Far-Forward and Far-Backward Detectors at the Electron-Ion Collider

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on behalf of the EPIC Collaboration

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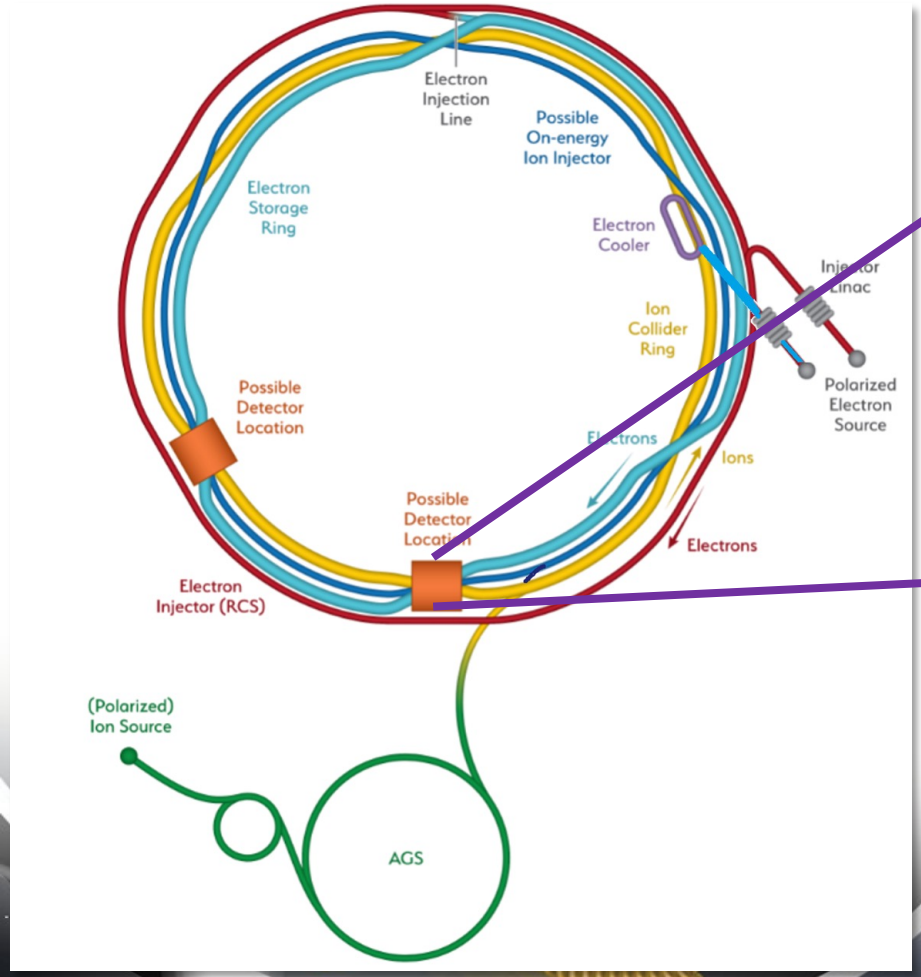
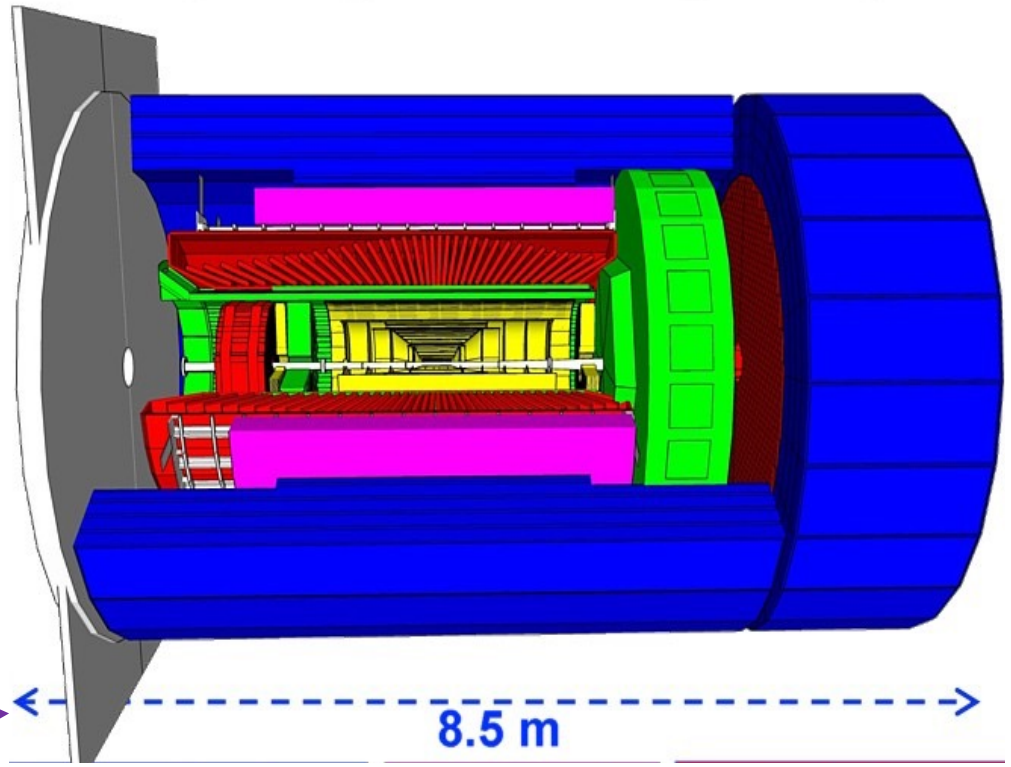
BROOKHAVEN NATIONAL LABORATORY
Jefferson Lab
U.S. DEPARTMENT OF ENERGY | Office of Science

The Electron-Ion Collider (EIC)

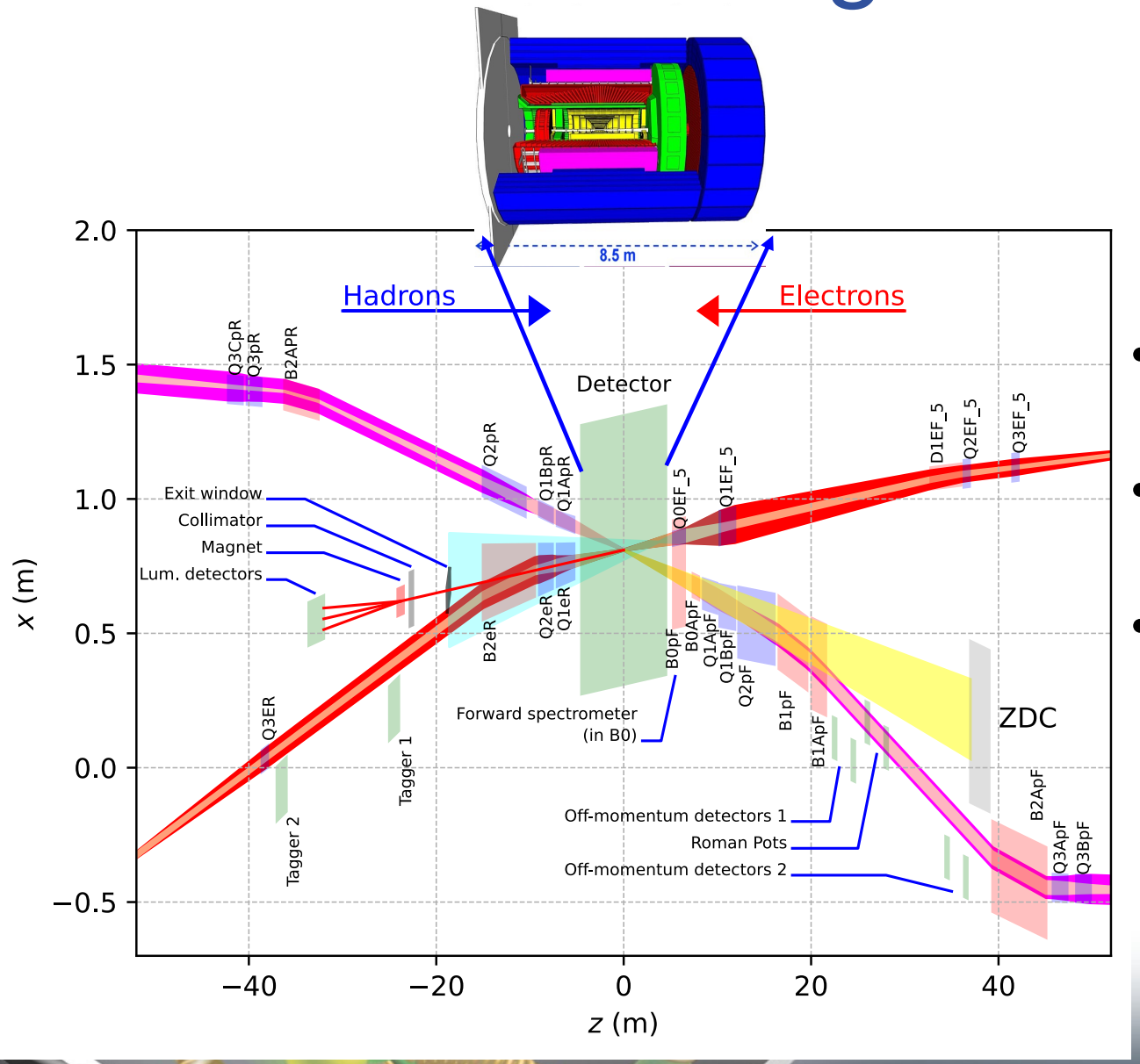
- Two interaction regions (IRs) for possible detector locations.
  - Only one IR (IP6) part of the project scope.





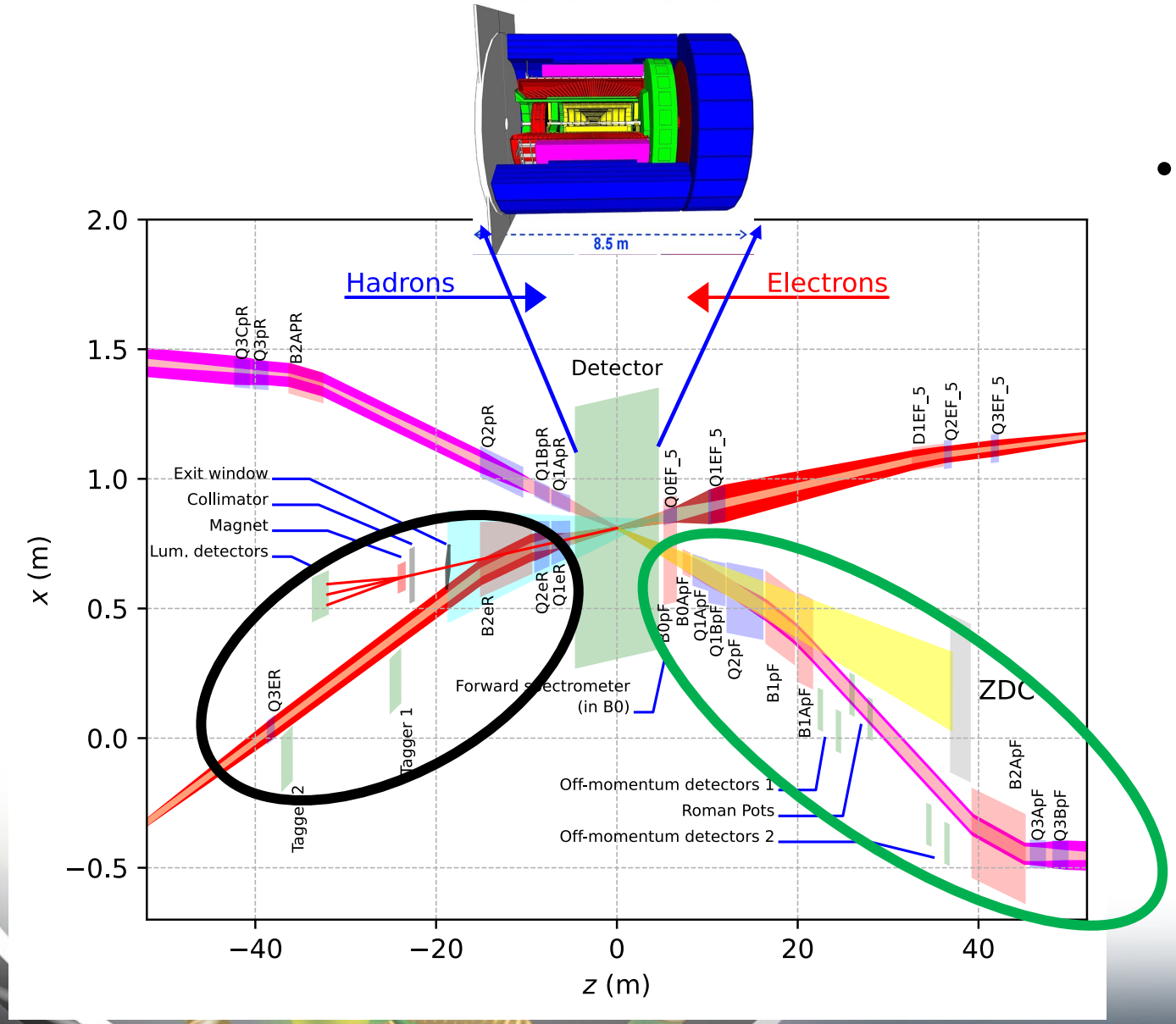
- Reference detector based on the 1.5T BaBar solenoid.
  - Contains detectors for tracking, PID, and calorimetry.
  - Integrated beam line detectors.

EIC Interaction Region



- Hadron and electron beams collide with a 25mrad crossing angle (in IP6).
- Design enables maximum luminosity reach of the EIC (10^{34} cm^{-2} s^{-1}).
- Complicated layout + limited space makes full detector integration a challenge!

EIC Far-Forward and Far-Backward Regions



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

The far-forward and backward systems are crucial for delivery of full EIC physics program!

Far-Backward Detectors

Luminosity Monitor

- Process of elastic bremsstrahlung, $ep \to e\gamma p$, $e\mathrm{Au} \to e\gamma\mathrm{Au}$
- Large cross section peaked for photons at small angles
- Two methods for γ detection: direct detector and $e^{\pm}$ spectrometer:

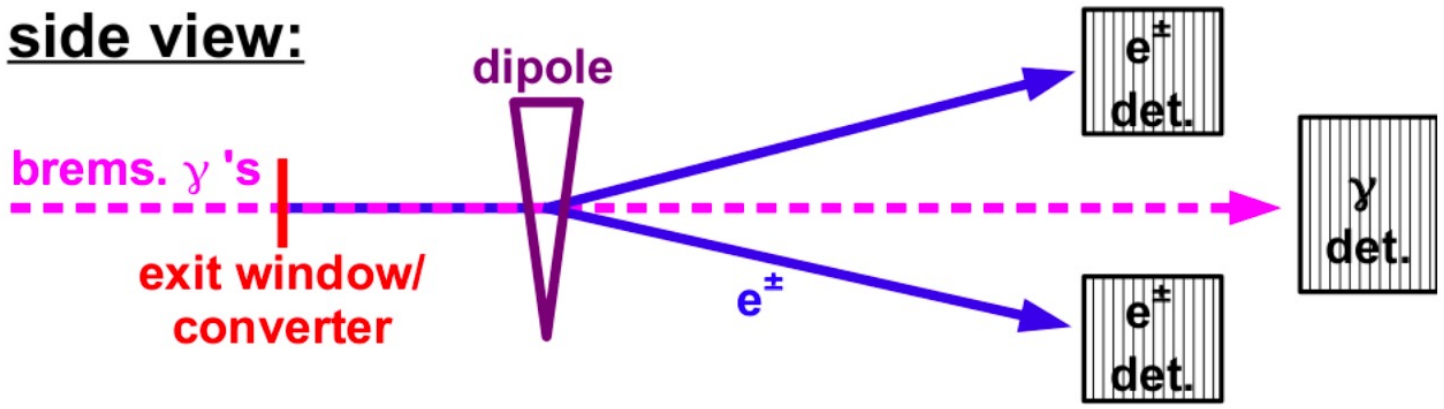


Figure: Cross section

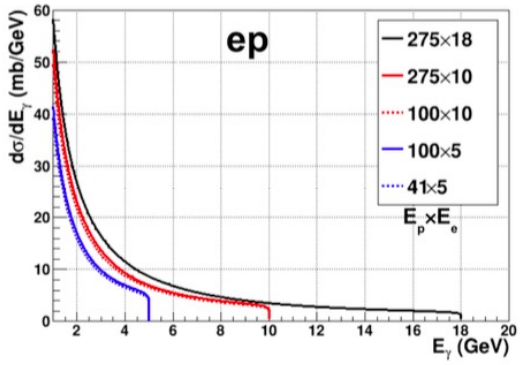
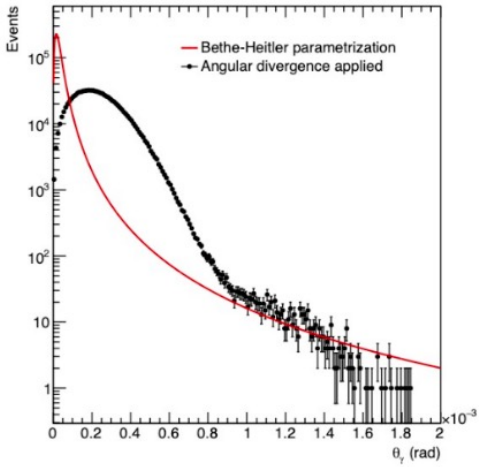


Figure: Angular distribution

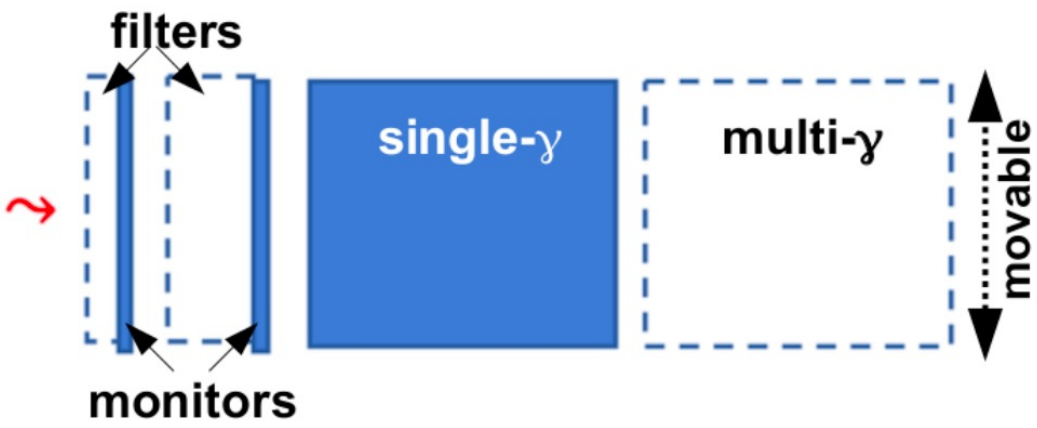


The cross section is precisely known from QED

Luminosity Monitor

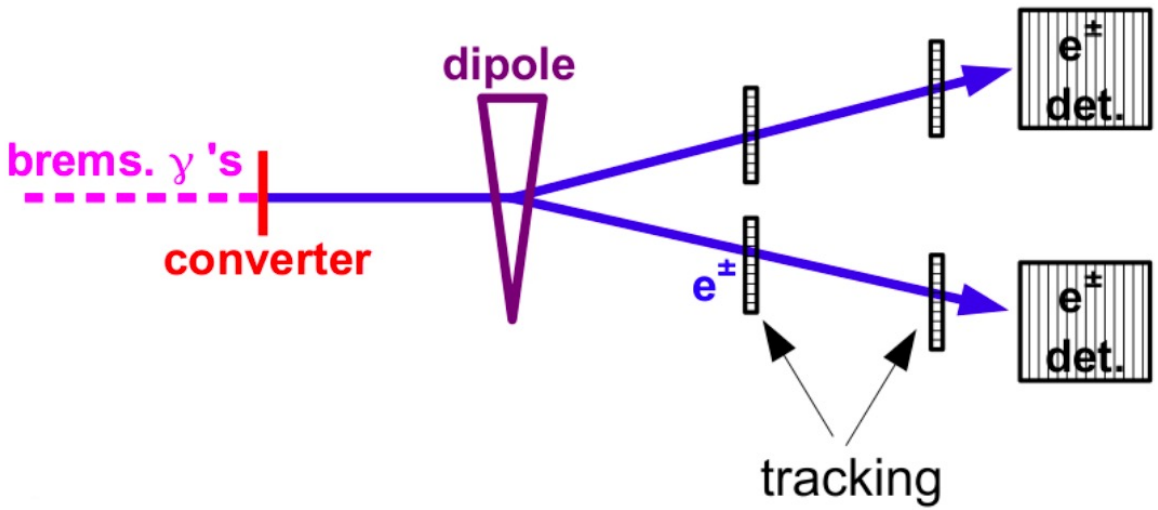
- Must make measurement in challenging environment.
  - High synchrotron radiation, high bremsstrahlung rates (~10 GHz), etc.
- Need ~1% for absolute luminosity measurement, ~10^{-4} for relative luminosity measurement.

