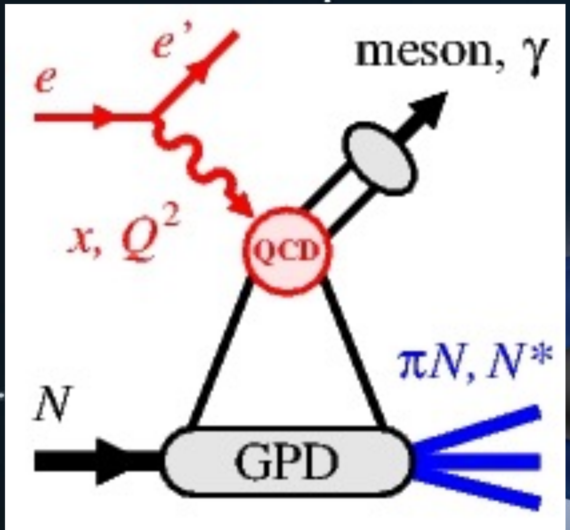


(some) Exclusive Physics Opportunities with Far-Forward Detectors at the EIC

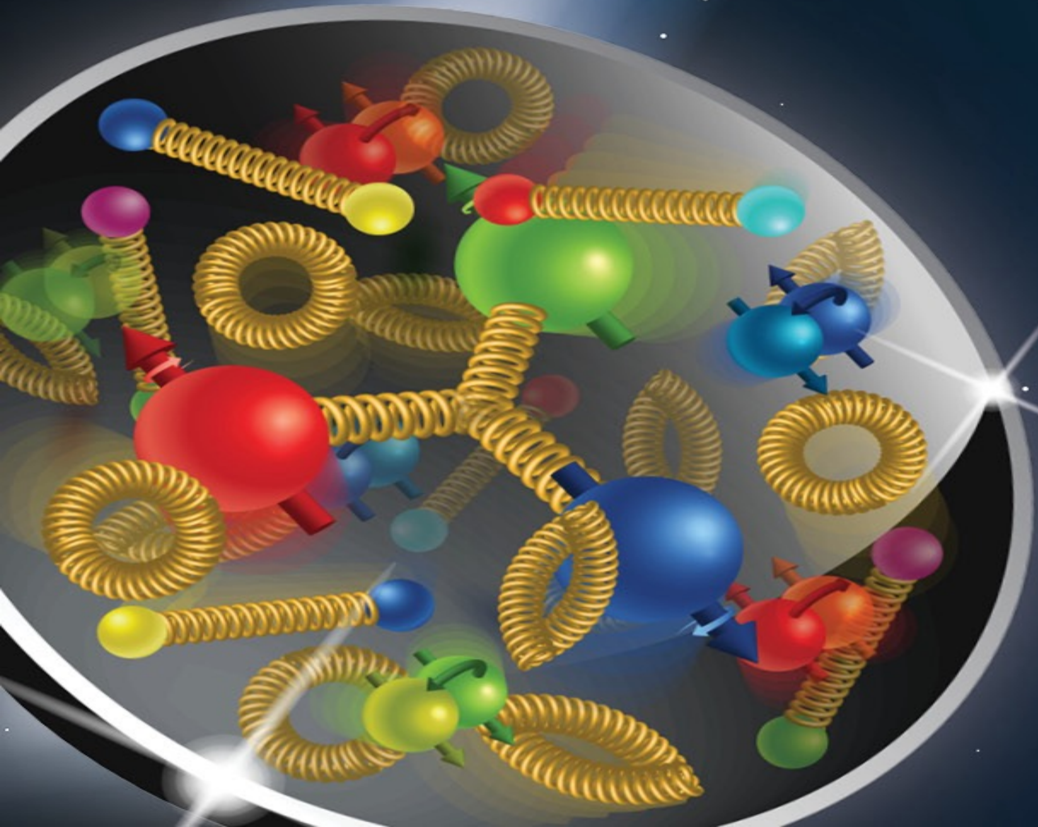
Alex Jentsch, *Brookhaven National Lab*

ajentsch@bnl.gov

ECT*-APCTP Joint Workshop: Exploring resonance structure with transition GPDs

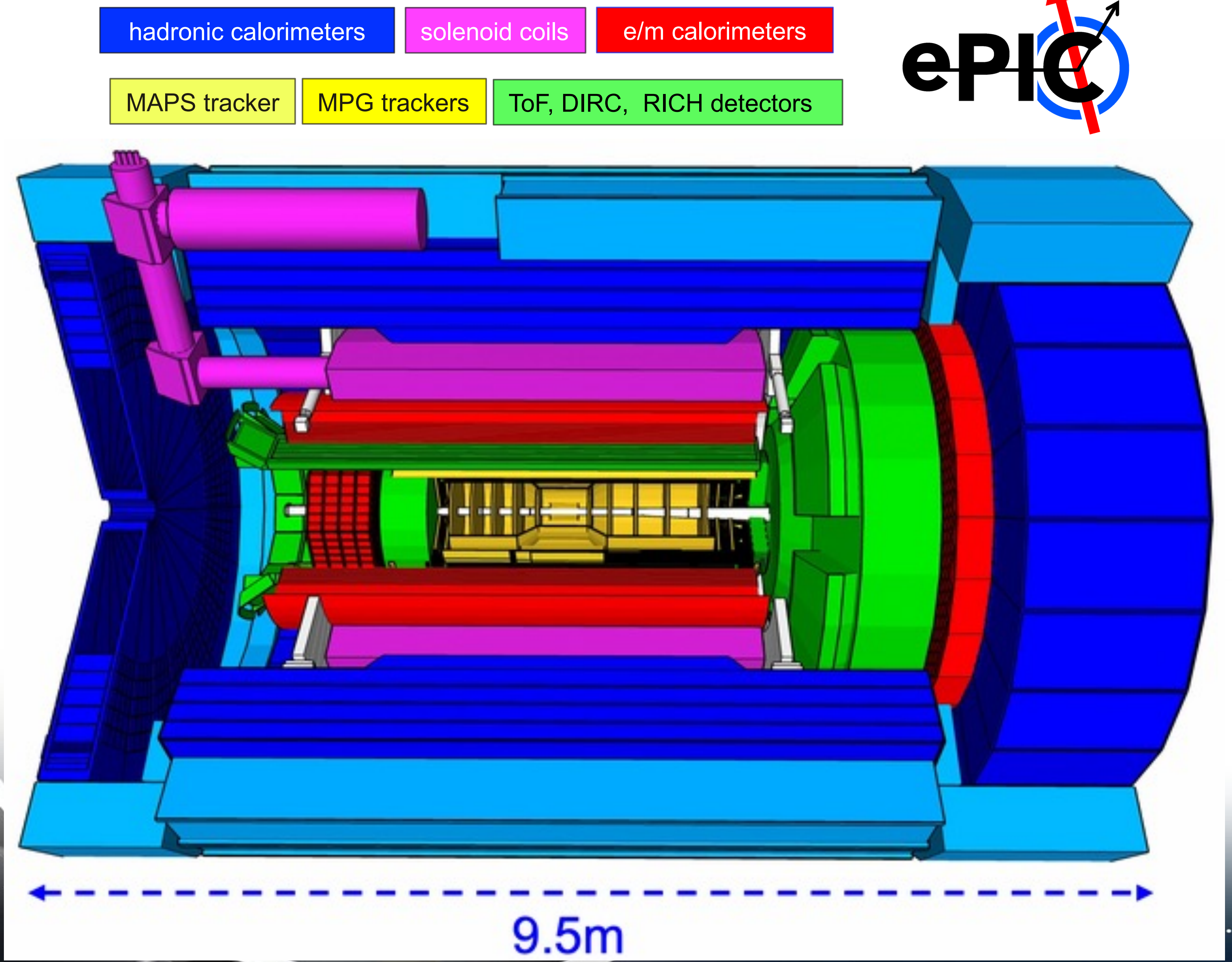
August 21st - 25th, 2023

ECT: Trento, Italy*



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

What is meant by Far-Forward?



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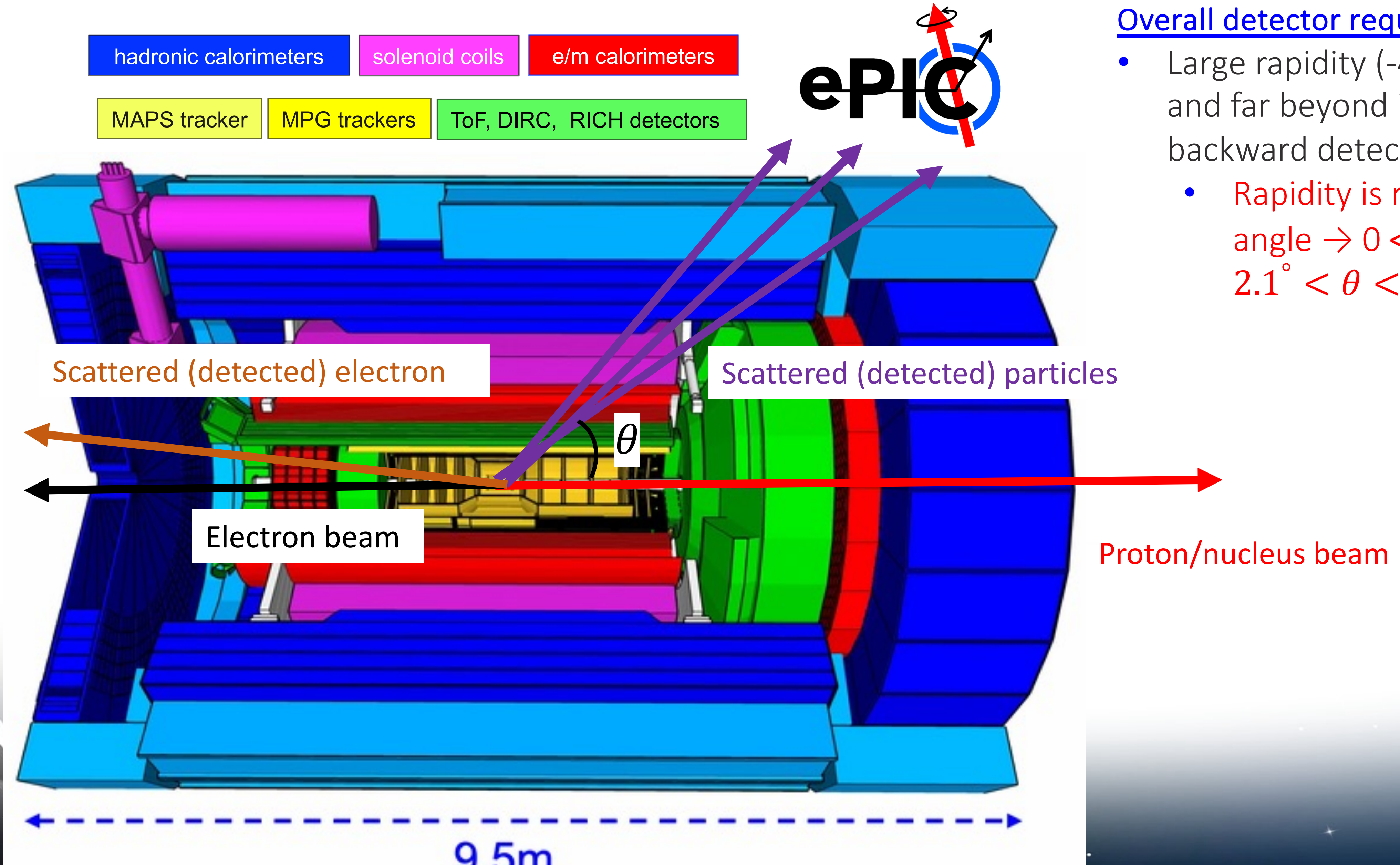


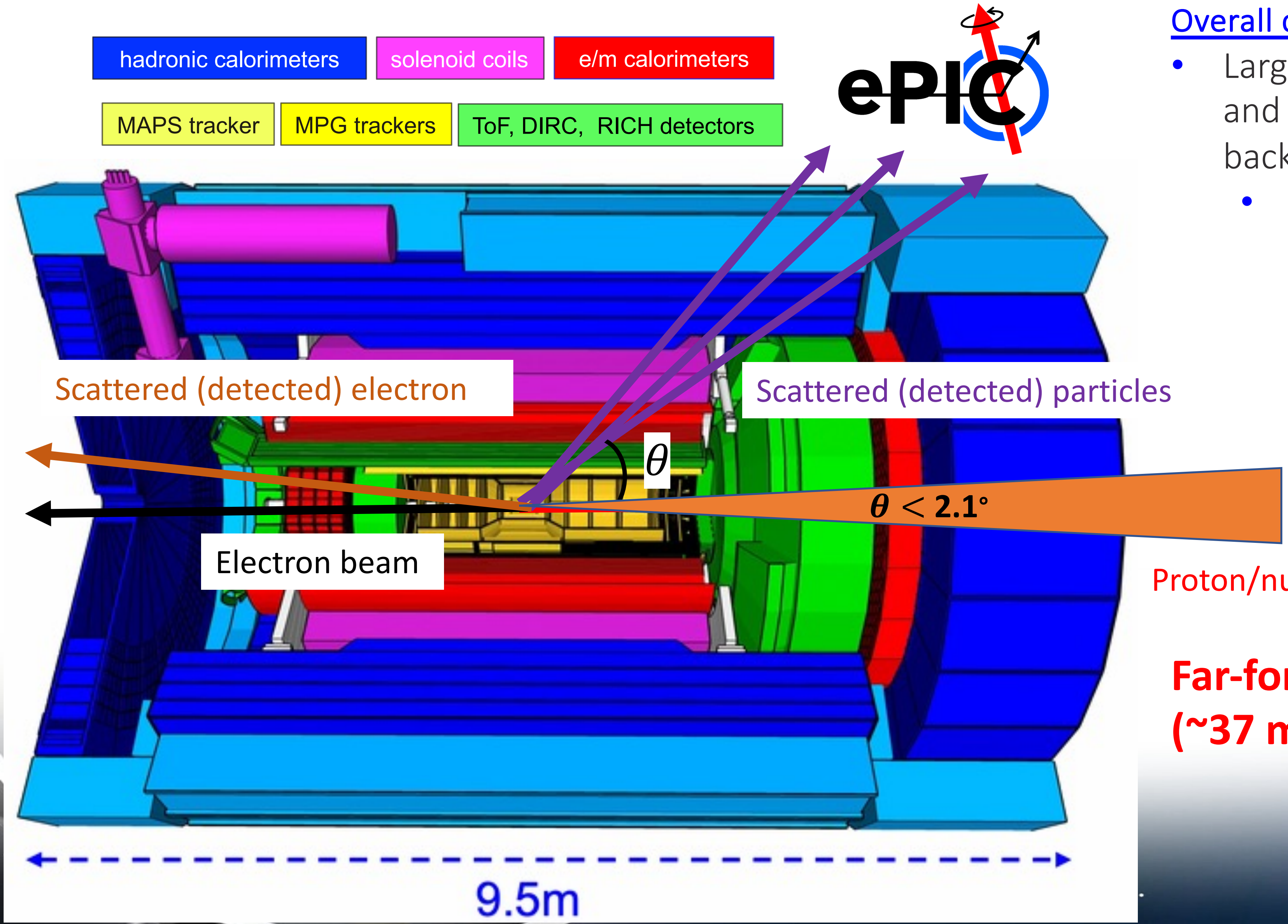
Overall detector requirements:

- 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?



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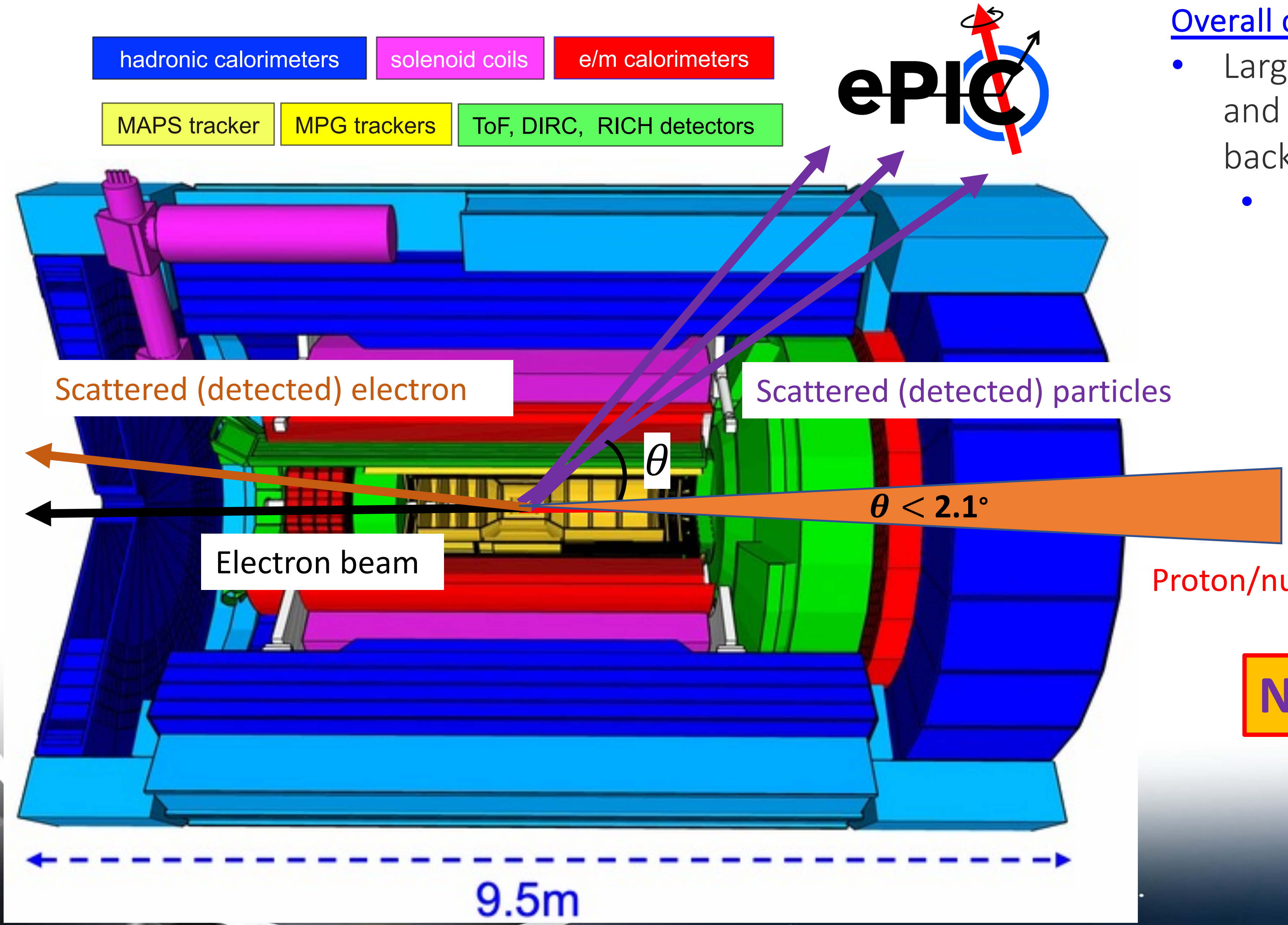
$$\eta = -ln(tan(\theta/2))$$

pseudorapidity

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

What is meant by Far-Forward?



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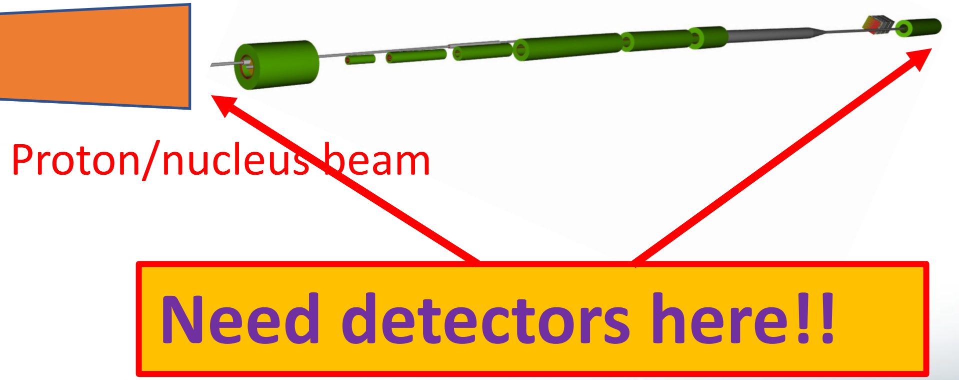
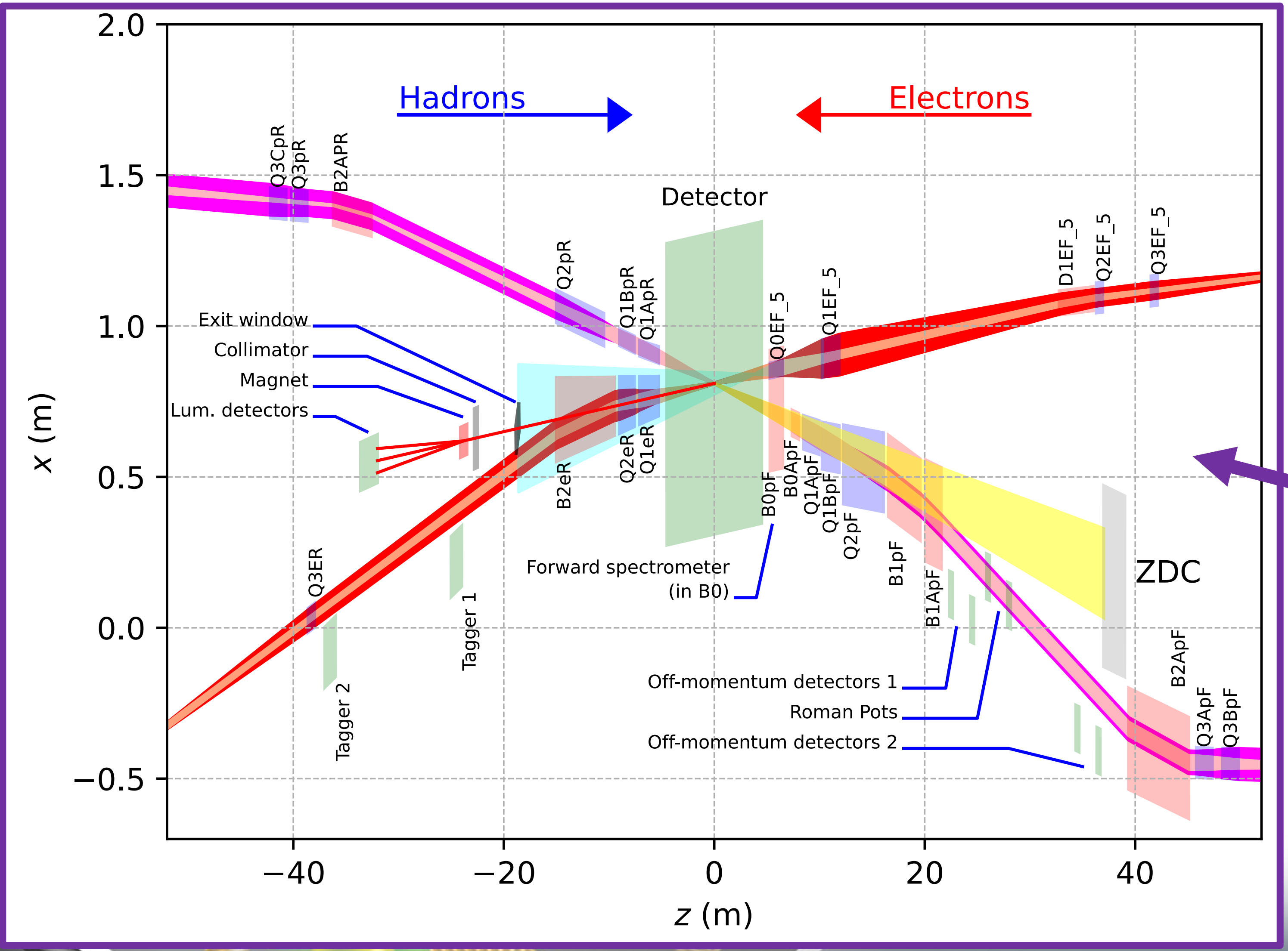
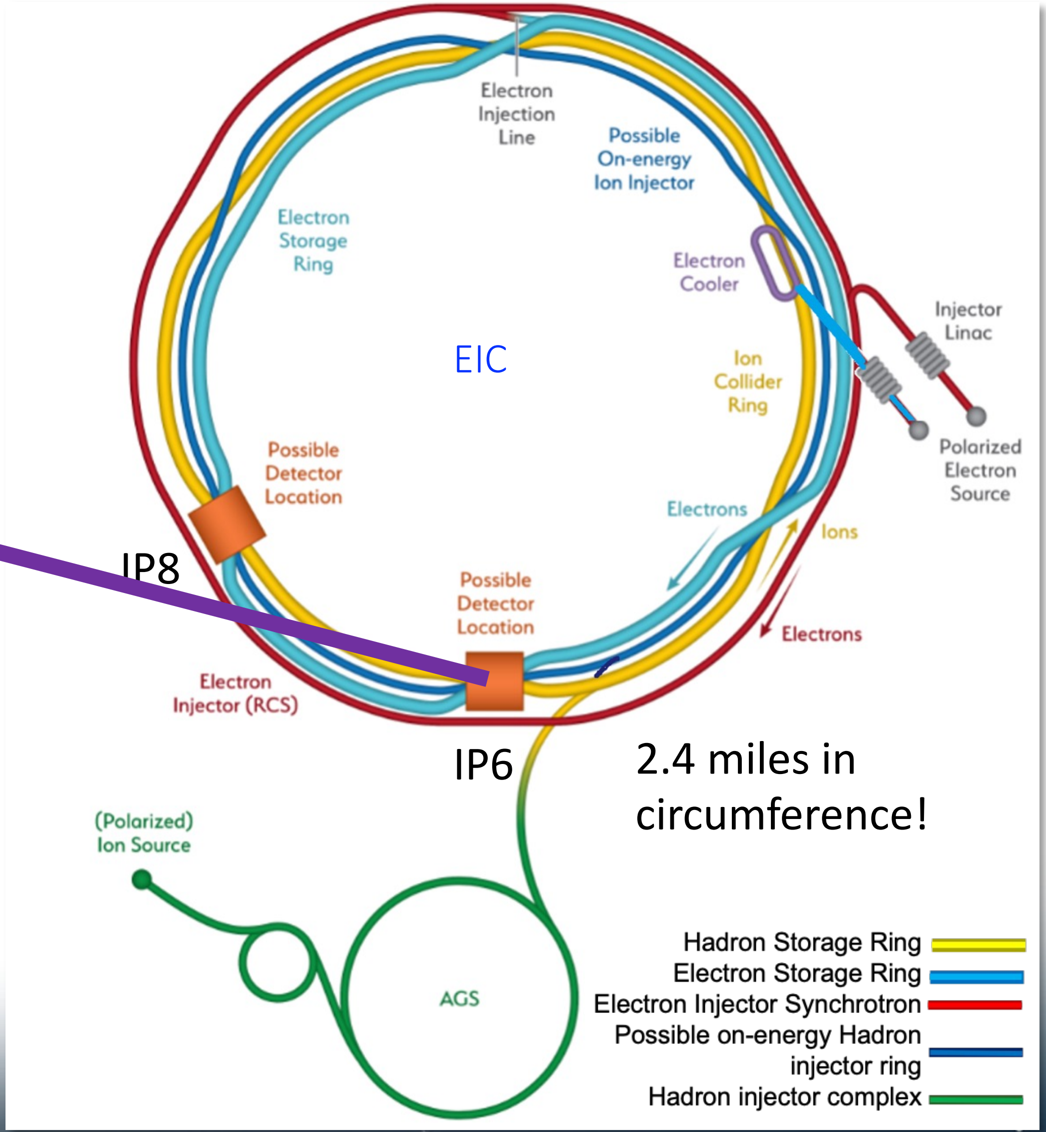
pseudorapidity



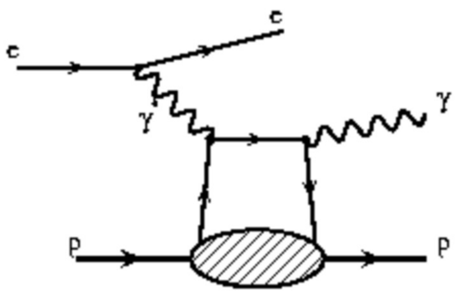




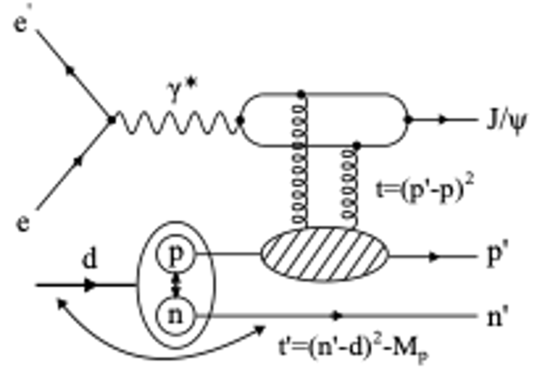
2.4 miles in circumference!

(some) Far-Forward Processes at the EIC

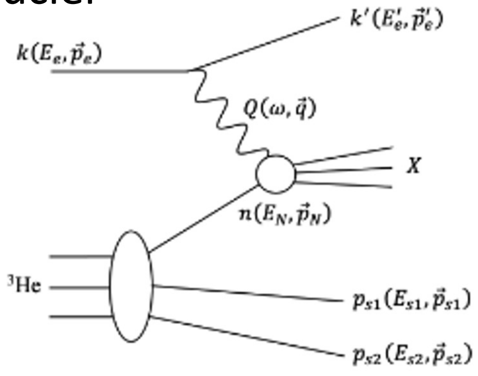
e+p DVCS



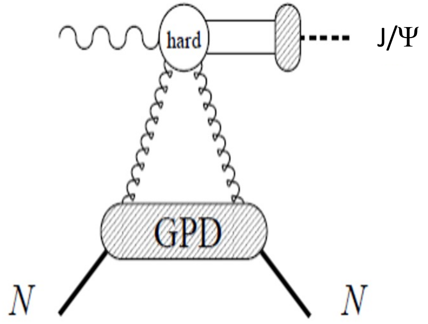
e+d exclusive J/Psi with p/n tagging



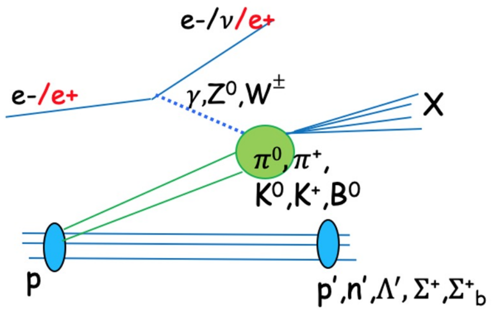
spectator tagging in light nuclei



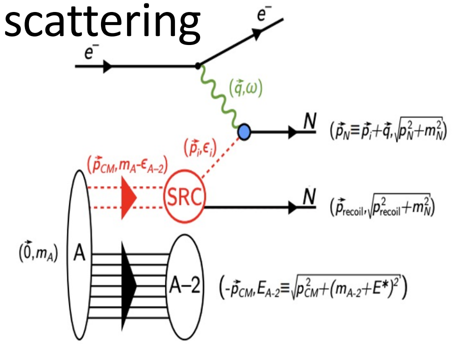
coherent/incoherent J/ψ production in e+A



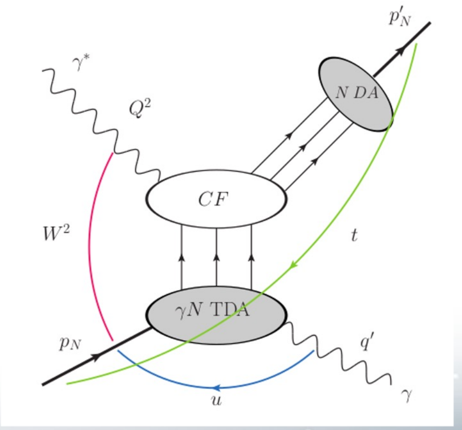
Sullivan process



Quasi-elastic electron scattering



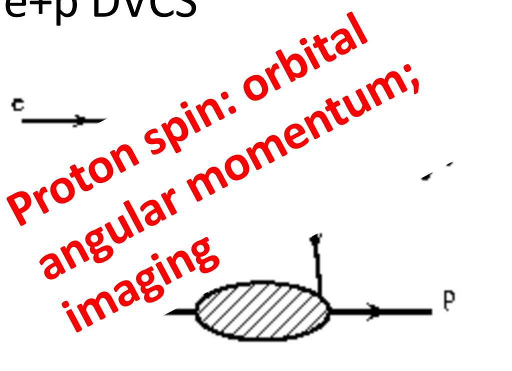
u-channel backward exclusive electroproduction



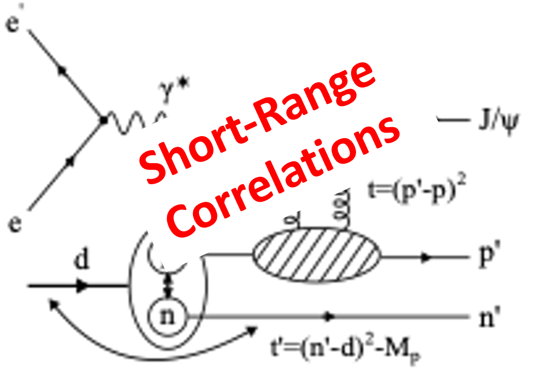
…and MANY more!

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

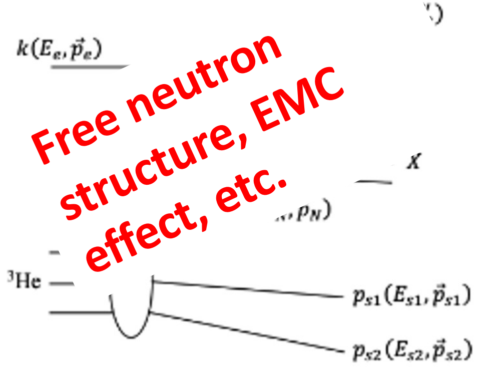
e+p DVCS



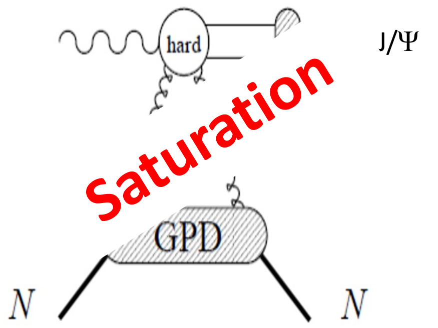
e+d exclusive J/Psi with p/n tagging



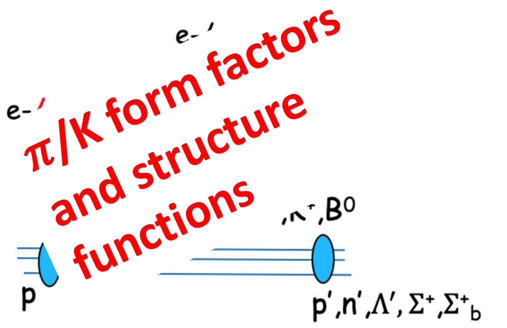
spectator tagging in light nuclei



coherent/incoherent J/ψ production in e+A



Sullivan process



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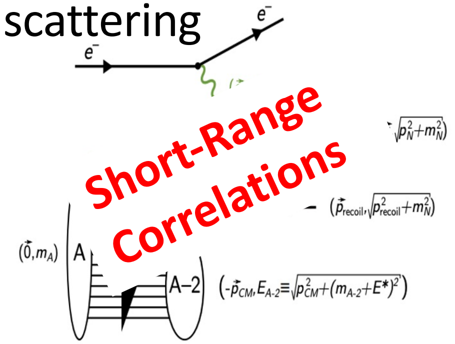
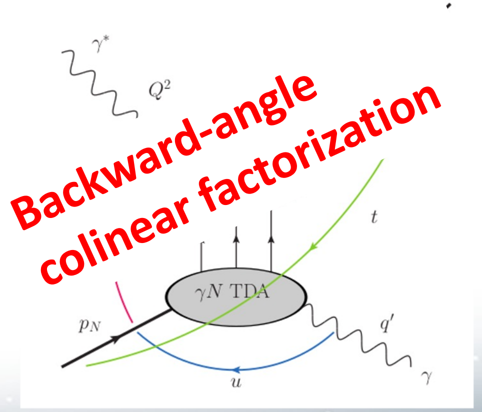


[1] Z. Tu, A. Jentsch, et al., Physics Letters B, (2020)
[2] I. Friscic, D. Nguyen, J. R. Pybus, A. Jentsch, *et al.*, Phys. Lett. B, **Volume 823**, 136726 (2021)
[3] W. Chang, E.C. Aschenauer, M. D. Baker, A. Jentsch, J.H. Lee, Z. Tu, Z. Yin, and L.Zheng, Phys. Rev. D **104**, 114030 (2021)
[4] A.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

u-channel backward exclusive electroproduction

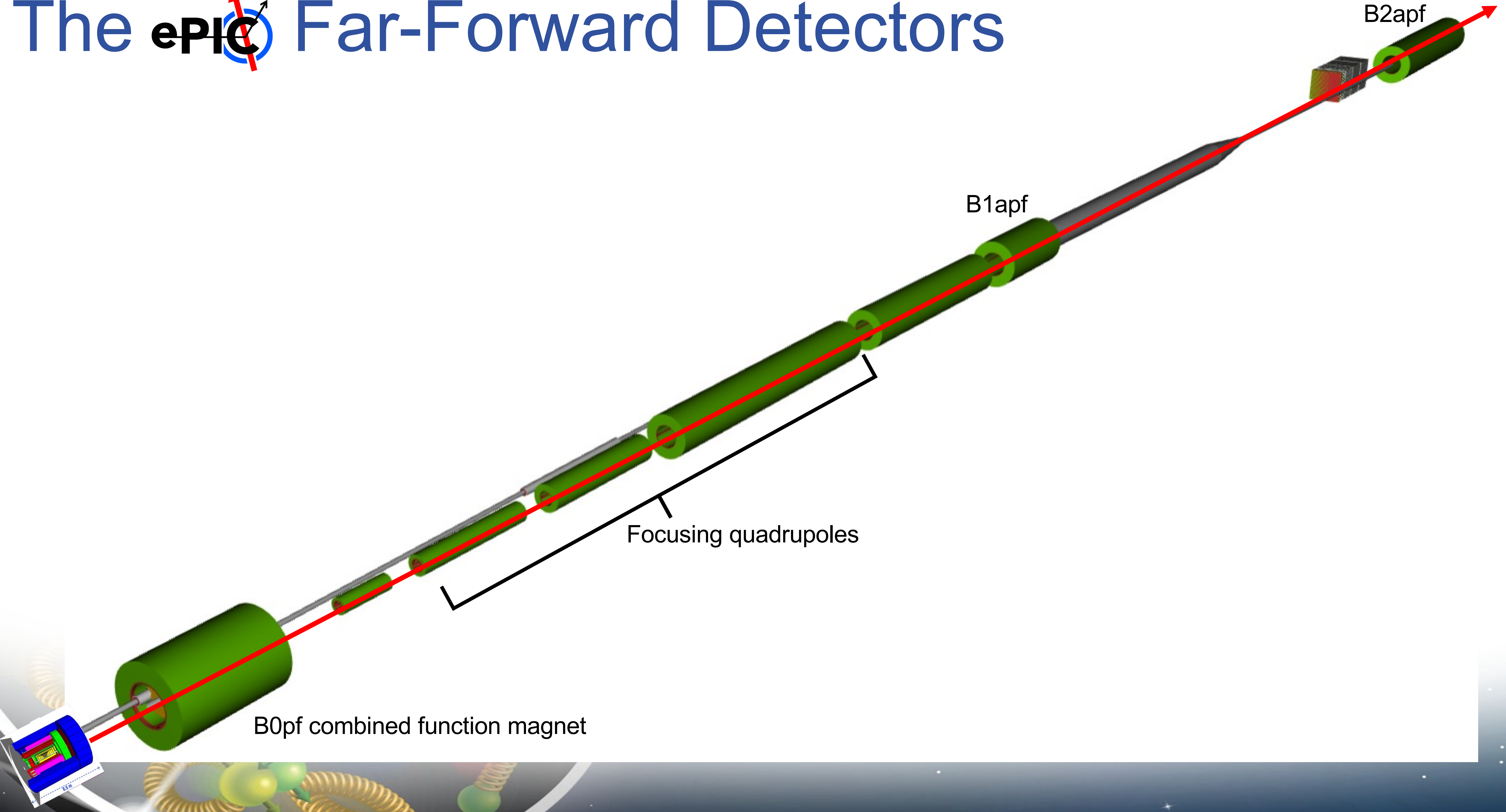


…and MANY more!

(some) Far-Forward **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 uniquely challenging due to integration with accelerator.

The ePIC Far-Forward Detectors



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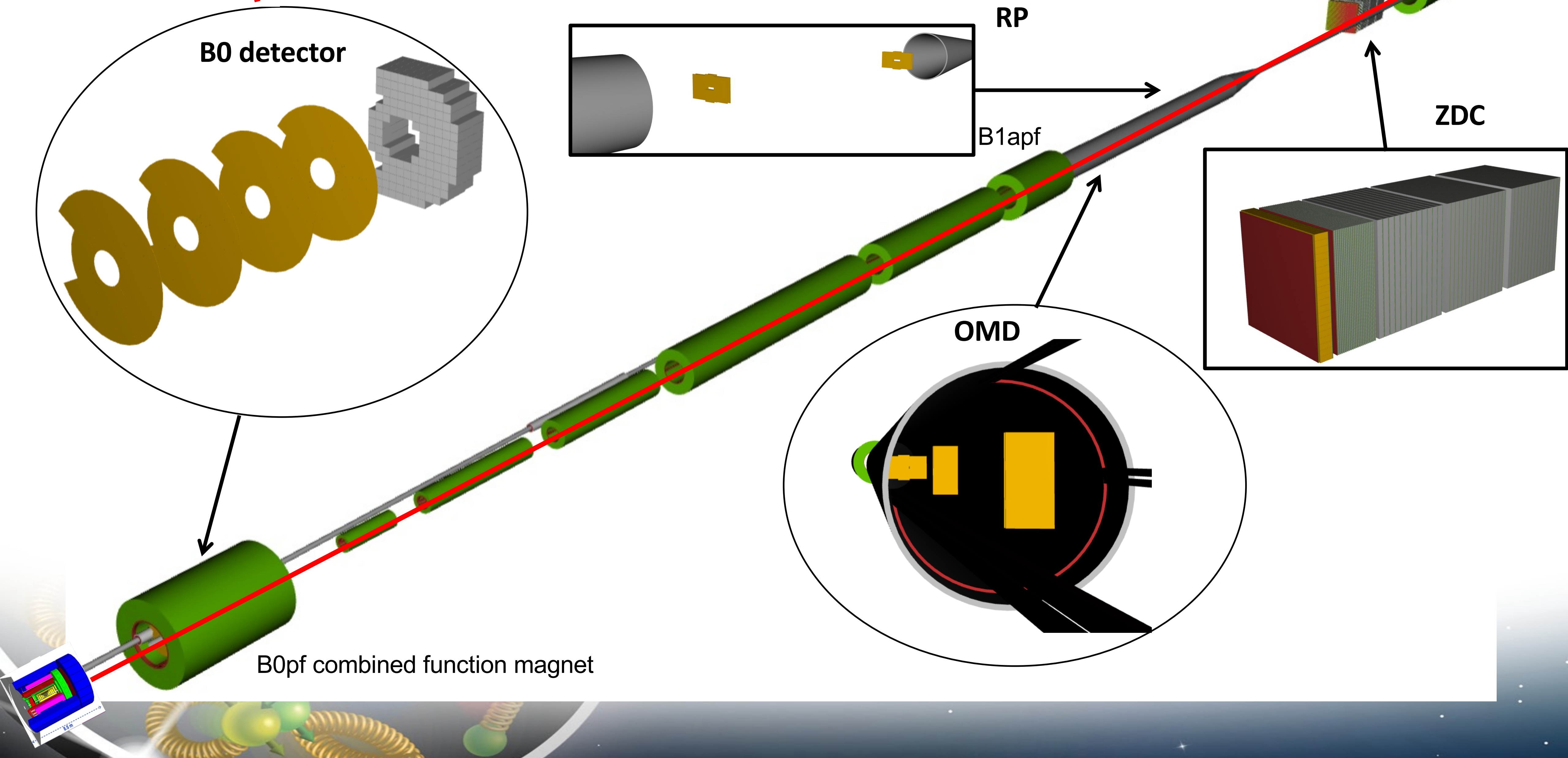

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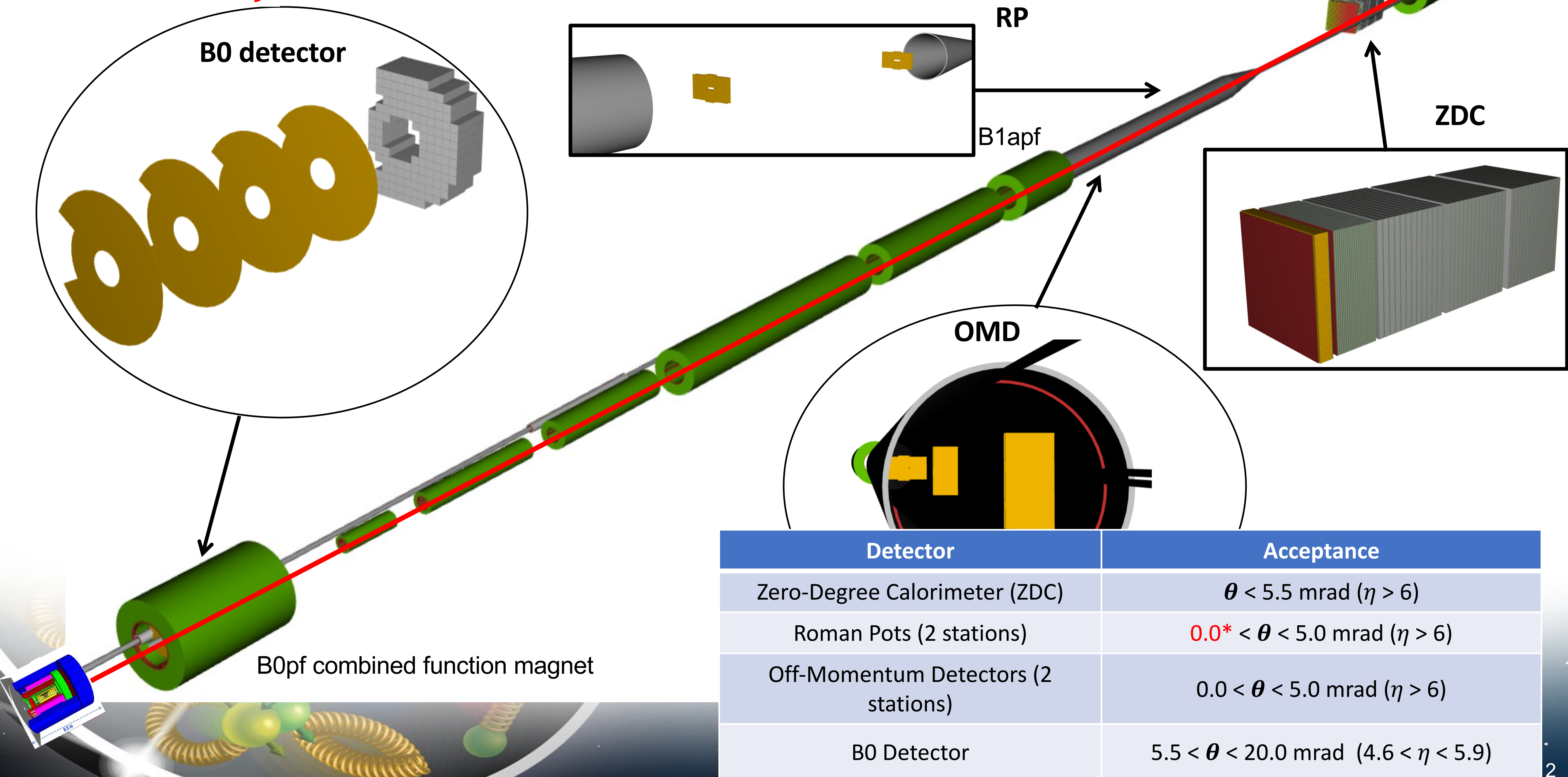
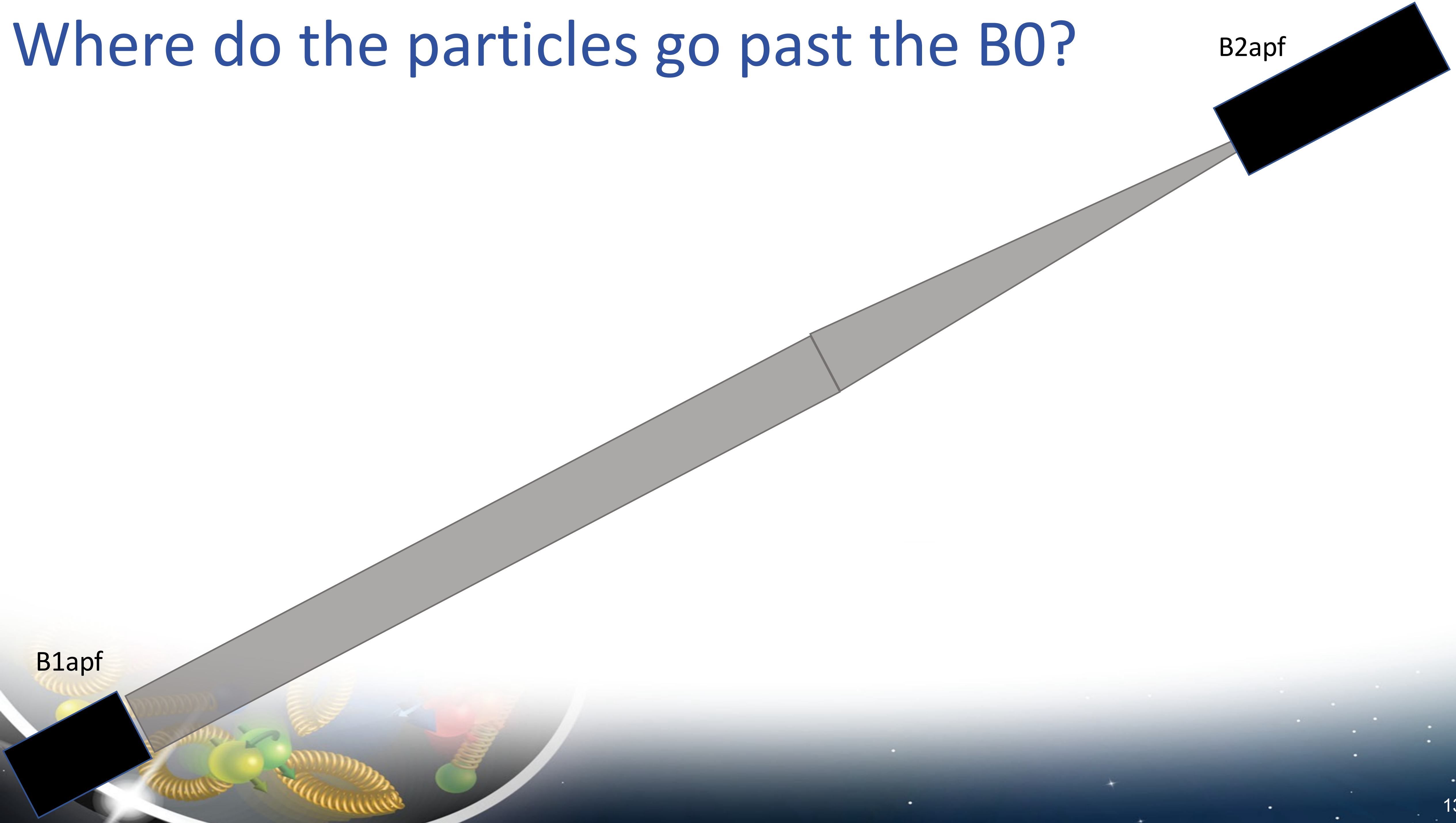


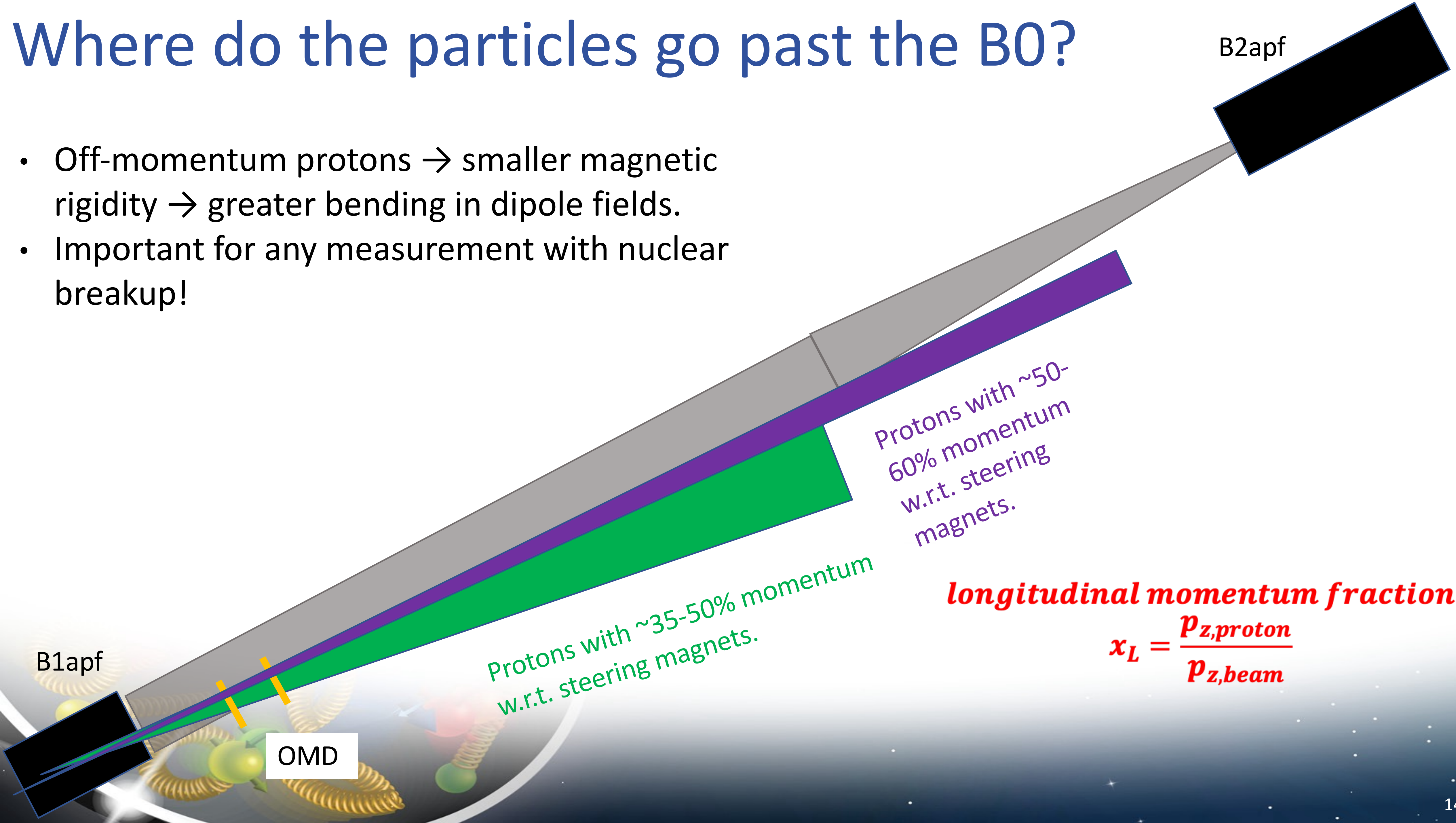
Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	$\theta < 5.5$ mrad ($\eta > 6$)
Roman Pots (2 stations)	0.0* $< \theta < 5.0$ mrad ($\eta > 6$)
Off-Momentum Detectors (2 stations)	$0.0 < \theta < 5.0$ mrad ($\eta > 6$)
B0 Detector	$5.5 < \theta < 20.0$ mrad ($4.6 < \eta < 5.9$)

