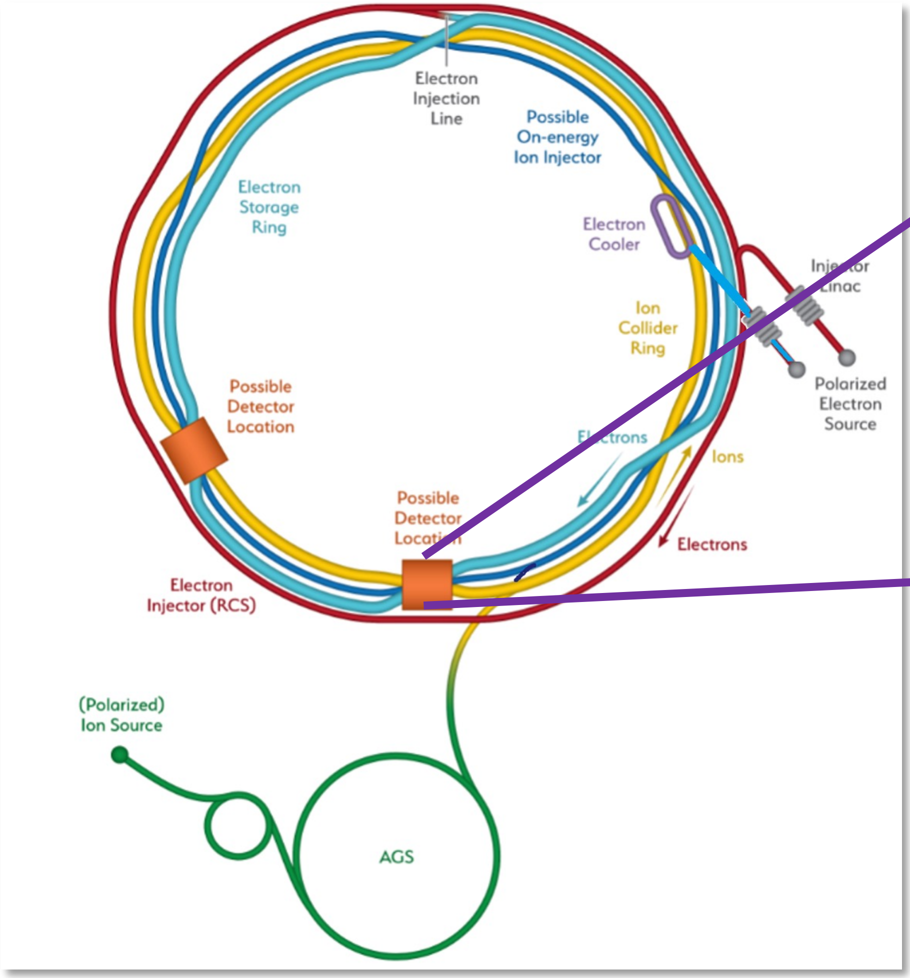
Far-Forward Detectors at the Electron-Ion Collider

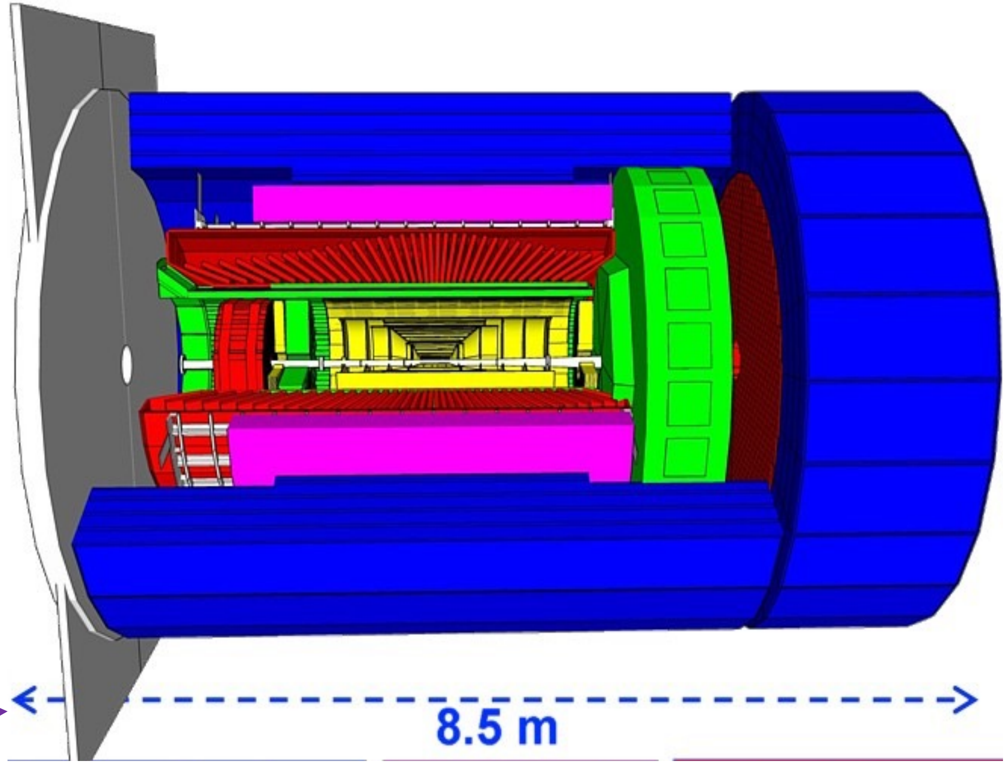
Michael Murray, Forward QCD

KU
THE UNIVERSITY OF

The Electron-Ion Collider (EIC)

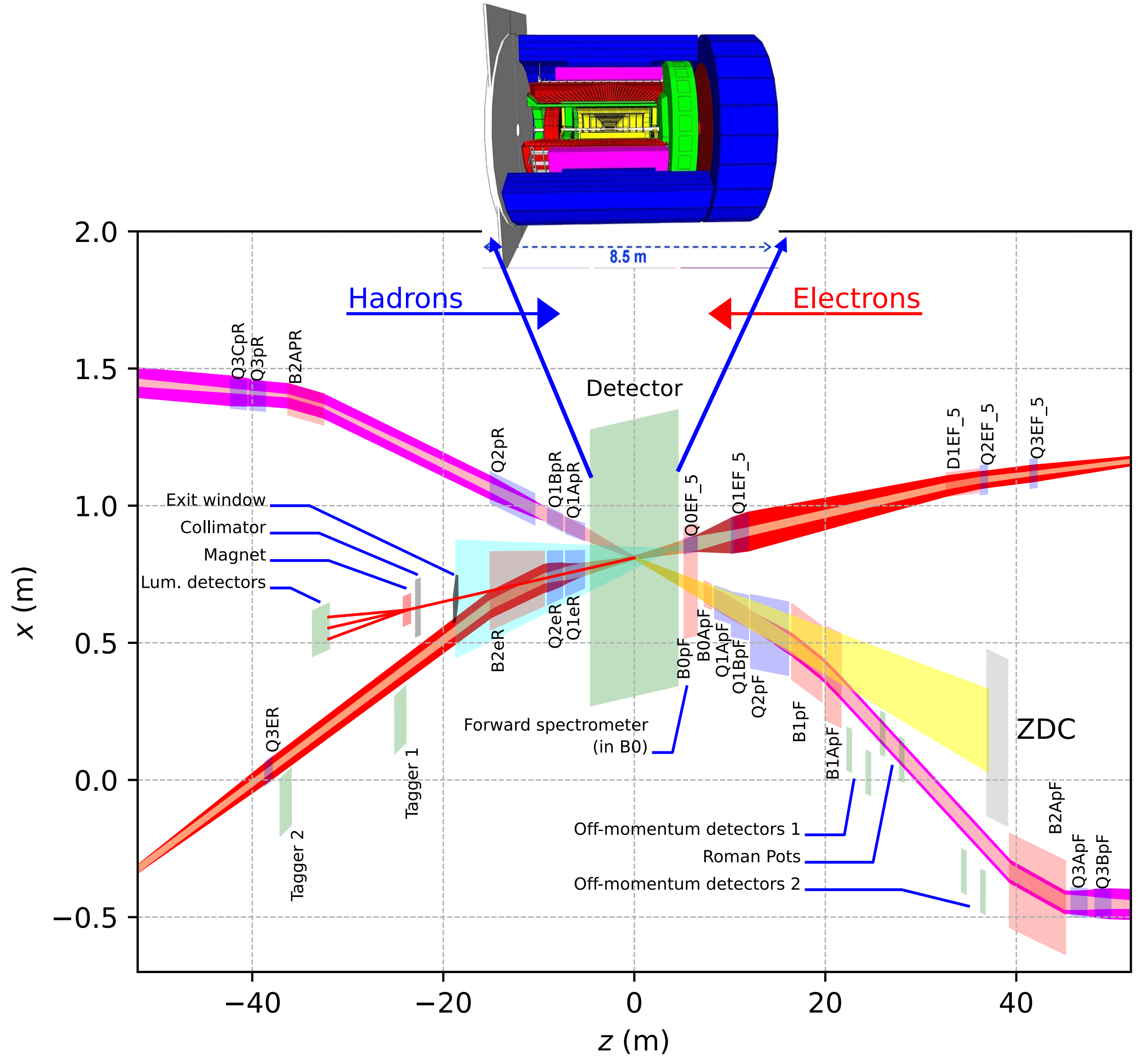
- Two interaction regions (IRs) for possible detector locations.
- Only one, IP6, in DOE project scope.





- ➢ Reference detector based on the 1.5T BaBar solenoid and ECCE reference design.
- ➢ Contains detectors for tracking, PID, and calorimetry.

The Electron-Ion Collider (EIC)



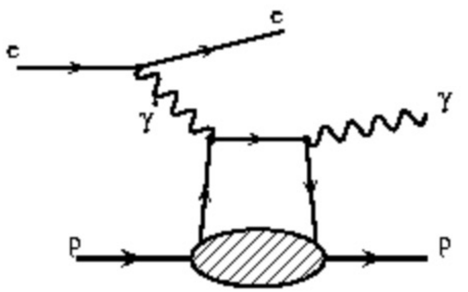
- In addition to the central detector → detectors integrated into the beamline on both the hadron-going (**far-forward**) and electron-going (**far-backward**) direction.

Detectors have to be very tightly integrated with machine. The large crossing angle and short bunch crossing time cause many challenges.

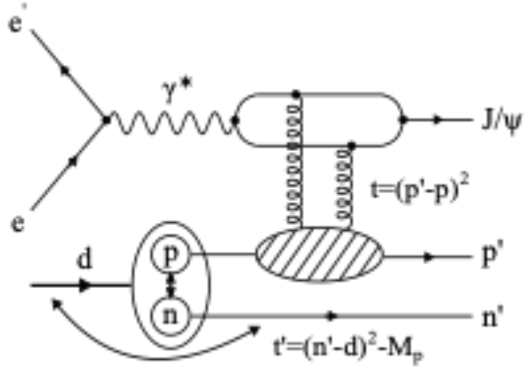
Great Fun

Far-Forward Physics at the EIC

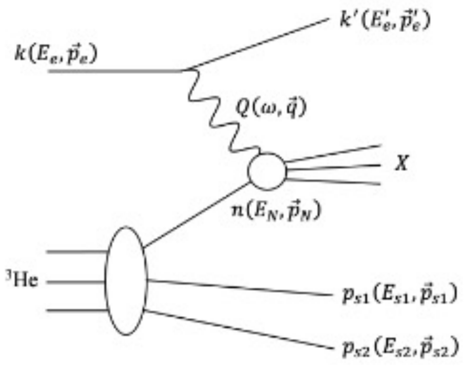
e+p DVCS



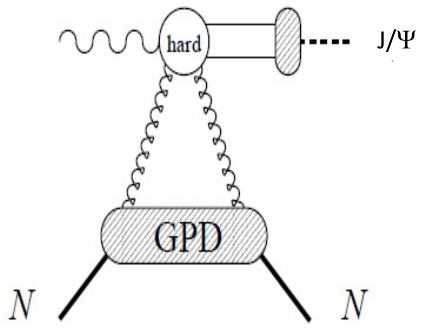
e+d exclusive J/Psi with p/n tagging



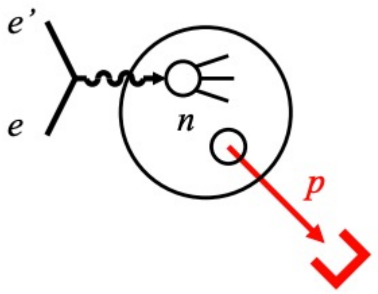
e+He3 spectator tagging



coherent/incoherent J/ψ production in e+A

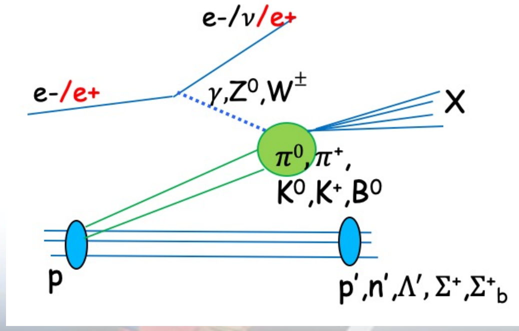


e+d DIS spectator tagging

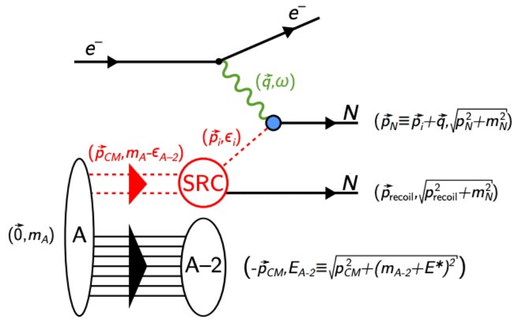


Meson structure:

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

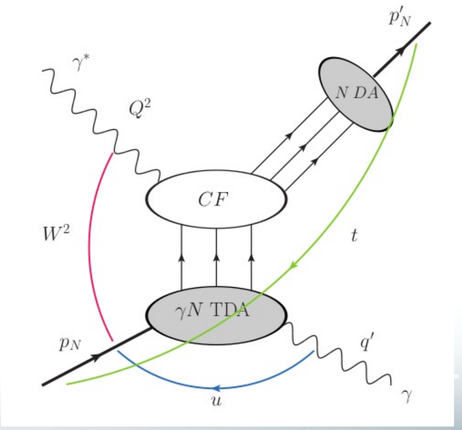


Quasi-elastic electron scattering



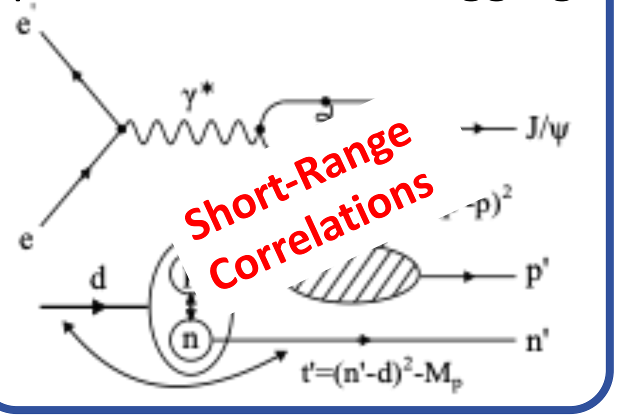
…and MANY more!

u-channel backward exclusive electroproduction

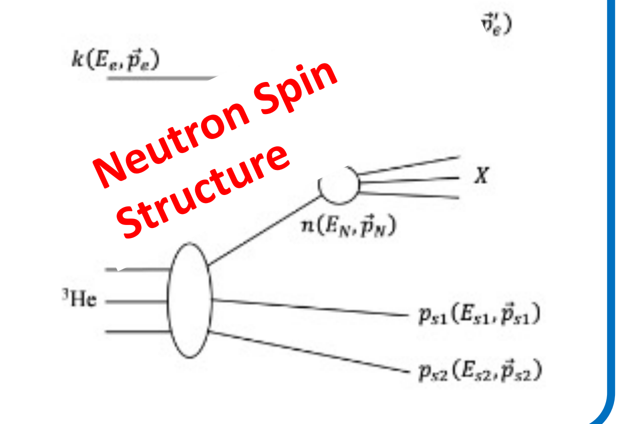


Far-Forward Physics at the EIC

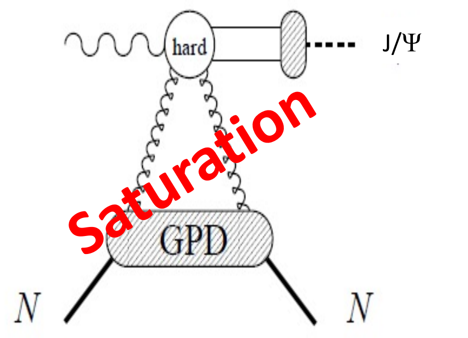
e+d exclusive J/Psi with proton or neutron tagging[1]



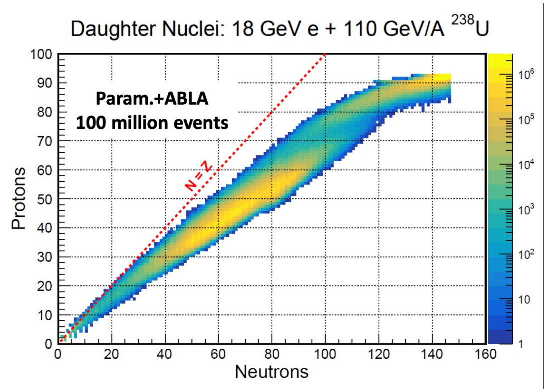
e+He3 spectator tagging[2]



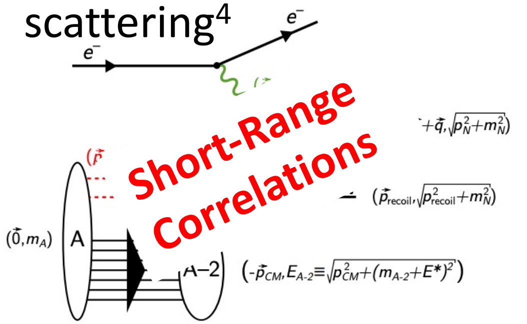
coherent/incoherent J/ψ production in e+A[3]



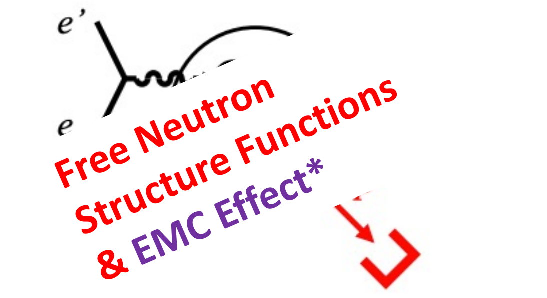
Rare isotopes**



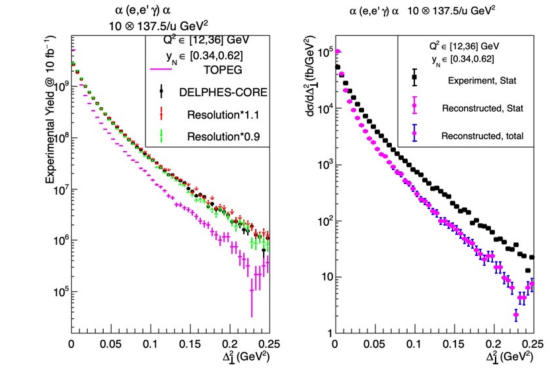
Quasi-elastic electron scattering[4]



e+d DIS spectator tagging[5]



e+He4 DVCS***



[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)

