from 30cm) to make room for EMCAL.
- Needs to be looked at with proper field map and layout.
- Resolution impact on physics still being evaluated.

Note: momentum resolution (dp/p) is ~2-4%, depending on configuration.

B0 EMCal - Performance

- Acceptance $5.5 < \theta < 23$ mrad
- Very low material budget in $5 < \eta < 5.5$

Particles within $5.5 < \theta < 15$ mrad don't cross the beampipe

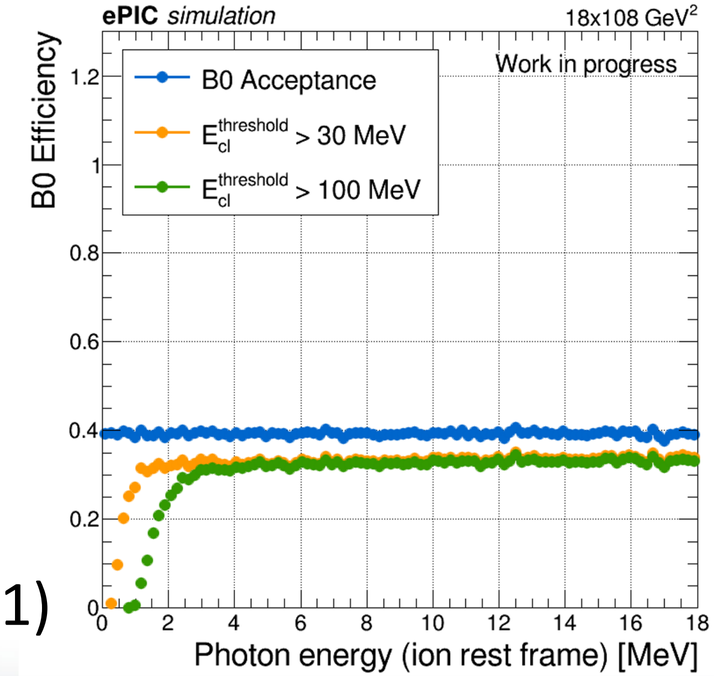


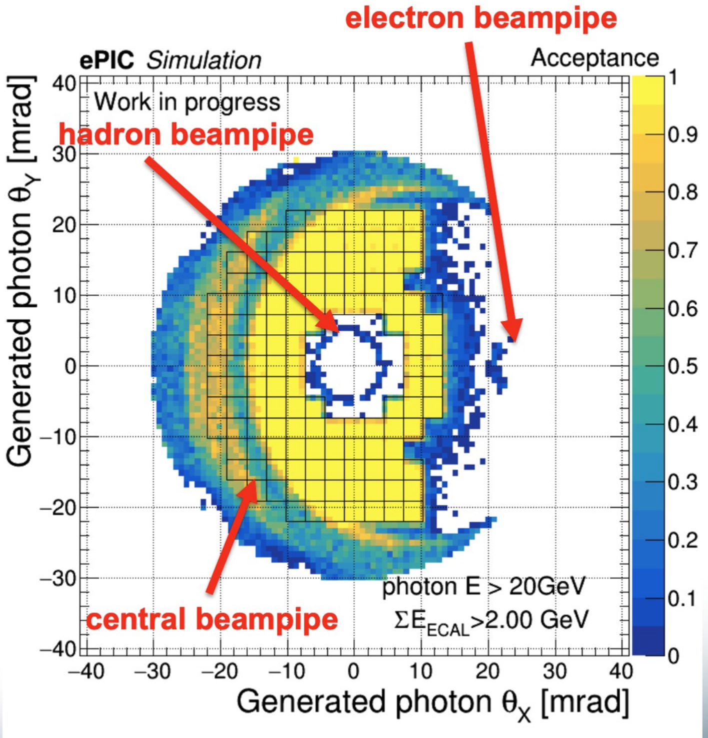
Photons:

- ➢ High acceptance in a broad energy range (> 100s MeV), including ~MeV de-excitation photons
- ➢ Energy resolution of 6-7%
- ➢ Position resolution of ~3 mm

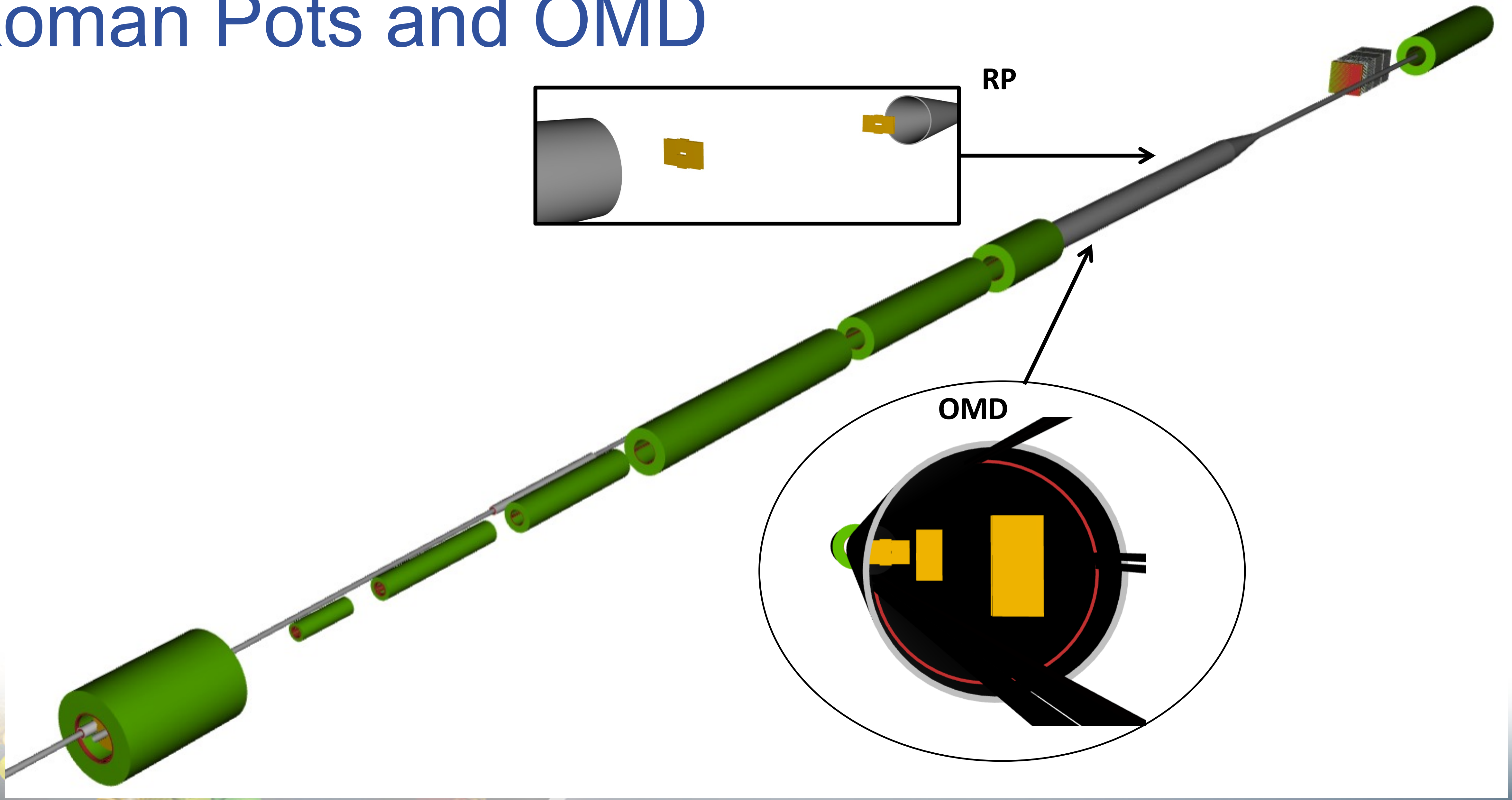
Neutrons:

- ➢ 50% detection efficiency (λ is almost 1)





Roman Pots and OMD



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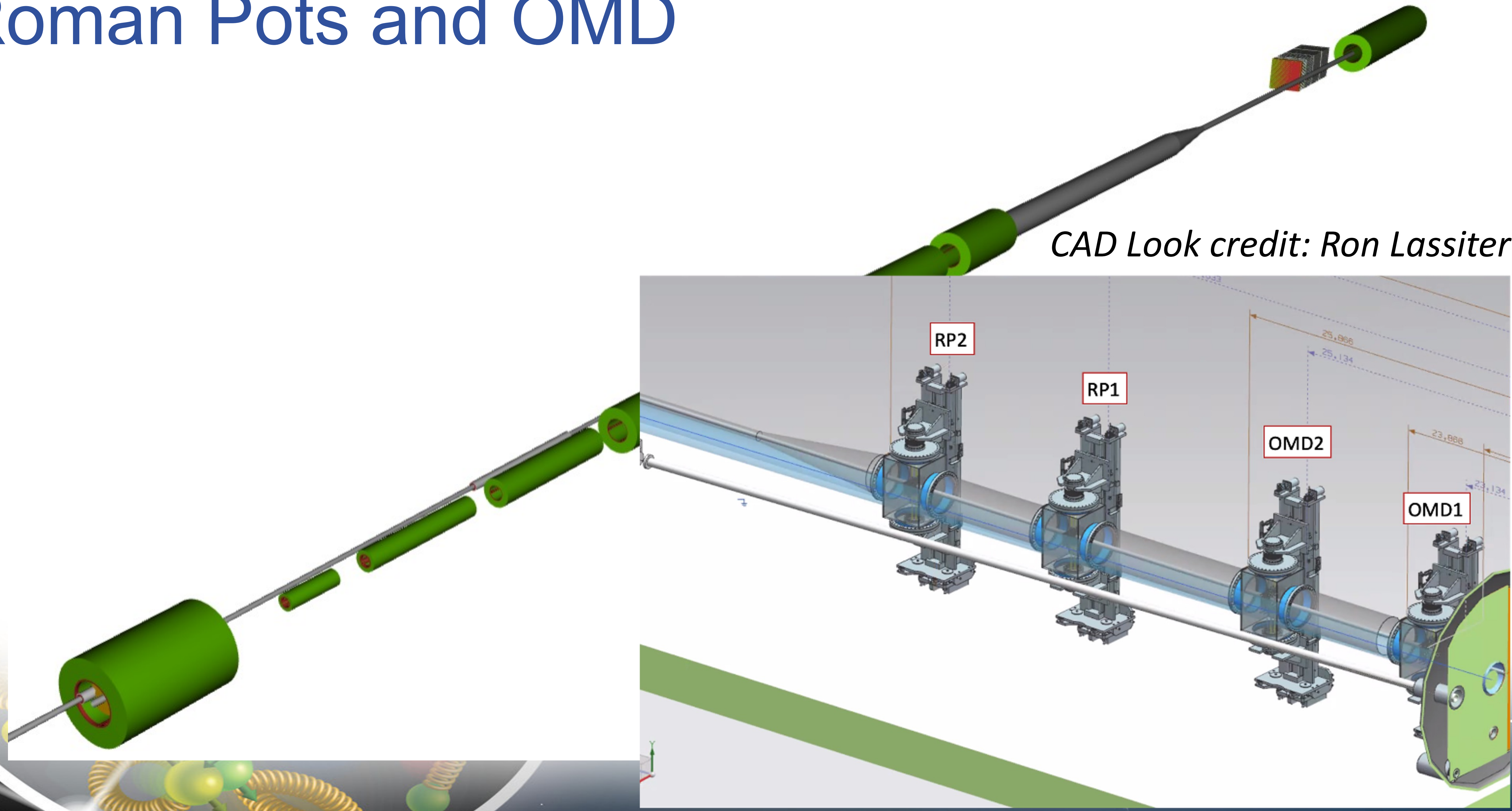

CAD Look credit: Ron Lassiter

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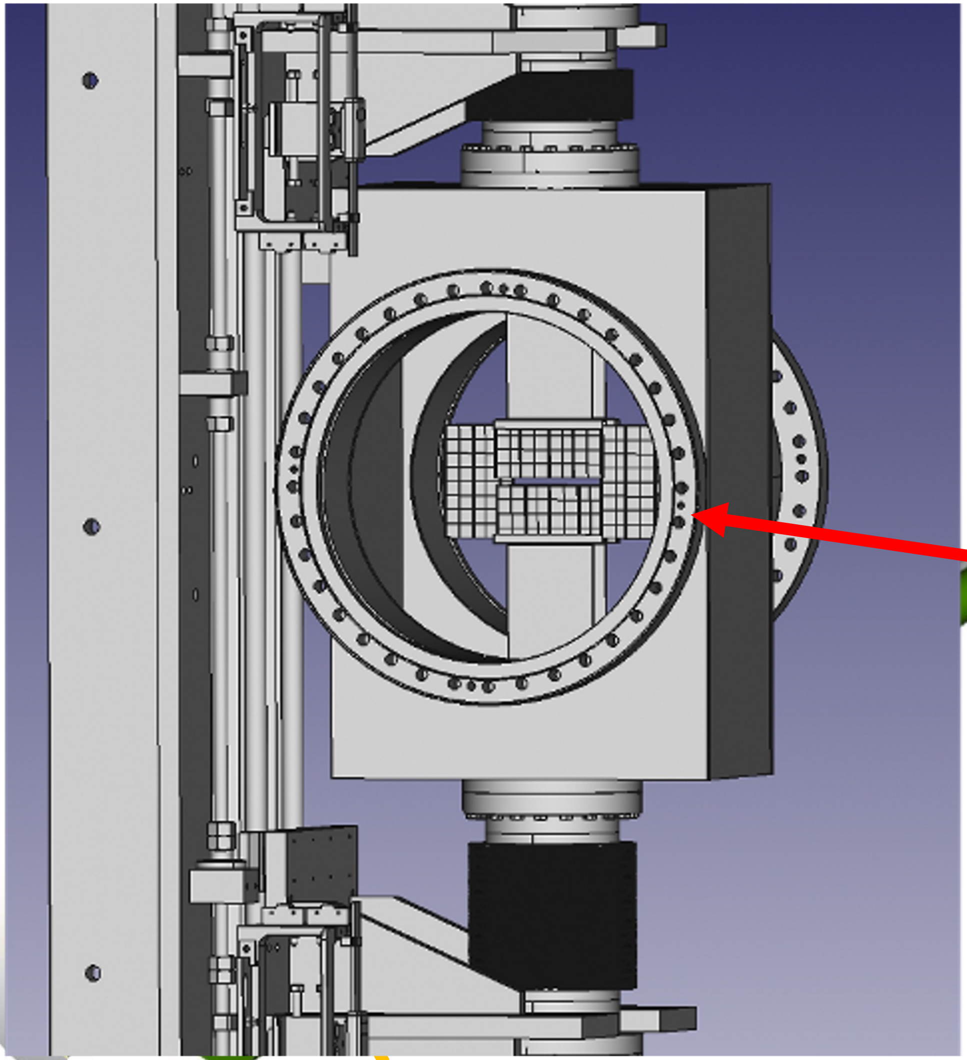

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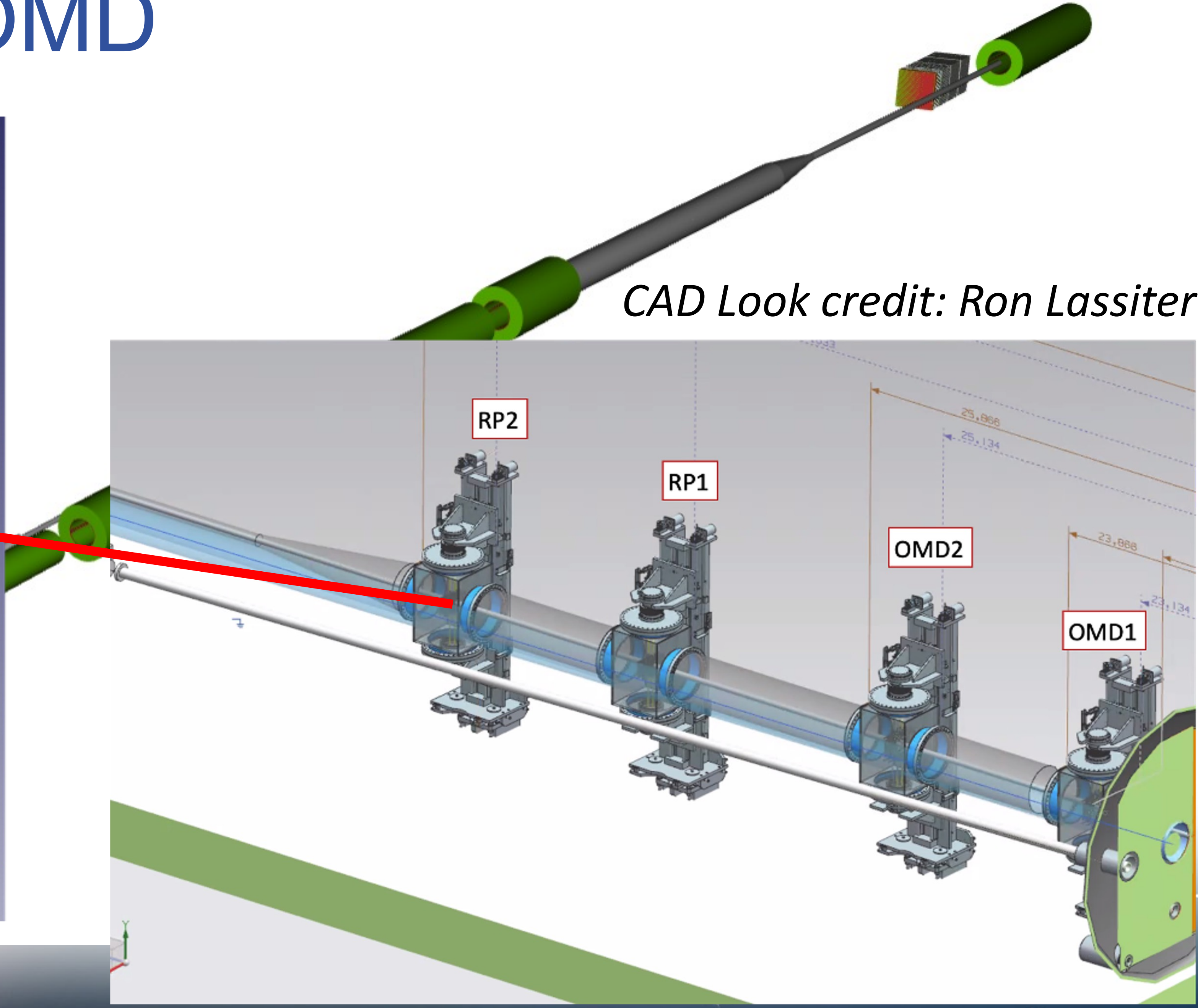

