Detector 1 Far-Forward Subsystems

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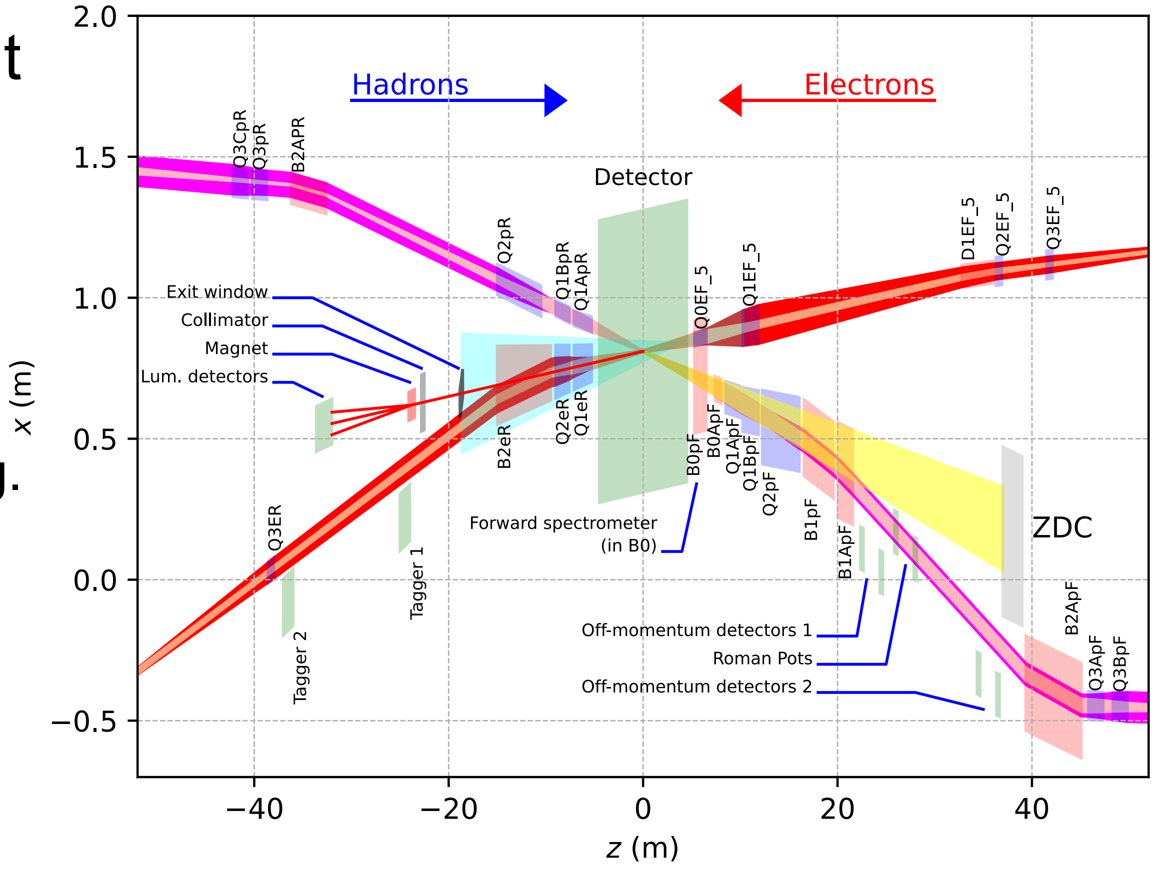
Detector 1 General Meeting

May 13th, 2022

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

Some Preliminaries

- Mostly focus on what was covered in the recent Far-Forward/Far-Backward technical review.
  - Thursday April 27th, 2022
- Main goal for the group is to advance the **technical design.**
  - Primary technology choices already made, alternatives identified.
  - Integration issues will drive a few final decisions (e.g. calorimetry in the B0).
  - As engineering developments are made, integrate into GEANT4 simulations and study impact.



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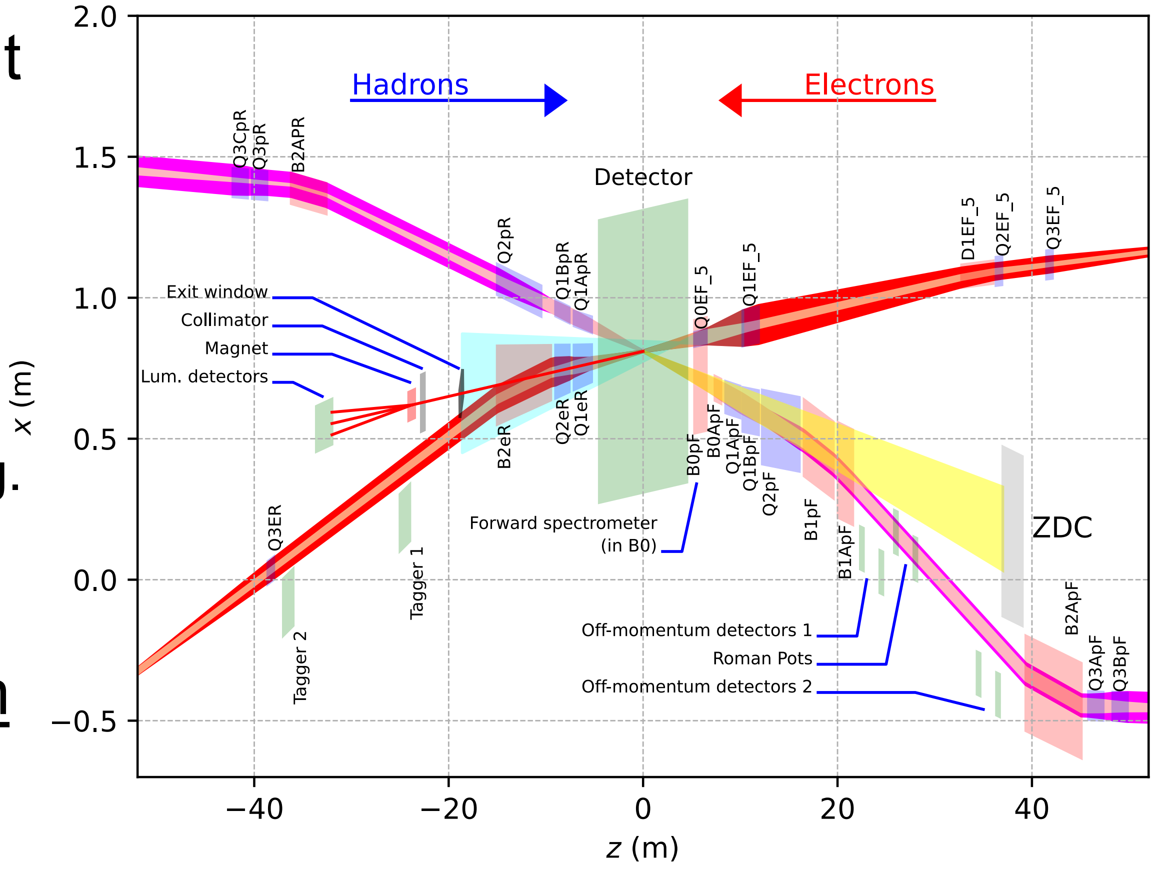
  - As engineering developments are made, integrate into GEANT4 simulations and study impact.
- Weekly meetings: <u>Every other Tuesday @ 9am EDT.</u>
  - Indico: https://indico.bnl.gov/category/407/
- Convener's emails can be found on the Wiki.
  - https://wiki.bnl.gov/eic-project-detector/index.php/Collaboration#Collaboration



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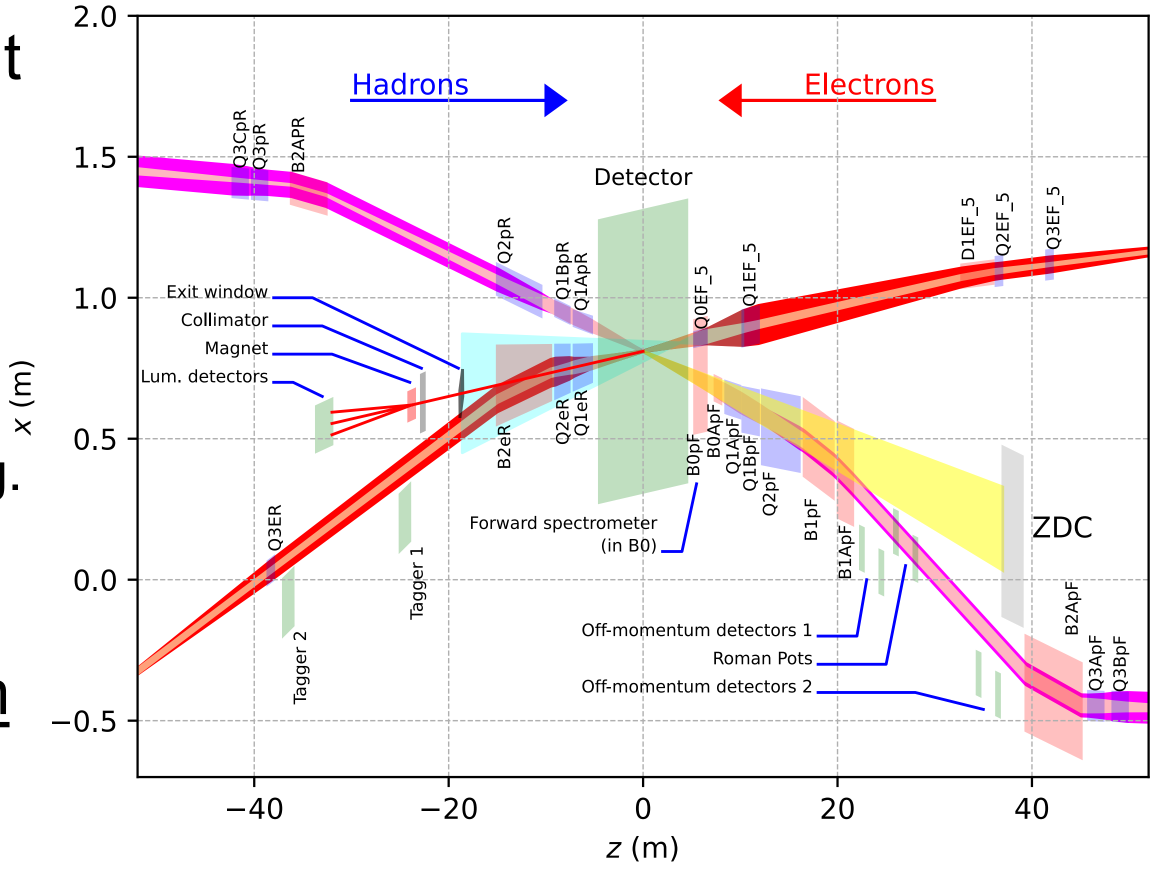
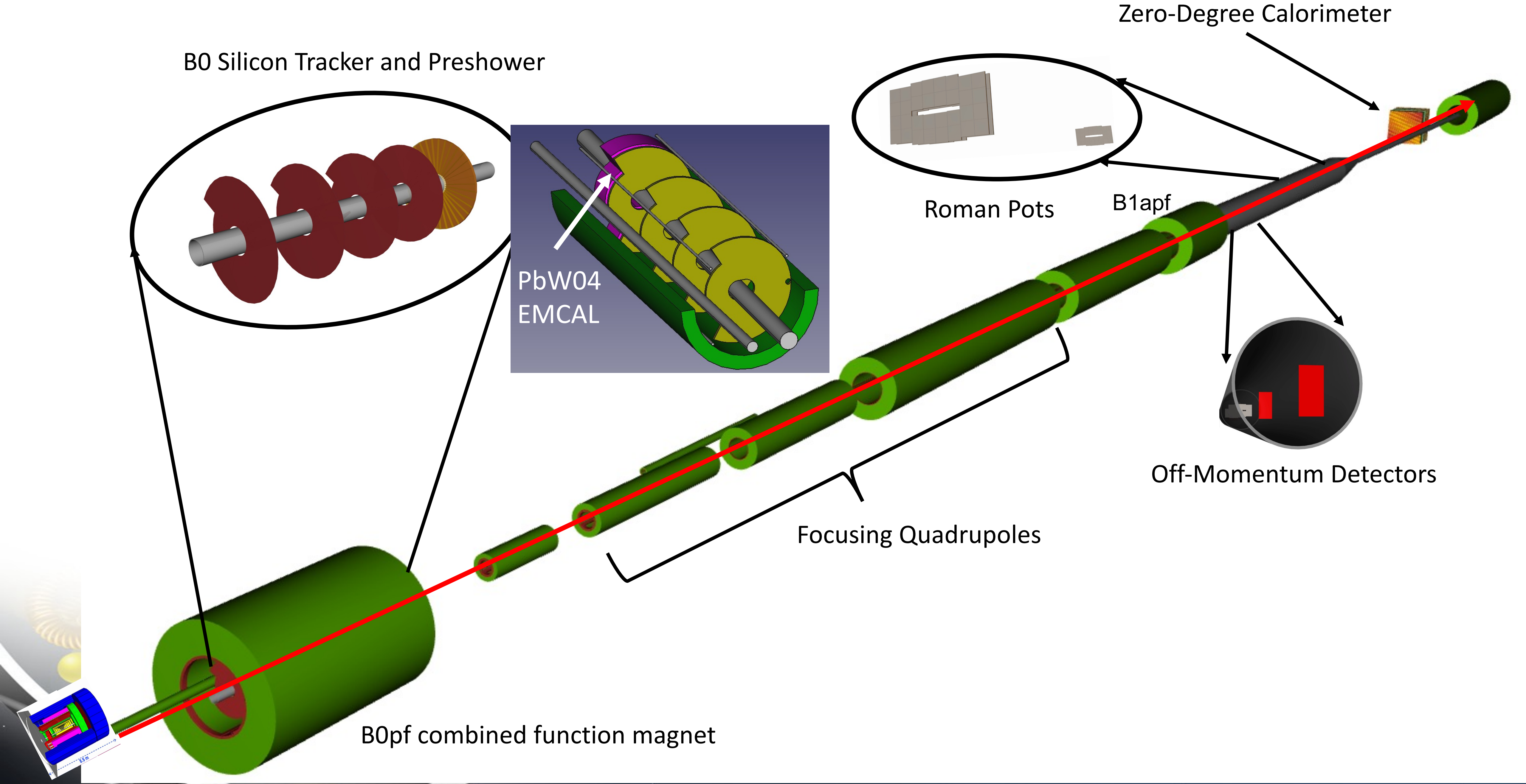
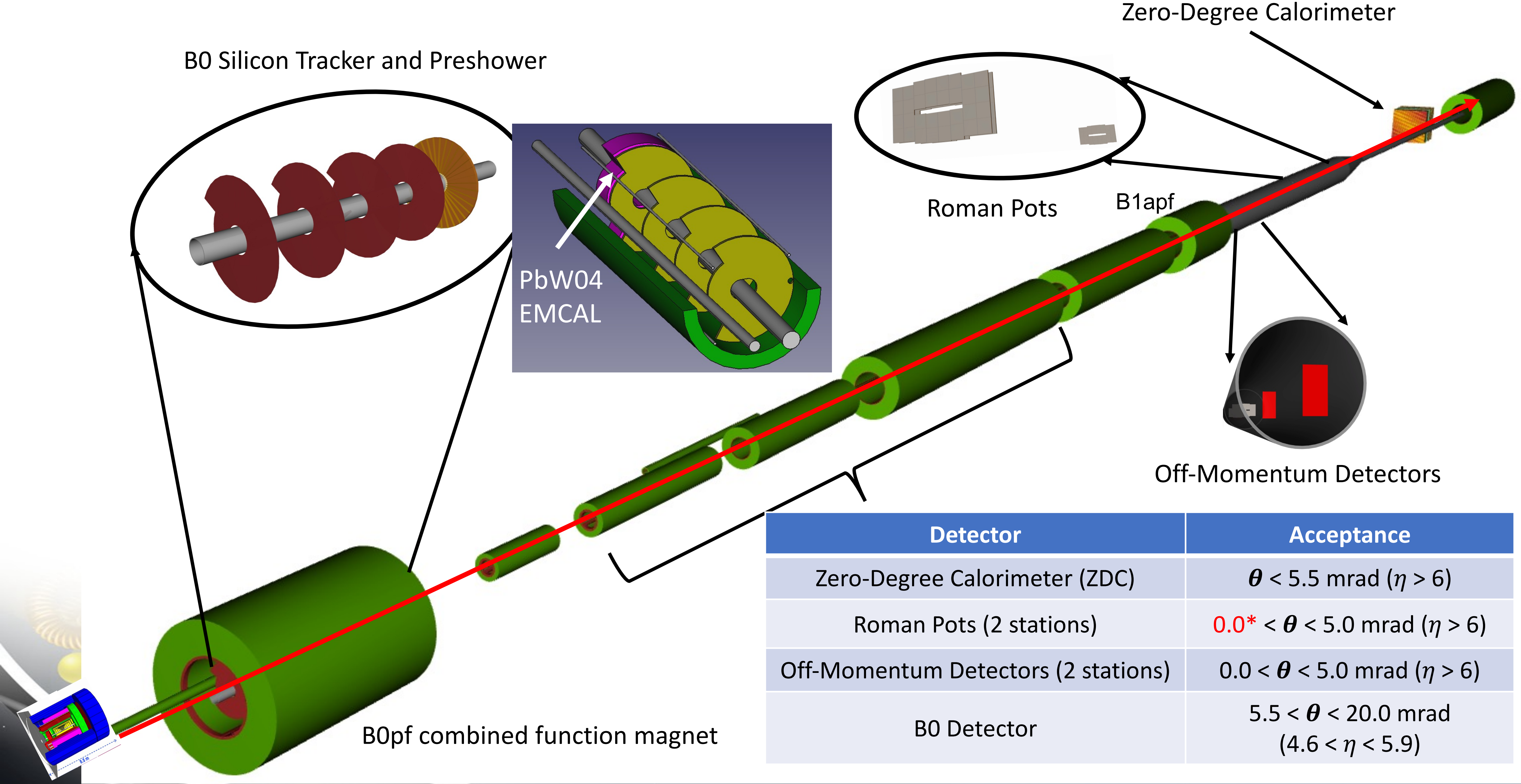


Merging of ECCE and ATHENA groups was seamless. Many of us worked together on the Yellow Report, and there were only very minor differences in the FF design between the two groups.

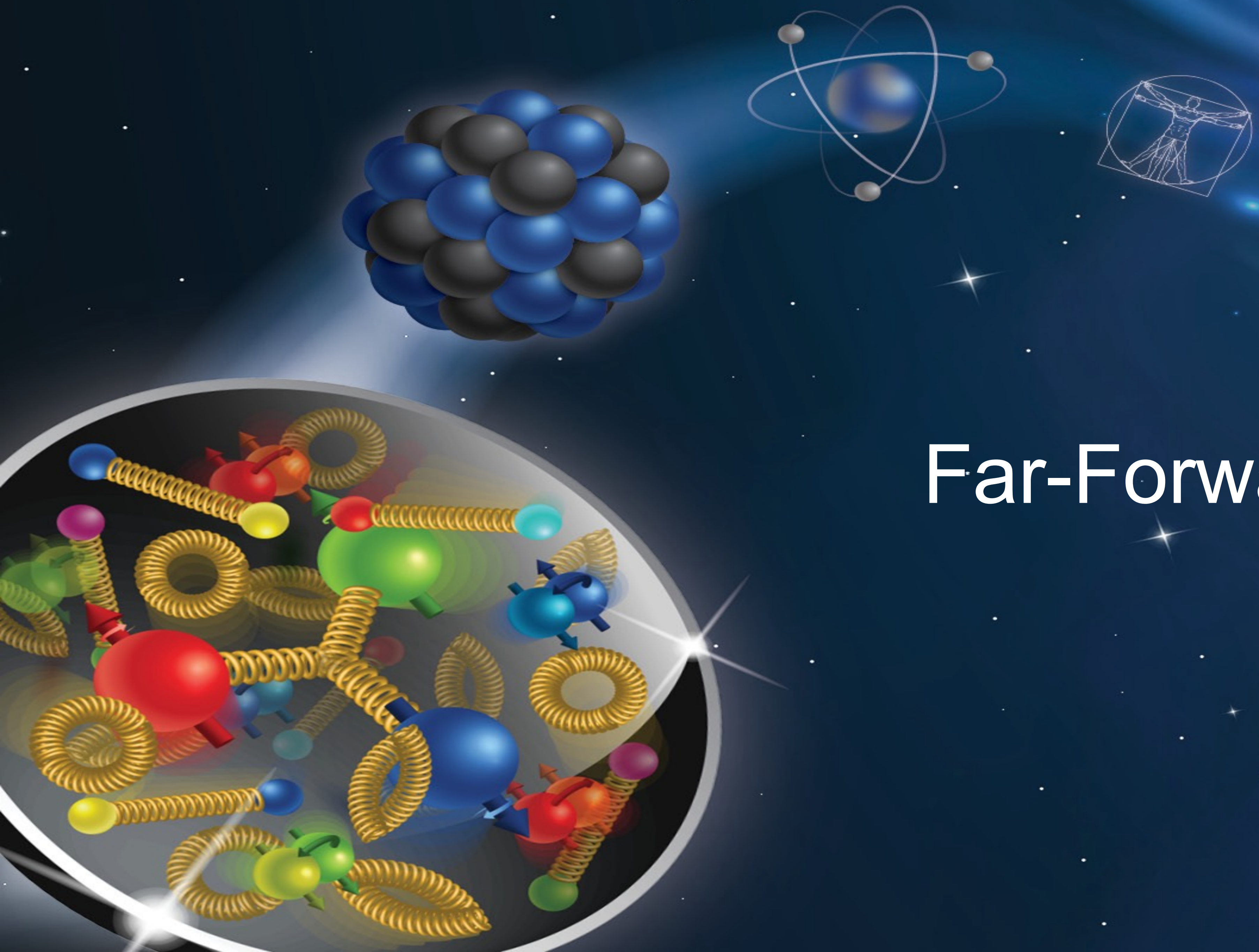
The Far-Forward Detectors



The Far-Forward Detectors



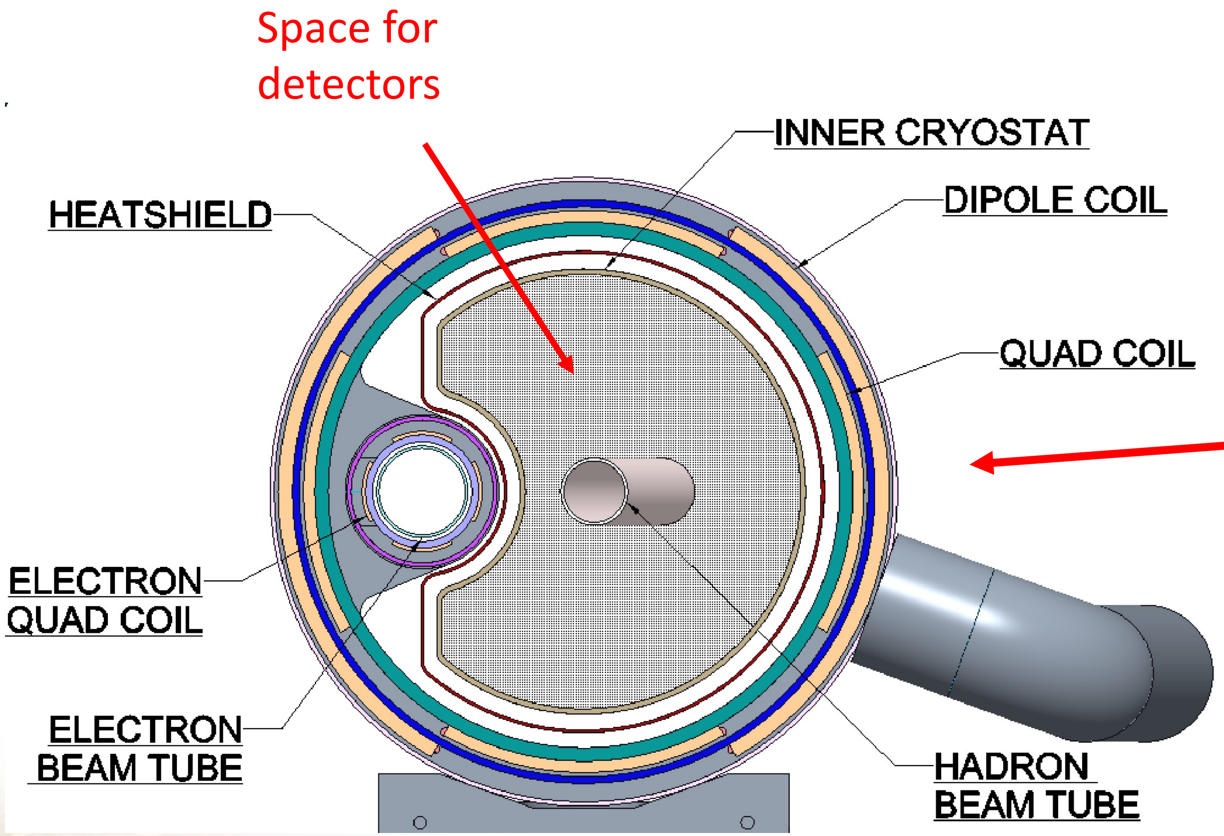
Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	θ < 5.5 mrad (η > 6)
Roman Pots (2 stations)	0.0* < θ < 5.0 mrad (η > 6)
Off-Momentum Detectors (2 stations)	0.0 < θ < 5.0 mrad (η > 6)
B0 Detector	5.5 < θ < 20.0 mrad (4.6 < η < 5.9)

