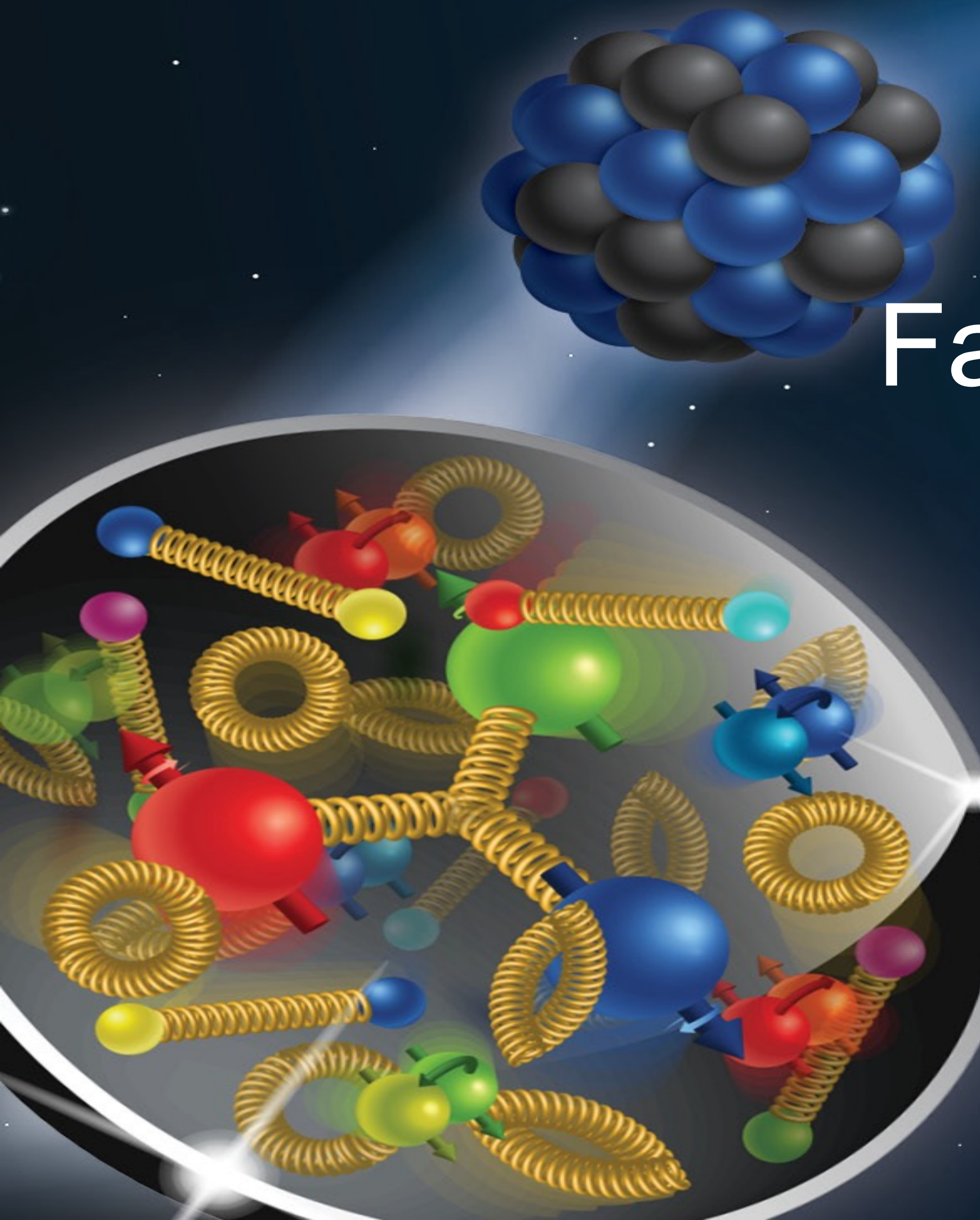
Far-Forward and Far-Backward Detectors at the EIC



Alex Jentsch (Brookhaven National Laboratory)

For the ePIC Collaboration

RHIC/AGS Annual User's Meeting

August 1st-4th, 2023

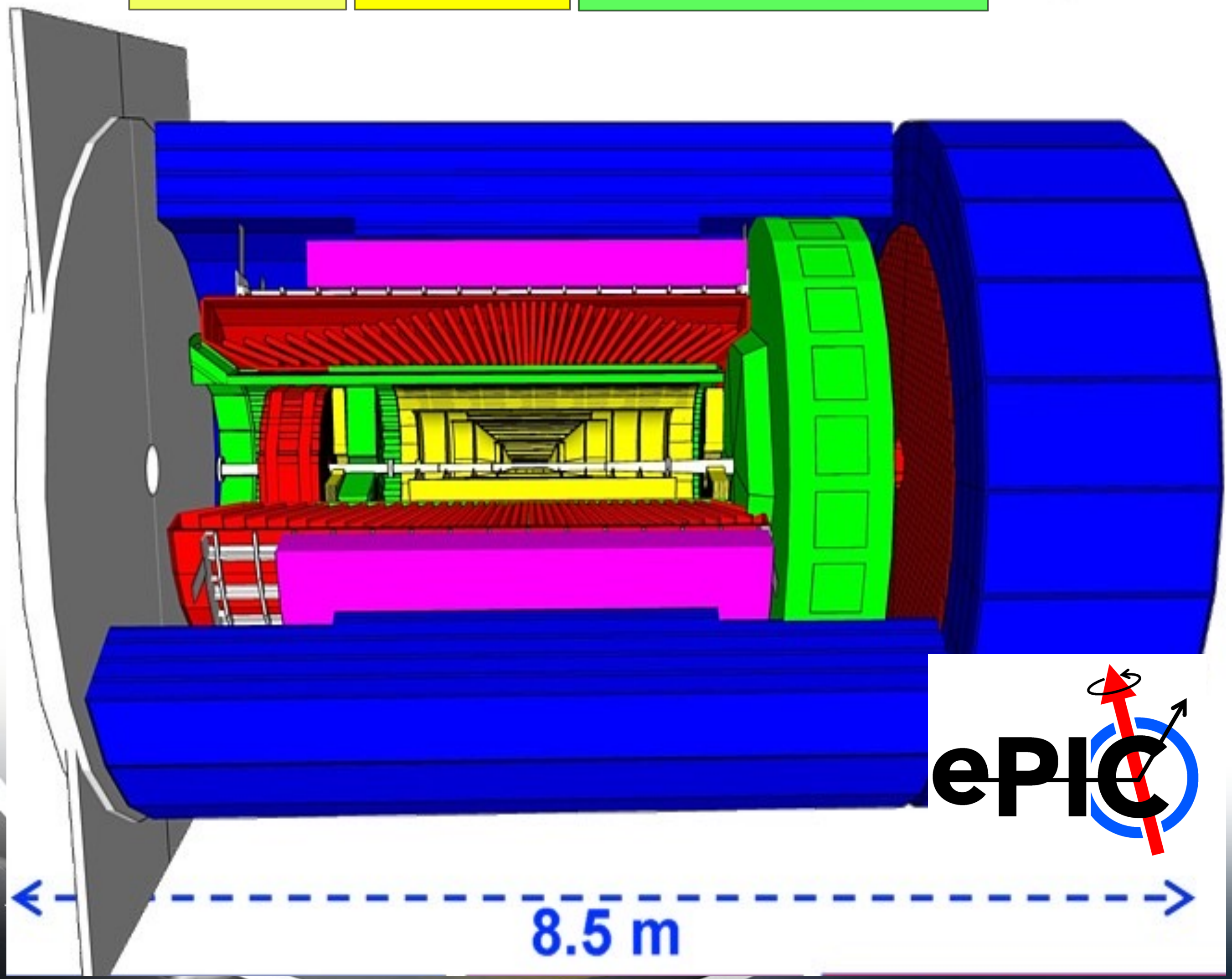
Upton, NY

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

What is meant by Far-Forward?

hadronic calorimeters | solenoid coils | e/m calorimeters

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



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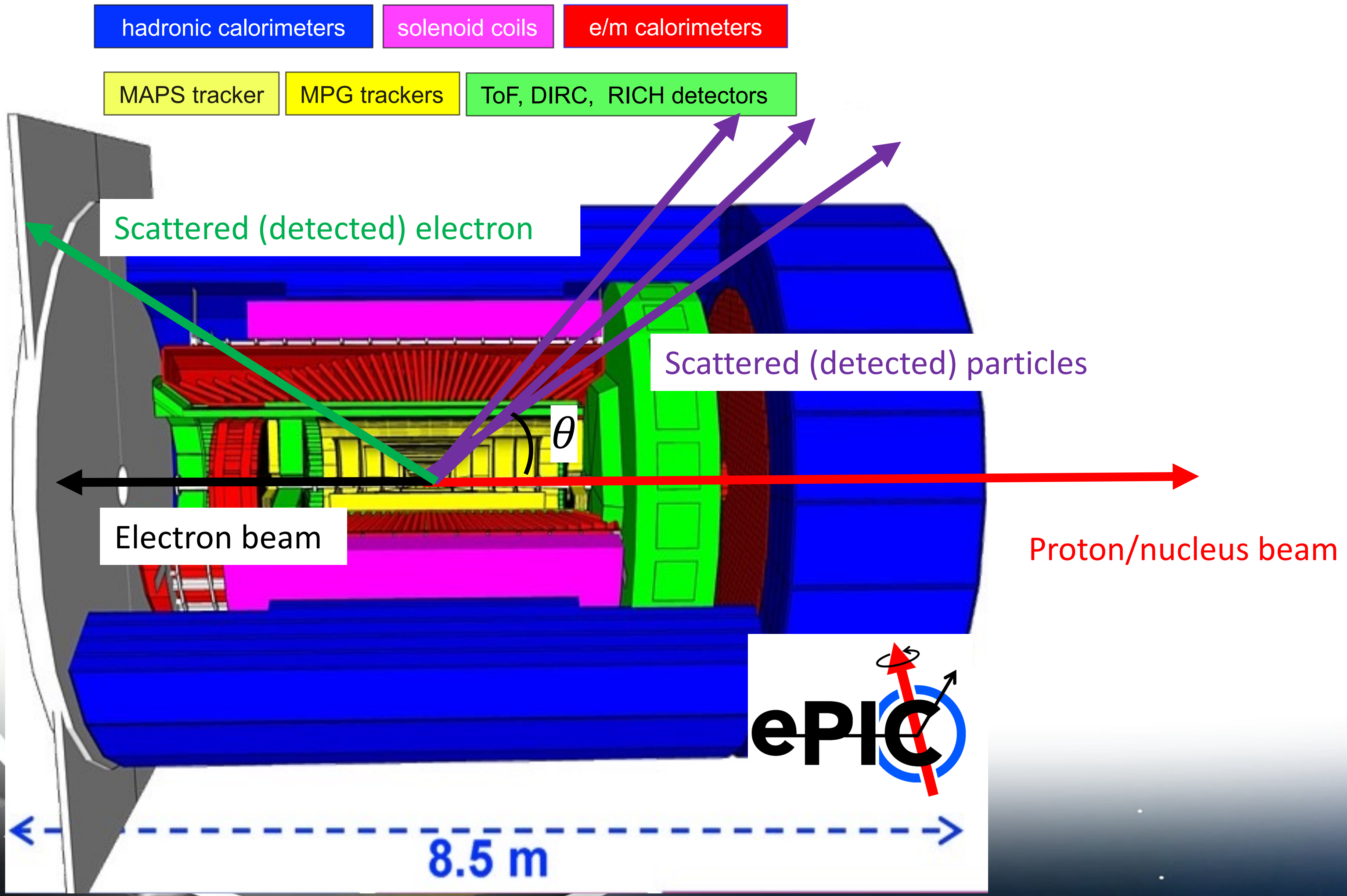

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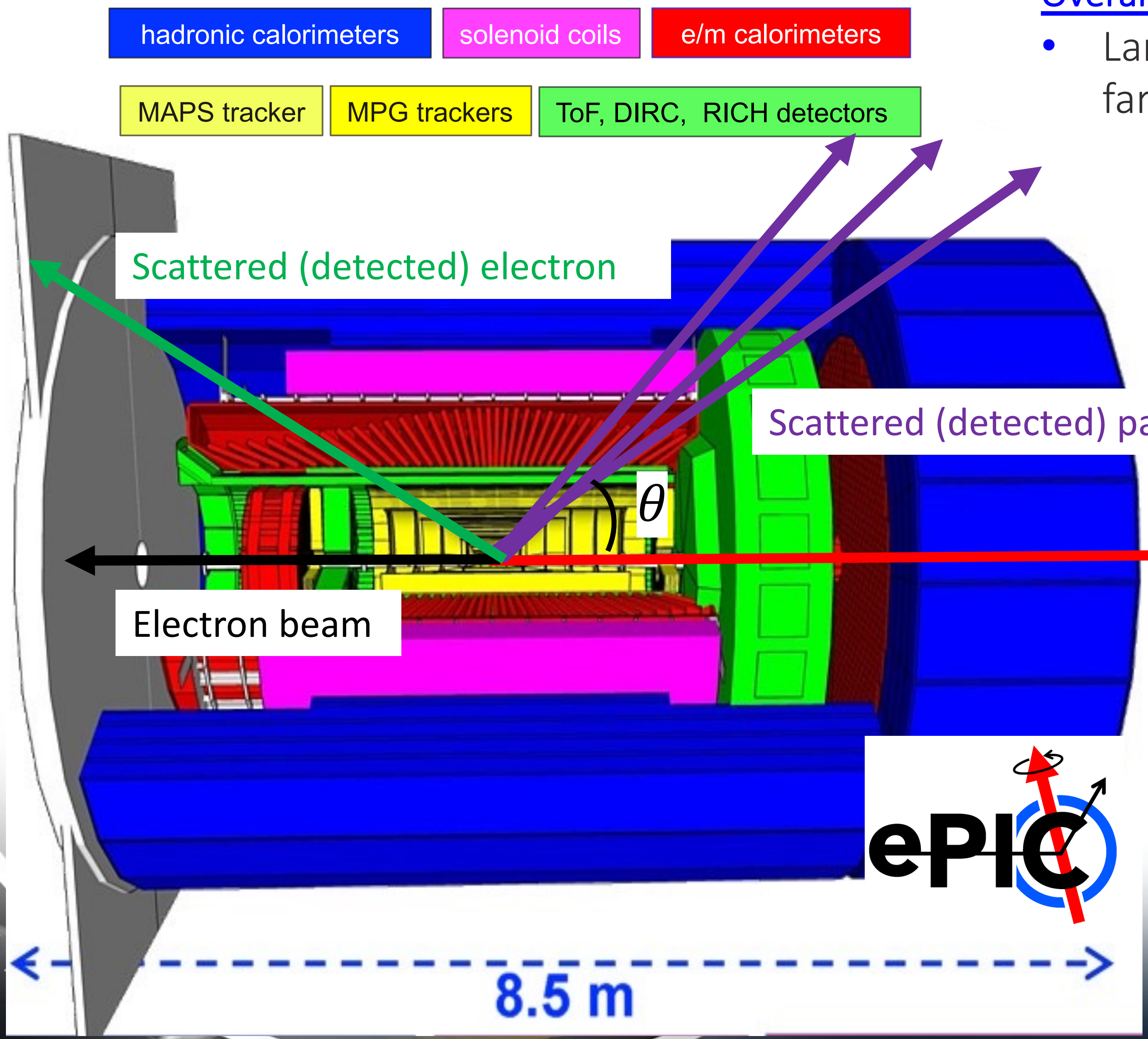


Proton/nucleus beam

Overall detector requirements:

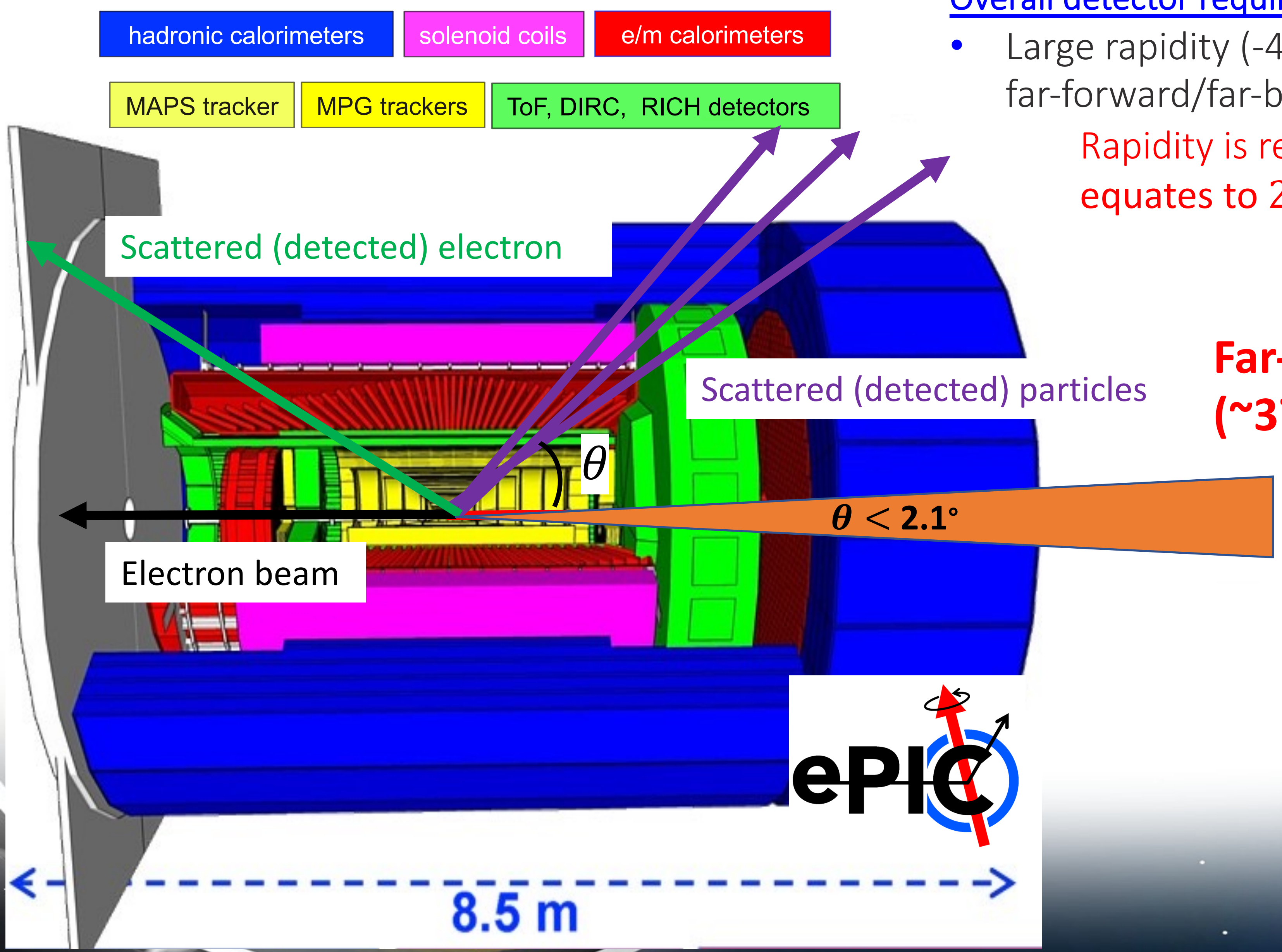
- Large rapidity (-4 < η < 4) coverage; and far beyond in far-forward/far-backward detector regions

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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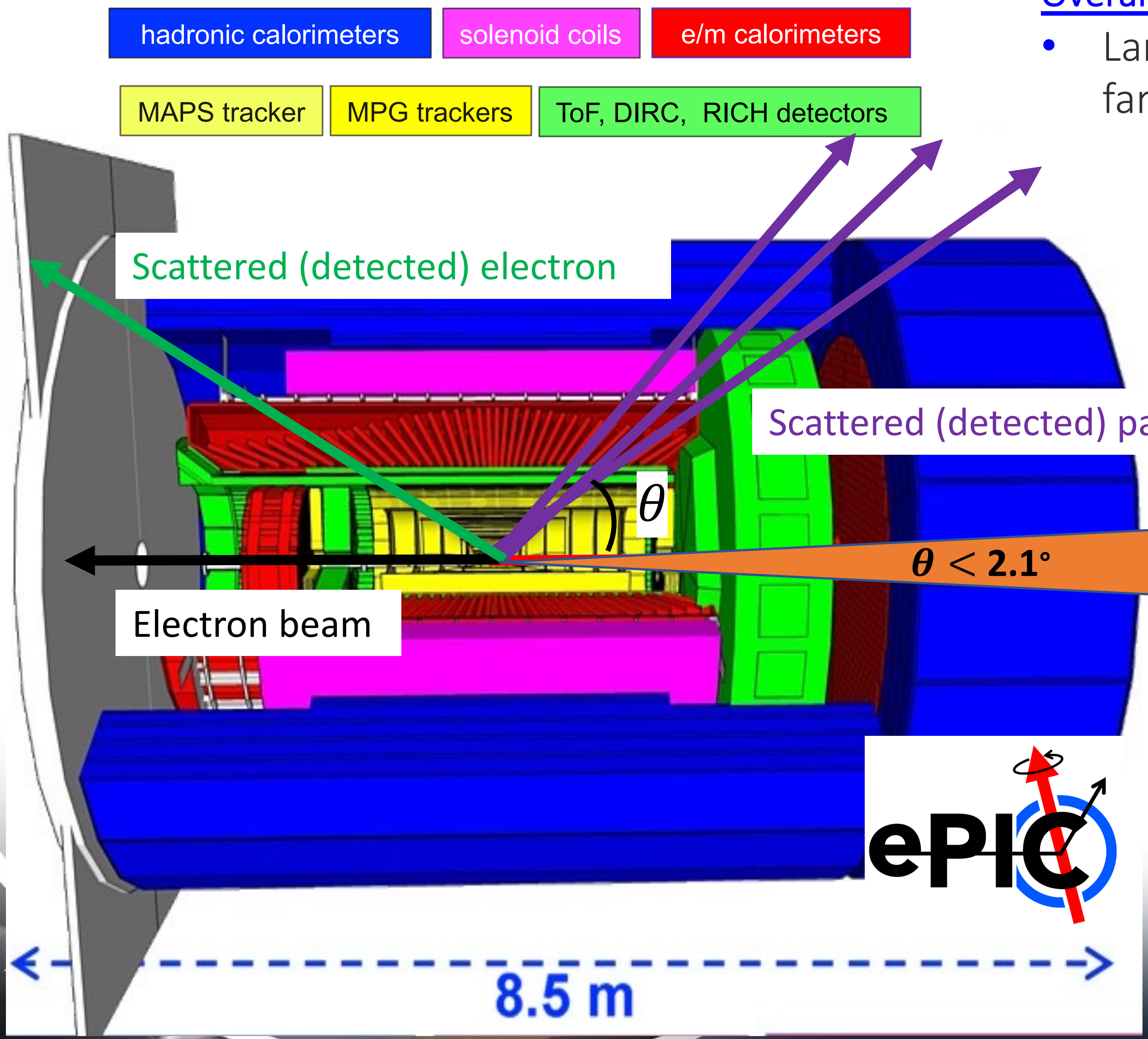
pseudorapidity

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

What is meant by Far-Forward?



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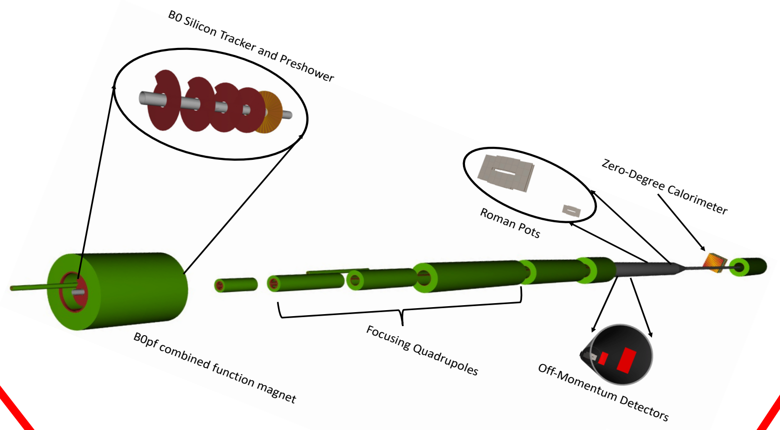
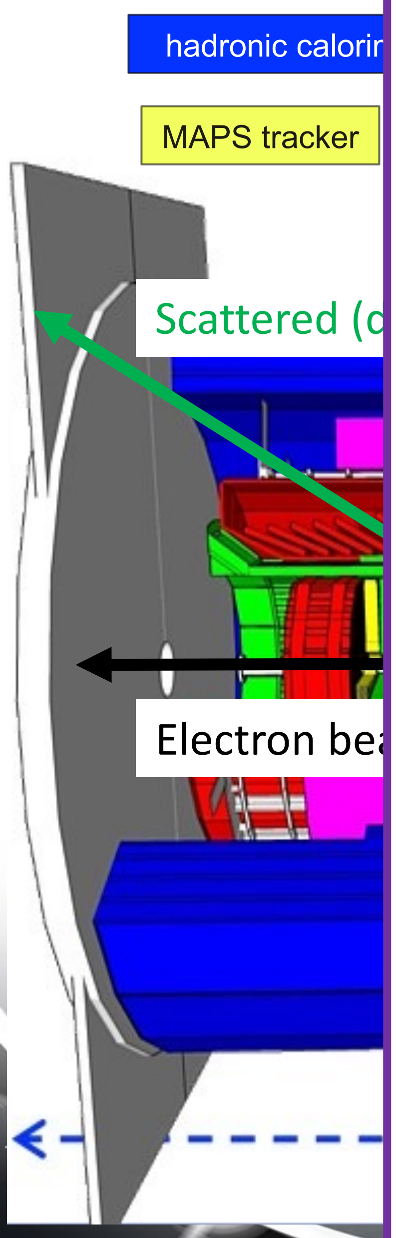
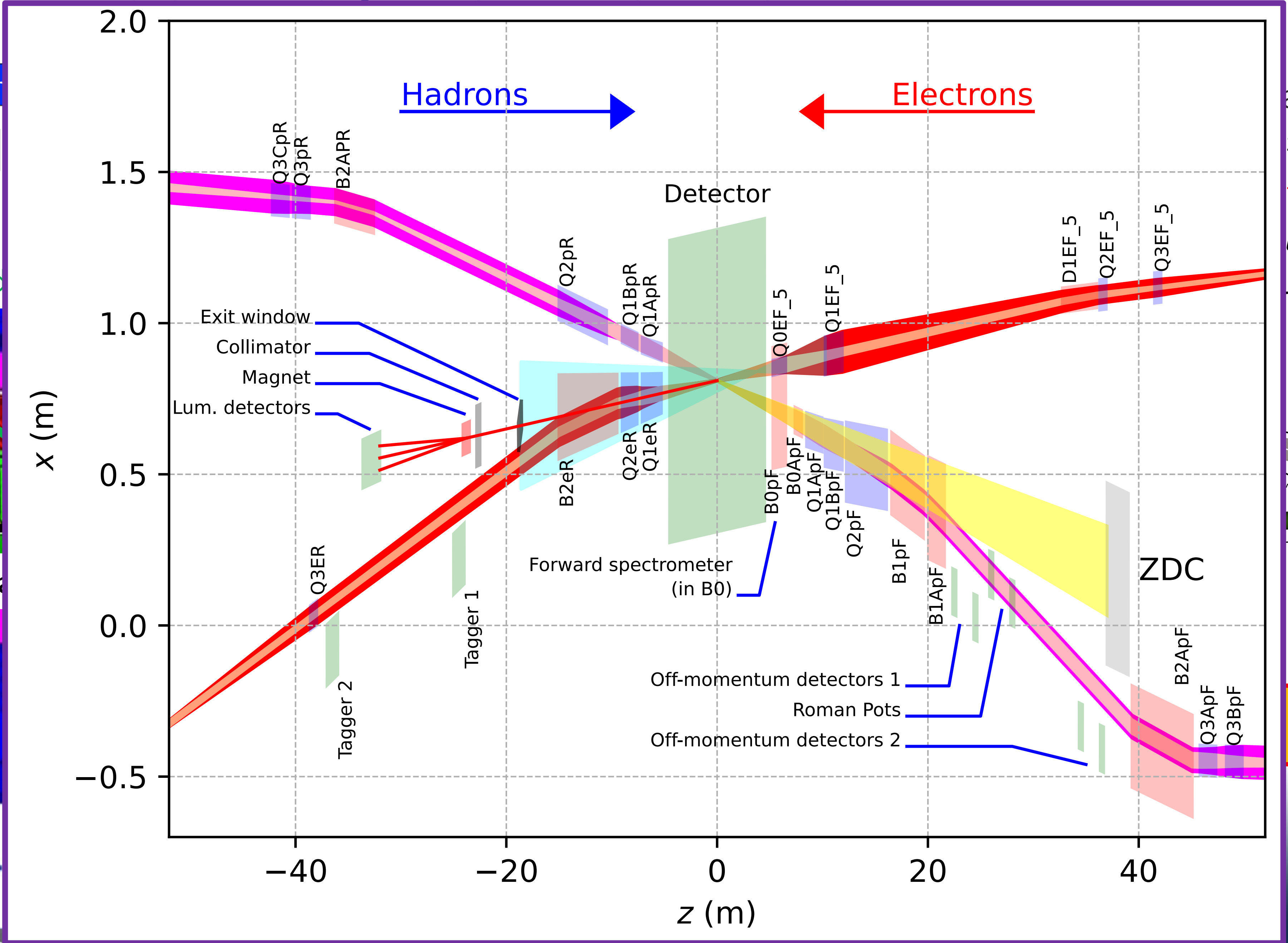


Need detectors here!!

What is meant by Far-Forward?





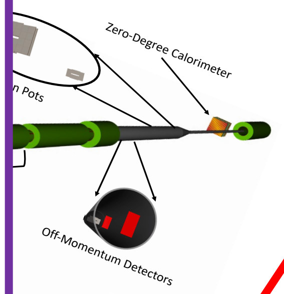
ar beyond in

s

→ 0 < η < 4

$ln(tan(\theta/2))$

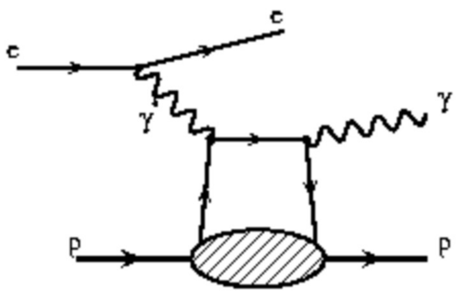
udorapidity



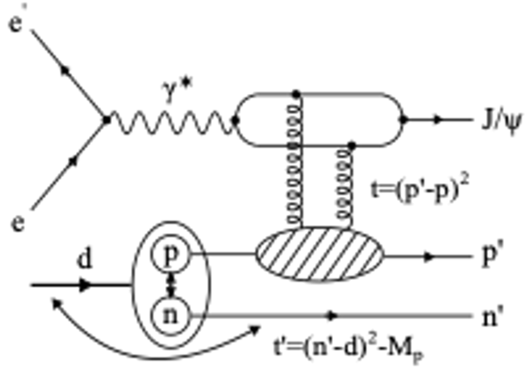
here!!