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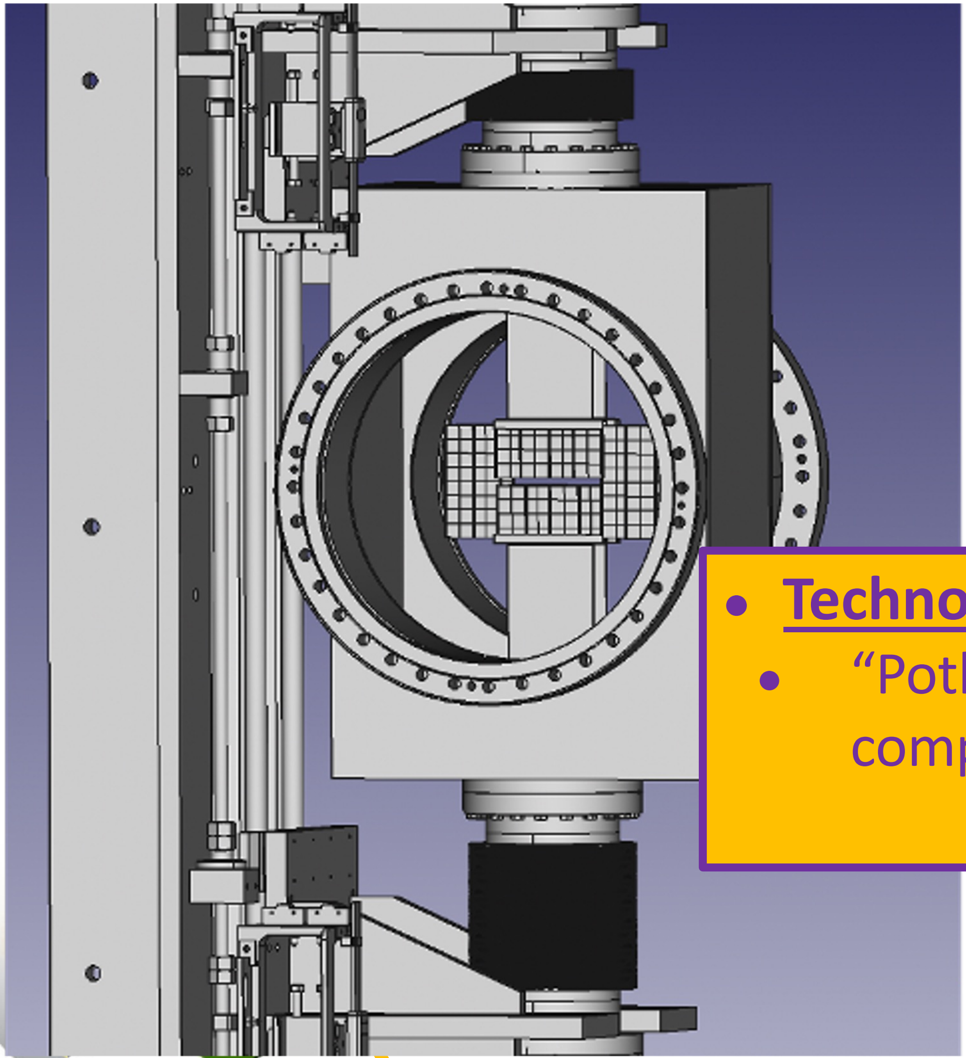

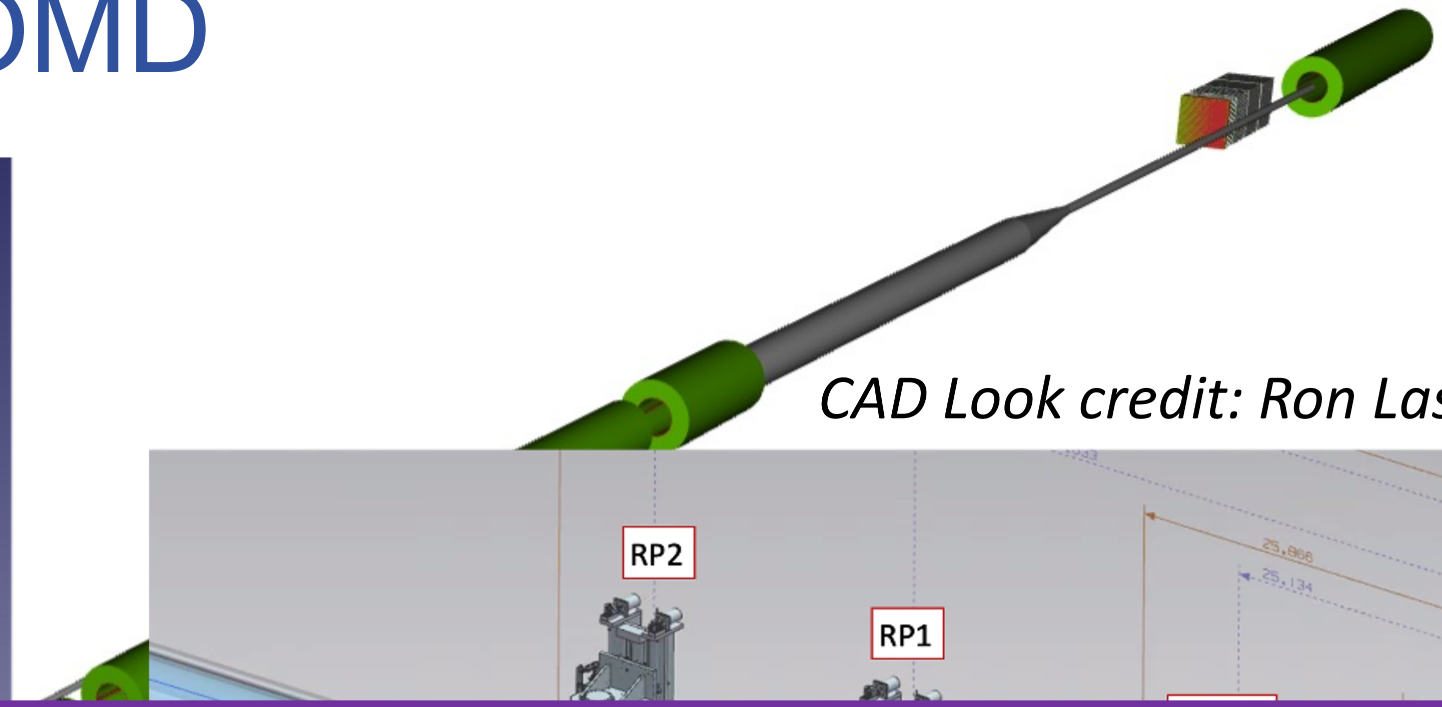

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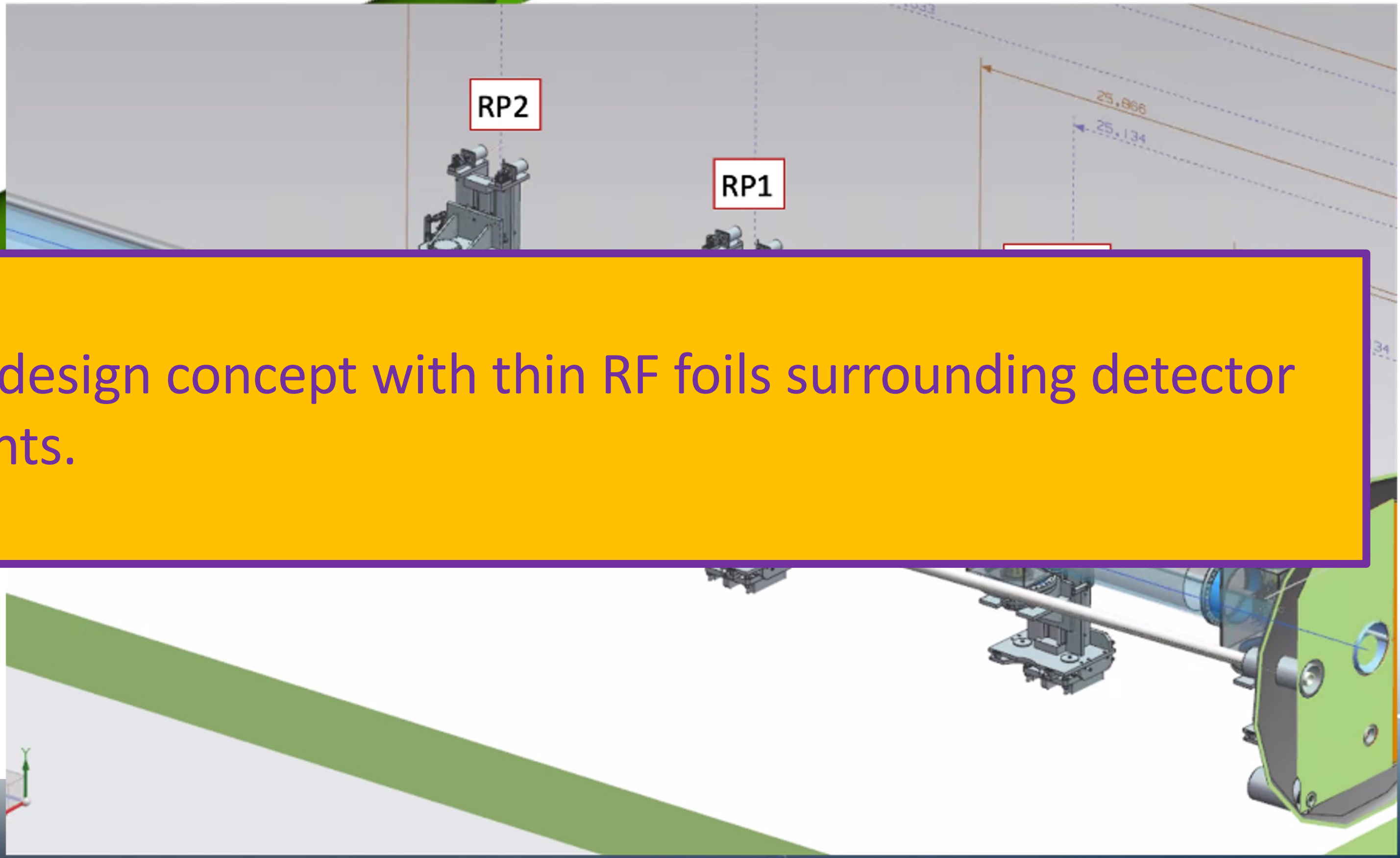
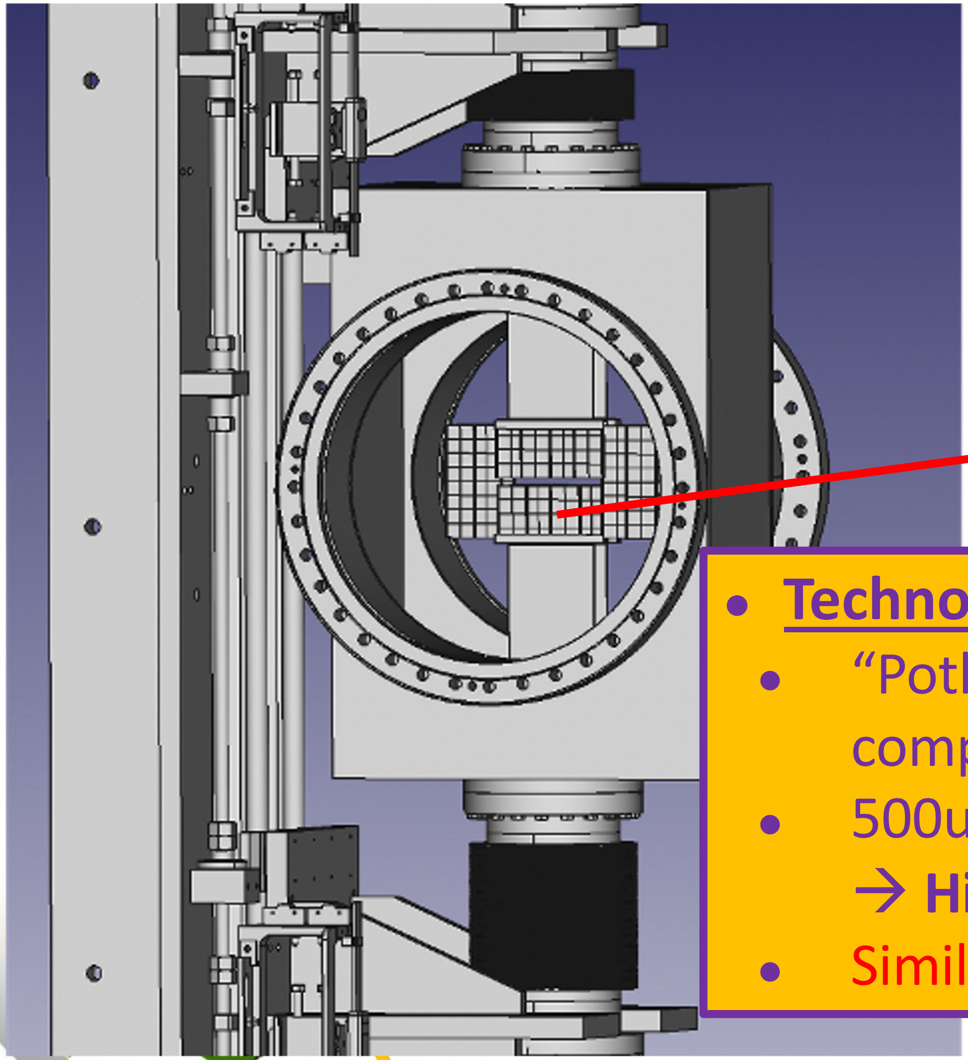
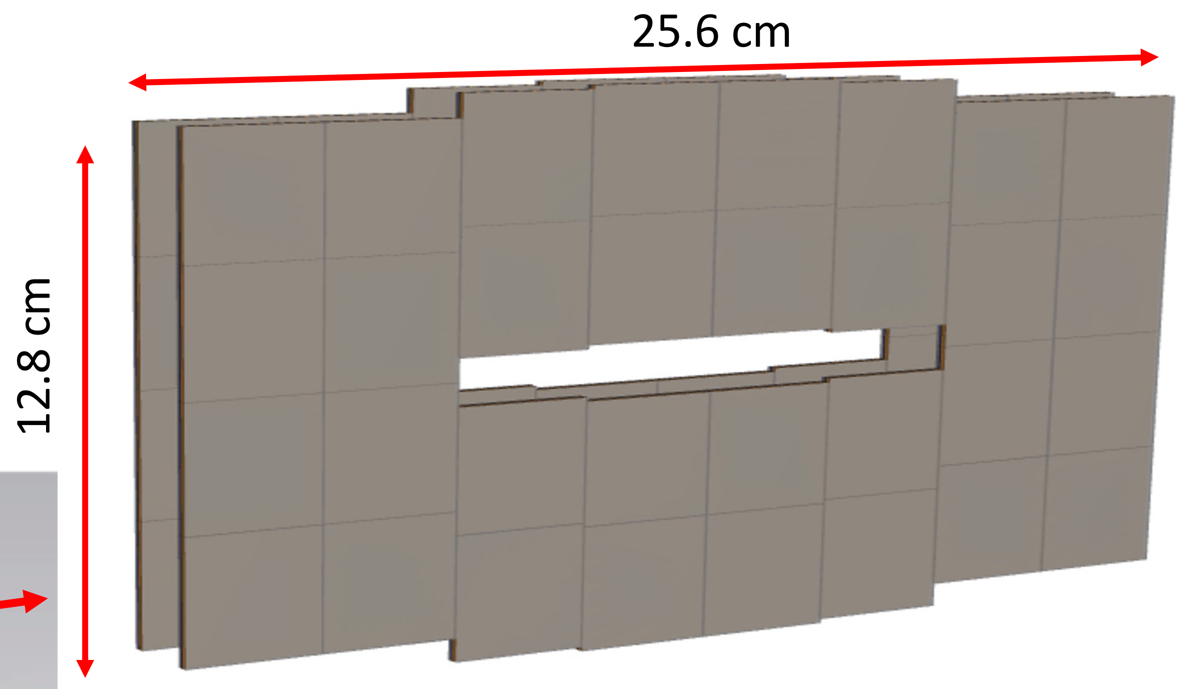


- <u>**Technology**</u>
  - "Potless" design concept with thin RF foils surrounding detector components.