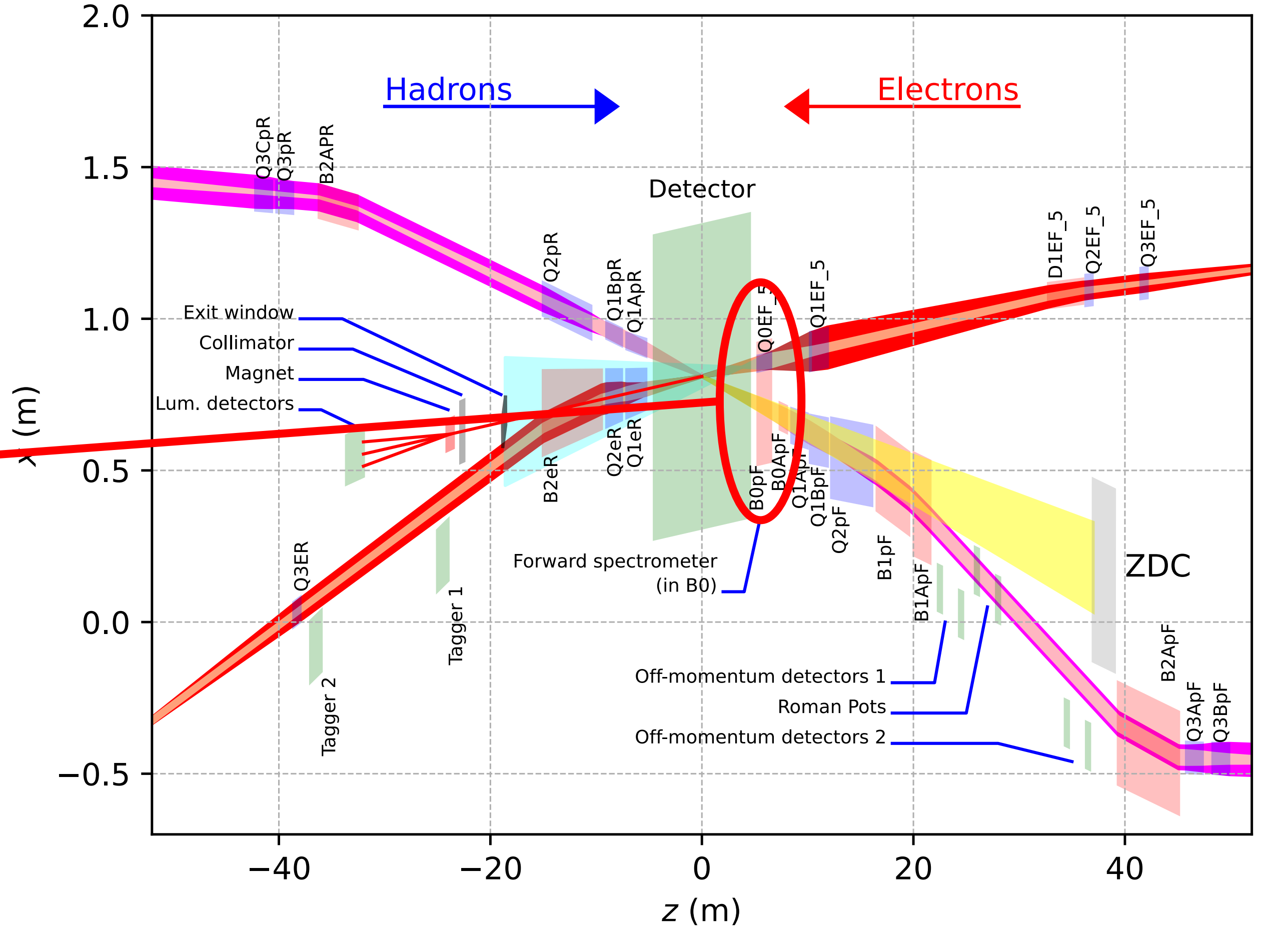


Far-Forward Detector Subsystems

B0 Detectors

Integrated with B0pf combined function magnet.

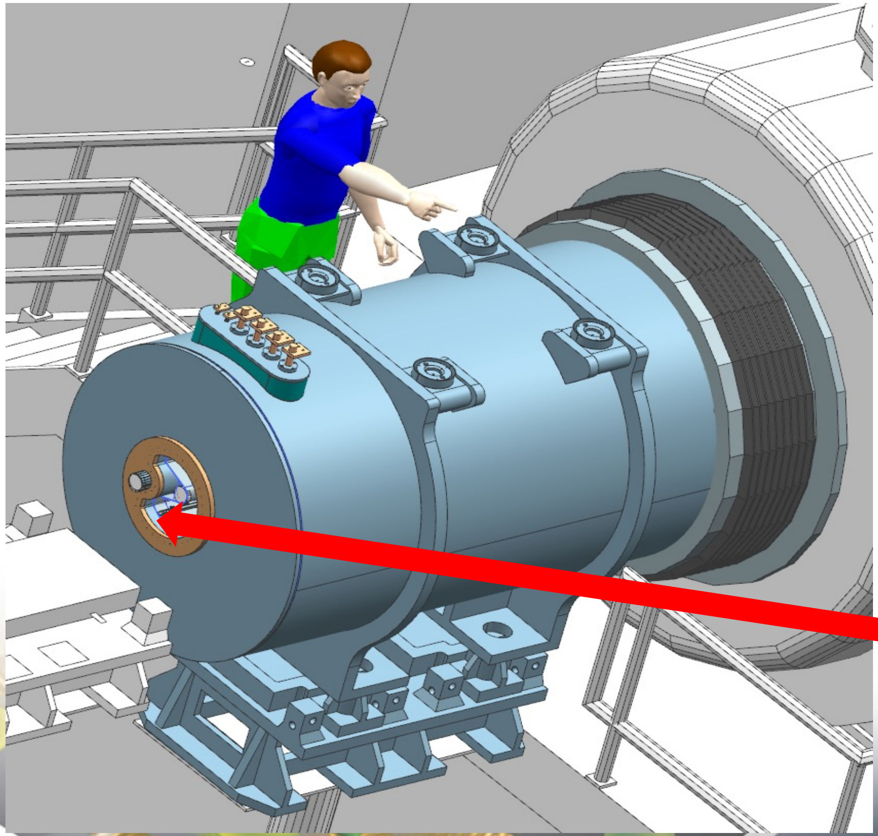


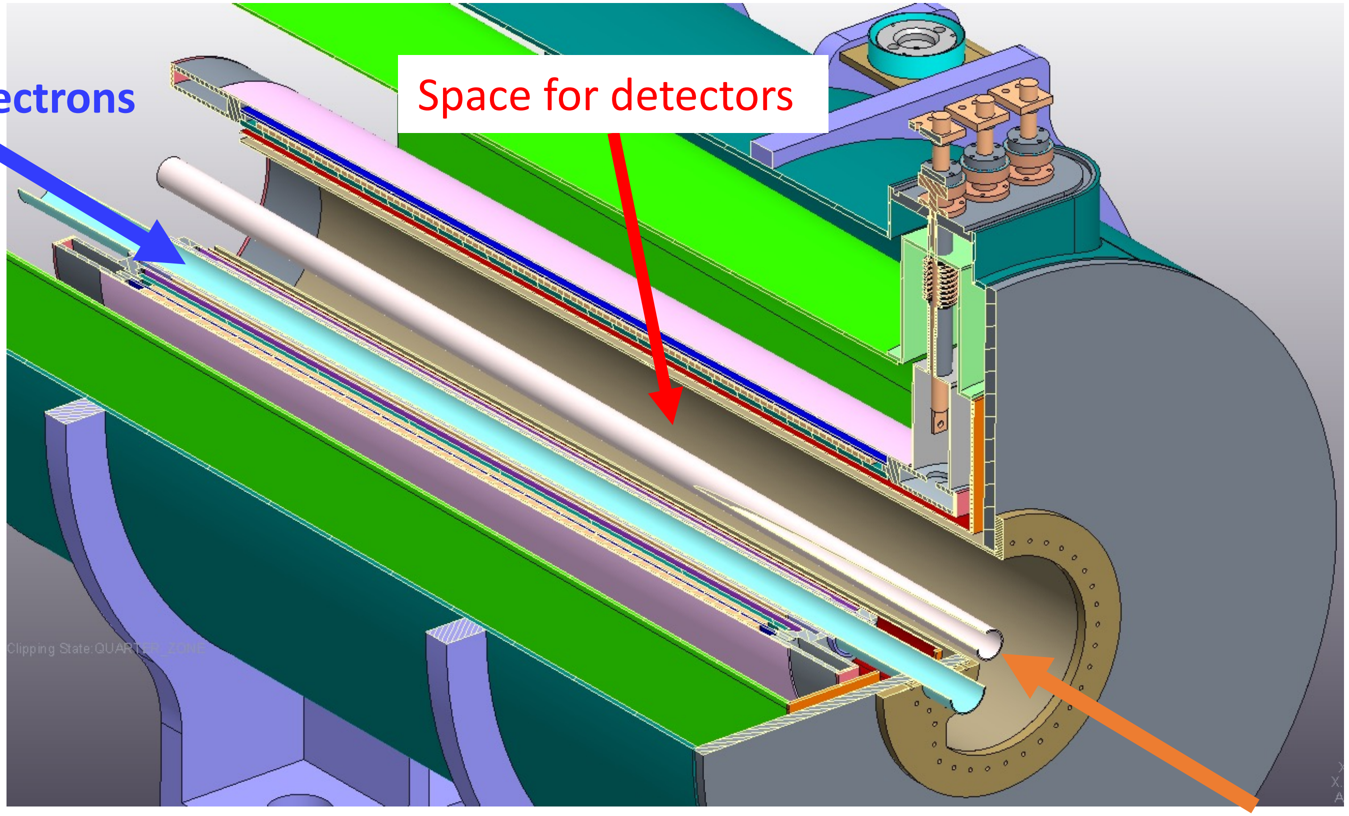


B0 Detectors

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

Credit to Ron Lassiter



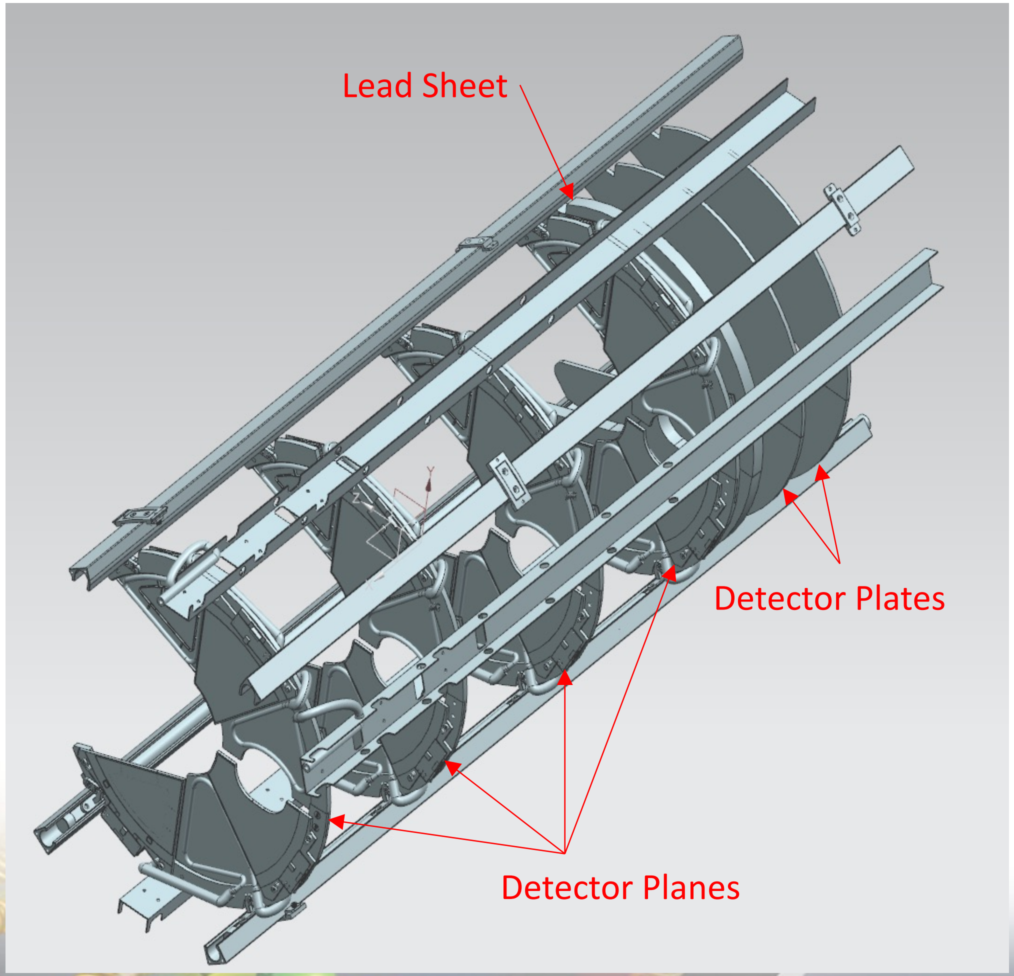


This is the opening where the detector planes will be inserted

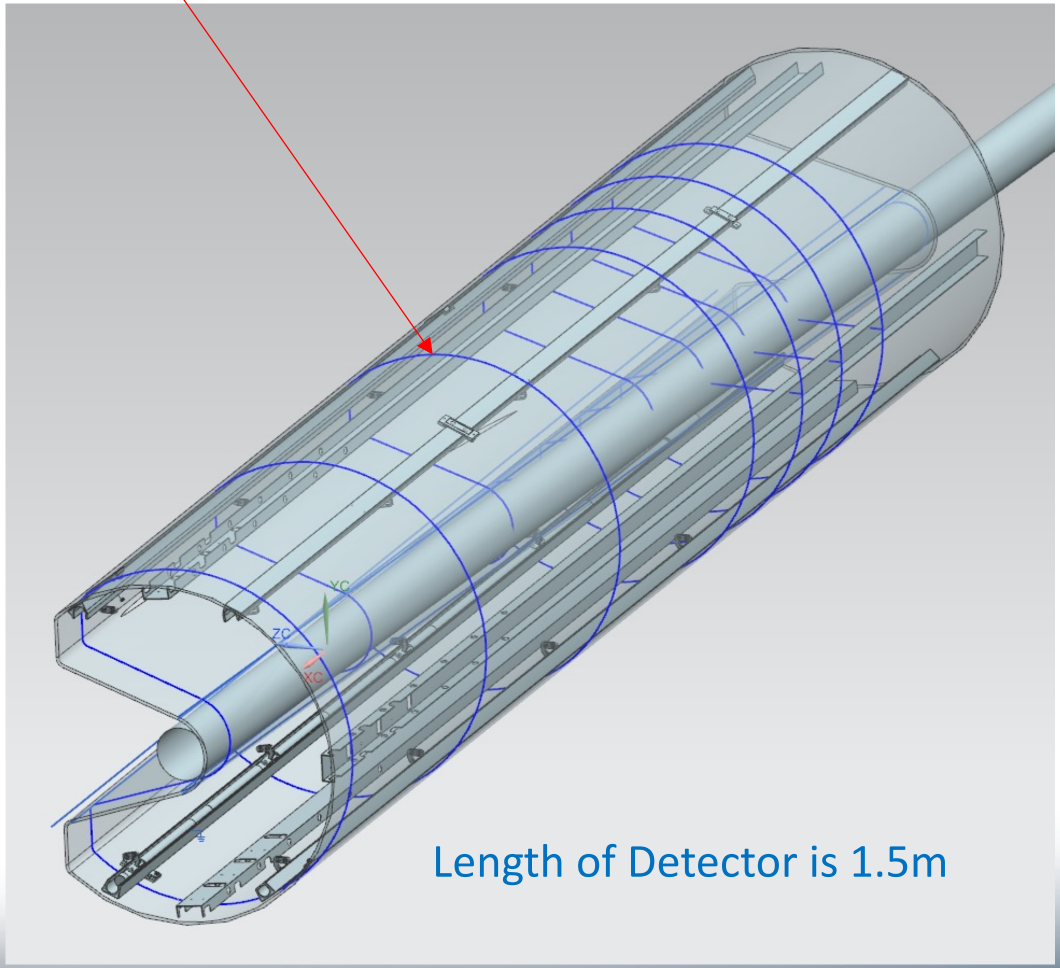
Preliminary Parameters:
229.5cm x 121.1cm x 195cm
(Actual length will be shorter)

B0 Detectors in CAD

Credit to Ron Lassiter



Blue lines represent where element locations are along beamline



B0 Detectors in CAD

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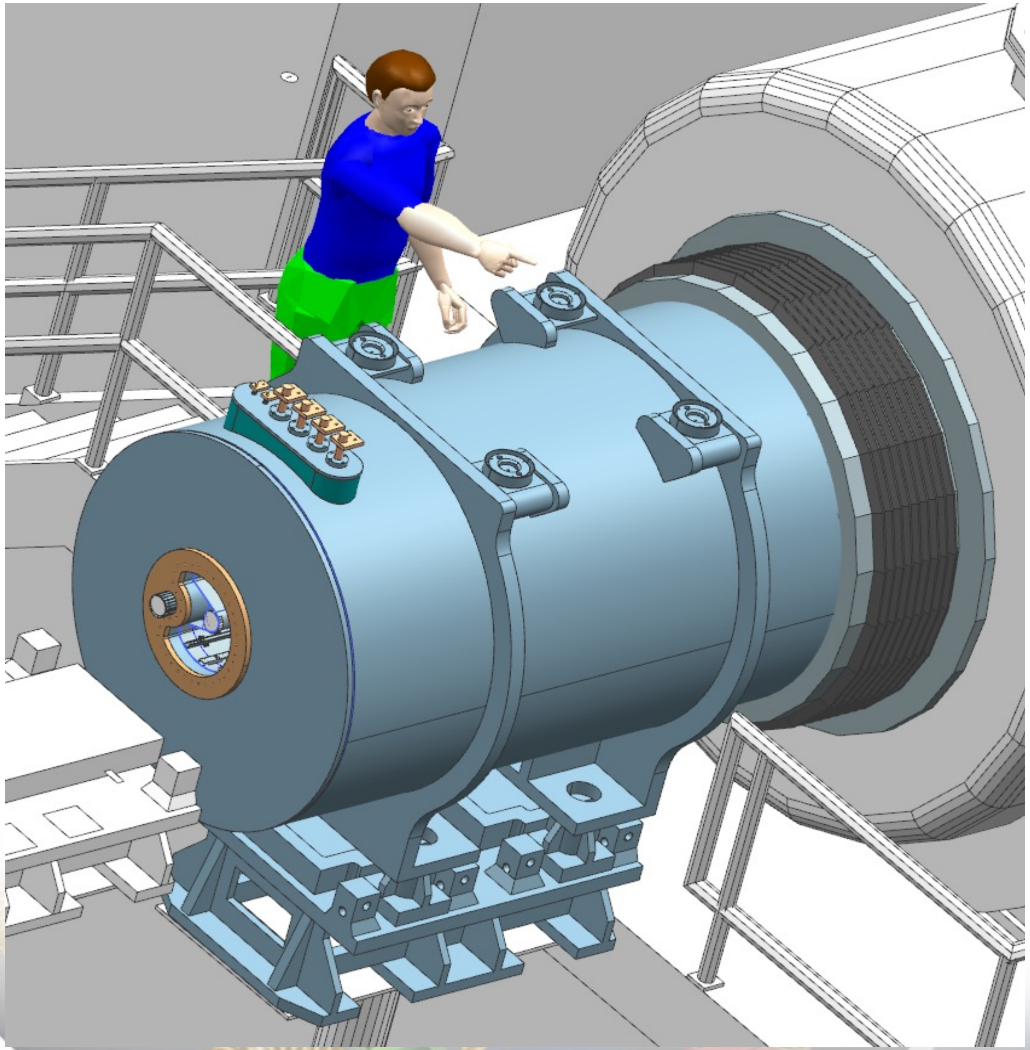
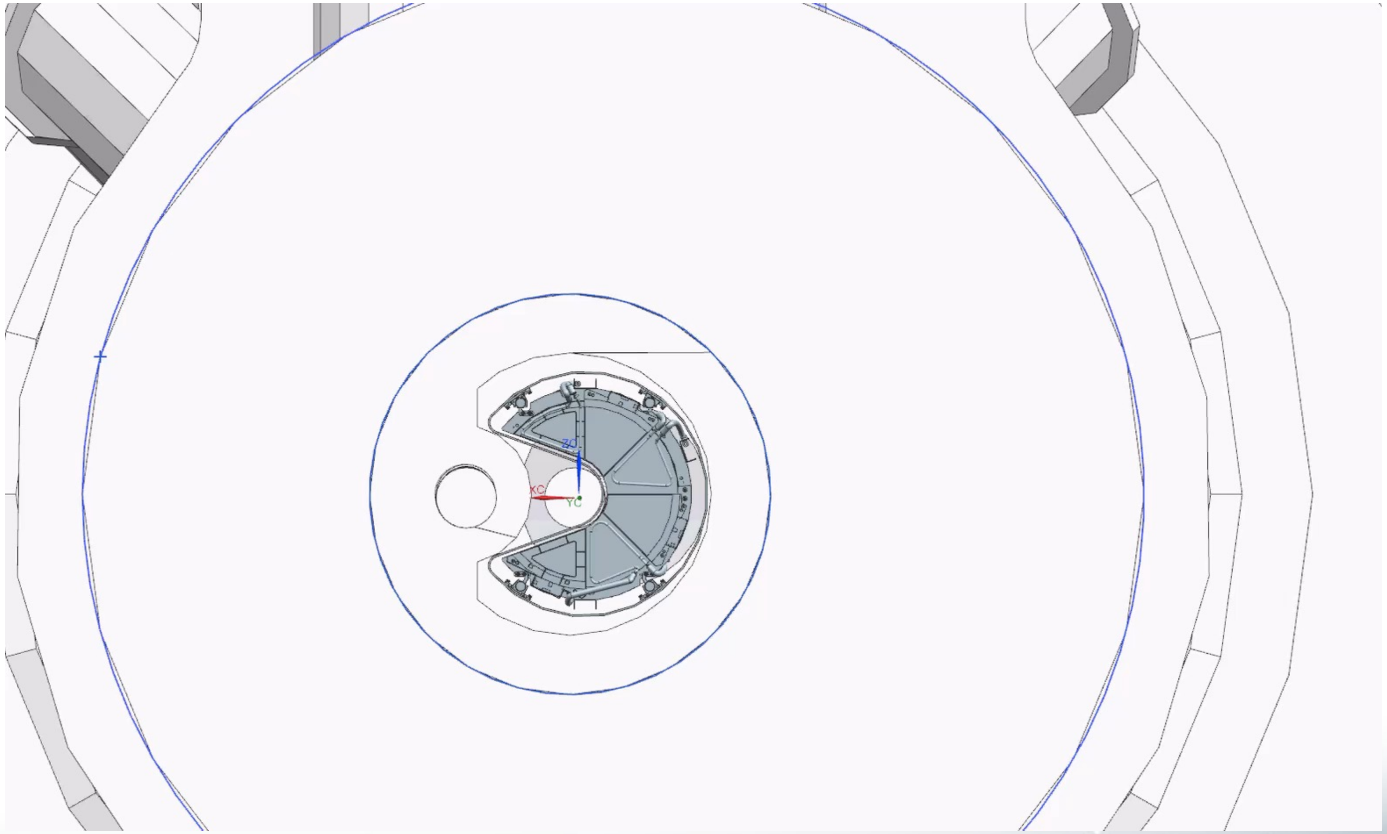


