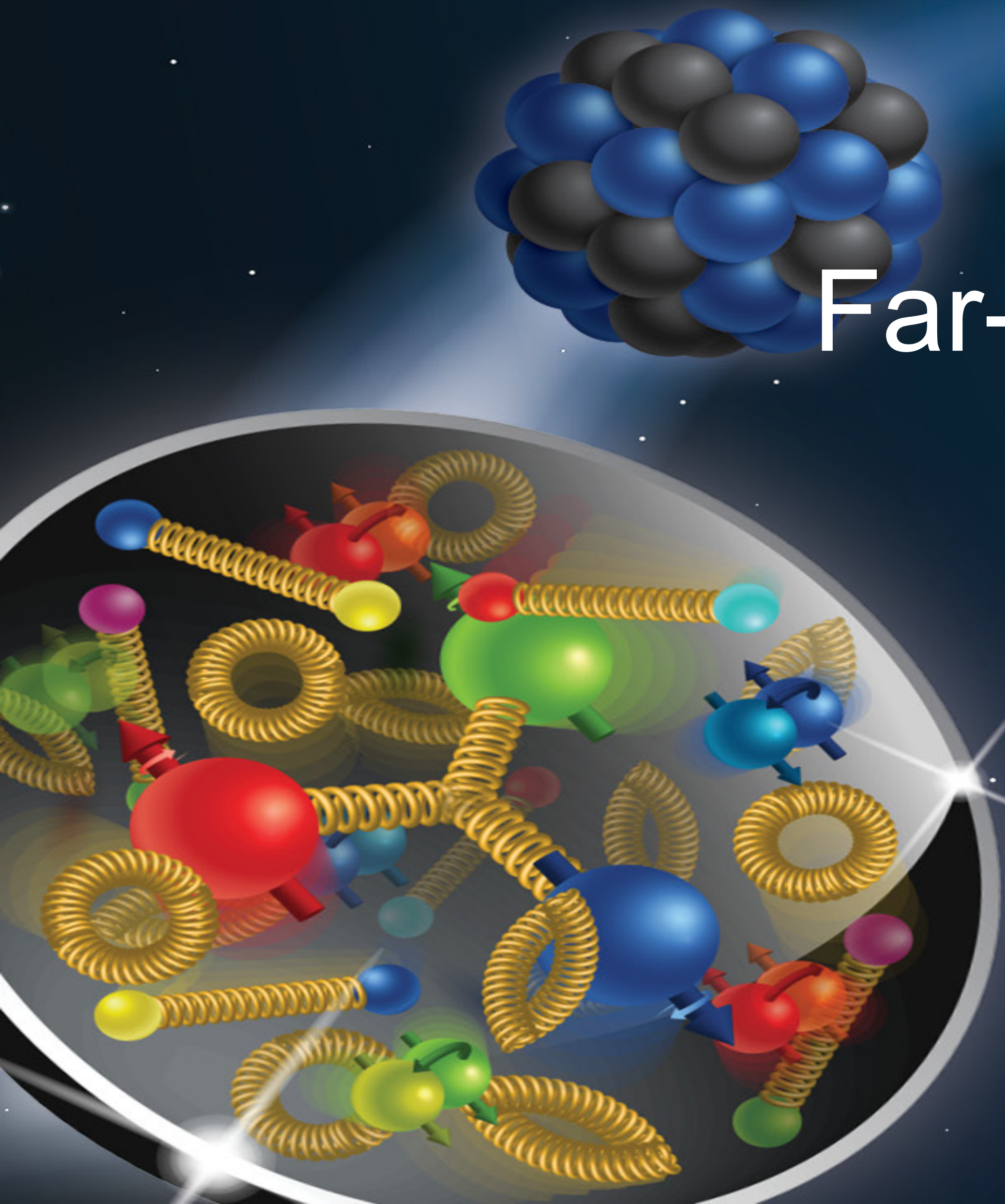

Far-Forward Physics @ the EIC: Lecture 2

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EIC Summer School

July 11th - 22nd, 2022

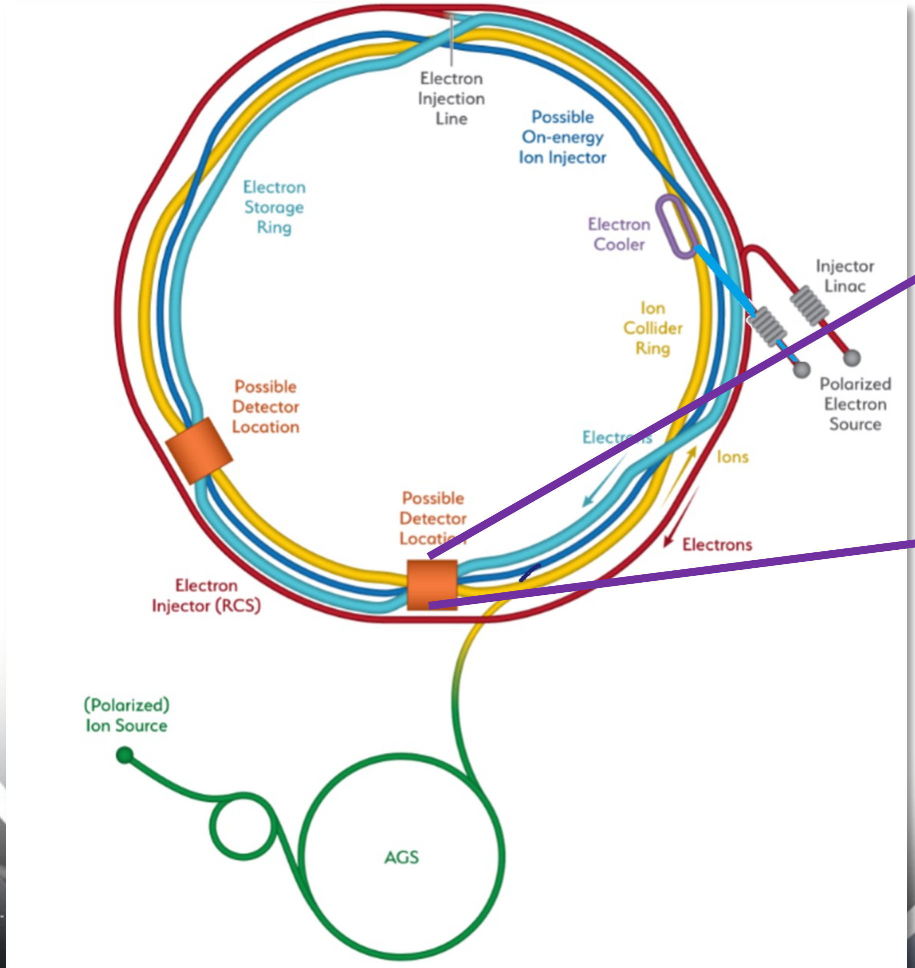
Stony Brook University

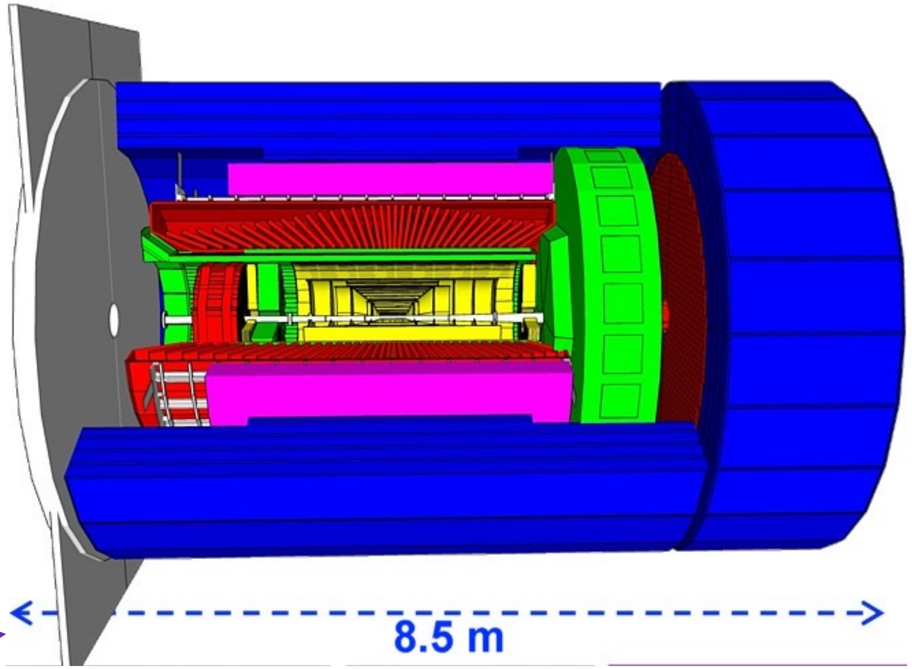
I hate outlines

- Lecture 1 (yesterday)
  - Introduce basic idea of “far-forward” physics, with great damage done to proper terminology.
  - Discuss some examples which I find interesting, and for which a direct observable can be described.
- Lecture 2 (today)
  - Discuss the “how” for measuring these final-states.
  - Bludgeon you with a few details to provide more than just an overview.
  - Learn how the various detectors are related to the various final states discussed yesterday.

The EIC detector(s)

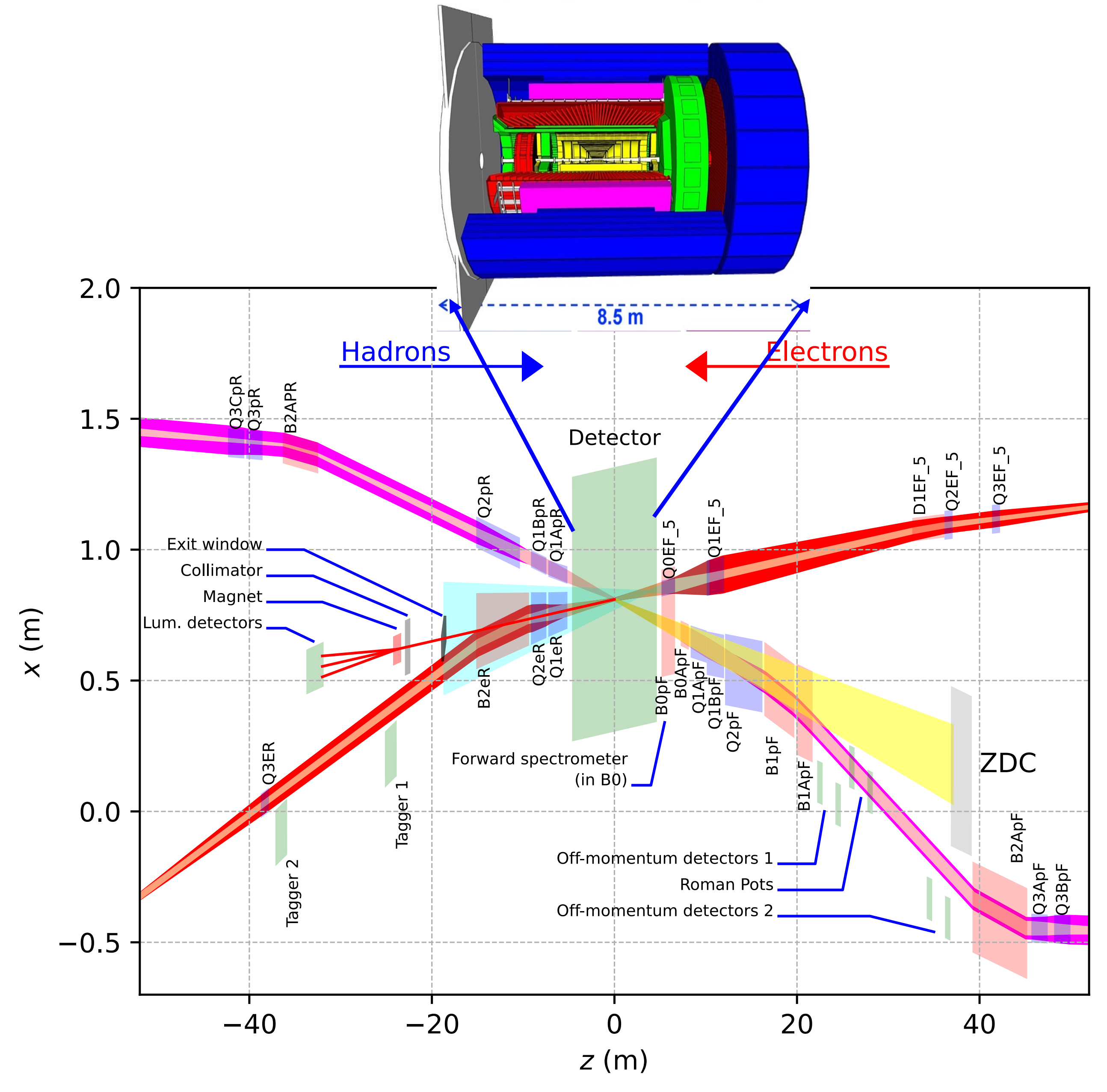
- Two interaction regions (IRs) for possible detector locations.
  - Only one IR (IP6) part of the project scope.





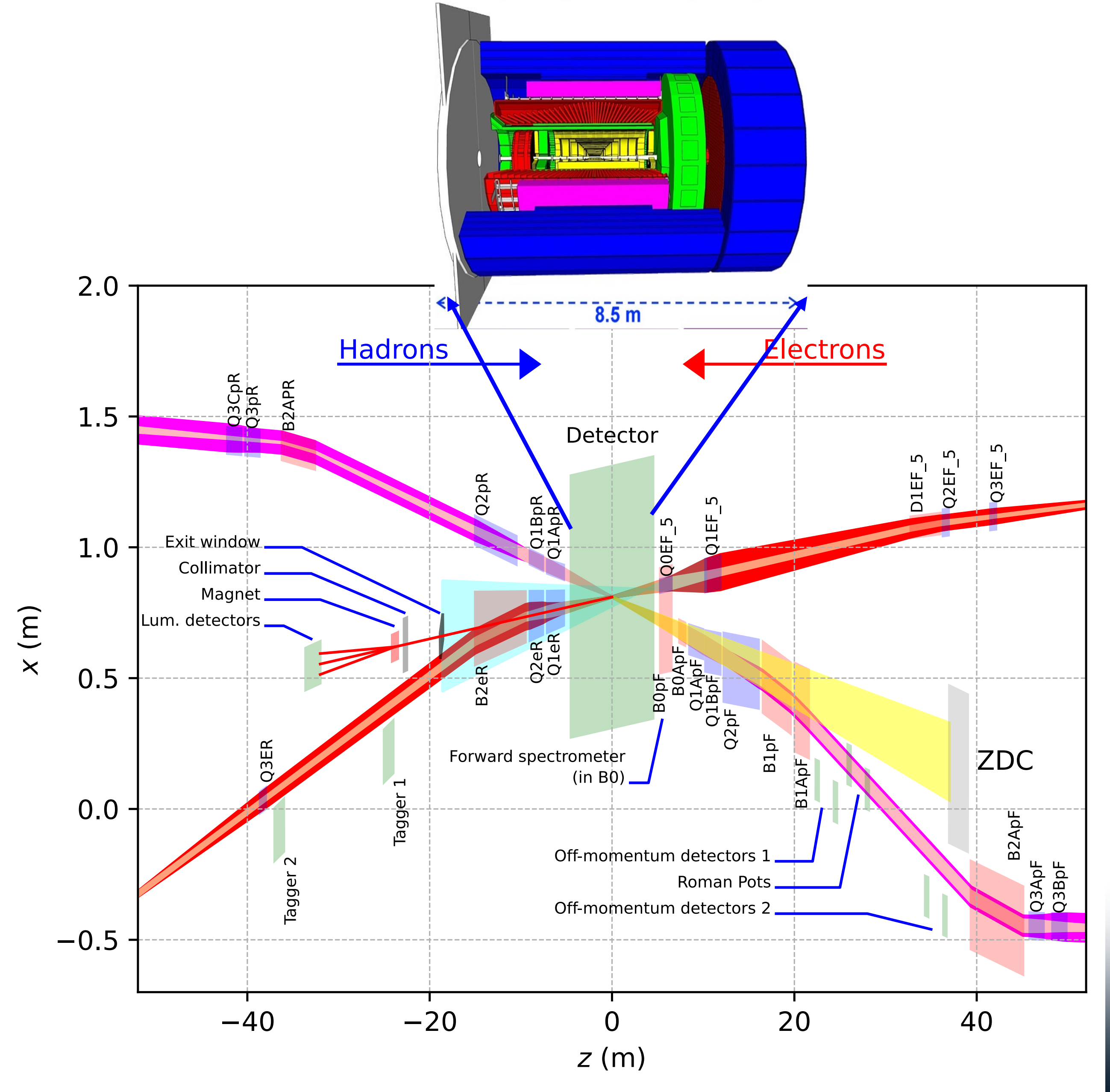
- ➢ Reference detector based on the 1.5T BaBar solenoid and ECCE reference design.
  - ➢ Contains detectors for tracking, PID, and calorimetry.
- ➢ Second detector possible, but funding must be raised to support it.

EIC Detector 1 – IP6



- In addition to the central detector → detectors integrated into the beamline on both the hadron-going (far-forward) and electron-going (**far-backward**) direction.
  - Requires special considerations for the machine-detector interface.

EIC Detector 1 – IP6



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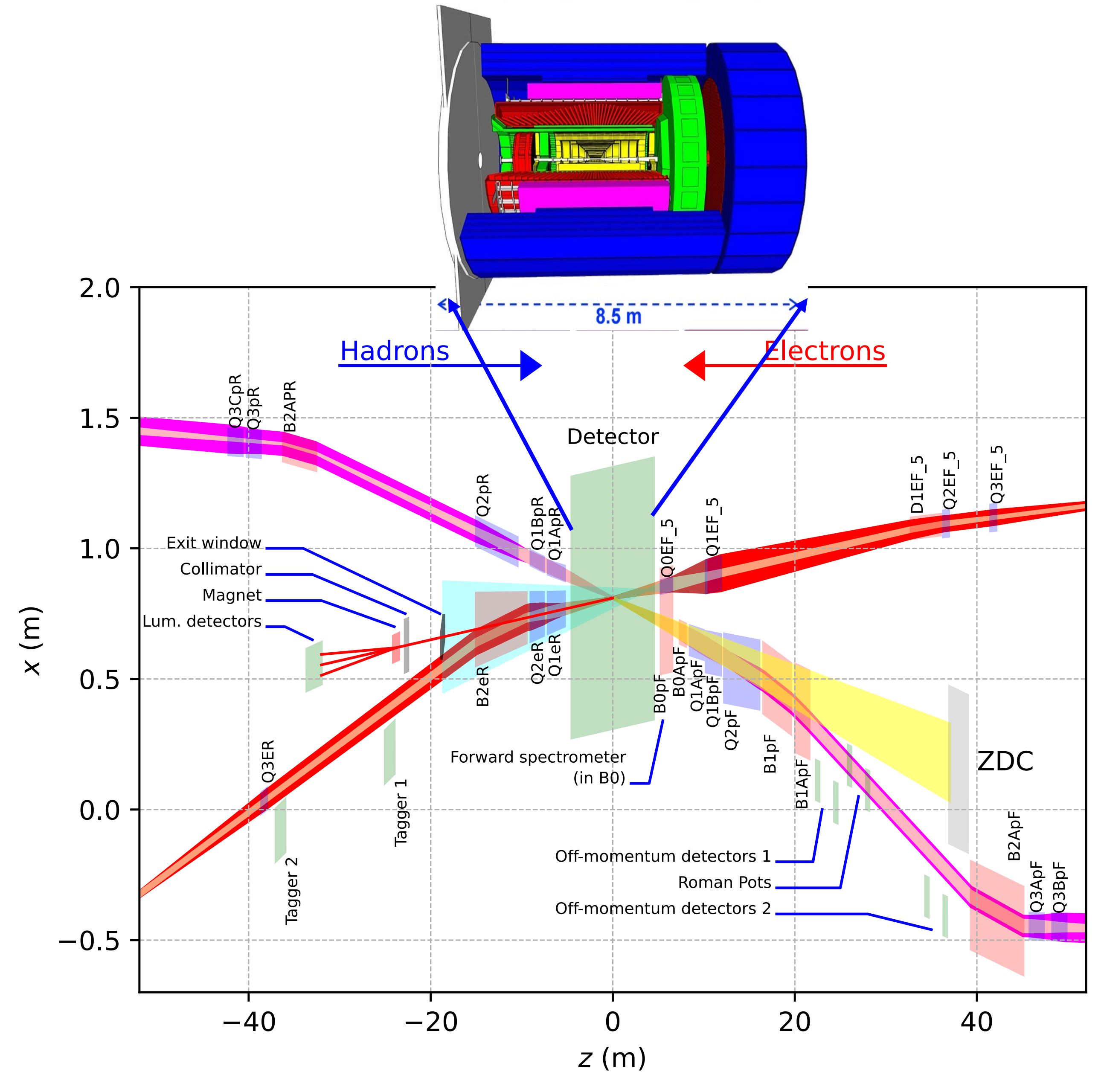
The far-forward system functions almost like an independent spectrometer experiment at the EIC!

EIC Detector 1 – IP6



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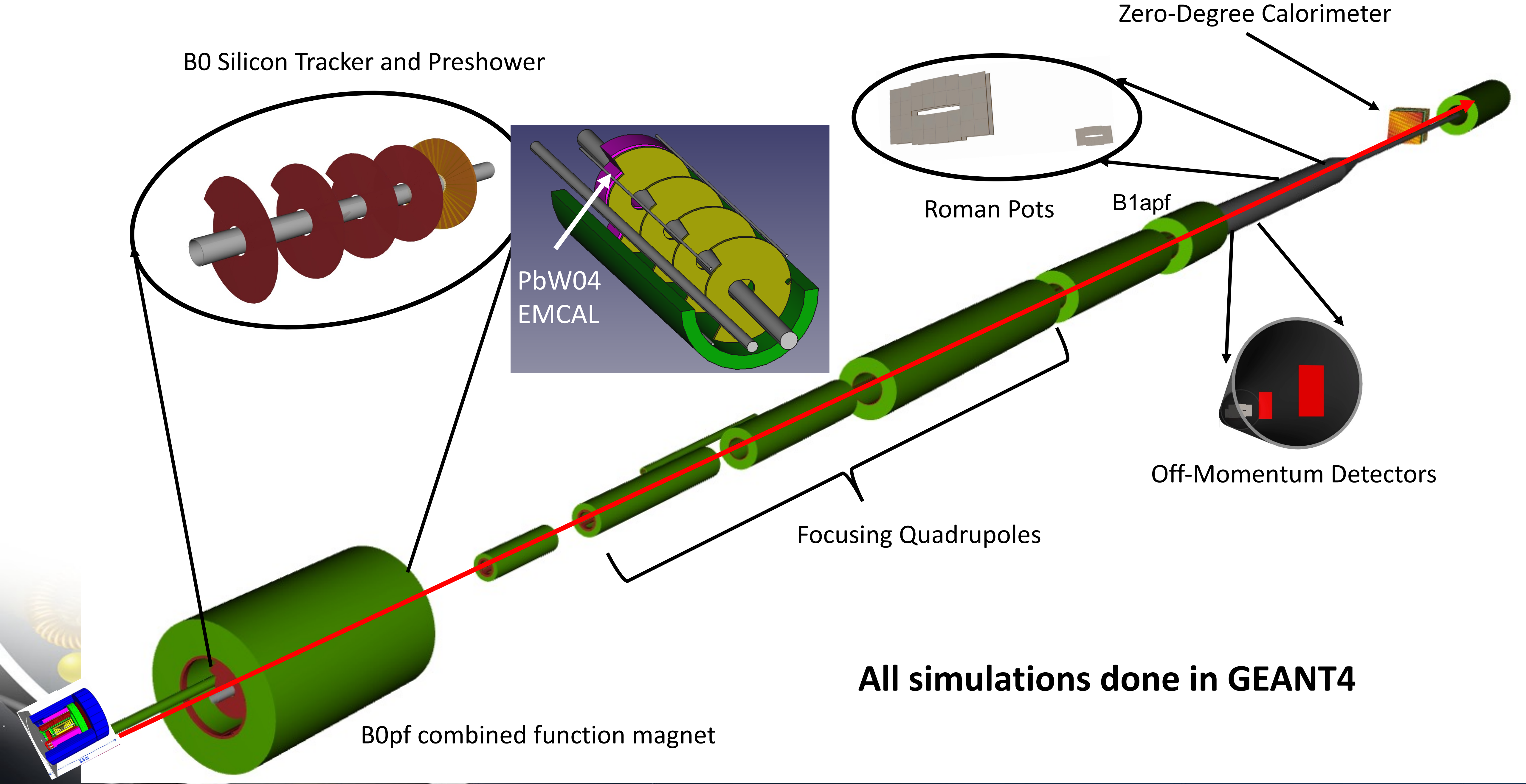
The far-forward system functions almost like an independent spectrometer experiment at the EIC!

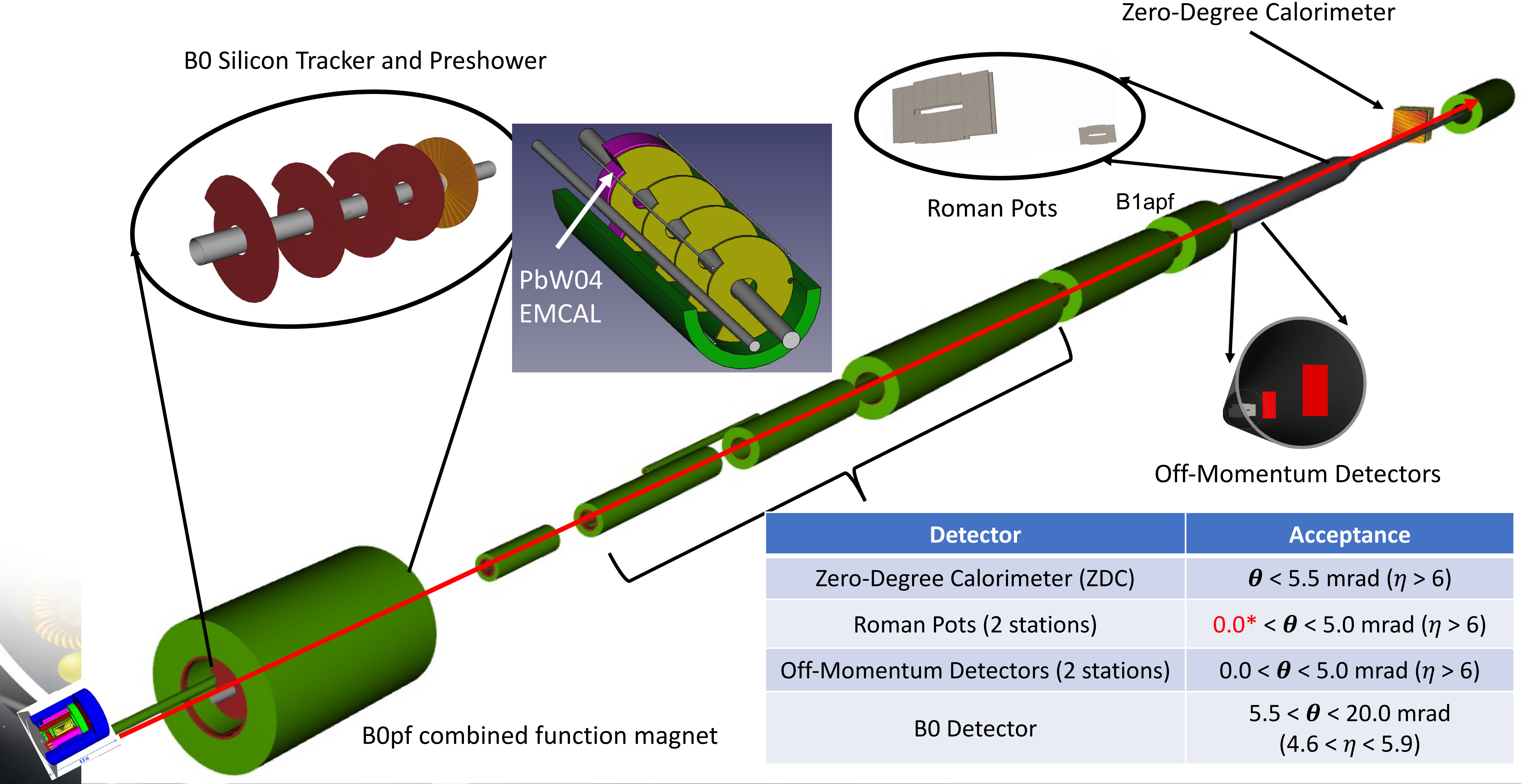
We will focus on the detector setup for IP6, but I will discuss what we gain with IP8 at the end.

The Far-Forward Detectors



All simulations done in GEANT4

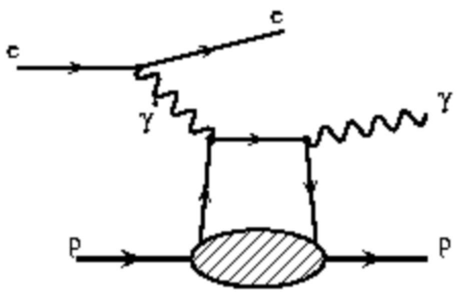
The Far-Forward Detectors



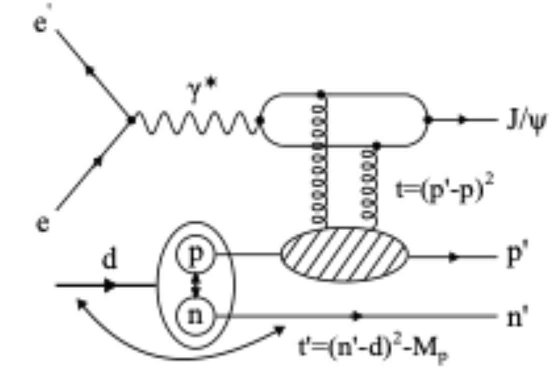
Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	θ < 5.5 mrad (η > 6)
Roman Pots (2 stations)	0.0* < θ < 5.0 mrad (η > 6)
Off-Momentum Detectors (2 stations)	0.0 < θ < 5.0 mrad (η > 6)
B0 Detector	5.5 < θ < 20.0 mrad (4.6 < η < 5.9)

Far-Forward Processes at the EIC

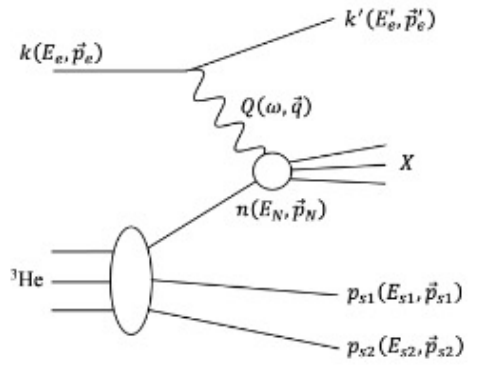
e+p DVCS



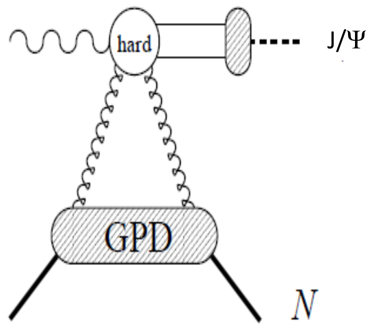
e+d exclusive J/Psi with p/n tagging



e+He3 spectator tagging

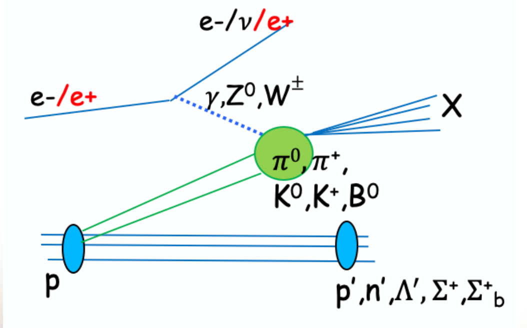


coherent/incoherent J/ψ production in e+A

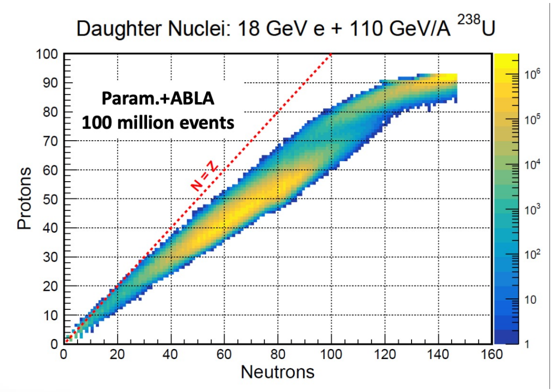


Meson structure:

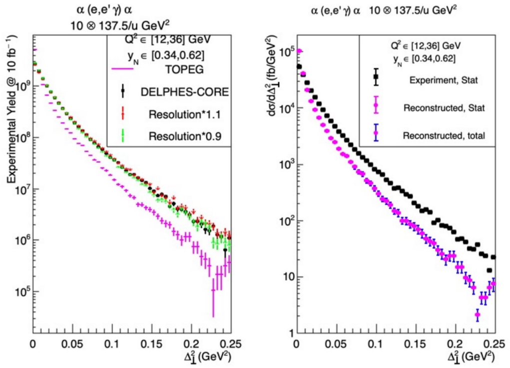
- ep→ (π) →e' n X
- $\Lambda \rightarrow p\pi^-$ and $\Lambda \rightarrow n\pi^0$



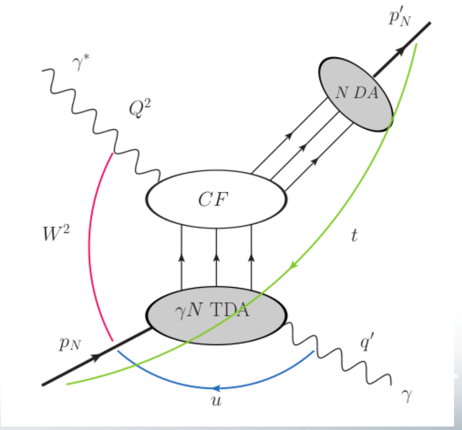
Rare isotopes



e+He4 DVCS



u-channel backward exclusive electroproduction



…and MANY more!

Far-Forward Processes 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 require tailored detector subsystems.

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- Placing of far-forward detectors uniquely challenging due to presence of machine components, space constraint, apertures, etc.

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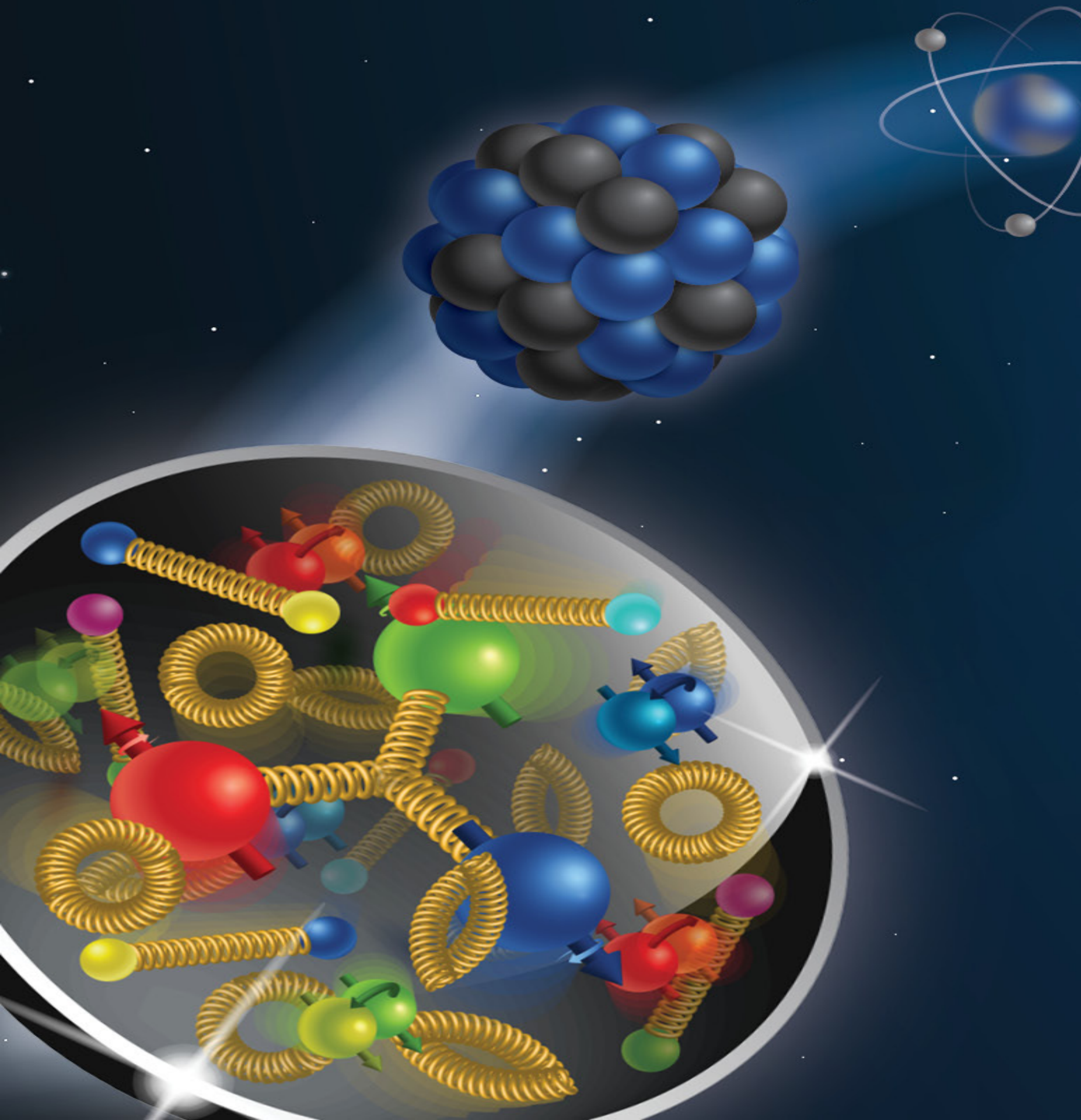
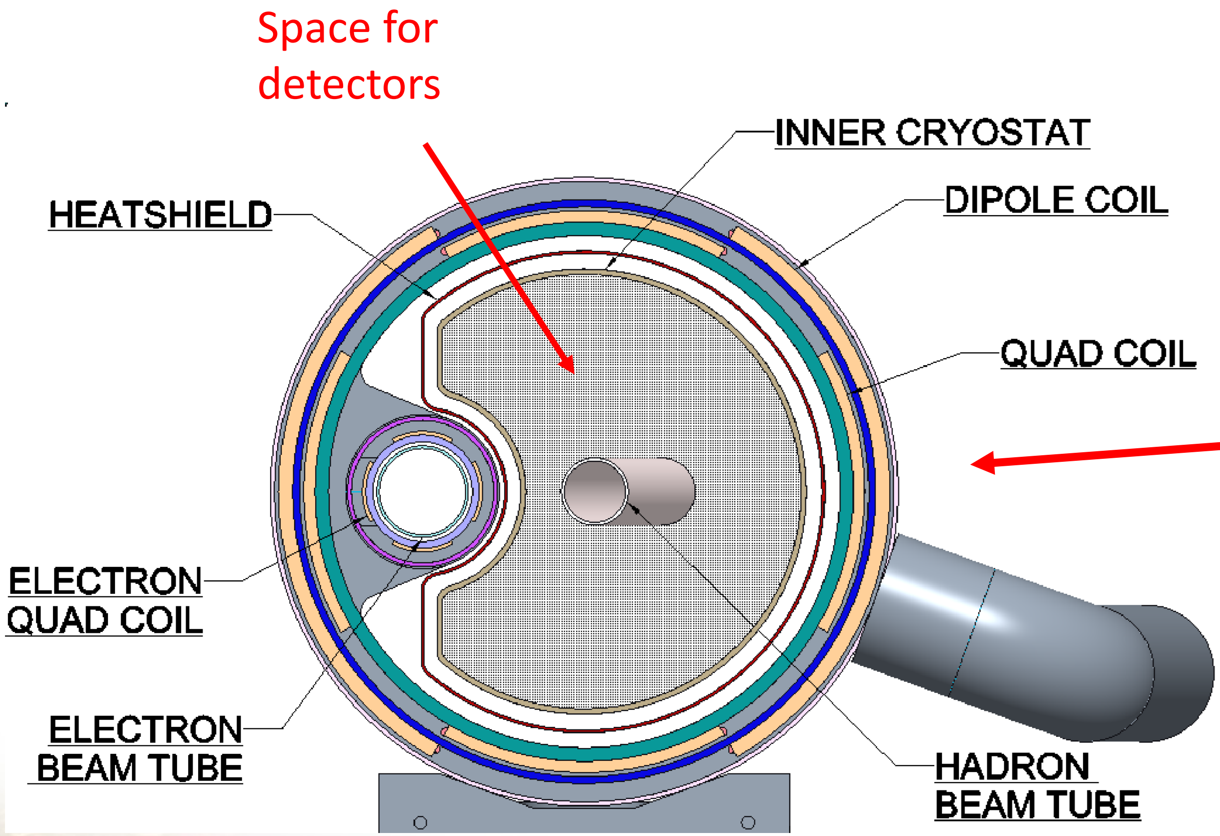
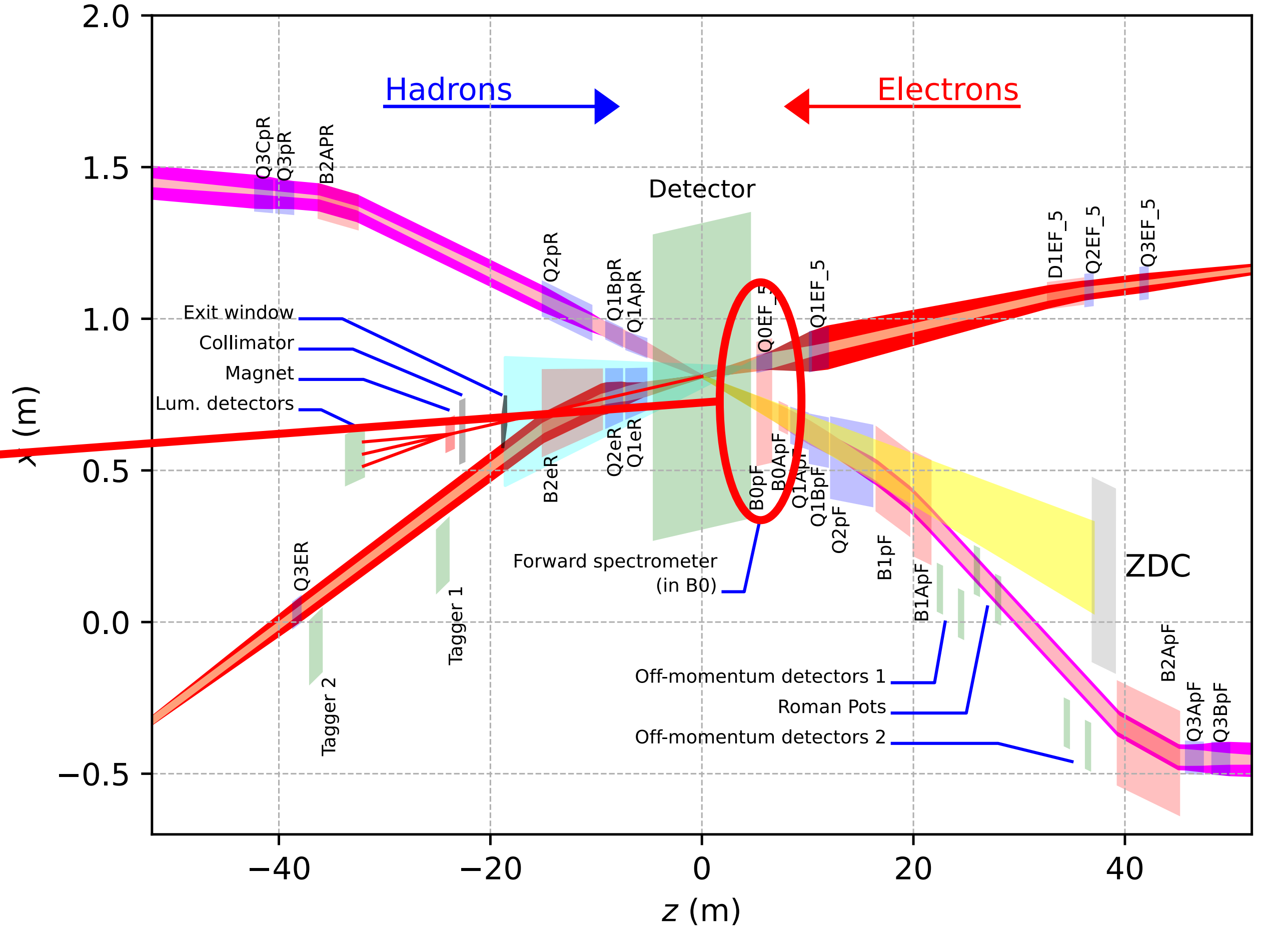
- Placing of far-forward detectors uniquely challenging due to presence of machine components, space constraint, apertures, etc.
- Conceptual design and basic studies to establish requirements complete – we are moving on toward full engineering design!