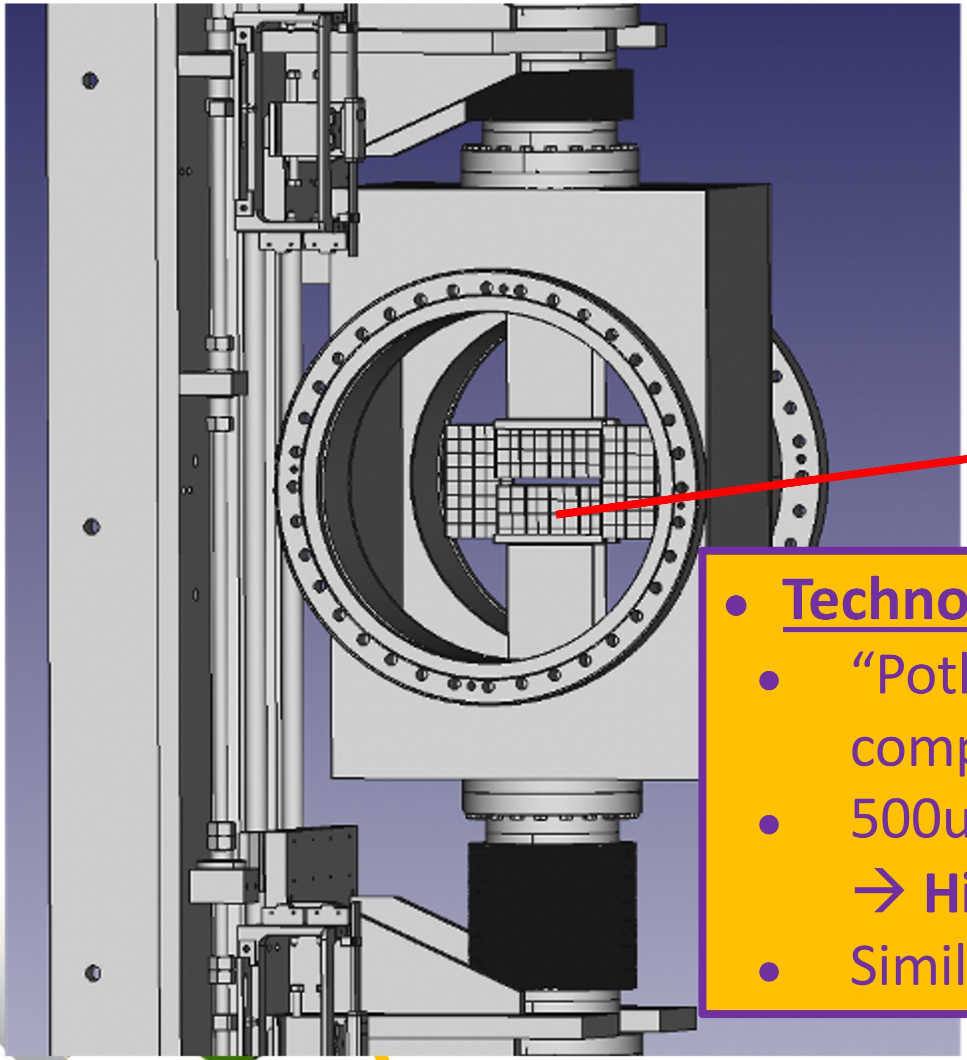
Roman Pots and OMD

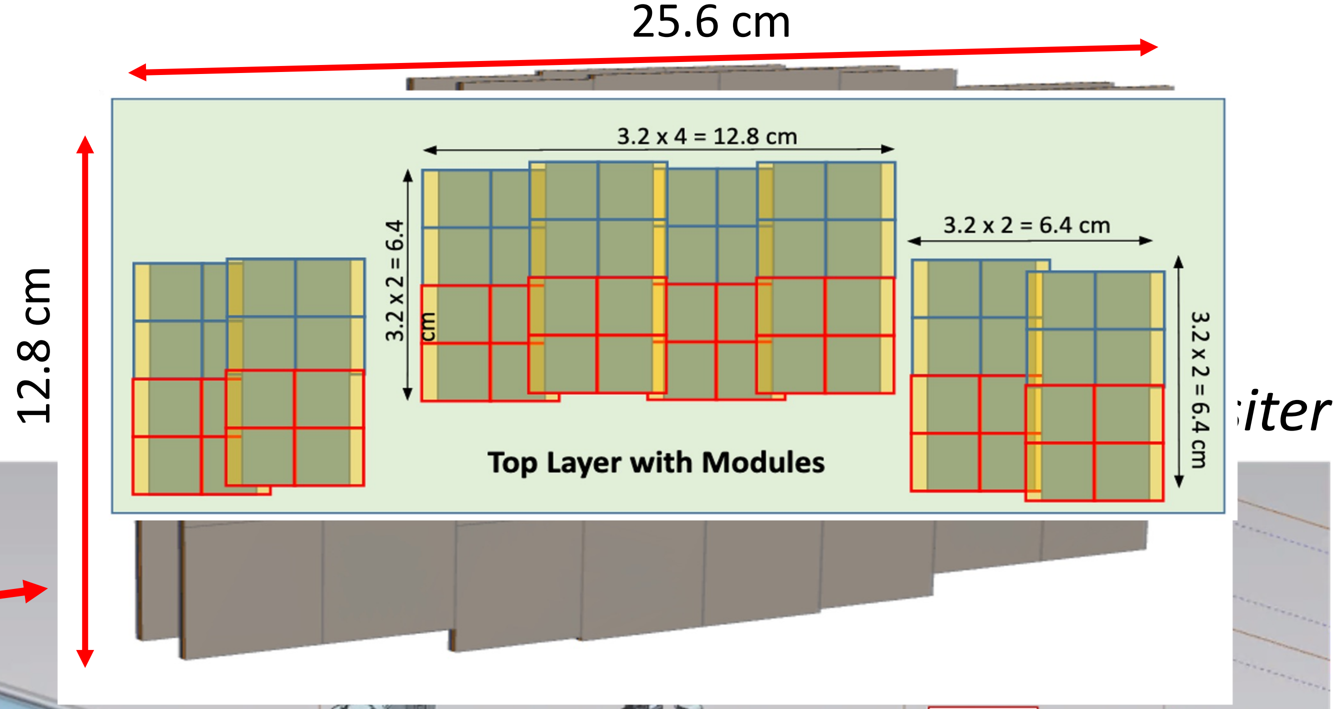




- <u>**Technology**</u>
  - "Potless" design concept with thin RF foils surrounding detector components.
  - 500um, **pixilated AC-LGAD sensor**, with 30-40ps timing resolution → **High-precision space and time information!**
  - Similar concept for the OMD, just different active area and shape.

Roman Pots and OMD





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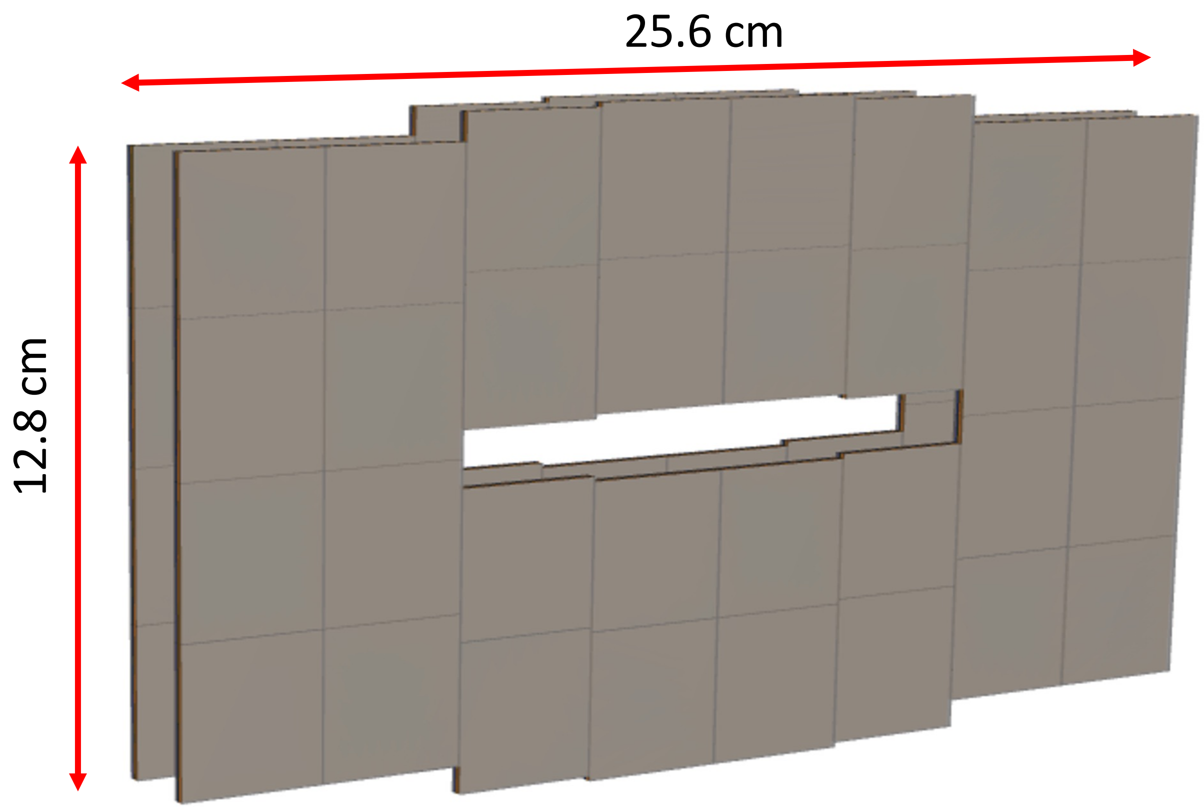
More engineering work is currently underway to optimize the layout, support structure, cooling, and movement systems for inserting the detectors into the beamline.

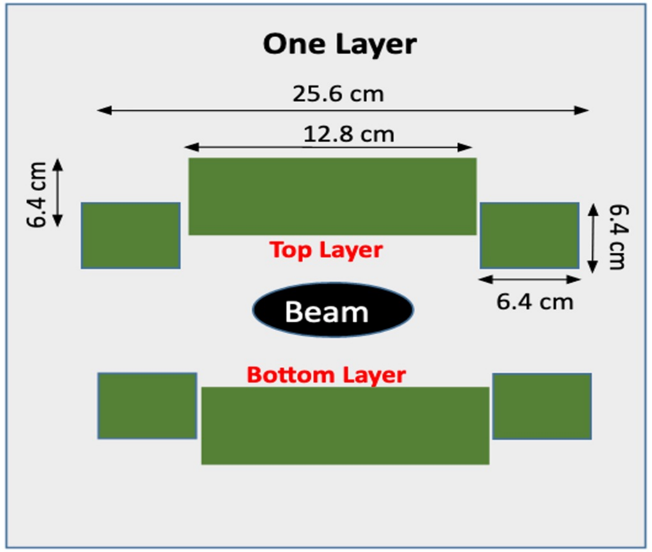
Roman "Pots" @ the EIC

$\sigma(z)$ is the Gaussian width of the beam, $\beta(z)$ is the RMS transverse beam size, ε is the beam emittance, and D is the momentum dispersion.

$$\sigma_{x,y} = \sqrt{\beta(z)_{x,y}\epsilon_{x,y} + \left(D_{x,y}\frac{\Delta p}{p}\right)^2}$$



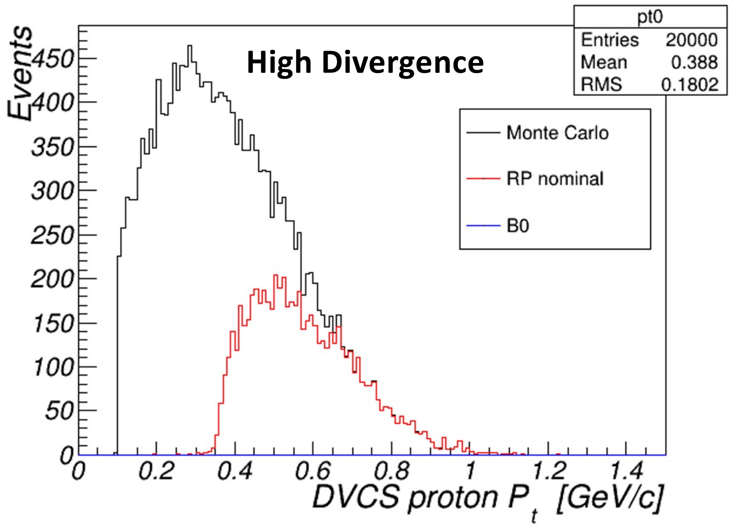
DD4HEP Simulation

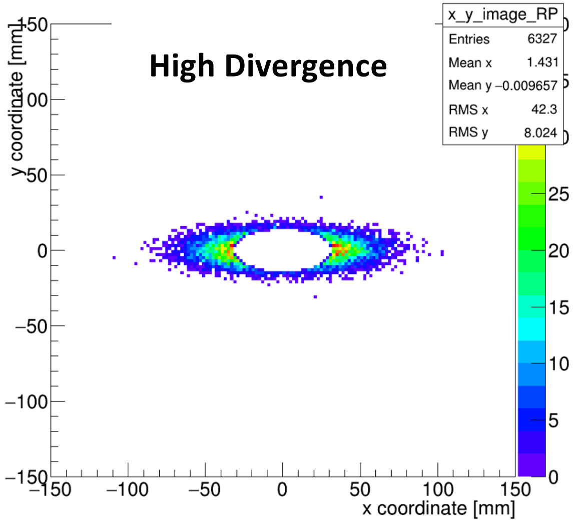


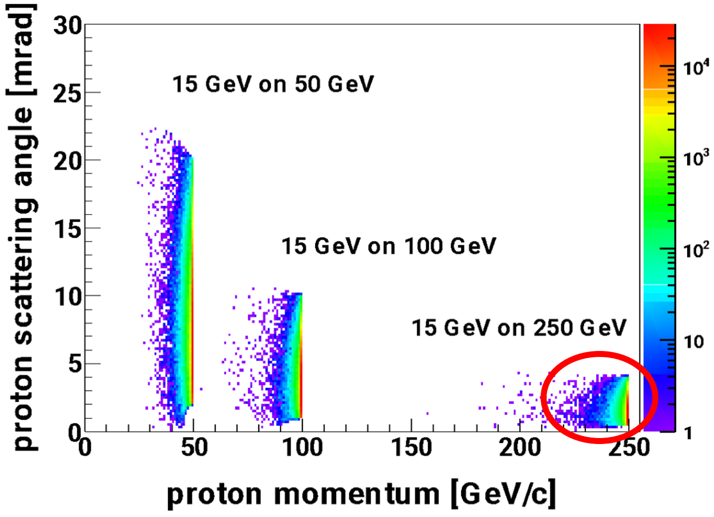
- <u>**Low-pT cutoff determined by beam optics.**</u>
  - **The safe distance is ~10σ from the beam center.**
  - **1σ ~ 1mm**
- **These optics choices change with energy, but can also be changed within a single energy to maximize *either acceptance at the RP, or the luminosity.***

Digression: Machine Optics (IP6)

275 GeV DVCS Proton Acceptance







<u>High Divergence:</u> smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

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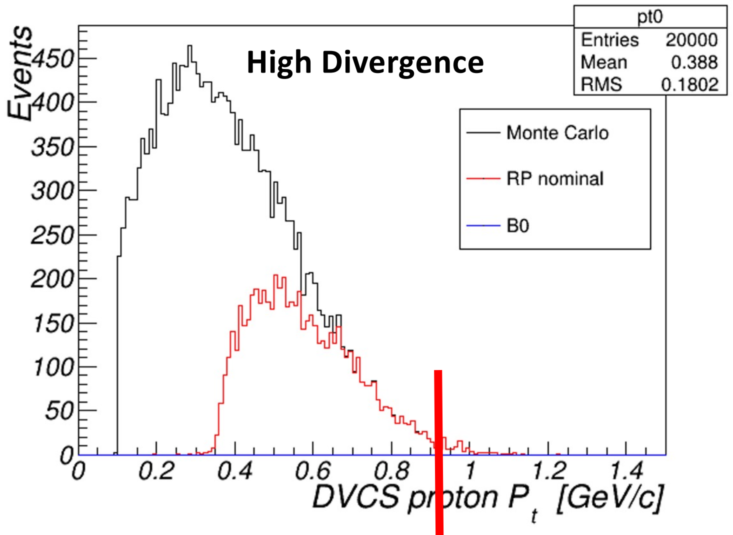