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

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

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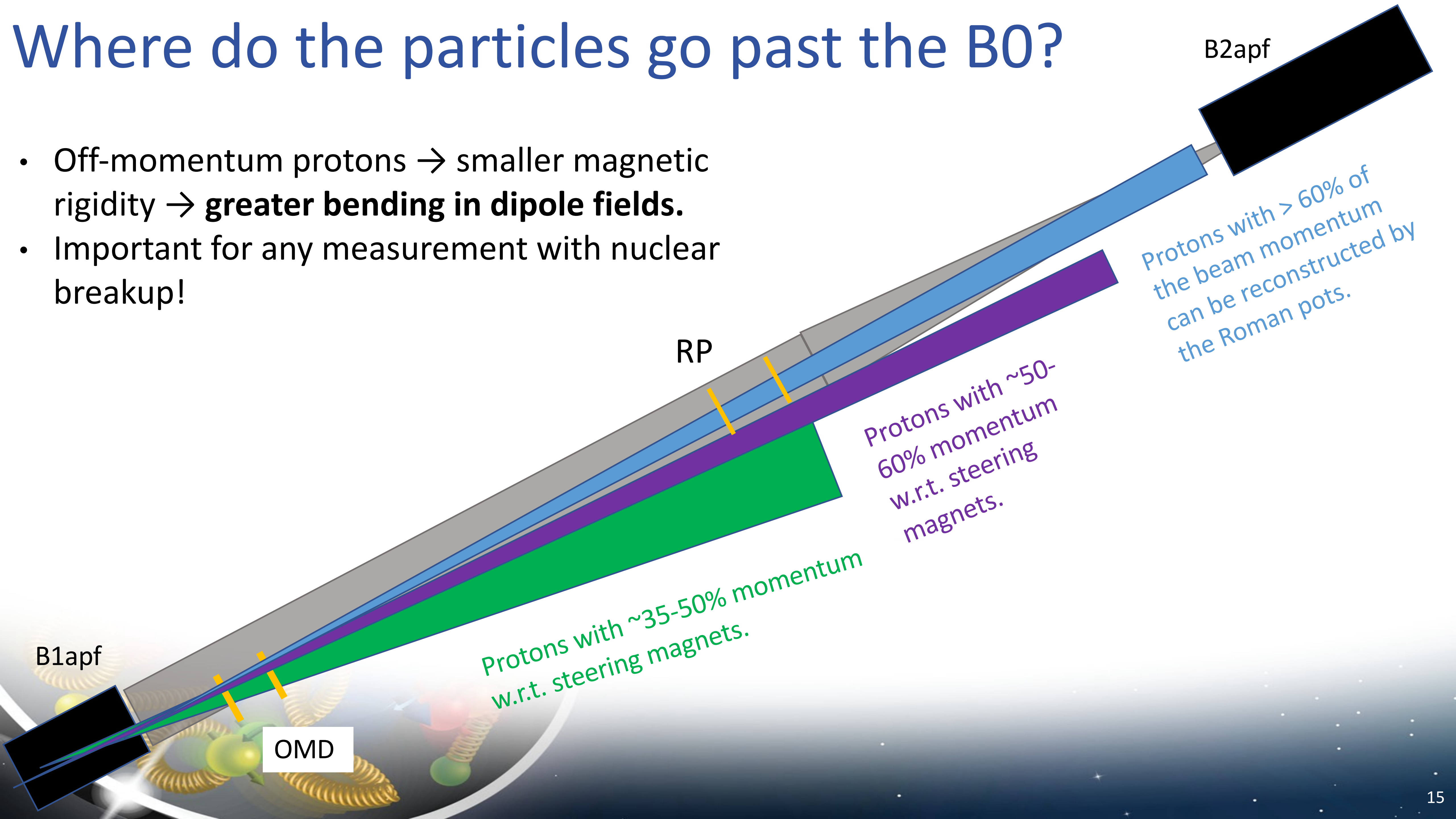

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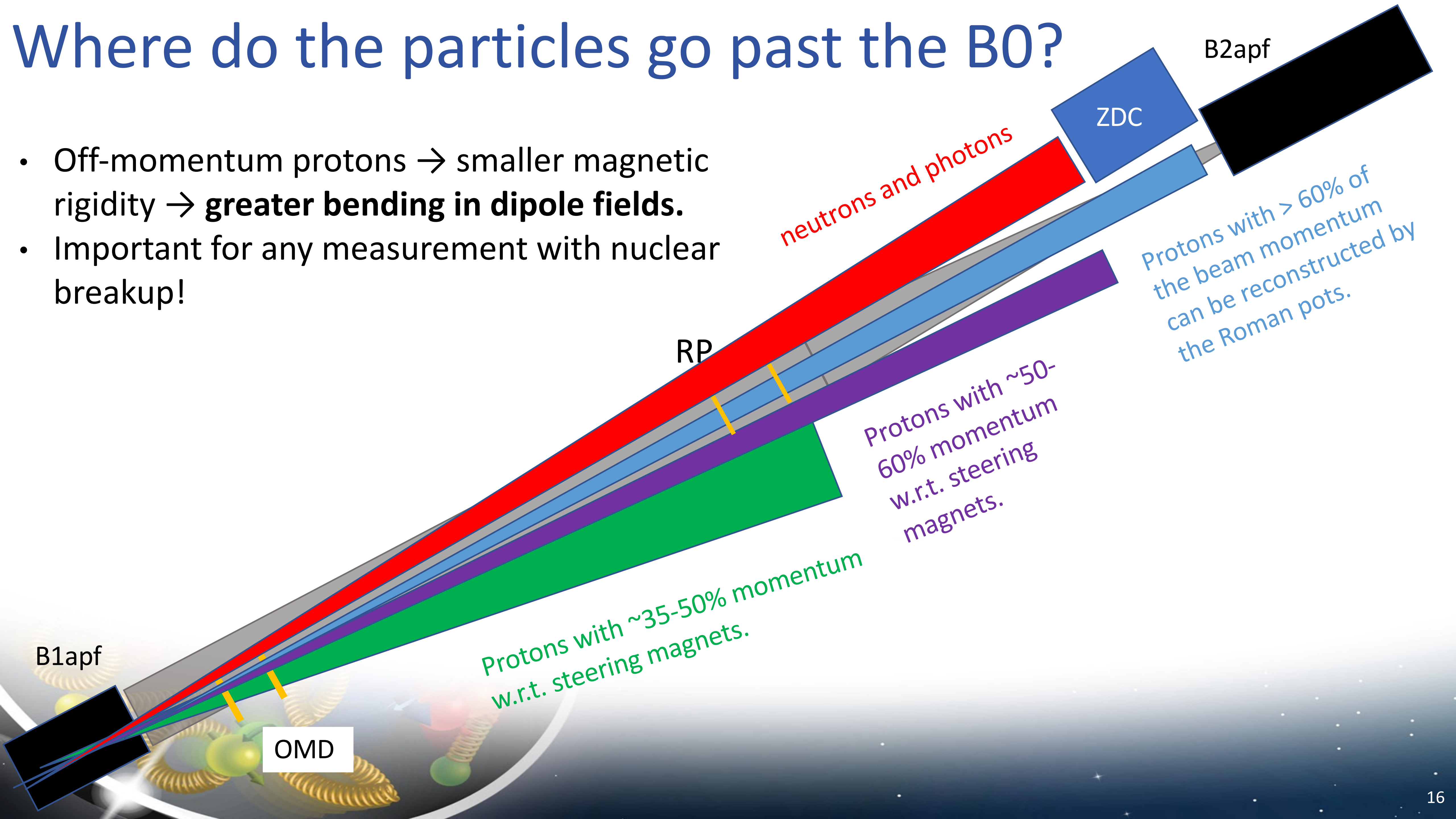
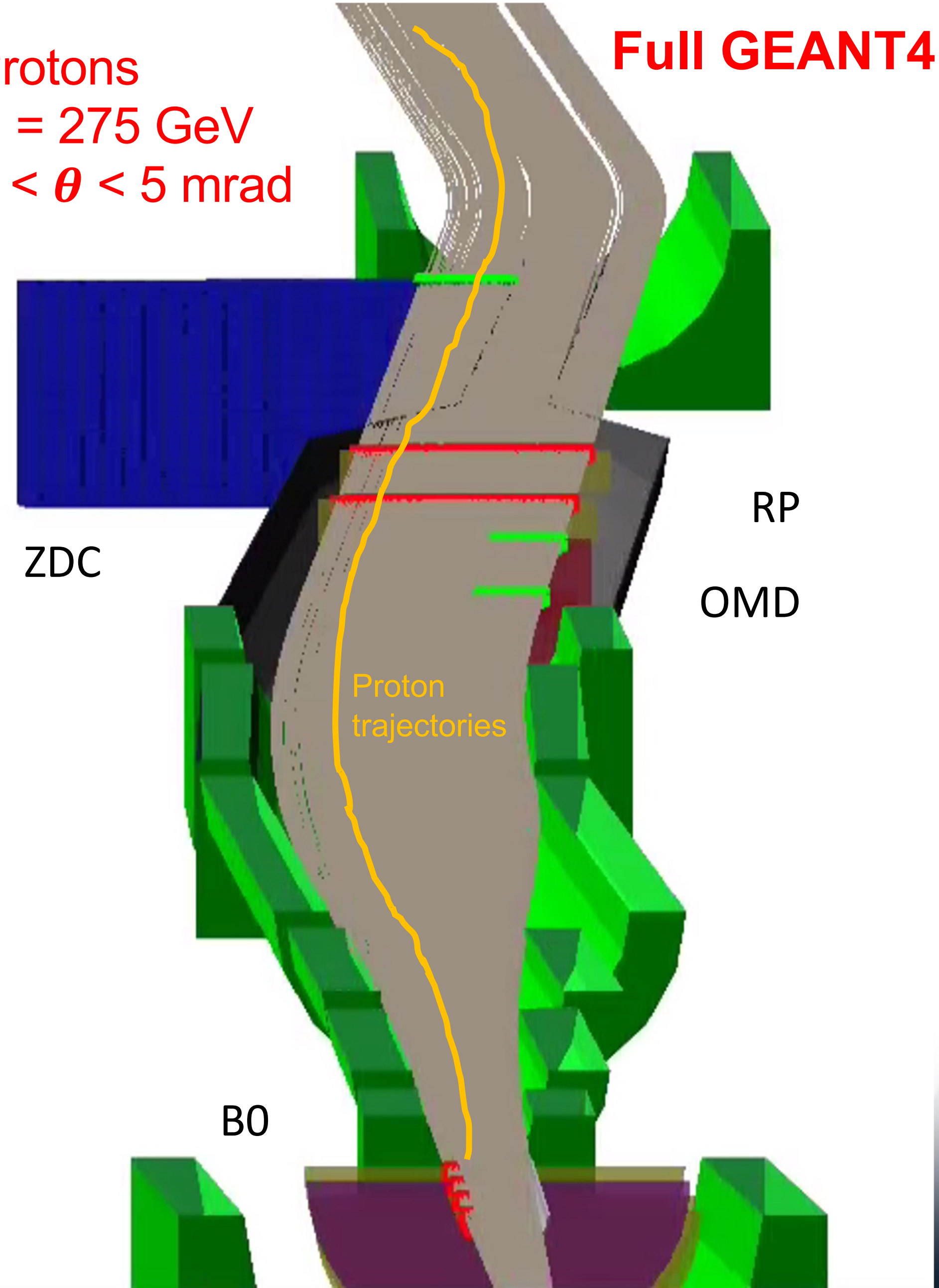


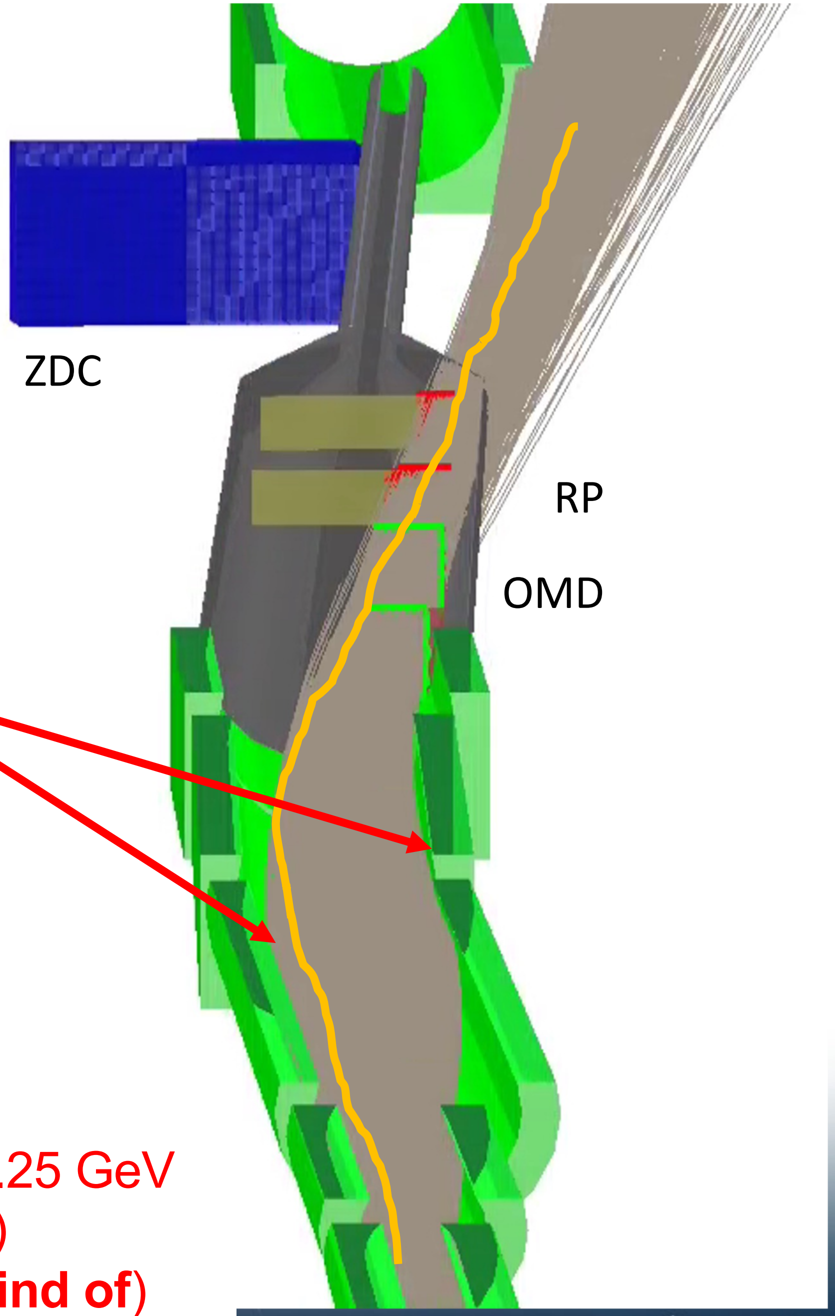
Roman Pots and OMD

Protons
E = 275 GeV
0 < θ < 5 mrad

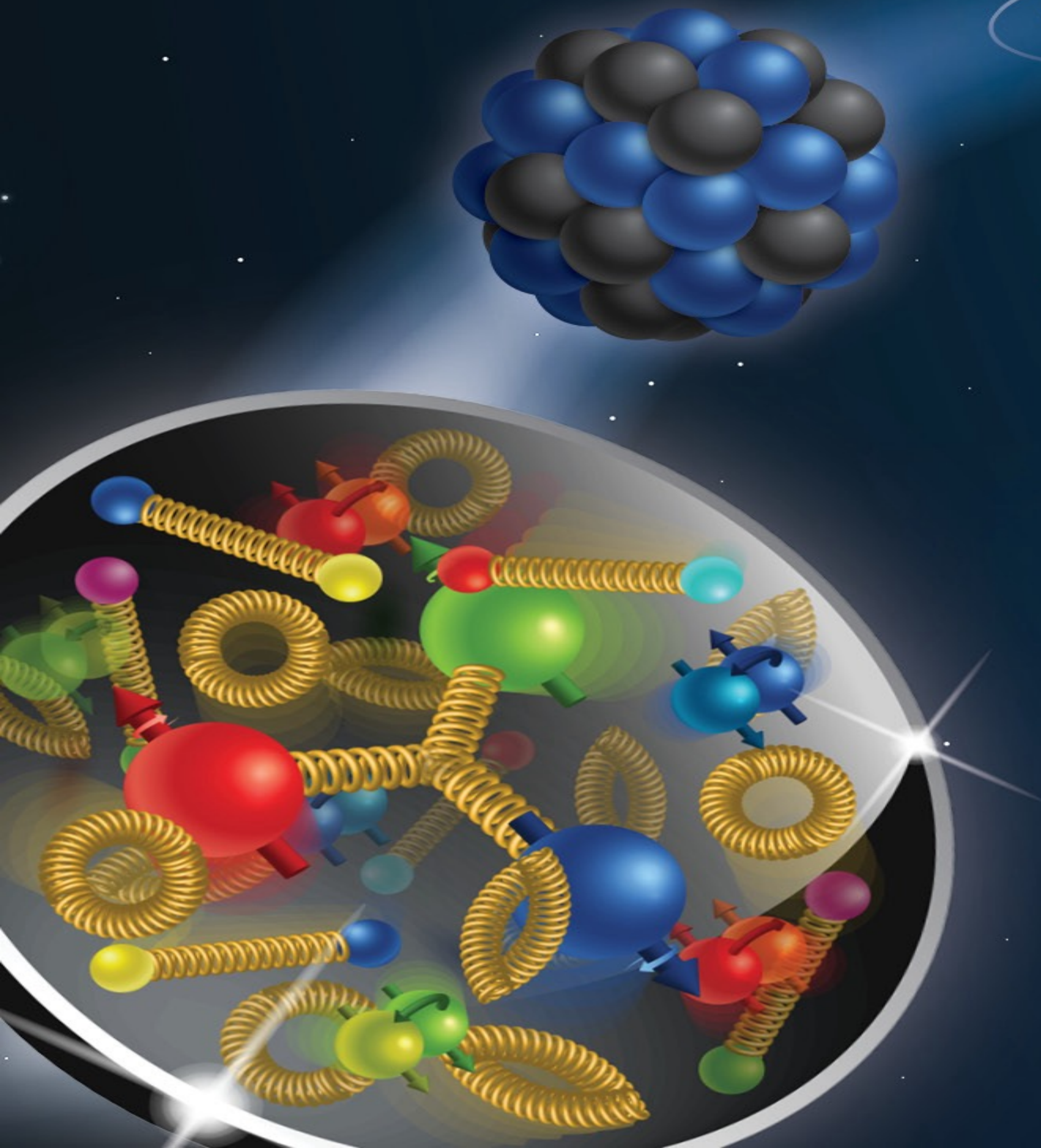
Full GEANT4 simulation.



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



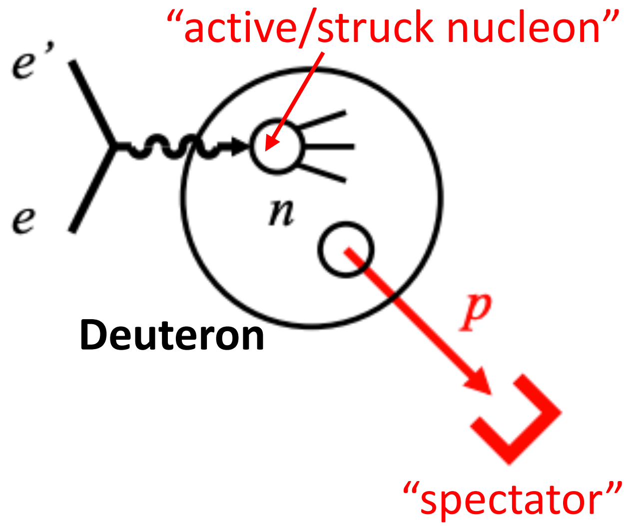
Protons
123.75 < E < 151.25 GeV
(45% < xL < 55%)
0 < θ < 5 mrad (**kind of**)

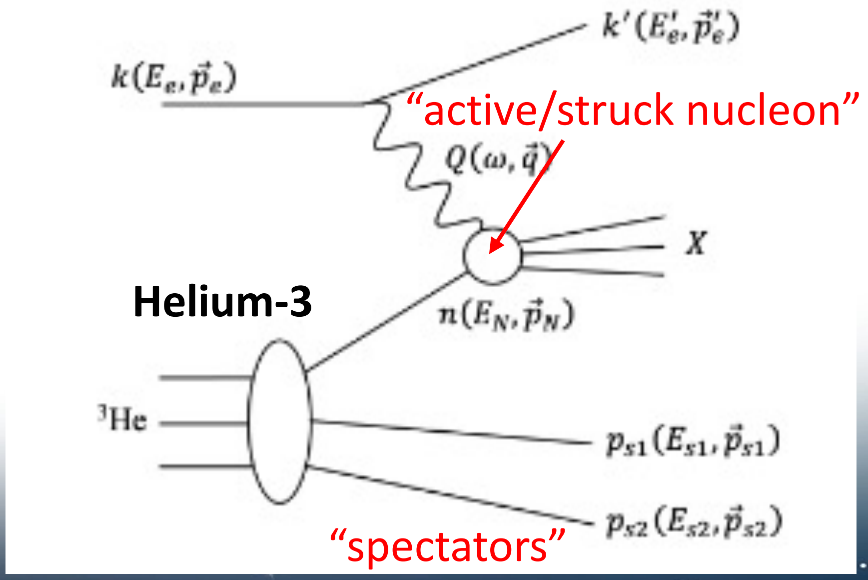


My Interest: Deuterons as an unexpected QCD laboratory at the EIC.

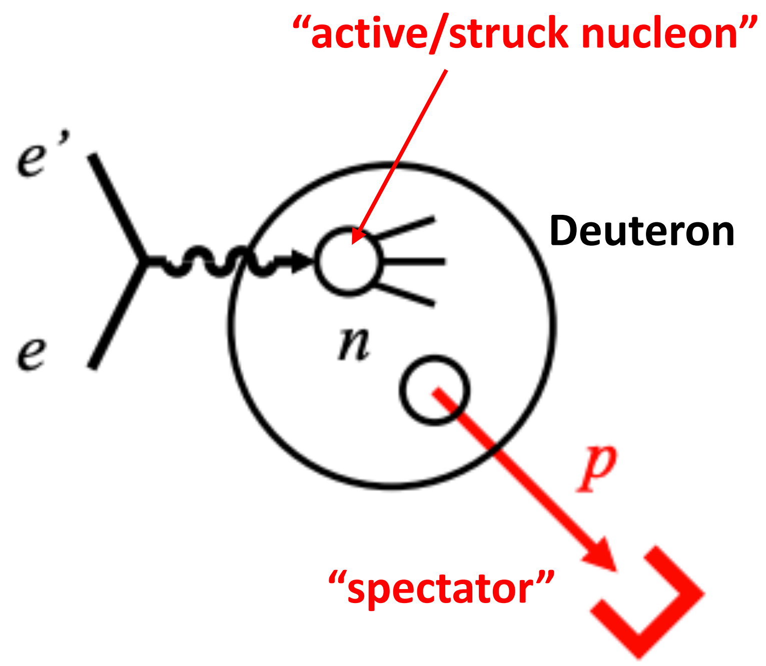
Deuteron tagged DIS as a tool at the EIC

- **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 DIS with deuterons

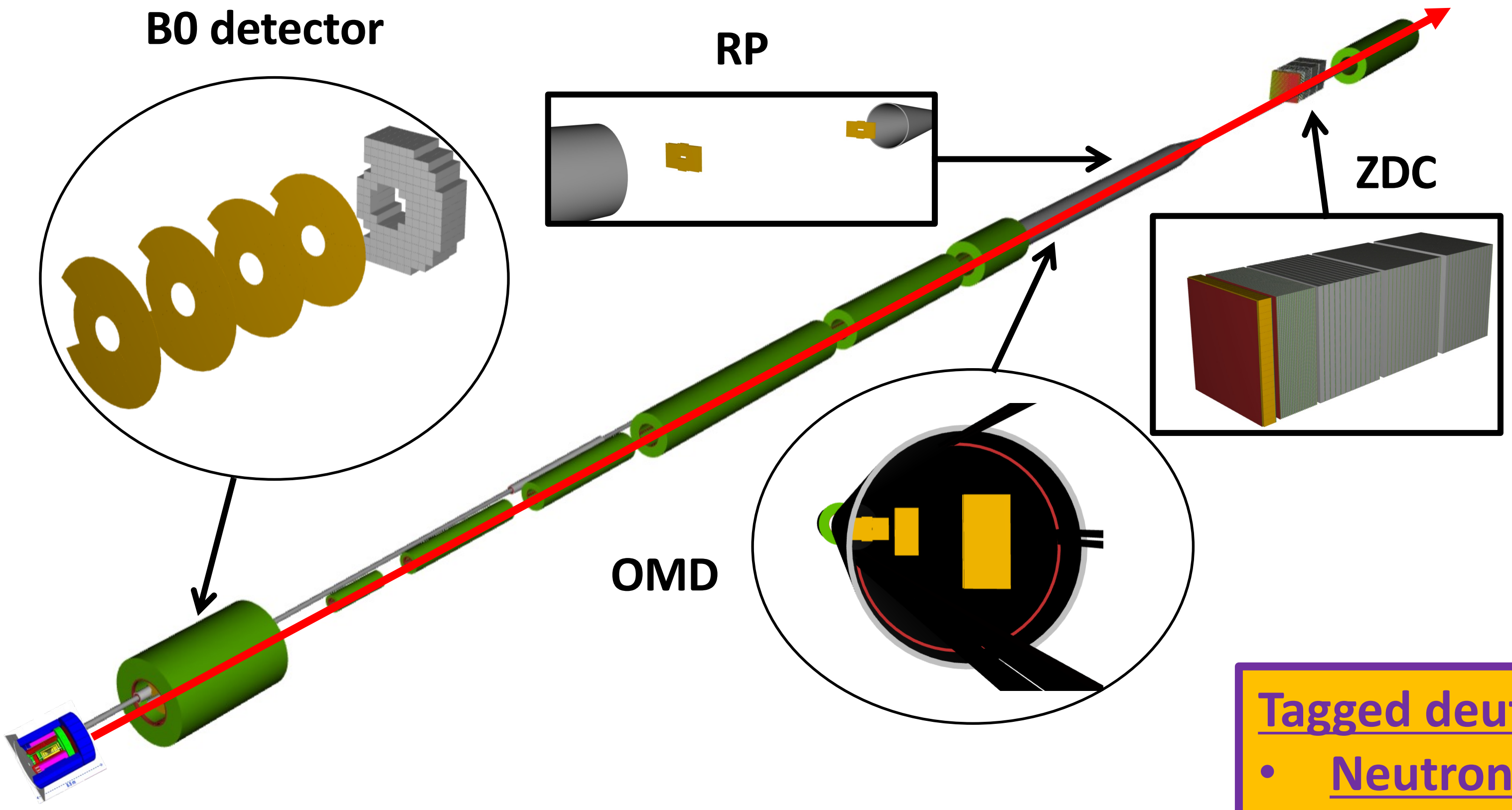


- Spectator kinematics → determines nuclear configuration.
  - **Loosely bound configuration** – enables extraction of free nucleon structure via pole extrapolation (previous study[2]).
  - **Configuration with strongly-interacting nucleons** – opens up study of nuclear modifications.
    - Differential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

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

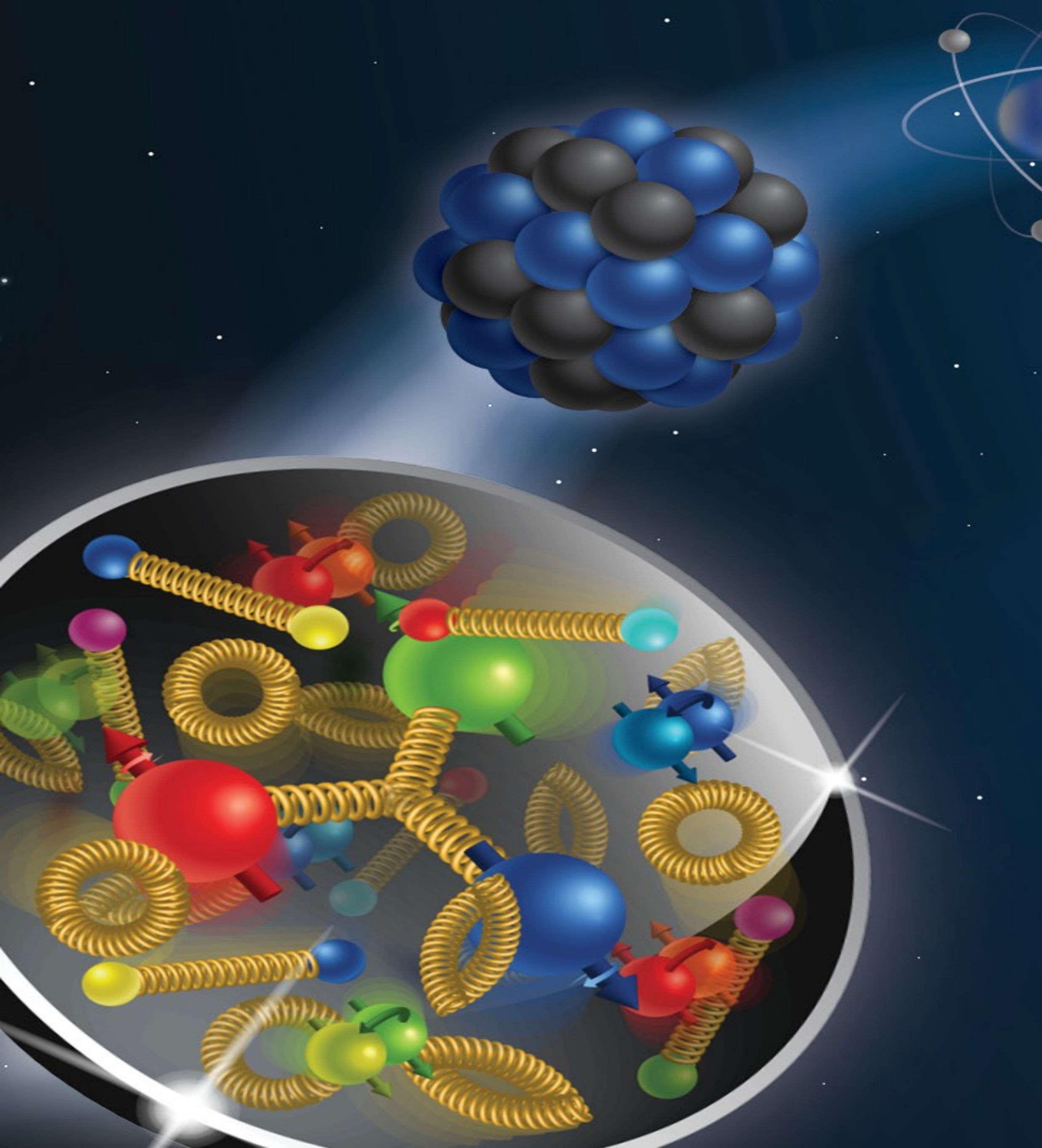
[2] A. Jentsch, Z. Tu, and C. Weiss, Phys. Rev. C **104,** 065205, (2021) **(Editor's Suggestion)**

Full Detector Simulations – Tagged Spectators



Tagged deuteron spectators

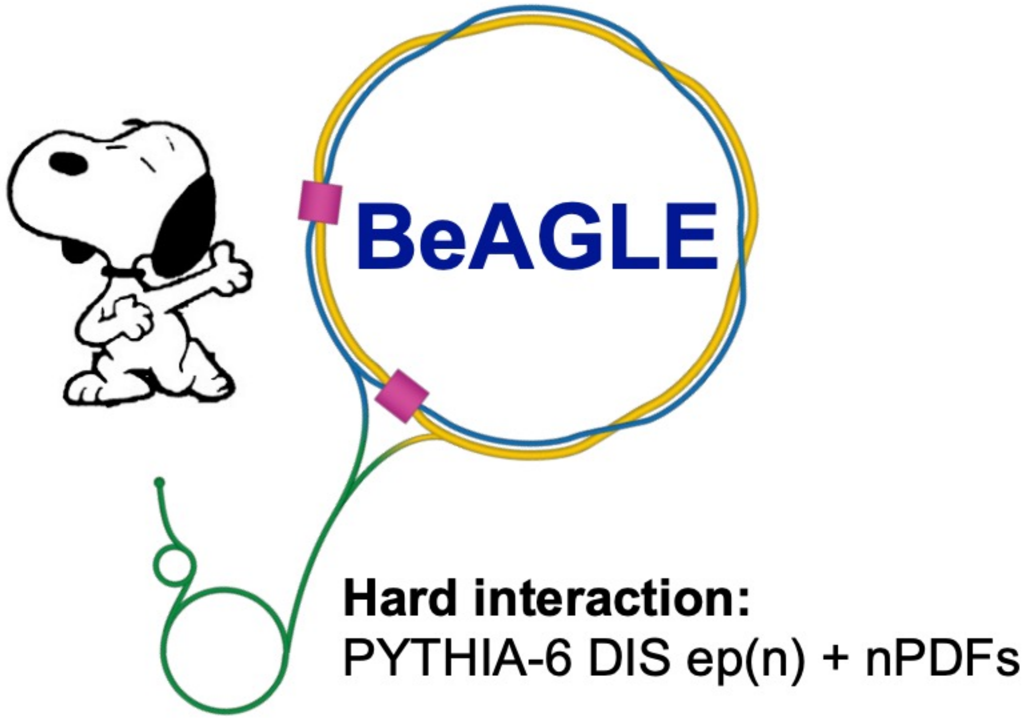
- **Neutrons:** reconstructed in ZDC ($\theta < 5$ mrad acceptance).
- **Protons:** reconstructed in B0 tracker ($6 < \theta < 20$ mrad) and off-momentum detectors ($\theta < 5$ mrad).



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



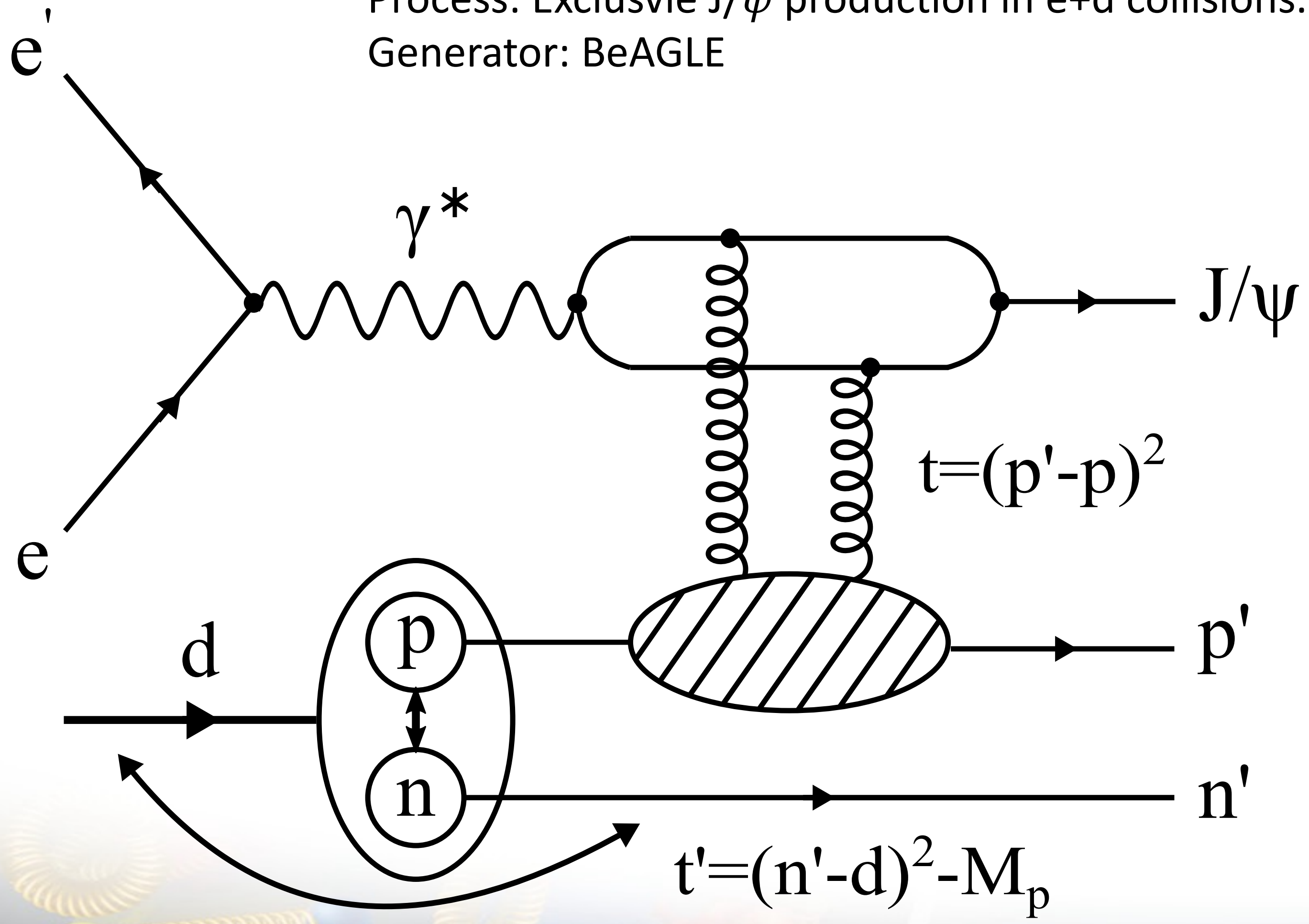
Wan Chang, Elke-Caroline Aschenauer, Mark D. Baker, Alexander Jentsch, Jeong-Hun Lee, Zhoudunming Tu, Zhongbao Yin, and Liang Zheng
Phys. Rev. D **106**, 012007 (2022)

- 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)

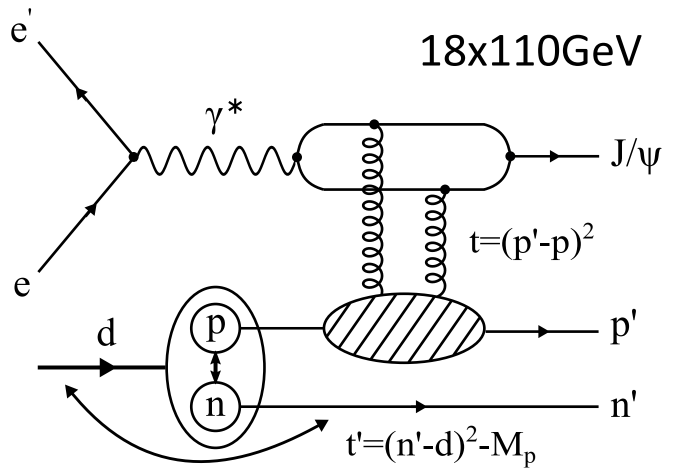
Process: Exclusvie J/ψ production in e+d collisions.
Generator: BeAGLE



- 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!

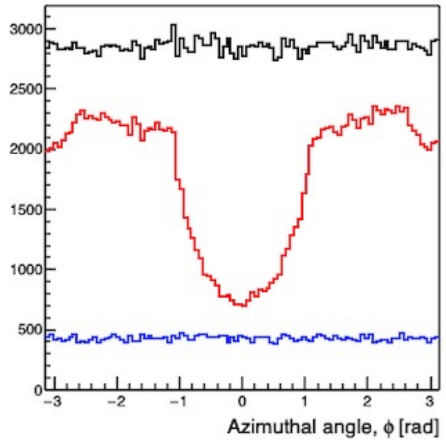
Short-Range Correlations in Deuterons

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



Neutron "spectator" case.

"active" protons



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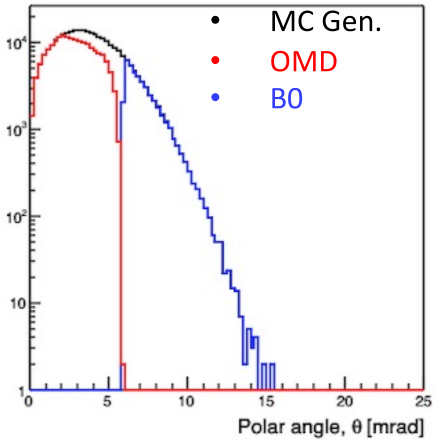

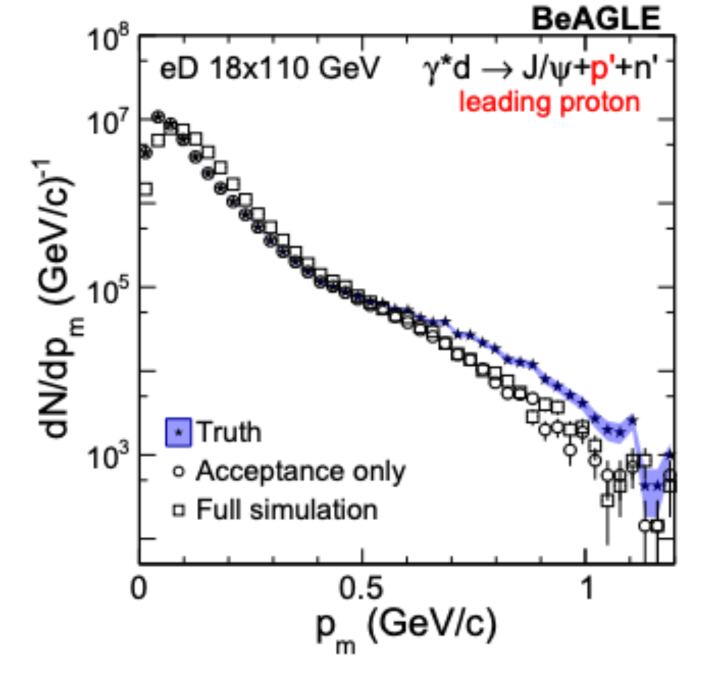

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Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)

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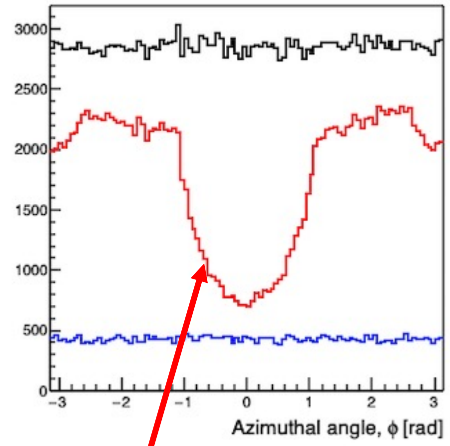

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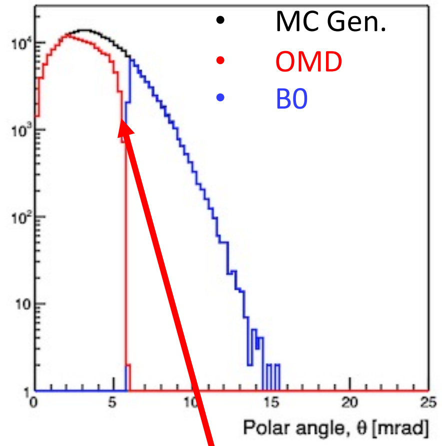
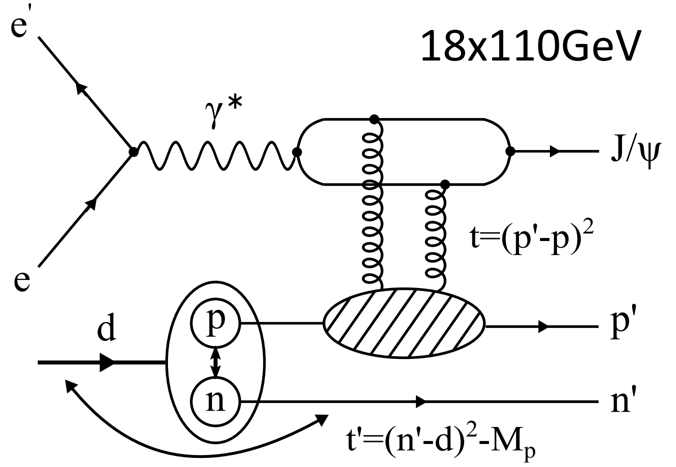
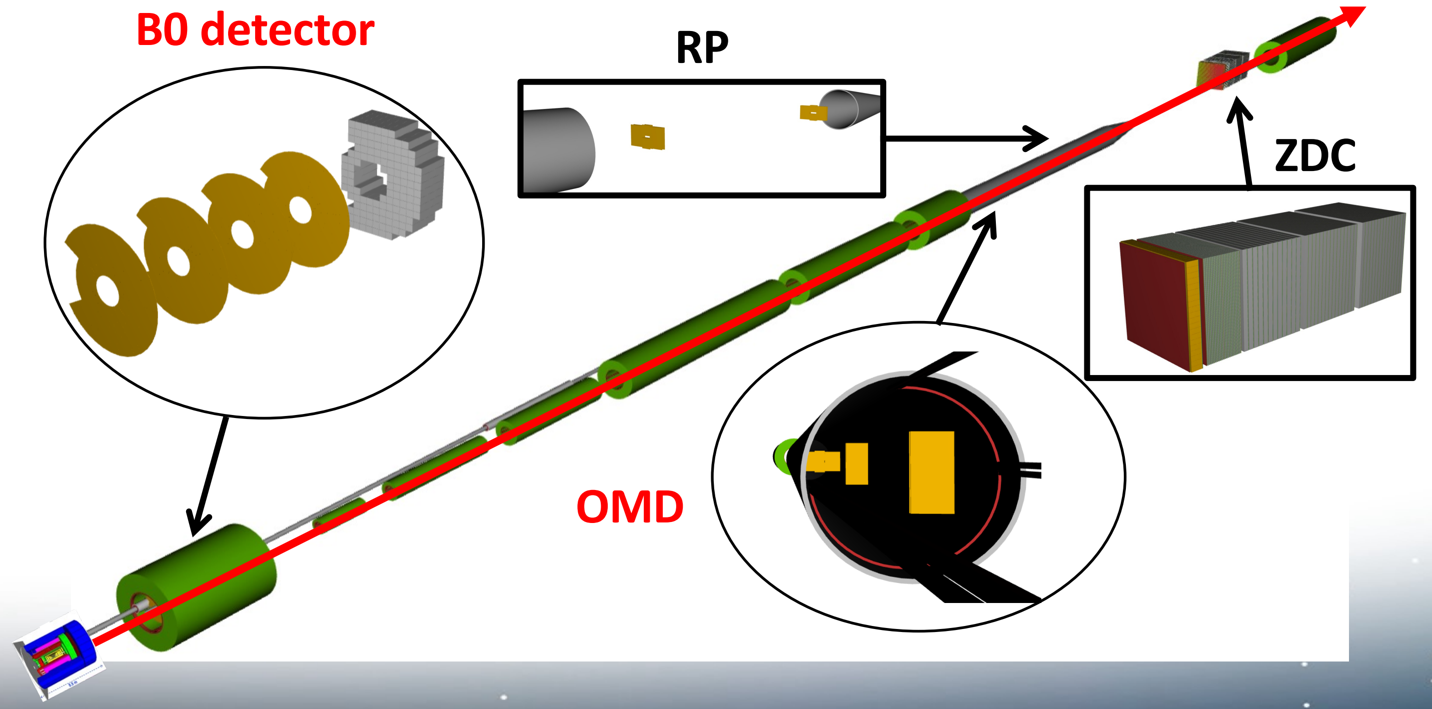


Off-momentum protons lost in quadrupole magnets.

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



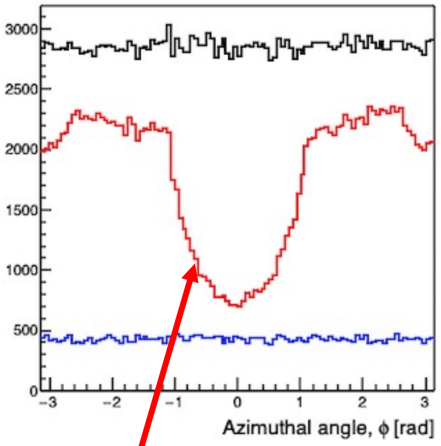
Neutron "spectator" case.



Short-Range Correlations in Deuterons

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

"active" protons



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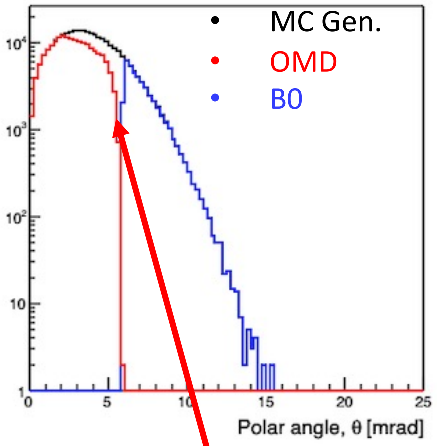

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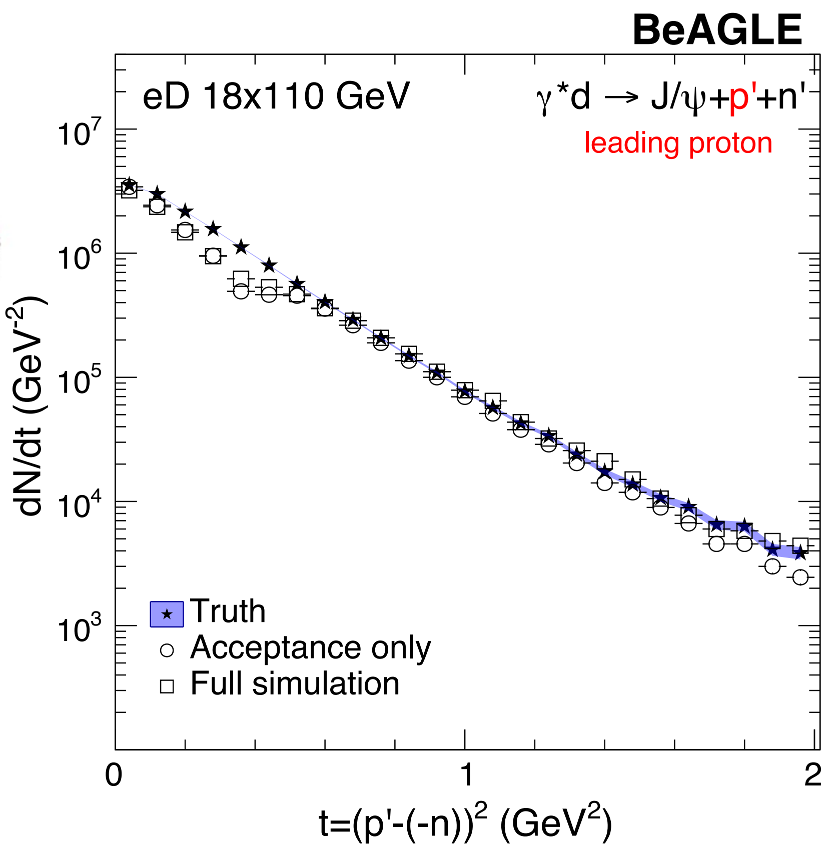
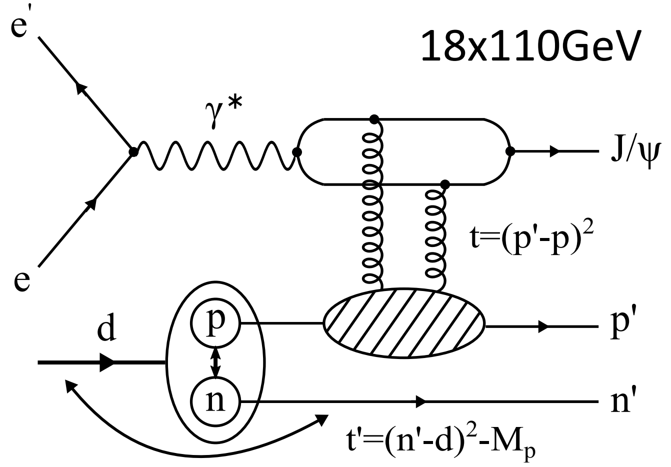
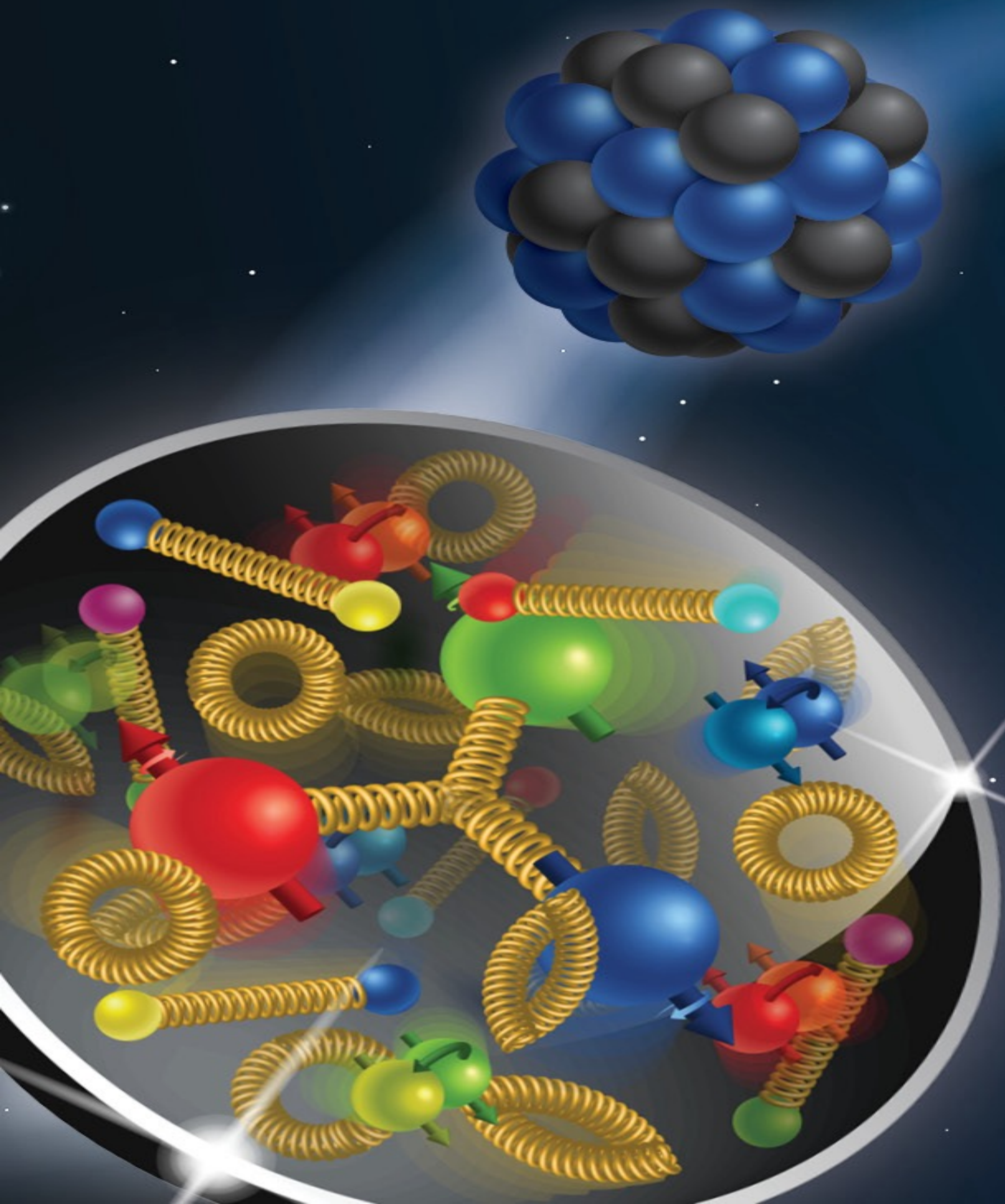




t-reconstruction using double-tagging (both proton and neutron reconstructed).

