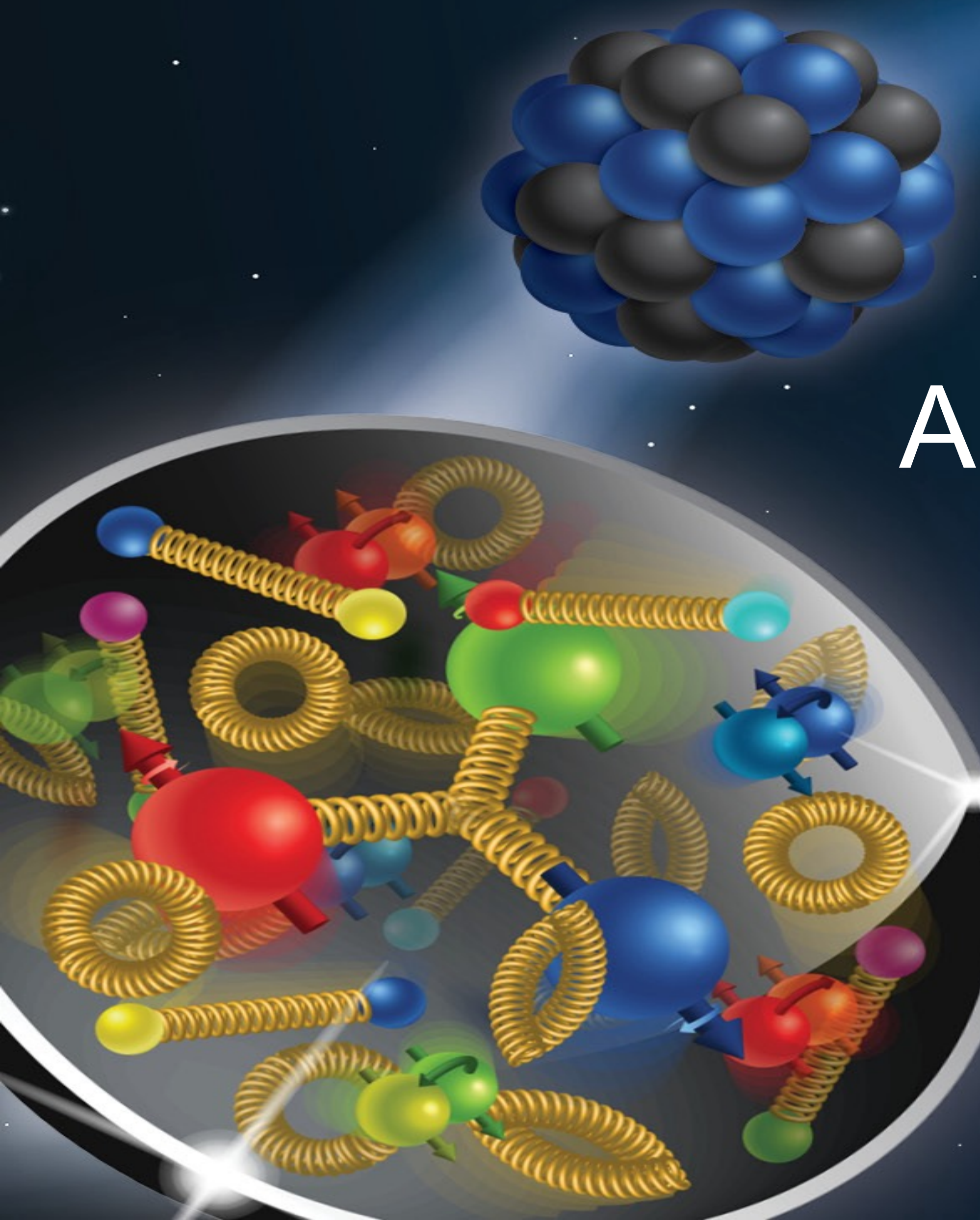

AC-LGADs for the Far-Forward Detectors at the EIC

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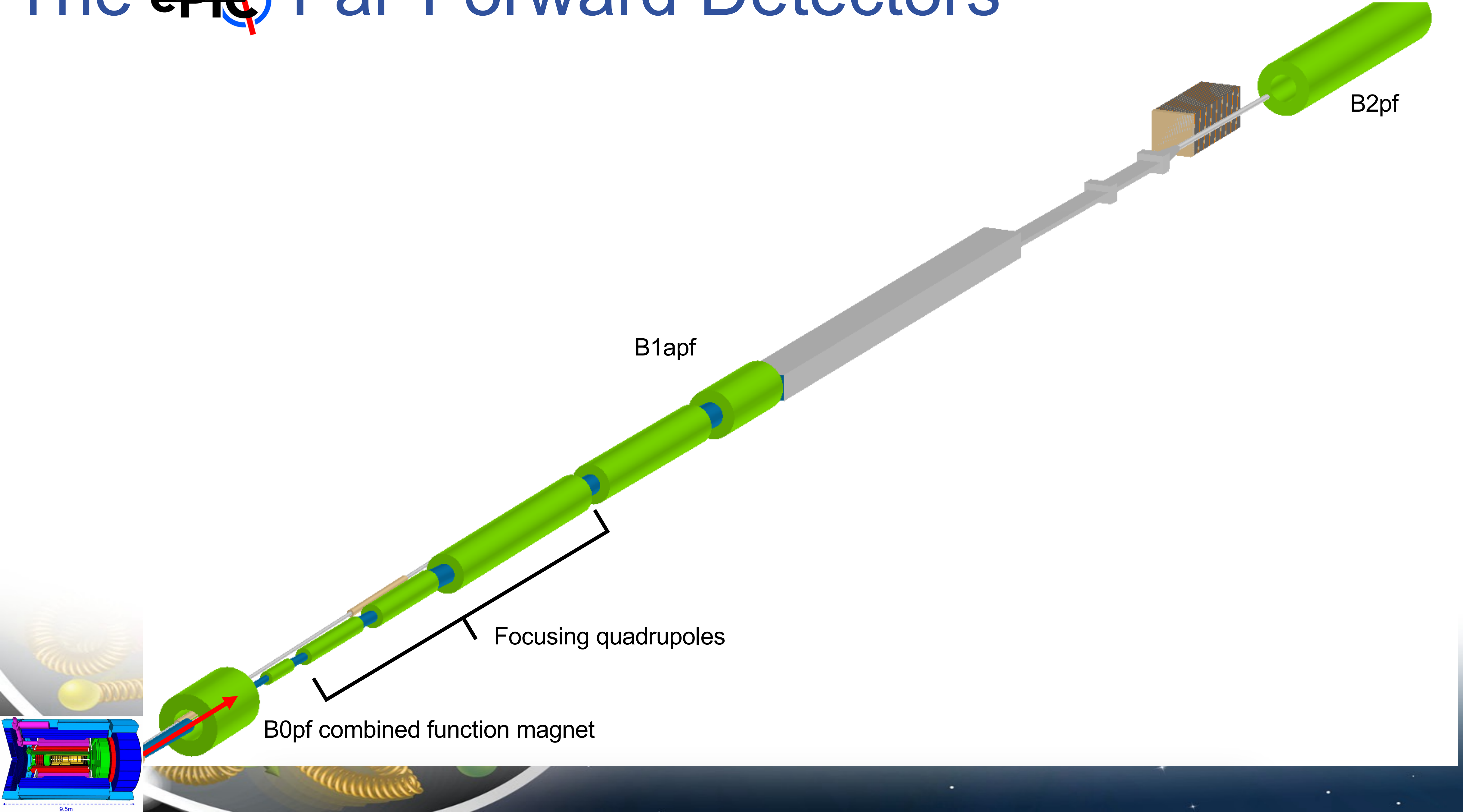
July 26th, 2024

BROOKHAVEN NATIONAL LABORATORY

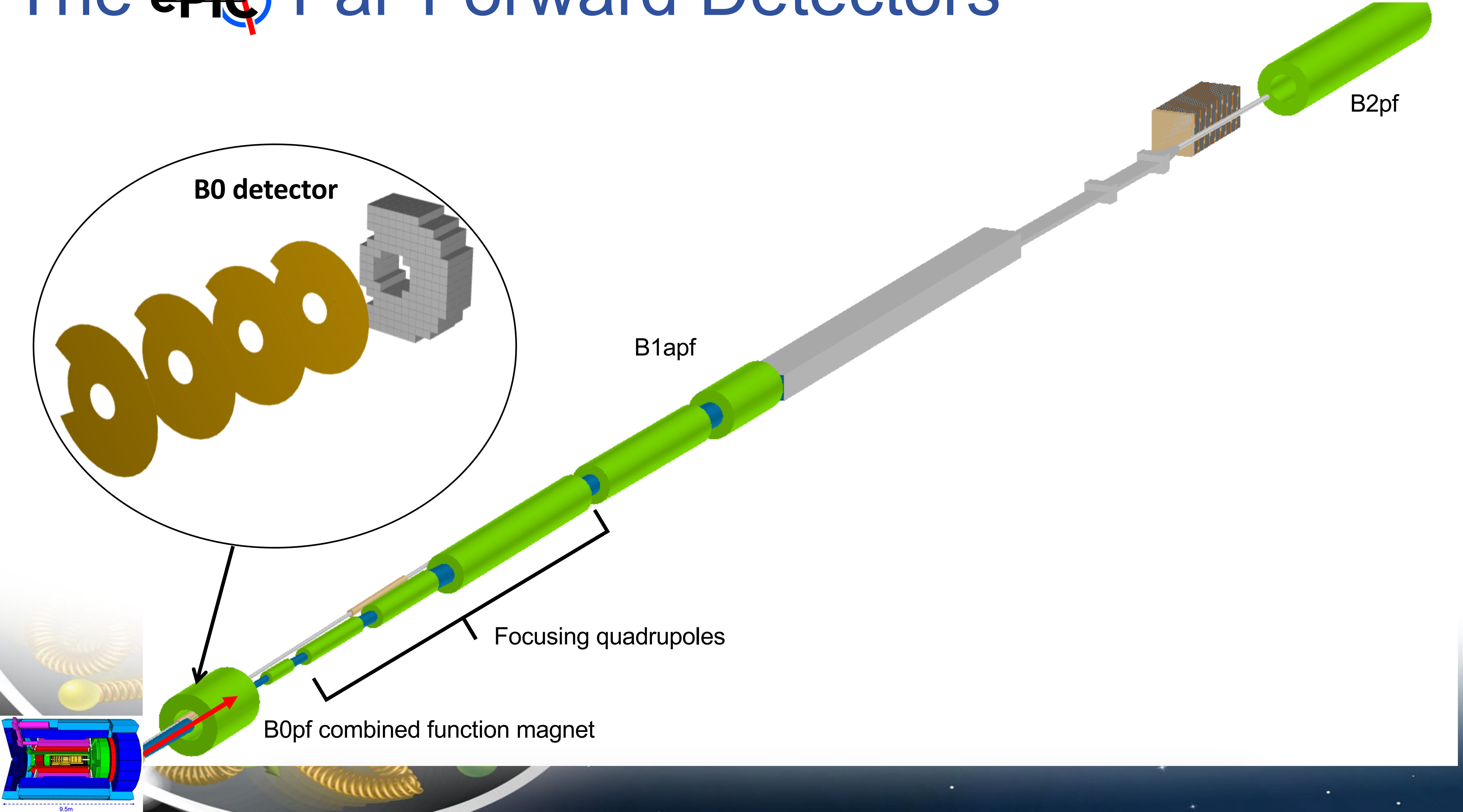
Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