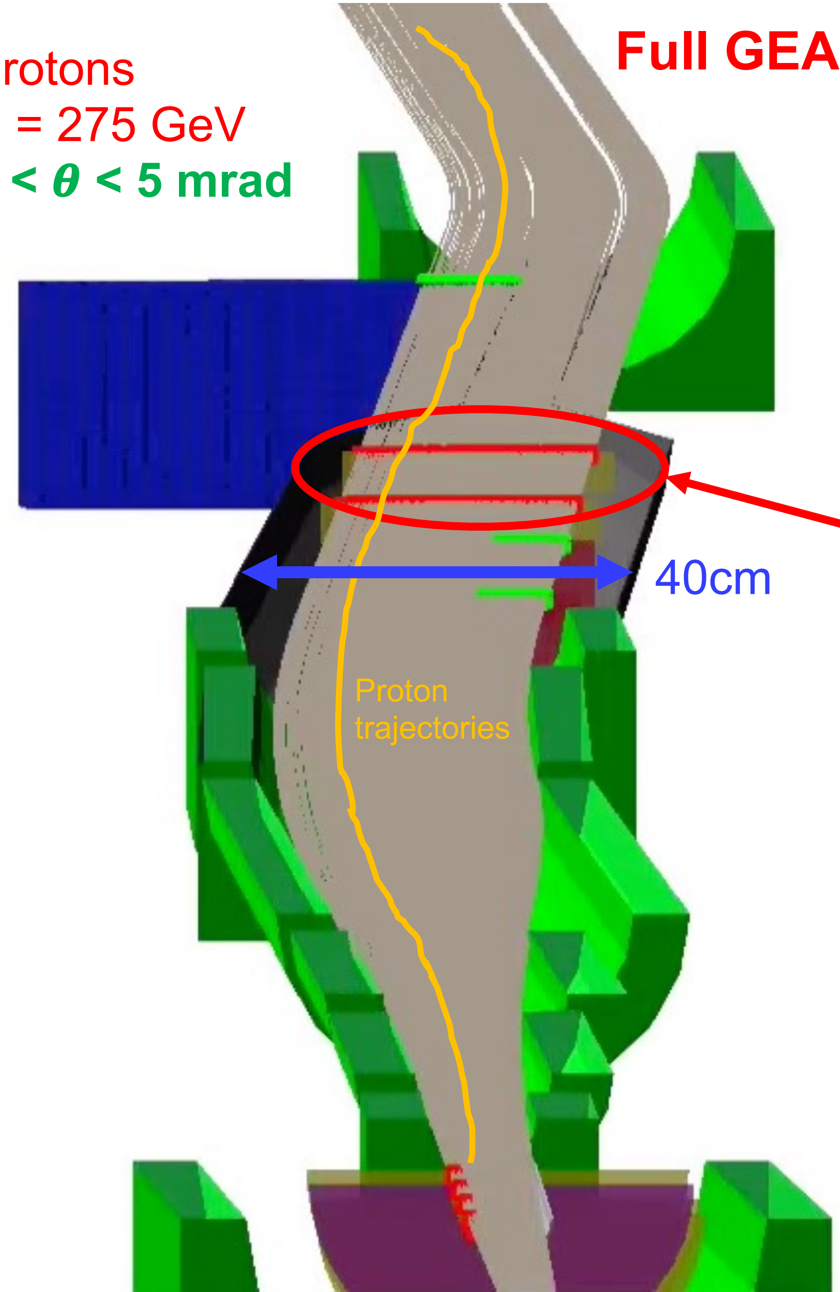
Maintenance can ONLY be performed when the main detector is rolled-out of the IR.

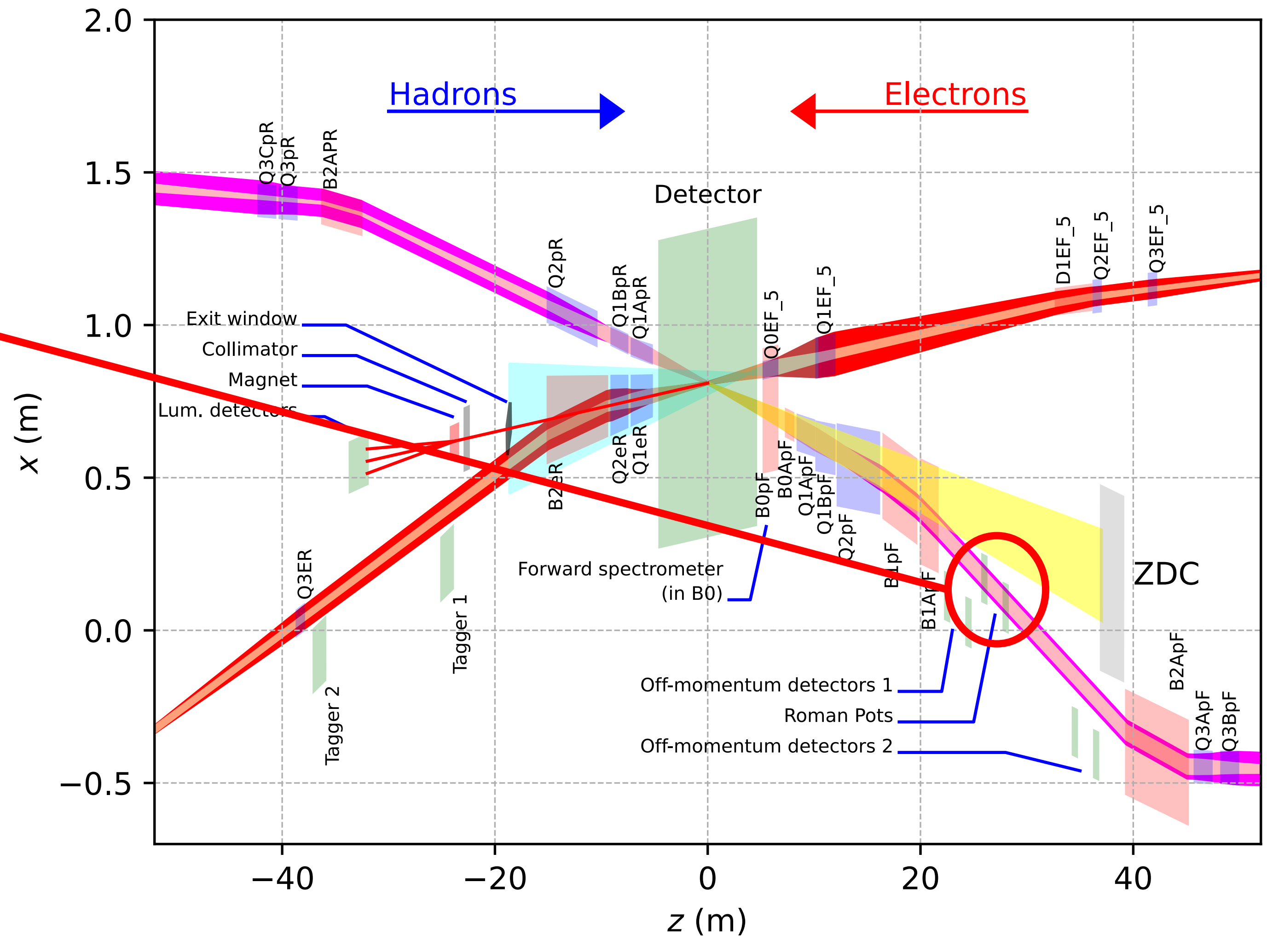


Roman Pots @ the EIC

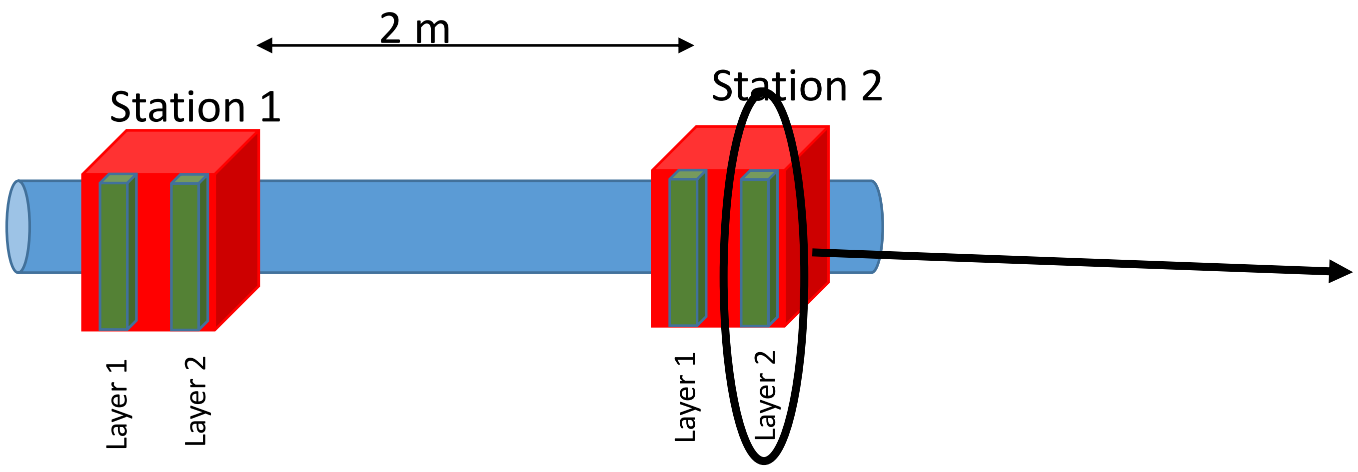
Protons
E = 275 GeV
0 < θ < 5 mrad

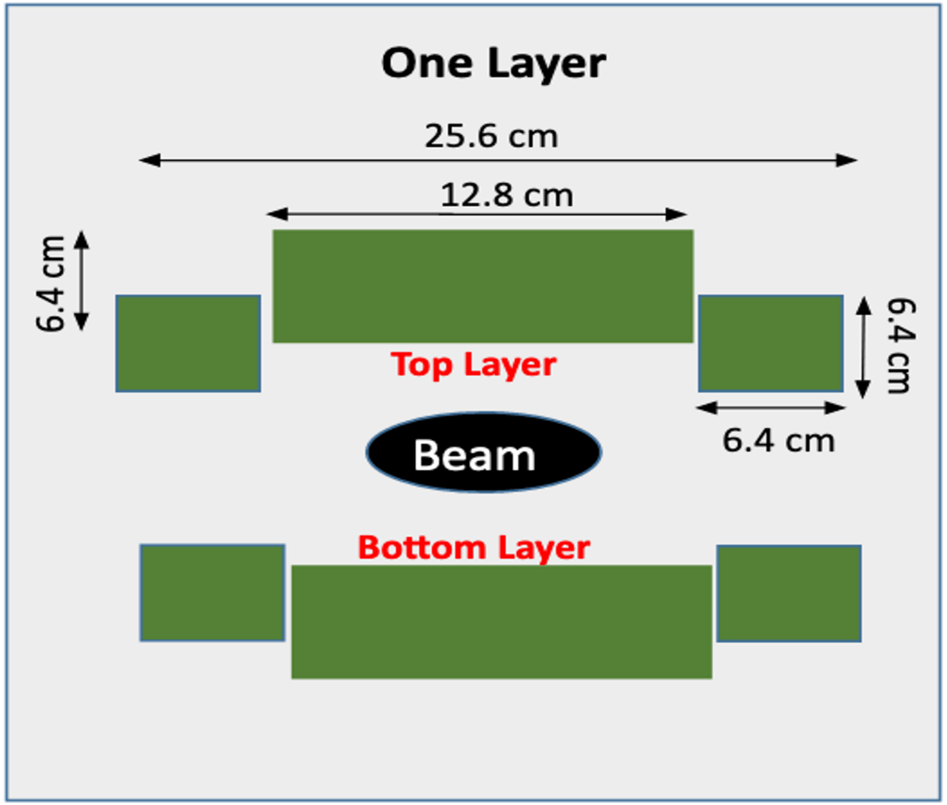
Full GEANT4 simulation.





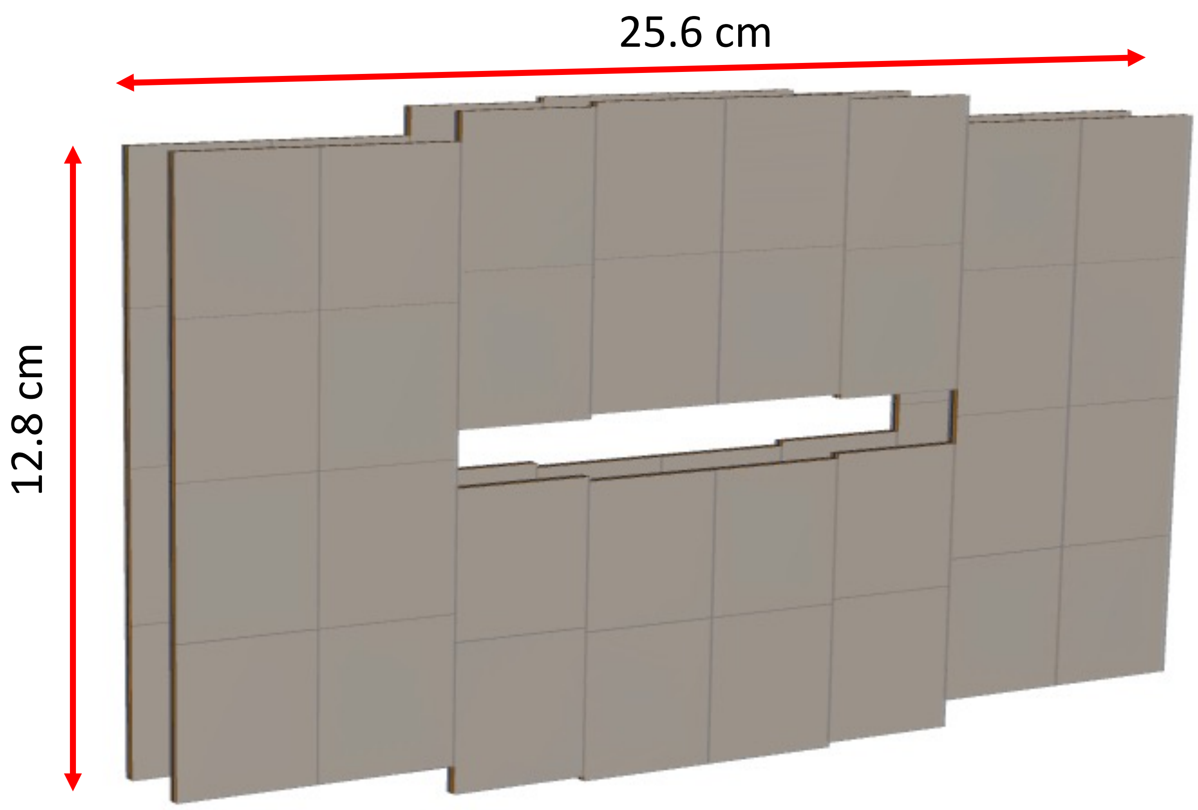
Roman "Pots" @ the EIC



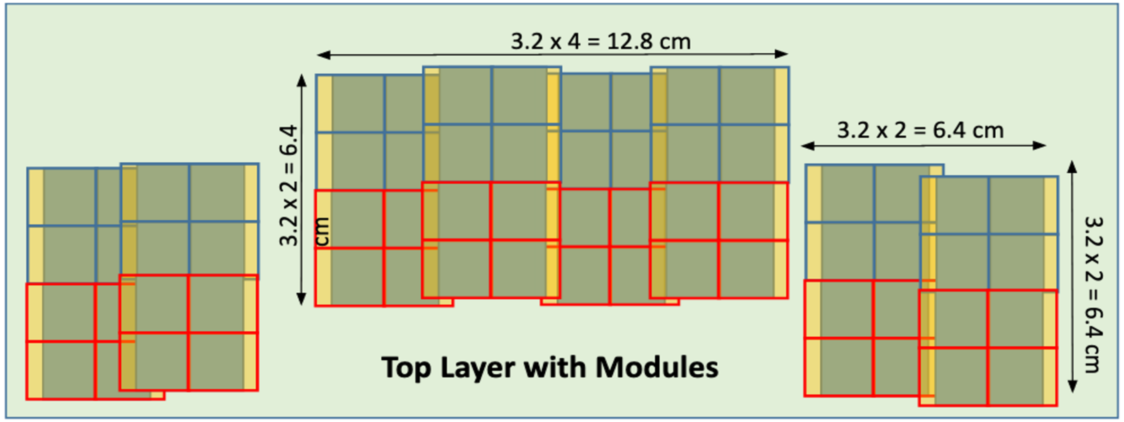


- Silicon detectors placed directly into machine vacuum!
  - Allows maximal geometric coverage!
- Need space for detector insertion tooling and support structure.

Roman "Pots" @ the EIC

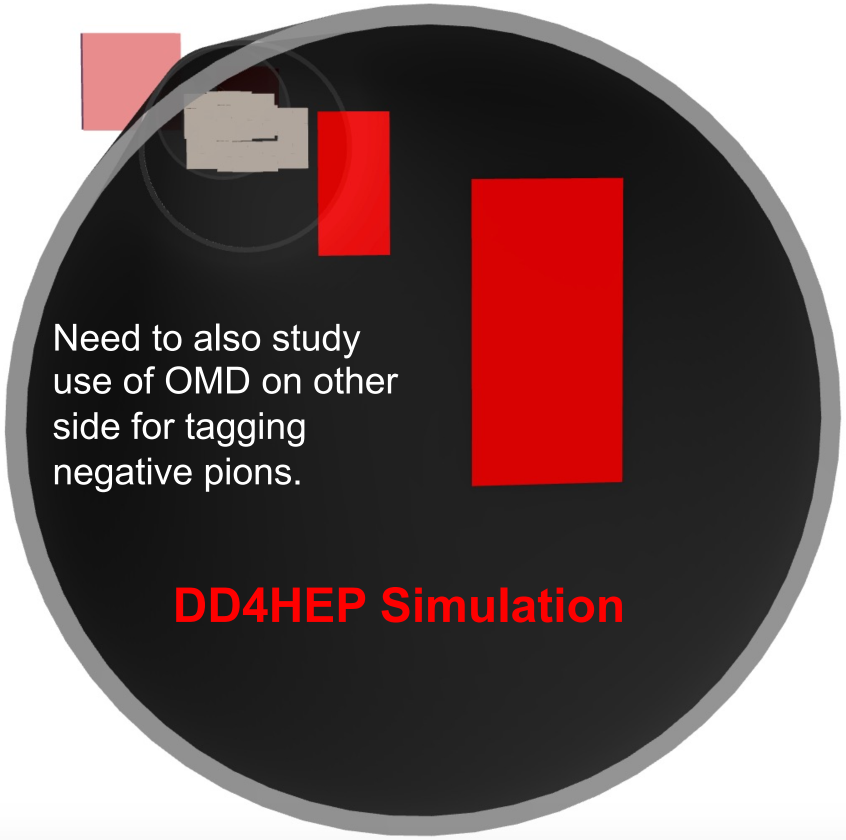


DD4HEP Simulation



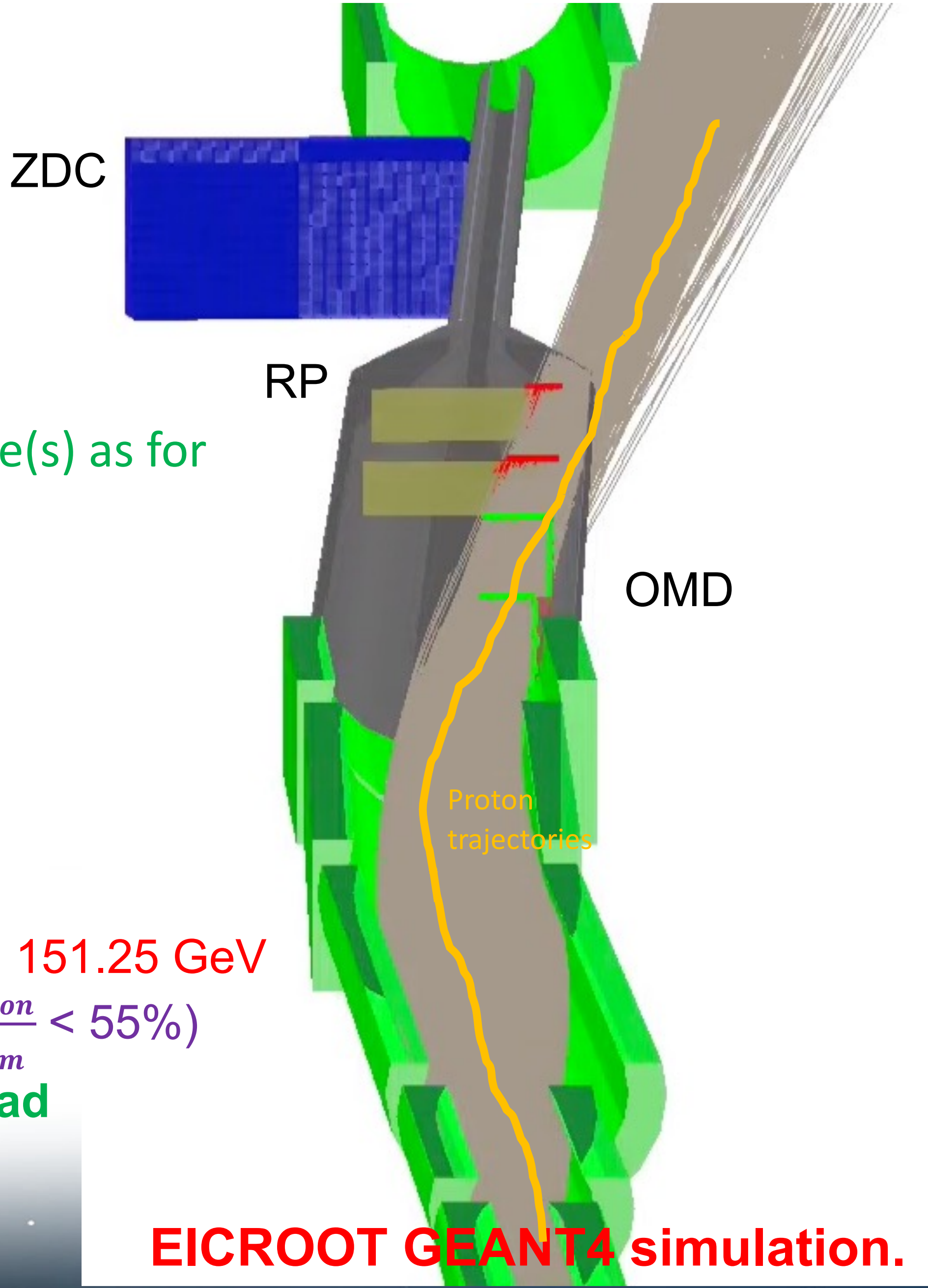
- **<u>Two main options</u>**
  - ➢ AC-LGAD sensor provides both fine pixilation (~140um spatial resolution), and fast timing (~35ps).
  - ➢ MAPS + LYSO timing layer.
- "Potless" design concept with thin RF foils surrounding detector components.