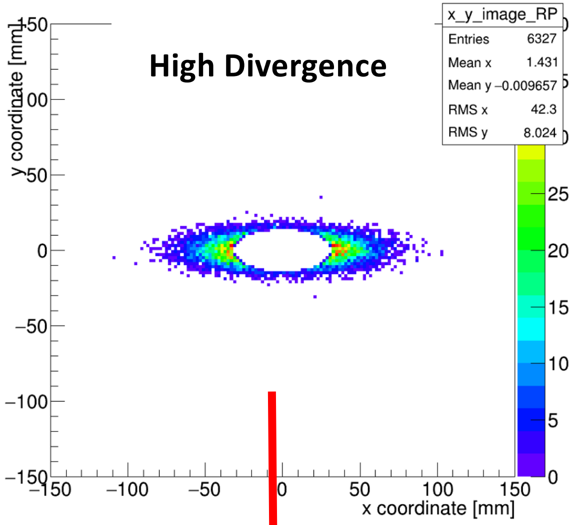

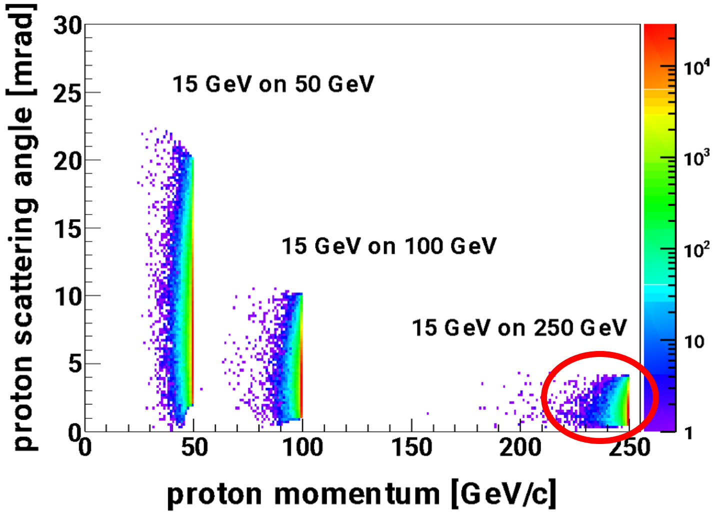

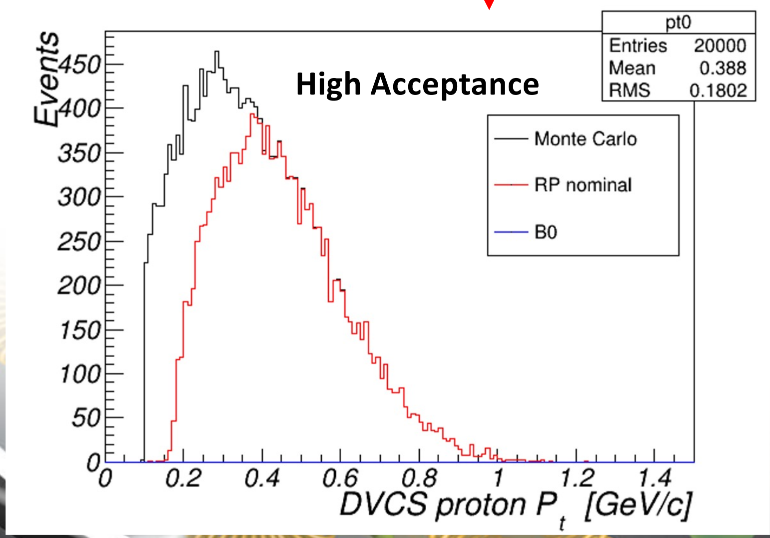

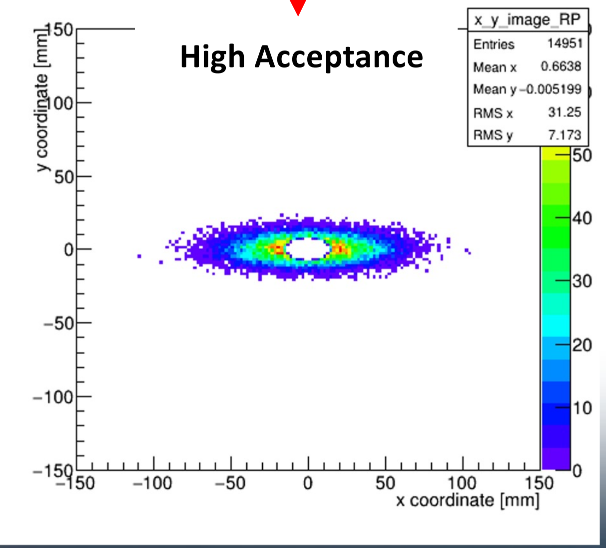

High Divergence: smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

High Acceptance: larger β^* at IP, smaller $\beta(z = 30m)$ -> lower lumi., smaller beam at RP

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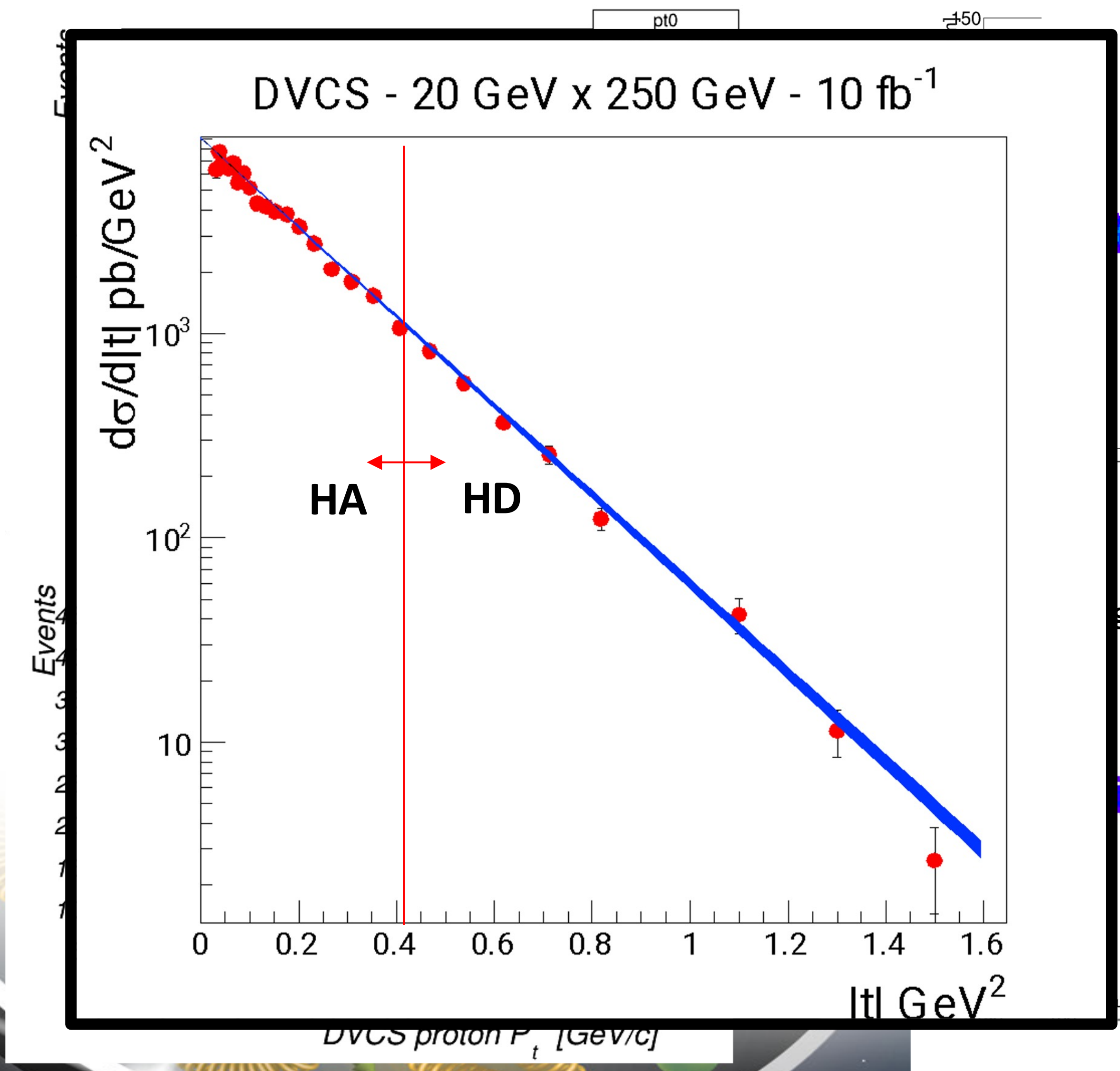
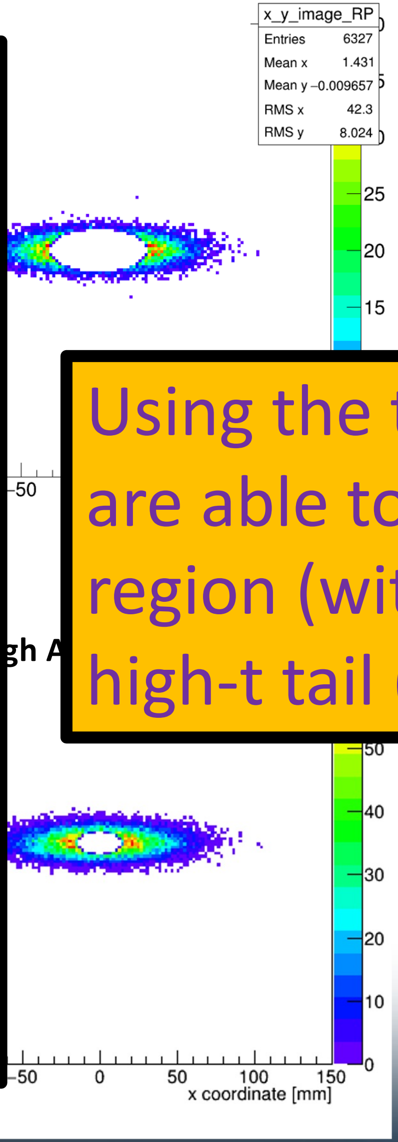
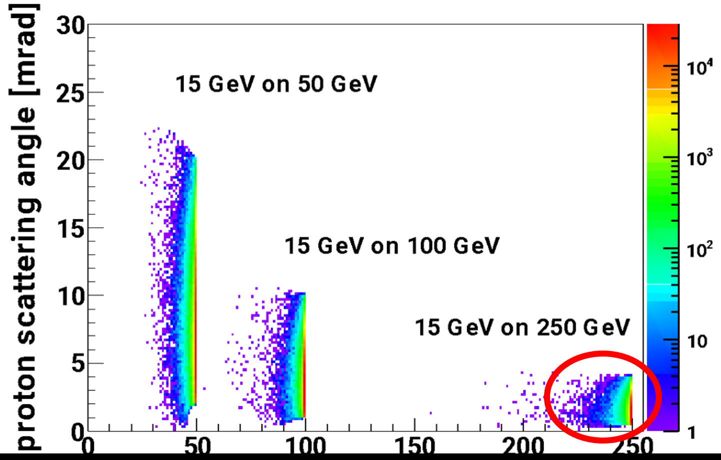




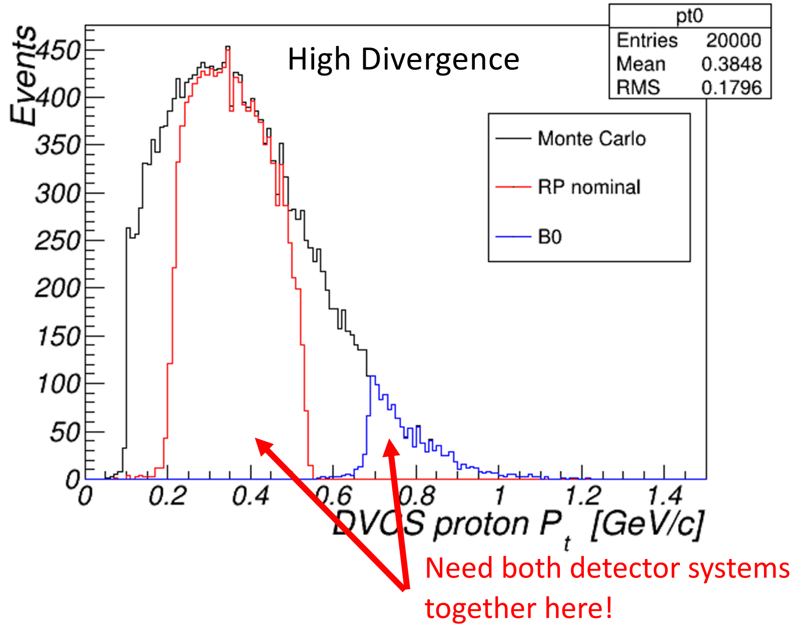


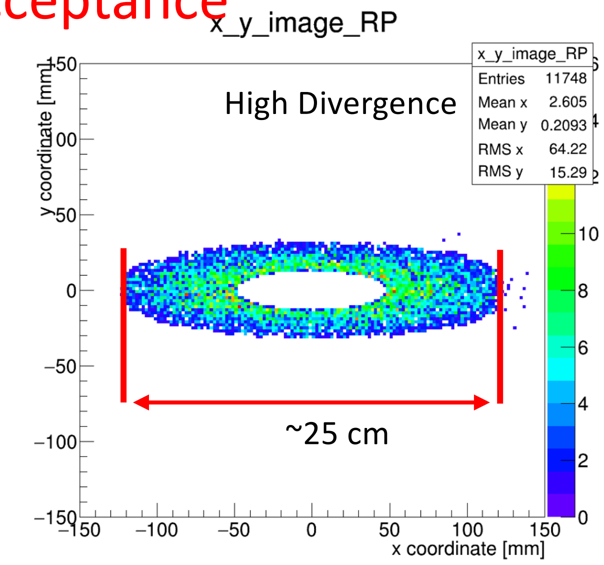
Using the two configurations, we are able to measure the low-t region (with better acceptance) and high-t tail (with higher luminosity).

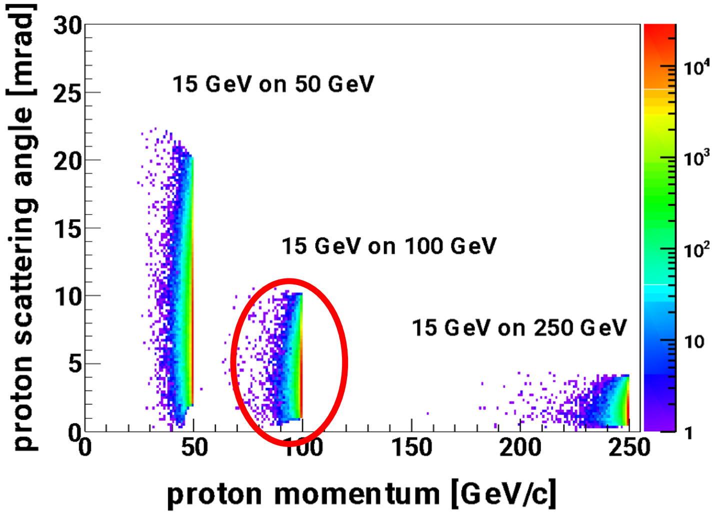
High Acceptance: larger β^* at IP, smaller $\beta(z = 30m)$ -> lower lumi., smaller beam at RP

Digression: Machine Optics (IP6)