(some) Far-Forward Processes at the EIC

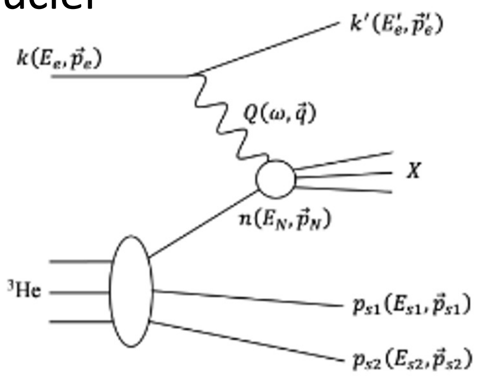
e+p DVCS



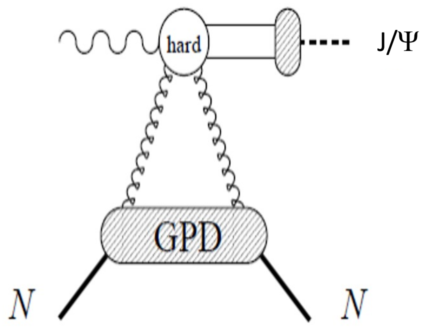
e+d exclusive J/Psi with p/n tagging



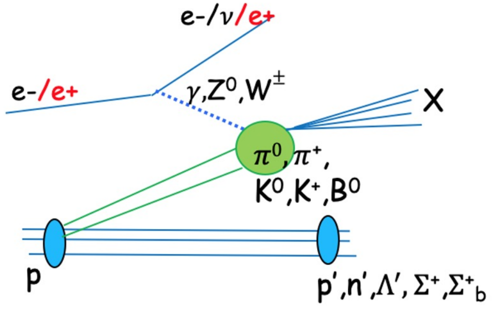
spectator tagging in light nuclei



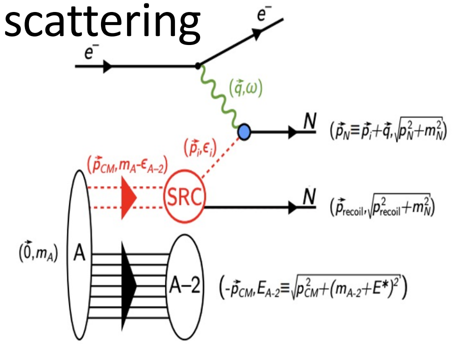
coherent/incoherent J/ψ production in e+A



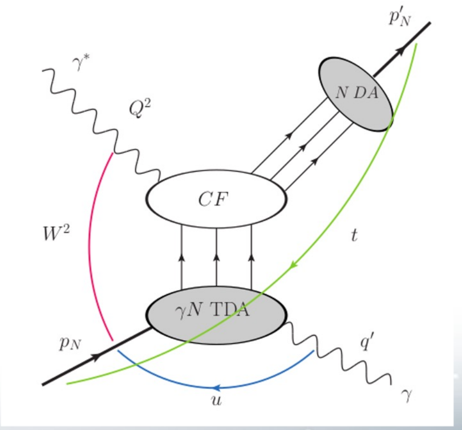
Sullivan process



Quasi-elastic electron scattering



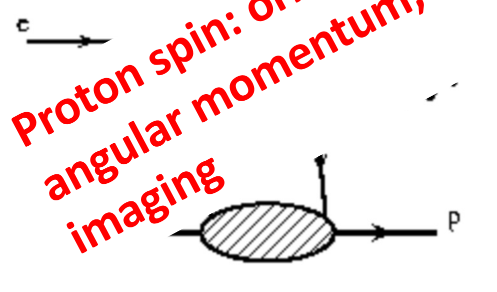
u-channel backward exclusive electroproduction



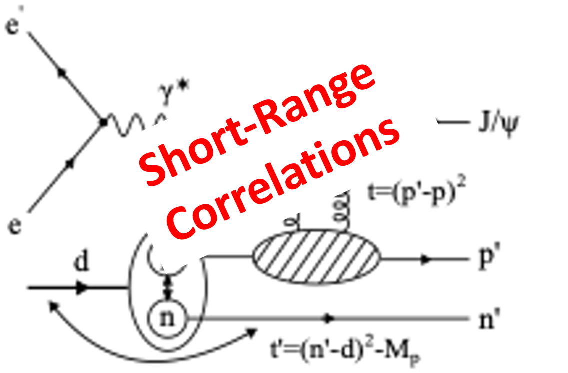
…and MANY more!

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

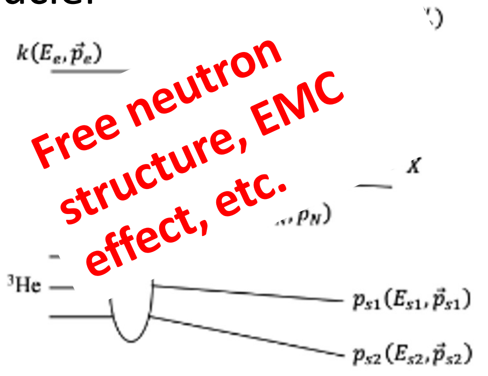
e+p DVCS



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



spectator tagging in light nuclei



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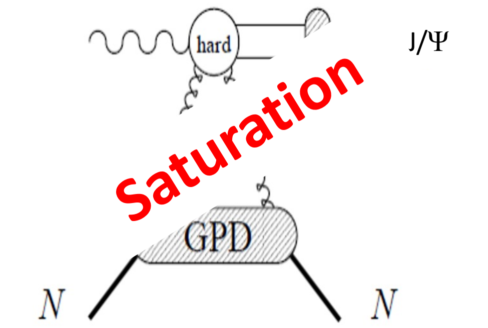
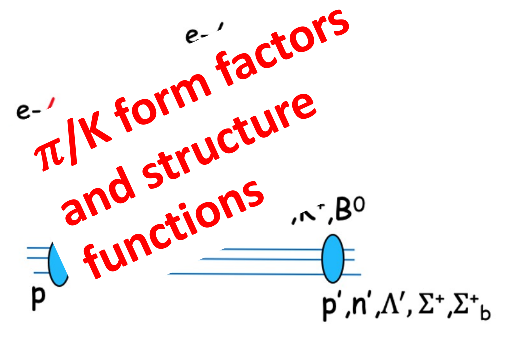


Sullivan process



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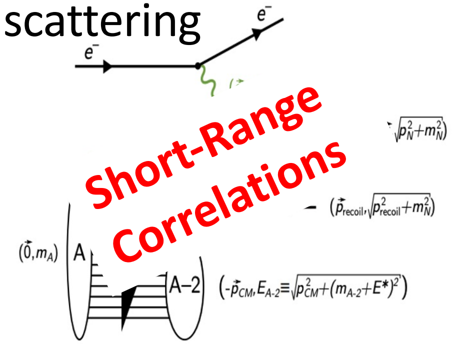
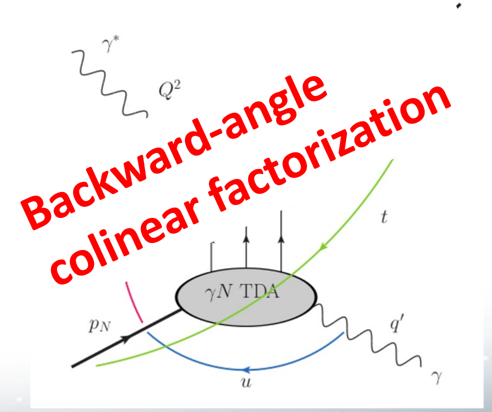


[1] Z. Tu, A. Jentsch, et al., Physics Letters B, (2020)
[2] I. Friscic, D. Nguyen, J. R. Pybus, A. Jentsch, *et al.*, Phys. Lett. B, **Volume 823**, 136726 (2021)
[3] W. Chang, E.C. Aschenauer, M. D. Baker, A. Jentsch, J.H. Lee, Z. Tu, Z. Yin, and L.Zheng, Phys. Rev. D **104**, 114030 (2021)
[4] A.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

u-channel backward exclusive electroproduction

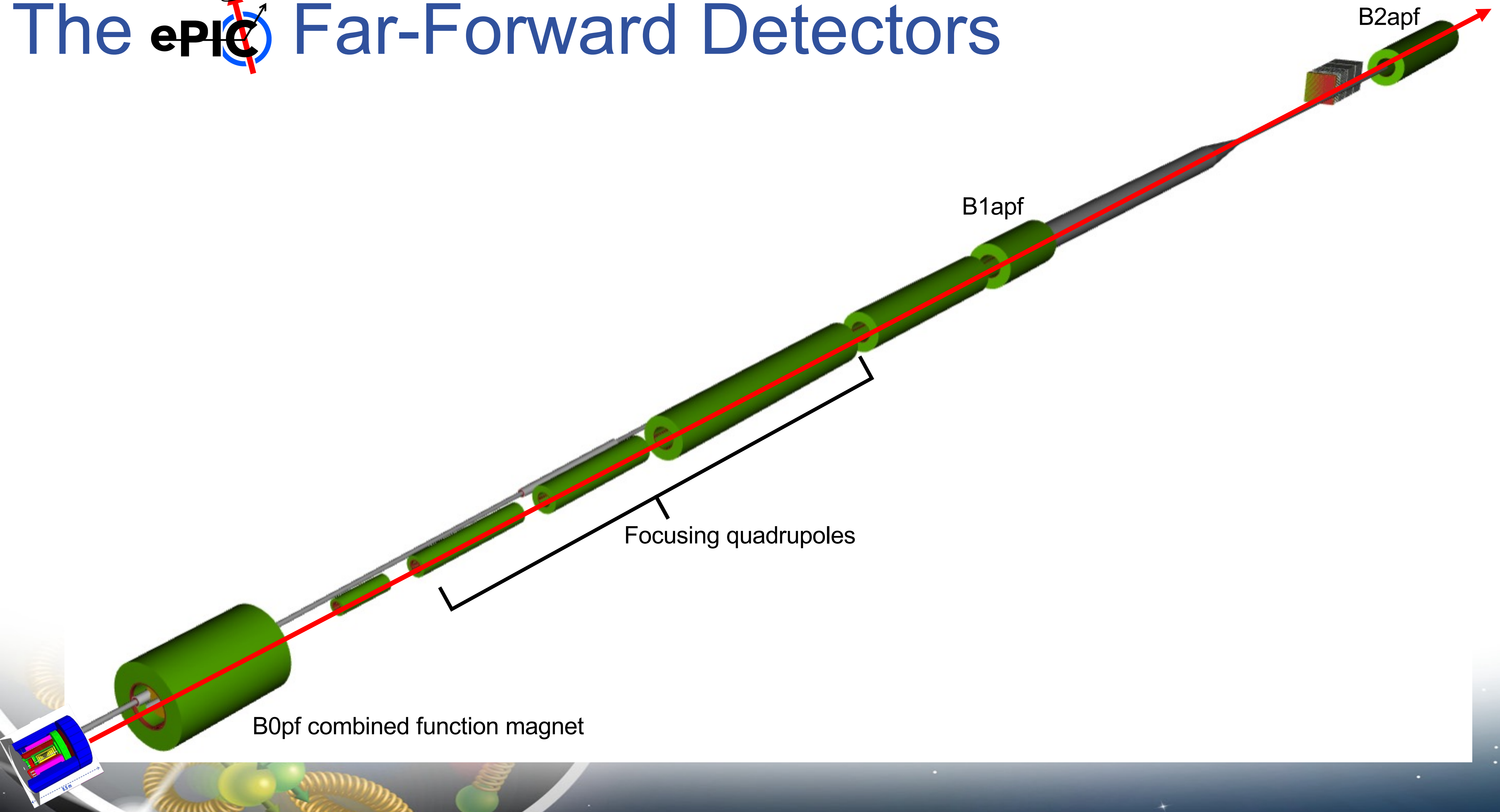


…and MANY more!

(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 collision systems 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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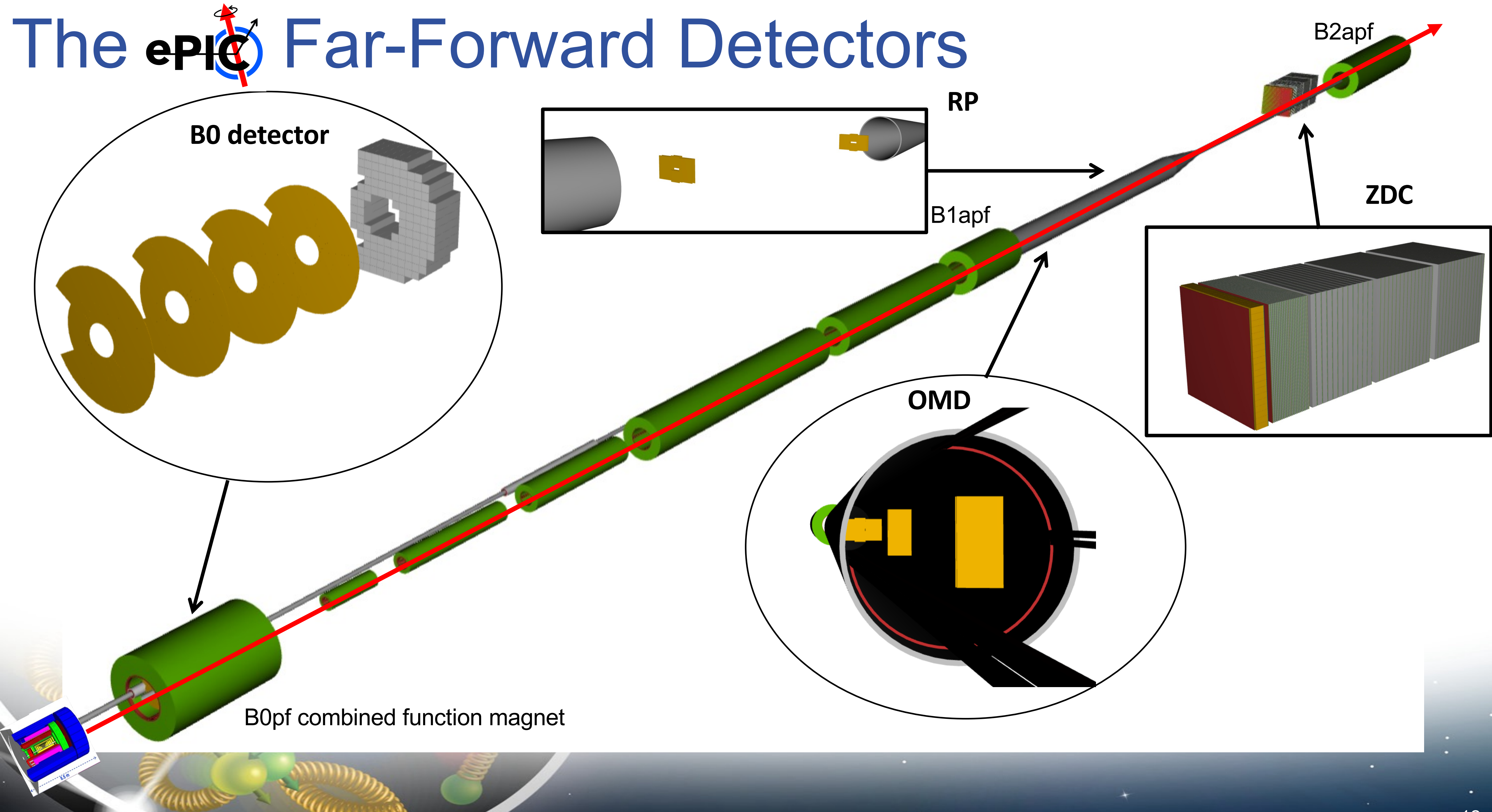

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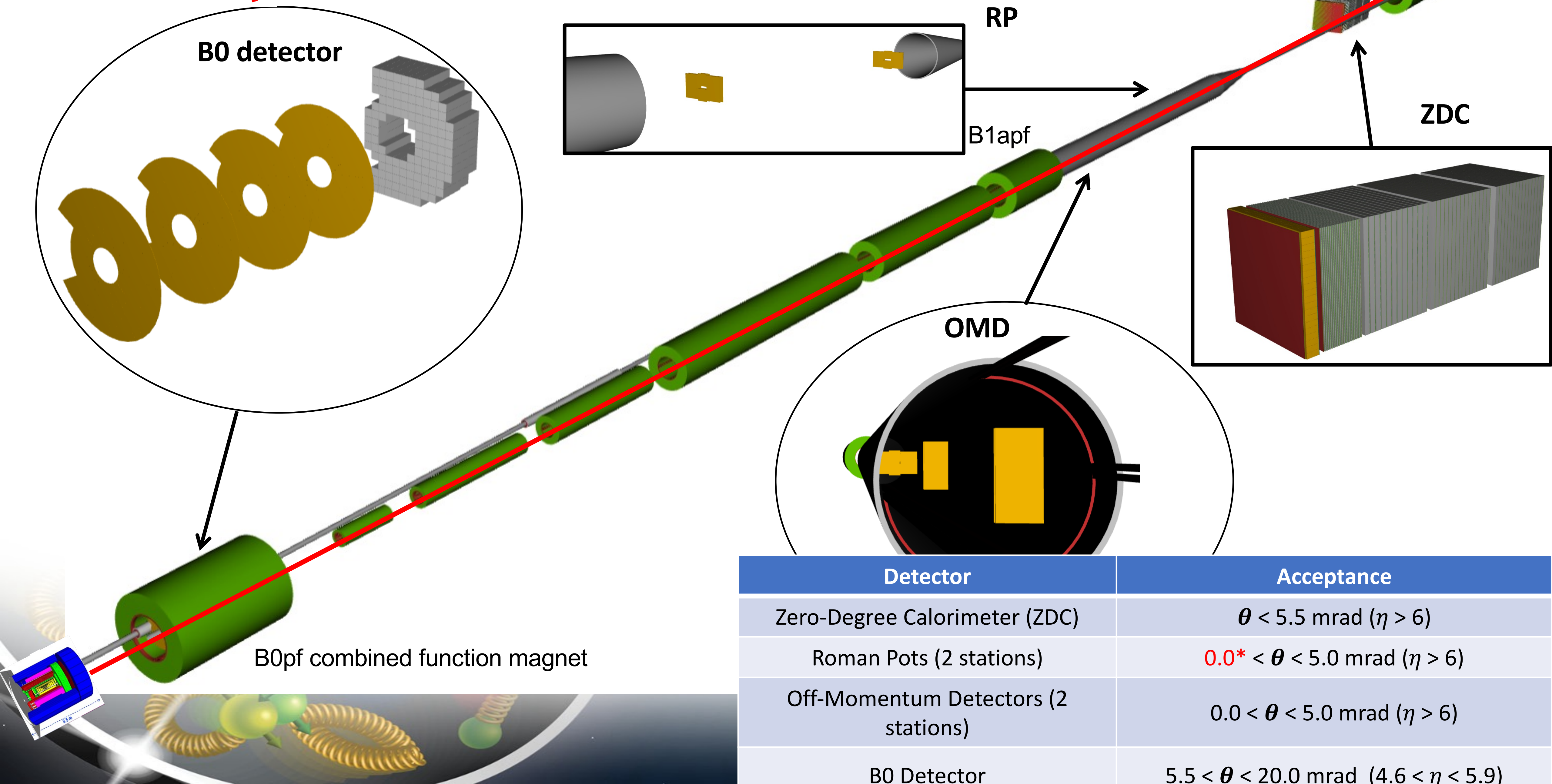
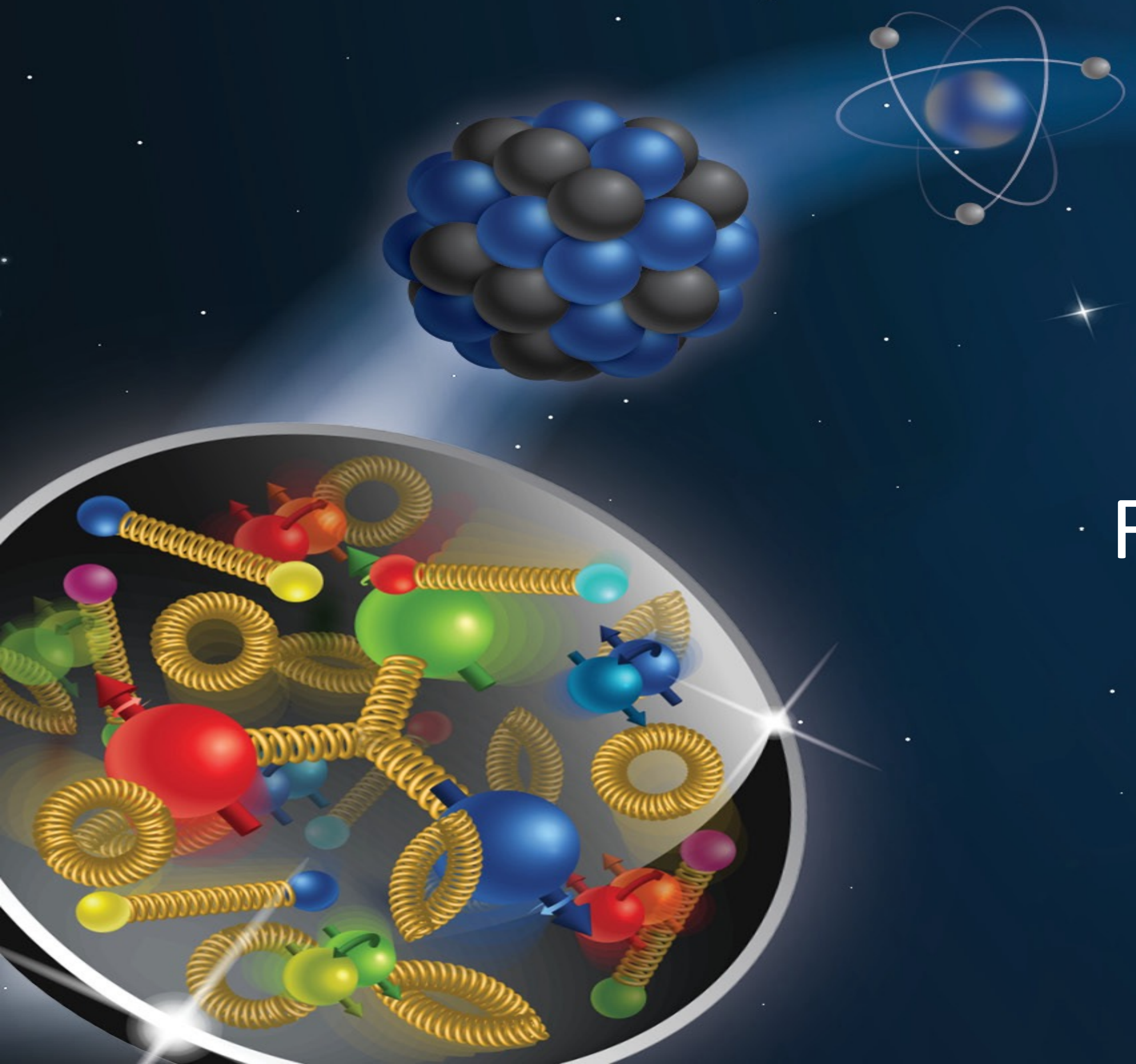


Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	θ < 5.5 mrad (η > 6)
Roman Pots (2 stations)	0.0* < θ < 5.0 mrad (η > 6)
Off-Momentum Detectors (2 stations)	0.0 < θ < 5.0 mrad (η > 6)
B0 Detector	5.5 < θ < 20.0 mrad (4.6 < η < 5.9)

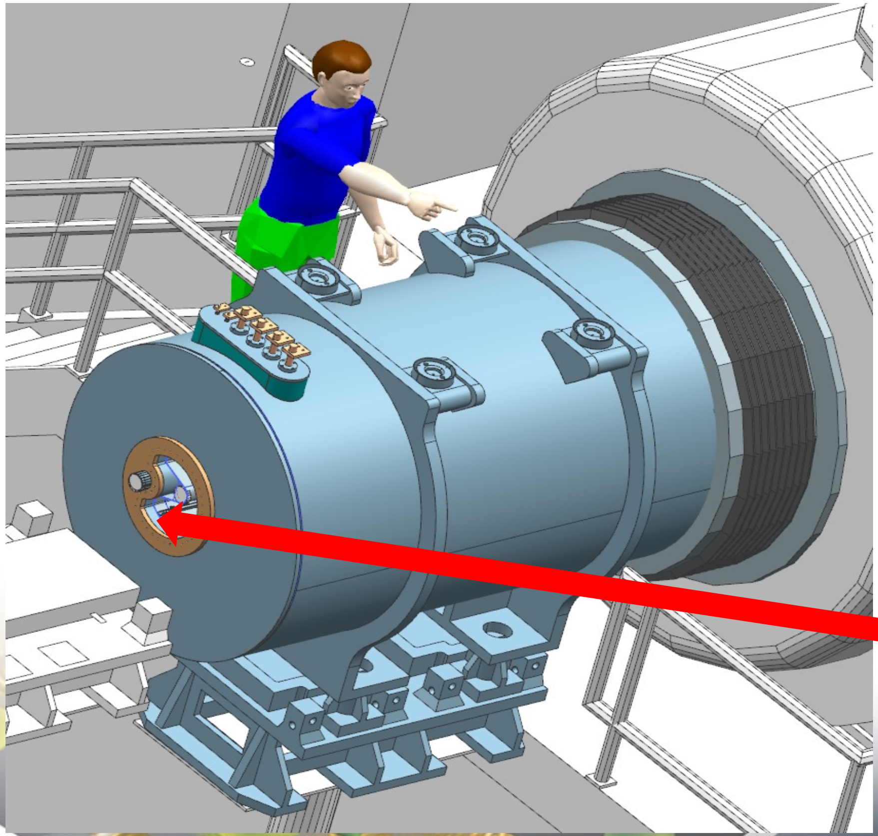


Far-Forward Detector Subsystems

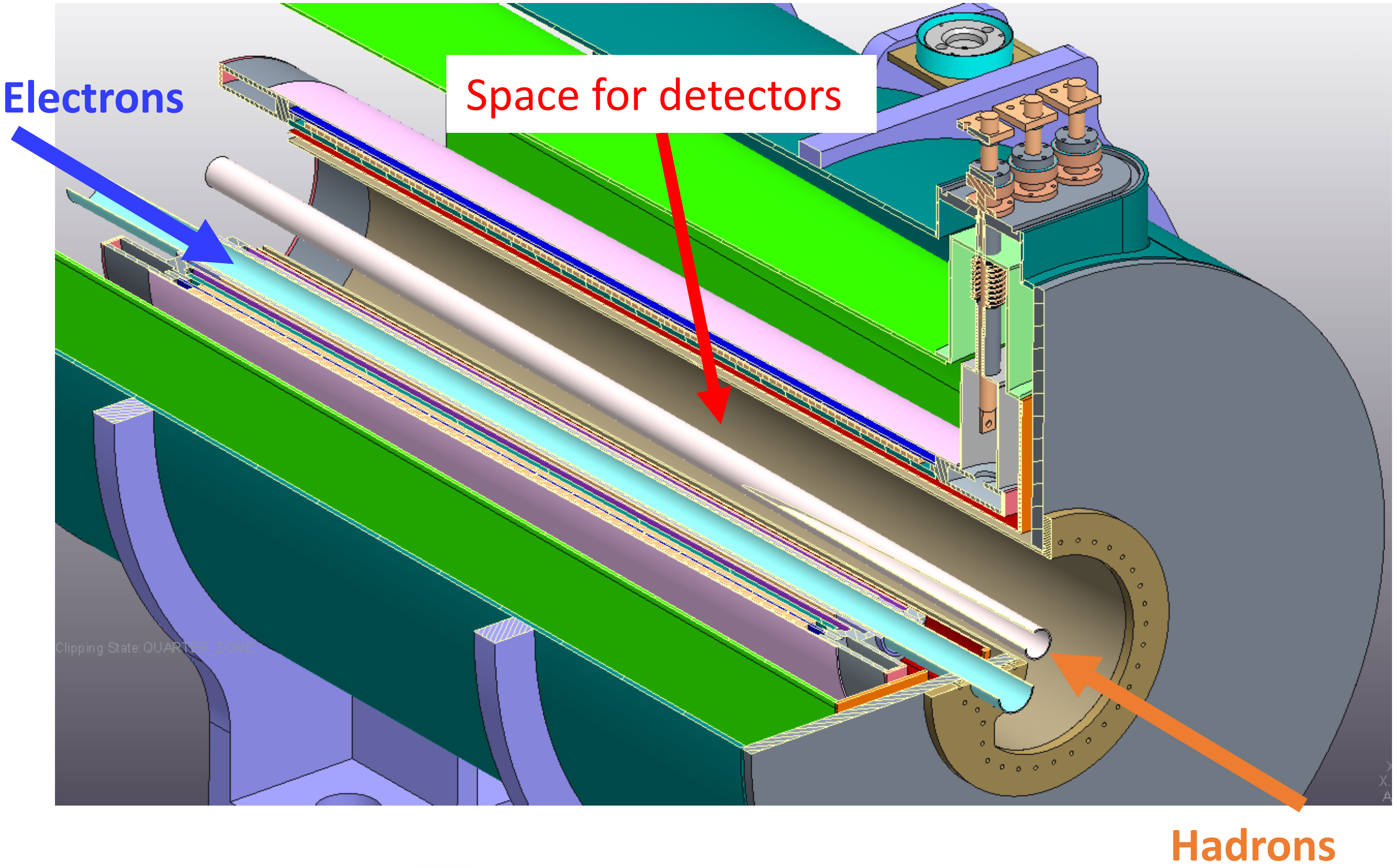
B0 Detectors

- Charged particle reconstruction and photon tagging.
  - MAPS for tracking + timing layer (e.g. LGADs).
  - Photon detection (tagging or full reco).