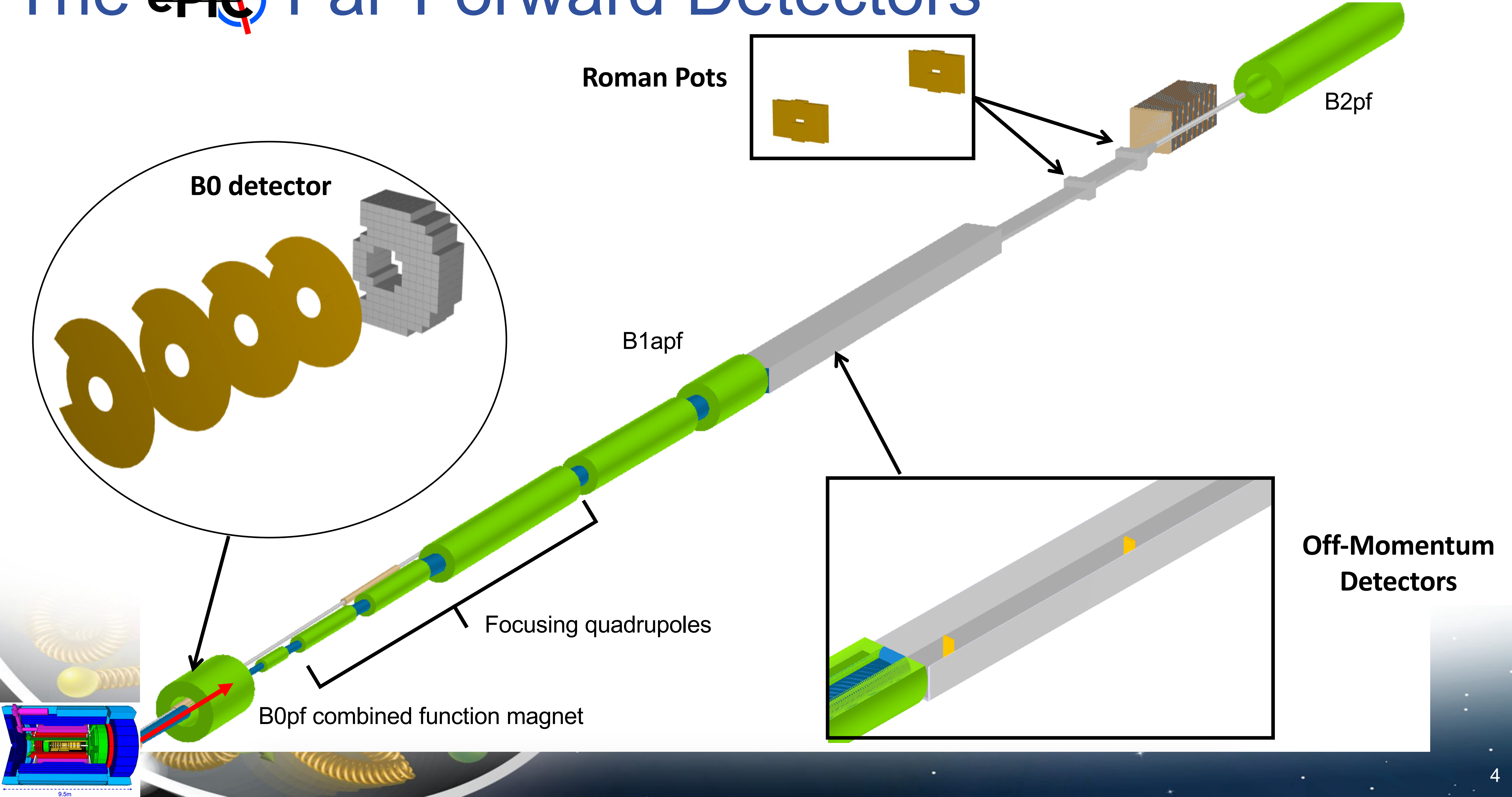
The ePIC Far-Forward Detectors



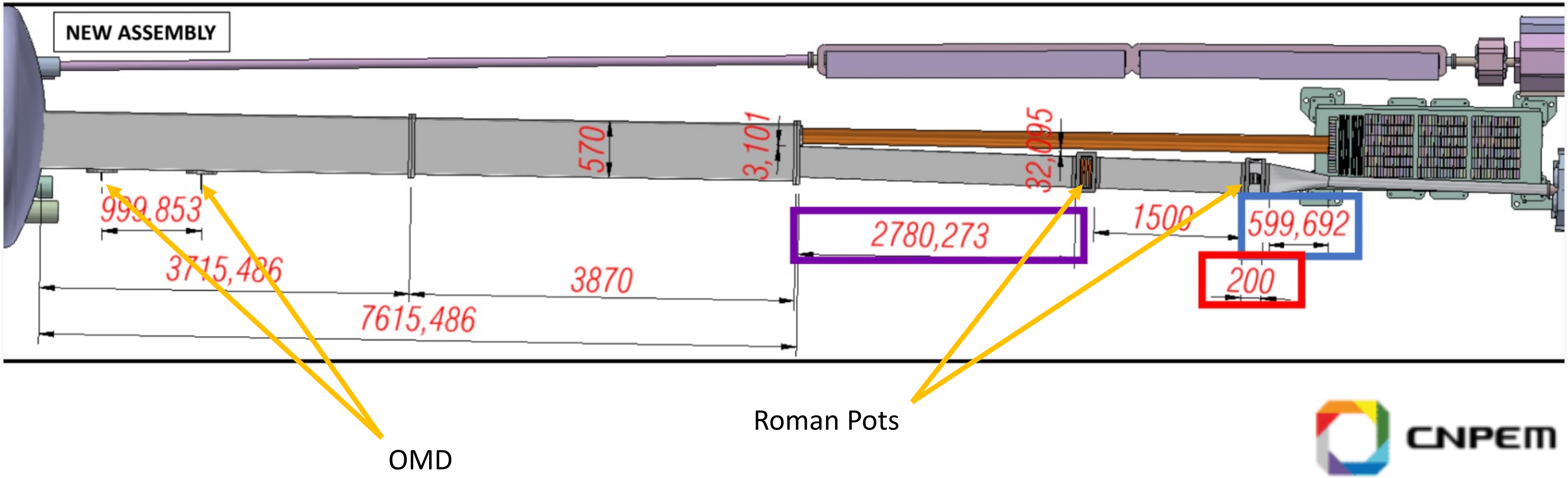
The ePIC Far-Forward Detectors



The ePIC Far-Forward Detectors

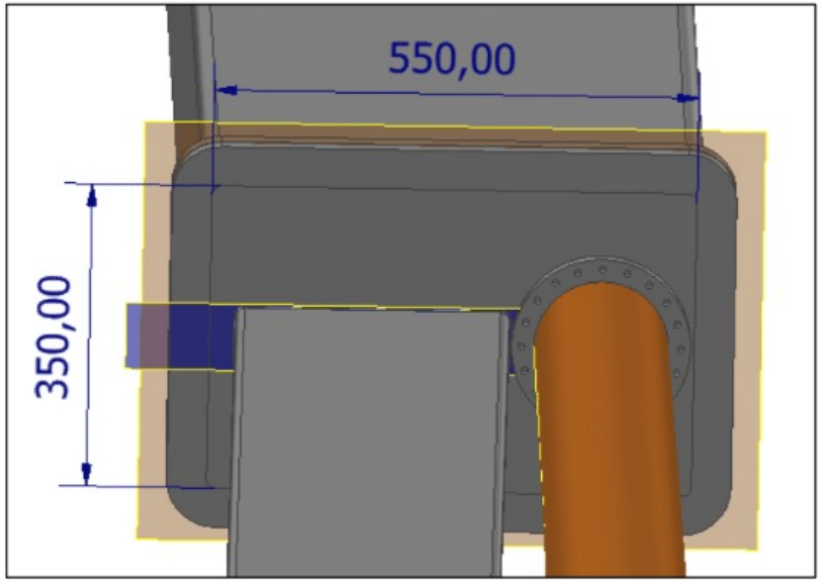


Preliminary CAD drawings of RP and OMD Supports and Magnet Cryostats



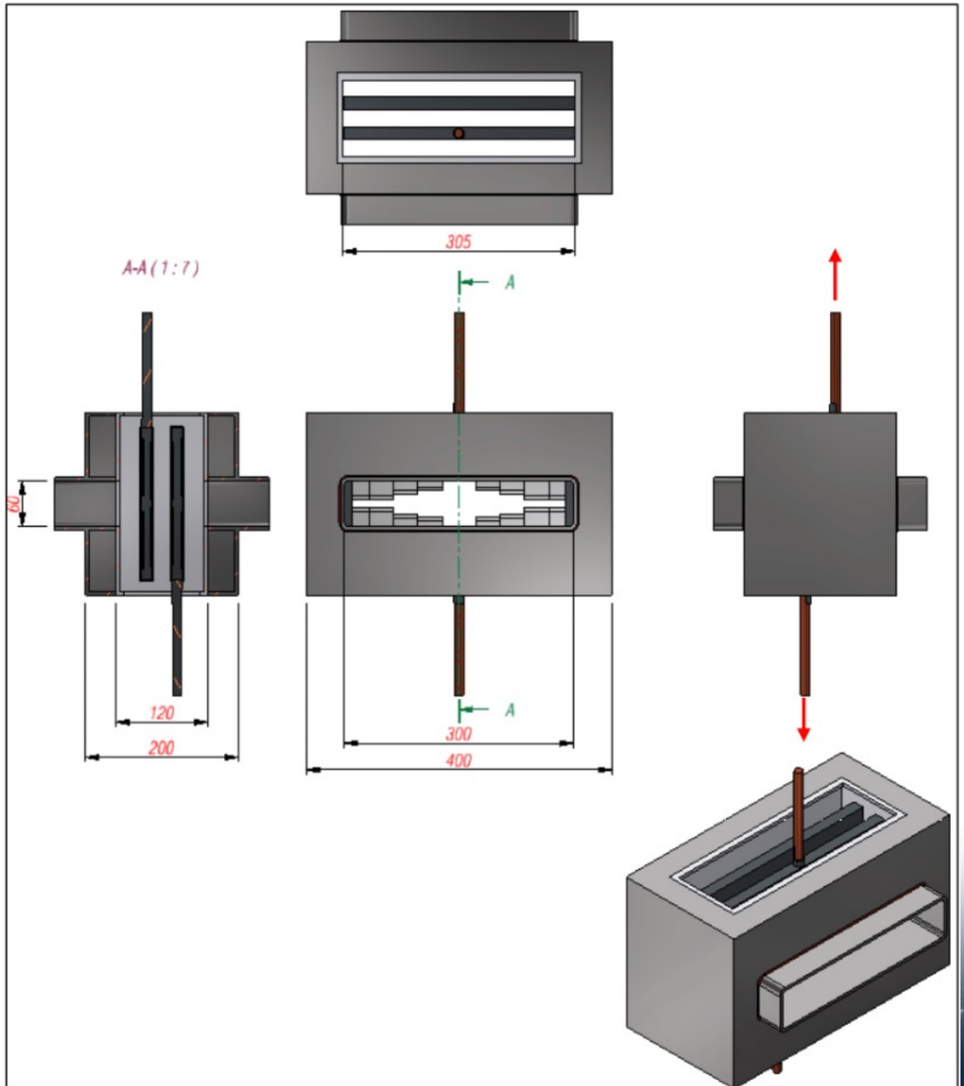
Preliminary CAD drawings of RP and OMD Supports and Magnet Cryostats

New 550x350 mm inner dimensions chamber



Transition region from larger beam pipe containing OMD to smaller pipe containing RP (left) and exit window for neutrals (right).

New Concept



Scattering chamber design for RP sensor packages.

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Roman Pots and OMD

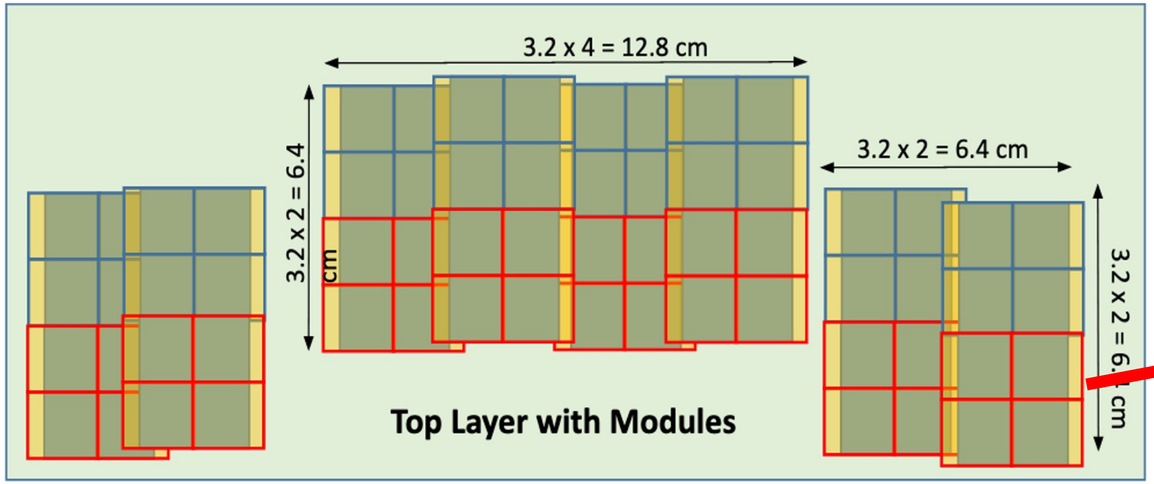
- **Technology**
  - “Potless” design concept with thin RF foils surrounding detector components.
  - 500um, **pixilated AC-LGAD sensor**, with 30-40ps timing resolution → **High-precision space and time information!**
  - Similar concept for the OMD, just different active area and shape.

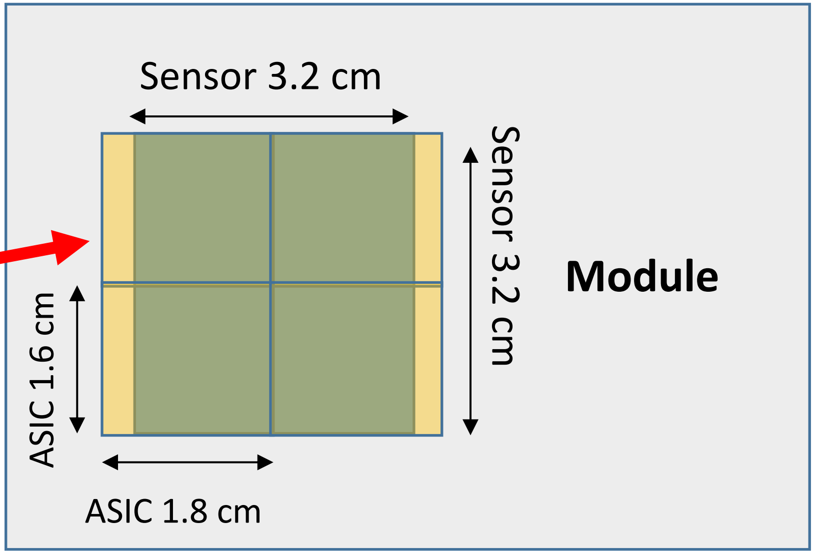
More engineering work is currently underway to optimize the layout, support structure, cooling, and movement systems for inserting the detectors into the beamline.

Roman Pots

We are finalizing plans to likely move to a "one sensor, one ASIC" concept to simplify the sensor and module production.

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

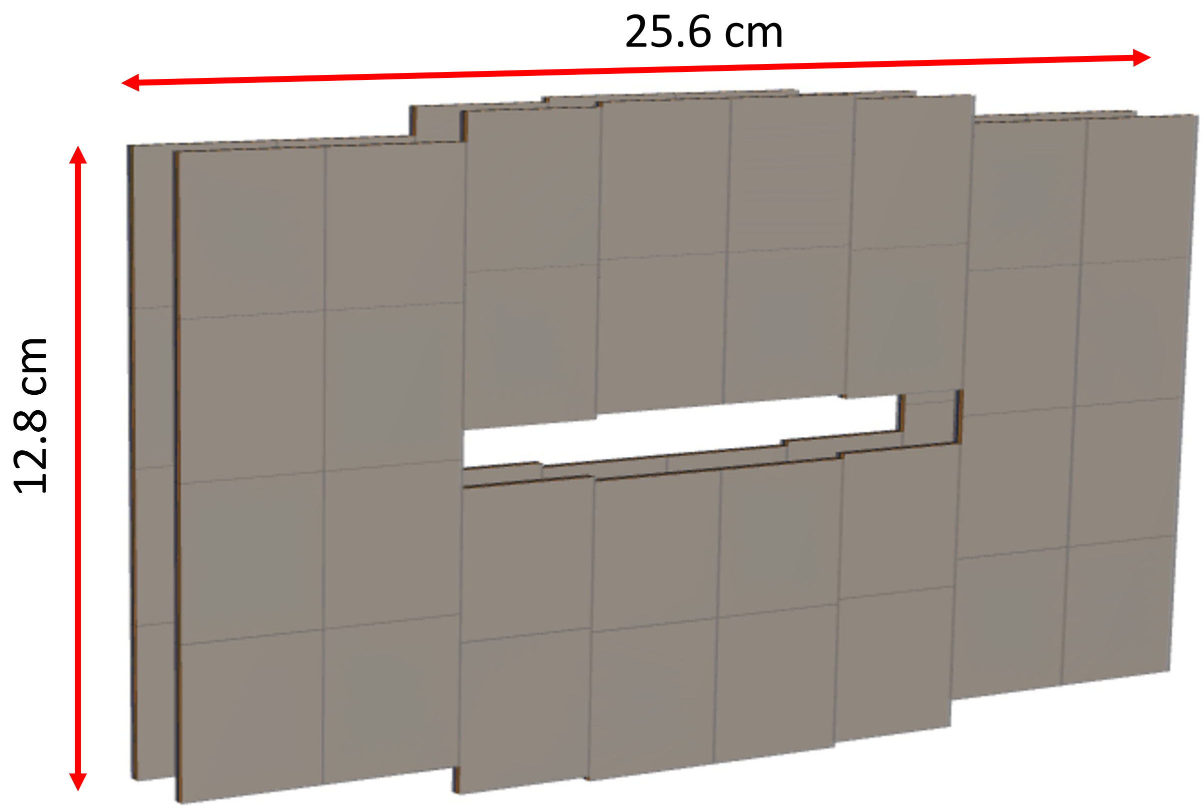




- Current R&D aimed at customizing ASIC readout chip (ALTIROC) for use with AC-LGADs.