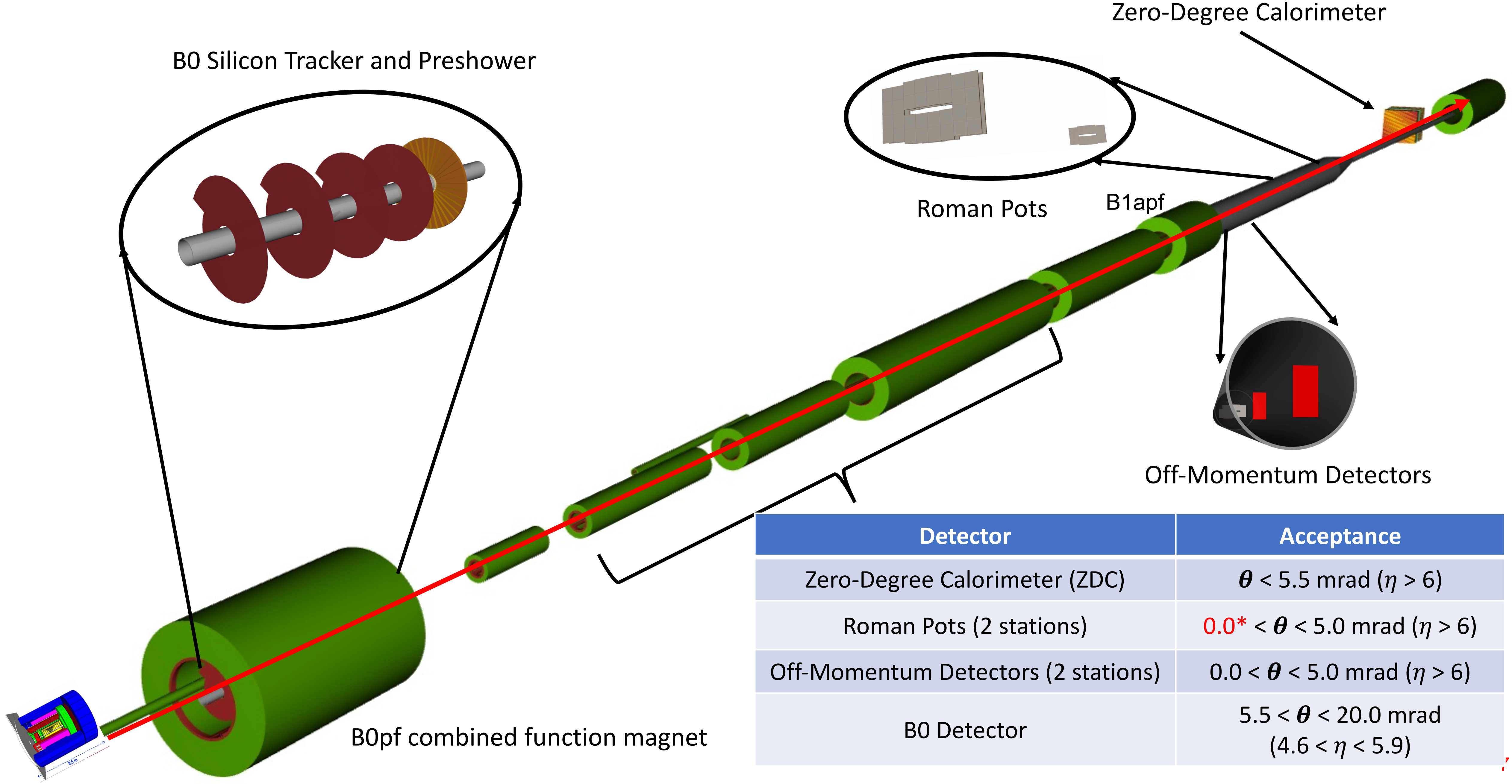
[4] F. Hauenstein, AJ, J. R. Pybus, A. Kiral, M. D. Baker, Y. Furletova, O. Hen, D. W. Higinbotham, C. Hyde, V. Morozov, D. Romanov, and L. B. Weinstein, Phys. Rev. C **105**, 034001 (2022)

[5] AJ, Z. Tu, and C. Weiss, Phys. Rev. C **104,** 065205 (2021) **(Editor's Suggestion)**

Far-Forward Physics at the EIC

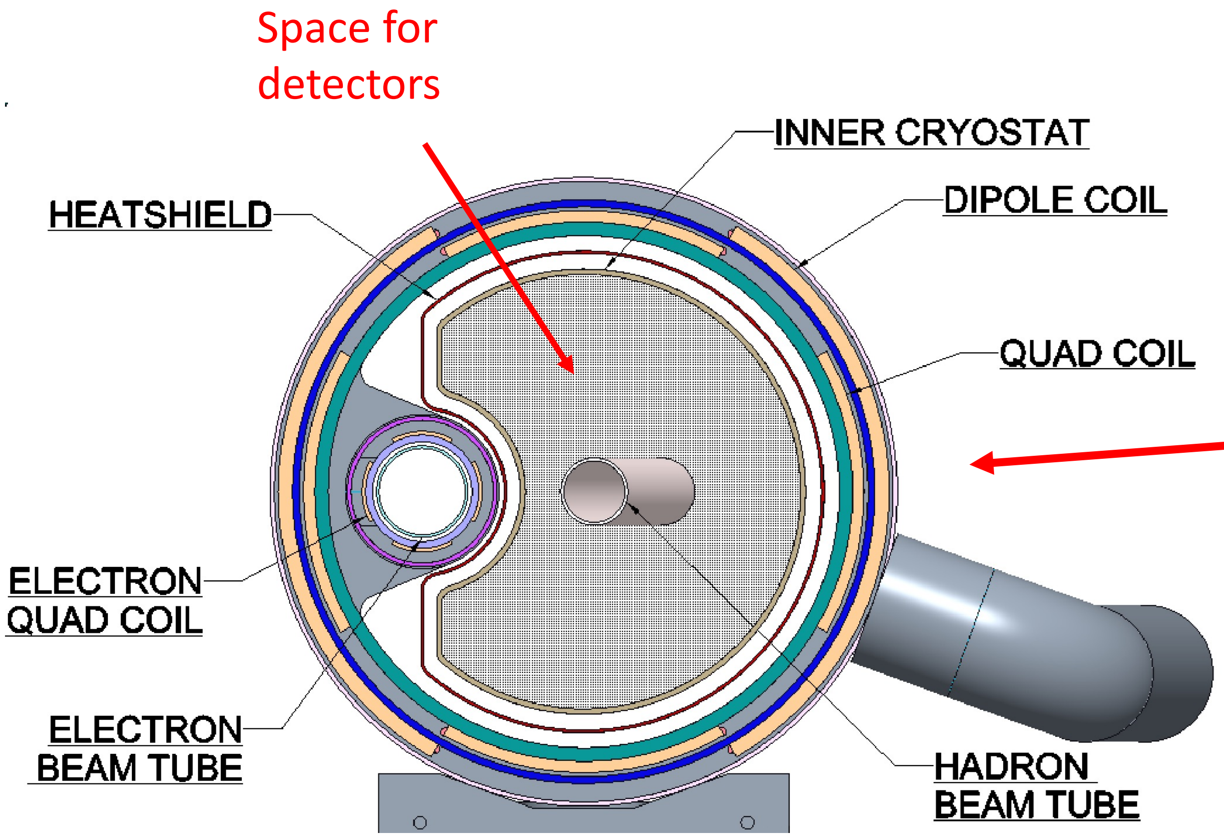
- Physics channels require tagging of **charged hadrons** (protons, pions) or **neutral particles** (neutrons, photons) at **very-forward rapidities ($\eta > 4.5$).**
- Different final states $\longrightarrow$ tailored detector subsystems.
- Various collision systems and energies (h: 41, 100-275 GeV,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

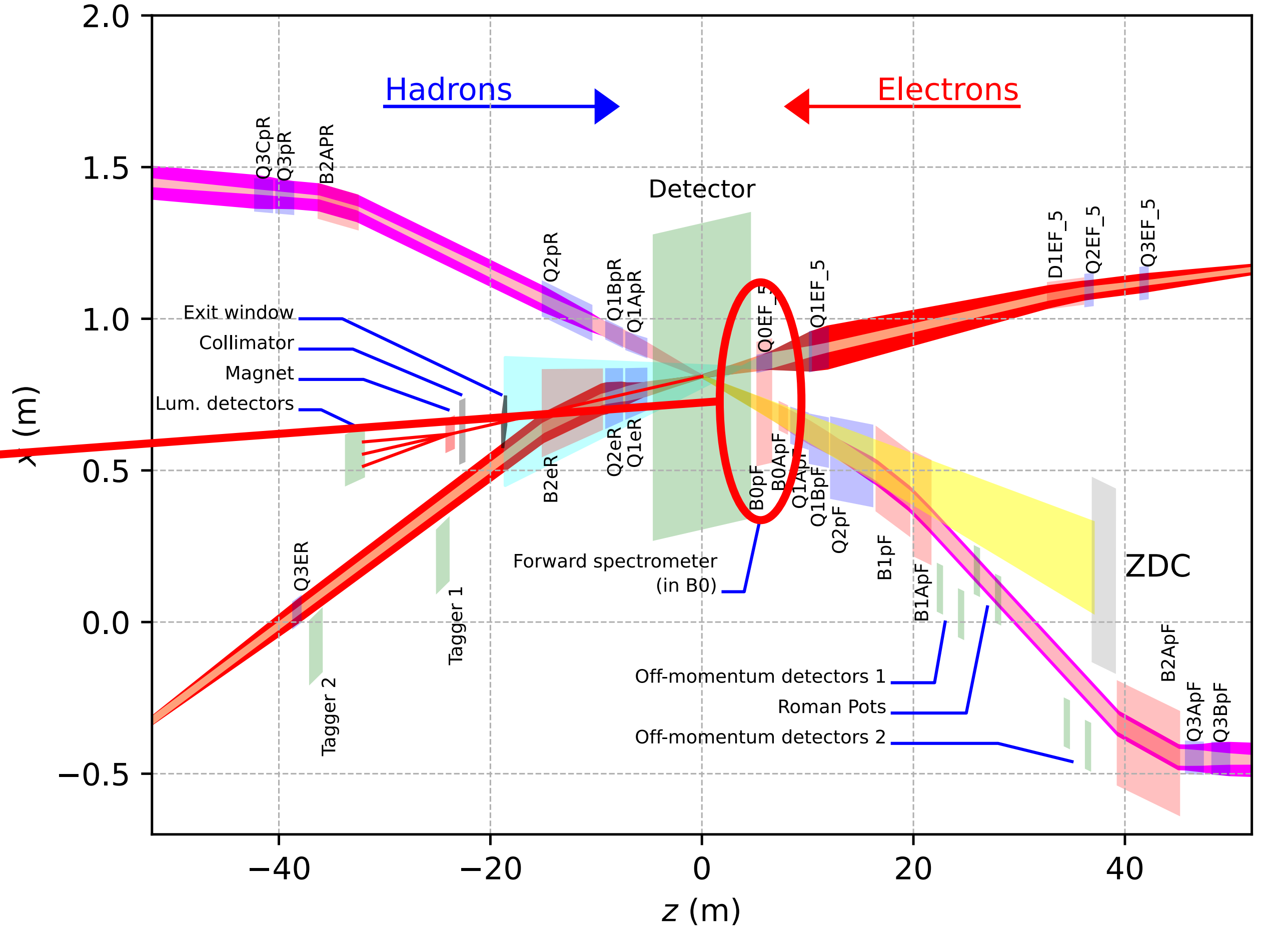
The Far-Forward Detectors



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

B0 Detectors

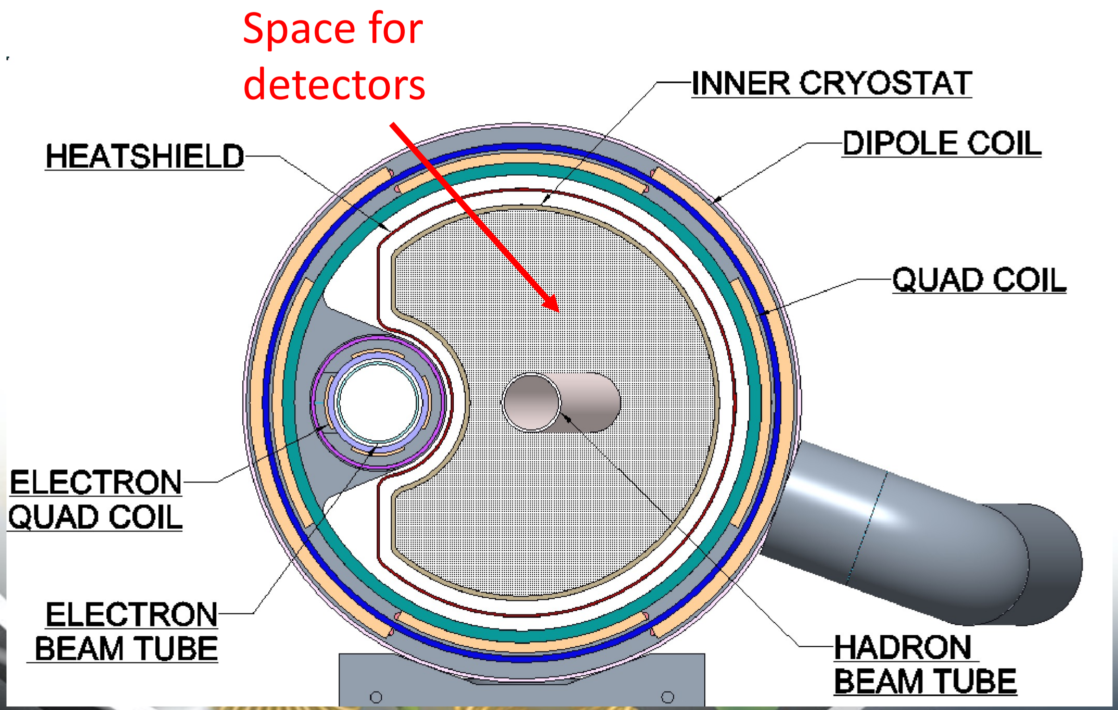


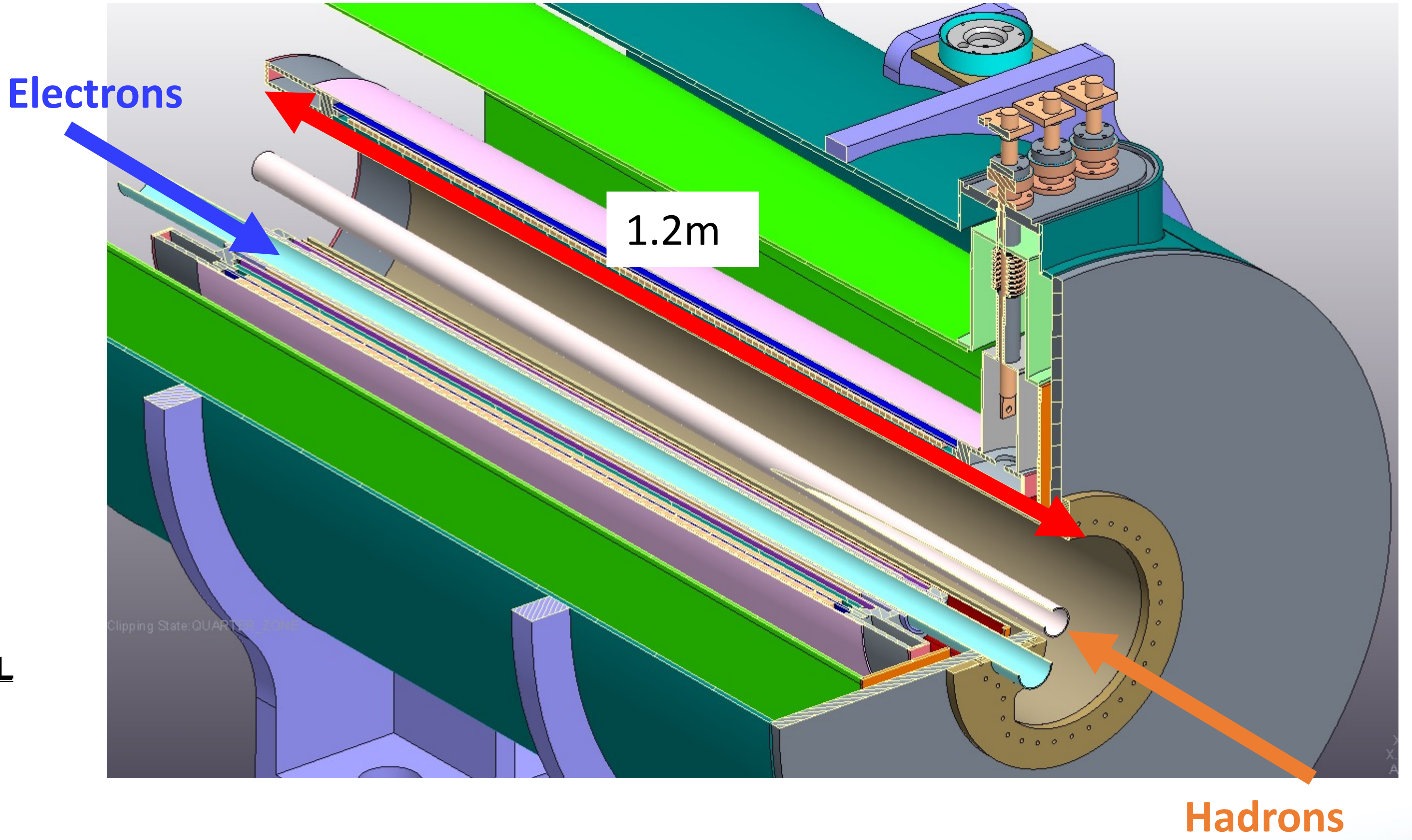


B0 Detectors

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

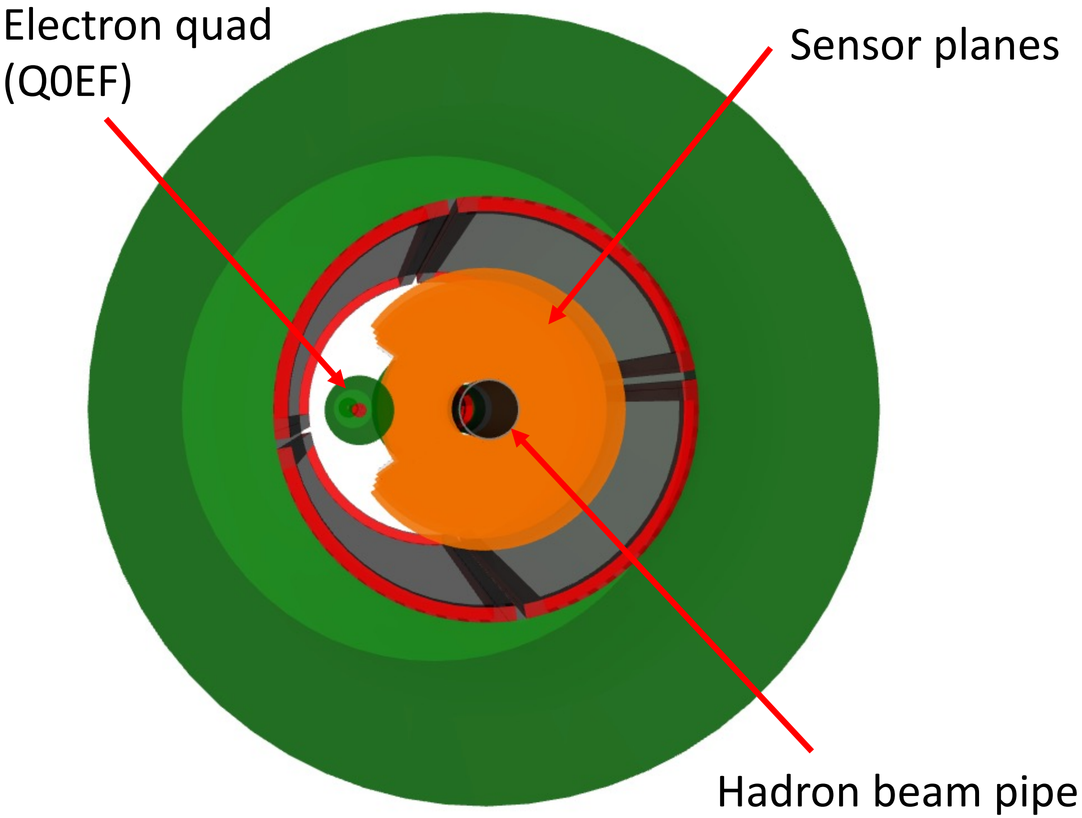
- Charged particle reconstruction and photon tagging.
- Precise tracking (~10um spatial resolution).
- Fast timing for background rejection and to remove crab smearing (~35ps).
- Photon detection (tagging or full reco).