Credit to Ron Lassiter



This is the opening where the detector planes will be inserted



Preliminary Parameters:
229.5cm x 121.1cm x 195cm
(Actual length will be shorter)

BeeDetectors

CAD Look credit: Jonathan Smith

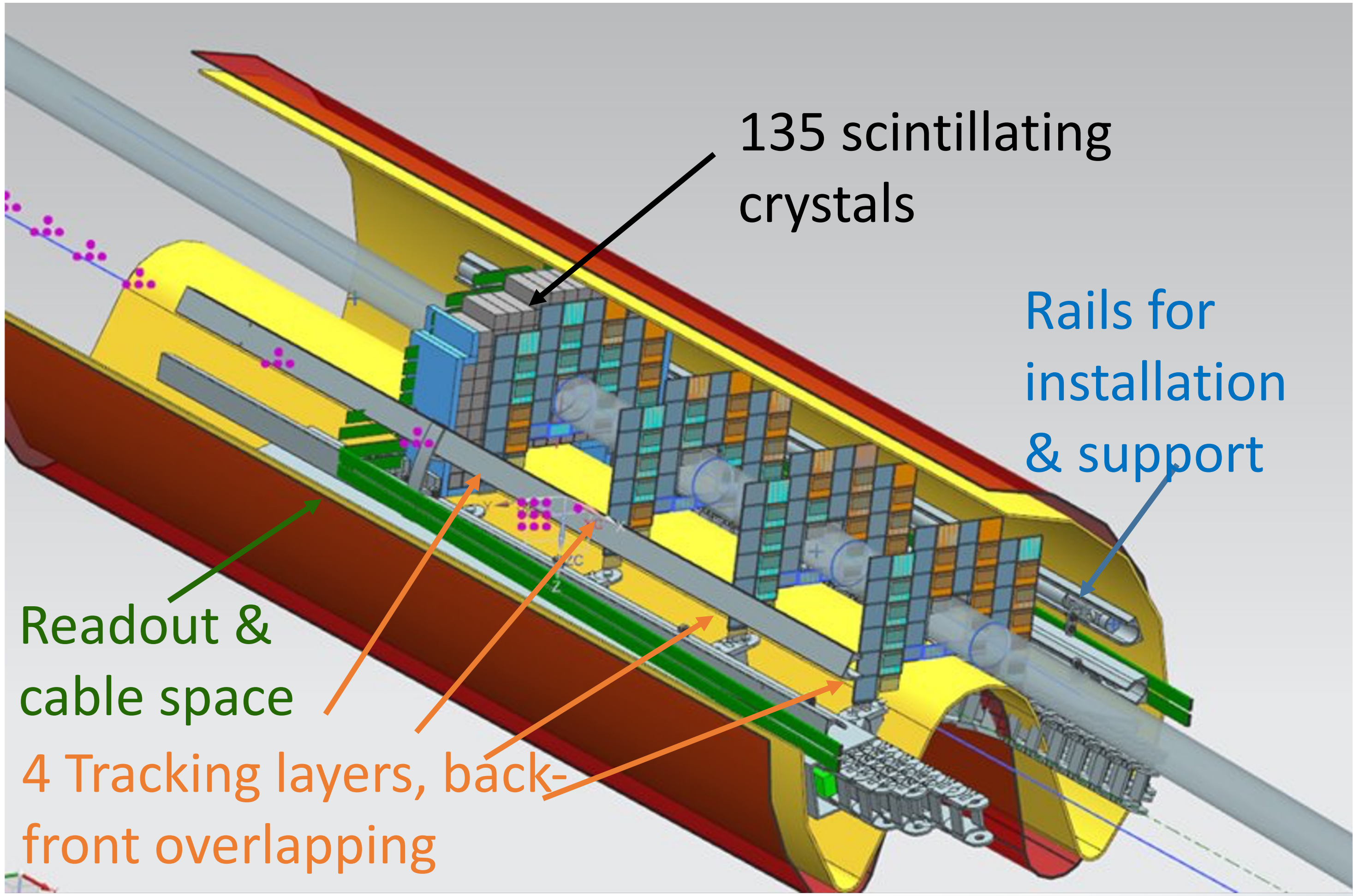
Design for two detectors is converging:

Si Tracker:

- 4 Layers of AC-LGAD
- Great timing capabilities
- Sufficient position resolution by utilizing charge sharing
- 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

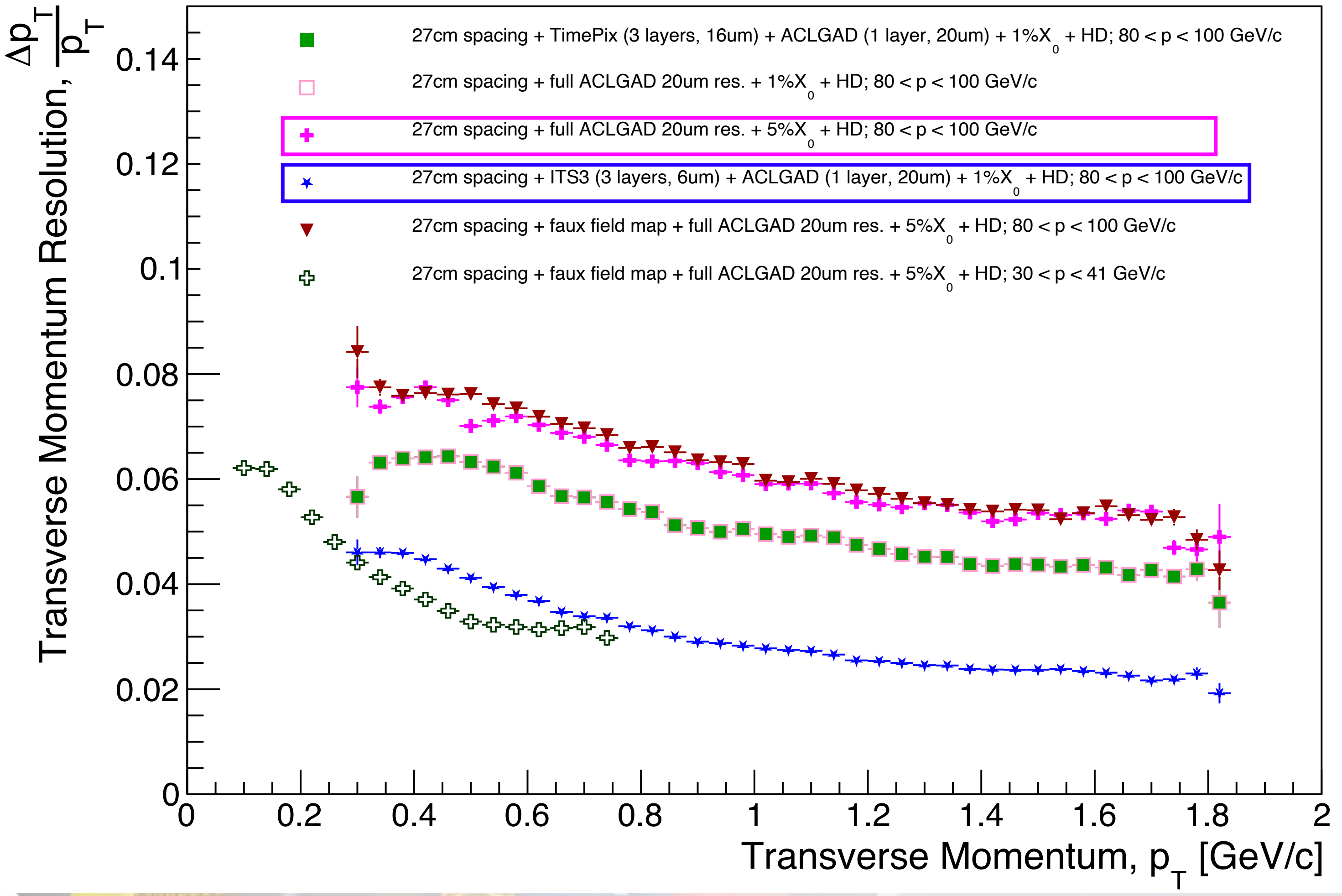
Si Tracker:

- Resolution plots made by Alex J 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 (more in FF weekly meeting)
- Sensitivity to soft photons (see Eden M. talk at the EICUG EC workshop early this week)

BEE Tracking - Performance



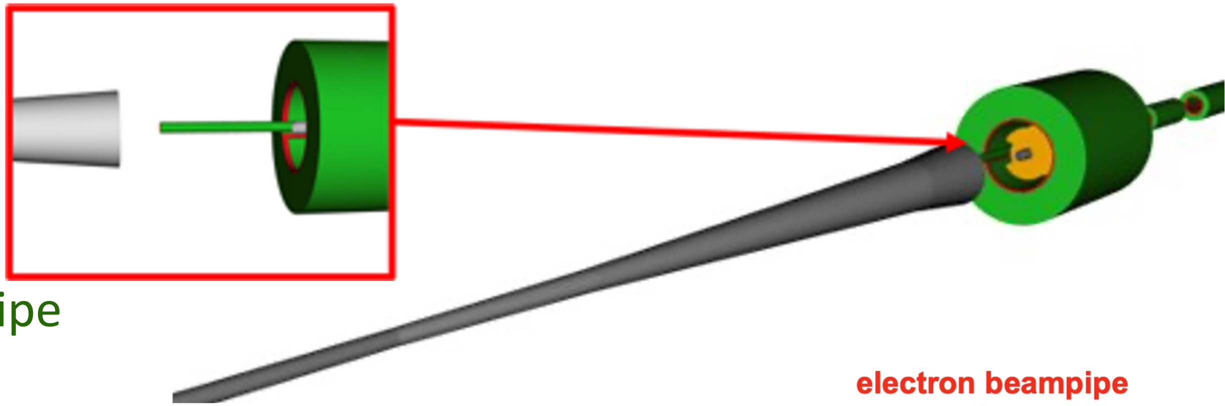
- 27cm spacing with fully AC-LGAD system and 5% radiation length may be the most-realistic option.
- Needs to be looked at with proper field map and layout.
- Is this resolution going to be a problem?

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

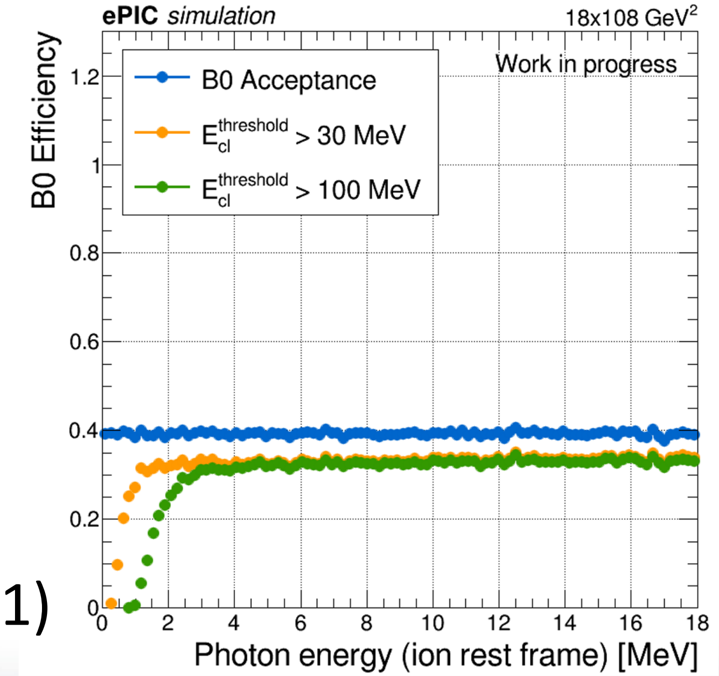


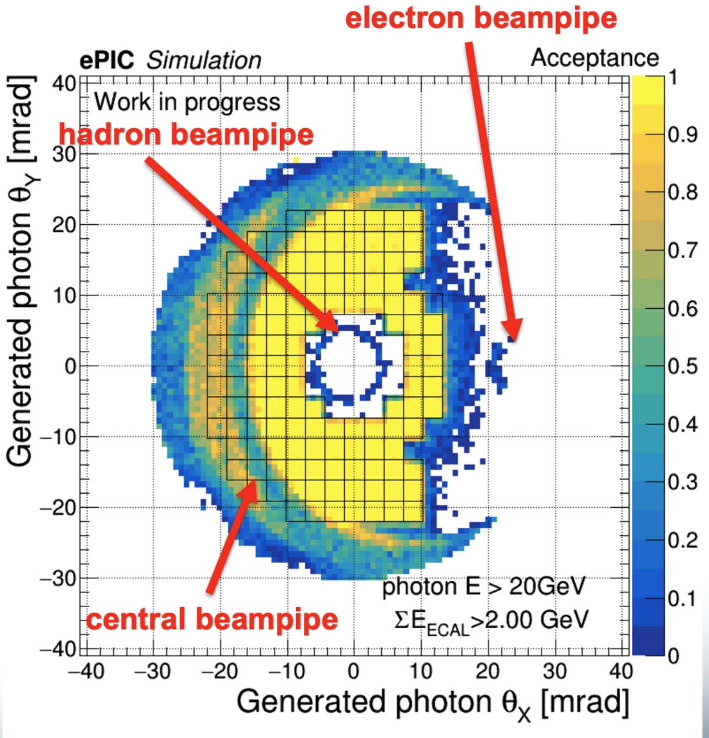
Photons:

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

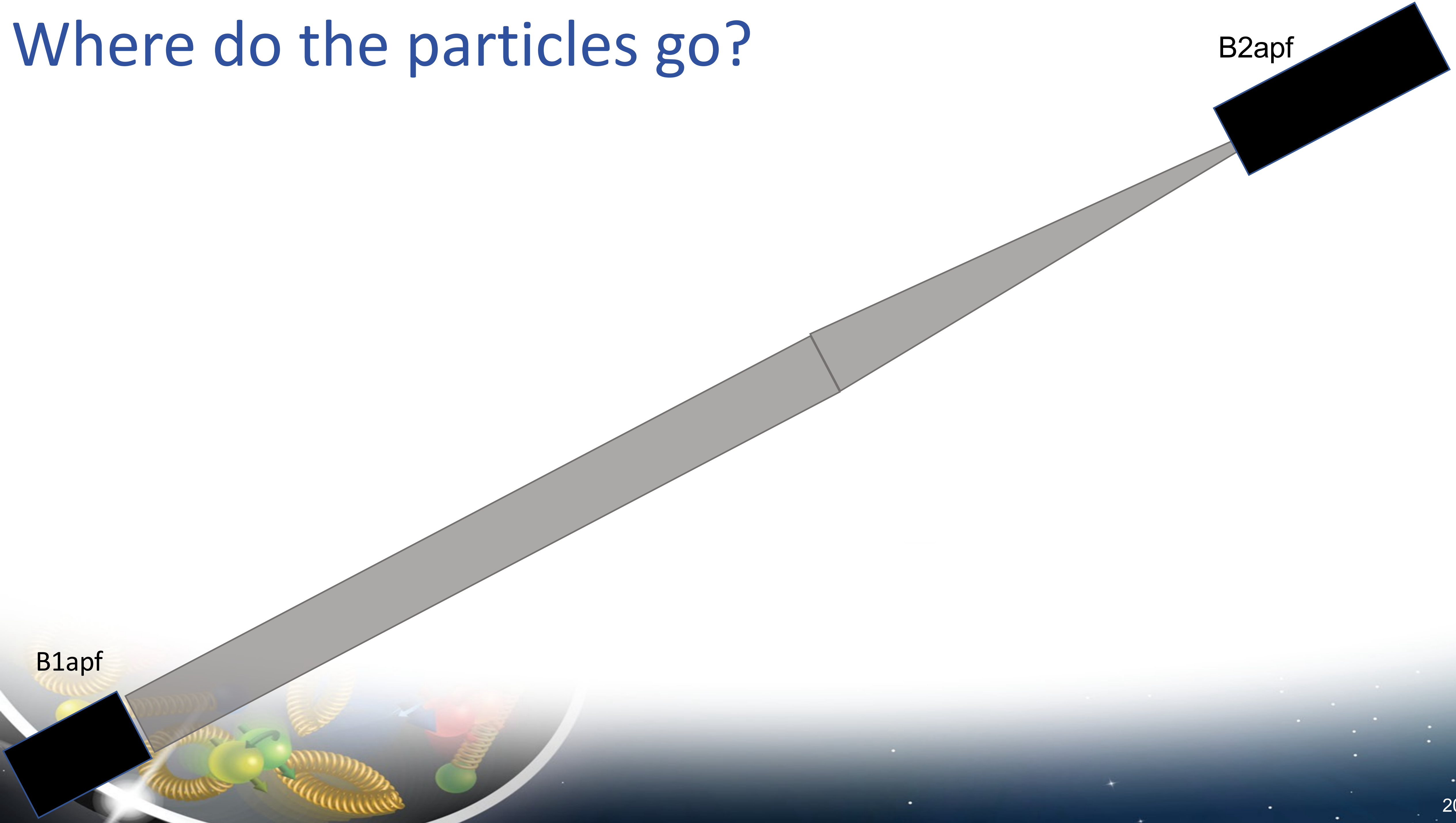
Neutrons:

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



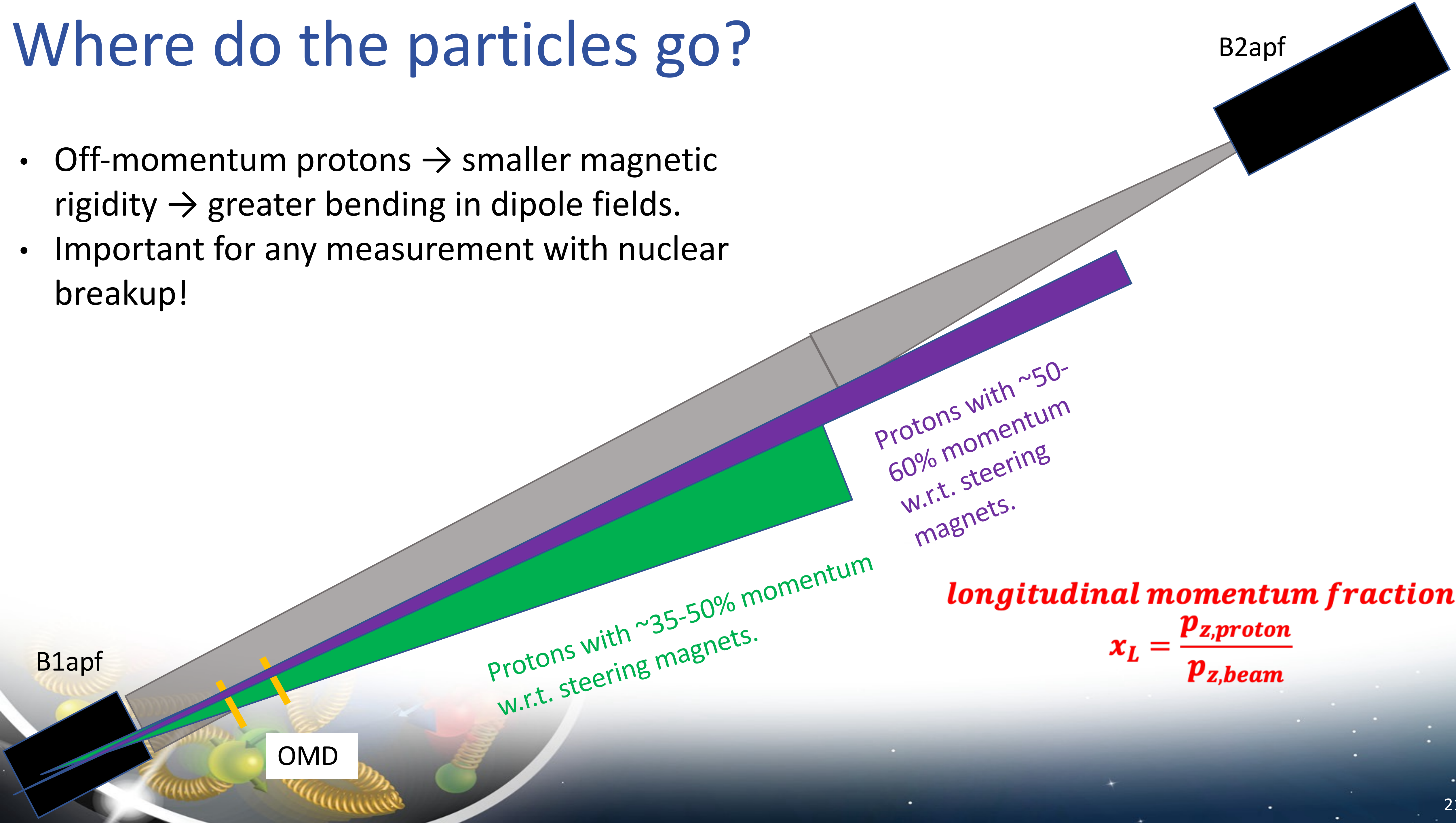


Where do the particles go?



Where do the particles go?

- 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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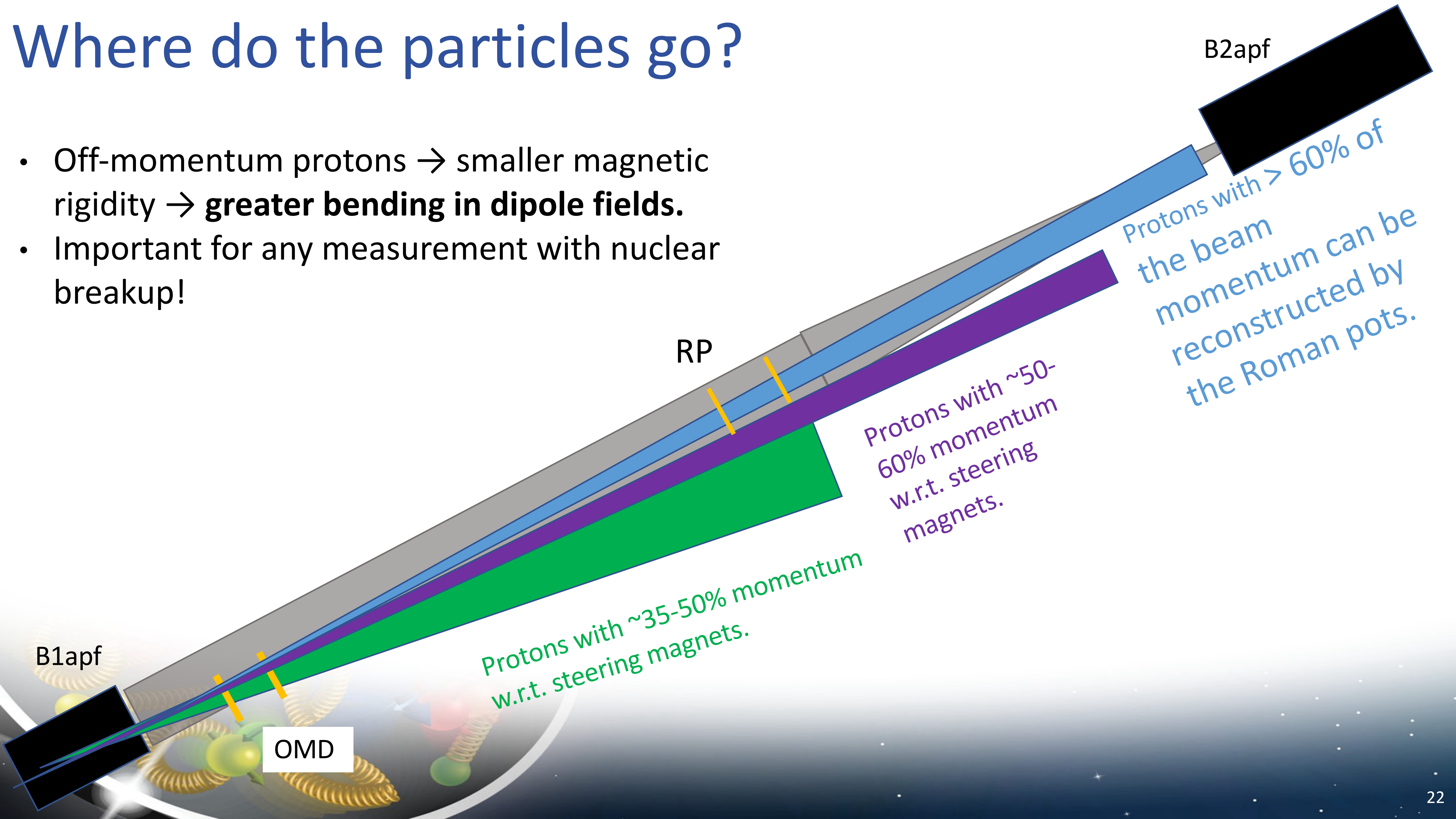

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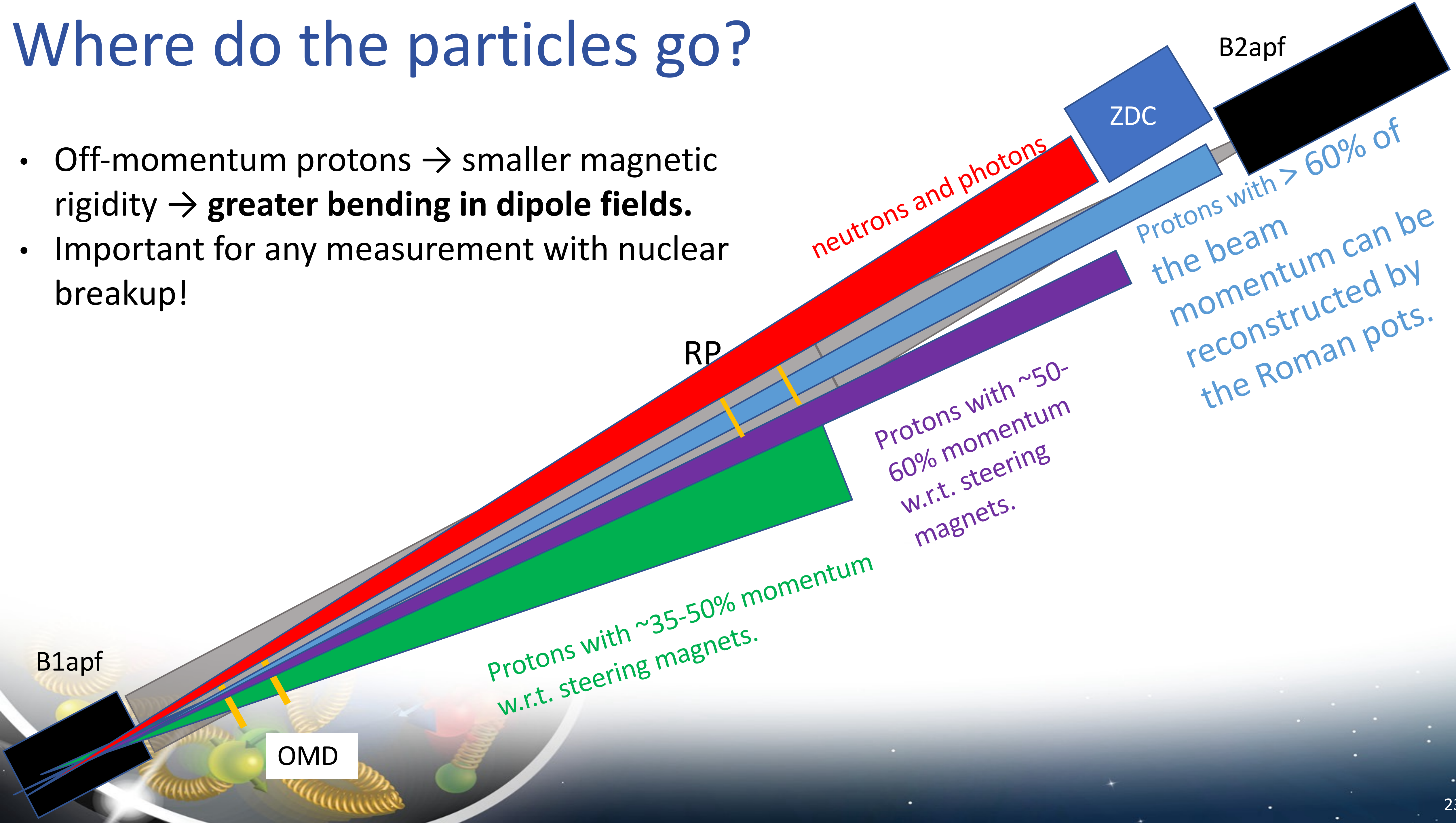
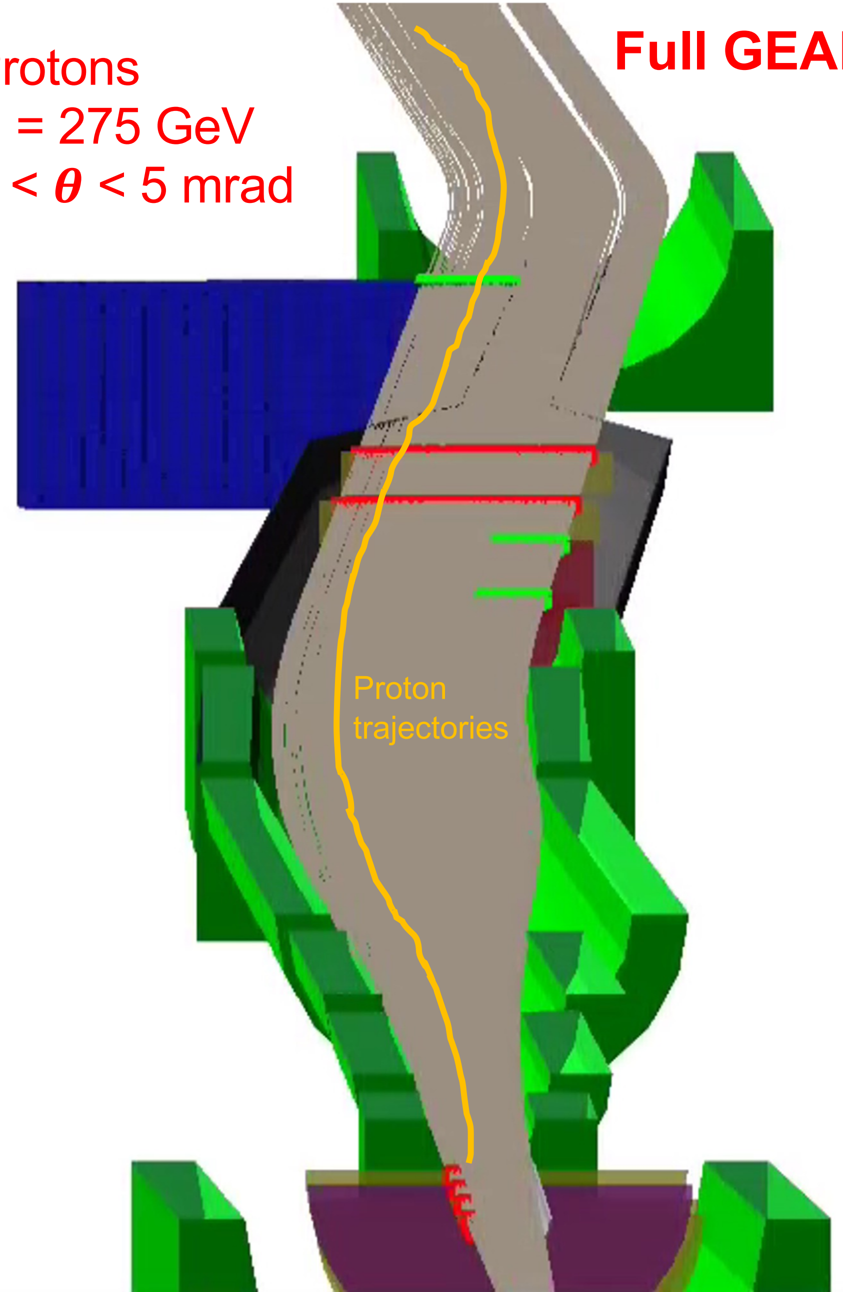
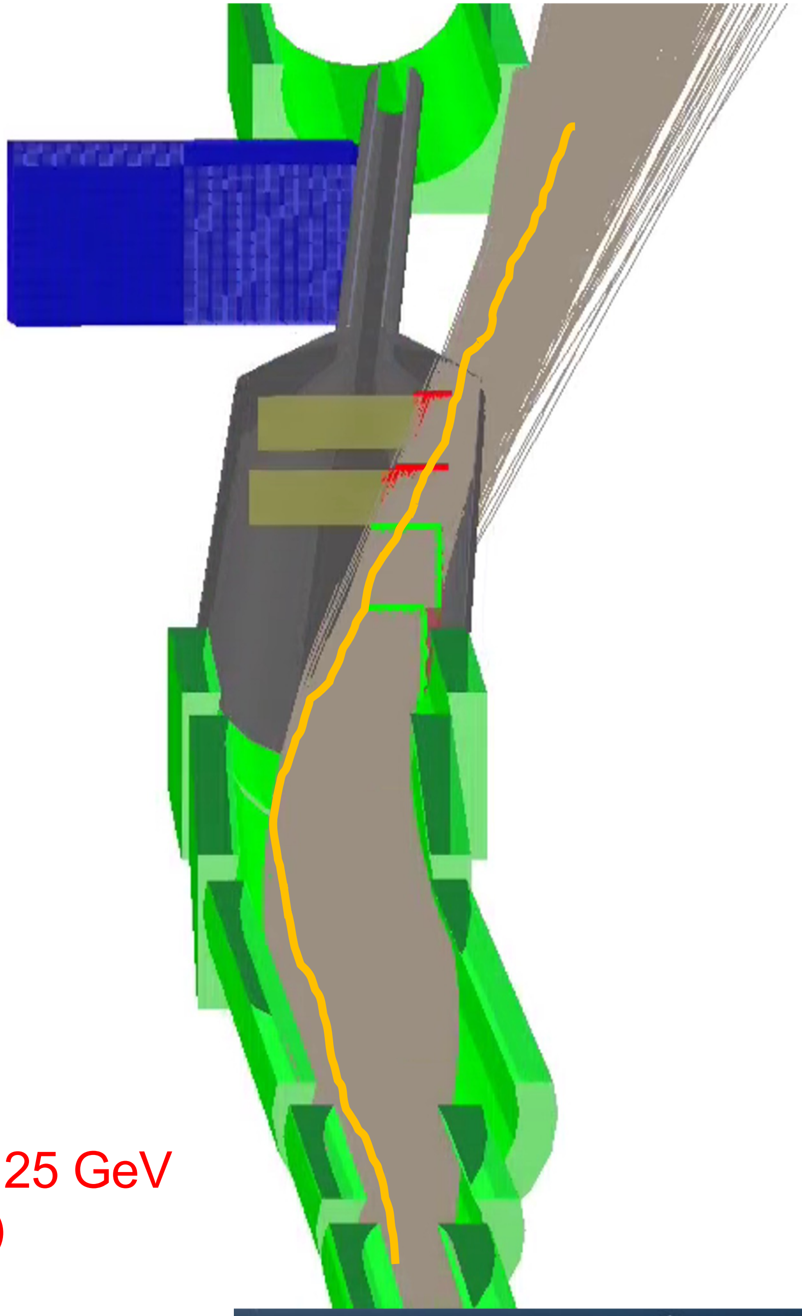


Roman Pots and OMD

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

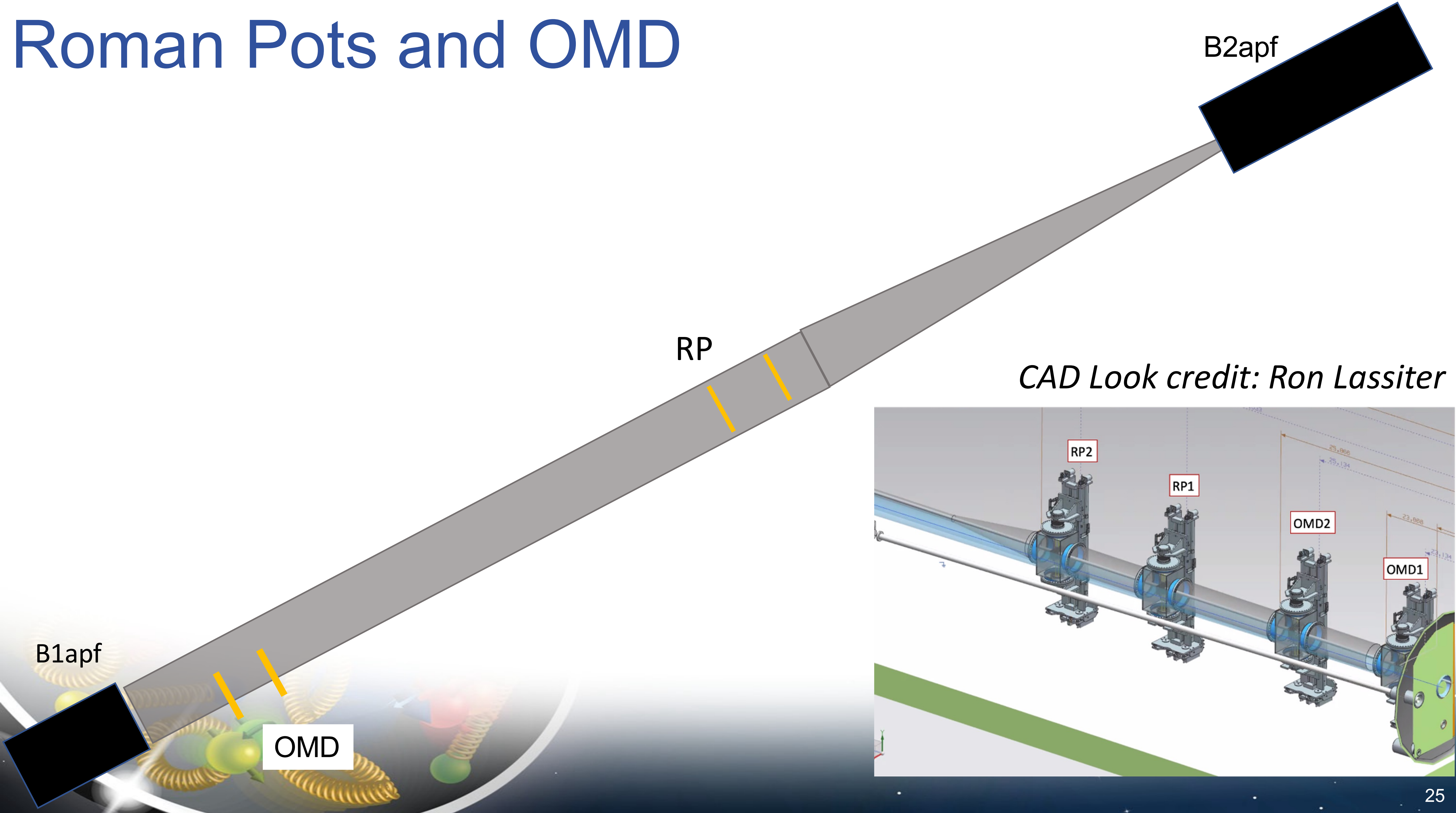
Full GEANT4 simulation.