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

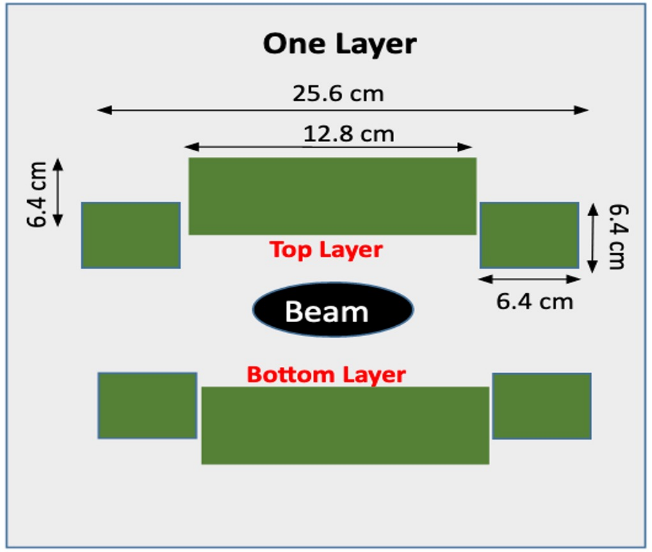
Roman "Pots" @ the EIC



DD4HEP Simulation

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

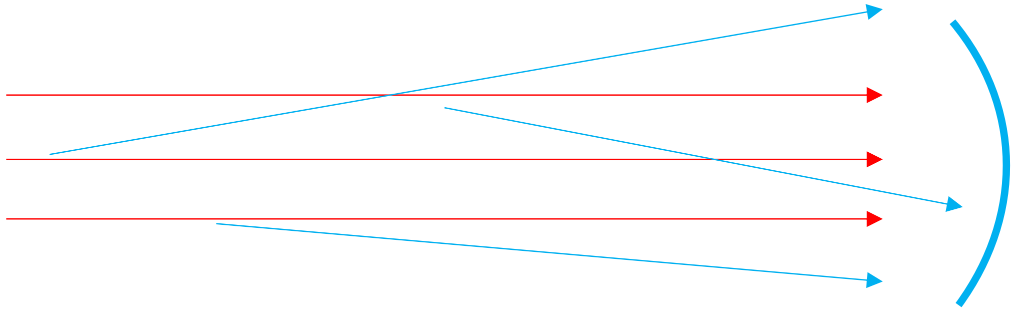
$$\sigma_{x,y} = \sqrt{\beta(z)_{x,y}\epsilon_{x,y} + \left(D_{x,y}\frac{\Delta p}{p}\right)^2}$$



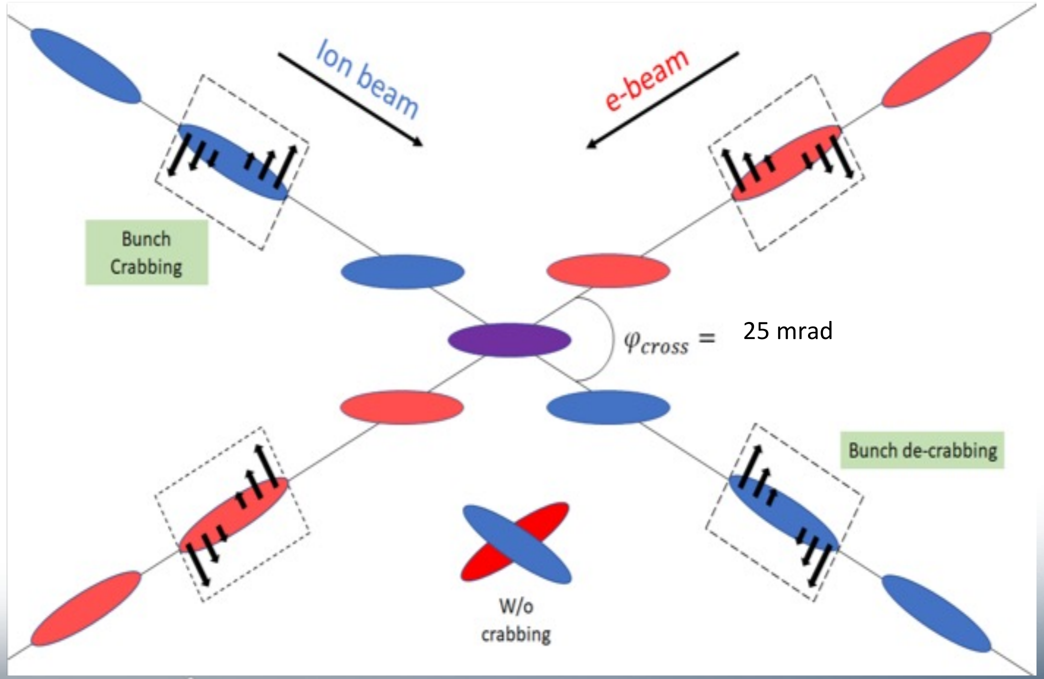
- **<u>Low-pT cutoff determined by beam optics.</u>**
  - **The safe distance is ~10σ from the beam center.**
  - **$1\sigma \sim 1$mm**
- **These optics choices change with energy, but can also be changed within a single energy to maximize *either acceptance at the RP, or the luminosity.***

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.



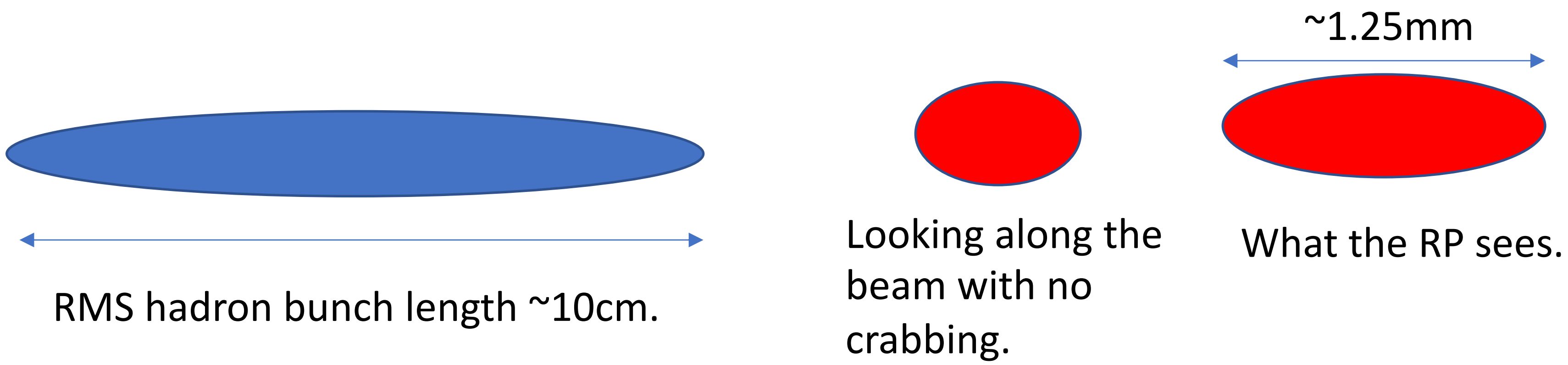
- Crab cavity rotation
  - Can perform rotations of the beam bunches in 2D.
  - Used to account for the luminosity drop due to the crossing angle – allows for head-on collisions to still take place.



These effects introduce smearing in our momentum reconstruction.

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?



- 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

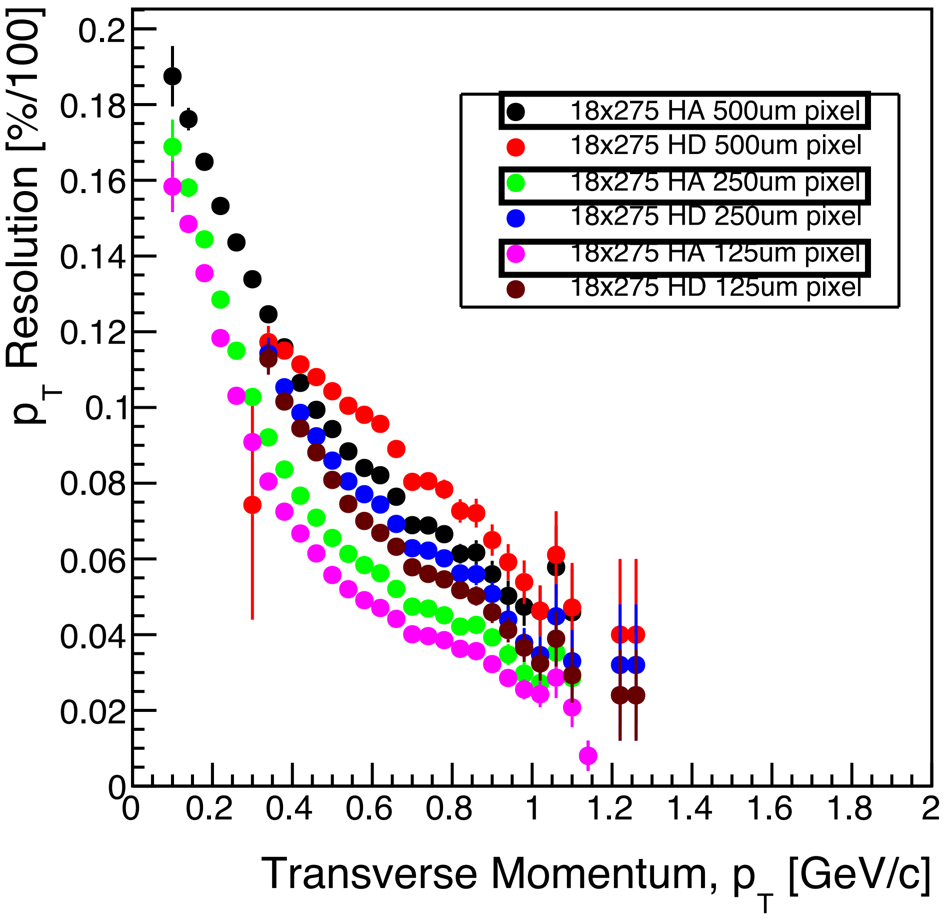
Primary vertex smearing from crab cavity rotation.

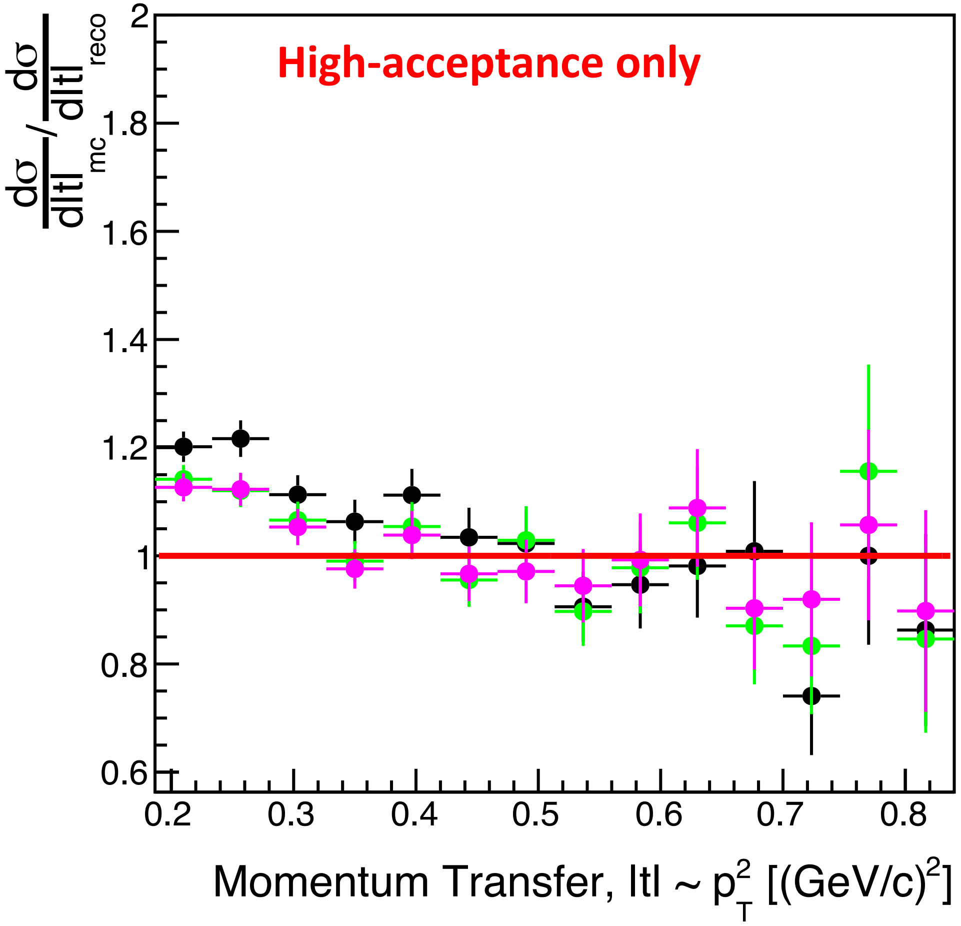
Smearing from finite pixel size.

	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

Detailed RP Momentum Resolution - 18x275 GeV





- 500um = no charge sharing
- 250um = charge sharing, x2 improvement
- 125um = charge sharing, x4 improvement

- Each case includes all beam effects.

Updated requirements study:
https://indico.bnl.gov/event/23526/contributions/91953/attachments/54667/93524/requirements_RP_OMD_5_21_2024.pdf

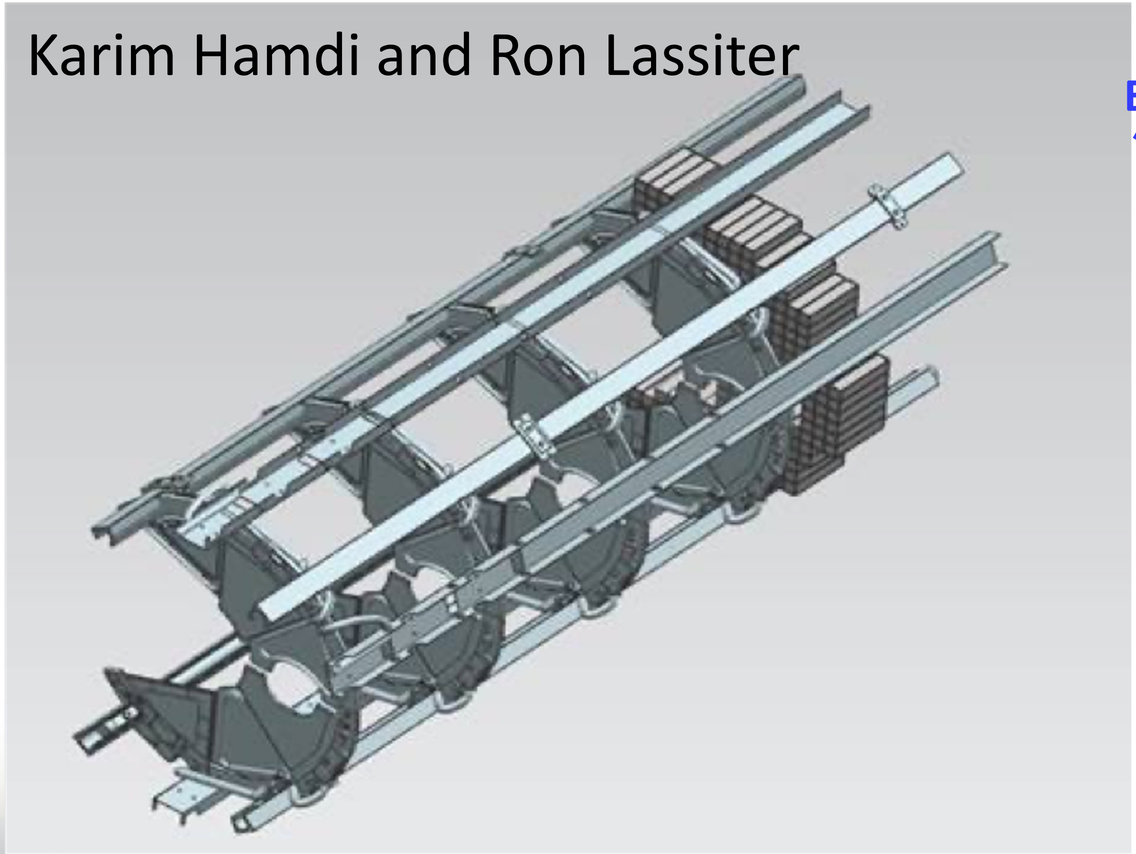
- Goal is to extract slope of t-distribution.
- Ratio indicates expected capability.
- pT resolution < ~7% has minimal impact on the t-distribution.