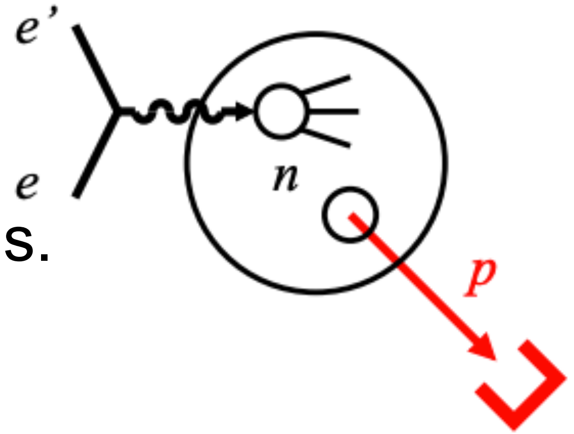
➢ **Spectator information is the "dial" for the SRC region.**



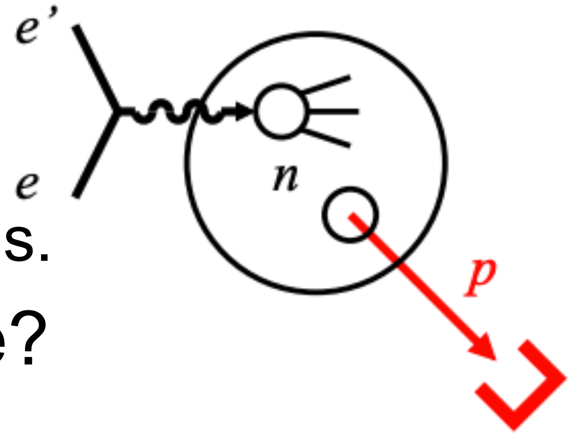
Deuterons: Free Neutron Structure

Neutron Structure

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

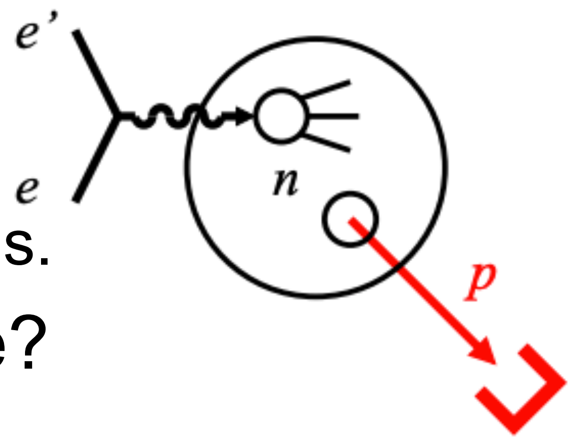


Neutron Structure



- Protons well-studied at HERA -> So…why the neutron?
  - 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



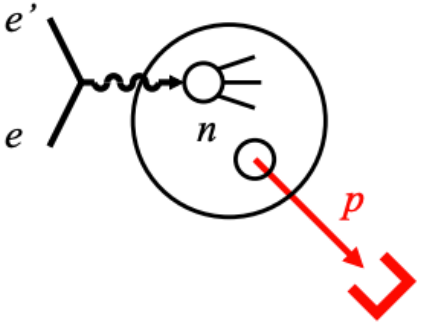
- Protons well-studied at HERA -> So…why the neutron?
  - Flavor separation, baseline for studies of nuclear modifications.
- What makes the free neutron structure hard to measure?
  - Can only access neutrons *in a nucleus.*
  - Includes nuclear binding effects, Fermi motion, etc.

- 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 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



spectator nucleon (p_{pT}, α_p)

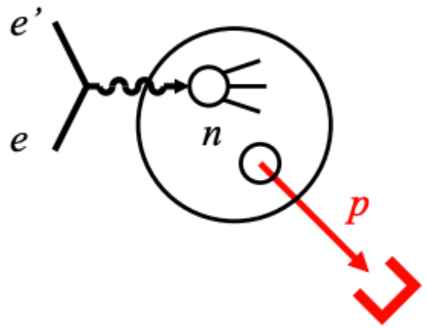
α_p: light-cone momentum fraction

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

S_d: deuteron spectral function pole

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



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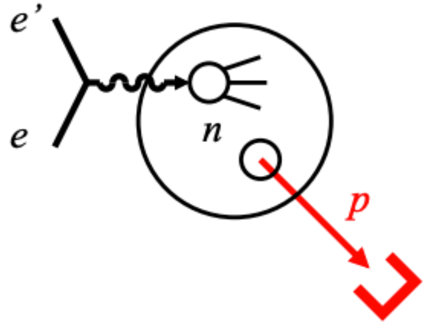
- Measure the cross-section differential on the spectator kinematics.
  - Spectator kinematics provide control knob on the nuclear configuration.
- Solve for the deuteron reduced cross section.

Tagged Deuteron Cross Section



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- 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.

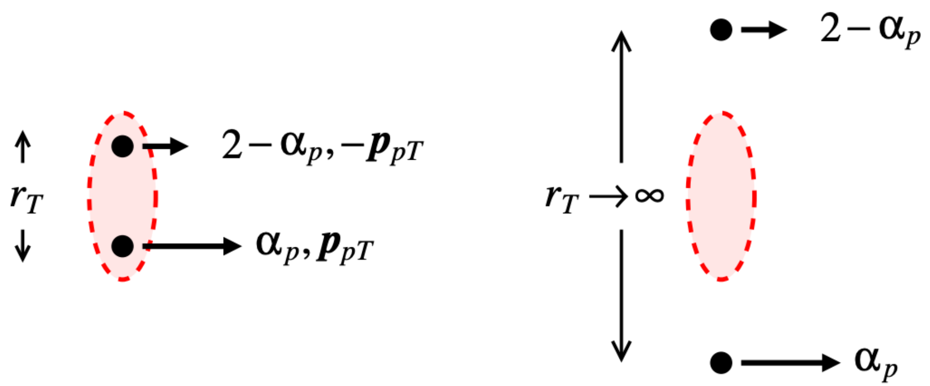
$$\sigma_{red,d}(x, Q^2; p_{pT}, \alpha_p) = [2(2\pi)^3] \times S_d(p_{pT}, \alpha_p)[pole] \times \sigma_{red,n}(x, Q^2)$$

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

$p_{pT}^2 \to -a_T^2$
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.

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

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

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

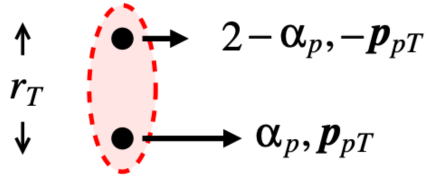
$$a_T^2 = m_N^2 - \alpha_p(2-\alpha_p)\frac{M_d^2}{4}$$

$R = residue\ of\ spectral\ function$

$a_T^2 = position\ of\ pole$

Pole Extrapolation

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



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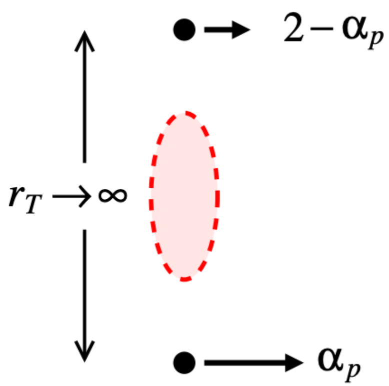

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  - The resulting distribution is the active nucleon reduced cross section as a function of p_{pT}^2.

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

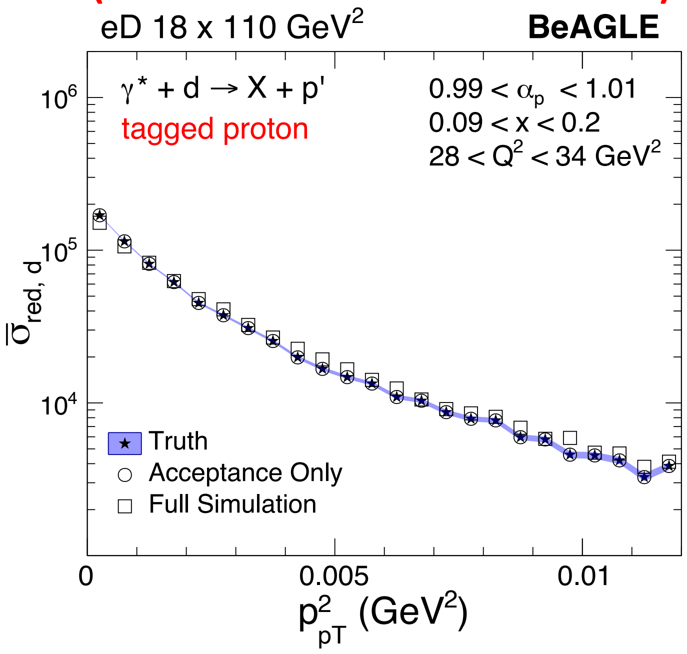
$$S_d(p_{pT}, \alpha_p)[pole] = \frac{R}{(p_{pT}^2 + a_T^2)^2}$$ Deuteron spectral function

- 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)

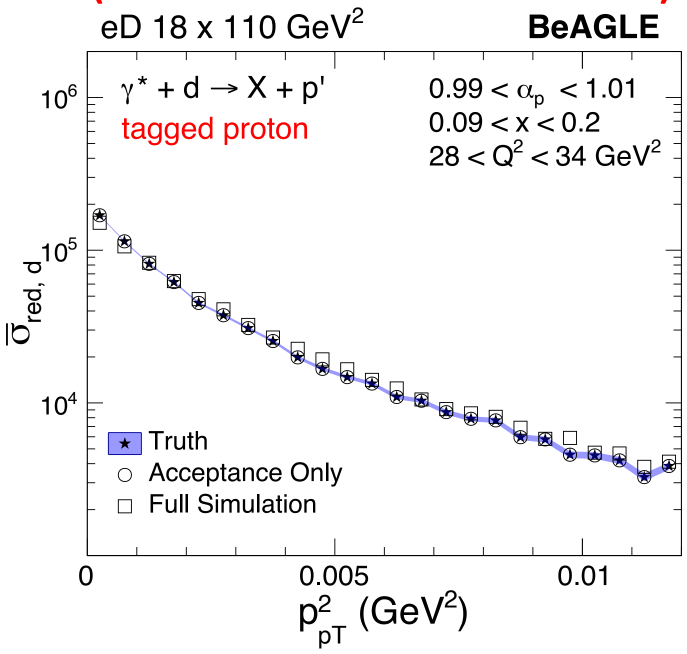


- Start with the deuteron reduced cross section → **direct measurement!**

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.

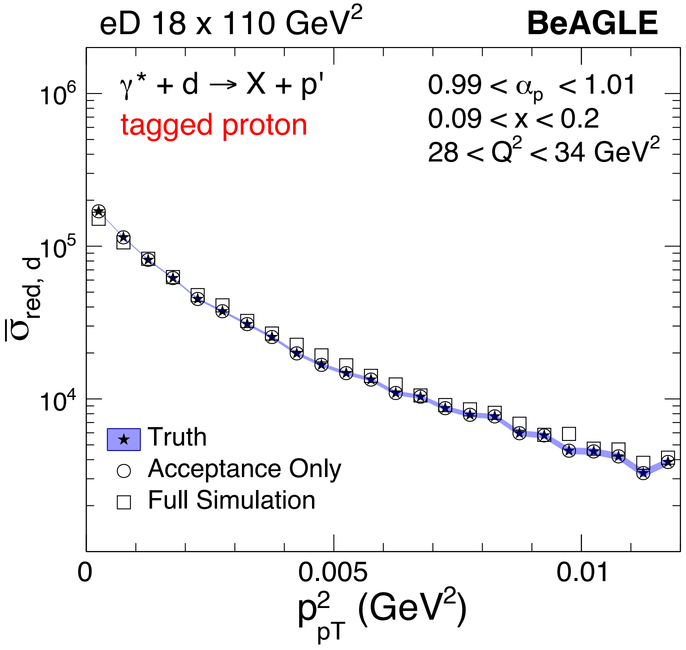
$$\times \quad \frac{1}{S_d(p_{pT}, \alpha_p)[pole]}$$

(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)**

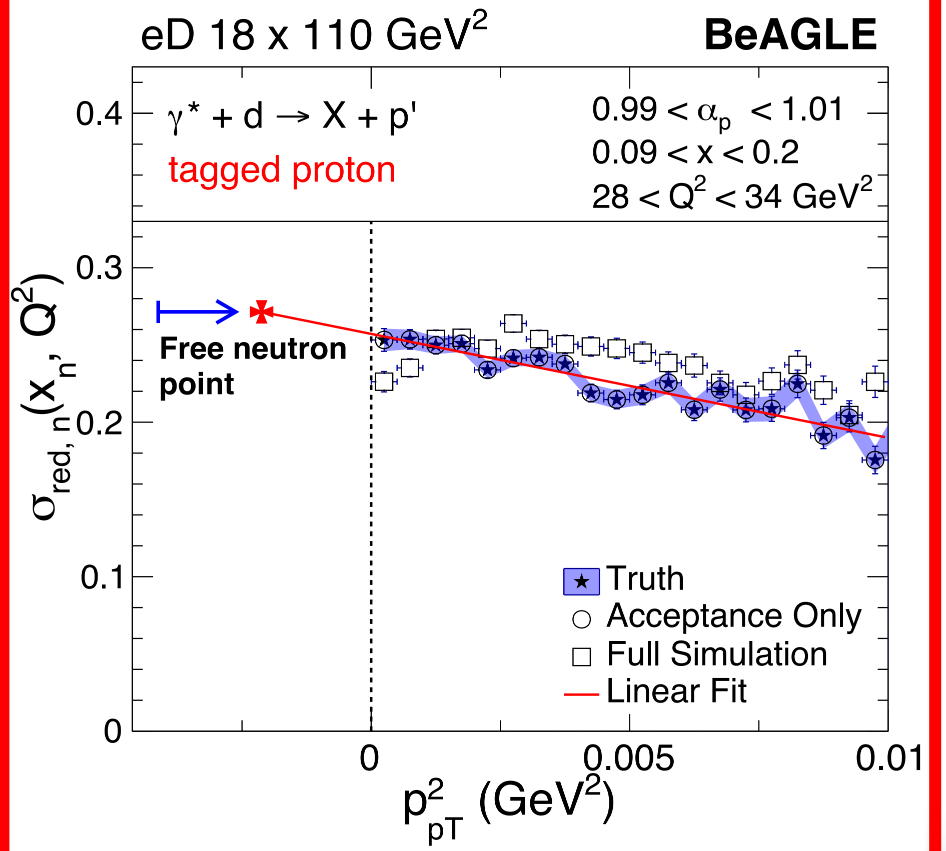
(deuteron reduced cross section)



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

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

(inverse pole of deuteron spectral function)



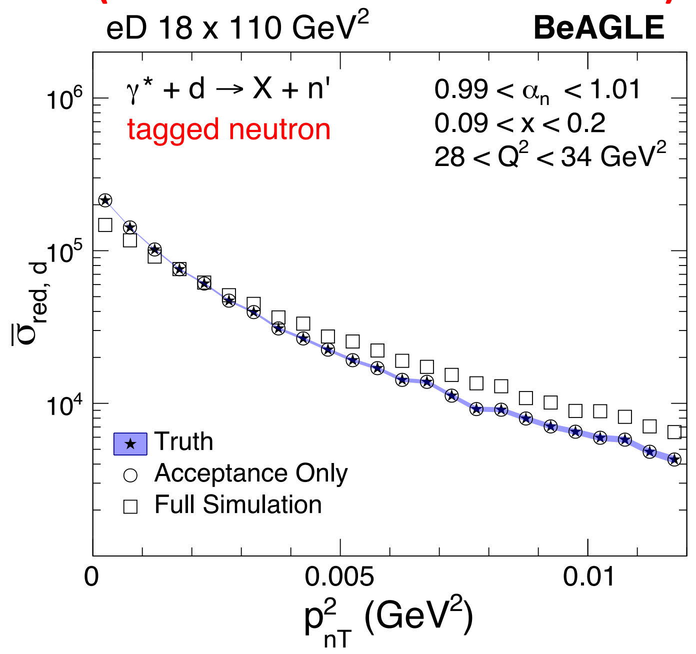
(Active nucleon reduced cross section)

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

Free Proton F_2 Extraction

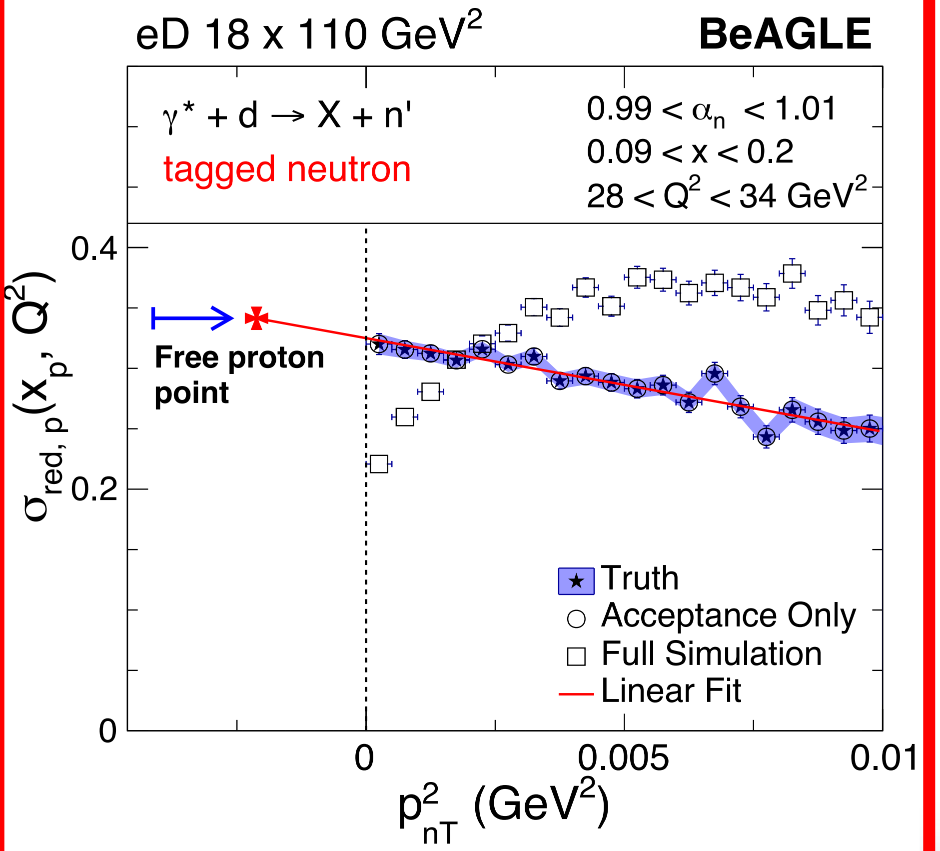
A. Jentsch, Z. Tu, and C. Weiss, Phys. Rev. C **104,** 065205, (2021) **(Editor's Suggestion)**

(deuteron reduced cross section)



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

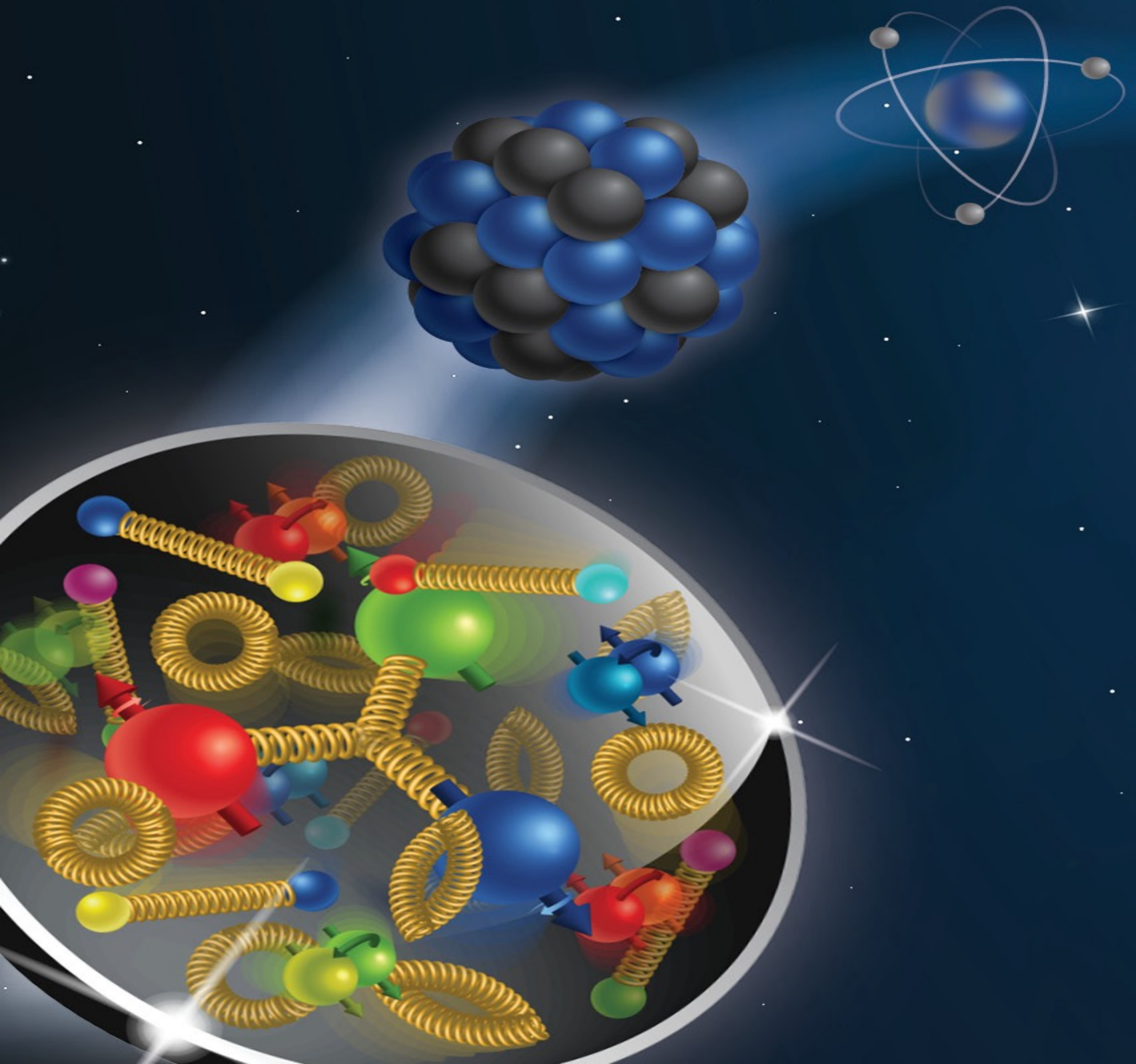
(inverse pole of deuteron spectral function)



(Active nucleon reduced cross section)

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

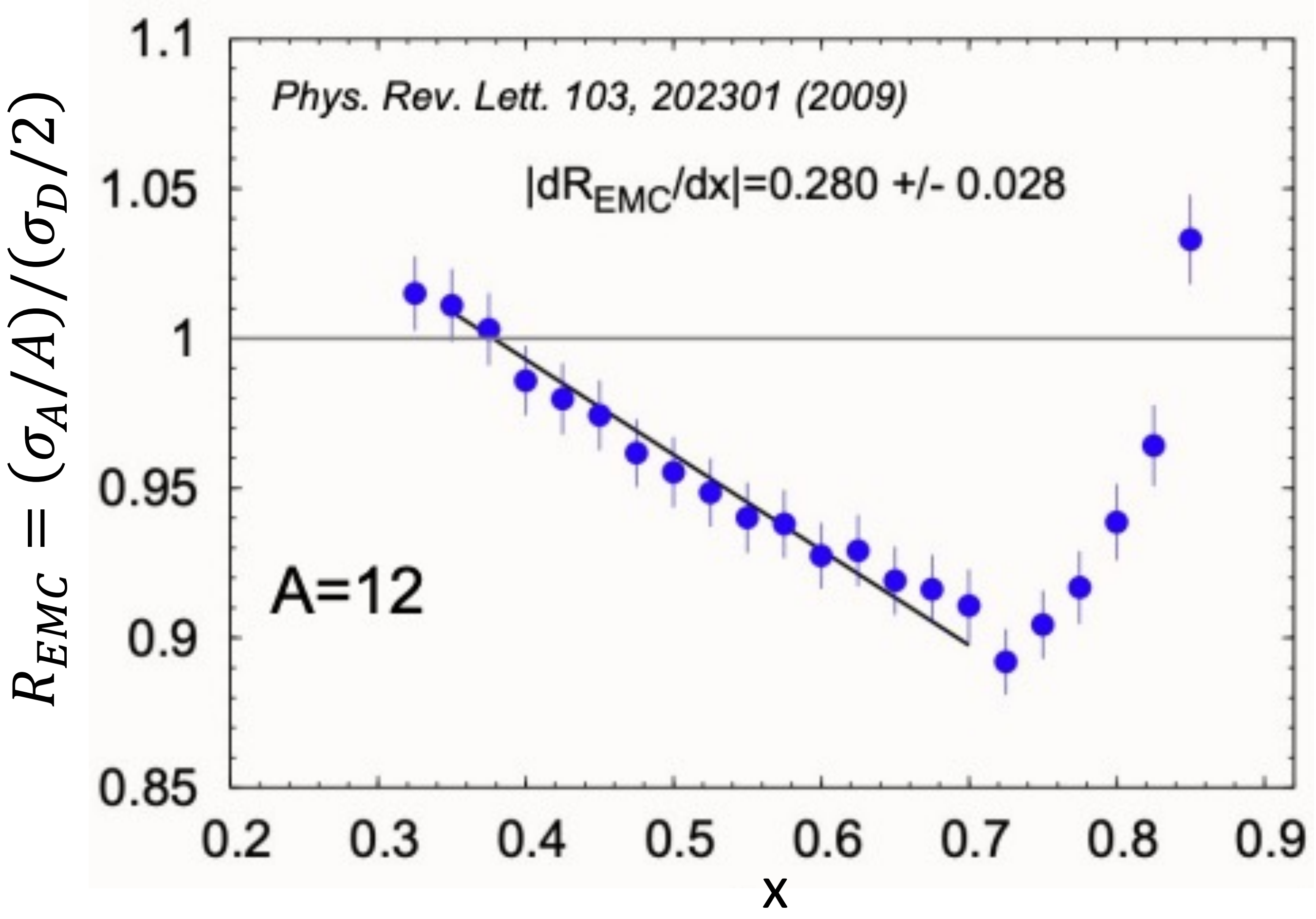
Measurement of ***proton*** **F_2** using this method provides ability to directly estimate systematics for extrapolation procedure, since proton F_2 directly measurable in e+p scattering!

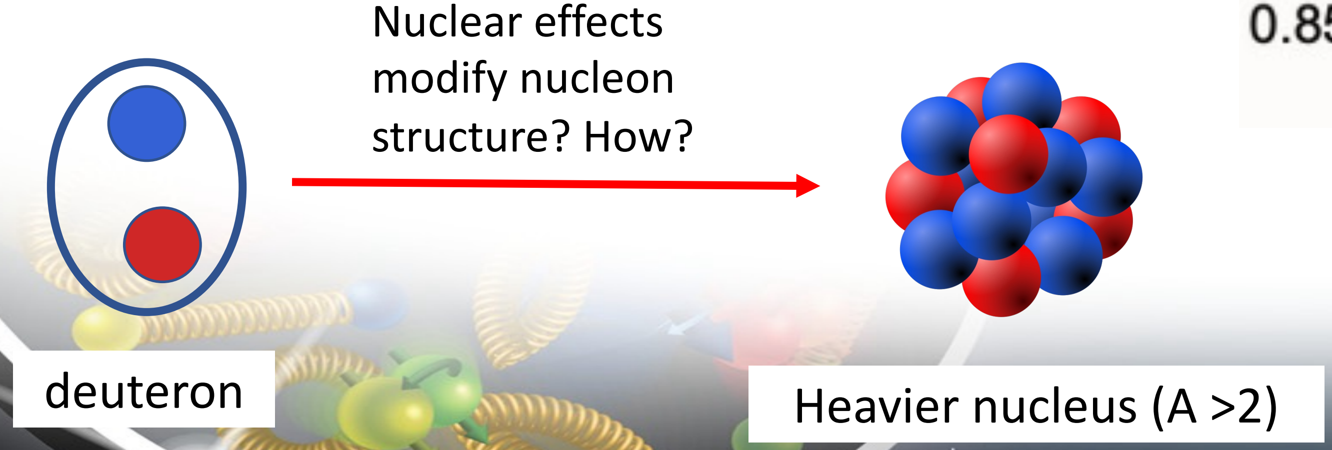


Deuterons:
The EMC Effect
(on-going study)

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**!



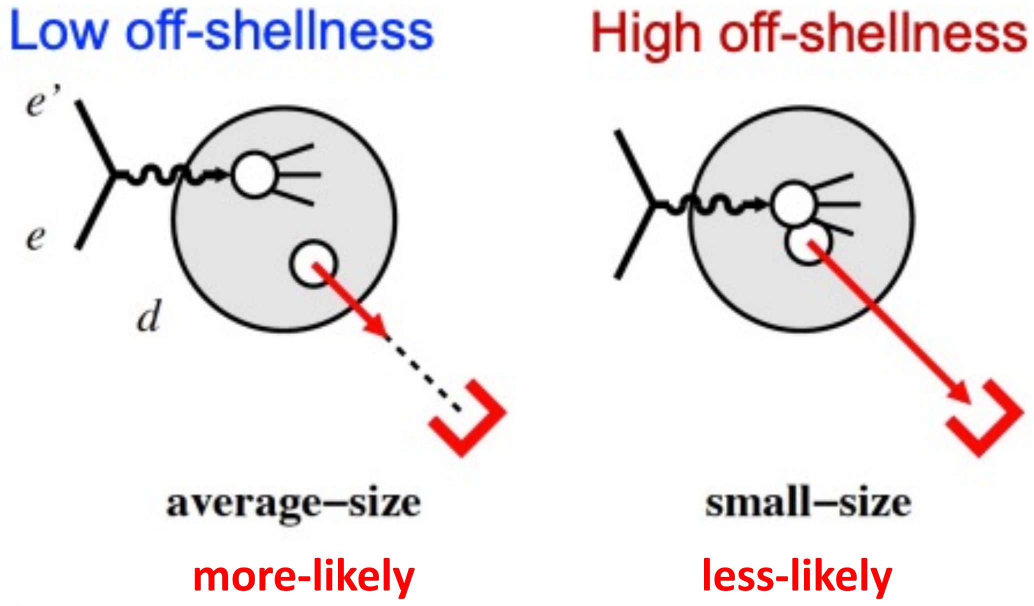


Understanding the origin of the EMC effect and nuclear modifications of prime interest in nuclear physics!

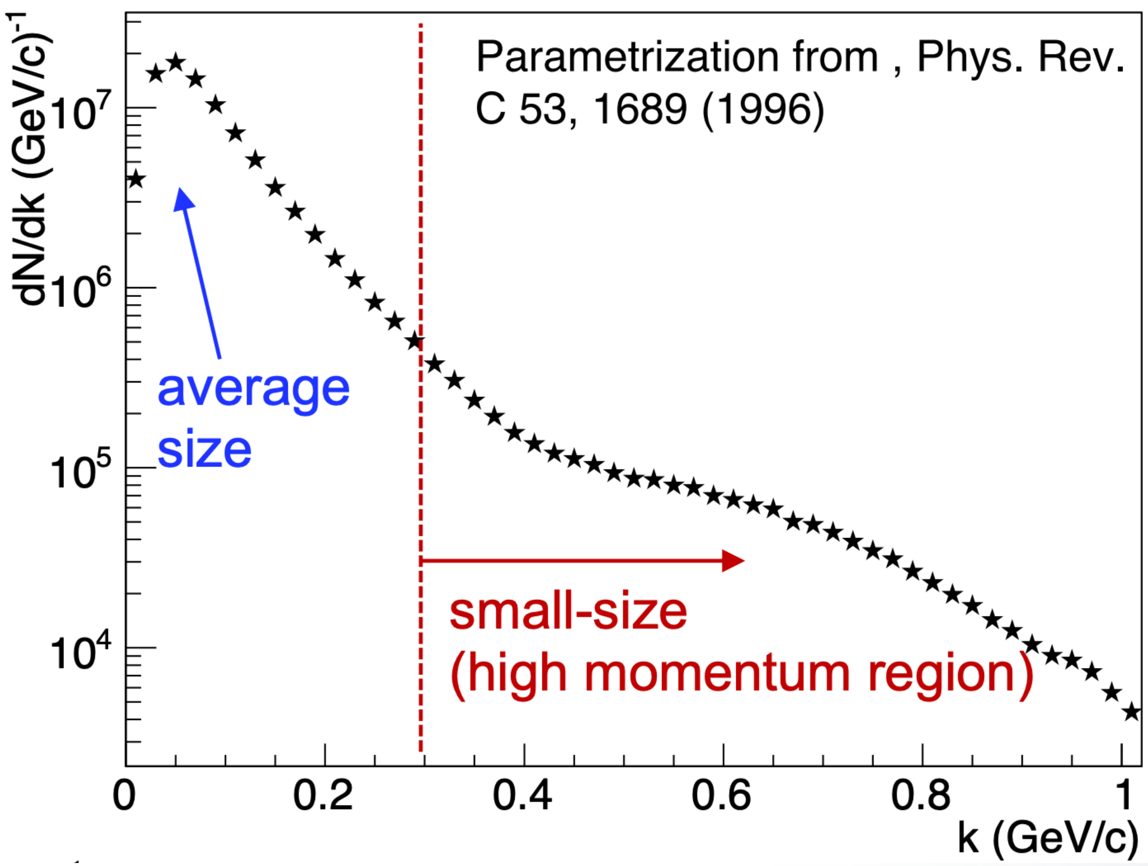
The Deuteron – a stand-alone lab for nuclear physics

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

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



Deuteron: nucleon internal momentum

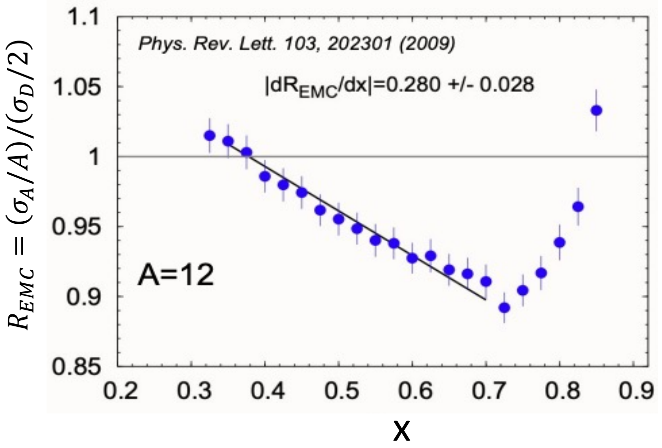


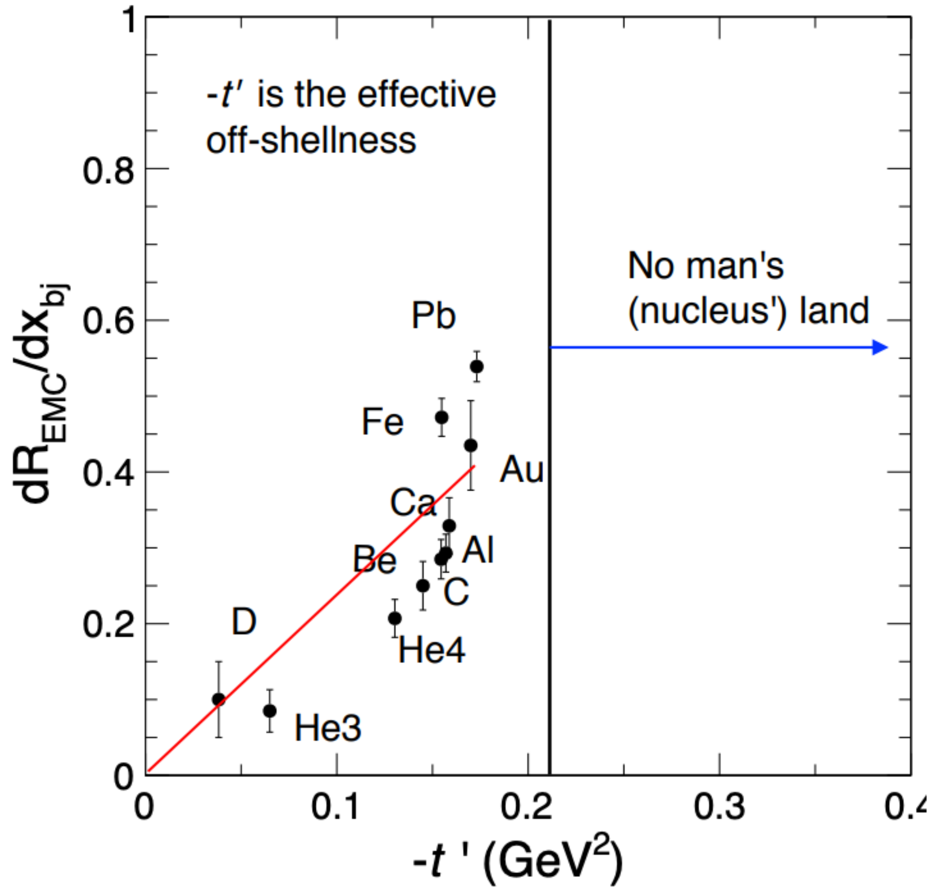
$$-t'^2 = M_N^2 - (p_d - p_p)^2$$

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)

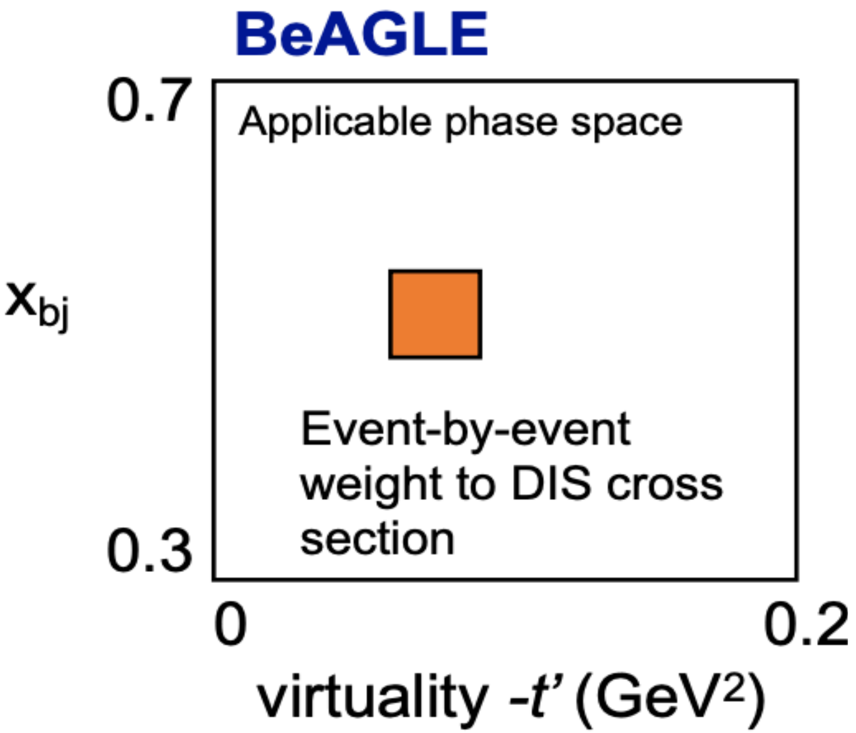
Linear fit to virtuality dependence → Minimal parametrization:

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

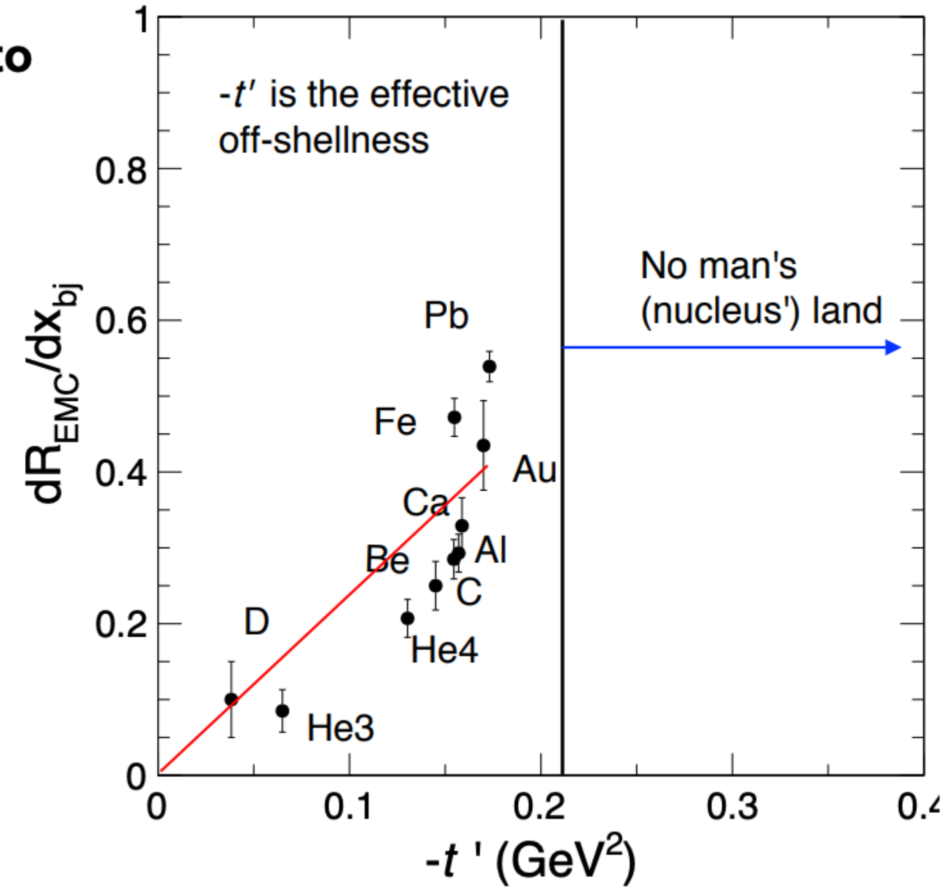
C. Ciofi *et al.,* Phys. Rev. C **76**, 055206 (2007)

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…

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)

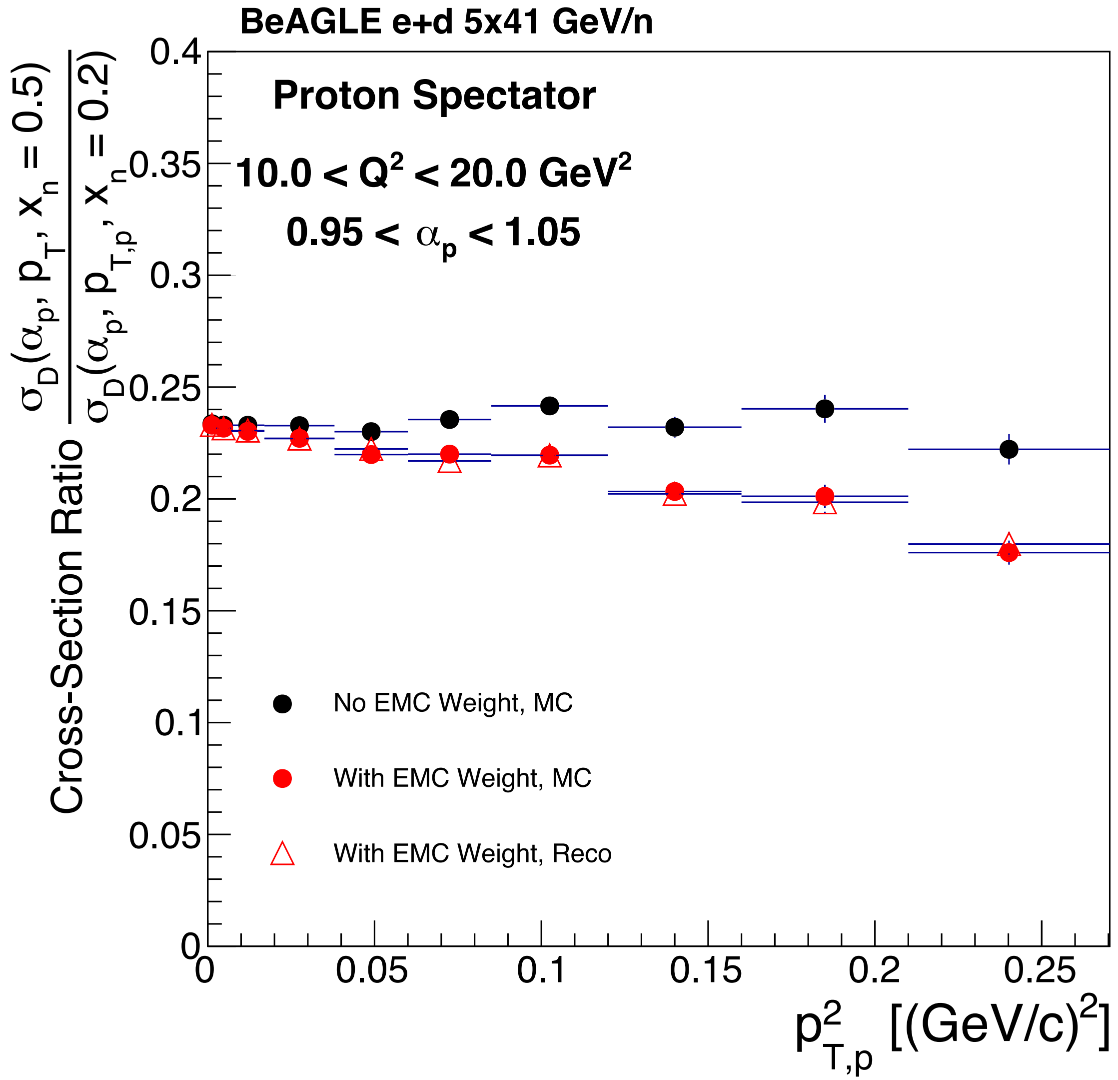
➢ Quantity allows direct comparison of cross section with and without EMC weight (x ~ 0.2 chosen to avoid anti-shadowing region).

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

The EMC Effect @ the EIC

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

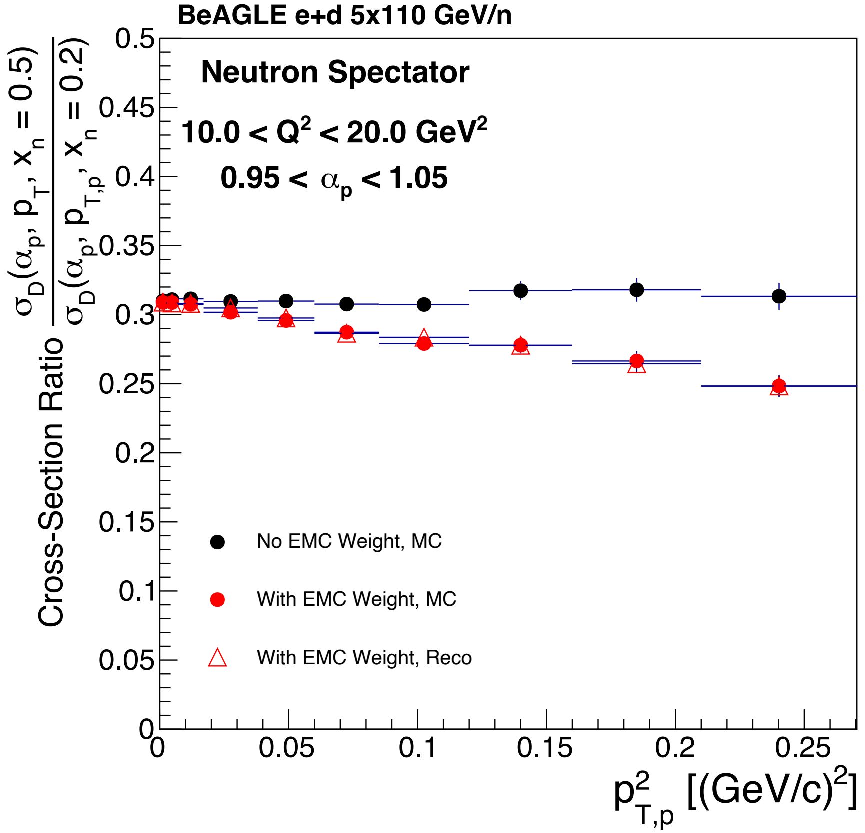
- Approach:
  - Measure deuteron reduced cross-section σ_D, with and without the off-shell effects included.
    - No FSI included.
  - Ratio of σ_D **inside and outside the EMC region** (e.g. x ~ 0.5 and x ~ 0.2)
  - Establish required integrated luminosity.
    - **Challenging measurement → high-x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

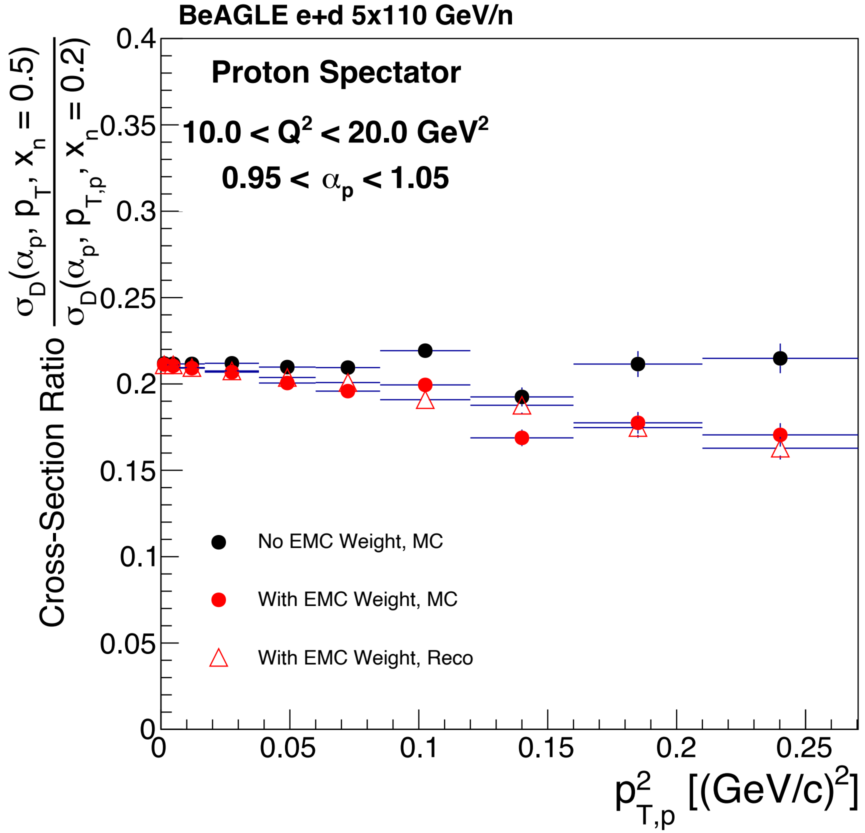


The EMC Effect @ the EIC

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

- EIC versatility → different beam energy configurations!