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

Roman Pots and OMD



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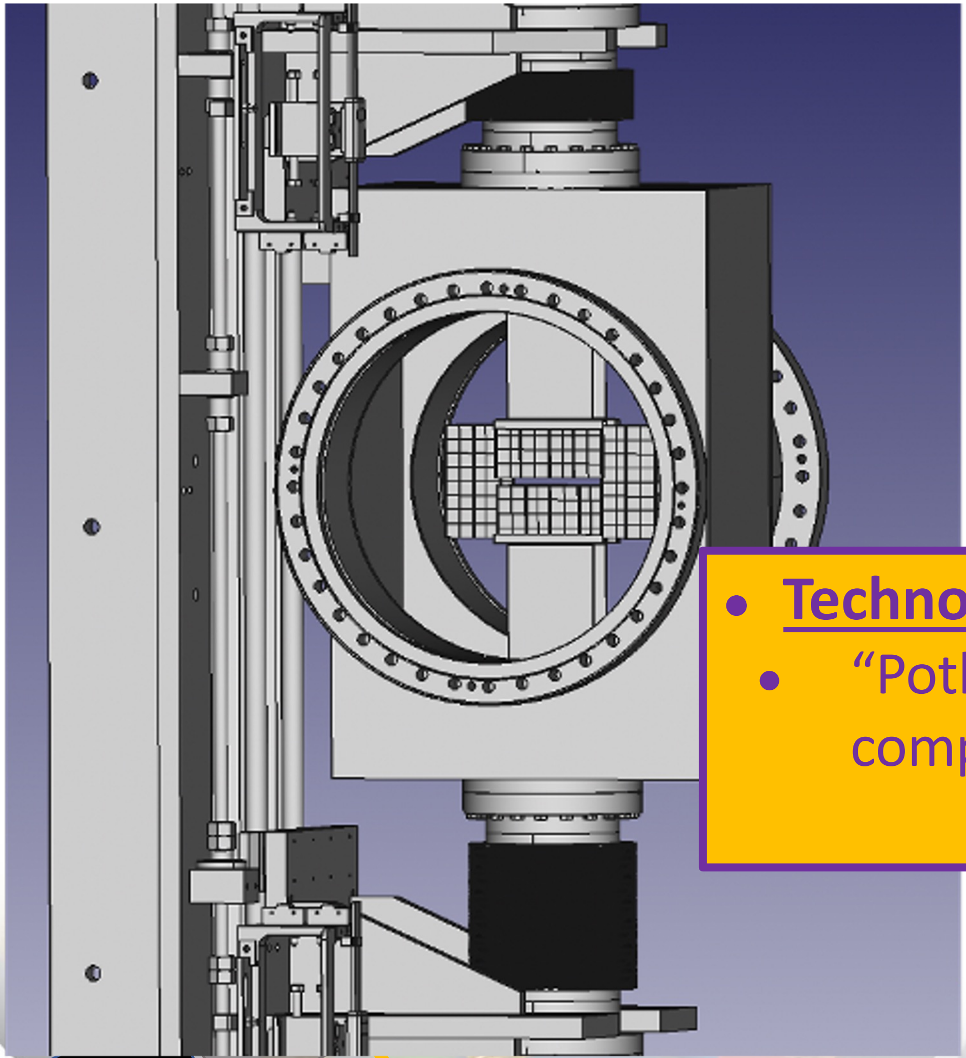
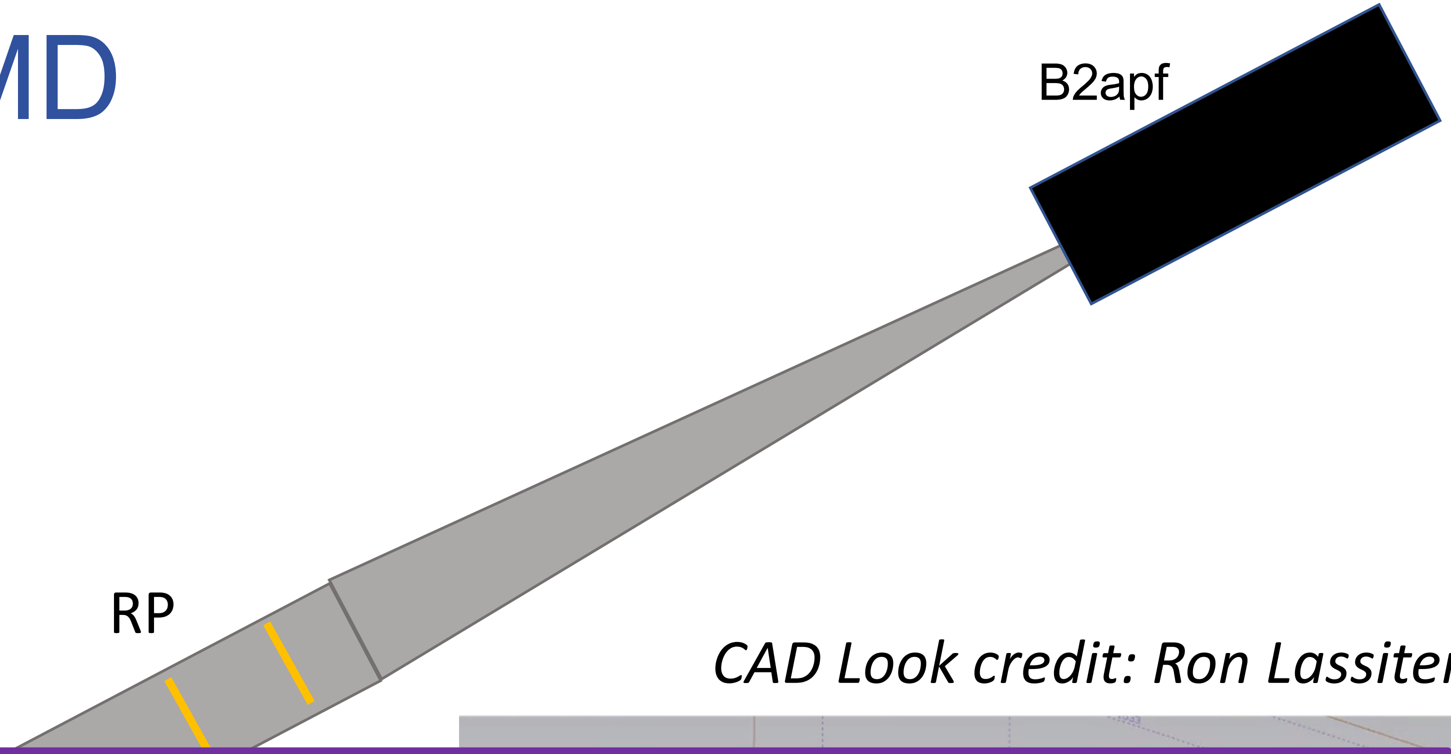
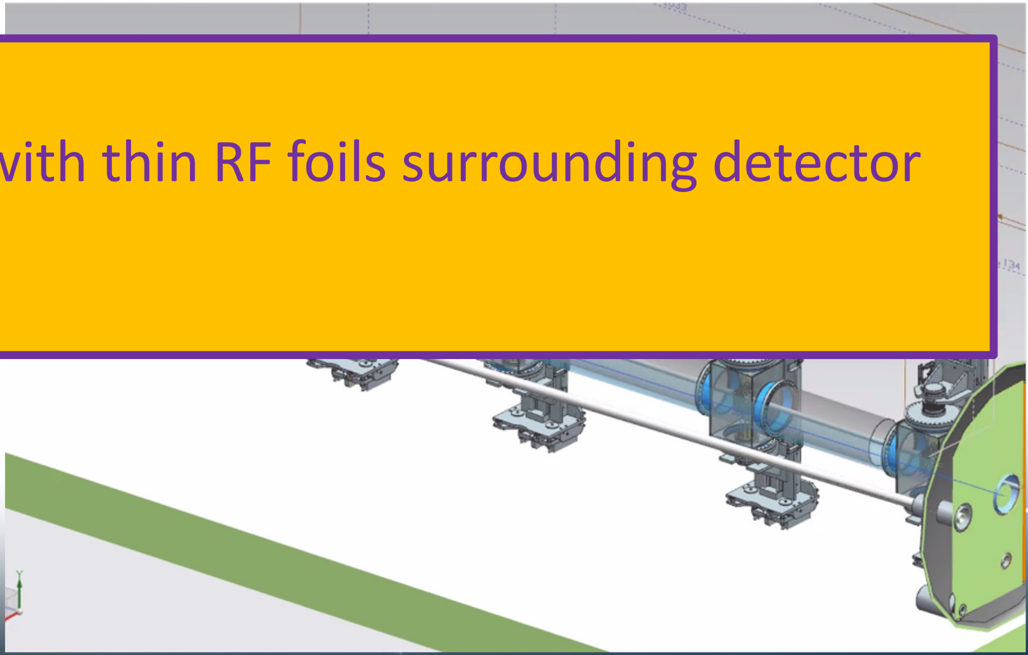


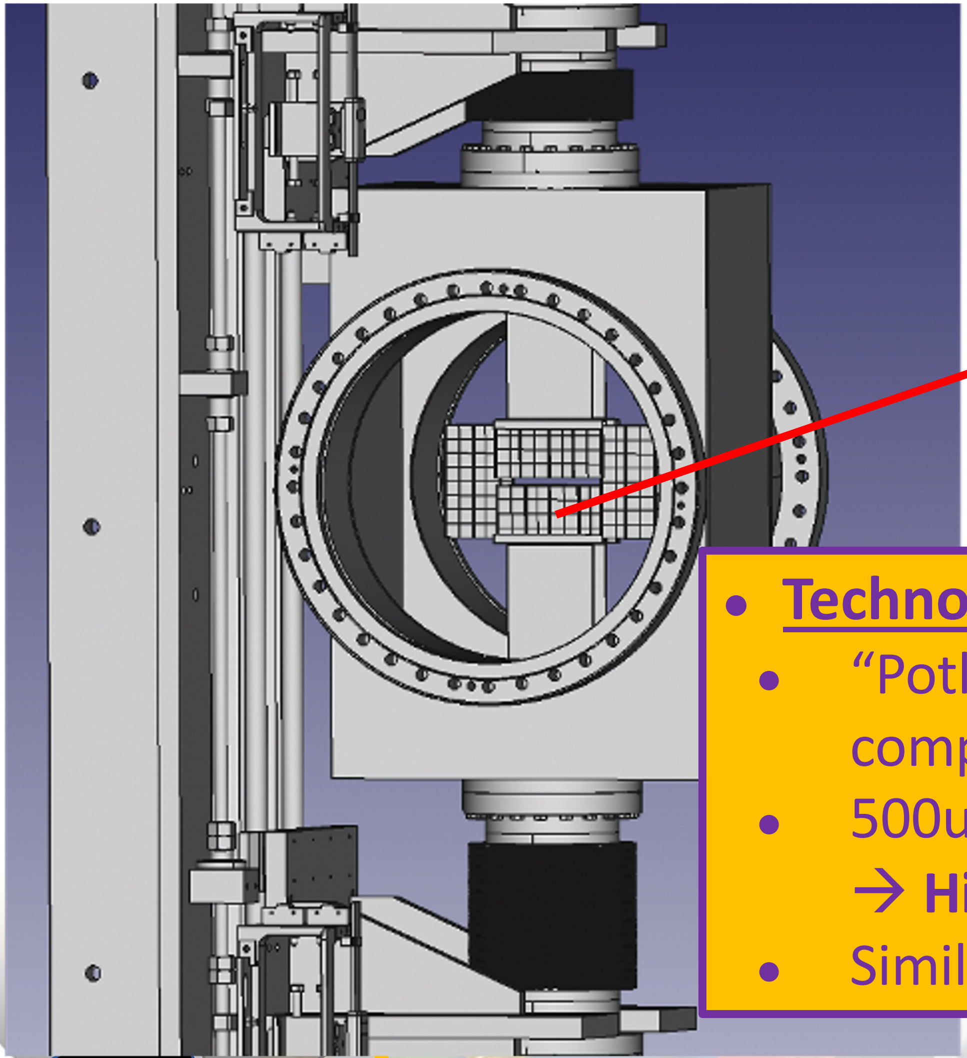


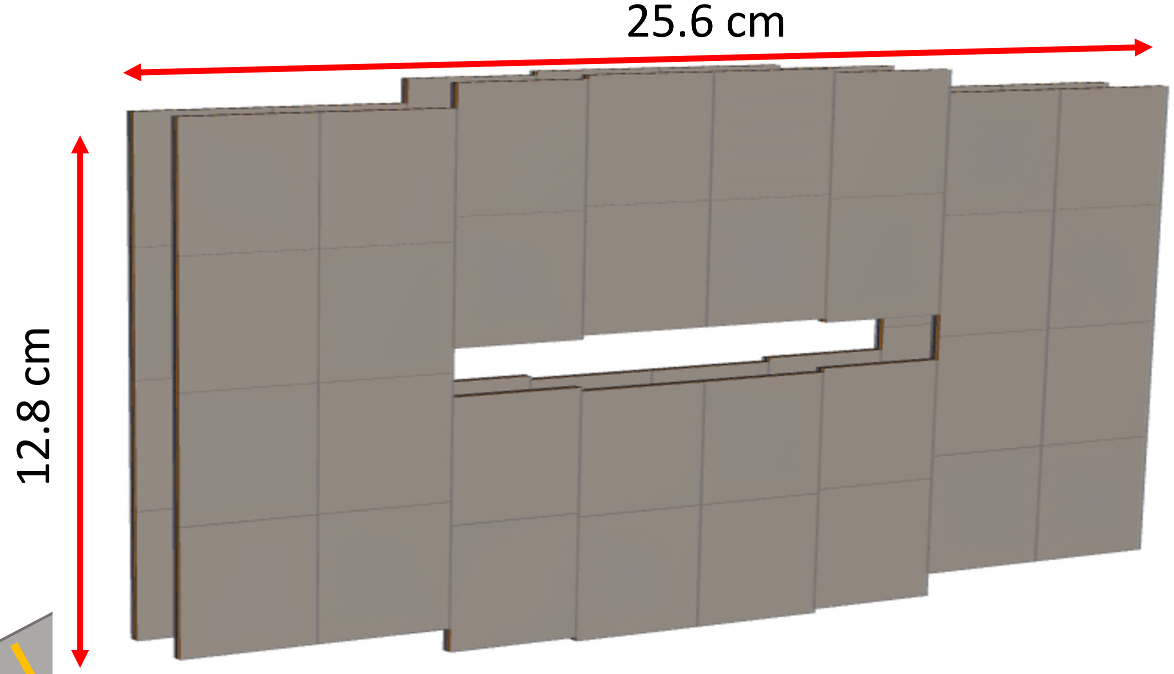
CAD Look credit: Ron Lassiter

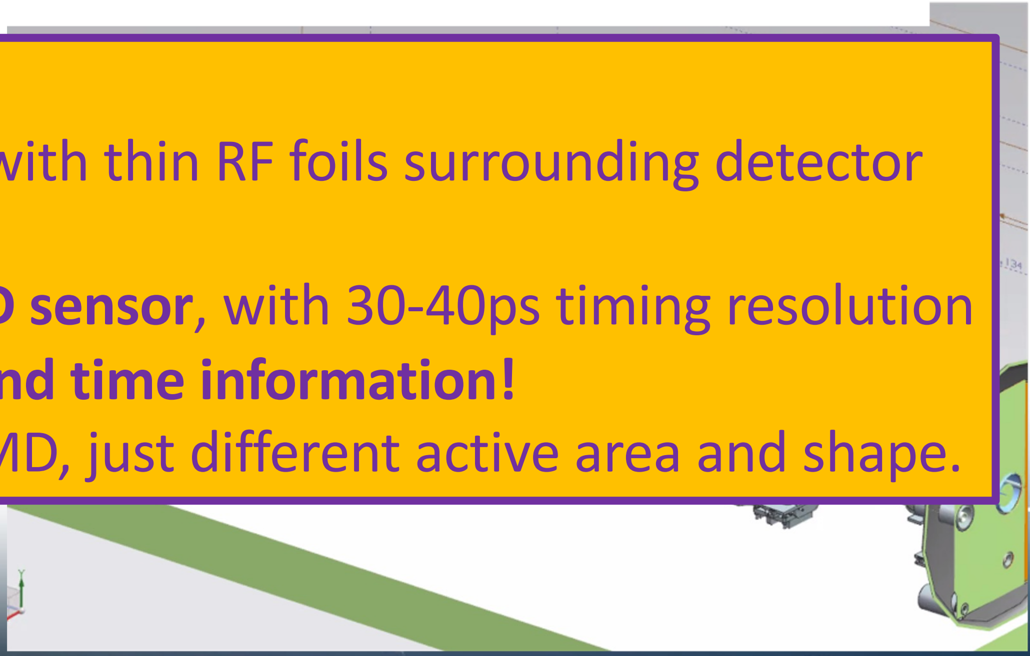


- **Technology**
  - “Potless” design concept with thin RF foils surrounding detector components.

Roman Pots and OMD



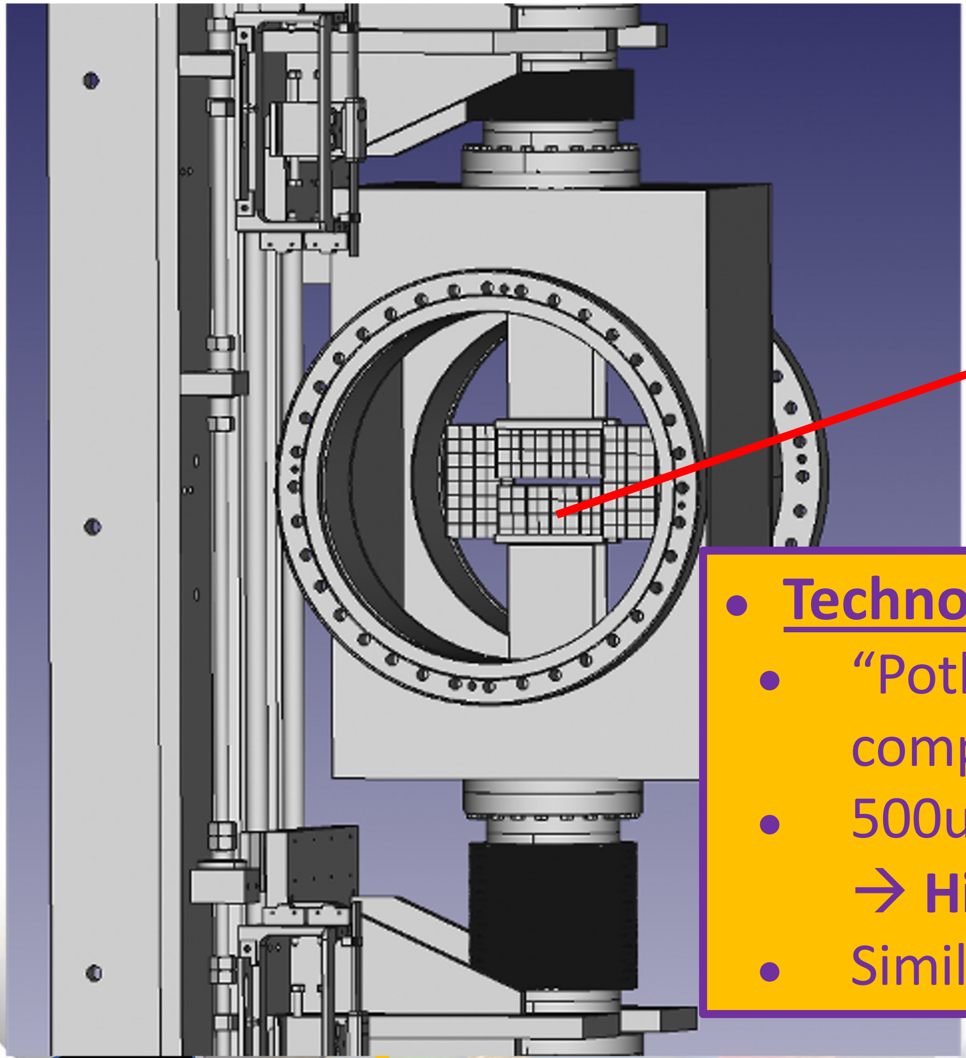


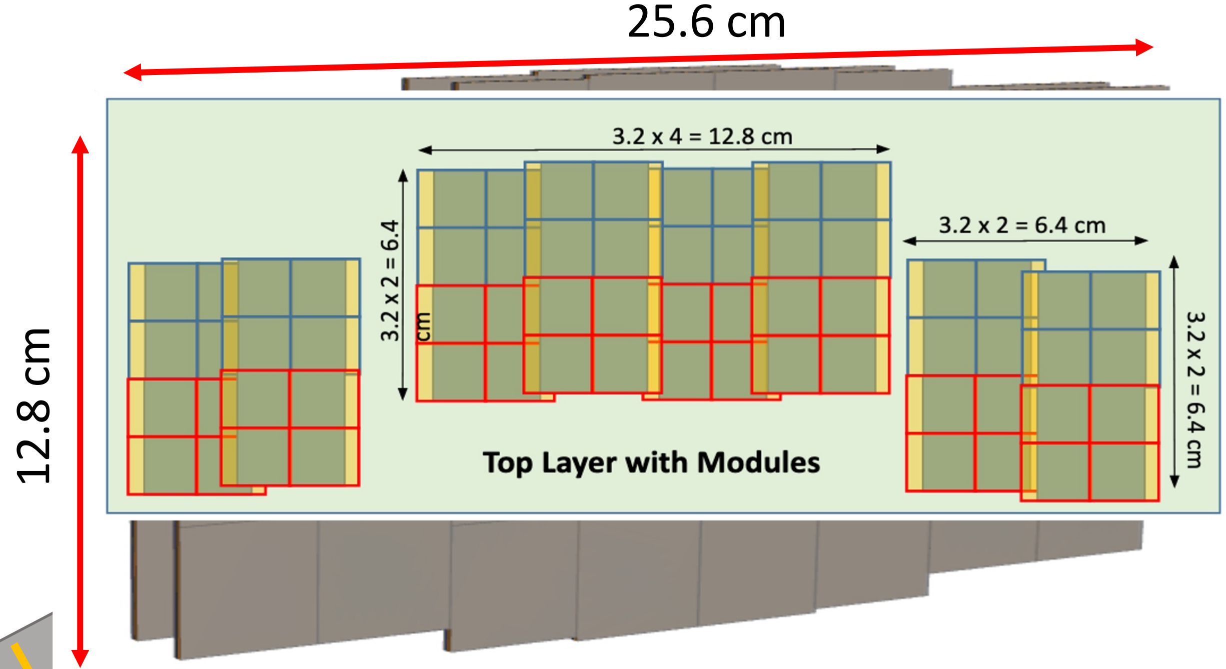


- **Technology**
  - “Potless” design concept with thin RF foils surrounding detector components.
  - 500um, **pixilated AC-LGAD sensor**, with 30-40ps timing resolution → **High-precision space and time information!**
  - Similar concept for the OMD, just different active area and shape.

OMD

Roman Pots and OMD





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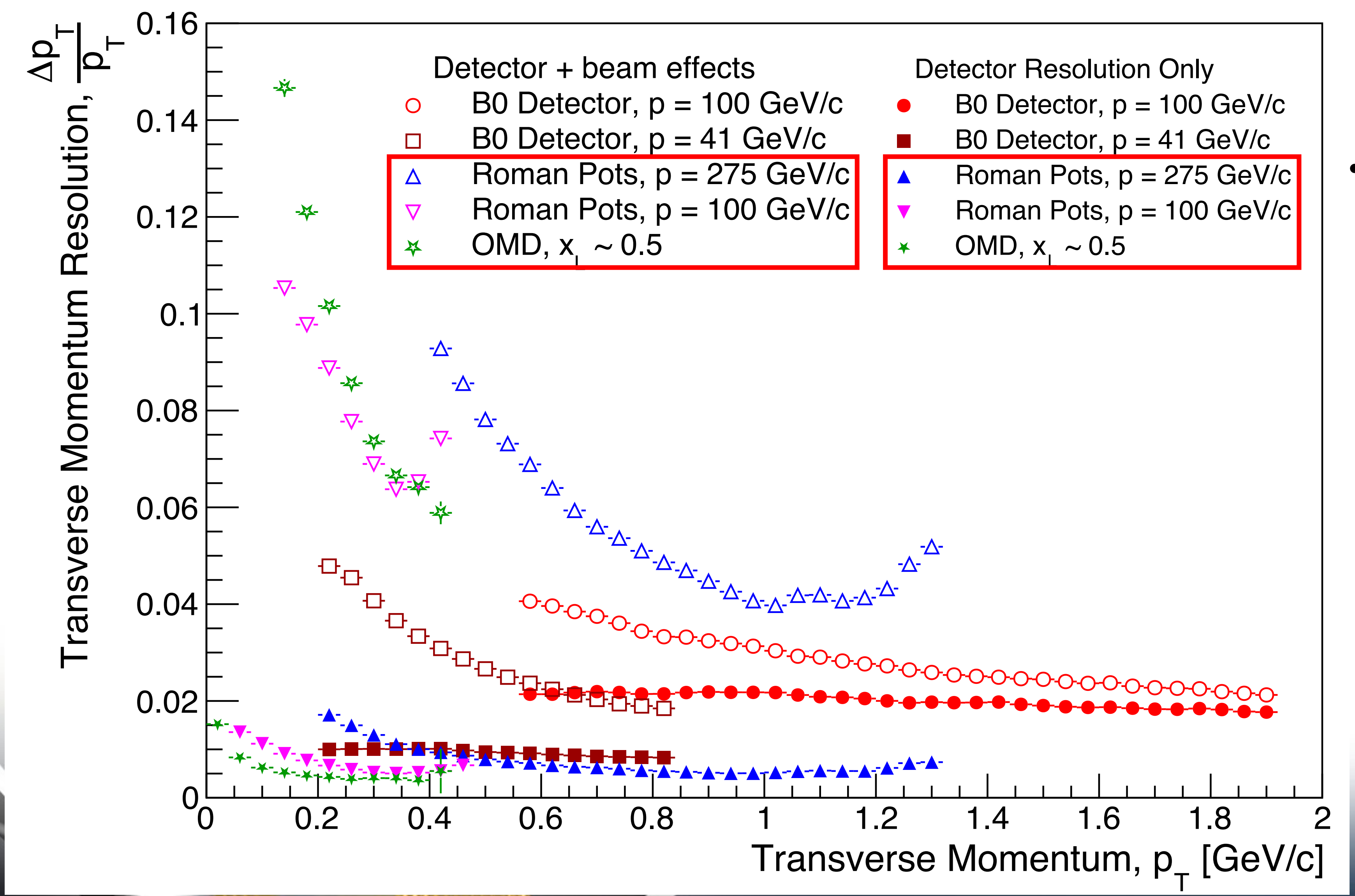
  - 500um, **pixilated AC-LGAD sensor**, with 30-40ps timing resolution → **High-precision space and time information!**
  - Similar concept for the OMD, just different active area and shape.