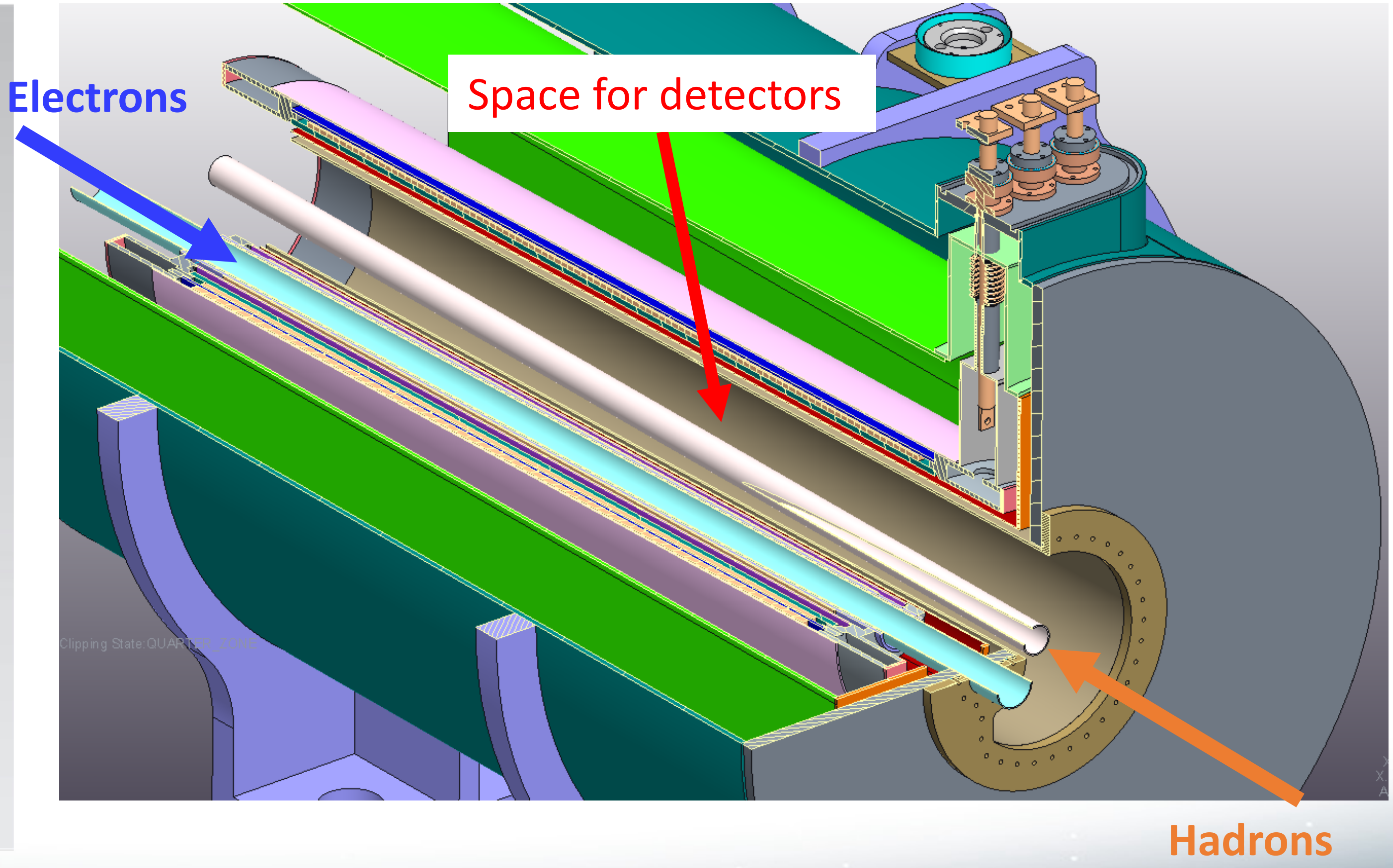
What about the B0 tracker?

- Originally planned to use ITS3 (3 layers) + AC-LGAD (1 layer) to get 5-10um spatial resolution, combined with precise timing of AC-LGADs.
- Long integration window for ITS3 sensors a major problem for the high occupancy environment of the B0 tracker.
  - https://wiki.bnl.gov/EPIC/index.php?title=Background
- Looking at AC-LGADs as an option for the full subsystem → will the worsening of the spatial resolution be tolerable?
  - Beam tests demonstrate AC-LGADs achieving ~ 20um spatial resolution with charge sharing: https://indico.bnl.gov/event/19471/

B0 Detectors

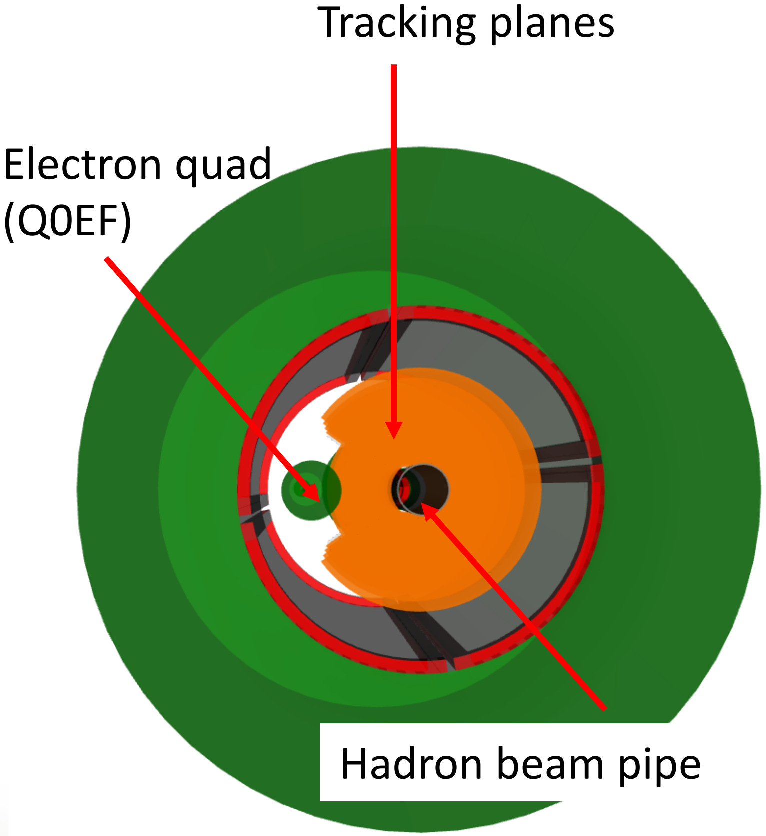
- Detector subsystem embedded in an accelerator magnet.



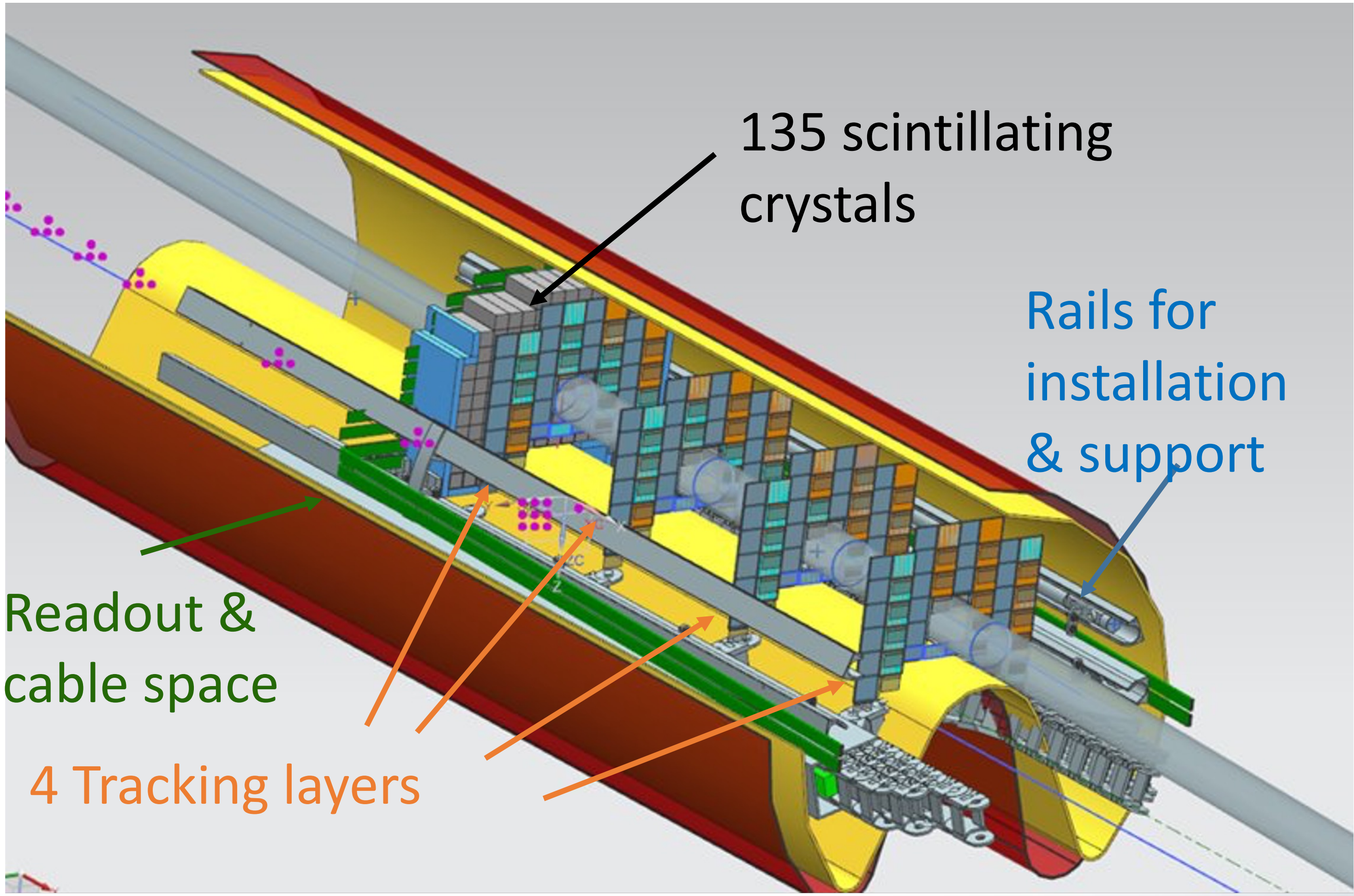


B0 Tracking and EMCAL Detectors

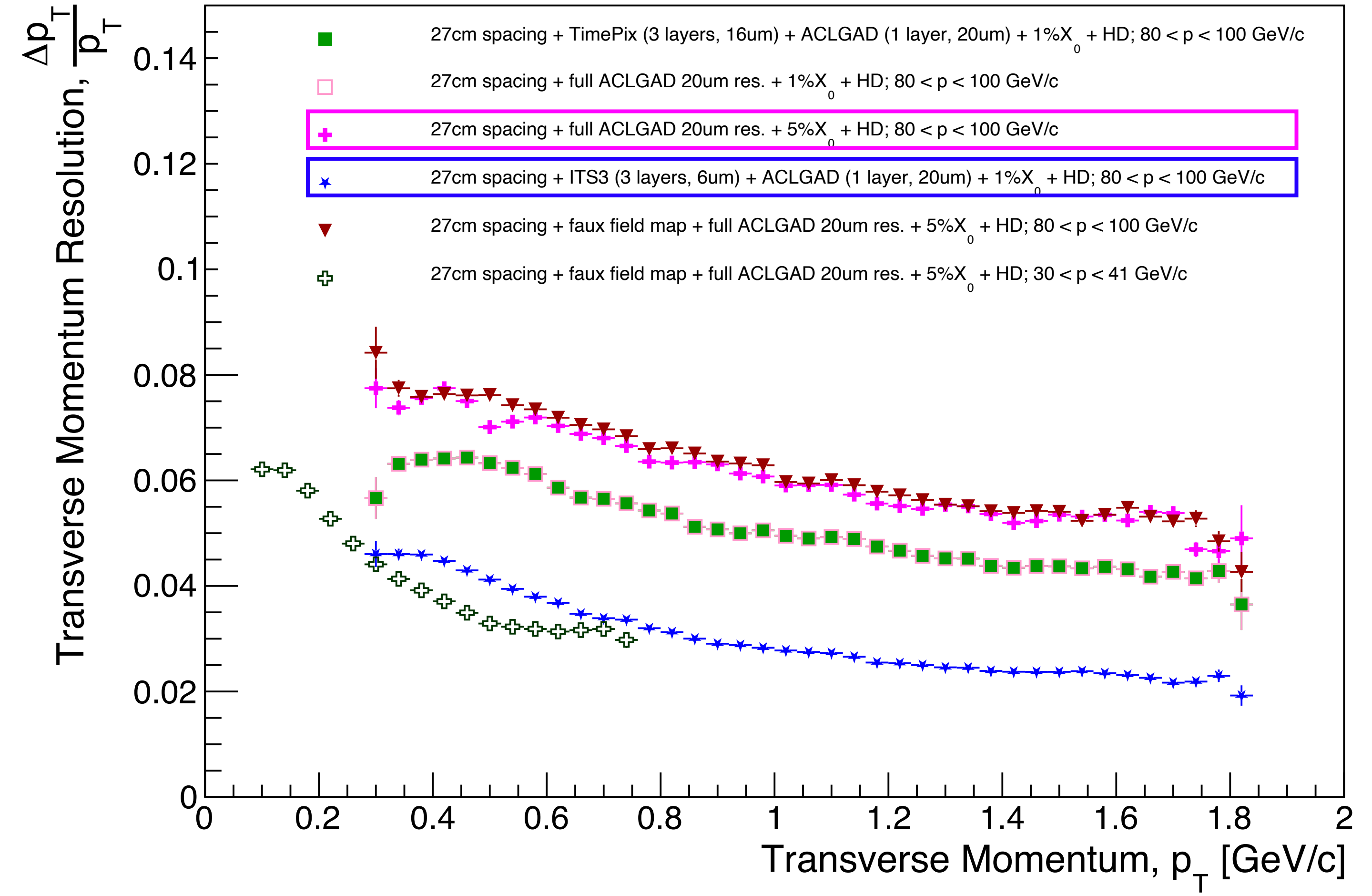
CAD Look credit: Jonathan Smith



ePIC DD4HEP Simulation

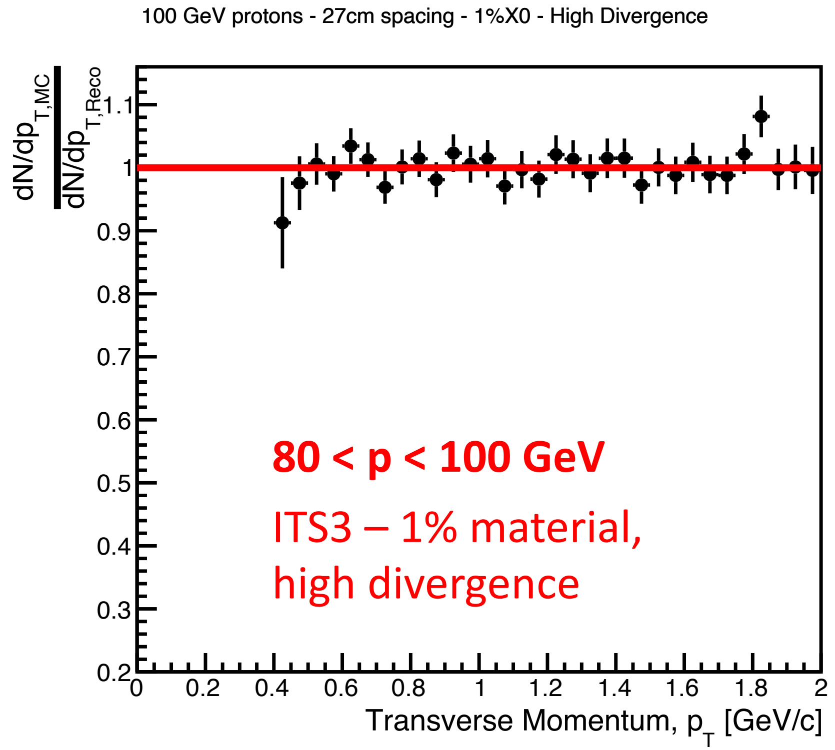


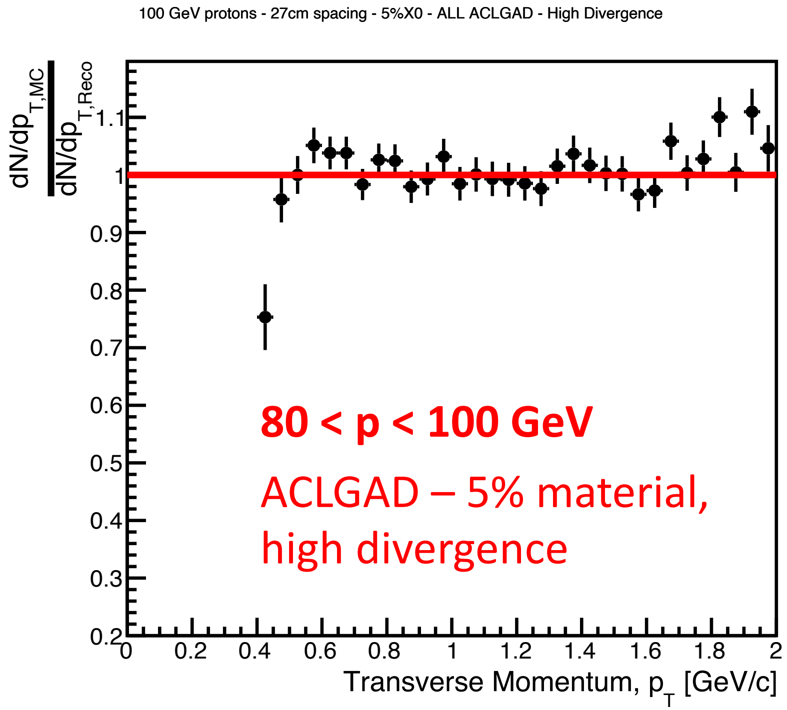
B0 tracking: new technology + material assumptions (first tests last Summer)



- 27cm spacing with fully AC-LGAD system and 5% radiation length may be the most-realistic option.
  - Constant & uniform magnetic field for tracker.
- **<u>Note:</u>** p resolution is ~ 2-4%, depending on configuration.