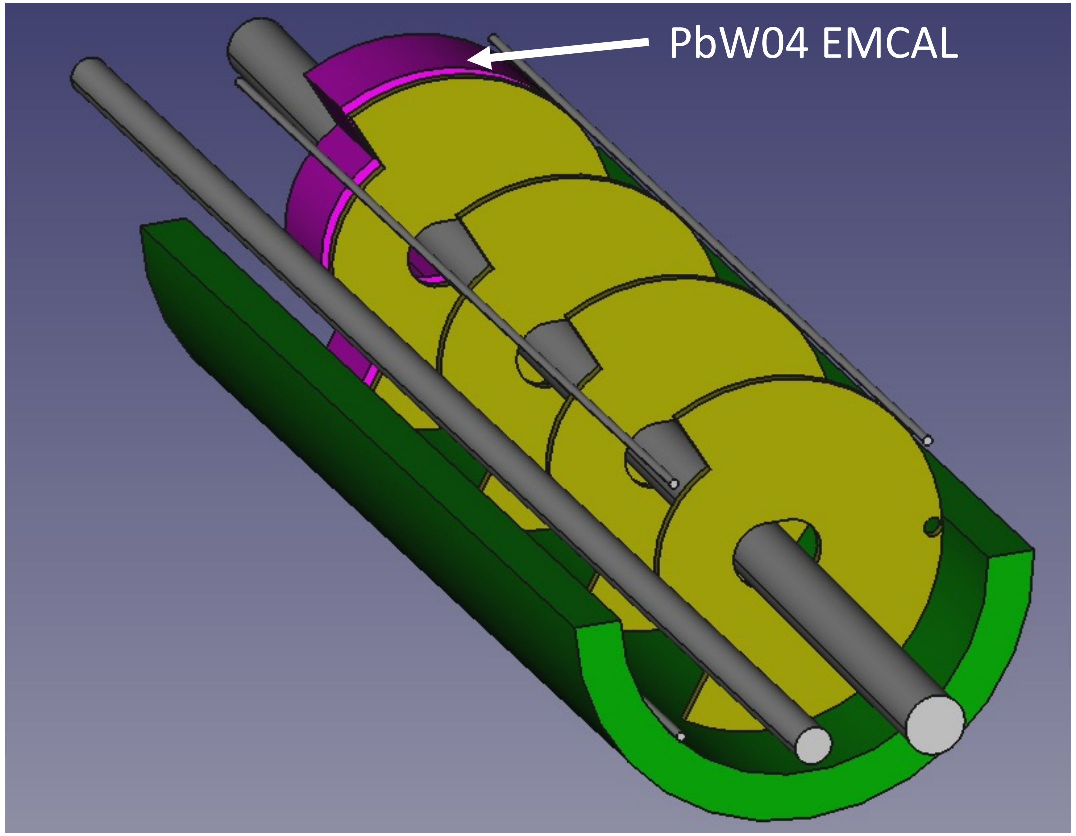


B0 Detectors

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

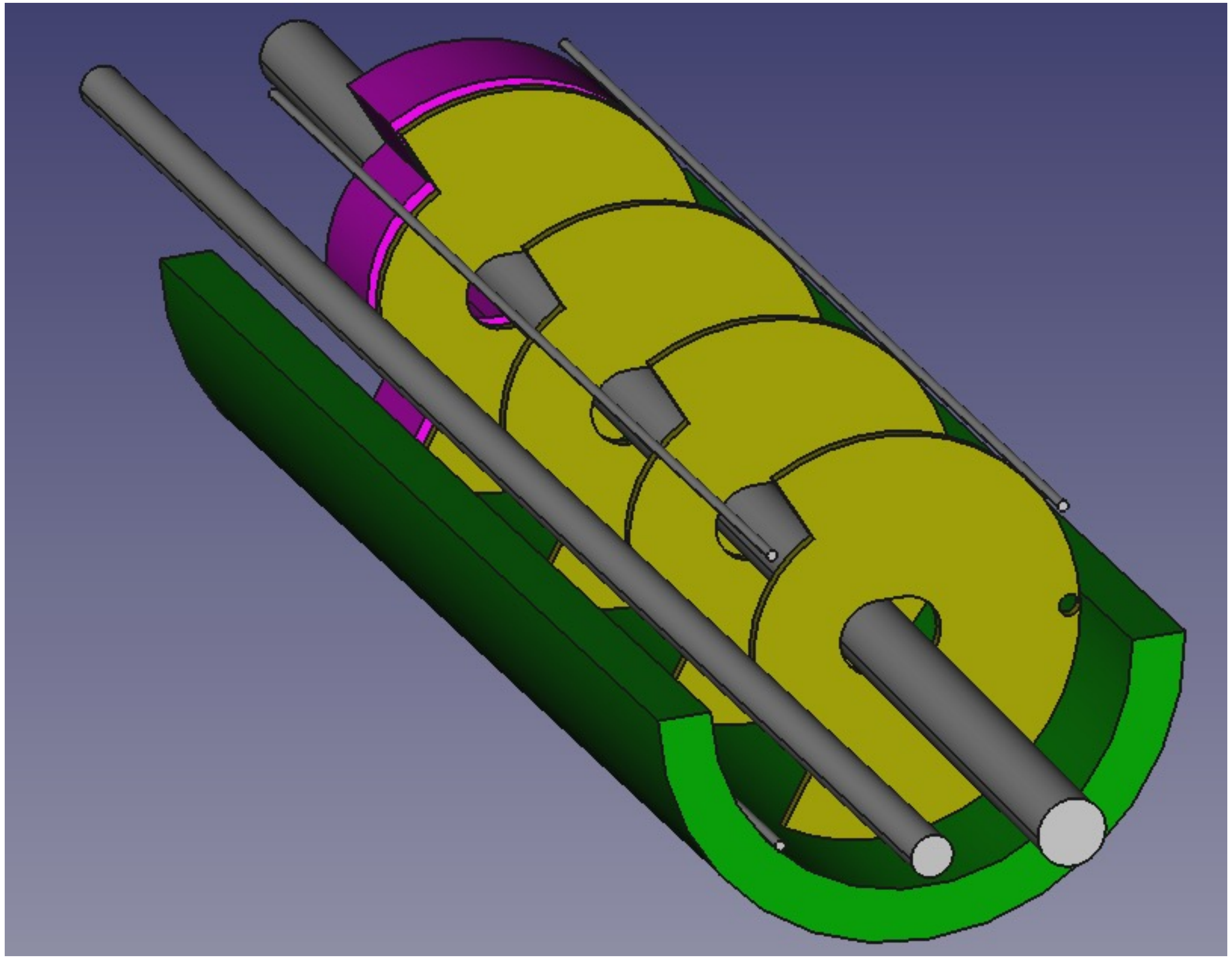


DD4HEP Simulation



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

B0-detectors (calorimetry)

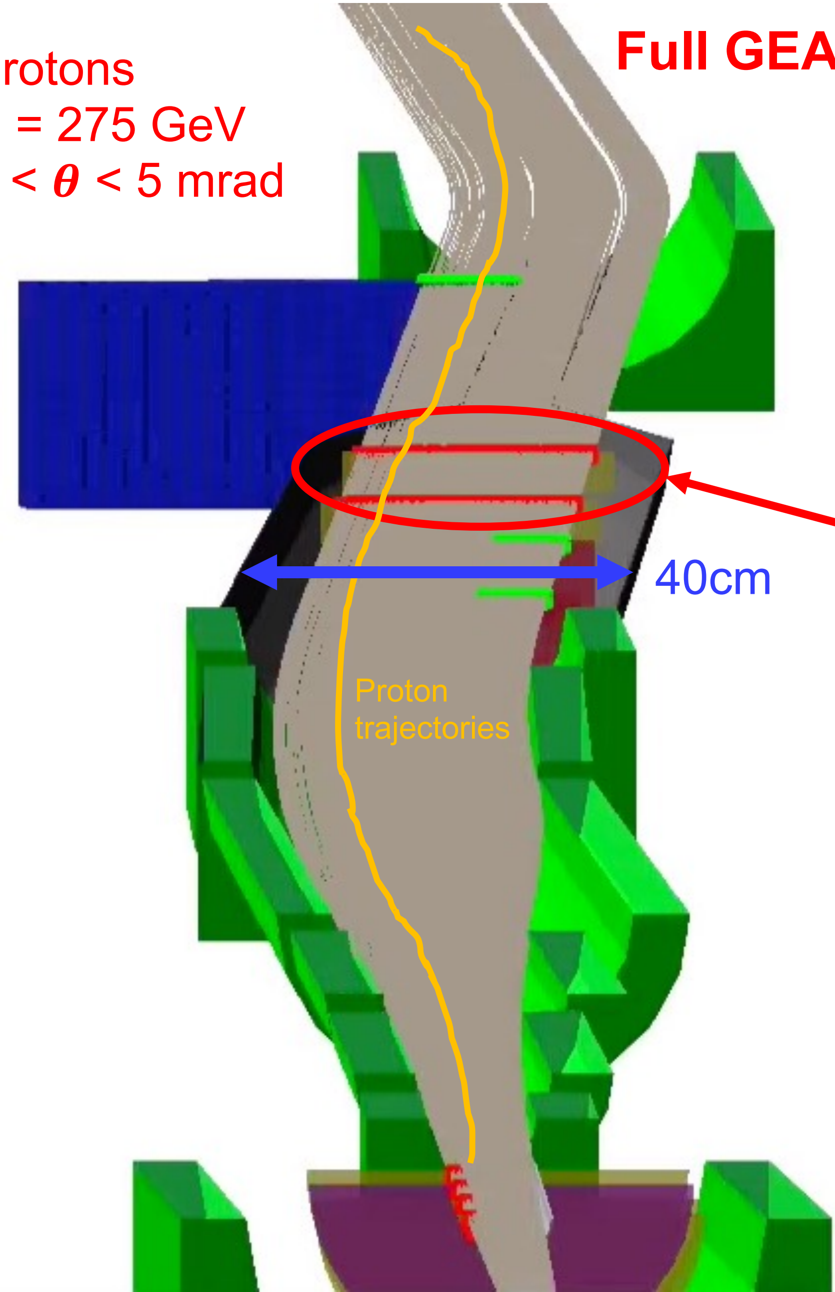


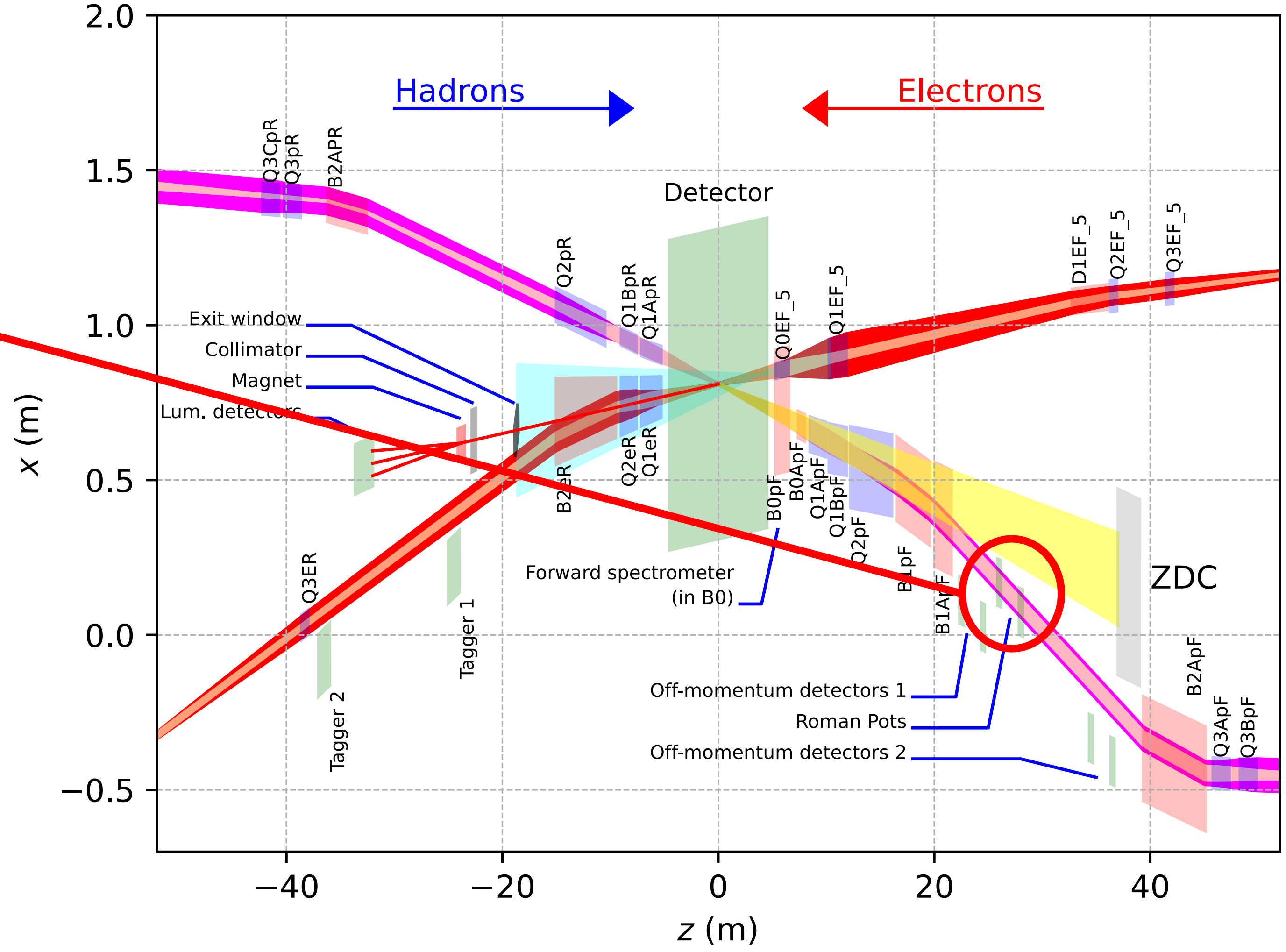
- For studies of *u*-Channel (Backward-angle) exclusive electroproduction, need capability to reconstruct photons from π^0 decays.
  - Physics beyond the EIC white paper!
- Would require full EMCAL with high granularity and energy resolution.
  - ➢ PbWO4 used in ECCE studies.
- Longitudinal space in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

Roman Pots @ the EIC

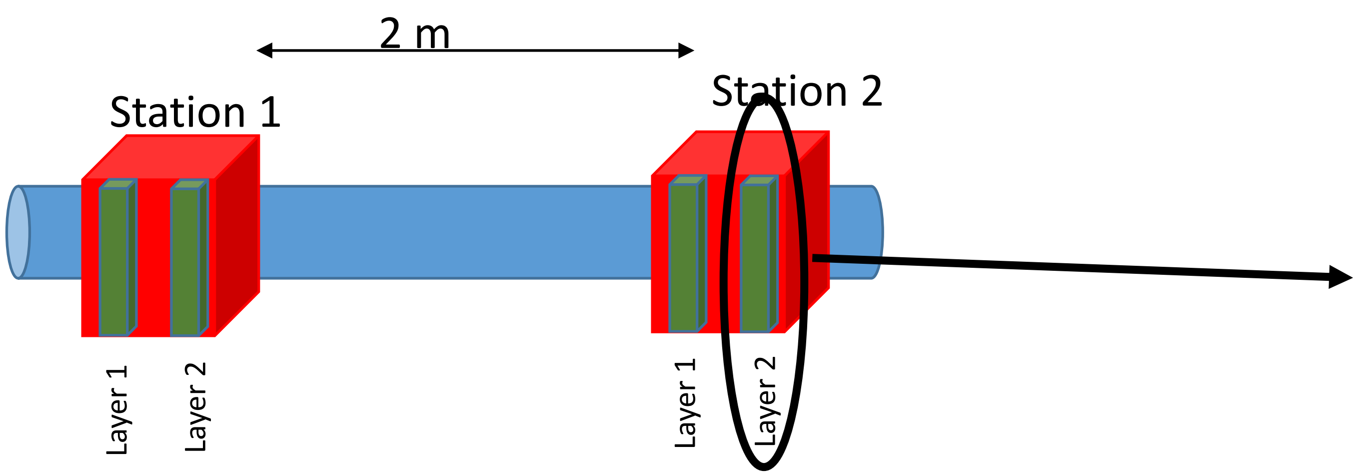
Protons
E = 275 GeV
$0 < \theta < 5$ mrad

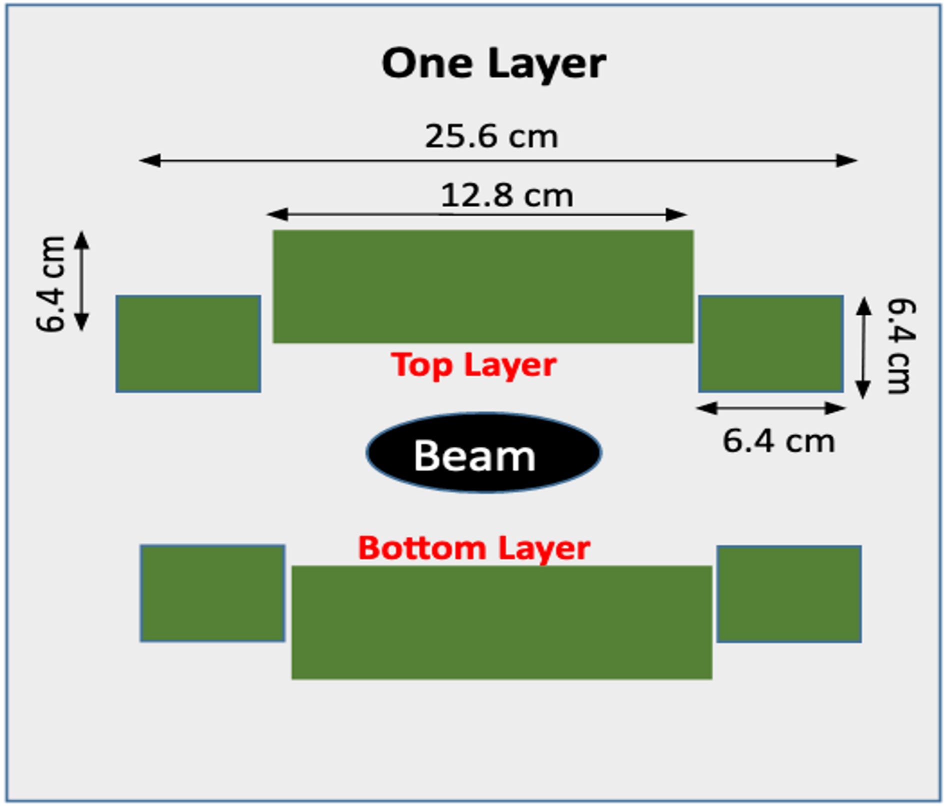
Full GEANT4 simulation.