Far-Forward Detector Subsystems

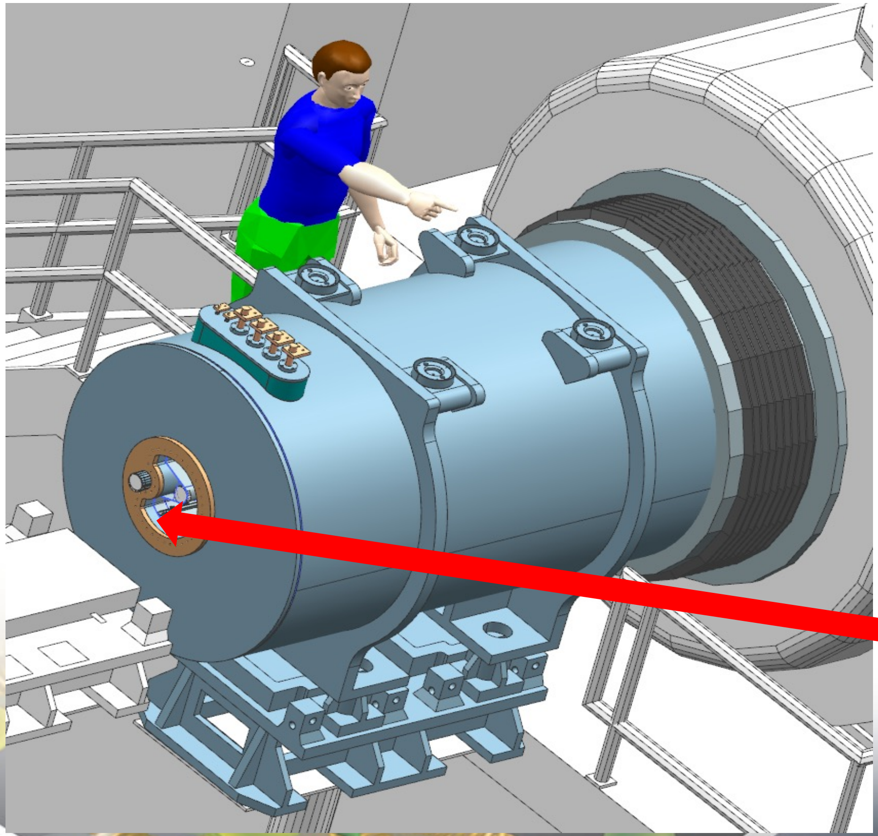
B0 Detectors

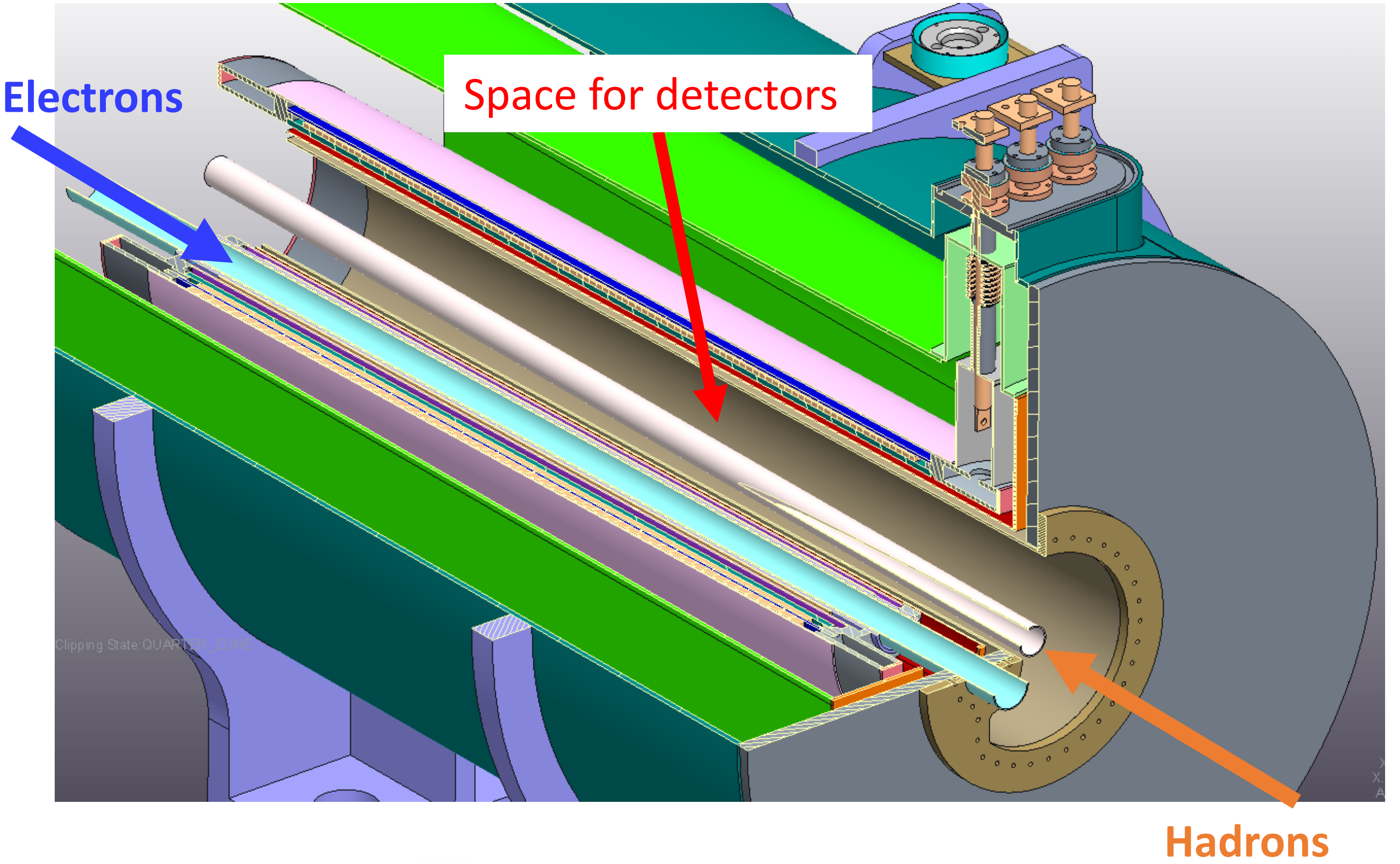




B0 Detectors

- Charged particle reconstruction and photon tagging.
  - Precise tracking (~10um spatial resolution).
  - Fast timing for background rejection and to remove crab smearing (~35ps).
  - Photon detection (tagging or full reco).



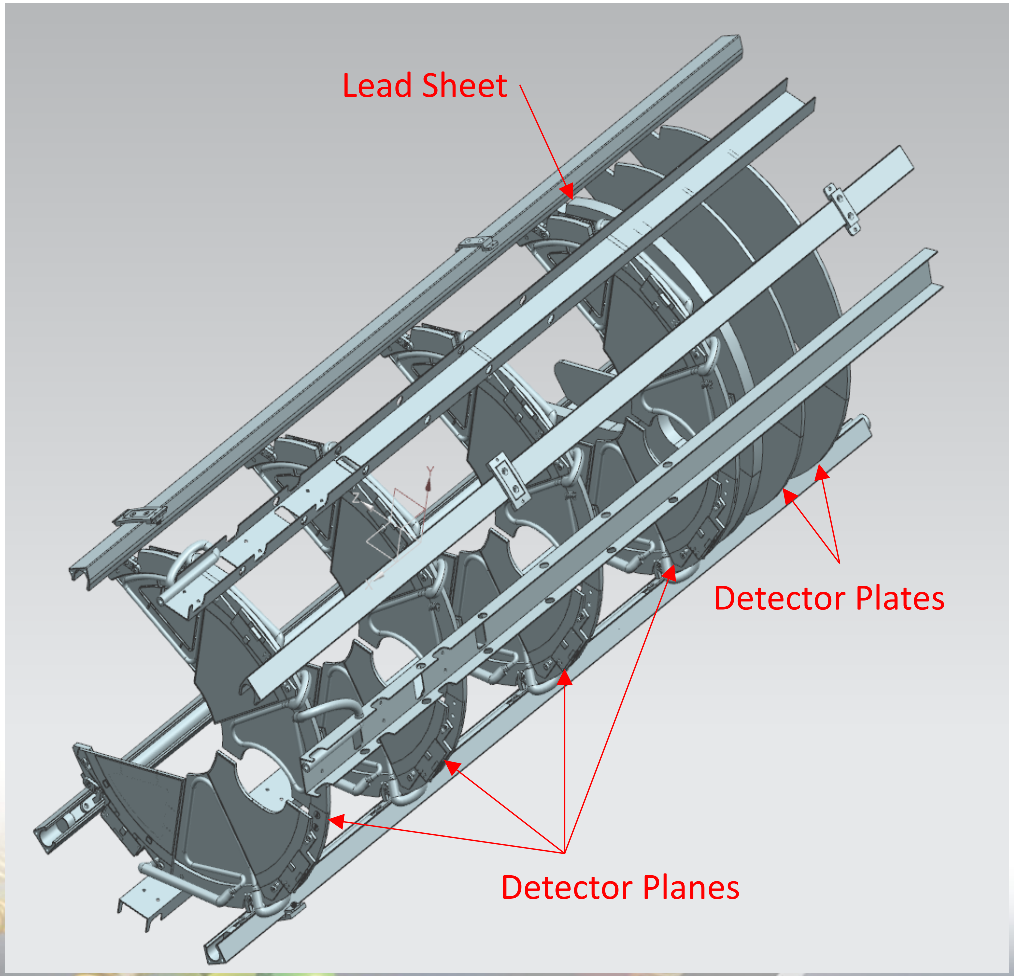


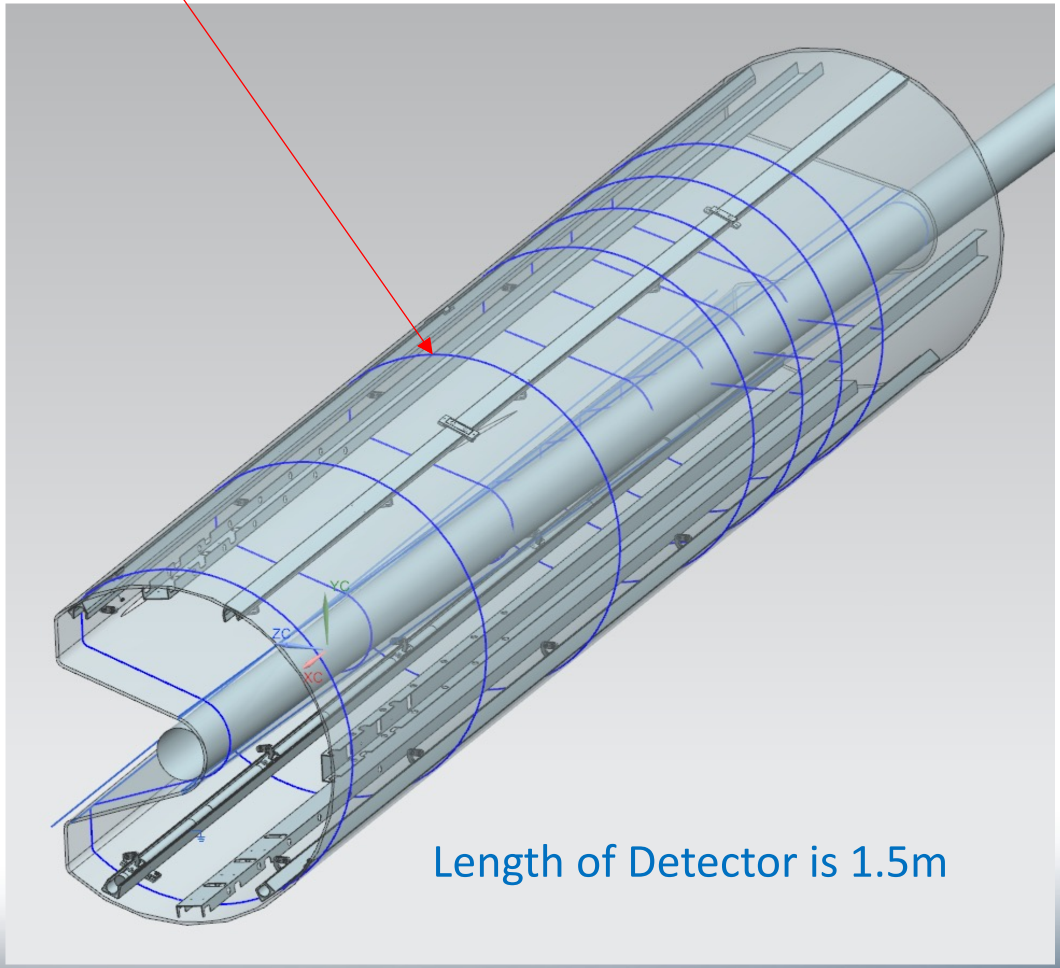
This is the opening where the detector planes will be inserted

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

B0 Detectors in CAD

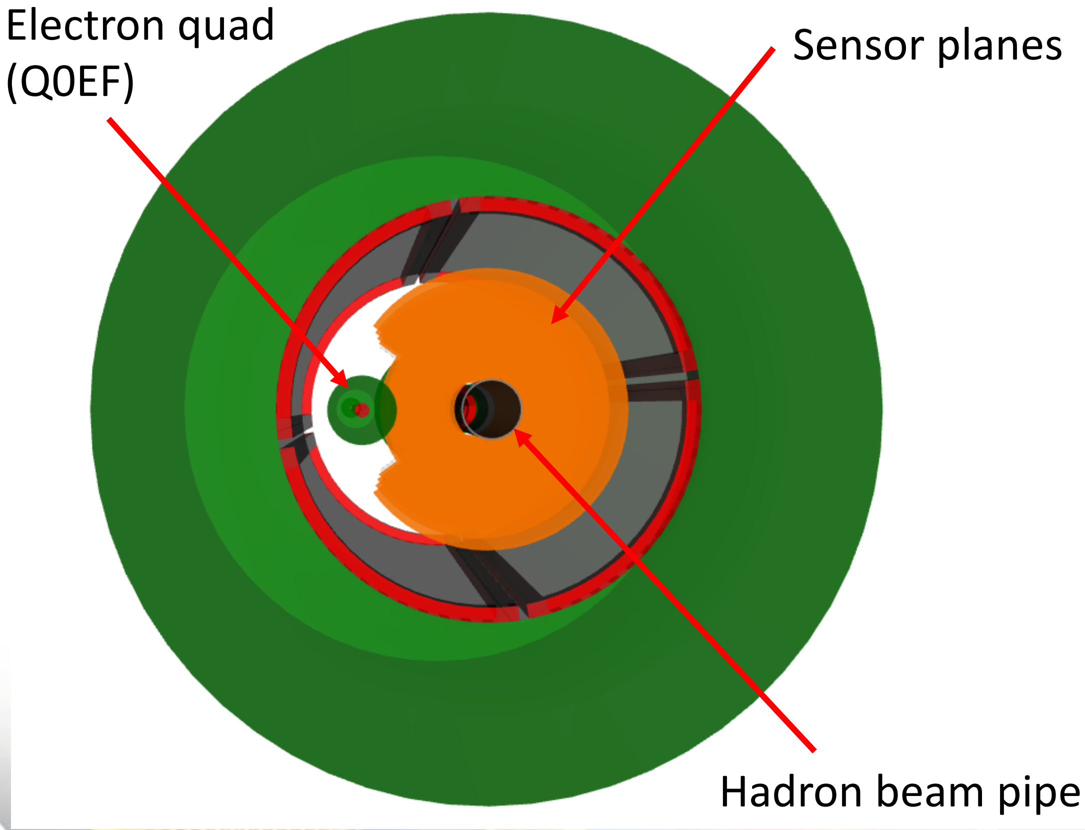
Blue lines represent where element locations are along beamline



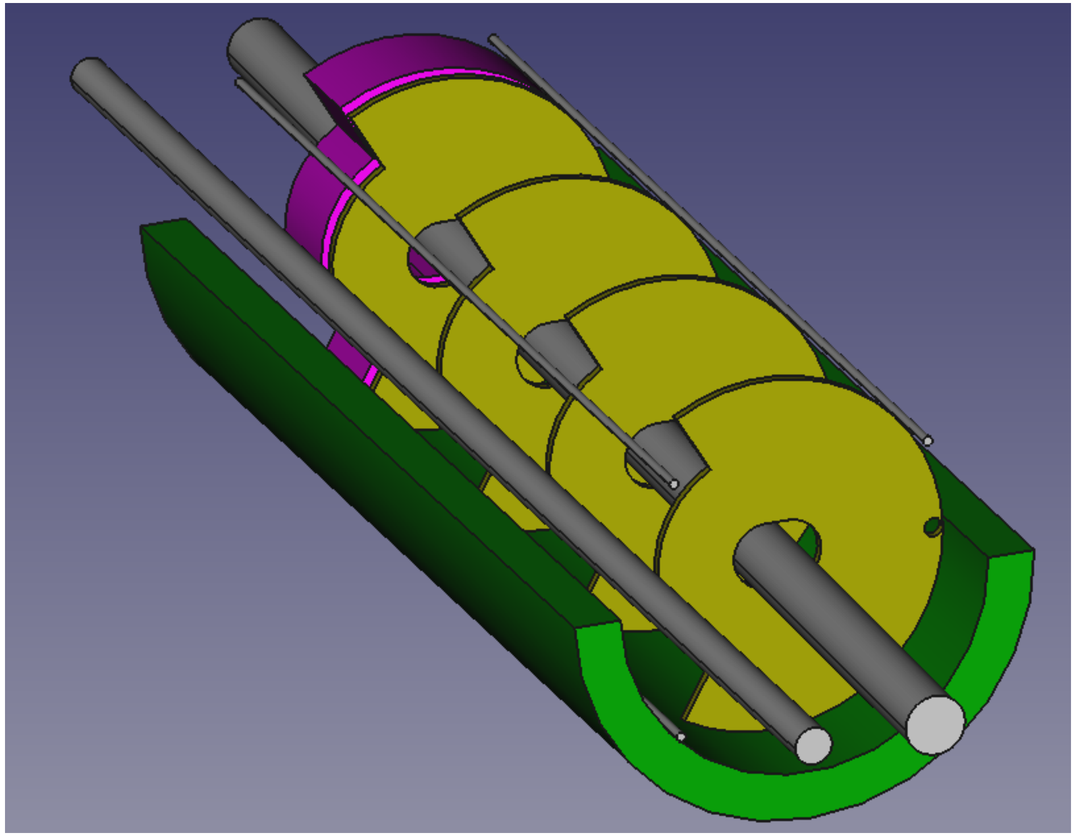


B0-detectors

(5.5 < θ < 20.0 mrad)



DD4HEP Simulation

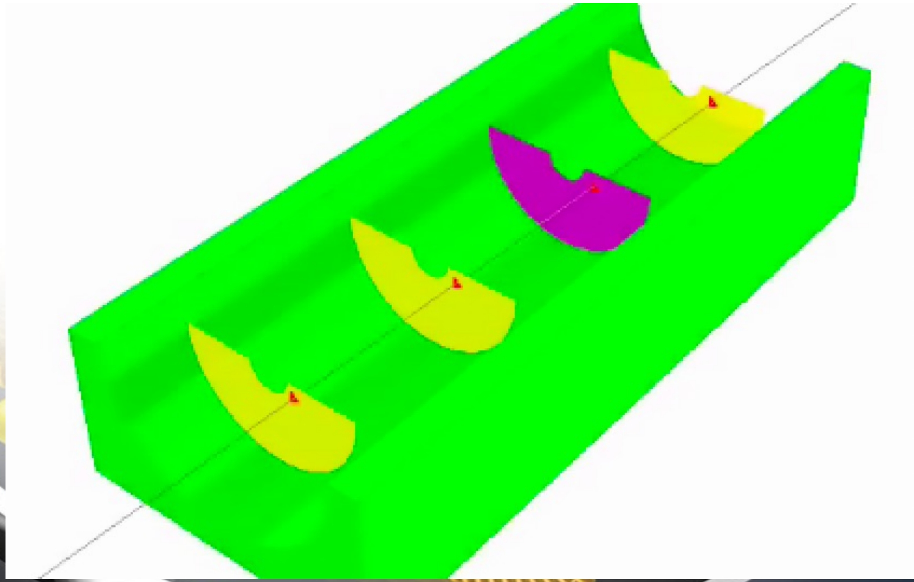


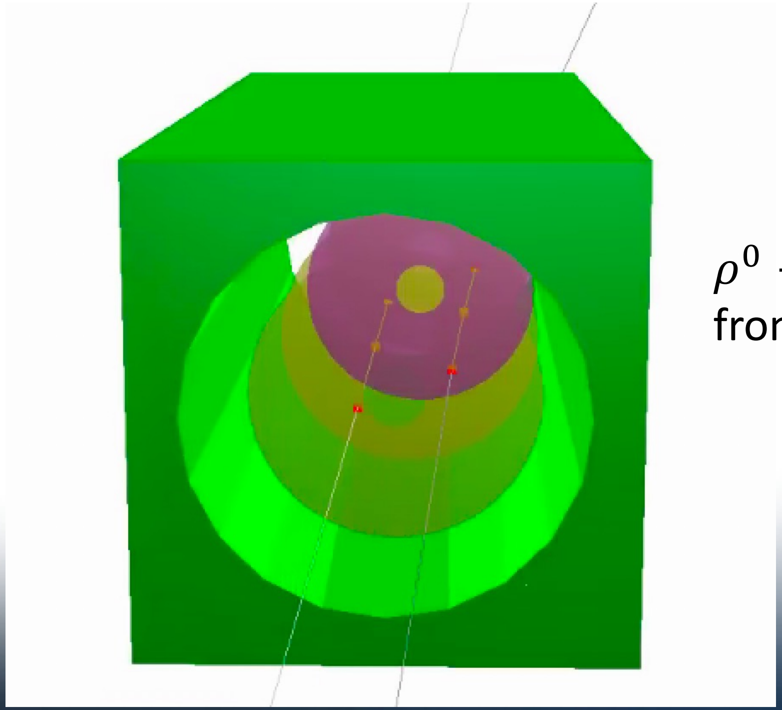
- Higher granularity silicon (e.g. MAPS) required.
- Tagging photons important in differentiating between coherent and incoherent heavy-nuclear scattering, and for reconstructing $\pi^0 \rightarrow \gamma\gamma$.
  - **Space is a major concern here – an EMCAL is highly preferred, but may only have space for a preshower.**

Why are the B0 detectors useful?

- 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.
- Calorimetry needed for backward u-channel DVCS measurements.

GEANT simulation: 100 GeV proton



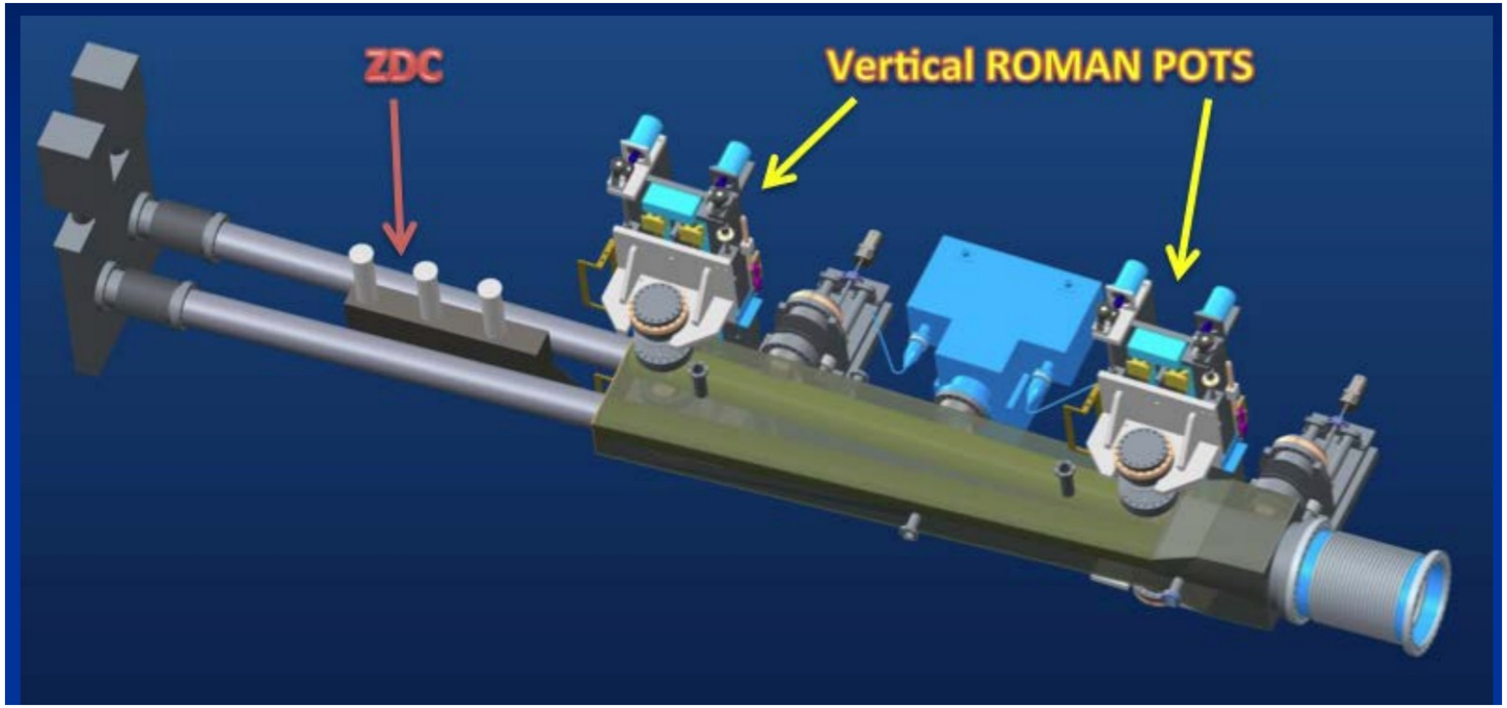


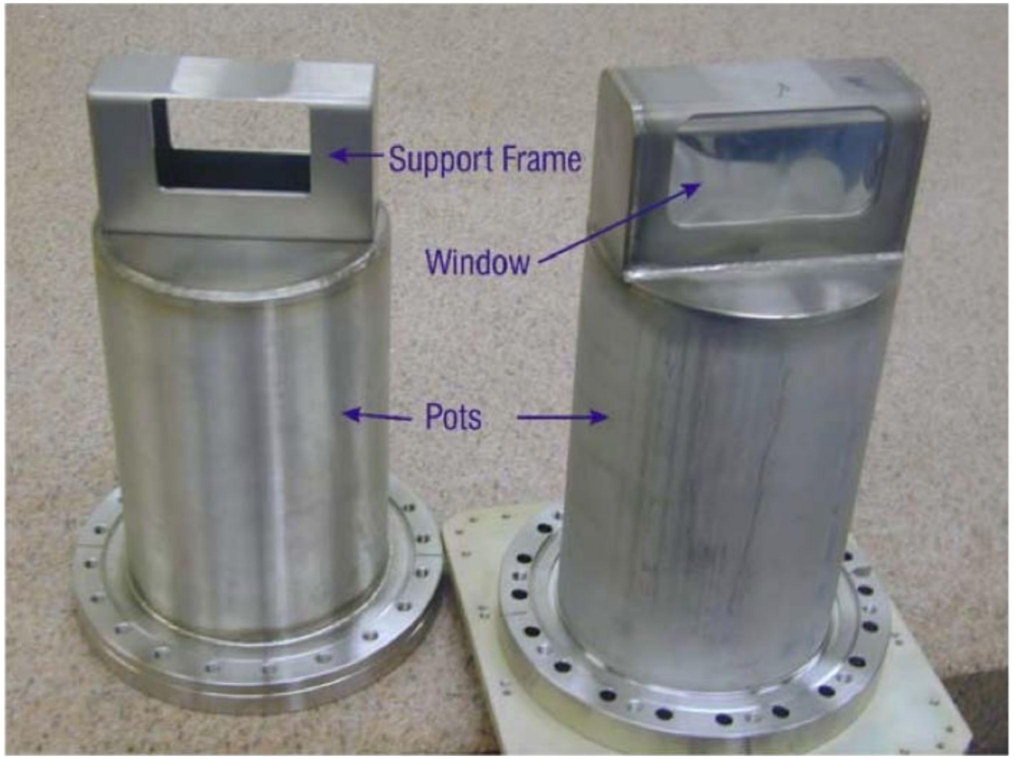
$\rho^0 \rightarrow \pi^+\pi^-$ decay
from u-channel production

Roman Pots

- Place roman pottery into the particle accelerator → learn the deep mysteries of the universe?

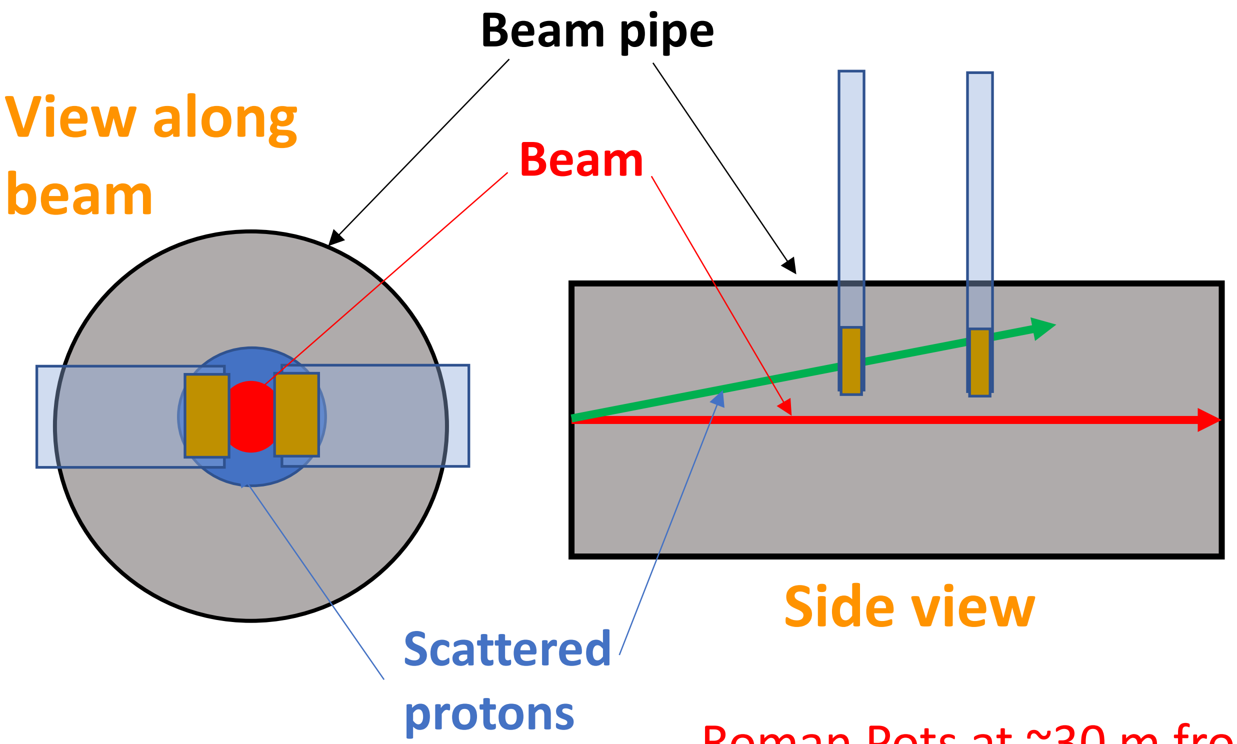
Roman Pots





Roman pots at STAR – used to measure p+p elastic scattering.