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

Summary of Detector Performance

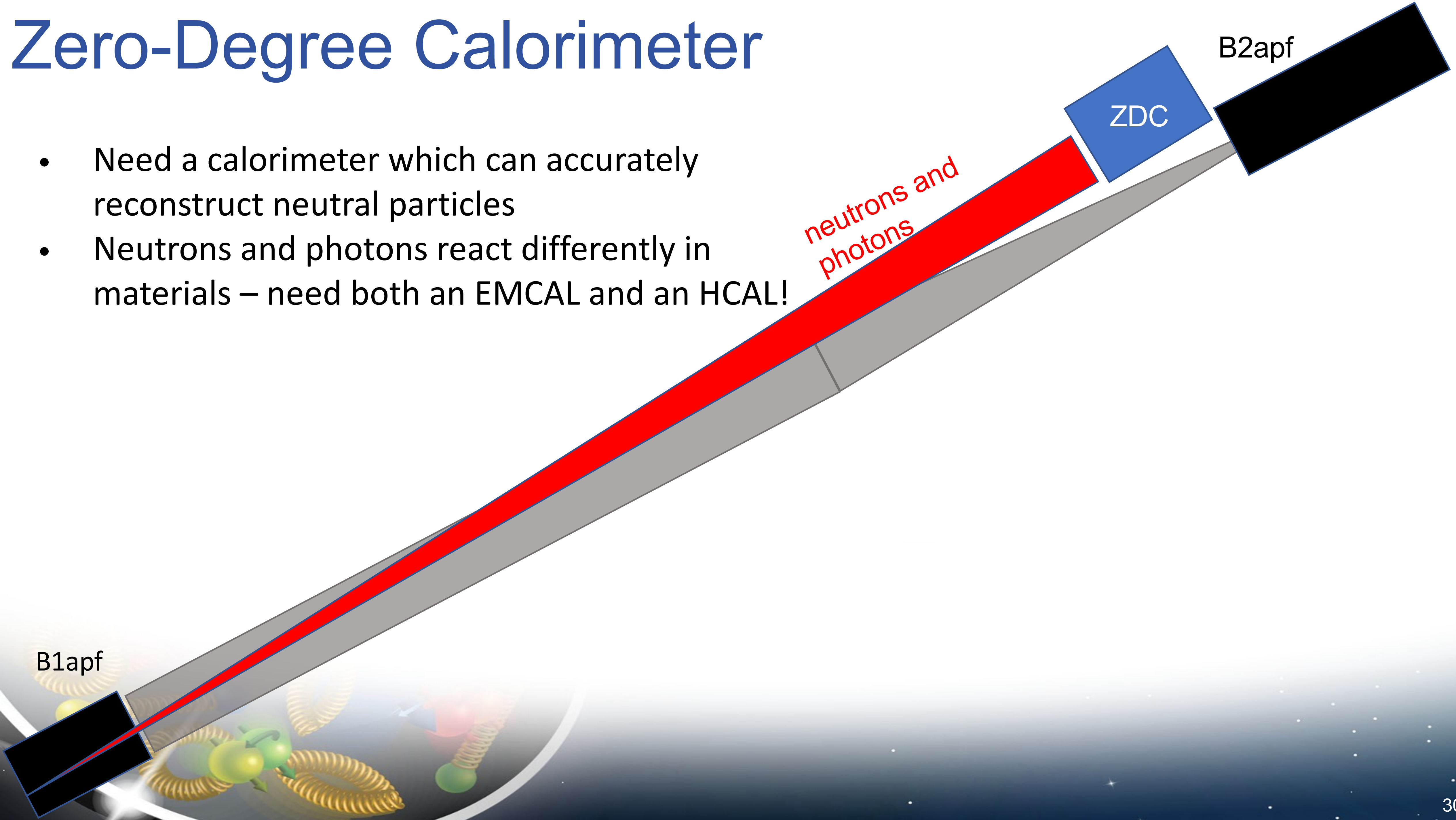


- All beam effects included!
  - Angular divergence.
  - Crossing angle.
  - Crab rotation/vertex smearing.

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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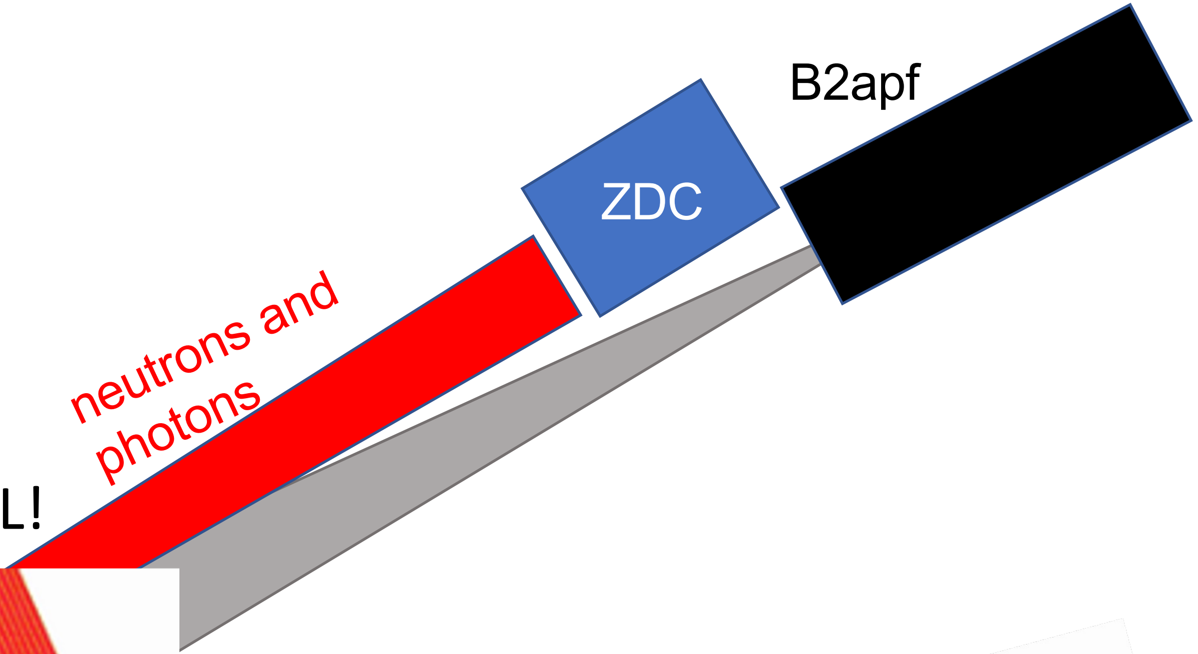
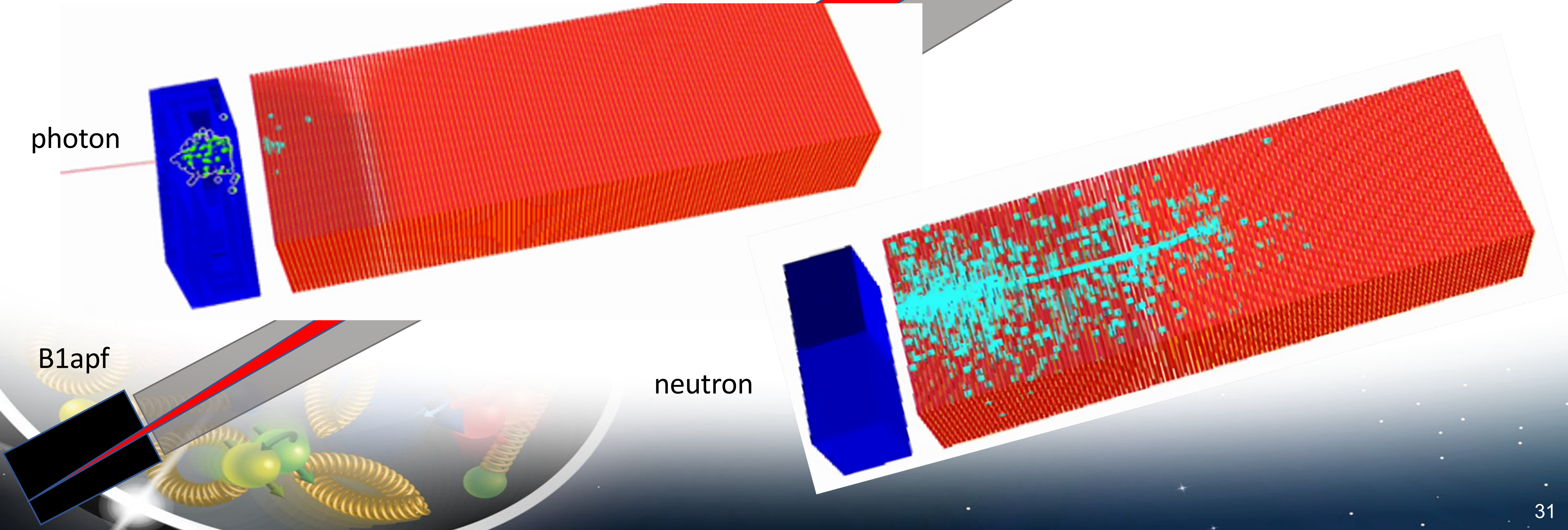


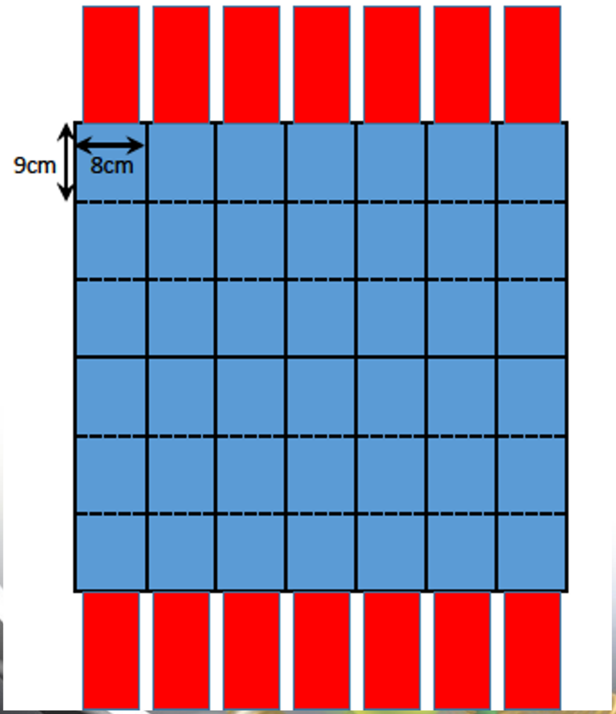


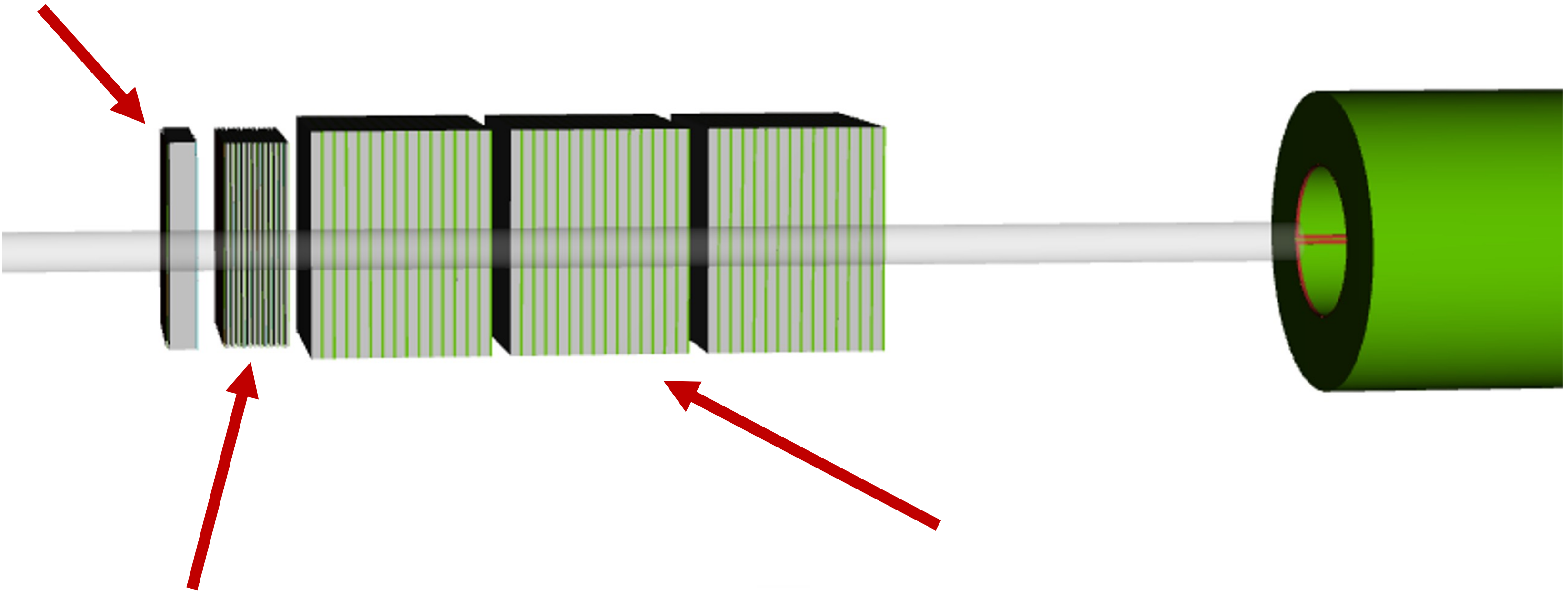
ZDC - What's New

- 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

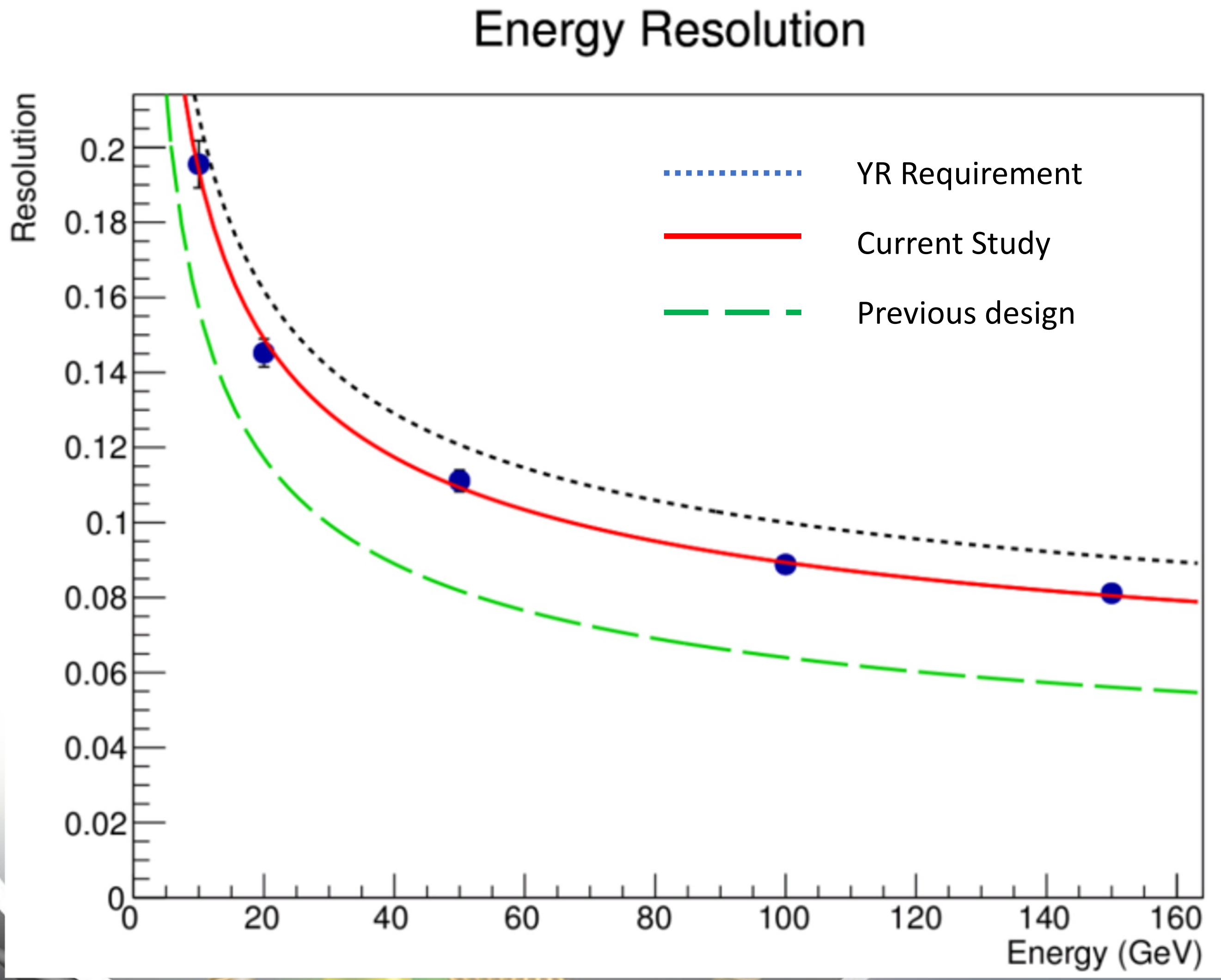


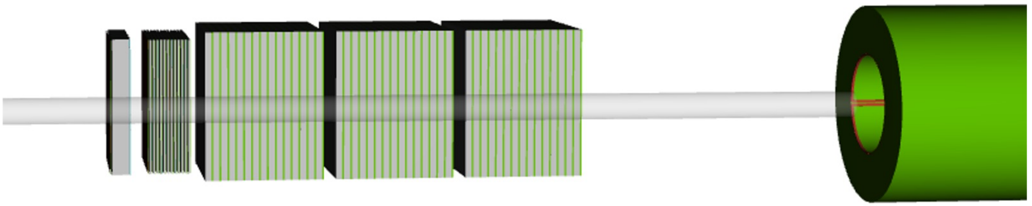


- W/Silicon Imaging EMCAL
  - Transverse size (x,y) = (56, 54) cm
  - 12 layers (~$24\chi_0$)

- Pb-Scintillator (+ fused silica)
  - Towers of 10cm x 10cm x 48cm, each module 60cm x 60cm x 48cm
  - 3 modules

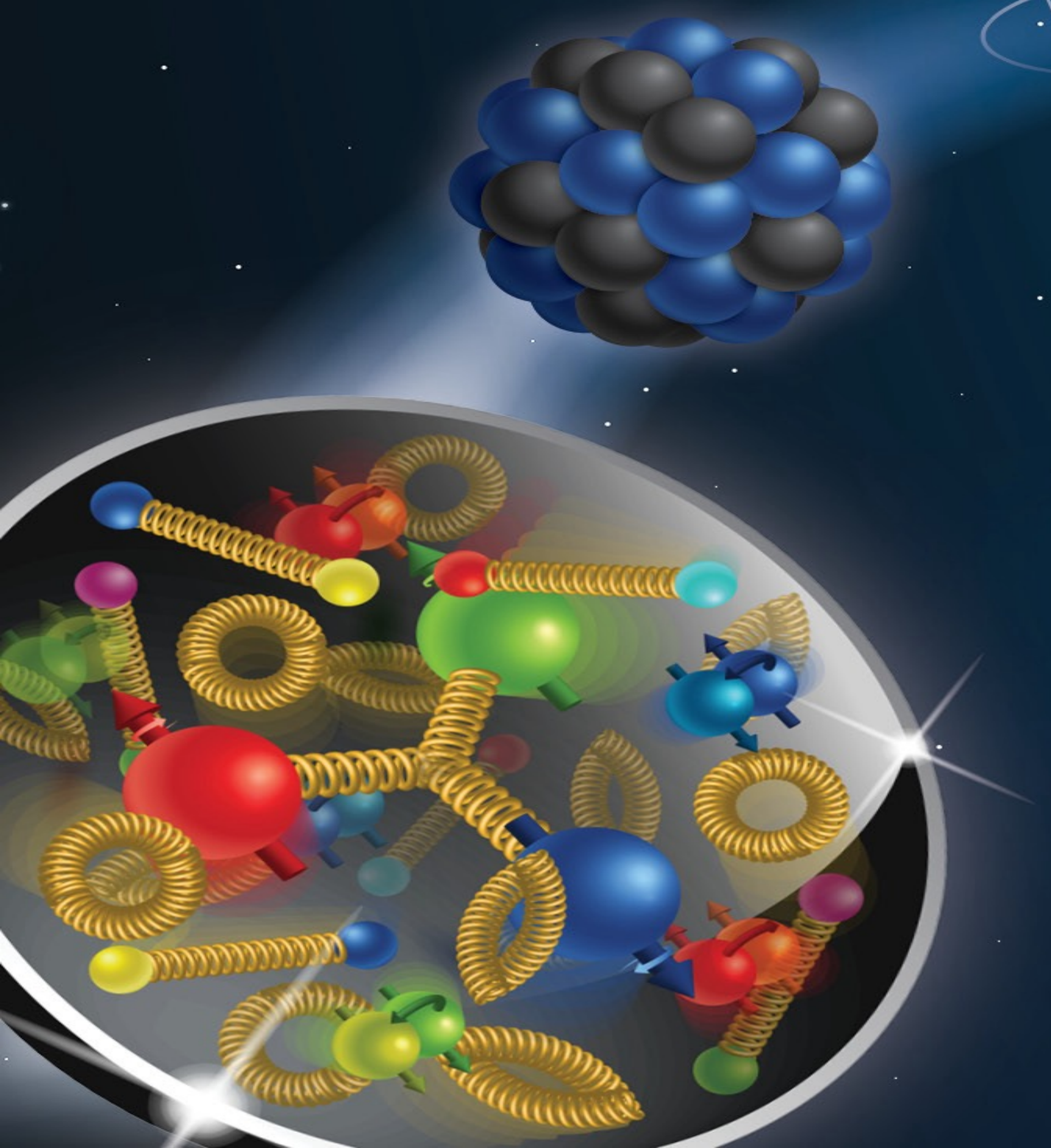
ZDC - Performance





- 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 stud ? place for the imaging part of HCAL



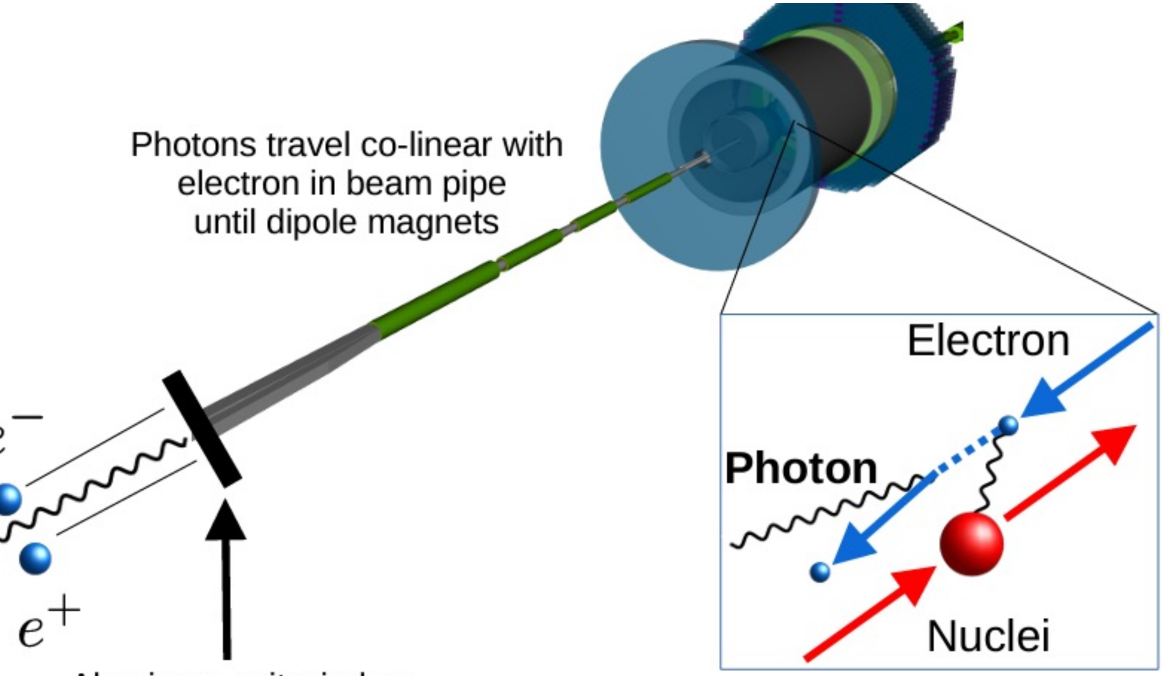
Far-Backward Detectors

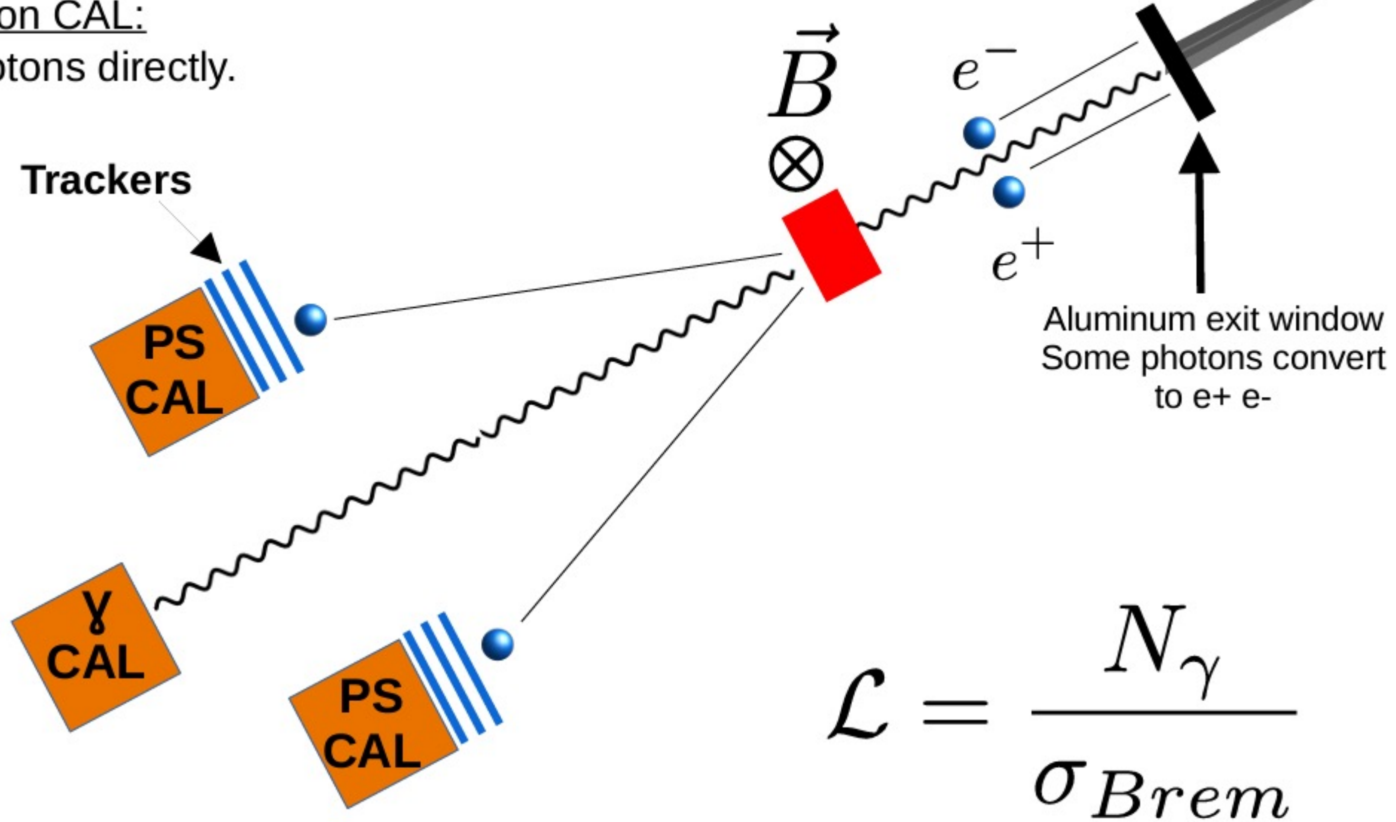
Measuring Luminosity

Experimental Goal:
Count the number of Bremsstrahlung photons: N_γ

Pair Spectrometer (PS):
Counts pair conversions

Direct photon CAL:
Counts photons directly.