100 GeV DVCS Proton Acceptance







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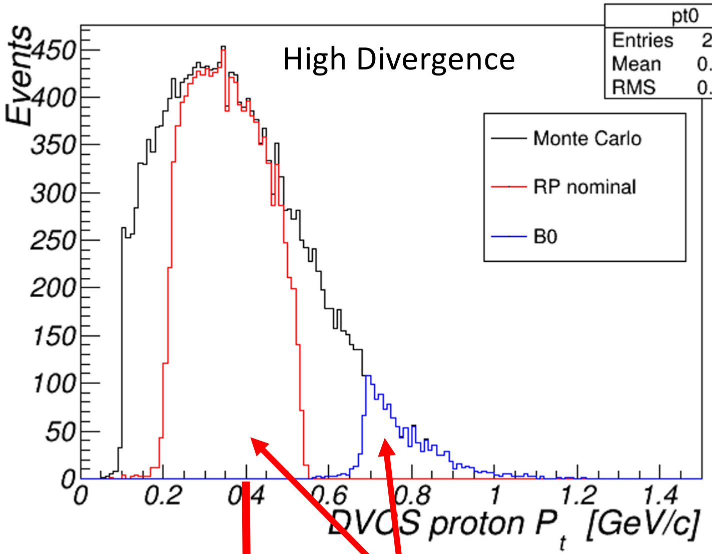
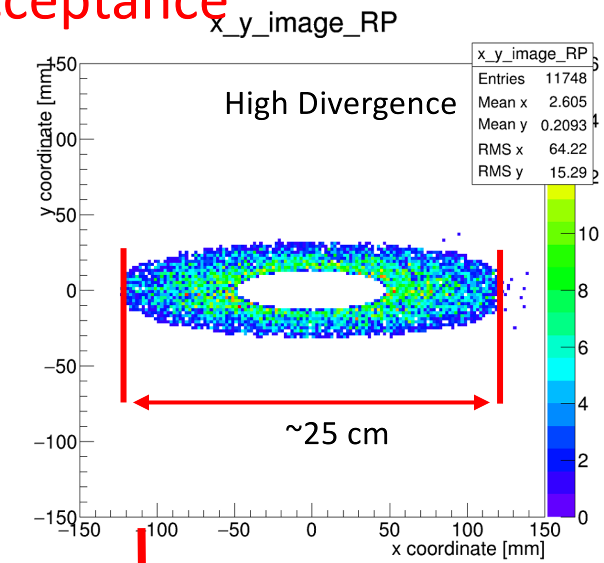
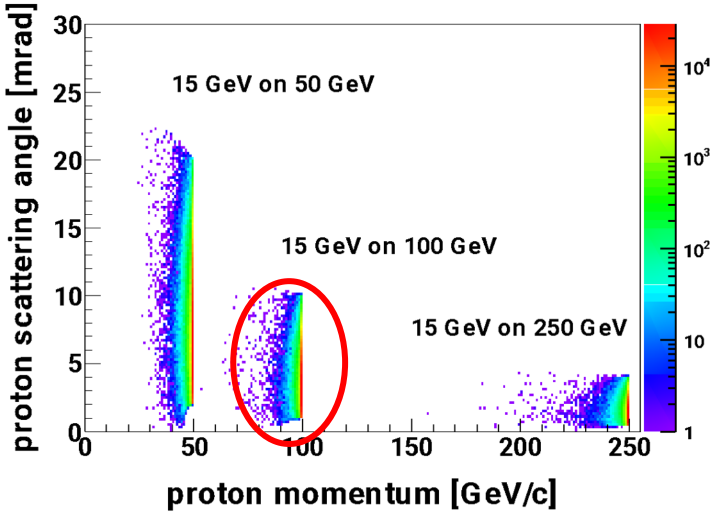
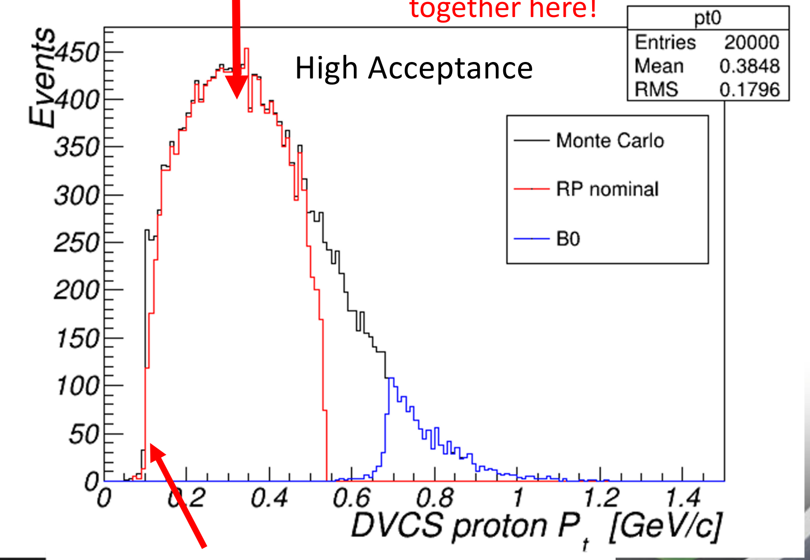
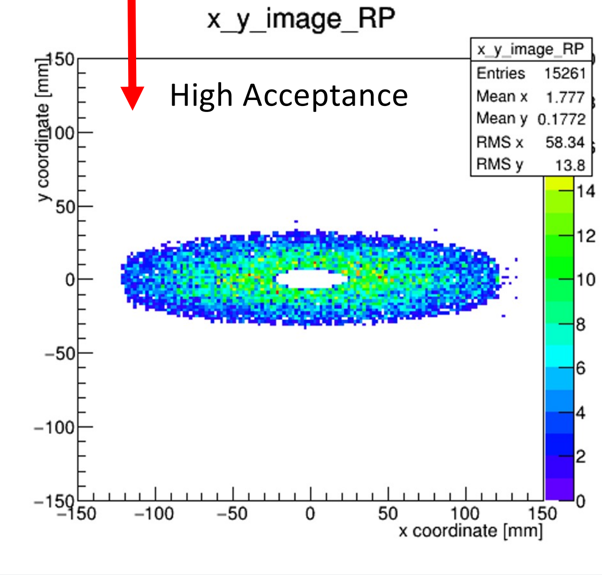






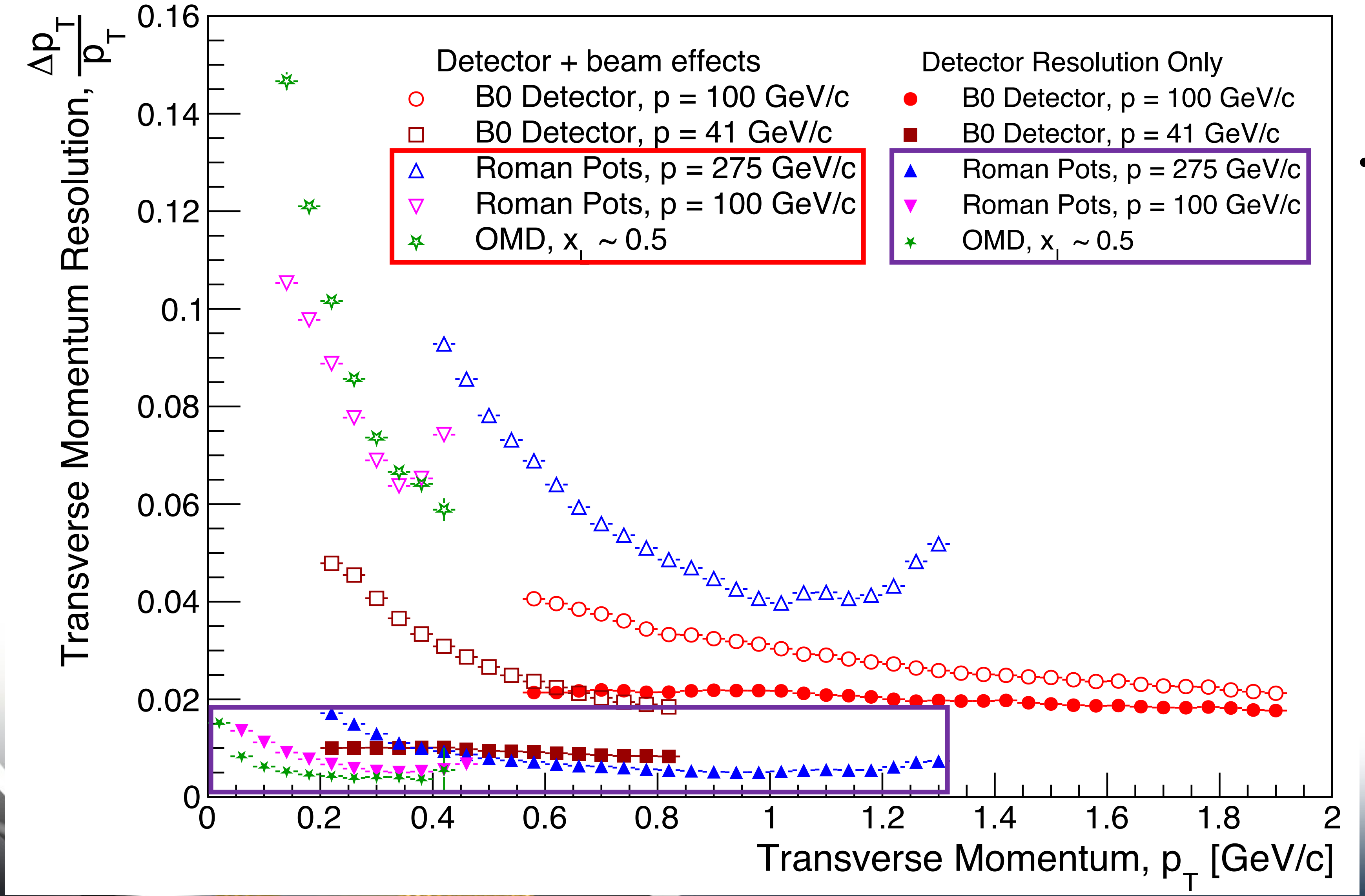
Need both detector systems together here!





Improves low p_t acceptance.

Summary of Detector Performance

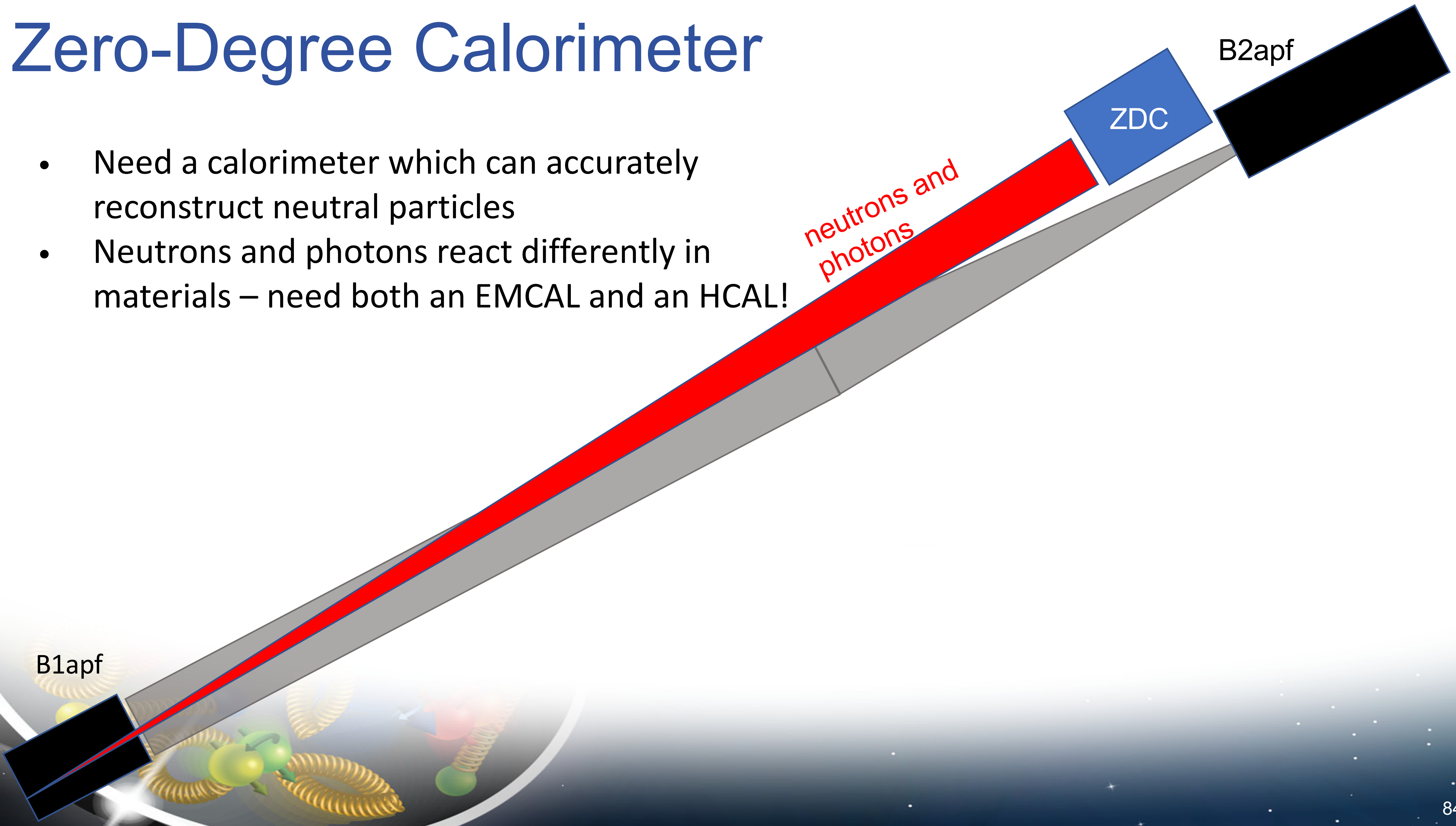


- All beam effects included!
  - Angular divergence.
  - Crossing angle.
  - Crab rotation/vertex smearing.

Beam effects the dominant source of momentum smearing!

Zero-Degree Calorimeter

- Need a calorimeter which can accurately reconstruct neutral particles
- Neutrons and photons react differently in materials – need both an EMCAL and an HCAL!



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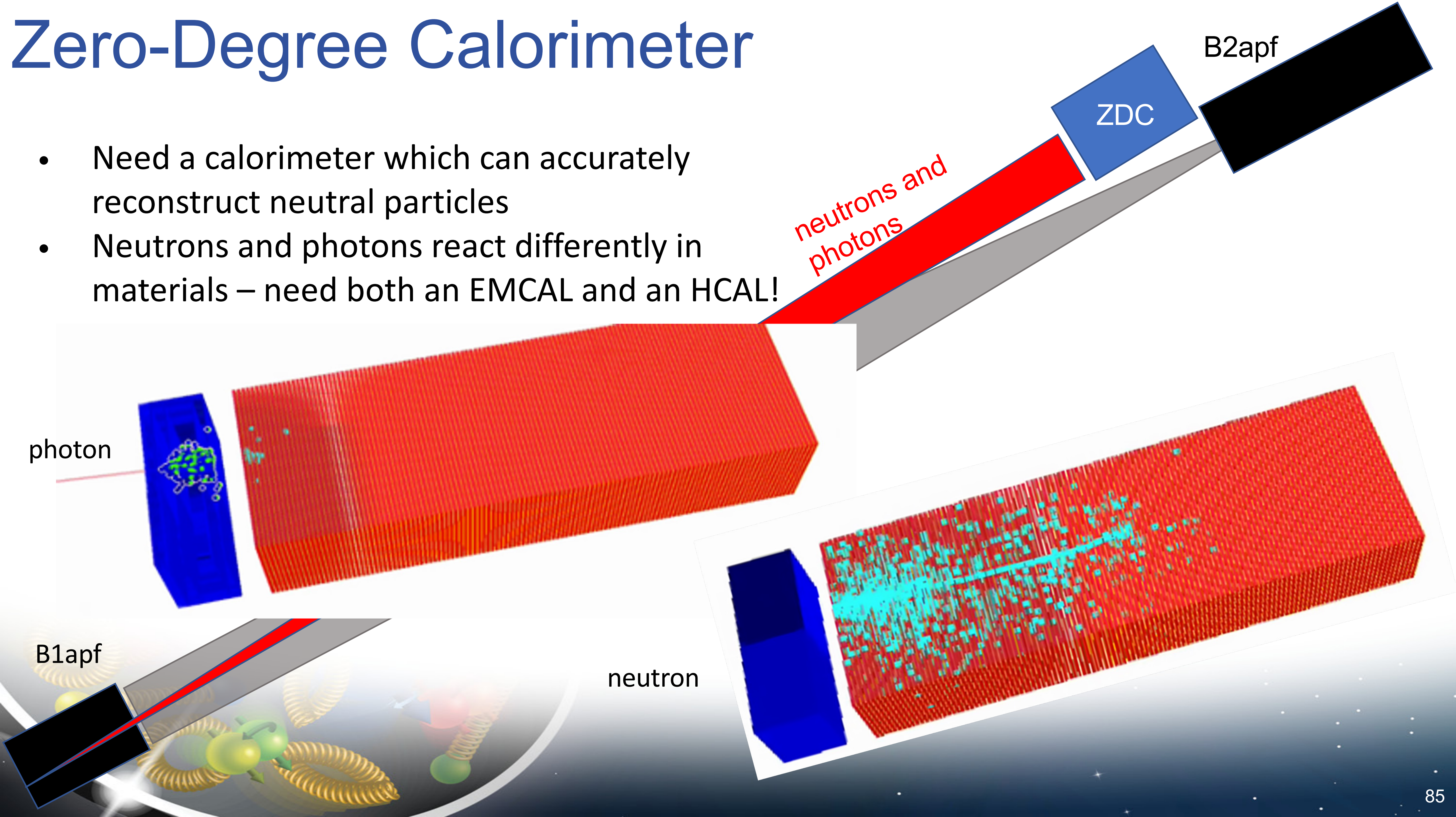
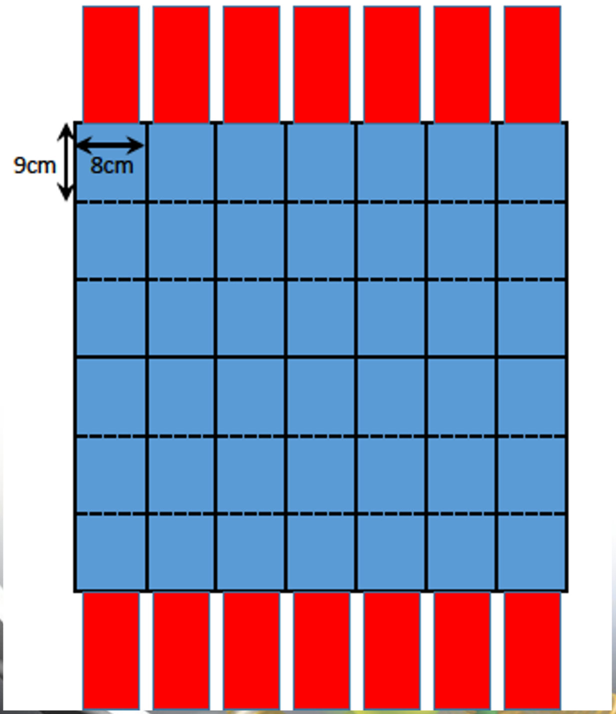