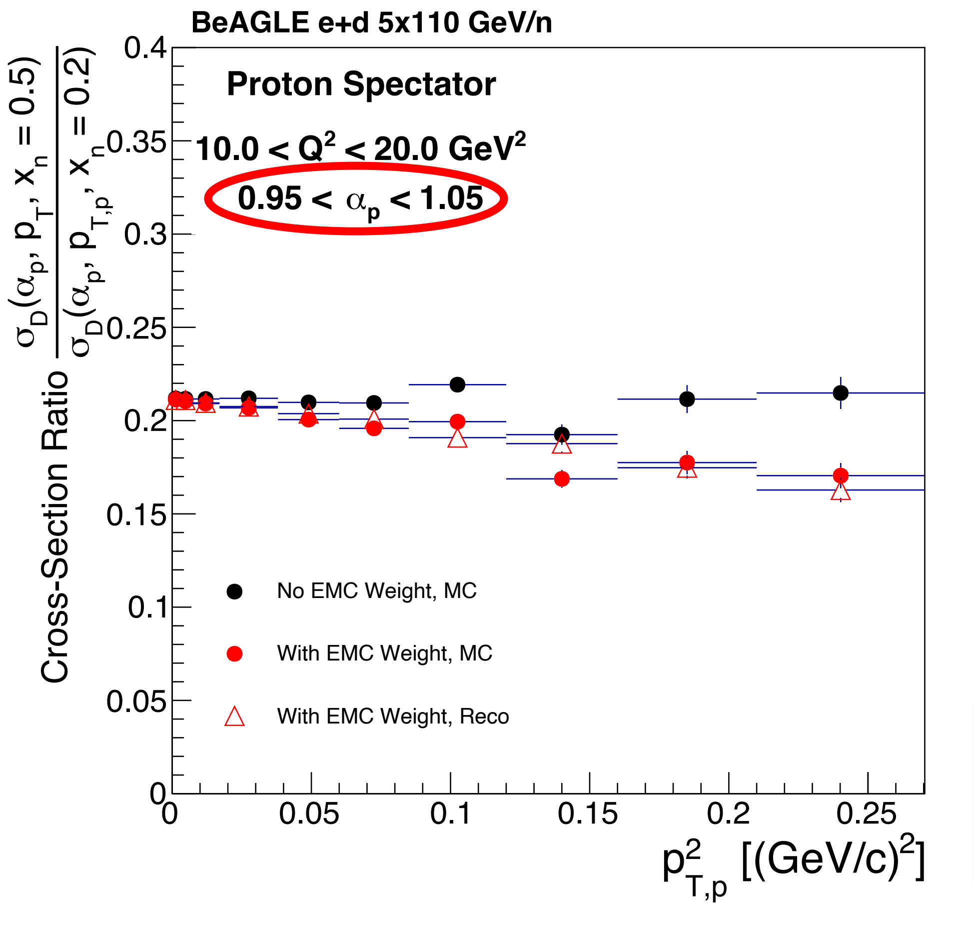




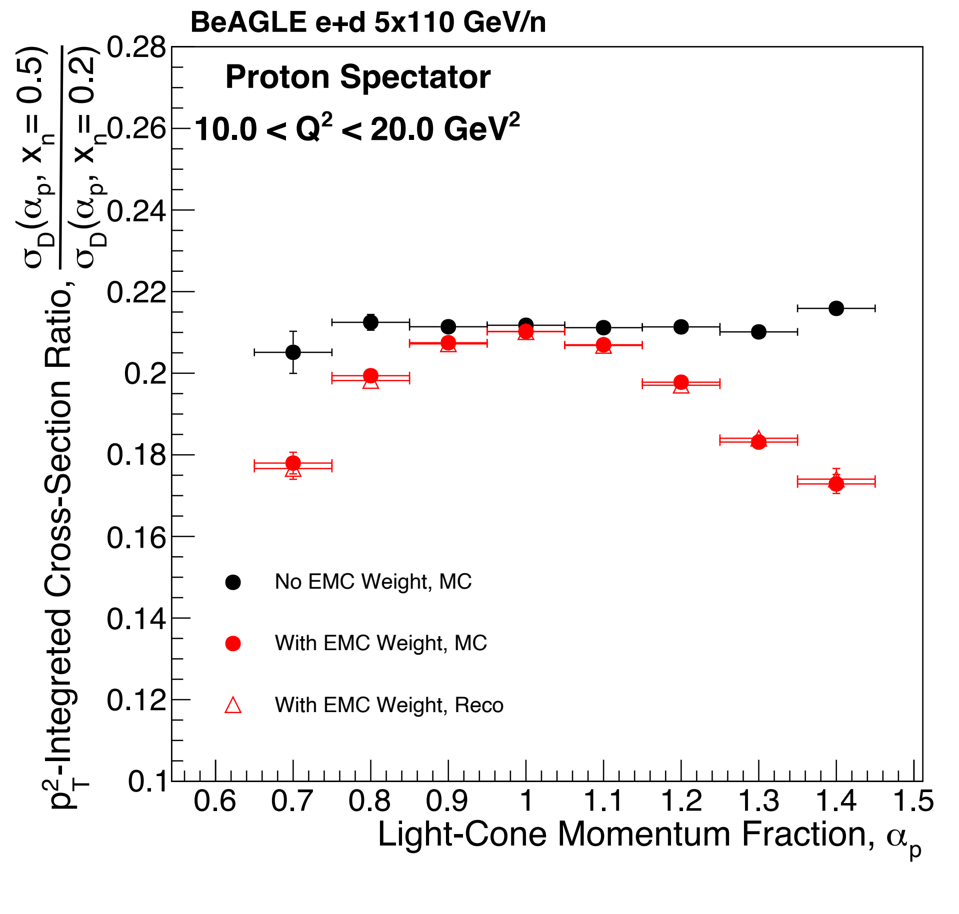
- Higher energy configuration (5x110 GeV/n).
- **More favorable detector acceptance → study of proton *and* neutron spectators with same beam configuration.**
- Measurement of same observable with different beam energies/spectator reconstruction enables better understanding of experimental systematics.

Different nuclear configurations

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

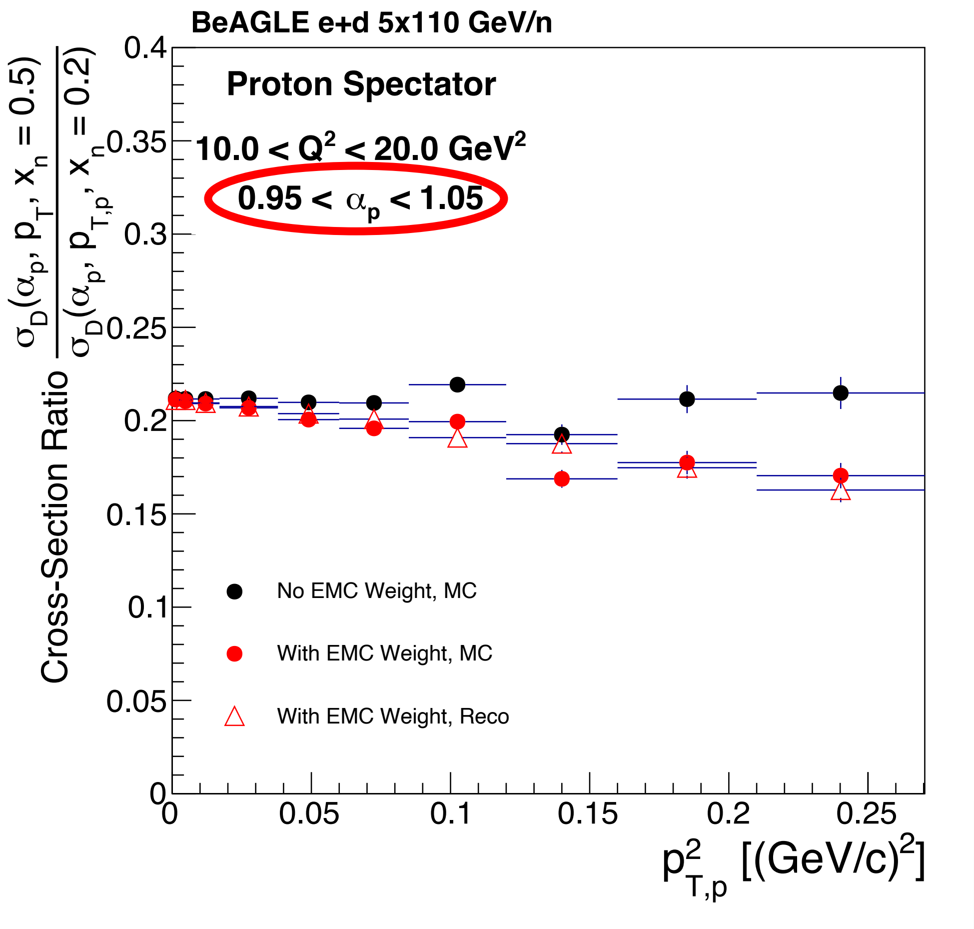


Integrate cross section over $p_{T,p}^2$ in each α bin.

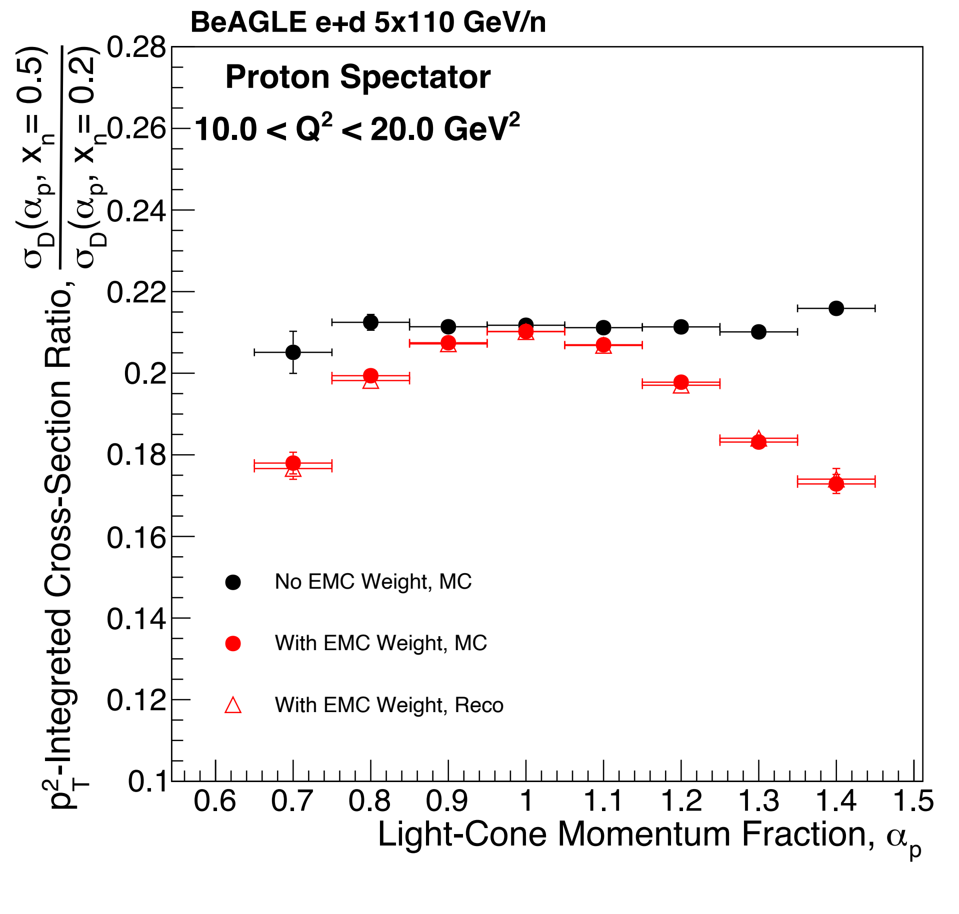


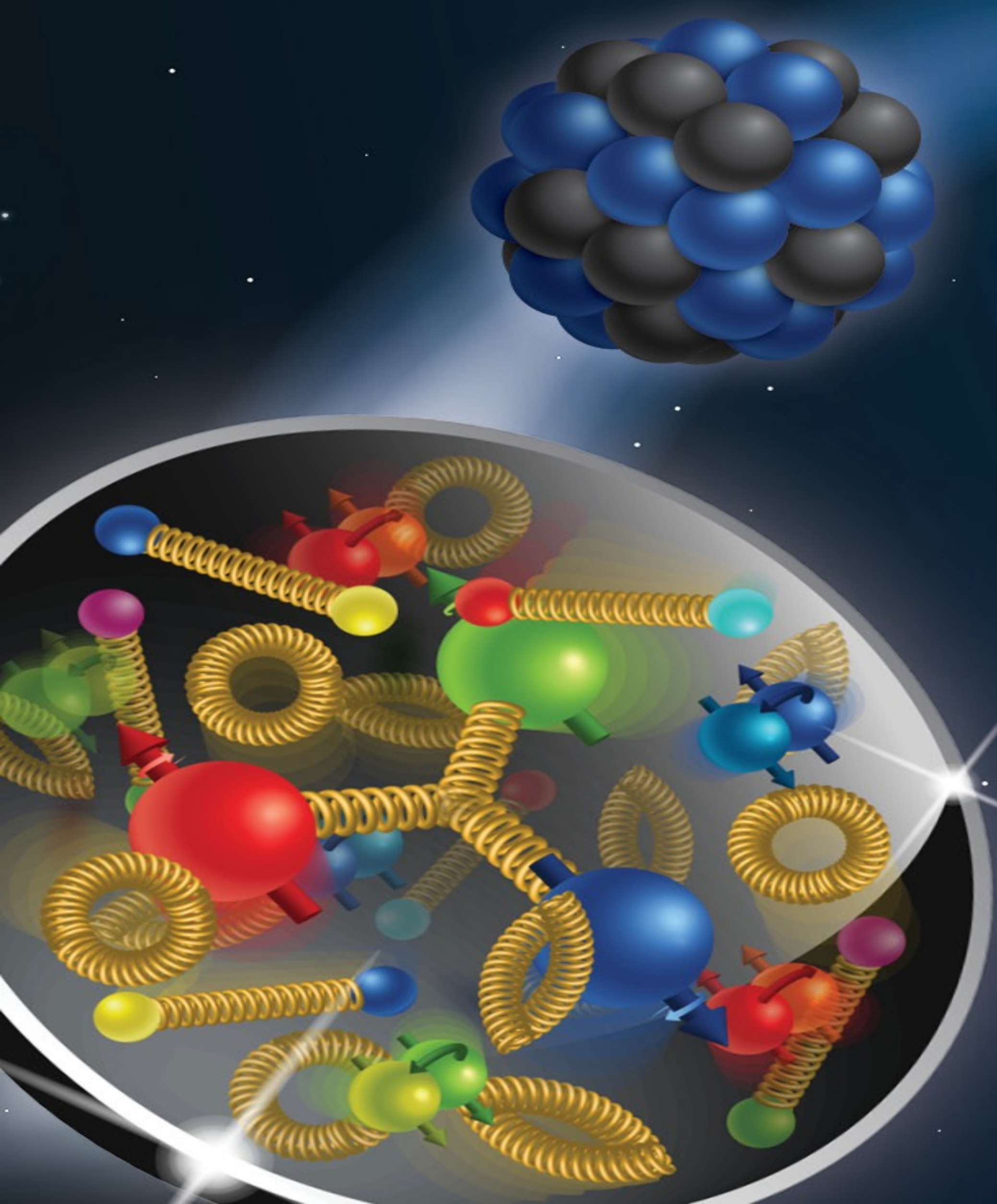
Different nuclear configurations

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



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



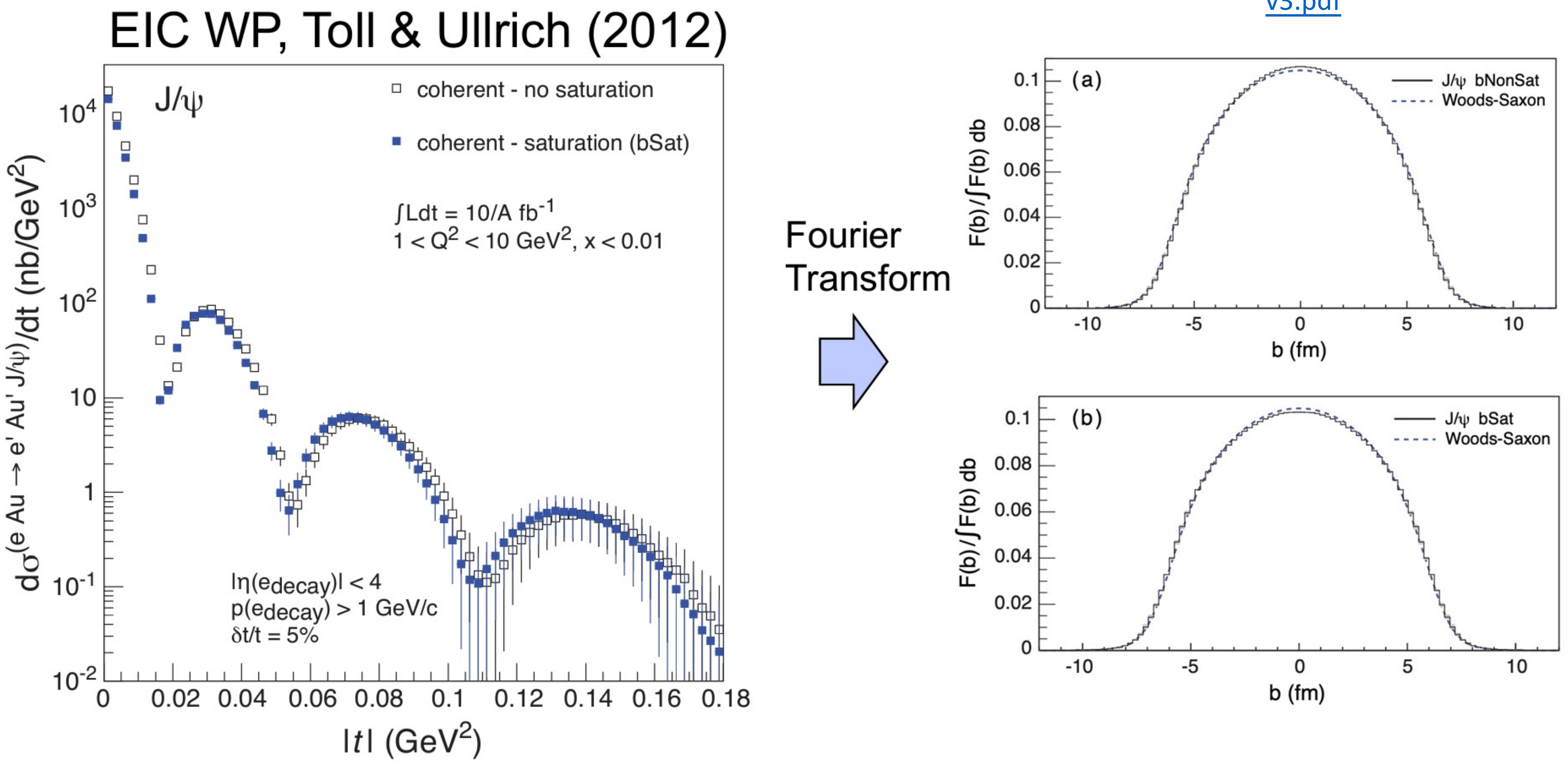


What about e + (heavy)A?

J/ψ in e+A as a tool for nuclear imaging

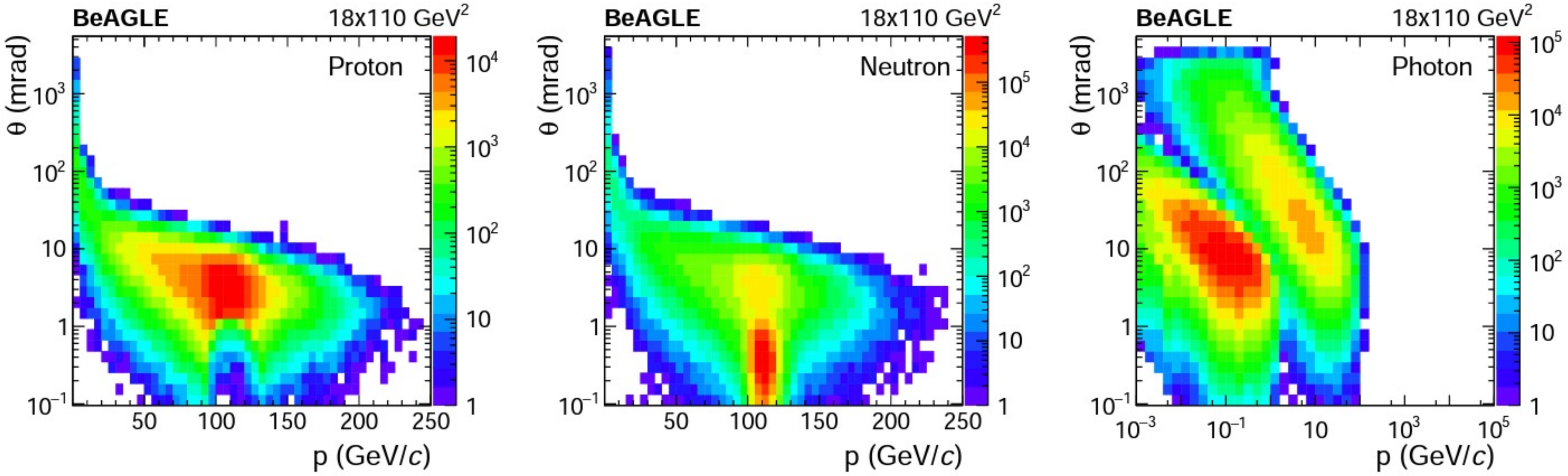
From K. Tu @ DIS 2023: https://indico.cern.ch/event/1199314/contributions/5189840/attachments/2621029/4531556/ePIC-exclusive-slides-Tu-v3.pdf

EIC White Paper: golden channel



Vetoing Incoherent Background Using FF

Process in BeAGLE: incoherent J/ψ production e+Pb → e + J/ψ + X (18x110 GeV/n)



Production of protons, neutrons, and photons from breakup of lead nucleus using BeAGLE.

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)

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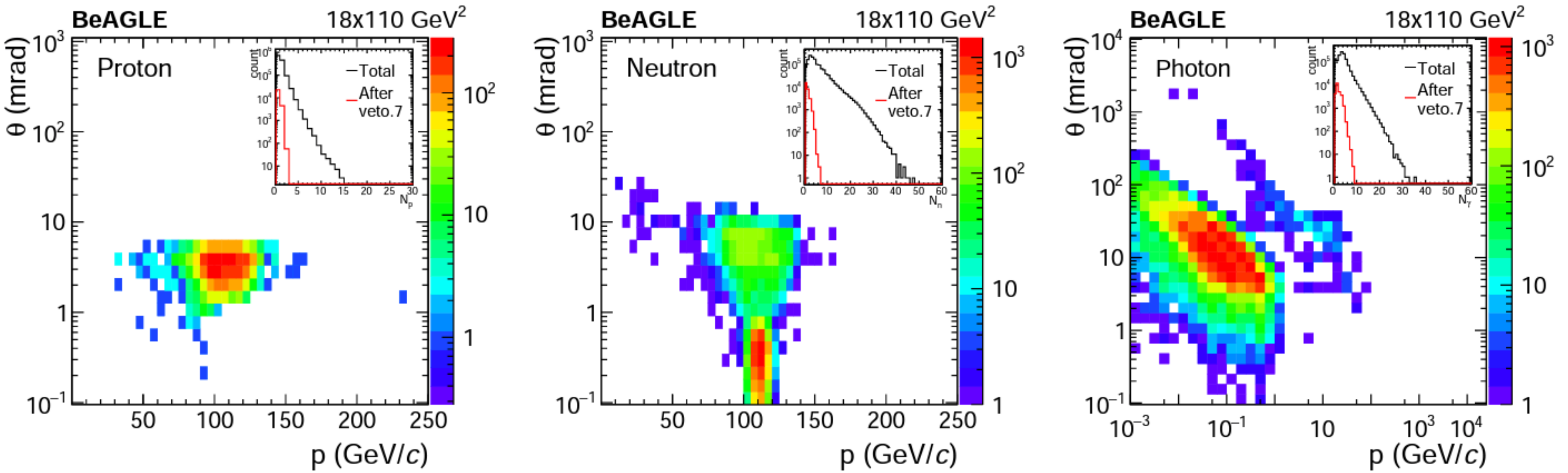
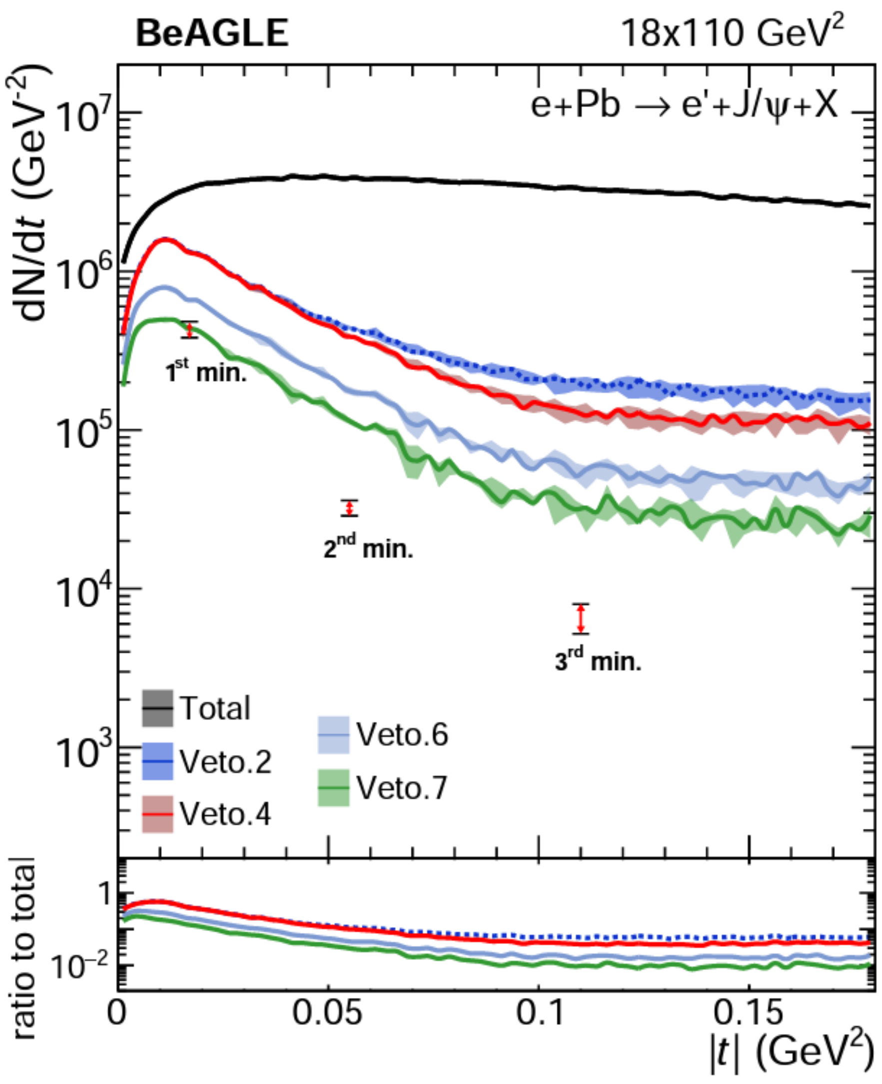


Tagging of protons, neutrons, and photons from breakup of lead nucleus using BeAGLE in **FF detectors**.

Particles tagged in all 4 far-forward detectors.

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)

Vetoing Incoherent Background Using FF



Different t-distribution curves are shown with different FF detectors vetoing particles. All vetoes shown here assume an exclusivity cut in the main detector (scattered electron + J/psi).

- ZDC neutron only
- ZDC neutron + RP proton + OMD proton
- ZDC neutron + RP proton + OMD proton + B0 proton and photon
- ZDC neutron + RP proton + OMD proton + B0 proton and photon + ZDC photon (> 50 MeV)

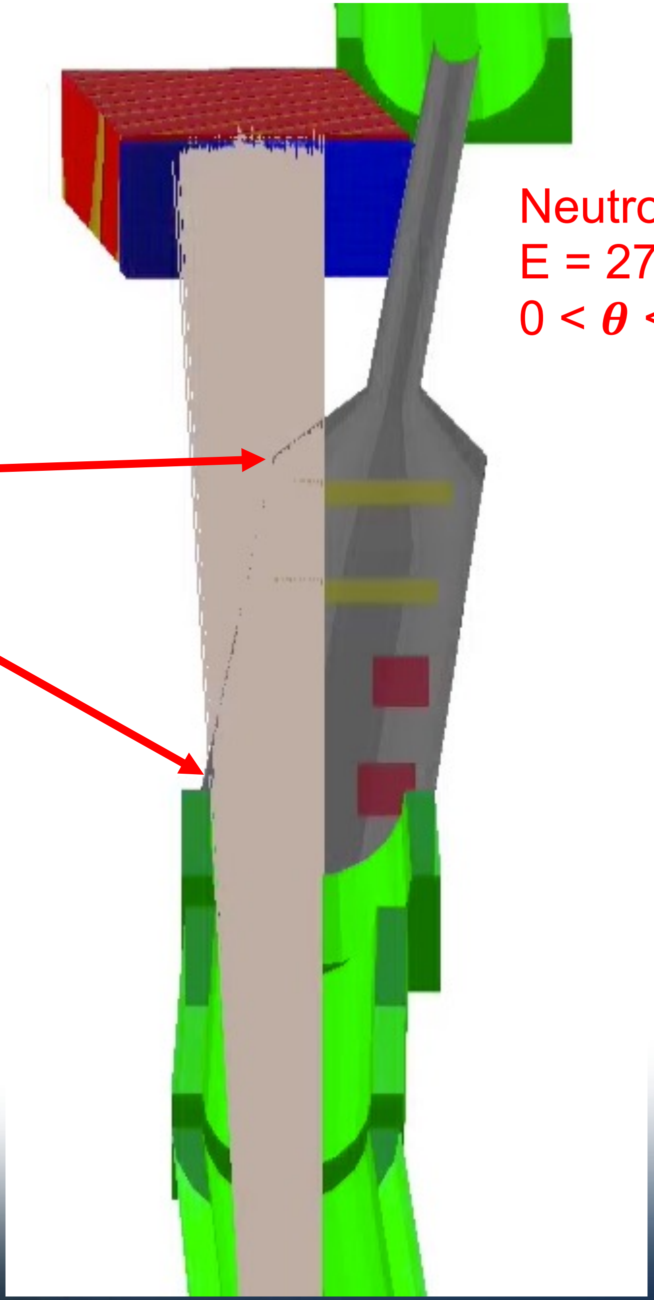
The "best" curve represents the FULL far-forward acceptance, but also includes an unoptimized beam pipe which can reduce the efficiency for the ZDC (especially low E photons).

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)

ZDC & neutral particle exit

Want to have as large an incident angle with the beam pipe as possible.

This is the problem area → shallow incident angle can increase effective material thickness by ~ factor of 10!!

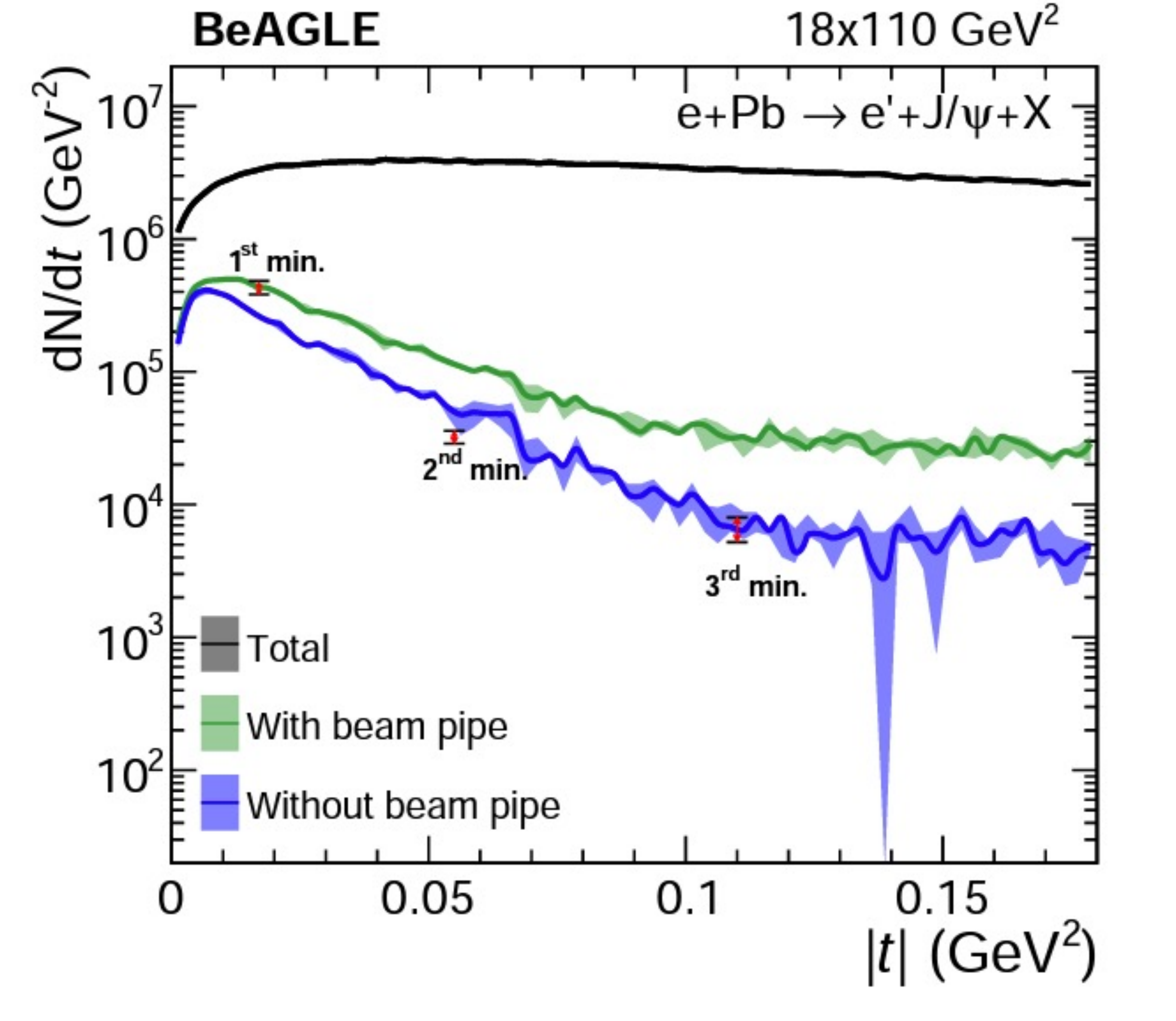


Neutrons
E = 275 GeV
$0 < \theta < 5$ mrad

This will reduce our detection efficiency beyond just the aperture limit!

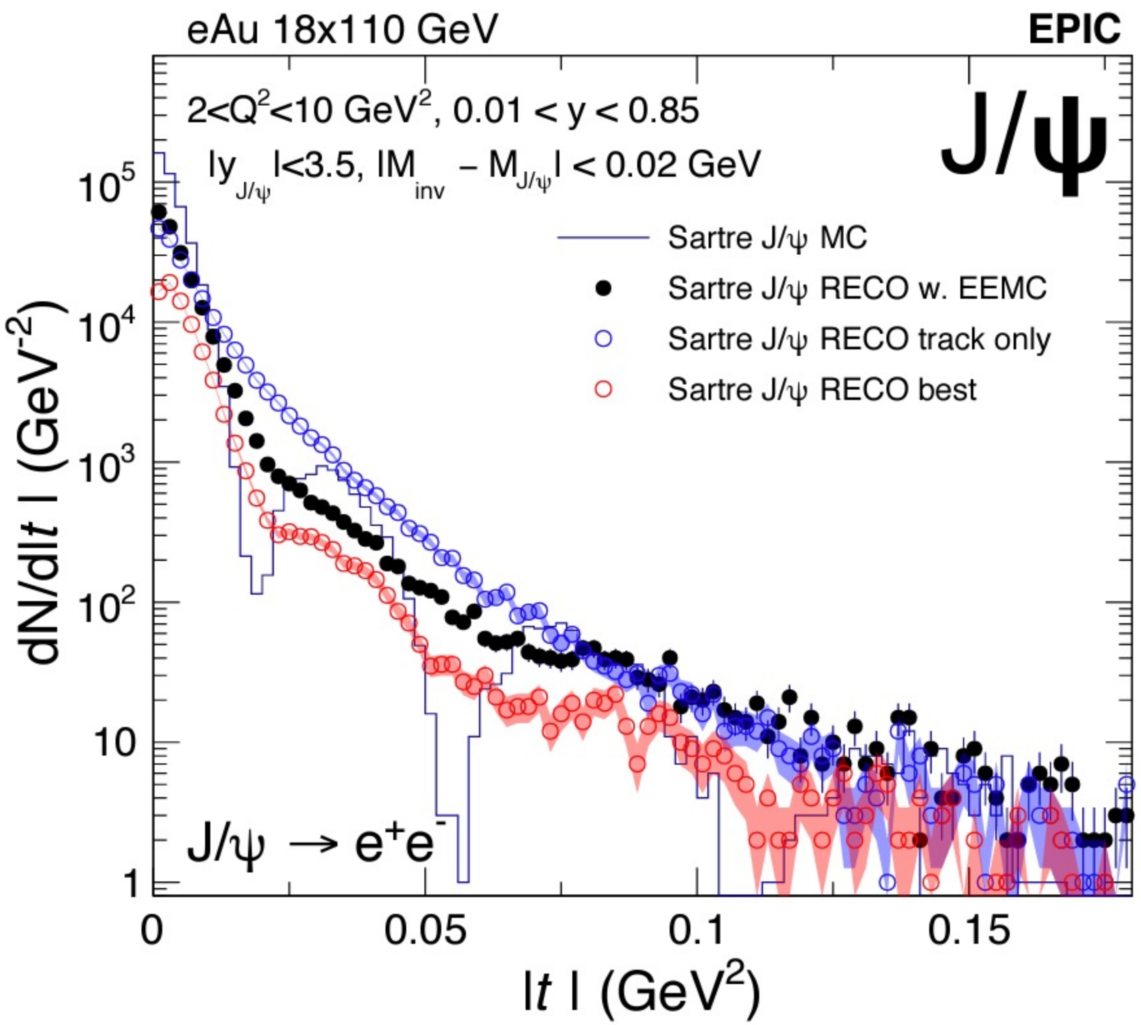
- **Updated design in-production.**

Vetoing Incoherent Background Using FF



Optimizing the beam pipe exit for neutral particles will have a major impact on the vetoing efficiency (in-progress now!).

Measuring t-distribution → Full ePIC simulations

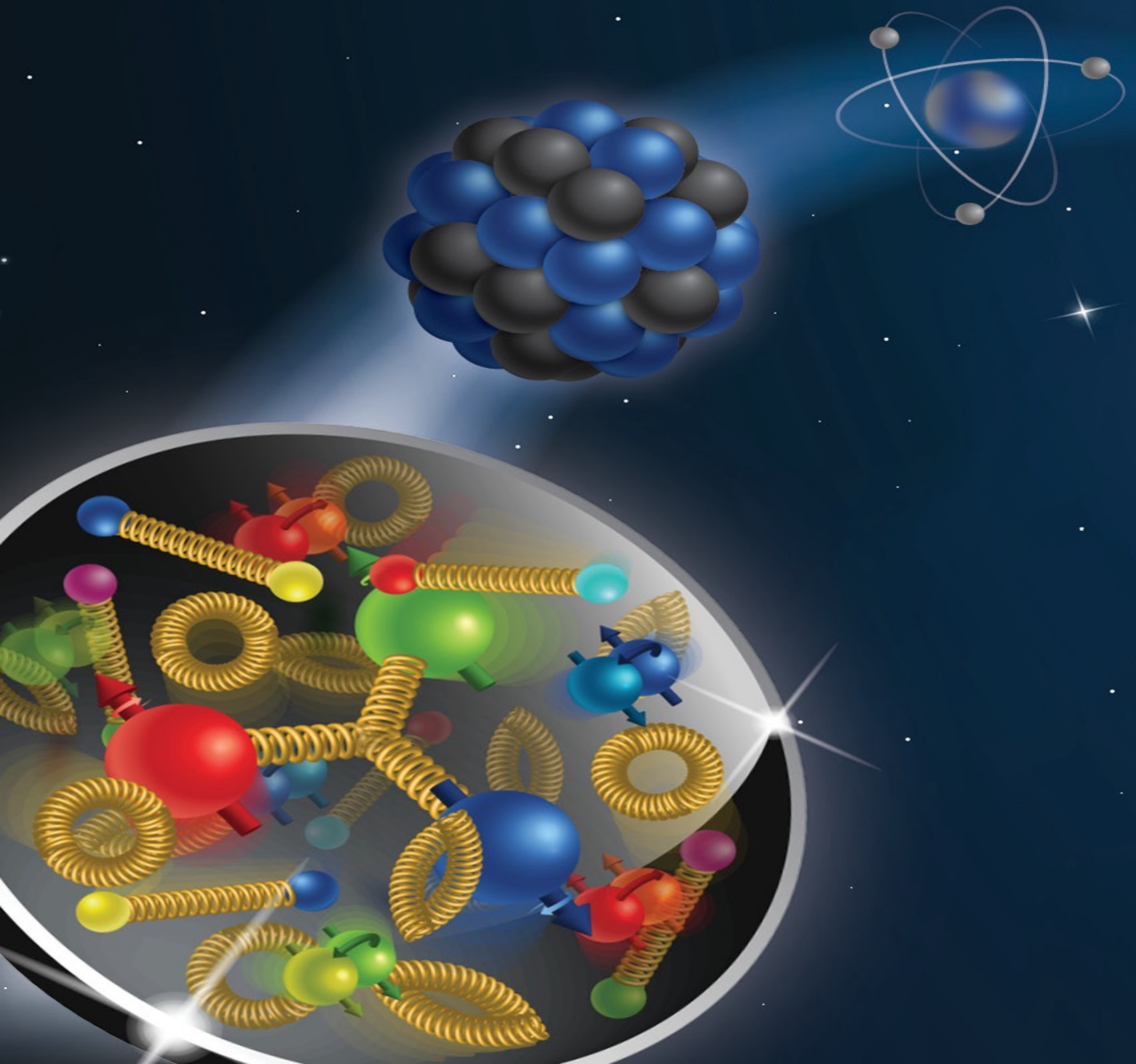


From K. Tu @ DIS 2023: https://indico.cern.ch/event/1199314/contributions/5189840/attachments/2621029/4531556/ePIC-exclusive-slides-Tu-v3.pdf

Legend details:

- w. EEMC: electron energy from EEMC, electron mass (PDG), angle (eta,phi) from tracking; φ→KK from tracking.
- Track only: e', φ→KK, all from tracking
- Best: average of the above 2 E-by-E.

Improvements from *algorithm*:
- The two methods can be used together to further improve the $|t|$ resolution.

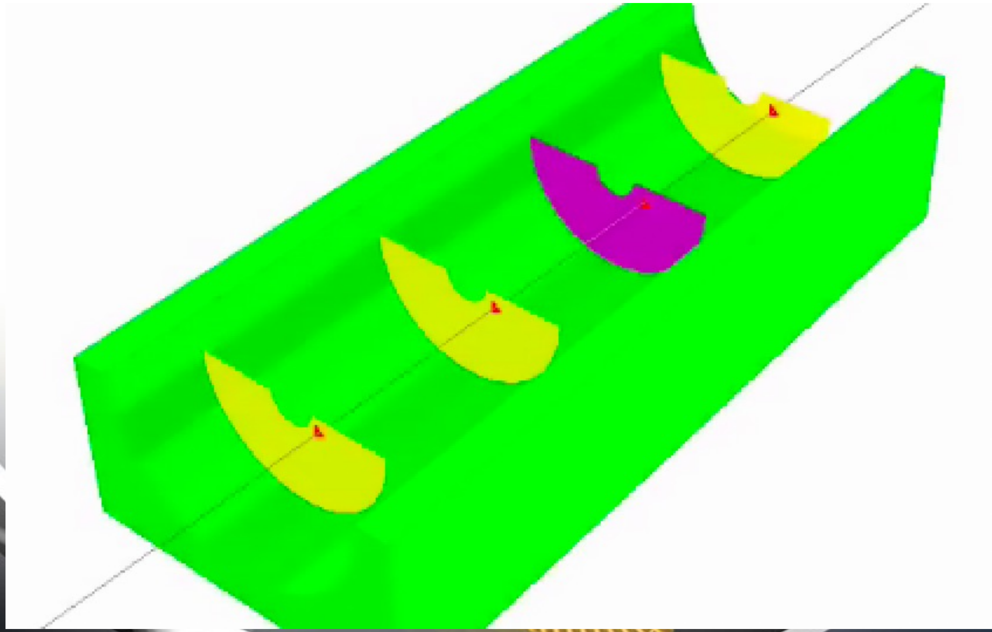


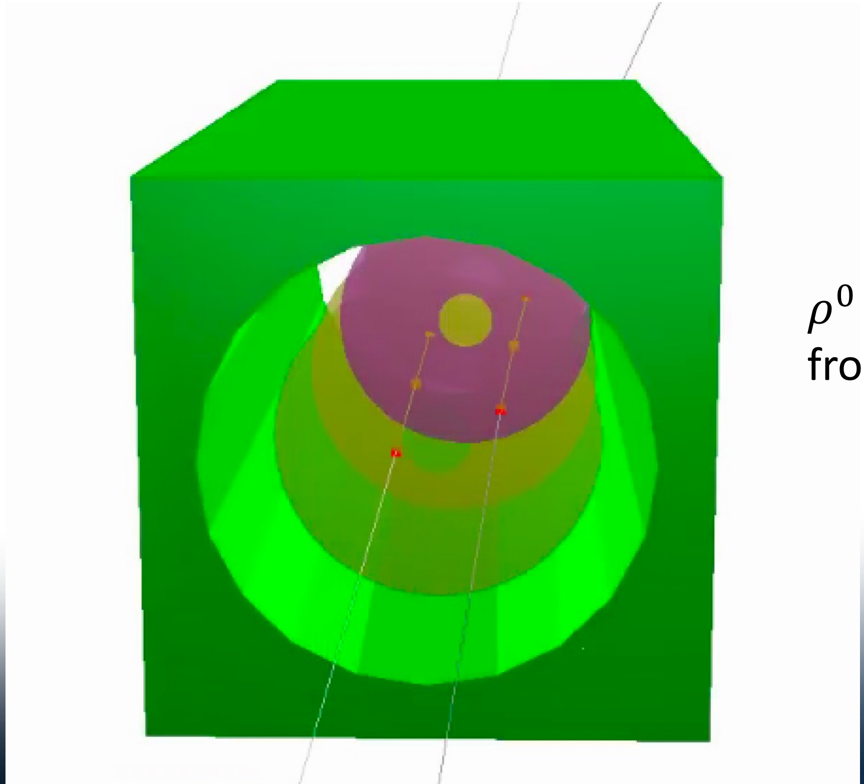
Prospects for Far-Forward Lambda

The importance of the B0 for the meson program

- Needed for measuring final states with θ > 5.5 mrad.
  - Especially important at medium and low hadron beam energies at the EIC.
- Important for incoherent vetoing in e+A (heavy nuclear) collisions.
  - Charged particles and photons.
- The B0 tracking system behaves like a normal spectrometer, so anything which decays with particles in its acceptance can be reconstructed just like in the forward tracking disks!

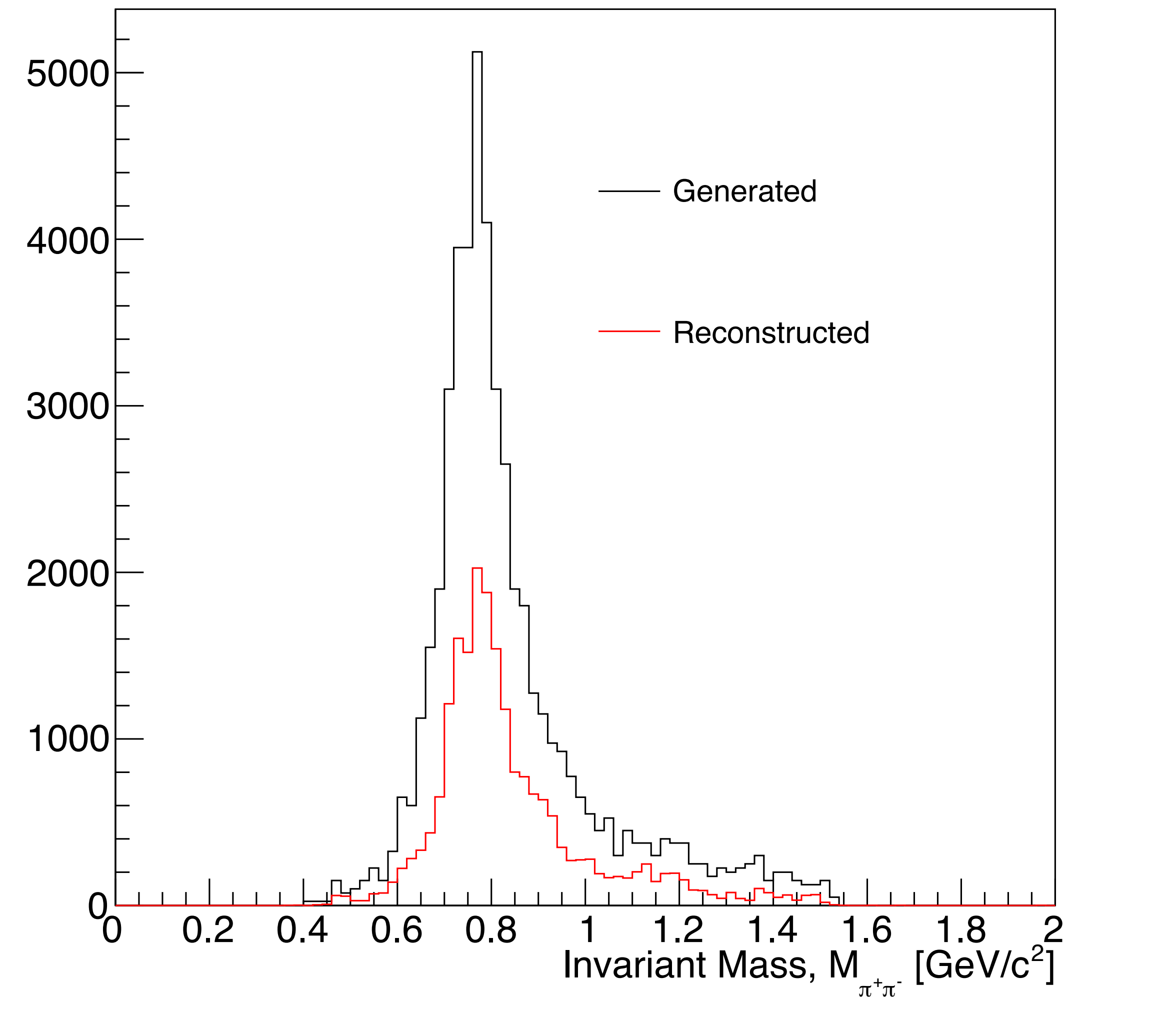
GEANT simulation: 100 GeV proton



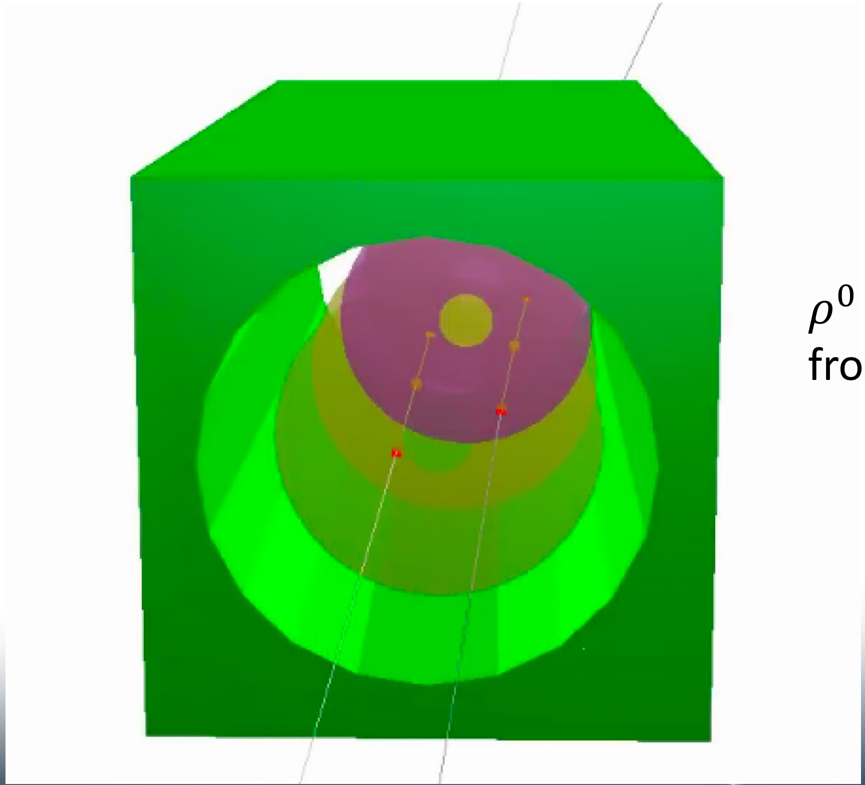


$\rho^0 \rightarrow \pi^+\pi^-$ decay
from u-channel production

The importance of the B0 for the meson program



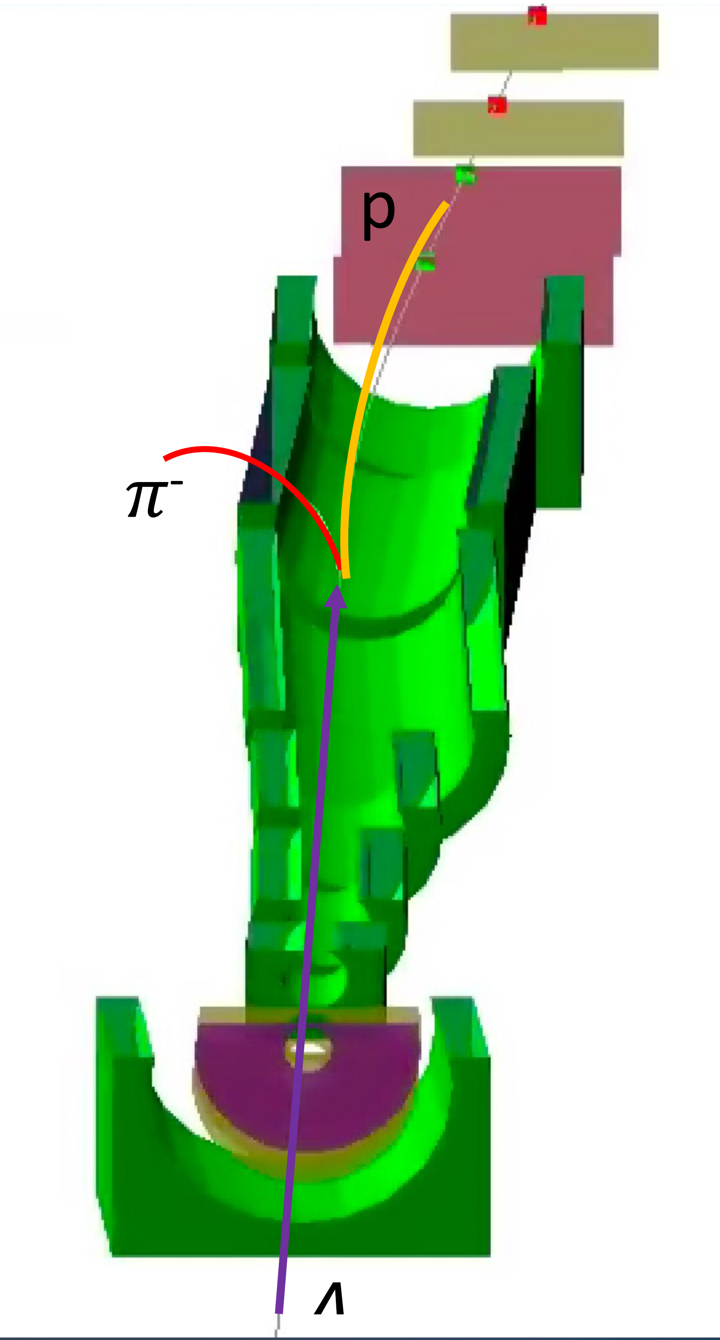
- $\rho^0 \to \pi^+\pi^-$ decay studied with eSTARLight 5x41 events (generated by Zach Sweger).
- Reconstruction performed with EicRoot.