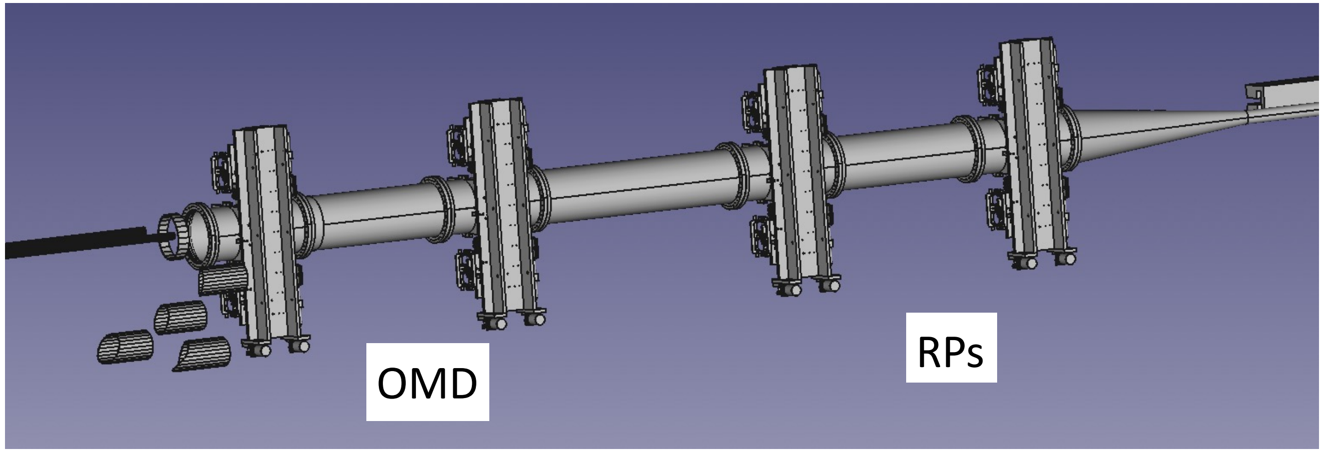




Roman "Pots" @ the EIC

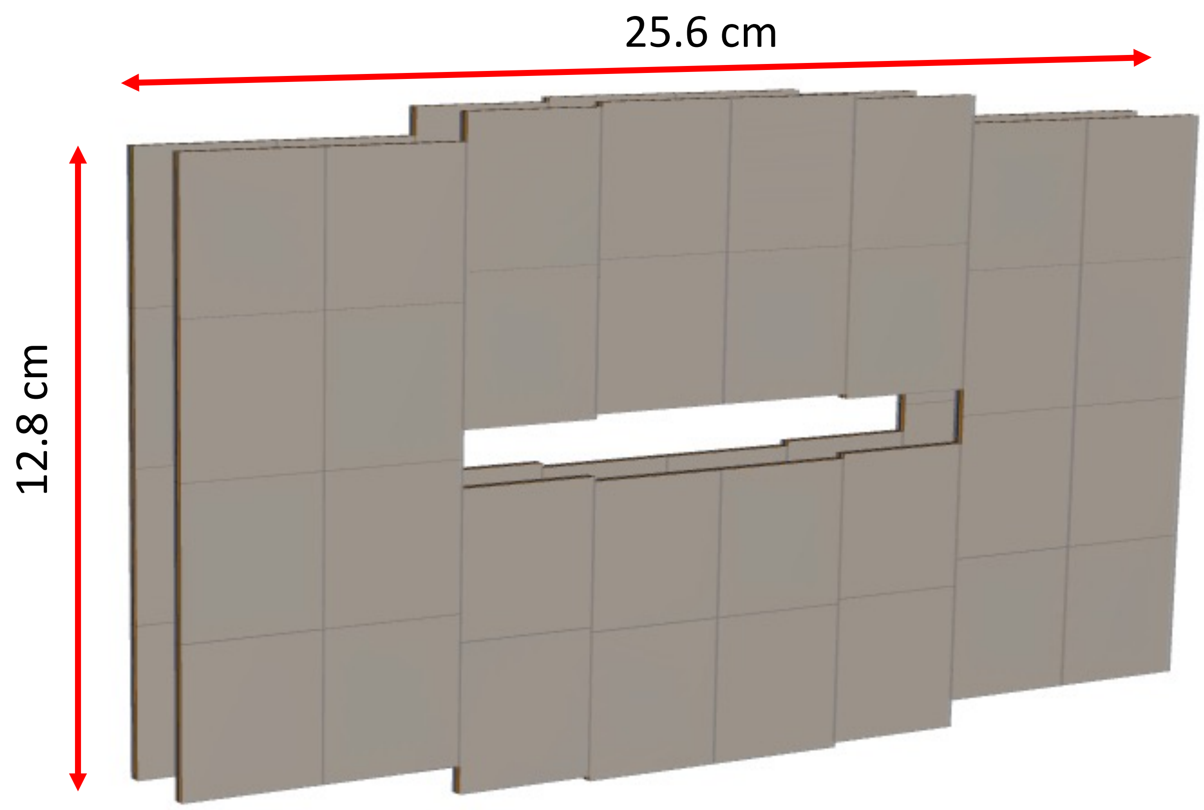




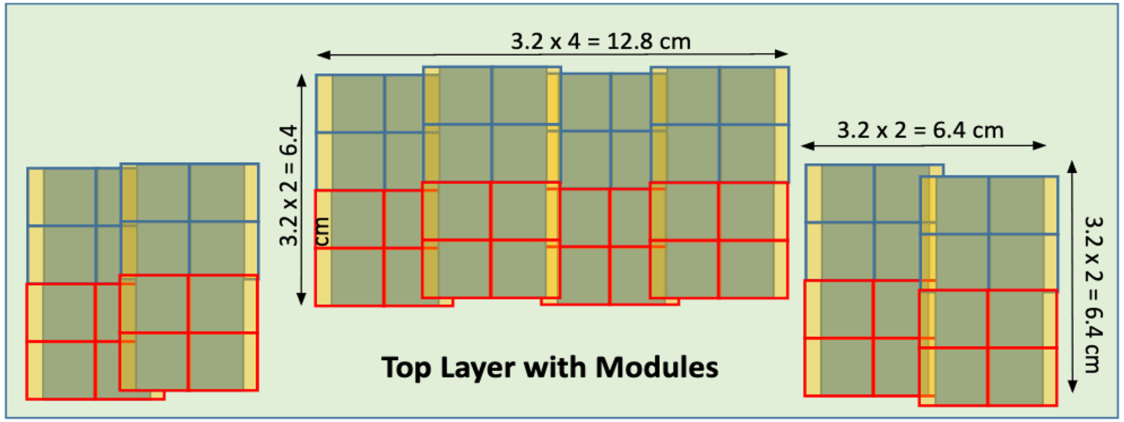


- Putting silicondirectly into machine vacuum maximizes geometric coverage
- Need space for detector insertion tooling and support structure.
- Cooling is vital

Roman “Pots” @ the EIC

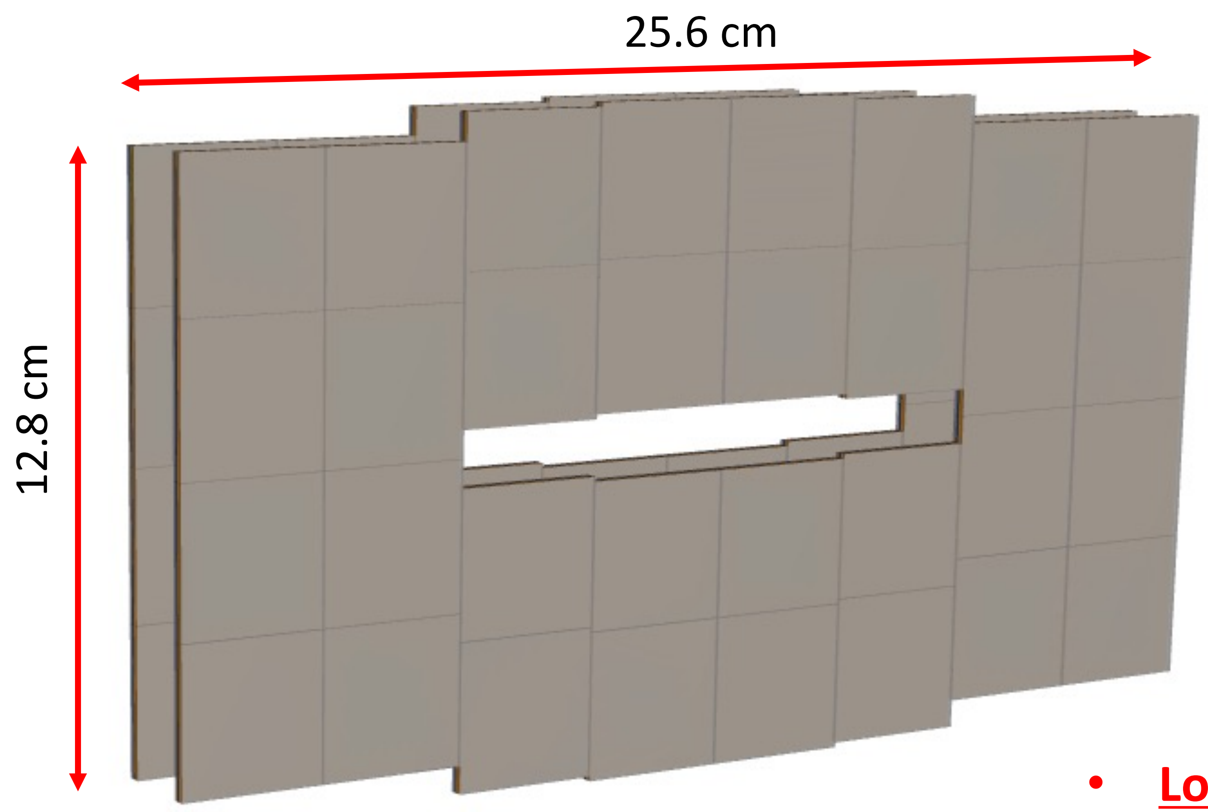


DD4HEP Simulation



- **<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.

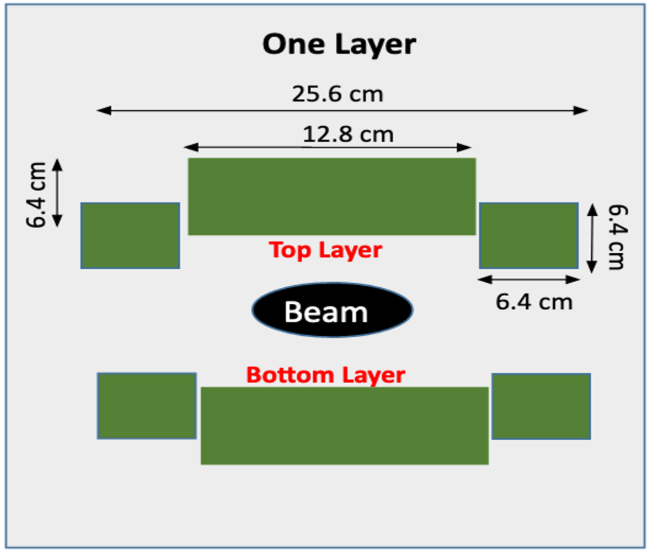
Roman “Pots” @ the EIC



DD4HEP Simulation

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

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



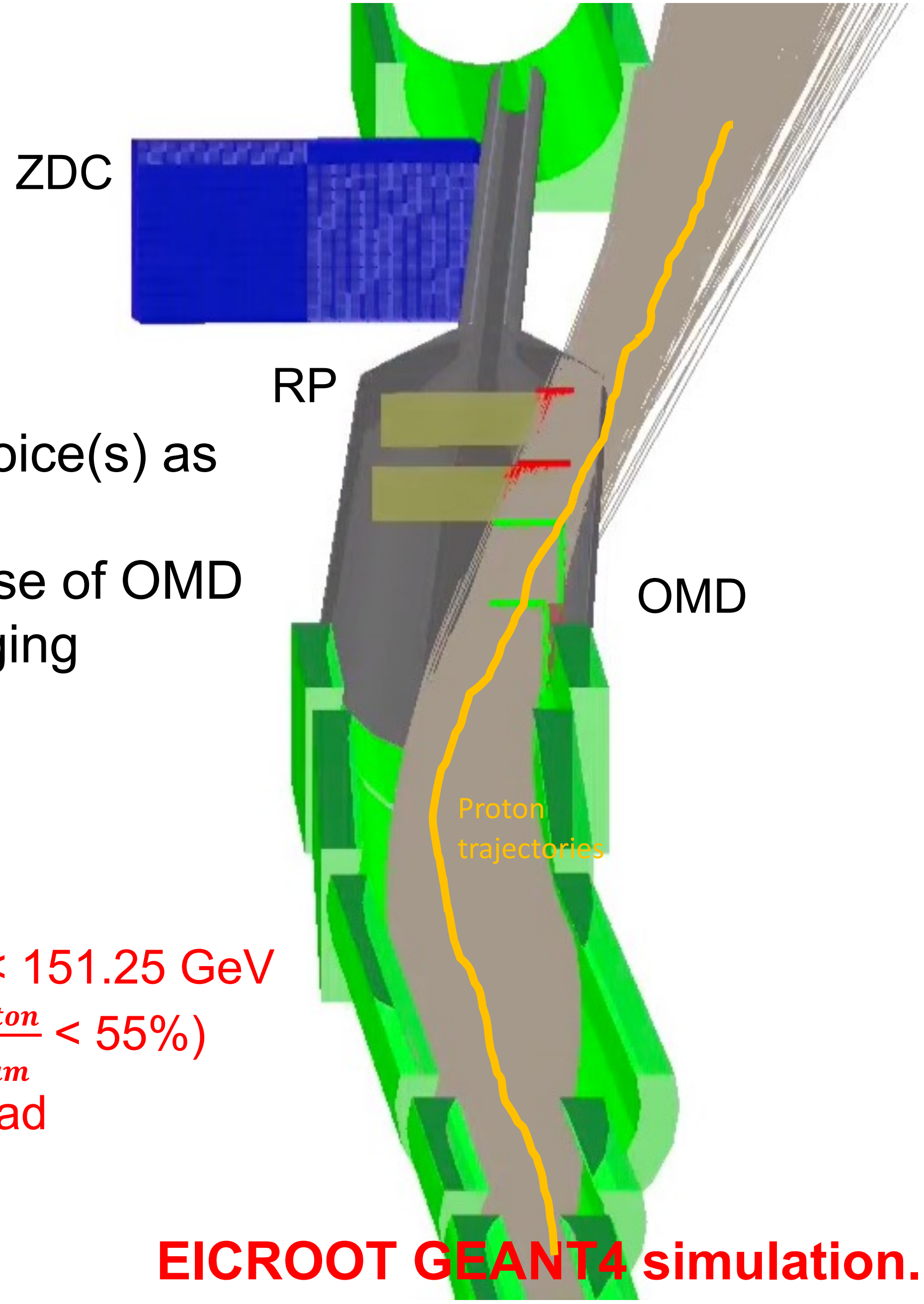
- **Low-pT cutoff determined by beam optics.**
  - **The safe distance is ~10σ from the beam center.**
  - **$1\sigma \sim 1$mm**
- **Optics choices change with energy, but be changed within a single energy to maximize *either acceptance at the RP, or the luminosity.***

Off-Momentum Detectors

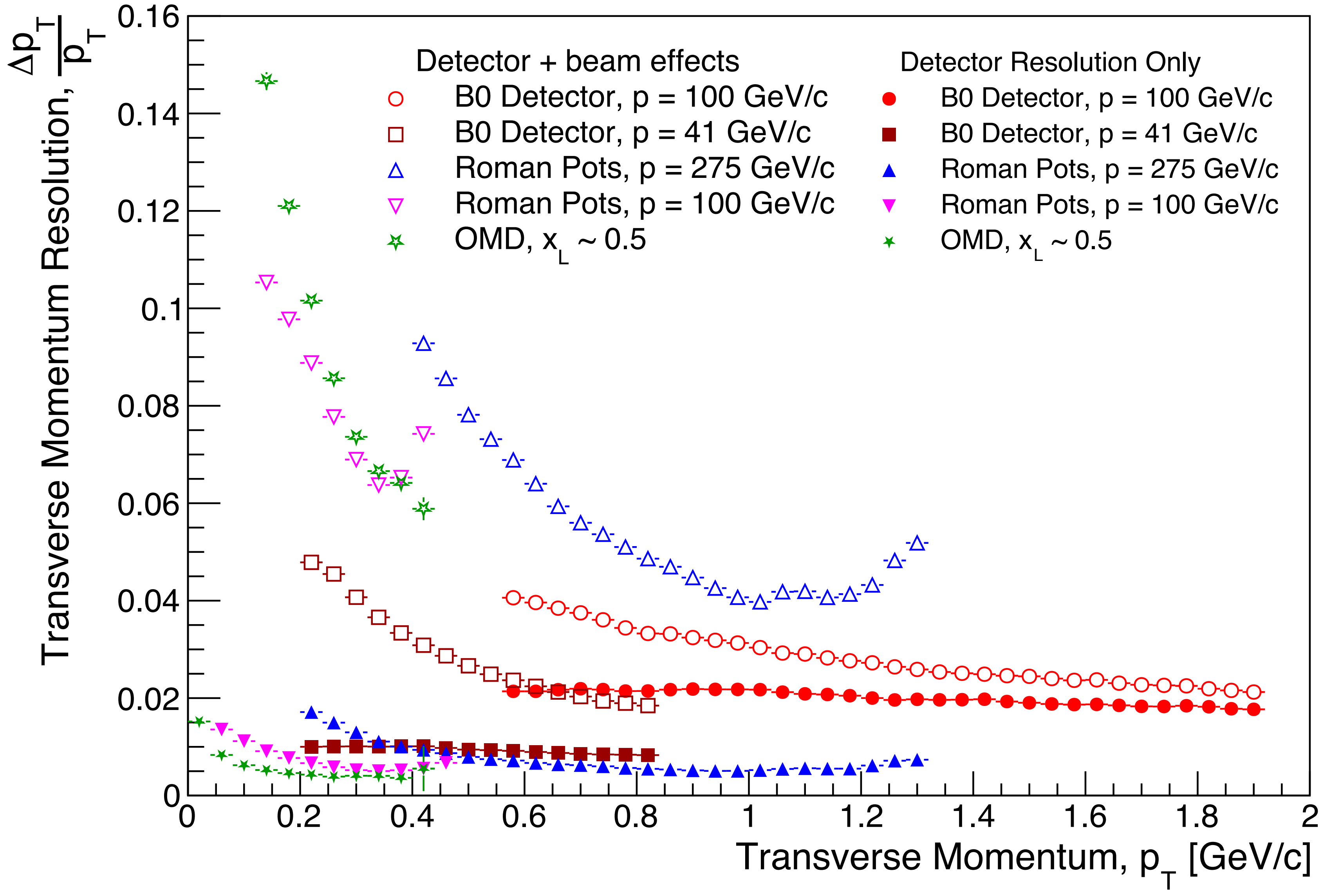
Off-momentum detectors implemented as horizontal ”Roman Pots” style sensors.

- 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
$(45\% < \frac{p_{z,proton}}{p_{z,beam}} < 55\%)$
$0 < \theta < 5$ mrad



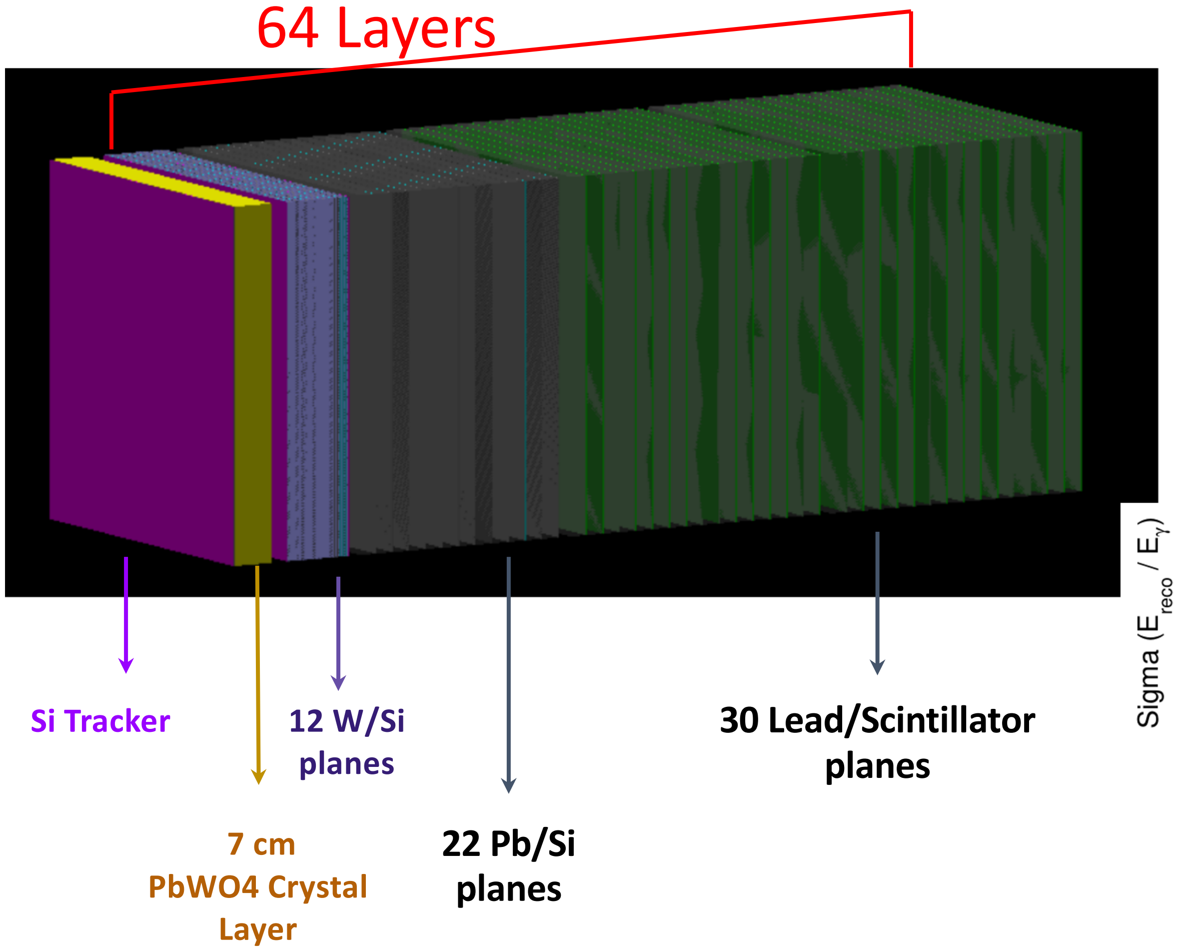
Summary of Detector Performance (Trackers)



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

Beam effects the dominant source of momentum smearing!