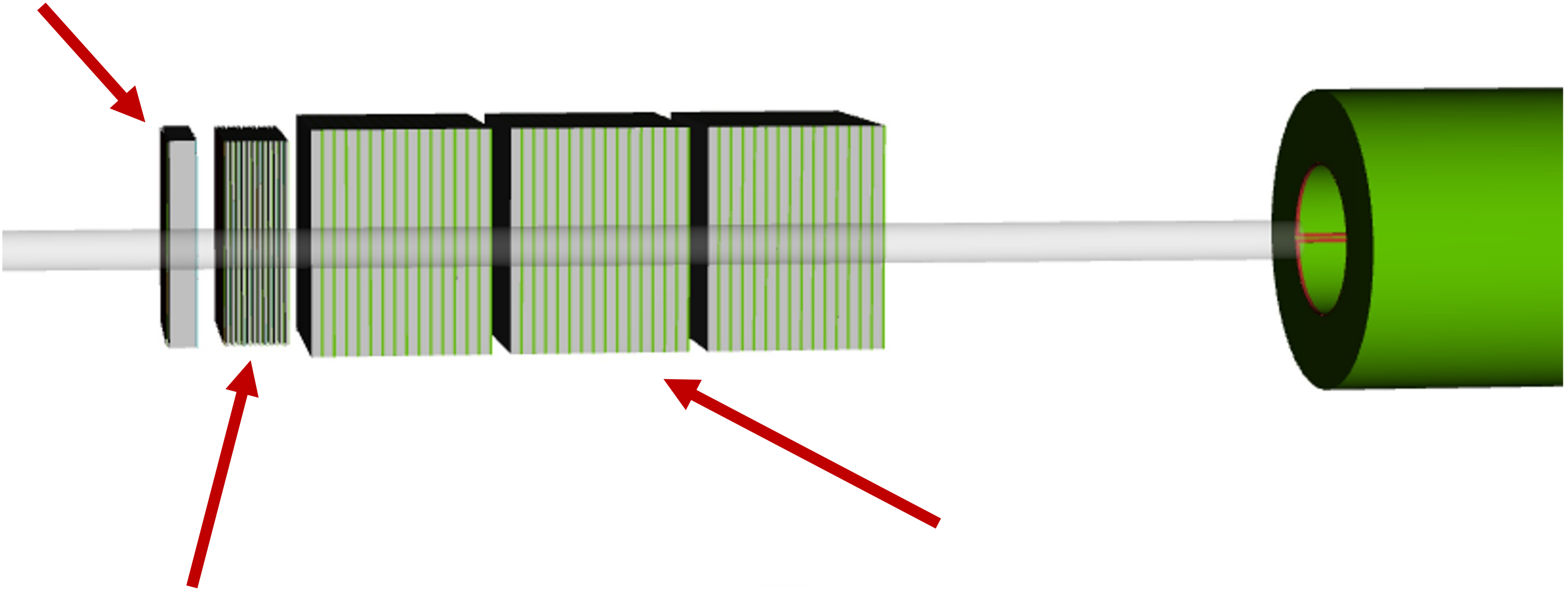
ZDC - What's New

- 1st Silicon & crystal calorimeter (PbWO4 or LYSO):
  - Smaller lateral dimension (x, y) = (56, 54) cm.

Overall length within 2m limit

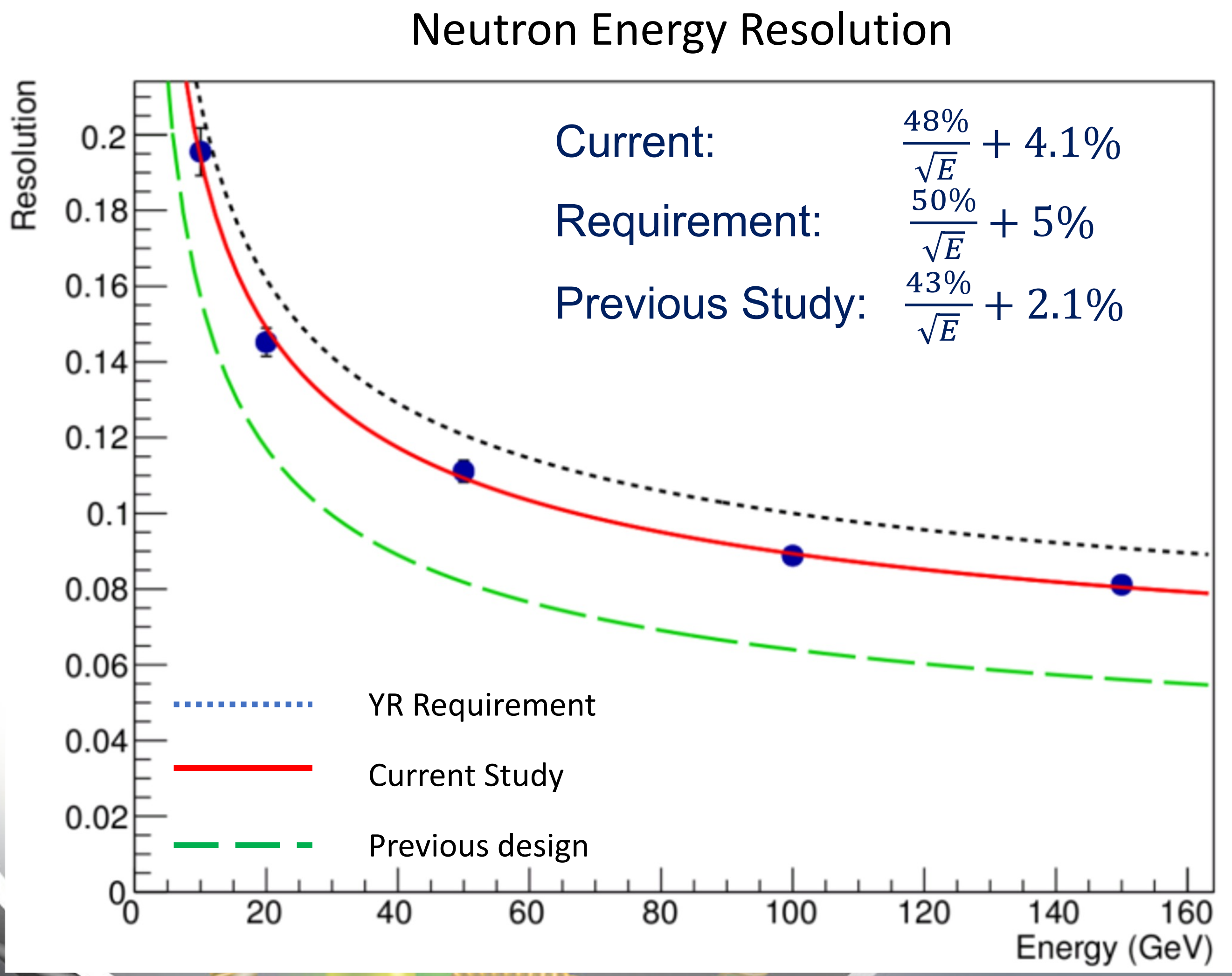
Readout setup from top & bottom

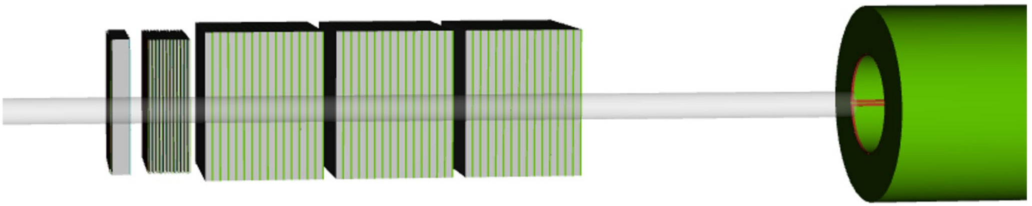




- W/Silicon Imaging EMCAL
  - Transverse size (x,y) = (56, 54) cm
  - 12 layers (~$24\chi_0$)
- Pb-Scintillator (+ fused silica)
  - Towers of 10cm x 10cm x 48cm, each module 60cm x 60cm x 48cm
  - 3 modules

ZDC - Performance





- Energy resolution in the new design acceptable → Optimization, test of different ideas within the size limit.

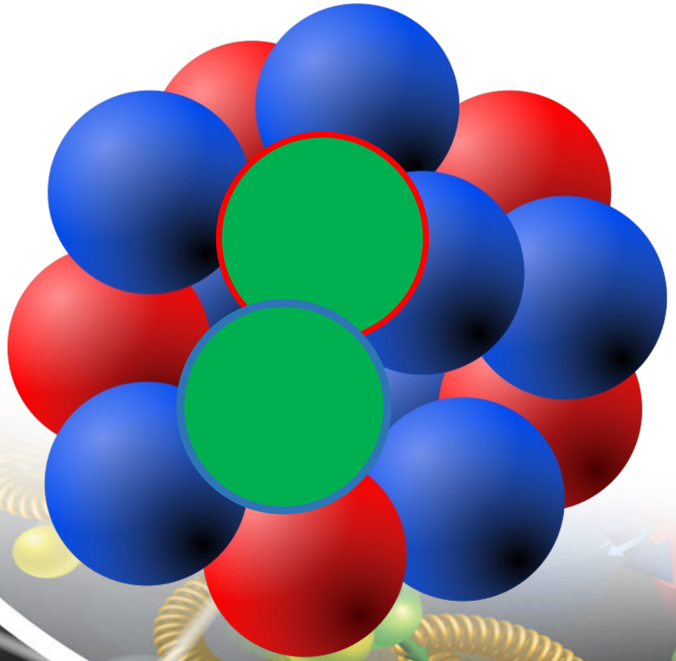
- Next steps:
  - Implementation of reconstruction
  - Position resolution & shower development study ongoing for the imaging part of HCAL

Short-Range Correlations

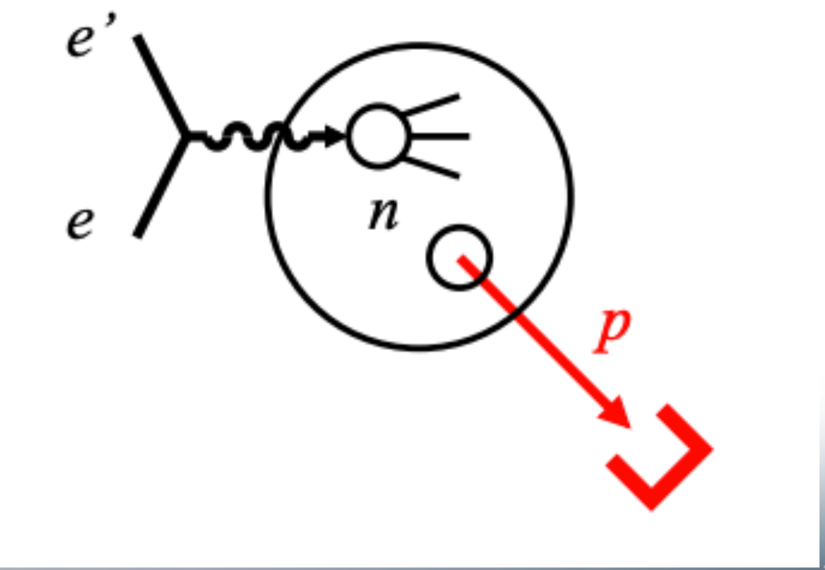
"The nucleus can often be approximated as an independent collection of protons and neutrons confined in a volume, but for short periods of time, the nucleons in the nucleus can strongly overlap. This quantum mechanical overlapping, known as a nucleon-nucleon short-range correlation, is a manifestation 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!



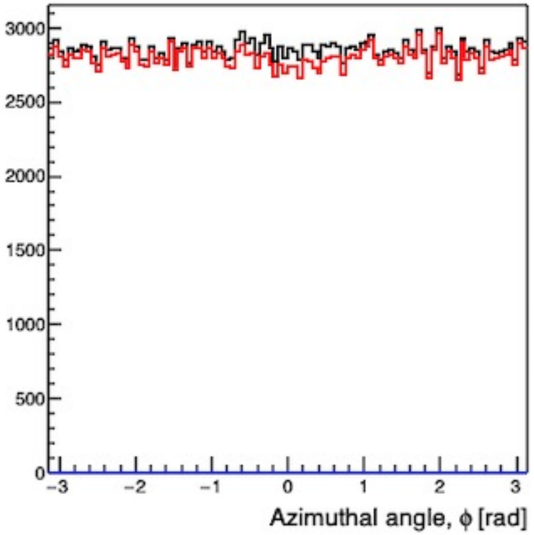
Use deuteron as "SRC laboratory", where nucleon kinematics are readily accessible.



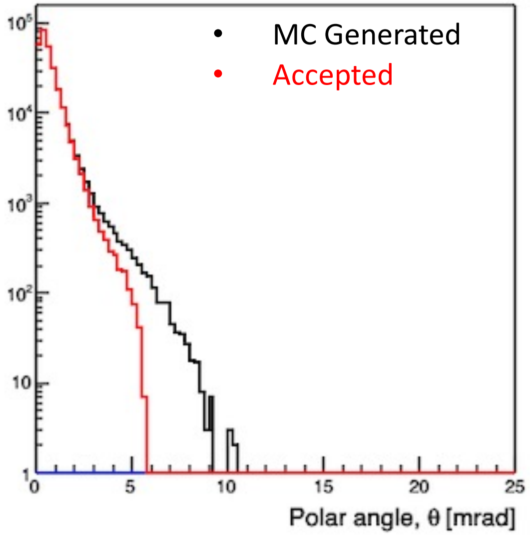
Short-Range Correlations in Deuterons

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

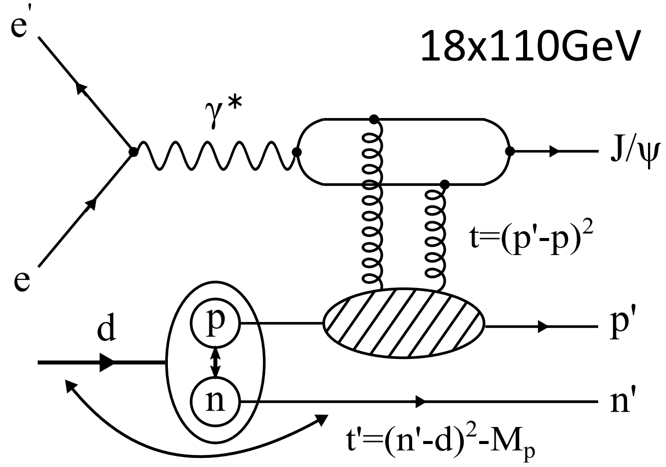
Protons



Protons



18x110GeV



Proton "spectator" case.

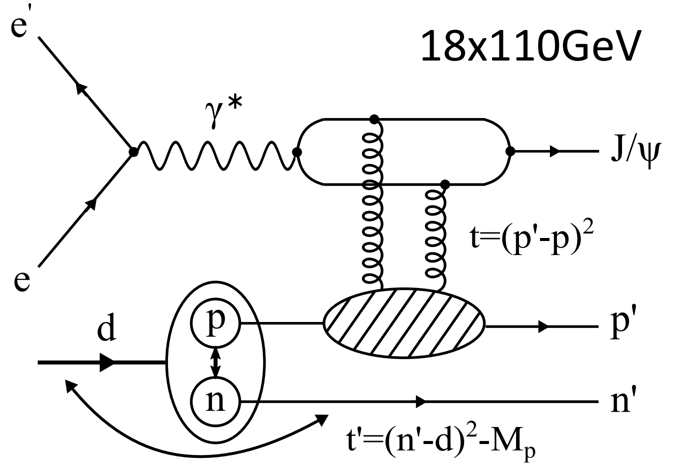
Particular process in BeAGLE: incoherent diffractive J/ψ production off bounded nucleons.

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

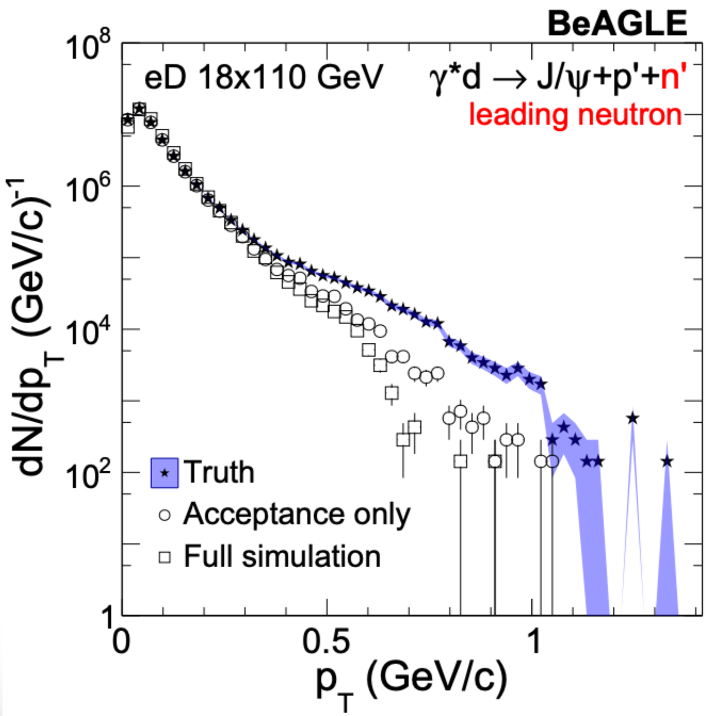
Acceptance refers to particles which are actually captured by the detector.