Off-Momentum Detectors



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

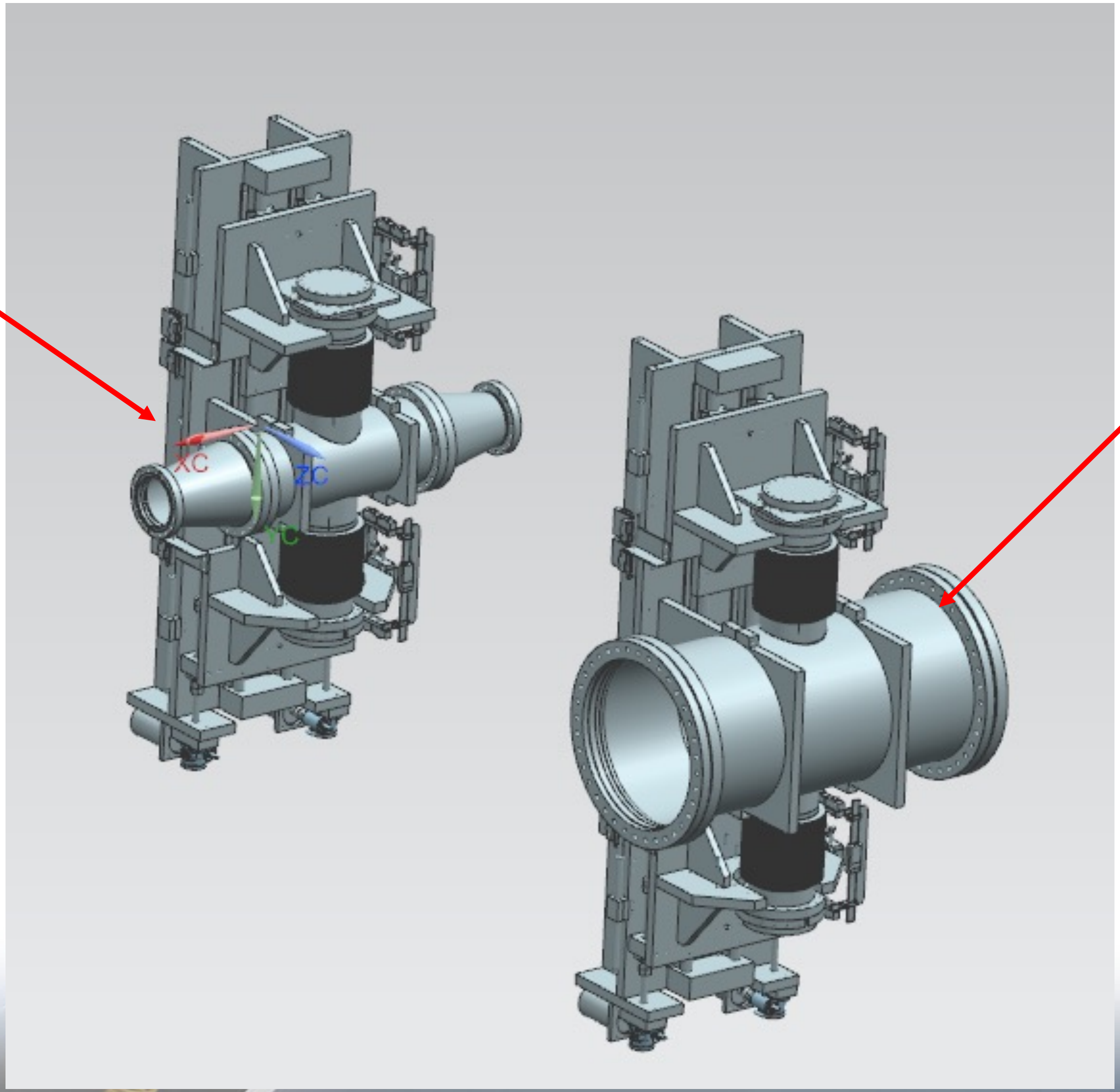
- Same technology choice(s) as for the Roman Pots.



Protons
123.75 < E < 151.25 GeV
$(45\% < \frac{p_{z,proton}}{p_{z,beam}} < 55\%)$
$0 < \theta < 5$ mrad

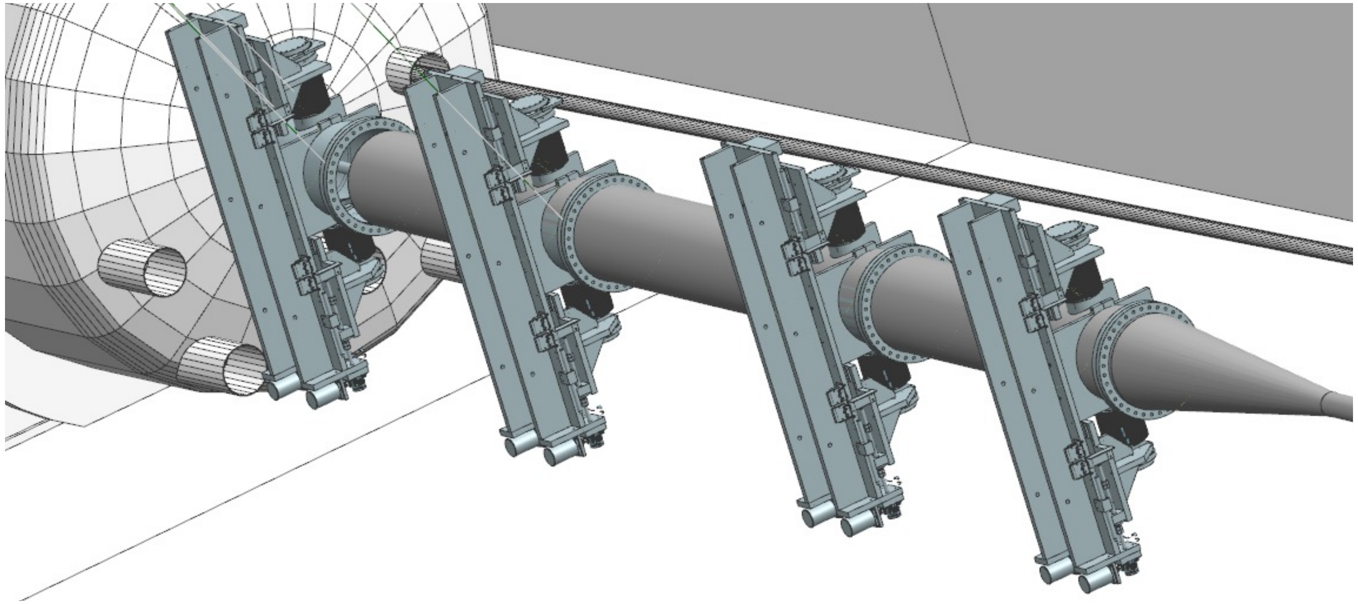
Roman Pots and Off-Momentum Detectors

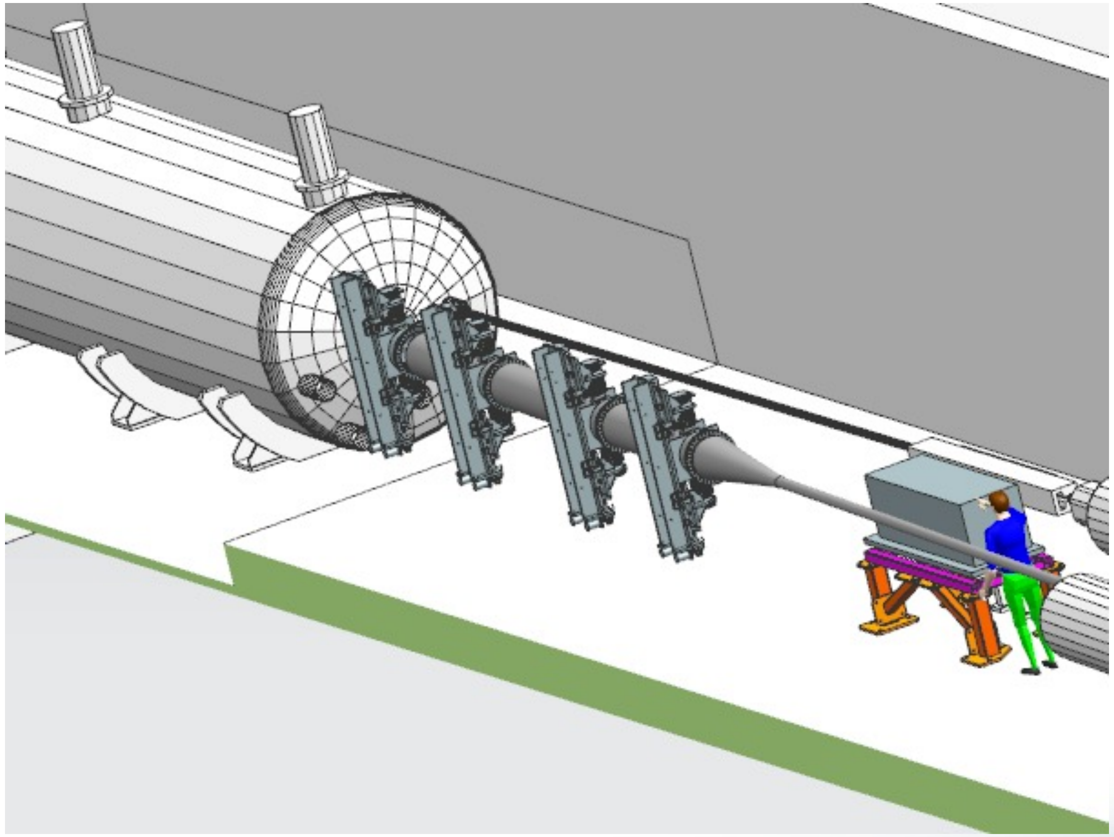
Initial step file inspired by STAR



Updated model in NX with different beamtube size

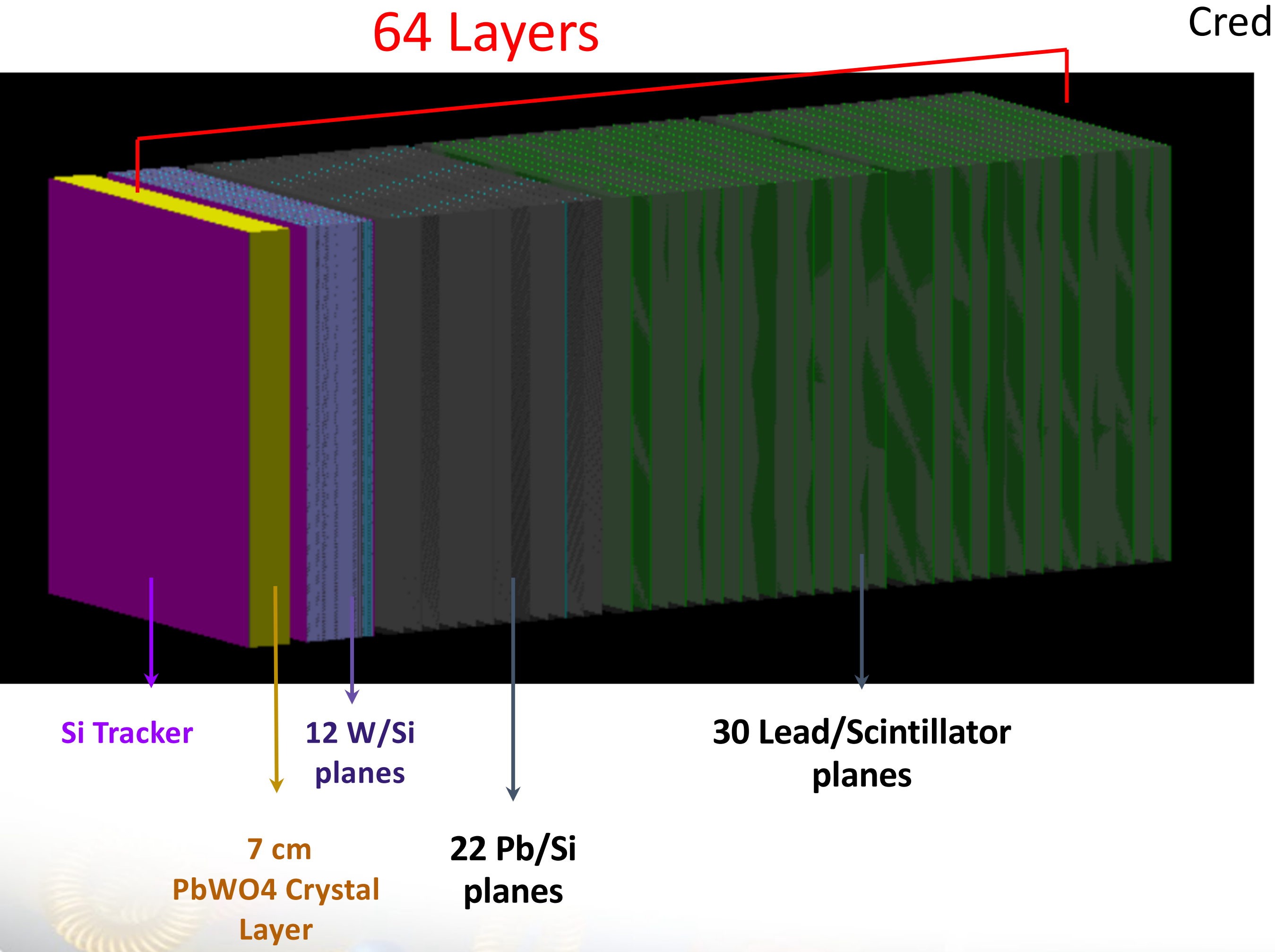
Preliminary CAD drawings of RP and OMD Supports and Magnet Cryostats





Zero-Degree Calorimeter

Credit to Shima Shimizu



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

Size and approximate weight (~5 tons) given to engineers.

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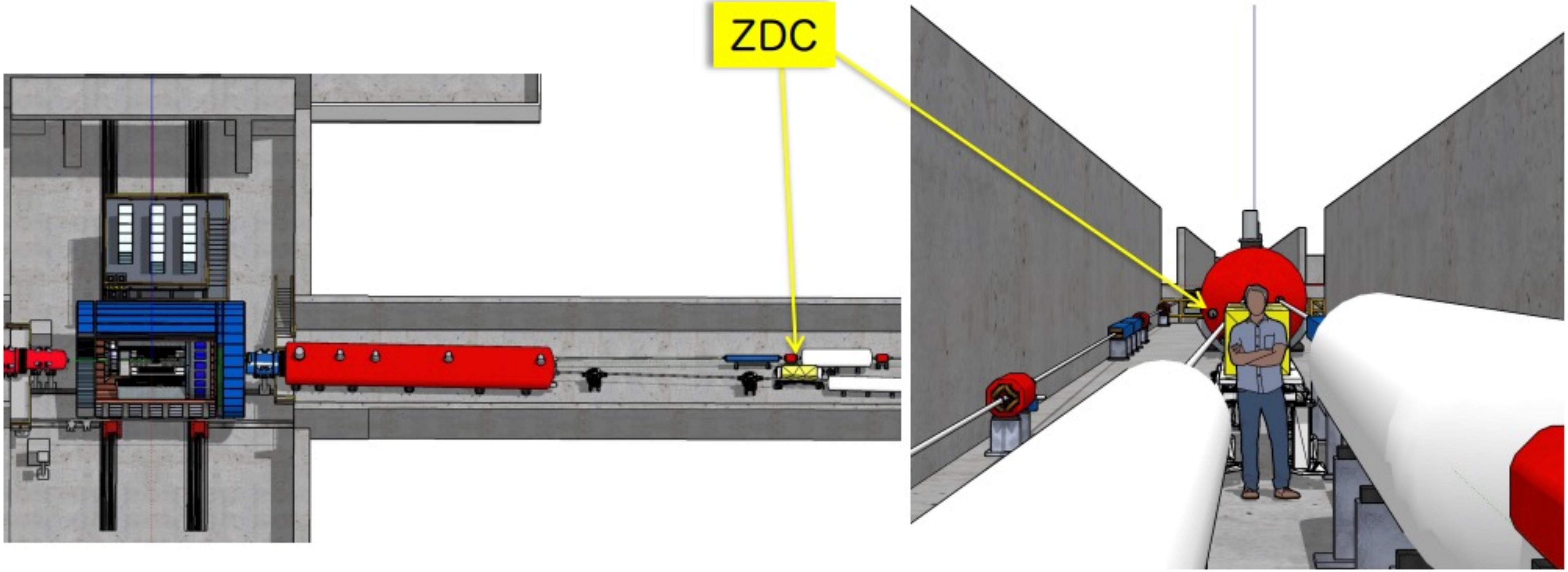
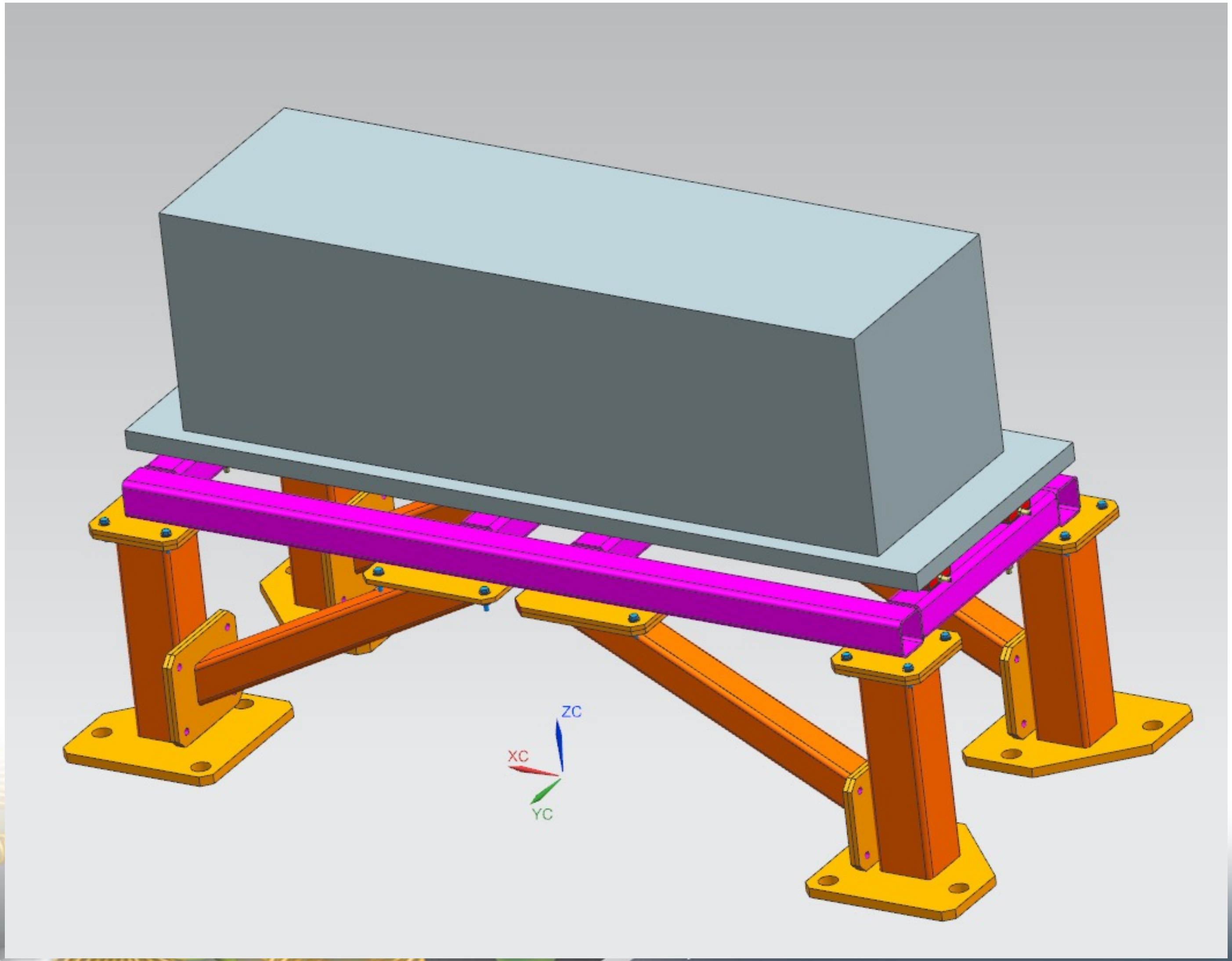


Zero-Degree Calorimeter with Stand

Credit to Ron Lassiter



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

Summary and Takeaways

- All FF detector acceptances and detector performance well-understood with currently available information.
  - Exhaustive studies in the Yellow Report, and **numerous** impact studies done.
  - Some final choices on technology underway.
- 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!!!

Technical review was just performed a few weeks ago for the FF and FB subsystems.

Technical Review

Independent review panel was convened, and 11 experts gave presentations on the various aspects of the far-forward and far-backward design and integration.