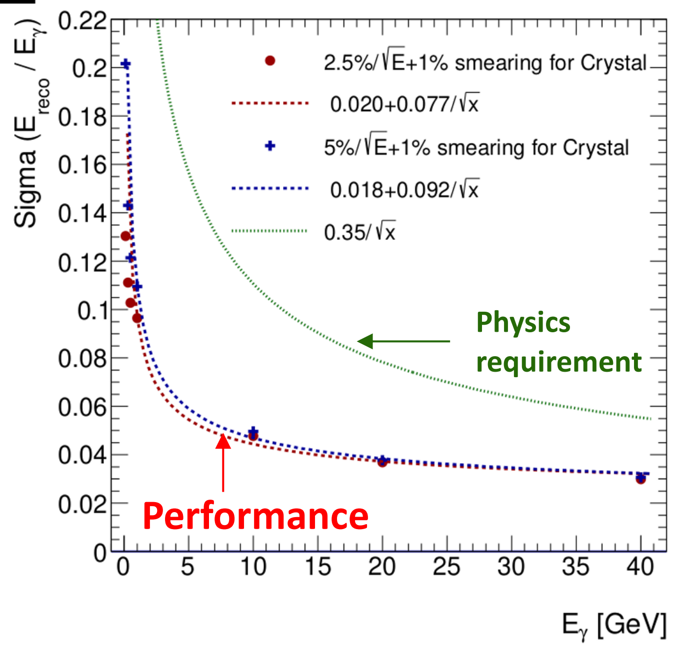
Zero-Degree Calorimeter



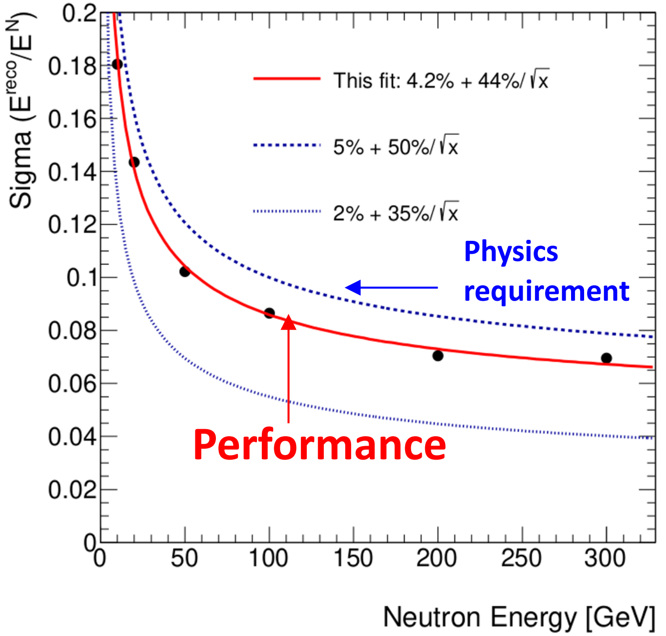
Credit to Shima Shimizu (Kobe U. , Japan)

- **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

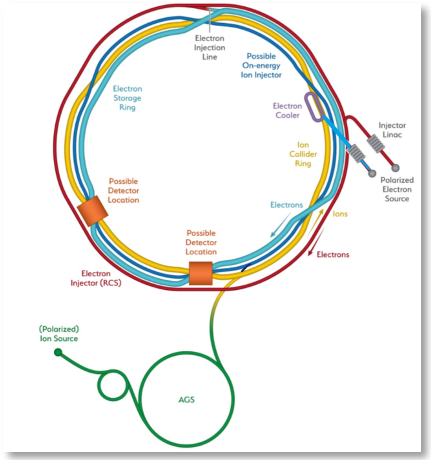


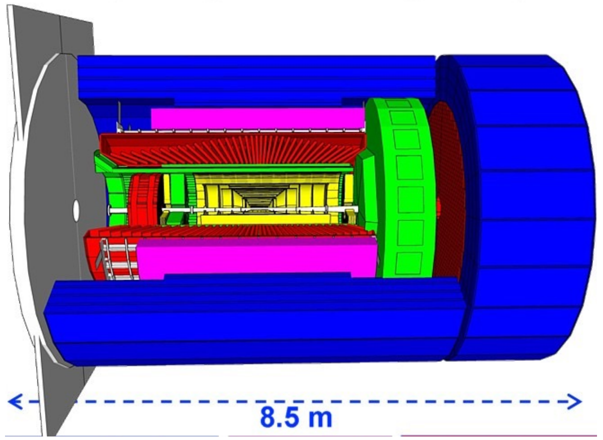
Neutron energy resolution

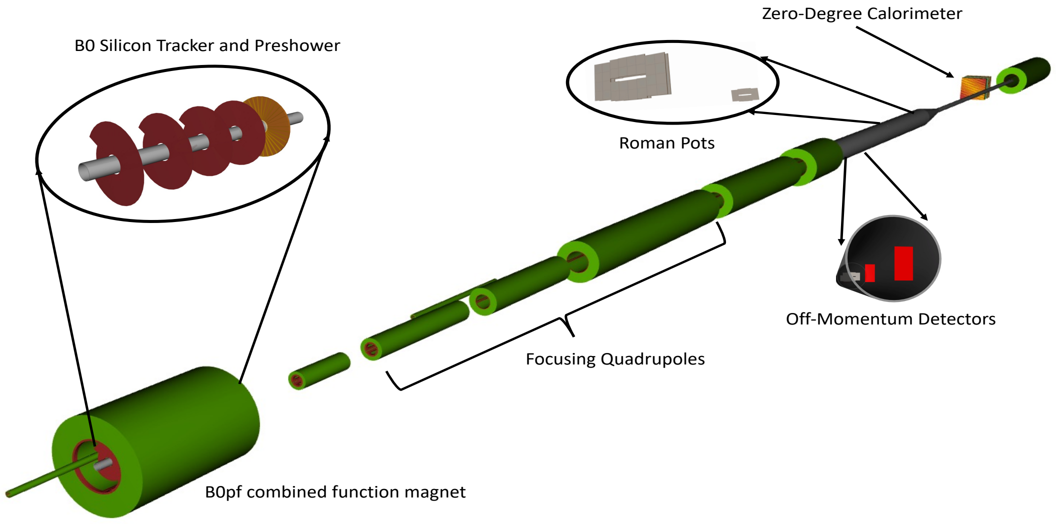


Summary and Takeaways

- All FF detector acceptances and detector performance well-understood with currently available information.
  - Numerous impact studies done!
  - Some final choices on technology underway → also important for IP8 complementarity.
  - Full effort benefitted from three (ECCE, ATHENA, CORE) proposals to identify multiple technology solutions!
- 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!!!

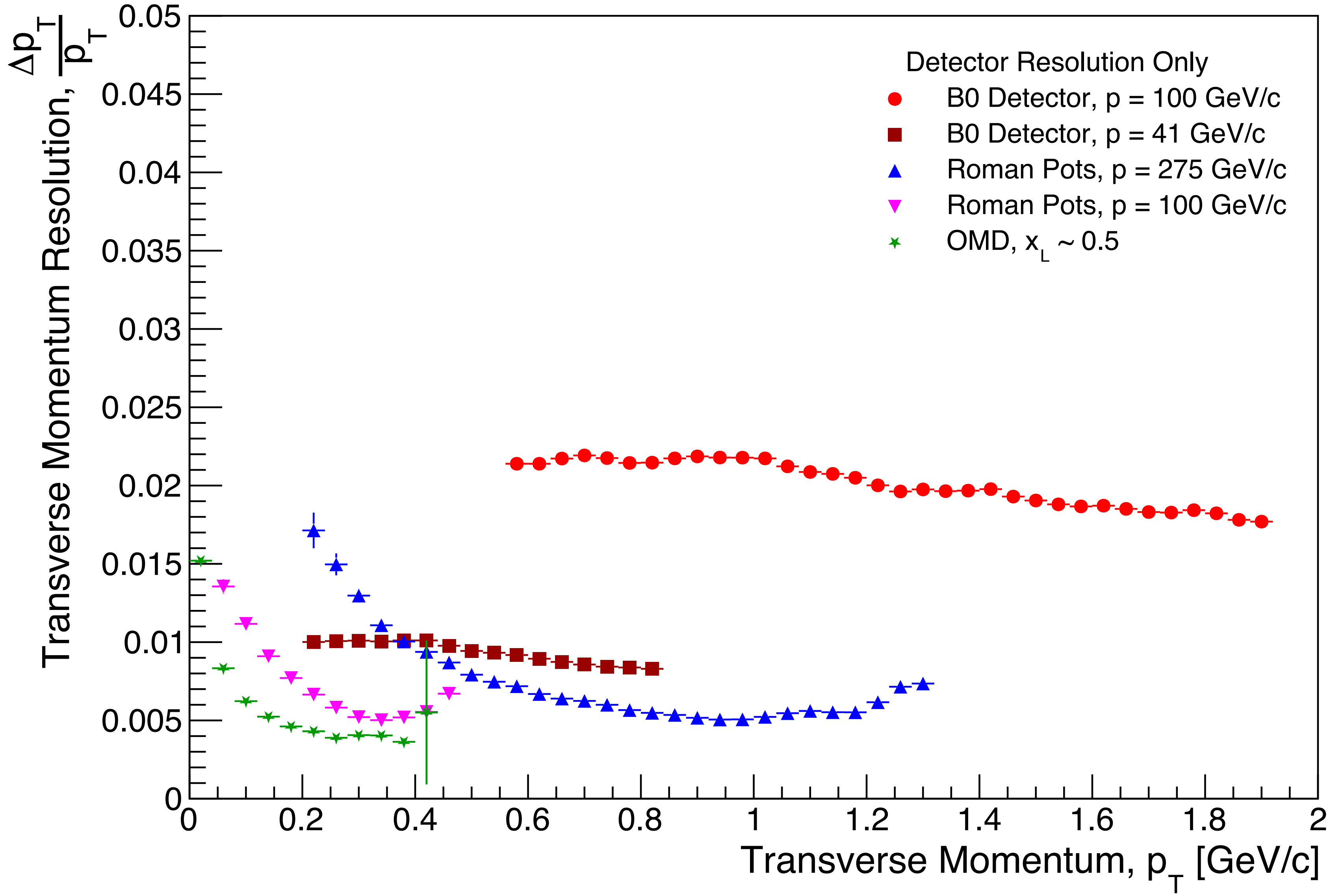






Backup

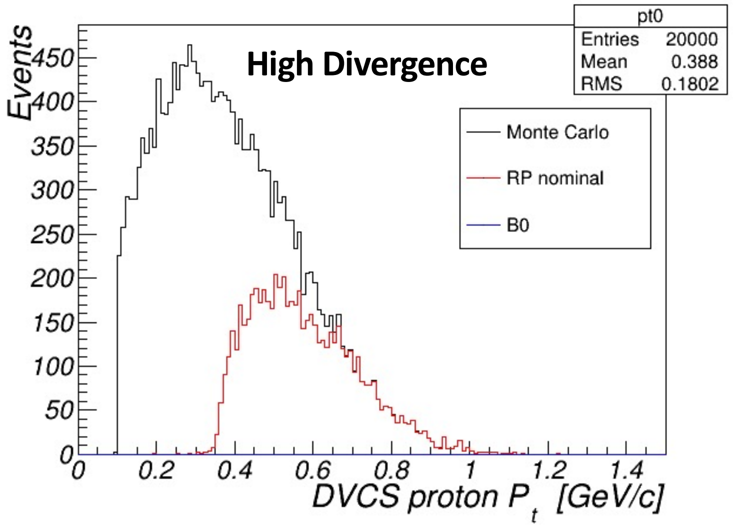
Summary of Detector Performance (Trackers)

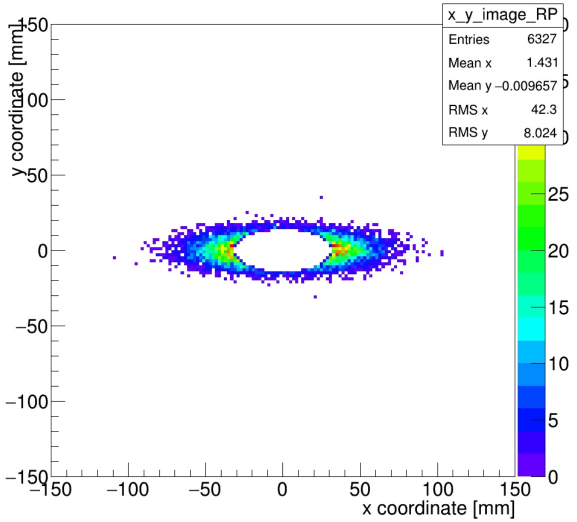


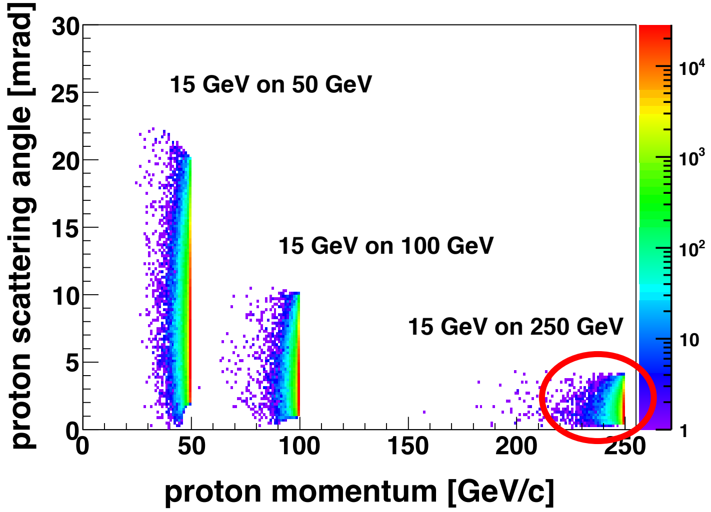
- Includes realistic considerations for pixel sizes and materials
  - More work needed on support structure and associated impacts.
- Roman Pots and Off-Momentum detectors suffer from additional smearing due to improper transfer matrix reconstruction.
  - This problem is close to being solved!

Digression: Machine Optics

275 GeV DVCS Proton Acceptance



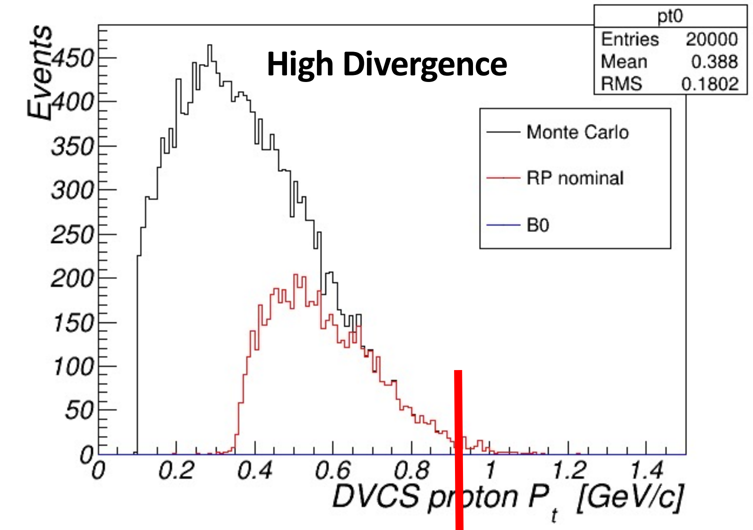


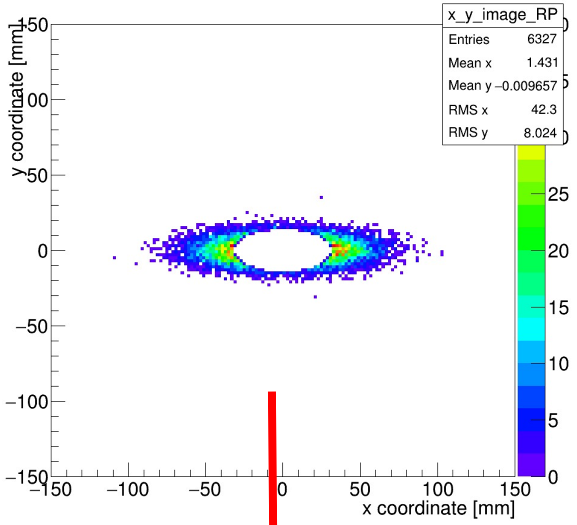


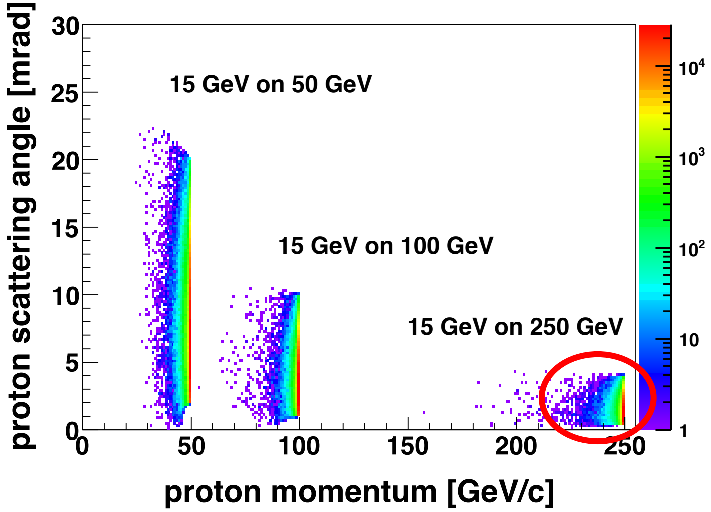
High Divergence: smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