B0 tracking: Impact on pT spectra



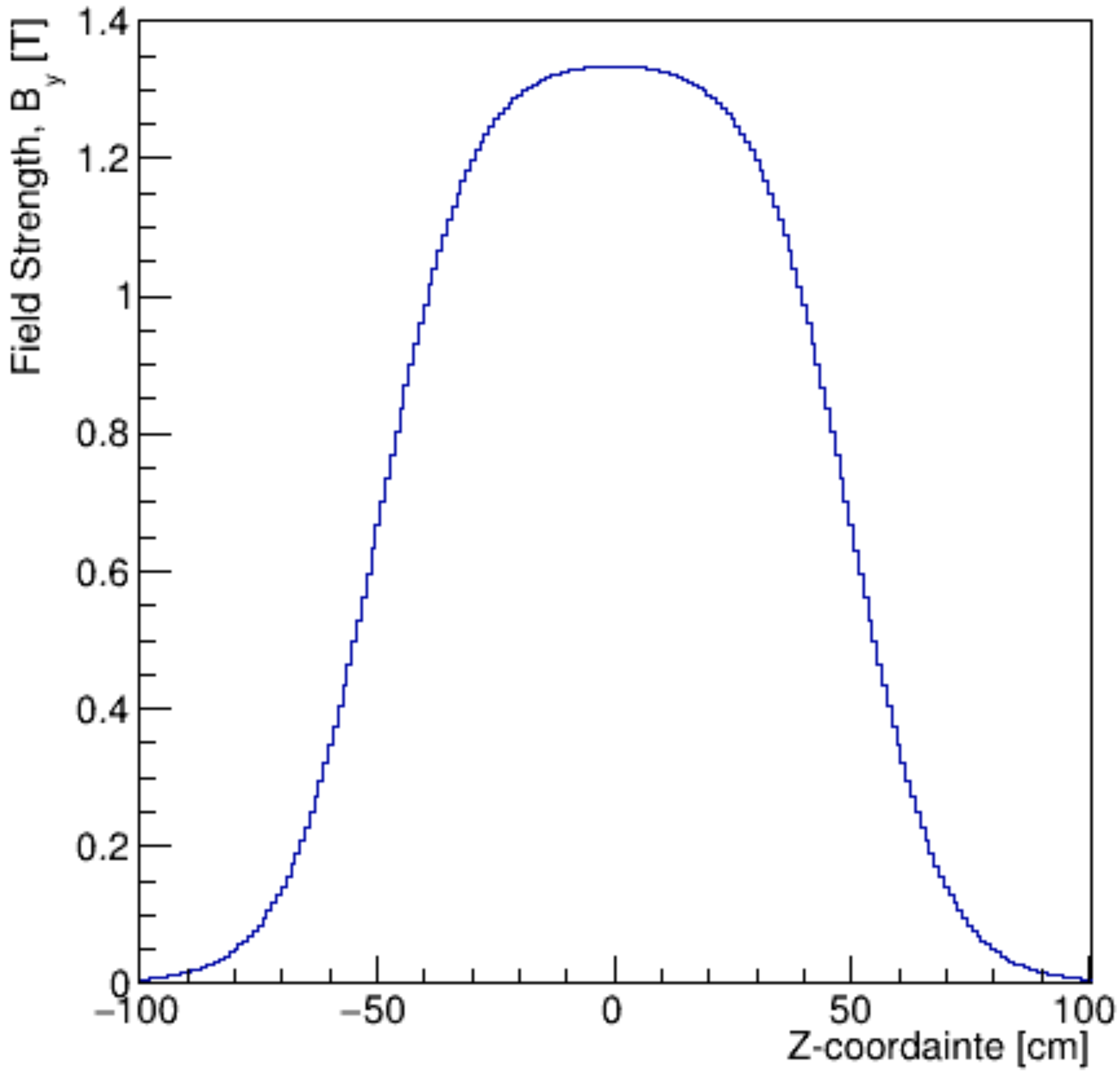


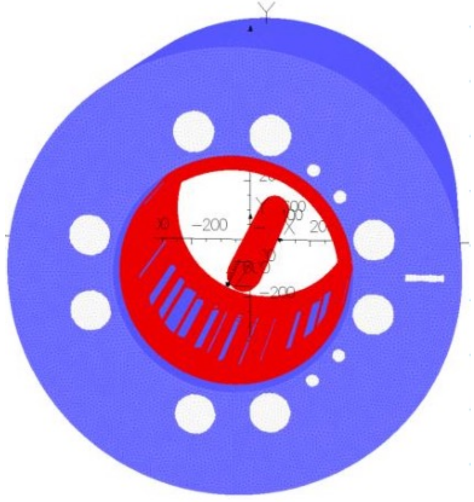
- Full study: https://indico.bnl.gov/event/19620/
- Information passed to PWG in June 2023.

Recent update: B0 Field Map

- Previous studies done with constant, uniform dipole + quadrupole fields.
- Studies now moving forward with correct field map in the B0.
  - Information pulled from here:
    - https://wiki.bnl.gov/EPIC/images/e/ef/12212022_-_Set_up_to_do_3D_field_map.pdf
    - https://wiki.bnl.gov/EPIC/images/1/1b/B0_field_map_23dec2022.txt.zip
- Map given in 1cm steps → lots of information for the detector simulations, reduced to 10cm steps in z for processing.
  - Fully implemented in DD4HEP, but not merged into main repo (still need to study use of field map with the rest of the FF magnets before making it the standard).
  - ✓Field lines then rotated and translated to correct simulation coordinate system.
  - ✓Field values checked at various locations to ensure correct usage.

B0 Field Map



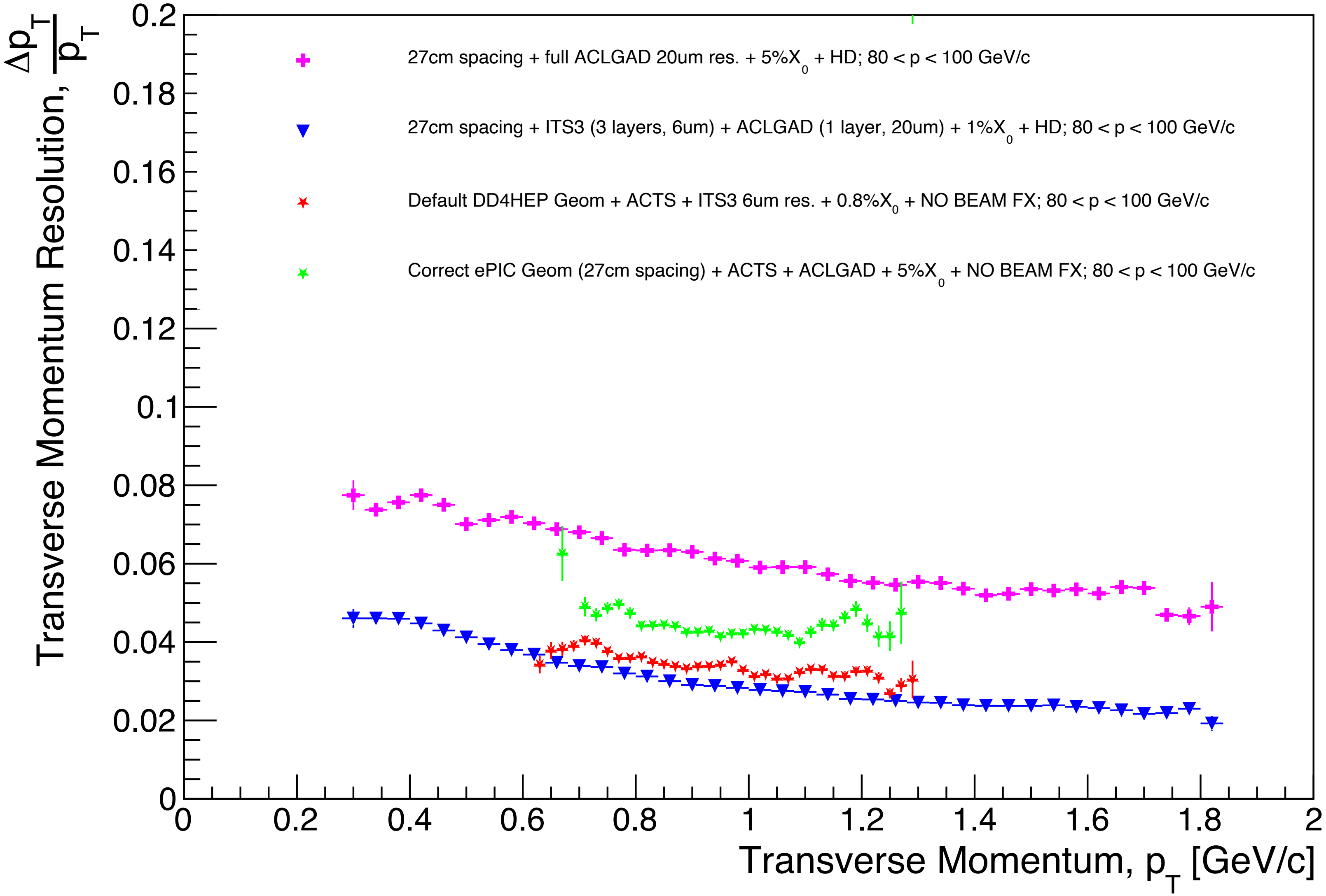


```
e-beam @ +34 mm and hadrons @ -126 mm
(neglecting 25 mrad angle) in this model

Z=0 is center of the magnet @ 6.4m
```

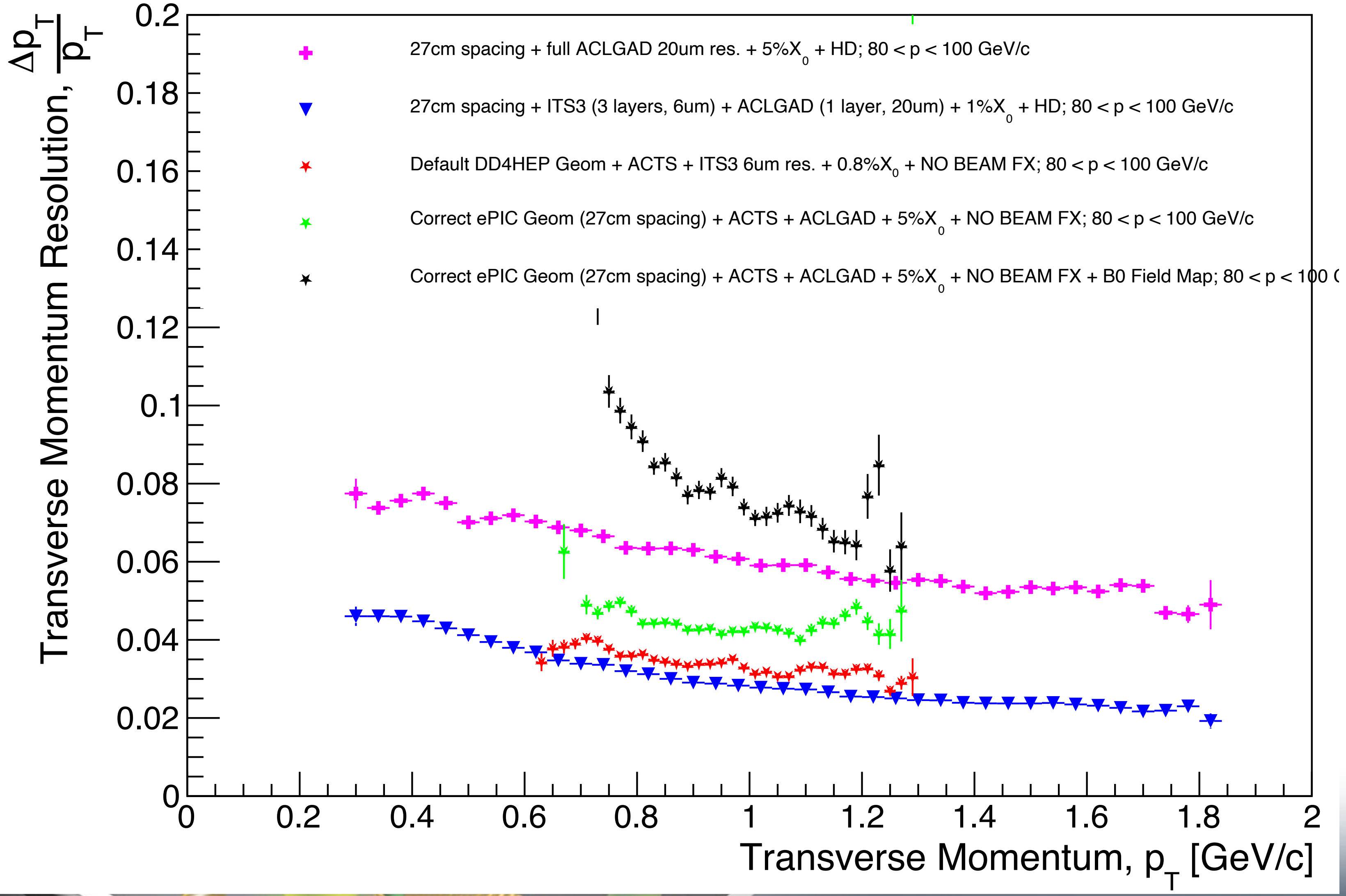
- X = -126 mm, y = 0 mm (before rotation and shift to fit along beamline).
  - By field strength along the hadron beam.
  - Gaussian field shape!