- Review organized and led by Yulia Furletova
- **Panel**
  - Wolfram Zeuner – CERN
  - Gerrit van Nieuwenhuizen – BNL
  - Fulvia Pilat – ORNL
- Review happened on April 27th, 2022.
- Many observers were invited to see the talks and the discussions.

Technical Review

1. Are the technical performance requirements appropriately defined and complete for this stage of the project?
2. Are the plans for achieving detector performance and construction sufficiently developed and documented for the present phase of the project?
3. Are the current designs for detectors and electronics readout likely to achieve the performance requirements with a low risk of cost increases, schedule delays, and technical problems?
4. Are the sub-detector fabrication and assembly plans consistent with the overall project and detector schedule?
5. Are the plans for detector integration in the interaction region appropriately developed for the present phase of the project?
6. Have ES&H considerations been adequately incorporated into the designs at their present stage?

Technical Review

1. Are the technical performance requirements appropriately defined and complete for this stage of the project?
    - YES, but continuous effort needed to advance technical integration
2. Are the plans for achieving detector performance and construction sufficiently developed and documented for the present phase of the project?
    - YES, for the scope presented
3. Are the current designs for detectors and electronics readout likely to achieve the performance requirements with a low risk of cost increases, schedule delays, and technical problems?
    - YES, for detectors. Not enough information was presented on electronics readout.
4. Are the sub-detector fabrication and assembly plans consistent with the overall project and detector schedule?
    - YES
5. Are the plans for detector integration in the interaction region appropriately developed for the present phase of the project?
    - YES
6. Have ES&H considerations been adequately incorporated into the designs at their present stage?
    - YES, but a formal plan for quality control and assurance is needed

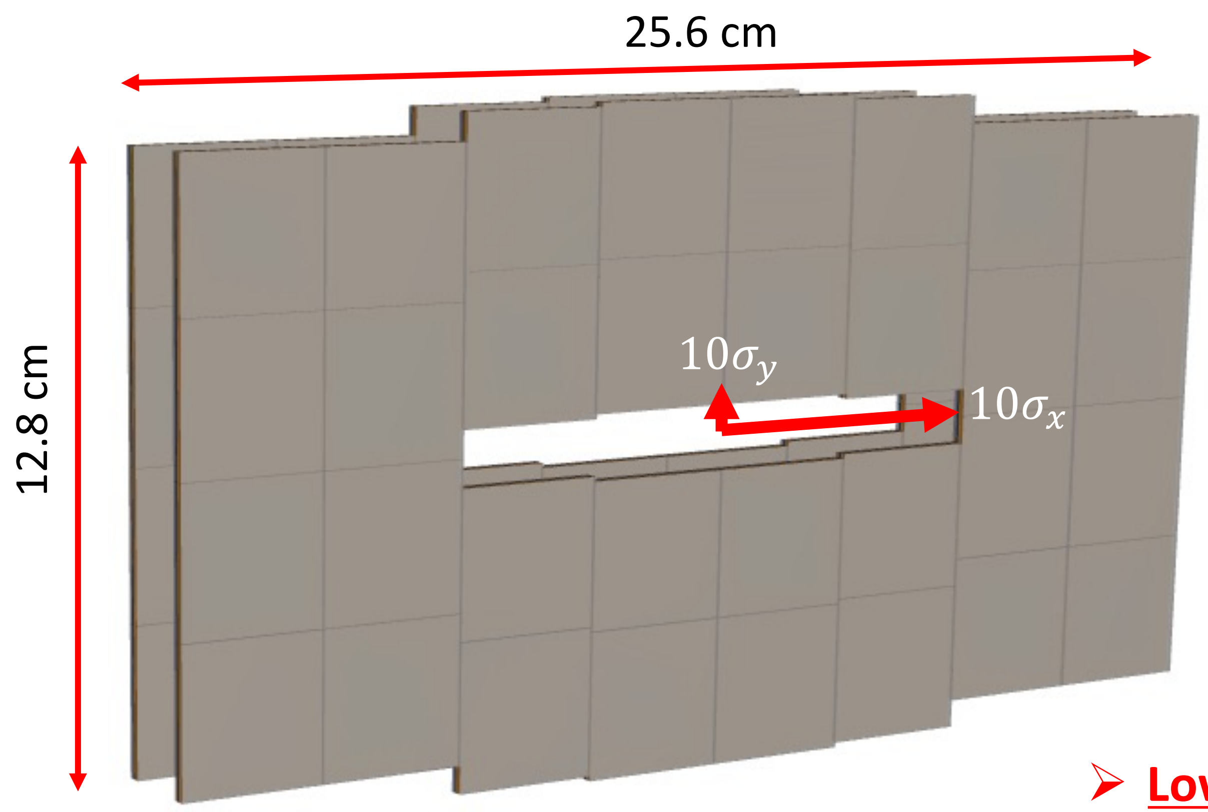
Backup

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.

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



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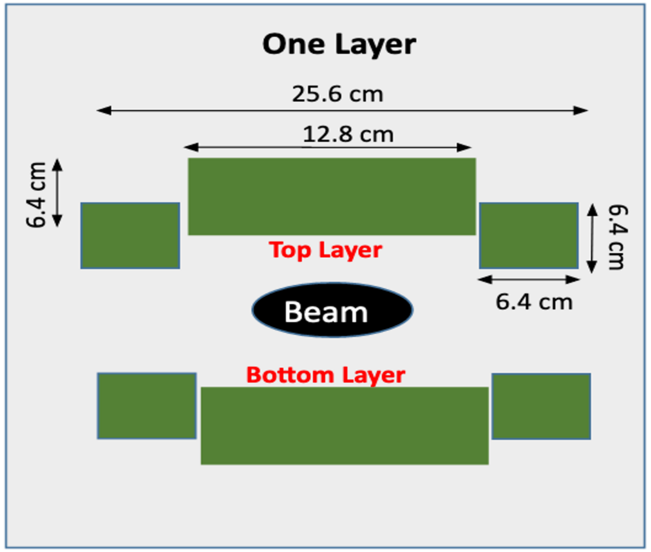
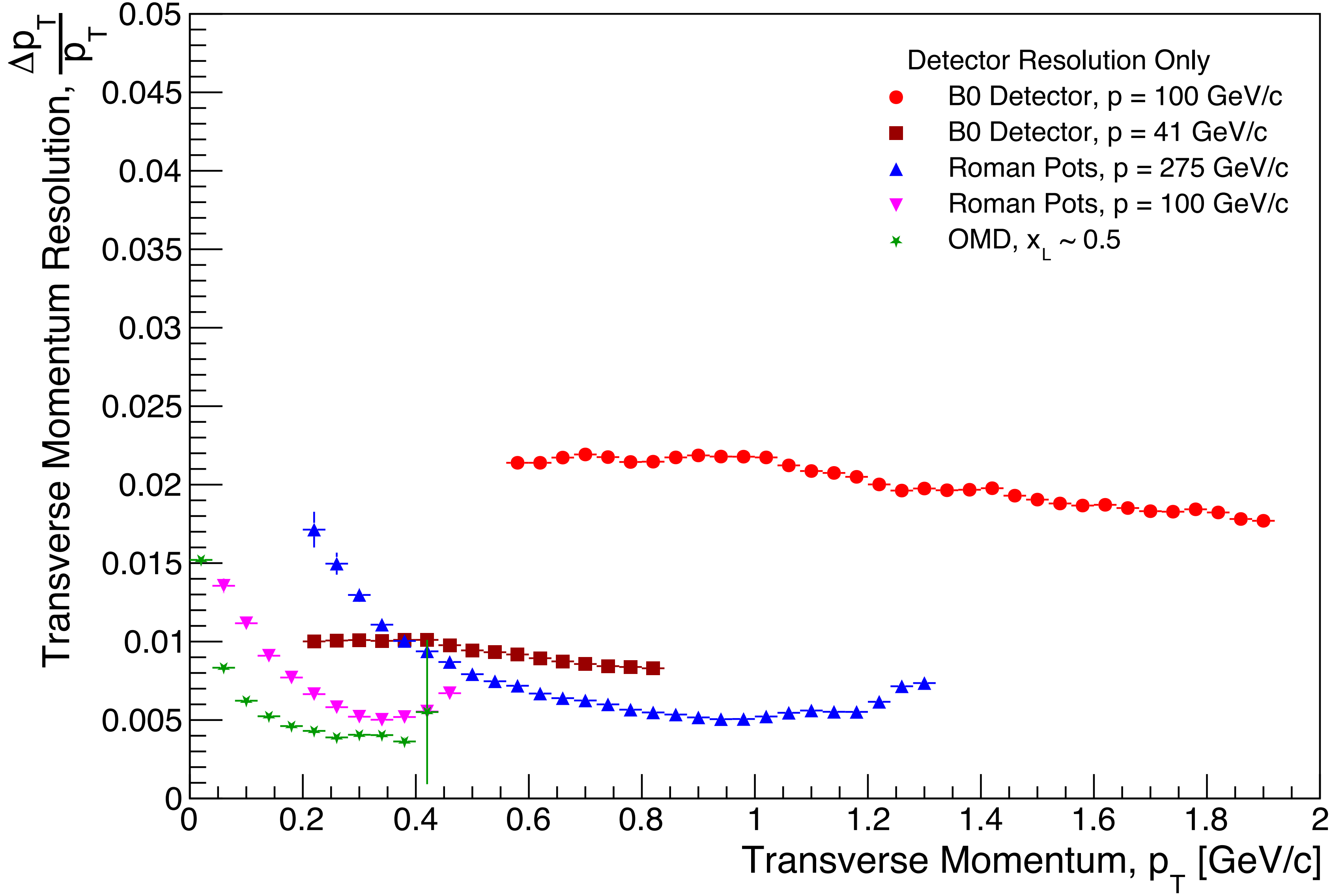


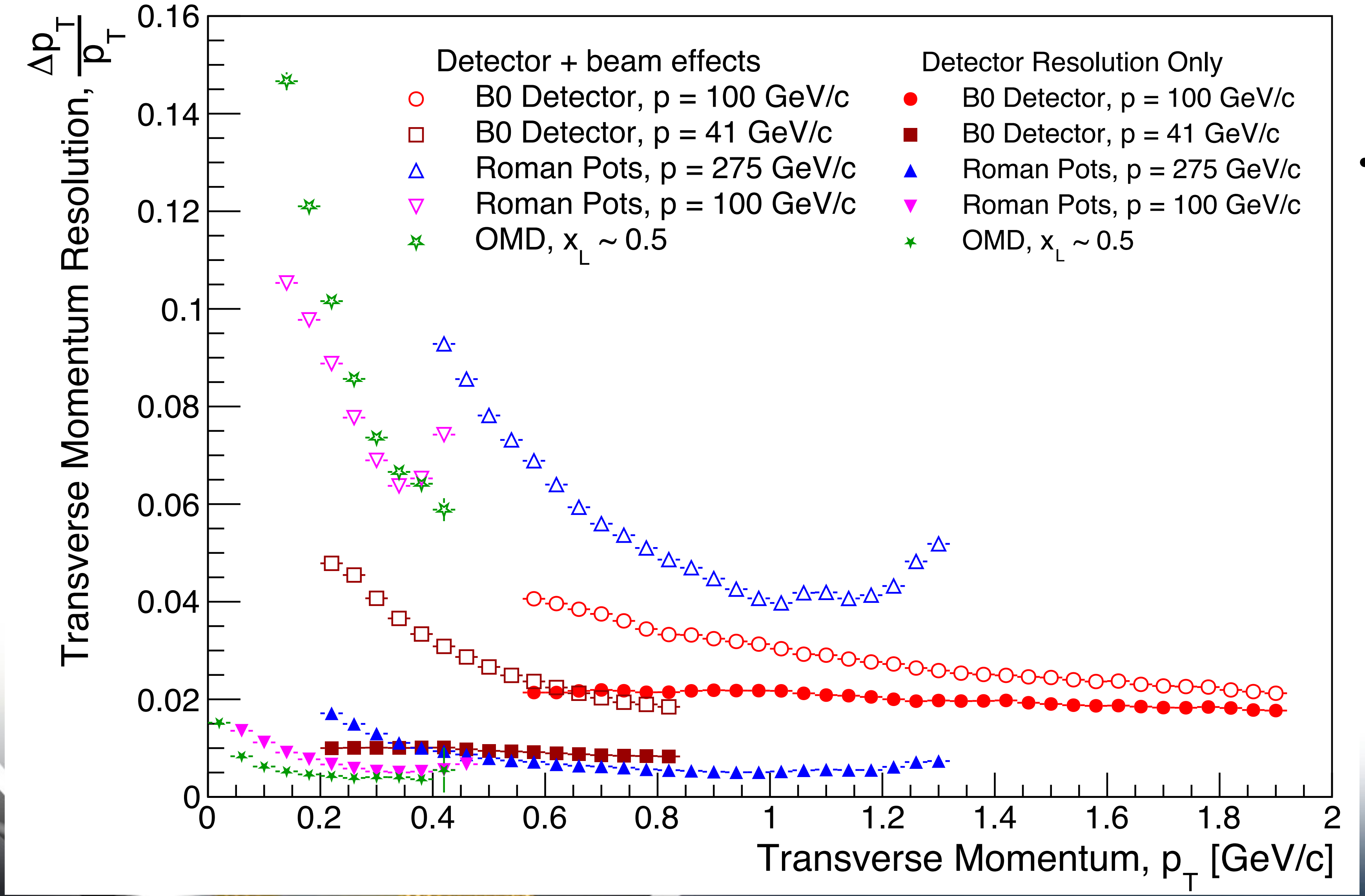
- **Low-pT cutoff determined by beam optics.**
  - **The safe distance is ~10σ from the beam center.**
  - **$1\sigma \sim 1$mm**
- **These optics choices change with energy, but can also be changed within a single energy to maximize *either acceptance at the RP, or the luminosity.***

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!

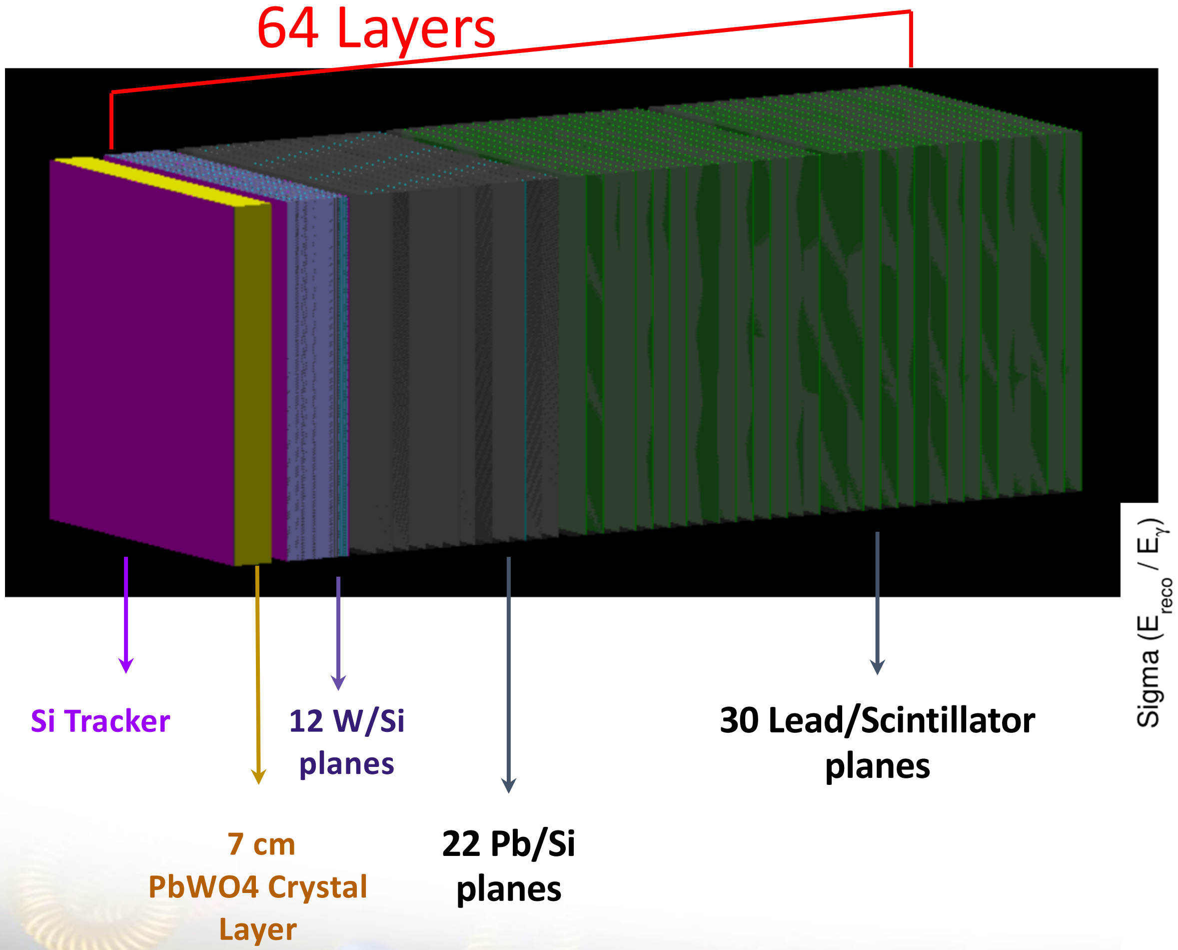
Summary of Detector Performance (Trackers)



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

Beam effects the dominant source of momentum smearing!

Zero-Degree Calorimeter



Credit to Shima Shimizu (Kobe U. , Japan)

Thanks to Bill Li for providing the slide!

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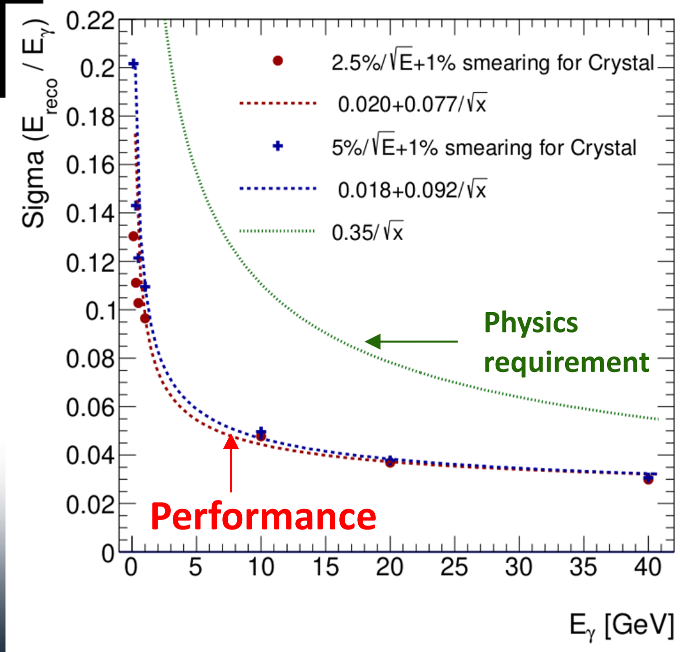
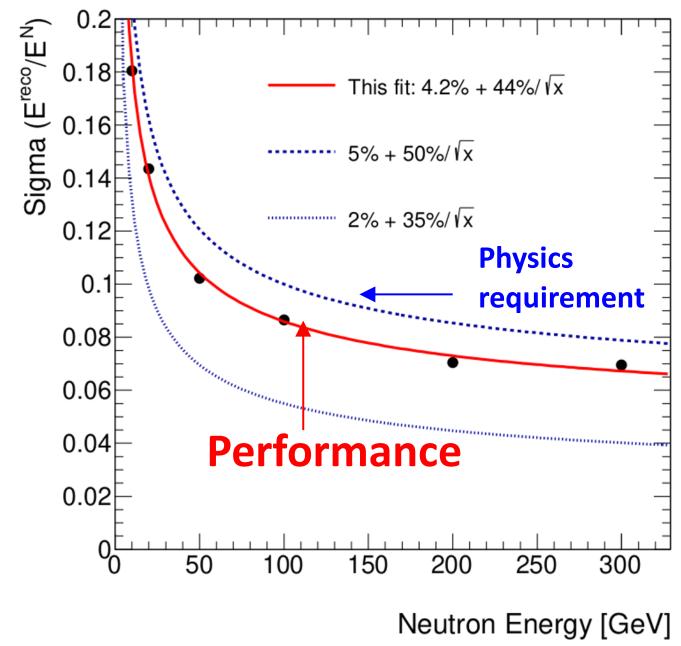
Photon energy resolution