Dominant part of total inelastic cross section is QED Bremsstrahlung, σ_{Brem}, which is **Precisely Calculable**

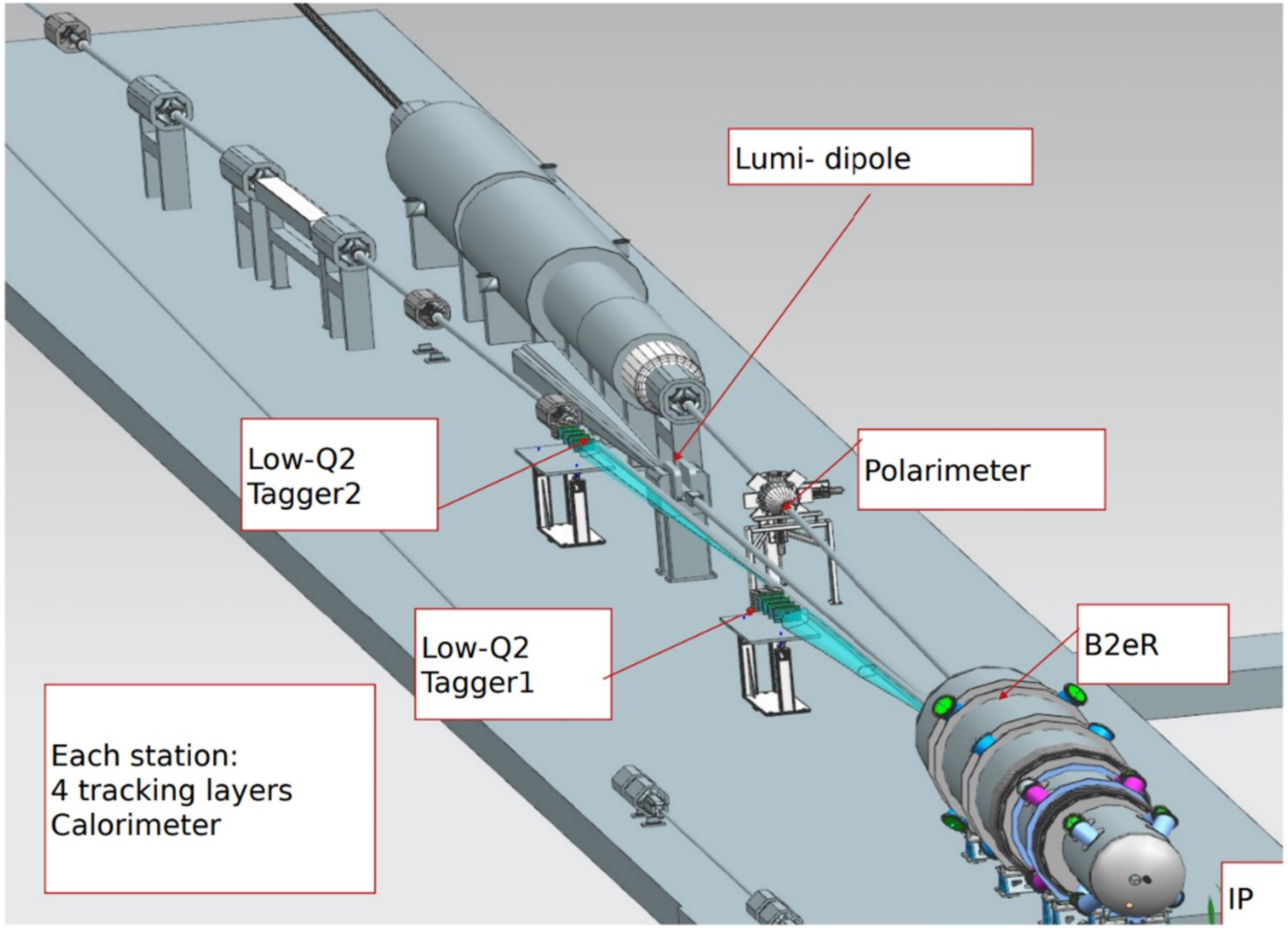
$$\mathcal{L} = \frac{N_\gamma}{\sigma_{Brem}}$$

https://indico.cern.ch/event/1238718/contributions/5431923/attachments/2687365/4665564/Dhevan_PS_ePIC_ColabMeeting_July29_2023.pdf

Slide from Dhevan Gangadharan and Nick Zachariou

Tagging Electrons at Low-Q^2

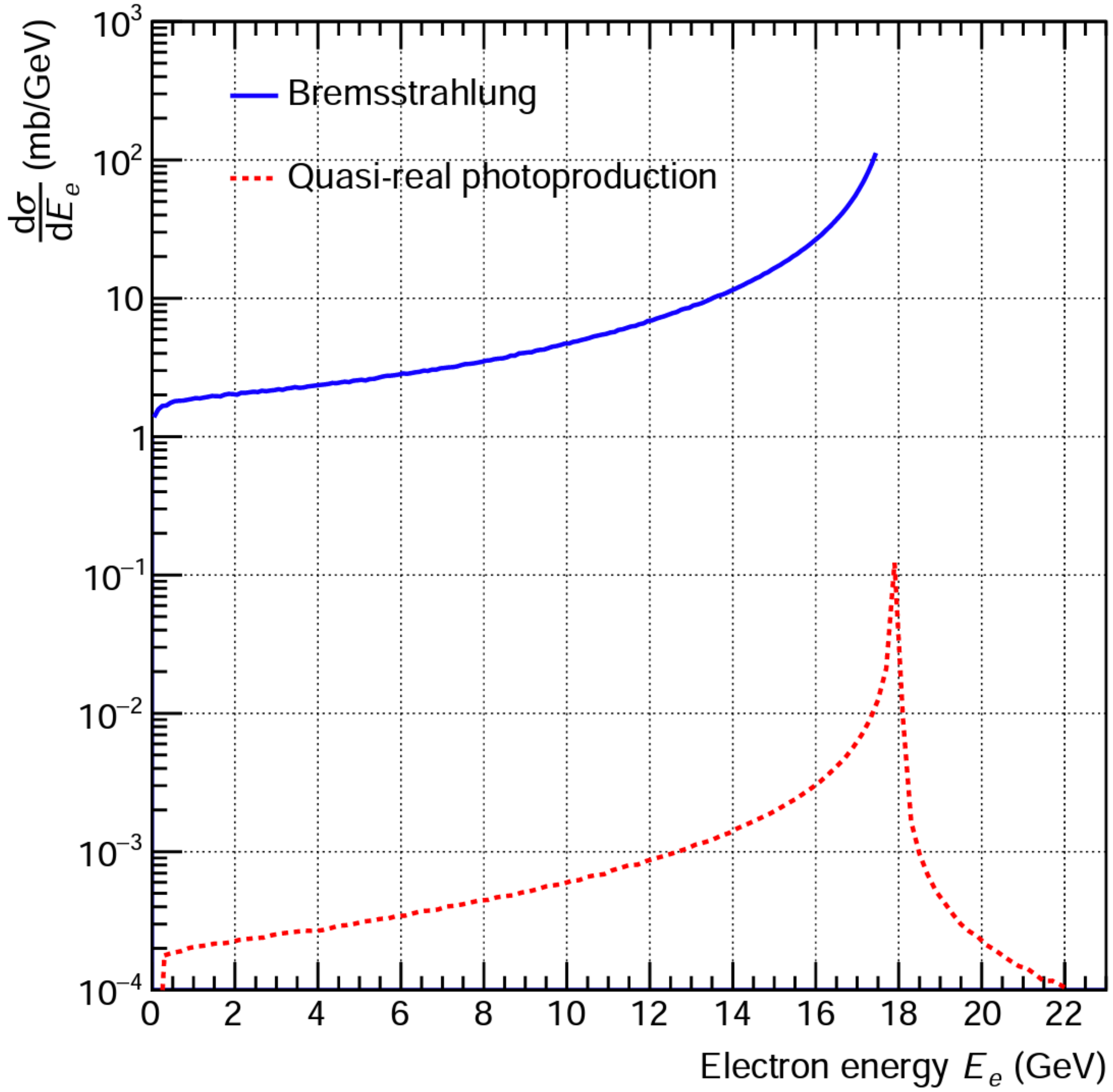
- Jaroslav Adam (Project Lead)
  `jaroslav.adam@fjfi.cvut.cz`
- Simon Gardner (Technical Lead)
  `Simon.Gardner@Glasgow.ac.uk`
- Two low-Q^2 tagger detectors along outgoing electron beam pipe
- Placed at about -20 m and -36 m from IP



Slide from Jaroslav Adam (CTU)

Tagging Electrons at Low-Q^2

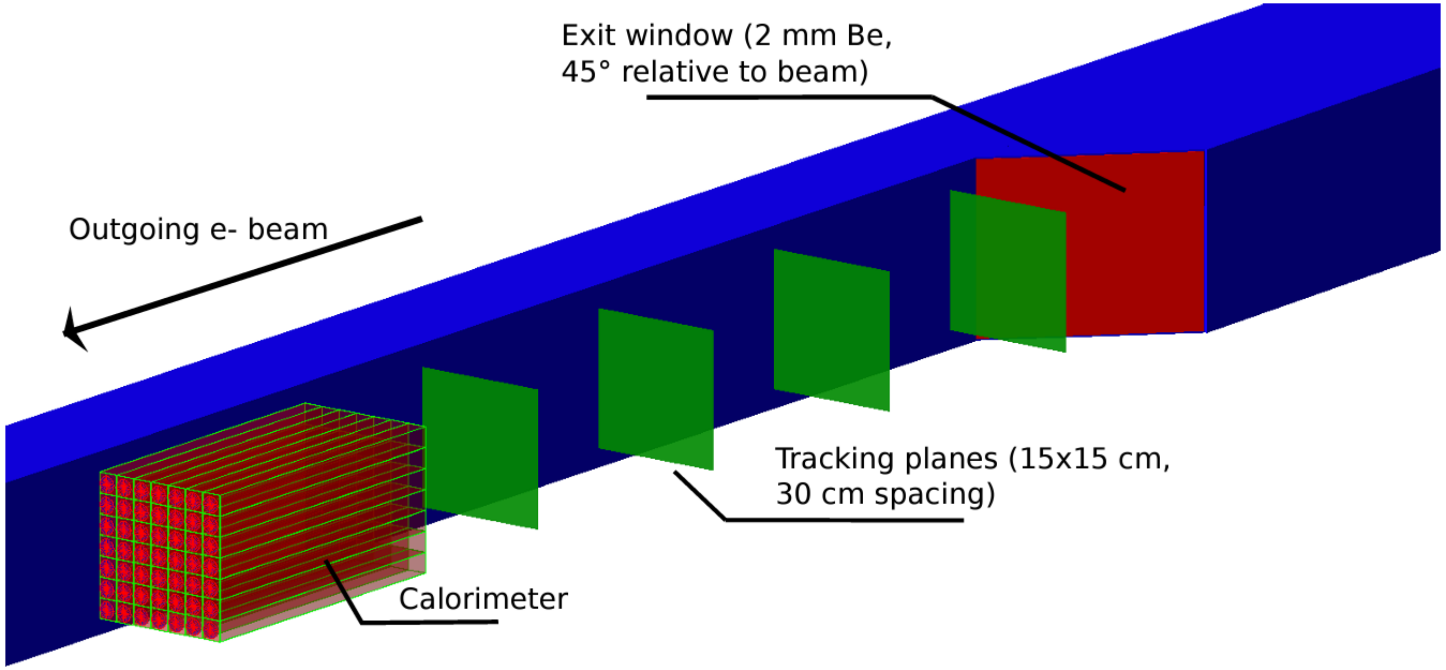
- Photoproduction in $10^{-3} \lesssim Q^2 \lesssim 10^{-1}$ GeV^2
- Scattered electrons for meson spectroscopy and exclusive pair production
- Help for luminosity measurement by coincidence with pair spectrometer
- Large background and event rates due to Bethe-Heitler bremsstrahlung – illustrated by comparing to photoproduction cross section
- The background can be mitigated by good tracking and Q^2 reconstruction

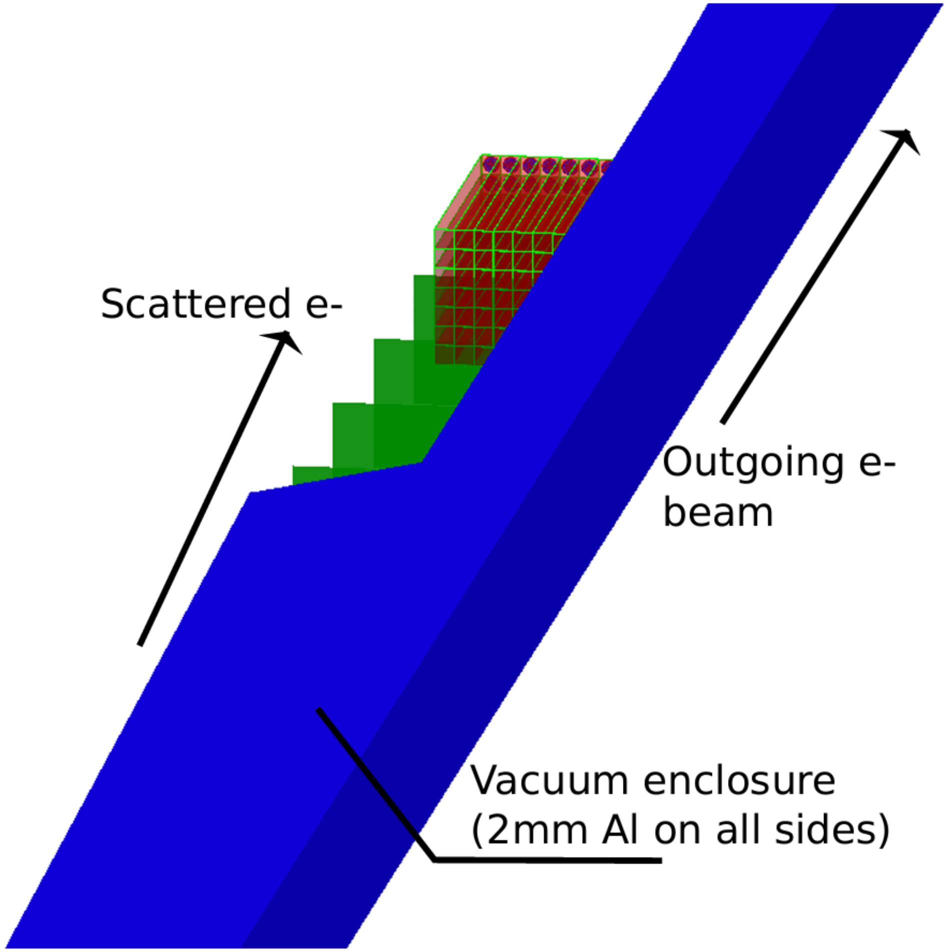


Slide from Jaroslav Adam (CTU)

Tagging Electrons at Low-Q^2

- Detectors outside beam vacuum
- Several considerations for exit window (material, thin mesh followed by 90° exit window)

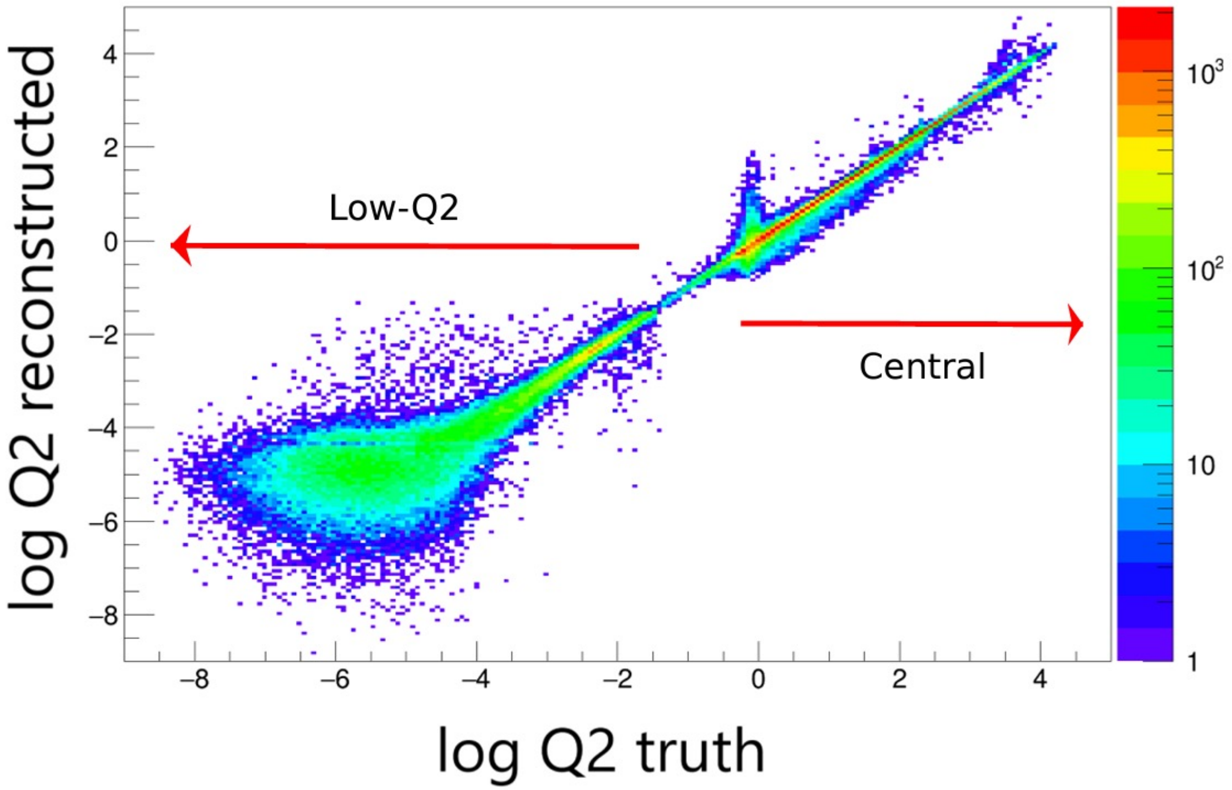




Slide from Jaroslav Adam (CTU)

Low-Q^2 Reconstruction

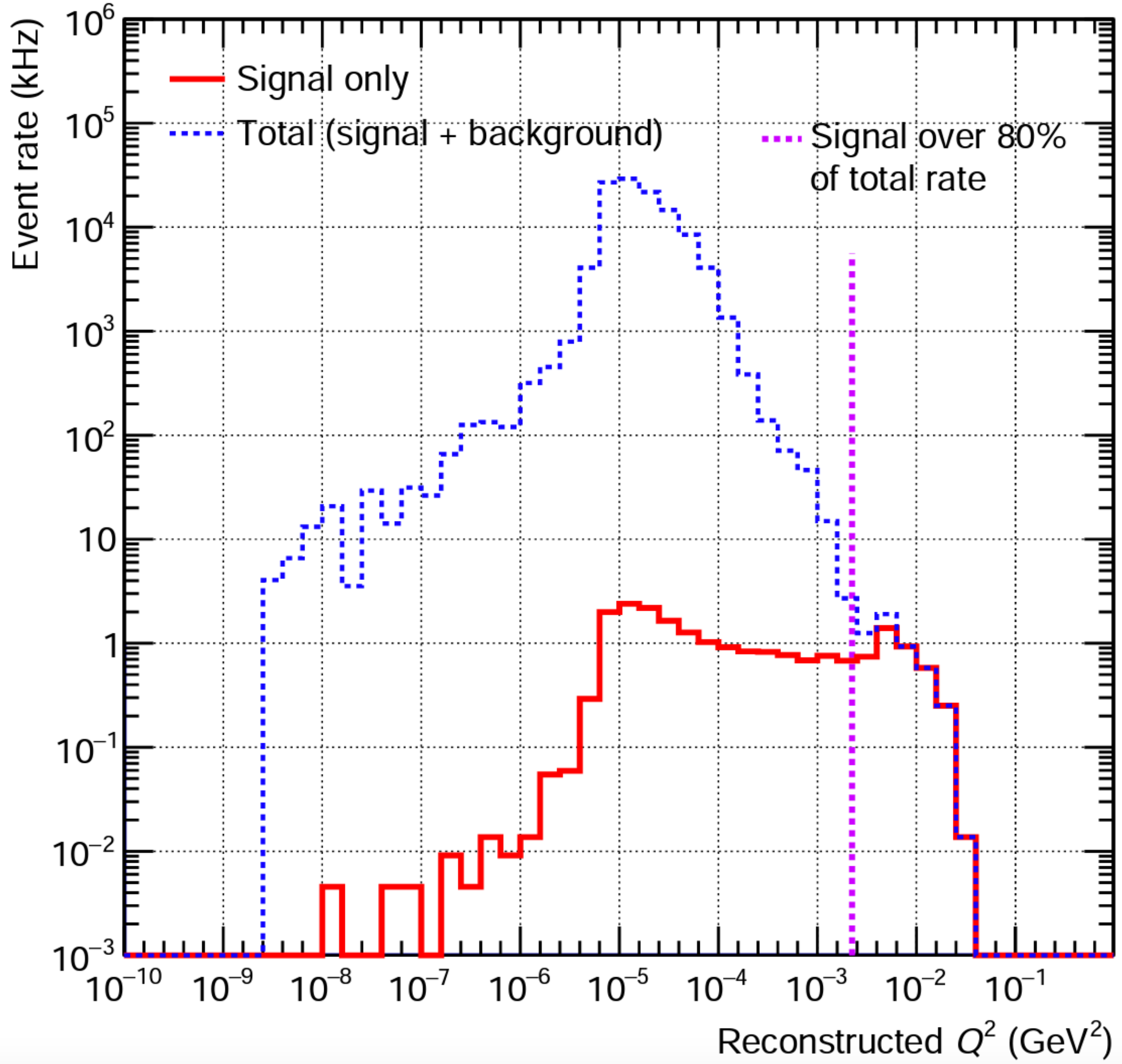
- Two different ML algorithms giving compatible results
- The algorithms connect reconstructed tracks to kinematics of original scattered electrons (energy and polar and azimuthal angle)
- Q^2 is obtained from electron energy and polar angle
- Plot shows combined reconstruction in low-Q^2 taggers and central detector



Slide from Jaroslav Adam (CTU)

Low-Q^2 Reconstruction

- Mixed hepmc of signal (quasi-real photoproduction) and background (Bethe-Heitler) events
- Event rates are obtained as a function of reconstructed Q^2
- Background tracks reconstruct dominantly to very low Q^2



Slide from Jaroslav Adam (CTU)

Summary and Takeaways

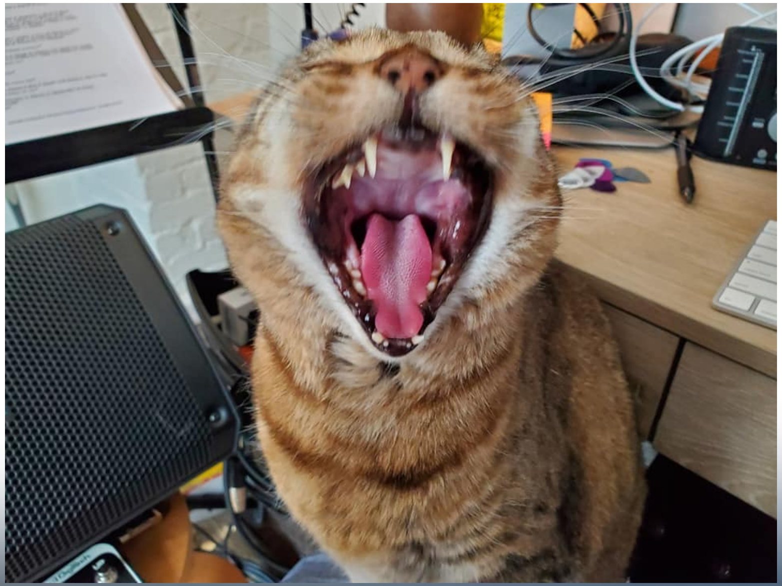
- Far-Forward and Far-Backward detectors uniquely challenging!
  - Integrated with beamline → crowded area, complicated constraints on rates, beam operations, etc.
  - Trying to cover broad phase space not covered by main detector → Crucial for physics program!
- Technologies identified for the all subsystems, and simulations have been carried out → engineering design underway for CD-2/3A

Thank you!

Julep

They (mostly) get along.

Lilu

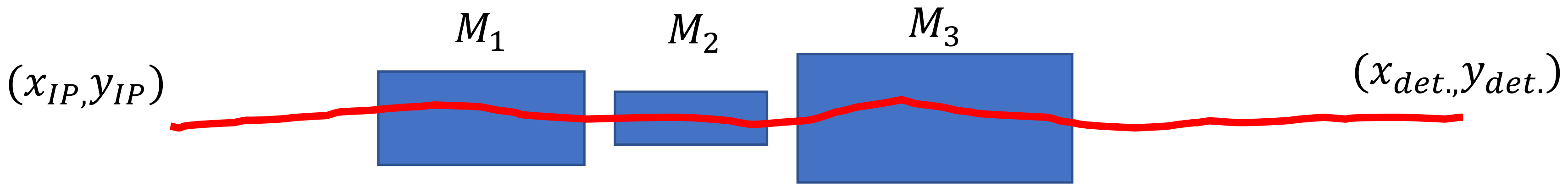


She's in a death metal band.

Backup

Preliminaries

- The EIC physics program includes reconstruction of final states with very far-forward protons, from many different possible collision systems.
  - e+p scattering, e+d/e+He3/e+A (proton(s) from nuclear breakup).
  - Produces protons with a broad range in longitudinal momentum, which then traverse the full hadron-going lattice (dipoles and quads).
- Momentum reconstruction requires *transfer matrices* to describe particle motion through the magnets.



$$\begin{pmatrix} x_{ip} \\ \theta_{x,ip} \\ y_{ip} \\ \theta_{y,ip} \\ z_{ip} \\ \Delta p/p \end{pmatrix} = \begin{pmatrix} a_0 & a_1 & a_2 & a_3 & a_4 & a_5 \\ b_0 & b_1 & b_2 & b_3 & b_4 & b_5 \\ c_0 & c_1 & c_2 & c_3 & c_4 & c_5 \\ d_0 & d_1 & d_2 & d_3 & d_4 & d_5 \\ e_0 & e_1 & e_2 & e_3 & e_4 & e_5 \\ f_0 & f_1 & f_2 & f_3 & f_4 & f_5 \end{pmatrix} \begin{pmatrix} x_{det.} \\ \theta_{x,det.} \\ y_{det.} \\ \theta_{y,det.} \\ z_{det.} \\ \Delta p/p \end{pmatrix}$$

$$M_{transfer} = M_1 M_2 M_3 \ldots$$

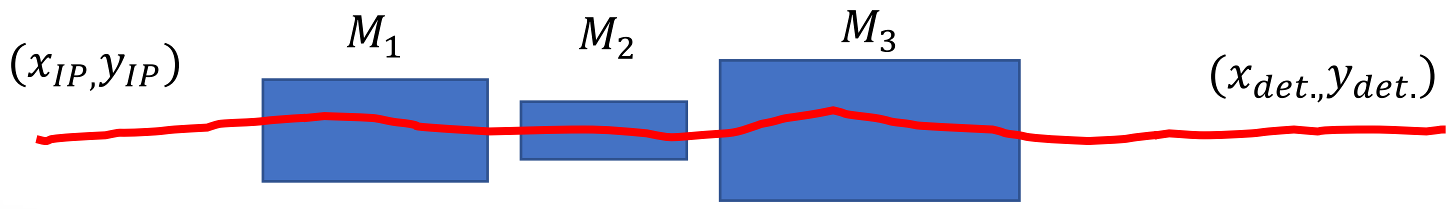
- Transforms coordinates at detectors (position, angle) to original IP coordinates.
- Matrix unique for different positions along the beam-axis!

Preliminaries

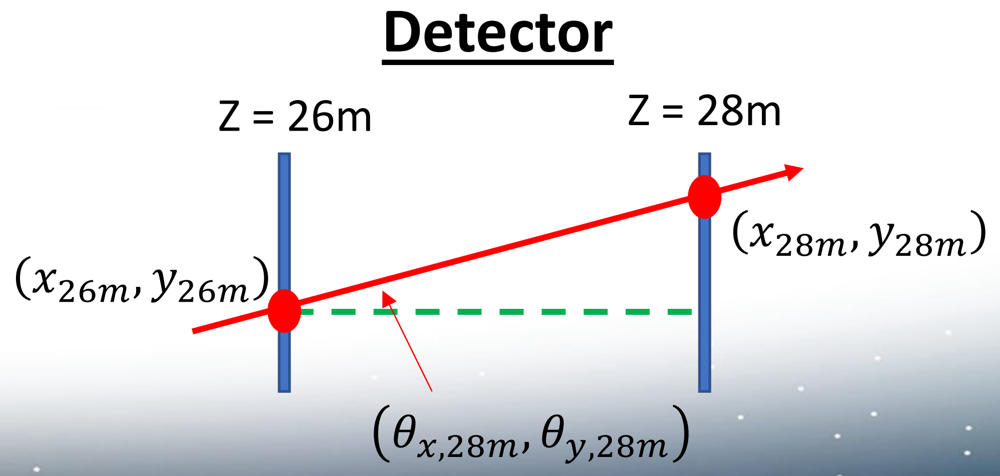
$$\begin{pmatrix} 1.88 & 28.97 & .0 & 0.0 & 0.0 & 0.25 \\ -0.0211 & 0.21 & 0.0 & 0.0 & 0.0 & -0.034 \\ 0.0 & 0.0 & -2.26 & 3.78 & 0.0 & 0.0 \\ 0.0 & 0.0 & -0.18 & -0.145 & 0.0 & 0.0 \\ 0.057 & 1.014 & 0.0 & 0.0 & 1.0 & 0.026 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 1.0 \end{pmatrix} \begin{pmatrix} x_{ip} \\ \theta_{xip} \\ y_{ip} \\ \theta_{yip} \\ z_{ip} \\ \Delta p/p \end{pmatrix} = \begin{pmatrix} x_{28m} \\ \theta_{x,28m} \\ y_{28m} \\ \theta_{y28m} \\ z_{28m} \\ \Delta p/p \end{pmatrix}$$

From BMAD – central trajectory 275 GeV proton

- Matrix describes how particles travel through the magnets toward the detector.



$$M_{transfer} = M_1 M_2 M_3 \ldots$$

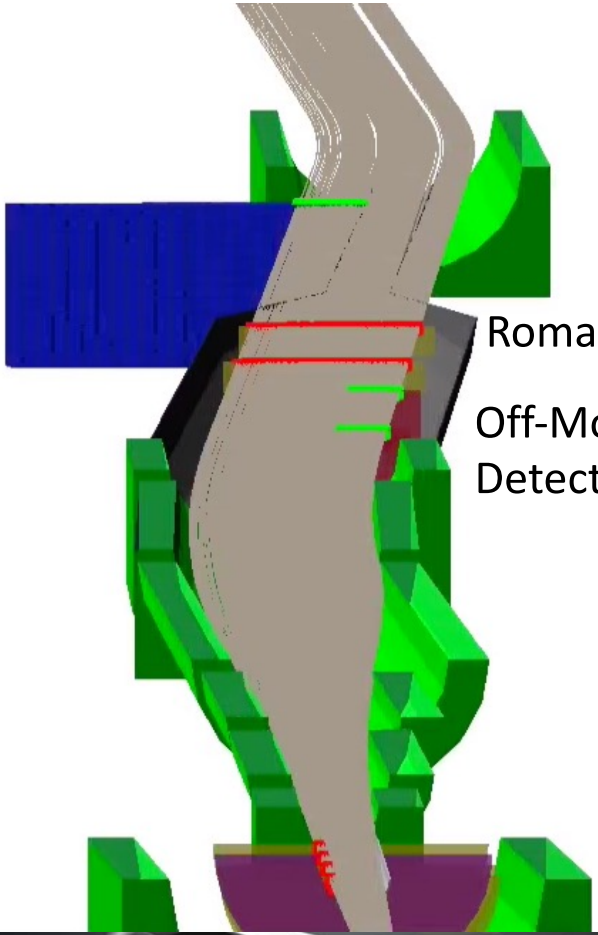


Matrix enables reconstruction of scattering information at the IP using only local hits at the detector.

The Problem

$$\begin{pmatrix} 1.88 & 28.97 & 0.0 & 0.0 & 0.0 & 0.25 \\ -0.0211 & 0.21 & 0.0 & 0.0 & 0.0 & -0.034 \\ 0.0 & 0.0 & -2.26 & 3.78 & 0.0 & 0.0 \\ 0.0 & 0.0 & -0.18 & -0.145 & 0.0 & 0.0 \\ 0.057 & 1.014 & 0.0 & 0.0 & 1.0 & 0.026 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 1.0 \end{pmatrix} \begin{pmatrix} x_{ip} \\ \theta_{xip} \\ y_{ip} \\ \theta_{yip} \\ z_{ip} \\ \Delta p/p \end{pmatrix} = \begin{pmatrix} x_{28m} \\ \theta_{x,28m} \\ y_{28m} \\ \theta_{y28m} \\ z_{28m} \\ \Delta p/p \end{pmatrix}$$

From BMAD – central trajectory 275 GeV proton



- Protons from nuclear breakup, or high-Q^2 e+p interactions → protons can have large deviations from central orbit momentum → **require unique matrices!**

longitudinal momentum fraction

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

Full GEANT4 simulation.

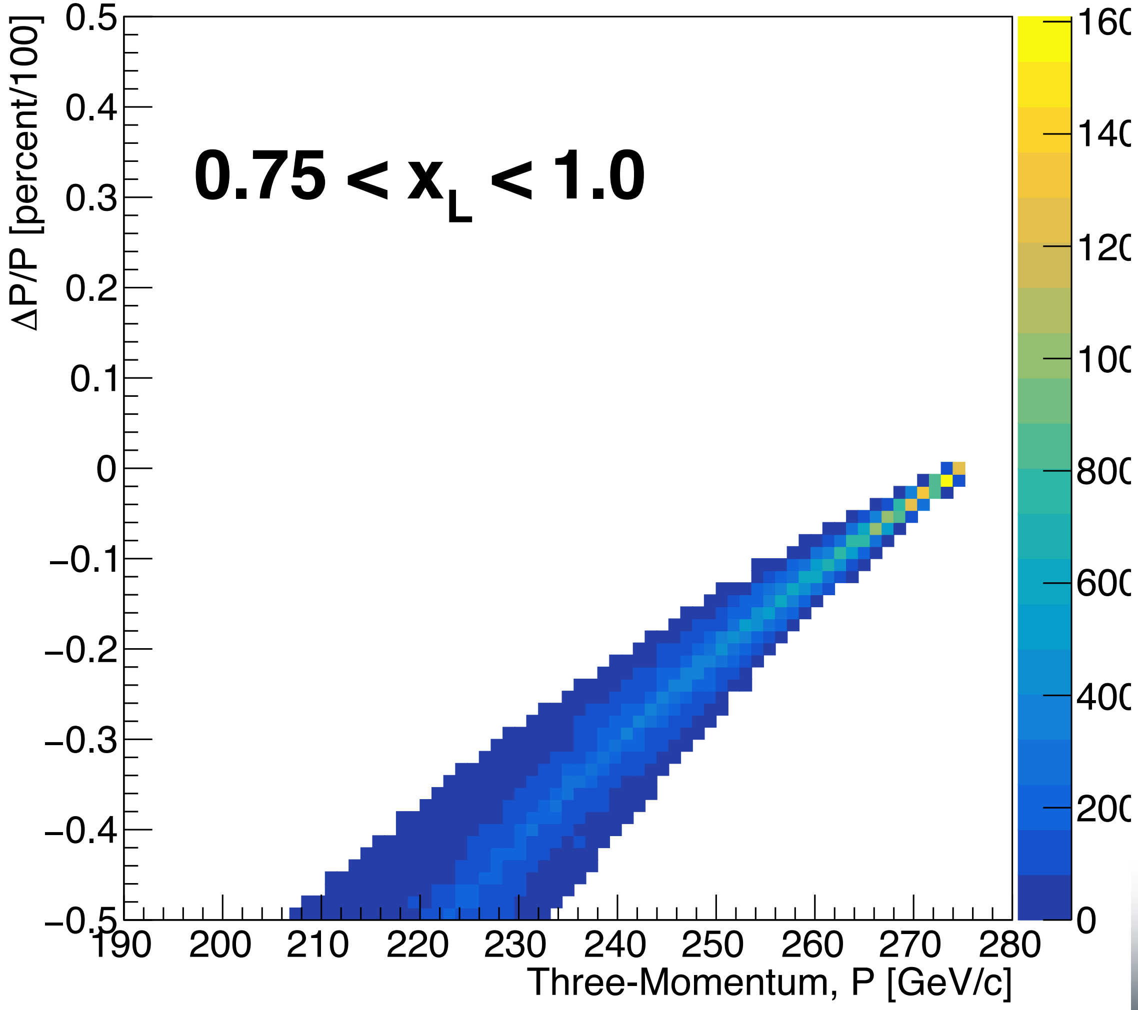
Protons
E = 275 GeV
$0 < \theta < 5$ mrad

For a 275 GeV beam, a 270 GeV proton has an x_L of 0.98.