Figure: Direct photon detector



- Simple concept, approximate measurement
- More γ incident in every bunch crossing
- Online machine performance

Figure: Pair spectrometer



- Precise measurement for physics results
- More complex implementation
- Not sensitive to synchrotron radiation

Luminosity Monitor

Luminosity monitor location

Figure: Towards central detector

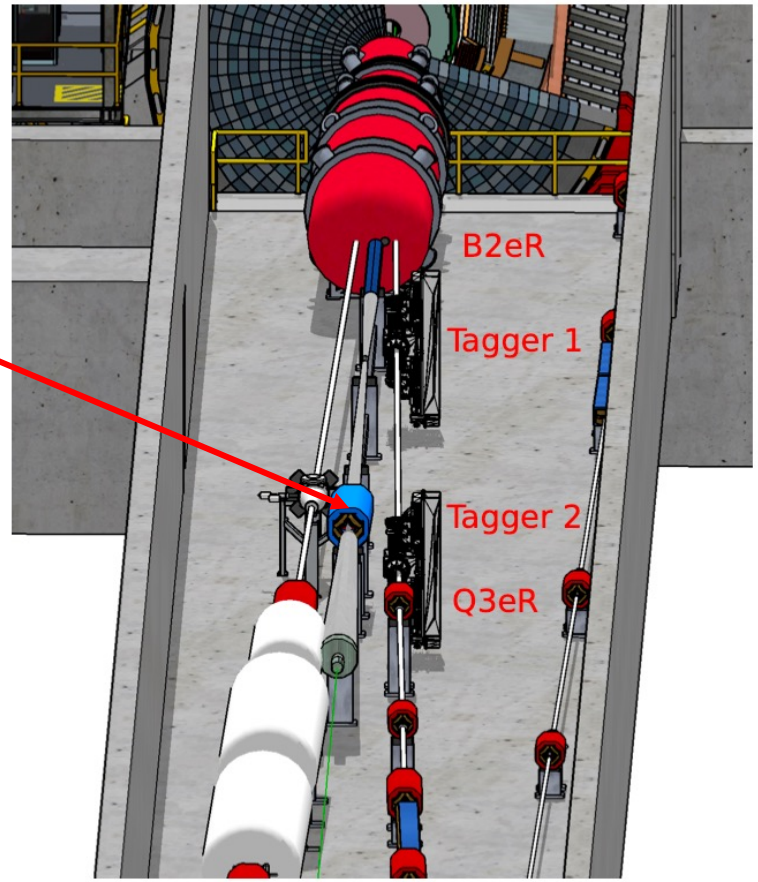
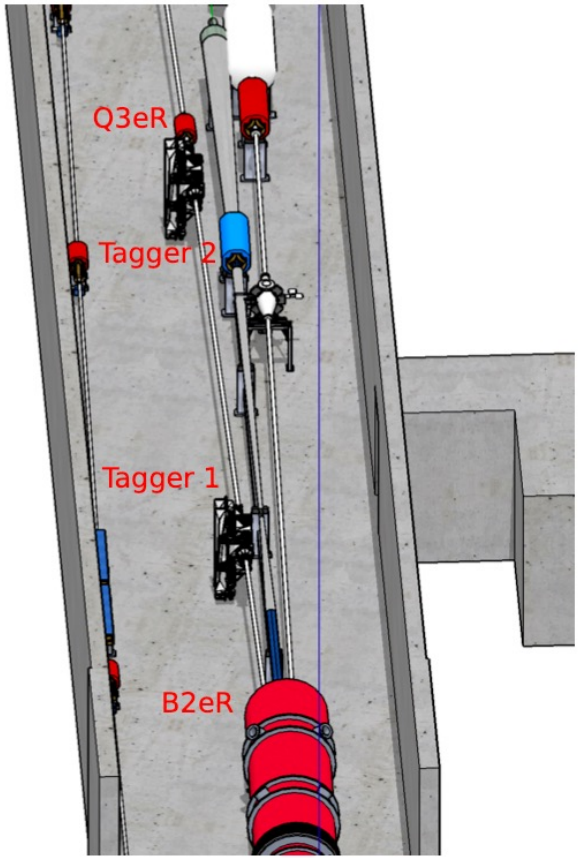


Figure: Towards the tunnel



Low-Q^2 Tagger

- Two detectors along the outgoing electron beam
- Same Q^2 is reached at different energies and angles:

Figure: Q^2 vs. energy and scattering angle

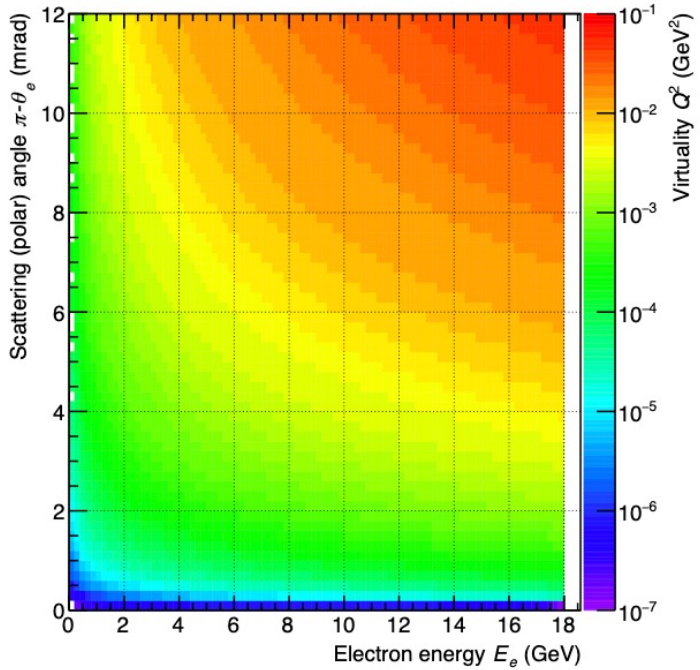


Figure: Towards central detector

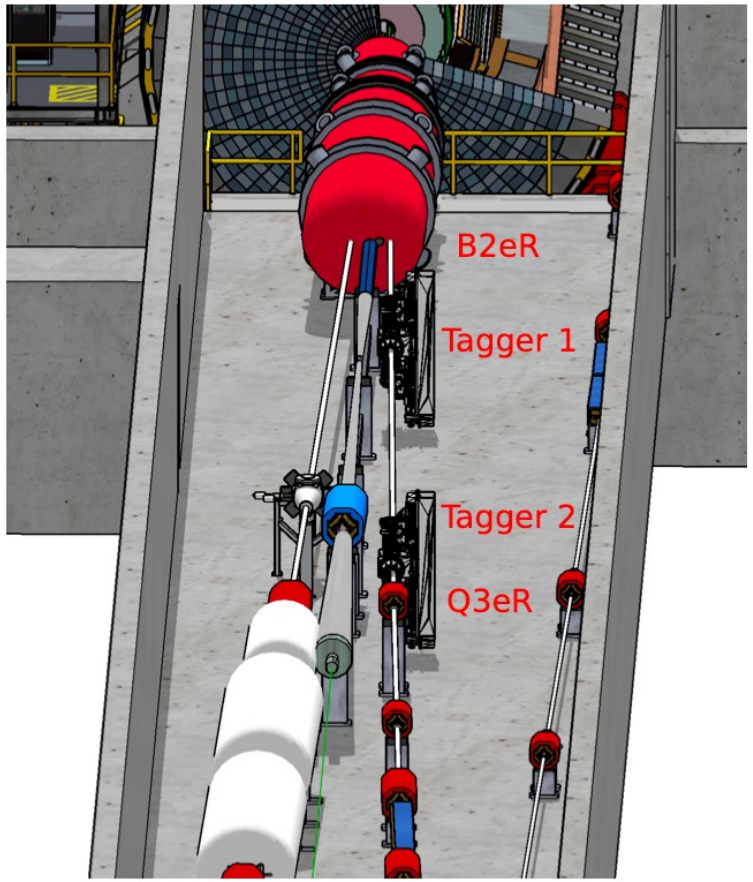
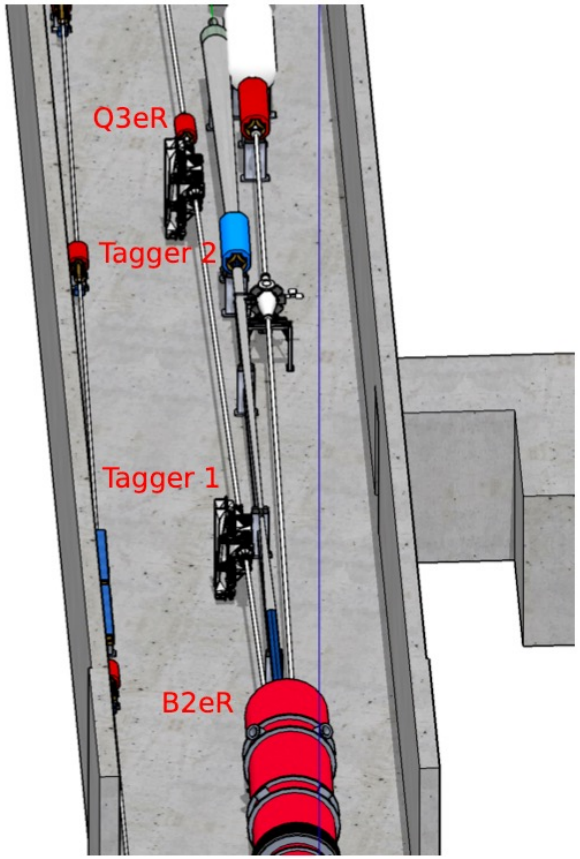
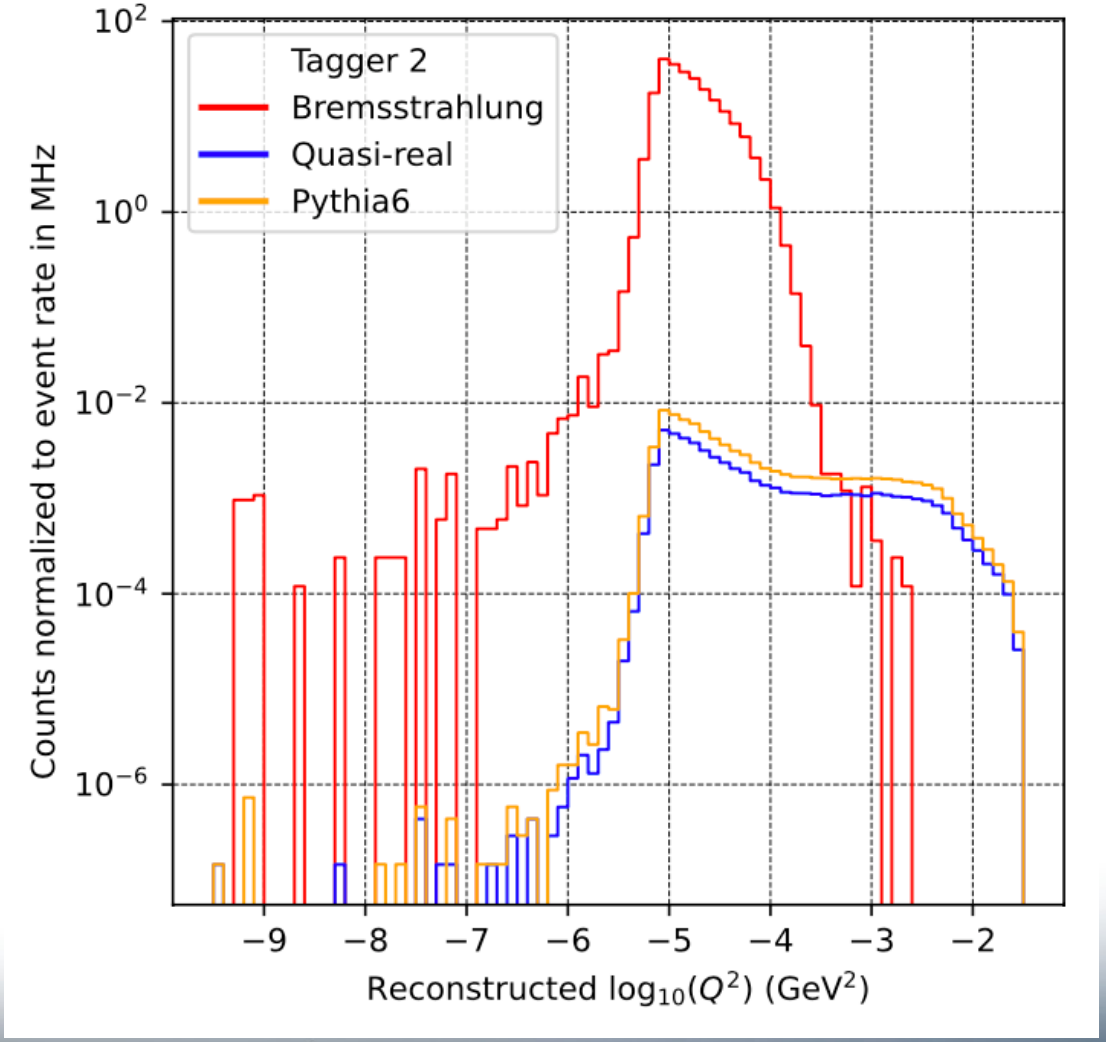


Figure: Towards the tunnel



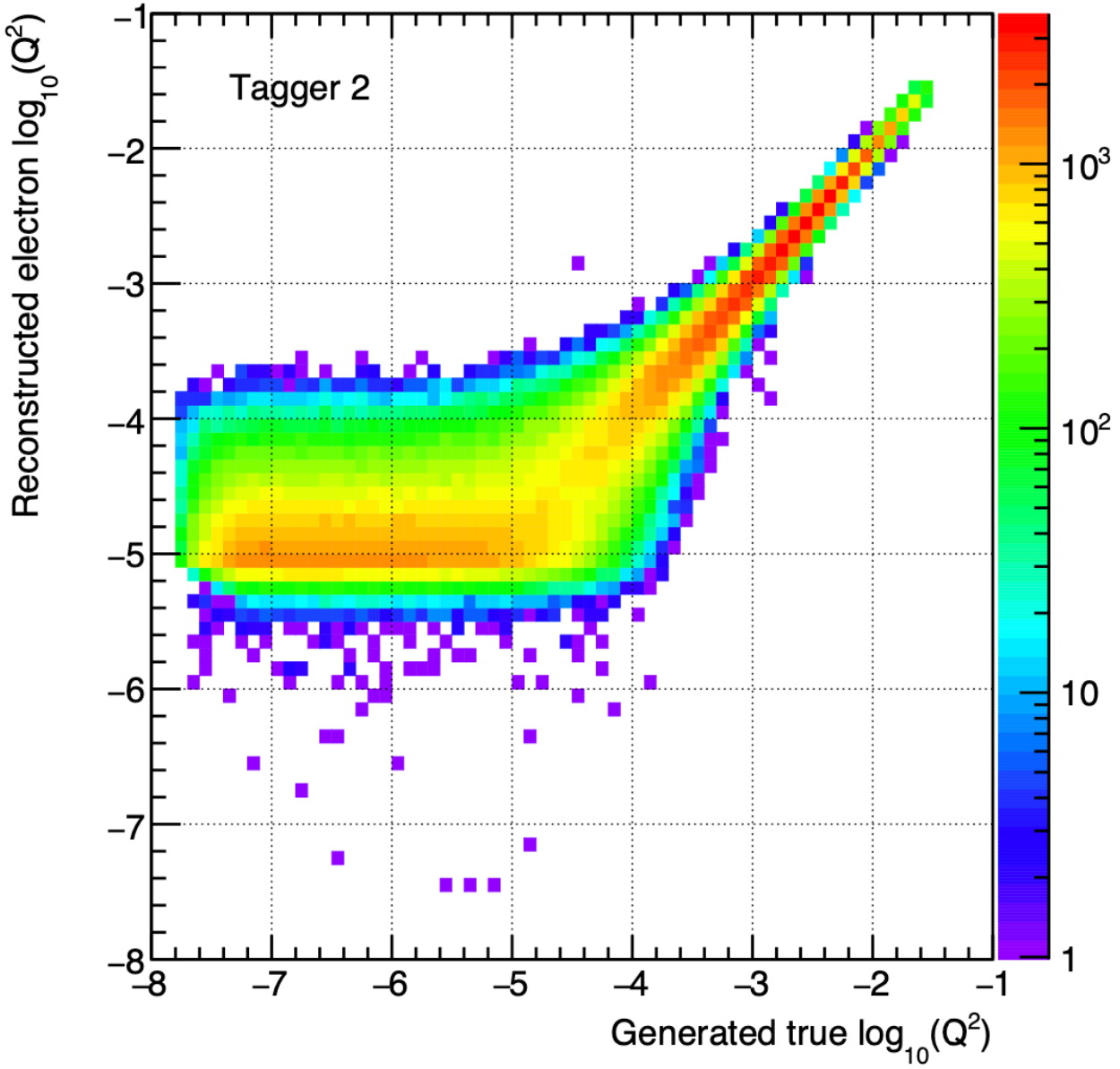
Low-Q^2 Tagger

- Production rates are dominated by large bremsstrahlung cross section
- The rates give normalization to spectrum of reconstructed Q^2
- Clean photoproduction signal can be taken over a limited region in Q^2
- Bremsstrahlung electron are important to calibrate the luminosity measurement



Low-Q^2 Tagger

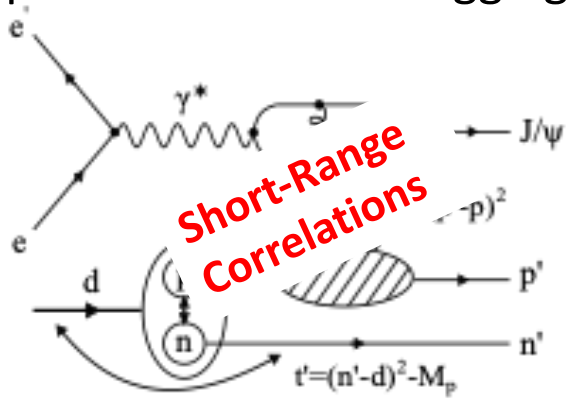
- Reconstructed virtuality Q^2 is compared to generated true event Q^2
- Machine learning connects detected track with original scattered electron
- The Q^2 is given by electron energy and scattering angle
- Beam effects (vertex spread, angular divergence) are included in the simulation
- Beam angular divergence limits the resolution at $Q^2 < 10^{-3}$ GeV^2



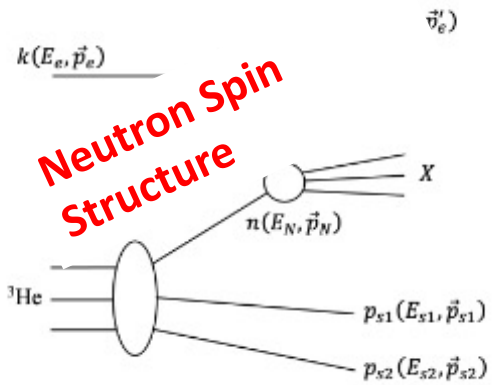
Far-Forward Detectors

Far-Forward Physics at the EIC

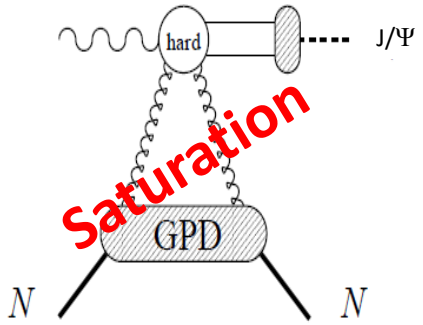
e+d exclusive J/Psi with proton or neutron tagging[1]



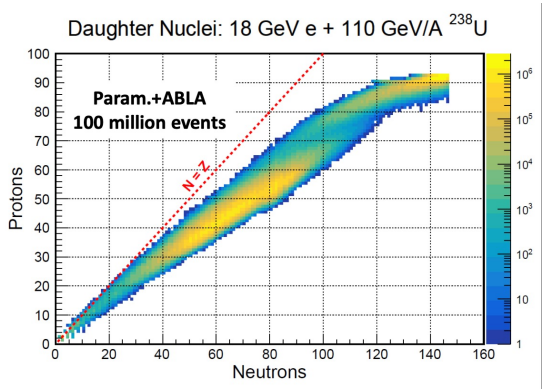
e+He3 spectator tagging[2]



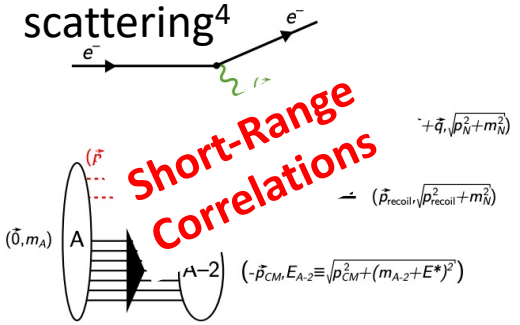
coherent/incoherent J/ψ production in e+A[3]



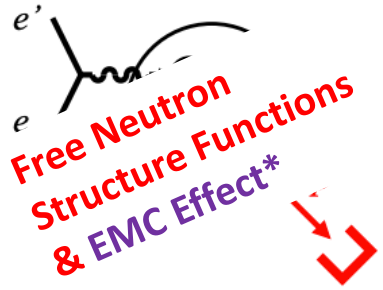
Rare isotopes**



Quasi-elastic electron scattering[4]

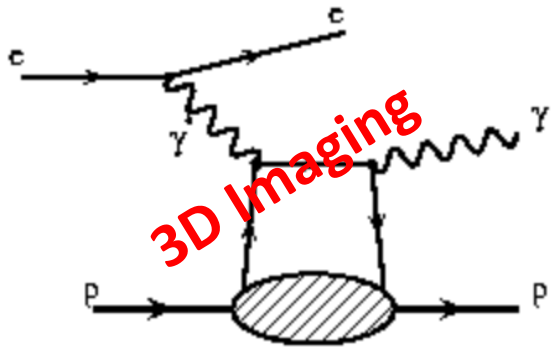


e+d DIS spectator tagging[5]



[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+p DVCS

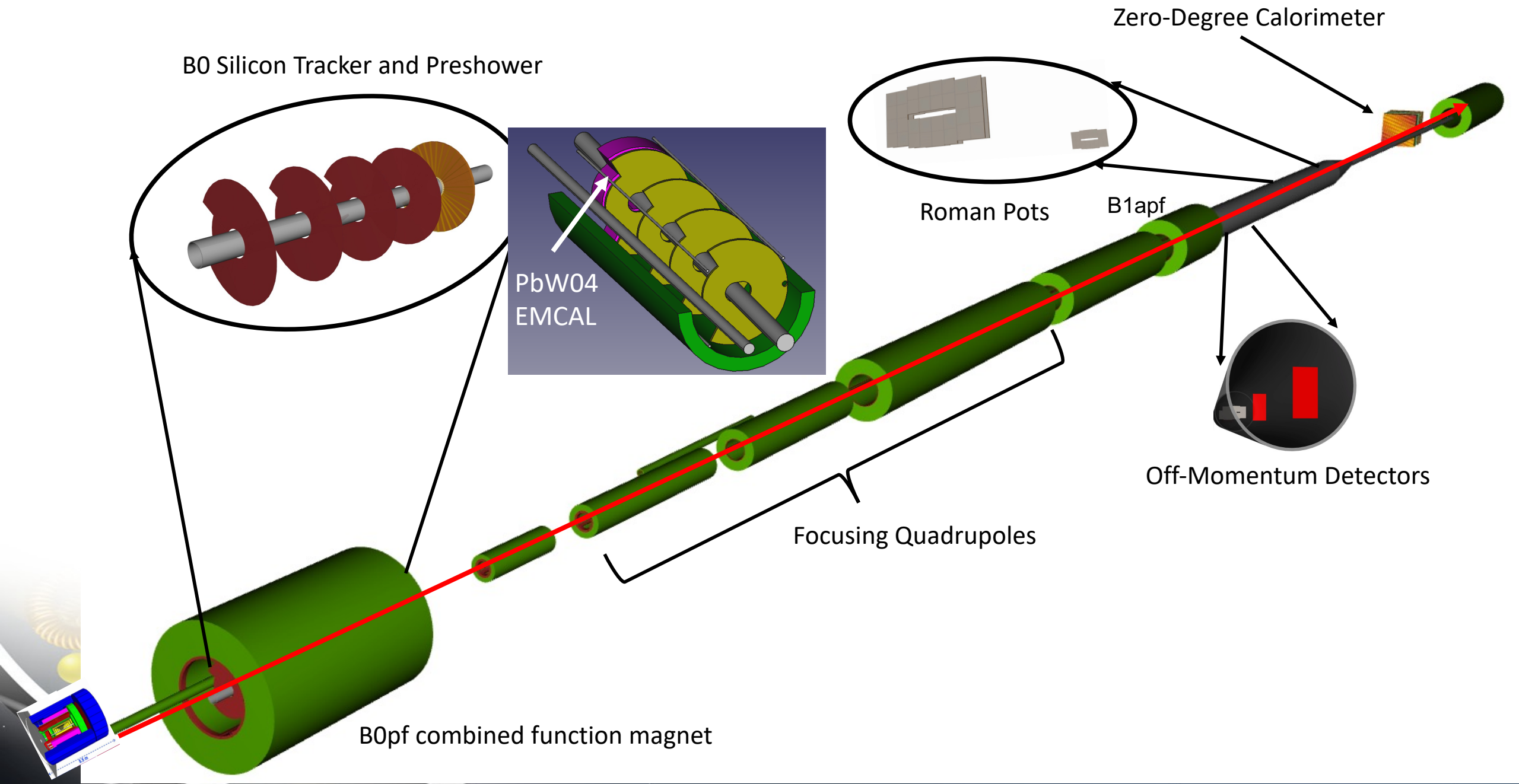


Many examples of detailed impact studies with full detector simulations! (non-exhaustive)