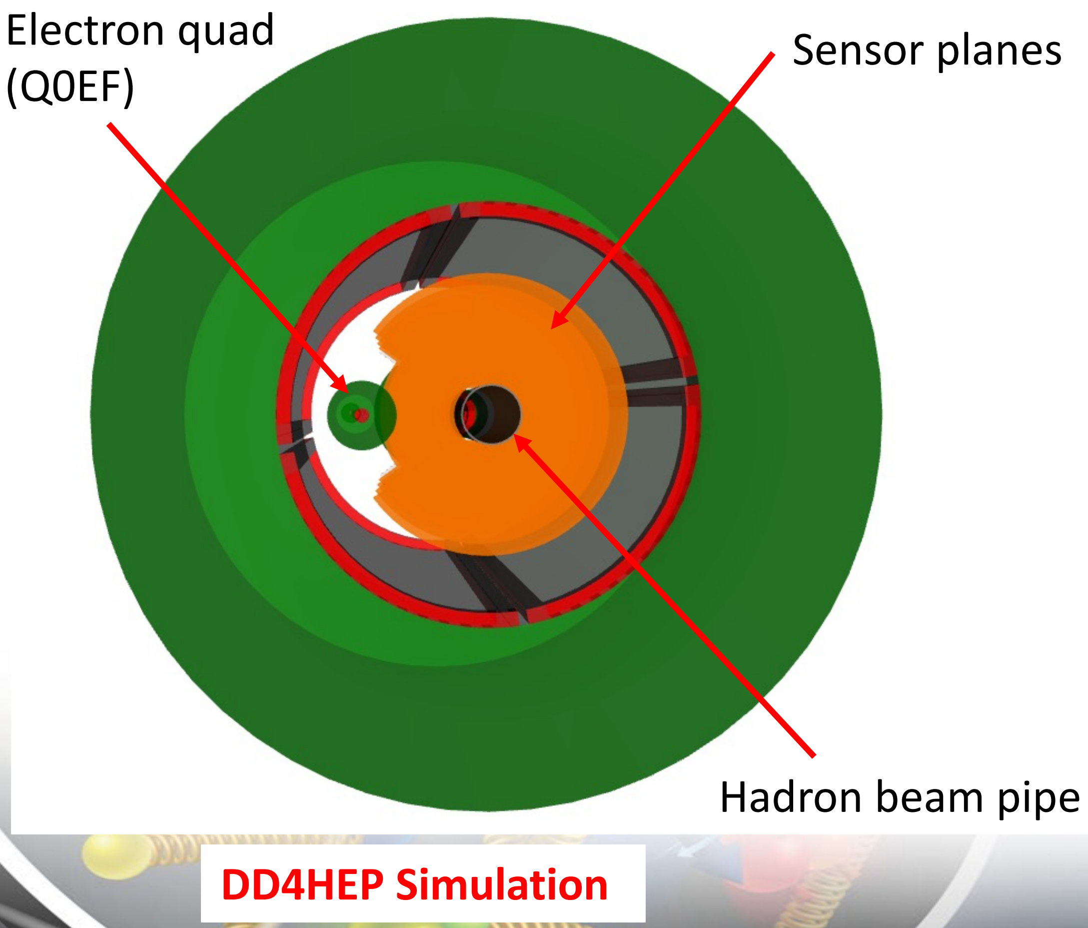


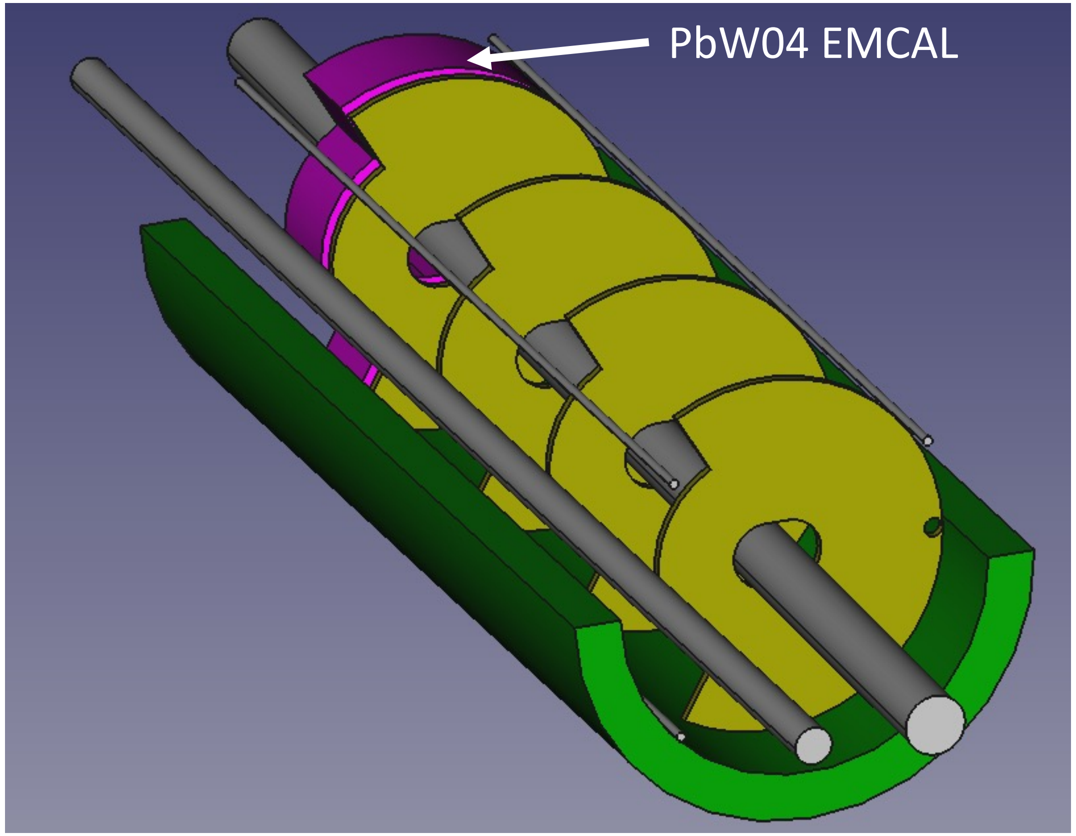
Neutron energy resolution



B0 Detectors

(5.5 < θ < 20.0 mrad)

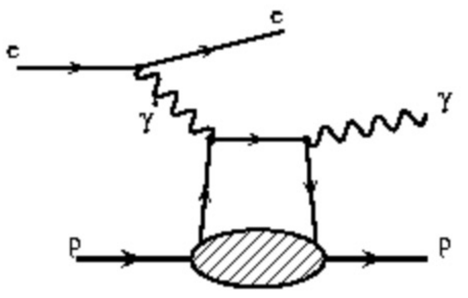




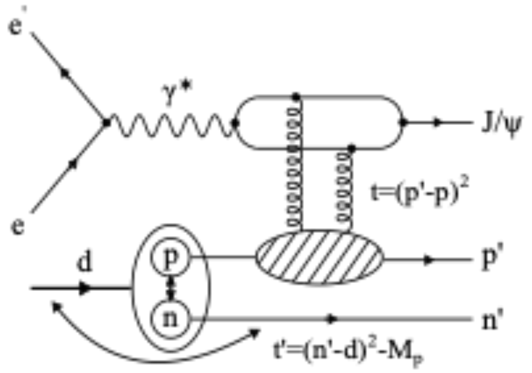
- Higher granularity silicon (e.g. MAPS) required.
- Tagging photons important in differentiating between coherent and incoherent heavy-nuclear scattering, and for reconstructing $\pi^0 \rightarrow \gamma\gamma$.
  - **Space is a major concern here – an EMCAL is highly preferred, but may only have space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

Far-Forward Physics at the EIC

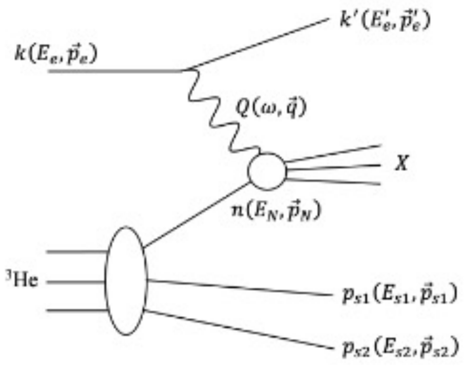
e+p DVCS



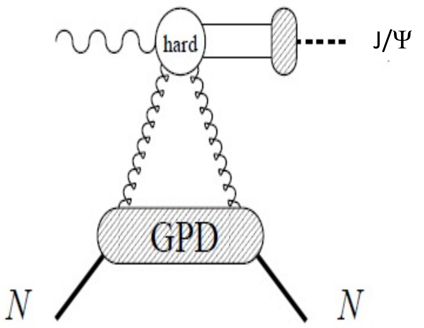
e+d exclusive J/Psi with p/n tagging



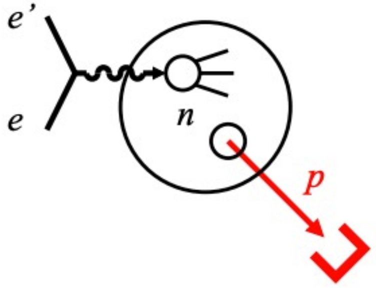
e+He3 spectator tagging



coherent/incoherent J/ψ production in e+A

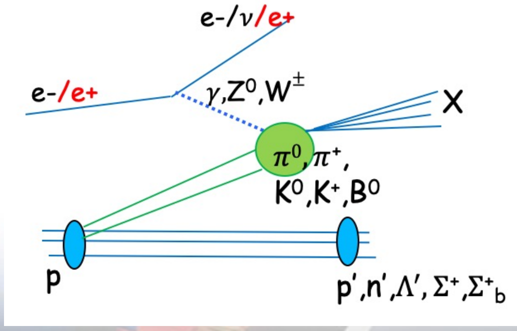


e+d DIS spectator tagging

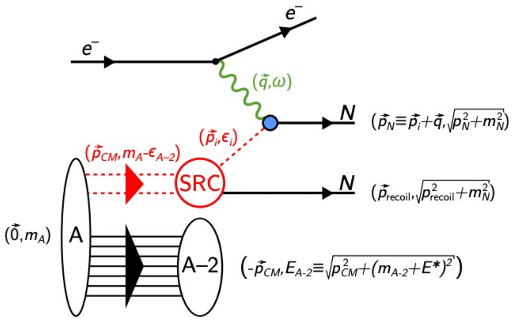


Meson structure:

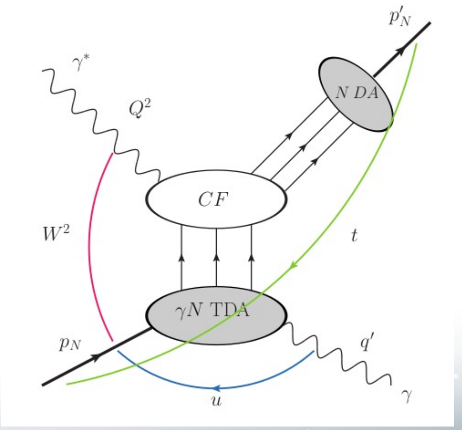
- ep→ (π) →e' n X
- $\Lambda \rightarrow p\pi^-$ and $\Lambda \rightarrow n\pi^0$



Quasi-elastic electron scattering



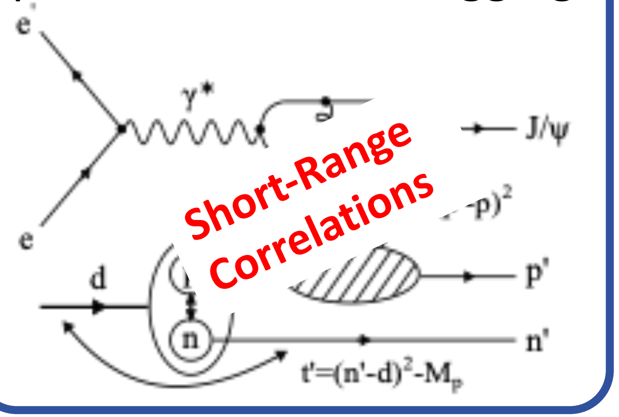
u-channel backward exclusive electroproduction



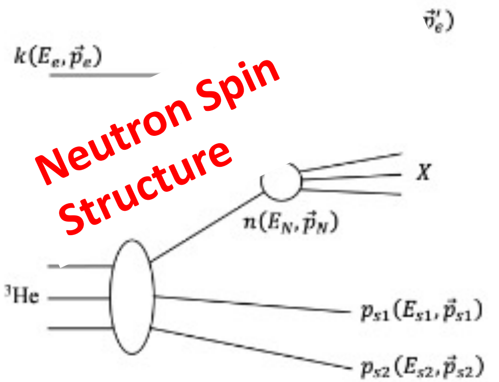
...and MANY more!

Far-Forward Physics at the EIC

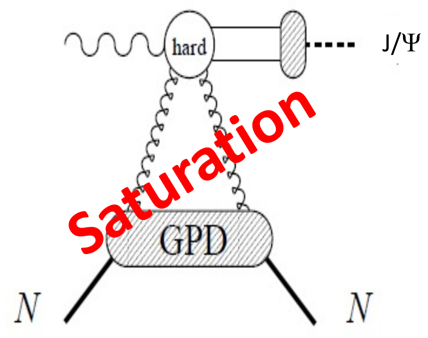
e+d exclusive J/Psi with proton or neutron tagging[1]



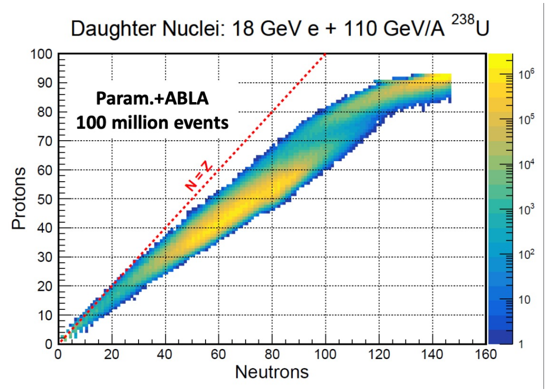
e+He3 spectator tagging[2]



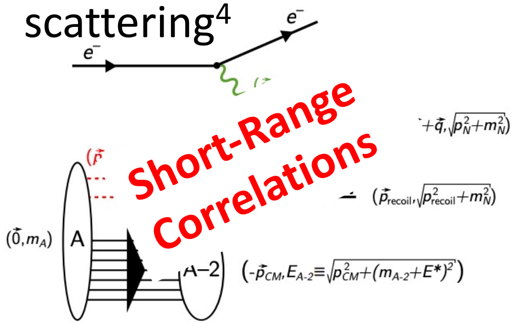
coherent/incoherent J/ψ production in e+A[3]



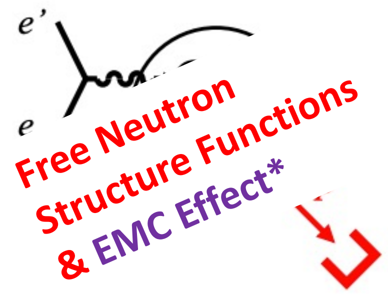
Rare isotopes**



Quasi-elastic electron scattering[4]

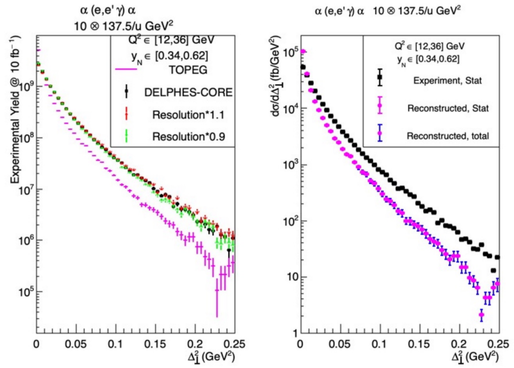


e+d DIS spectator tagging[5]



[1] Z. Tu, AJ, et al., Phys. Lett. B **811,** 135877 (2020)
[2] I. Friscic, D. Nguyen, J. R. Pybus, AJ, *et al.,* Phys. Lett. B, **823**, 136726 (2021)
[3] W. Chang, E.C. Aschenauer, M. D. Baker, AJ, J.H. Lee, Z. Tu, Z. Yin, and L. Zheng, Phys. Rev. D **104**, 114030 (2021)
[4] F. Hauenstein, AJ, J. R. Pybus, A. Kiral, M. D. Baker, Y. Furletova, O. Hen, D. W. Higinbotham, C. Hyde, V. Morozov, D. Romanov, and L. B. Weinstein, Phys. Rev. C **105**, 034001 (2022)
[5] AJ, Z. Tu, and C. Weiss, Phys. Rev. C **104,** 065205 (2021) **(Editor's Suggestion)**

e+He4 DVCS***



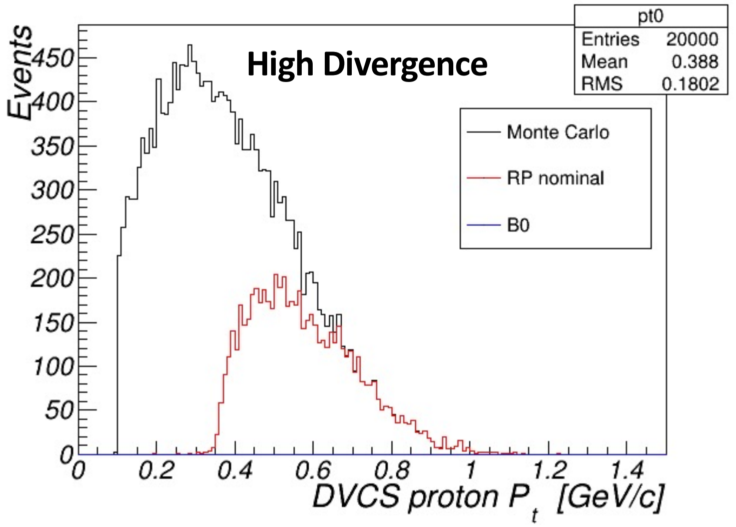
Many examples of detailed impact studies with full detector simulations! (non-exhaustive)

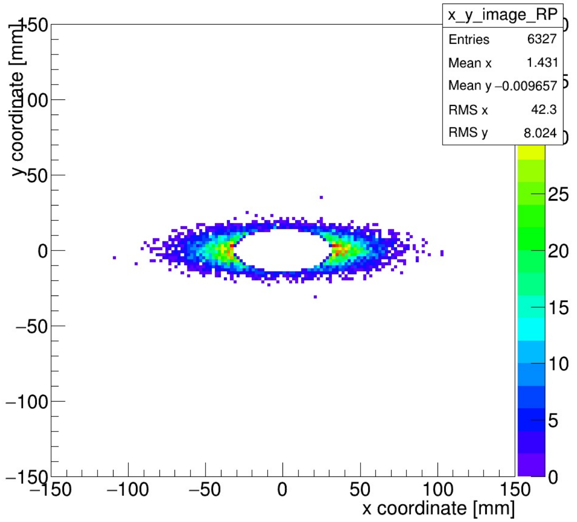
Far-Forward Physics at the EIC

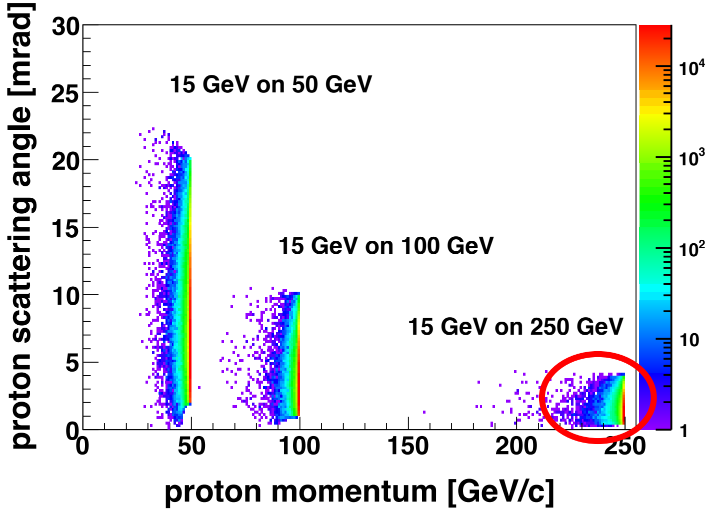
- Physics channels require tagging of **charged hadrons** (protons, pions) or **neutral particles** (neutrons, photons) at **very-forward rapidities ($\eta > 4.5$).**
- Different final states $\longrightarrow$ tailored detector subsystems.
- Various collision systems and energies (h: 41, 100-275 GeV, e: 5-18 GeV; e+p, e+d, e+Au, etc.).
- Placing of far-forward detectors uniquely challenging due to integration with accelerator.
- Details studied in EIC Yellow Report and Conceptual Design Report, and in the ATHENA, ECCE, and CORE EIC detector proposals.

Digression: Machine Optics

275 GeV DVCS Proton Acceptance



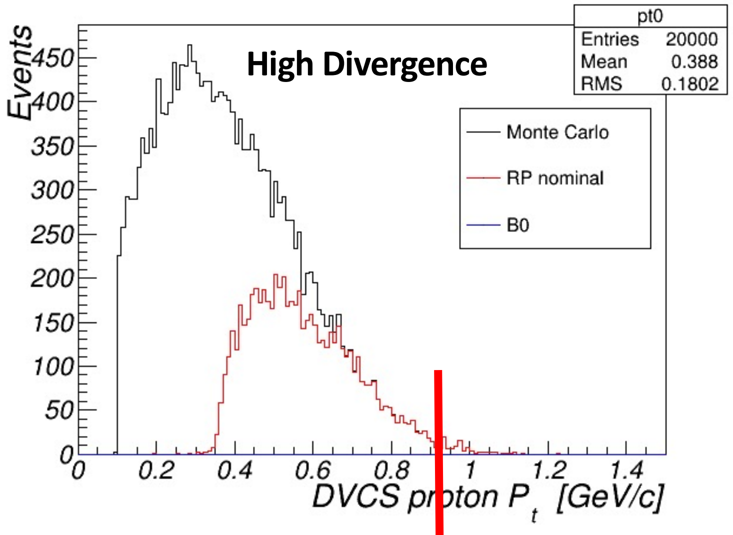


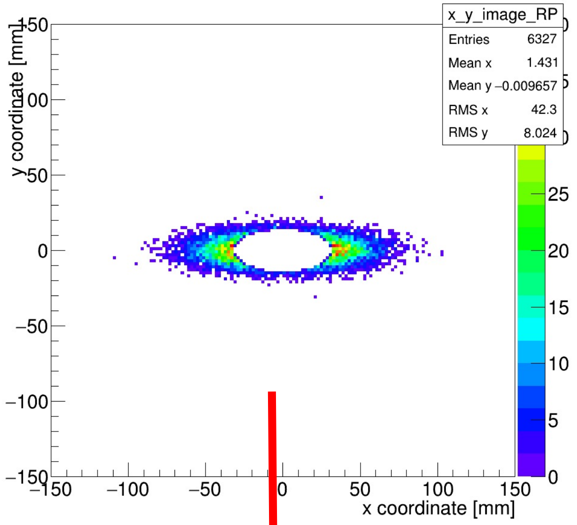


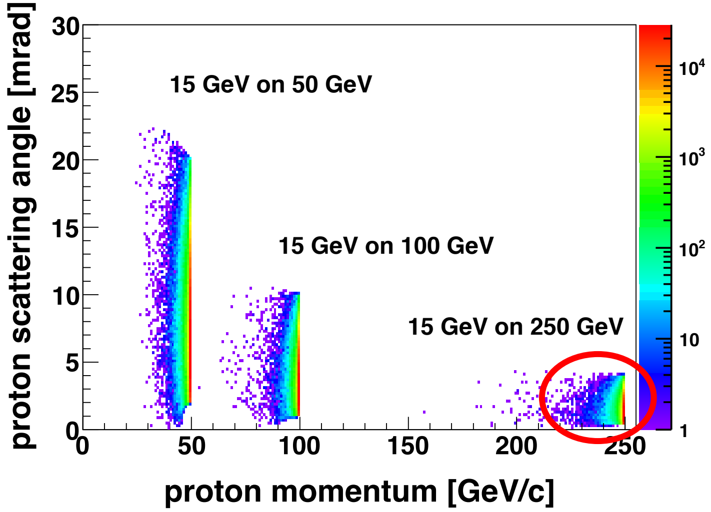
<u>High Divergence:</u> smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