B0 Tracking - Performance



- All of these assume constant dipole + quadrupole field through entire 1.2m long magnet volume.
- Green/Red assume 6 to 13 mrad cone of 80 to 100 GeV protons.
  - Aiming at ~symmetric portion of acceptance, conservative case for the tracking performance (100 GeV protons are very rigid)

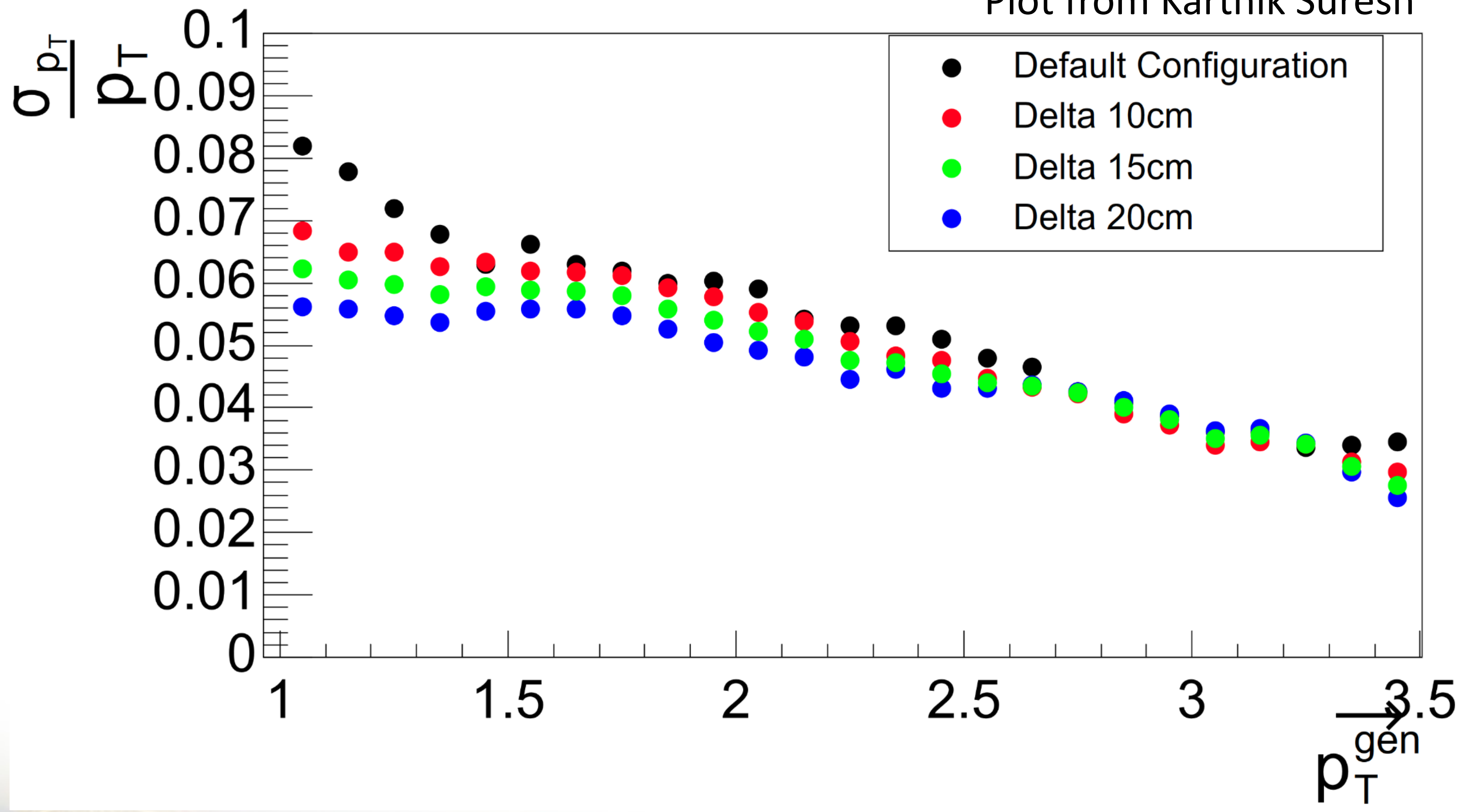
B0 Tracking - Performance



- Black: field map with nominal geometry (plane separation and central location).
- Assume 6 to 13 mrad cone of 80 to 100 GeV protons.

B0 Tracking - Performance

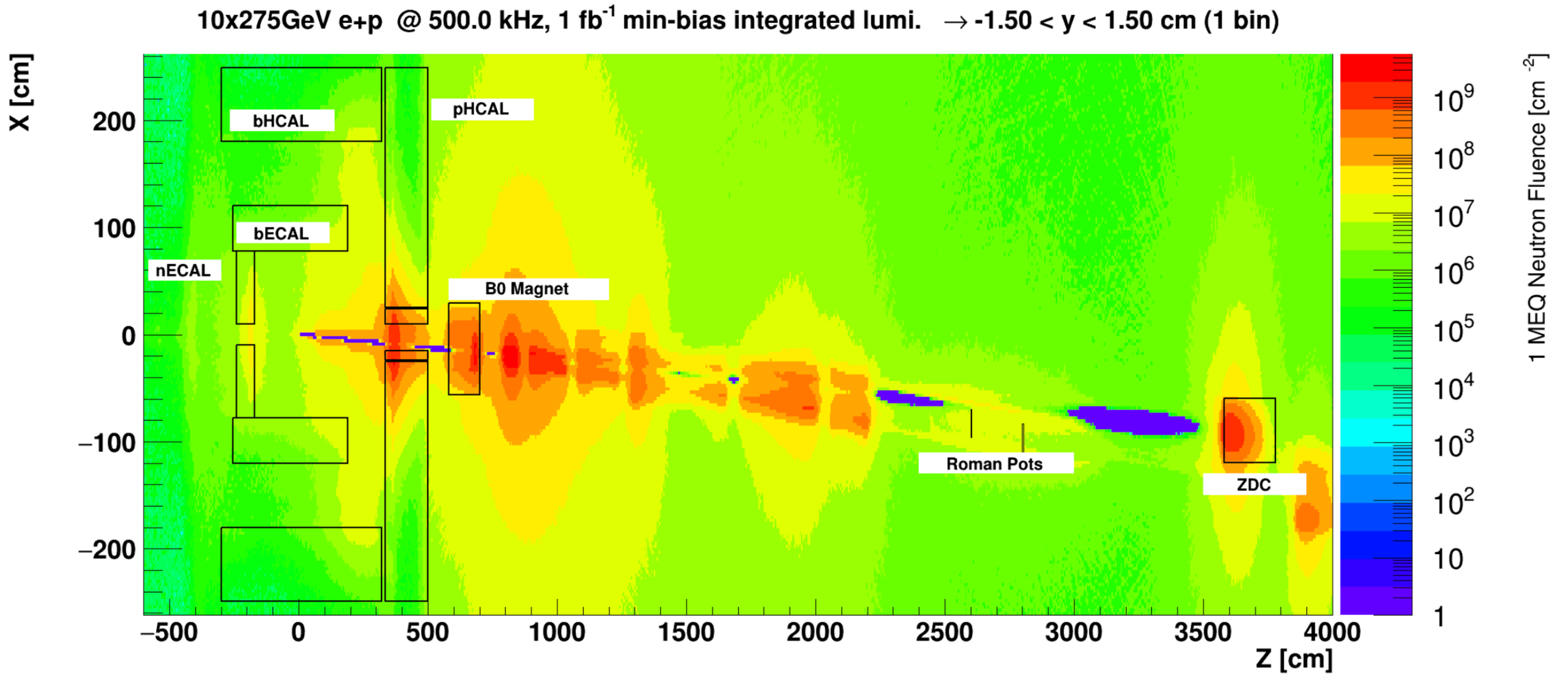
Plot from Karthik Suresh



- Work underway now to optimize tracker layout to obtain best-possible resolution.

Radiation Doses

https://wiki.bnl.gov/EPIC/index.php?title=Radiation_Doses



- Doses are ~1e2 smaller than LHC levels – more than tolerable for AC-LGADs.

Detector Summary

- **<u>Roman Pots:</u>**
  - 25.6cm x 12.8cm x 4 layers = 524k channels
- **<u>Off-Momentum Detectors:</u>**
  - ~9.6cm x 19.2cm x 4 layers = 295k channels
- **<u>B0 Tracker System:</u>**
  - “Pac-man” disks ~ 370 cm^2 per layer; 4 layers = 606k channels

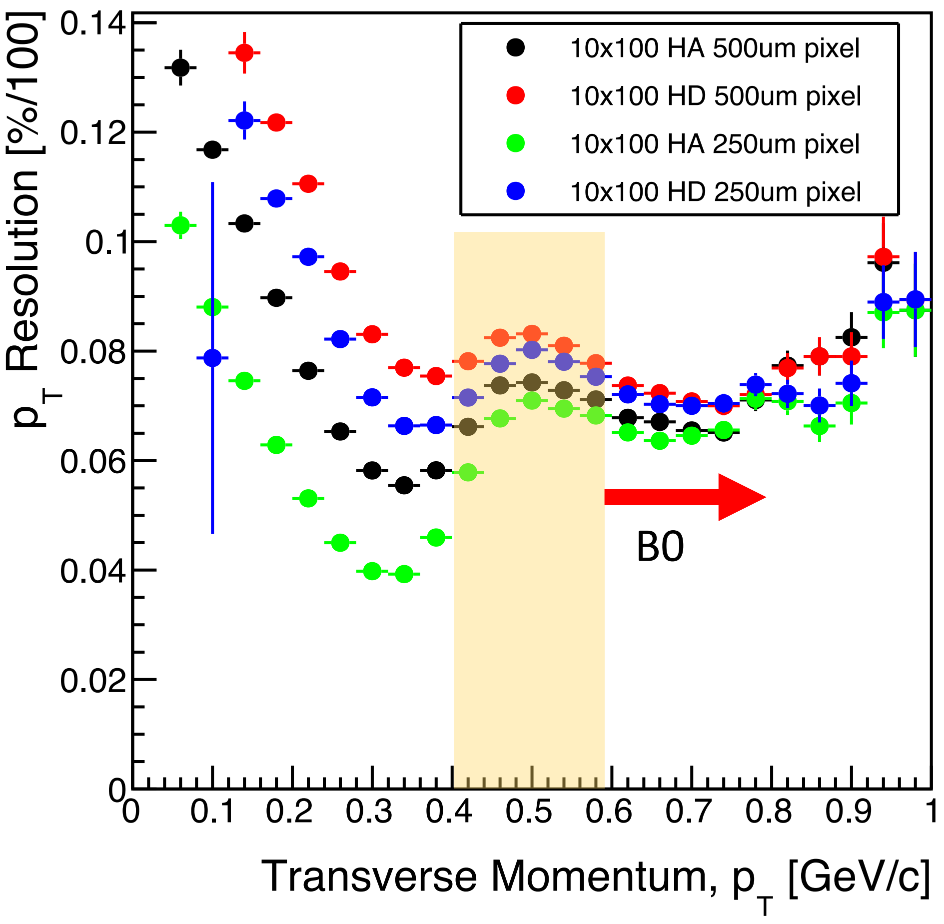
- Expected ASIC power consumption is 1-2 mW/channel – individual layers can produce ~ 100 Watts of heat.
  - B0 can use more-conventional cooling methods (e.g. air), but RP/OMD must use externally-cooled heat sinks.
- B0 and RP/OMD have different spatial constraints, in addition → further constraint on items such as FEB, etc.
  - We want to exploit common design elements as much as we possibly can.
- There is an especially large potential overlap between FTOF and B0 in terms of design, with a few things to be addressed to determine compatibility.
- RP/OMD sensor/ASIC/FEB layout approach is going to be similar to ATLAS HGTD - optimization of the sensor layout to avoid dead areas has to be synced with moving stages to surround the beam.

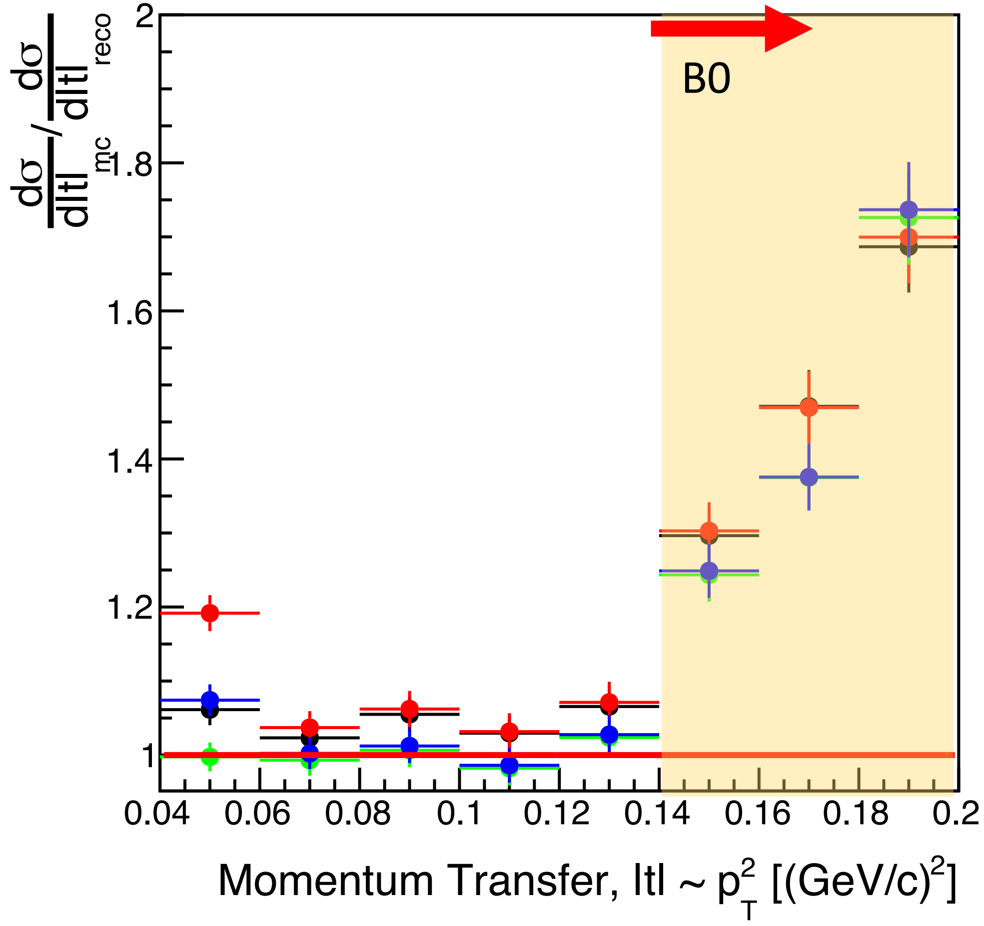
Summary

- Roman Pots (and Off-Momentum Detectors) requirements met by AC-LGADs.
  - Pixel size and timing requirement came from eRD24 studies for Roman pots and defined the present concept.
- B0 tracking performance relies entirely on charge sharing aspect of the AC-LGADs.
  - First radiation studies indicate that performance doesn't change much with doses expected at the EIC: https://indico.bnl.gov/event/23896/contributions/92852/attachments/55200/94468/110624_ePIC_irradiation_update.pdf

Backup

Detailed Momentum Resolution - 10x100 GeV

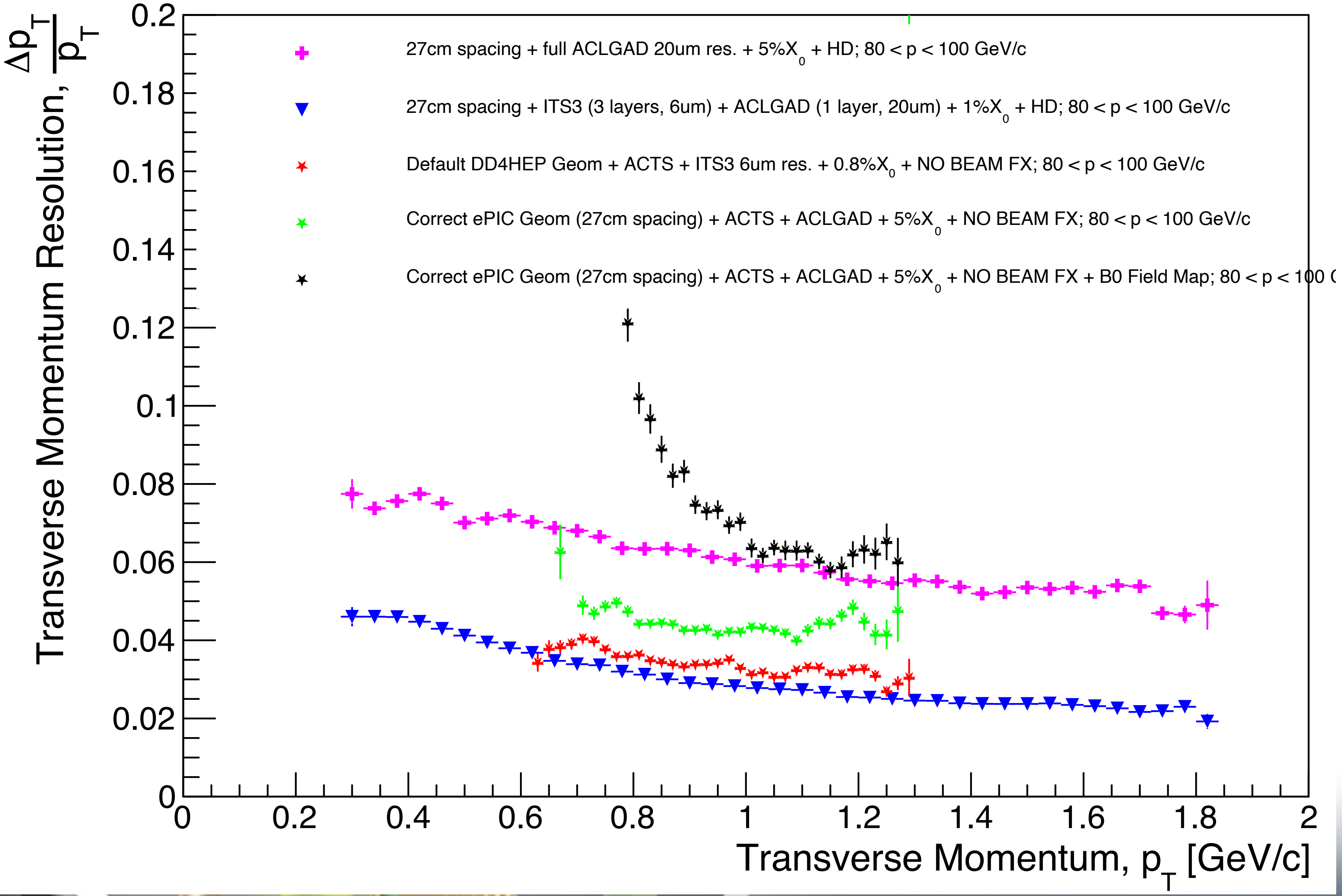




- **Yellow shaded area** is the acceptance gap between the RP and B0 detectors.
- No acceptance correction is applied here.