Far-Forward Physics at the EIC

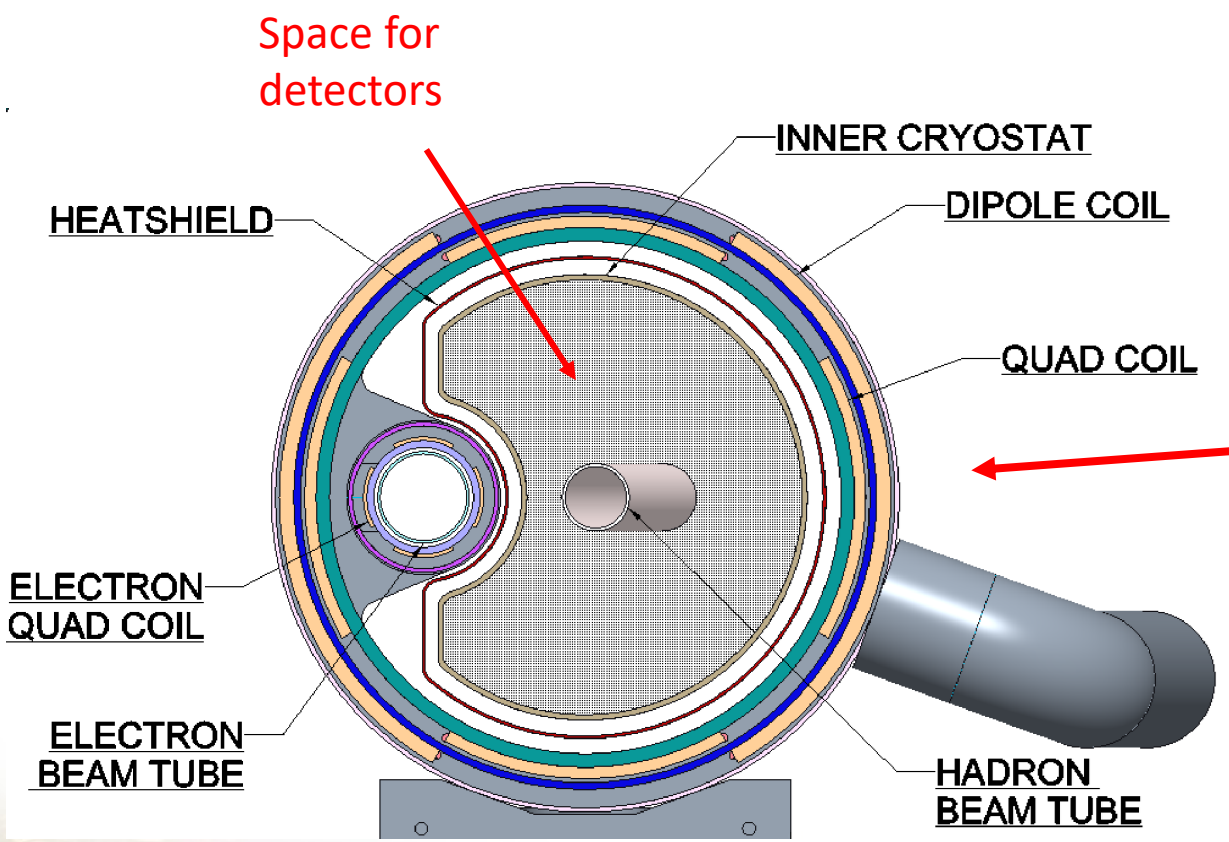
- Physics channels require tagging of **charged hadrons** (protons, pions) or **neutral particles** (neutrons, photons) at **very-forward rapidities ($\eta > 4.5$).**
- Different final states → tailored detector subsystems.
- Various collision systems and energies (h: 41, 100-275 GeV, e: 5-18 GeV; e+p, 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 the detector design proposals.

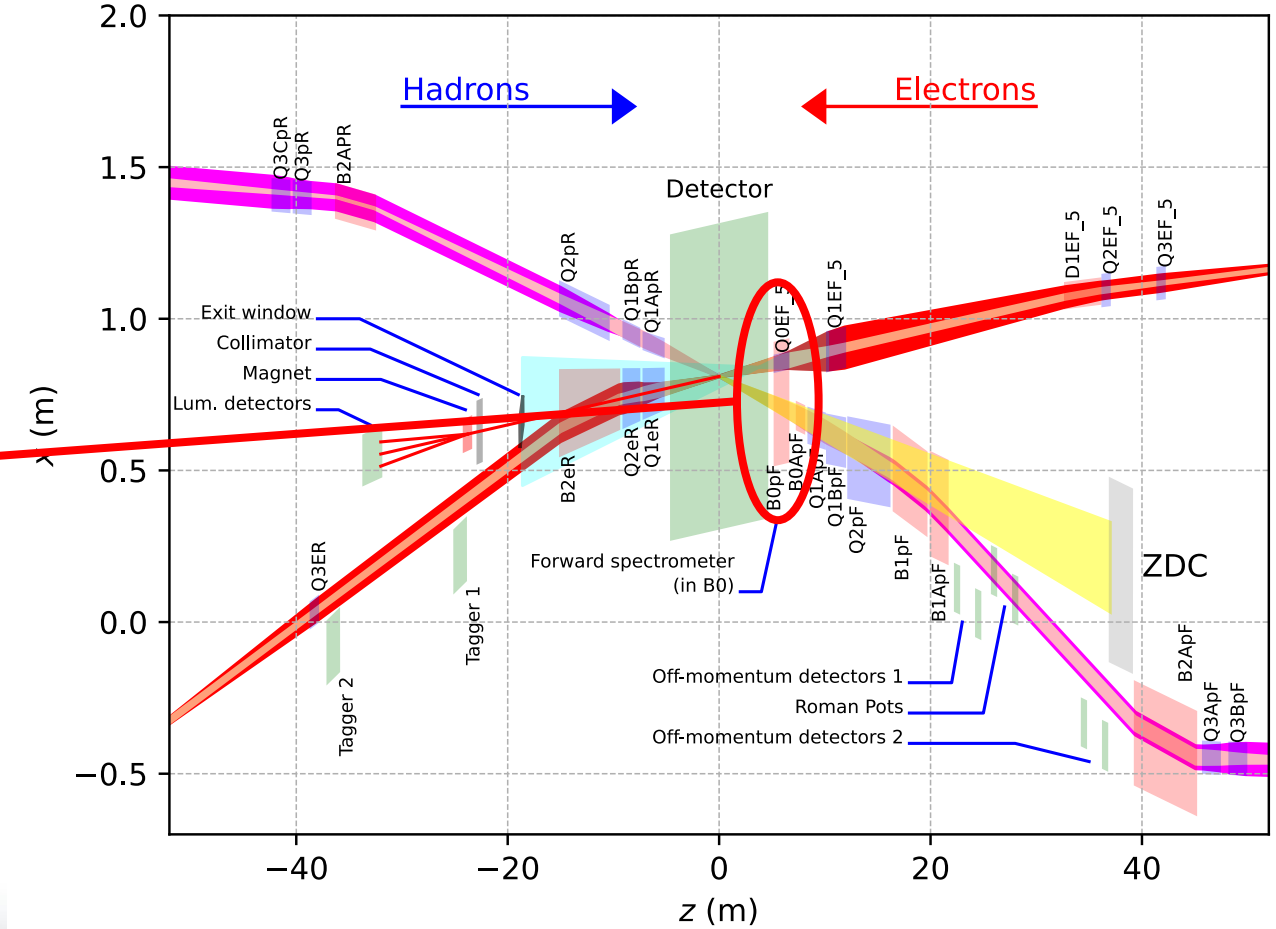
The Far-Forward Detectors



Far-Forward Detector Subsystems

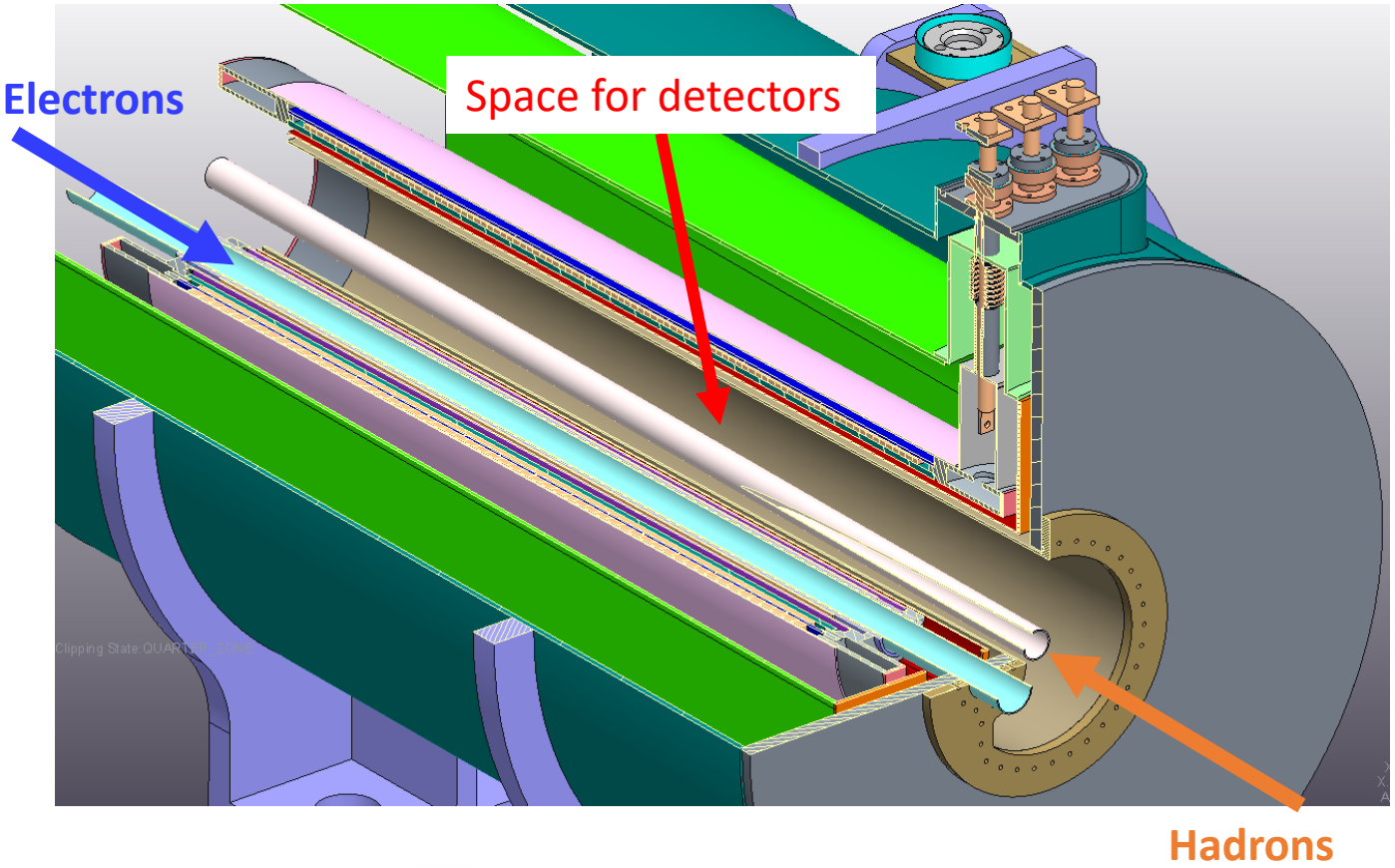
B0 Detectors



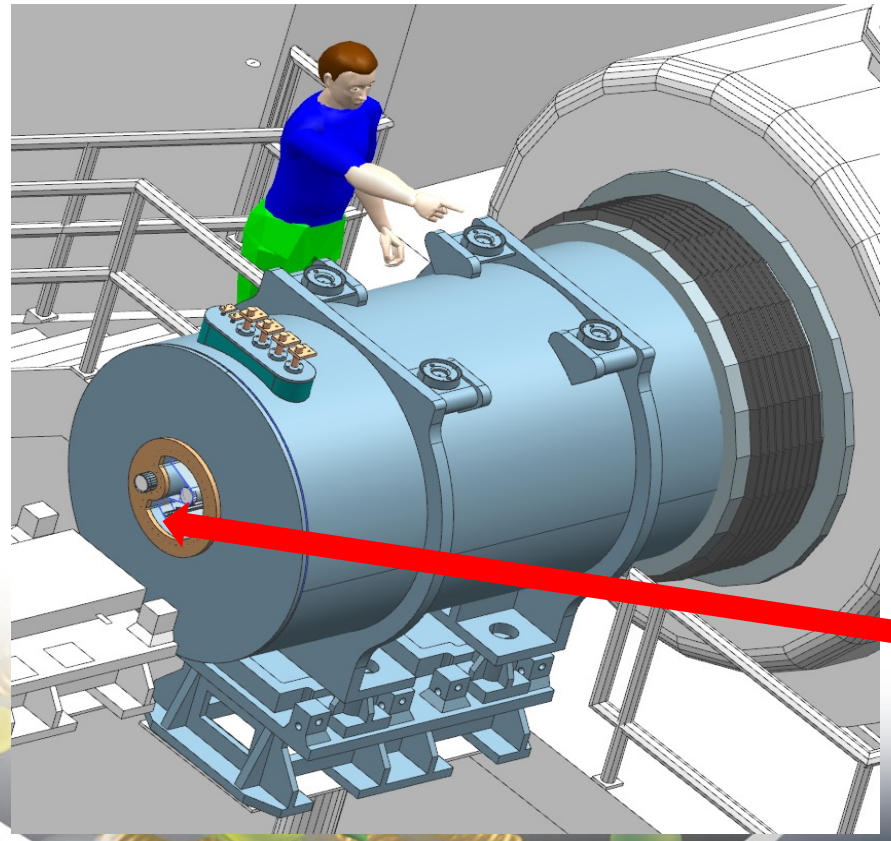


B0 Detectors

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



Credit to Ron Lassiter

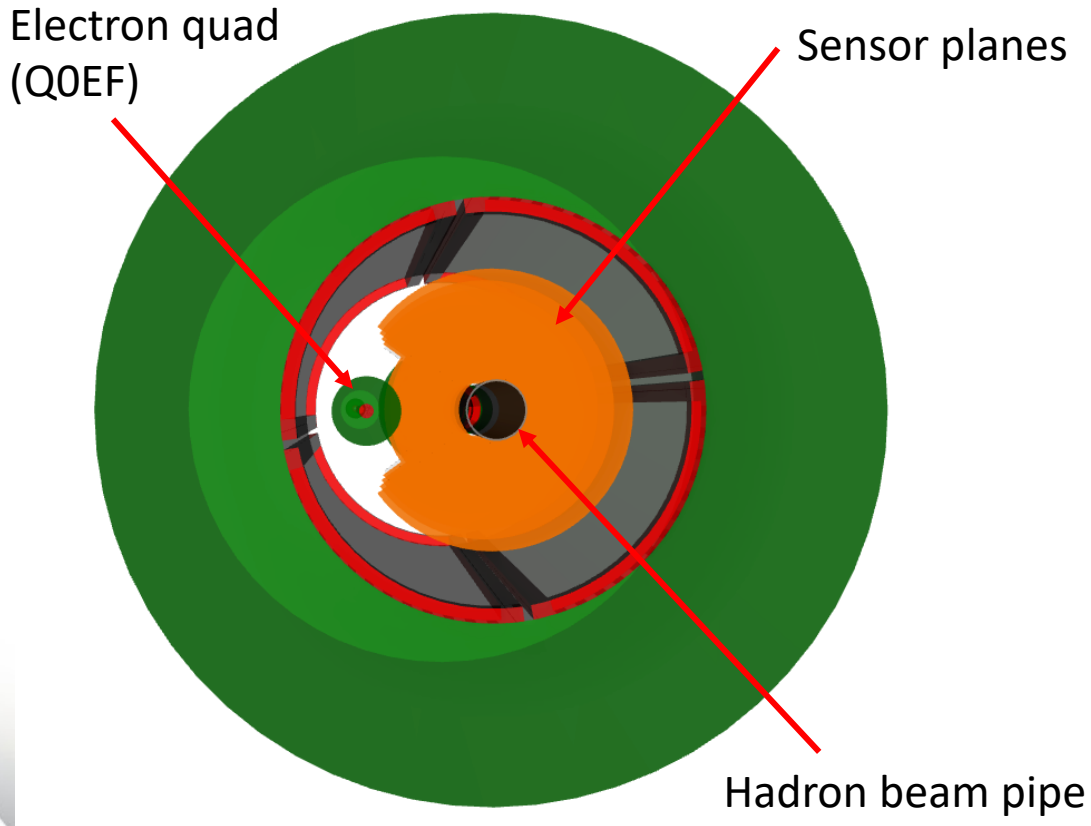


This is the opening where the detector planes will be inserted

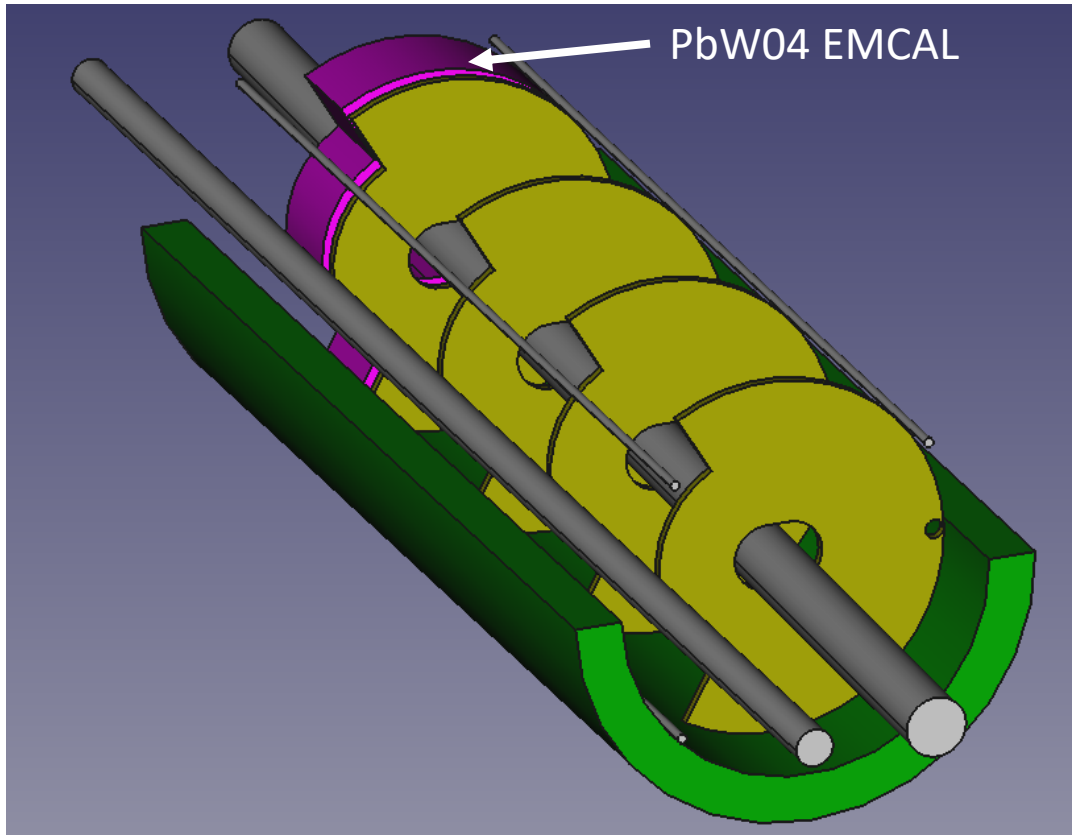
Preliminary Parameters:
229.5cm x 121.1cm x 195cm
(Actual length will be shorter)

B0 Detectors

(5.5 < $\boldsymbol{\theta}$ < 20.0 mrad)



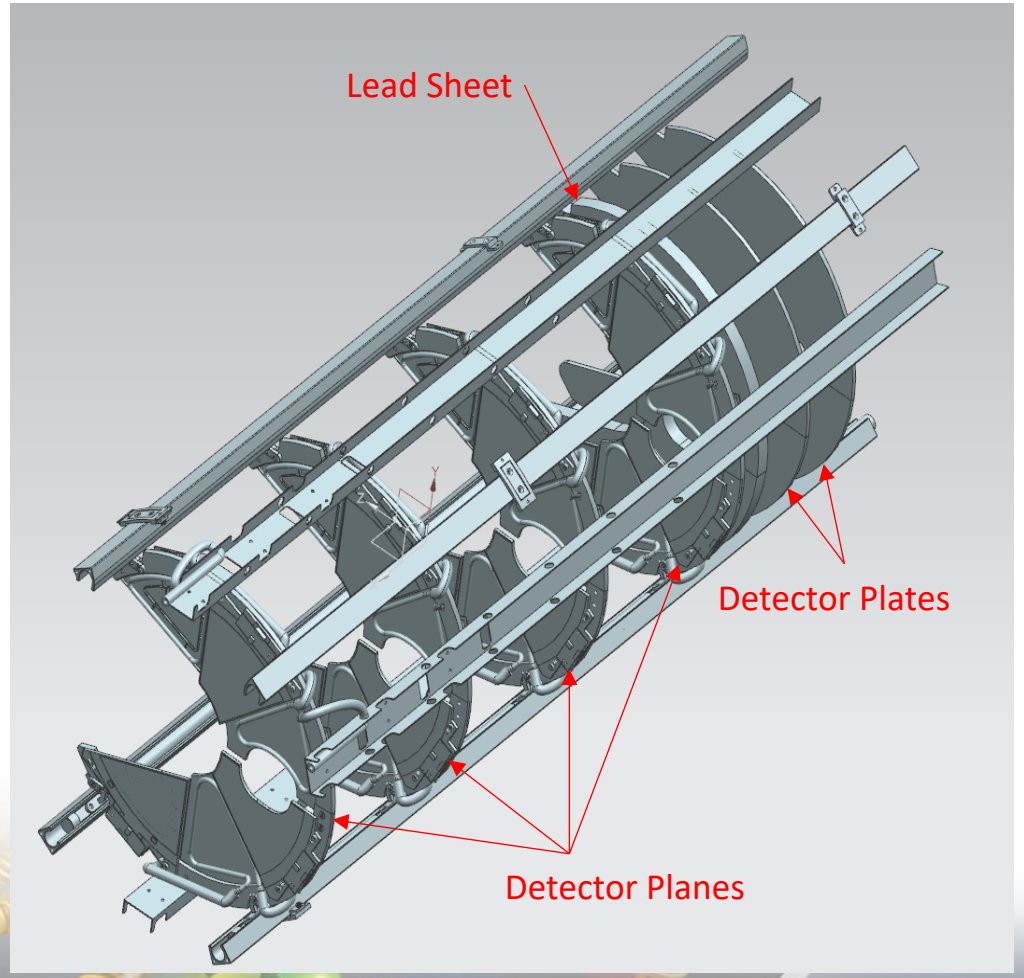
DD4HEP Simulation



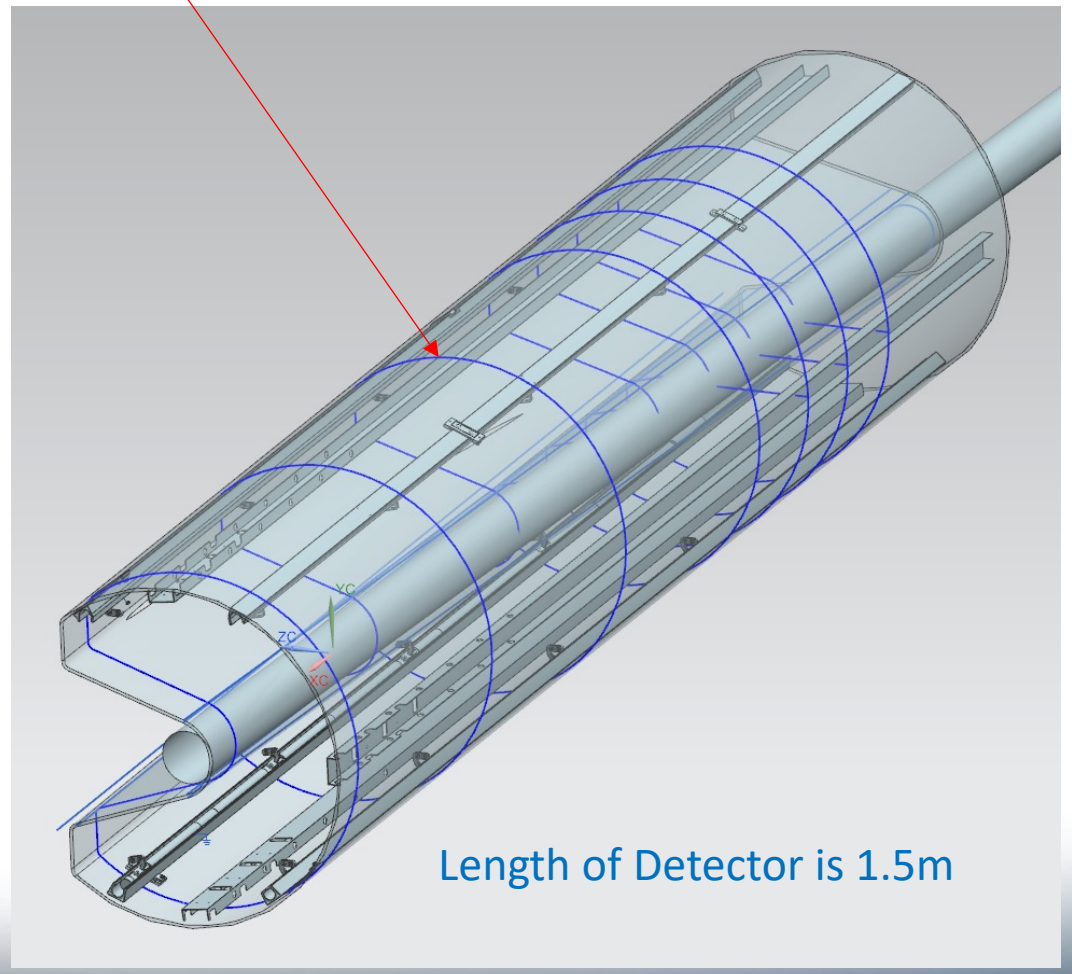
- Higher granularity silicon (e.g. MAPS) required.
- Tagging photons important in differentiating between coherent and incoherent heavy-nuclear scattering, and for reconstructing $\pi^0 \to \gamma\gamma$.
  - **Space is a major concern here – <u>an EMCAL</u> is highly preferred, but may only have space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