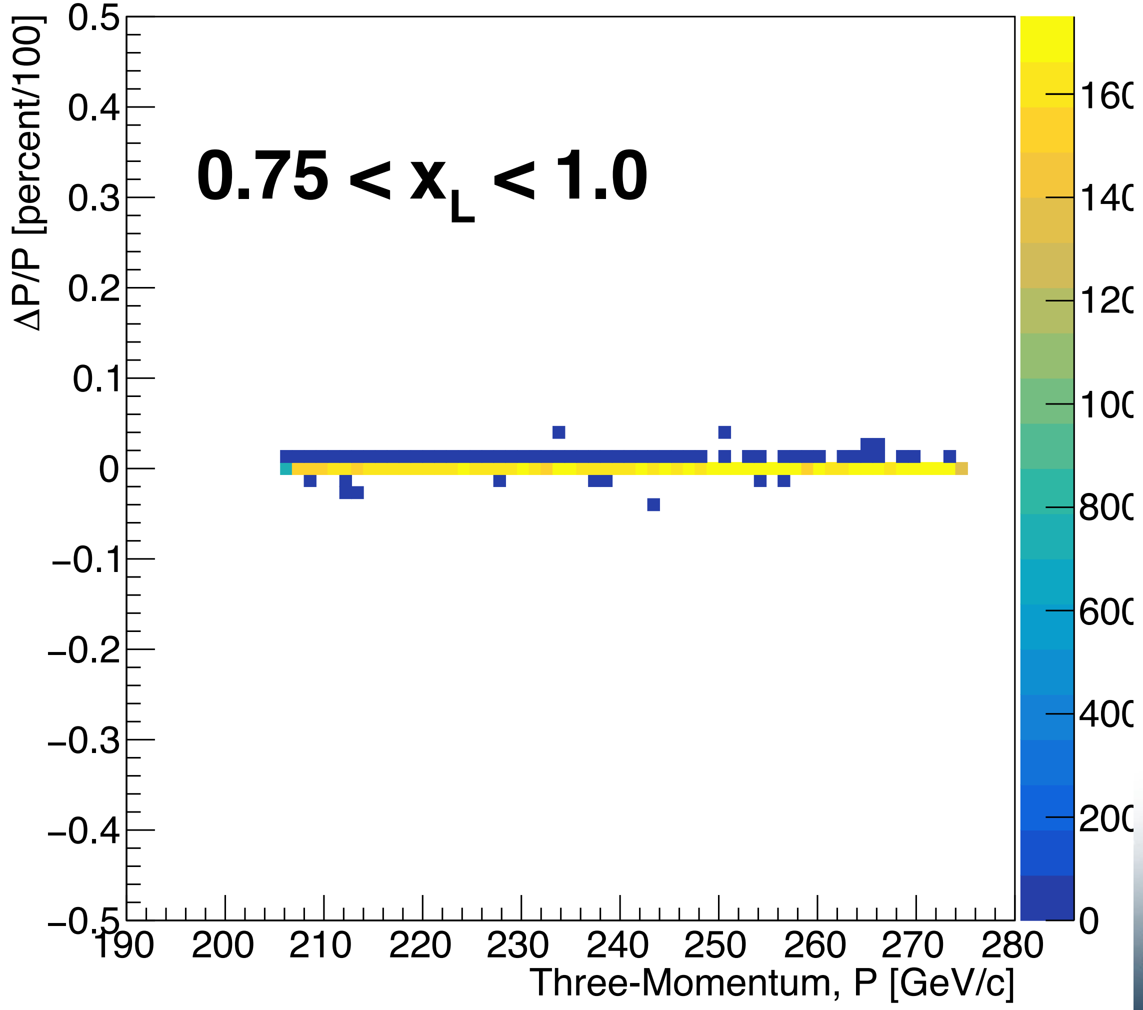
Results - Momentum

- Comparing “static” BMAD matrix (left) with dynamic matrix calculation (right).

“static” BMAD matrix

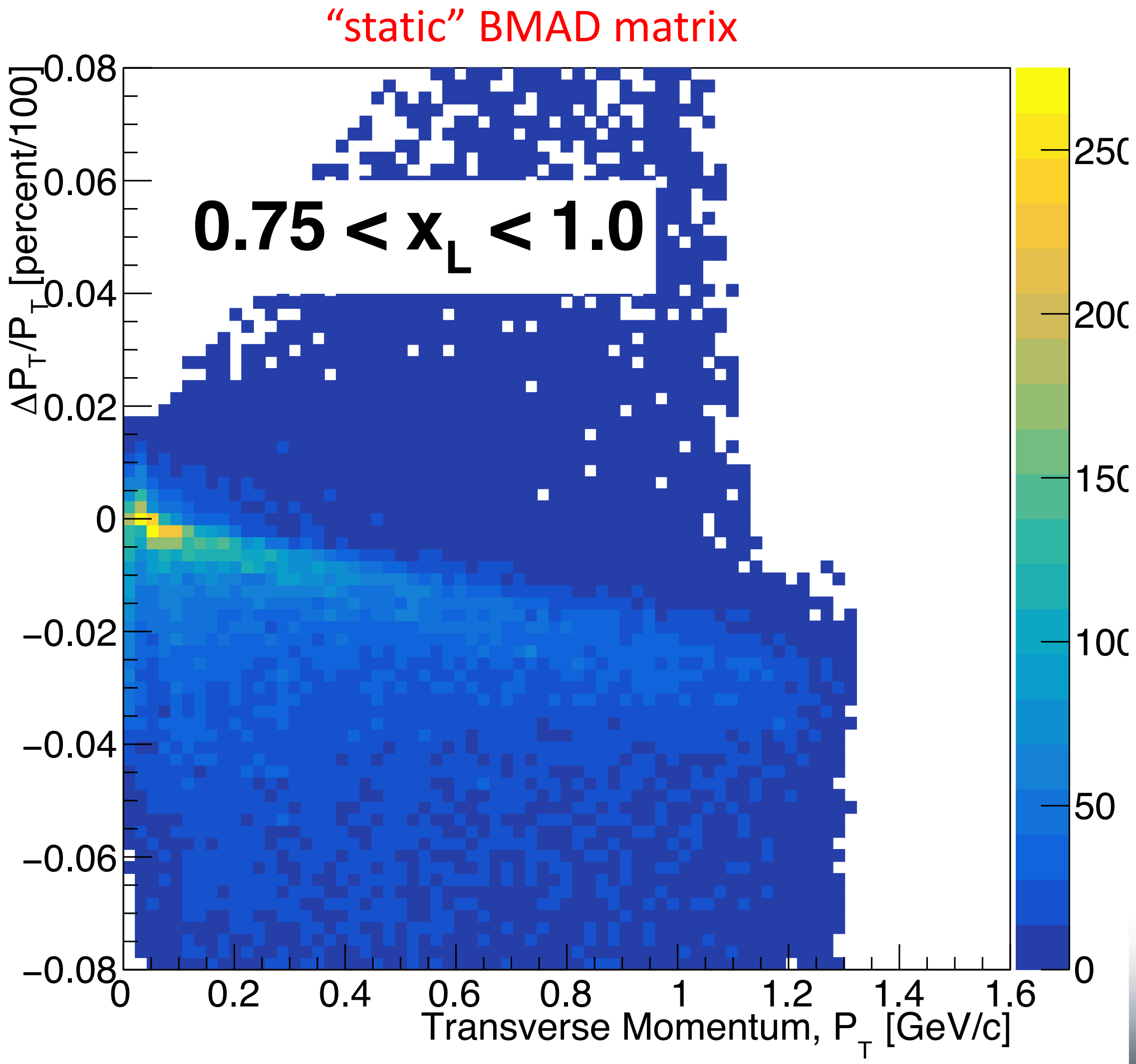


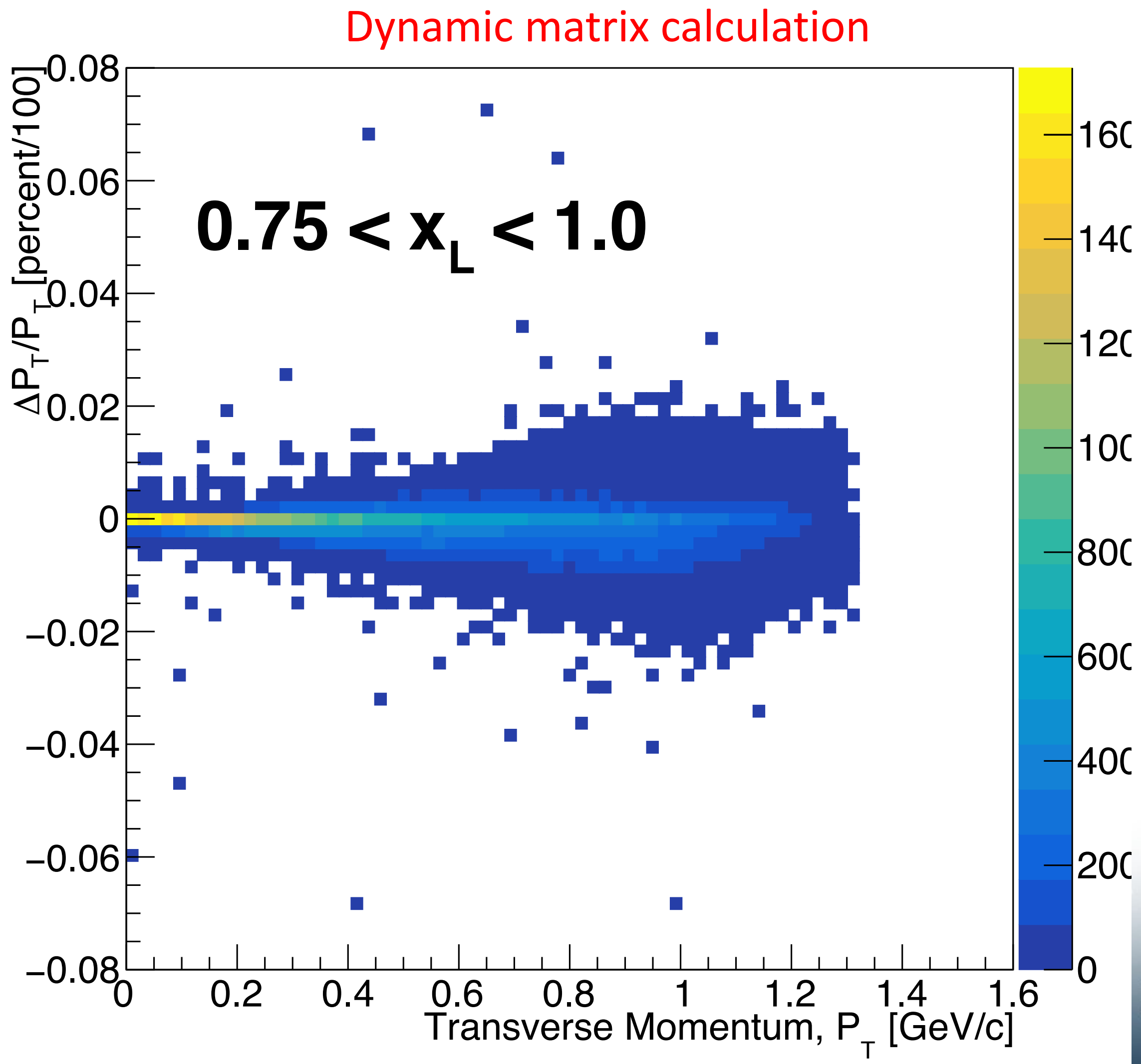
Dynamic matrix calculation



Results - p_T

- Comparing “static” BMAD matrix (left) with dynamic matrix calculation (right).

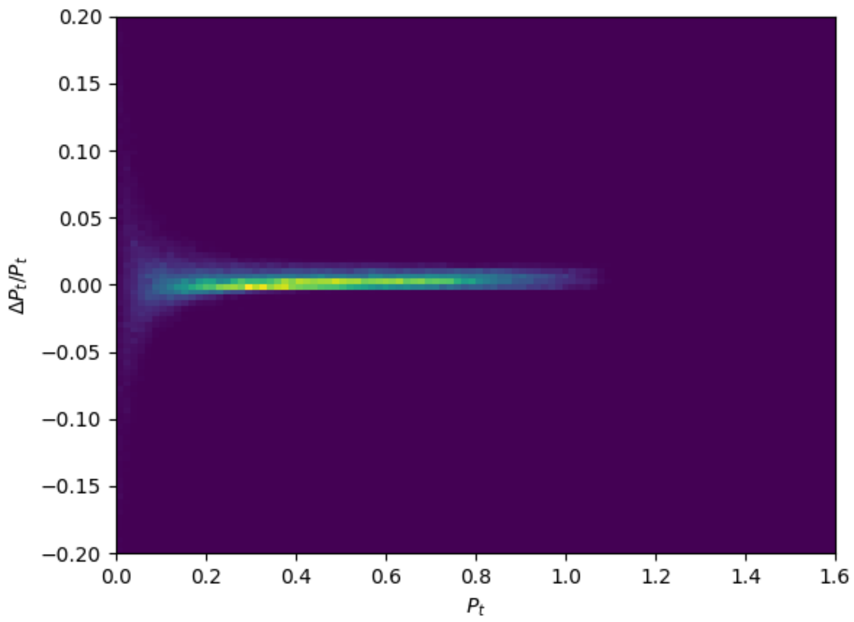


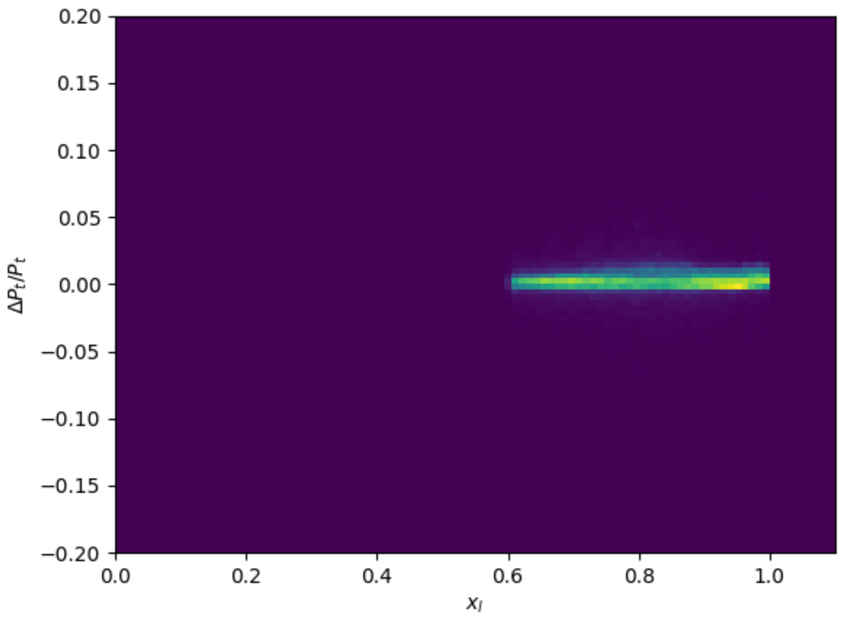


Reconstruction

- <u>**General methods for tracking:**</u>
  - **Matrix method (standard)** → should always have access to this to check performance.
  - **Machine learning methods** → more-general for broader set of final-state momenta.

$$\begin{pmatrix} x \\ \theta_x \\ y \\ \theta_y \end{pmatrix} \rightarrow (P_z) \qquad \begin{pmatrix} x \\ \theta_x \\ P_z \end{pmatrix} \rightarrow (P_x) \qquad \begin{pmatrix} y \\ \theta_y \\ P_z \end{pmatrix} \rightarrow (P_y)$$



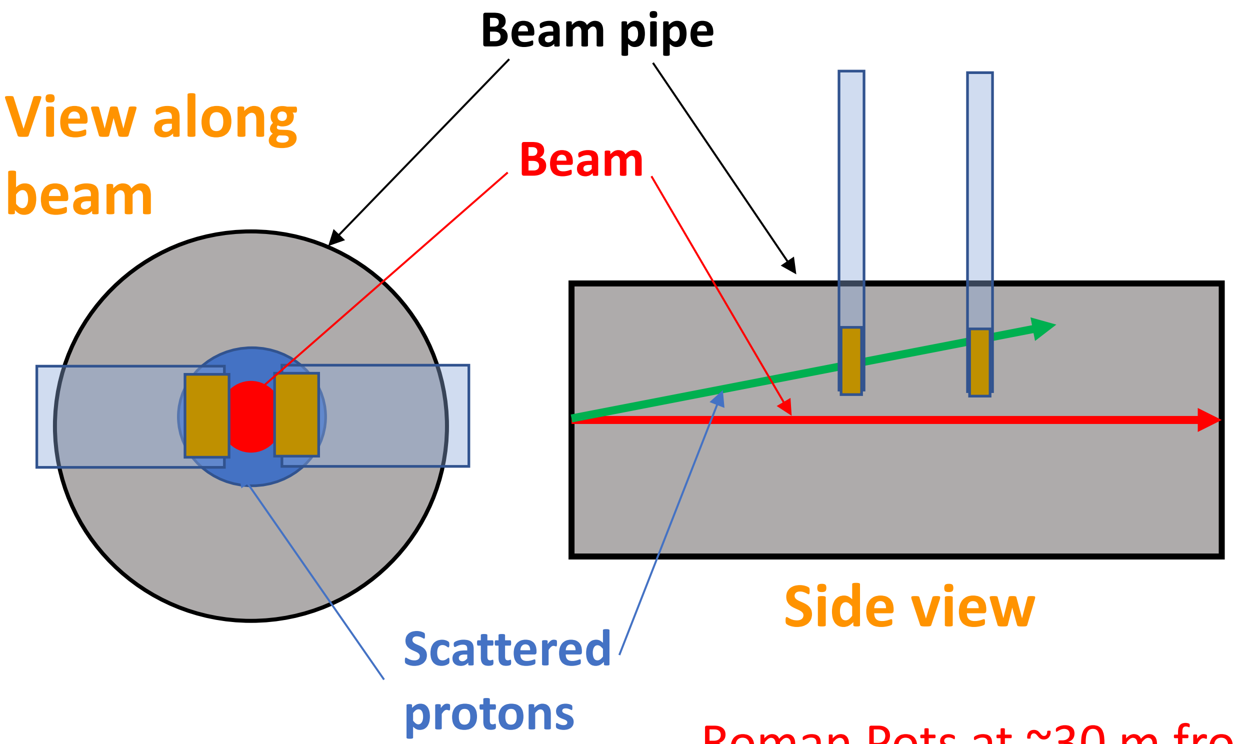


- **Framework:** PyTorch
- **Architecture:** Multi-Layer Perceptron
- **3 Independent Models:**
- **5 Hidden Layers, 128 Neurons**
- **Loss Function:** Huber Loss
- **Optimizer:** Adam
- Performance is excellent for P_z and shows little dependence on x_L
- P_t performance is good, but needs further optimization, and performance suffers at very low P_t

Progress on RP reconstruction.

David Ruth & Sakib Rahman

Roman Pots



$$\begin{pmatrix} x_D \\ \Theta_D^x \\ y_D \\ \Theta_D^y \end{pmatrix} = \begin{pmatrix} a_{11} & L_{eff}^x & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & L_{eff}^y \\ a_{41} & a_{42} & a_{43} & a_{44} \end{pmatrix} \begin{pmatrix} x_0 \\ \Theta_x^* \\ y_0 \\ \Theta_y^* \end{pmatrix}$$

x_0, y_0: Position at Interaction Point

Θ^*_x, Θ^*_y: Scattering Angle at IP

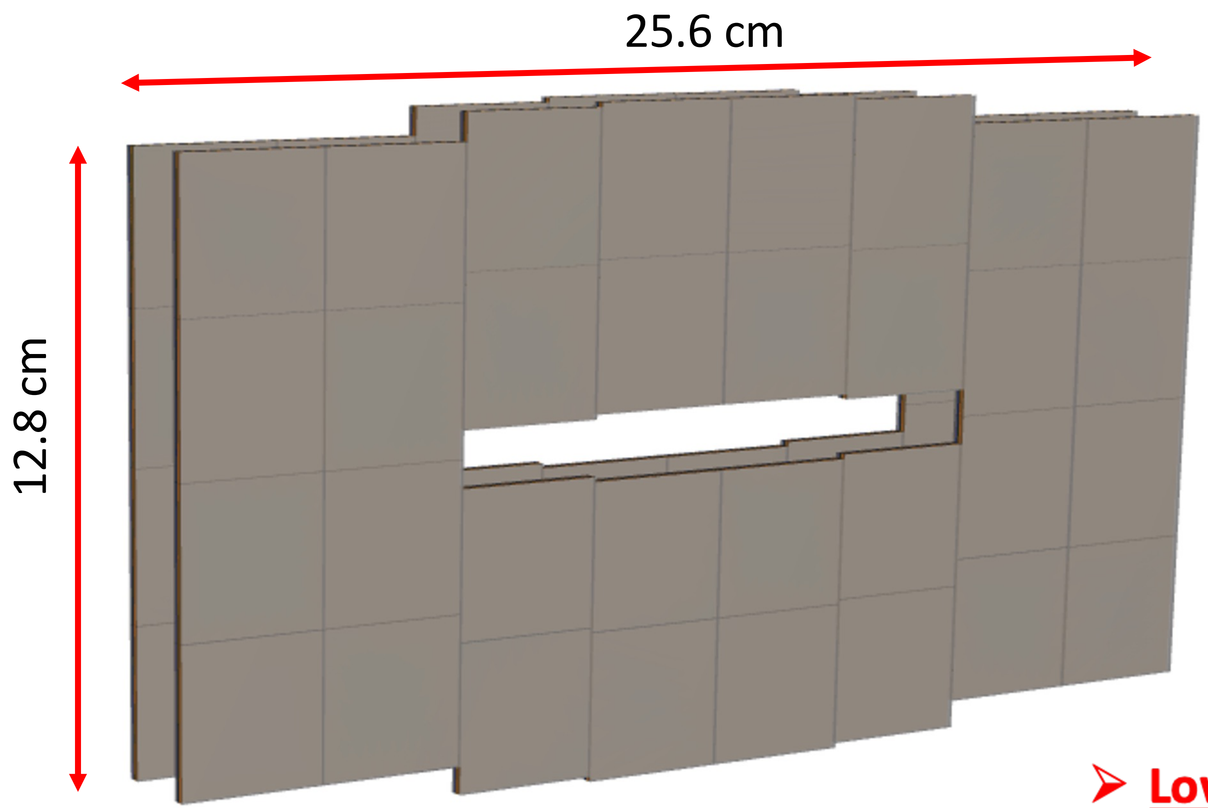
x_D, y_D : Position at Detector

Θ^x_D, Θ^y_D : Angle at Detector

Roman Pots at ~30 m from IP → $\theta \backsim$ 0 - 5 mrad

- Roman Pots are silicon sensors placed in a “pot”, which is then injected into the beam pipe, tens of meters or more from the interaction point (IP).
- Momentum reconstruction carried out using matrix transport of protons through magnetic lattice.

Roman "Pots" @ the EIC

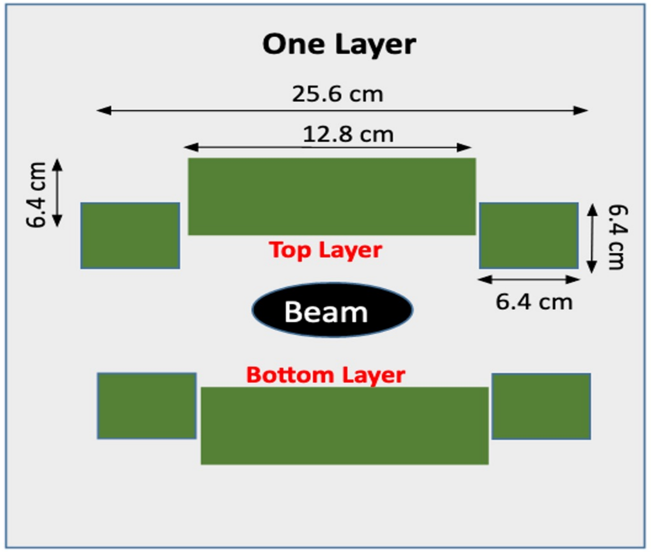


DD4HEP Simulation

$\sigma(z)$ is the Gaussian width of the beam, $\beta(z)$ is the RMS transverse beam size.

ε is the beam emittance.

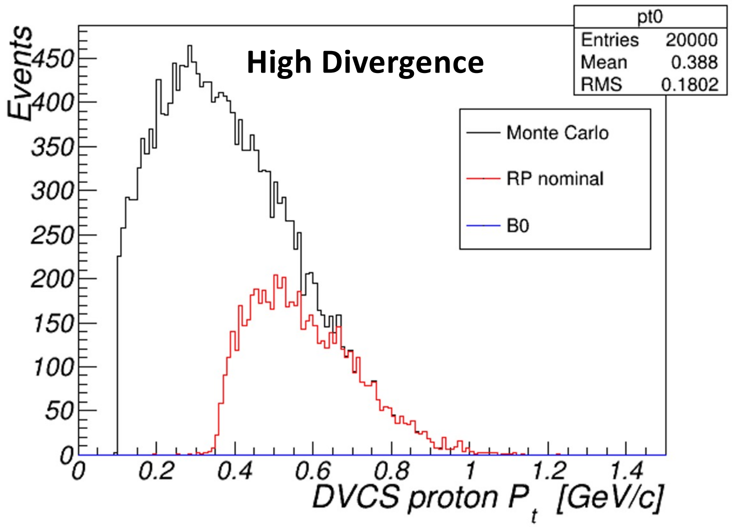
$$\sigma(z) = \sqrt{\varepsilon \cdot \beta(z}$$

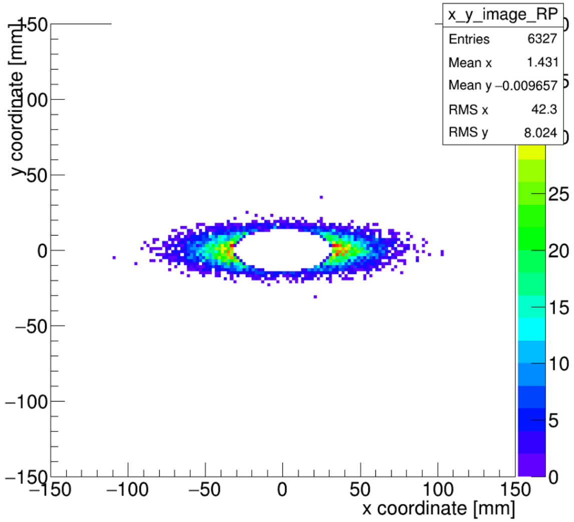


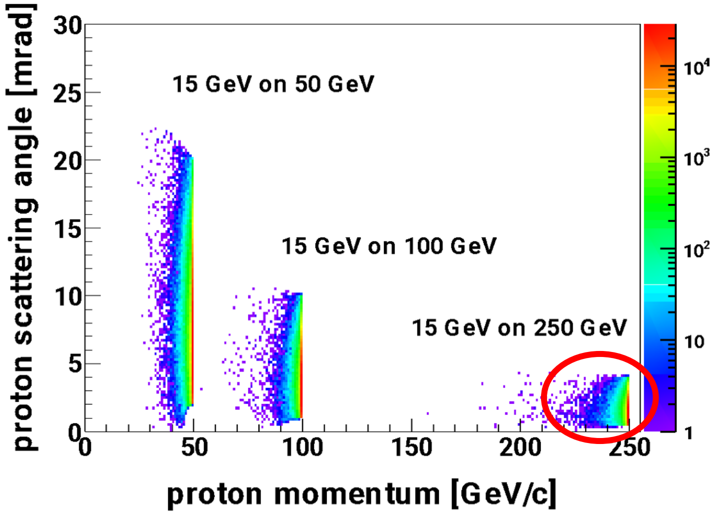
- **Low-pT cutoff determined by beam optics.**
  - **The safe distance is ~10σ from the beam center.**
  - **1σ ~ 1mm**
- **These optics choices change with energy, but can also be changed within a single energy to maximize *either acceptance at the RP, or the luminosity*.**

Digression: Machine Optics

275 GeV DVCS Proton Acceptance



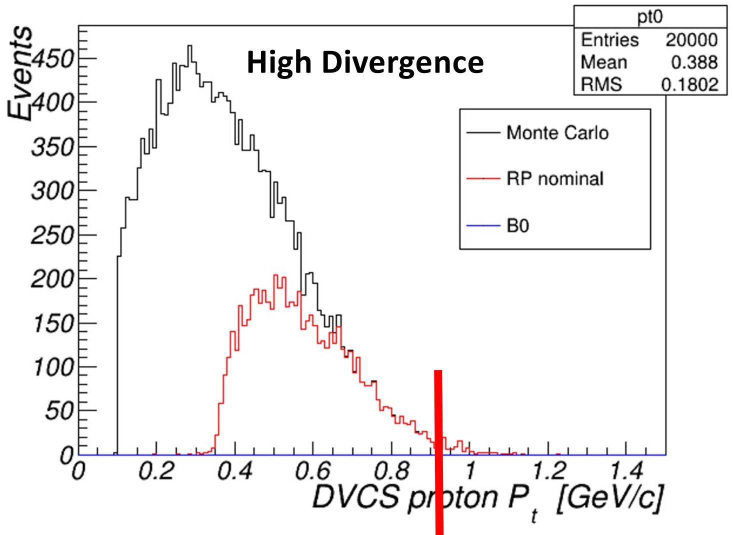


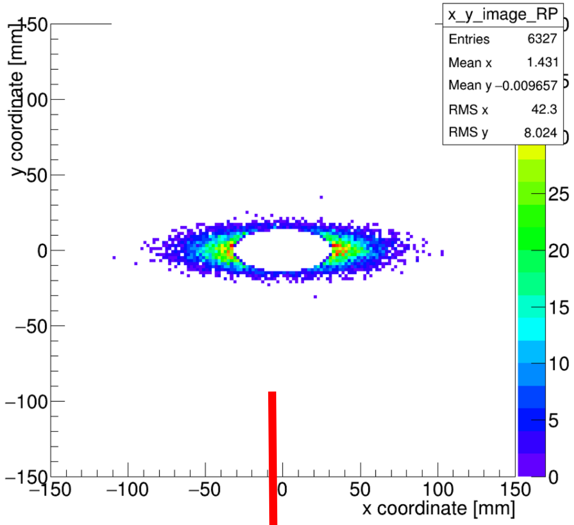


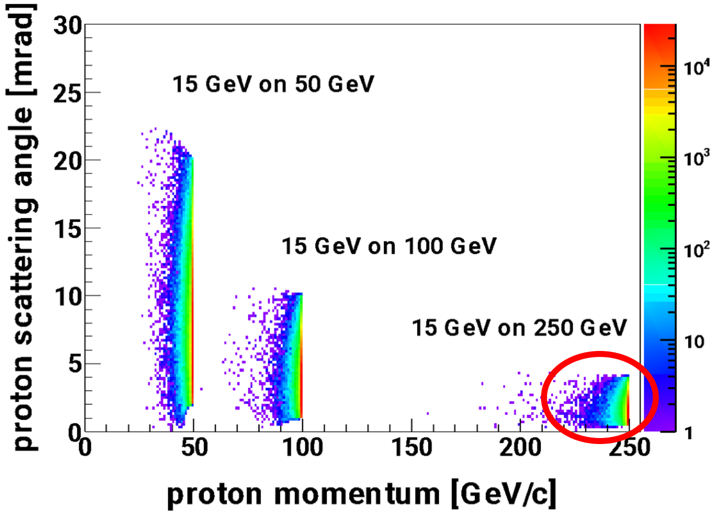
High Divergence: smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