- Zoom-in to relevant RP range.
- Since angular divergence is smaller in the 100 GeV beam, the spatial resolution has a larger impact.

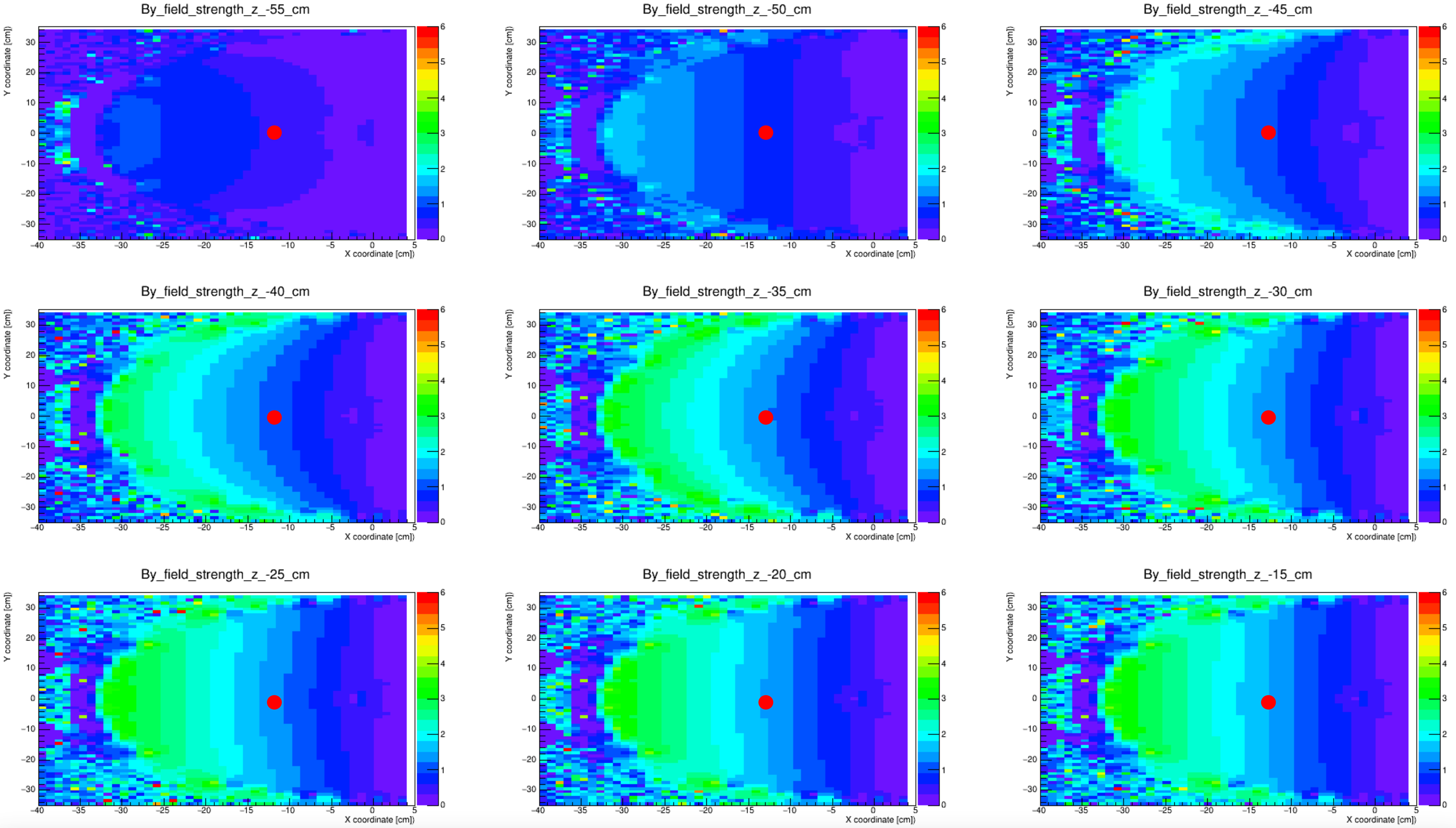
B0 Tracking - Performance



- Black: tracker shifted away from IP by 10cm.
- Assume 6 to 13 mrad cone of 80 to 100 GeV protons.

B0 Field Map

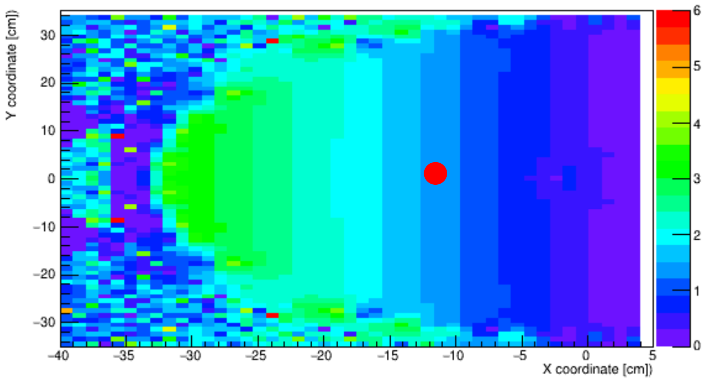
Left to right, top to bottom – increasing Z (IP to center of magnet)



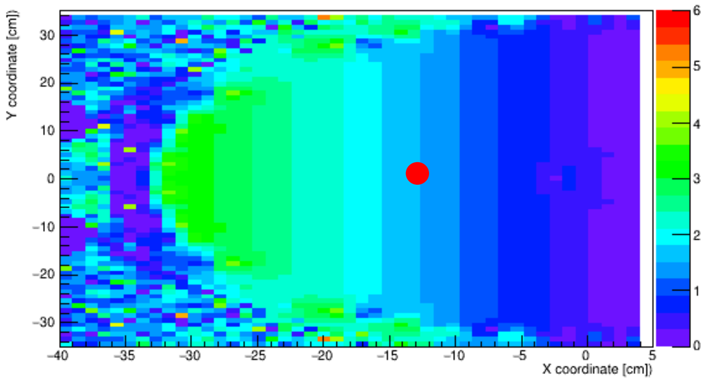
B0 Field Map

Left to right, top to bottom – increasing Z (IP to center of magnet)