B0 Detectors in CAD

Credit to Ron Lassiter



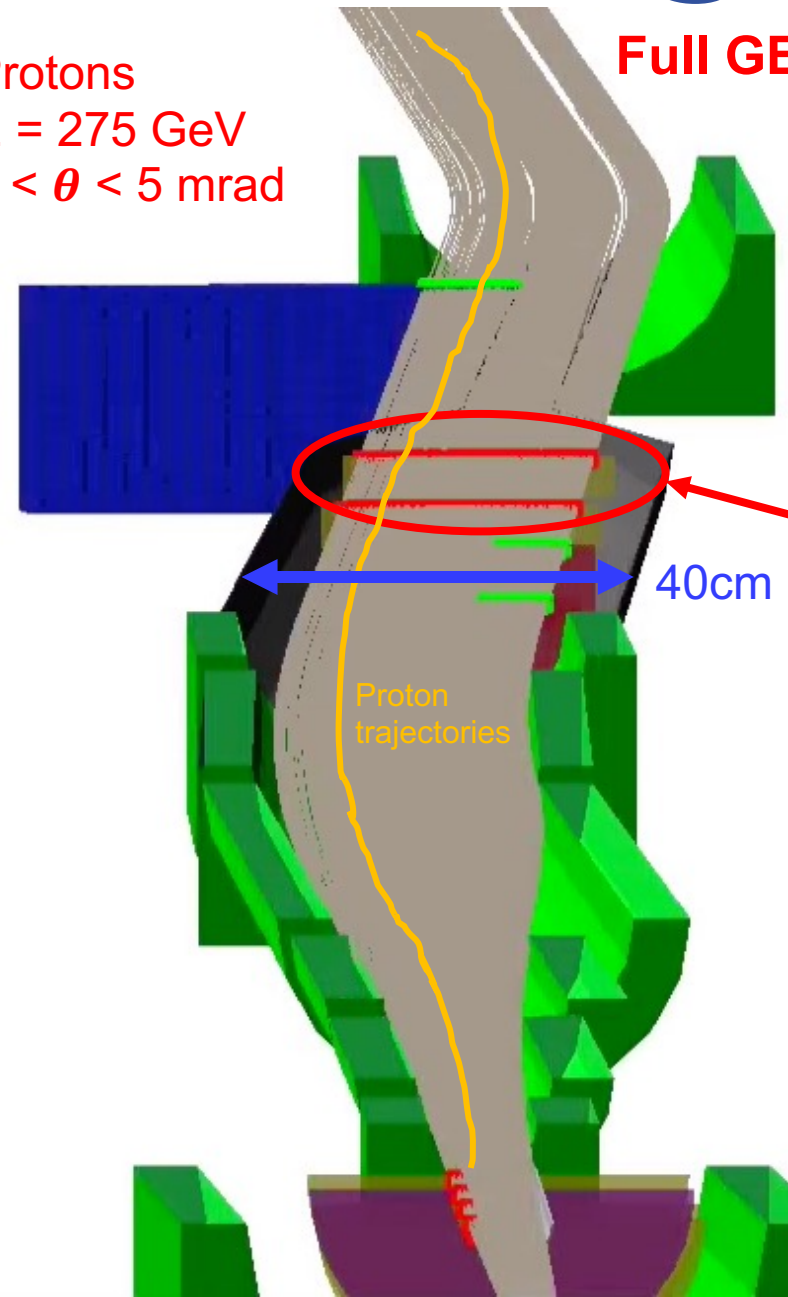
Blue lines represent where element locations are along beamline

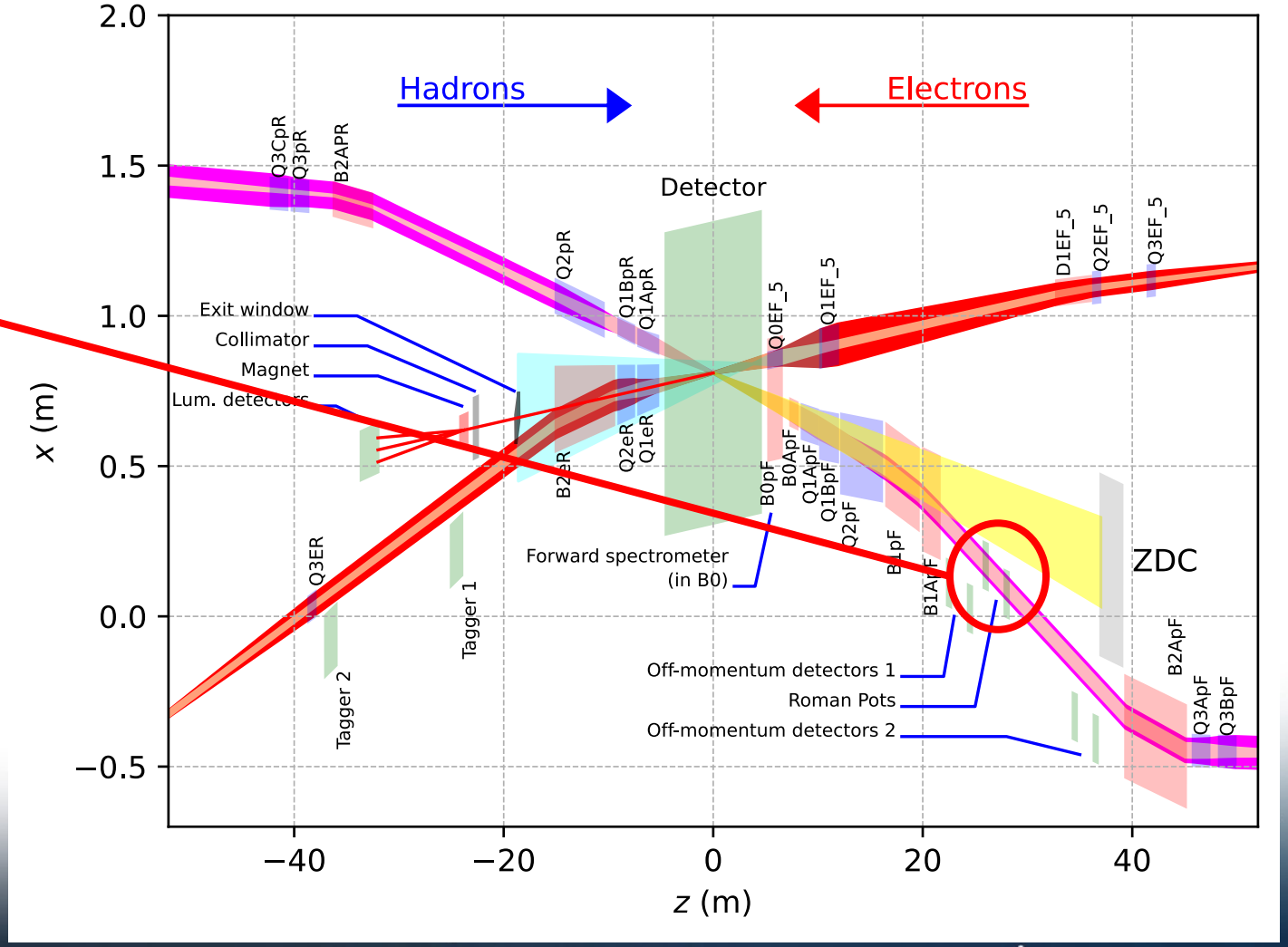


Roman Pots @ the EIC

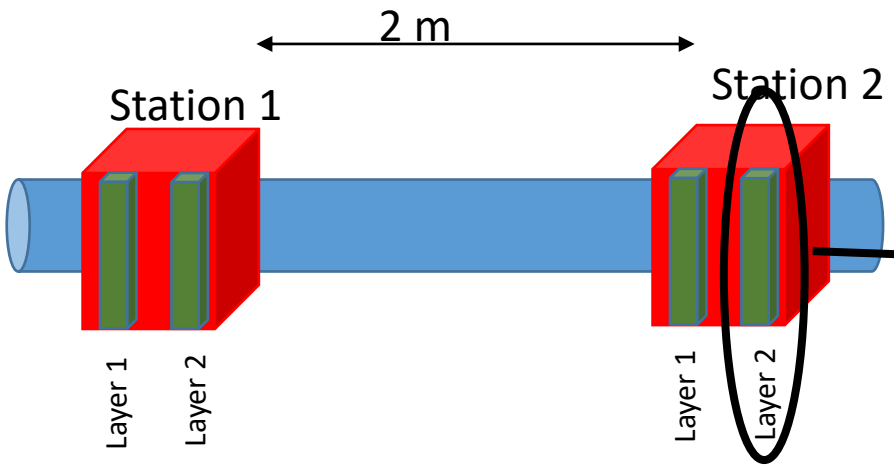
Full GEANT4 simulation.

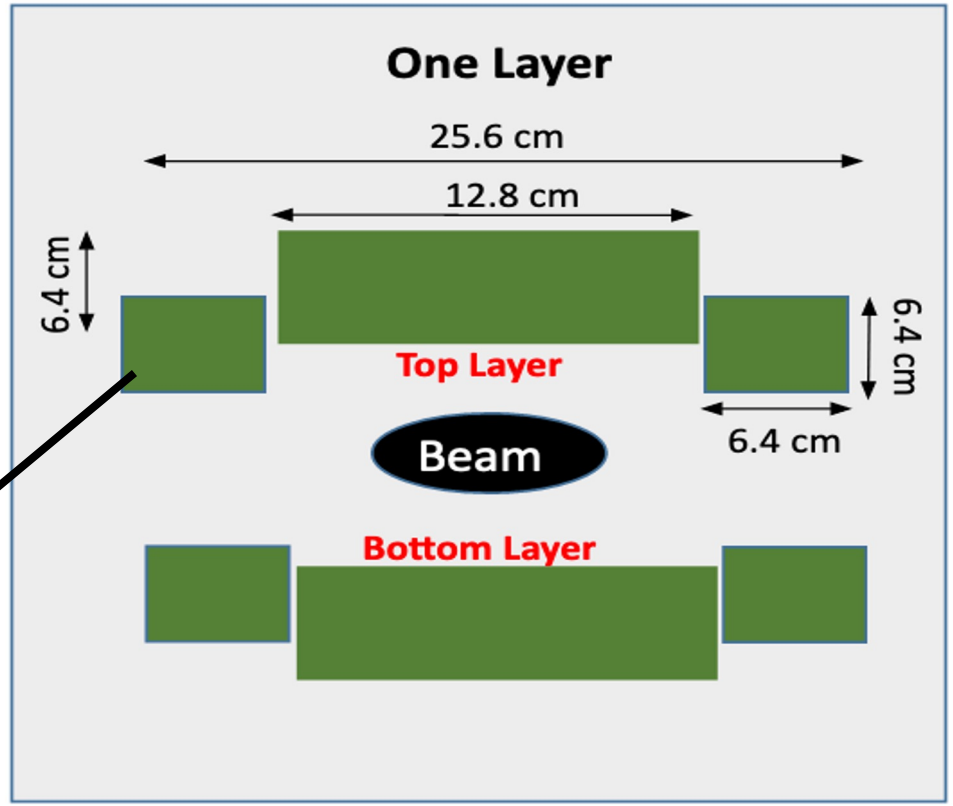
Protons
E = 275 GeV
0 < θ < 5 mrad

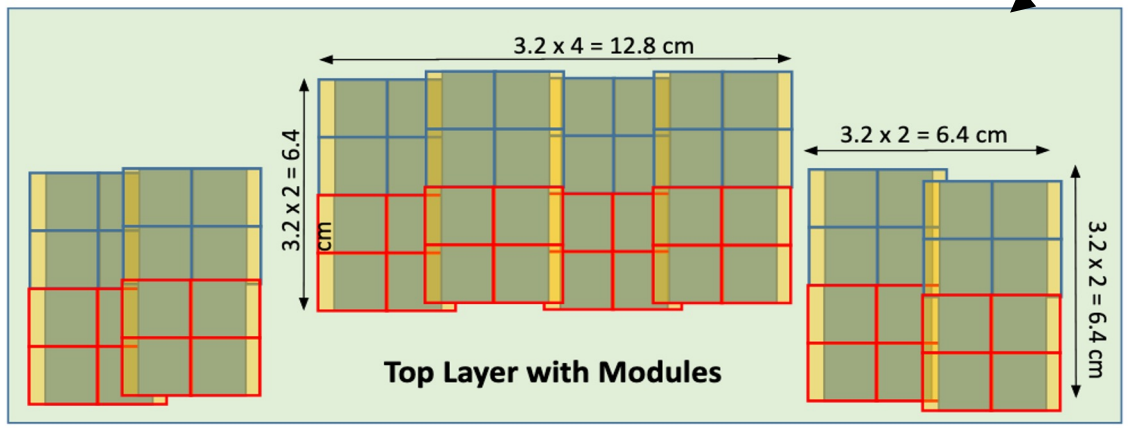




Roman "Pots" @ the EIC





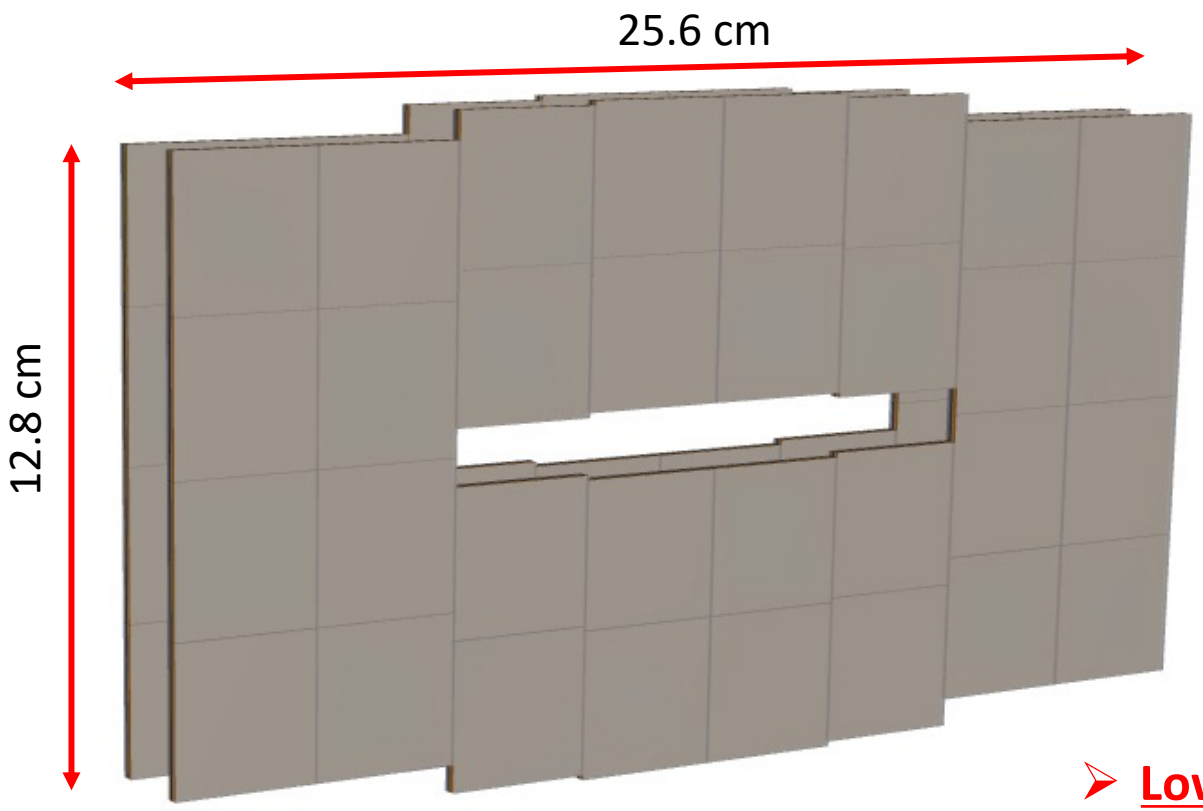


- Silicon detectors placed directly into machine vacuum!
  - Allows maximal geometric coverage!
- **<u>Technology:</u>** AC-LGAD sensor provides both fine pixilation (~140um spatial resolution), and fast timing (~35ps).