$\rho^0 \to \pi^+\pi^-$ decay
from u-channel production

Lambda Decay (p + π^-)

- Boost causes the lambda to be able to decay 10s of meters from the IP.
  - Significant problem since reconstruction of this displaced secondary vertex within the hadron magnets is very challenging.



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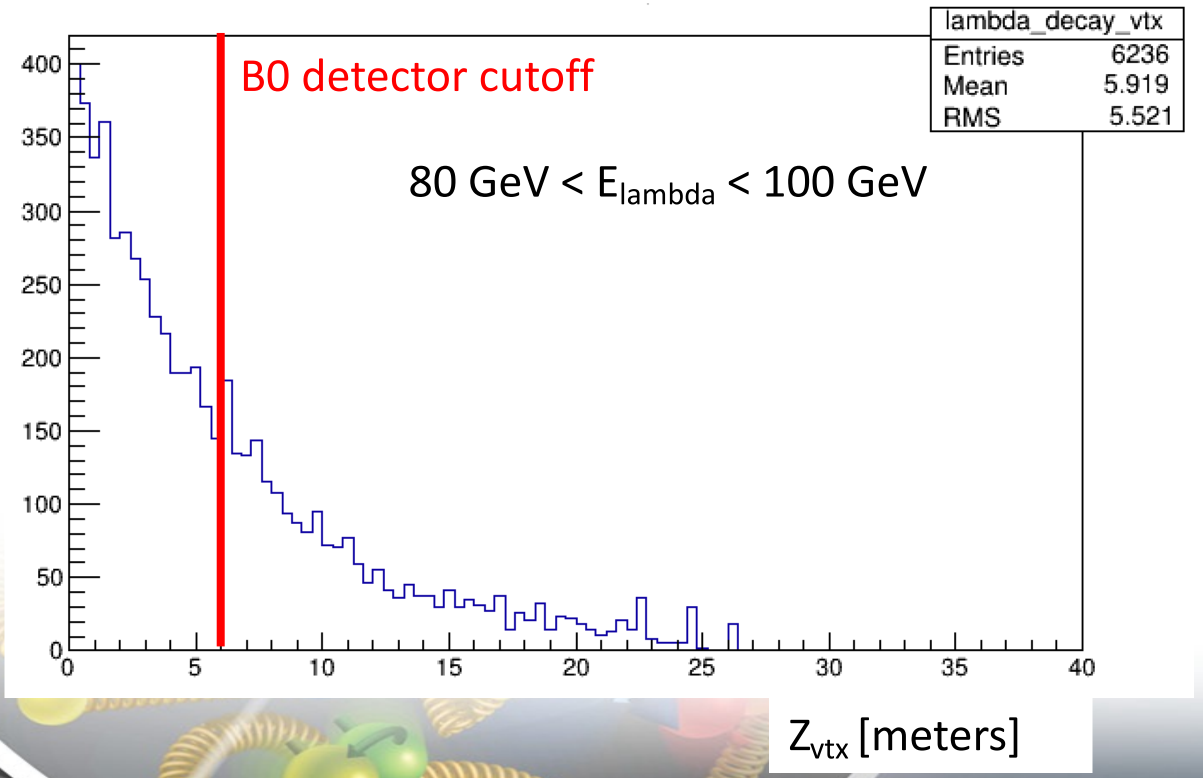

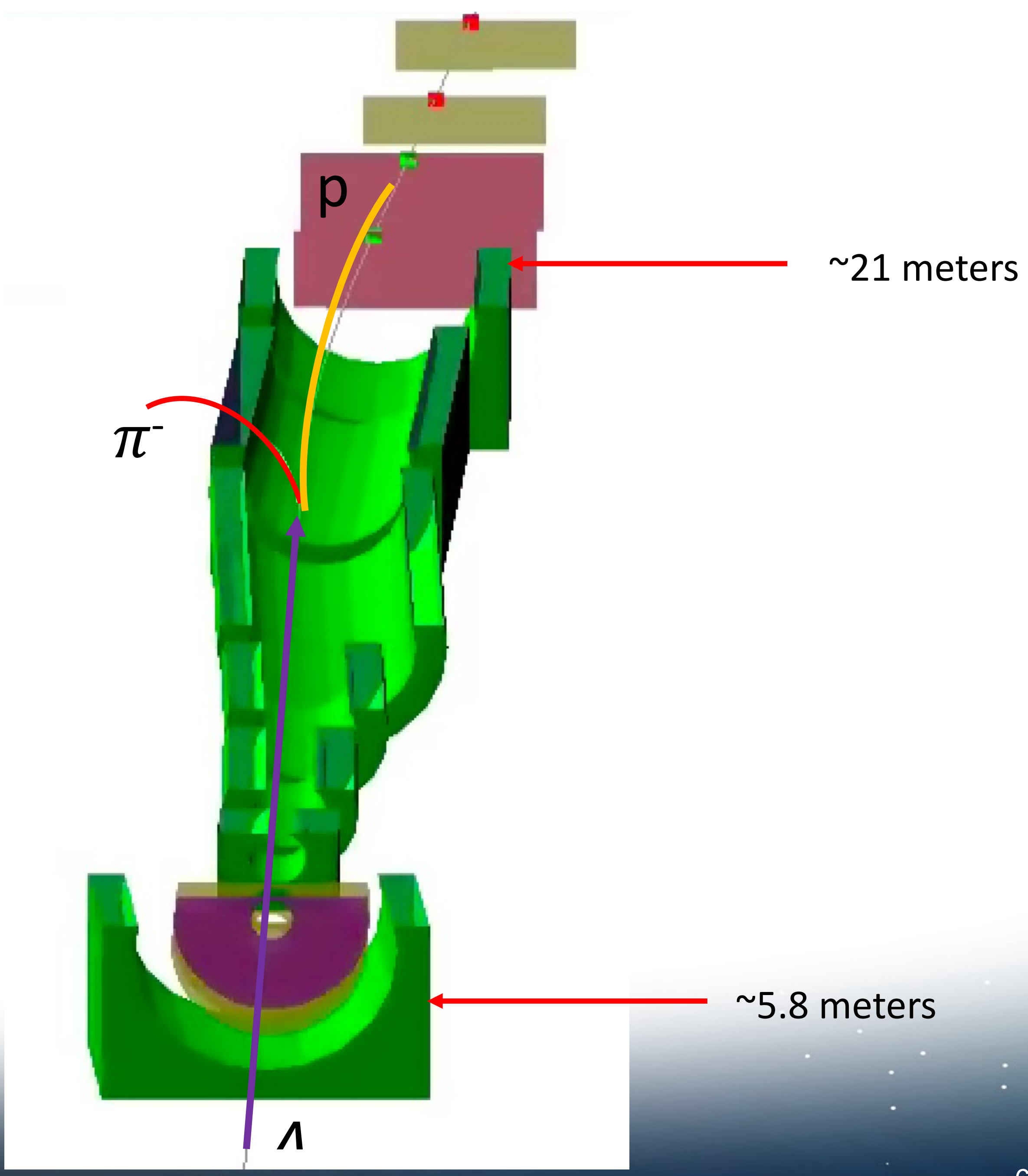

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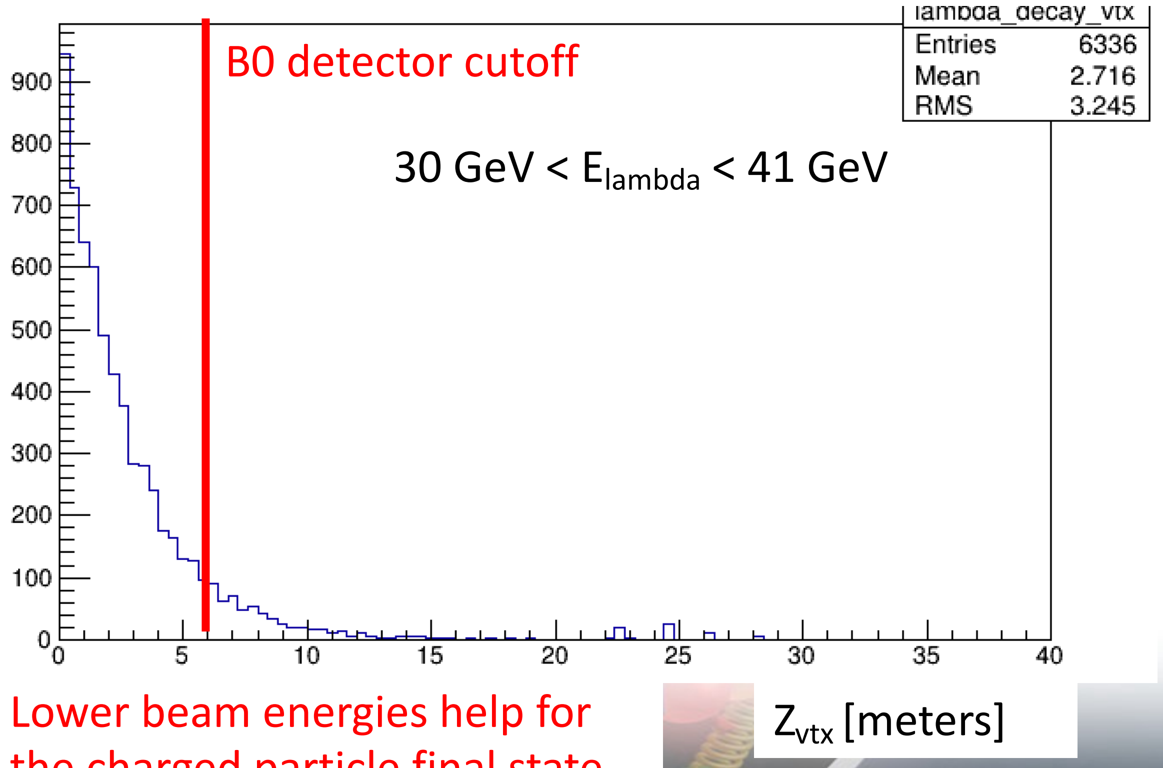
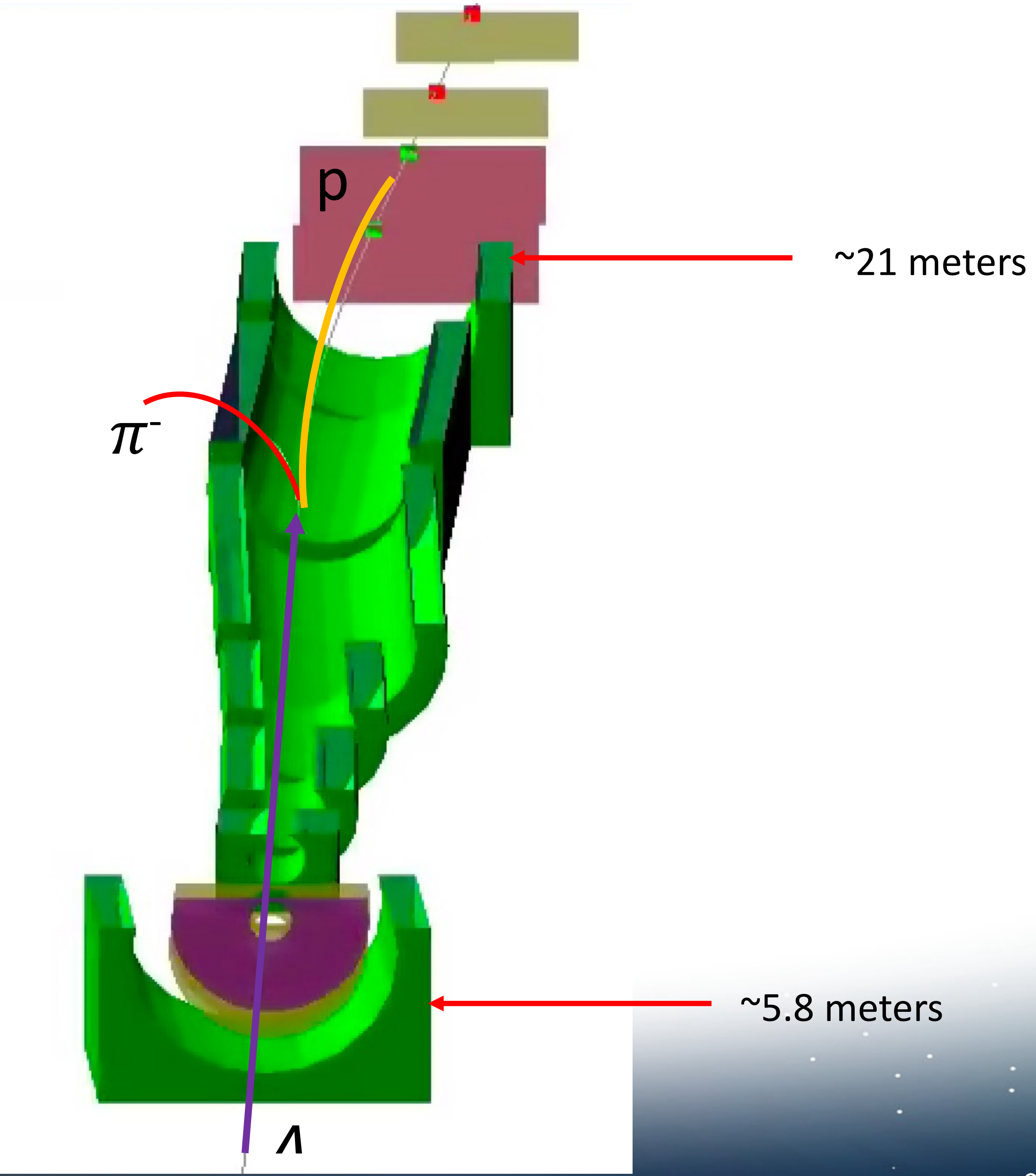
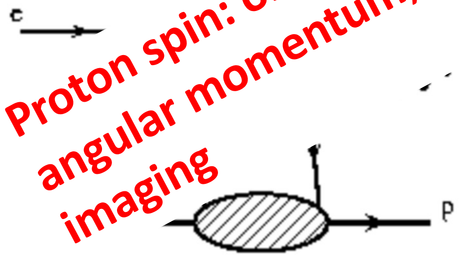


Lower beam energies help for the charged particle final state.



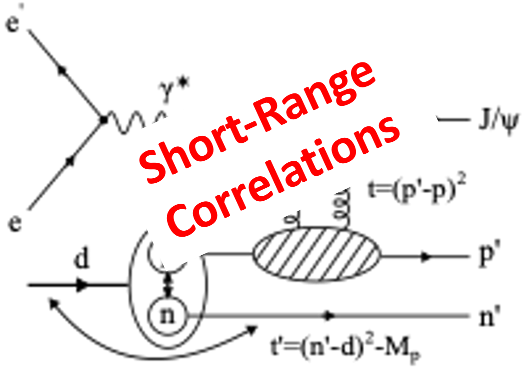
(some) Far-Forward **Physics** at the EIC

e+p DVCS



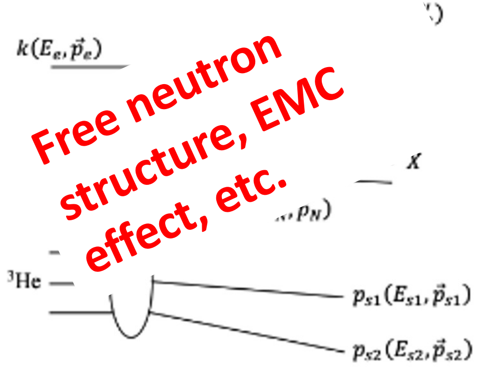
Proton spin: orbital angular momentum; imaging

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



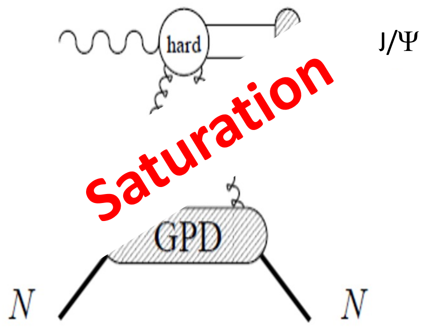
Short-Range Correlations

spectator tagging in light nuclei



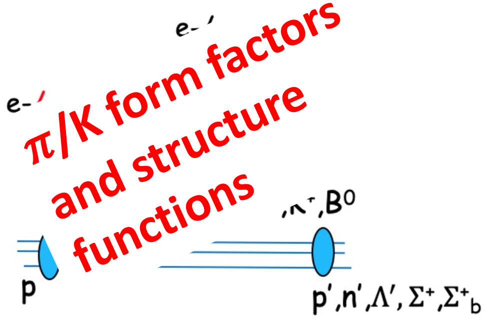
Free neutron structure, EMC effect, etc.

coherent/incoherent J/ψ production in e+A



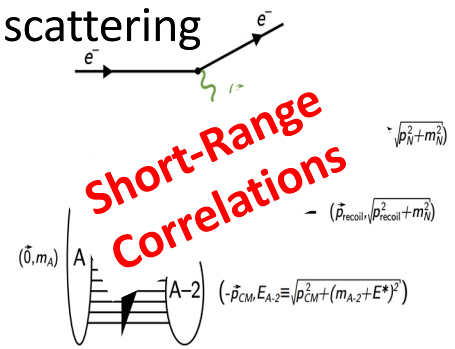
Saturation

Sullivan process



π/K form factors and structure functions

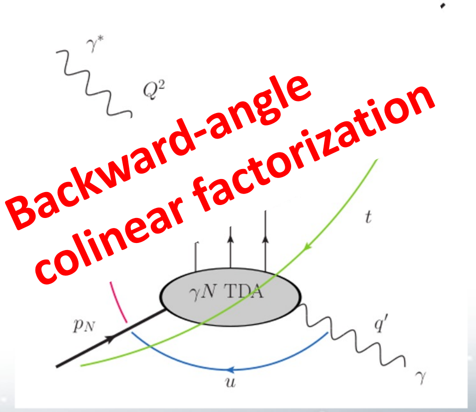
Quasi-elastic electron scattering



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

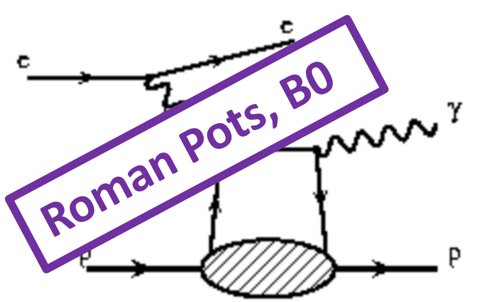


Backward-angle colinear factorization

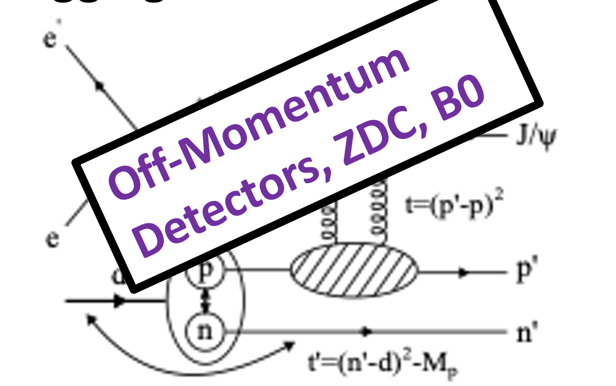
…and MANY more!

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

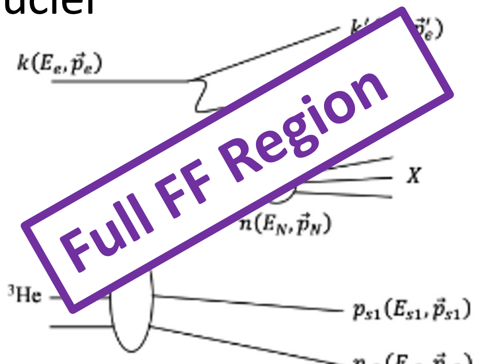
e+p DVCS



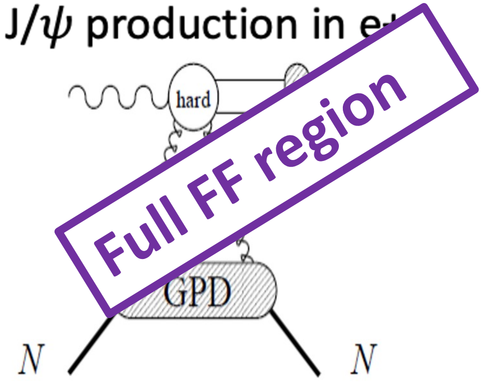
e+d exclusive J/Psi with p/n tagging



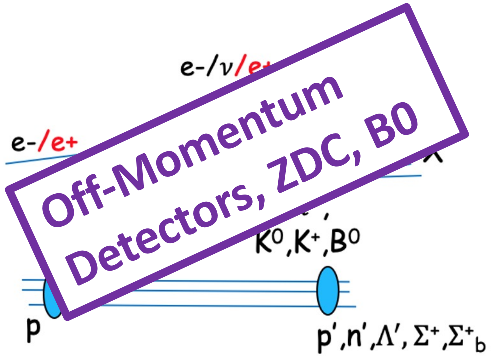
spectator tagging in light nuclei



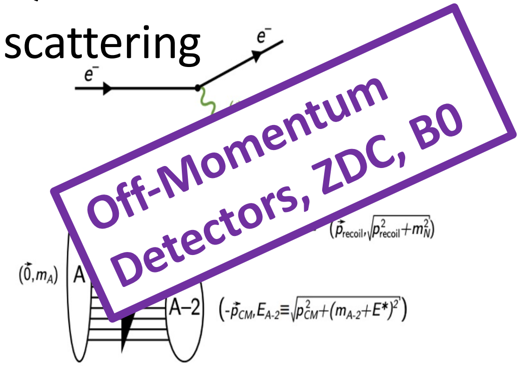
coherent/incoherent J/ψ production in e



Sullivan process



Quasi-elastic electron scattering



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

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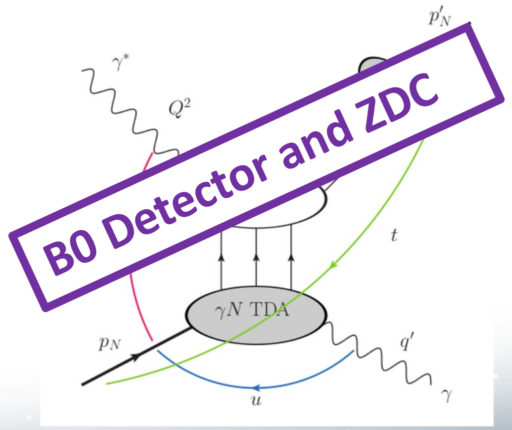


…and MANY more!

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

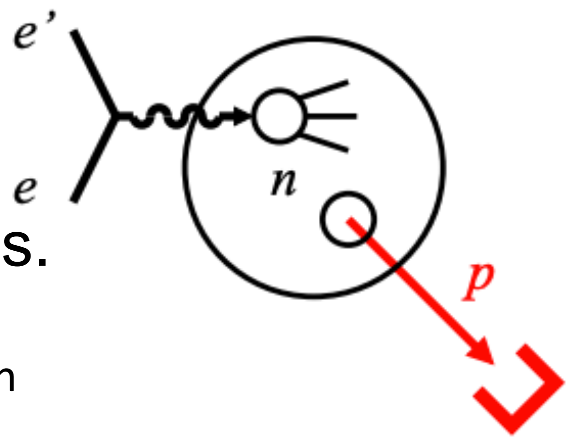
Subscribe to mailing list through: https://lists.bnl.gov/mailman/listinfo/eic-projdet-farforw-l

ePIC

Backup

Neutron Structure

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



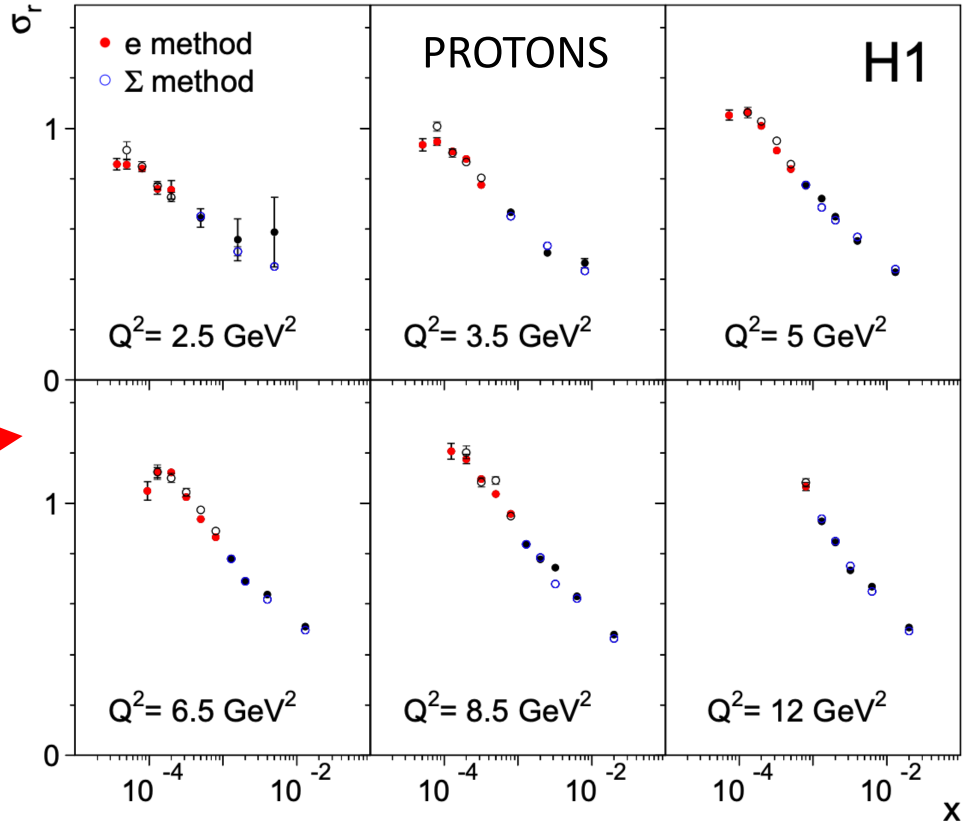
$$\sigma_r = \frac{Q^4 x}{2\pi\alpha^2[1+(1-y)^2]} \cdot \frac{d^2\sigma}{dx\, dQ^2} = F_2(x,Q^2) - f(y)\cdot F_L(x,Q^2)$$

Reduced cross section

"Flux factor" Differential cross section Structure functions

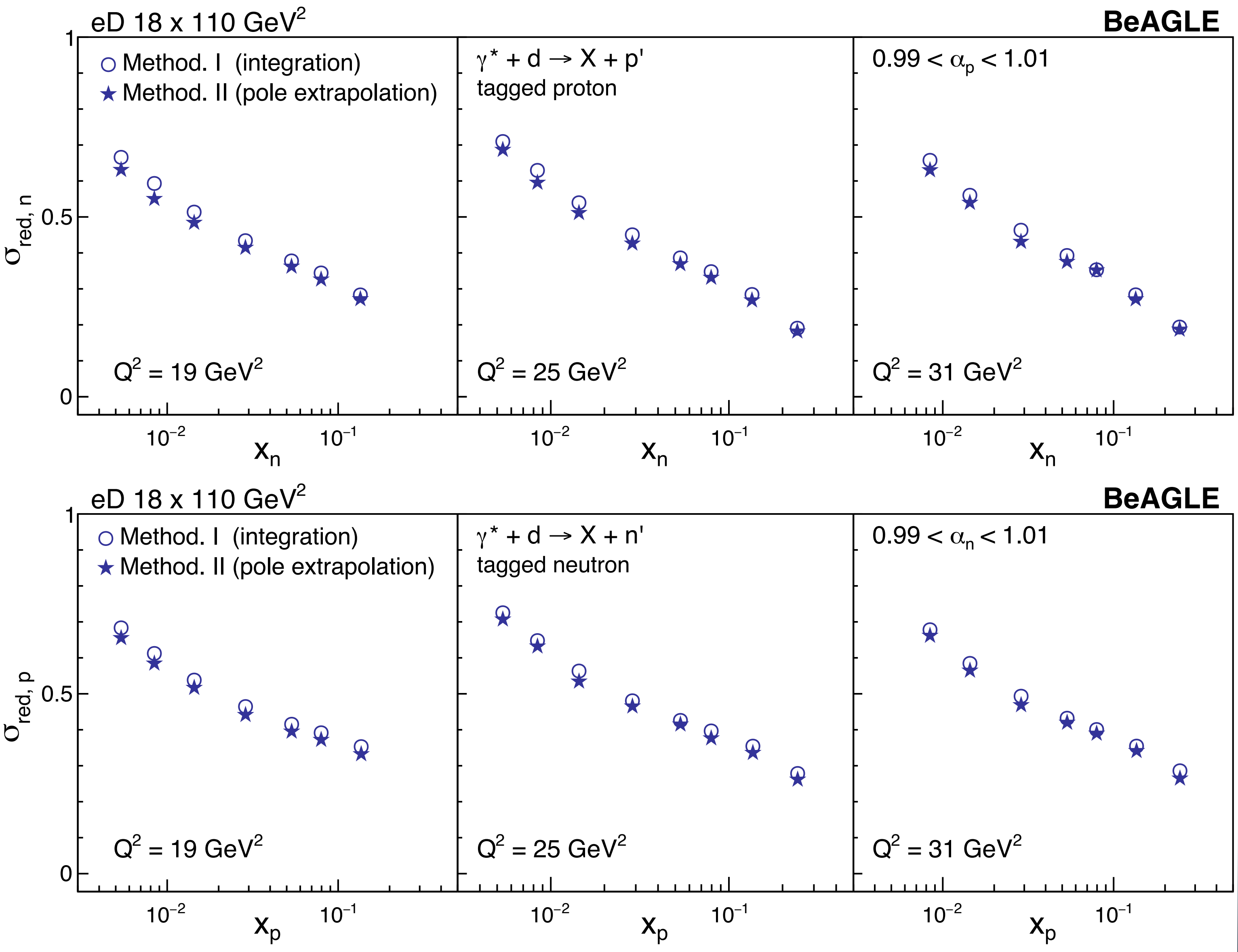
Some useful HERA references for measurements on proton

- 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)**

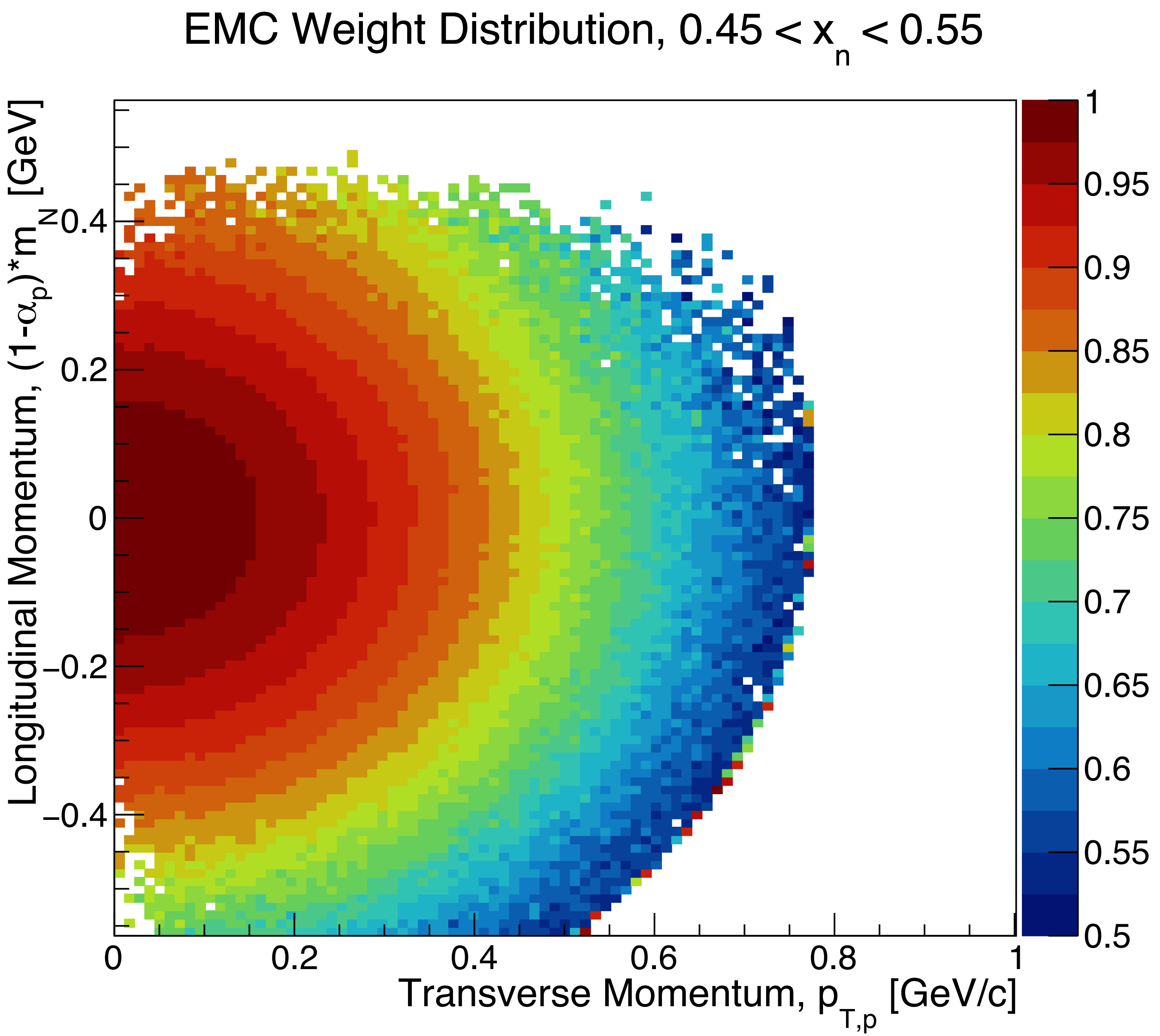


<u>Open circles:</u> "inclusive" measurement.
<u>Stars:</u> pole extrapolation procedure.

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!

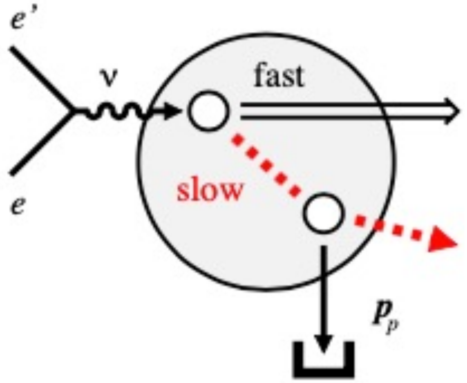
Simulating the EMC Effect in BeAGLE

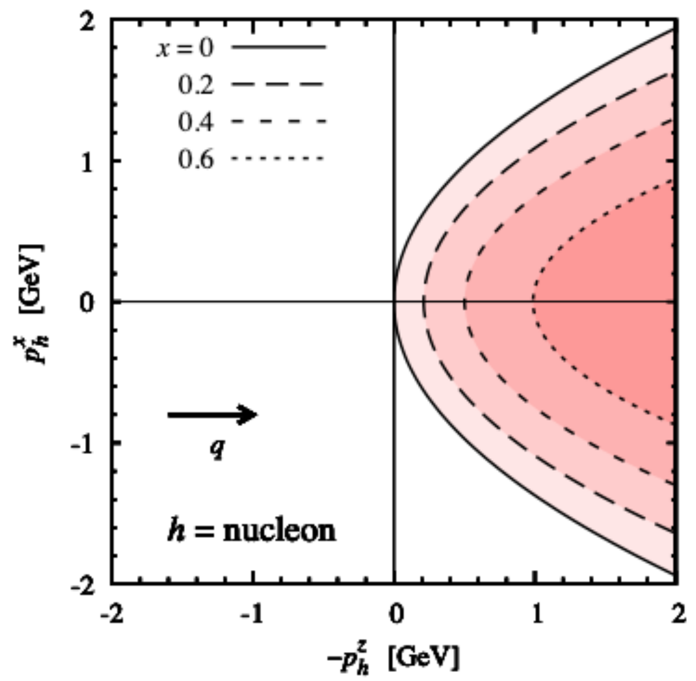


<u>Result → EMC Weight in BeaGLE</u>

- 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.

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

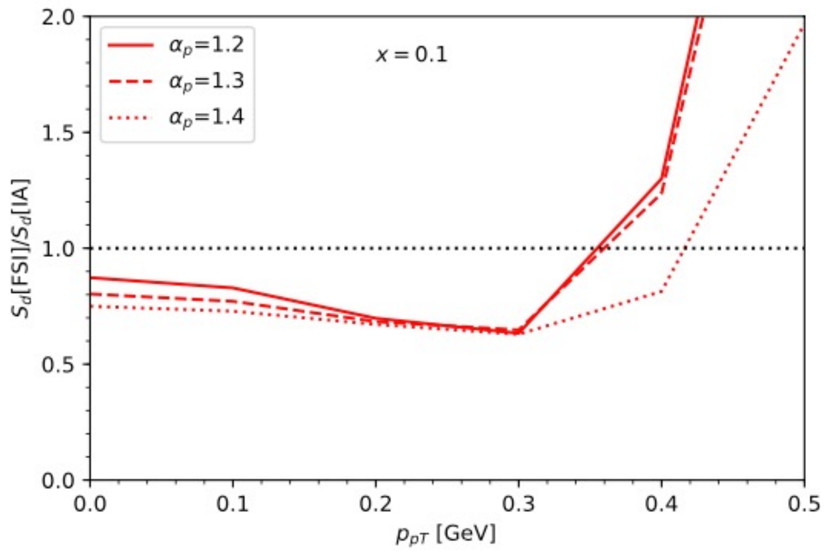
- $\nu \gg$ hadronic scale: large phase space for hadron production.
- "Fast" hadrons $E_h = \mathcal{O}(\nu)$ → current fragmentation region: Formed outside the nucleus, interaction with the spectator suppressed.
- "Slow" hadrons $E_h = \mathcal{O}(1\ GeV)$ → target fragmentation region: Formed inside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

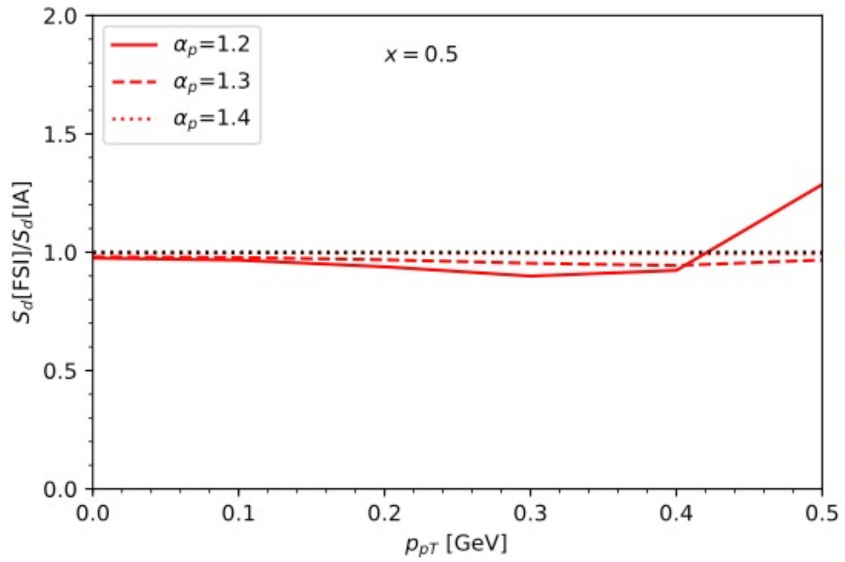
Implementation

- 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

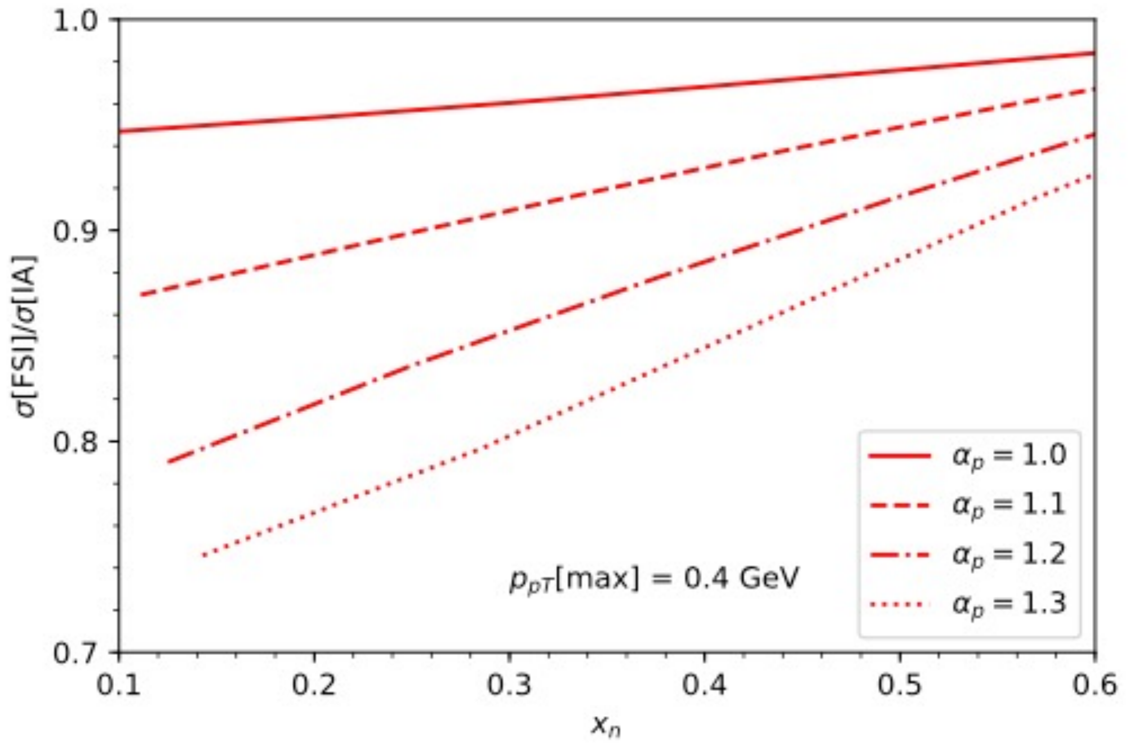
FSI: Kinematic Dependence





- 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

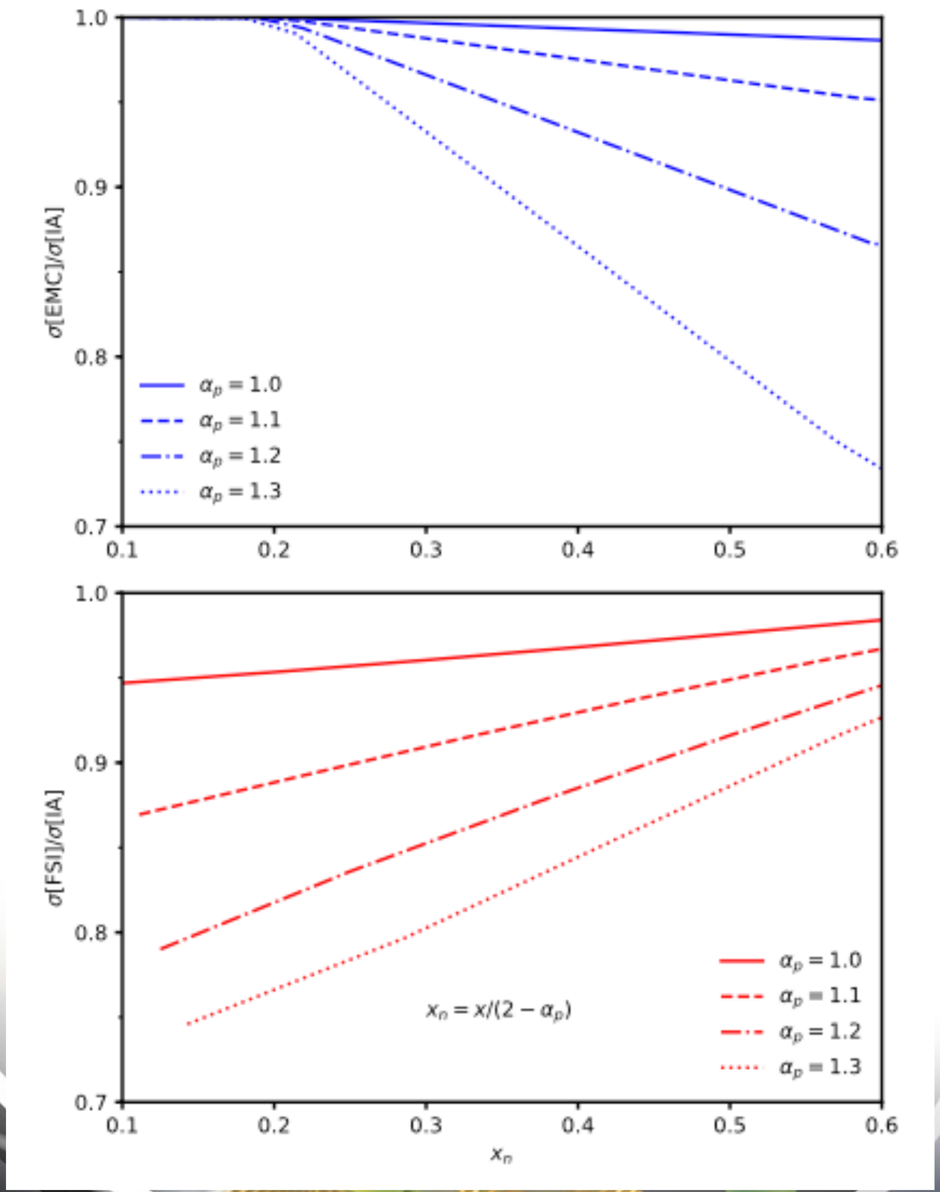


- p_{pT} - integrated cross section:

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

- 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!

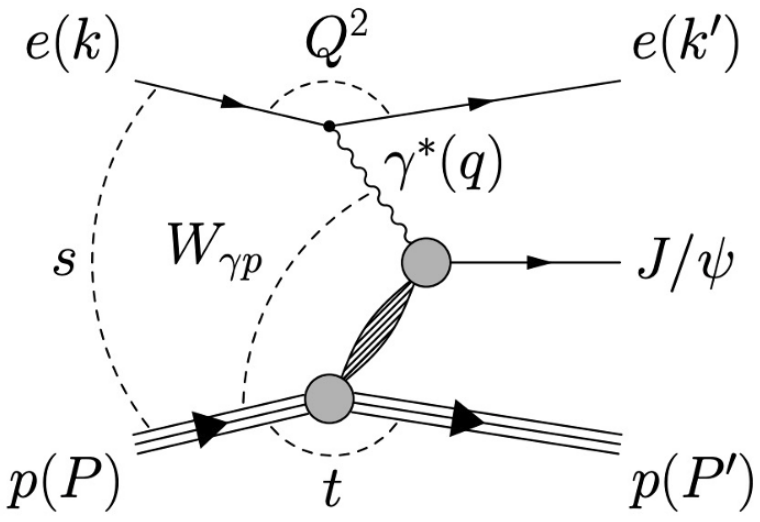
Measuring t-distribution

From K. Tu @ DIS 2023:
https://indico.cern.ch/event/1199314/contributions/5189840/attachments/2621029/4531556/ePIC-exclusive-slides-Tu-v3.pdf

Reconstruction method of $-t$

- Method Exact (E): $-t = -(\boldsymbol{p}_{e}-\boldsymbol{p}_{e'}-\boldsymbol{p}_{VM})^2 = -(\boldsymbol{p}_{A'} - \boldsymbol{p}_{A})^2$
- Method Approximate (A) (UPCs) $-t = (p_{T,e'}+p_{T,VM})^2$
- Method with **exclusivity corrected** (L): $-t = -(\boldsymbol{p}_{A',corr} - \boldsymbol{p}_{A})^2$,

where $\boldsymbol{p}_{A',corr}$ is constrained by exclusive reaction.



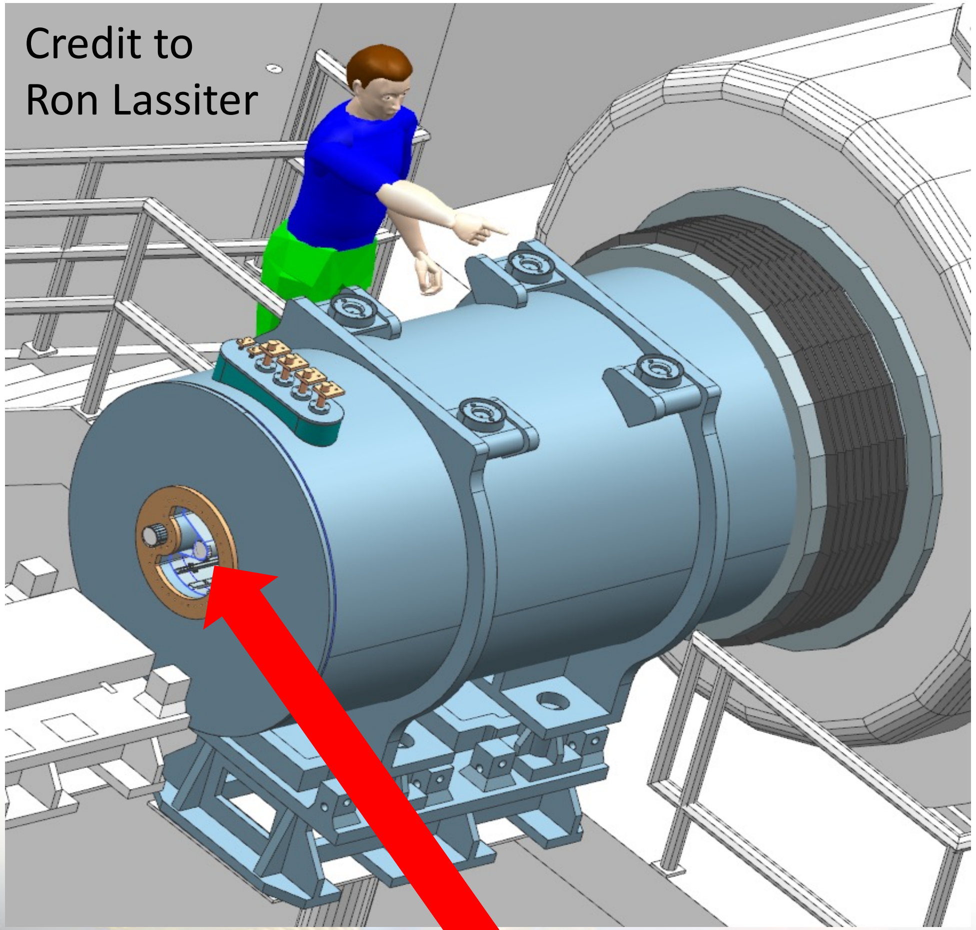
Best method concluded from the EIC Yellow Report* is with **exclusivity corrected**:

- Insensitive to beam effects, e.g., angular divergence and momentum spread.
- More precise than Method A for electroproduction

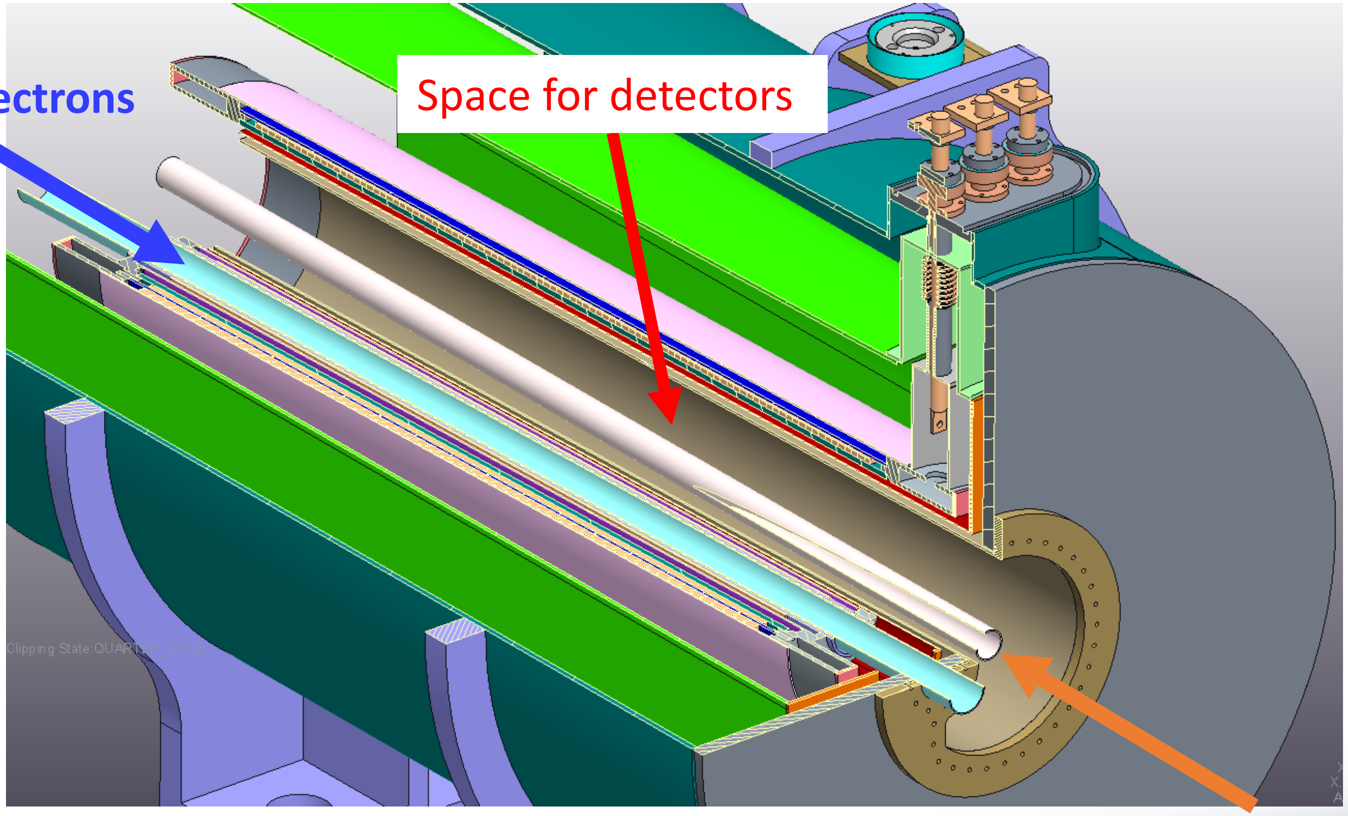
* *also known as `**Method L**` in the Yellow Report*

B0 Detectors

- Detector subsystem embedded in an accelerator magnet.