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

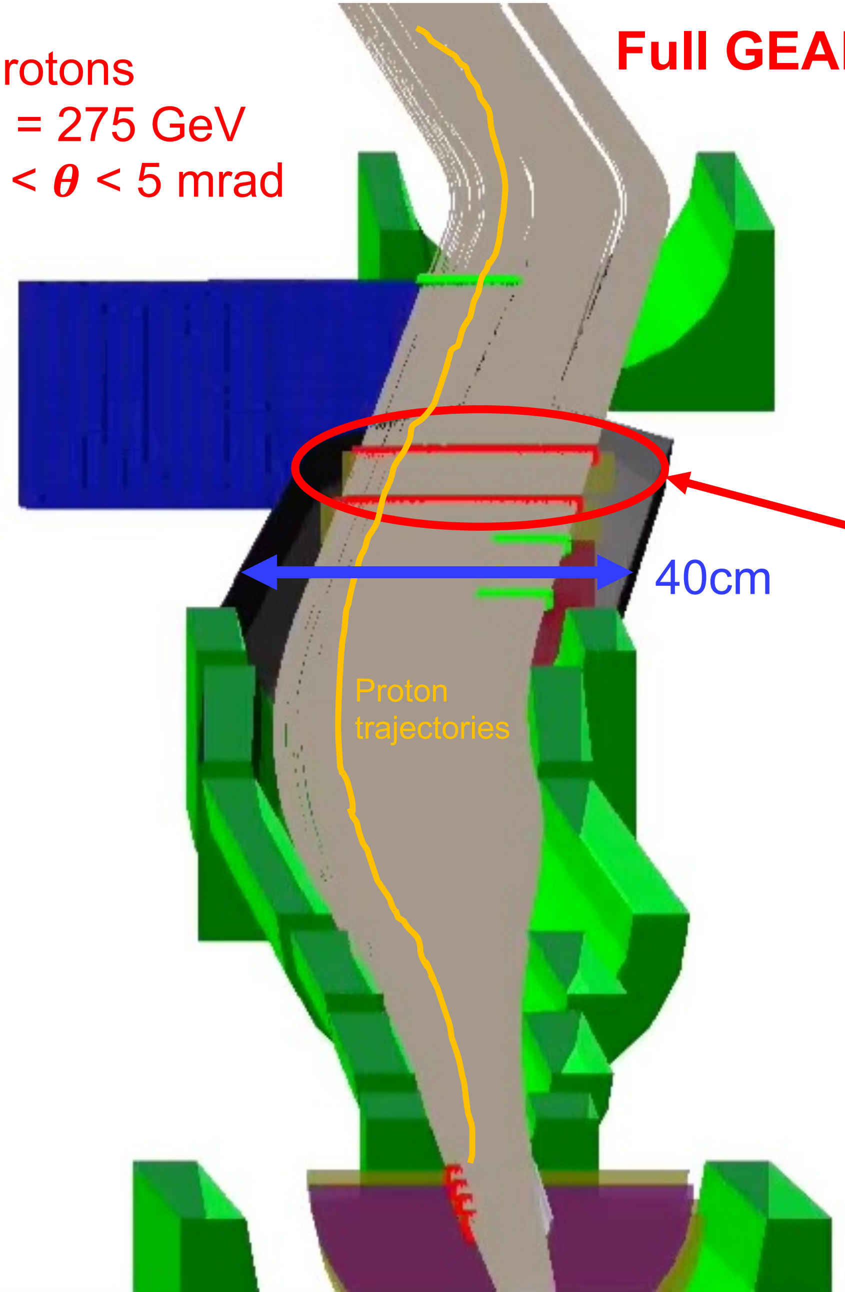
Roman Pots at ~30 m from IP → $\theta \backsim$ 0 - 5 mrad

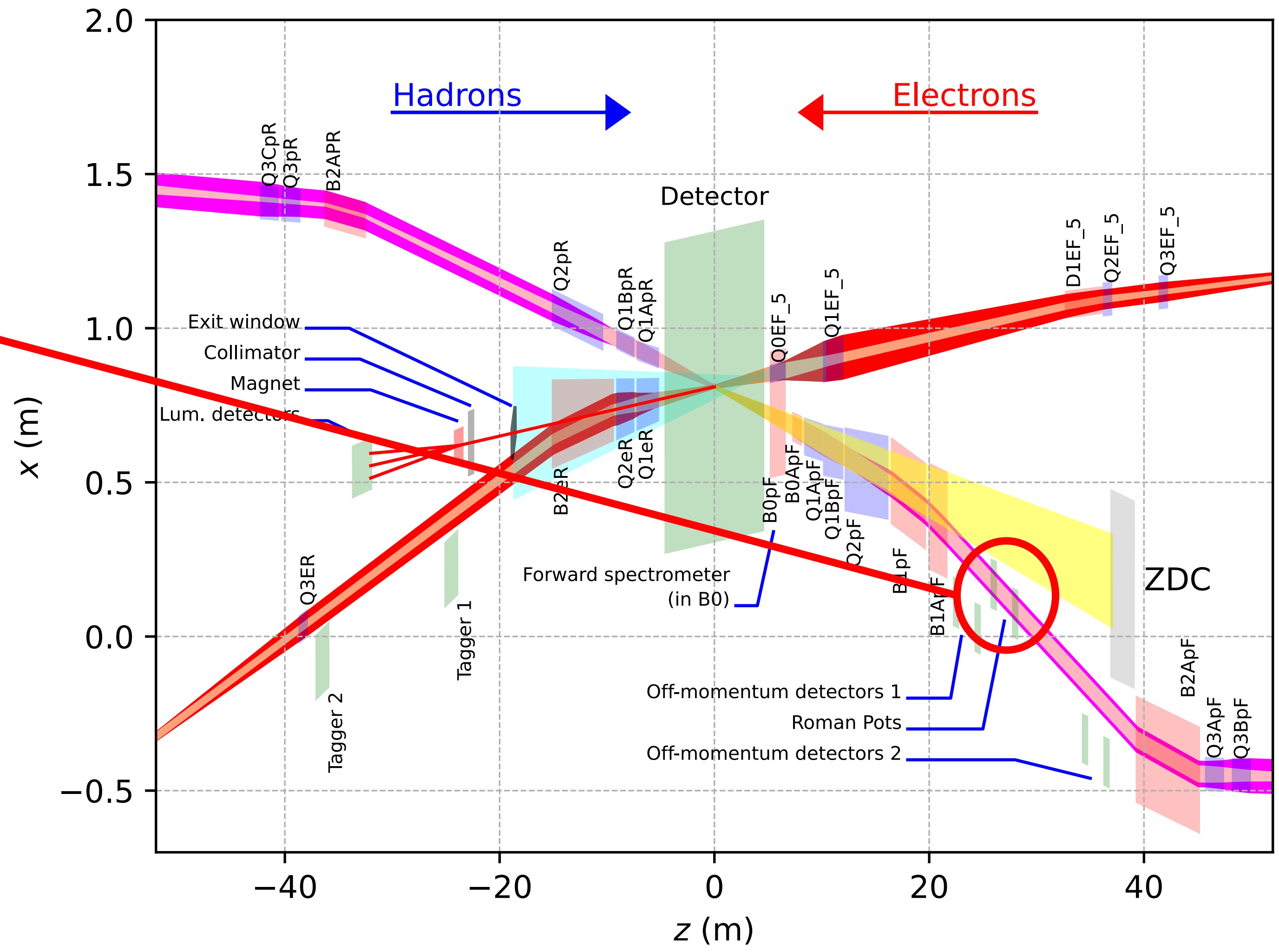
- Roman Pots are silicon sensors placed in a “pot”, which is then injected into the beam pipe, tens of meters or more from the interaction point (IP).
- Momentum reconstruction carried out using matrix transport of protons through magnetic lattice.

Roman Pots @ the EIC

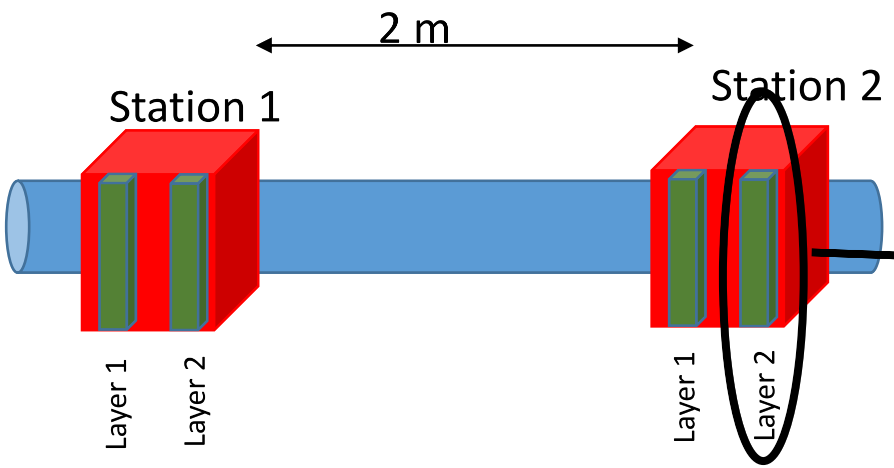
Protons
E = 275 GeV
$0 < \theta < 5$ mrad

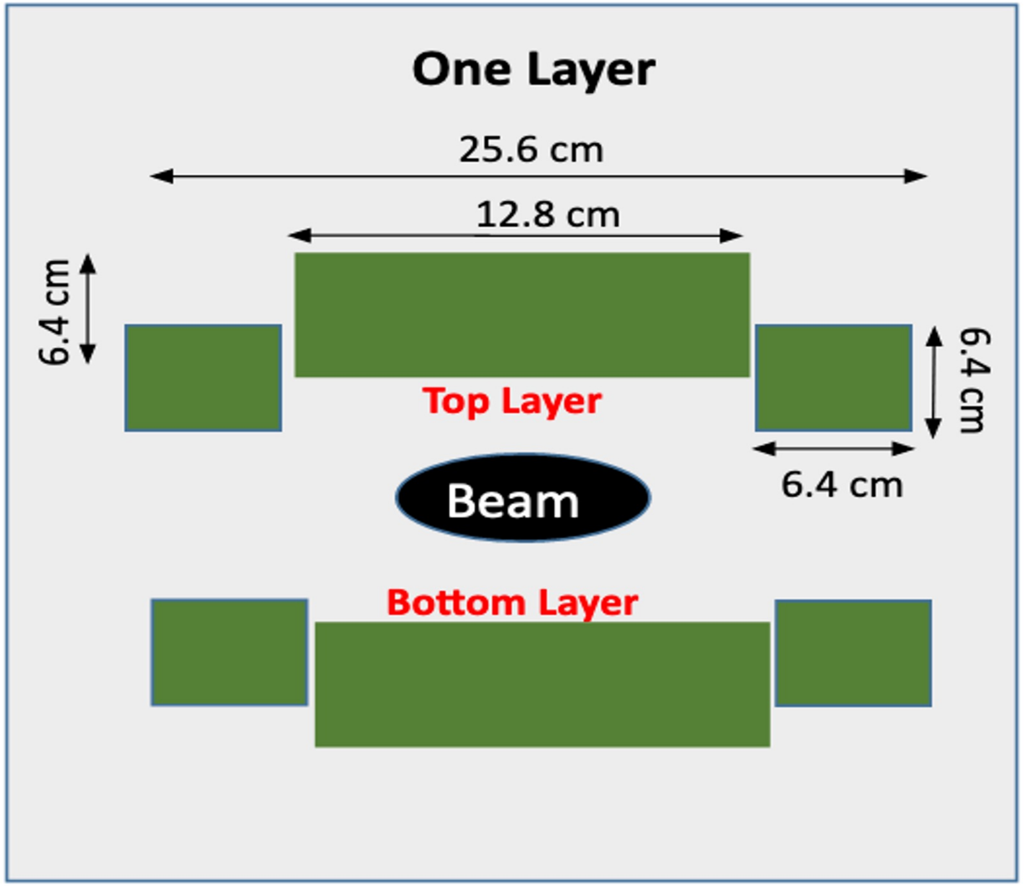
Full GEANT4 simulation.





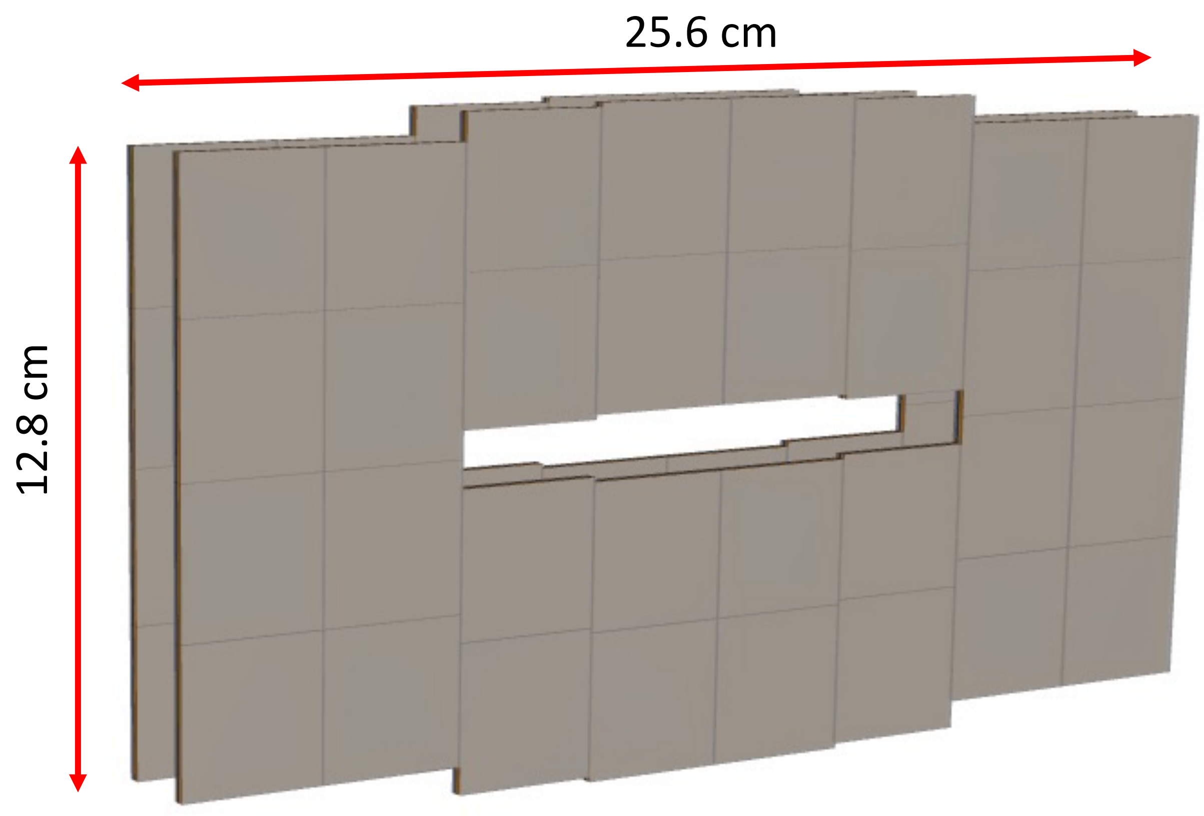
Roman "Pots" @ the EIC



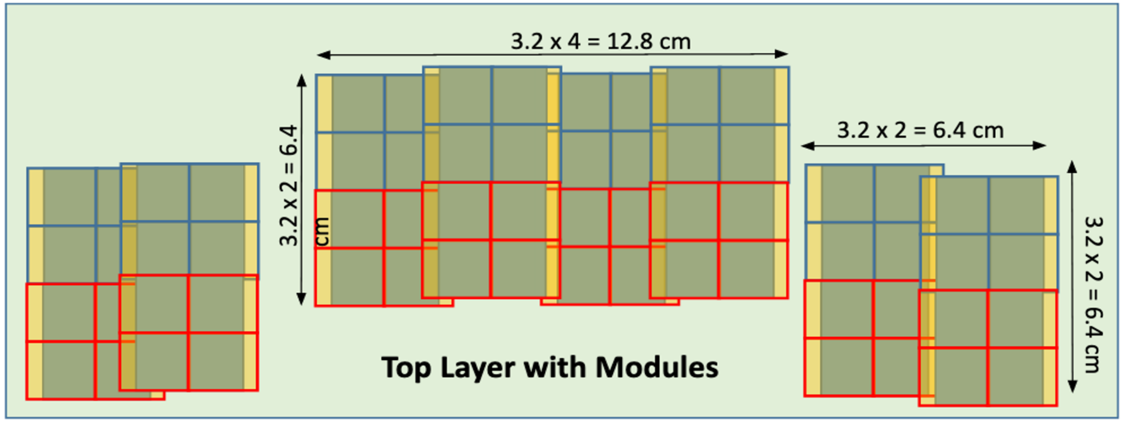


- Two stations, separated by 2 meters, each with two layers (minimum) of silicon detectors.
- Silicon detectors placed directly into machine vacuum!
  - Allows maximal geometric coverage!
- Need space for detector insertion tooling and support structure.

Roman "Pots" @ the EIC

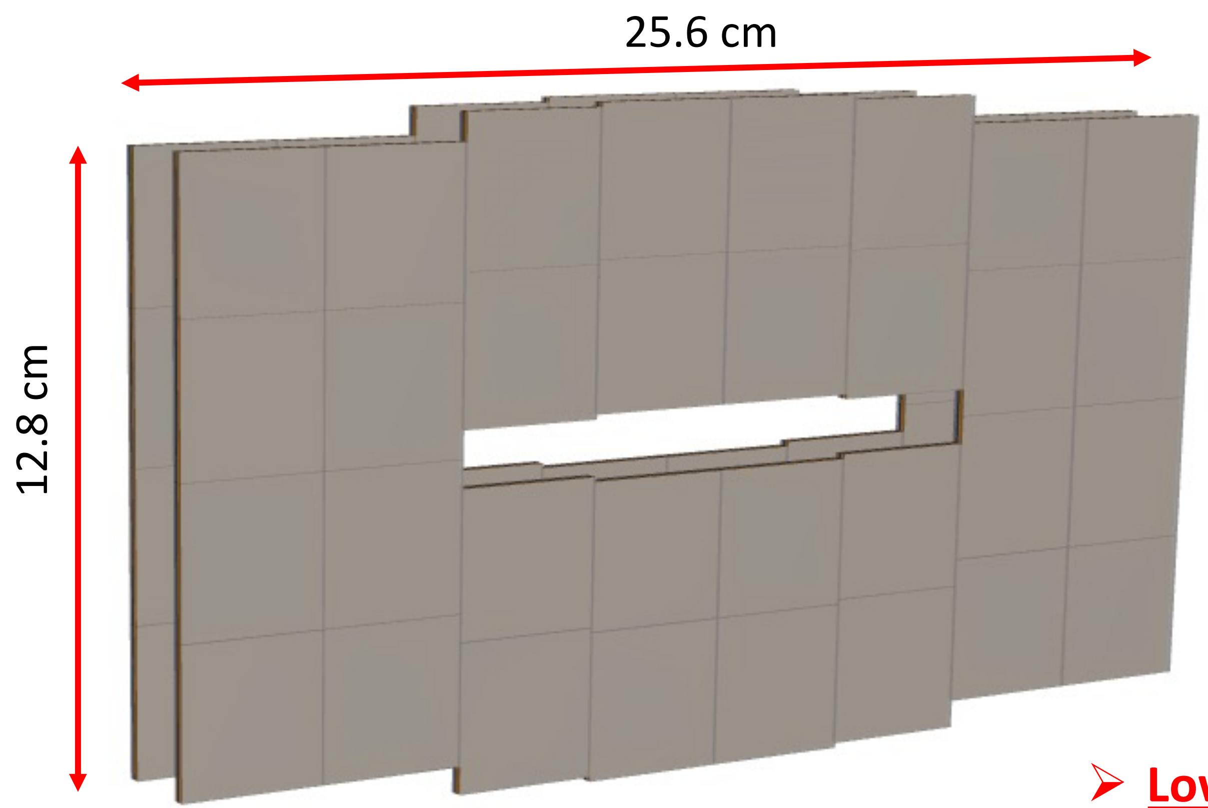


DD4HEP Simulation



- <u>**Two main options**</u>
  - ➢ AC-LGAD sensor provides both fine pixilation (~140um spatial resolution), and fast timing (~35ps).
  - ➢ MAPS + LYSO timing layer.
- "Potless" design concept with thin RF foils surrounding detector components.

Roman "Pots" @ the EIC

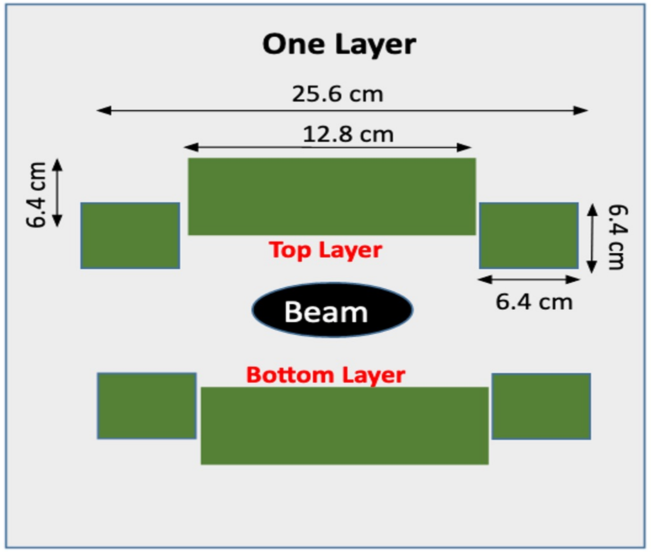


DD4HEP Simulation

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

ε is the beam emittance.

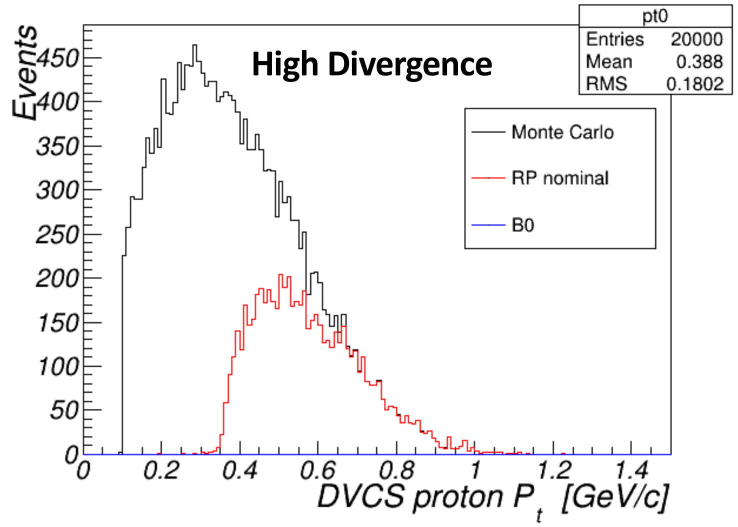
$$\sigma(z) = \sqrt{\varepsilon \cdot \beta(z))}$$

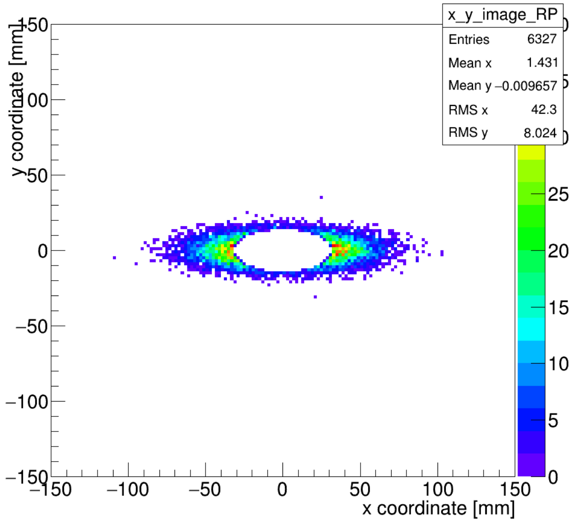


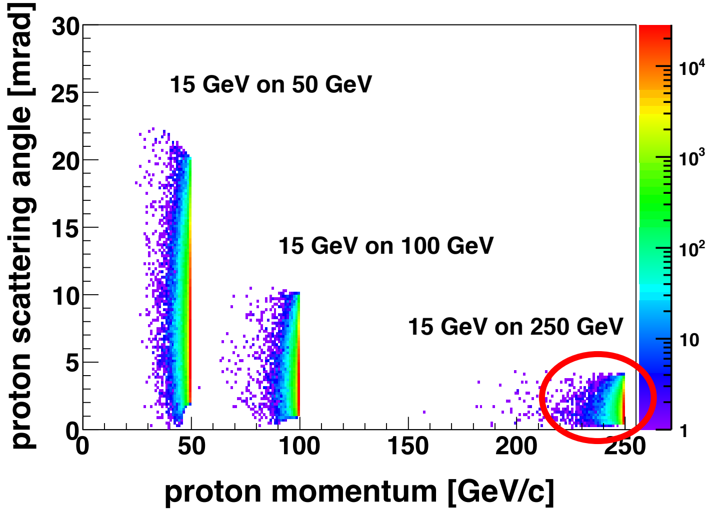
- **<u>Low-pT cutoff determined by beam optics.</u>**
  - **The safe distance is ~10σ from the beam center.**
  - **1σ ~ 1mm**
- **These optics choices change with energy, but can also be changed within a single energy to maximize *either acceptance at the RP, or the luminosity*.**

Digression: Machine Optics

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

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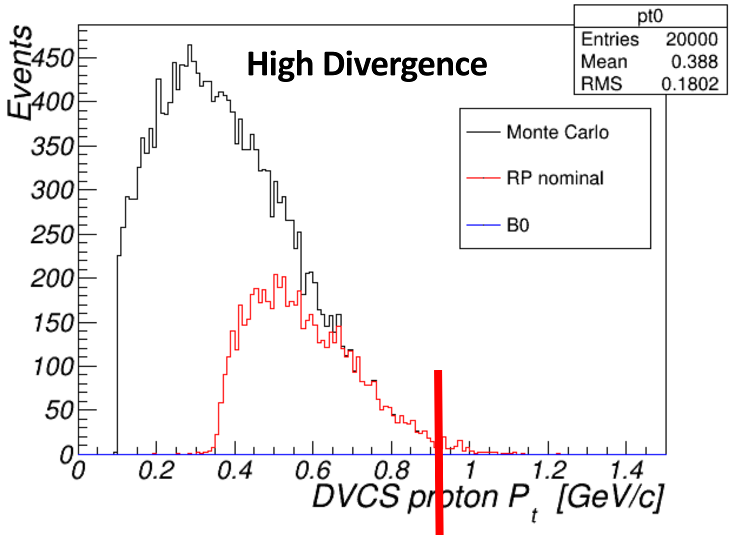

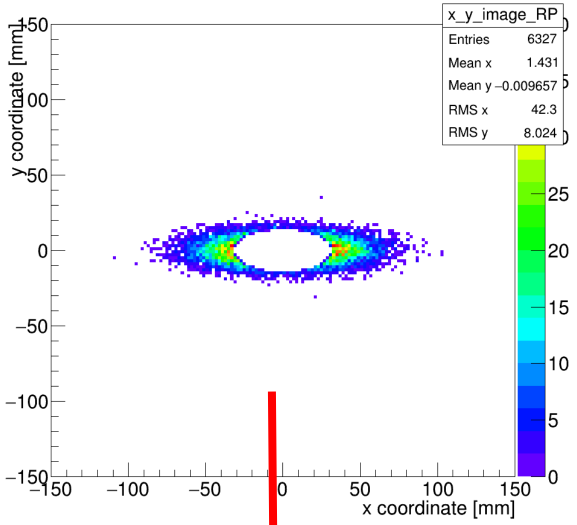

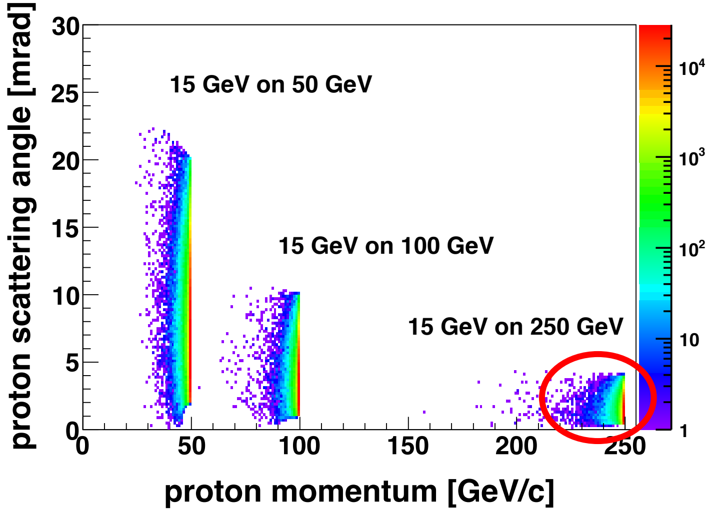

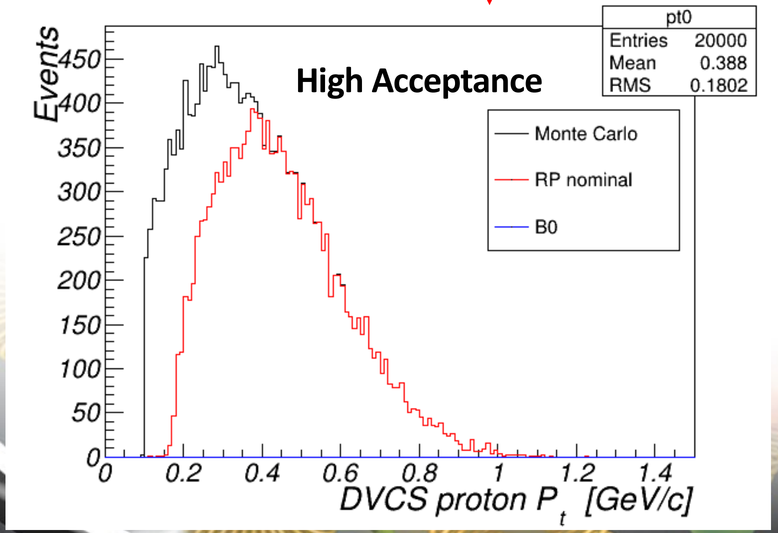

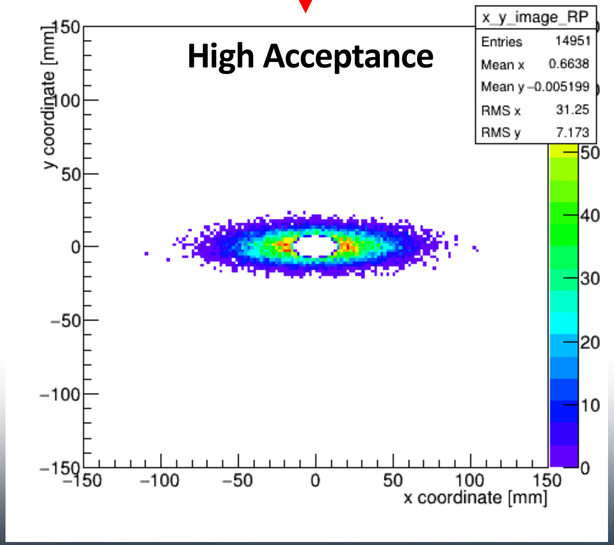

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High Acceptance: larger β^* at IP, smaller $\beta(z = 30m)$ -> lower lumi., smaller beam at RP

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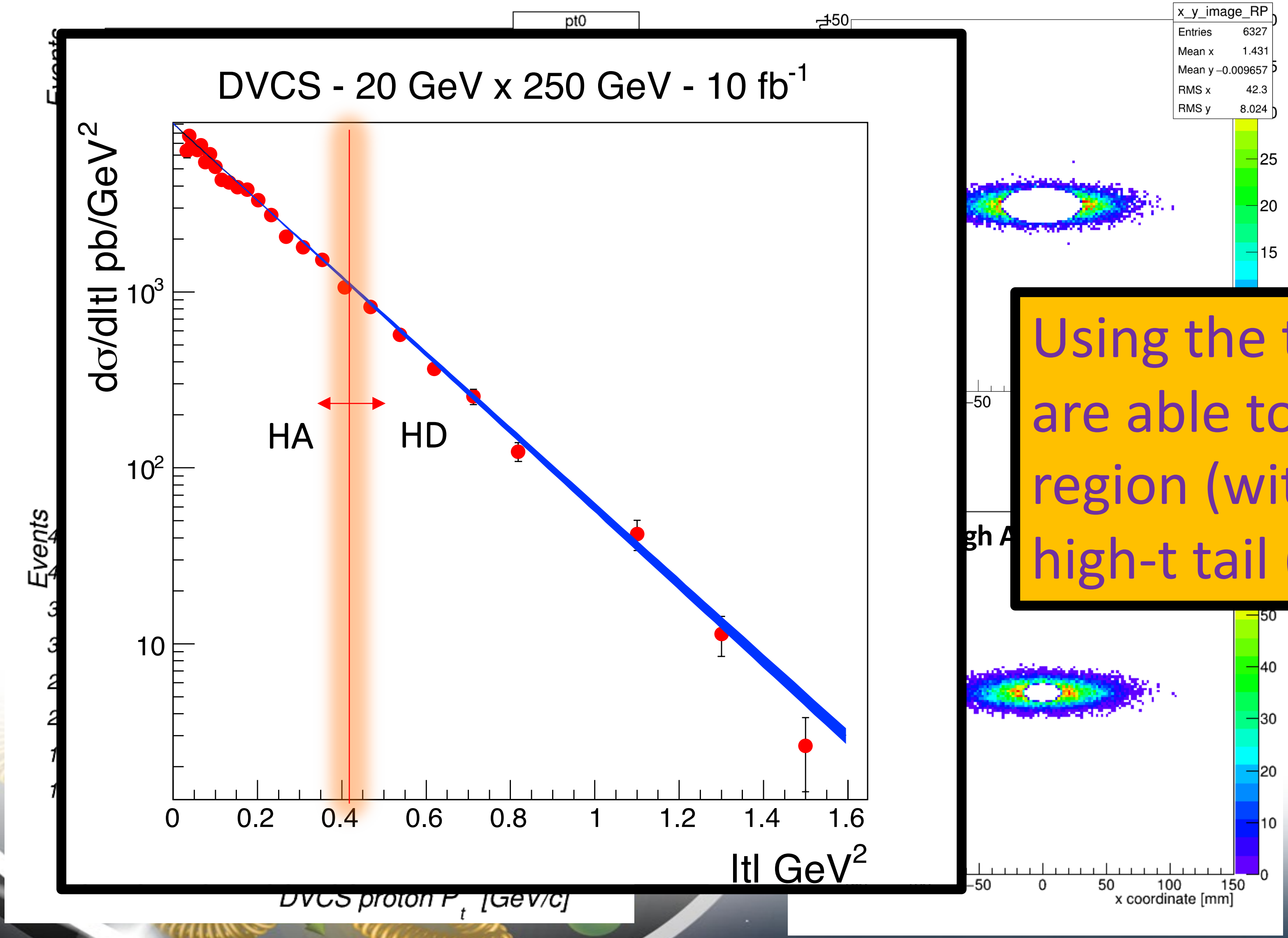
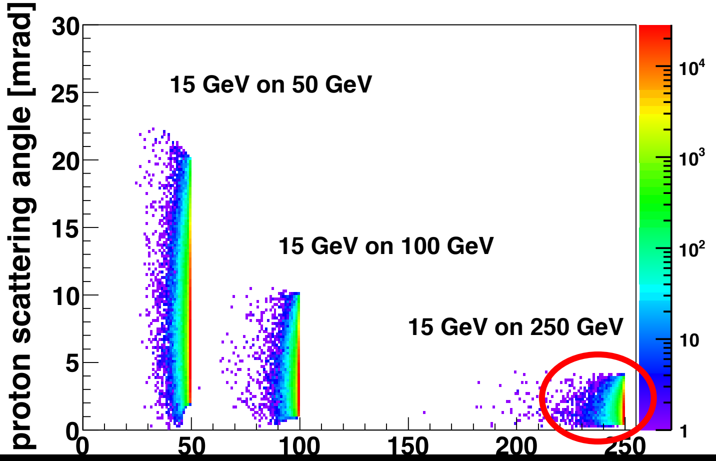


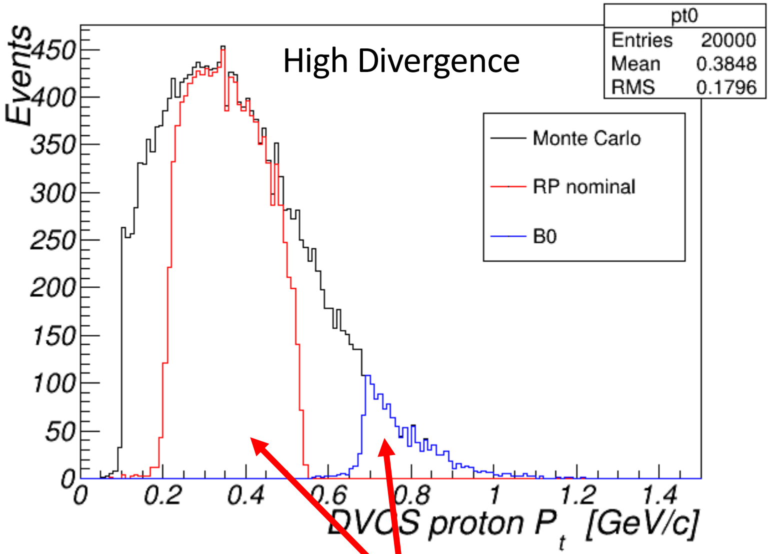


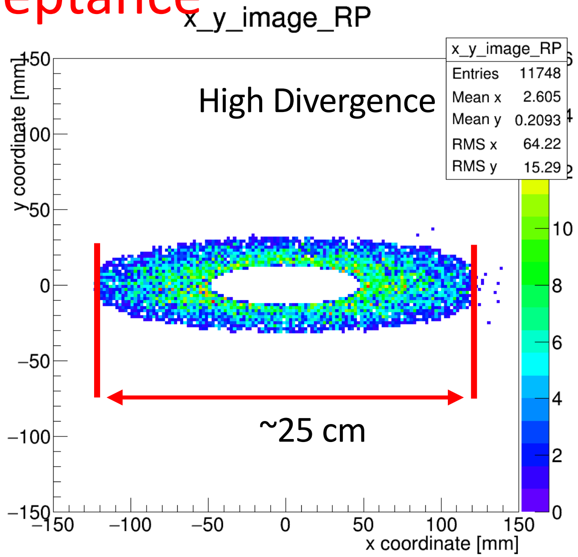
Using the two configurations, we are able to measure the low-t region (with better acceptance) and high-t tail (with higher luminosity).

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

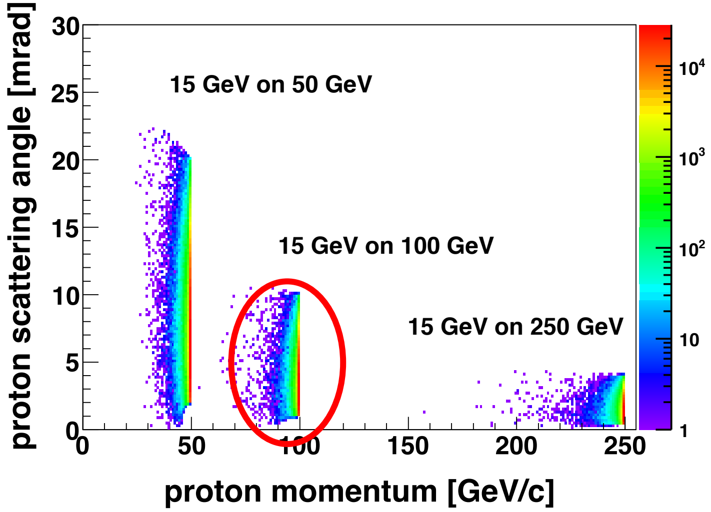
Digression: Machine Optics

100 GeV DVCS Proton Acceptance



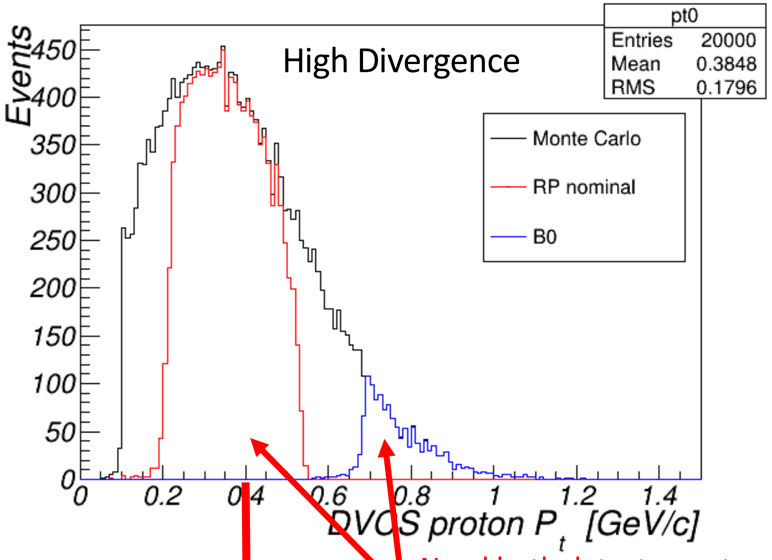


Need both detector systems together here!