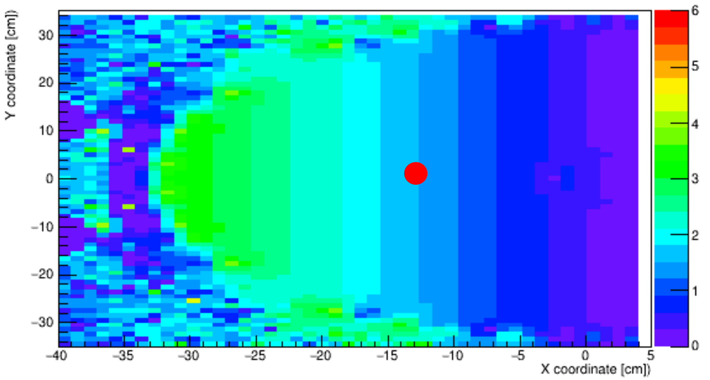
By_field_strength_z_-10_cm



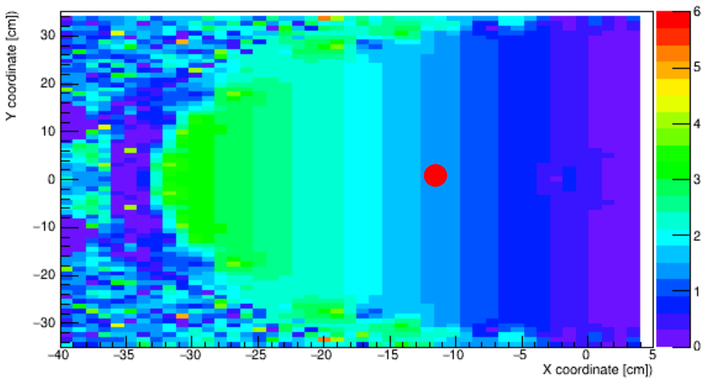
By_field_strength_z_-5_cm



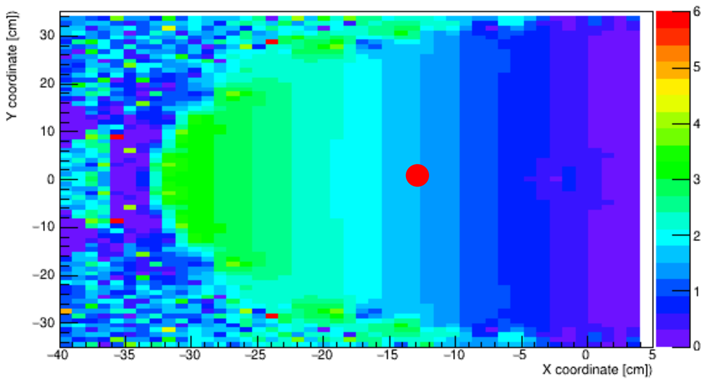
By_field_strength_z_0_cm



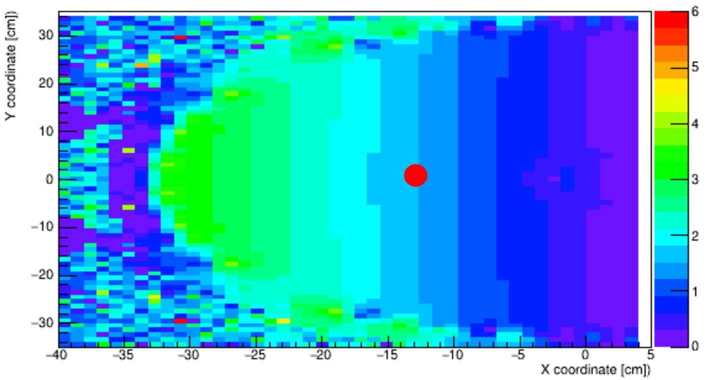
By_field_strength_z_5_cm



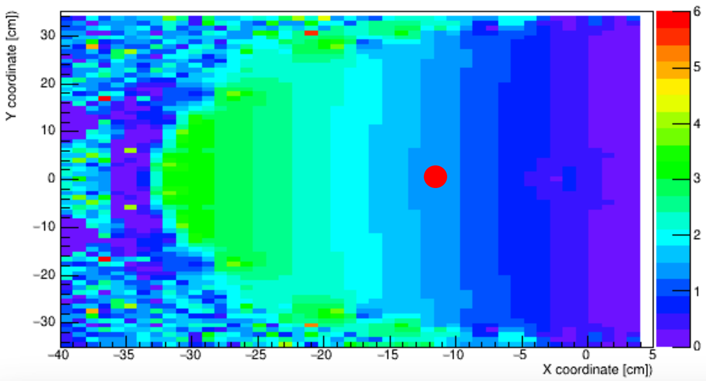
By_field_strength_z_10_cm



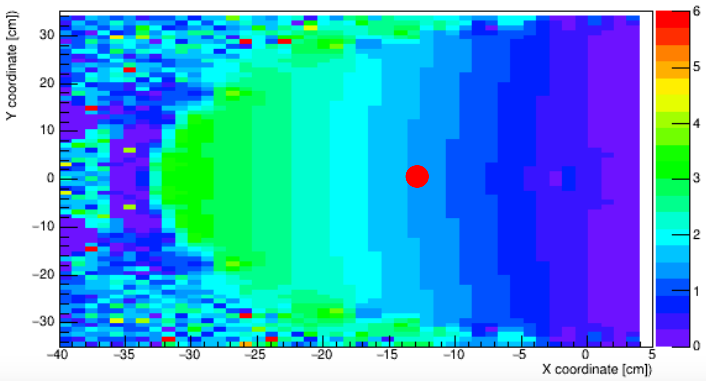
By_field_strength_z_15_cm



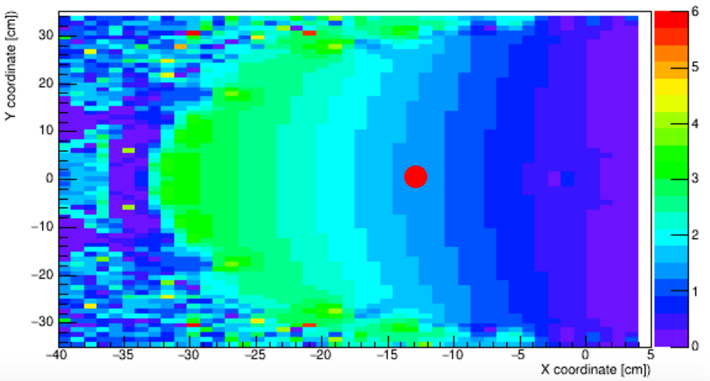
By_field_strength_z_20_cm



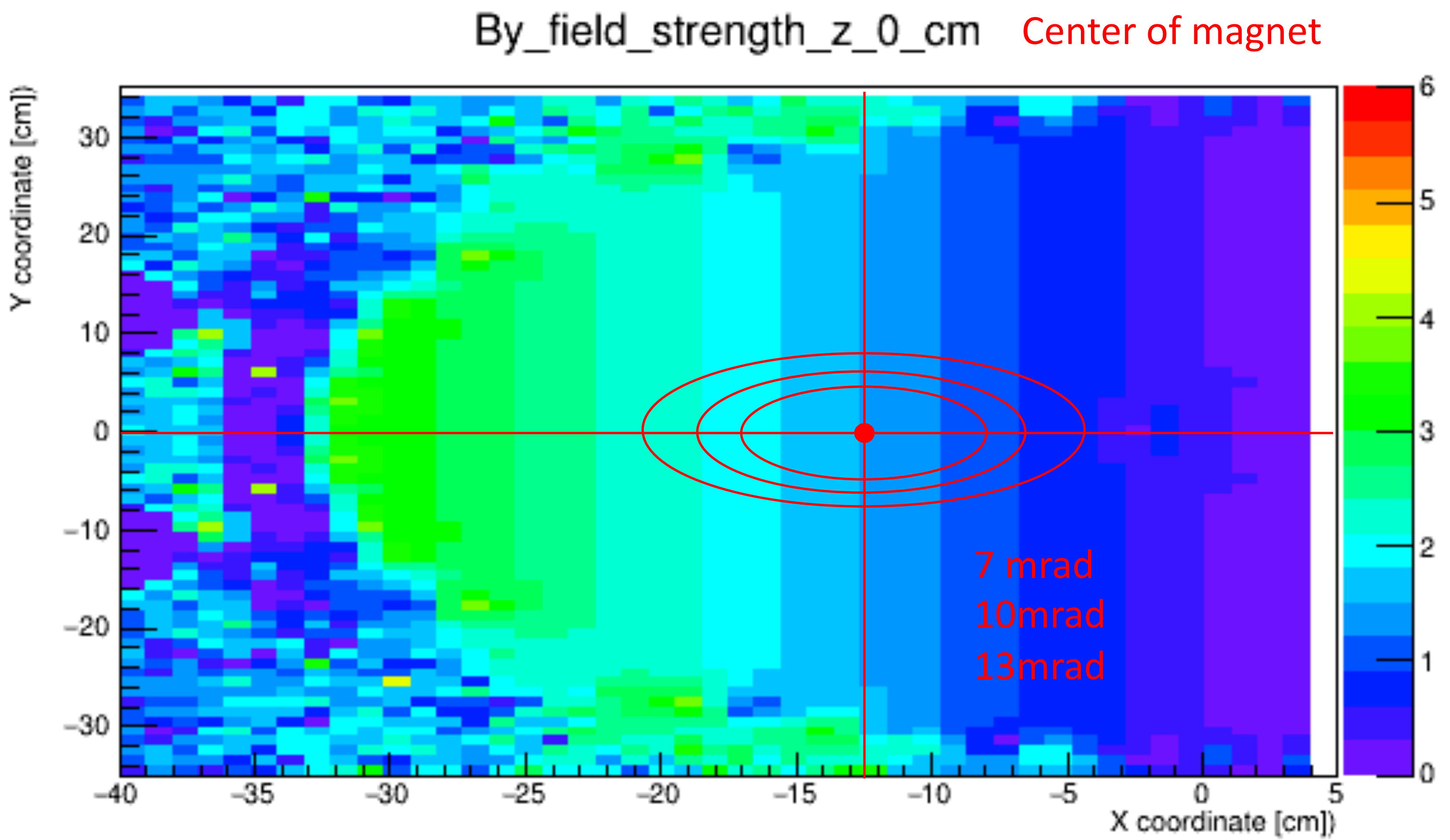
By_field_strength_z_25_cm



By_field_strength_z_30_cm



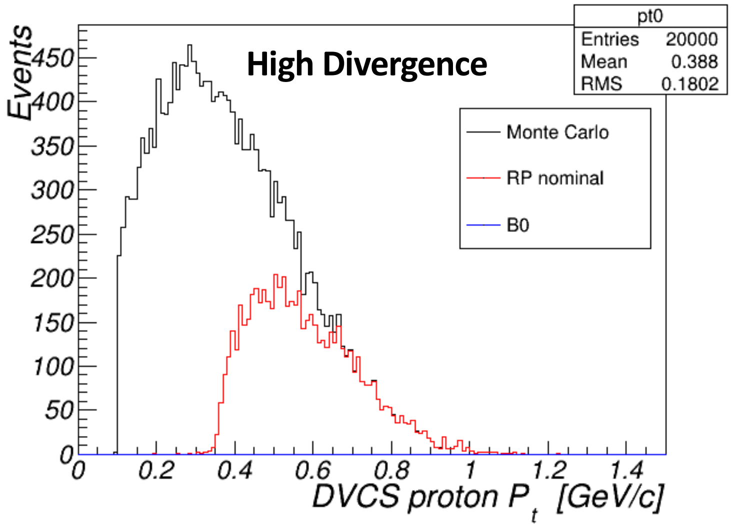
B0 Field Map

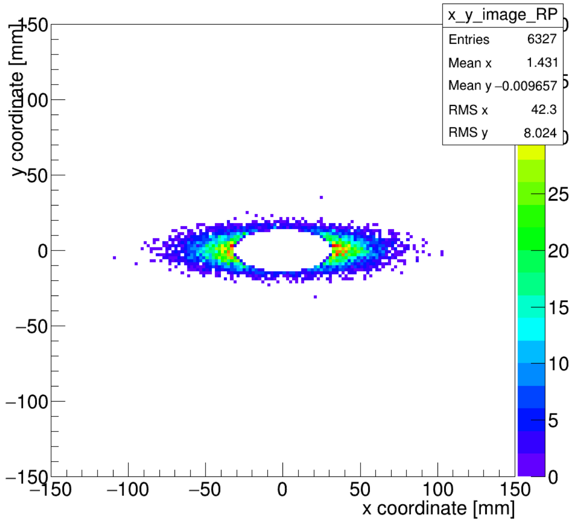


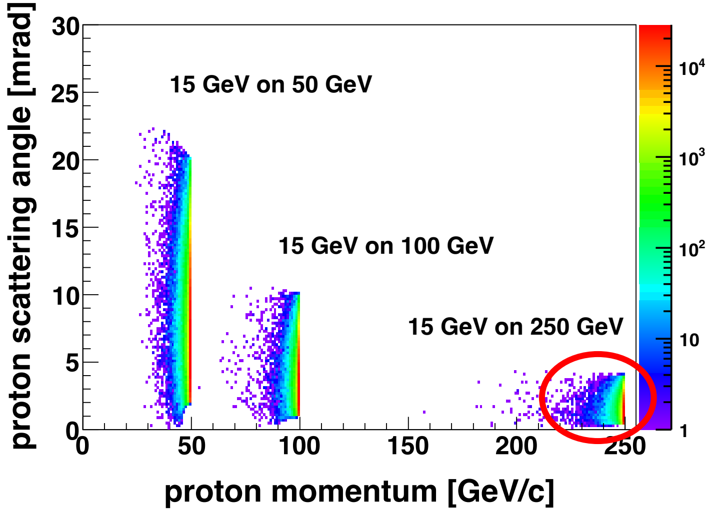
- Field seen by protons is pT/angle dependent – will add an additional smearing dependence on position within the magnetic field.

Digression: Machine Optics

275 GeV DVCS Proton Acceptance





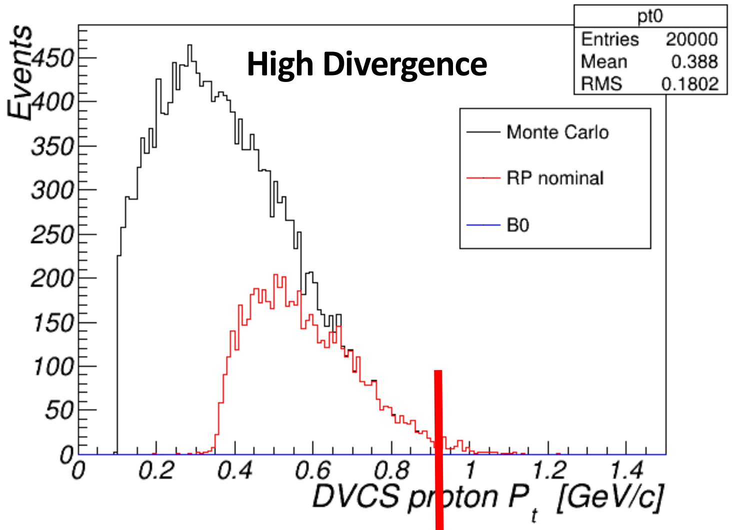


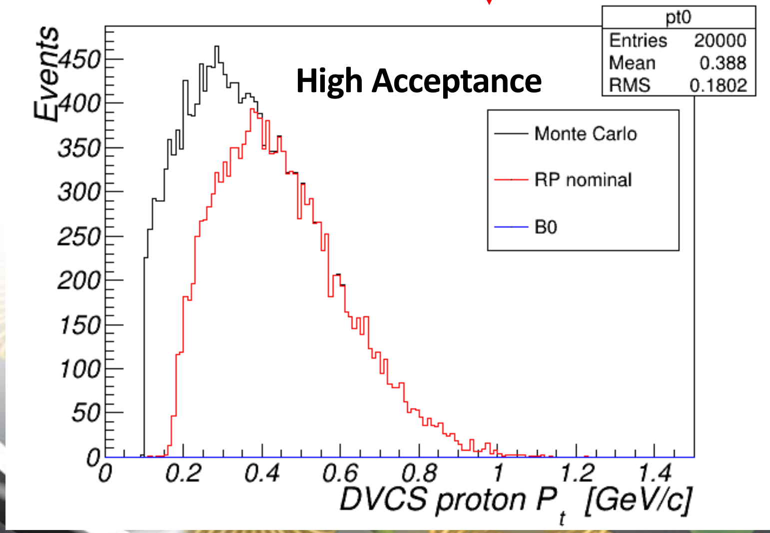
High Divergence: smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

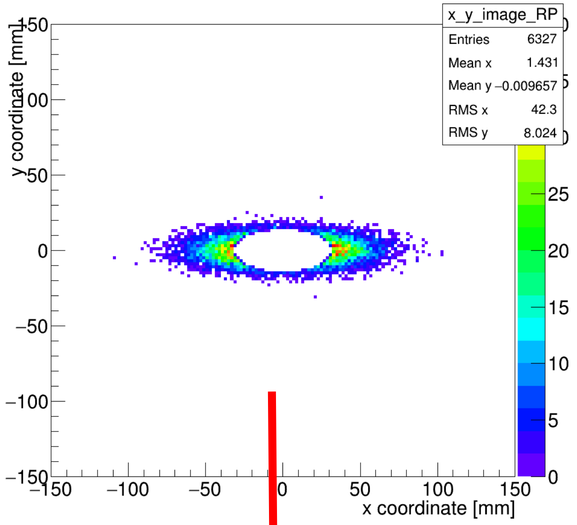
Digression: Machine Optics

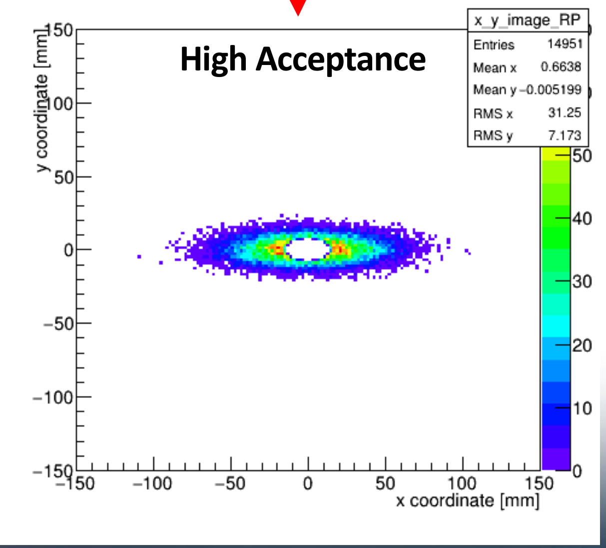
eRD24 Studies - 2020

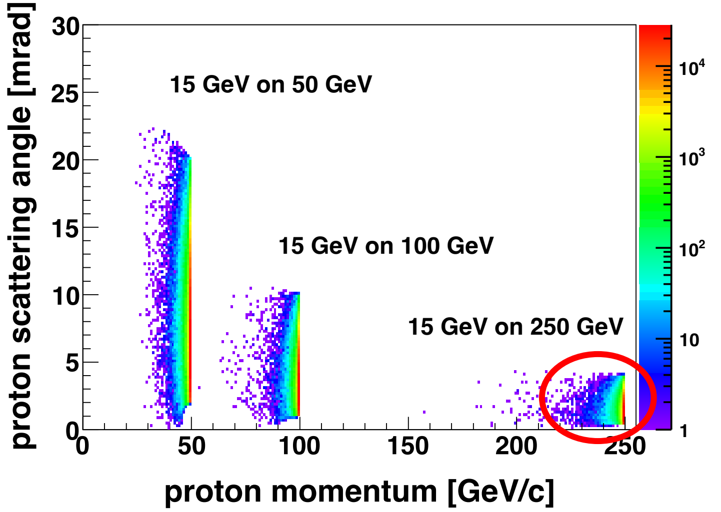
275 GeV DVCS Proton Acceptance









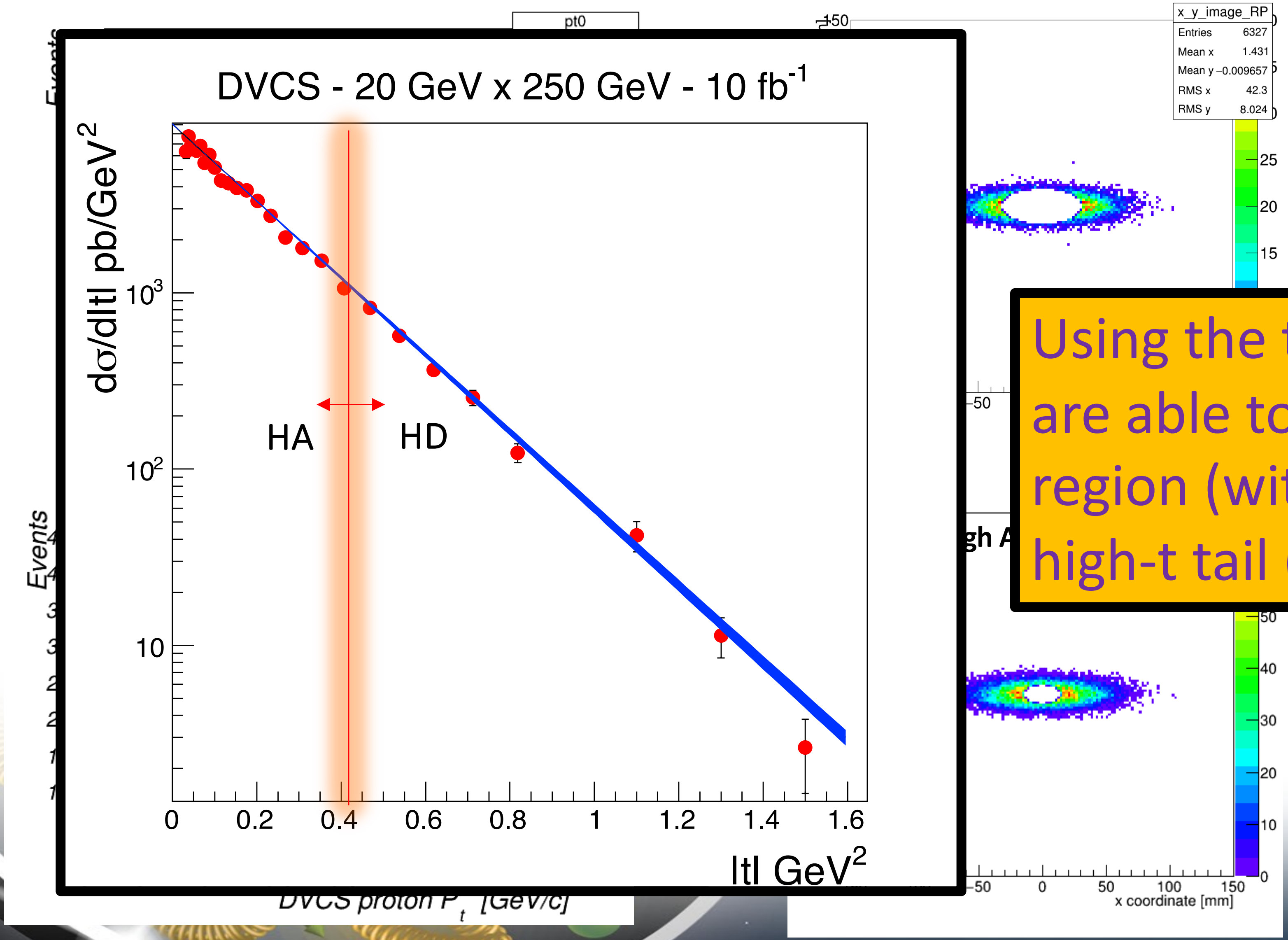


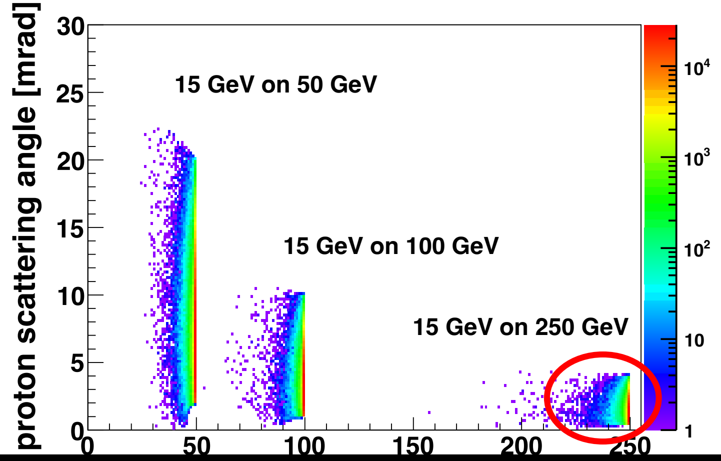
High Divergence: smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

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