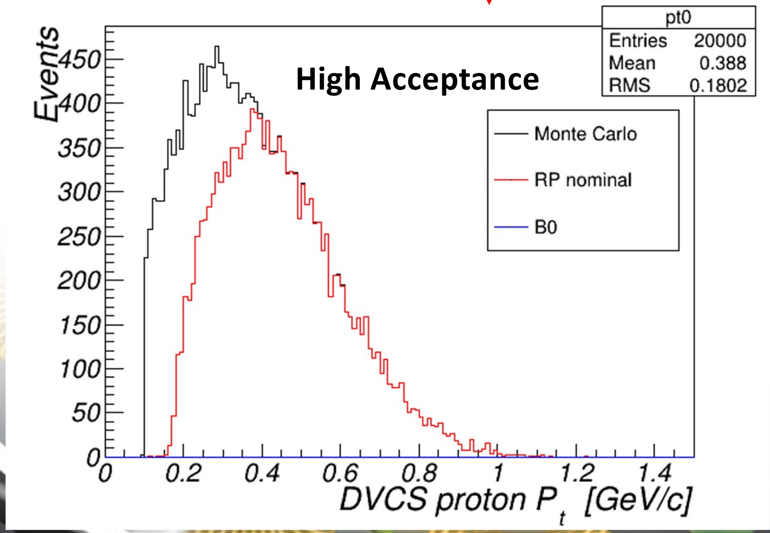
Digression: Machine Optics

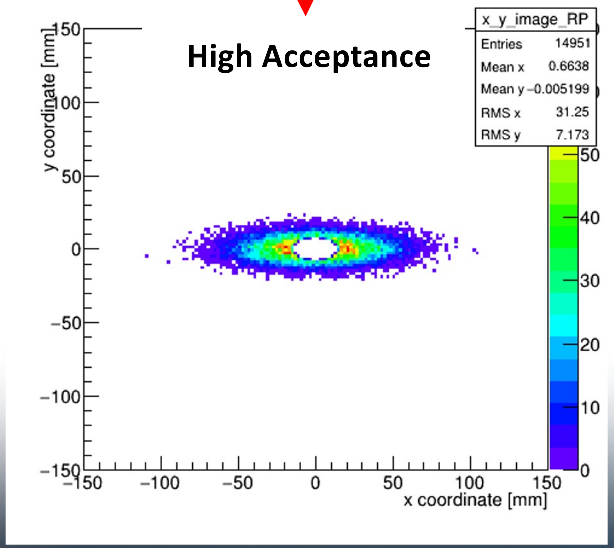
275 GeV DVCS Proton Acceptance









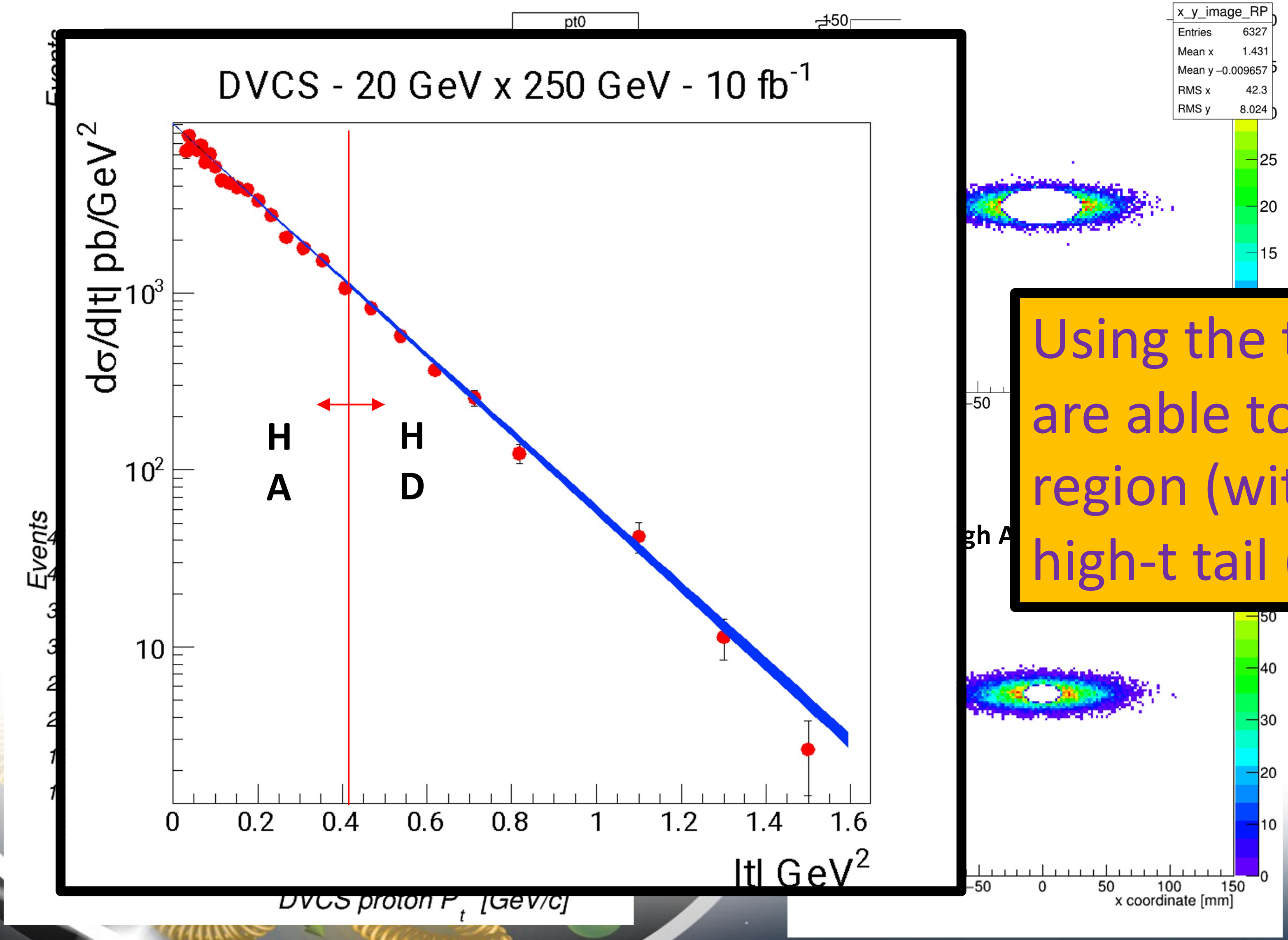


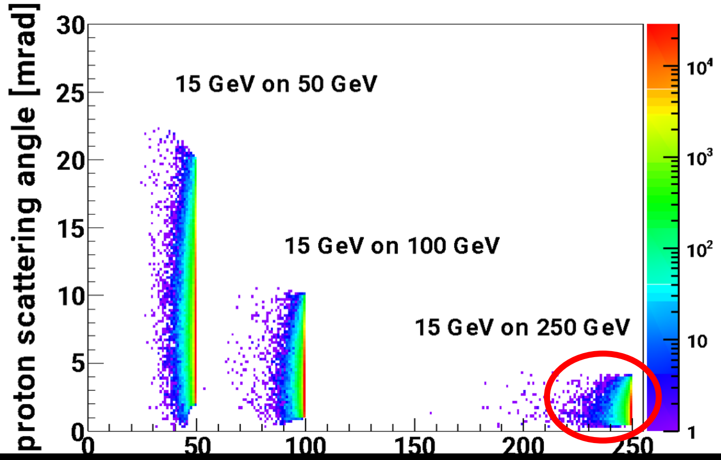
High Divergence: smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

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

Digression: Machine Optics

275 GeV DVCS Proton Acceptance



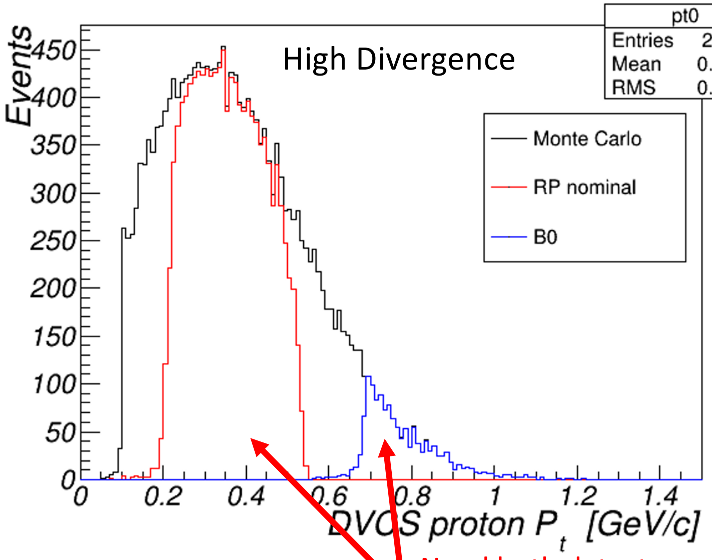


Using the two configurations, we are able to measure the low-t region (with better acceptance) and high-t tail (with higher luminosity).

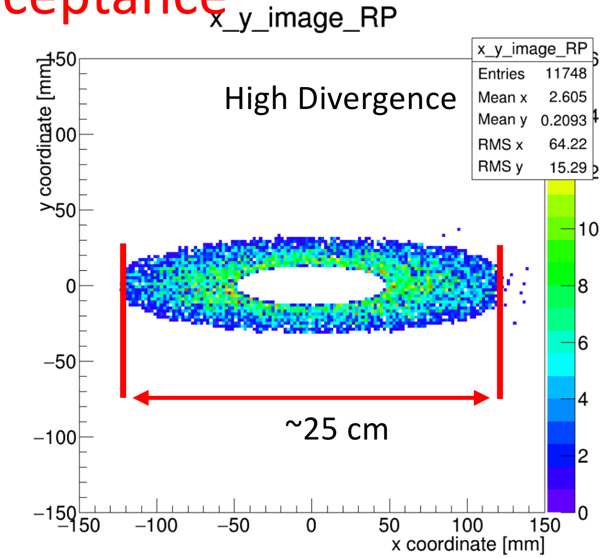
High Acceptance: larger β^* at IP, smaller $\beta(z = 30m)$ -> lower lumi., smaller beam at RP

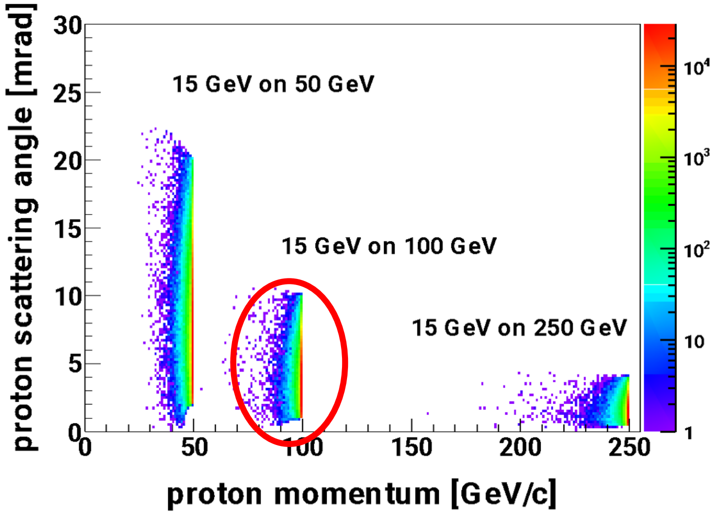
Digression: Machine Optics

100 GeV DVCS Proton Acceptance



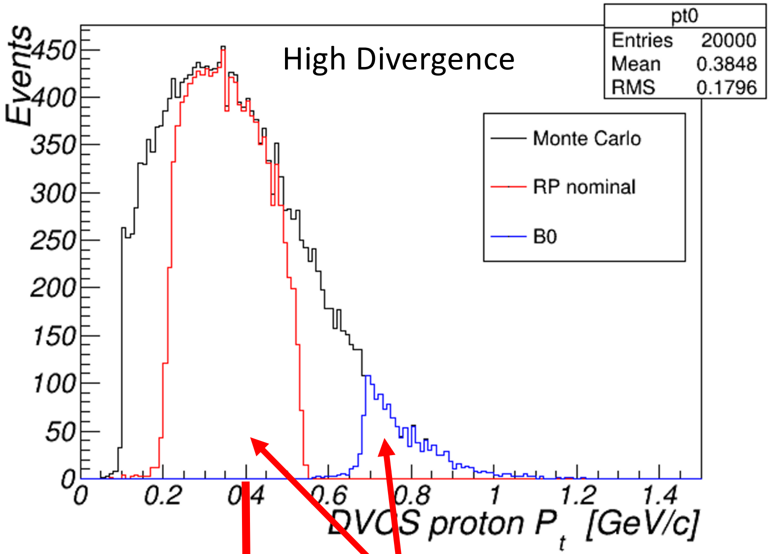
Need both detector systems together here!

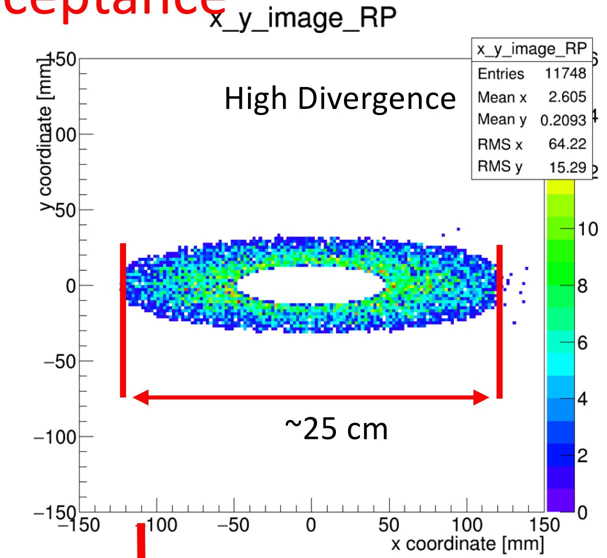


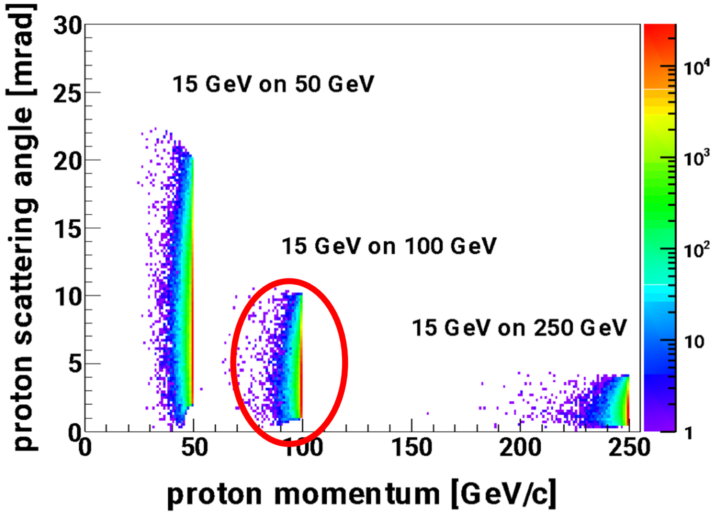


Digression: Machine Optics

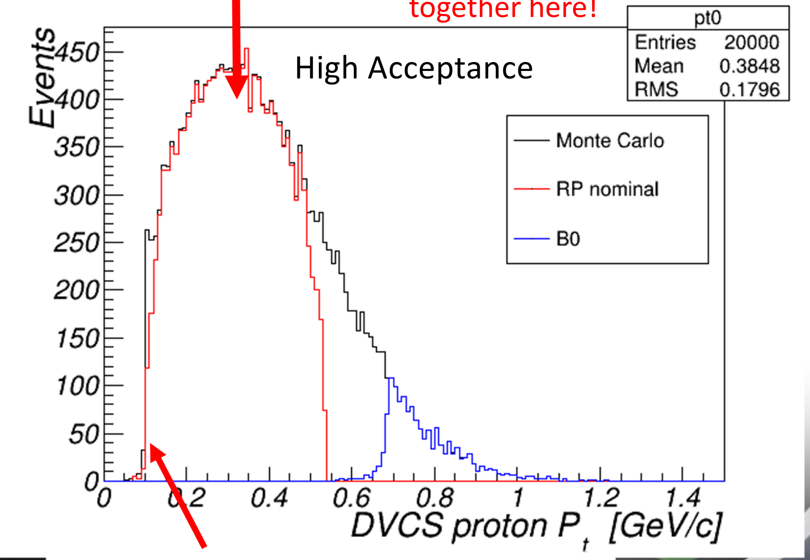
100 GeV DVCS Proton Acceptance

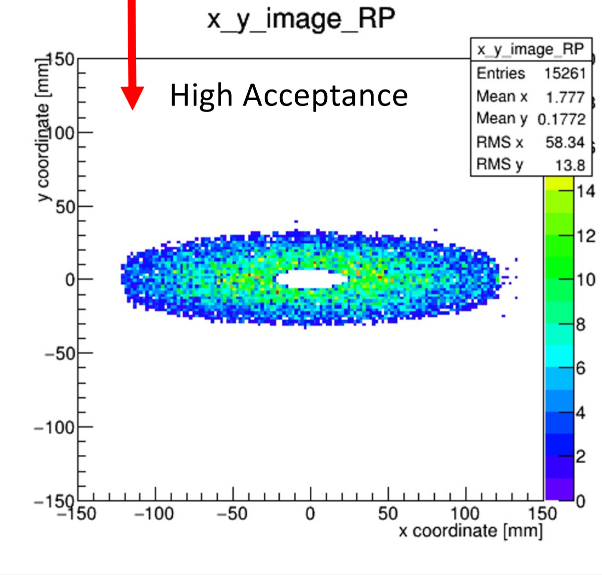






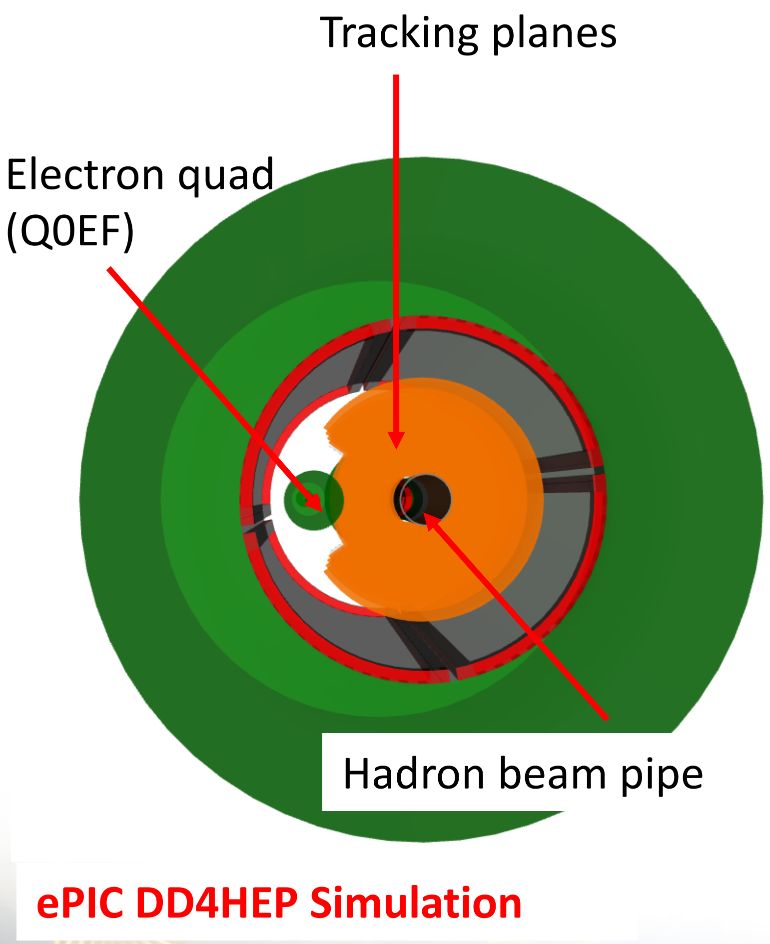
Need both detector systems together here!

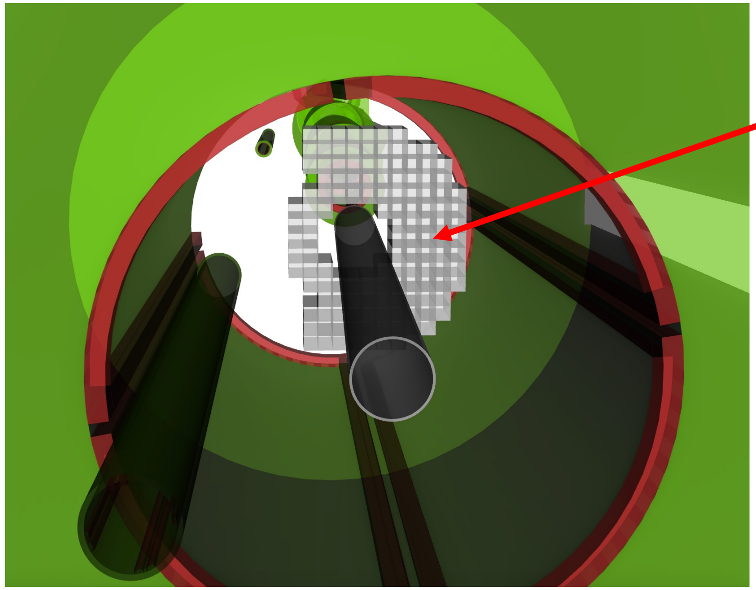




Improves low p_t acceptance.

B0 Tracking and EMCAL Detectors

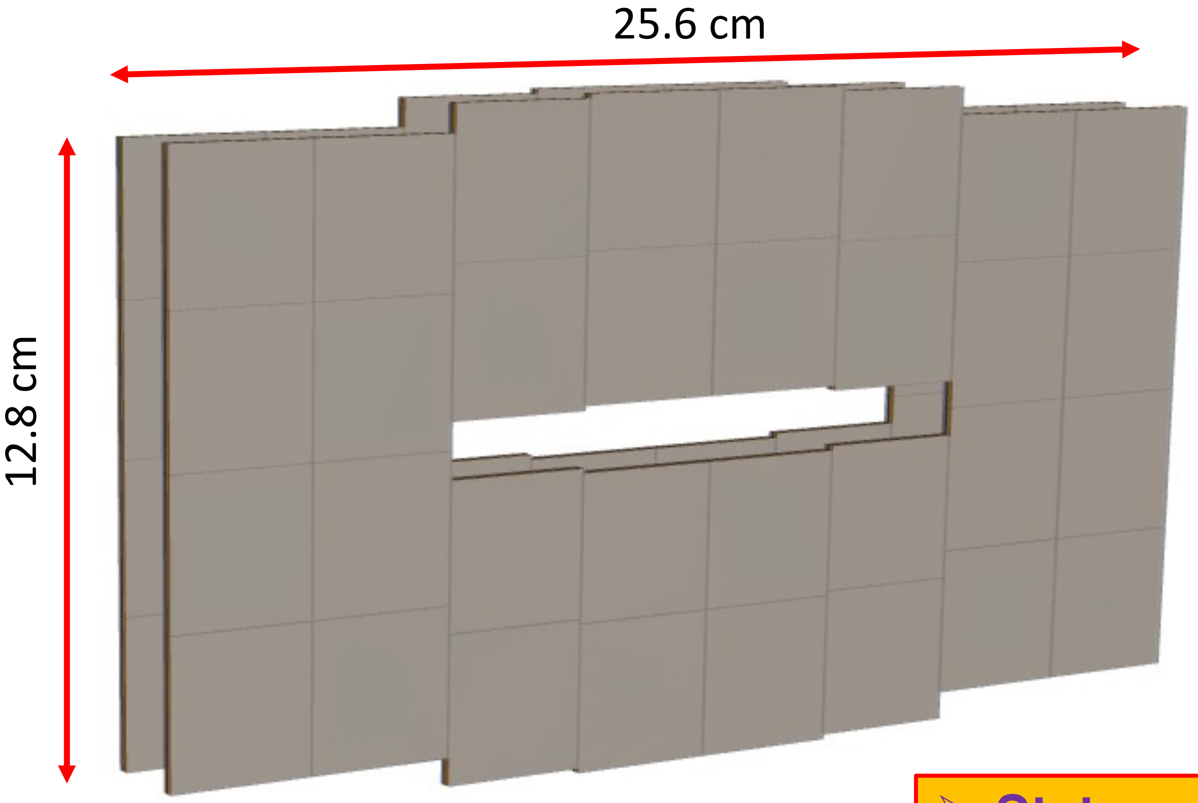




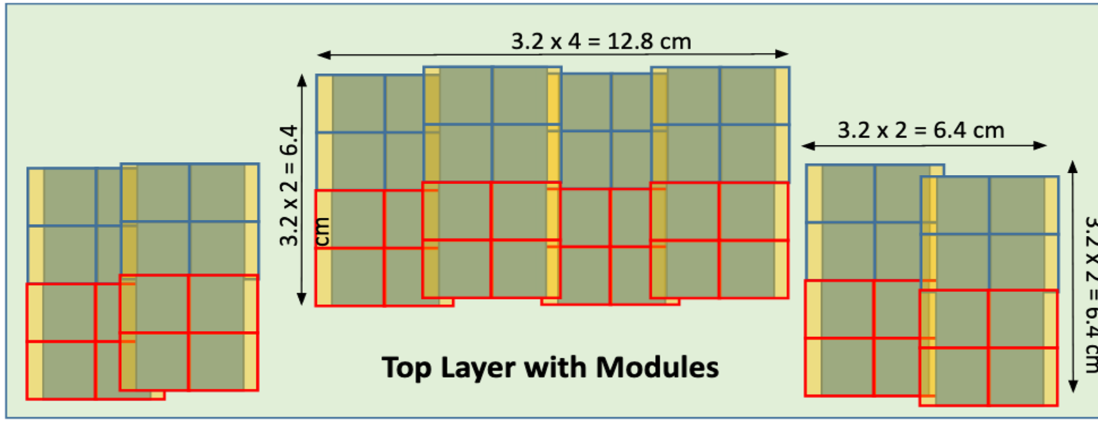
- **Technology choices:**
  - **Tracking: IT3 or ITS2 MAPS (3 layers) + AC-LGADs (1 layer; in middle)**
  - **PbWO4 EMCAL or silicon preshower, depending on available space in final B0pf magnet design (pending).**

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

Roman "Pots" @ the EIC



DD4HEP Simulation



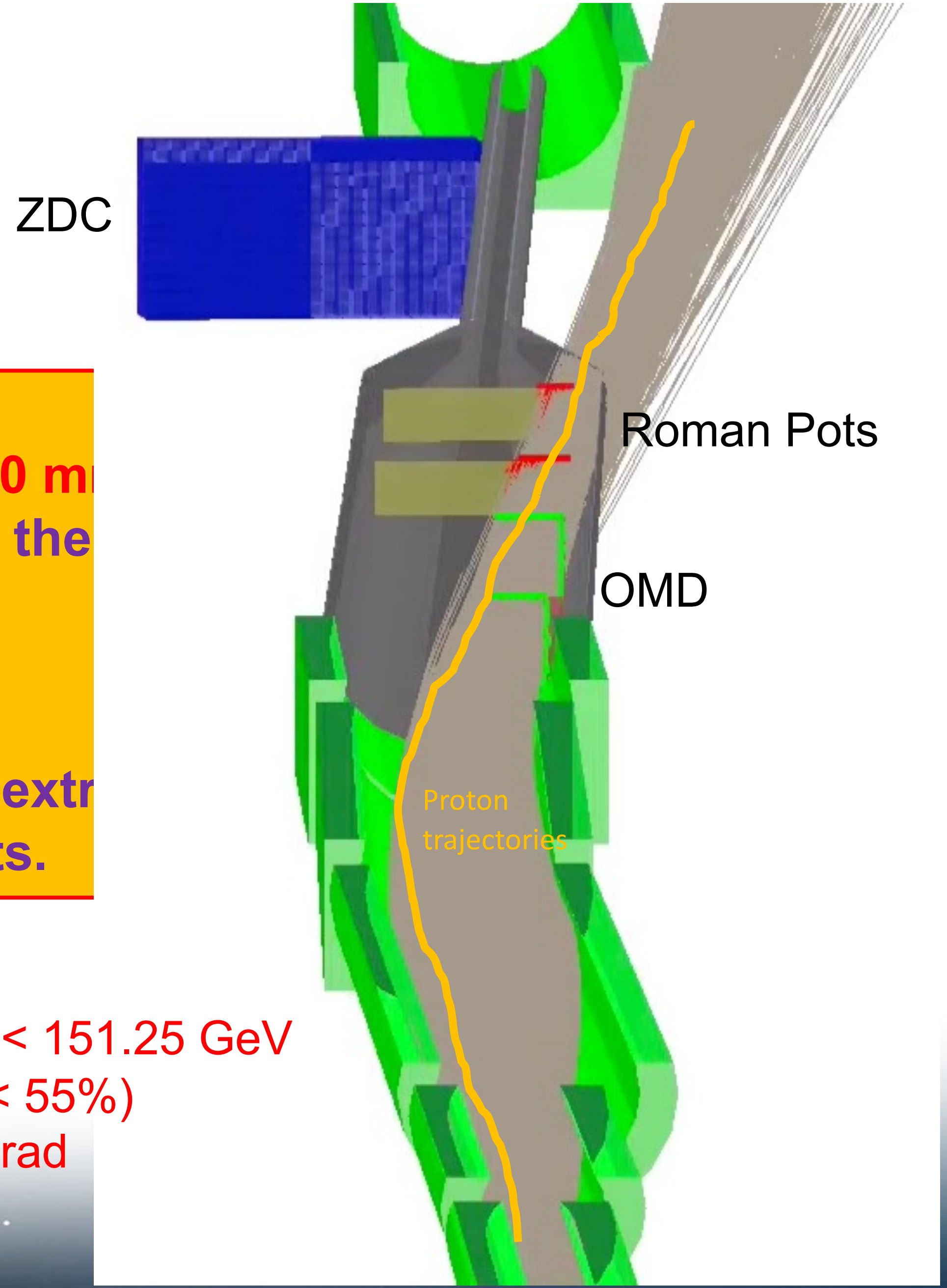
Technology

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

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

Off-Momentum Detectors

- **Status**
  - ✓ **Acceptance: 0.0 < θ < 5.0 m**
  - ✓ **Same technology as for the Roman Pots.**
  - ✓ **Even more-challenging reconstruction with off-momentum particles → extr orbit path in the magnets.**



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

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

The Far-Forward Detectors collaboration

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- Pacific Northwest National Lab, USA
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