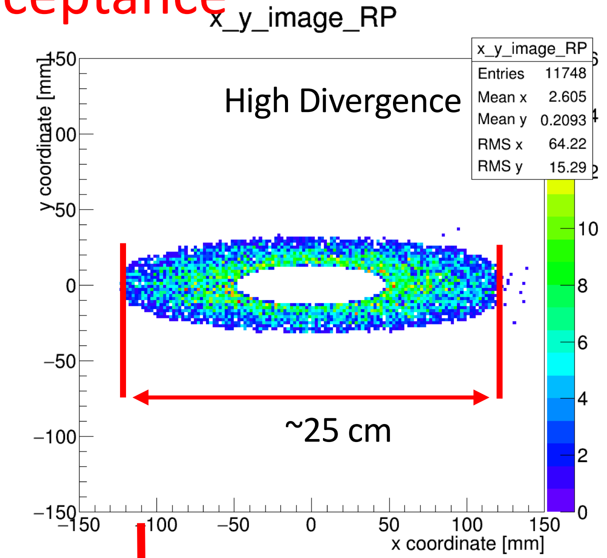


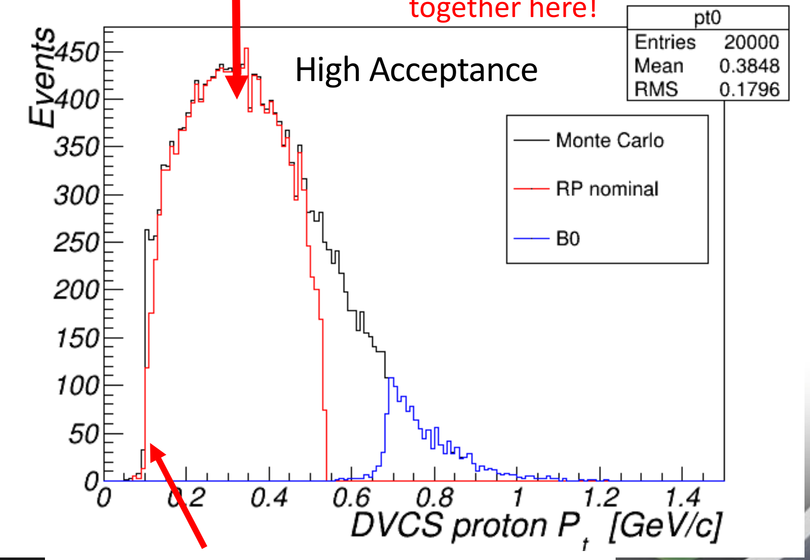
Digression: Machine Optics

100 GeV DVCS Proton Acceptance

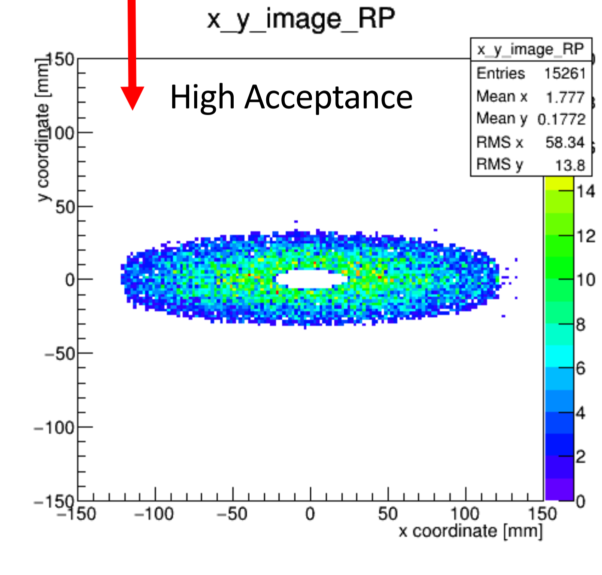


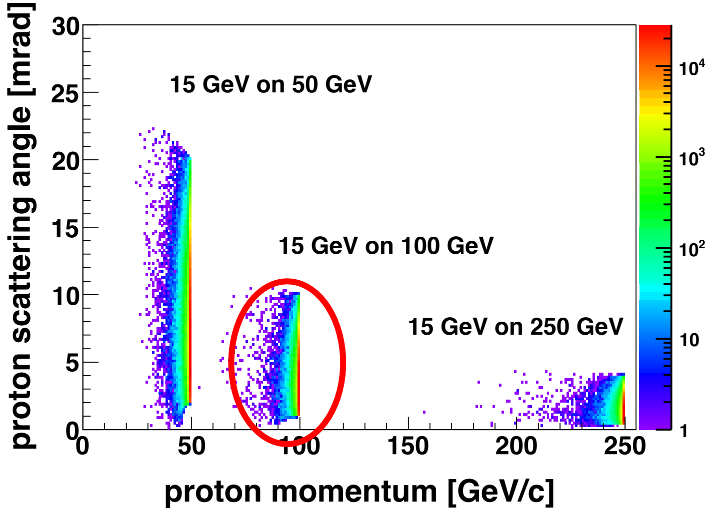
Need both detector systems together here!





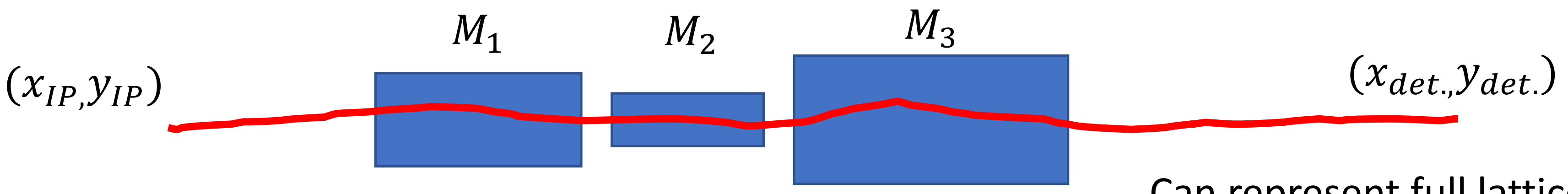
Improves low p_t acceptance.





Momentum Reconstruction with Roman Pots

- Use a matrix which describes the transport of a charged particle trajectory through the magnet lattice.
  - Matrix unique for different positions along the beam-axis (s)!
  - Transforms coordinates at detectors (position, angle) to original IP coordinates.
  - Proper usage assumes a reference orbit – all calculations MUST be done in that coordinate system!



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

Can represent full lattice with a single "transfer matrix" (also called "transfer map").

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

x_0, y_0: Position at Interaction Point

Θ^*_x, Θ^*_y: Scattering Angle at IP

x_D, y_D : Position at Detector

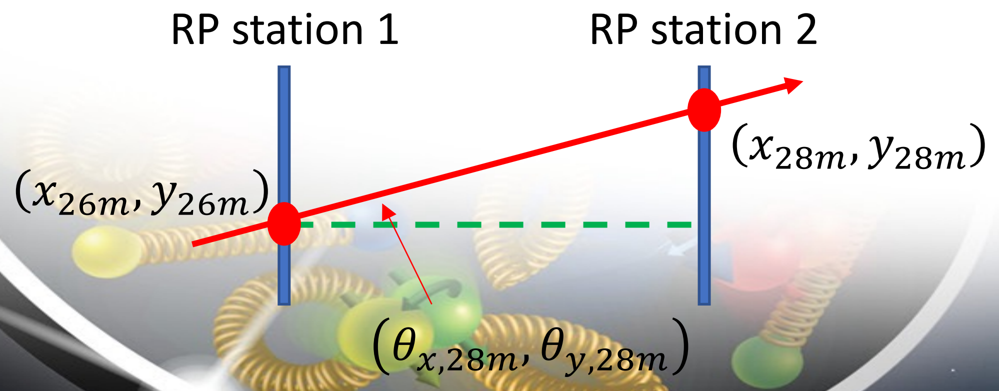
Θ^x_D, Θ^y_D : Angle at Detector

Momentum Reconstruction with Roman Pots

From BMAD!

$$\begin{pmatrix} 1.88481537 & 28.96766544 & 0.0000 & 0.0000 & 0.0000 & 0.24906255 \\ -0.02114673 & 0.20555261 & 0.0000 & 0.0000 & 0.0000 & -0.03322467 \\ 0.0000 & 0.0000 & -2.25541901 & 3.78031509 & 0.0000 & 0.0000 \\ 0.0000 & 0.0000 & -0.17782524 & -0.14532313 & 0.0000 & 0.0000 \\ 0.05735551 & 1.01363652 & 0.0000 & 0.0000 & 1.0000 & 0.02568709 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 1.0000 \end{pmatrix} \begin{pmatrix} x_{ip} \\ \theta_{xip} \\ y_{ip} \\ \theta_{yip} \\ z_{ip} \\ \Delta p/p \end{pmatrix} = \begin{pmatrix} x_{28m} \\ \theta_{x,28m} \\ y_{28m} \\ \theta_{y28m} \\ z_{28m} \\ \Delta p/p \end{pmatrix}$$

- Able to benchmark transport through lattice using machine codes, and comparing with what GEANT produces (e.g. what we calculate ”by hand” with GEANT).
  - The machine magnet code is called MAD-X or BMAD.
- **Question: what happens when our measured trajectory deviates too much from the reference orbit?**



$$(1.88)x_{ip}+(28.97)\theta_{xip} + (0.249)\frac{\Delta p}{p} = x_{28m}$$

… Etc.

$$(-0.0211)x_{ip} + (0.206)\theta_{xip} + (-0.033)\frac{\Delta p}{p} = \theta_{x,28m}$$

Momentum Reconstruction with Roman Pots

From BMAD!

$$\begin{pmatrix} 1.88481537 & 28.96766544 & 0.0000 & 0.0000 & 0.0000 & 0.24906255 \\ -0.02114673 & 0.20555261 & 0.0000 & 0.0000 & 0.0000 & -0.03322467 \\ 0.0000 & 0.0000 & -2.25541901 & 3.78031509 & 0.0000 & 0.0000 \\ 0.0000 & 0.0000 & -0.17782524 & -0.14532313 & 0.0000 & 0.0000 \\ 0.05735551 & 1.01363652 & 0.0000 & 0.0000 & 1.0000 & 0.02568709 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 1.0000 \end{pmatrix} \begin{pmatrix} x_{ip} \\ \theta_{xip} \\ y_{ip} \\ \theta_{yip} \\ z_{ip} \\ \Delta p/p \end{pmatrix} = \begin{pmatrix} x_{28m} \\ \theta_{x,28m} \\ y_{28m} \\ \theta_{y28m} \\ z_{28m} \\ \Delta p/p \end{pmatrix}$$

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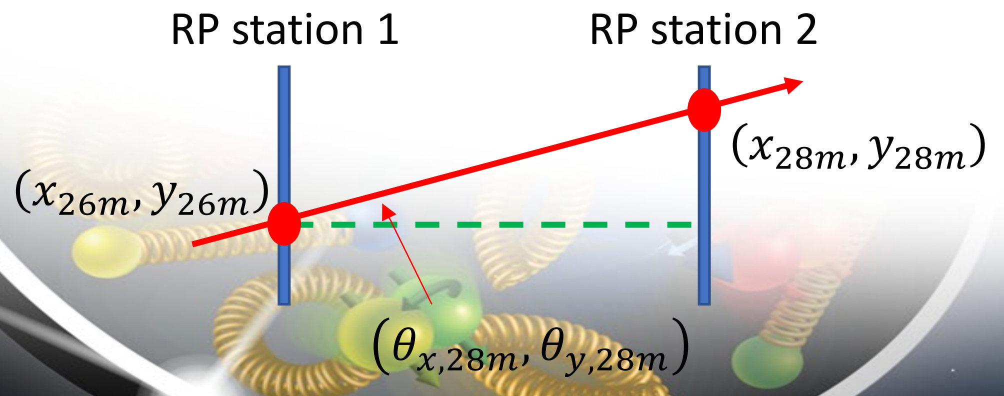


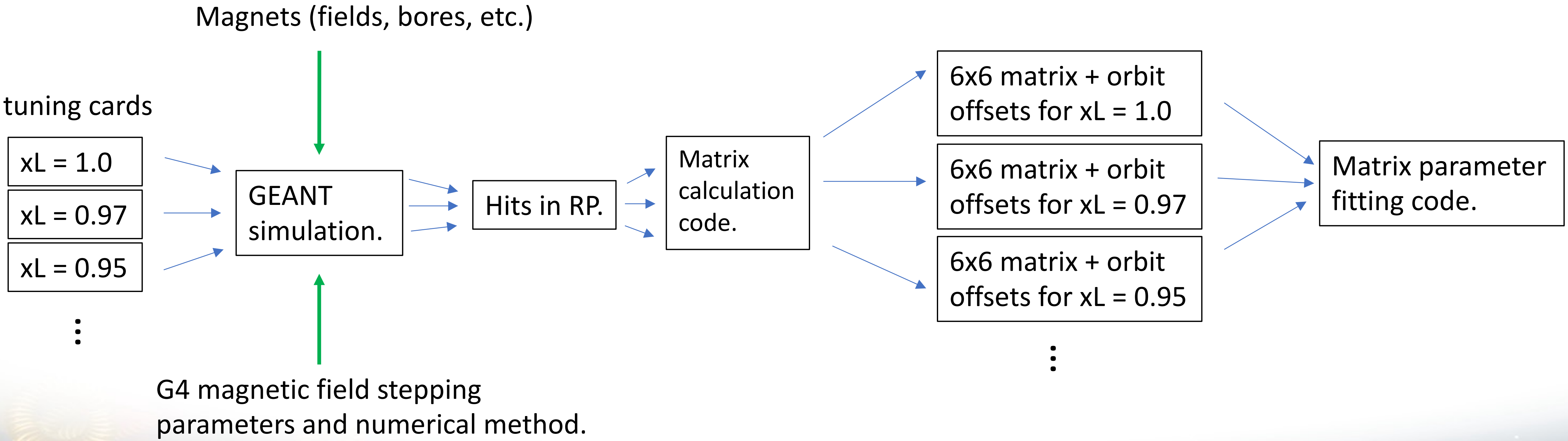
longitudinal momentum fraction

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

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

A Simplistic General Method

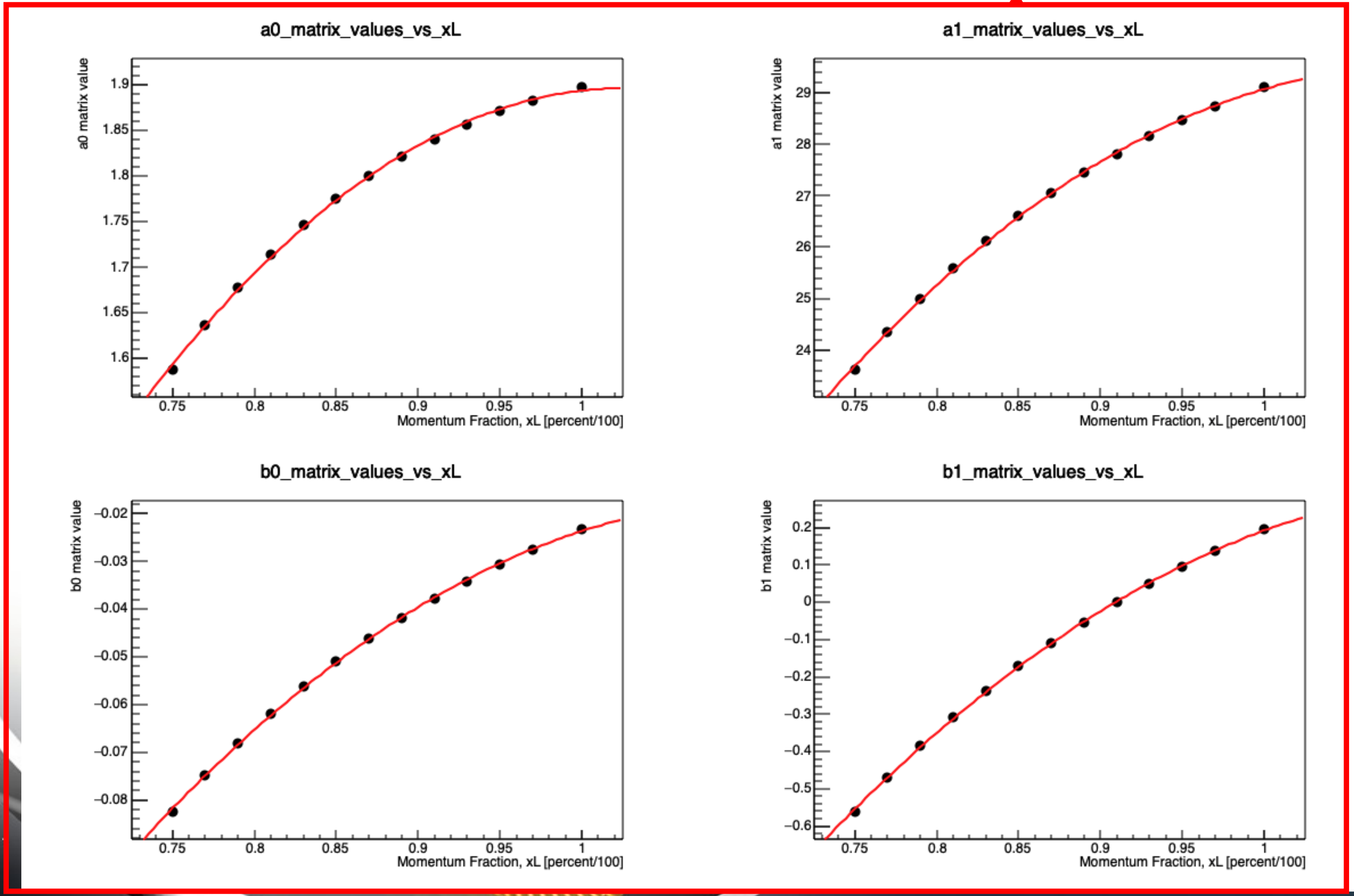
- Begin with a set of “input tuning cards” which contain many reference trajectories for calculating the matrices.



A Simplistic General Method

- Plot the 36 matrix values (and 4 offsets) as a function of xL.
- Fit the resulting plots with 2nd-degree polynomials.

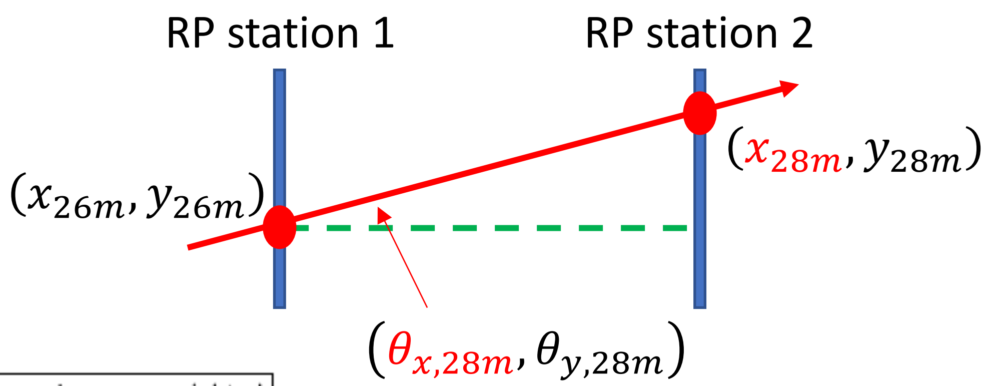
1.88481537	28.96766544	0.0000	0.0000	0.0000	0.24906255
−0.02114673	0.20555261	0.0000	0.0000	0.0000	−0.03322467
0.0000	0.0000	−2.25541901	3.78031509	0.0000	0.0000
0.0000	0.0000	−0.17782524	−0.14532313	0.0000	0.0000
0.05735551	1.01363652	0.0000	0.0000	1.0000	0.02568709
0.0000	0.0000	0.0000	0.0000	0.0000	1.0000

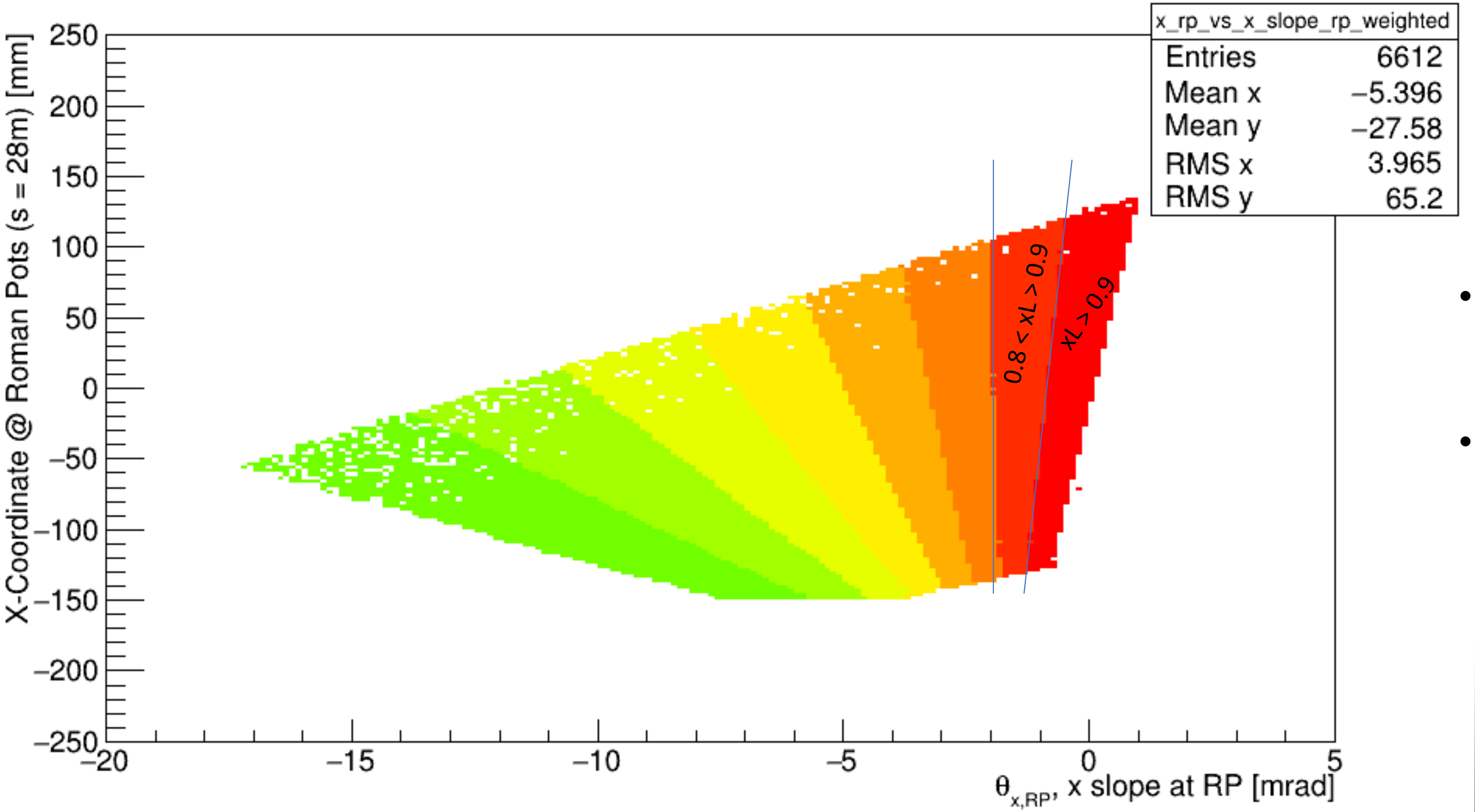


- The 40 fit functions (36 matrix parameters + 4 offsets) then represent the ingredients to calculate the needed matrix in real-time at reconstruction.
- All that is needed is a lookup table to get the xL value for an event based on the coordinates at the Roman Pots.

A Simplistic General Method

- Extract x_L value from lookup table for the $(\theta_{x,rp}, x_{rp})$ ordered pair.



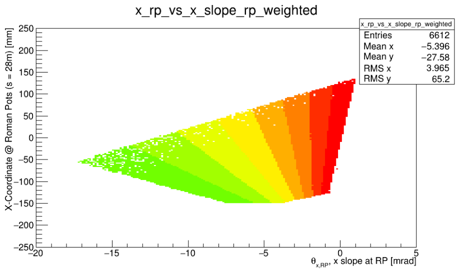


- "Chromaticity plot" serves as a lookup table to use RP coordinates to find the xL value.
- xL is then used to evaluate the correct matrix for reconstruction.

A Simplistic General Method

- Now we can "build" the correct matrix with the correct offset values for a given trajectory and perform our kinematic reconstruction.

Detector "hit" coordinates →



→ Lookup xL → Calculate matrix parameters and offsets from fit equations.

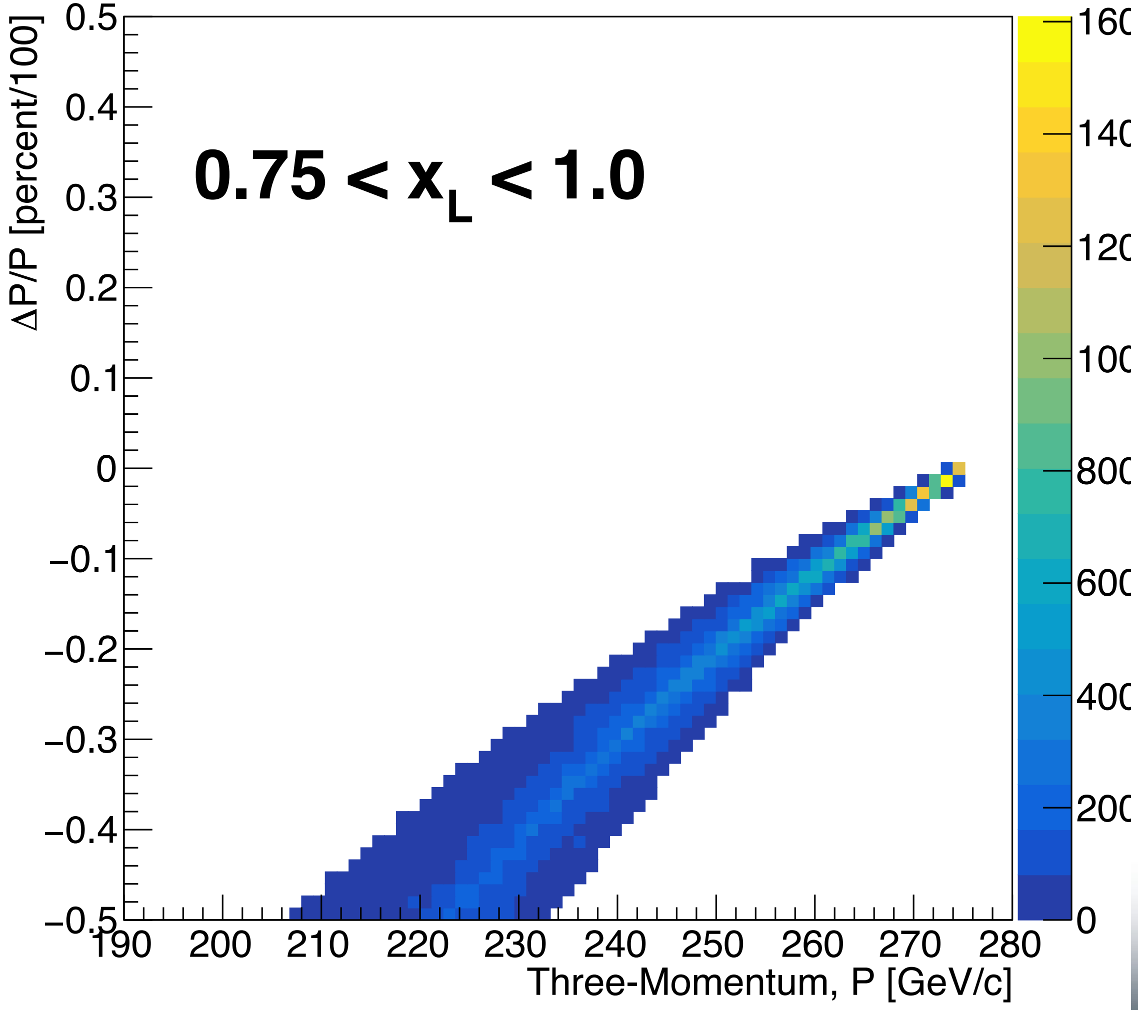
$$\begin{pmatrix} 1.88481537 & 28.96766544 & 0.0000 & 0.0000 & 0.0000 & 0.24906255 \\ -0.02114673 & 0.20555261 & 0.0000 & 0.0000 & 0.0000 & -0.03322467 \\ 0.0000 & 0.0000 & -2.25541901 & 3.78031509 & 0.0000 & 0.0000 \\ 0.0000 & 0.0000 & -0.17782524 & -0.14532313 & 0.0000 & 0.0000 \\ 0.05735551 & 1.01363652 & 0.0000 & 0.0000 & 1.0000 & 0.02568709 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 1.0000 \end{pmatrix}$$

→ Reconstructed momentum vector.

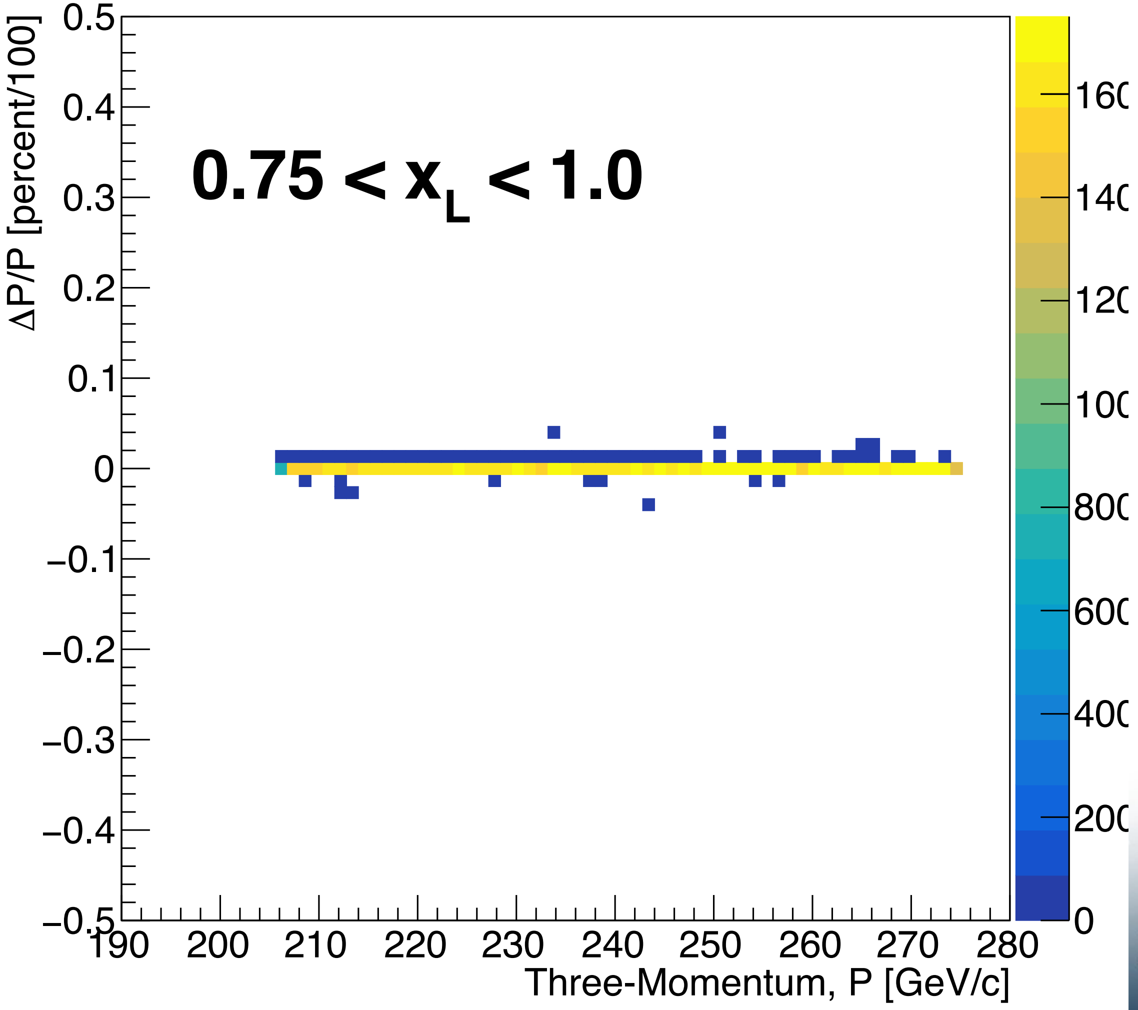
Results - Momentum

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

“static” BMAD matrix



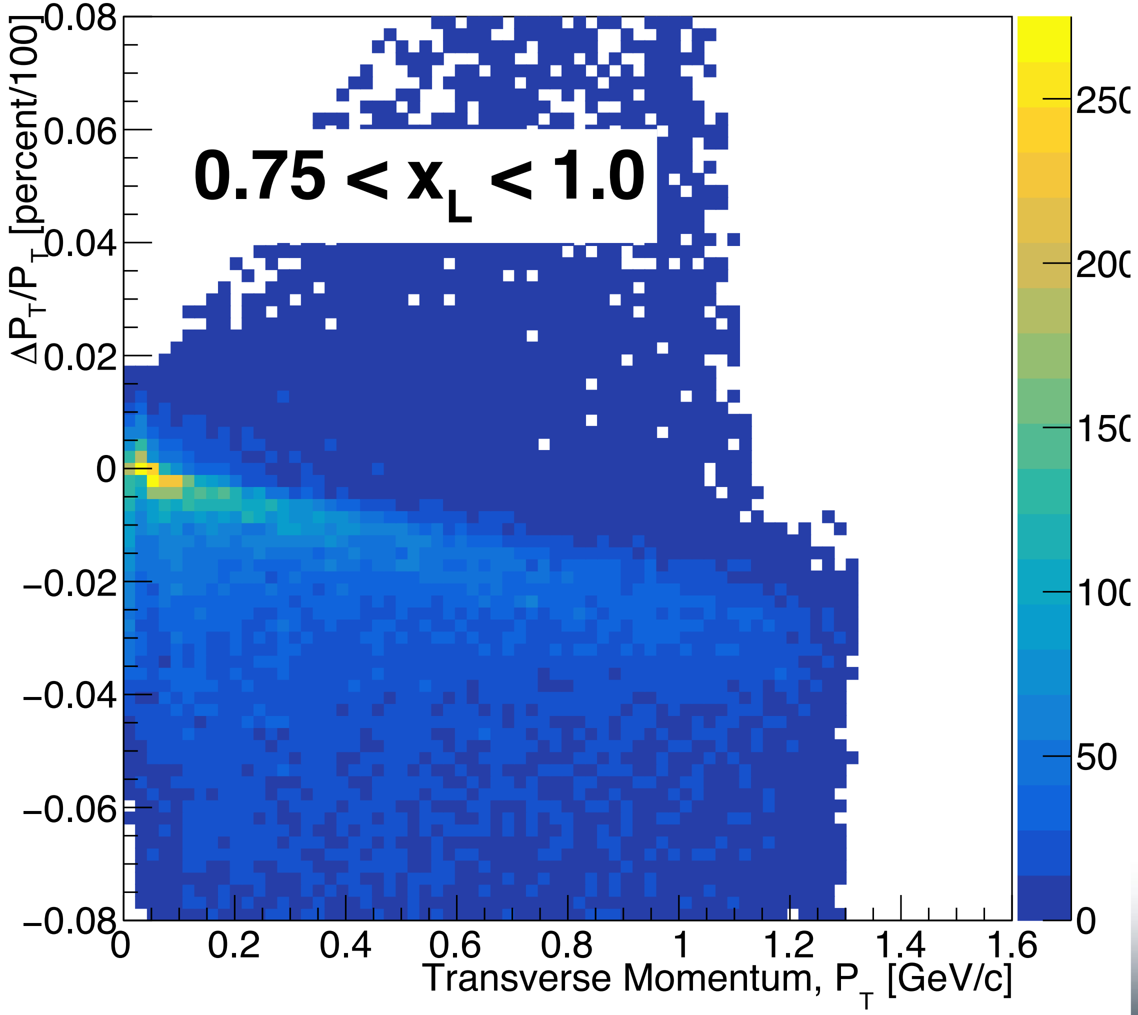
Dynamic matrix calculation



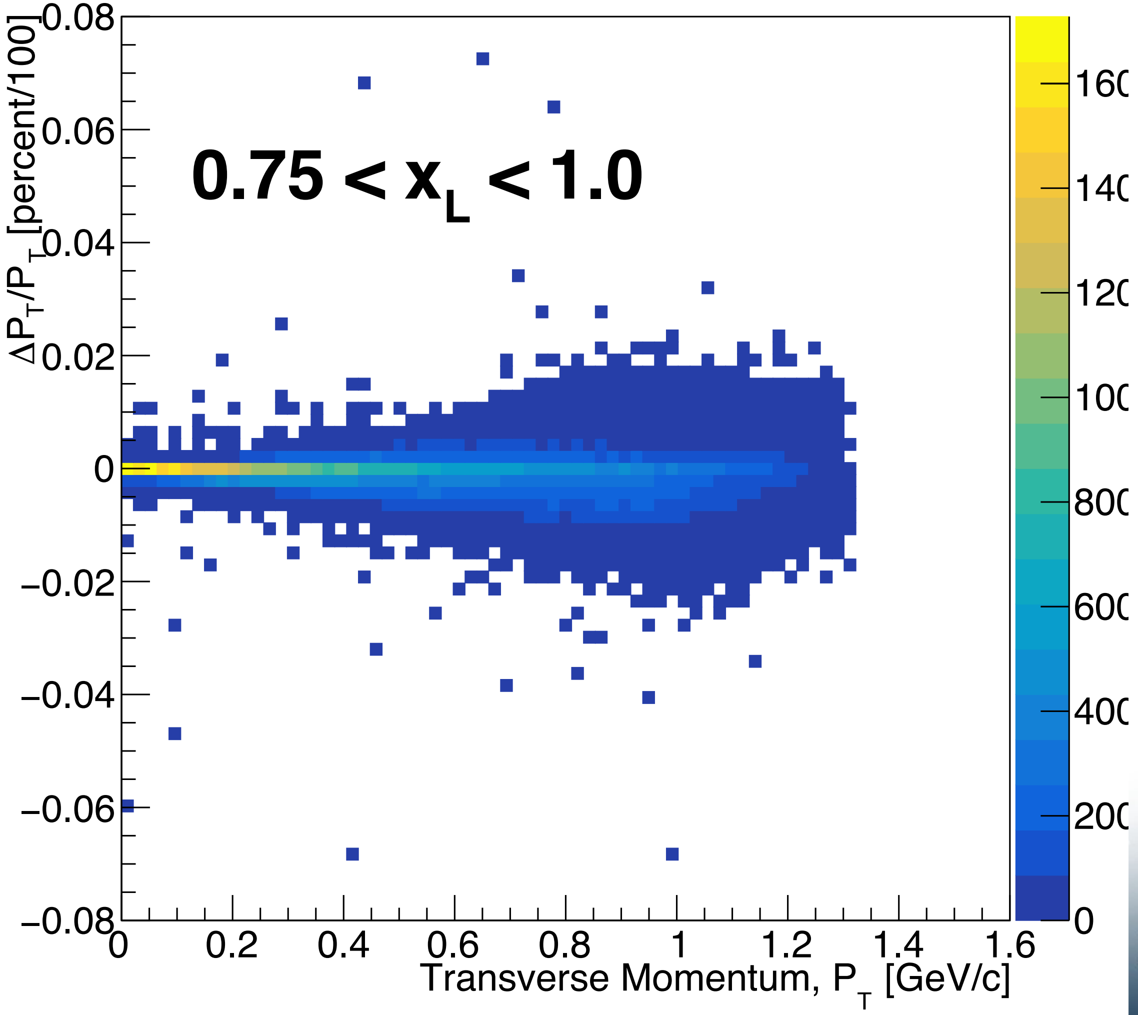
Results - pT

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

“static” BMAD matrix



Dynamic matrix calculation

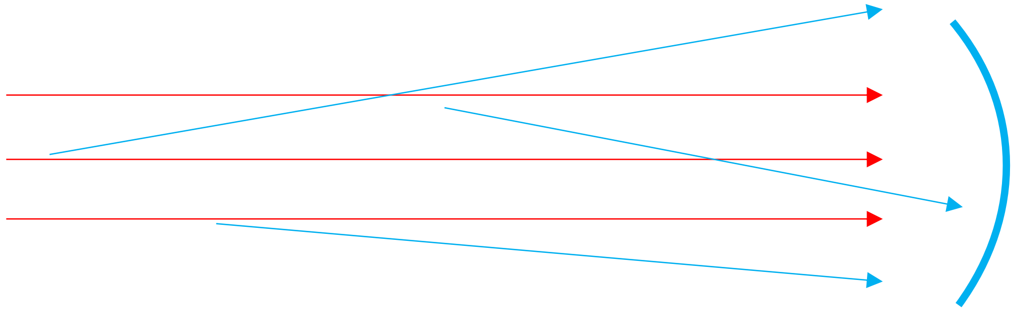


Some Final Comments on Reco in the RP

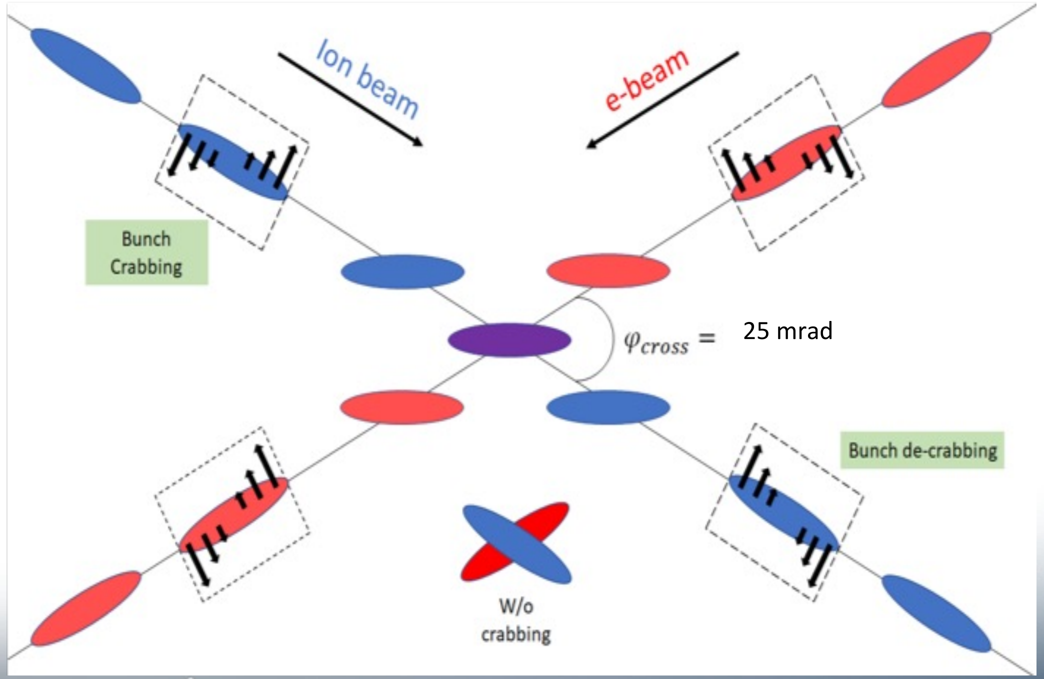
- The accelerator/machine folks are used to using BMAD/MAD-X → They do not know GEANT!
- As a result, we have to do our checks and studies in a common language to ensure errors/problems are caught early.
- The method presented will obviously be improved using machine learning methods, which is next on the list of things to do.