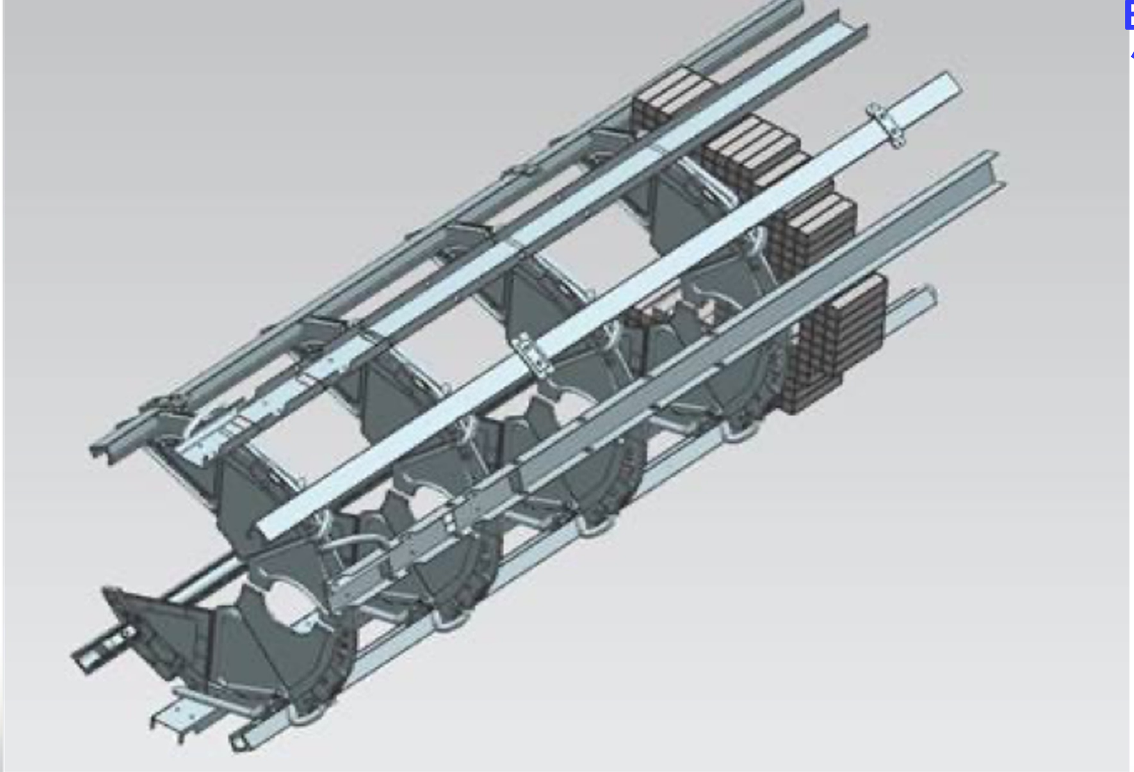
This is the opening where the detector planes will be inserted

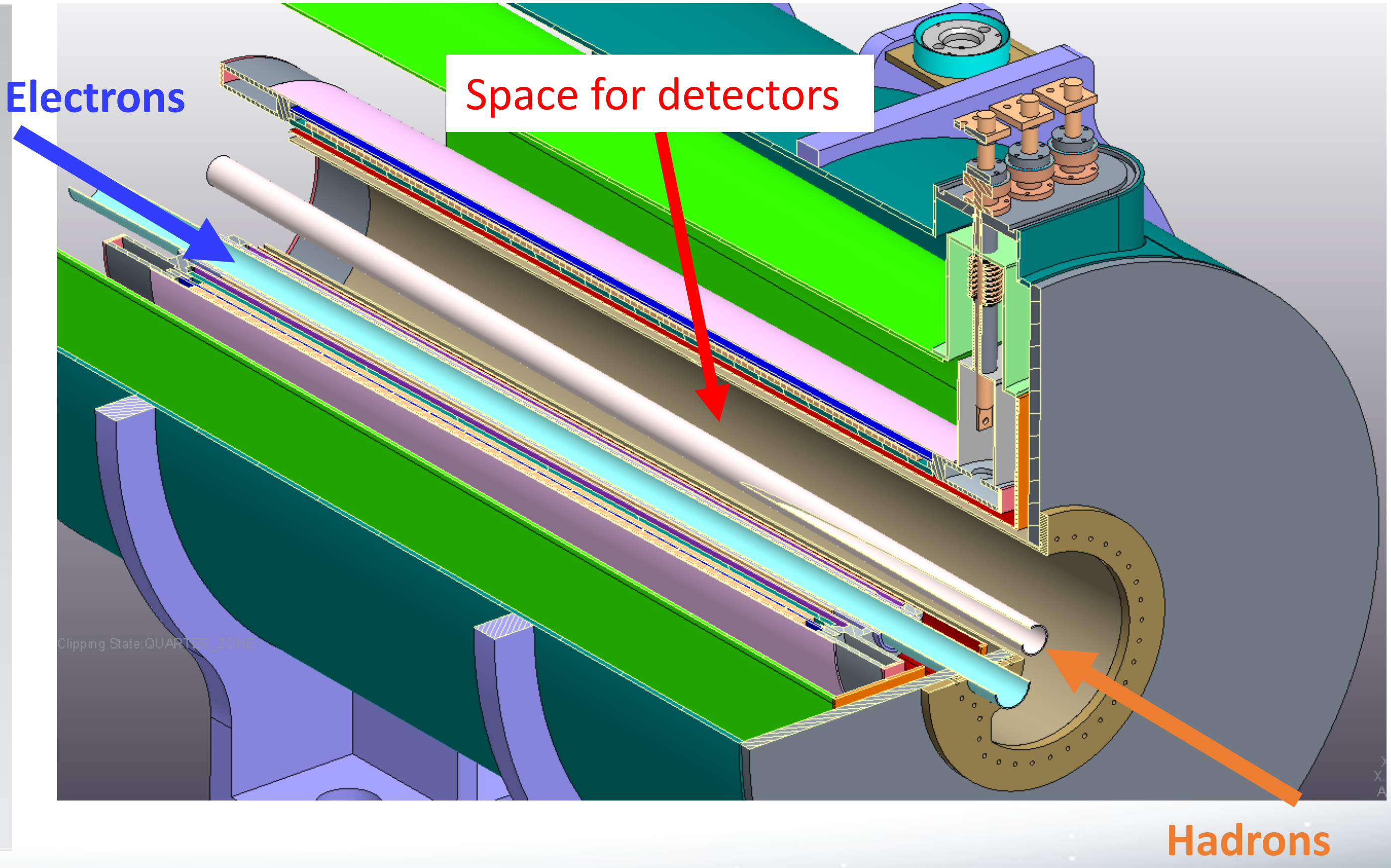


B0 Detectors

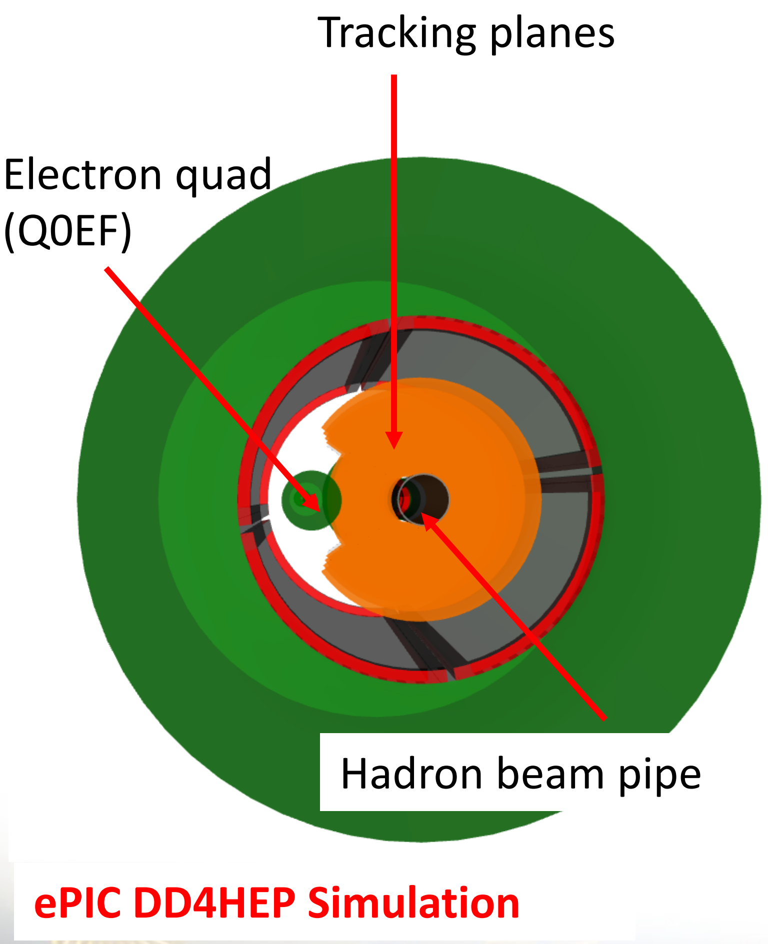
- Detector subsystem embedded in an accelerator magnet.

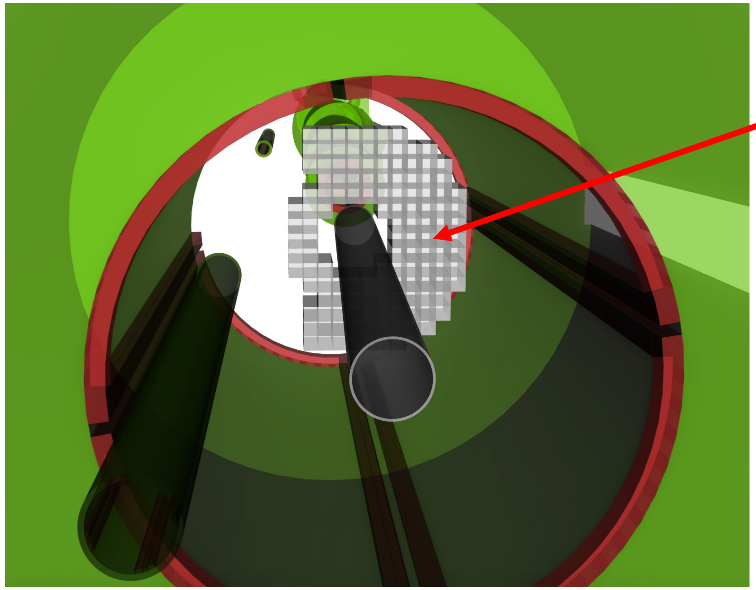
Karim Hamdi and Ron Lassiter





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

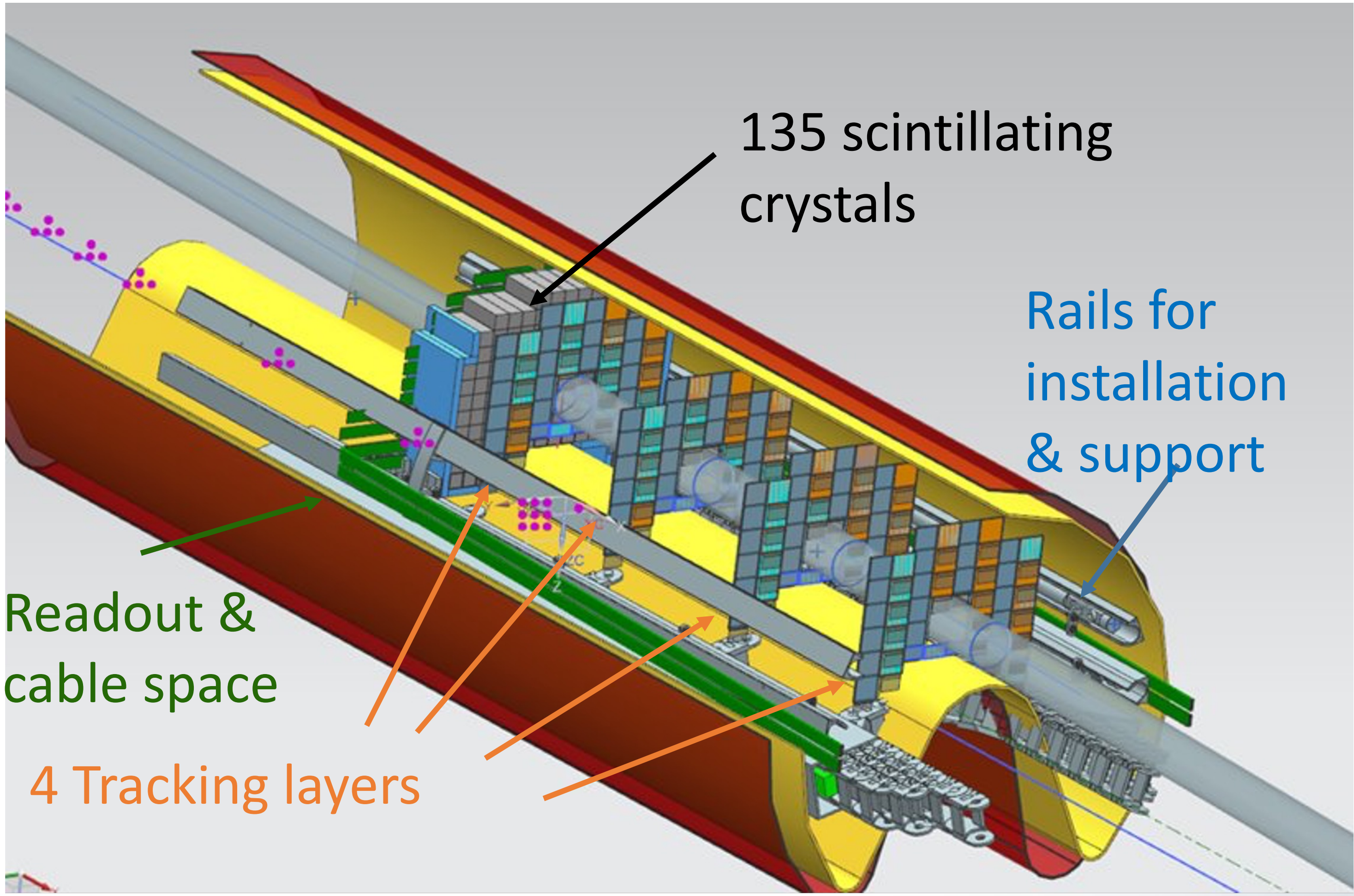
Design for two detectors is converging:

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

BeeDetectors - Simulation Studies

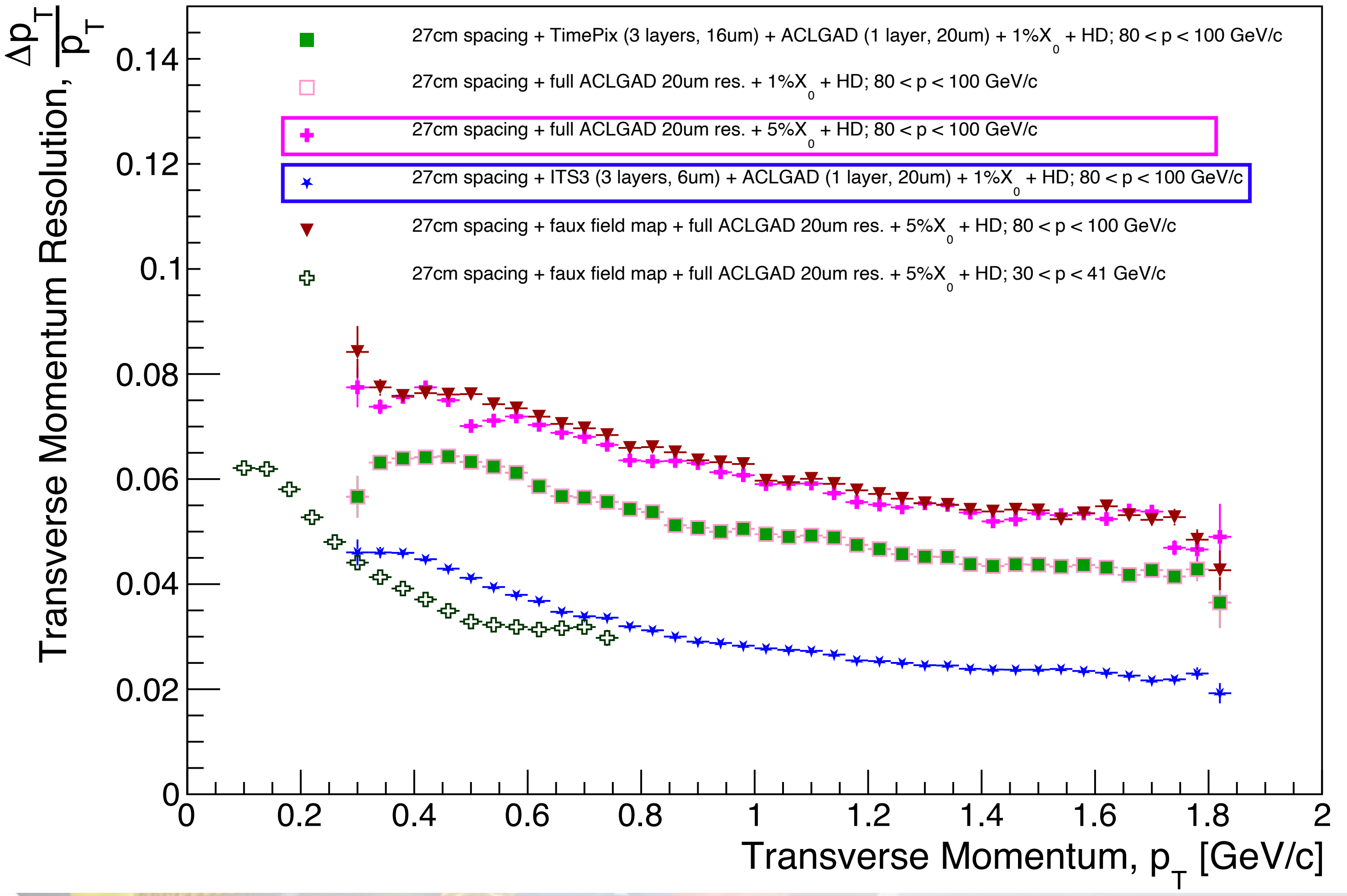
Si Tracker:

- 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)

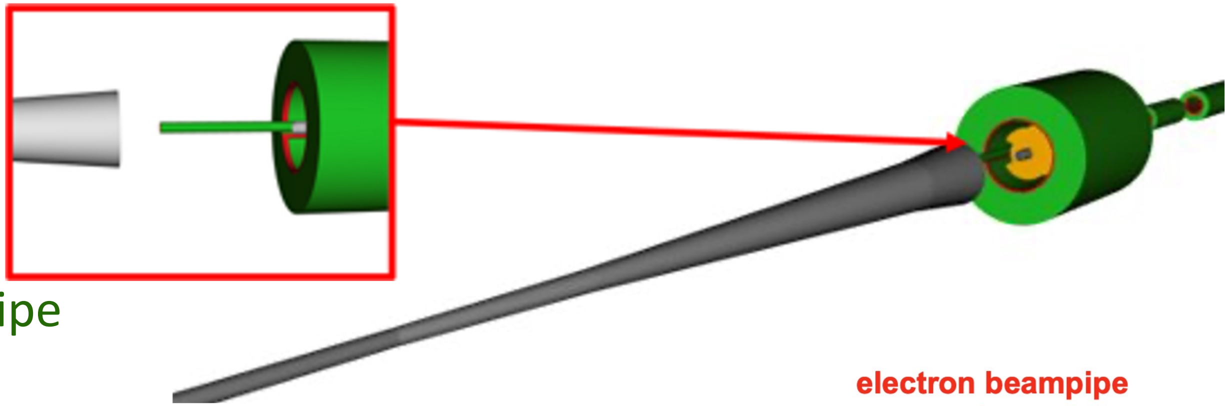
BEE Tracking - Performance



- 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.

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

B0 EMCal - Performance



- Acceptance 5.5 < θ < 23 mrad
- Very low material budget in 5 < η < 5.5

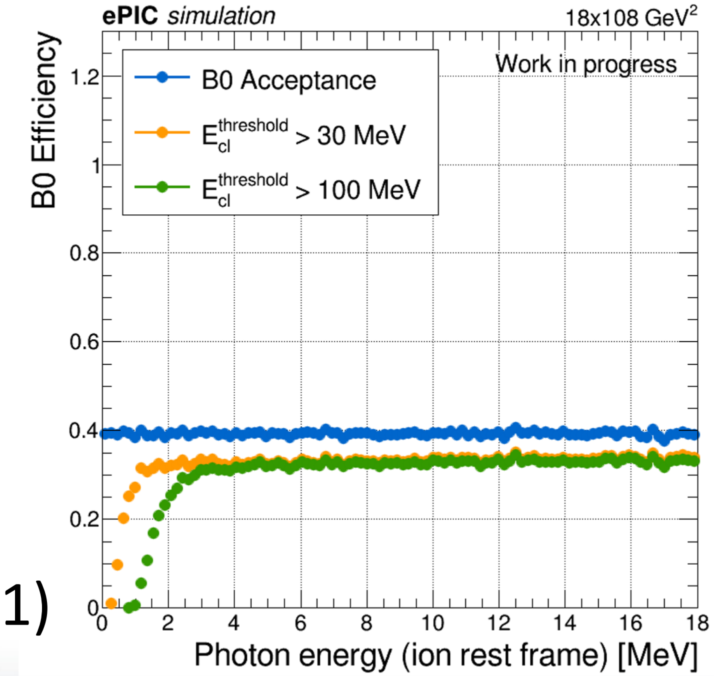
Particles within 5.5 < θ < 15 mrad don't cross the beampipe

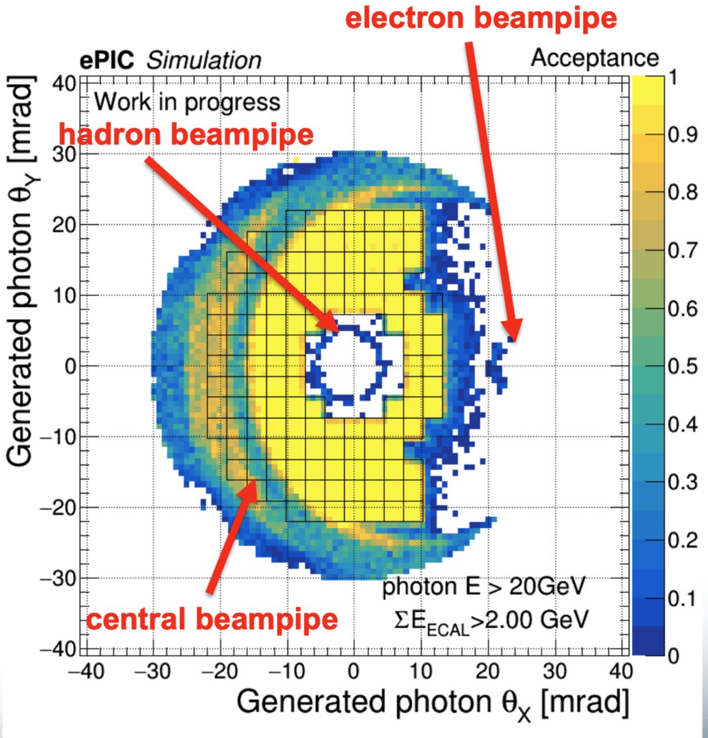
Photons:

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

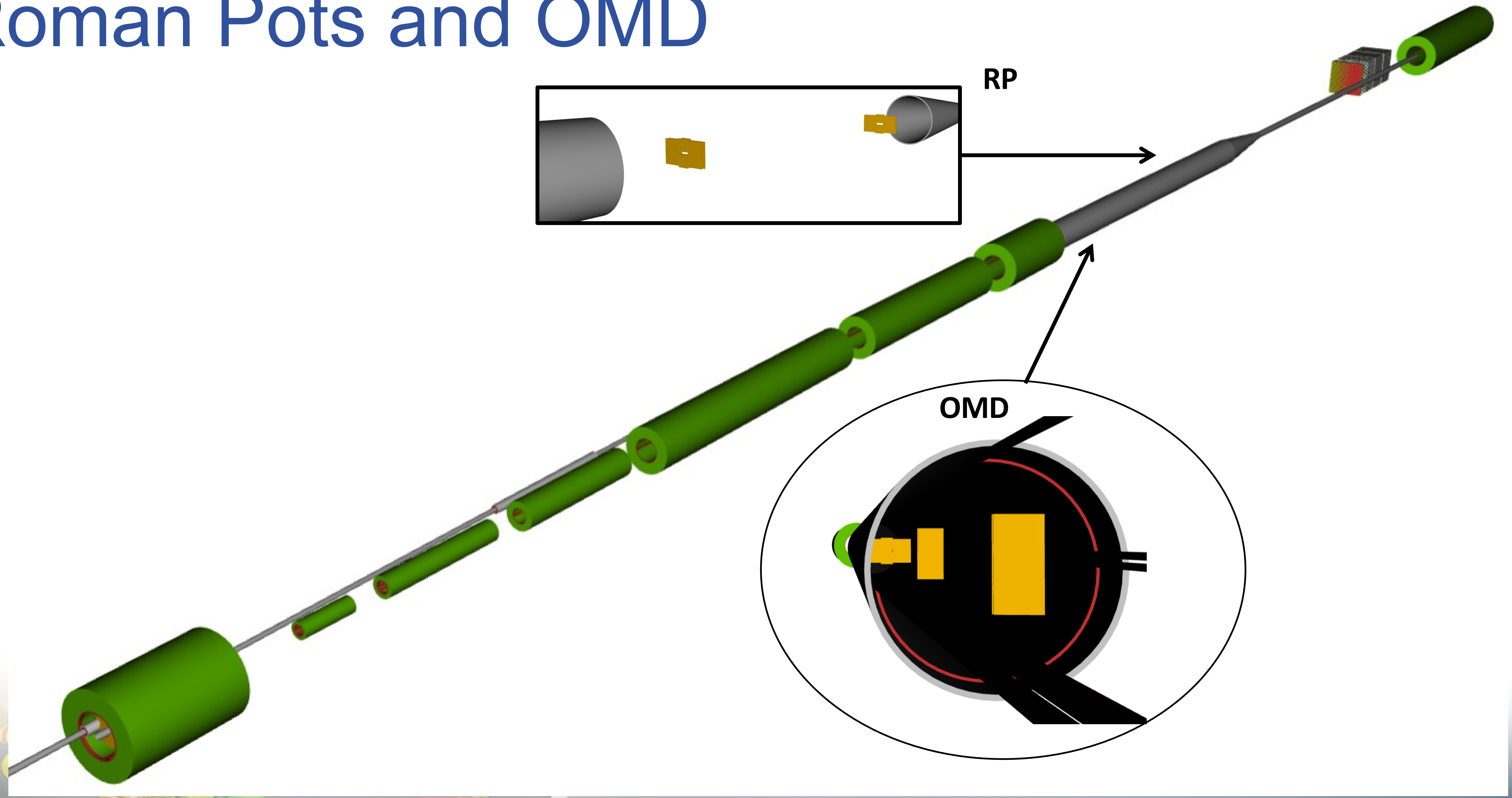
Neutrons:

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

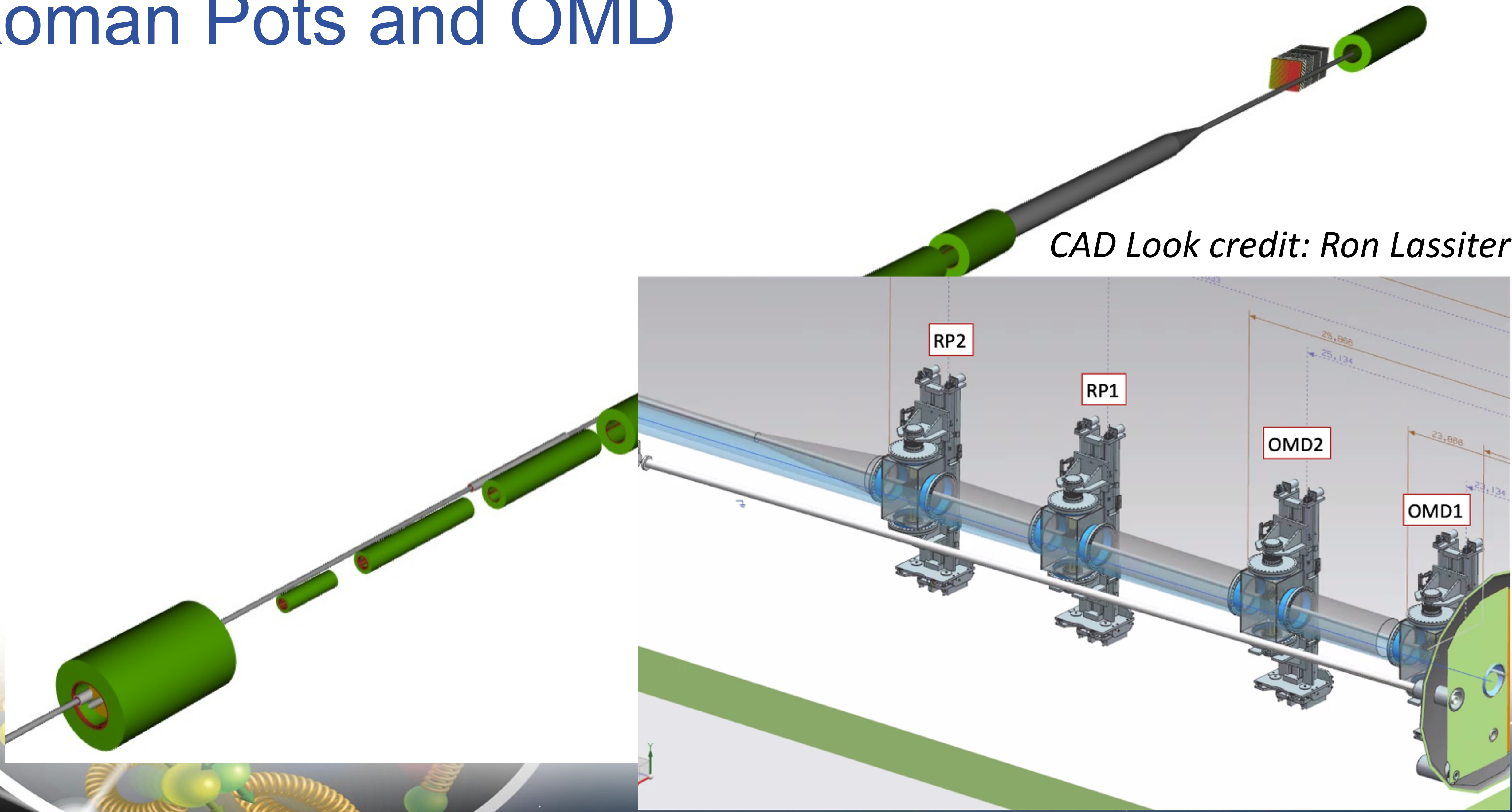




Roman Pots and OMD

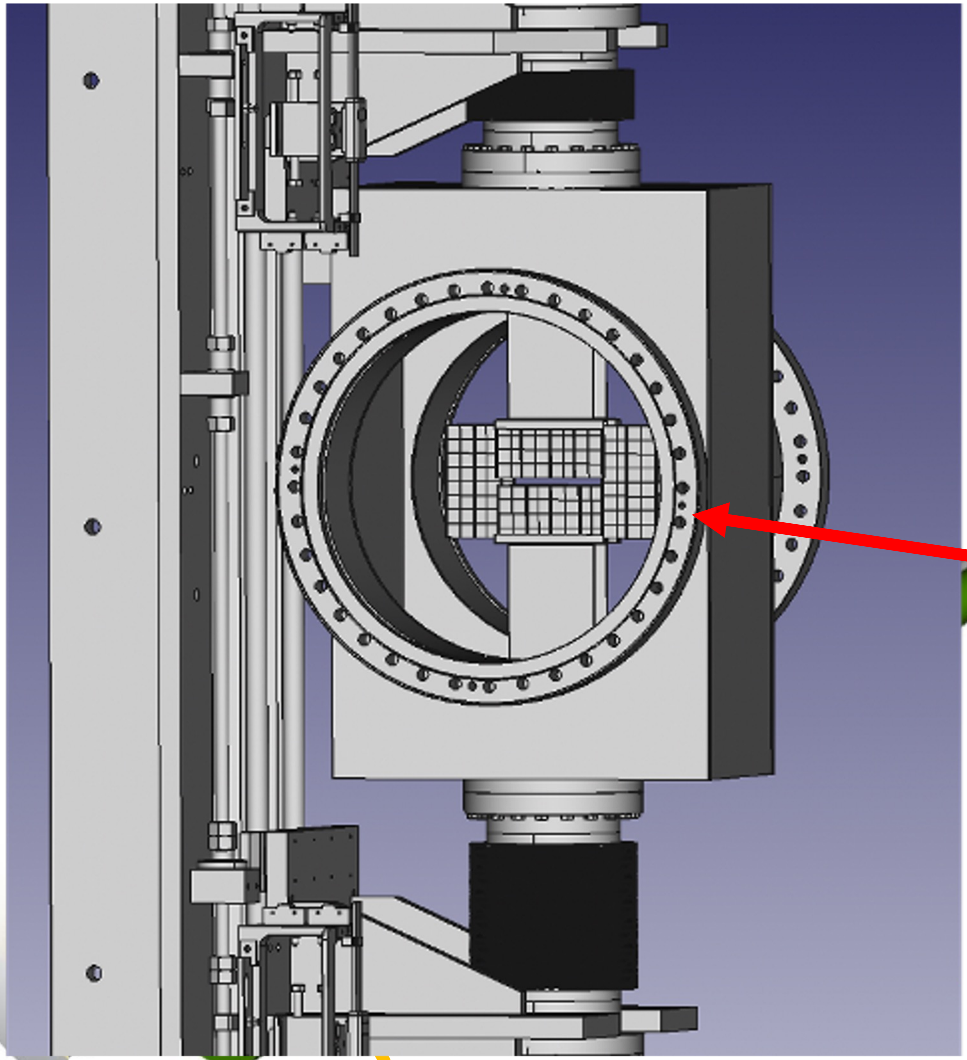


Roman Pots and OMD

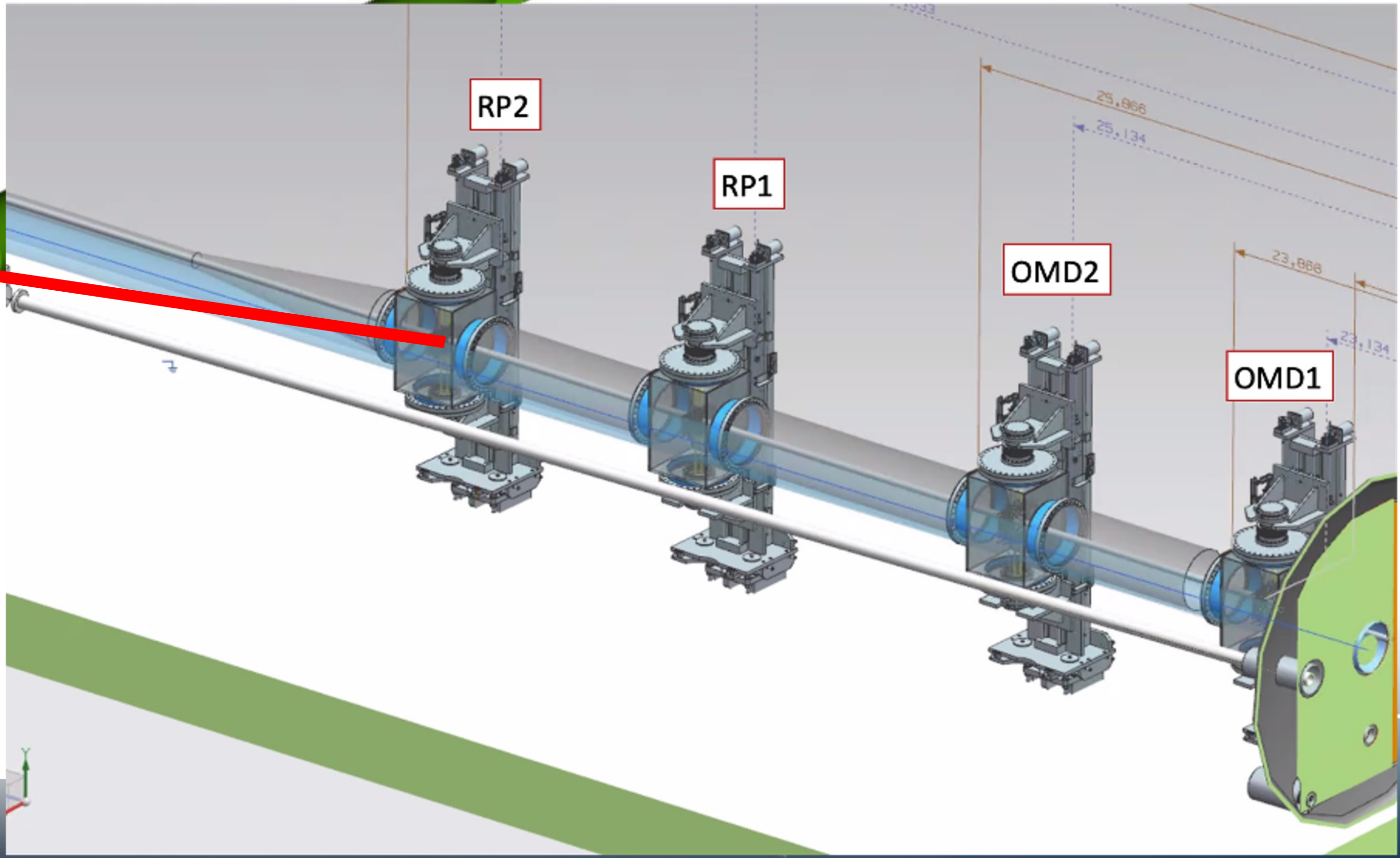


CAD Look credit: Ron Lassiter

Roman Pots and OMD



CAD Look credit: Ron Lassiter



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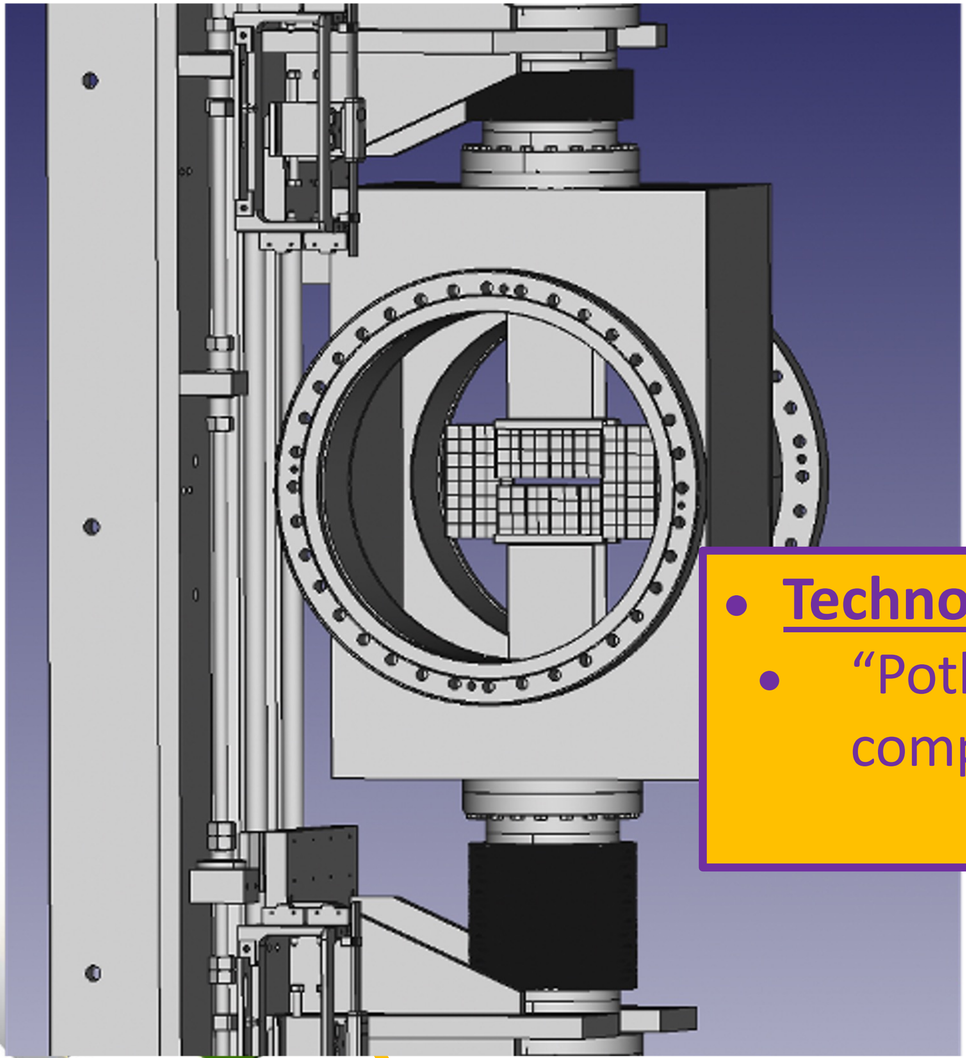
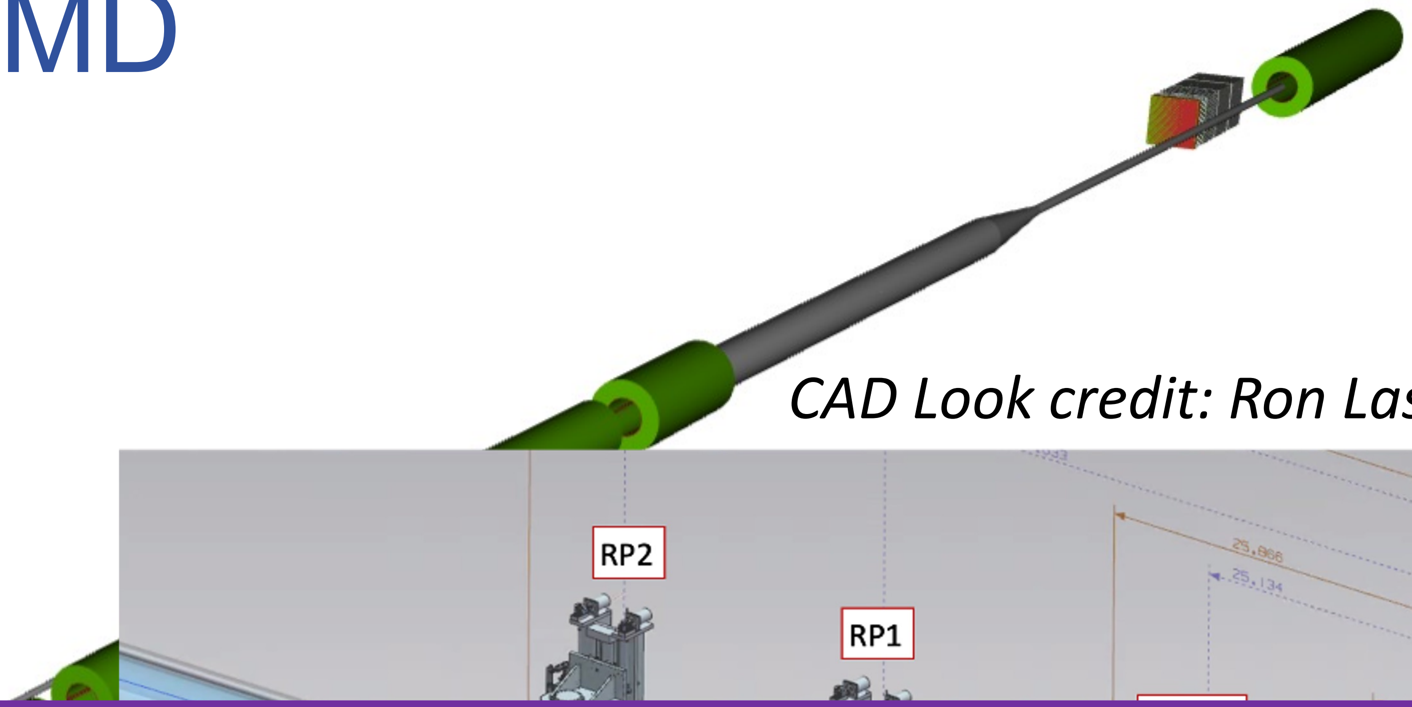
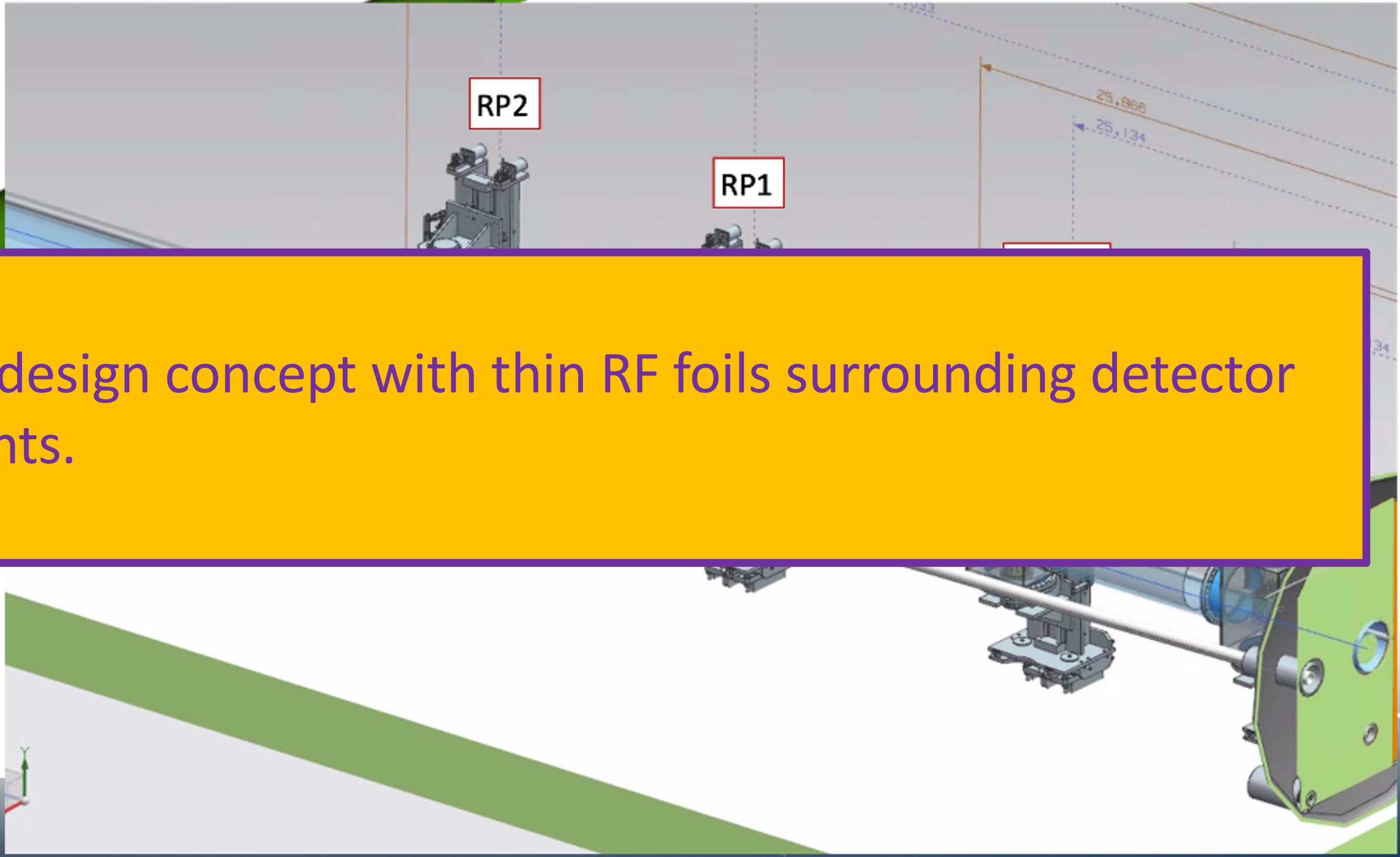


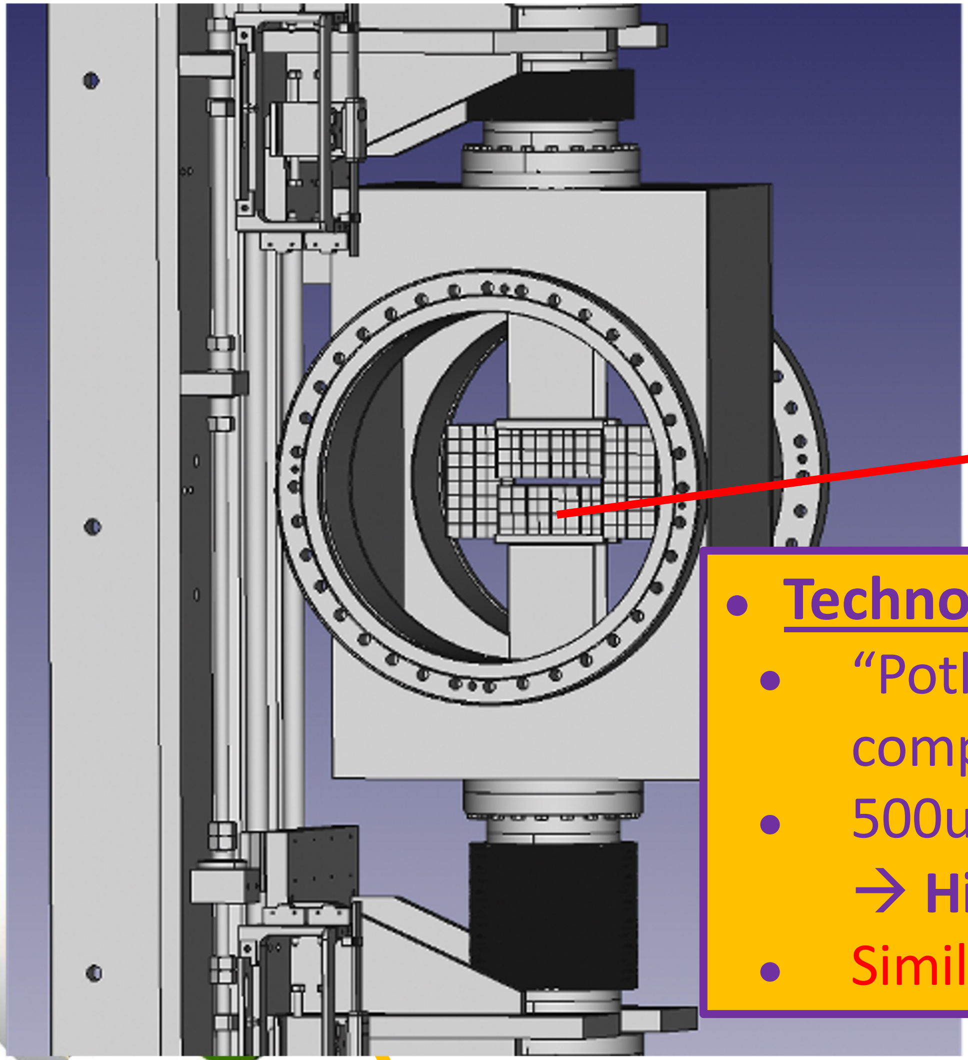


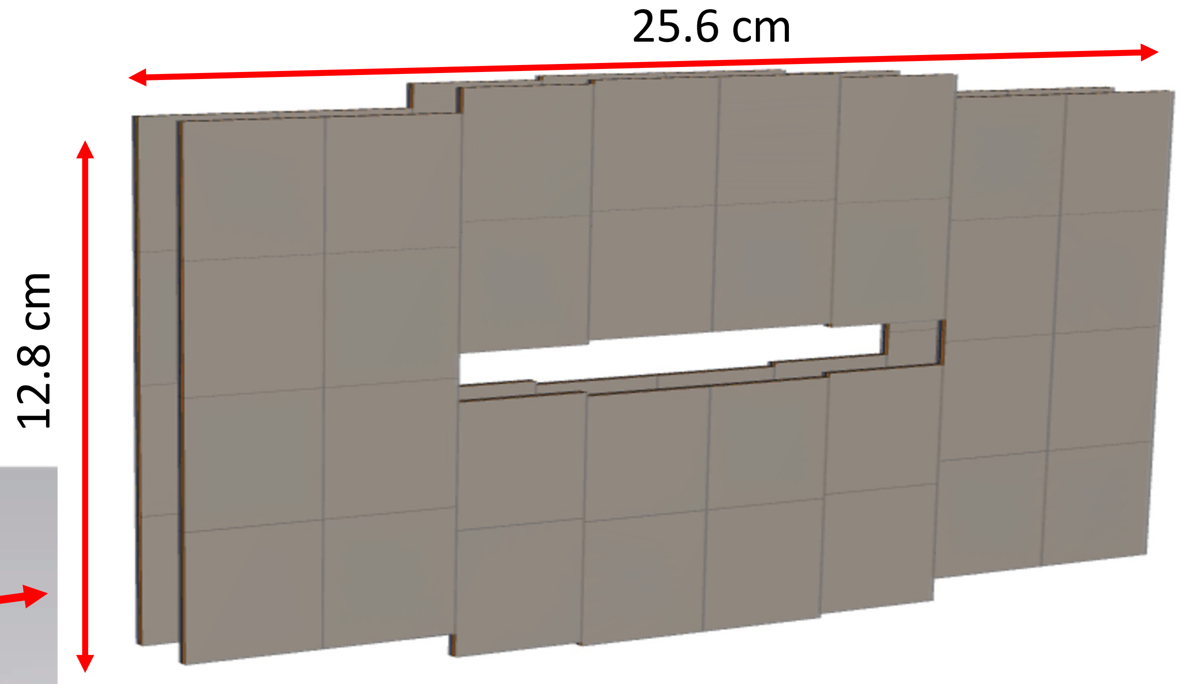
CAD Look credit: Ron Lassiter



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

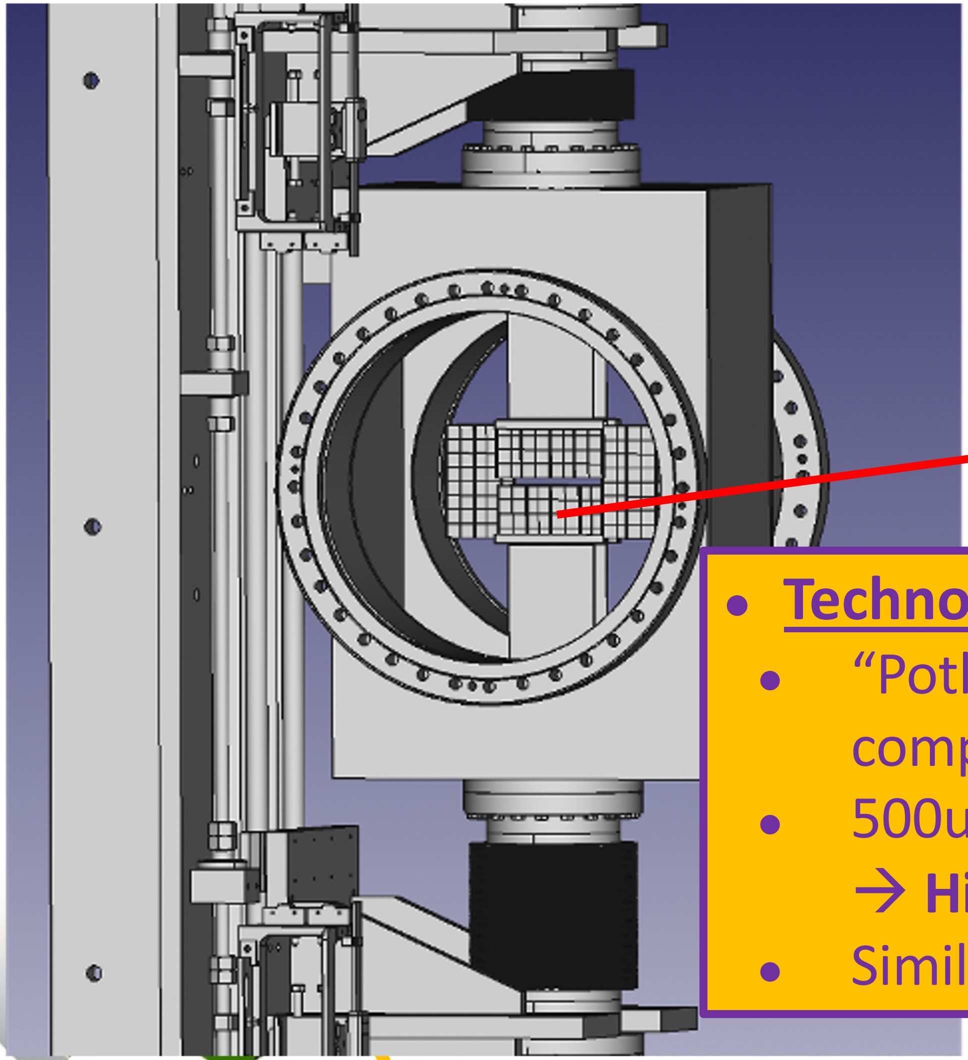
Roman Pots and OMD

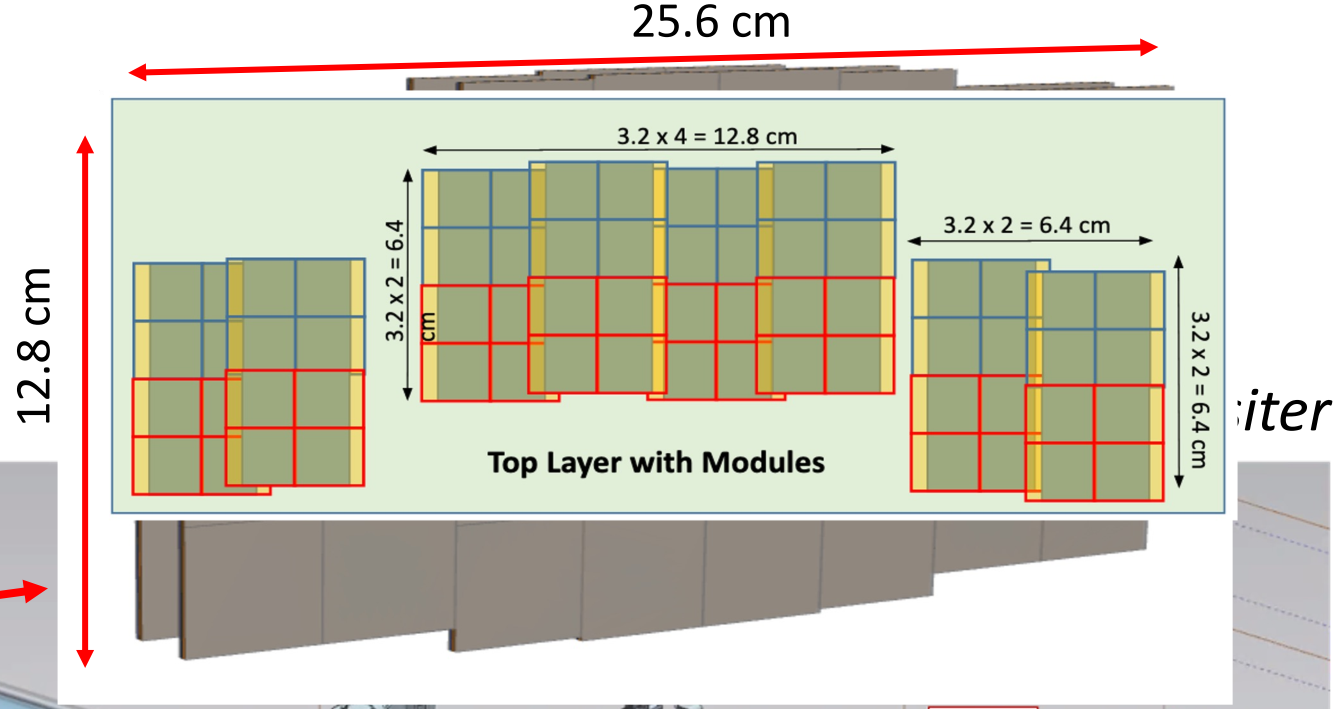




- **Technology**
  - "Potless" design concept with thin RF foils surrounding detector components.
  - 500um, **pixilated AC-LGAD sensor**, with 30-40ps timing resolution → **High-precision space and time information!**
  - Similar concept for the OMD, just different active area and shape.