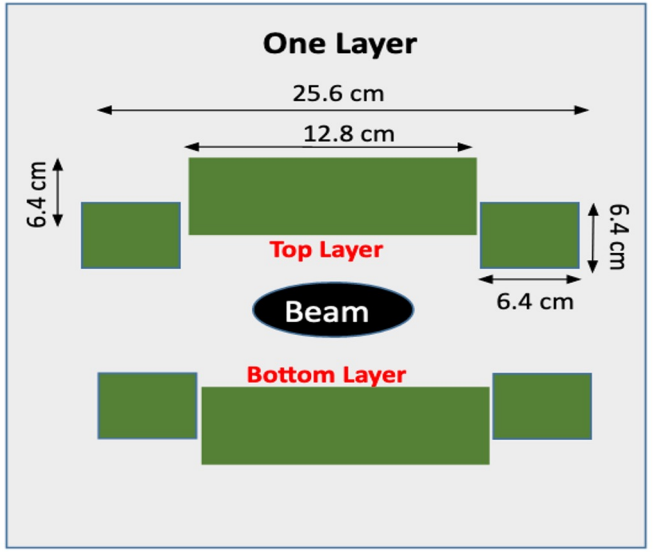
Roman "Pots" @ the EIC

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

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

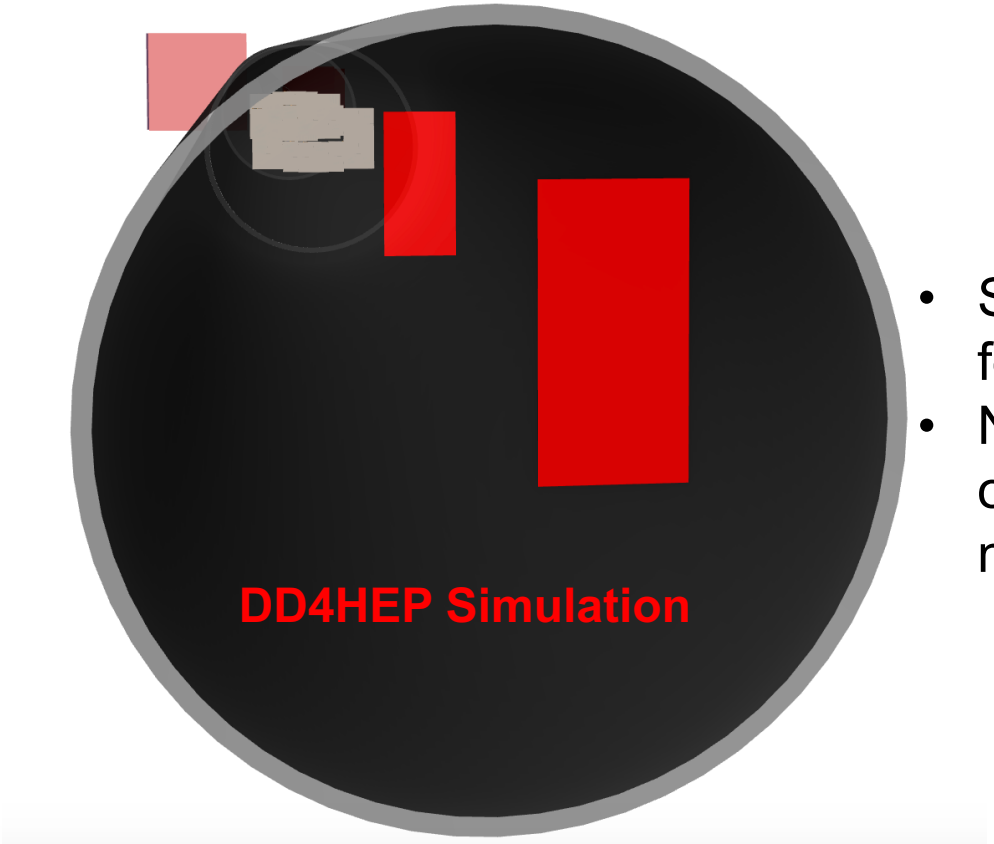


DD4HEP Simulation



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

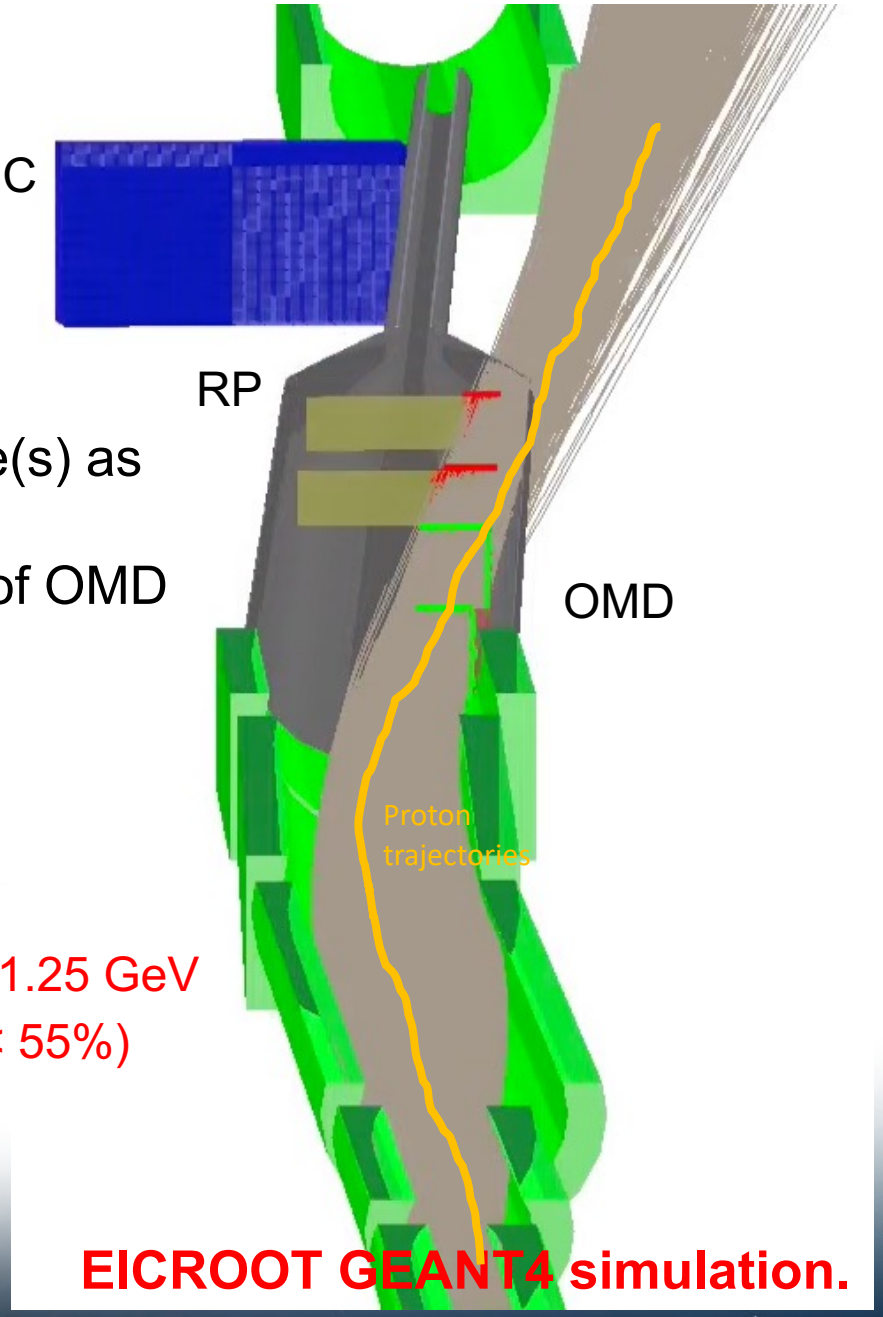
Off-Momentum Detectors



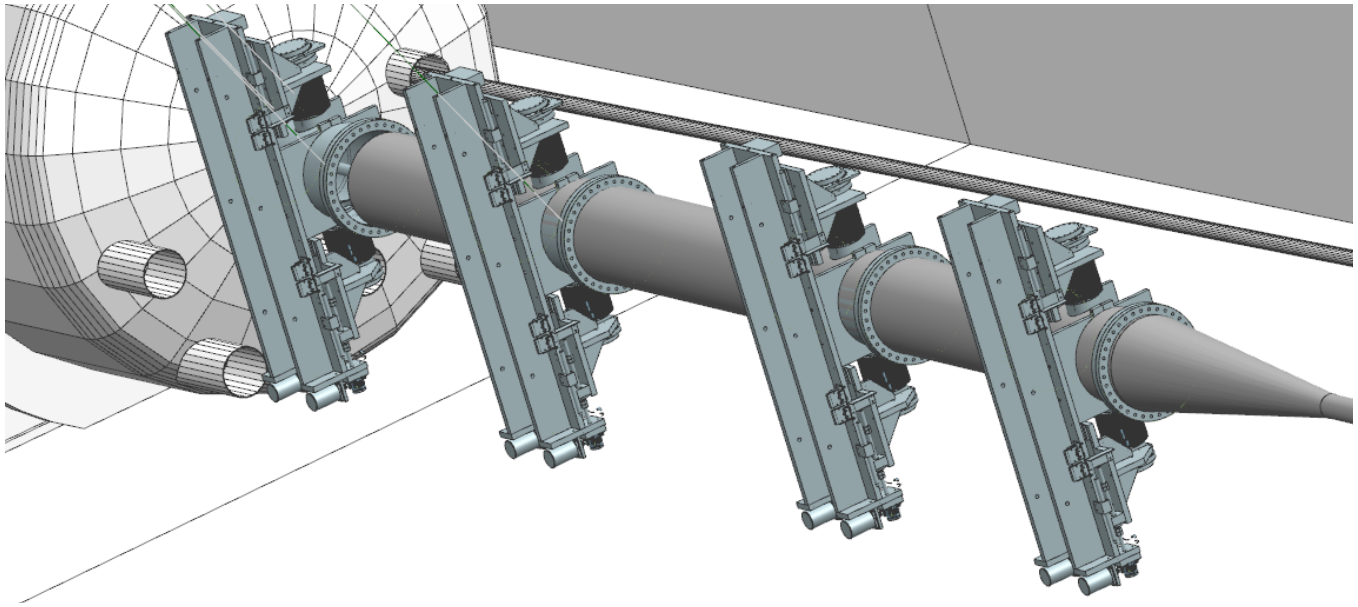
- Same technology choice(s) as for the Roman Pots.
- Need to also study use of OMD on other side for tagging negative pions.

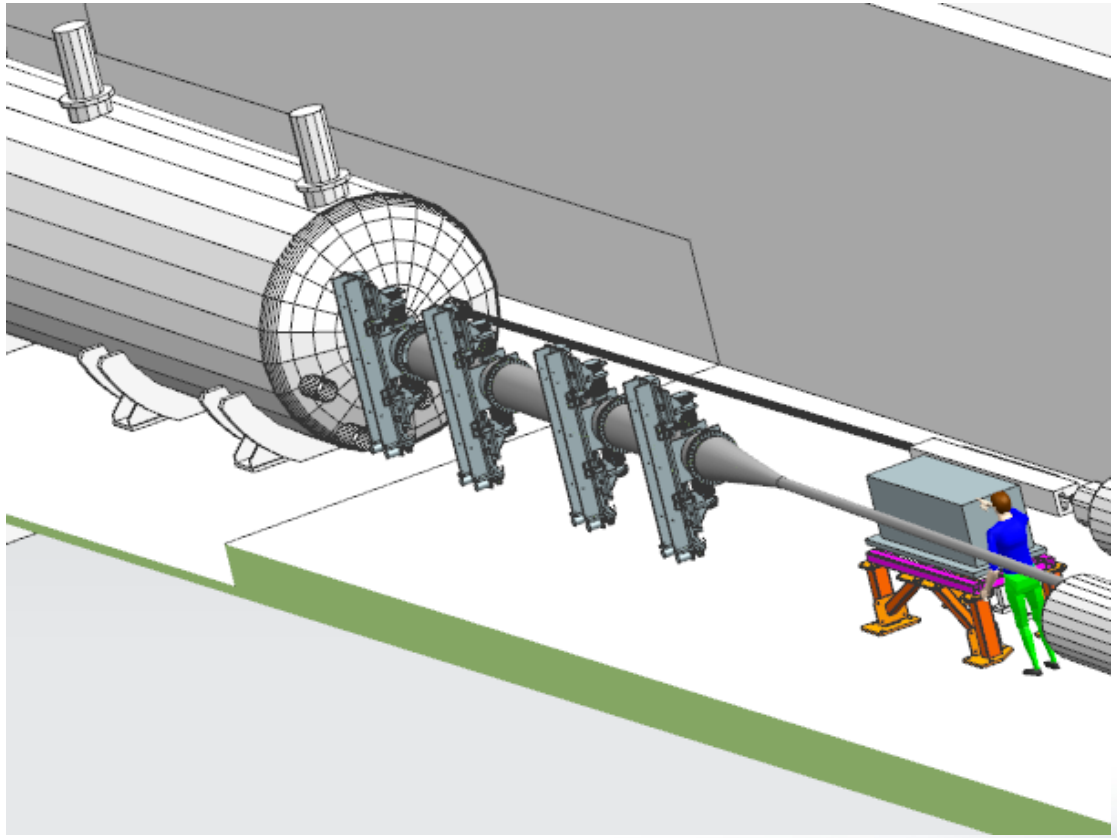
Off-momentum detectors implemented as horizontal ”Roman Pots” style sensors.

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

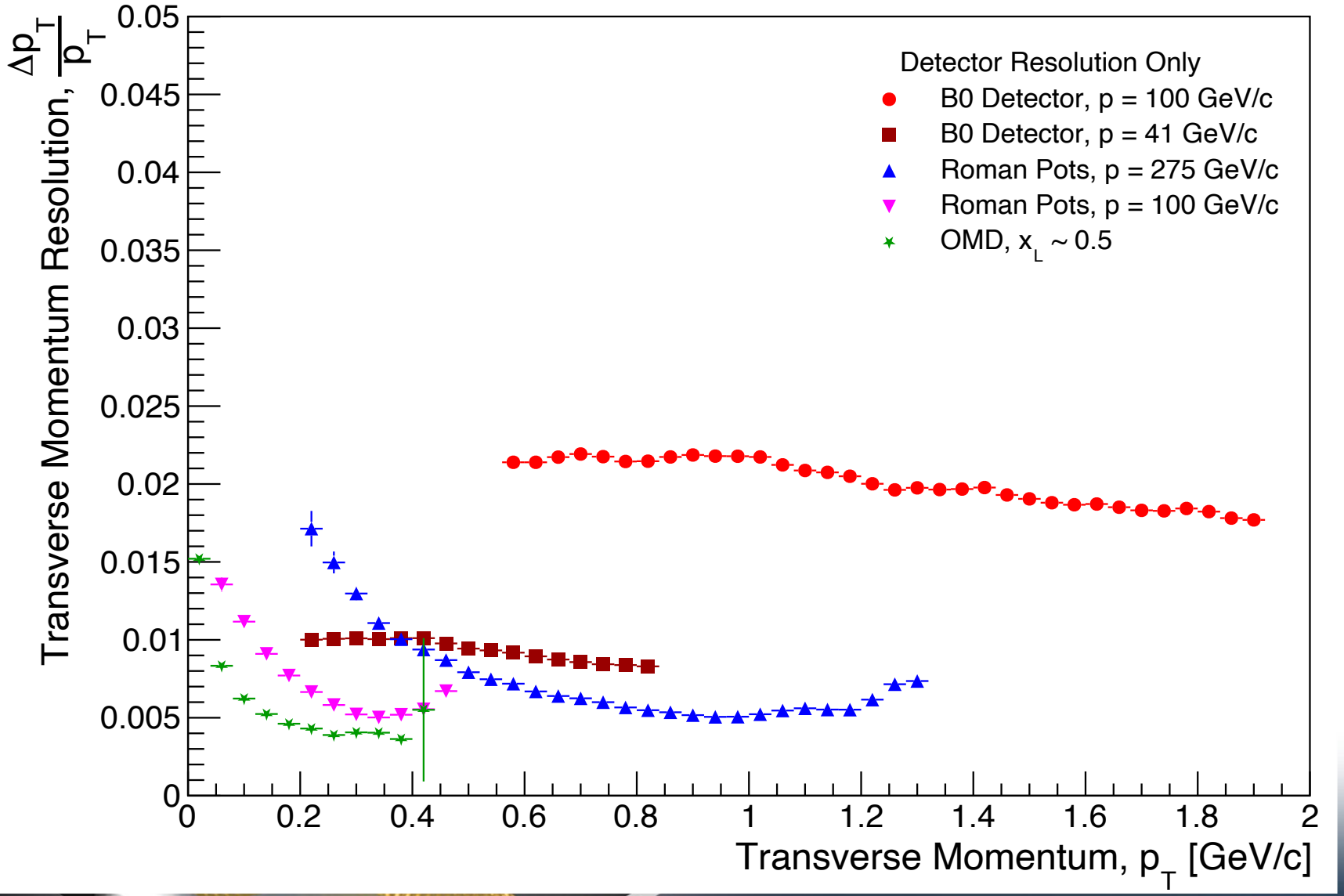


Preliminary CAD drawings of RP and OMD Supports and Magnet Cryostats





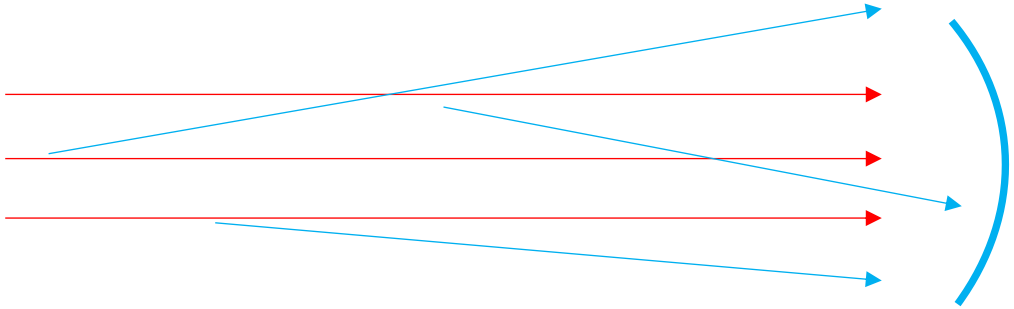
Summary of Detector Performance (Trackers)



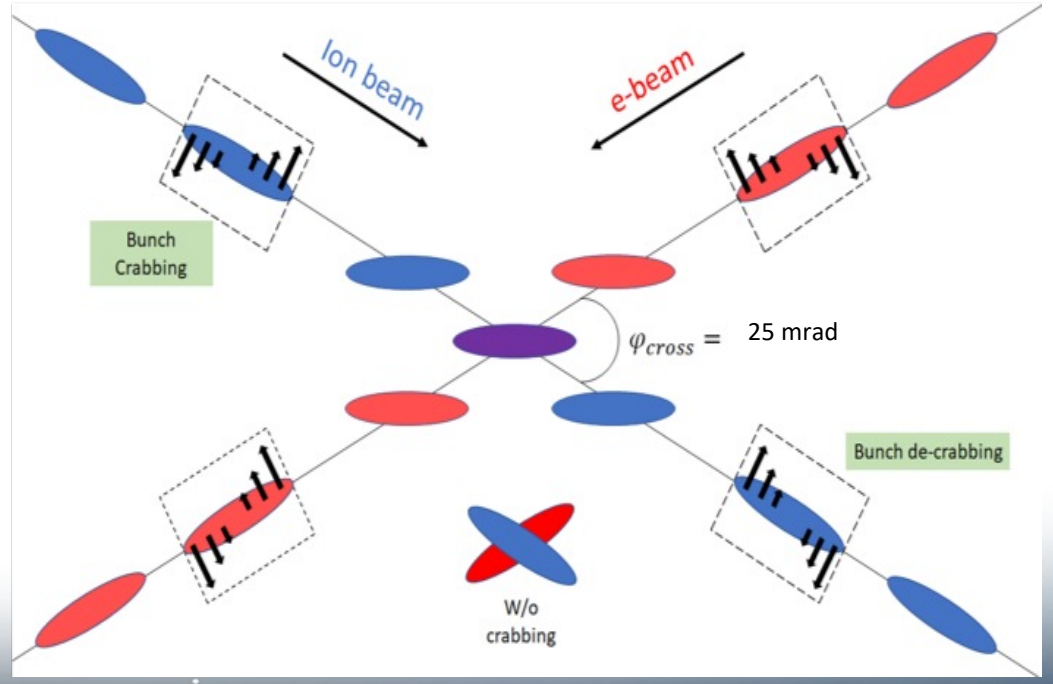
- Includes realistic considerations for pixel sizes and materials
  - More work needed on support structure and associated impacts.
- Roman Pots and Off-Momentum detectors suffer from additional smearing due to improper transfer matrix reconstruction.
  - This problem is close to being solved!

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.

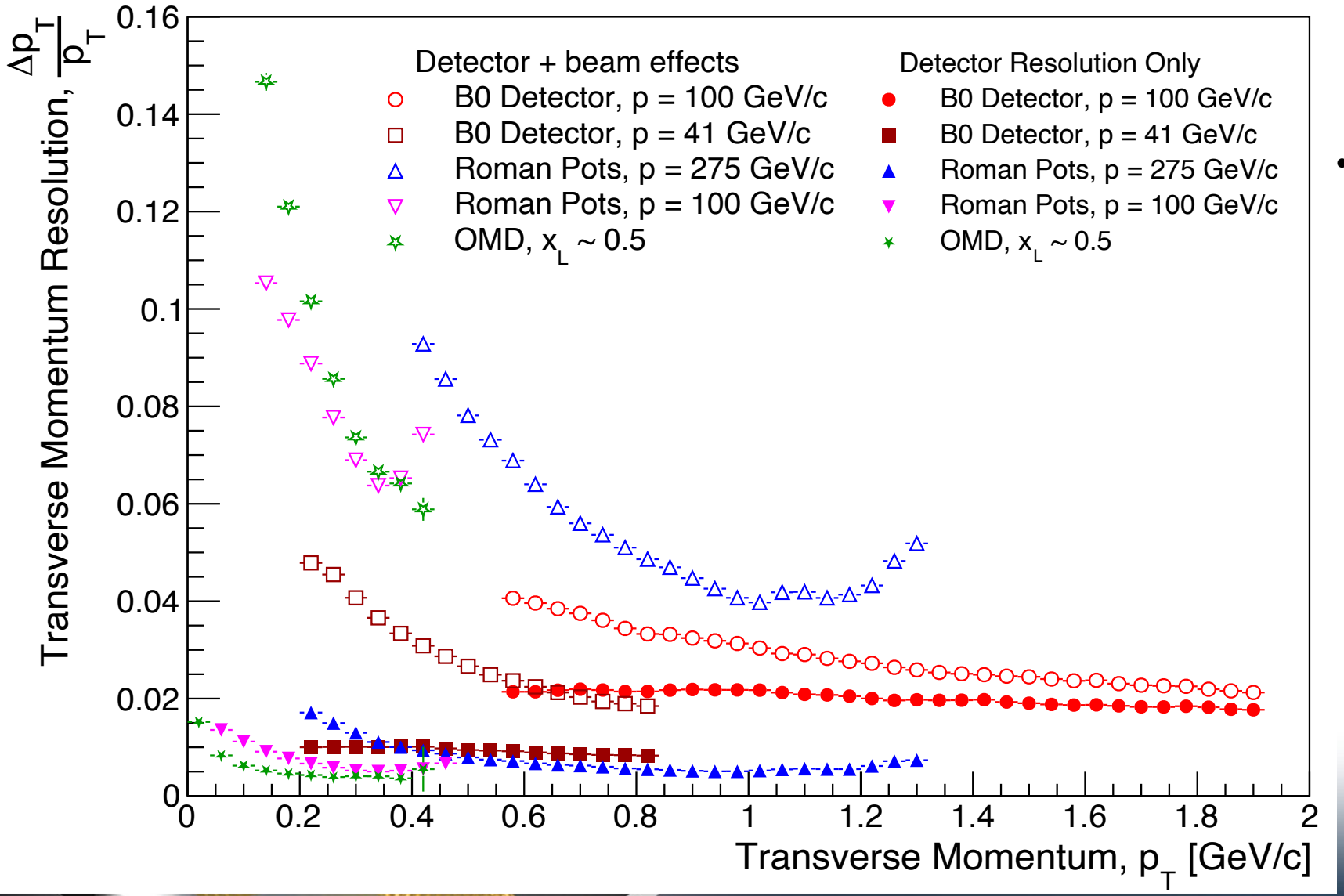


- Crab cavity rotation
  - Can perform rotations of the beam bunches in 2D.
  - Used to account for the luminosity drop due to the crossing angle – allows for head-on collisions to still take place.



These effects introduce smearing in our momentum reconstruction.

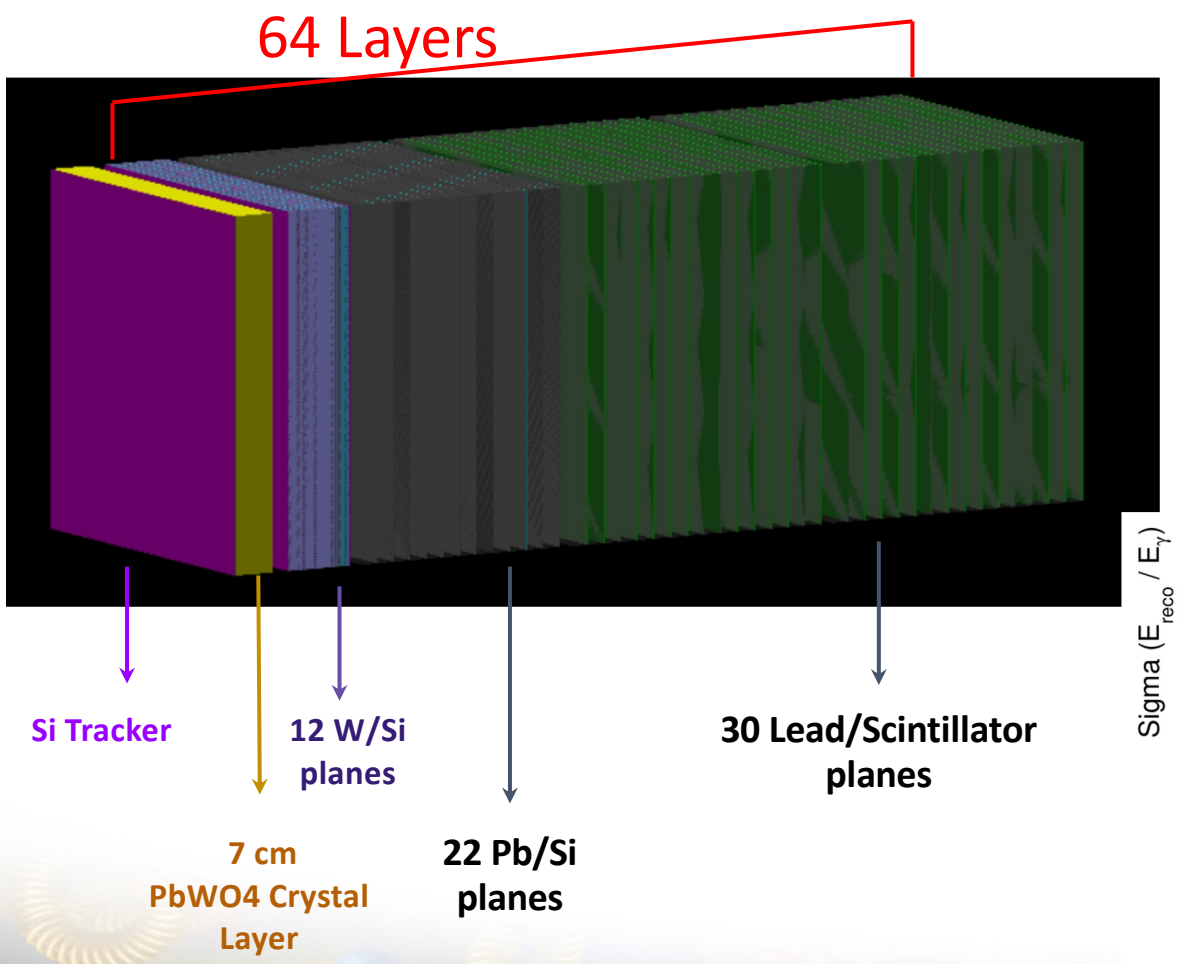
Summary of Detector Performance (Trackers)



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

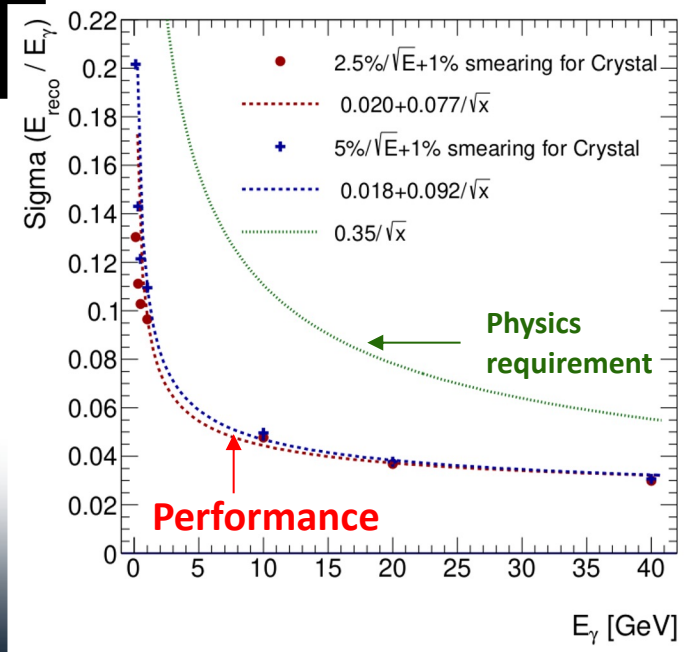
Beam effects the dominant source of momentum smearing!