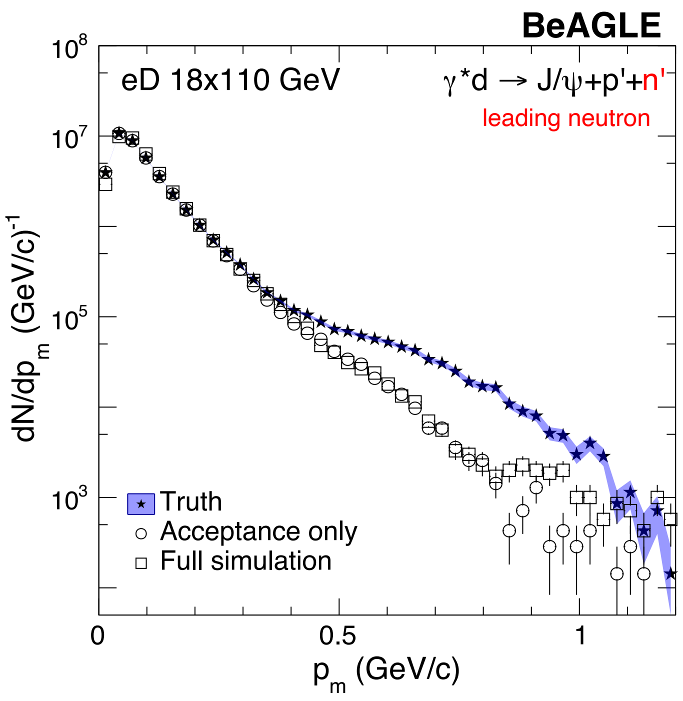
Short-Range Correlations in Deuterons

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.

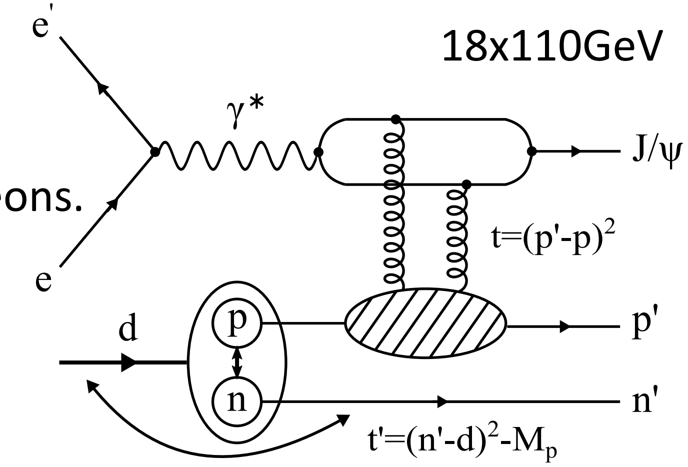
> **In the proton spectator case, essentially all spectators tagged up to pT ~ 600 MeV/c.**
> **Active neutrons only tagged up to 4.5 mrad → double-tagging efficiency very low.**

e+d Spectator Tagging

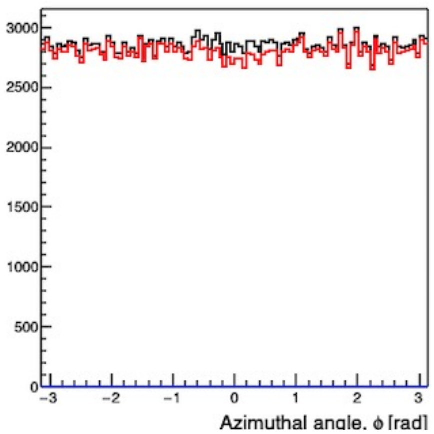
Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)

Proton spectator case.

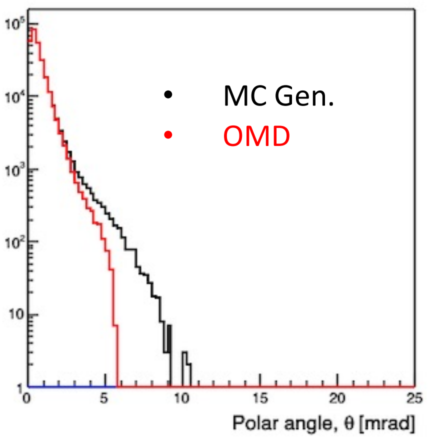
Particular process in BeAGLE: incoherent diffractive J/psi production off bounded nucleons.

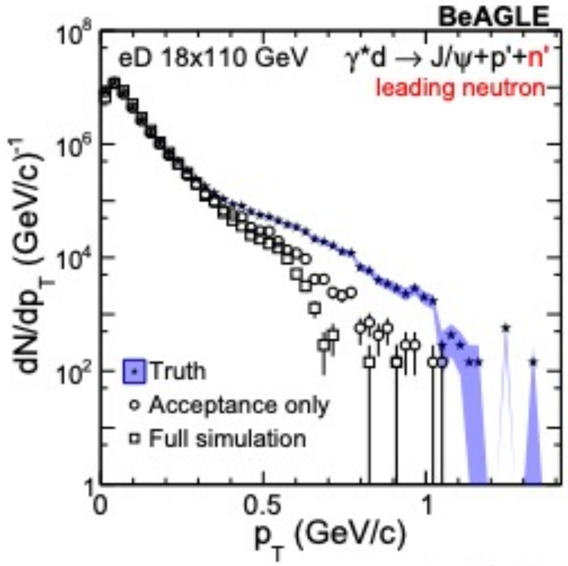


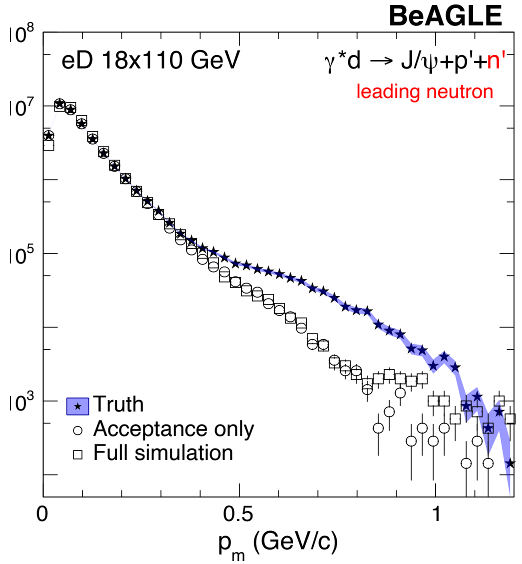
Protons

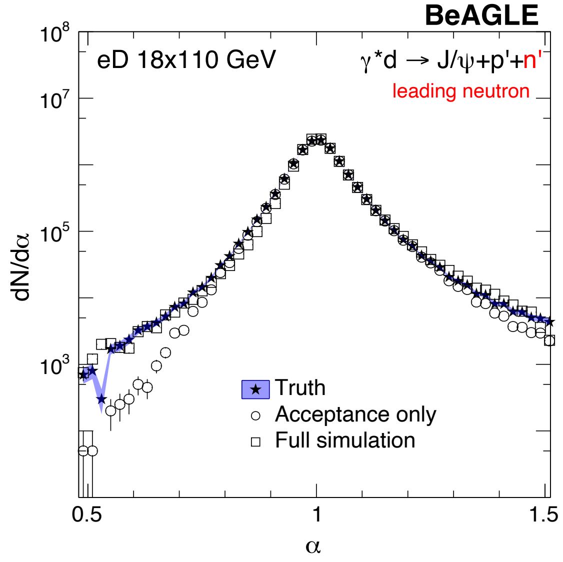


Protons



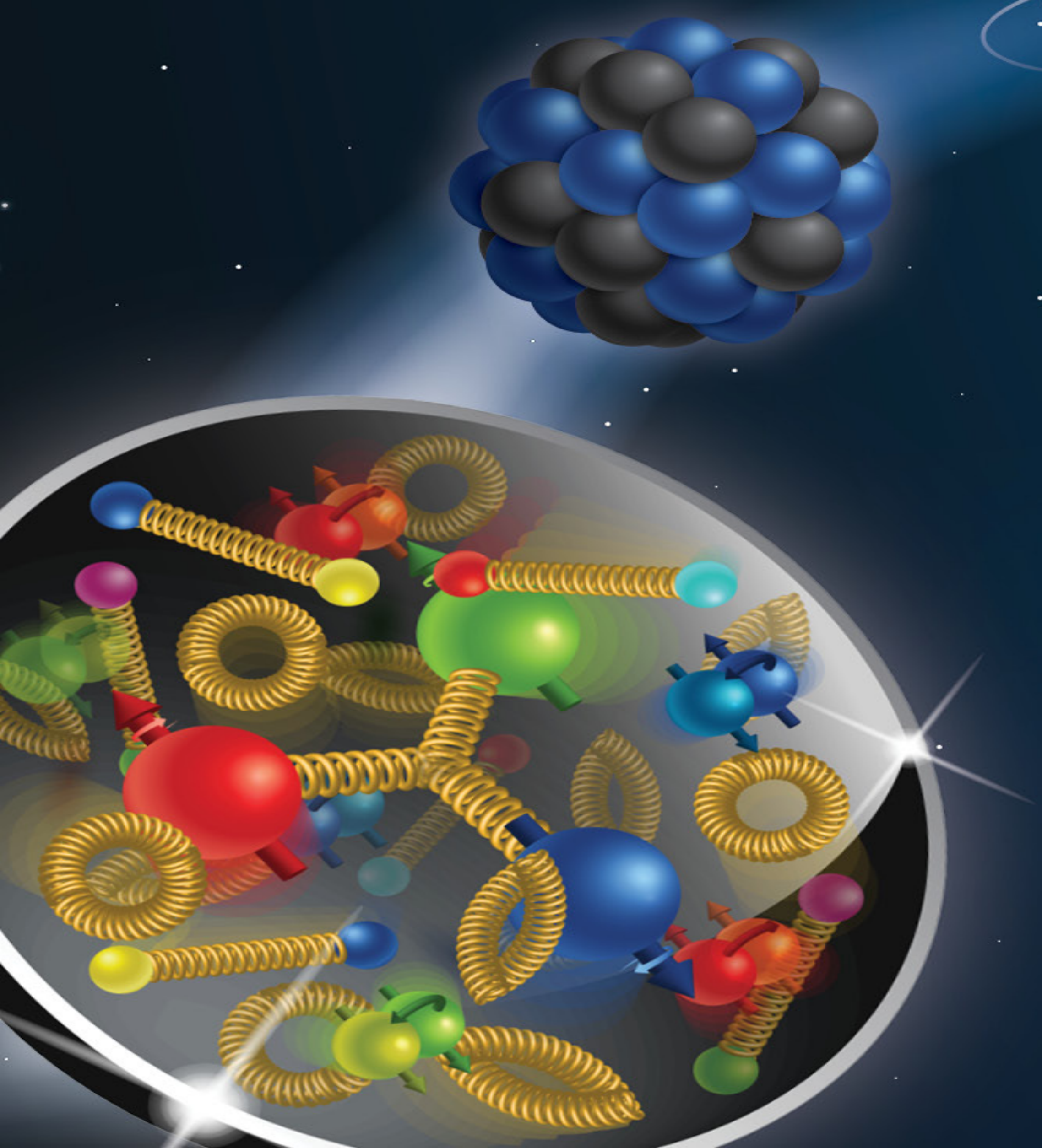






Spectator kinematic variables reconstructed over a broad range. Bin migration is observed due to smearing in the reconstruction. Each plot shows the MC (closed circles), acceptance effects only (open circles), and full reconstruction (open squares).

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

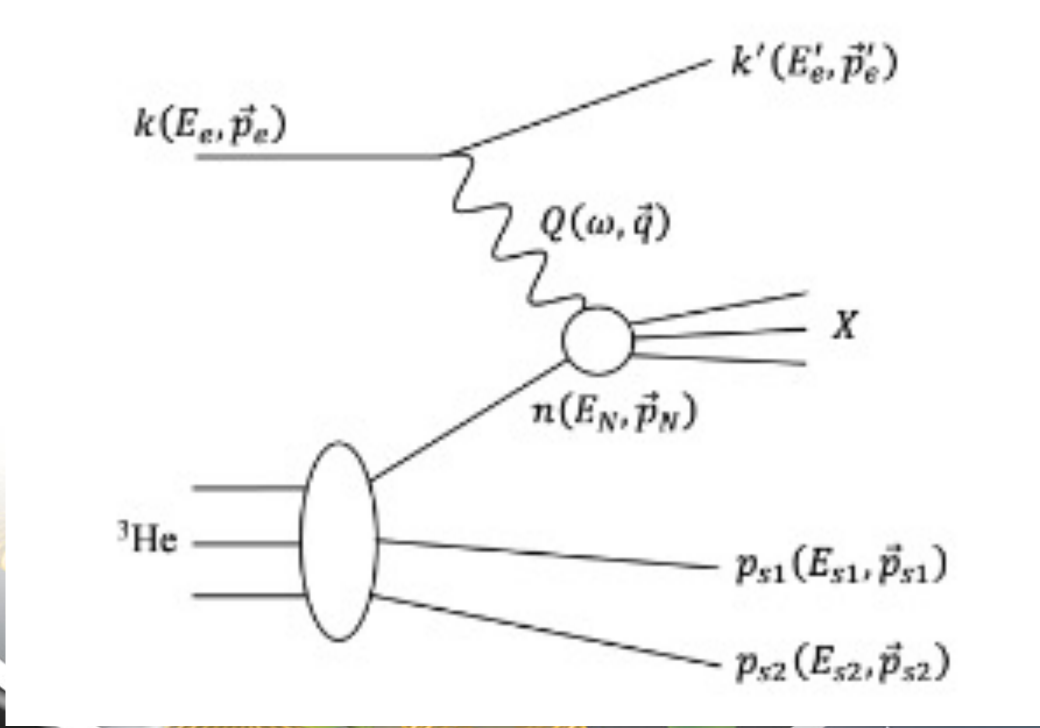


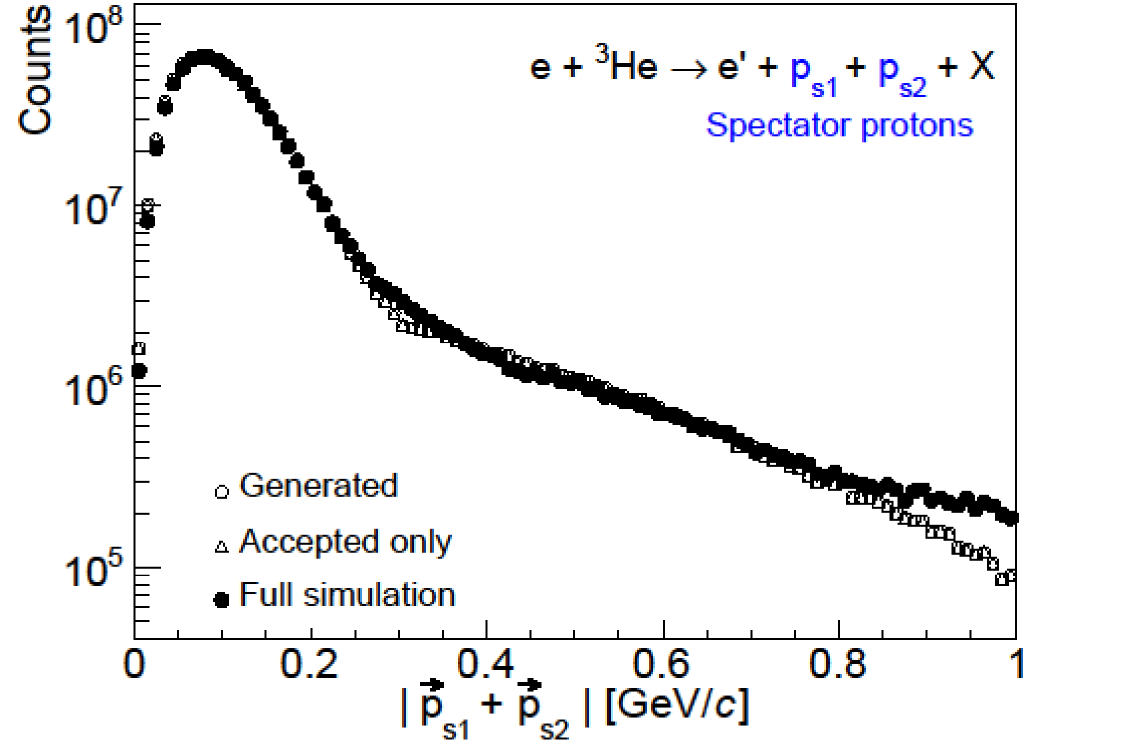
Light nuclei – Helium-3: Neutron Spin Structure

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.