Roman Pots and OMD





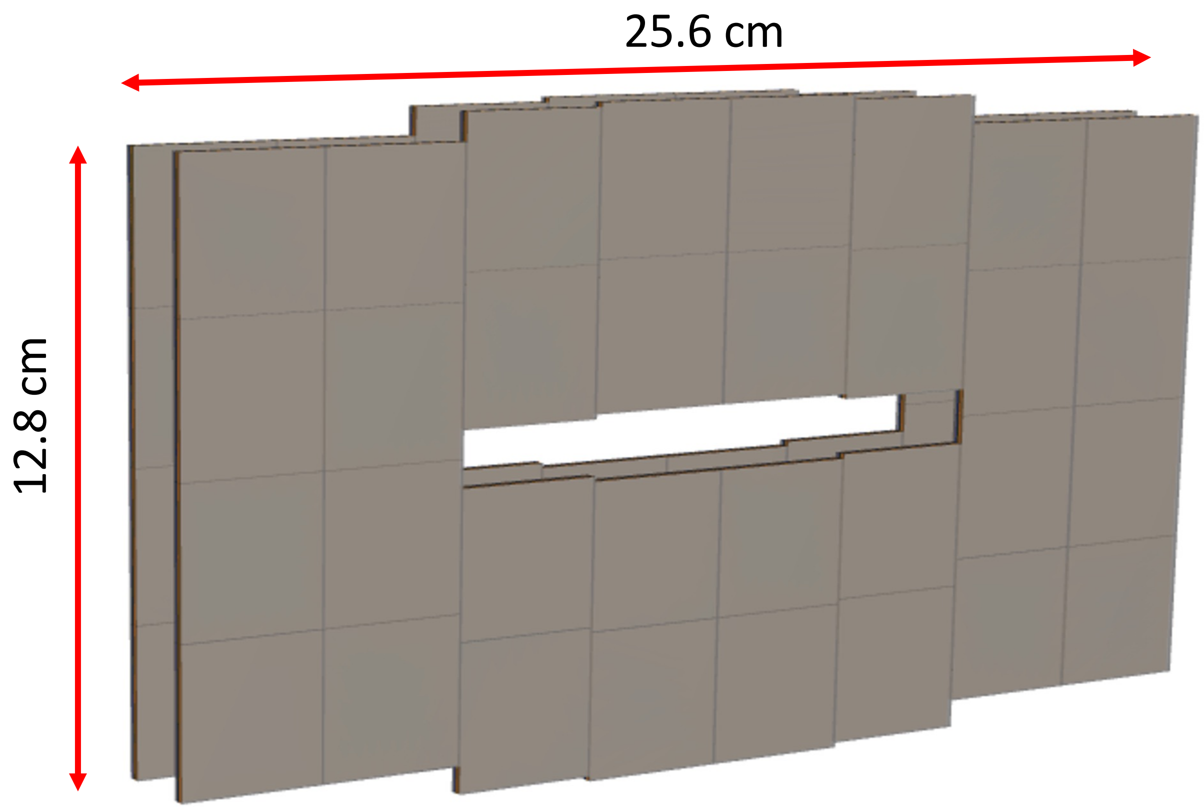
- **Technology**
  - "Potless" design concept with thin RF foils surrounding detector components.
  - 500um, **pixilated AC-LGAD sensor**, with 30-40ps timing resolution → **High-precision space and time information!**
  - Similar concept for the OMD, just different active area and shape.

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

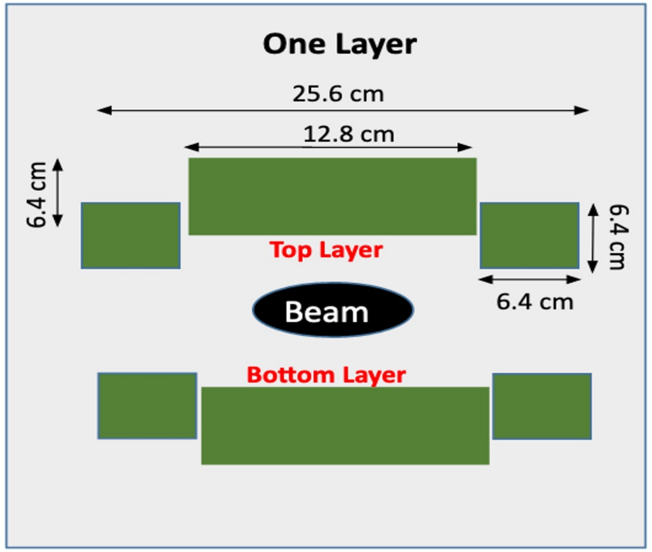
Roman "Pots" @ the EIC

$\sigma(z)$ 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.

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



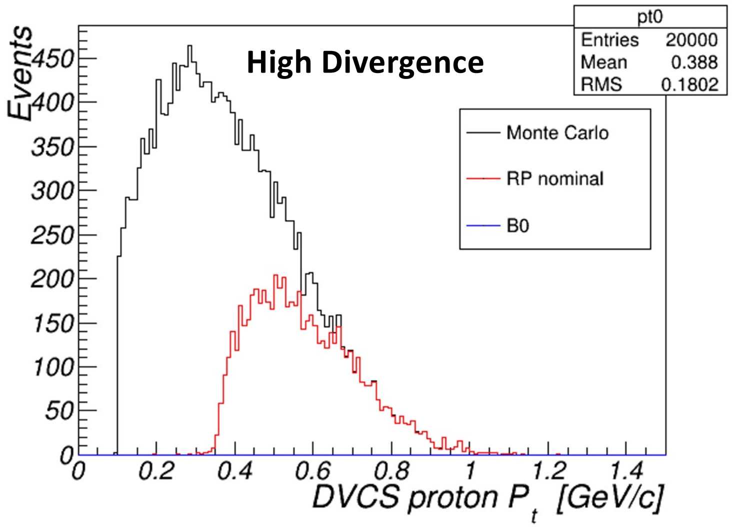
DD4HEP Simulation

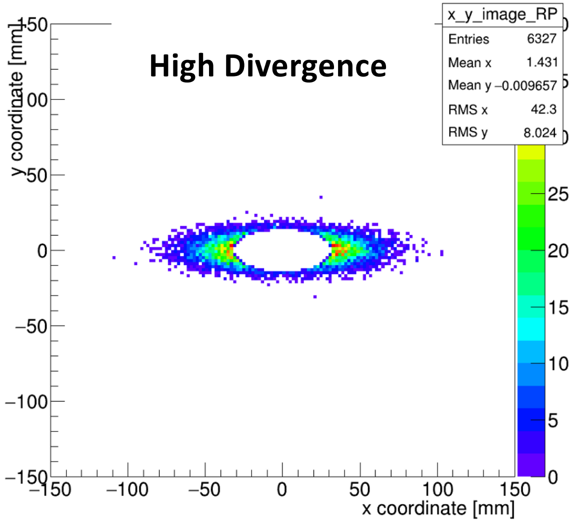


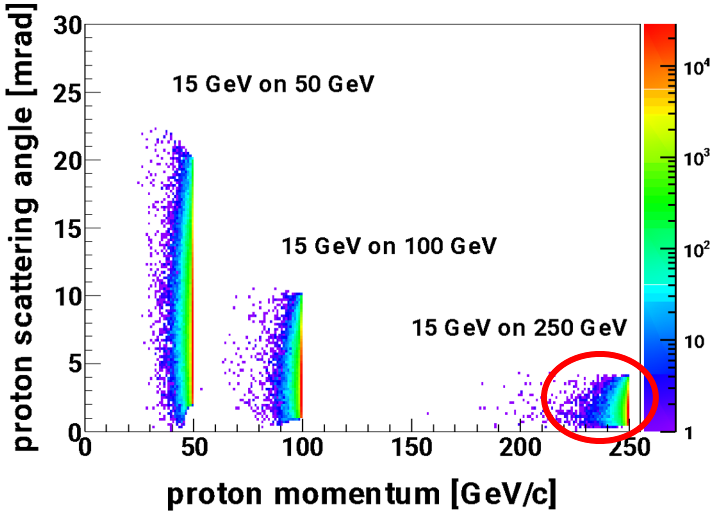
- **Low-pT cutoff determined by beam optics.**
  - **The safe distance is ~10σ from the beam center.**
  - **1σ ~ 1mm**
- **These optics choices change with energy, but can also be changed within a single energy to maximize *either acceptance at the RP, or the luminosity.***

Digression: Machine Optics (IP6)

275 GeV DVCS Proton Acceptance



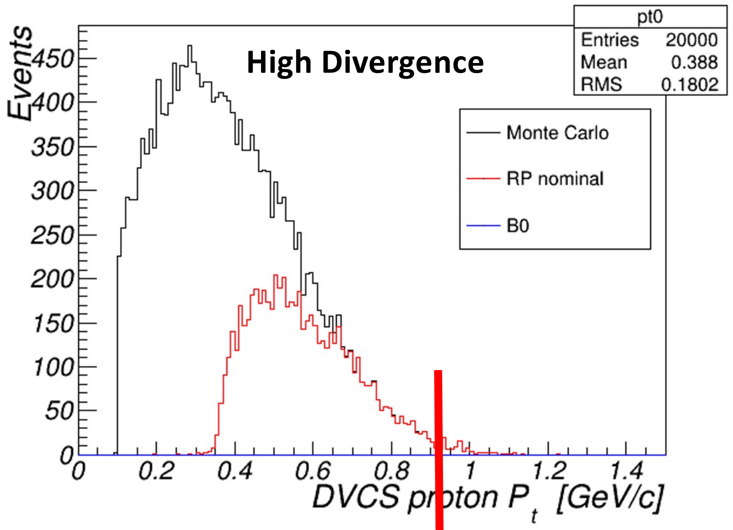


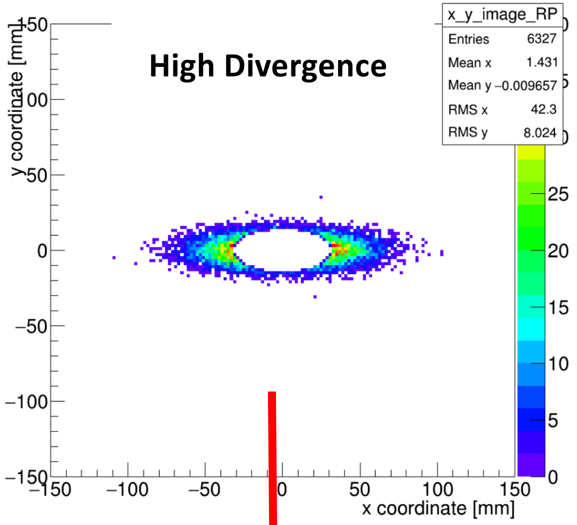


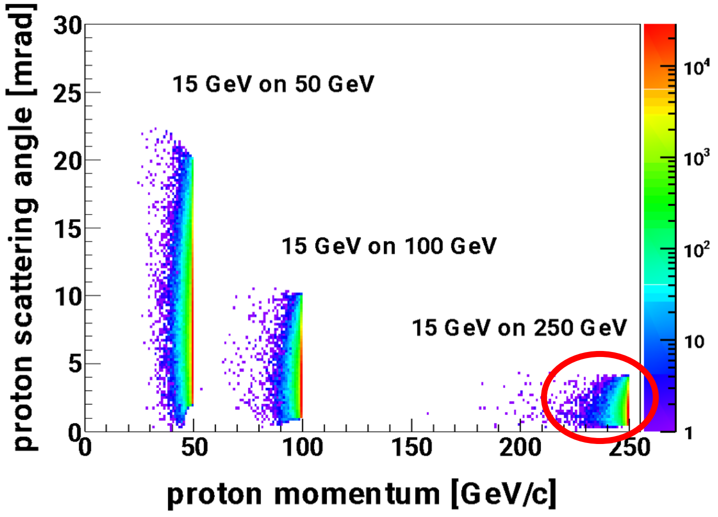
High Divergence: smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

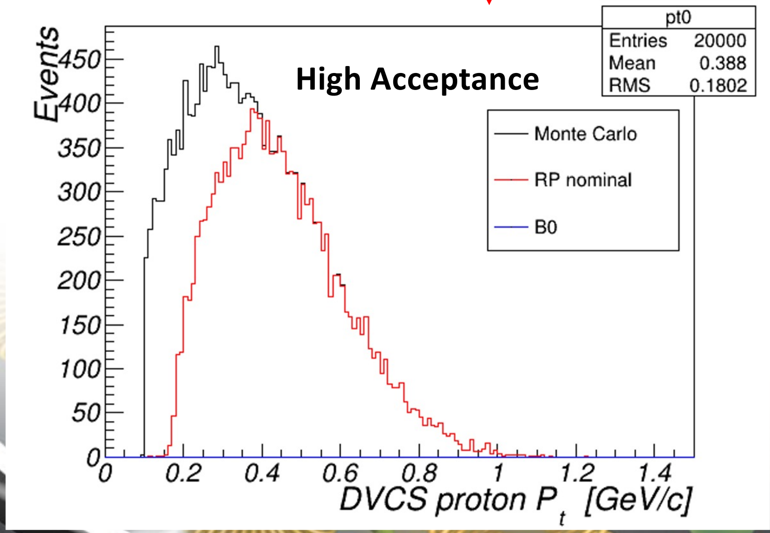
Digression: Machine Optics (IP6)

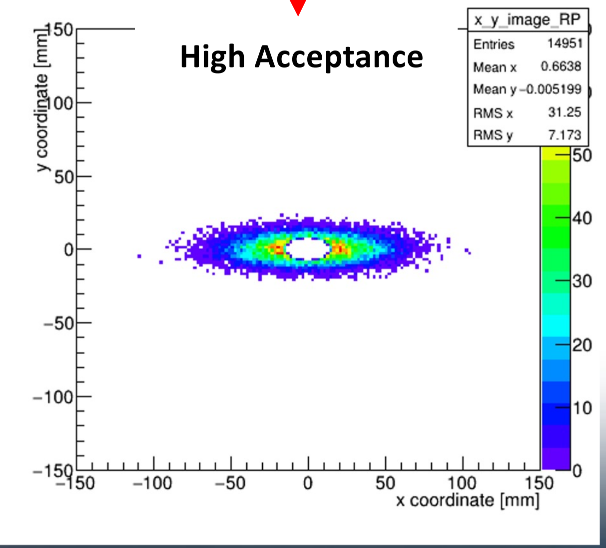
275 GeV DVCS Proton Acceptance











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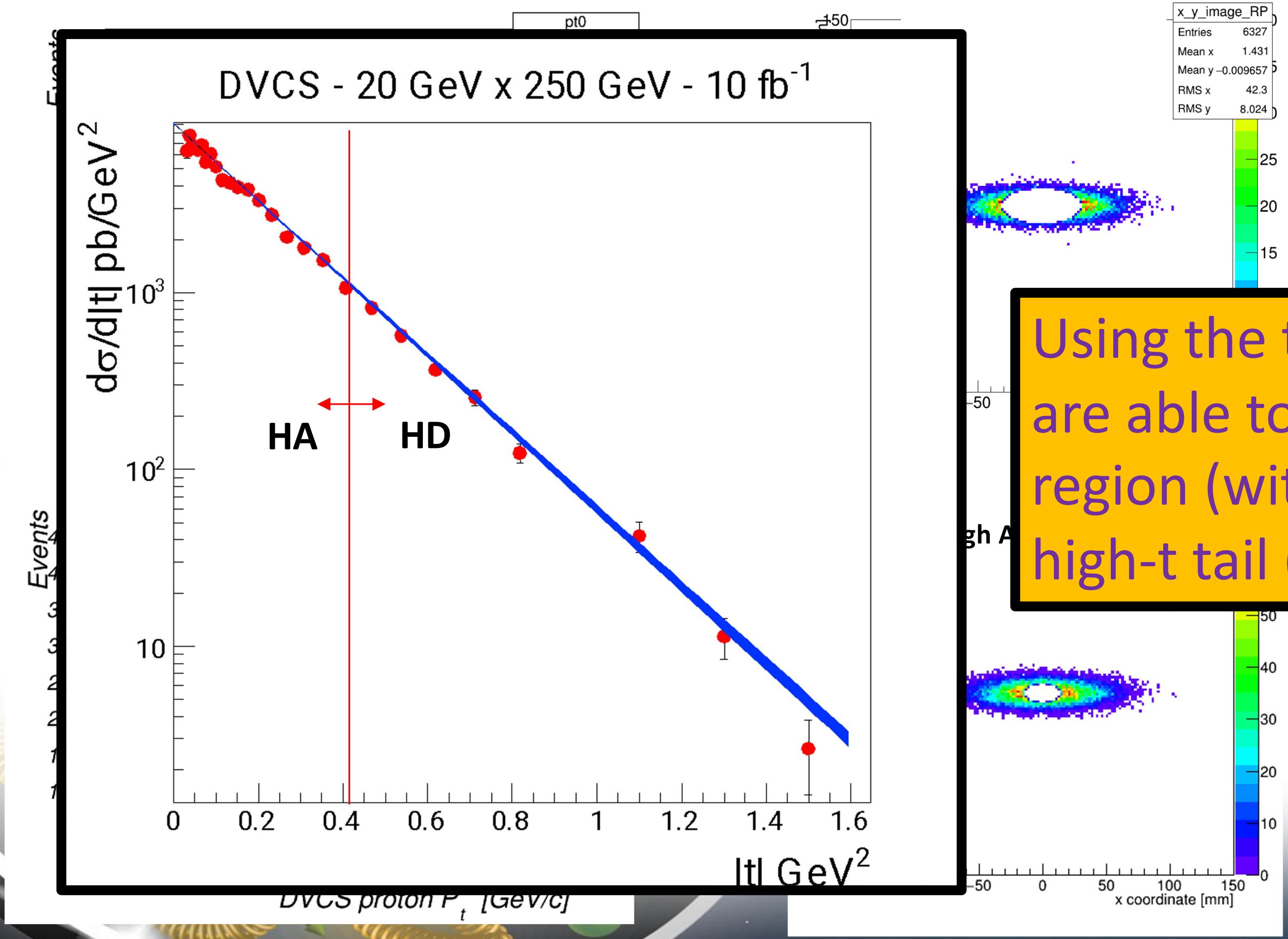
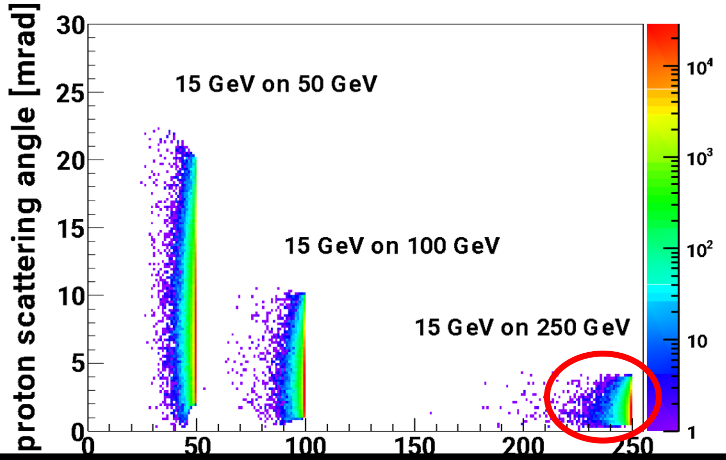


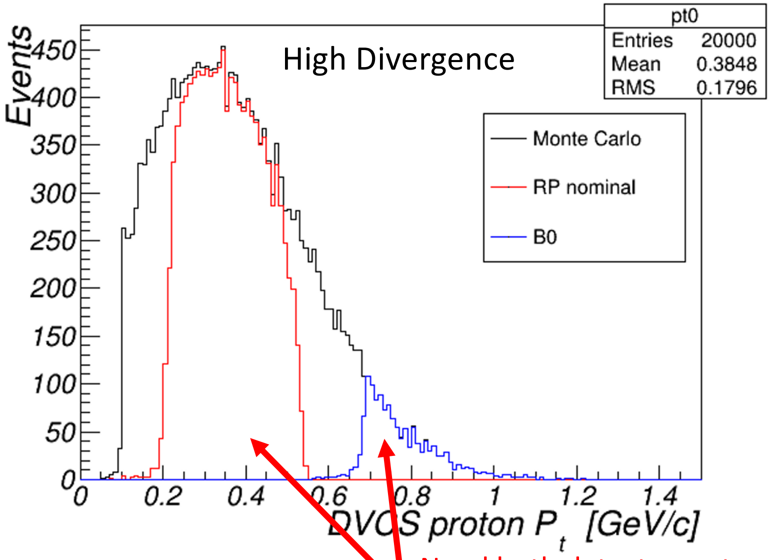


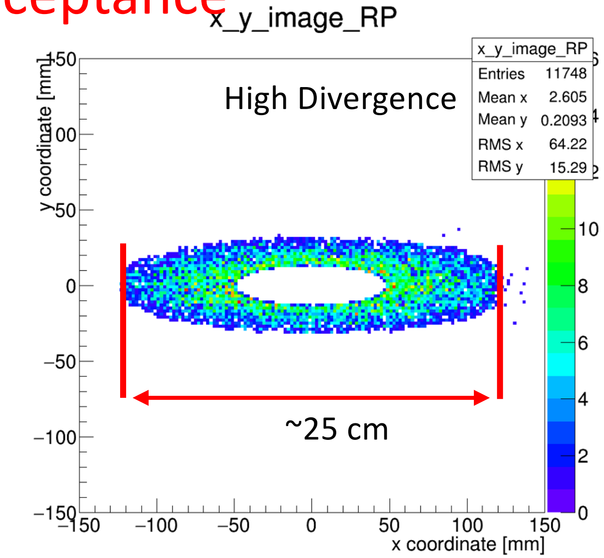
Using the two configurations, we are able to measure the low-t region (with better acceptance) and high-t tail (with higher luminosity).

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

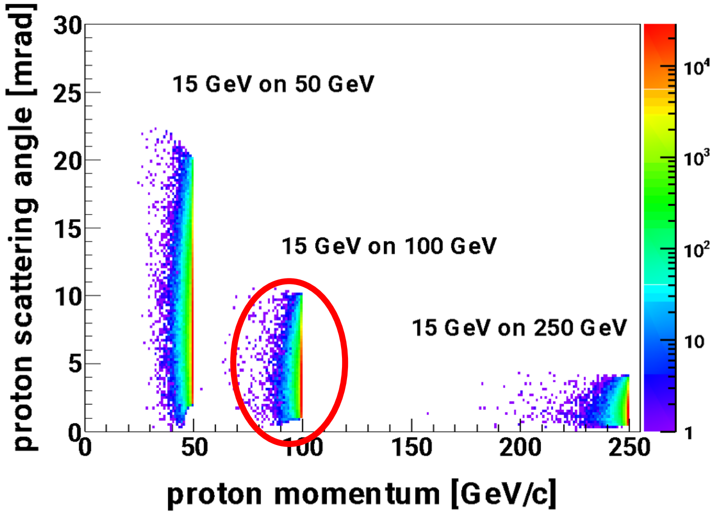
Digression: Machine Optics (IP6)

100 GeV DVCS Proton Acceptance





Need both detector systems together here!



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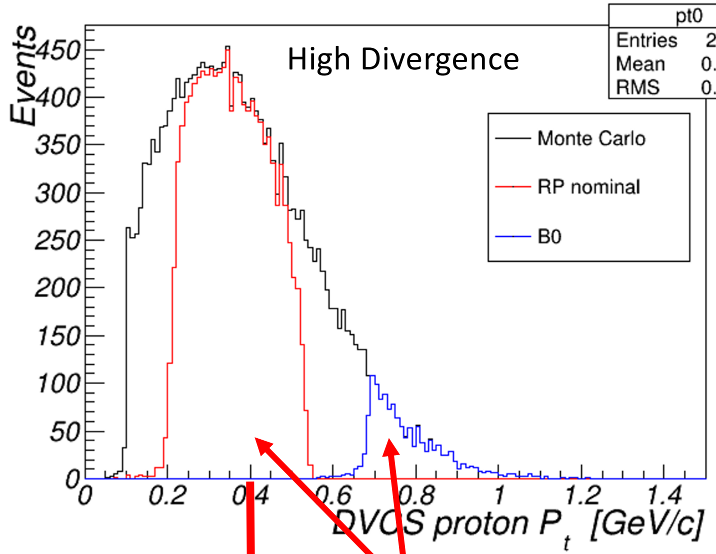

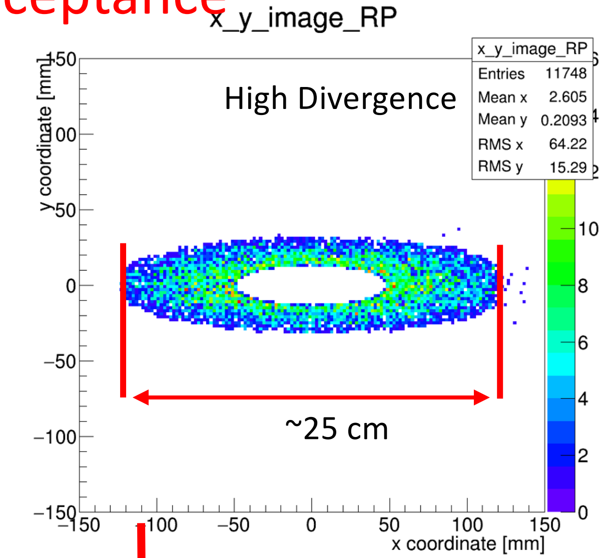

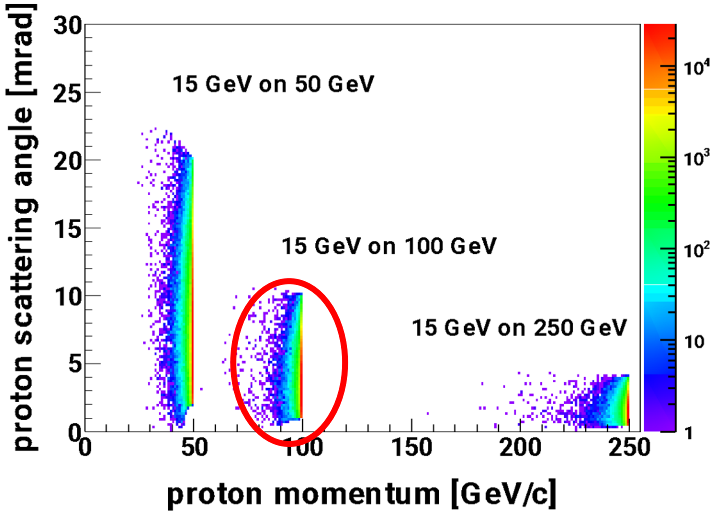

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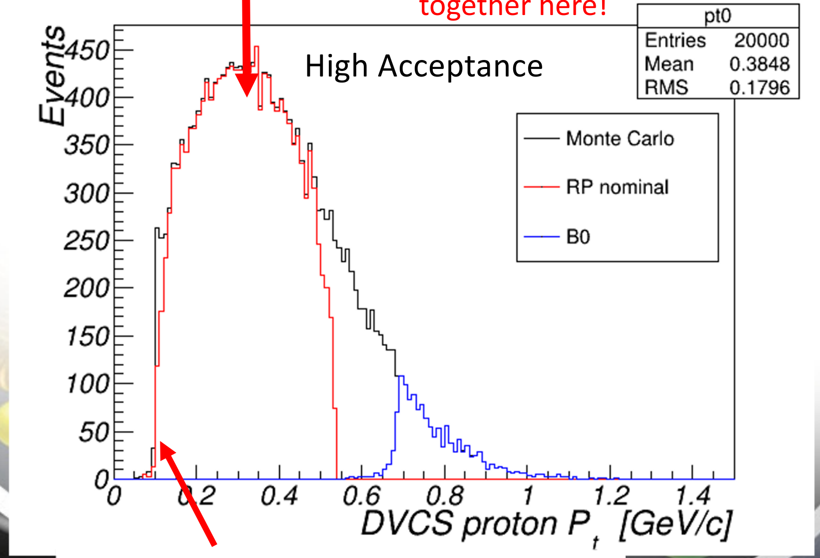
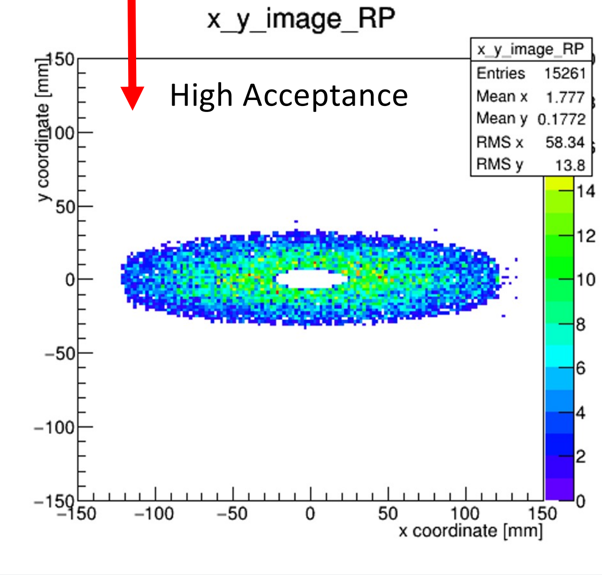
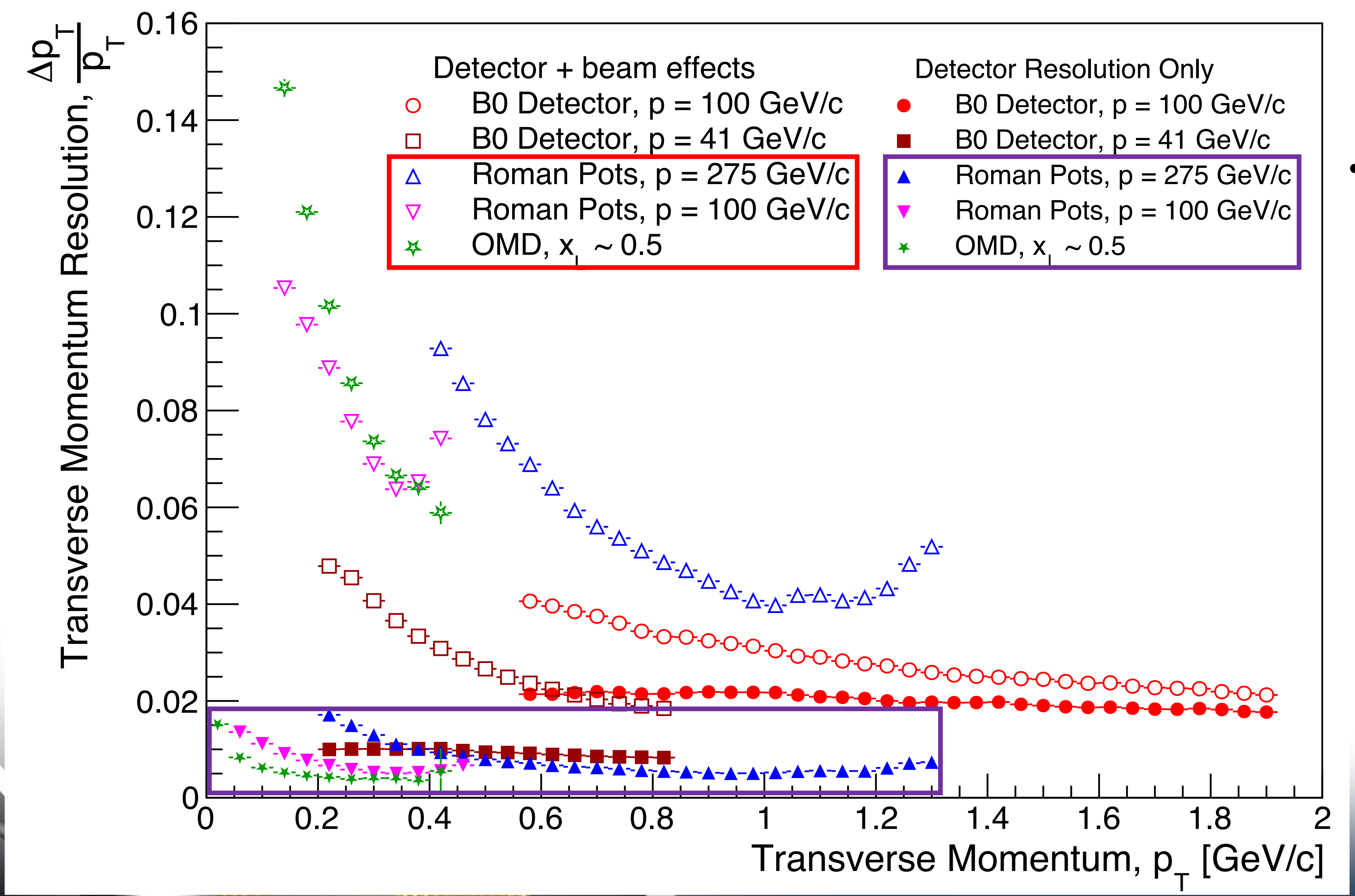




Improves low p_t acceptance.

Summary of Detector Performance

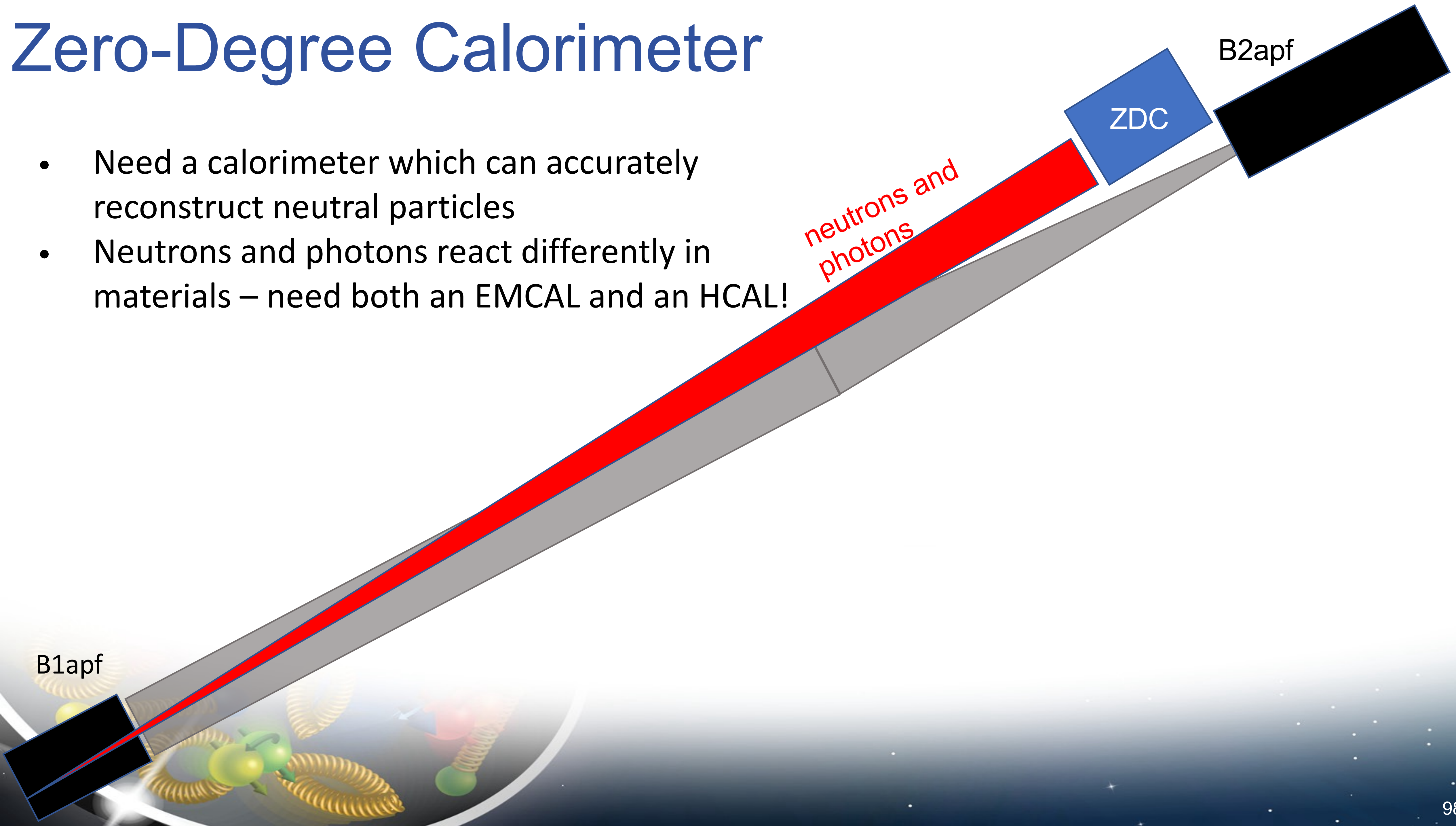


- All beam effects included!
  - Angular divergence.
  - Crossing angle.
  - Crab rotation/vertex smearing.

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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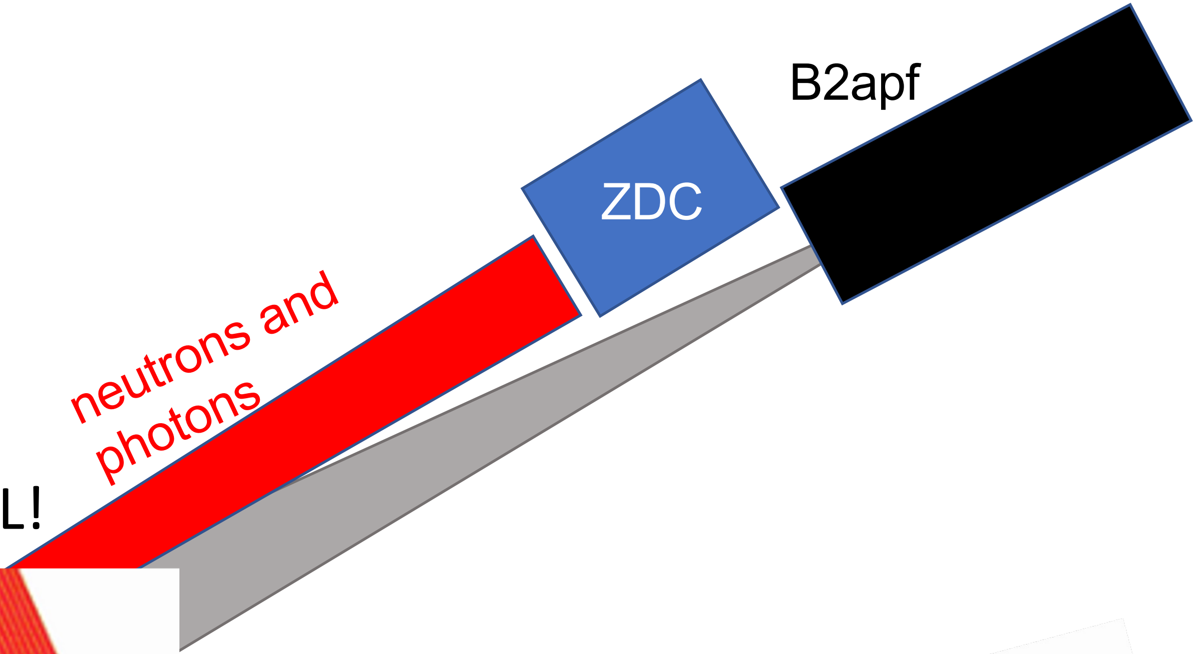
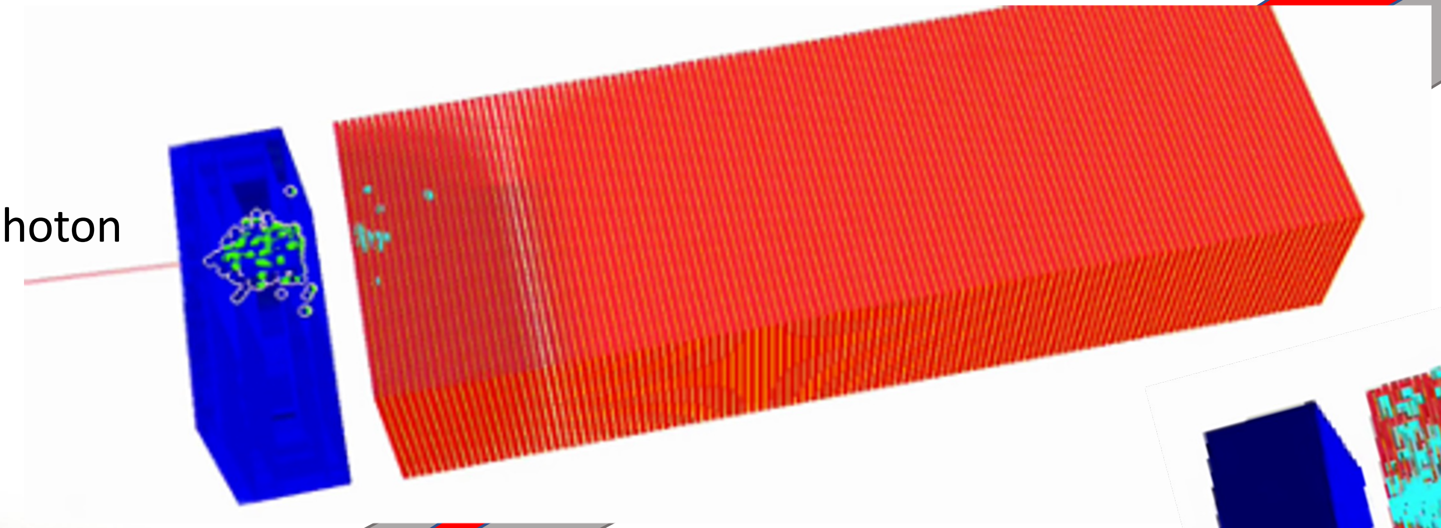
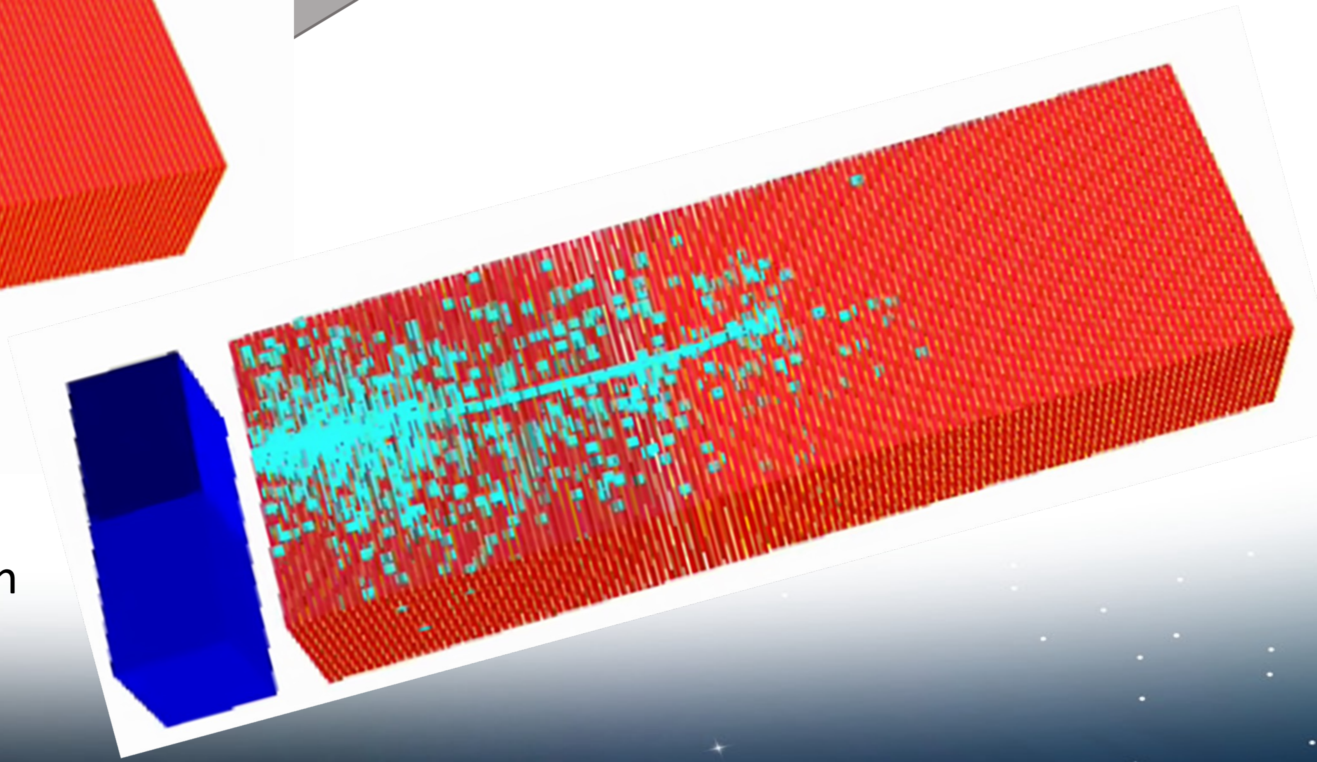
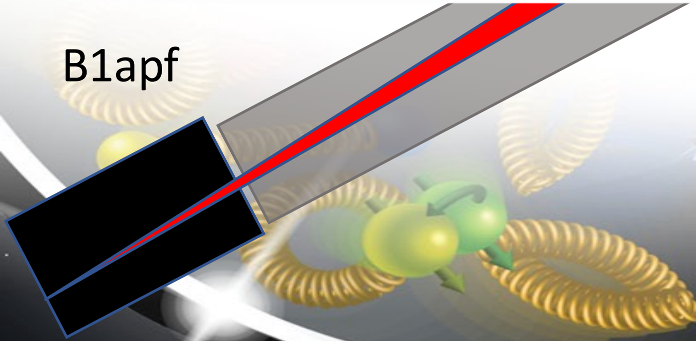






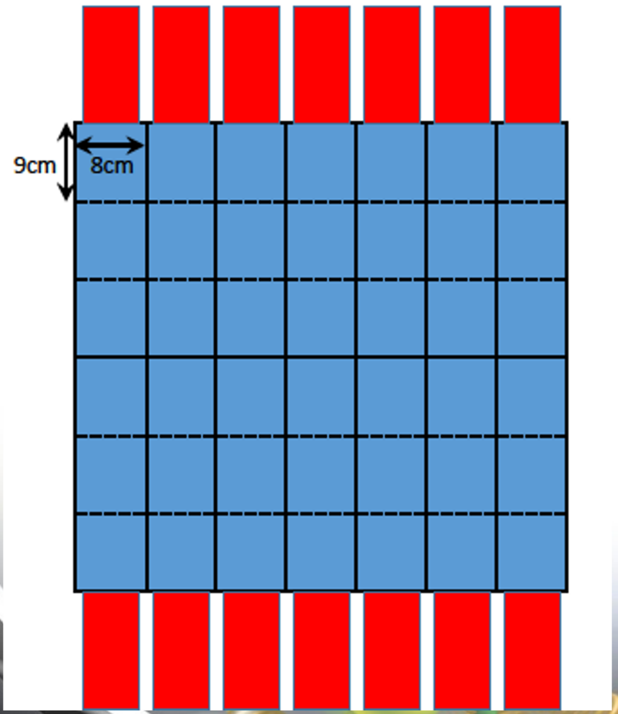


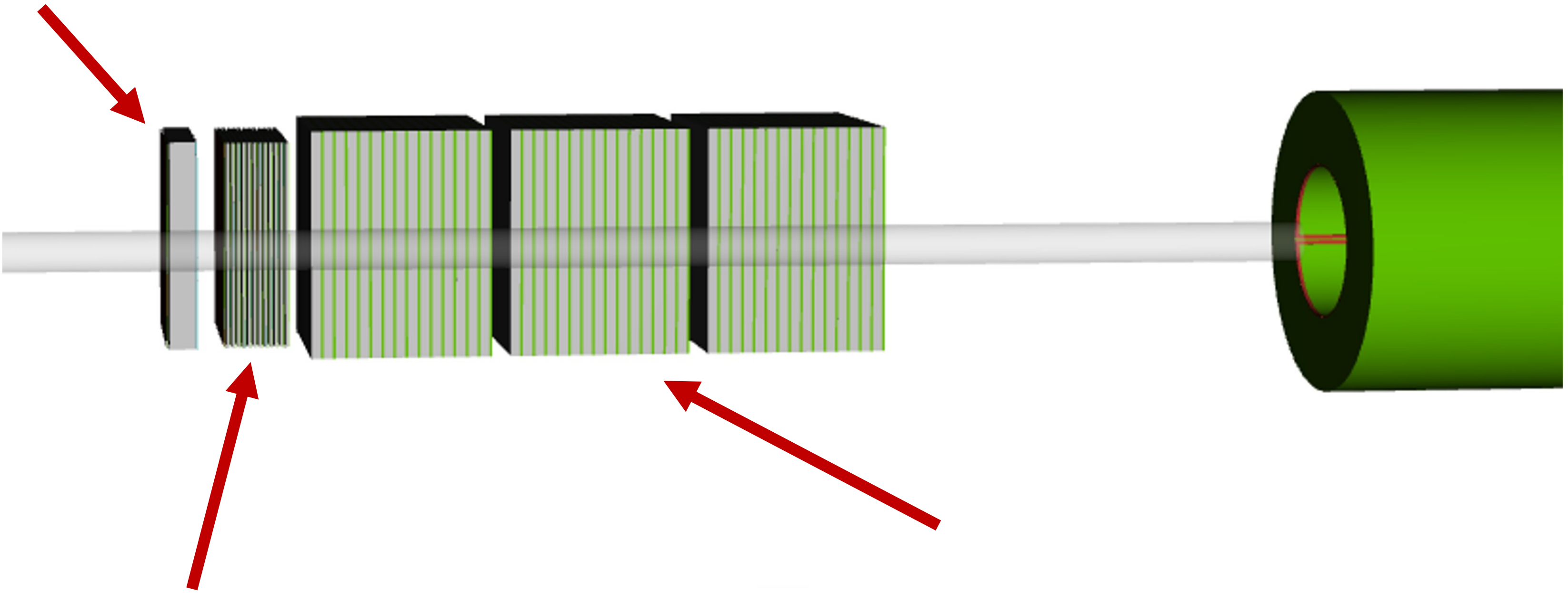
ZDC - What's New

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

Overall length within 2m limit

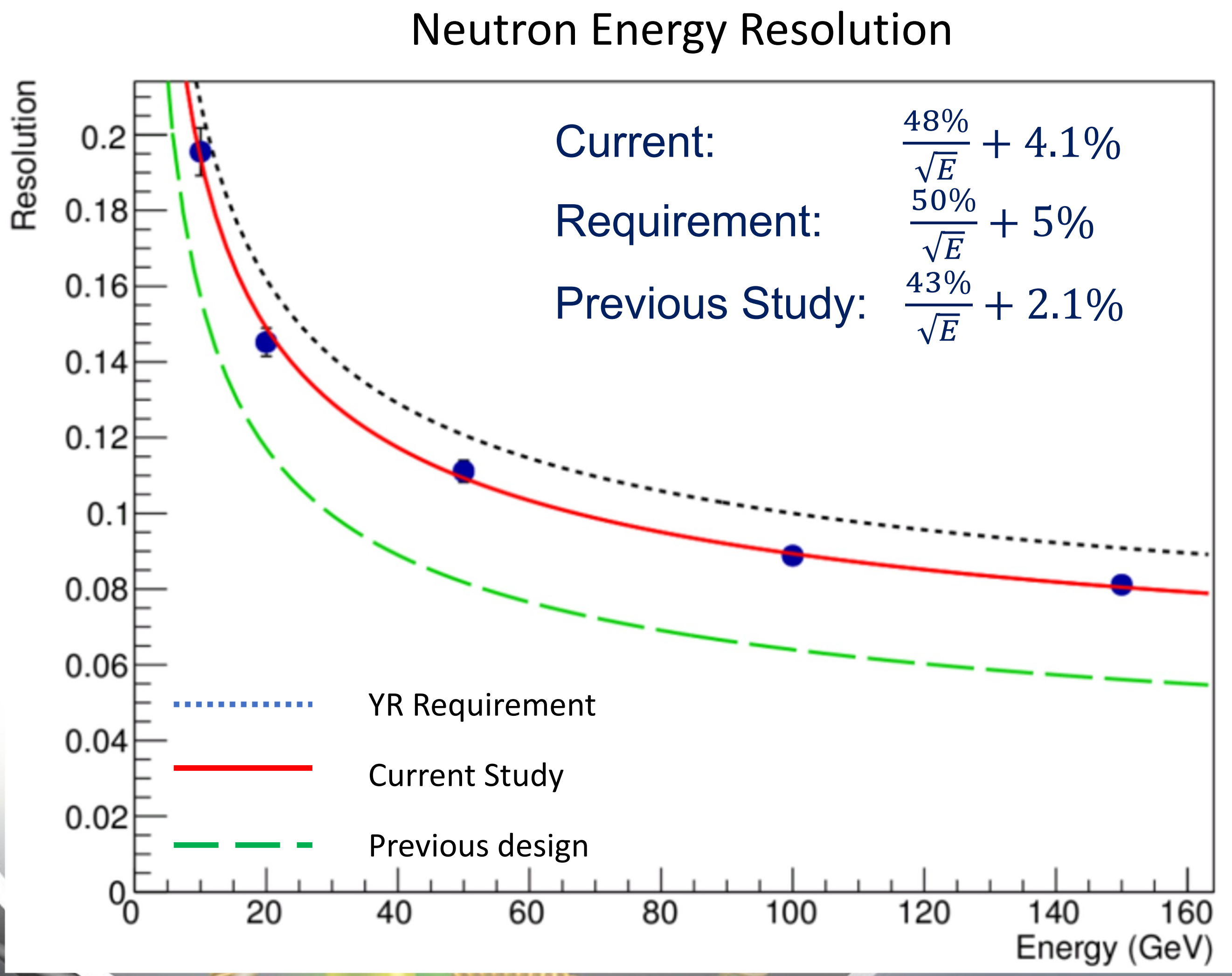
Readout setup from top & bottom

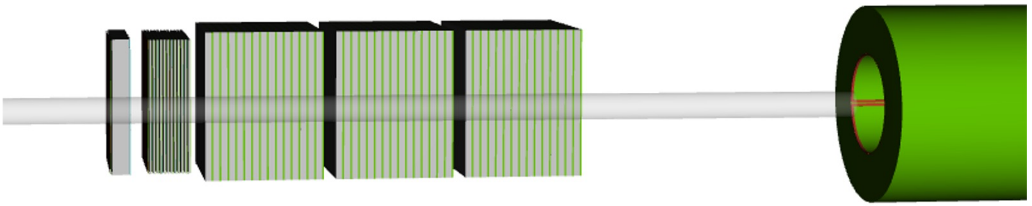




- W/Silicon Imaging EMCAL
  - Transverse size (x,y) = (56, 54) cm
  - 12 layers (~$24\chi_0$)
- Pb-Scintillator (+ fused silica)
  - Towers of 10cm x 10cm x 48cm, each module 60cm x 60cm x 48cm
  - 3 modules

ZDC - Performance



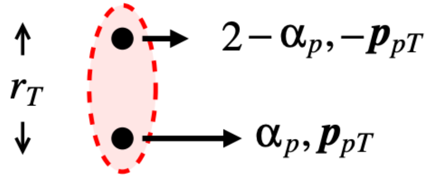


- Energy resolution in the new design acceptable → Optimization, test of different ideas within the size limit.