Zero-Degree Calorimeter

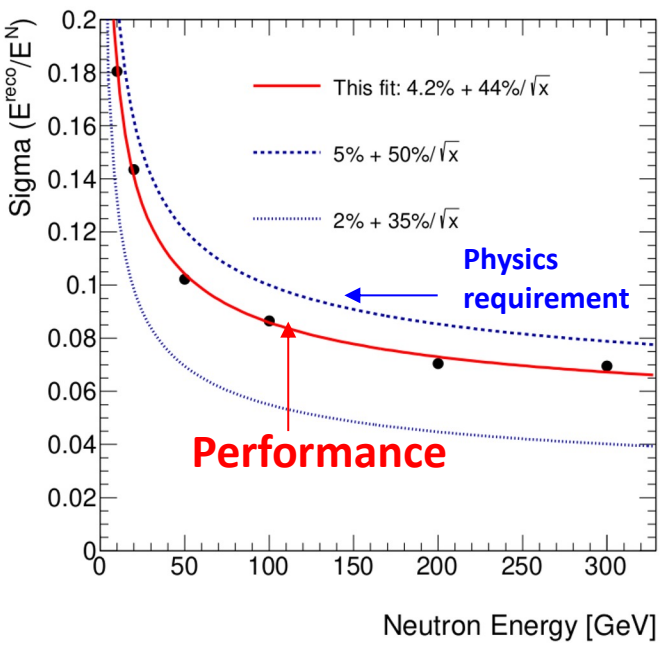


- **Zero Degree Calorimeter (improved ALICE design):**
  - **Dimension: 60 cm x 60 cm x 168 cm**
  - **30 m from IR**
  - **Detect spectator neutron**
  - **Acceptance: +4.5 mrad, -5.5mrad**
  - **Position resolution ~1.3mm at 40 GeV**
  - **Full reconstruction of photons (EMCAL) and neutrons (HCAL)**

Photon energy resolution



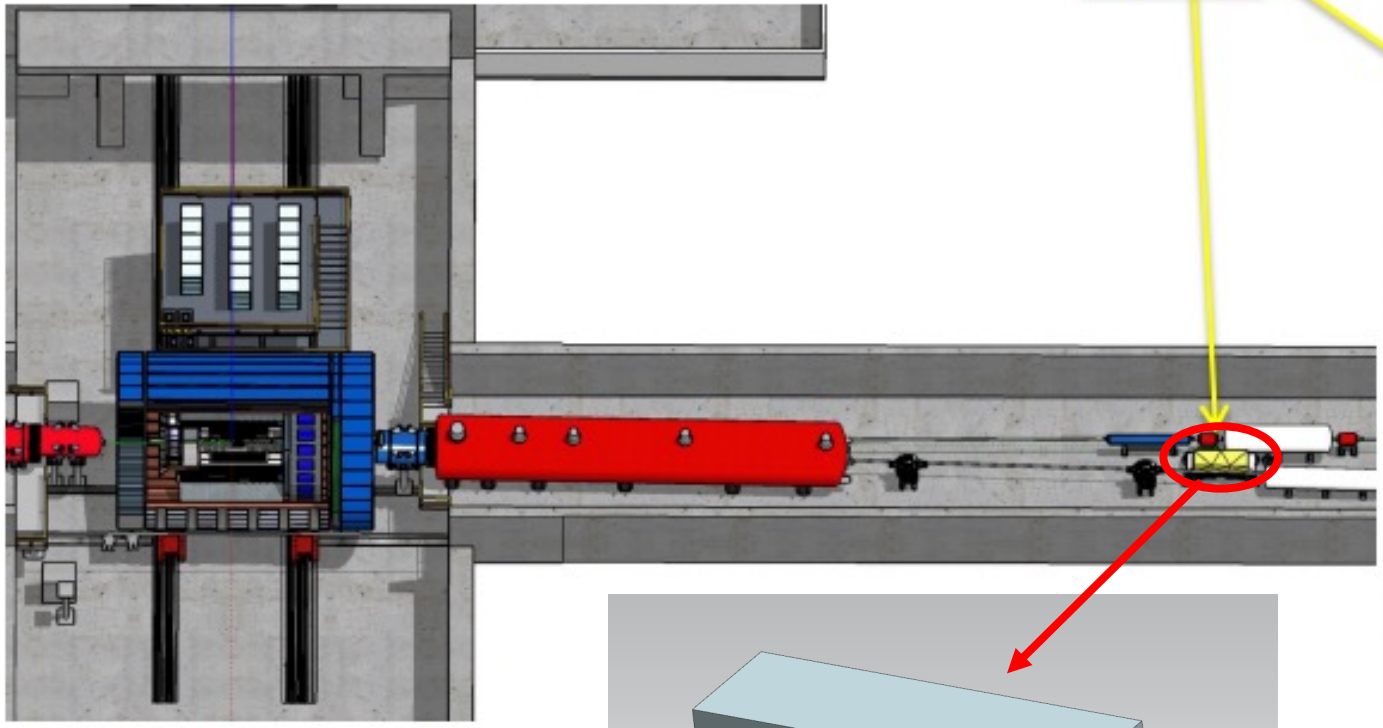
Neutron energy resolution

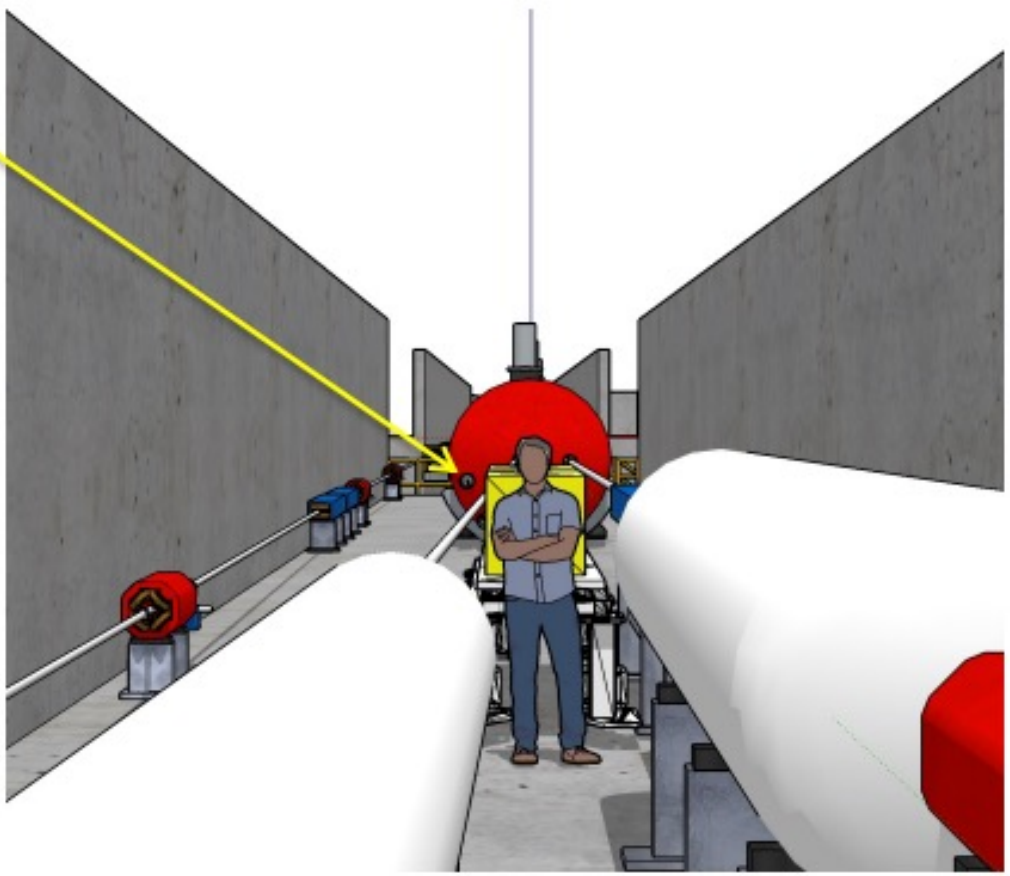


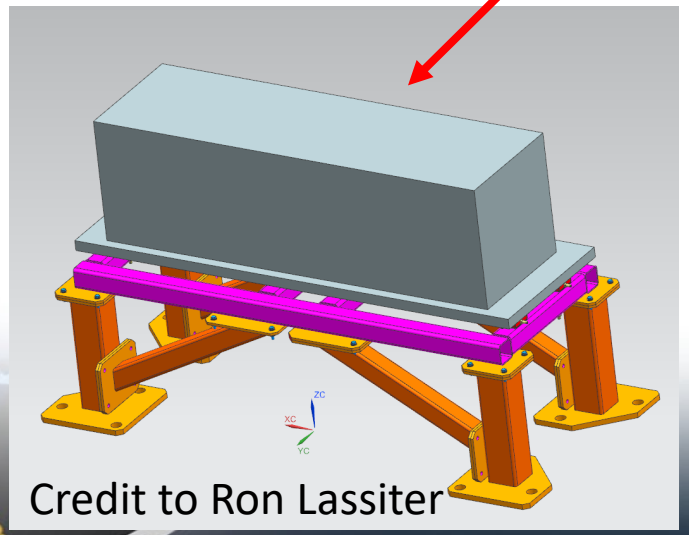
Credit to Shima Shimizu (Kobe U. , Japan)

Zero-Degree Calorimeter

Credit to Shima Shimizu







Credit to Ron Lassiter

Summary and Takeaways

- All FF detector acceptances and detector performance well-understood with currently available information.
  - Numerous impact studies done!
  - Primary technology choices done for all subsystems, with exception to systems dependent on evolving engineering design (e.g. B0 calorimetry).
- 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 work is currently on-going!
  - Very busy fall ahead of us!

Working Group Information

- **Far-Backward**
  - **Conveners:** Igor Korover <korover@mit.edu>, Nick Zachariou <nick.zachariou@york.ac.uk>, Krzyzstof Piotrzkowski <krzysztof.piotrzkowski@cern.ch>, Jaroslav Adam <jaroslavadam299@gmail.com>
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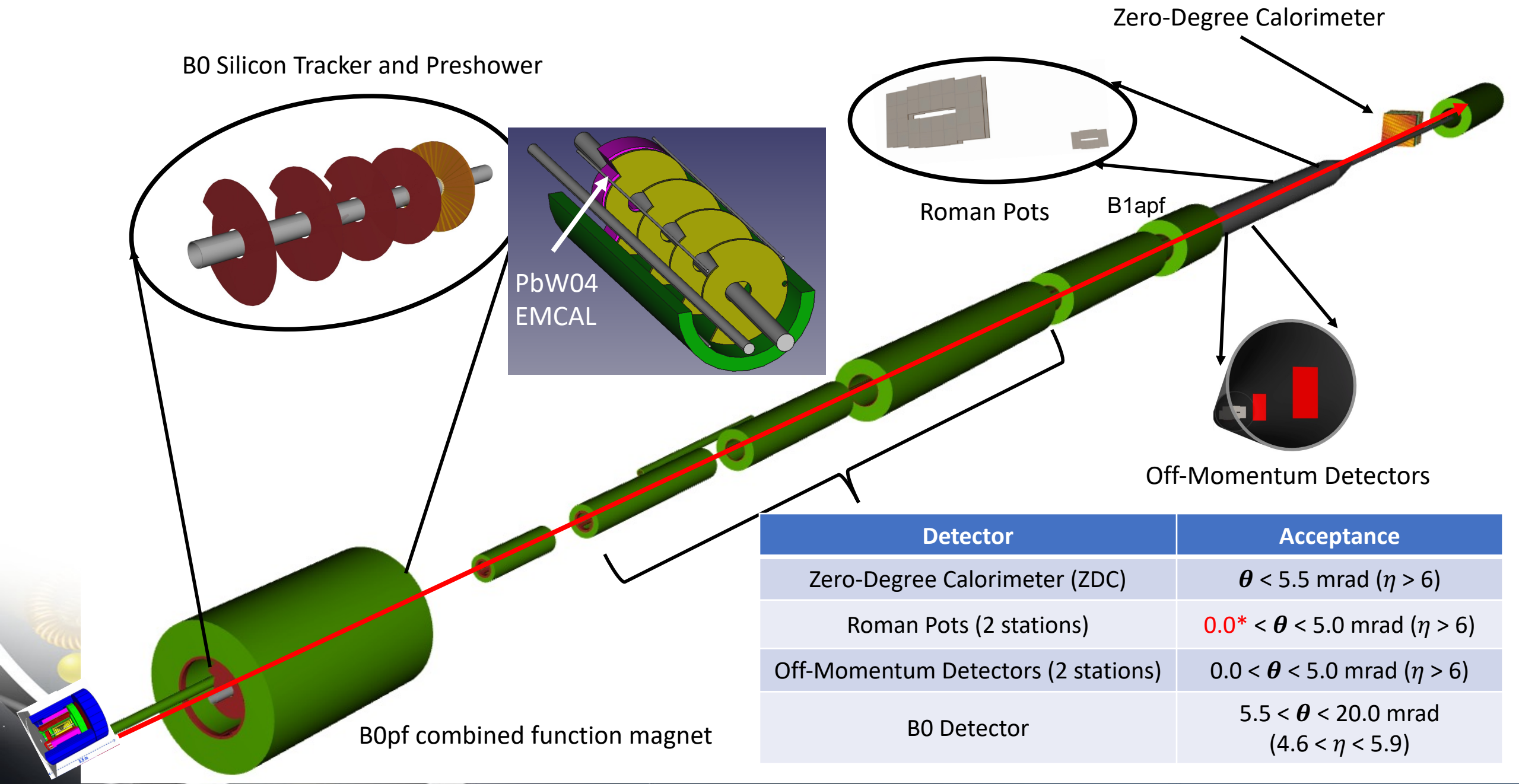
  - Email-list: eic-projdet-FarBack-l@lists.bnl.gov
  - Subscribe to mailing list through: https://lists.bnl.gov/mailman/listinfo/eic-projdet-farback-l

- **Far-Forward**
  - **Conveners:** Michael Murray <mjmurray@ku.edu>, Yuji Goto <goto@bnl.gov>, Alex Jentsch <ajentsch@bnl.gov>, John Arrington <jarrington@lbl.gov>
  - 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
  - Wiki: https://wiki.bnl.gov/EPIC/index.php?title=FarForward

Backup

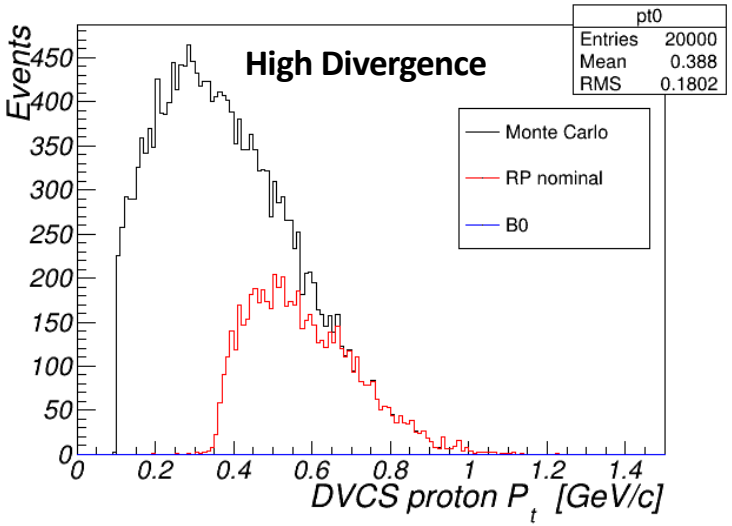
The Far-Forward Detectors

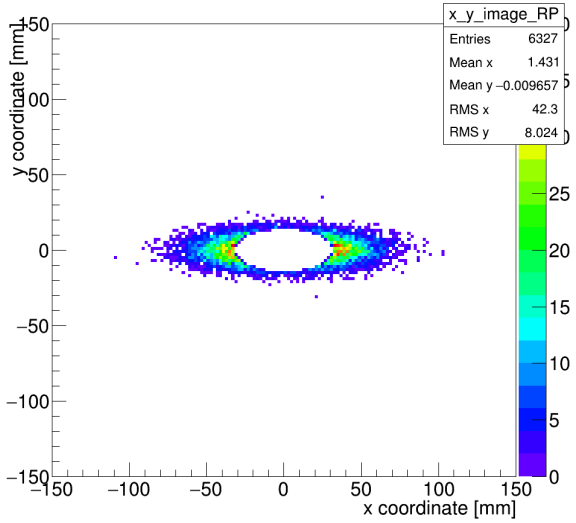


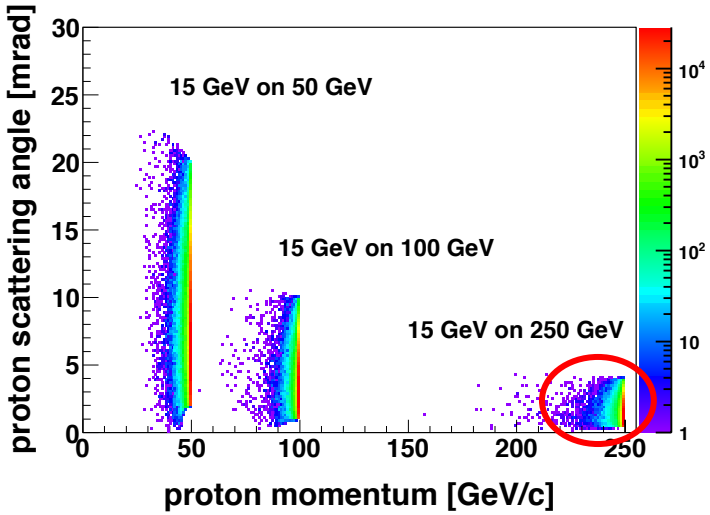
Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	$\boldsymbol{\theta} < 5.5$ mrad ($\eta > 6$)
Roman Pots (2 stations)	0.0* $< \boldsymbol{\theta} < 5.0$ mrad ($\eta > 6$)
Off-Momentum Detectors (2 stations)	$0.0 < \boldsymbol{\theta} < 5.0$ mrad ($\eta > 6$)
B0 Detector	$5.5 < \boldsymbol{\theta} 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

Digression: Machine Optics

275 GeV DVCS Proton Acceptance



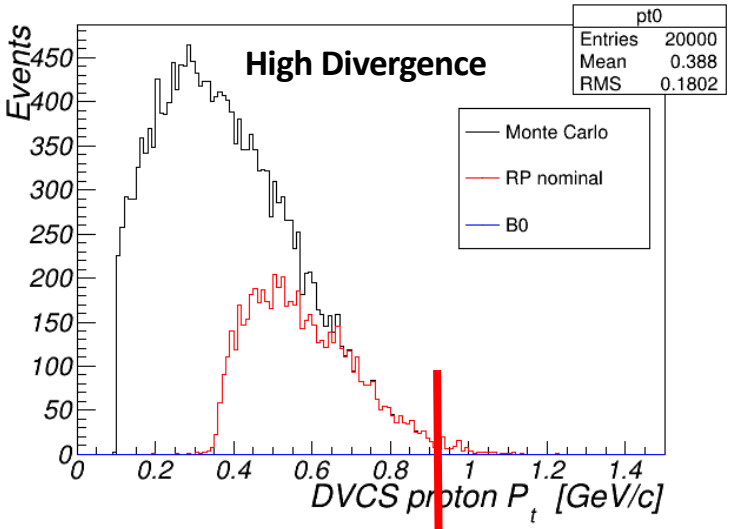


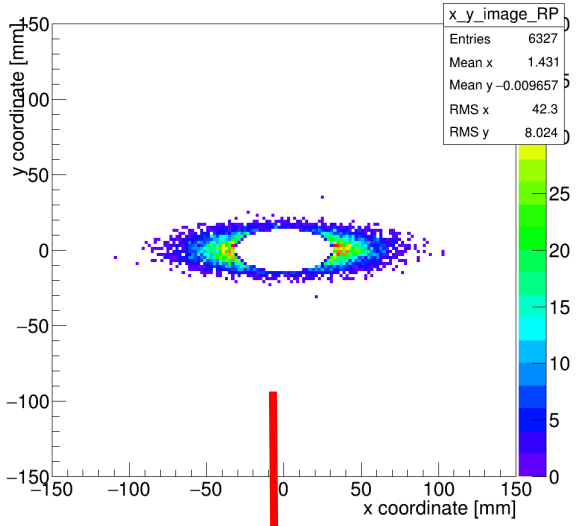


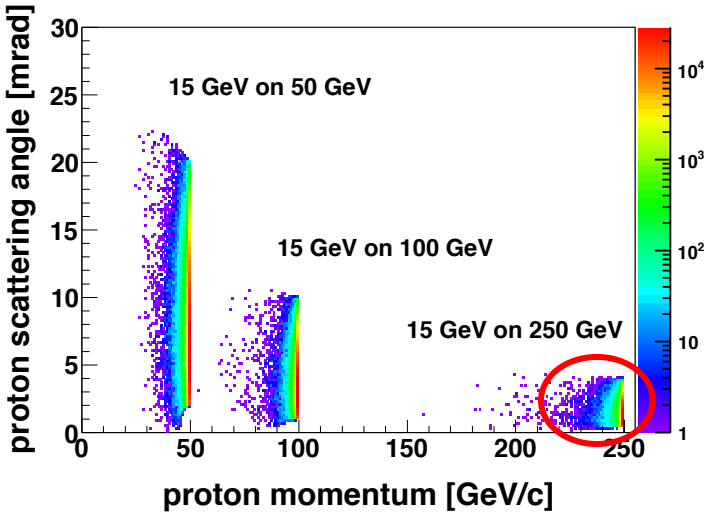
<u>High Divergence:</u> smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