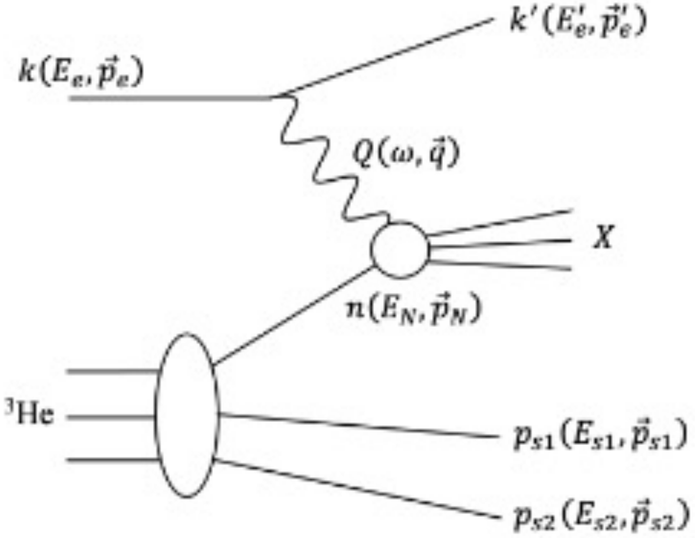


Neutron Spin Structure in He3

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

- Spin structure probed via spin asymmetries!

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

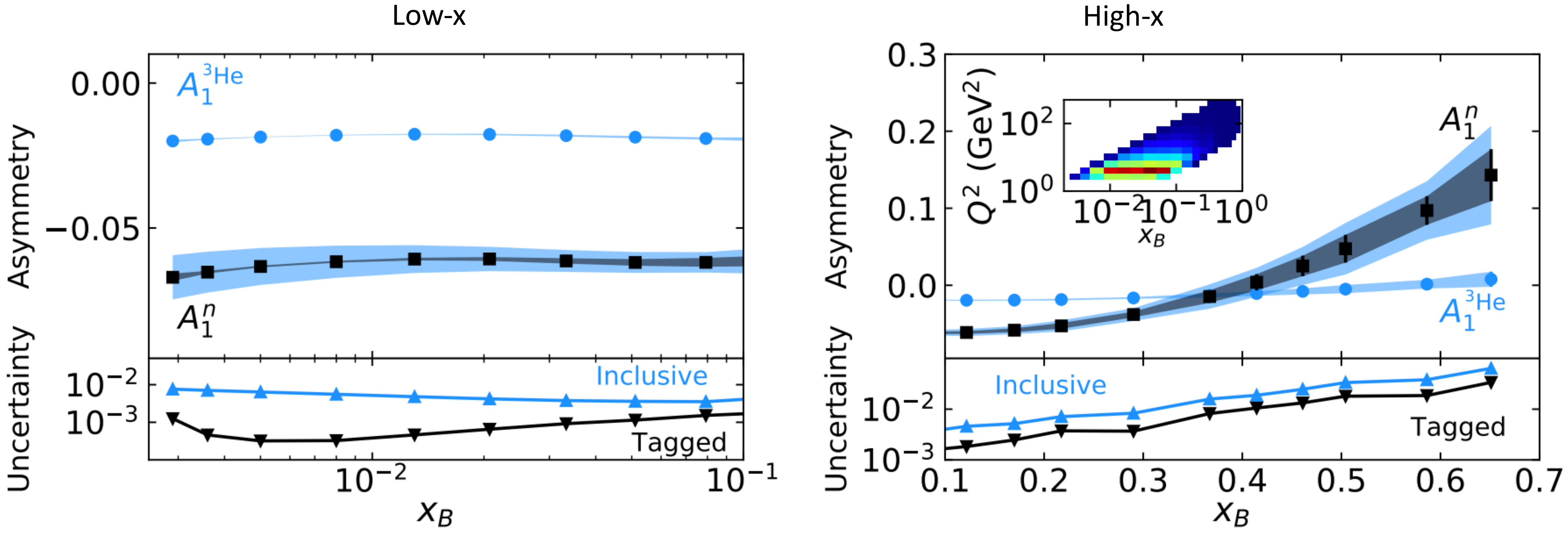


- (double) Tagged DIS measurement capable of measuring A_1^n directly!
- Complementary to measurements at JLAB.

Neutron Spin Structure in He3

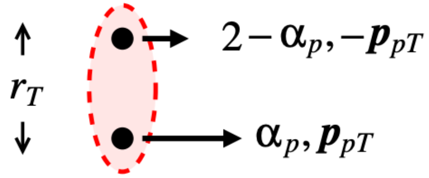
I. Friscic, D. Nguyen, J. R. Pybus, A. Jentsch, *et al.*, Phys. Lett. B, **Volume 823**, 136726 (2021)

- 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.

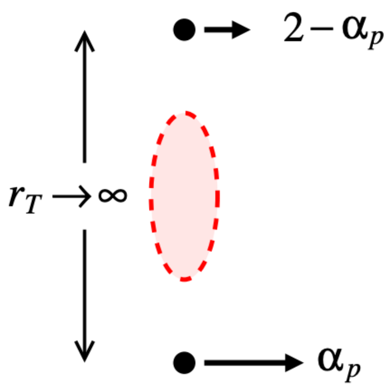


Pole Extrapolation

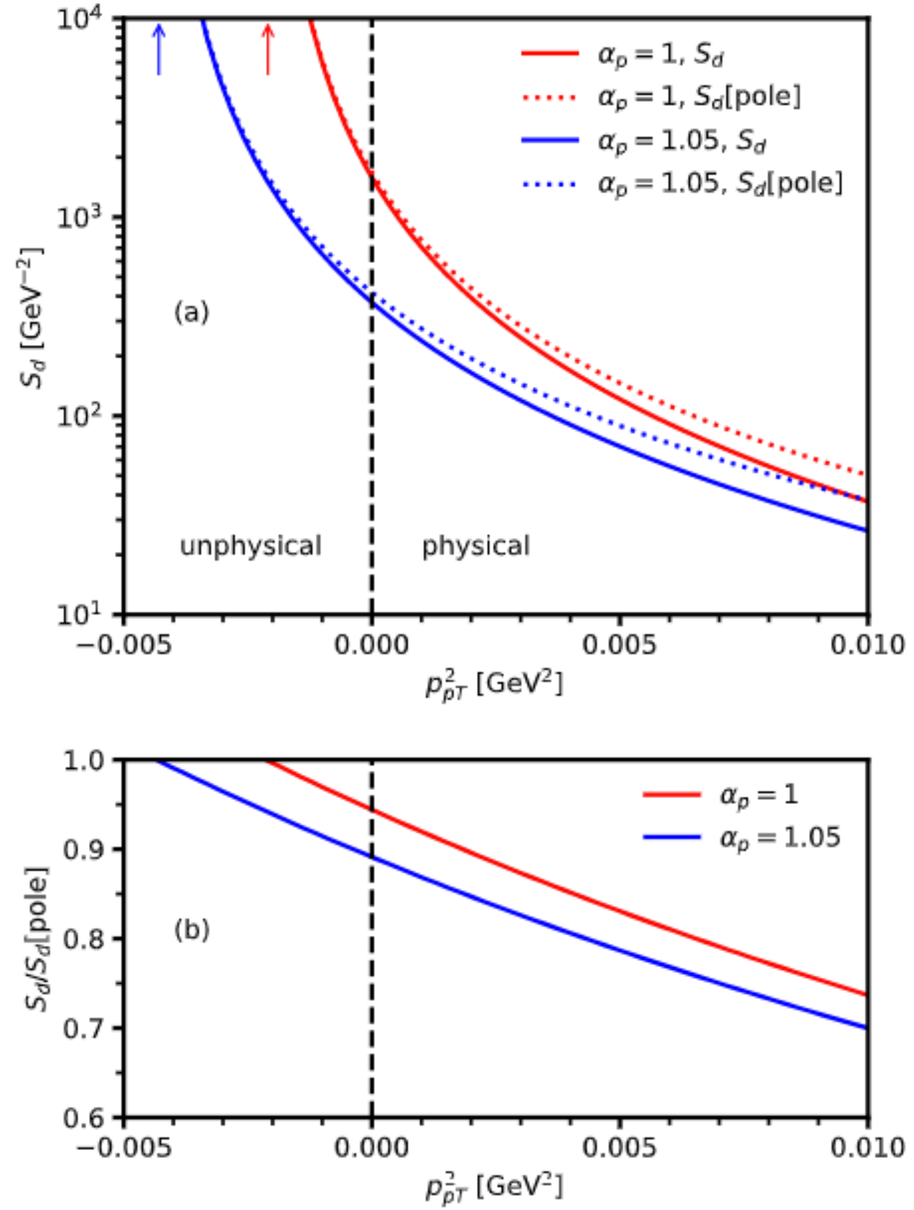
C. Weiss and W. Cosyn
Phys. Rev. C **102**, 065204 (2020)



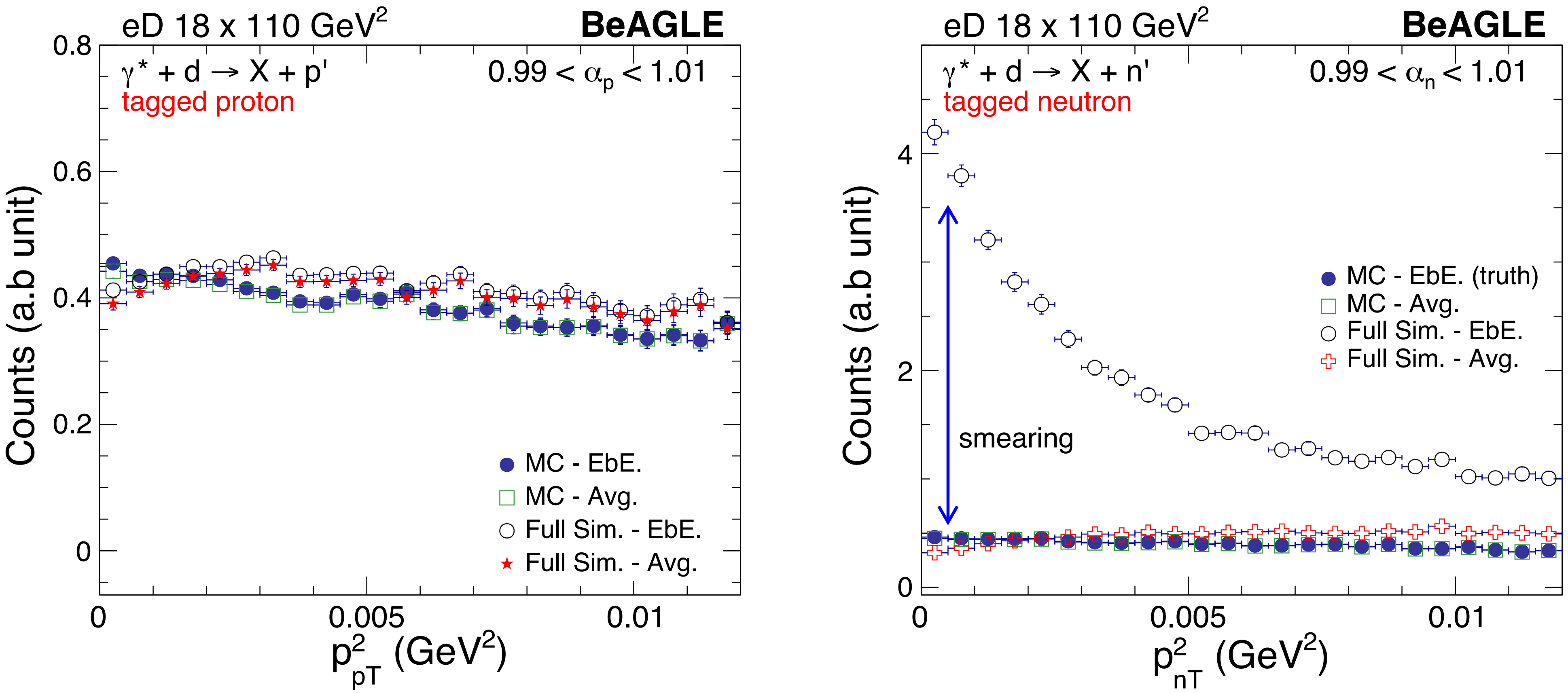
$p_{pT}^2 > 0$
physical region



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

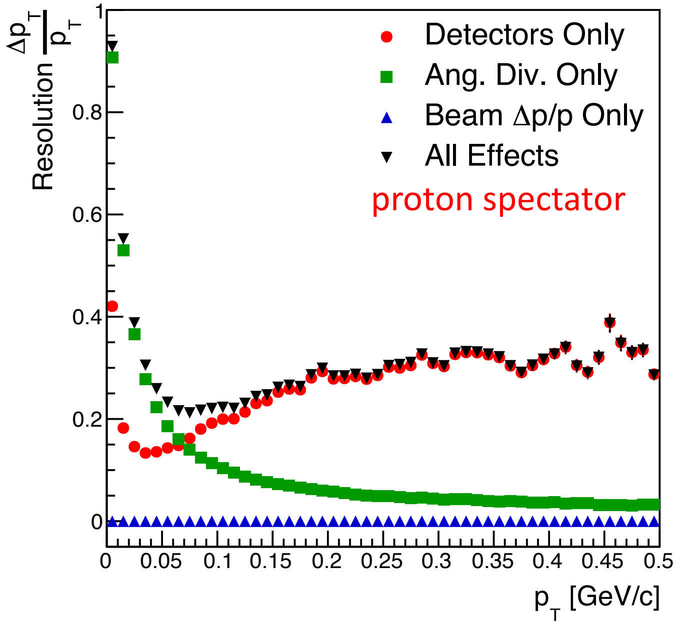


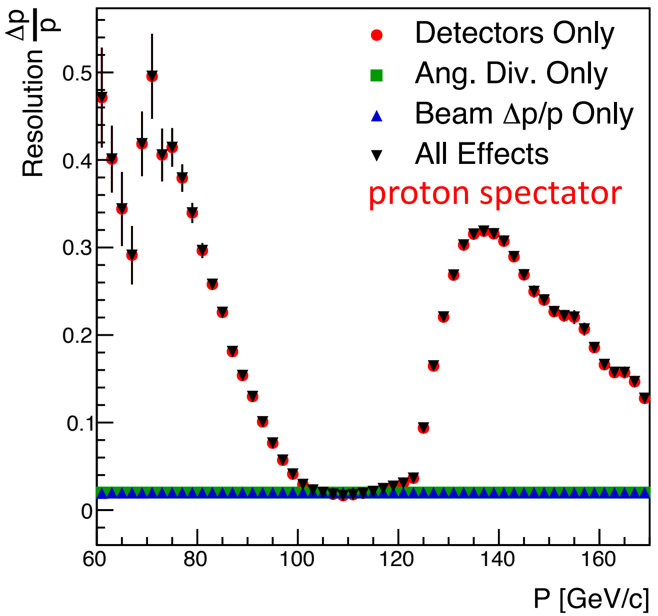
Effects of momentum smearing on pole factor

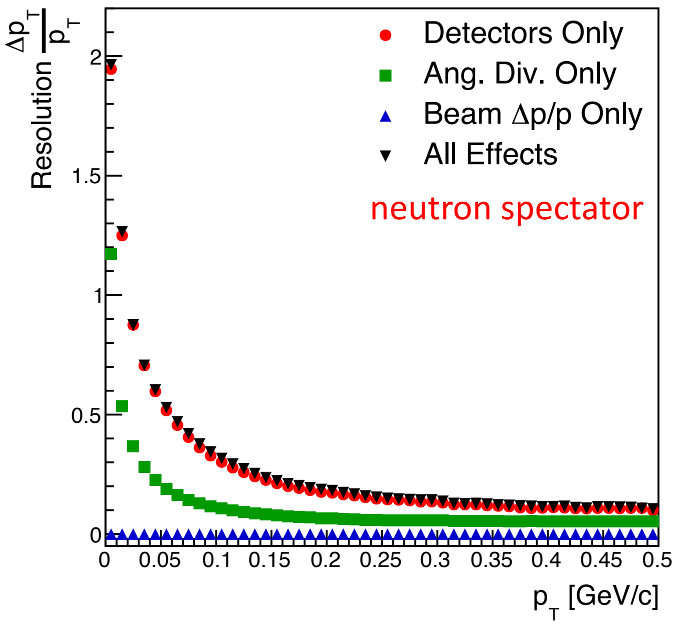


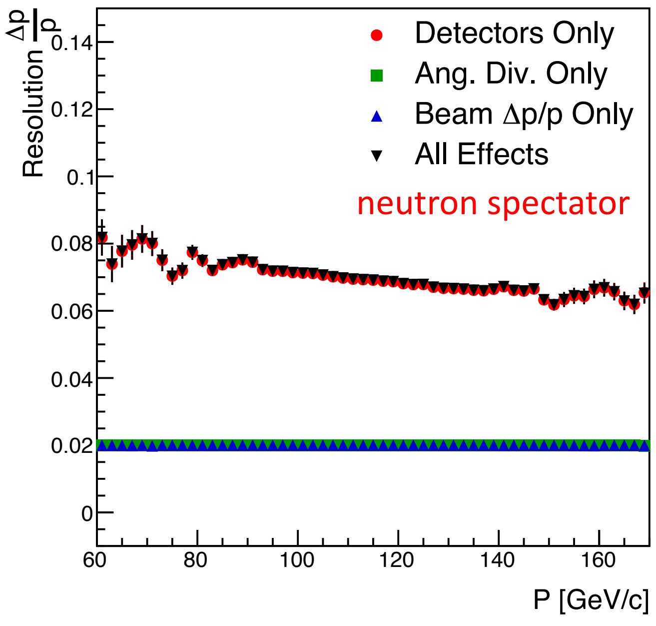
- Detector smearing has a drastic impact when the EbE method is used.
  - If you calculate the pole factor on an EbE basis with *smeared* spectator kinematic values, you now remove the pole factor for the wrong nuclear configuration!

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.