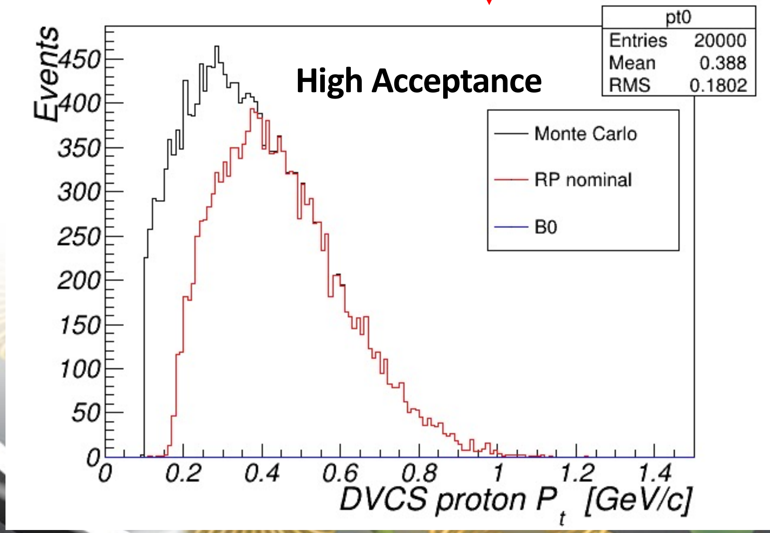
Digression: Machine Optics

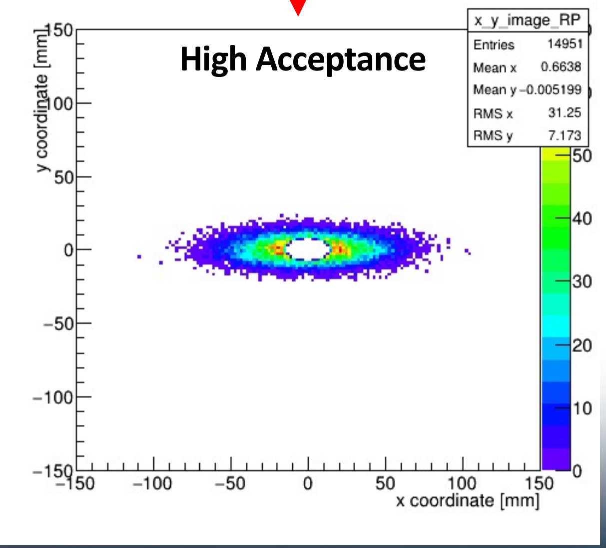
275 GeV DVCS Proton Acceptance









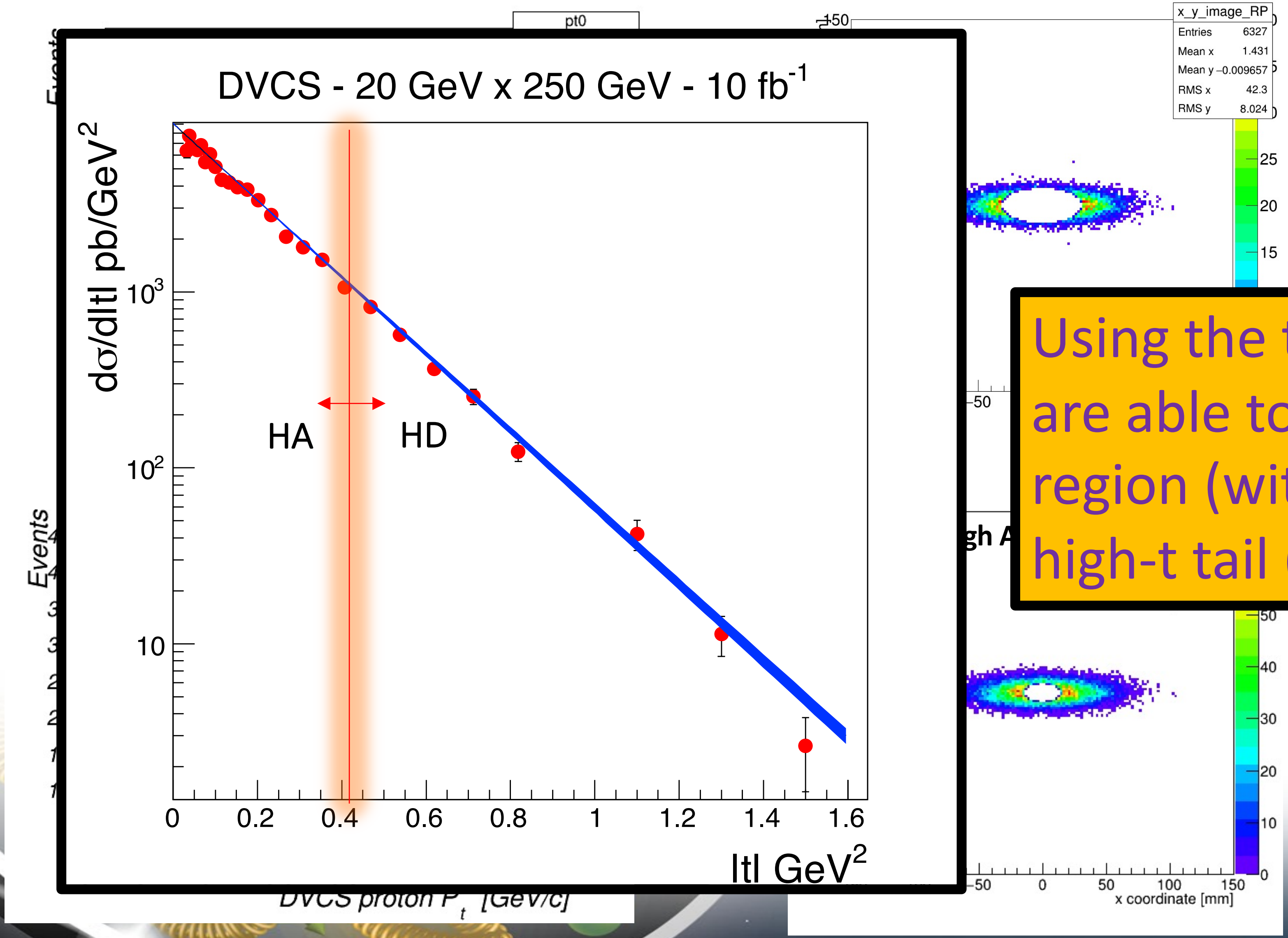


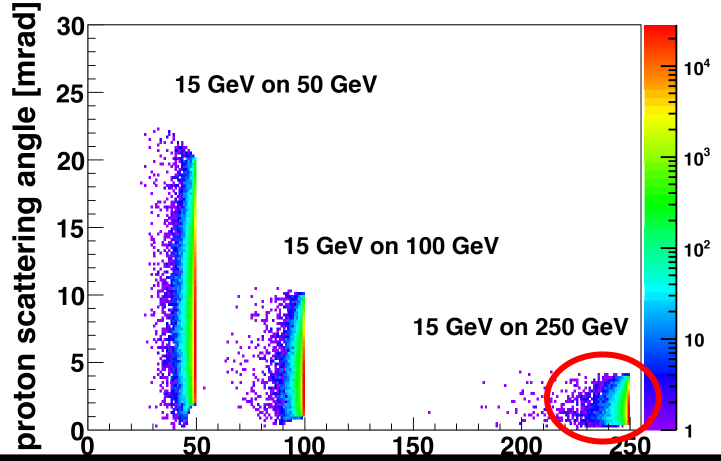
High Divergence: smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

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

Digression: Machine Optics

275 GeV DVCS Proton Acceptance

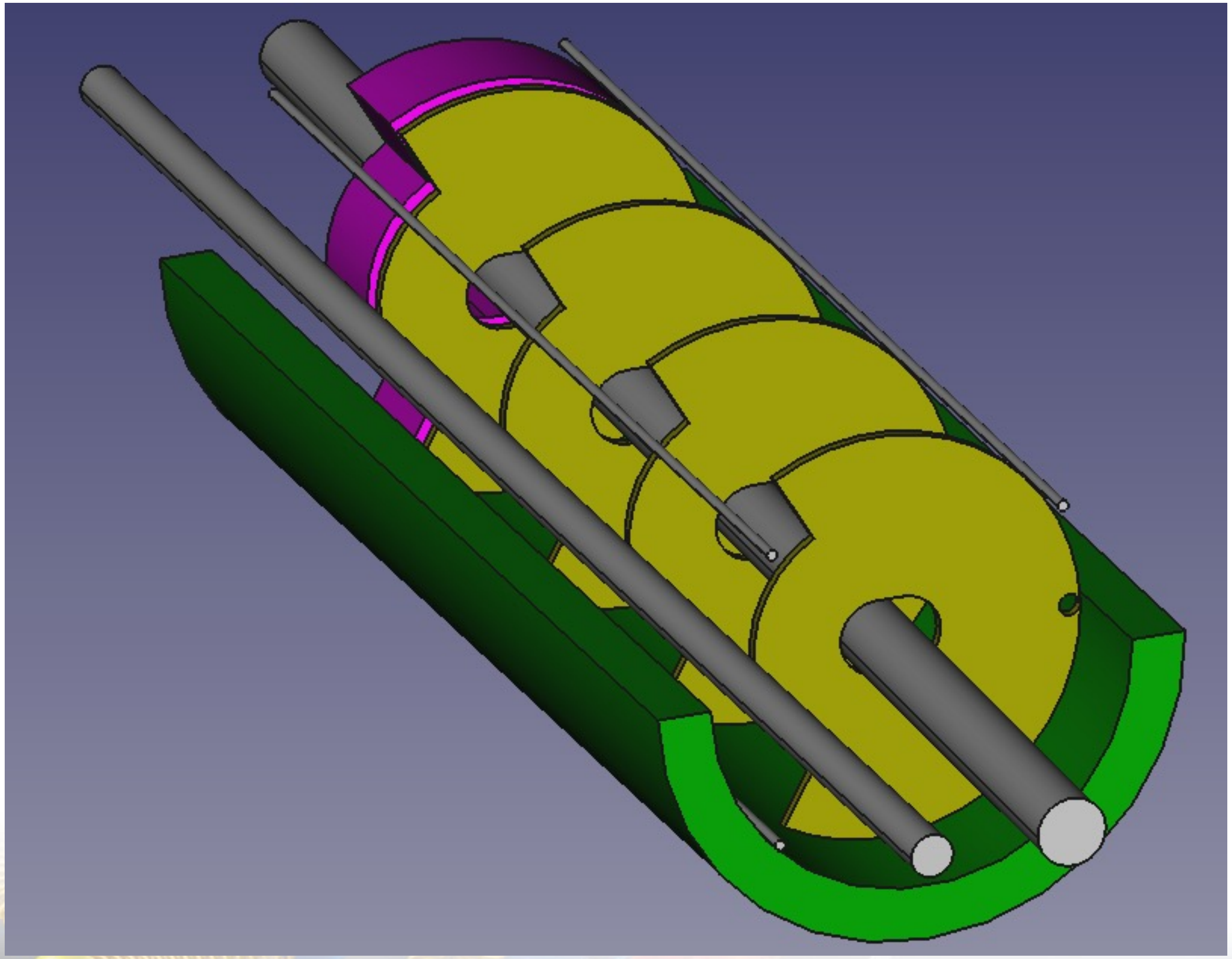




Using the two configurations, we are able to measure the low-t region (with better acceptance) and high-t tail (with higher luminosity).

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

B0-detectors (calorimetry)

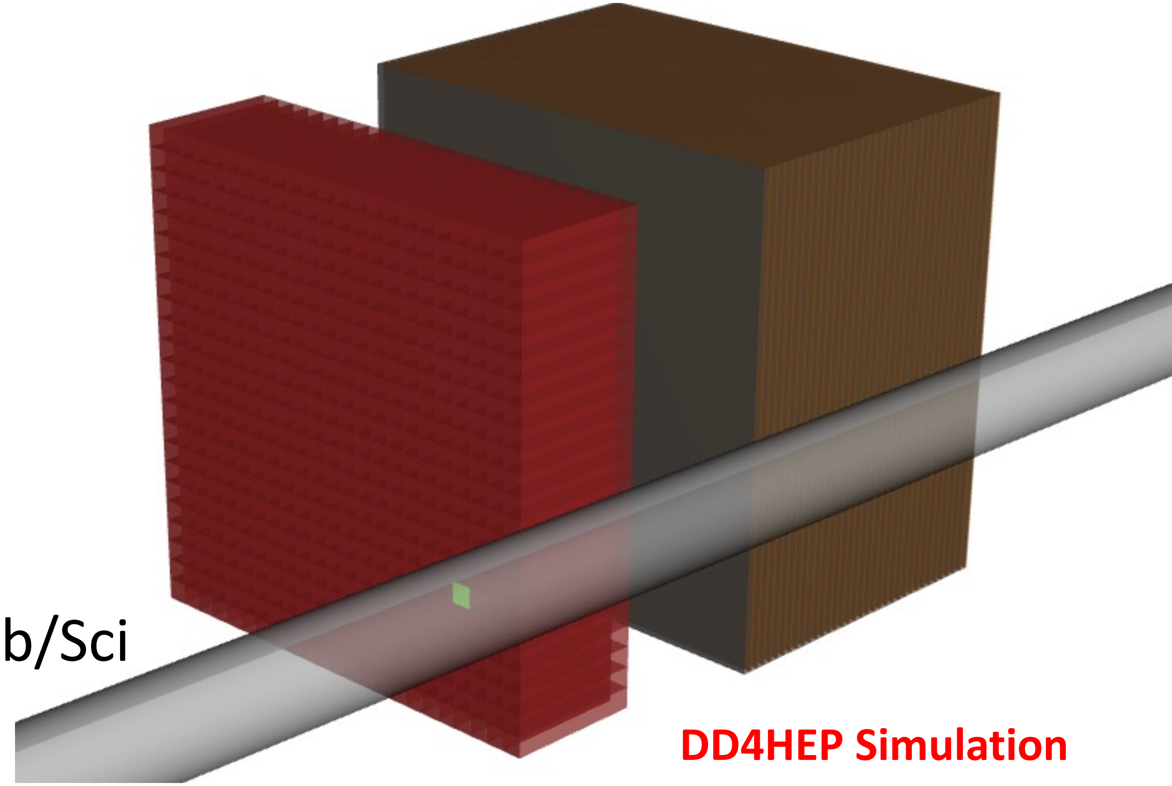


- For studies of *u*-Channel (Backward-angle) exclusive electroproduction, need capability to reconstruct photons from π^0 decays.
  - Physics beyond the EIC white paper!
- Would require full EMCAL with high granularity and energy resolution.
  - ➢ PbWO4 used in ECCE studies.
- Longitudinal space in B0pf magnet limited.
  - Would be a great candidate for an upgrade or for IP8 complementarity!

Thanks to Bill Li for the figure!

Zero-Degree Calorimeter (alt. option)

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



DD4HEP Simulation

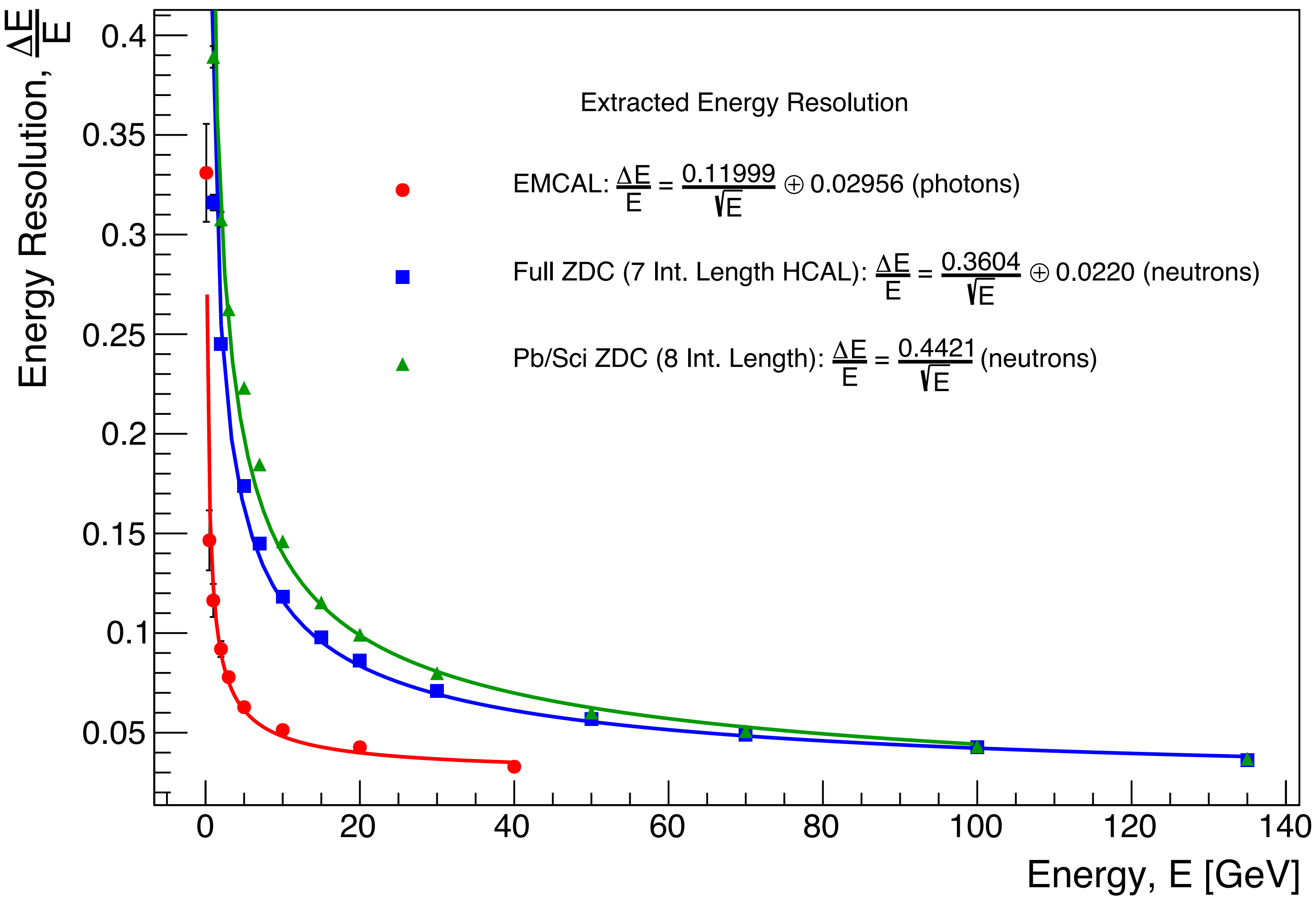
<u>EMCAL (W/SciFi):</u>

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

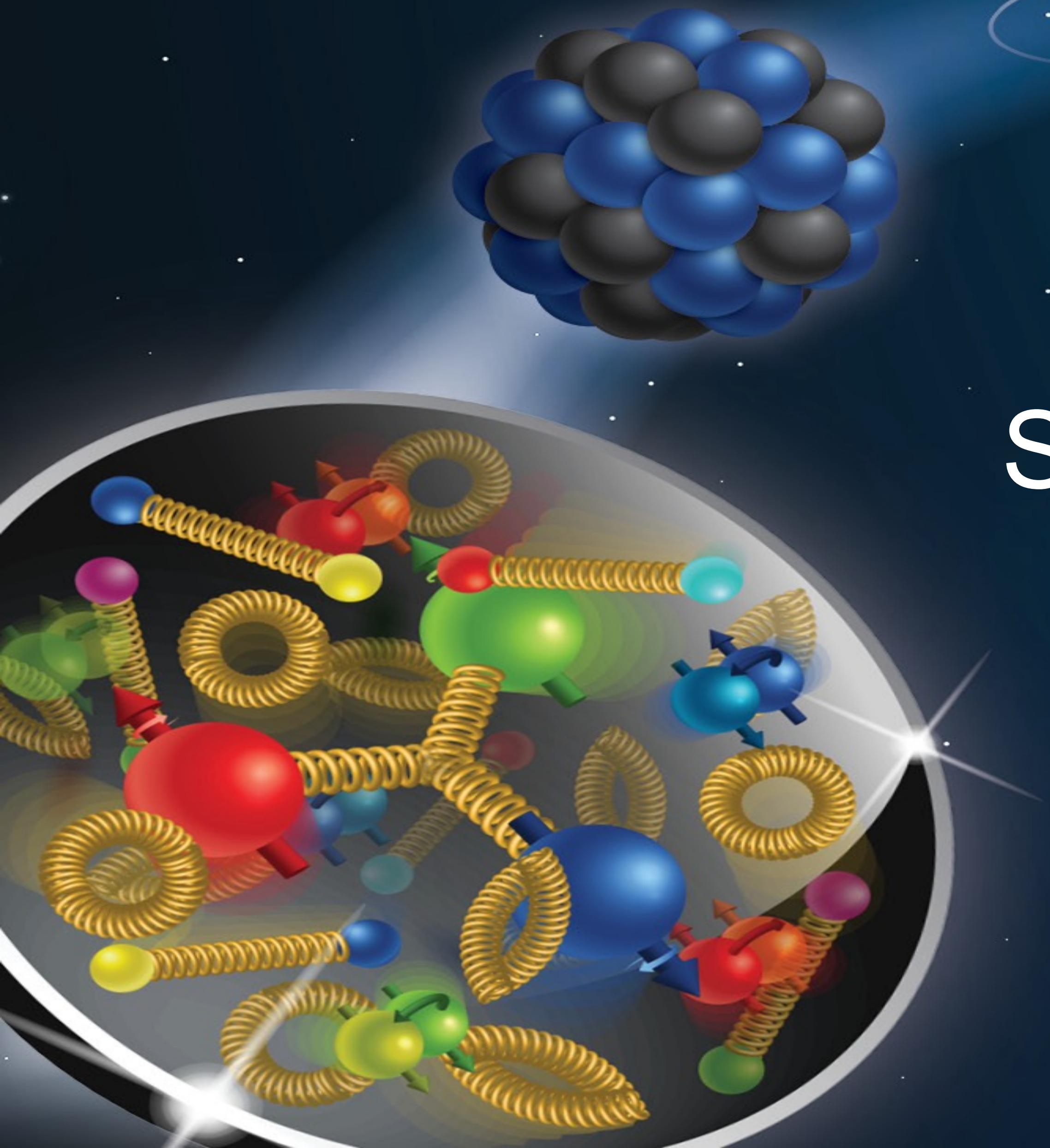
<u>HCAL (Pb/Sci):</u>

- 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)

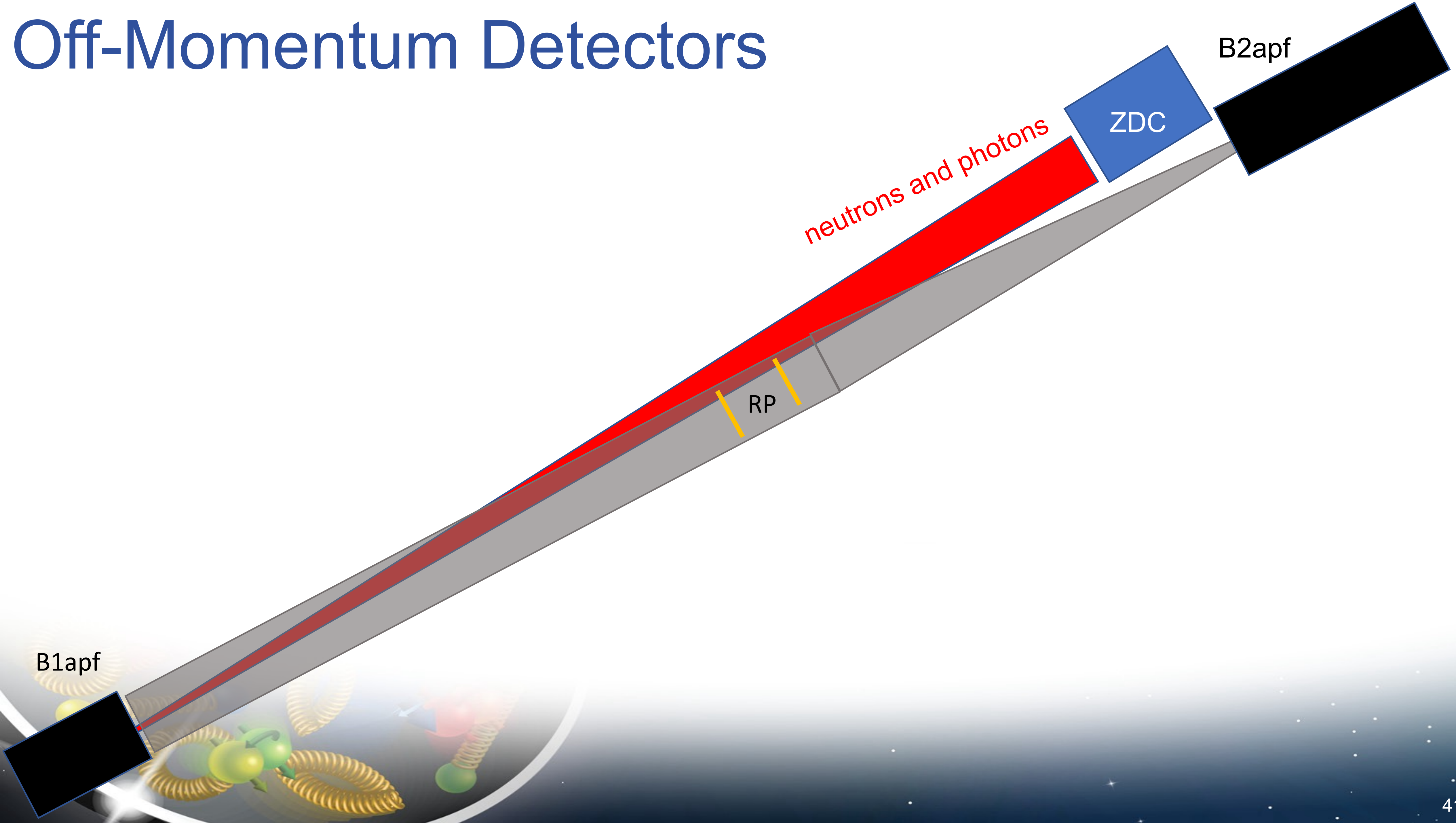


- **<u>Alt. ZDC</u>**
  - Comparisons made with simulations for pure Pb/Sci.
    - Performance in GEANT4 simulations consistent with test beam studies for similar construction.
  - Performance will worsen for particles with larger polar angles due to transverse leakage.