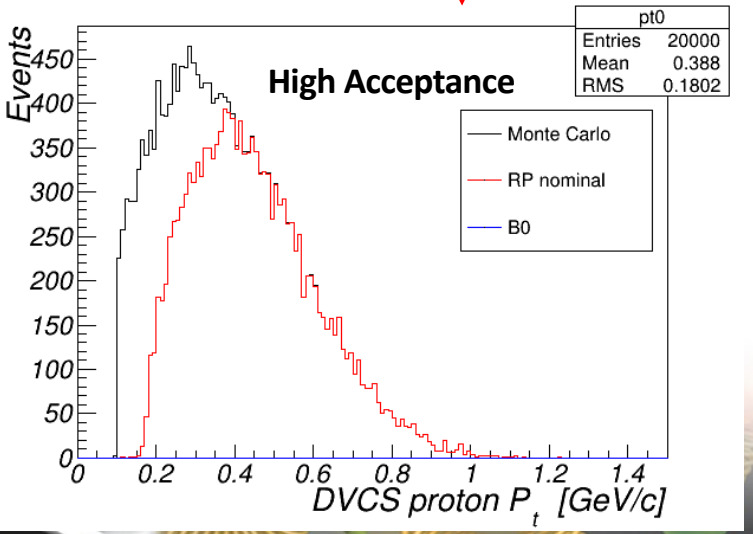
Digression: Machine Optics

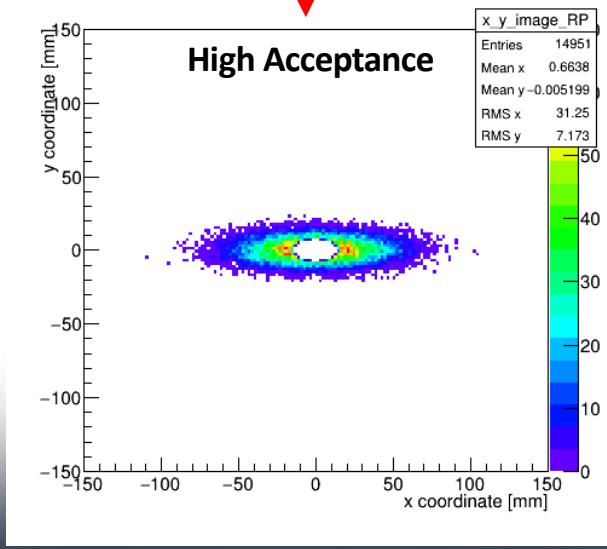
275 GeV DVCS Proton Acceptance









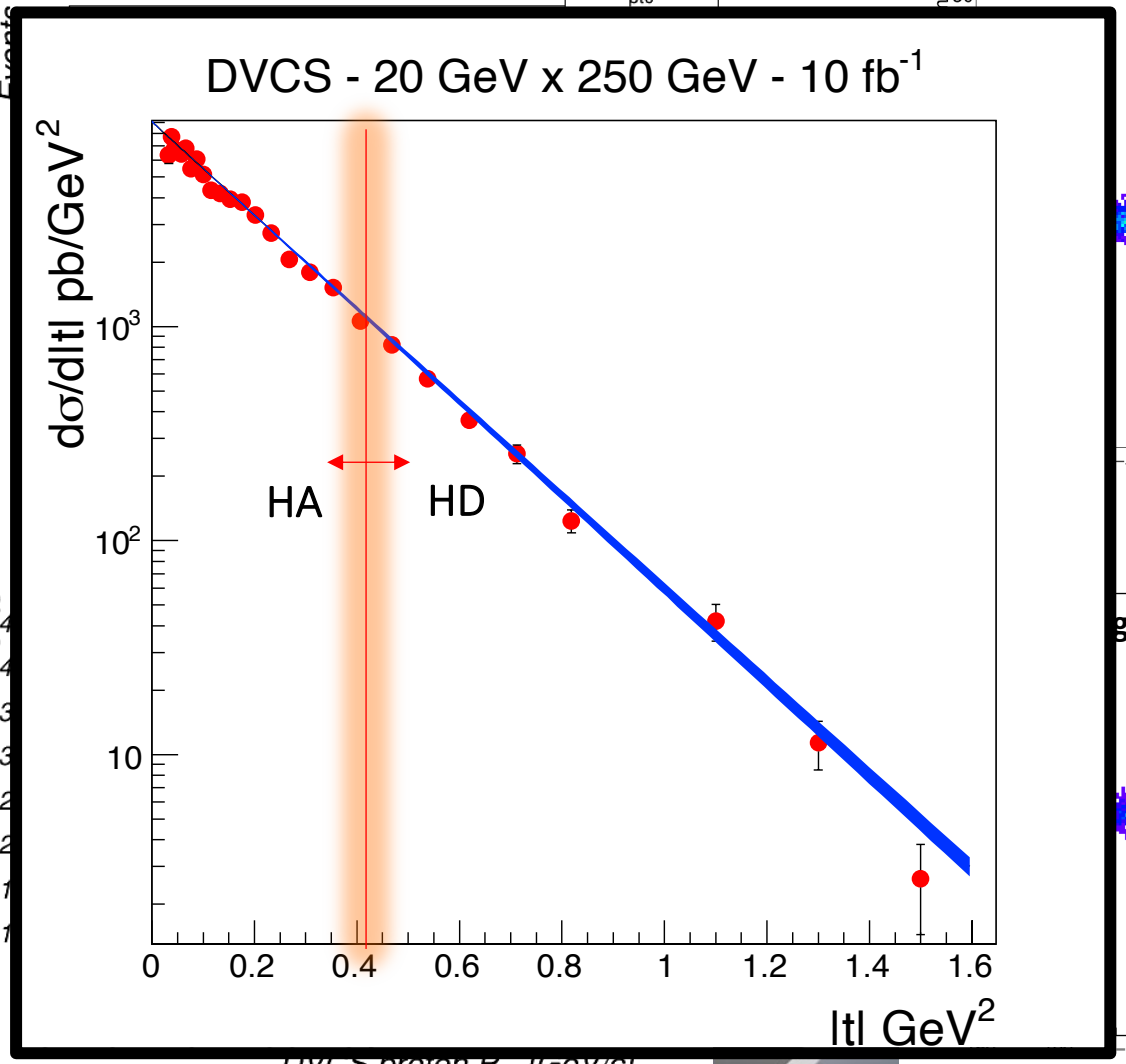


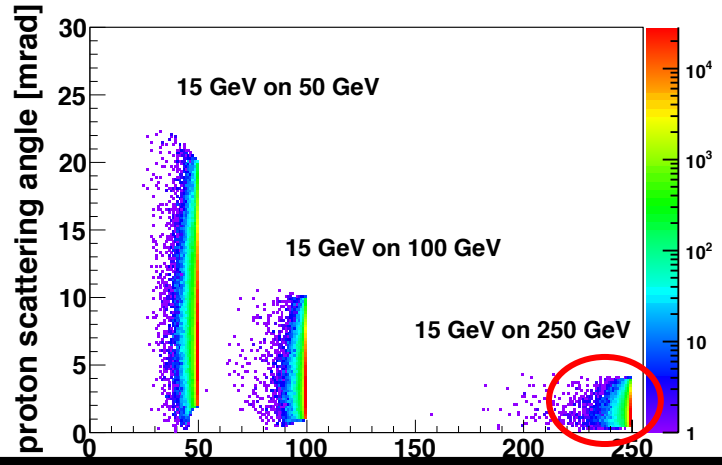
<u>High Divergence:</u> smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

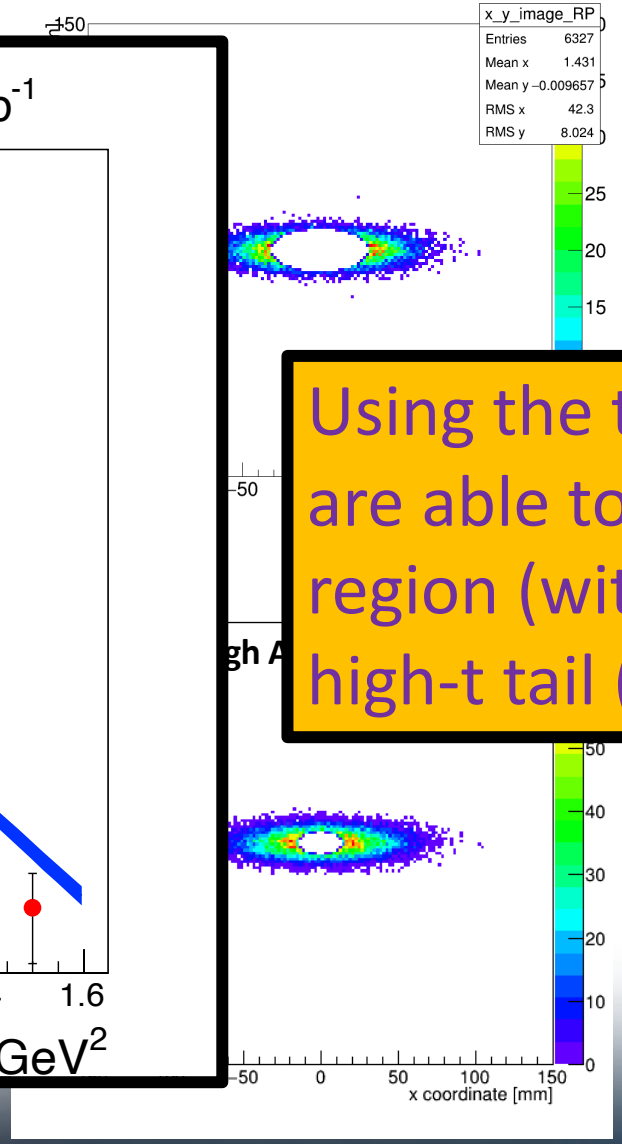
<u>High Acceptance:</u> larger β^* at IP, smaller $\beta(z = 30m)$ -> lower lumi., smaller beam at RP

Digression: Machine Optics

275 GeV DVCS Proton Acceptance

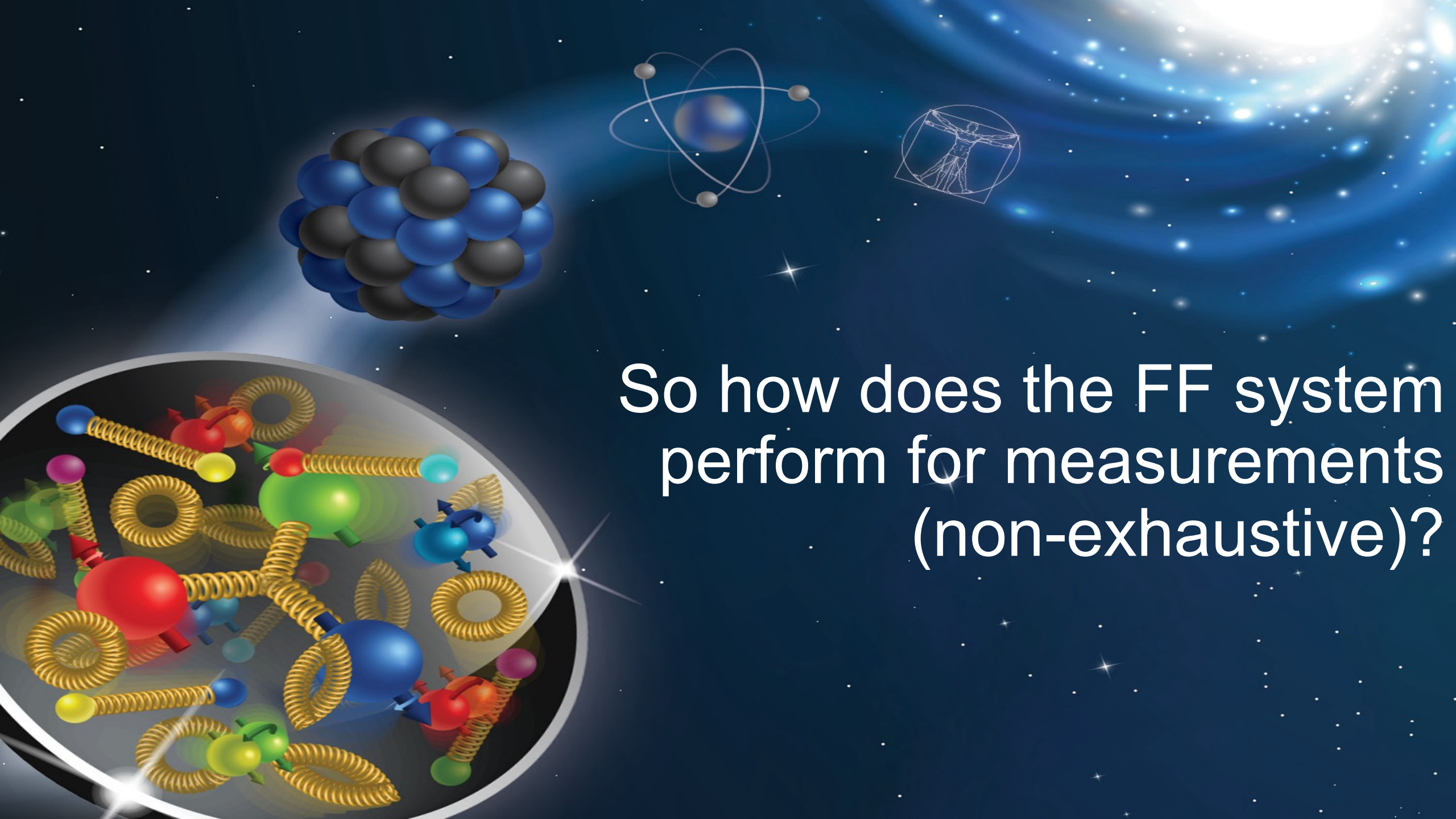






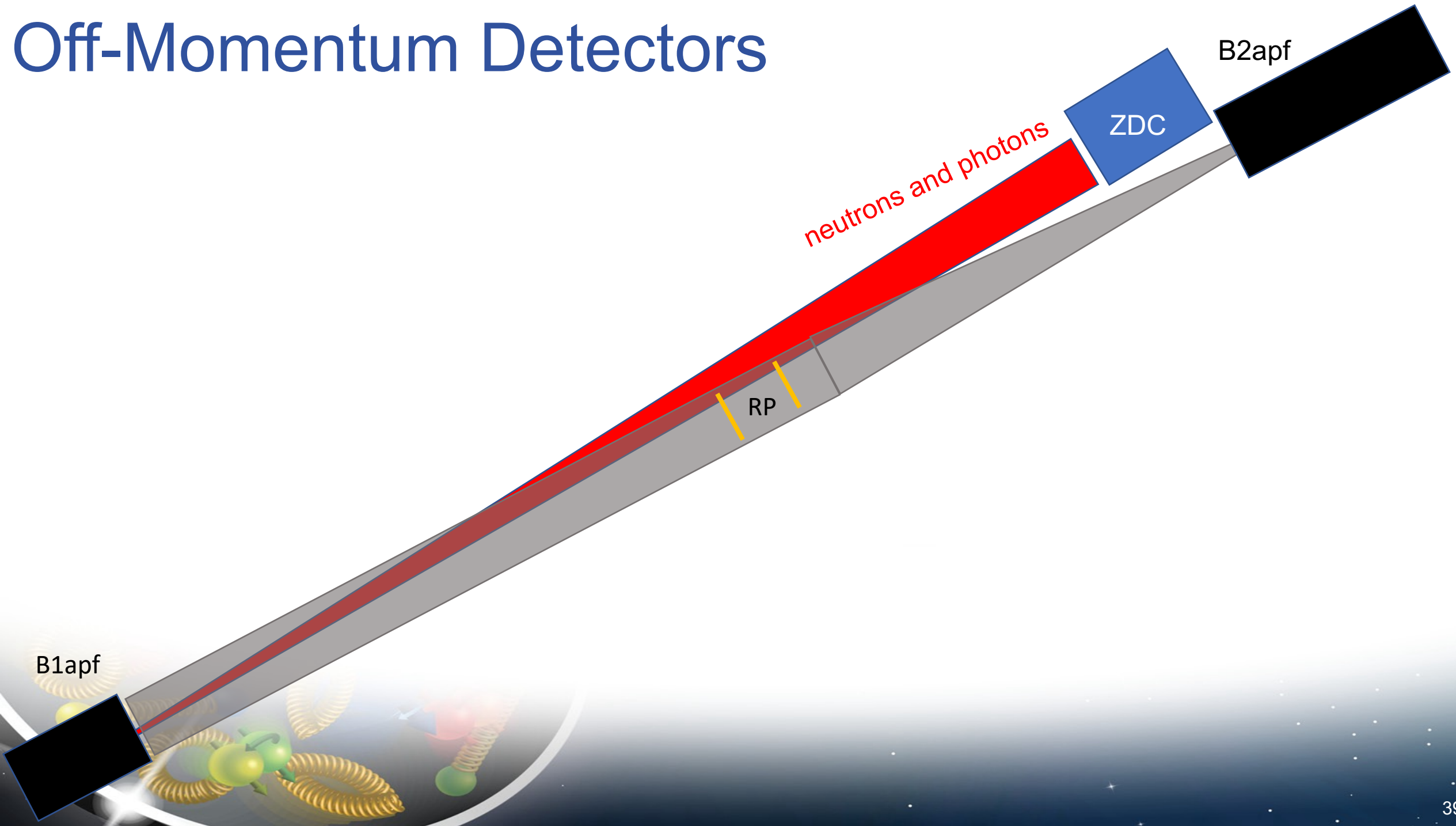
Using the two configurations, we are able to measure the low-t region (with better acceptance) and high-t tail (with higher luminosity).

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



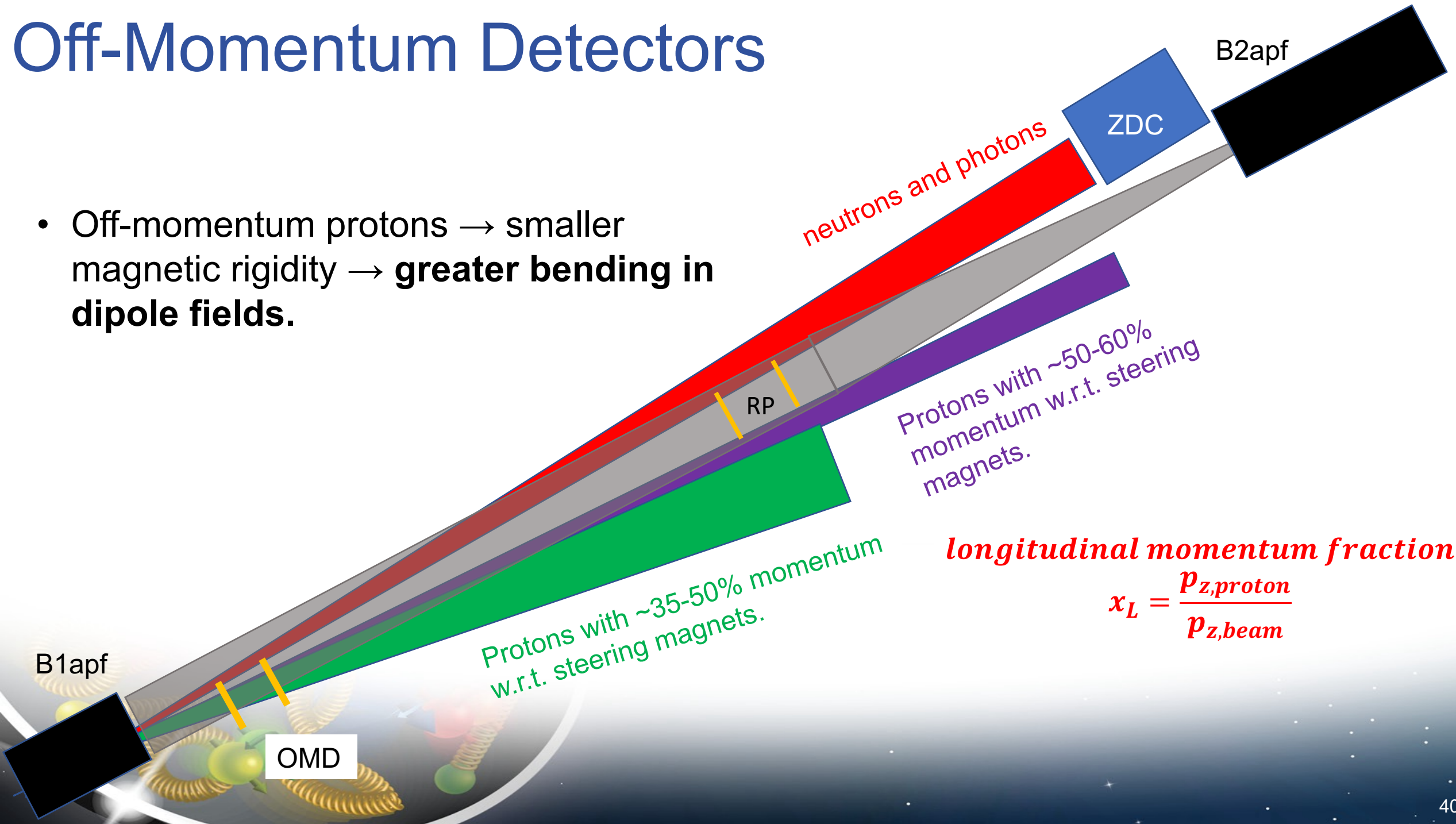
So how does the FF system perform for measurements (non-exhaustive)?