Digression: particle beams

- Angular divergence
  - Angular “spread” of the beam away from the central trajectory.
  - Gives some small initial transverse momentum to the beam particles.



- Crab cavity rotation
  - Can perform rotations of the beam bunches in 2D.
  - Used to account for the luminosity drop due to the crossing angle – allows for head-on collisions to still take place.

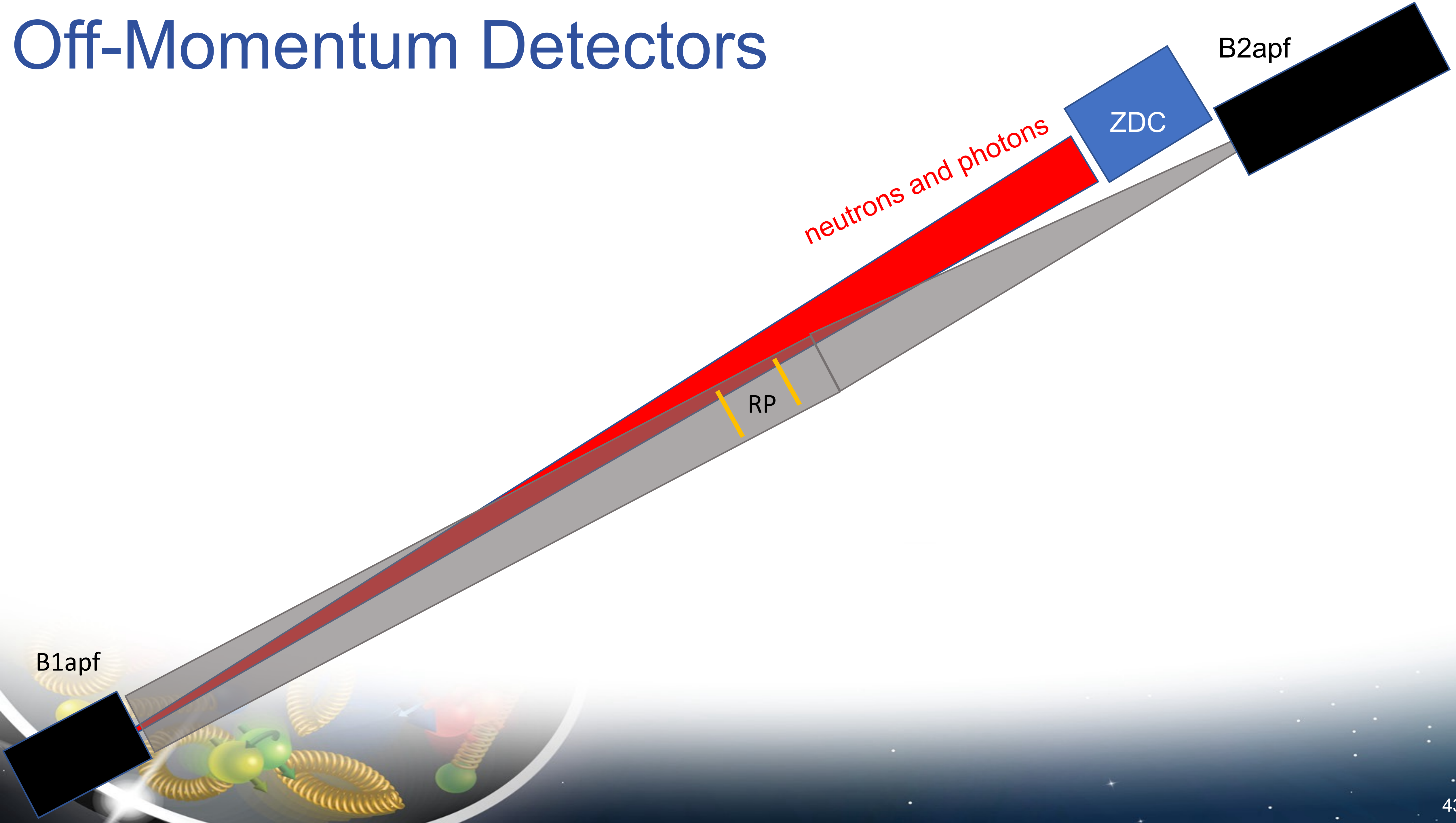


These effects introduce smearing in our momentum reconstruction.

Intermission: fun animal facts

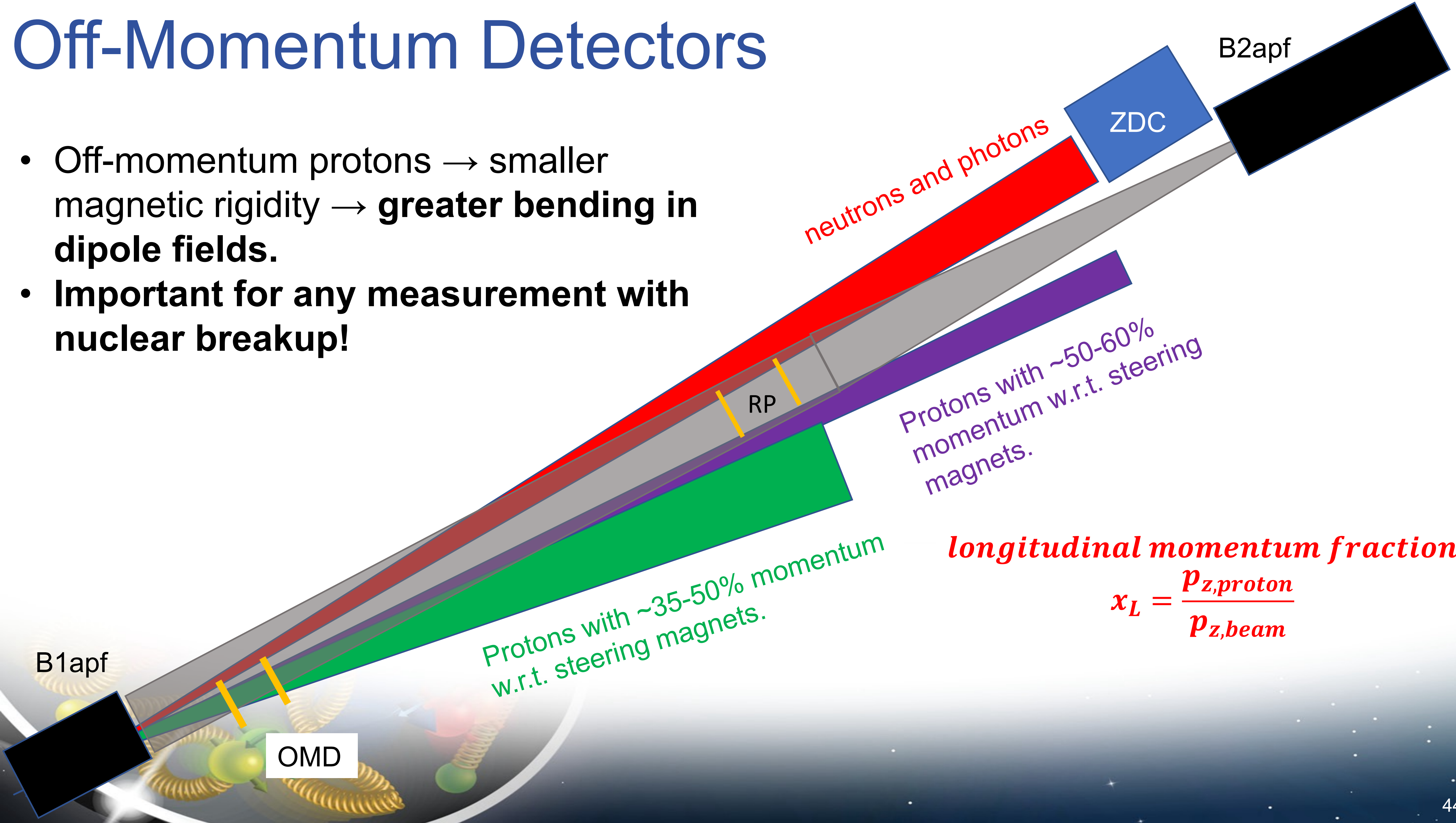
- Live primarily in desert regions in North Africa and Arabian peninsula.
- Their bat-like ears radiate body heat and help keep the foxes cool.
- They have been known to jump in the air 2 feet (.6 meters) high from a standing position, and they are able to leap a distance of 4 feet (1.2 meters).
- Live in adorable colonies of around 10 foxes.
- They are omnivorous, but they prefer Tex-Mex and craft beer.
  - Okay, maybe not, but if they tried it, they'd like it.

Off-Momentum Detectors



Off-Momentum Detectors

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



longitudinal momentum fraction

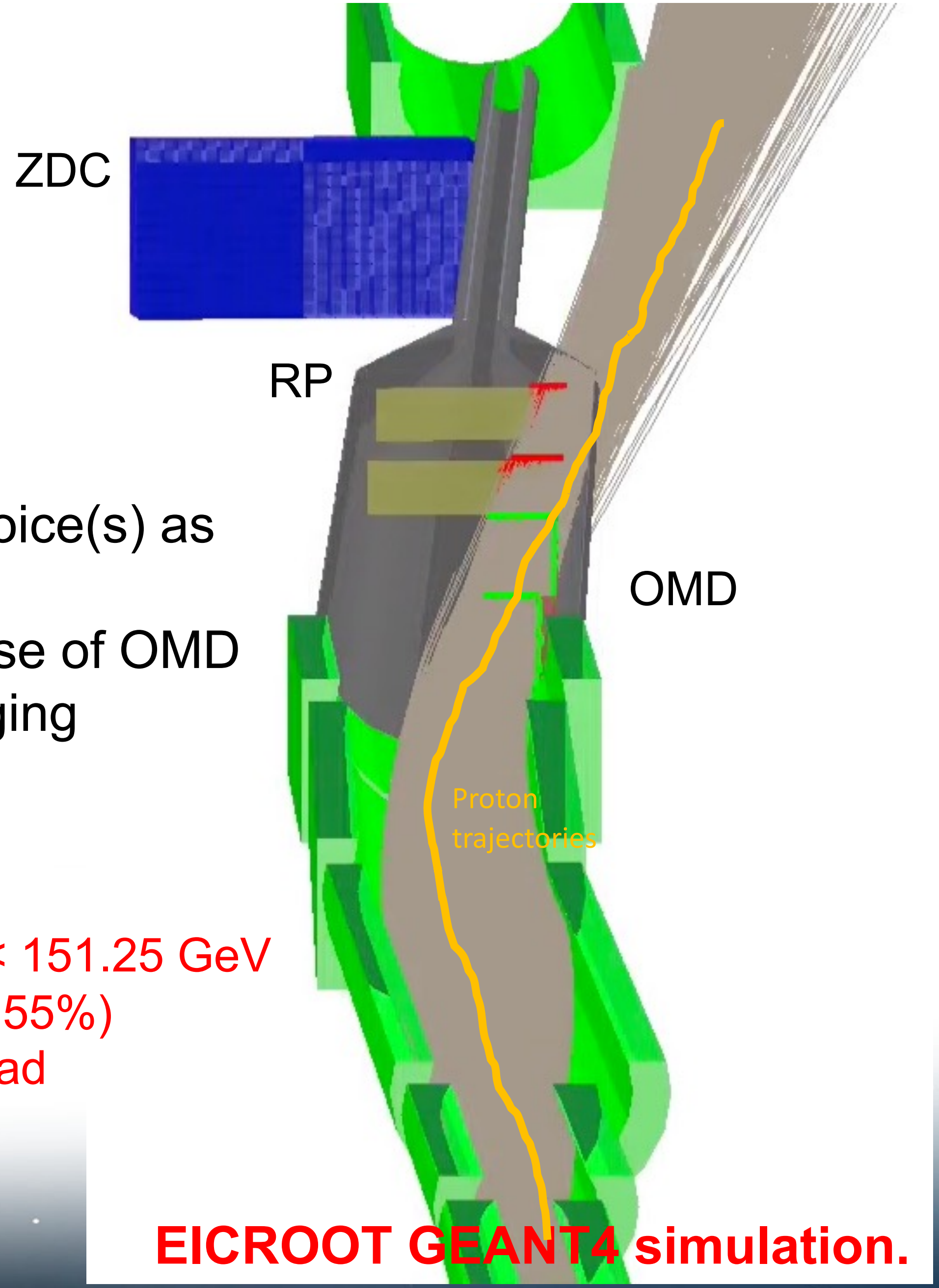
$$x_L = \frac{p_{z,proton}}{p_{z,beam}}$$

Off-Momentum Detectors

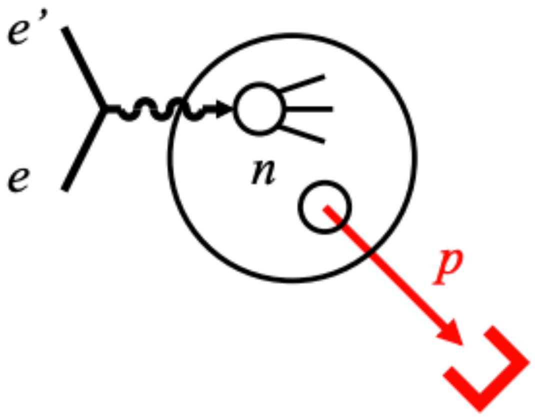
Off-momentum detectors implemented as horizontal ”Roman Pots” style sensors.

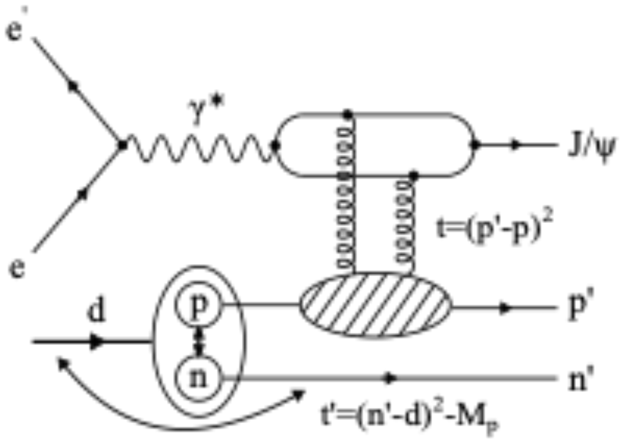
- Same technology choice(s) as for the Roman Pots.
- Need to also study use of OMD on other side for tagging negative pions.

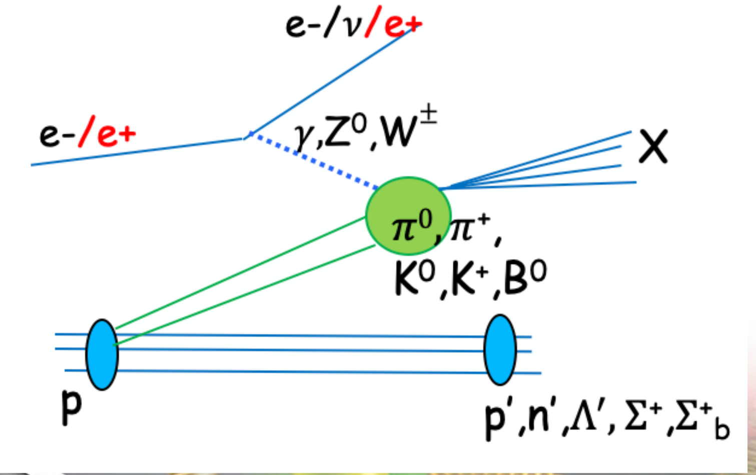
Protons
123.75 < E < 151.25 GeV
(45% < xL < 55%)
0 < θ < 5 mrad



Off-Momentum Detectors







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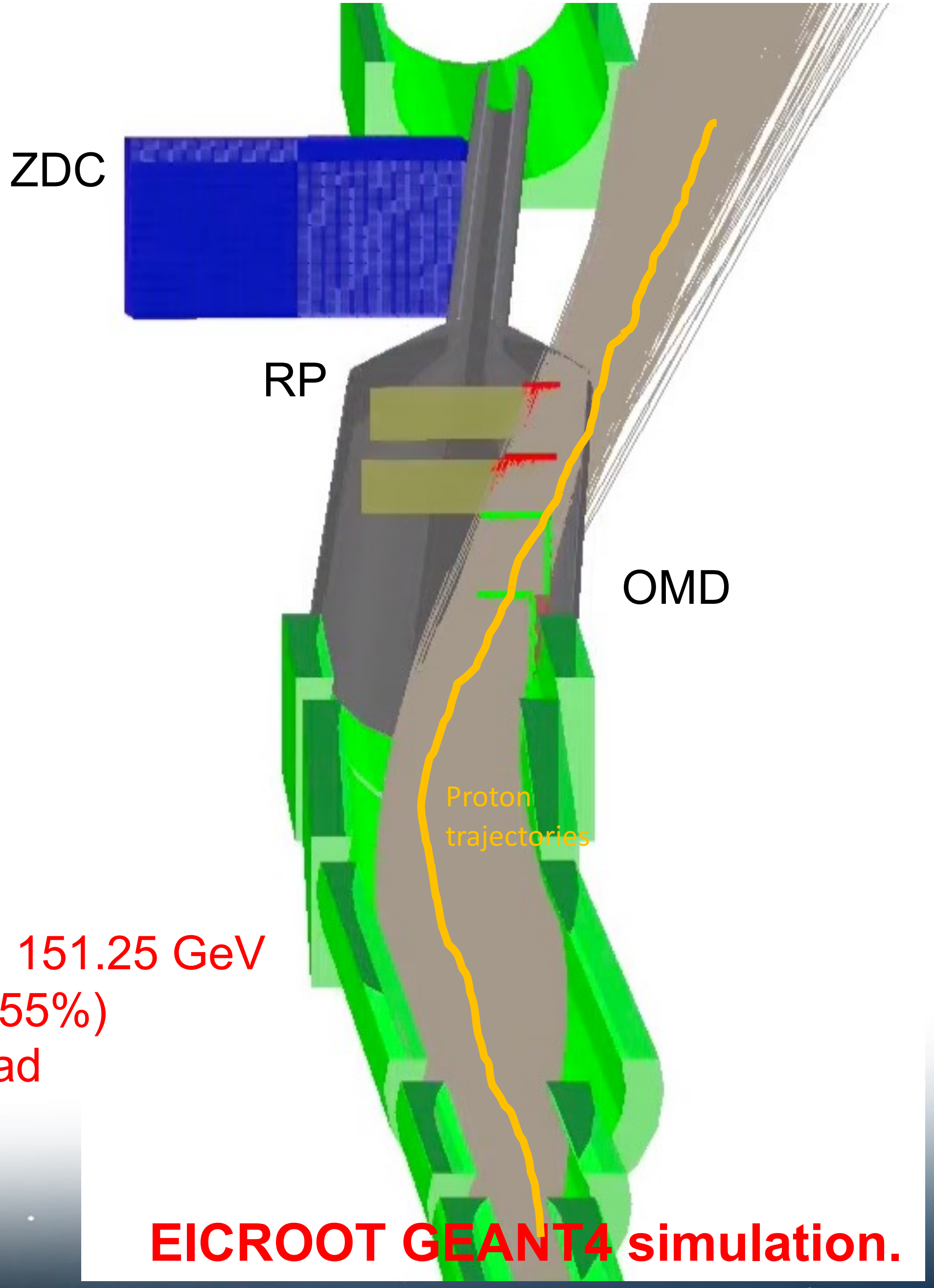
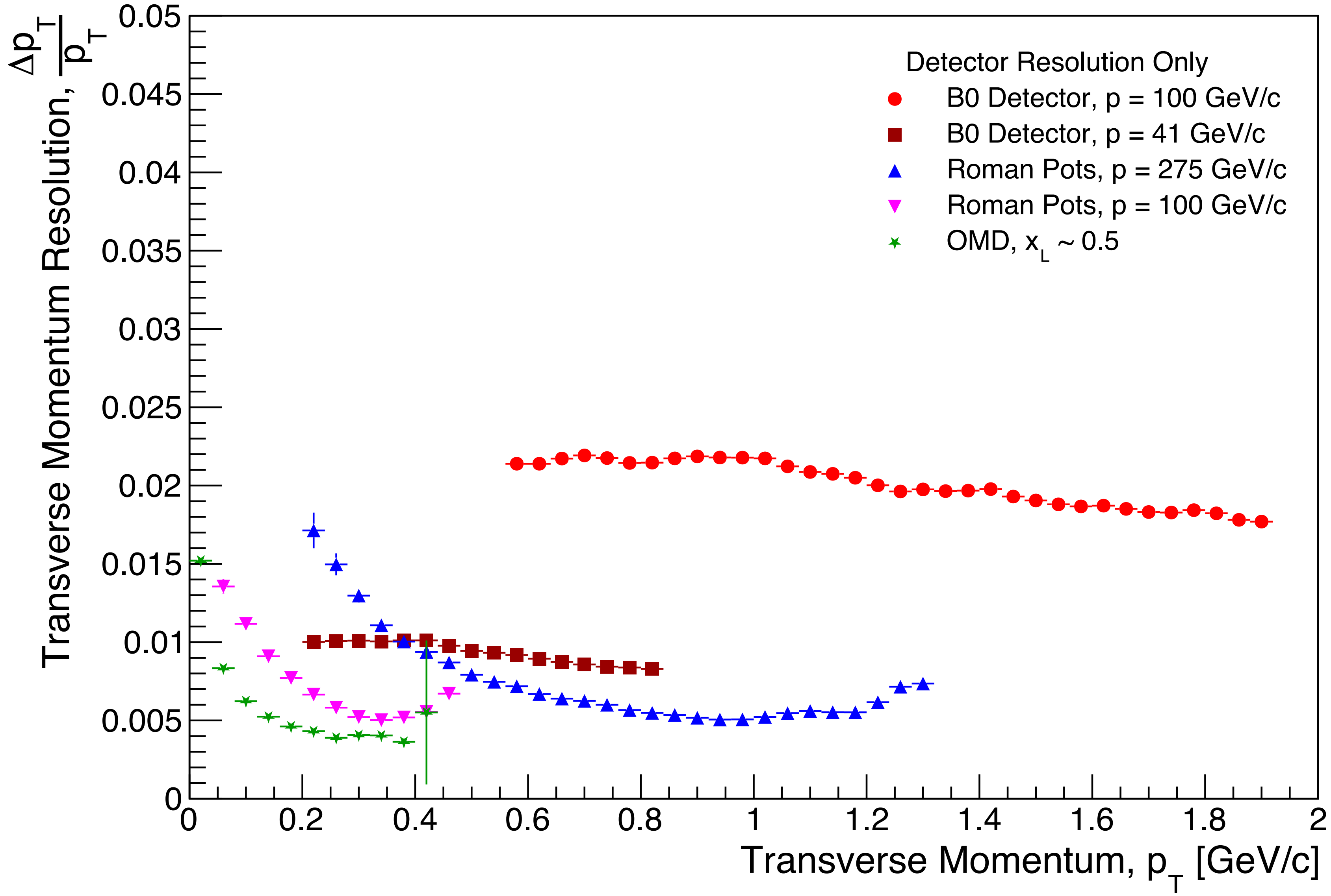
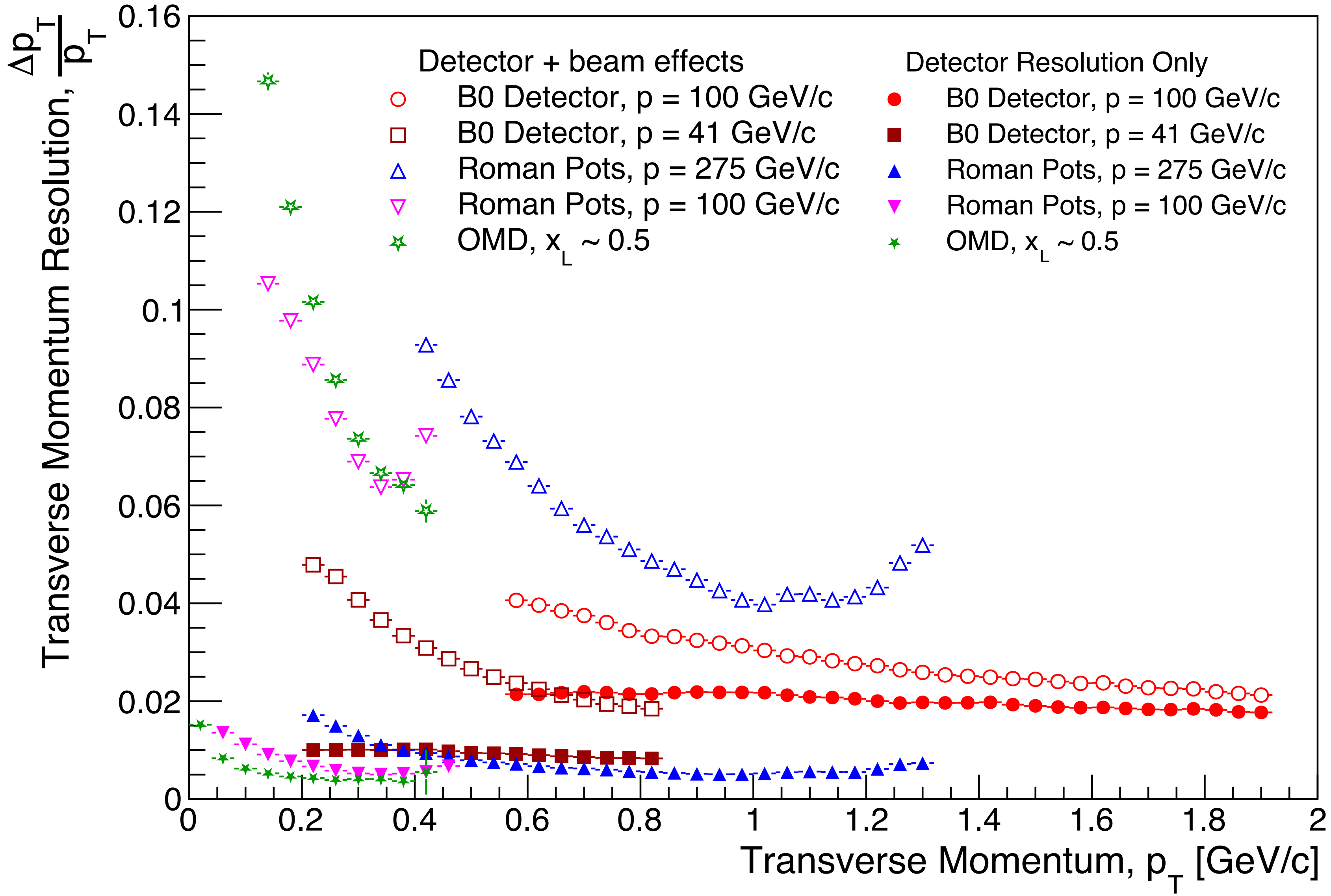


Summary of Detector Performance (Trackers)



- Includes realistic considerations for pixel sizes and materials
  - More work needed on support structure and associated impacts.
- Roman Pots and Off-Momentum detectors suffer from additional smearing due to improper transfer matrix reconstruction.
  - This problem is close to being solved!

Summary of Detector Performance (Trackers)

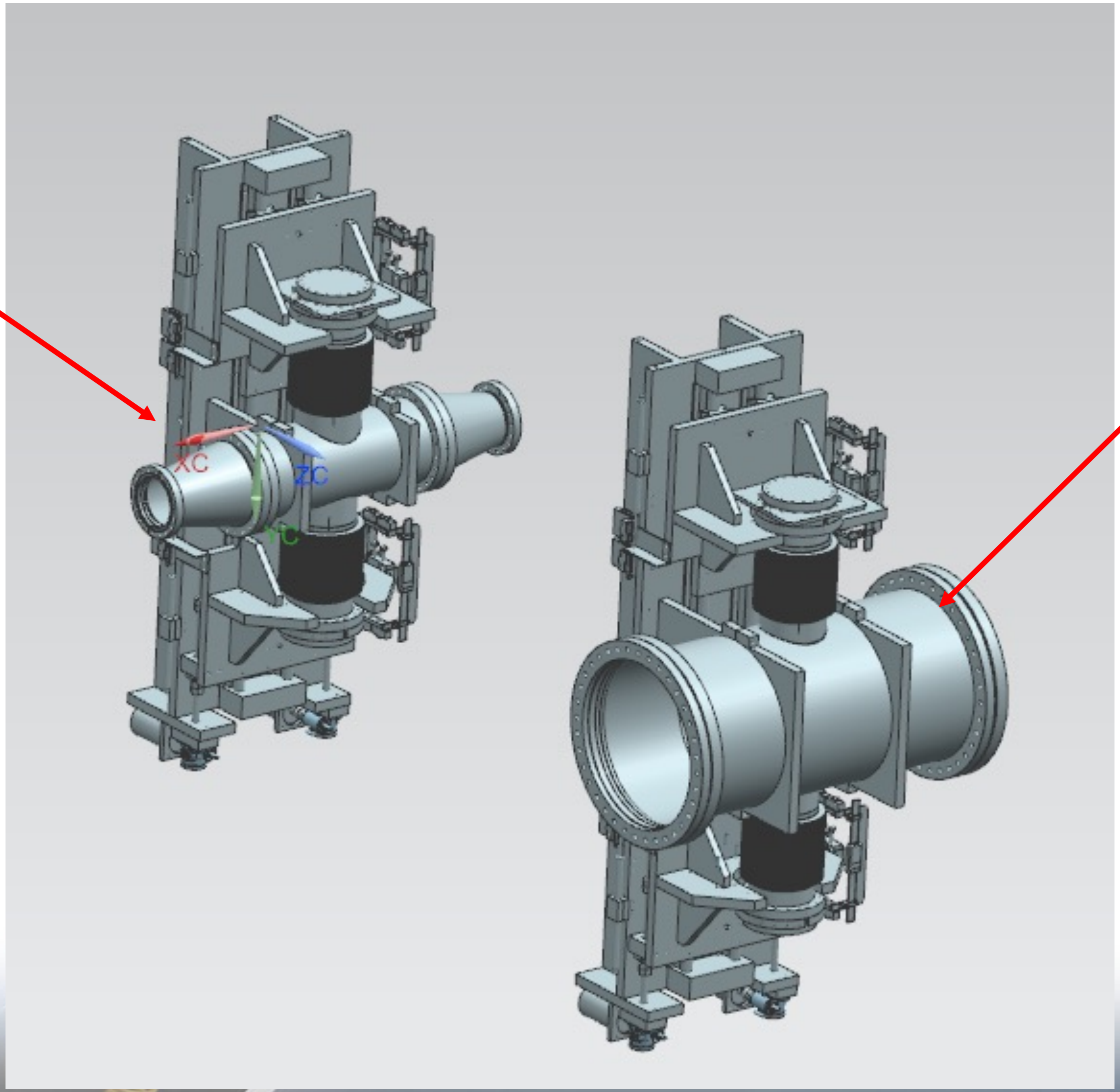


- All beam effects included!
    - Angular divergence.
    - Crossing angle.
    - Crab rotation/vertex smearing.

Beam effects the dominant source of momentum smearing!

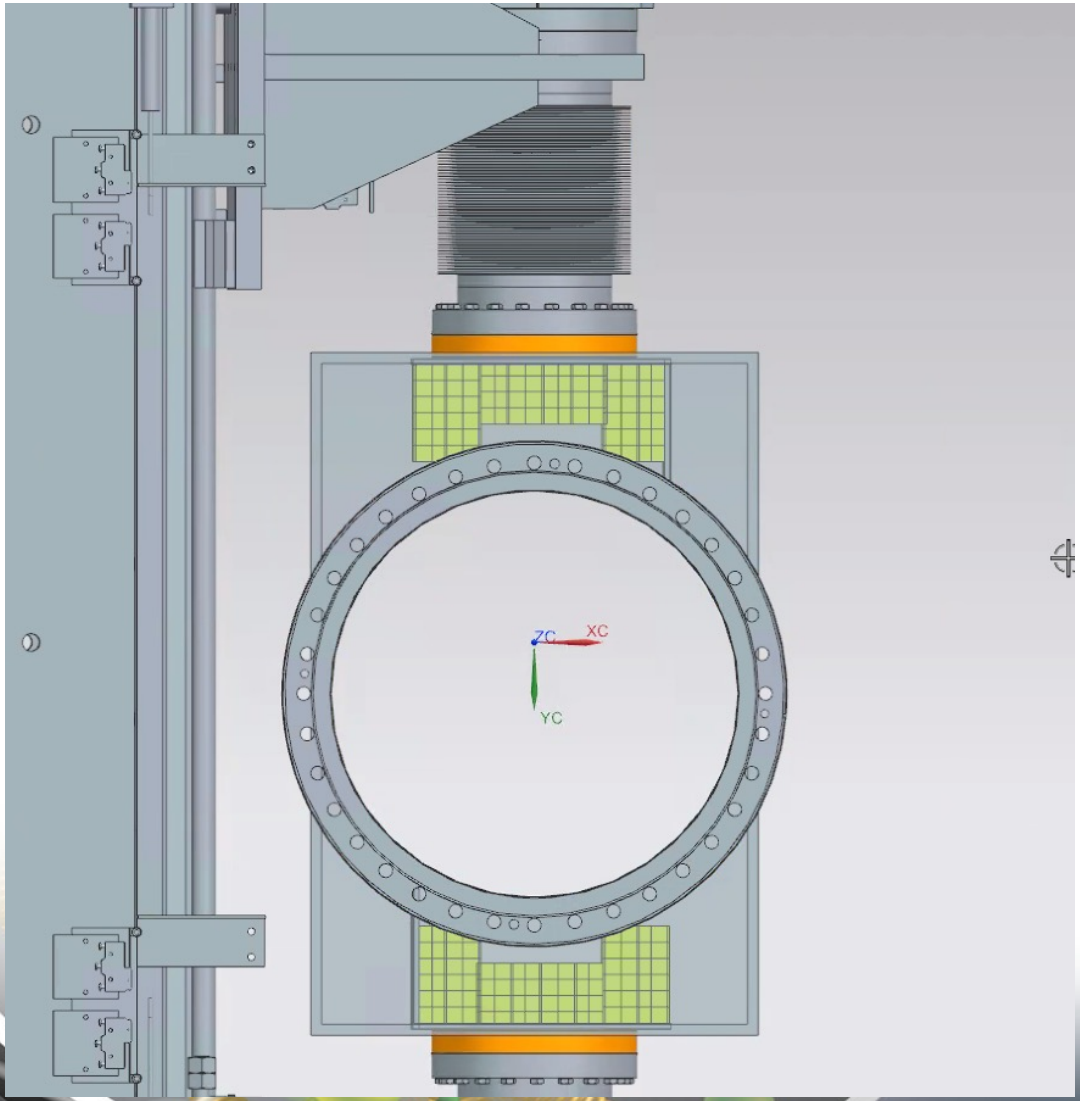
Roman Pots and Off-Momentum Detectors

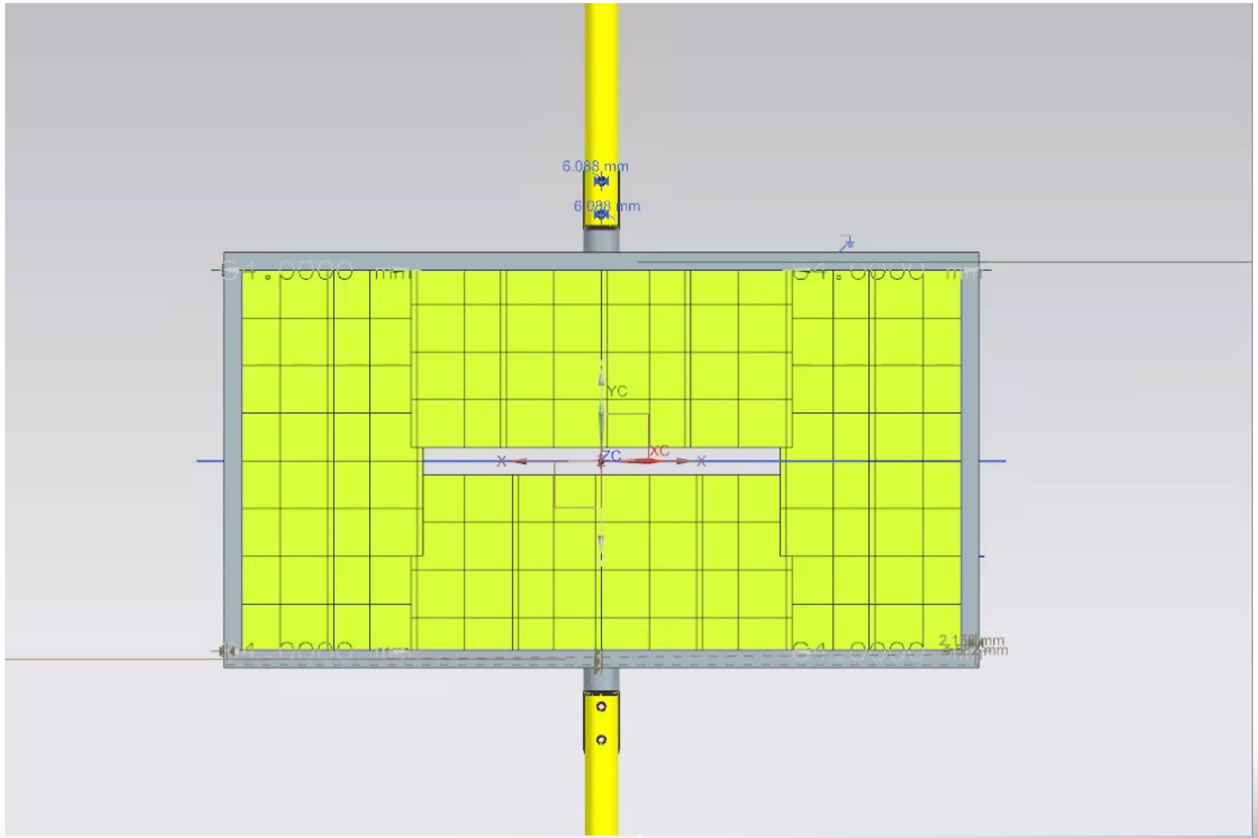
Initial step file inspired by STAR



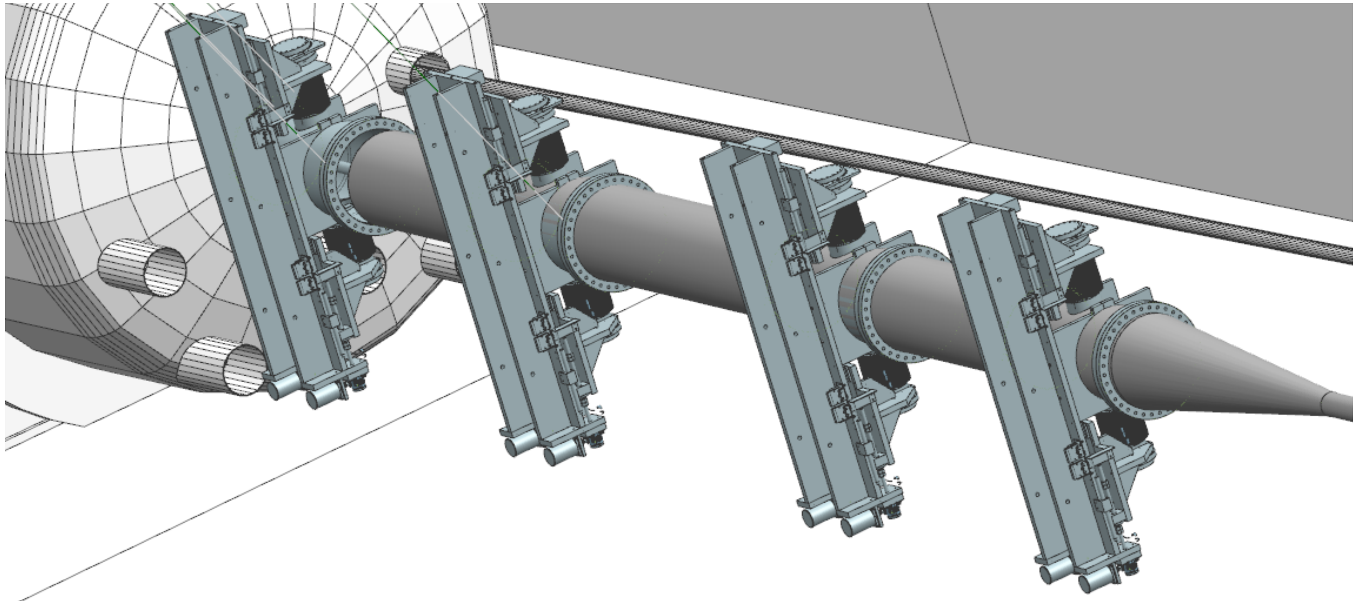
Updated model in NX with different beamtube size