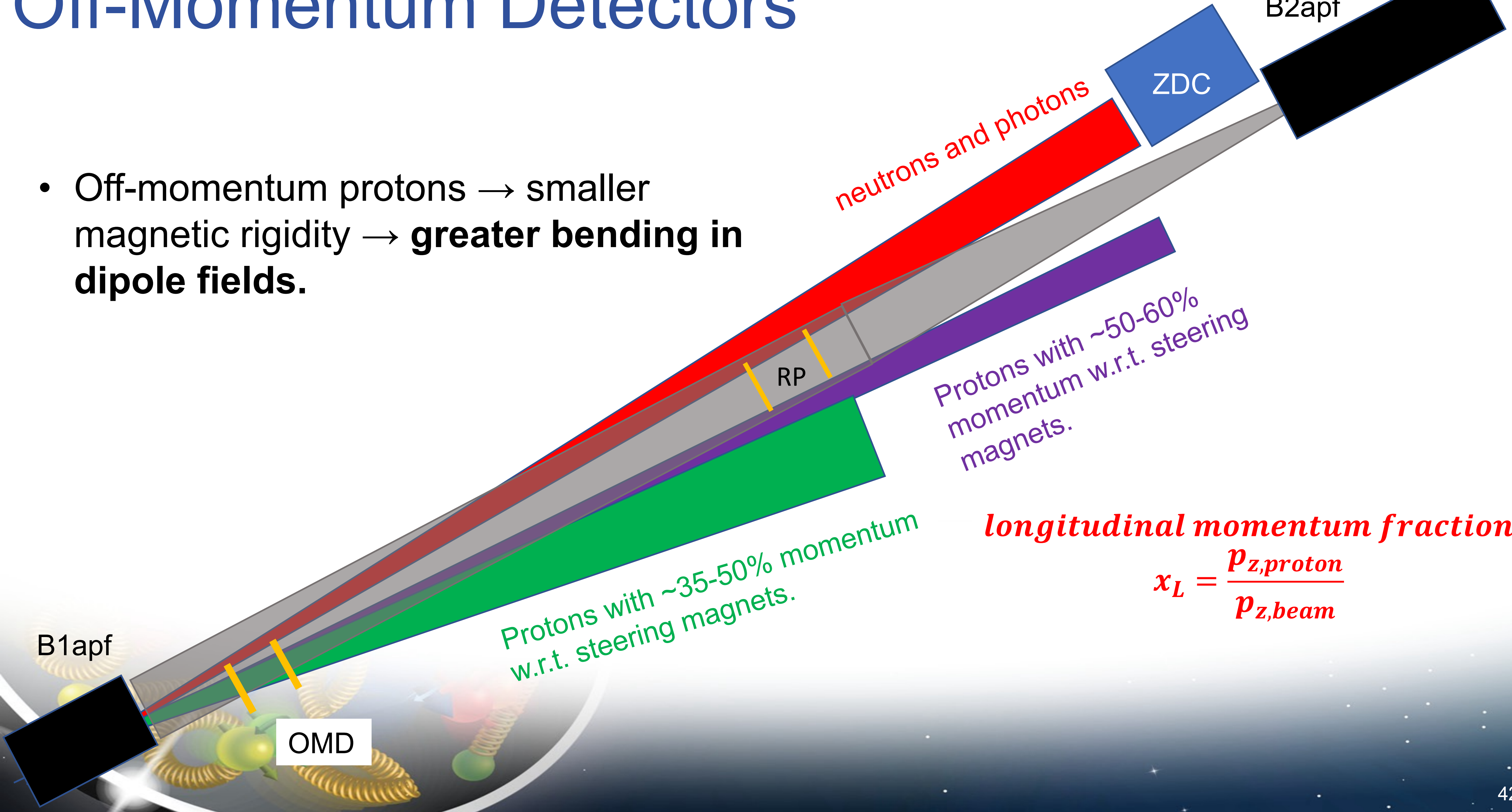
So how does the FF system perform for measurements (non-exhaustive)?

Off-Momentum Detectors



Off-Momentum Detectors

- Off-momentum protons → smaller magnetic rigidity → **greater bending in dipole fields.**

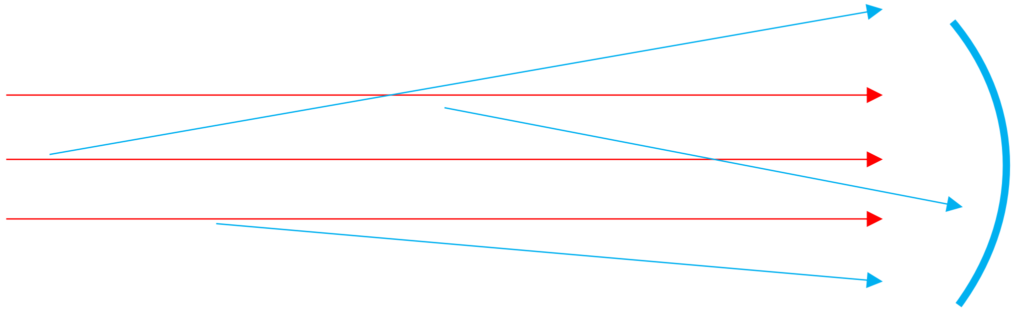


longitudinal momentum fraction

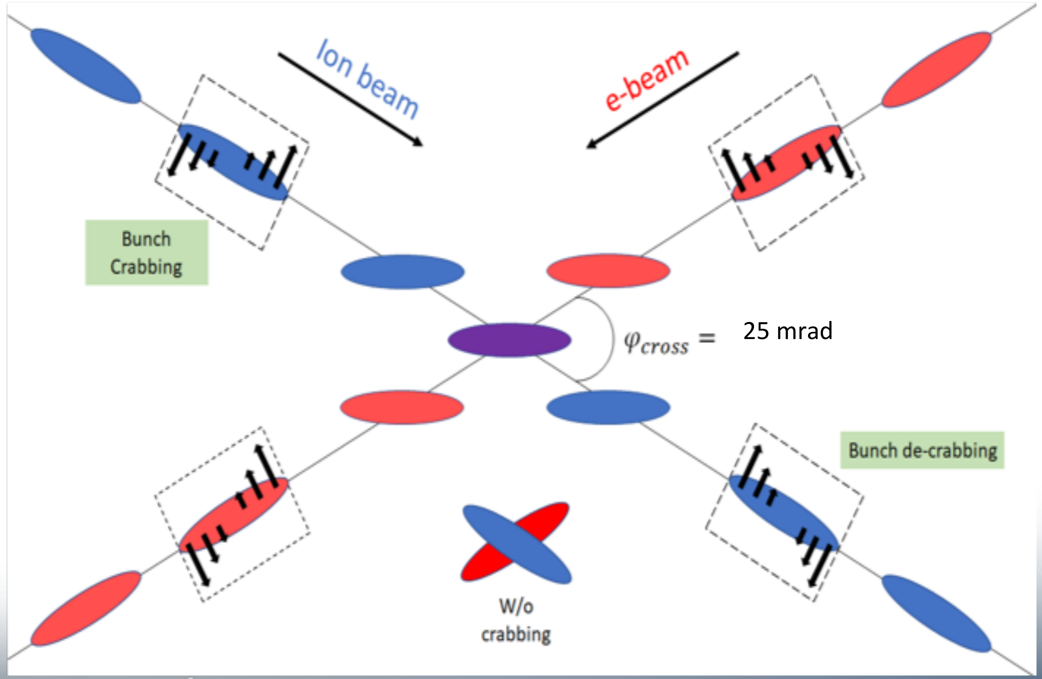
$$x_L = \frac{p_{z,proton}}{p_{z,beam}}$$

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.



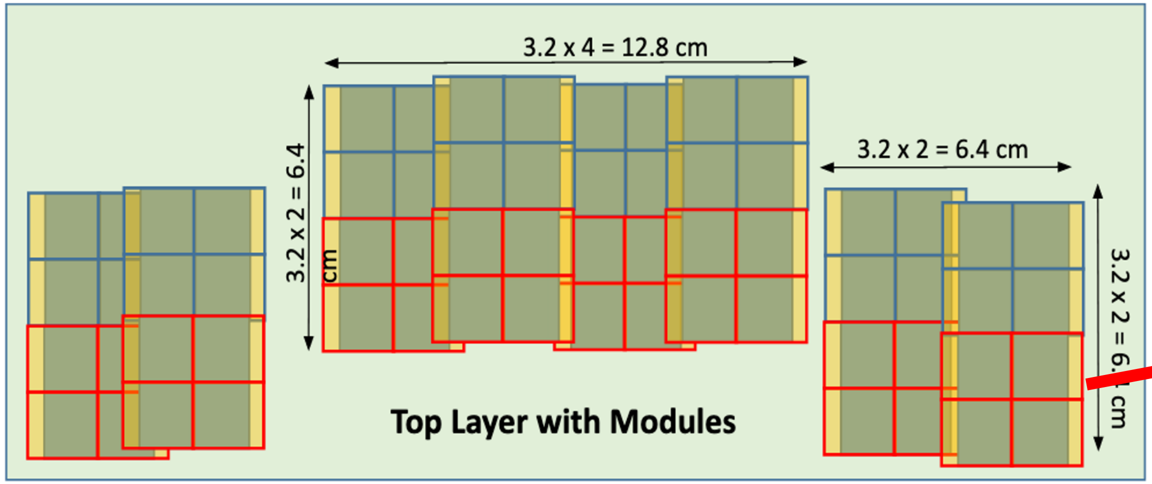
These effects introduce smearing in our momentum reconstruction.

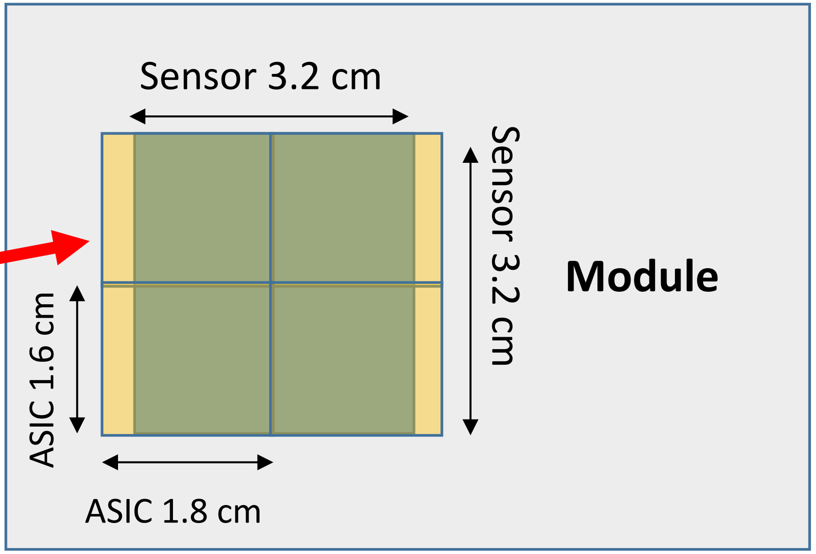
Roman Pots

- 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 with previous in-vacuum silicon detectors will be needed to design cooling scheme.
- 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.



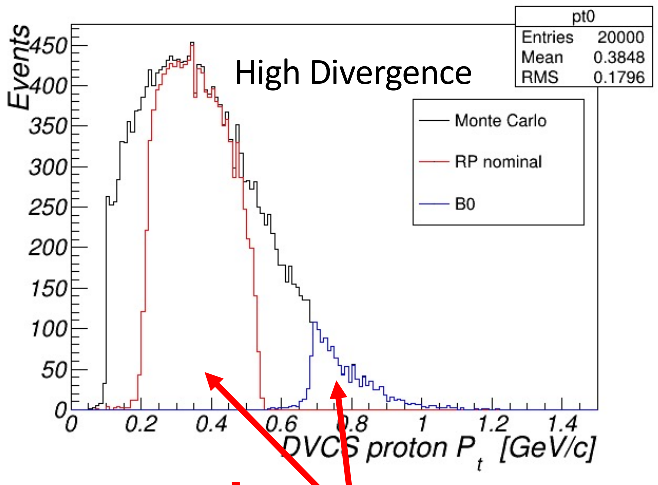


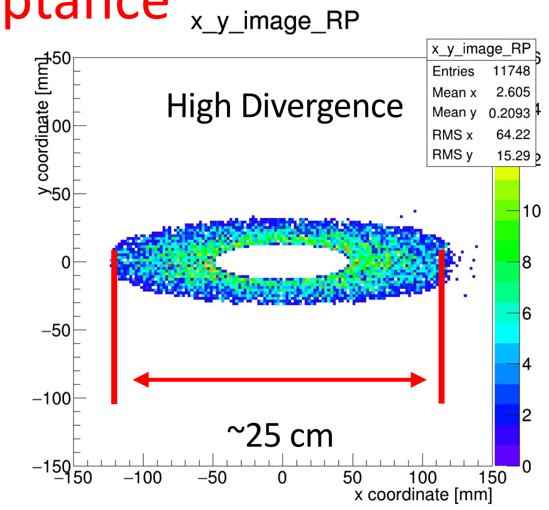
- Current R&D aimed at customizing ASIC readout chip (ALTIROC) for use with AC-LGADs.

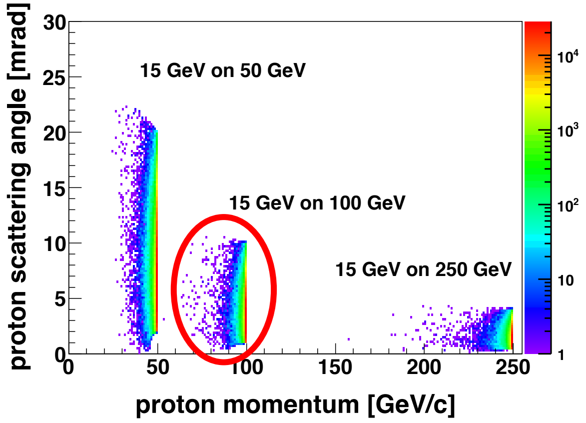
ASIC size	ASIC Pixel pitch	# Ch. per ASIC	# ASICs per module	Sensor area	# Mod. per layer	Total # ASICs	Total # Ch.	Total Si Area
1.6x1.8 cm^2	500 μm	32x32	4	3.2x3.2 cm^2	32	512	524,288	1,311 cm^2

Machine Optics: Roman Pots

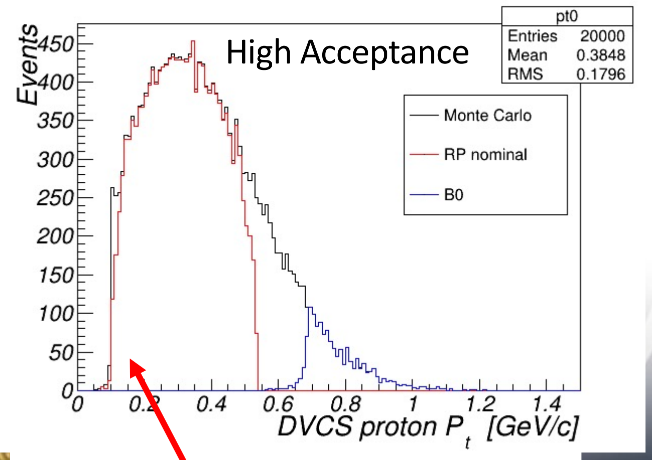
100 GeV DVCS Proton Acceptance

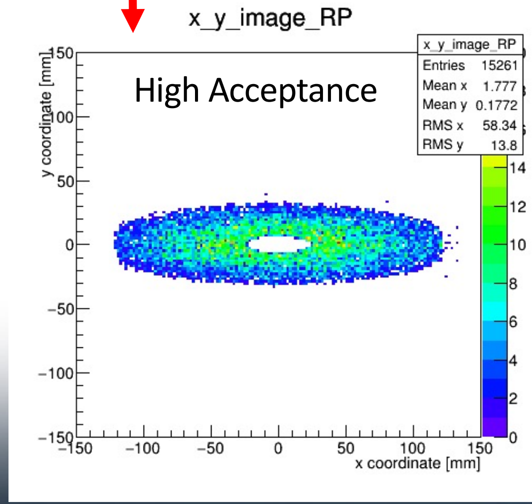






Need both detector systems together here!

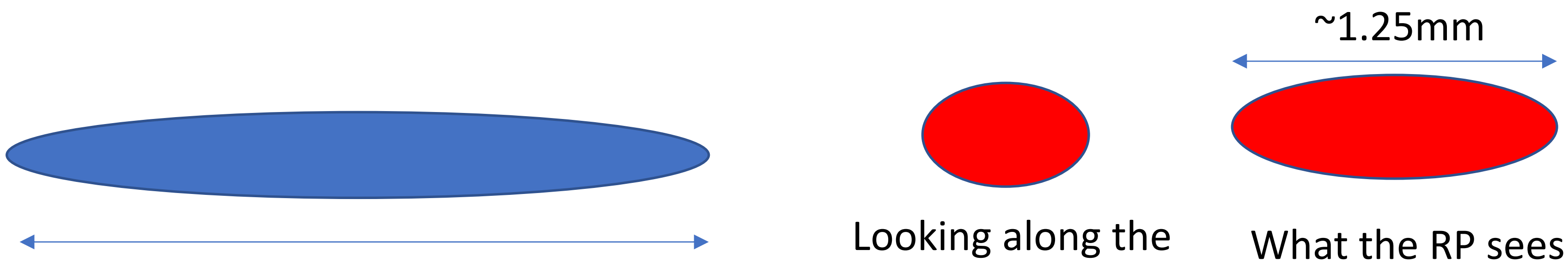




Improves low p_t acceptance.

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?



RMS hadron bunch length ~10cm.

Looking along the beam with no crabbing.

What the RP sees.

- 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.

> - **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).**

Momentum Resolution – Comparison

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

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

Angular divergence

Primary vertex smearing from crab cavity rotation.

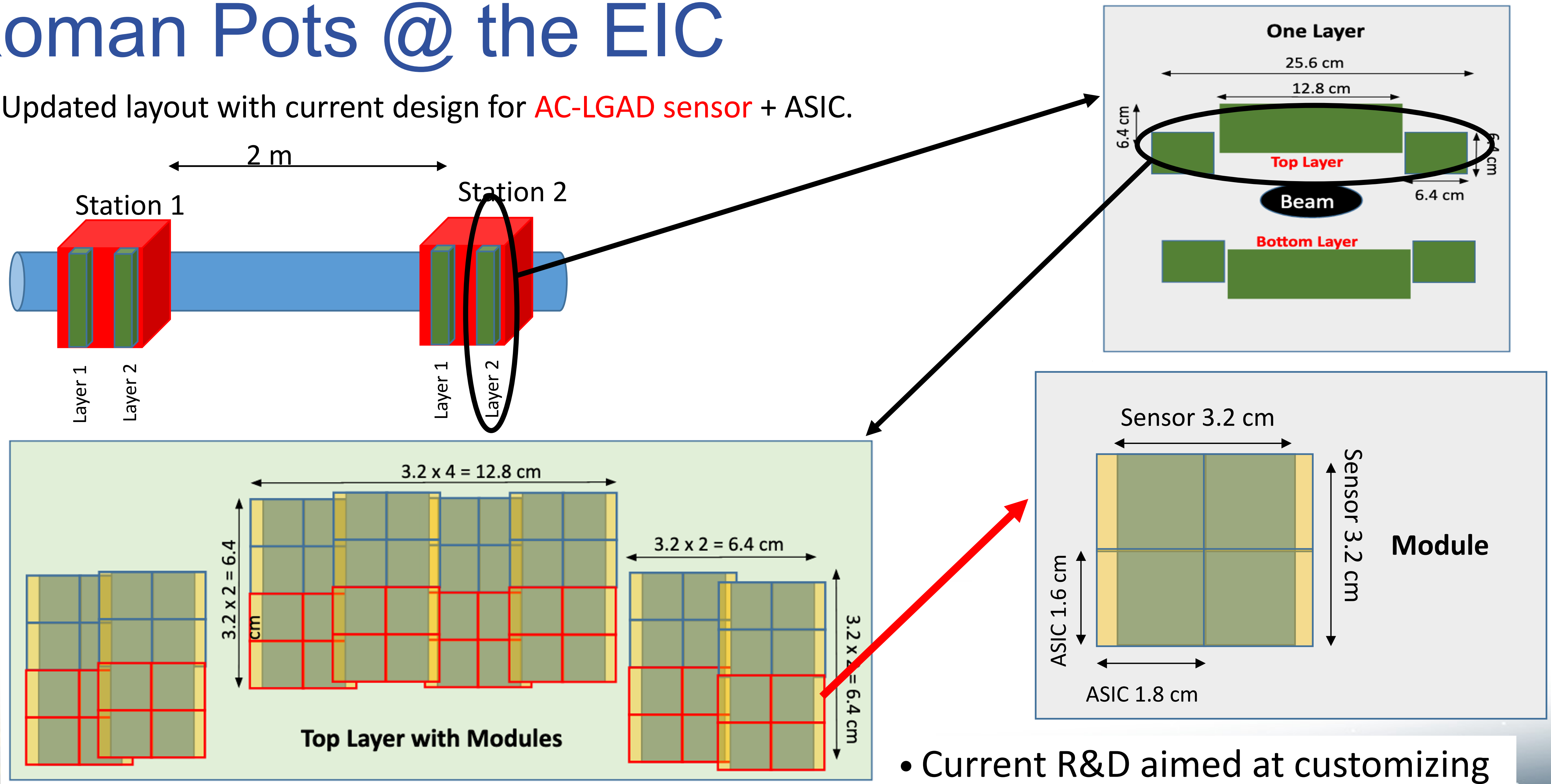
Smearing from finite pixel size.

	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.



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

Based on eRD24 R&D work.