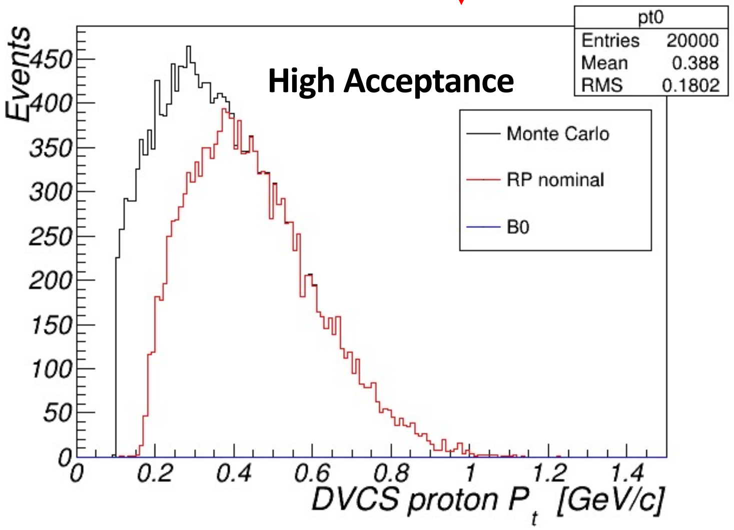
Digression: Machine Optics

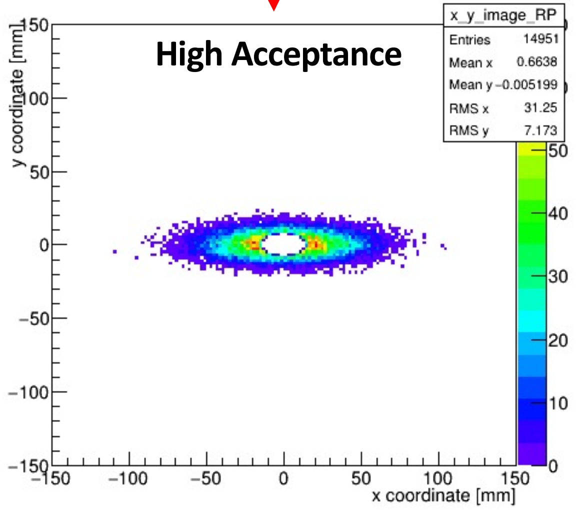
275 GeV DVCS Proton Acceptance









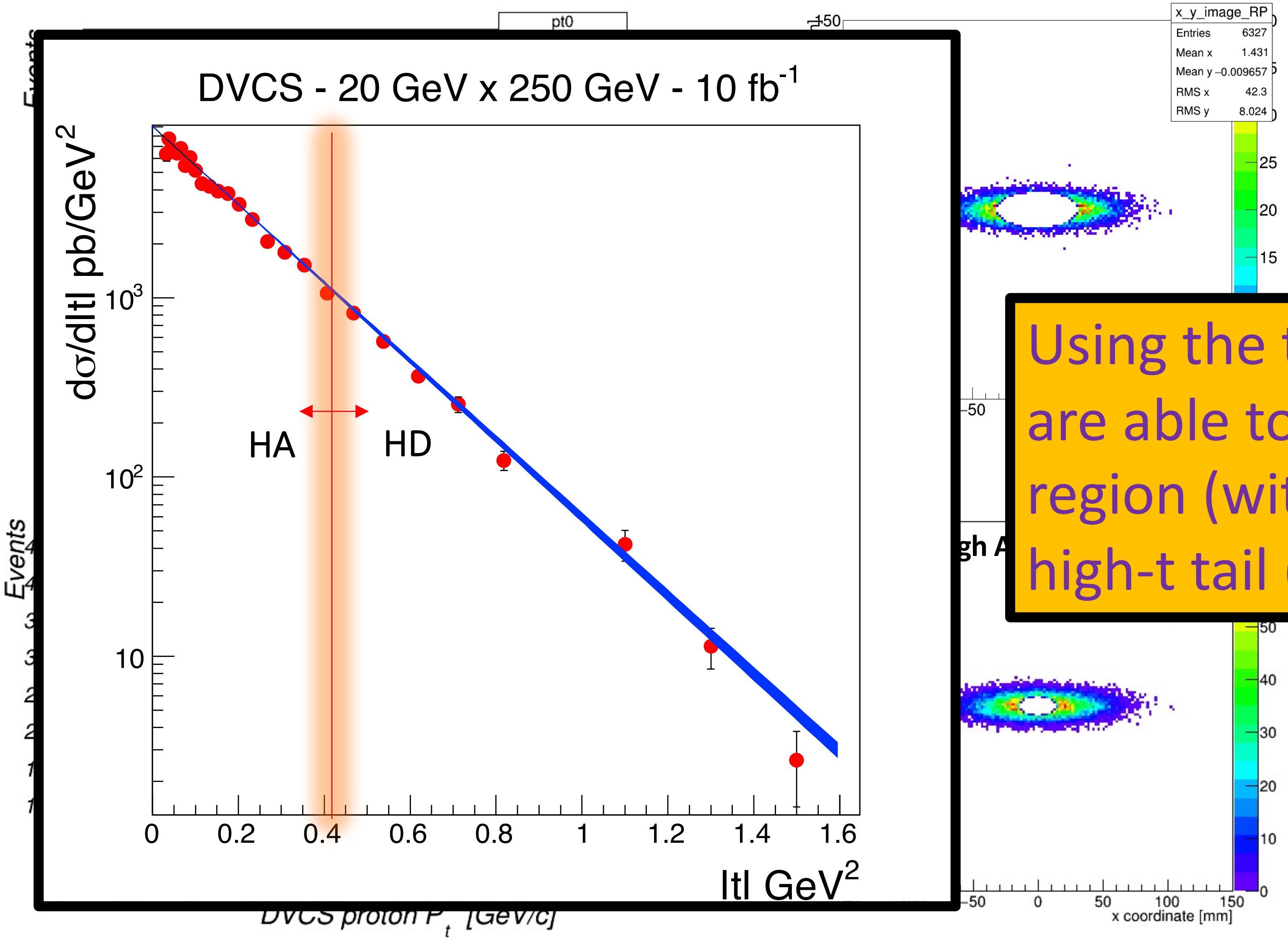


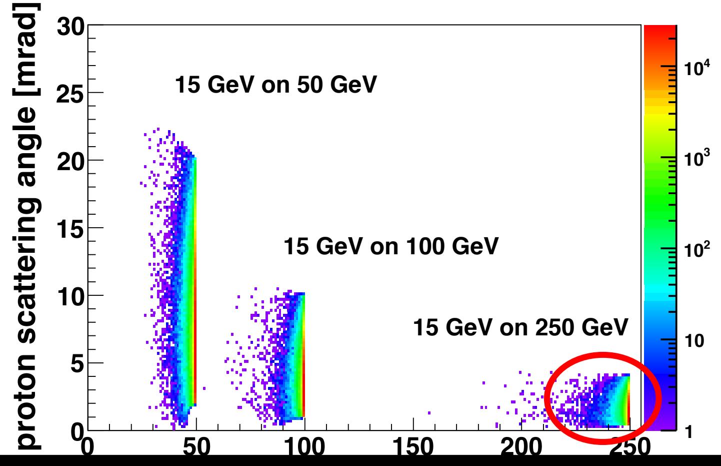
High Divergence: smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

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

Digression: Machine Optics

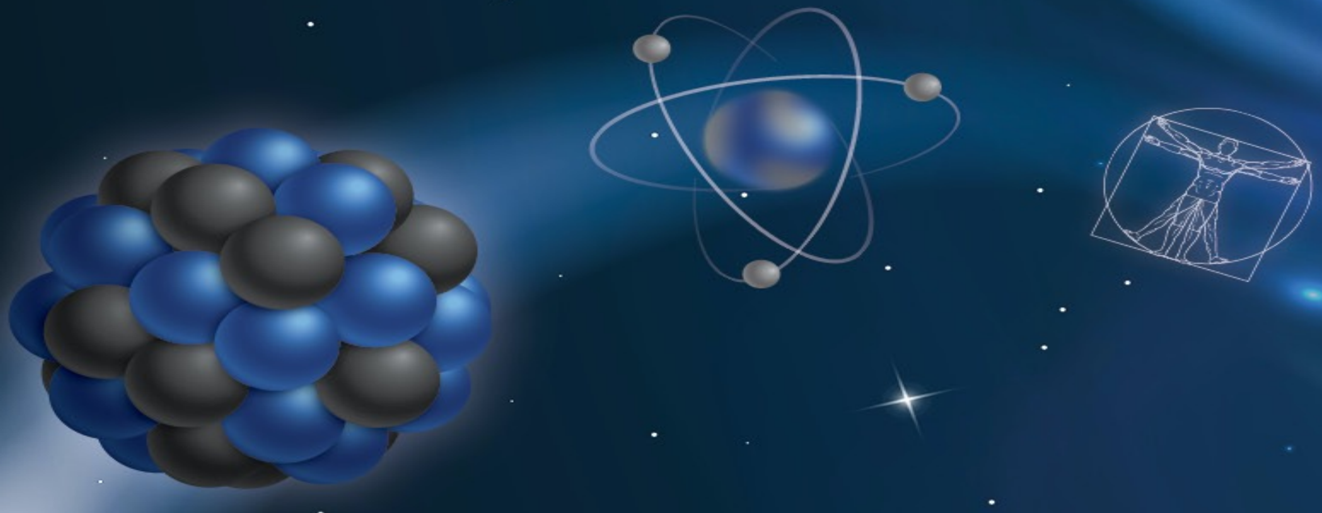
275 GeV DVCS Proton Acceptance

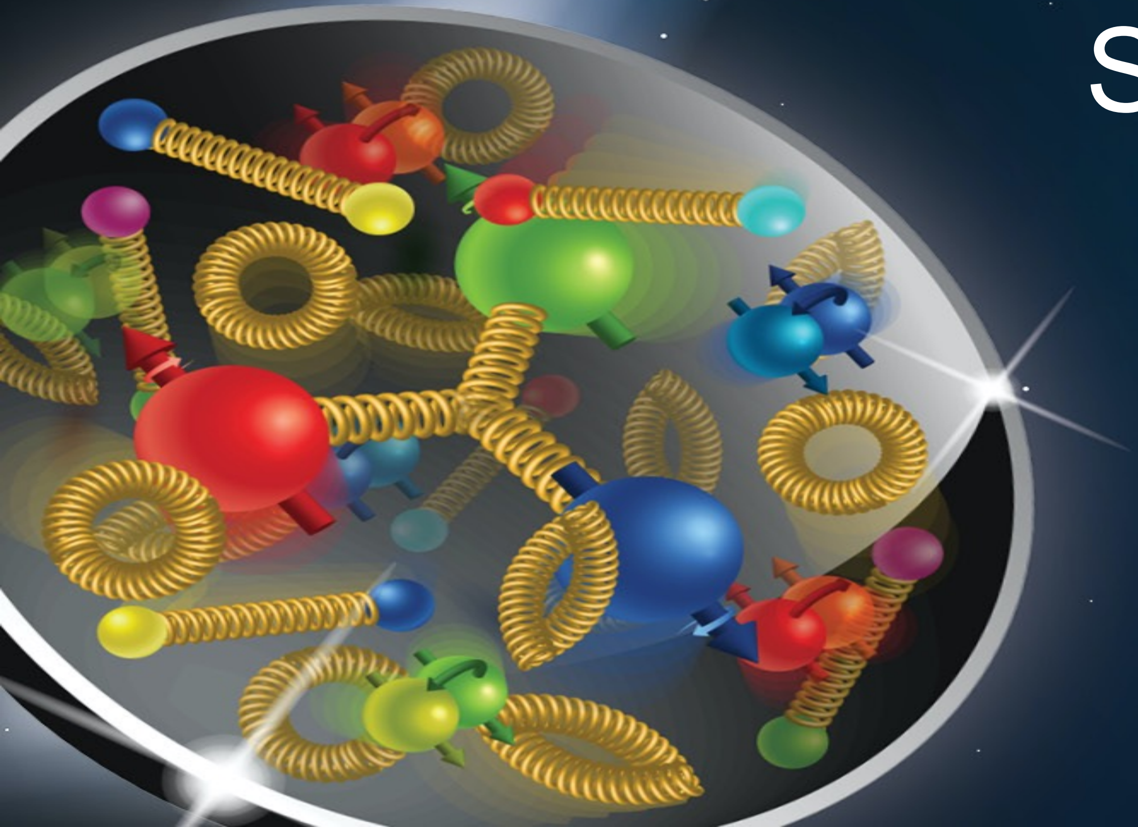




Using the two configurations, we are able to measure the low-t region (with better acceptance) and high-t tail (with higher luminosity).

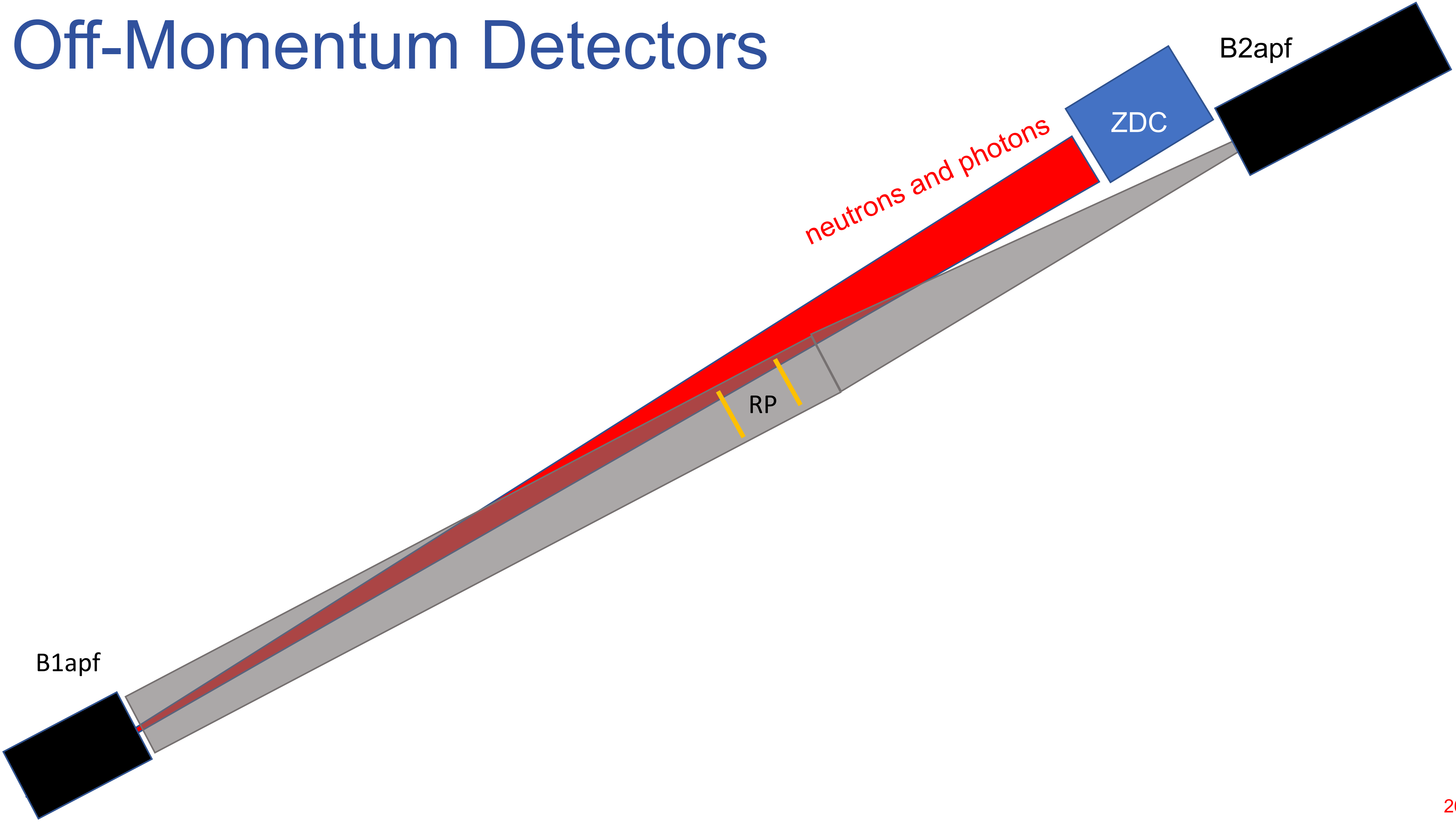
High Acceptance: larger β^* at IP, smaller $\beta(z = 30m)$ -> lower lumi., smaller beam at RP





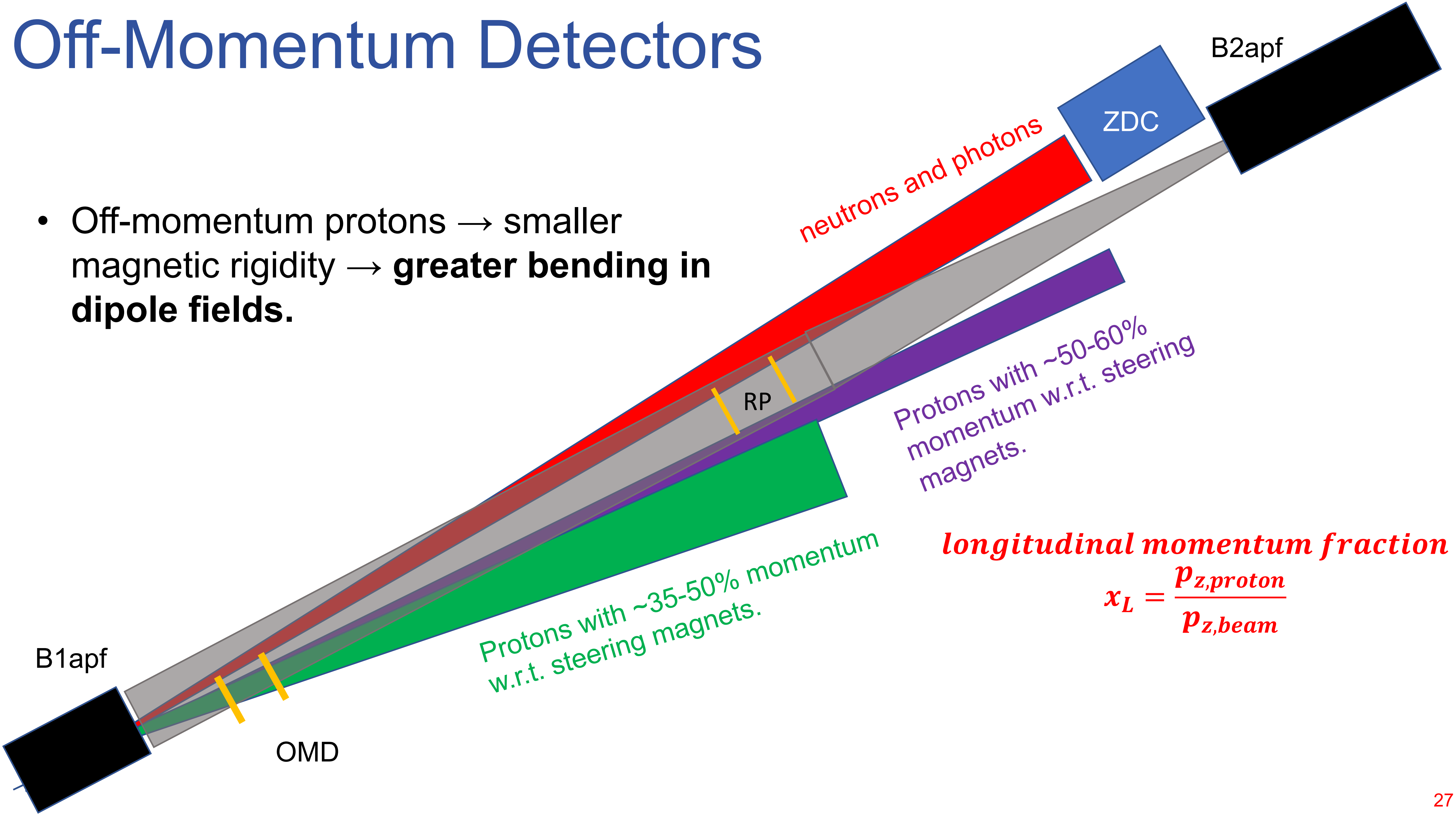
So how does the FF system perform for measurements (non-exhaustive)?

Off-Momentum Detectors



Off-Momentum Detectors

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

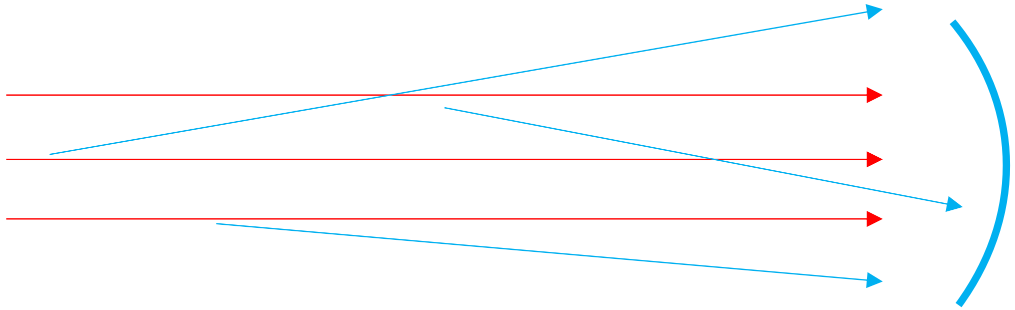


$$\textit{longitudinal momentum fraction}$$

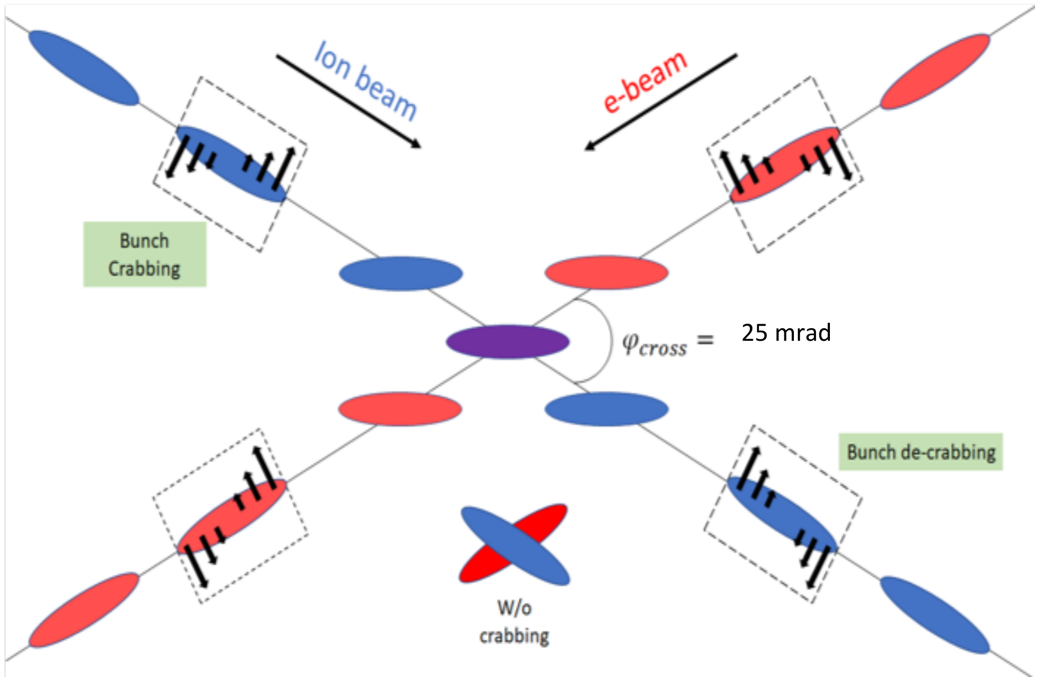
$$x_L = \frac{p_{z,proton}}{p_{z,beam}}$$

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.