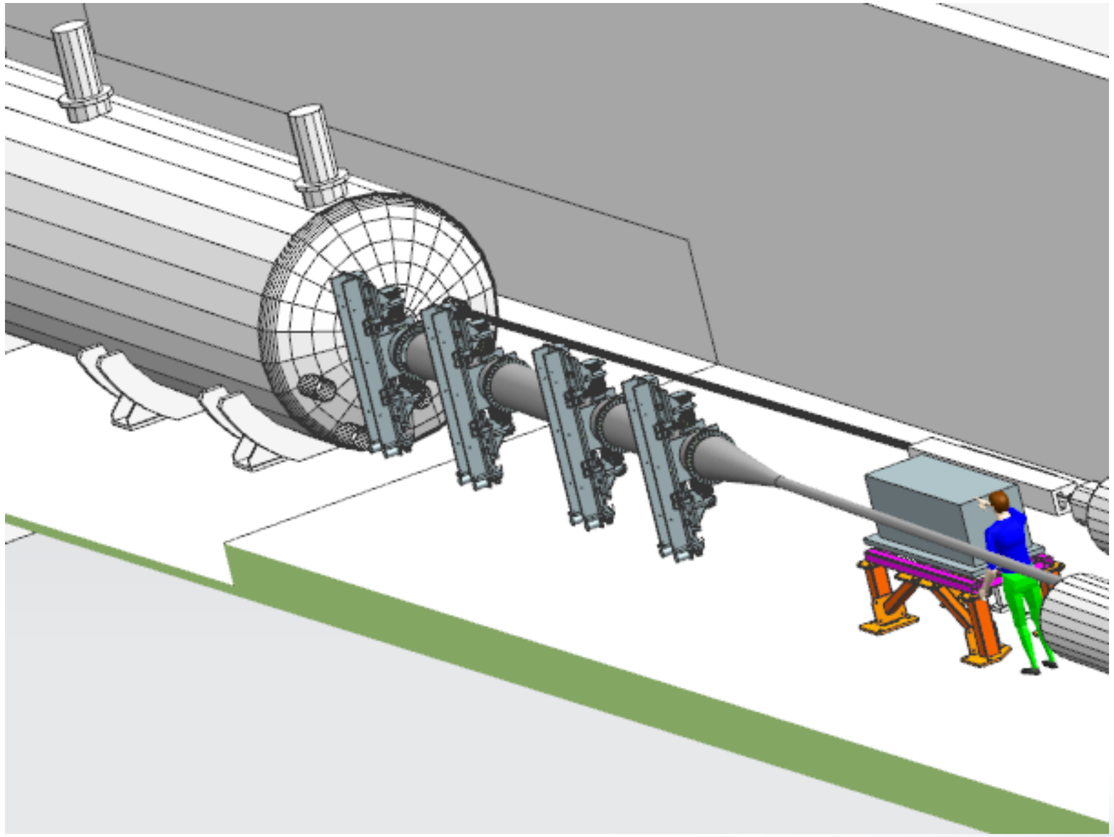
Roman Pots in CAD





Preliminary CAD drawings of RP and OMD Supports and Magnet Cryostats





Zero-Degree Calorimeter

- Need a calorimeter which can accurately reconstruct photons and neutrons from our various final states (e.g. tagged DIS, incoherent vetoing in e+A, backward u-channel omega production).
- Neutrons and photons react differently in materials – need both an EMCAL and an HCAL!

Zero-Degree Calorimeter

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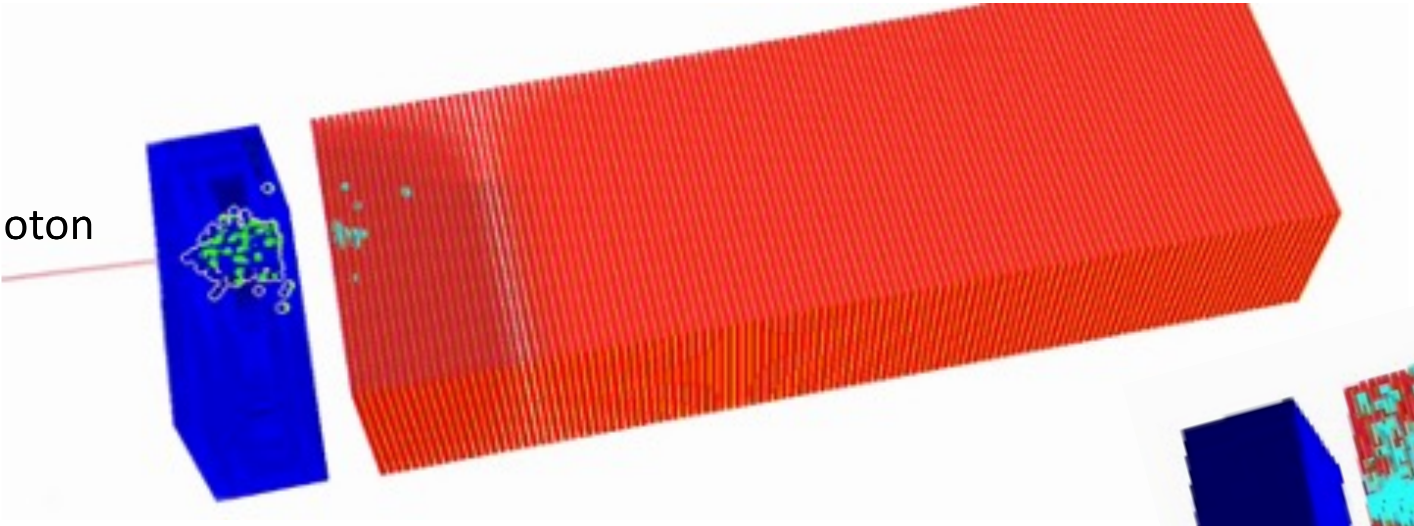
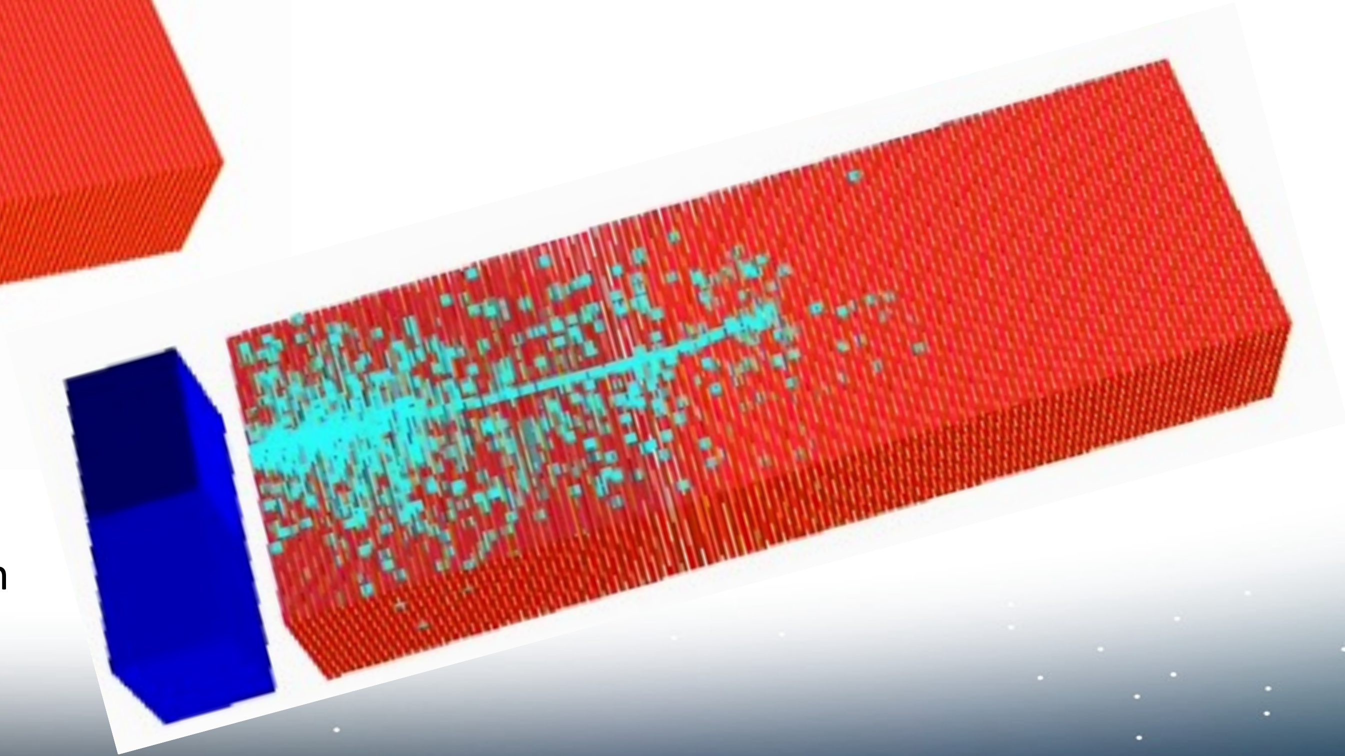
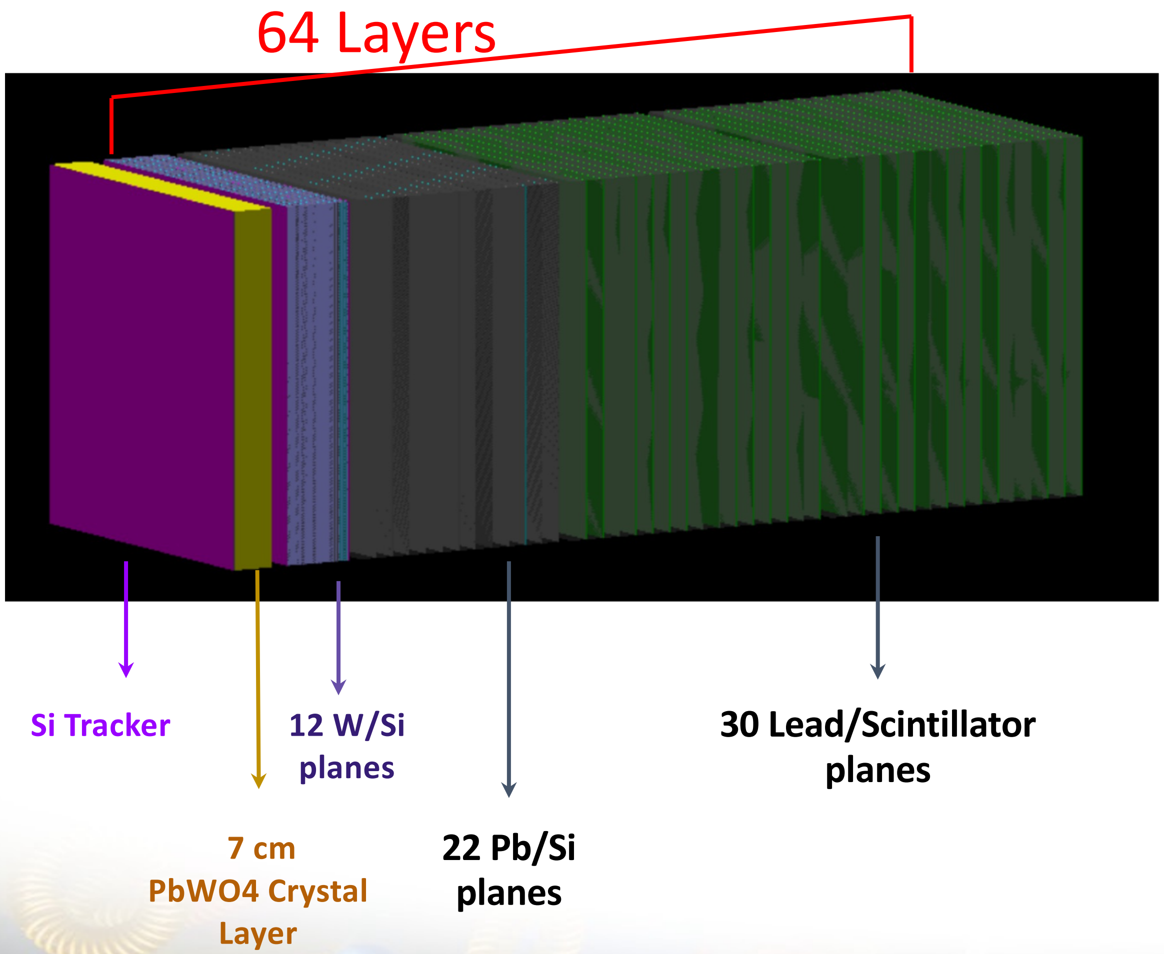
photon



neutron



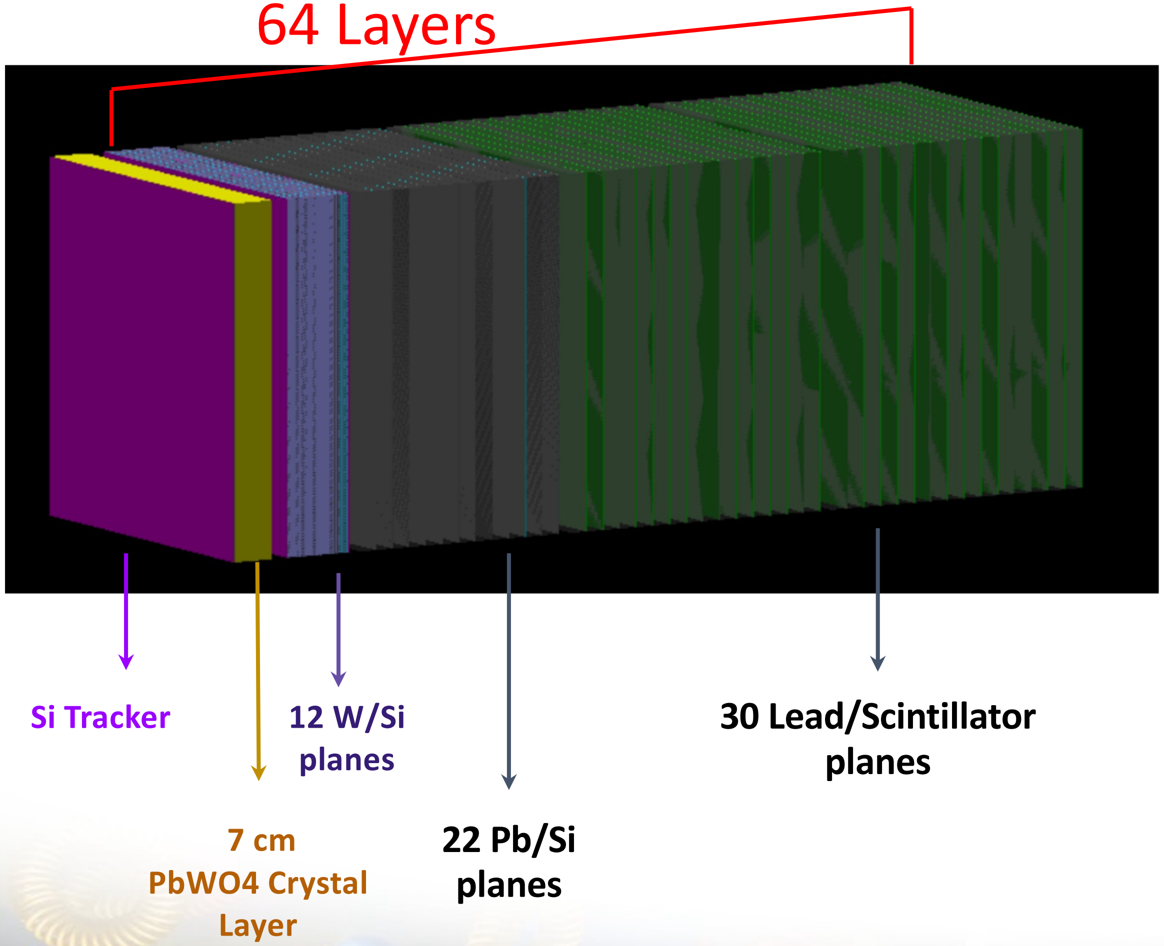
Zero-Degree Calorimeter



Credit to Shima Shimizu (Kobe U. , Japan)

- **Zero Degree Calorimeter (improved ALICE design):**
  - **Dimension: 60 cm x 60 cm x 168 cm**
  - **30 m from IR**
  - **Detect spectator nucleon**
  - **Acceptance: +4.5 mrad, -5.5mrad**
  - **Position resolution ~1.3mm at 40 GeV**
  - **Full reconstruction of photons (EMCAL) and neutrons (HCAL)**

Zero-Degree Calorimeter



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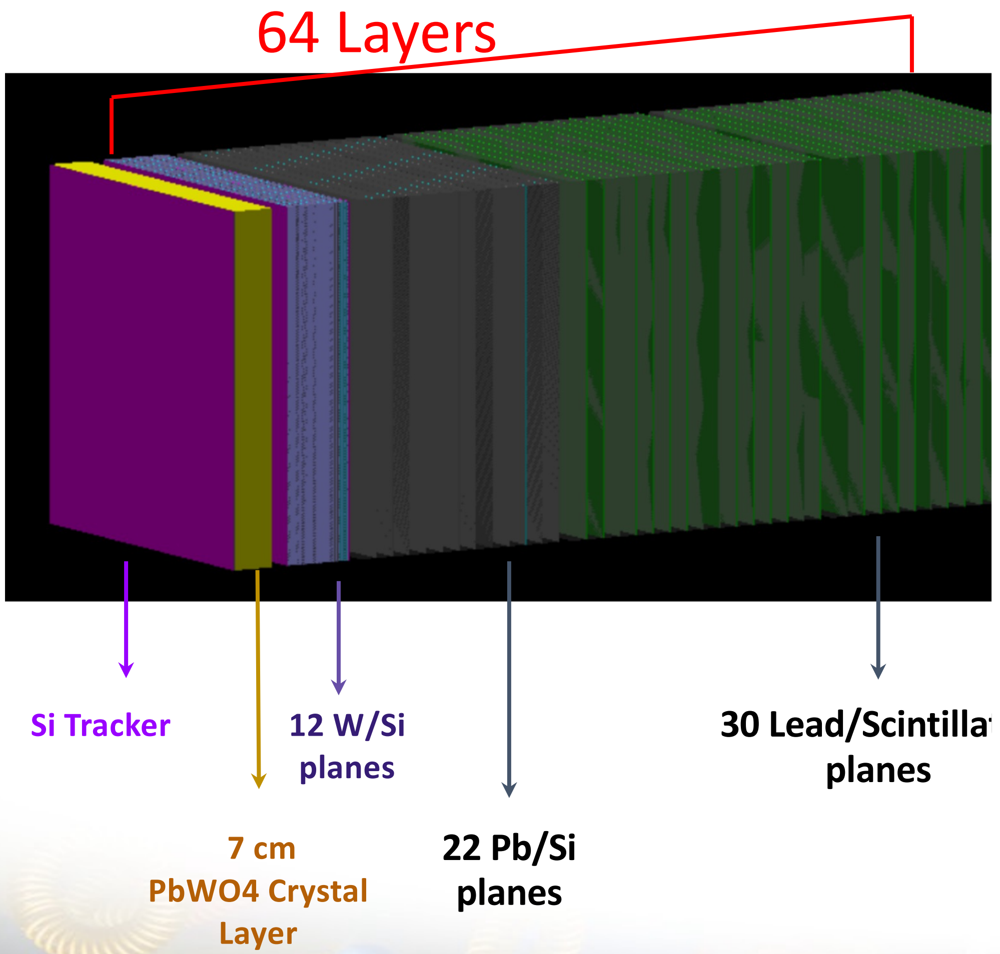
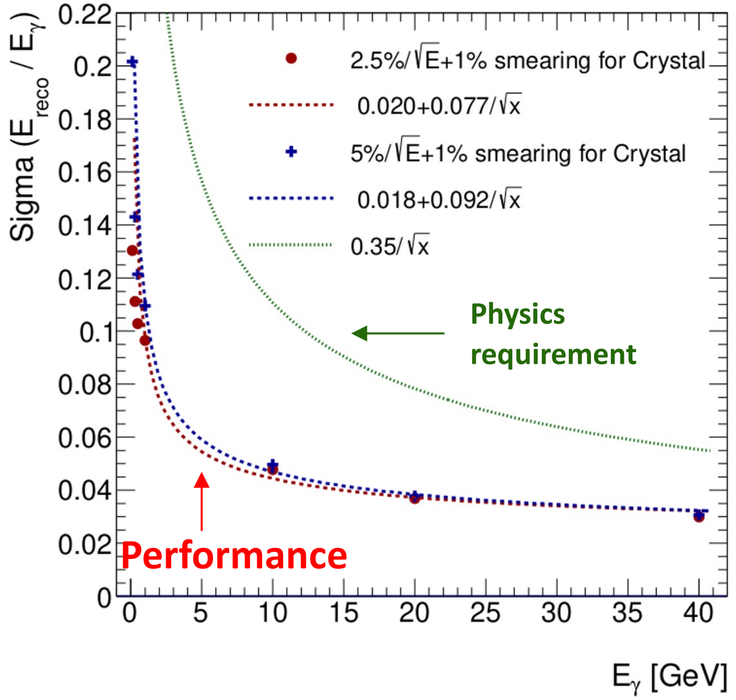
  - **Position resolution ~1.3mm at 40 GeV**
  - **Full reconstruction of photons (EMCAL) and neutrons (HCAL)**

- Sufficient calorimeter depth (radiation lengths, X_0 for photons/electrons; nuclear interaction lengths, λ_I for neutrons/hadrons)
  - Required for good energy resolution.
- Granularity needed for proper reconstruction of shower.
  - Finding the center of the shower needed to provide angular resolution to get neutron transverse momentum!

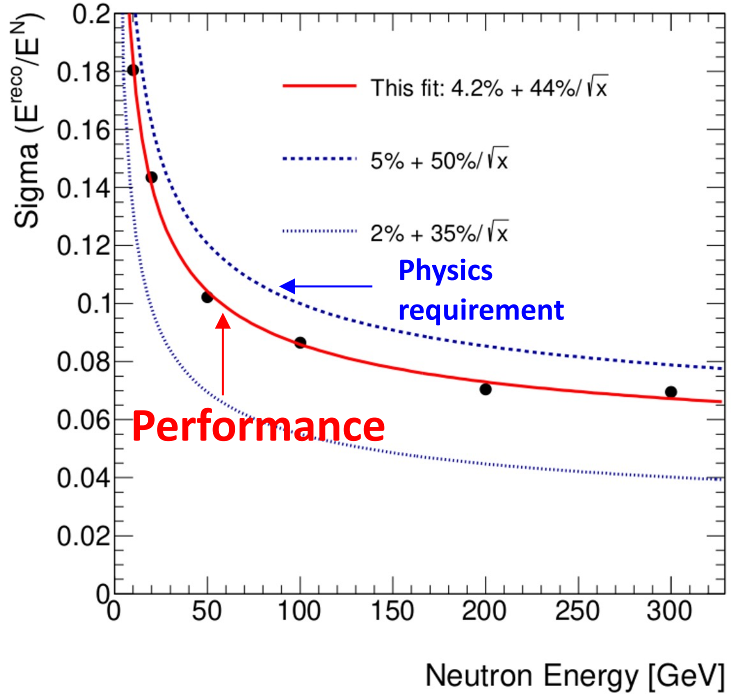
Zero-Degree Calorimeter



Photon energy resolution



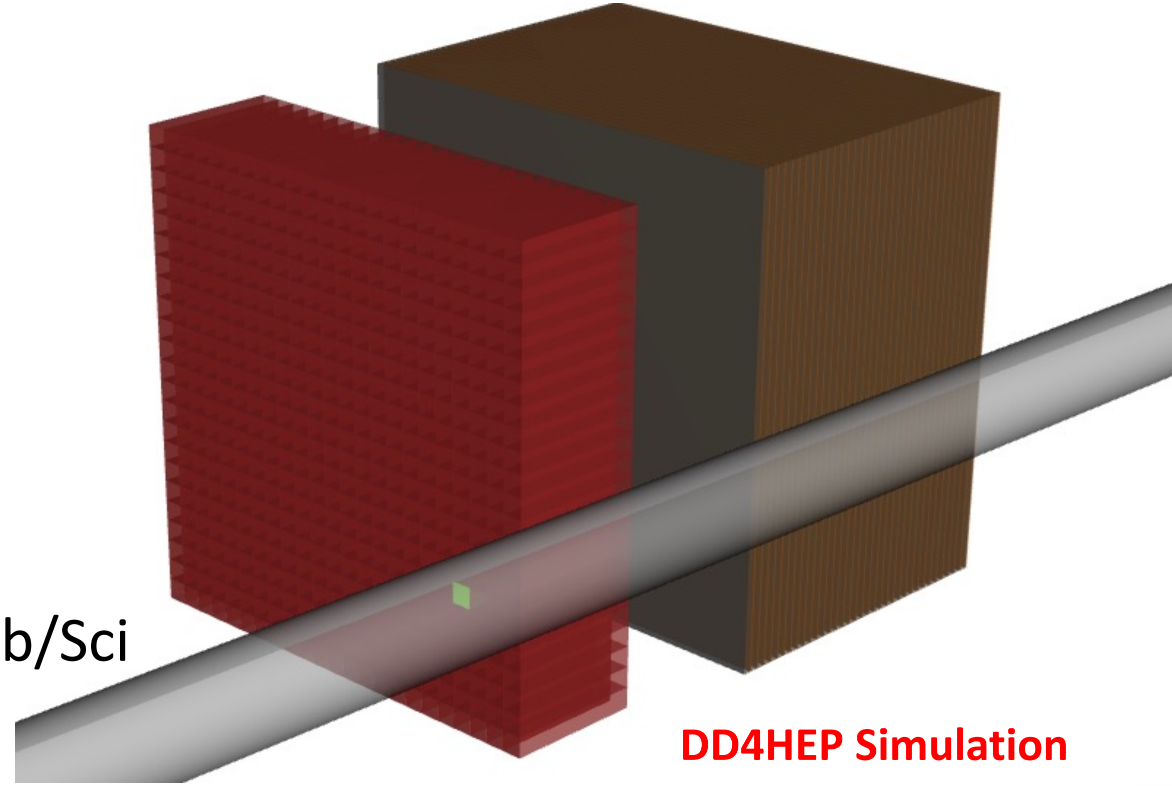
Neutron energy resolution



Credit to Shima Shimizu (Kobe U. , Japan)

Zero-Degree Calorimeter (alt. option)

Multi-functional design including EMCAL and HCAL, with imaging layers to improve pT/angular resolution for neutrons.



DD4HEP Simulation

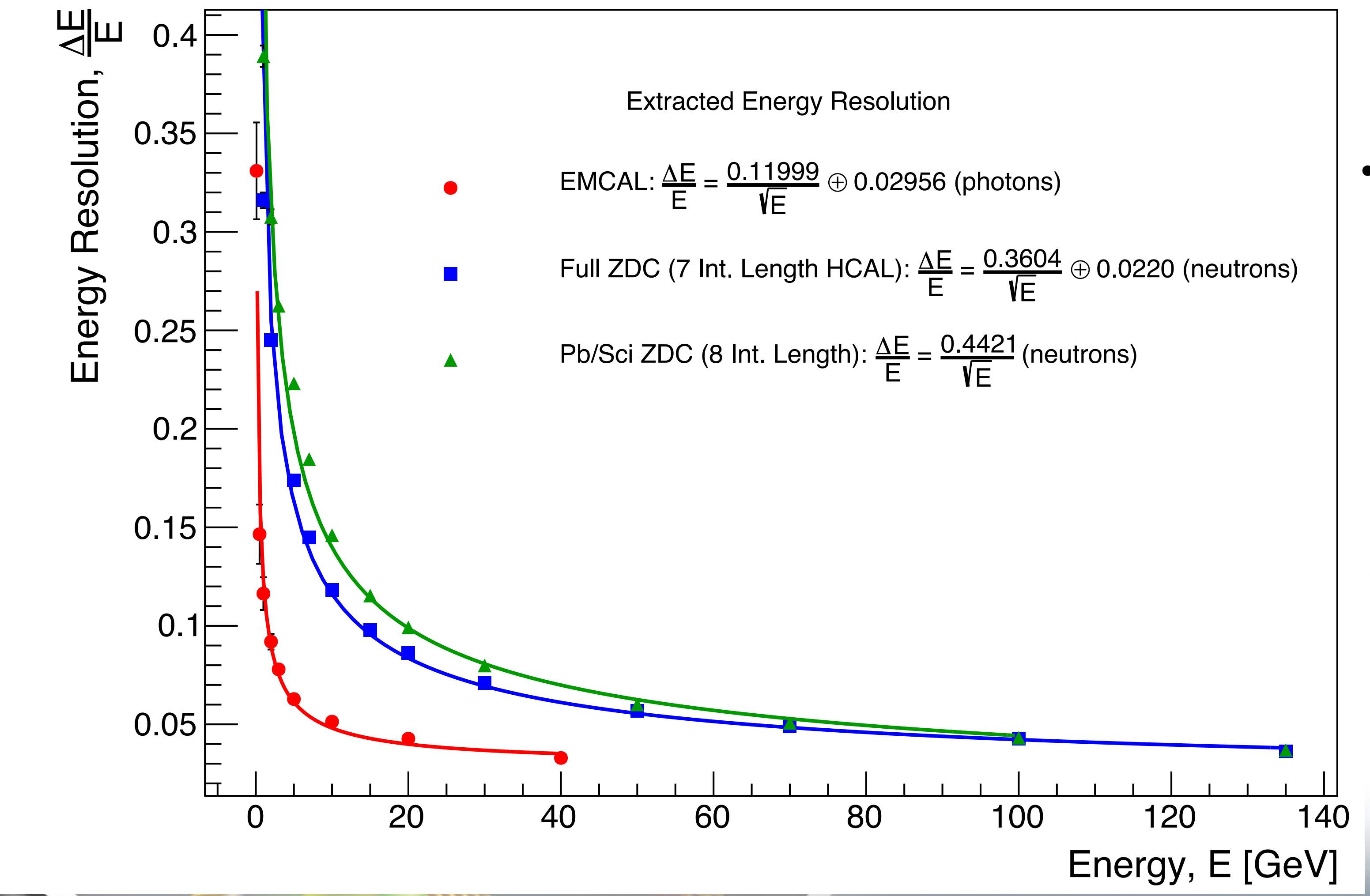
EMCAL (W/SciFi):

- Scintillating fibers embedded in W powder.
- Photon energy resolution $\frac{12\%}{\sqrt{E}} \oplus 3\%$.
- $23X_0$ and $1\lambda_I$

HCAL (Pb/Sci):

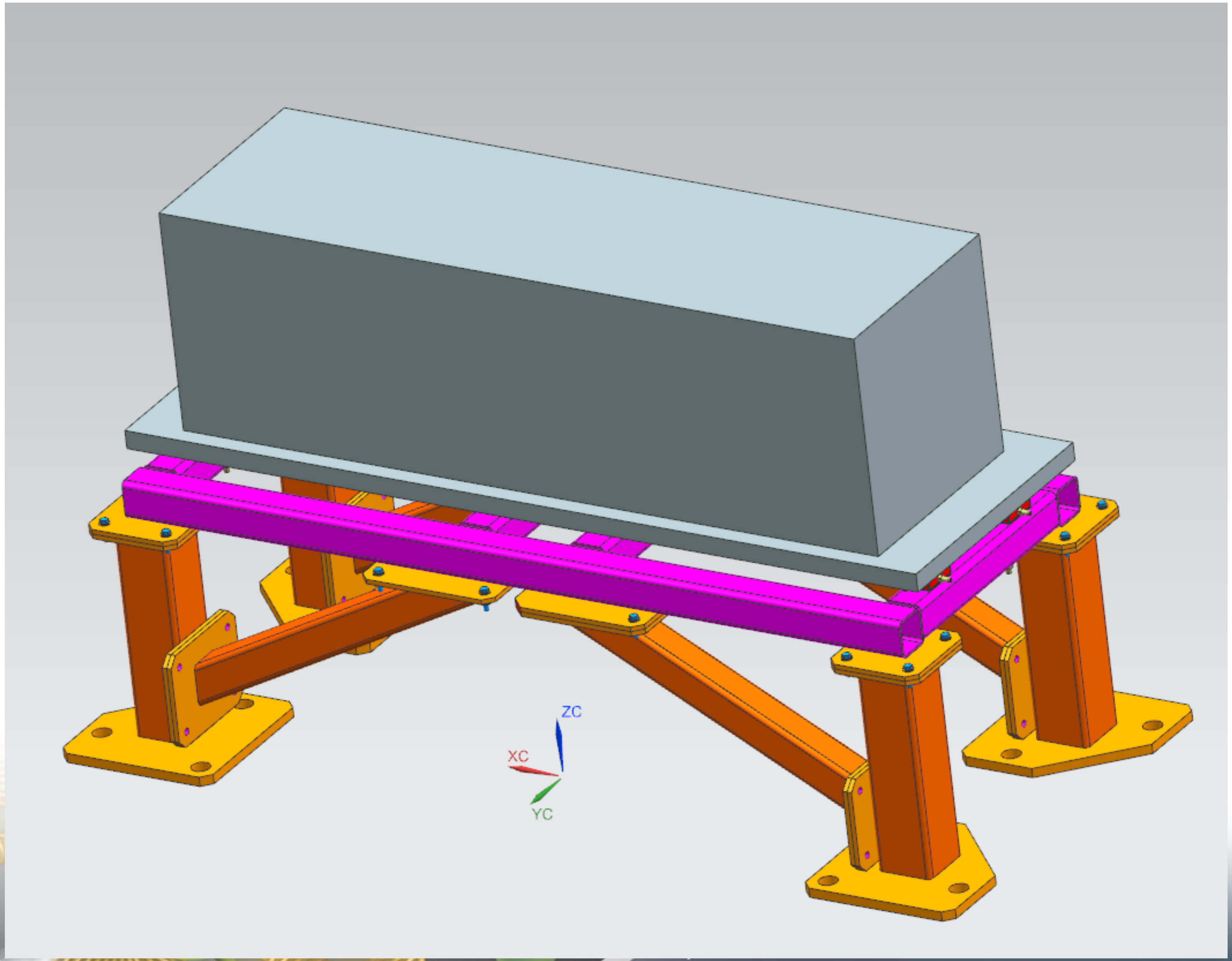
- Neutron energy resolution $\frac{36\%}{\sqrt{E}} \oplus 2.2\%$ - using Pb/Sci sampling HCAL with $7\lambda_I$, plus EMCAL section.
- Imaging layers could be silicon or scintillating fibers.
  - Need to better establish how many are needed and at what level of granularity to produce needed resolution.

Alt. ZDC Performance (E resolution)



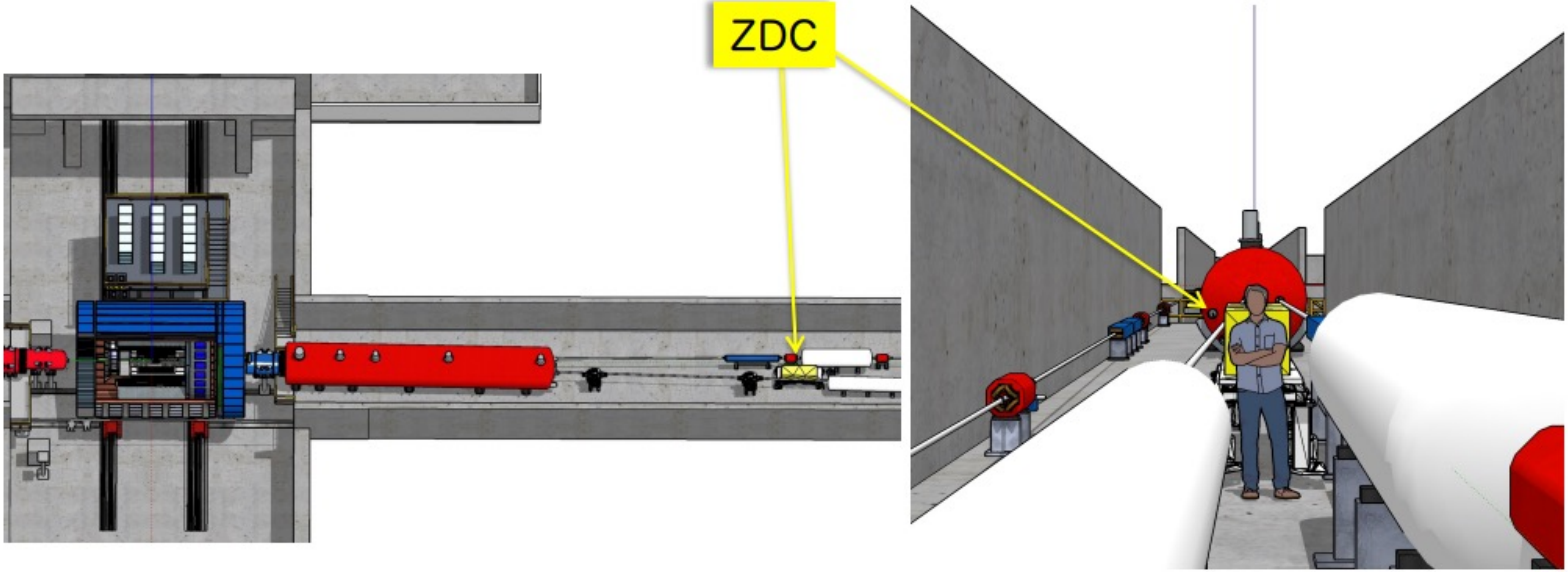
- **Alt. ZDC**
  - Comparisons made with simulations for pure Pb/Sci.
    - Performance in GEANT4 simulations consistent with test beam studies for similar construction.
  - Performance will worsen for particles with larger polar angles due to transverse leakage.