Off-Momentum Detectors



Off-Momentum Detectors

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

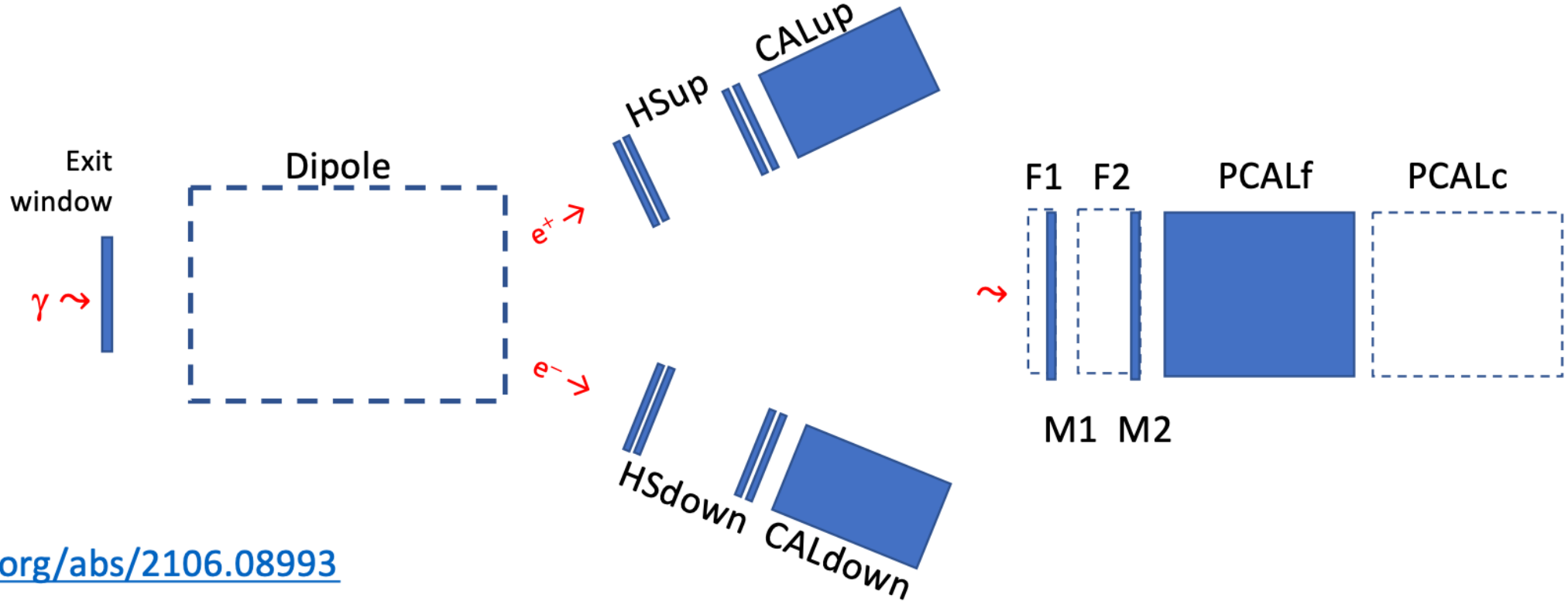


$$\textit{longitudinal momentum fraction}$$

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

Luminosity Monitor

- Must make measurement in challenging environment.
  - High synchrotron radiation, high bremsstrahlung rates (~10 GHz), etc.
- Need ~1% for absolute luminosity measurement, ~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.

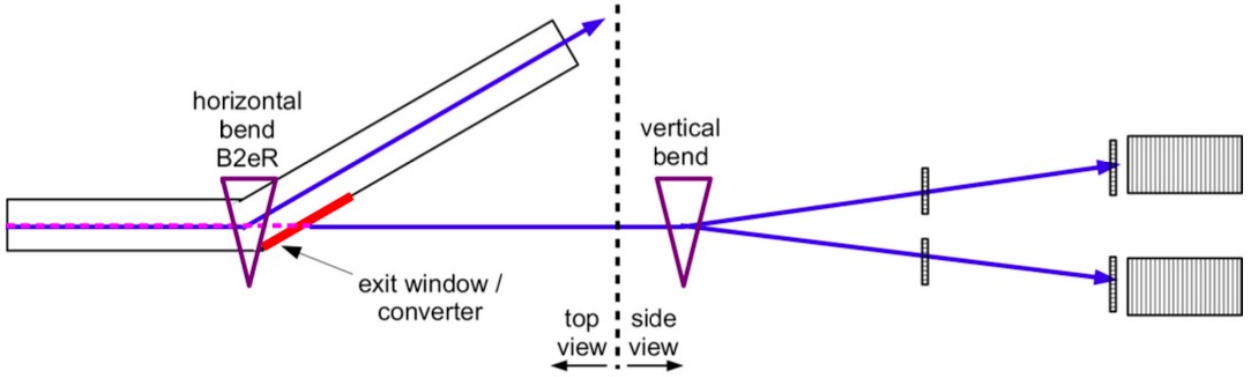


https://arxiv.org/abs/2106.08993

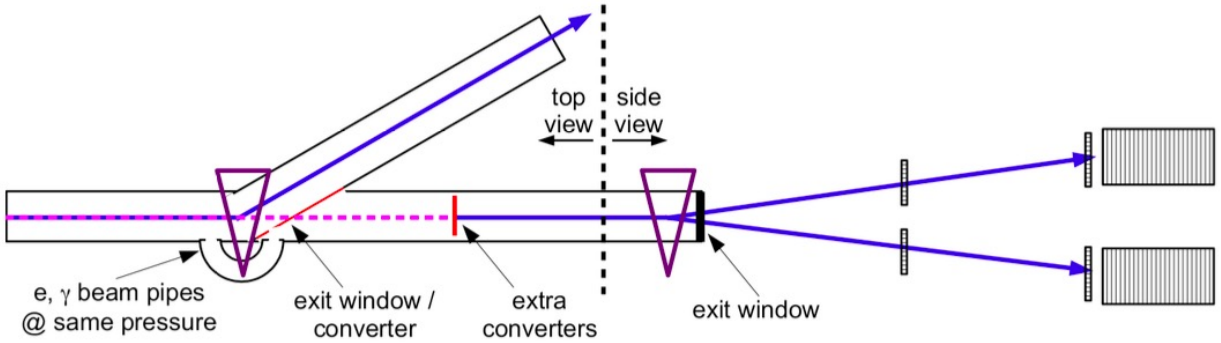
Luminosity Monitor

- Conversion layer is part of beam layout
- Need for precise knowledge of conversion probability
- Heat load from synchrotron radiation is incident on the layer
- Several considerations for the design:

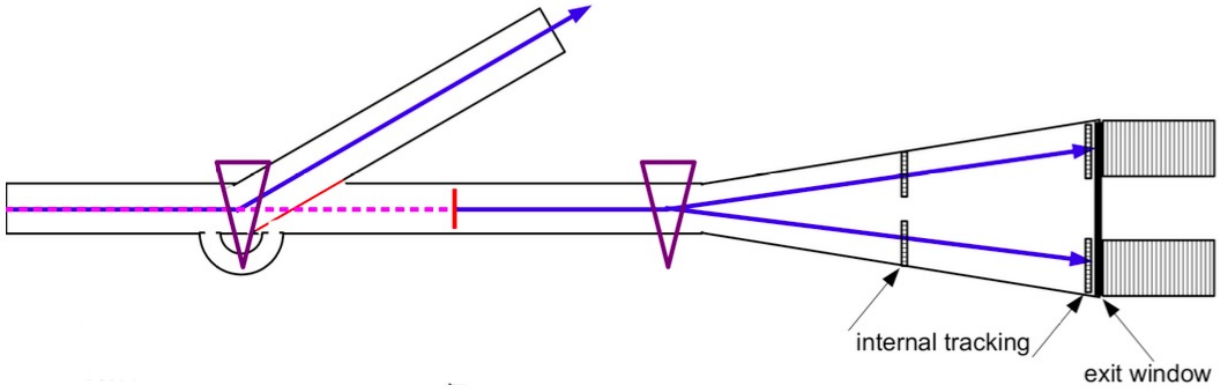
I: baseline design, converter holds the vacuum



II: thin converter in vacuum

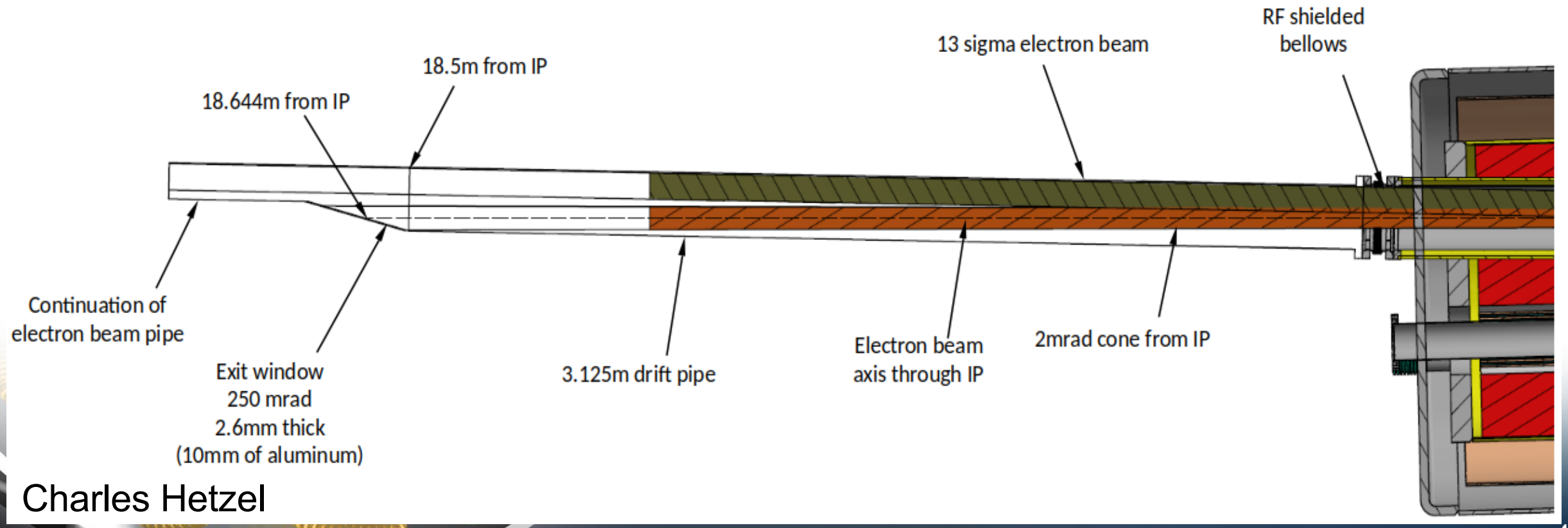


III: vacuum up to detectors



Exit window for luminosity monitor

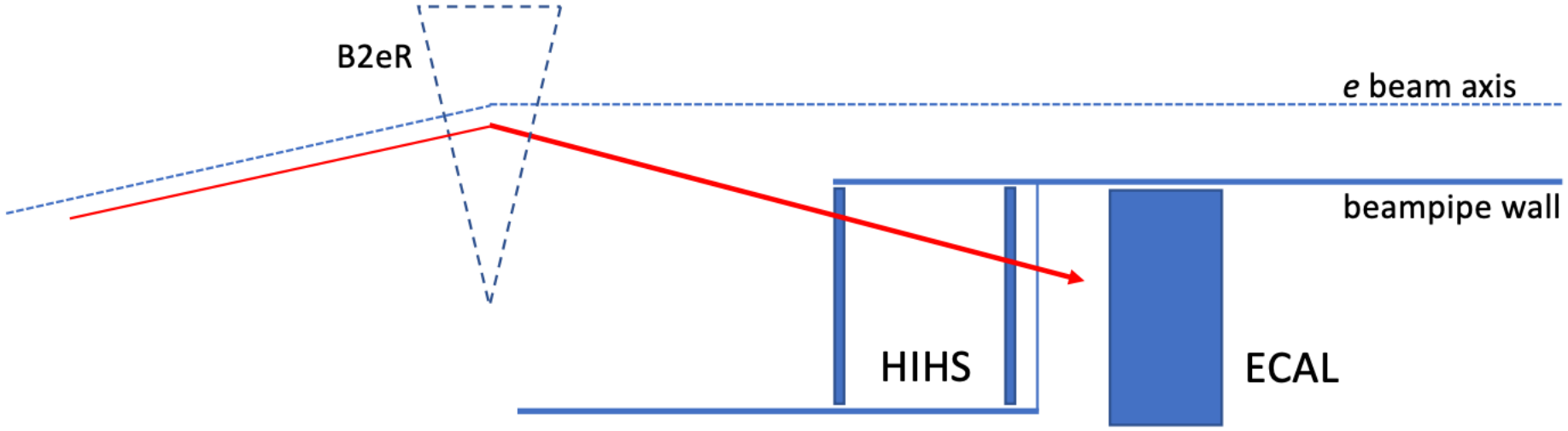
- Part of outgoing electron beam pipe
- Conversion layer for bremsstrahlung photons
- Tilt angle vs. electron (and photon) beam axis against synchrotron radiation



Charles Hetzel

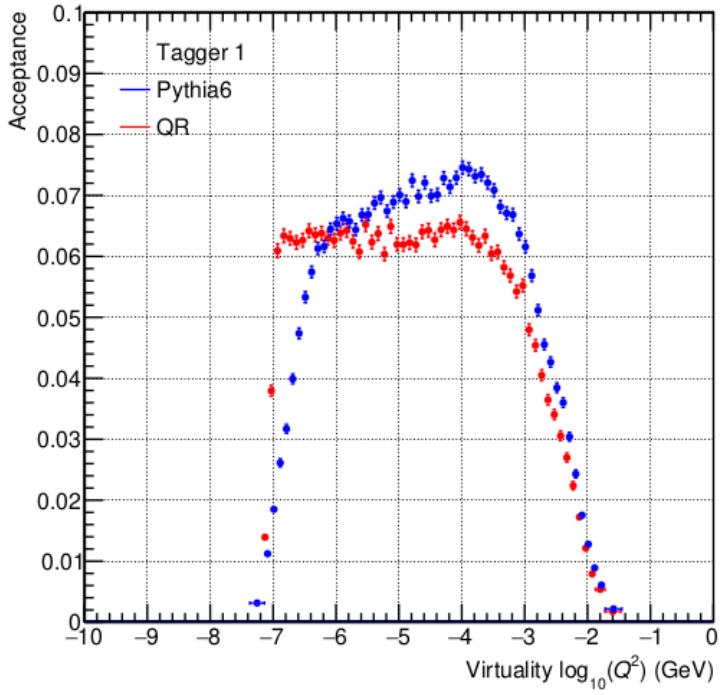
Low-Q^2 Taggers

- 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.

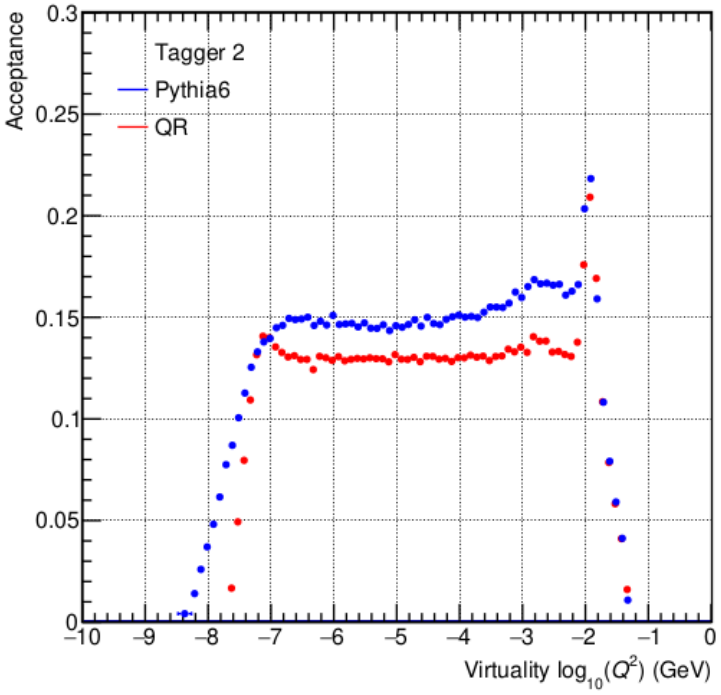


Performance for low-Q2 tagger

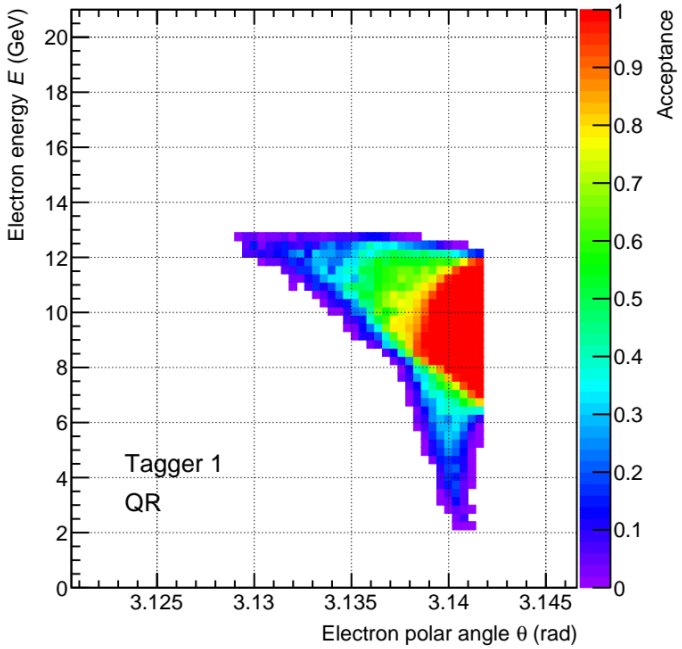
- Tagger 1 and 2 are placed closer (further) from the IP
- Overlap in Q2 acceptance (< 0.1 GeV^2)
- Complementary in electron energy (higher energies reach Tagger 2)
- Consistent for Pythia6 and quasi-real photoproduction (QR)

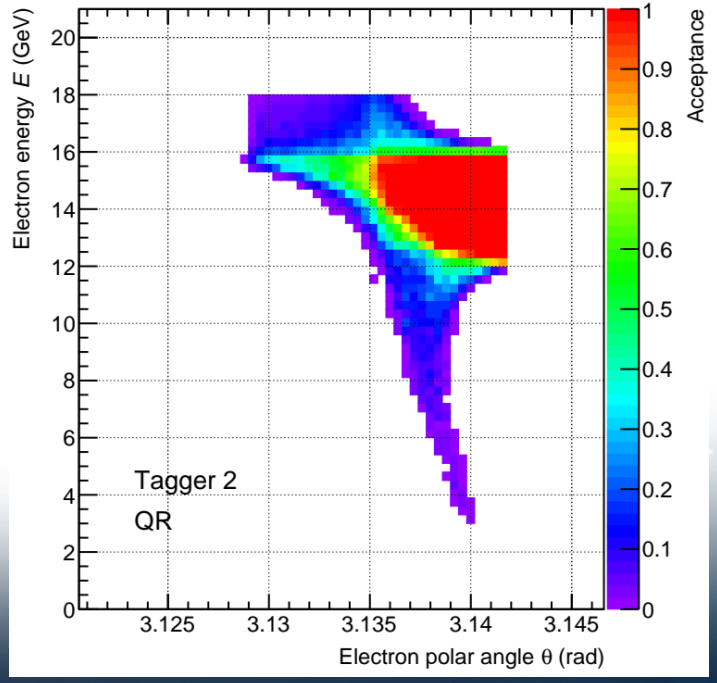


(a) Tagger 1



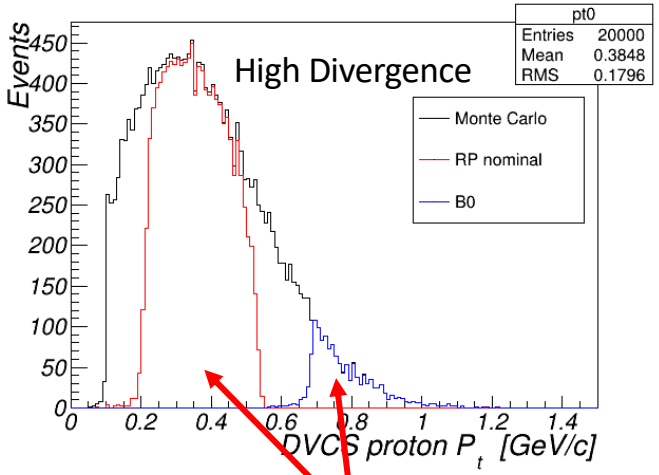
(b) Tagger 2

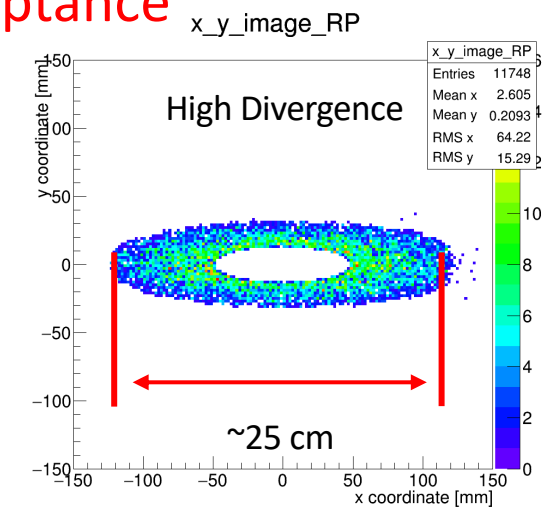


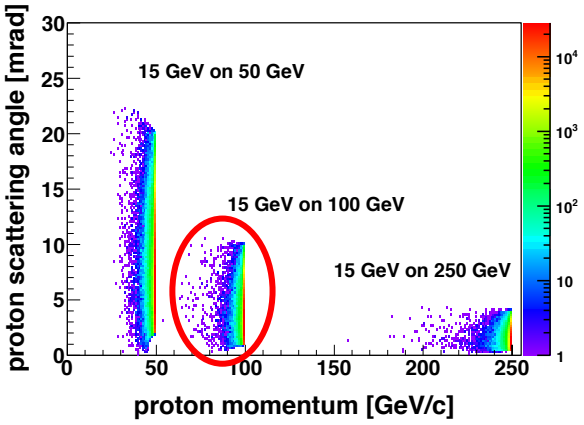


Machine Optics: Roman Pots

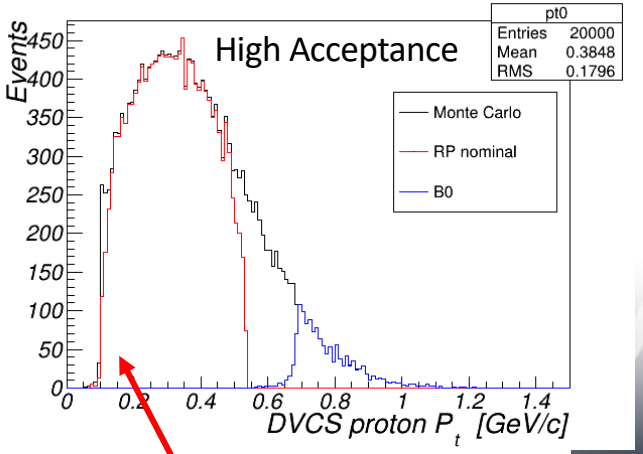
100 GeV DVCS Proton Acceptance

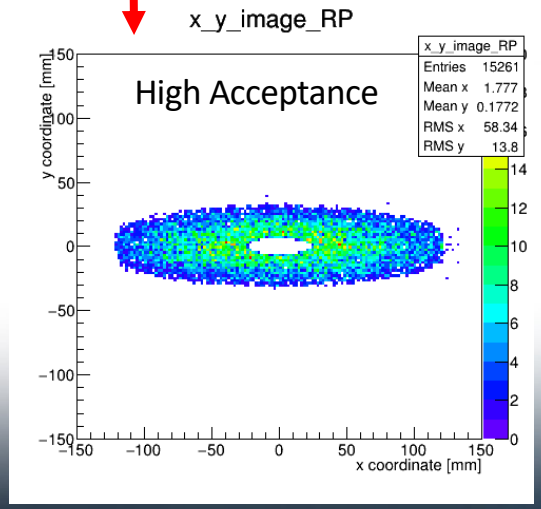






Need both detector systems together here!



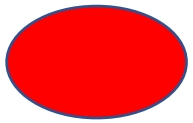


Improves low p_t acceptance.

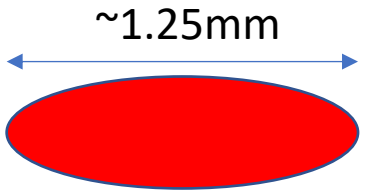
Momentum Resolution – Timing

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