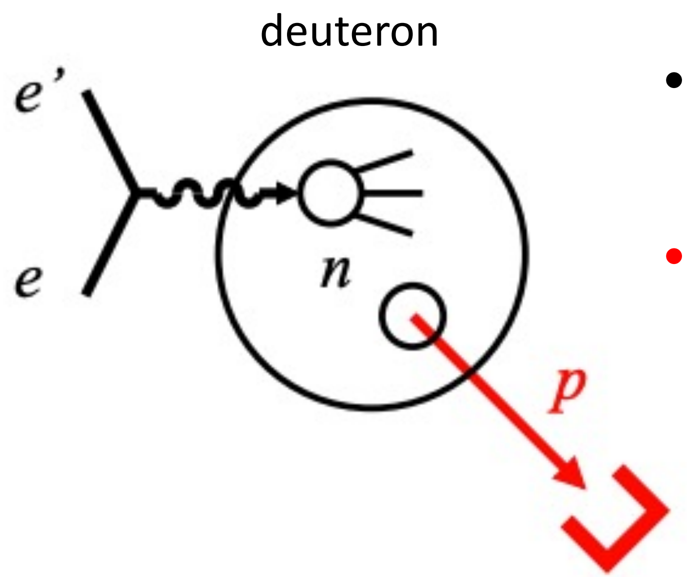
- Crab cavity rotation
  - Can perform rotations of the beam bunches in 2D.
  - Used to account for the luminosity drop due to the crossing angle – allows for head-on collisions to still take place.



These effects introduce smearing in our momentum reconstruction.

Spectator Tagging in Light Nuclei

EIC enables use of deuteron beams → the next best thing to a beam of neutrons!



- Measurements on unpolarized deuterons[1] (or polarized He-3)[2] at the EIC.
- Spectator proton momentum → enables selection of nuclear (p/n) configurations.
  - Extract free neutron structure function[3] → Not possible elsewhere!
  - Study nuclear modifications of both nucleons in the deuteron (study in progress).

[1] Z. Tu, A. Jentsch, et al., Physics Letters B, (2020)
[2] I. Friscic, D. Nguyen, J. R. Pybus, A. Jentsch, *et al.,* Phys. Lett. B, **Volume 823**, 136726 (2021)
[3] A. Jentsch, Z. Tu, and C. Weiss, Phys. Rev. C **104,** 065205, (2021) **(Editor's Suggestion)**

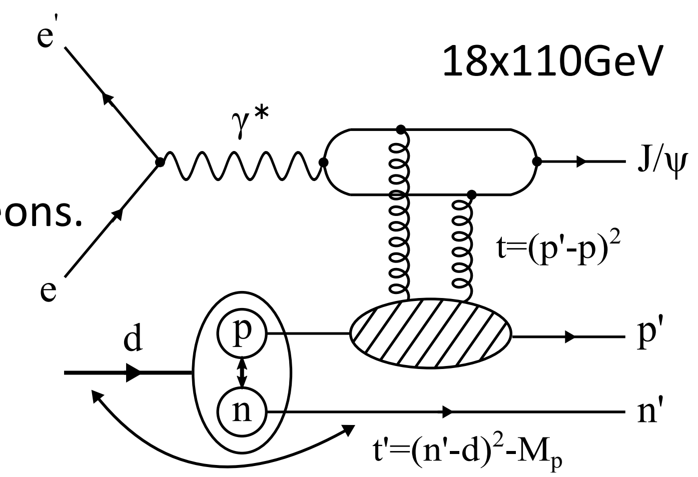
e+d Spectator Tagging

Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)

Proton spectator case.

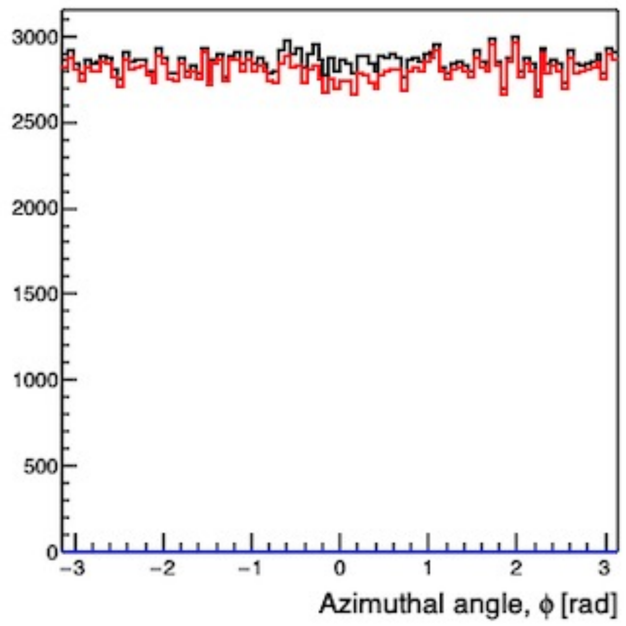
Particular process in BeAGLE: incoherent diffractive J/psi production off bounded nucleons.

Short-range correlations!

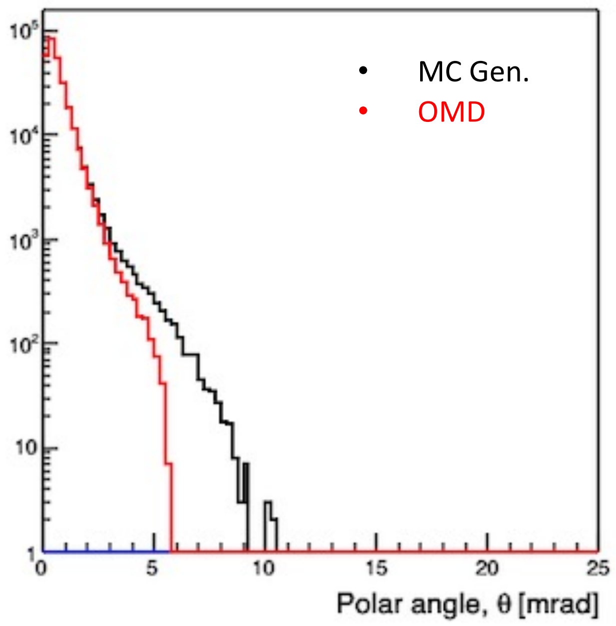


18x110GeV

Protons



Protons



<u>Spectator</u> proton acceptance (in the off-momentum detectors)

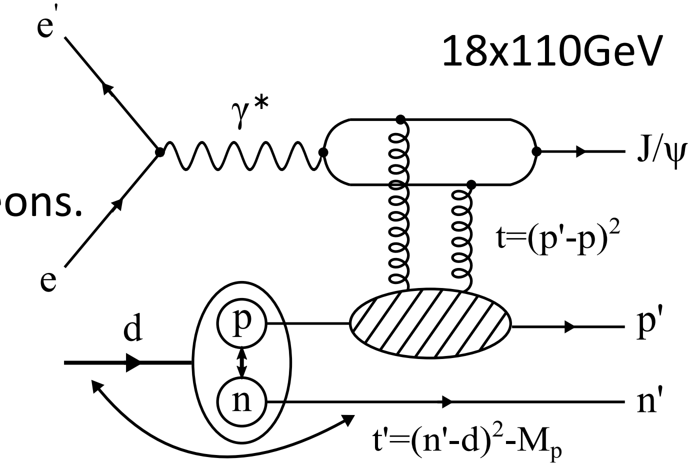
e+d Spectator Tagging

Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)

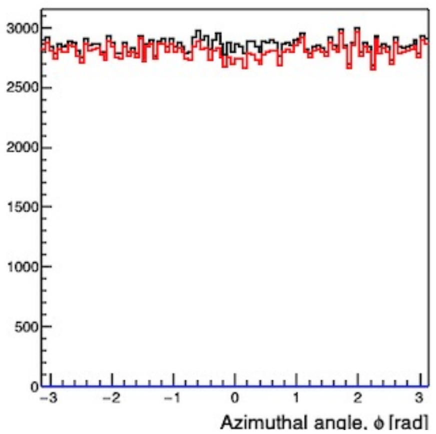
Proton spectator case.

Particular process in BeAGLE: incoherent diffractive J/psi production off bounded nucleons.

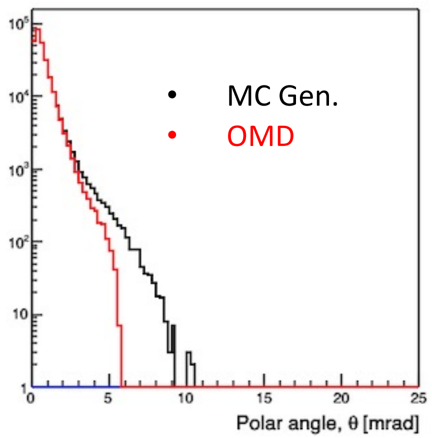
Short-range correlations!

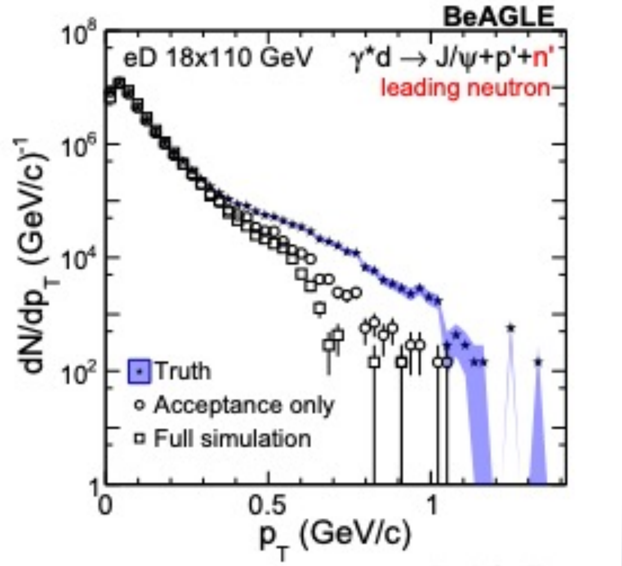


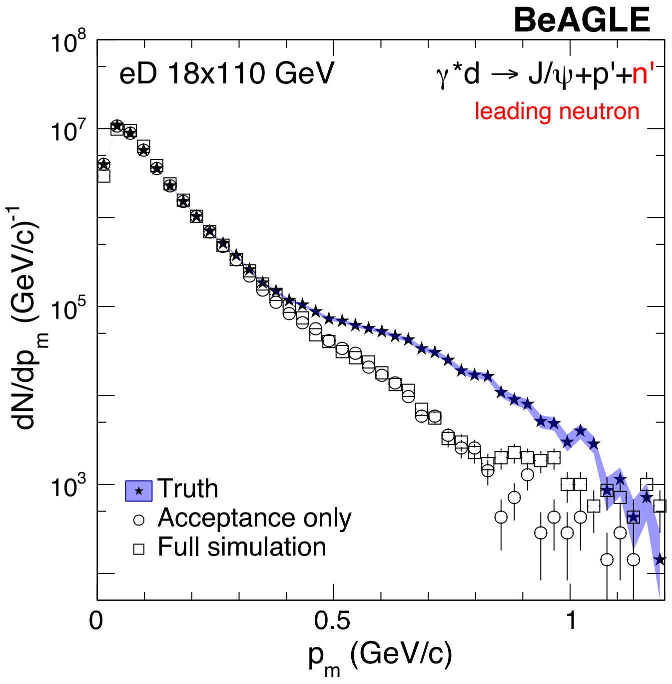
Protons



Protons







- Spectator kinematic variables reconstructed over a broad range.
- All beam/detector effects included.
- Bin migration is observed due to smearing in the reconstruction.

> **In the proton spectator case, essentially all spectators tagged.**
> **Active neutrons only tagged up to 4.5 mrad.**

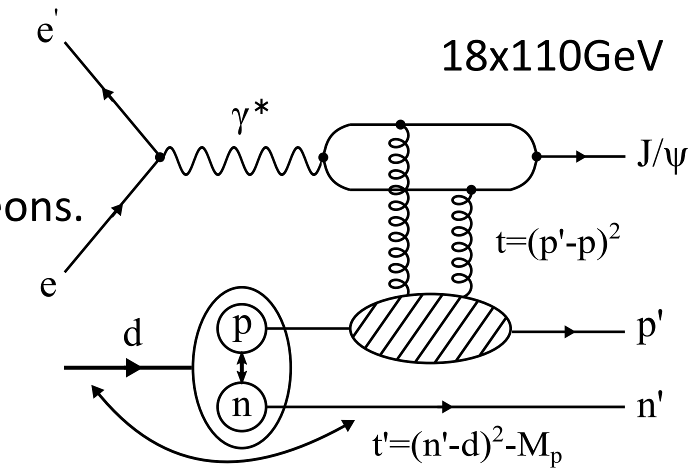
e+d Spectator Tagging

Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)

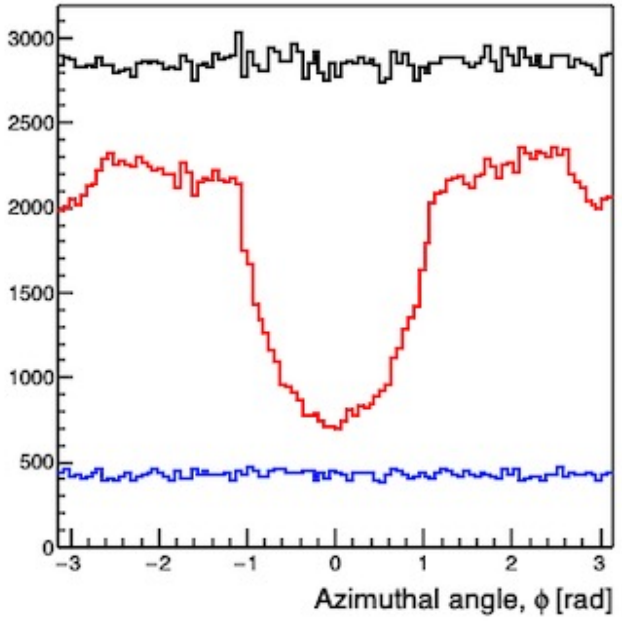
Neutron spectator case.

Particular process in BeAGLE: incoherent diffractive J/psi production off bounded nucleons.

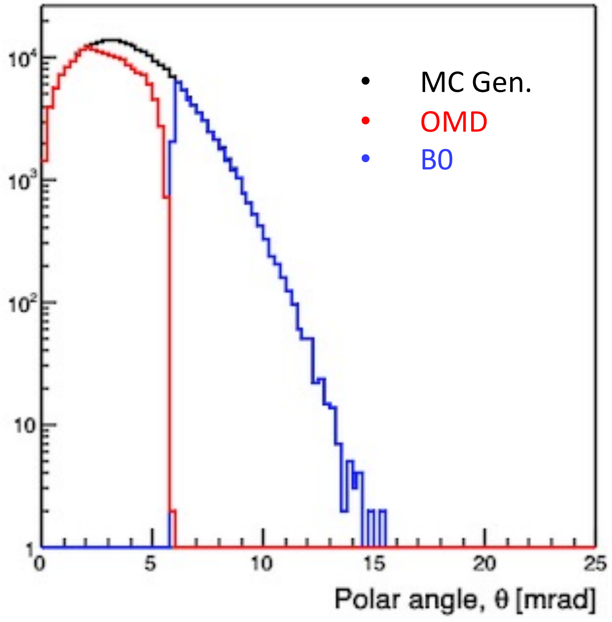
Short-range correlations!



Protons



Protons



<u>Active</u> proton acceptance!

Need multiple FF subsystems!

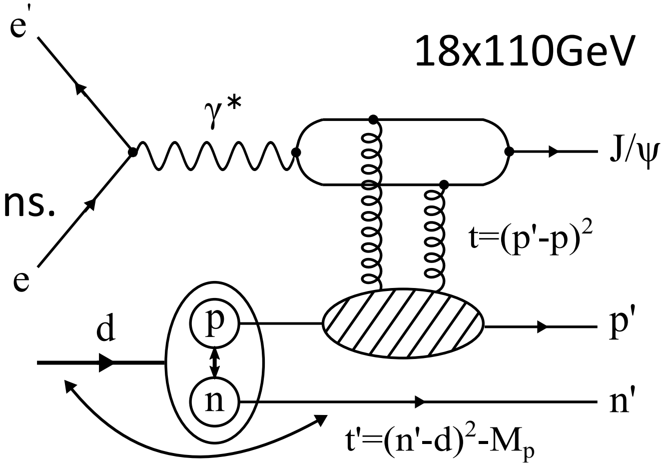
e+d Spectator Tagging

Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)

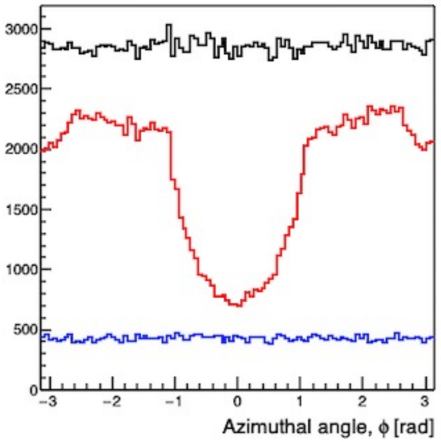
Neutron spectator case.

Particular process in BeAGLE: incoherent diffractive J/psi production off bounded nucleons.

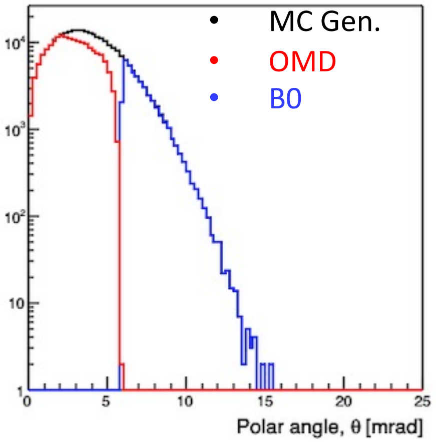
Short-range correlations!