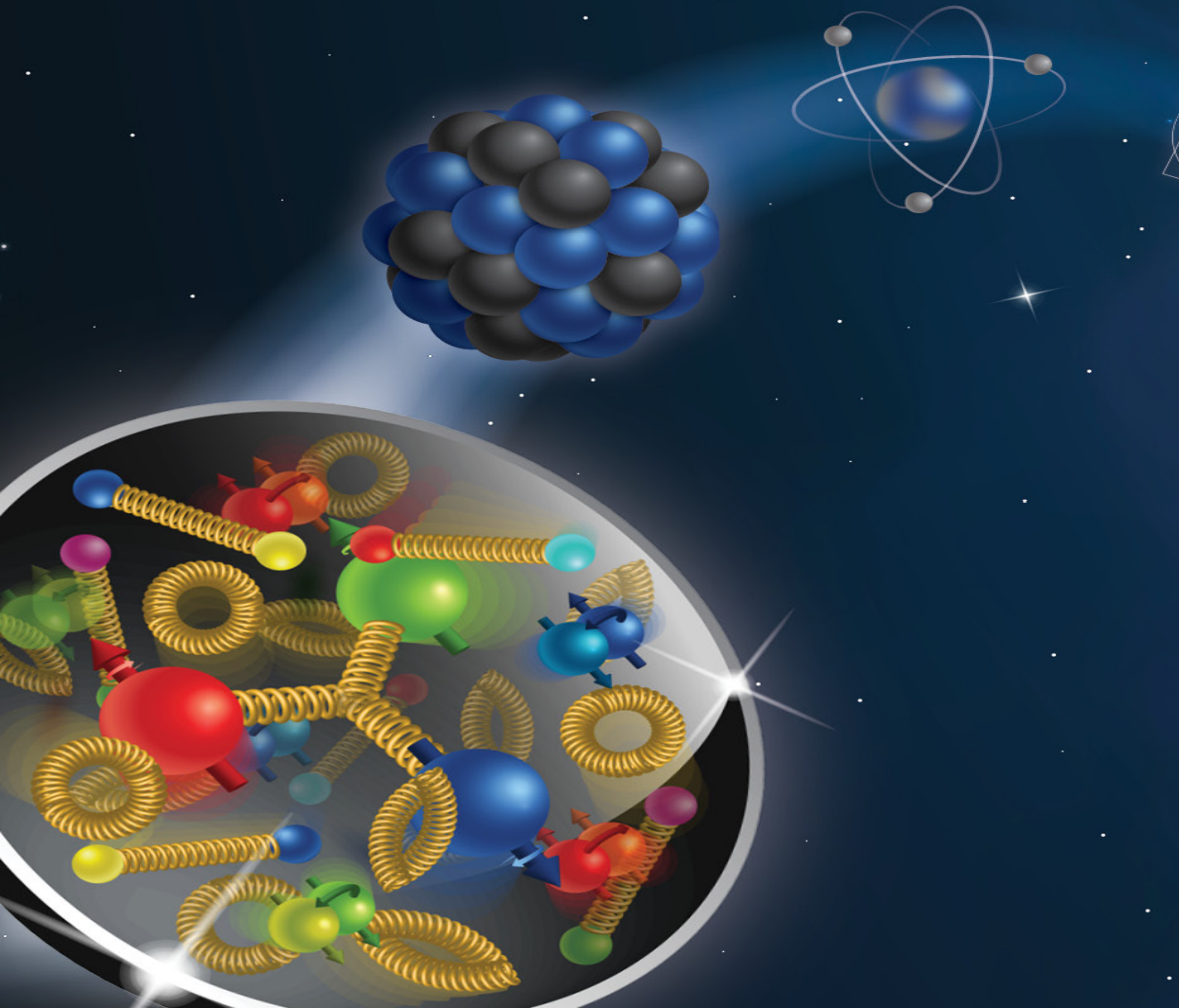
Zero-Degree Calorimeter with Stand



Preliminary Design of Zero--Degree Calorimeter with full support structure.

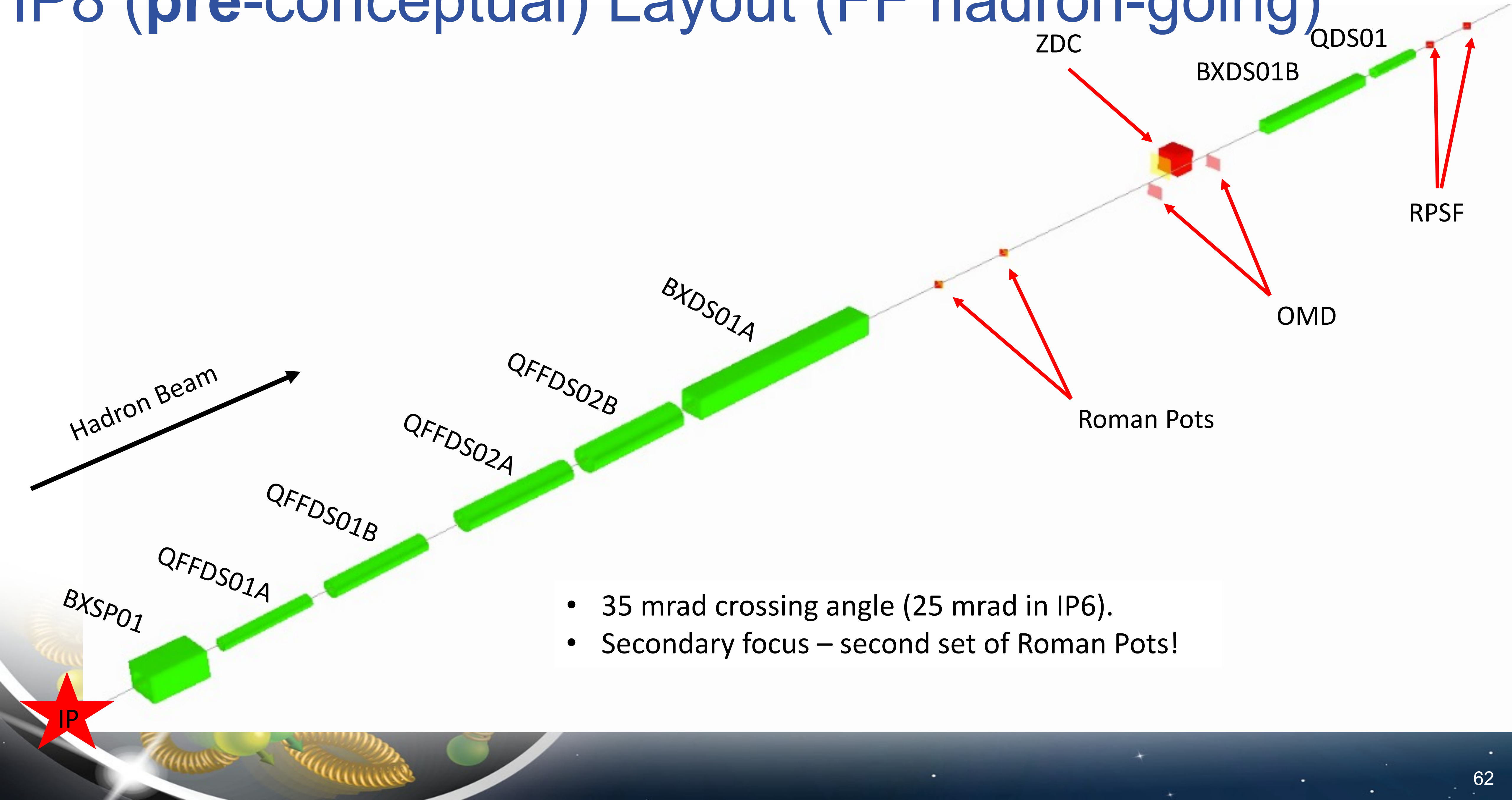
Zero-Degree Calorimeter





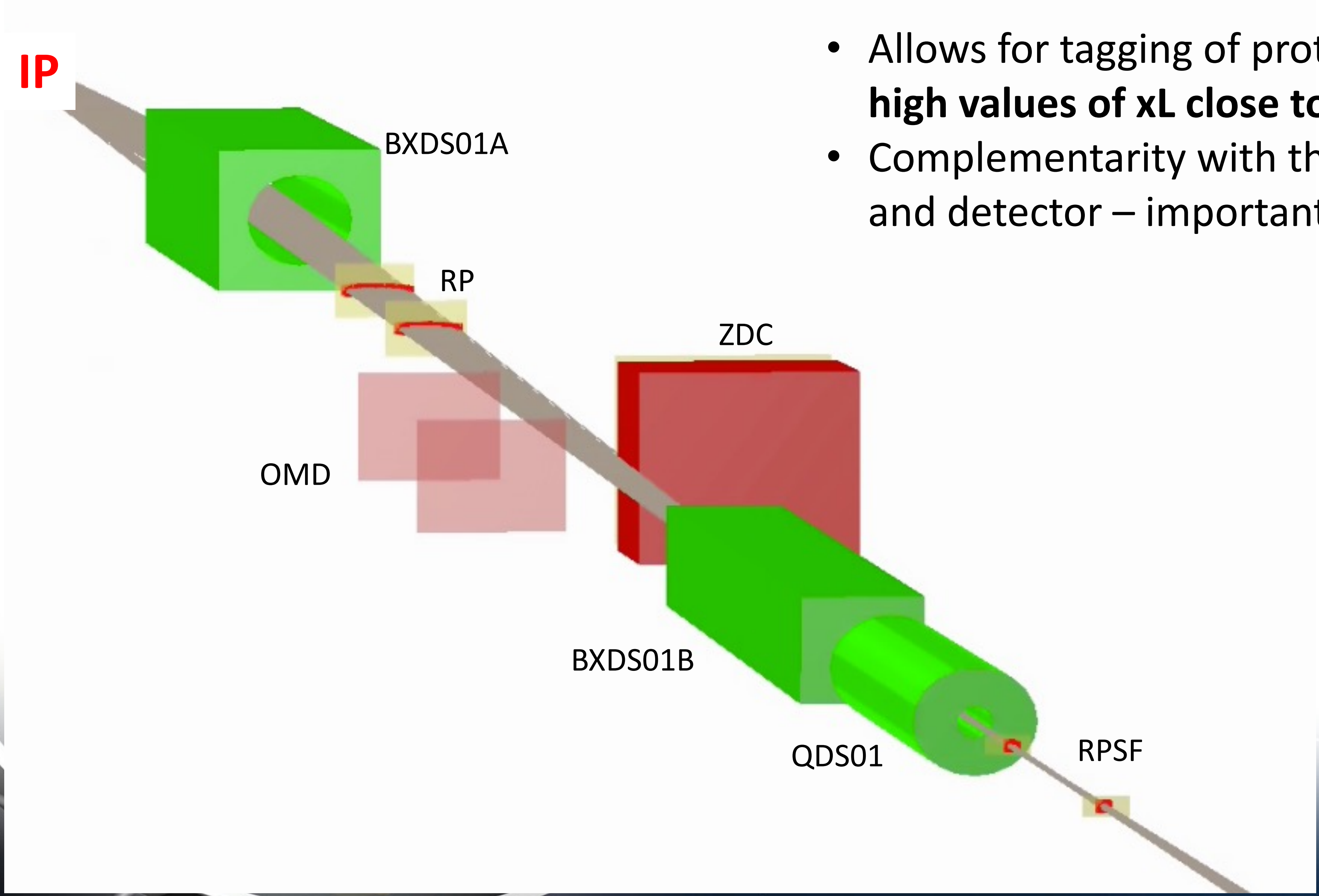
What about IP8?

IP8 (**pre**-conceptual) Layout (FF hadron-going)



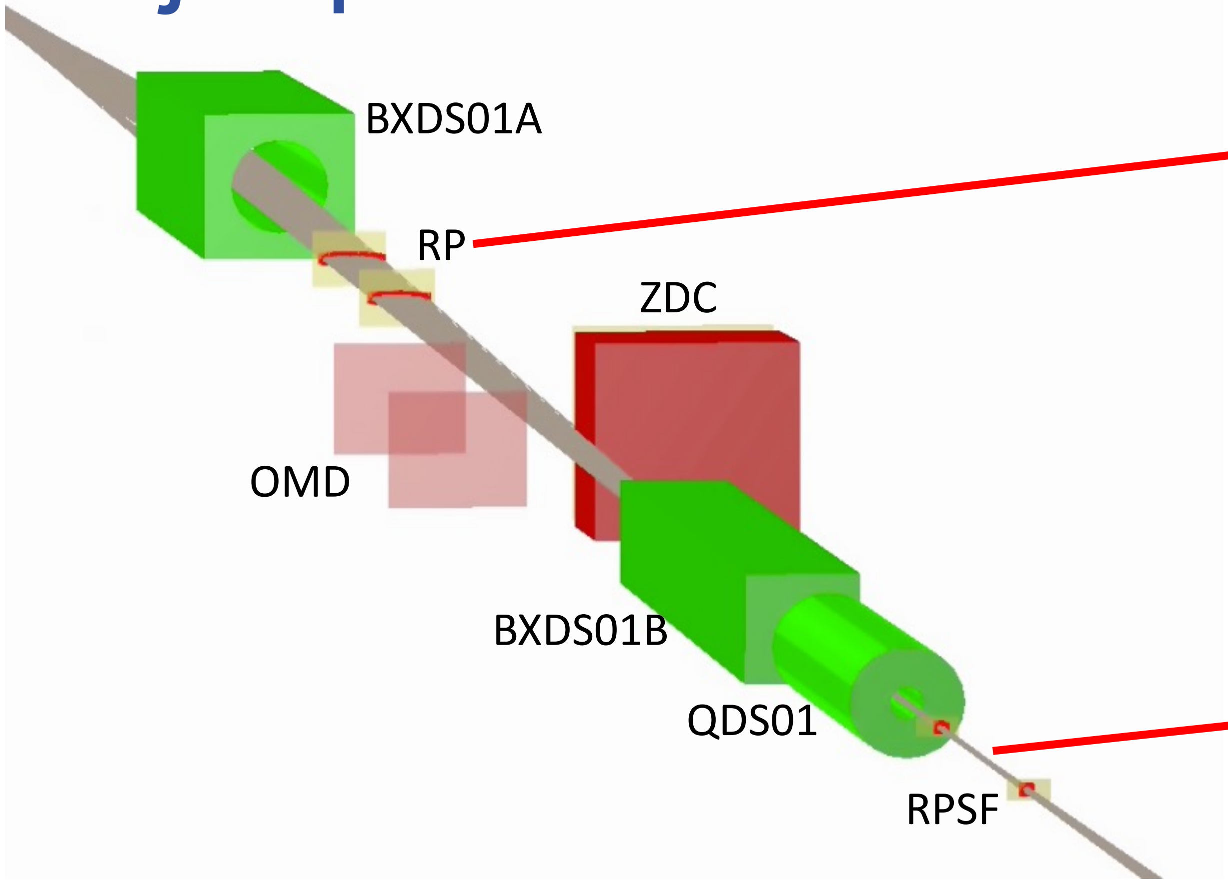
- 35 mrad crossing angle (25 mrad in IP6).
- Secondary focus – second set of Roman Pots!

Major potential benefit: Secondary Focus

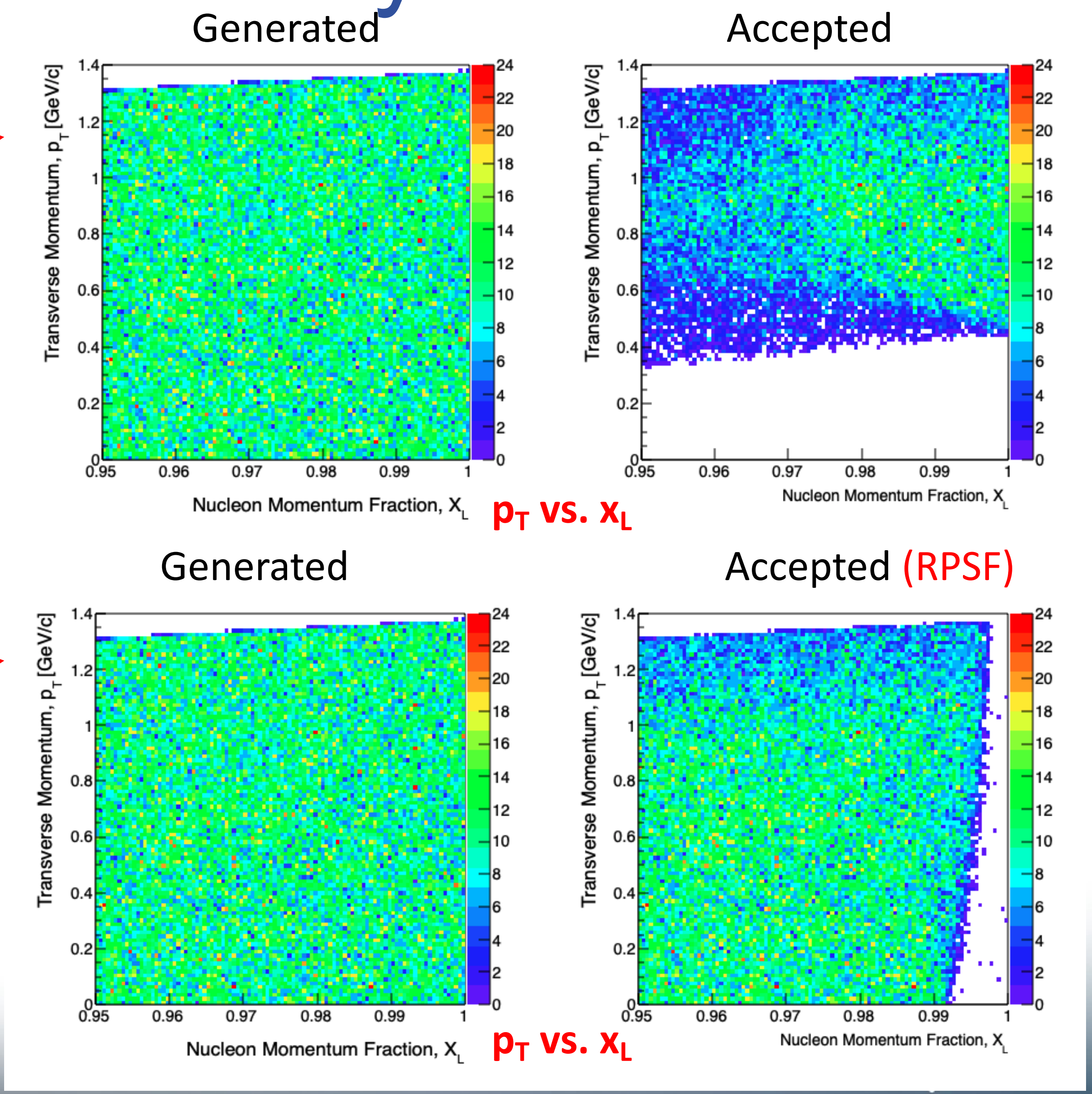


- Allows for tagging of protons and nuclei at very **high values of xL close to one** (pT ~ 0).
- Complementarity with the IP6 configuration and detector – important for the EIC!

Major potential benefit: Secondary Focus

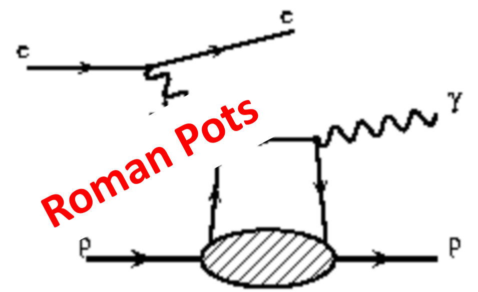


$$x_L = \frac{p_{z,particle}}{p_{beam}}$$



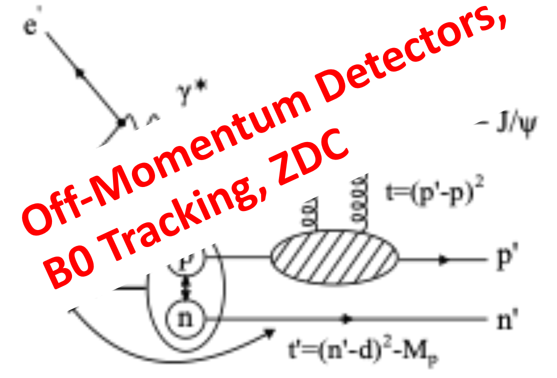
Far-Forward Processes at the EIC

e+p DVCS



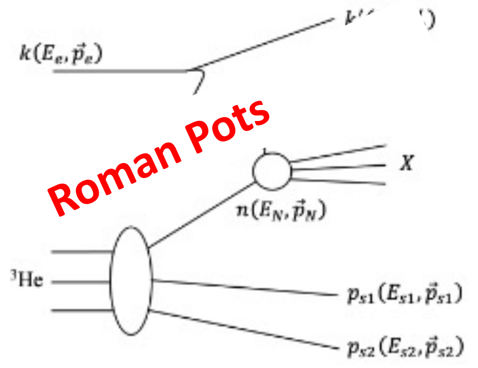
Roman Pots

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



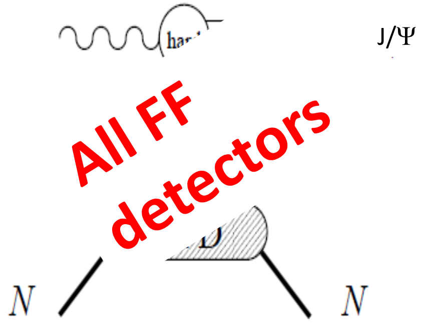
Off-Momentum Detectors, B0 Tracking, ZDC

e+He3 spectator tagging



Roman Pots

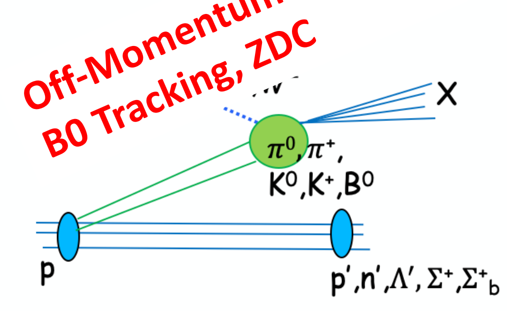
coherent/incoherent J/ψ production in e+A



All FF detectors

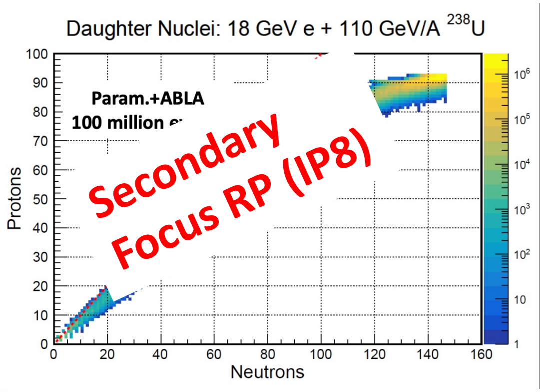
Meson structure:

- ep→ (π) →e' n X
- Λ →pπ^- and Λ



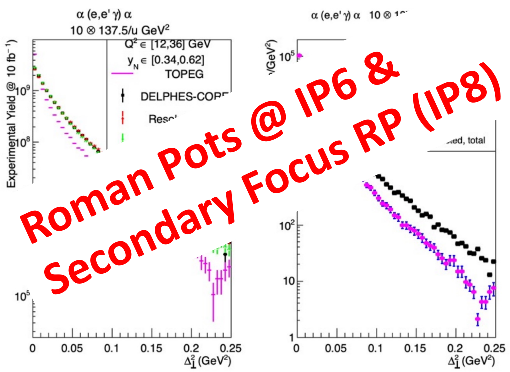
Off-Momentum Detectors, B0 Tracking, ZDC

Rare isotopes



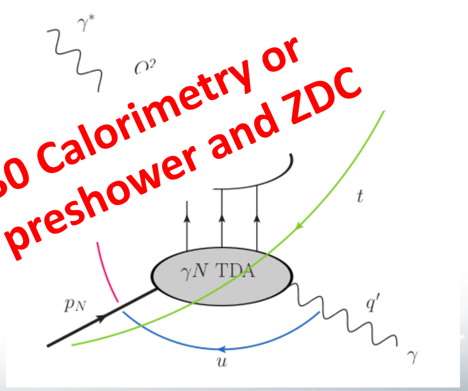
Secondary Focus RP (IP8)

e+He4 DVCS



Roman Pots @ IP6 & Secondary Focus RP (IP8)

u-channel backward exclusive electroproduction



B0 Calorimetry or preshower and ZDC

…and MANY more!

Summary and Takeaways

- All FF detector acceptances and detector performance well-understood with currently available information.
  - Numerous impact studies done!
    - Yellow Report, Detector proposals, and stand-alone impact studies.
  - Final technology choices identified, along with suitable alternate designs for risk mitigation.
- More realistic engineering considerations need to be added to simulations as design of IR vacuum system and magnets progresses toward CD-2/3a.
  - Lots of experience in performing these simulations, so this work will progress rapidly as engineering design matures.
  - Already well-established line of communication between detector and physics parties and the EIC machine/IR development group ⇒ Crucial for success!!!

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

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

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

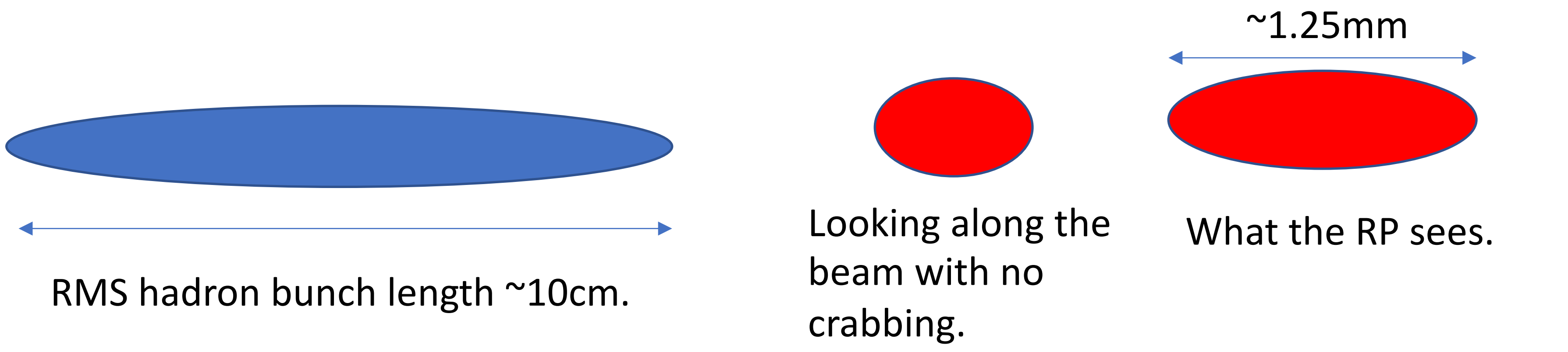
Email-list: eic-projdet-FarForw-l@lists.bnl.gov

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

Backup

Momentum Resolution – Timing

For exclusive reactions measured with the Roman Pots we need good timing to resolve the position of the interaction within the proton bunch. But what should the timing be?



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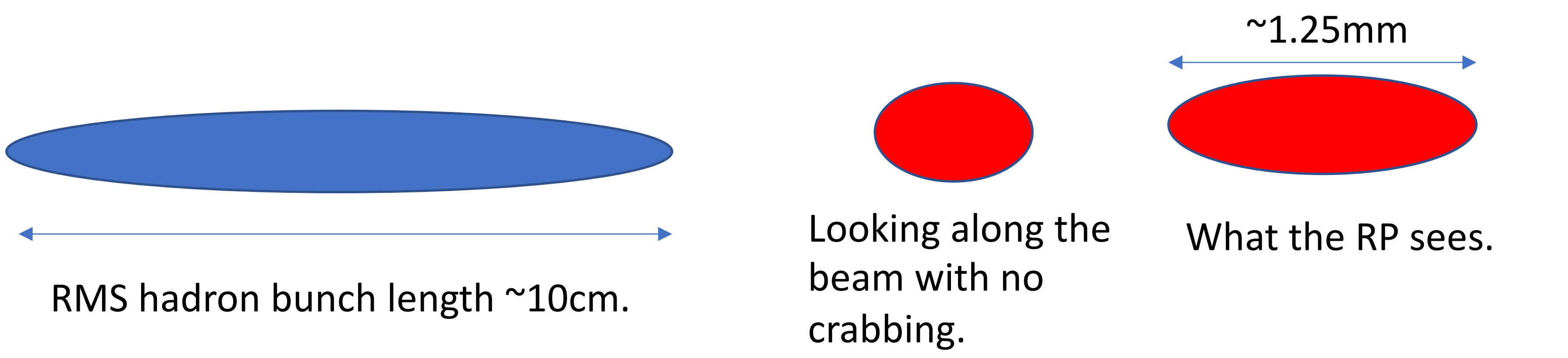

- Because of the rotation, the Roman Pots see the bunch crossing smeared in x.
- Vertex smearing = 12.5mrad (half the crossing angle) * 10cm = **1.25 mm**
- If the effective vertex smearing was **for a 1cm bunch**, we would have **.125mm** vertex smearing.
- The simulations were done with these two extrema and the results compared.

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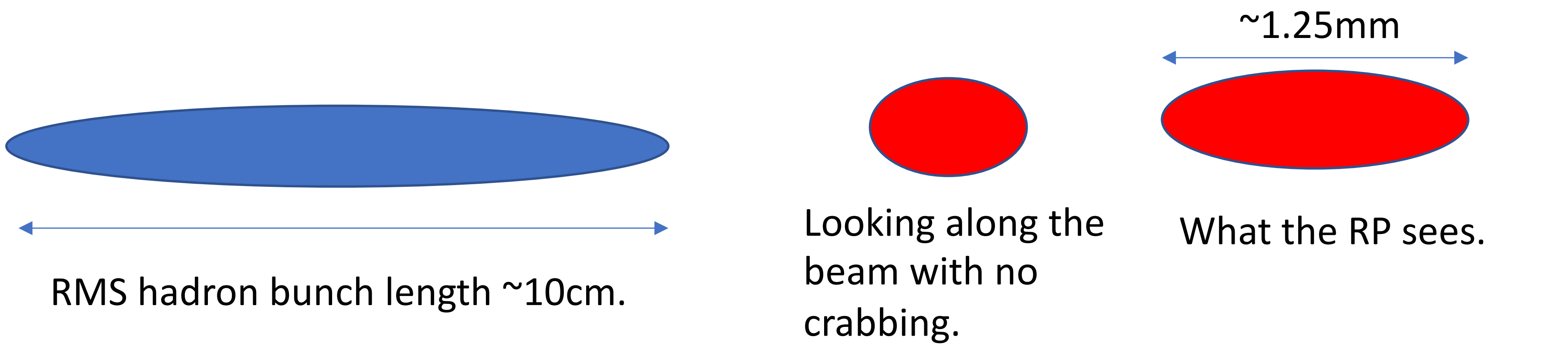

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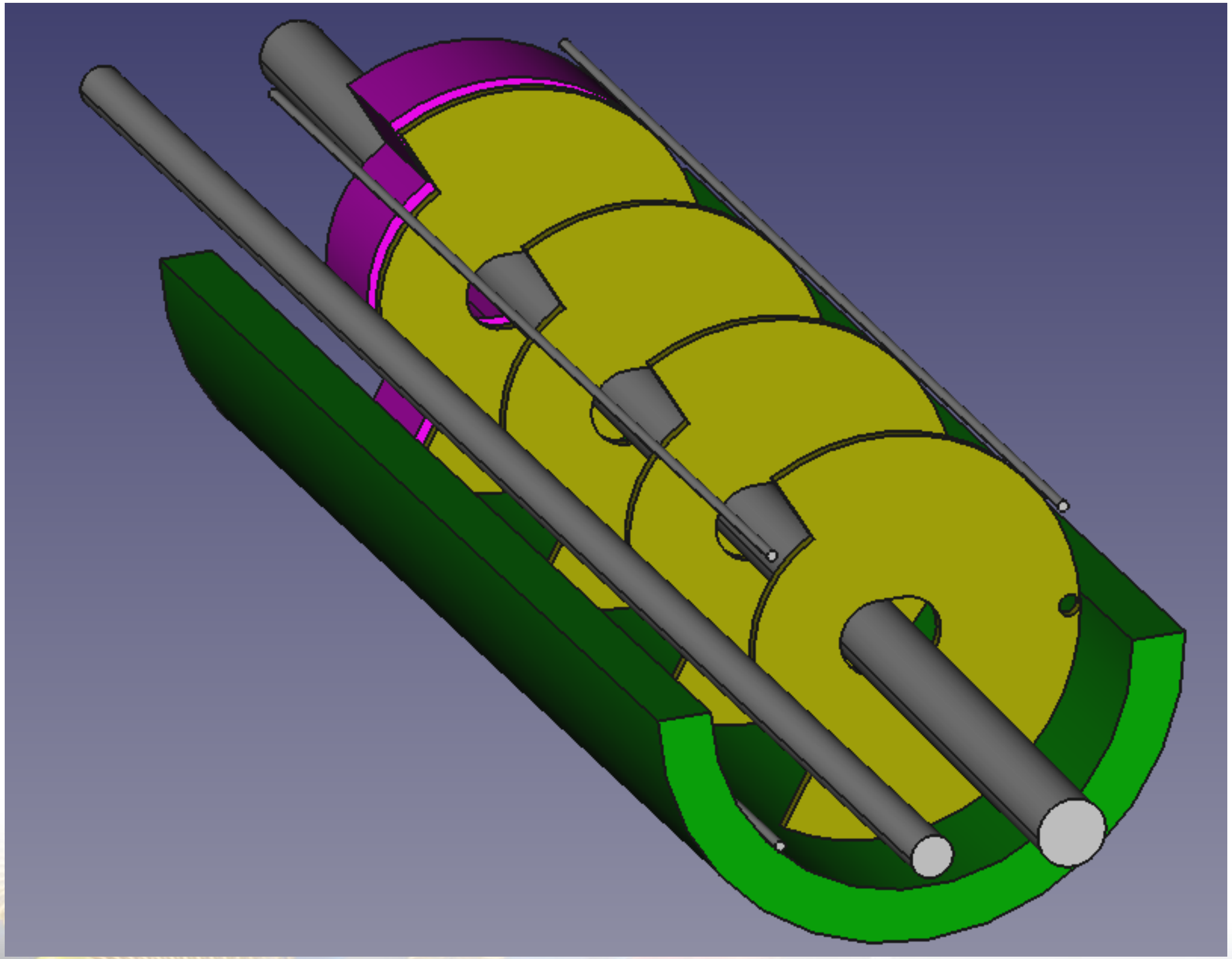
- The simulations were done with these two extrema and the results compared.

> - **From these comparisons, reducing the effective vertex smearing to that of the 1cm bunch length reduces the momentum smearing to negligible from this contribution.**
> - **This can be achieved with timing of ~ 35ps (1cm/speed of light).**

B0-detectors (calorimetry)

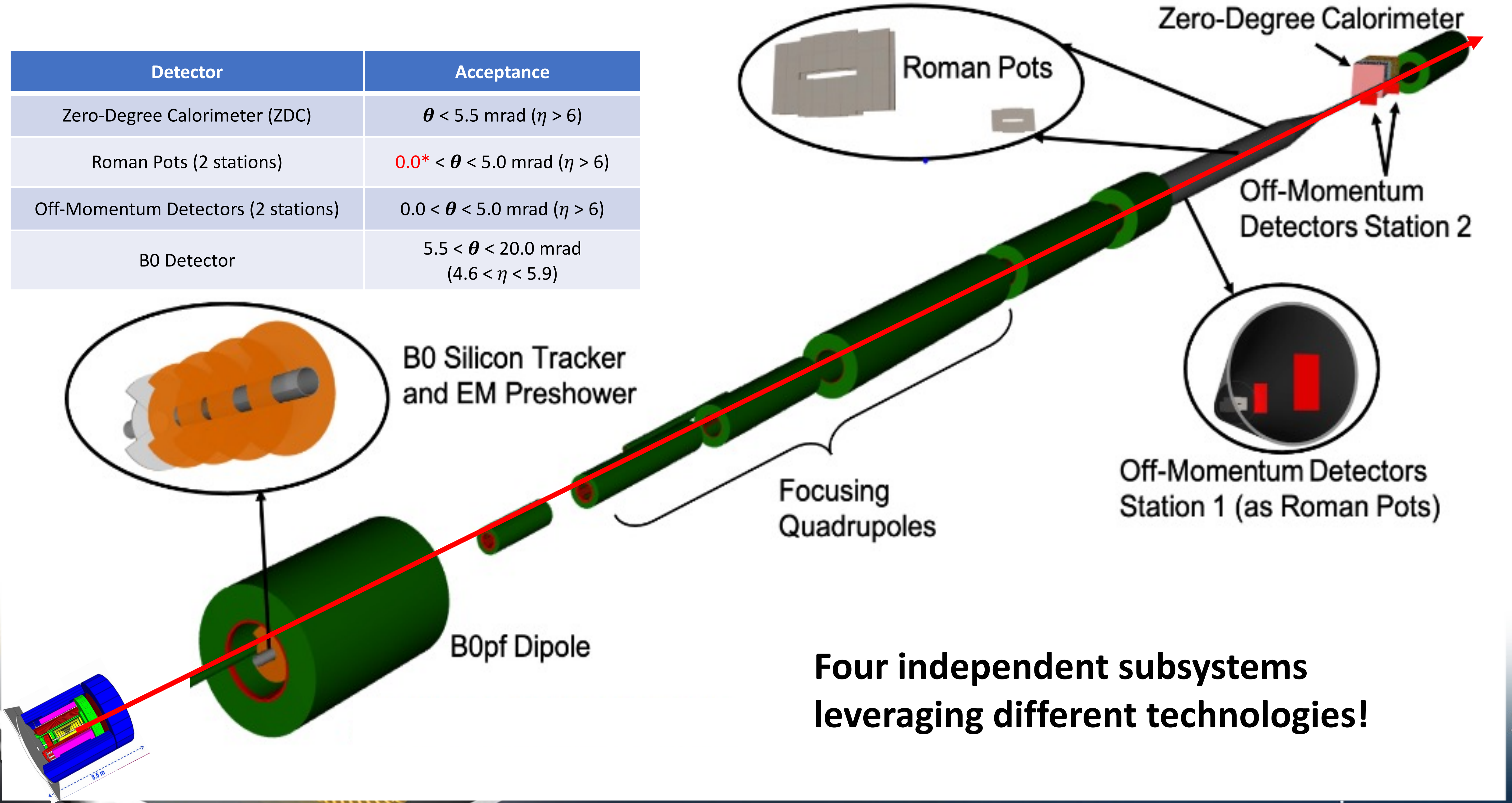


- For studies of *u*-Channel (Backward-angle) exclusive electroproduction, need capability to reconstruct photons from π^0 decays.
  - Physics beyond the EIC white paper!
- Would require full EMCAL with high granularity and energy resolution.
  - ➢ $PbWO_4$ used in ECCE studies.
- Longitudinal space in B0pf magnet limited.
  - Would be a great candidate for an upgrade or for IP8 complementarity!