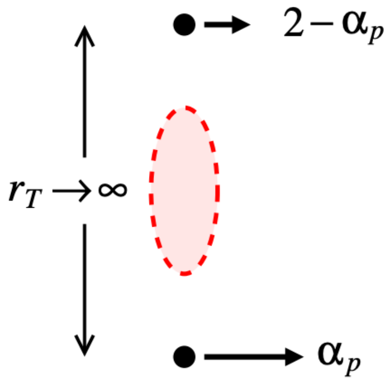
- Next steps:
  - Implementation of reconstruction
  - Position resolution & shower development study ongoing for the imaging part of HCAL

Pole Extrapolation

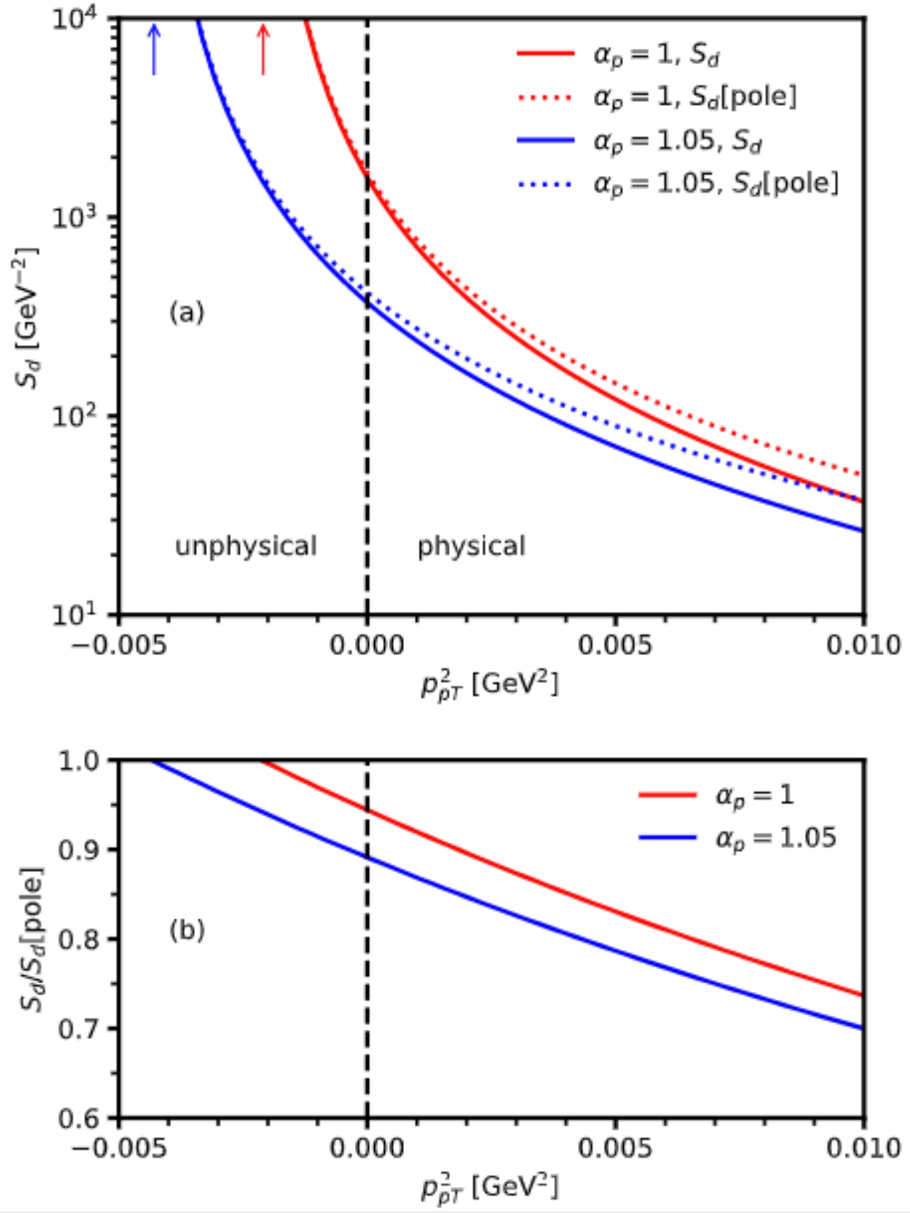
C. Weiss and W. Cosyn
Phys. Rev. C **102**, 065204 (2020)



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



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

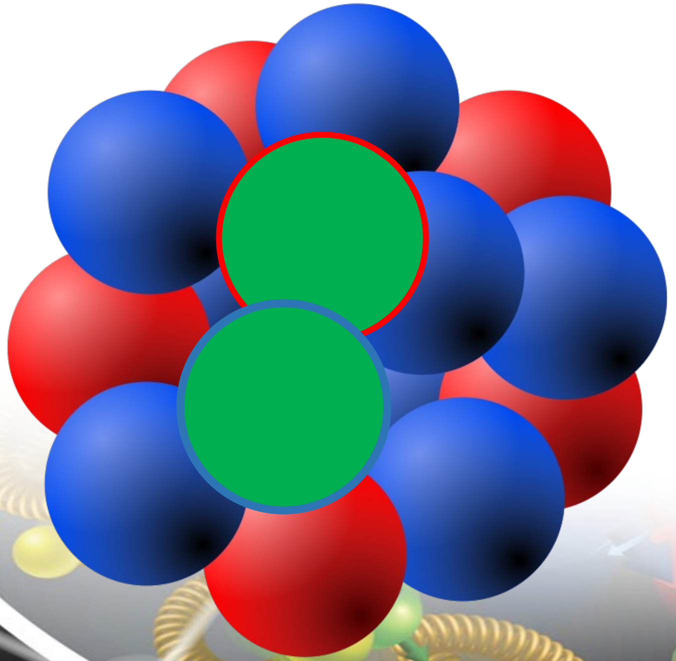


Short-Range Correlations

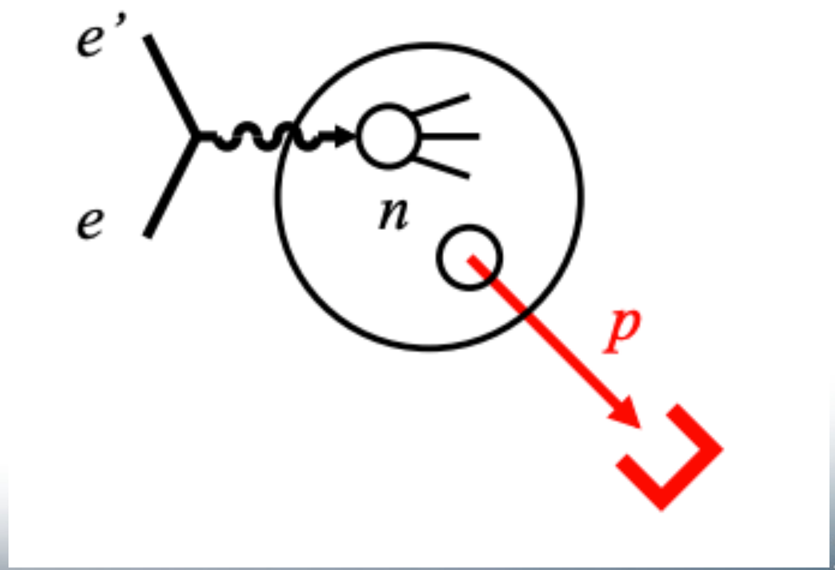
"The nucleus can often be approximated as an independent collection of protons and neutrons confined in a volume, but for short periods of time, the nucleons in the nucleus can strongly overlap. This quantum mechanical overlapping, known as a nucleon-nucleon short-range correlation, is a manifestation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



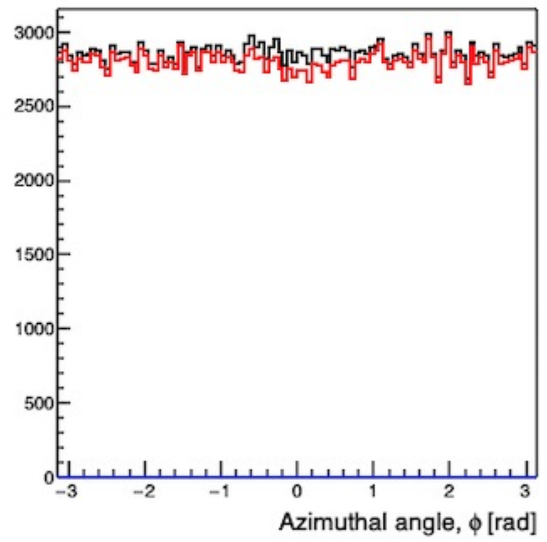
Use deuteron as "SRC laboratory", where nucleon kinematics are readily accessible.



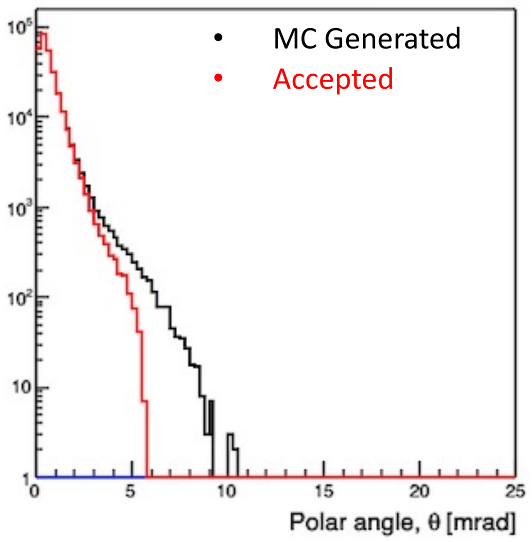
Short-Range Correlations in Deuterons

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

Protons

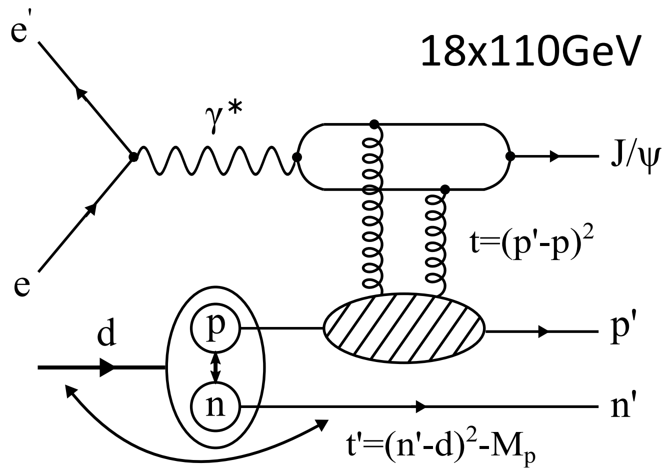


Protons



Proton "spectator" case.

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

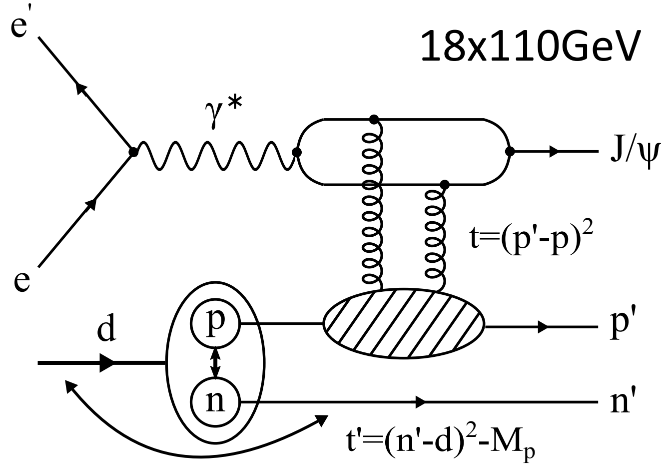


MC generated events shown in black – "accepted" protons in red.

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)



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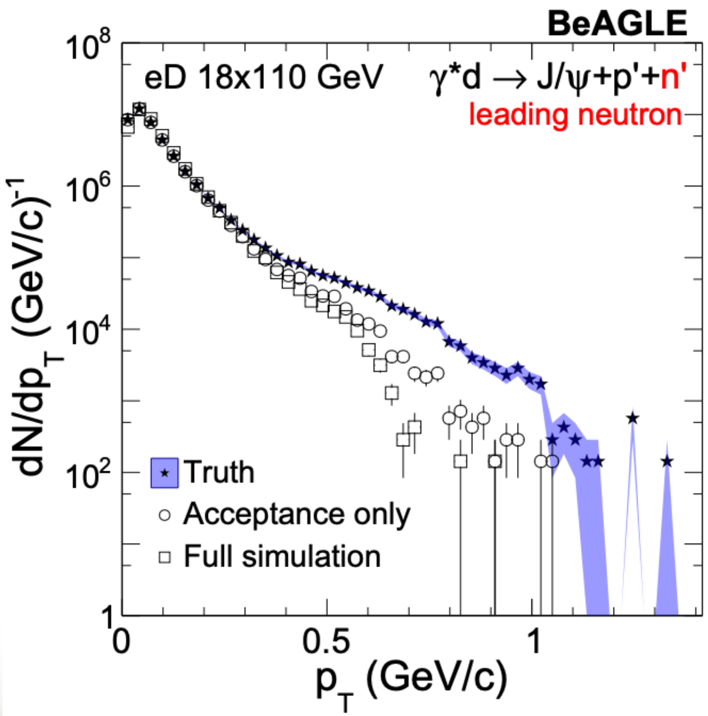
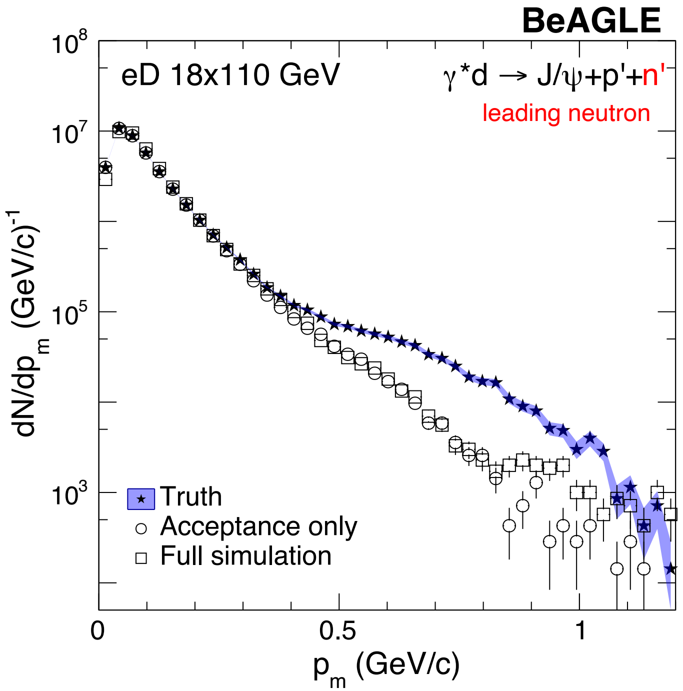


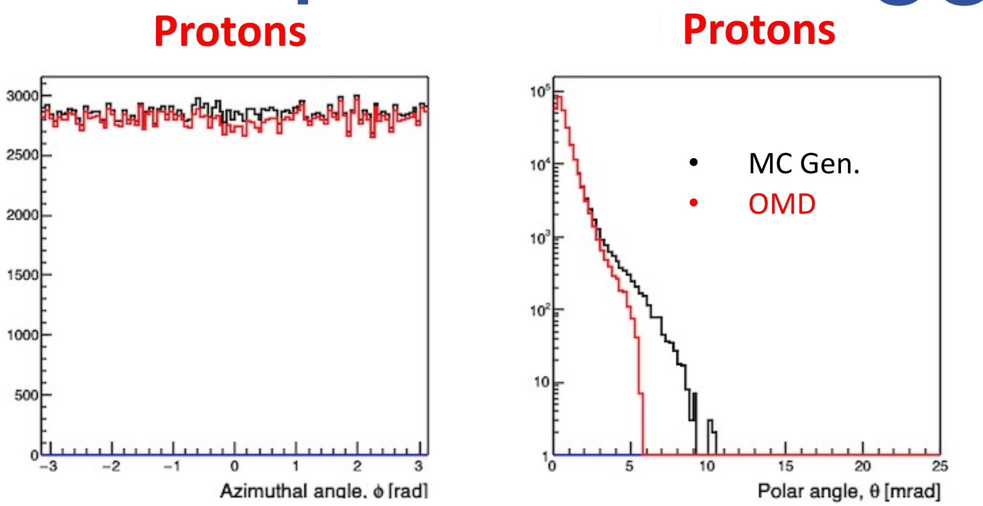


- Spectator kinematic variables reconstructed over a broad range.
- **All detector and beam effects included in the full GEANT simulations!**
    - Bin migration is observed due to smearing in the reconstruction.

➢ **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.**

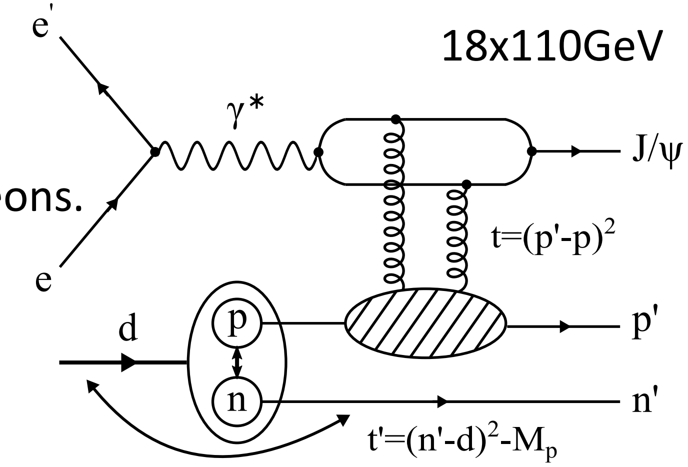
e+d Spectator Tagging

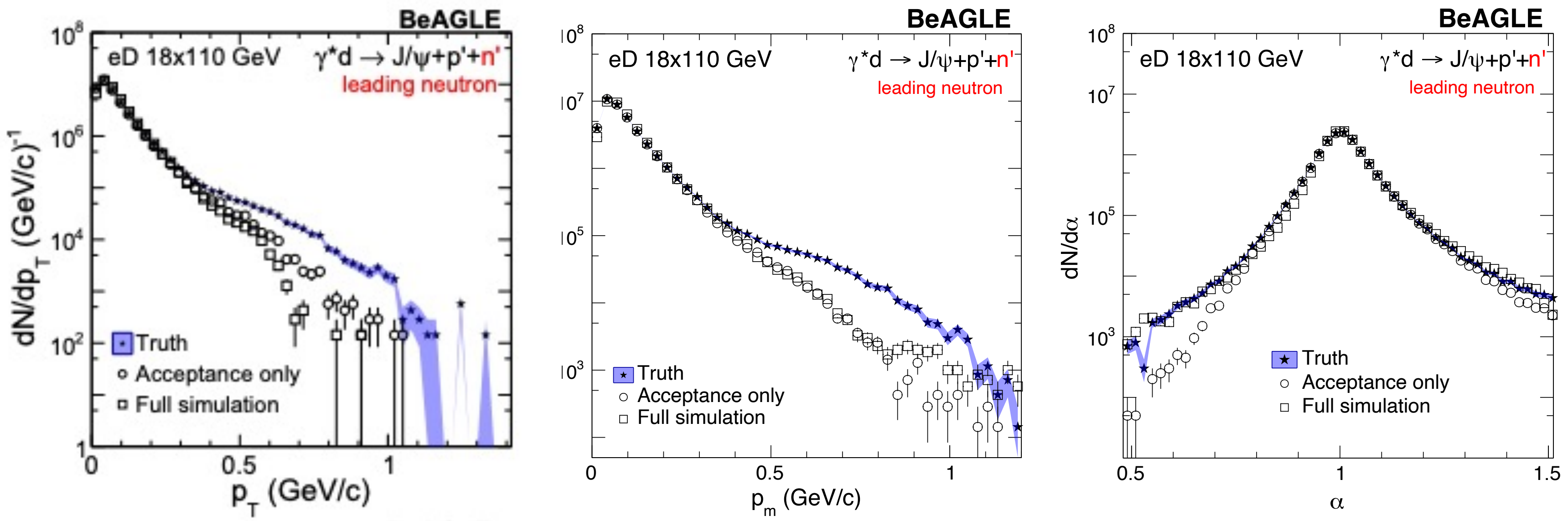
Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)



Proton spectator case.

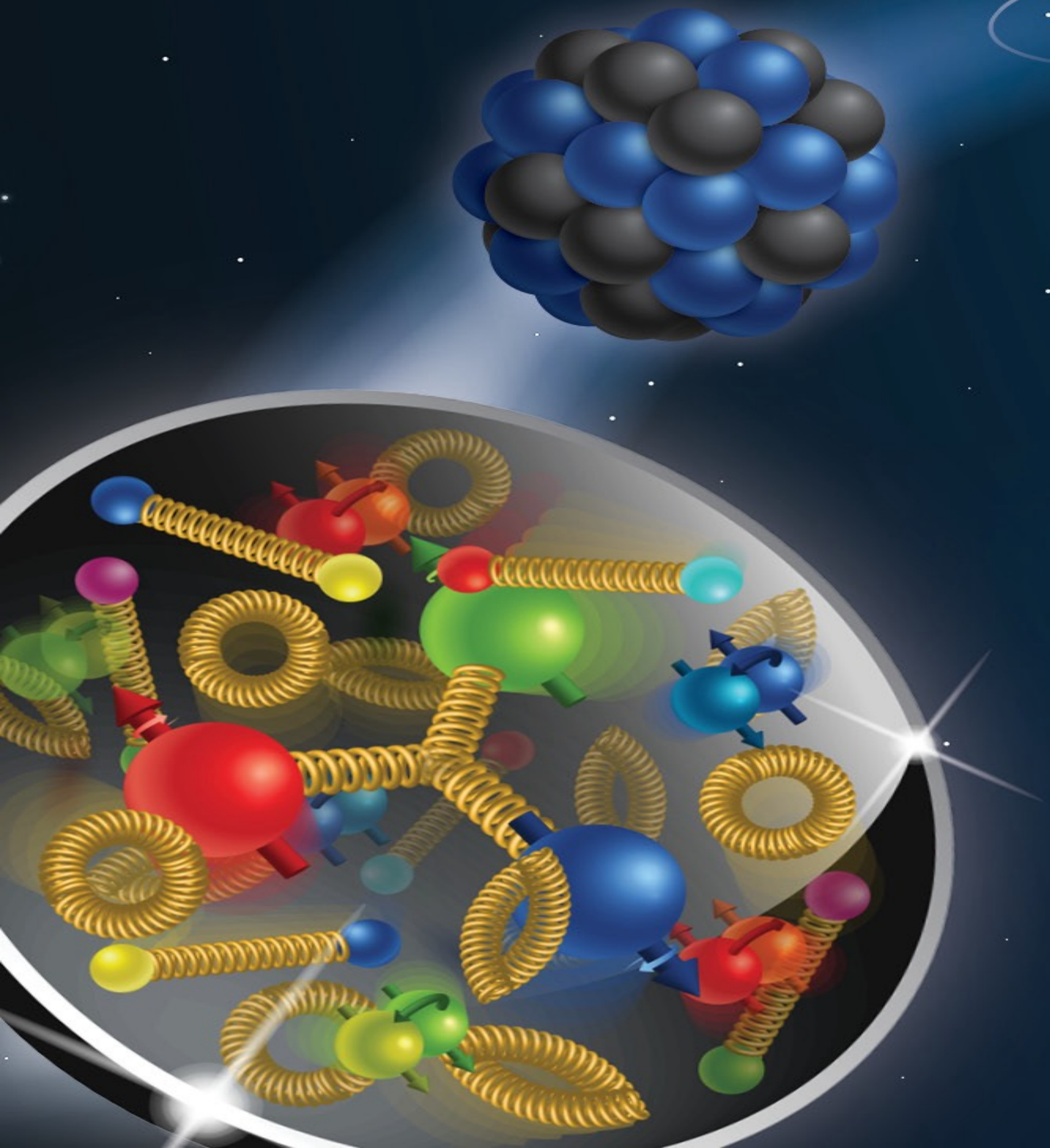
Particular process in BeAGLE: incoherent diffractive J/psi production off bounded nucleons.





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.**

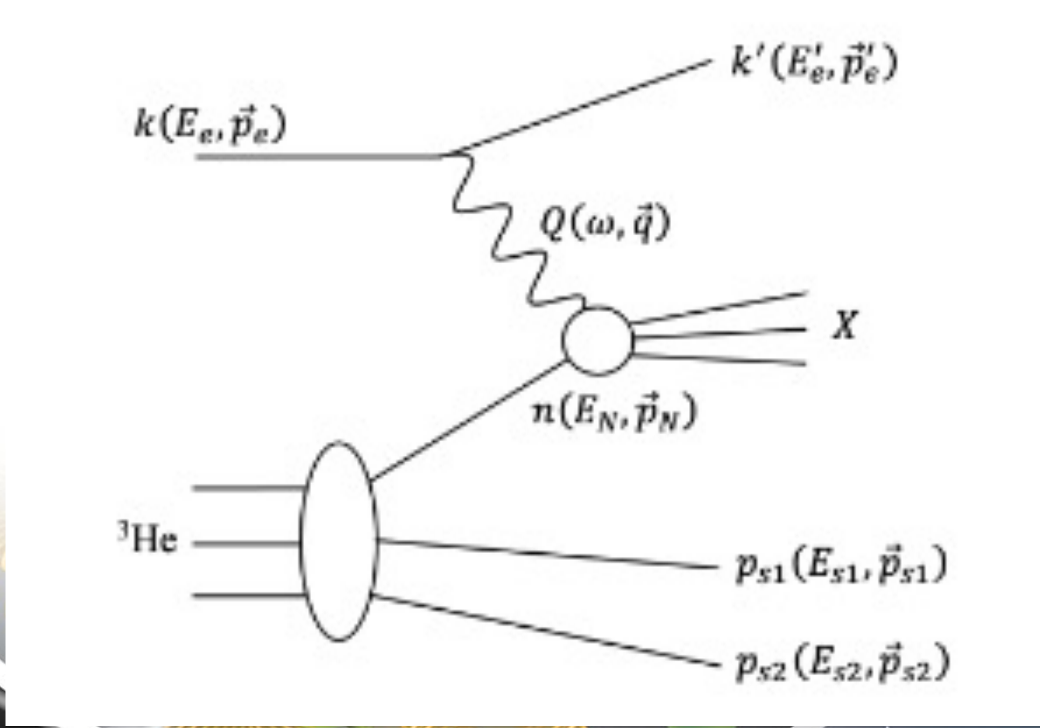


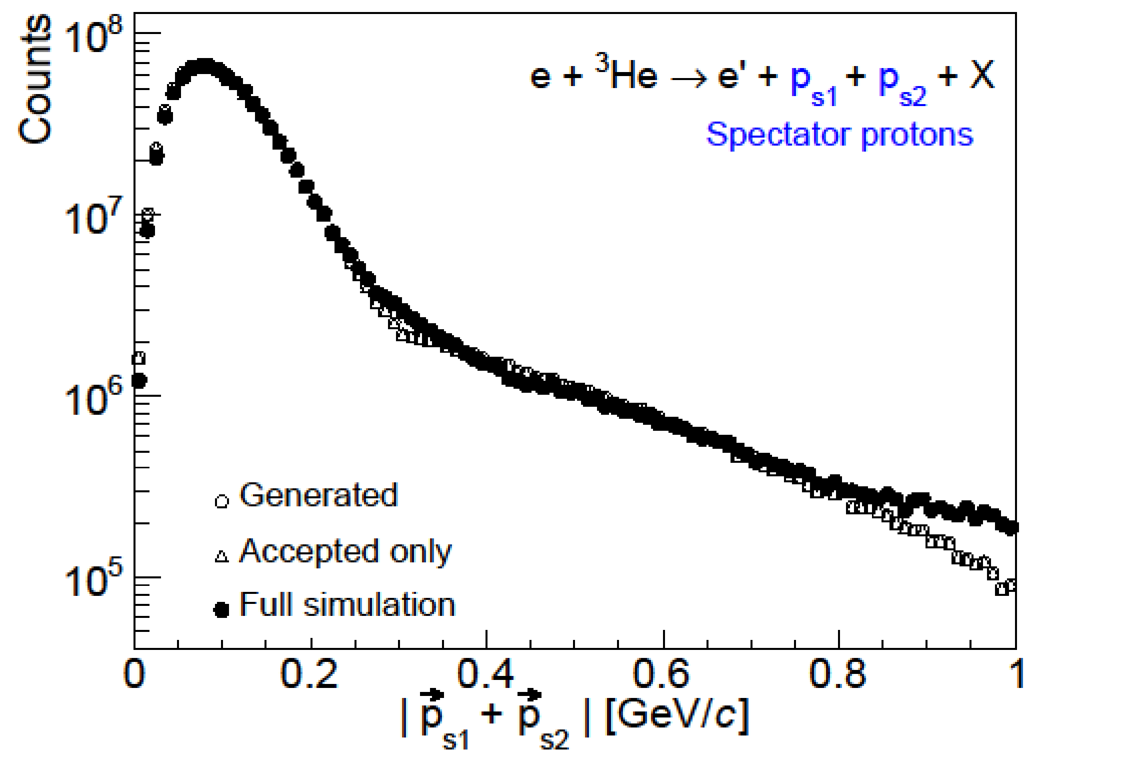
Light nuclei – Helium-3:
Neutron Spin Structure

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.



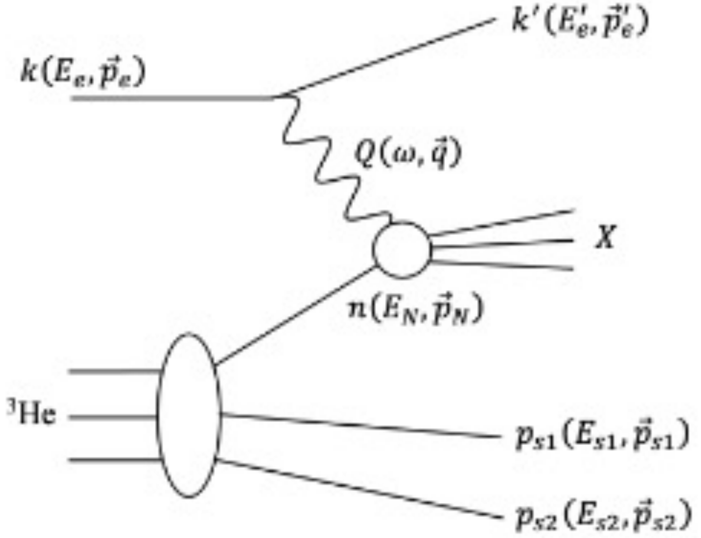


Neutron Spin Structure in He3

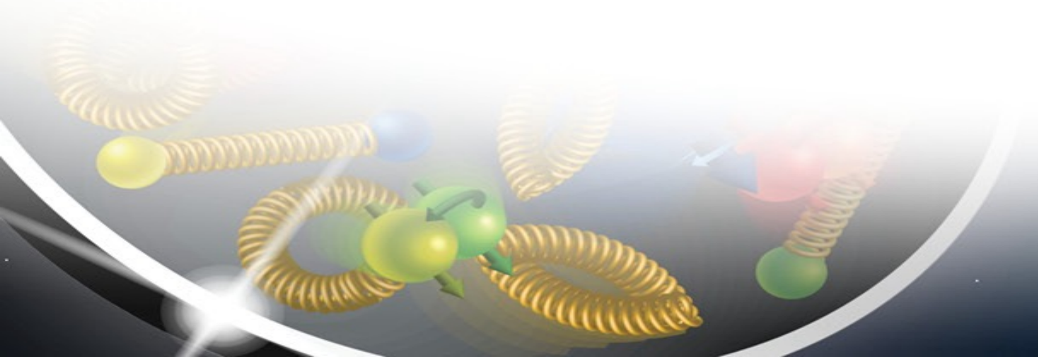
I. Friscic, D. Nguyen, J. R. Pybus, A. Jentsch, *et al.*, Phys. Lett. B, **Volume 823**, 136726 (2021)

- 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

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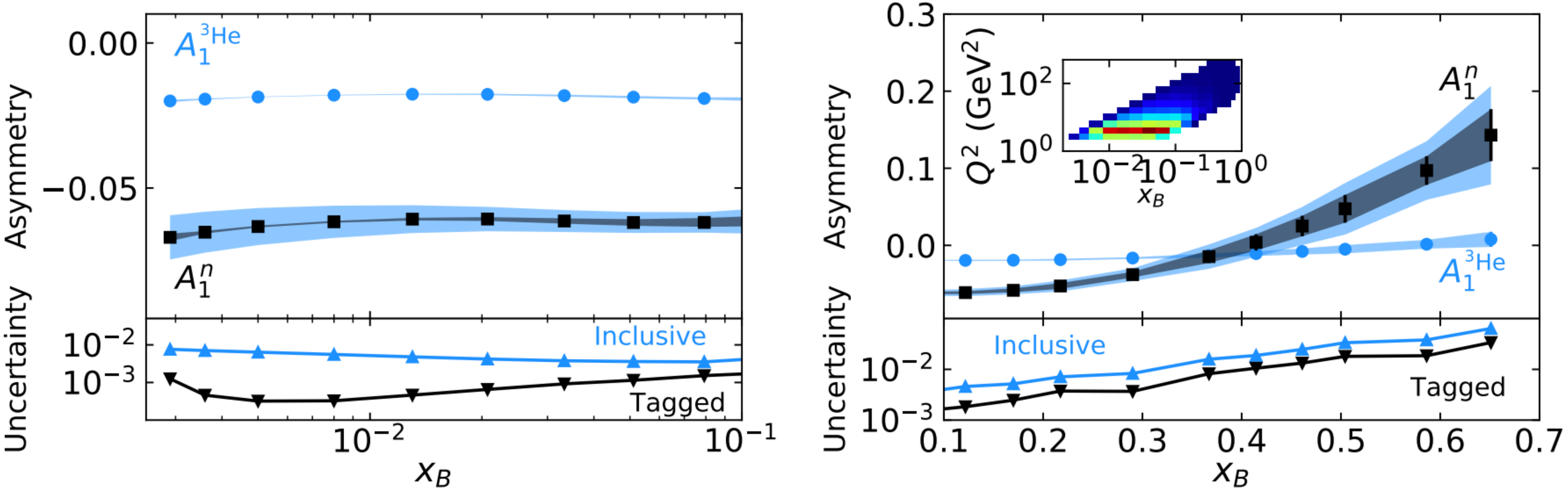
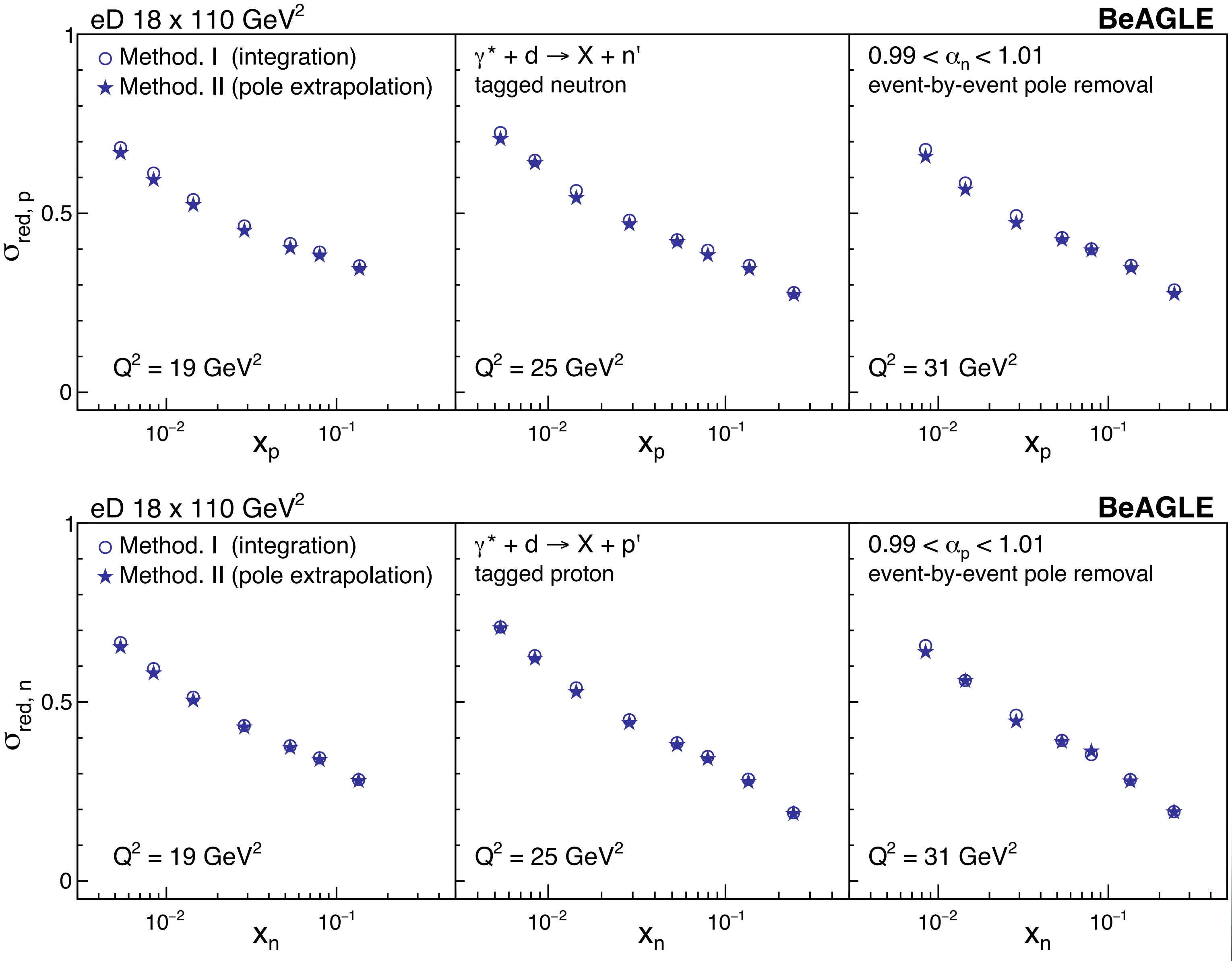
- Neutron spin asymmetries can be measured from kinematics of the tagged protons.
- EIC can build upon measurements at JLAB by reducing polarization uncertainties, and opening a broader Q^2 range for study.
- Can aid in our understanding of quark orbital angular momentum in nucleons.

Low-x

High-x

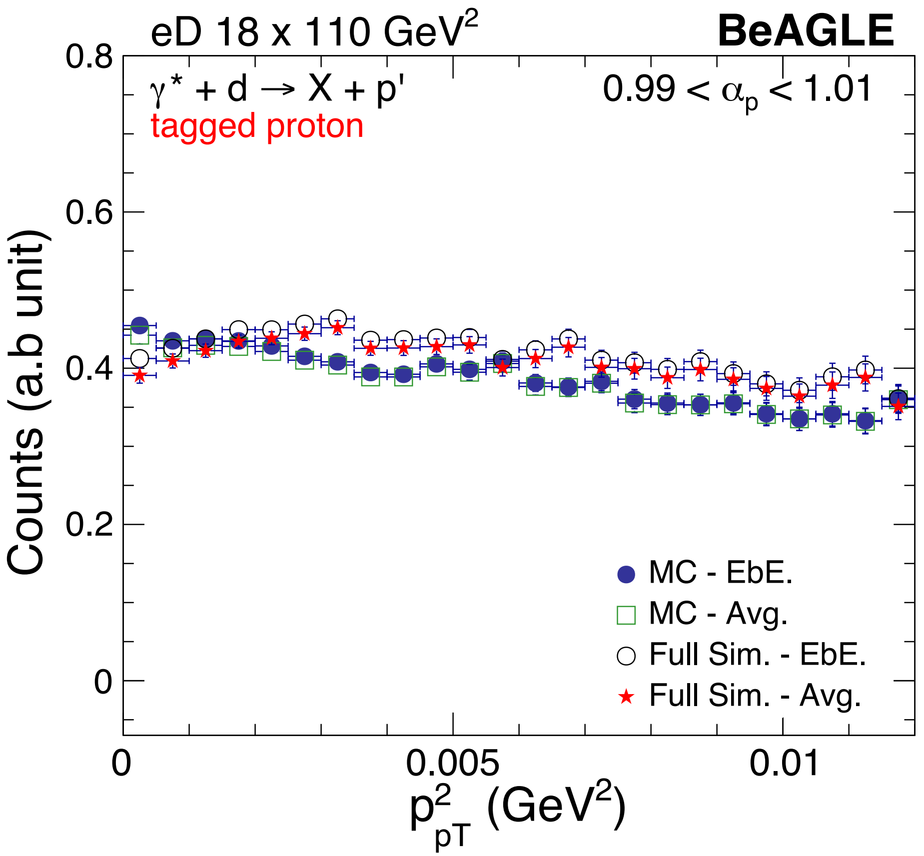


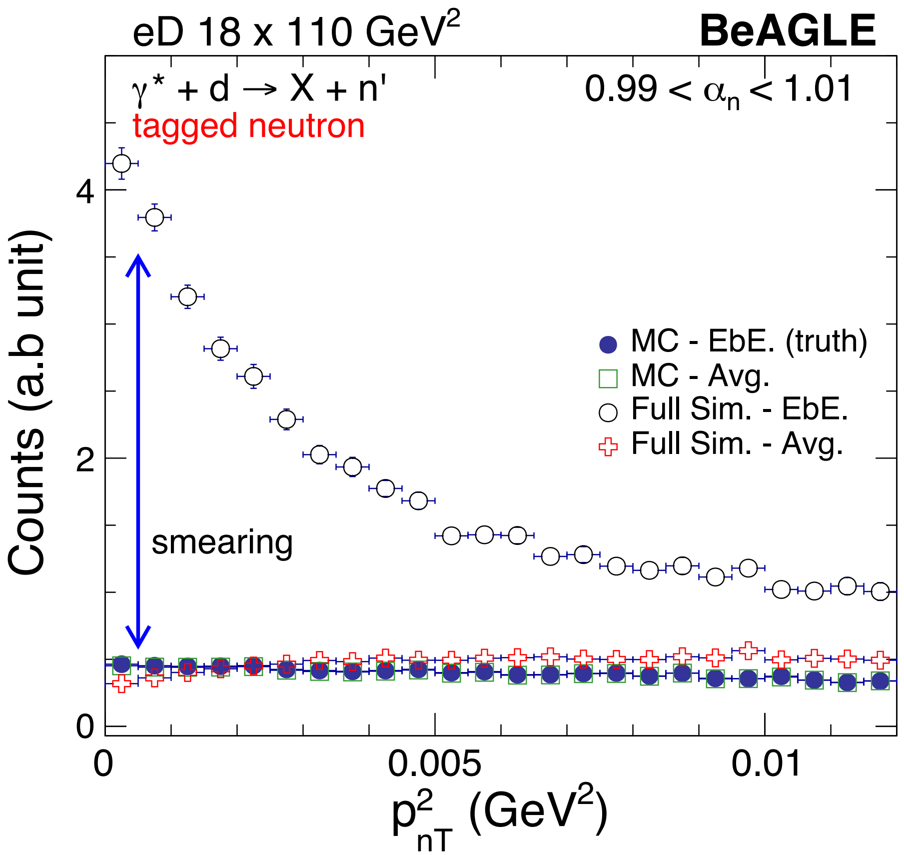
Closure Test – Event by Event Pole Removal



- 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.

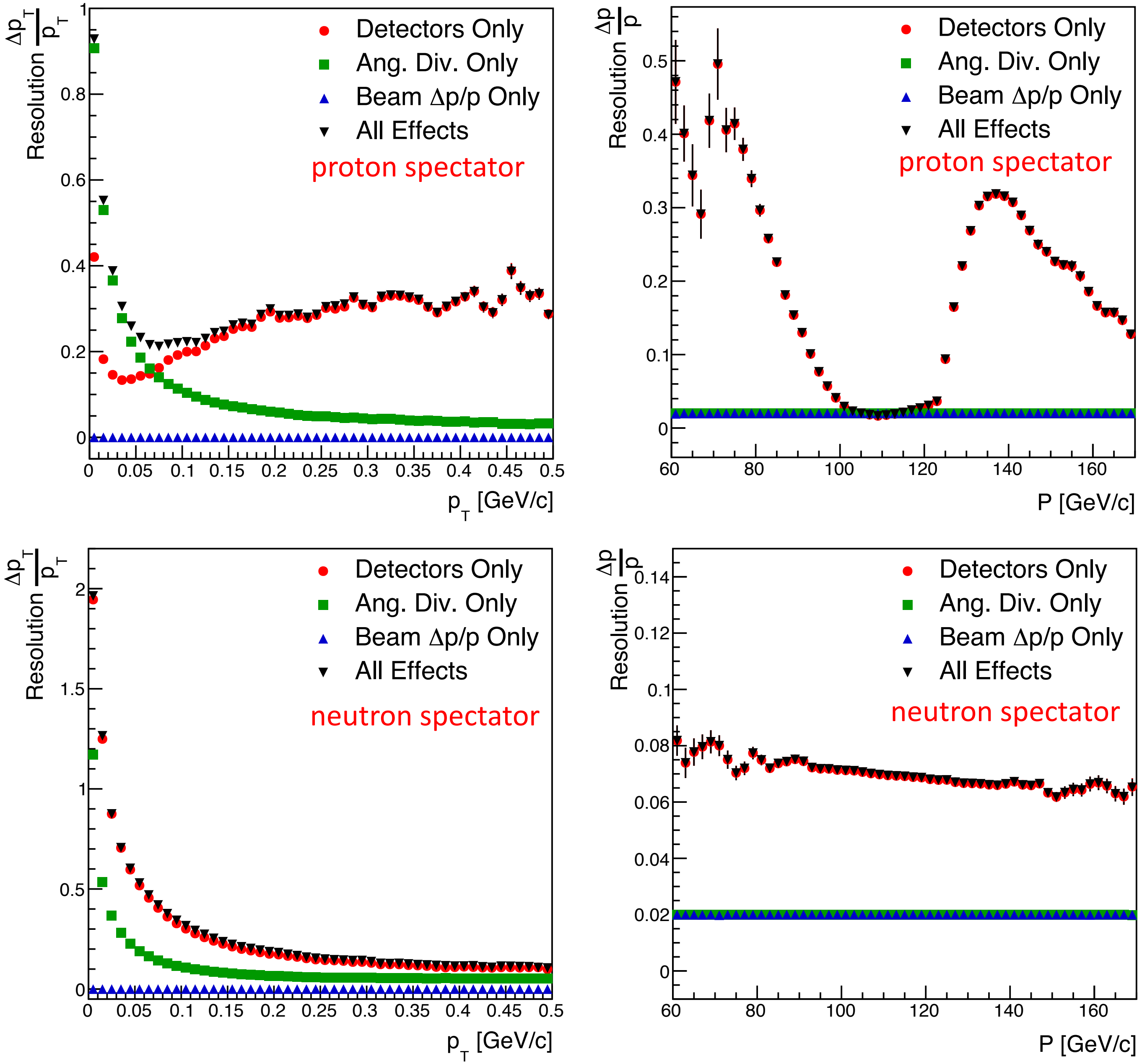
Effects of momentum smearing on pole factor





- 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.