Thanks to Bill Li for the figure!

The Far-Forward Detectors

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



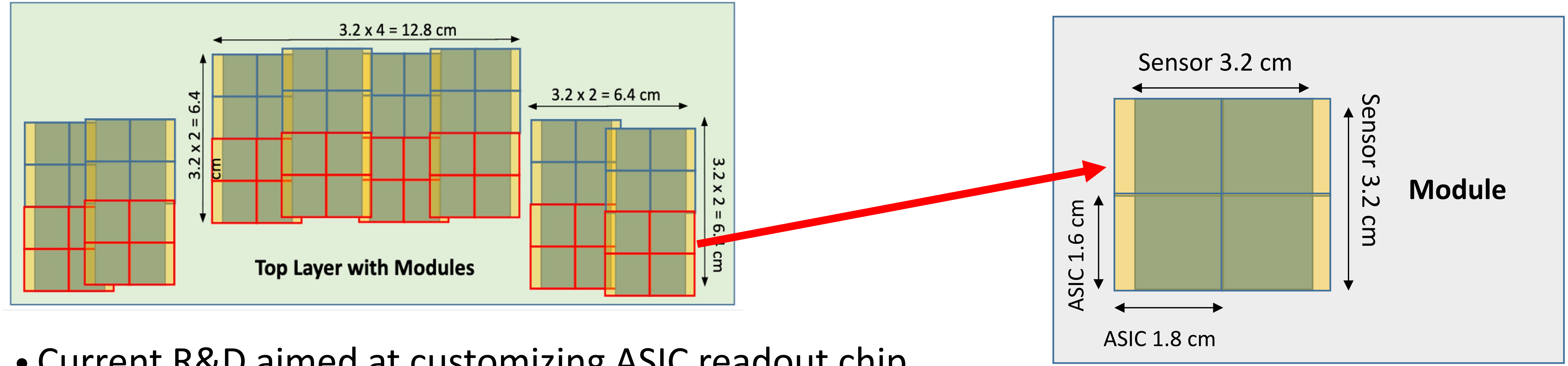
Four independent subsystems leveraging different technologies!

Roman Pots

- Active sensor area very large (26cm x 13cm).
- “Potless” design could make better use of space.
- With AC-LGADS + ALTIROC ASIC, current estimates of power dissipation around 400-500 watts for entire subsystem, so roughly 100 watts/layer.
    - With potless design, leveraging experience from LHCb VELO for cooling would allow for cooling of the electronics within the vacuum.
- Support structure only to be placed between hadron pipe and wall to avoid interference with the ZDC.

Roman Pots

- Updated layout with current design for AC-LGAD sensor + ASIC.

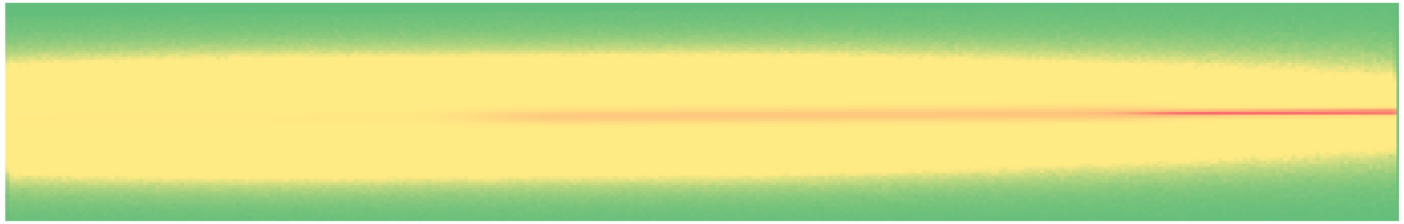


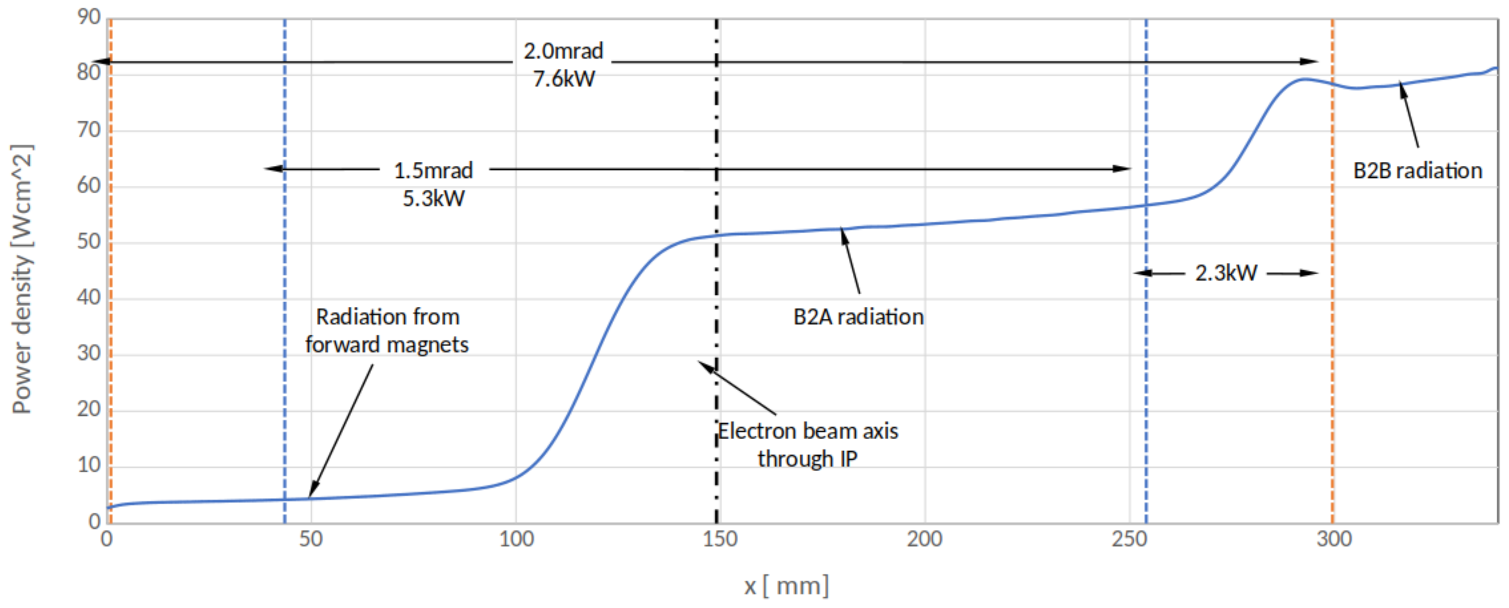
- Current R&D aimed at customizing ASIC readout chip (ALTIROC) for use with AC-LGADs.

ASIC size	ASIC Pixel pitch	# Ch. per ASIC	# ASICs per module	Sensor area	# Mod. per layer	Total # ASICs	Total # Ch.	Total Si Area
1.6x1.8 cm^2	500 μm	32x32	4	3.2x3.2 cm^2	32	512	524,288	1,311 cm^2

Power by synchrotron radiation on the exit window

- Power density imposed by synchrotron radiation
- 1.5 mrad and 2.0 mrad indicate possible acceptance to bremsstrahlung photons

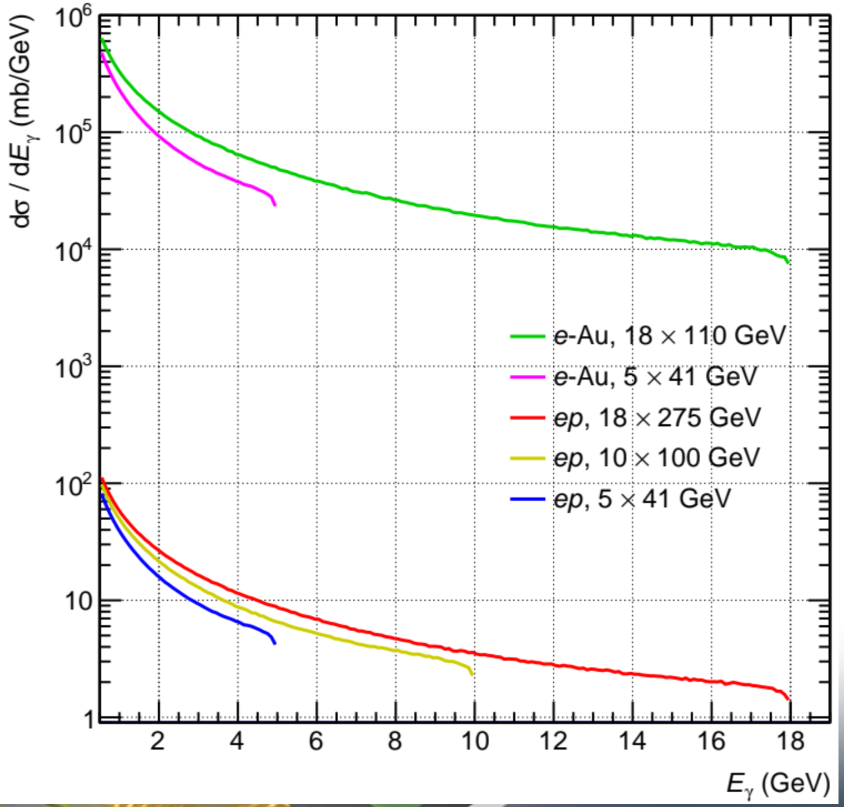


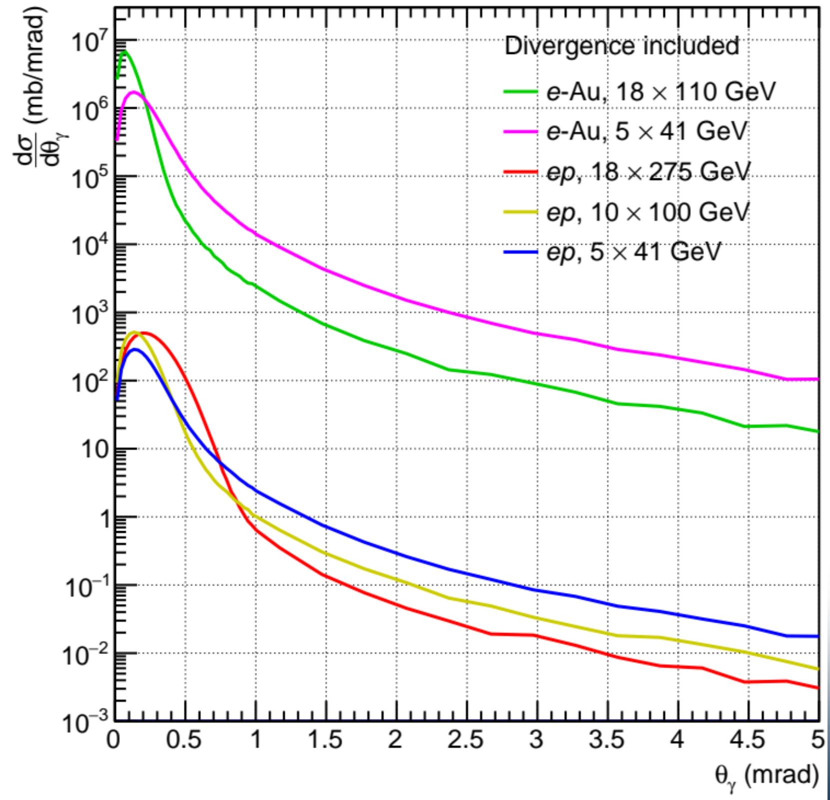


Charles Hetzel

Bremsstrahlung cross section in photon energy and polar angle

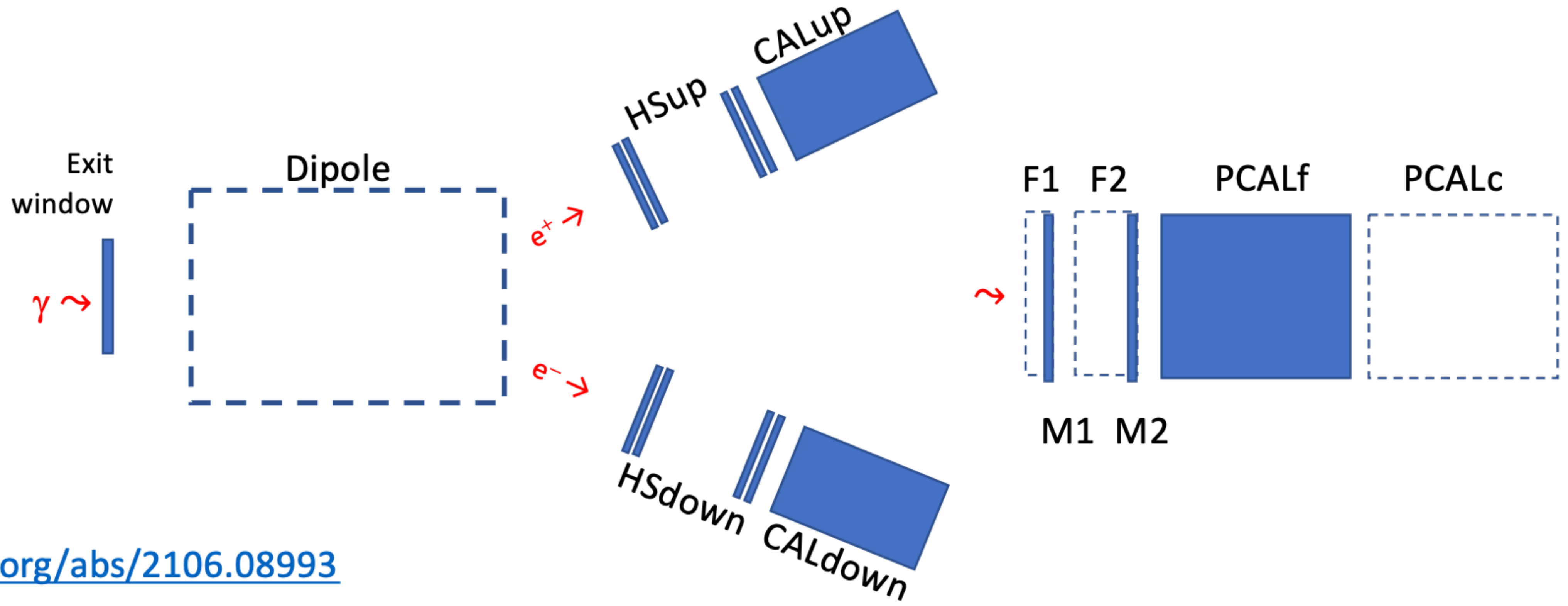
- Large cross sections especially in e-Au, dedicated event generator, arXiv:2105.10570
- Angular divergence has a strong effect at small angles





Luminosity Monitor

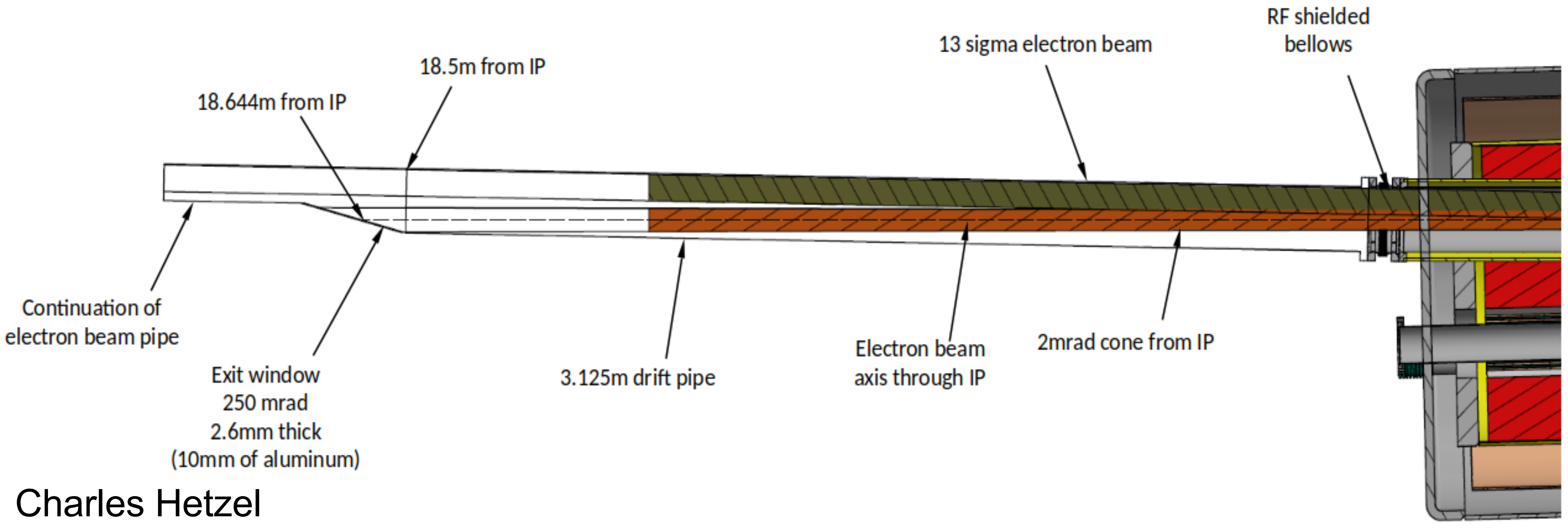
- Must make measurement in challenging environment.
  - High synchrotron radiation, high bremsstrahlung rates (~10 GHz), etc.
- Need ~1% for absolute luminosity measurement, $\sim 10^{-4}$ for relative luminosity measurement.
- Can make direct photon measurement, or indirect via pair conversion in exit window, where e^+e^- pair is steered toward two calorimeters opposite a dipole magnet.
- Direct photon calorimeter includes moveable SR filters/monitors (F1 and F2), and has configurations for high (PCALf) and low (PCALc) luminosity running.



https://arxiv.org/abs/2106.08993

Exit window for luminosity monitor

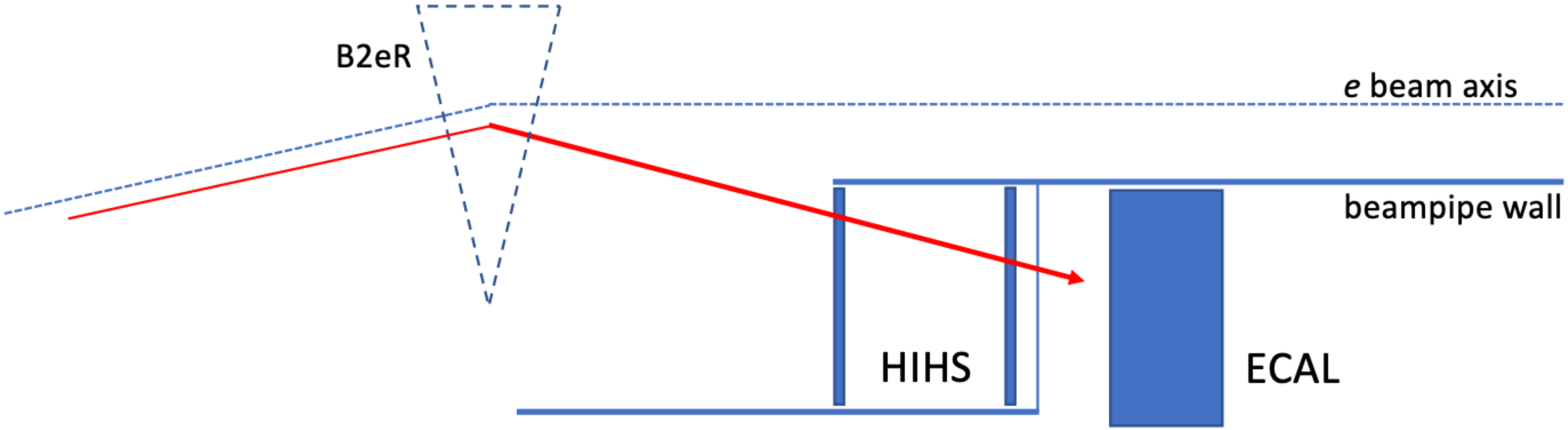
- Part of outgoing electron beam pipe
- Conversion layer for bremsstrahlung photons
- Tilt angle vs. electron (and photon) beam axis against synchrotron radiation



Charles Hetzel

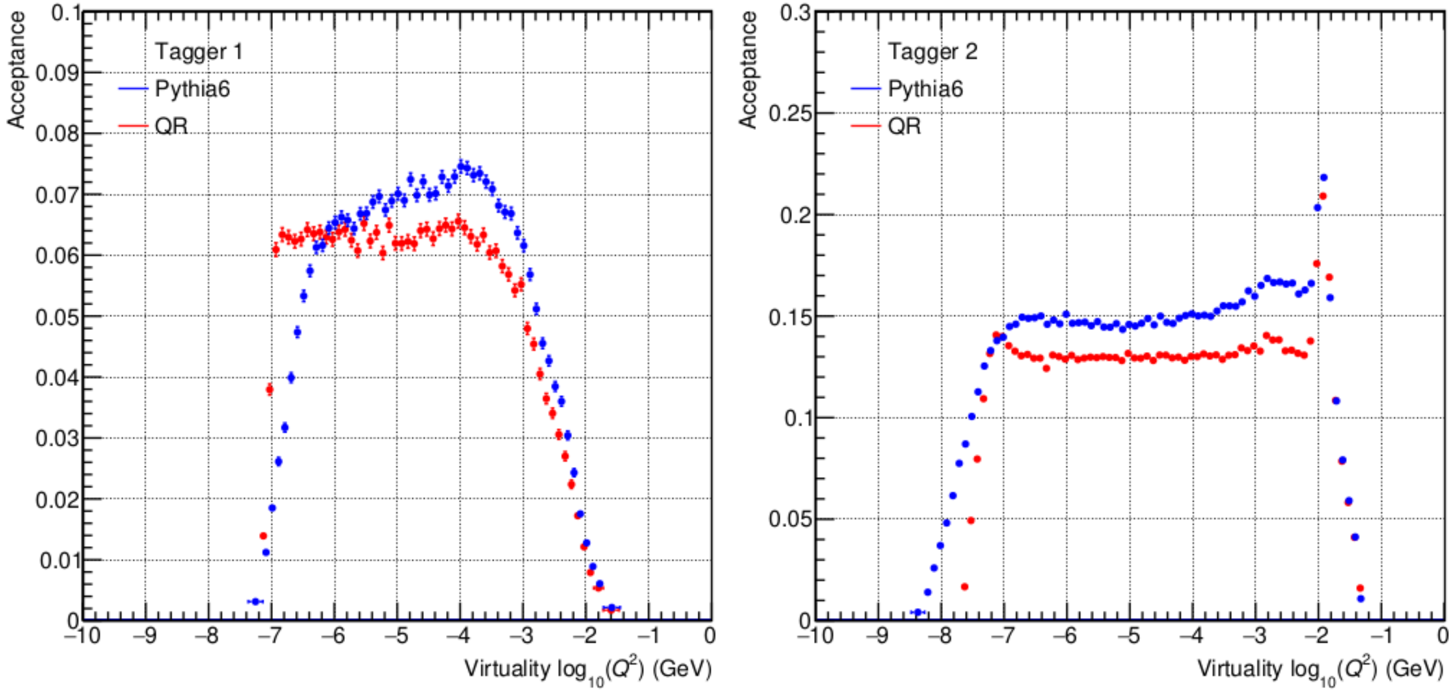
Low-Q^2 Taggers

- Two taggers for reconstructing electrons from low-Q^2 ($< 10^{-1}$ GeV^2) reactions.
- Combination of EM calorimetry for energy reconstruction, and silicon layers (High Resolution Hodoscope – HIHS) for position and angular resolution.

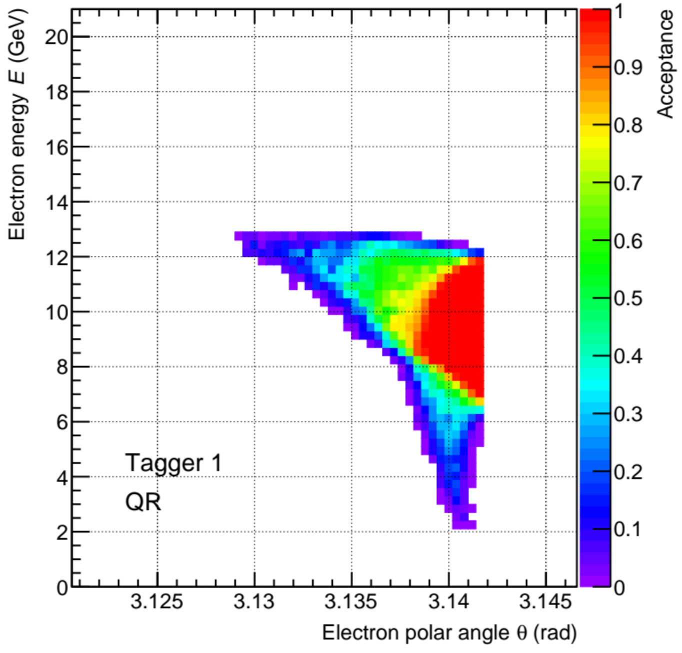


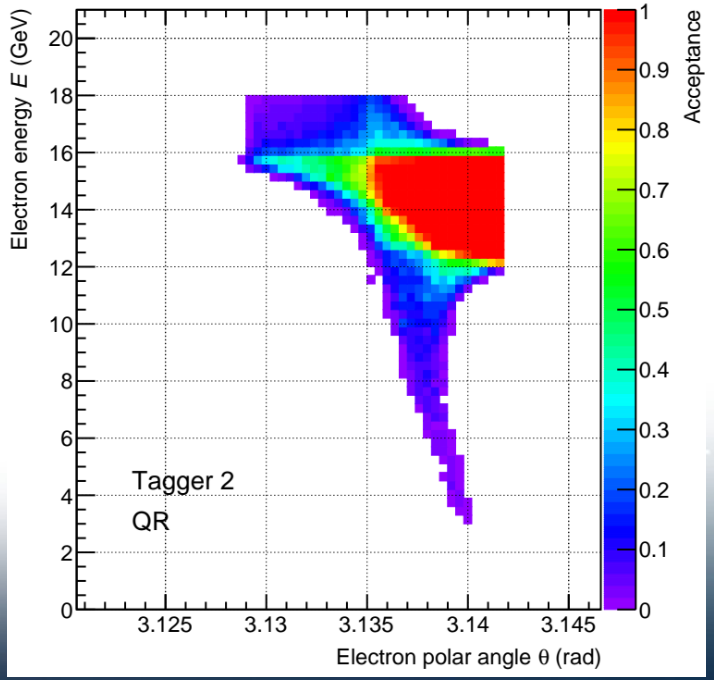
Performance for low-Q2 tagger

- Tagger 1 and 2 are placed closer (further) from the IP
- Overlap in Q2 acceptance (< 0.1 GeV^2)
- Complementary in electron energy (higher energies reach Tagger 2)
- Consistent for Pythia6 and quasi-real photoproduction (QR)



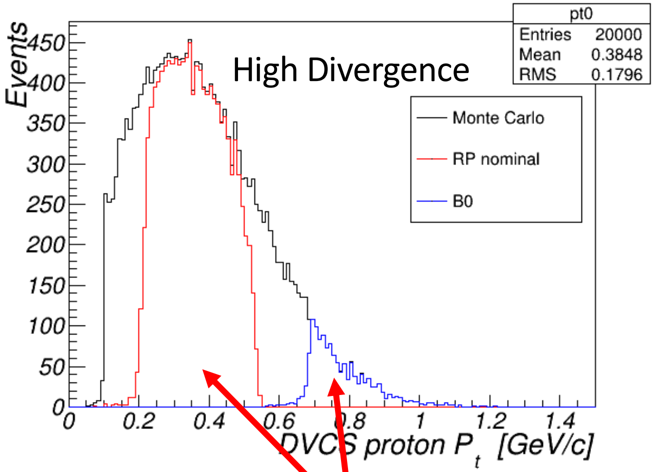
(a) Tagger 1 (b) Tagger 2

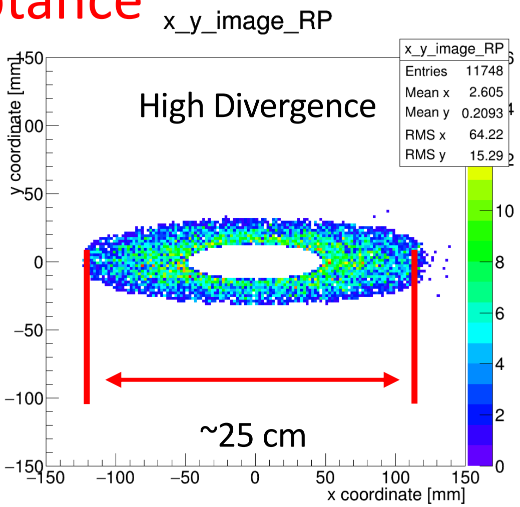


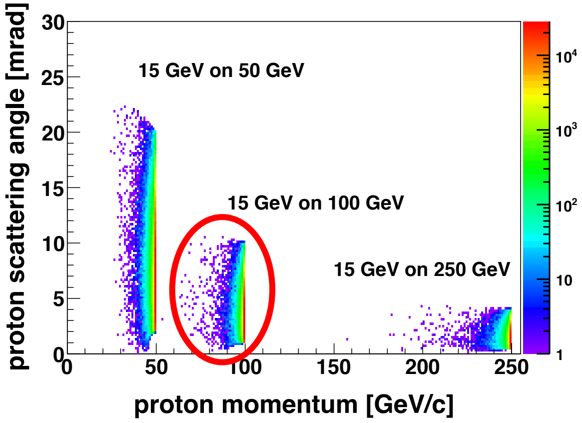


Machine Optics: Roman Pots

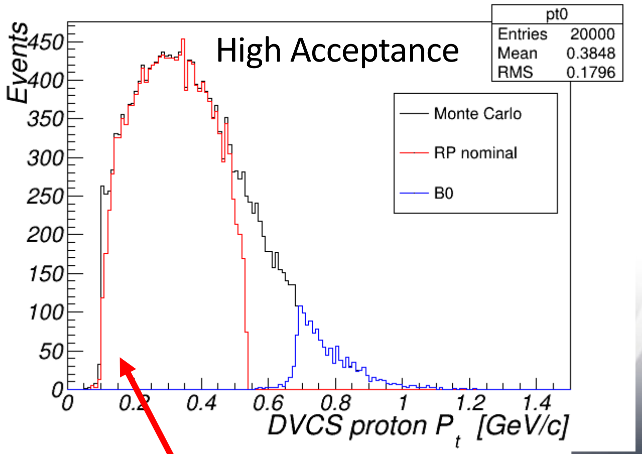
100 GeV DVCS Proton Acceptance

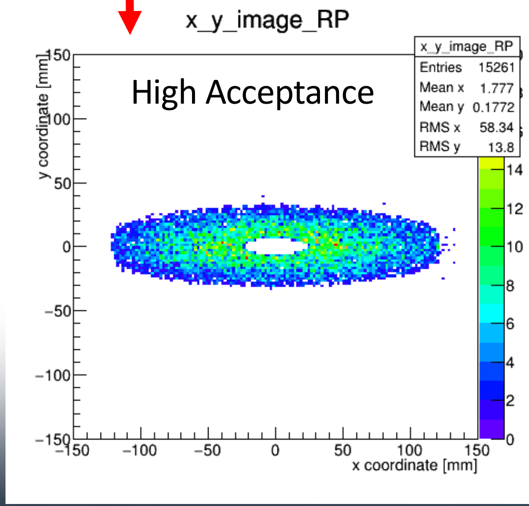






Need both detector systems together here!





Improves low p_t acceptance.

Momentum Resolution – Comparison

- The various contributions add in quadrature (this was checked empirically, measuring each effect independently).

$$\Delta p_{t,total} = \sqrt{(\Delta p_{t,AD})^2 + (\Delta p_{t,CC})^2 + (\Delta p_{t,pxl})^2}$$

$(\Delta p_{t,AD})^2$: Angular divergence

$(\Delta p_{t,CC})^2$: Primary vertex smearing from crab cavity rotation.

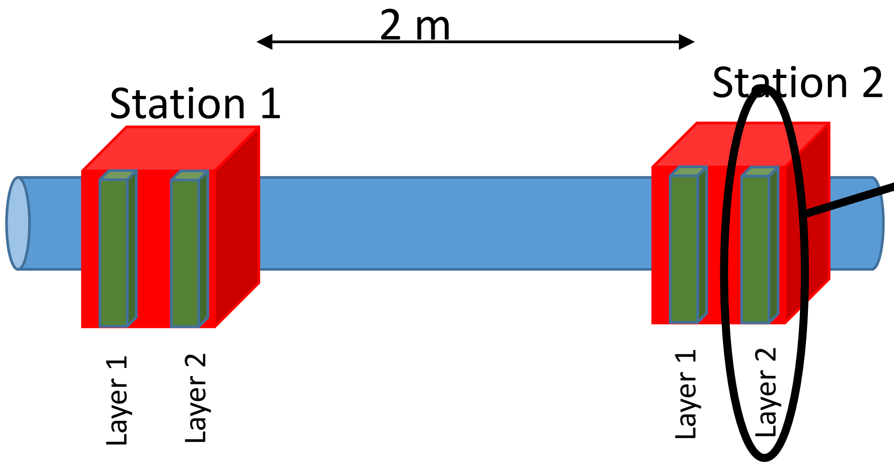
$(\Delta p_{t,pxl})^2$: Smearing from finite pixel size.

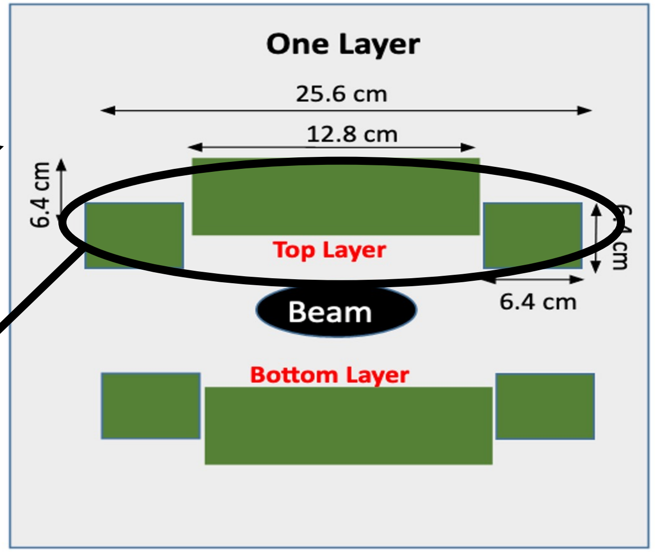
	Ang Div. (HD)	Ang Div. (HA)	Vtx Smear	250um pxl	500um pxl	1.3mm pxl
$\Delta p_{t,total}$ [MeV/c] - 275 GeV	40	28	20	6	11	26
$\Delta p_{t,total}$ [MeV/c] - 100 GeV	22	11	9	9	11	16
$\Delta p_{t,total}$ [MeV/c] - 41 GeV	14	-	10	9	10	12

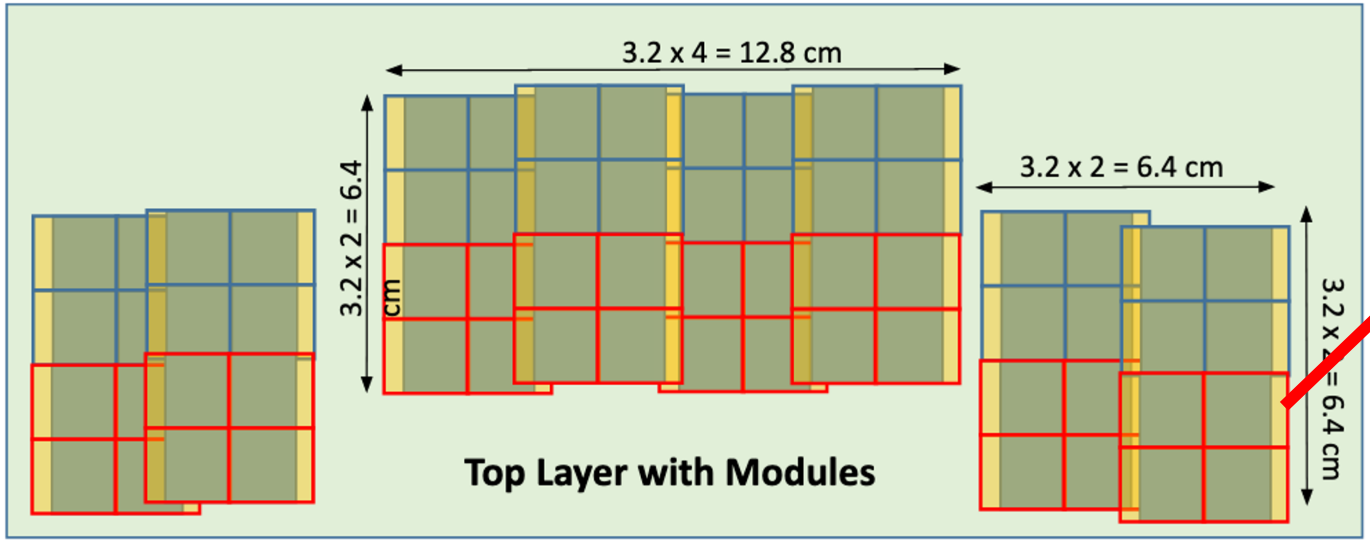
- **Beam angular divergence**
  - Beam property, can't correct for it – sets the lower bound of smearing.
  - Subject to change (i.e. get better) – beam parameters not yet set in stone
- **Vertex smearing from crab rotation**
  - Correctable with good timing (~35ps)
- **Finite pixel size on sensor**
  - 500um seems like the best compromise between potential cost and smearing

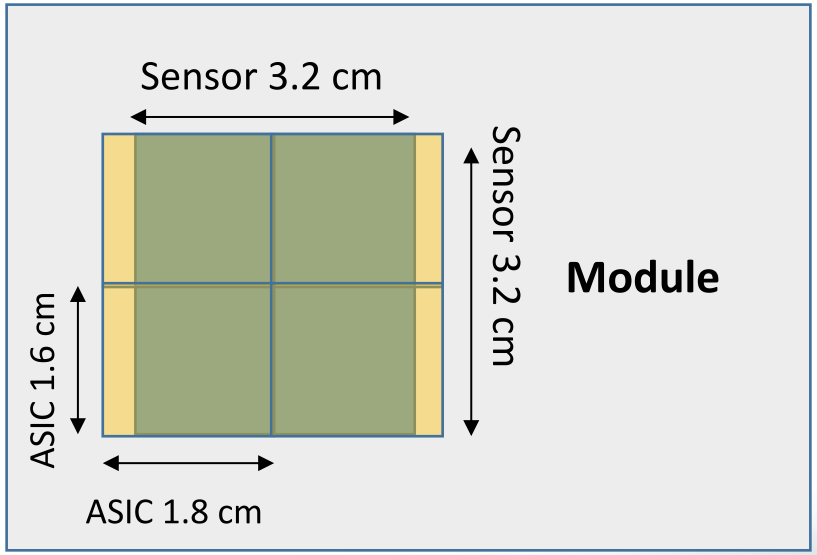
Roman Pots @ the EIC

- Updated layout with current design for AC-LGAD sensor + ASIC.









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Based on eRD24 R&D work.