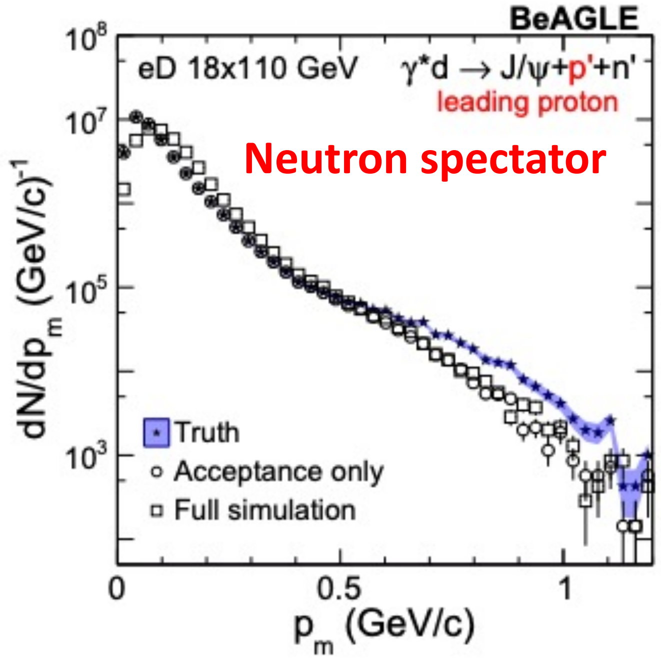


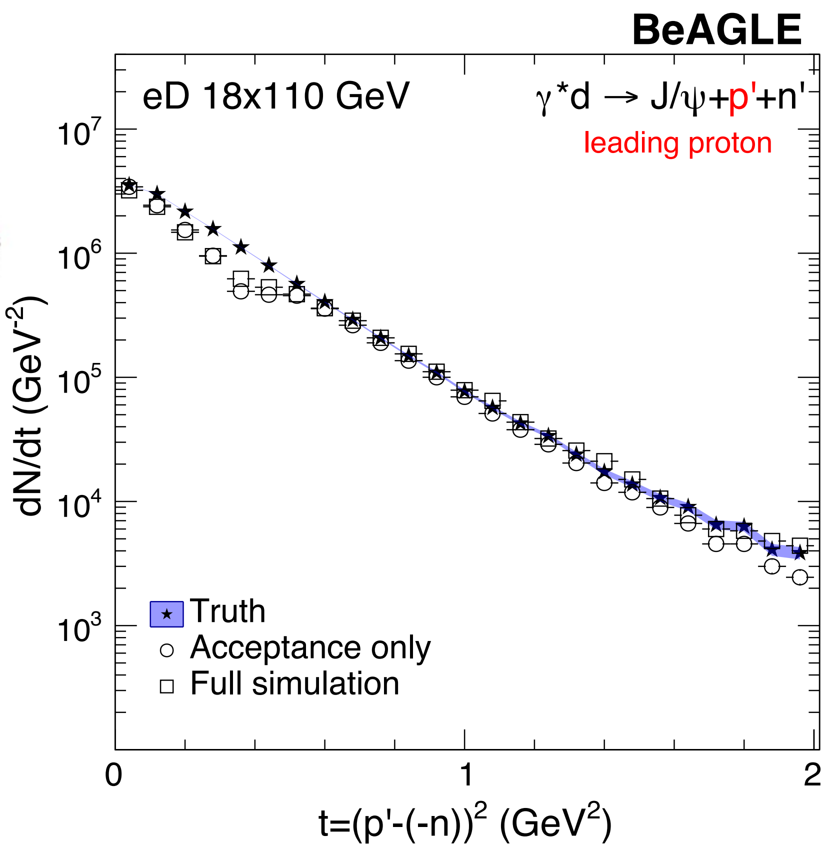
Protons



Protons





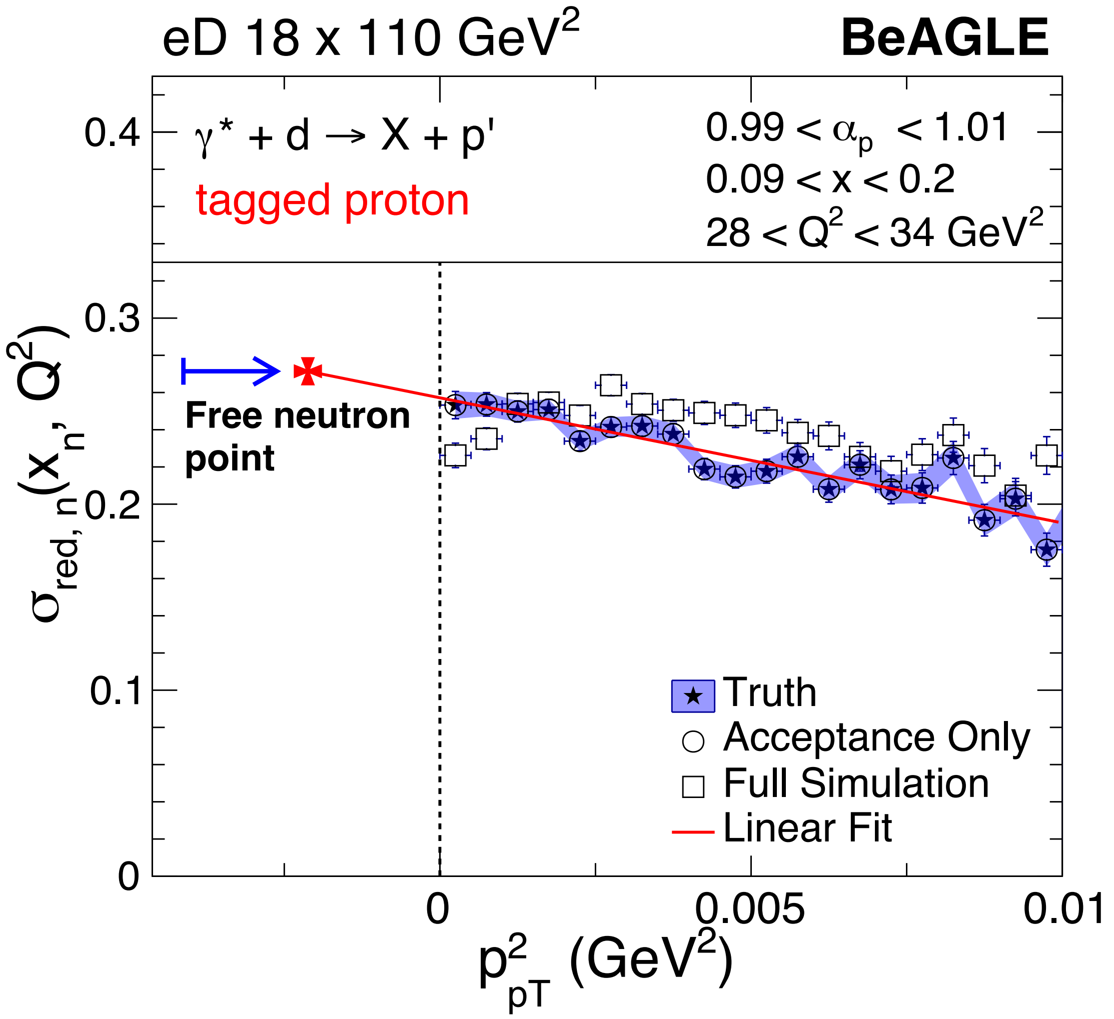


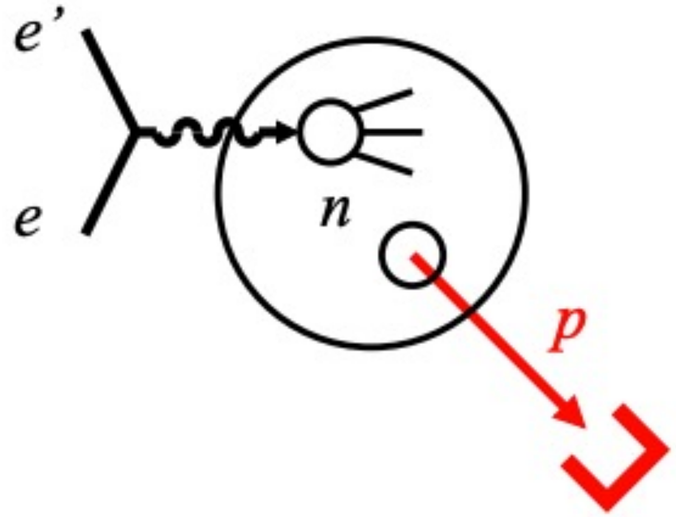
t-reconstruction using **double-tagging (both proton and neutron).** Takes advantage of combined B0 + off-momentum detector coverage. Better coverage in the neutron spectator case.

➢ **Spectator information is the “dial” for the SRC region.**

Free Neutron F_2 Extraction

(Active nucleon reduced cross section) ~ F_2





- Cross-section as a function of the proton spectator kinematics → dial to select nuclear configuration → allows extrapolation to "free" neutron region.
- Enables measurement of **free** neutron structure function!

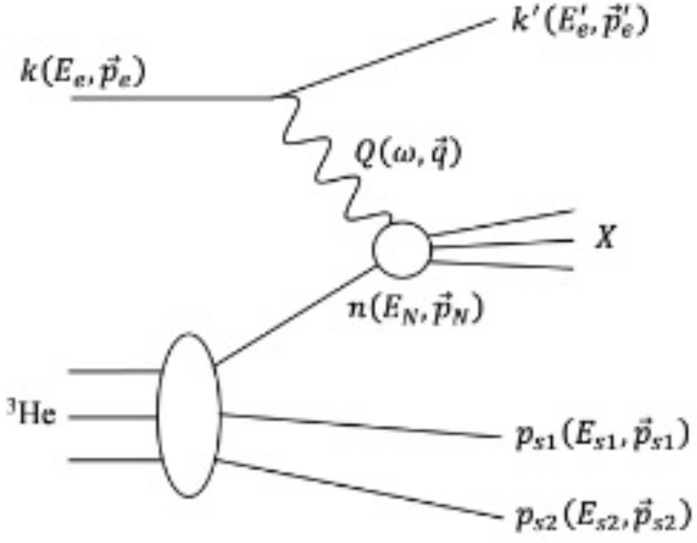
$$P_{pT}^2 = p_{px}^2 + p_{py}^2$$

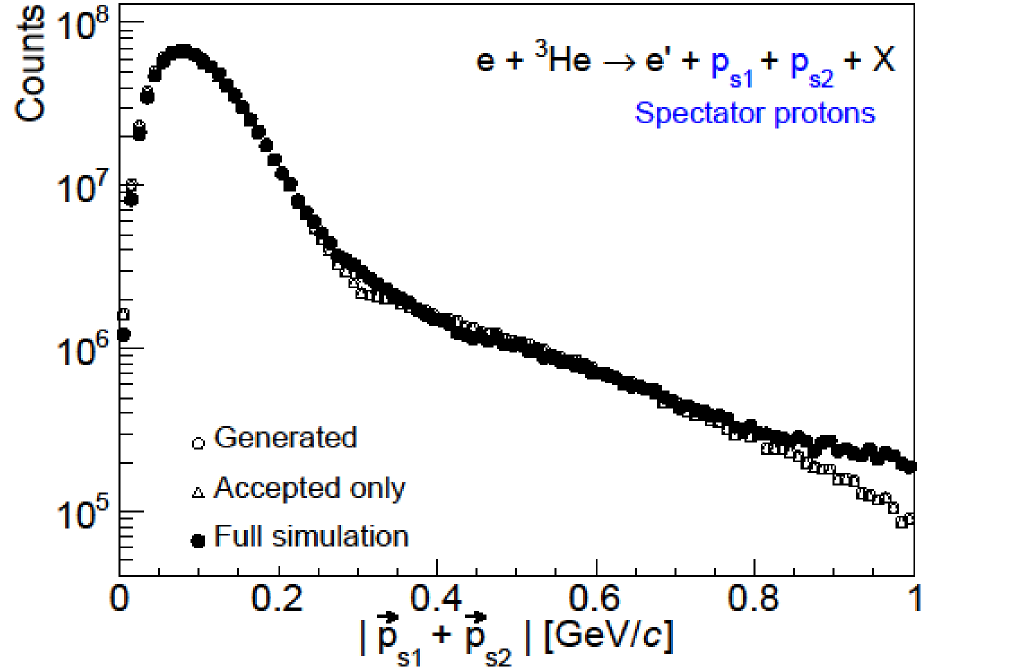
$\sigma_{red,n} \sim F_{2,n}$ (cross section)

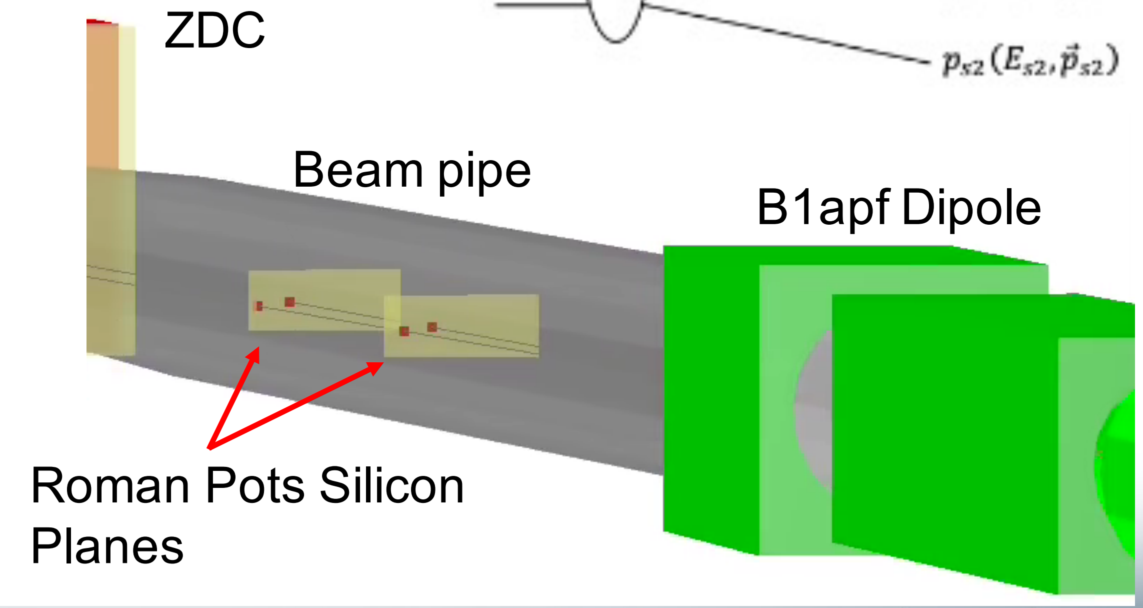
A. Jentsch, Z. Tu, and C. Weiss, Phys. Rev. C **104,** 065205, (2021) **(Editor's Suggestion)**

Neutron Spin Structure in He3

- Studies of neutron structure with a *polarized* neutron.
- More challenging final state tagging since *both* protons must be tagged in the FF region.
- MC events generated with CLASDIS in fixed-target frame, and then boosted to collider frame.



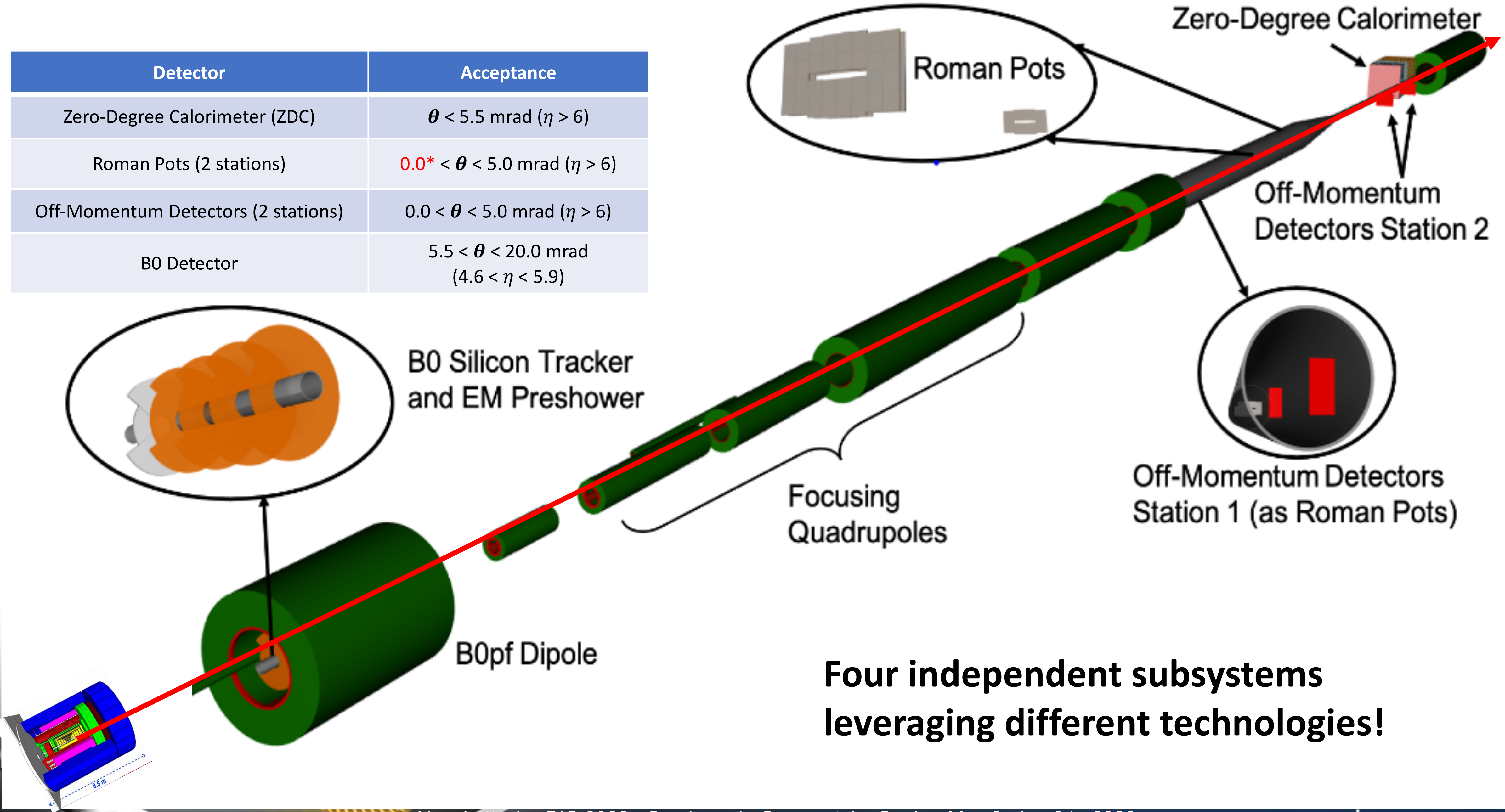




I. Friscic, D. Nguyen, J. R. Pybus, A. Jentsch, *et al.*, Phys. Lett. B, **Volume 823**, 136726 (2021)

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 ($4.6 < \eta < 5.9$)



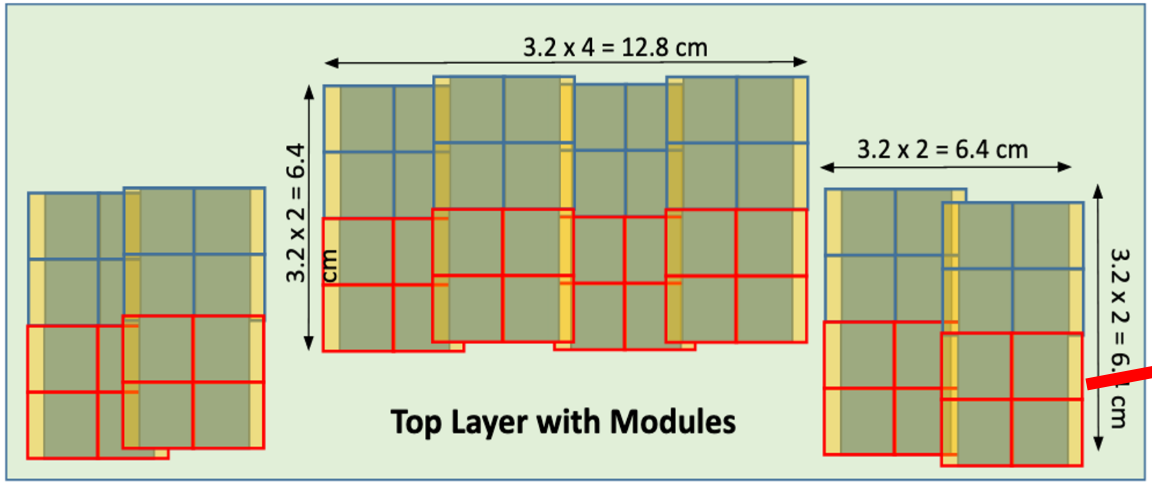
Four independent subsystems leveraging different technologies!

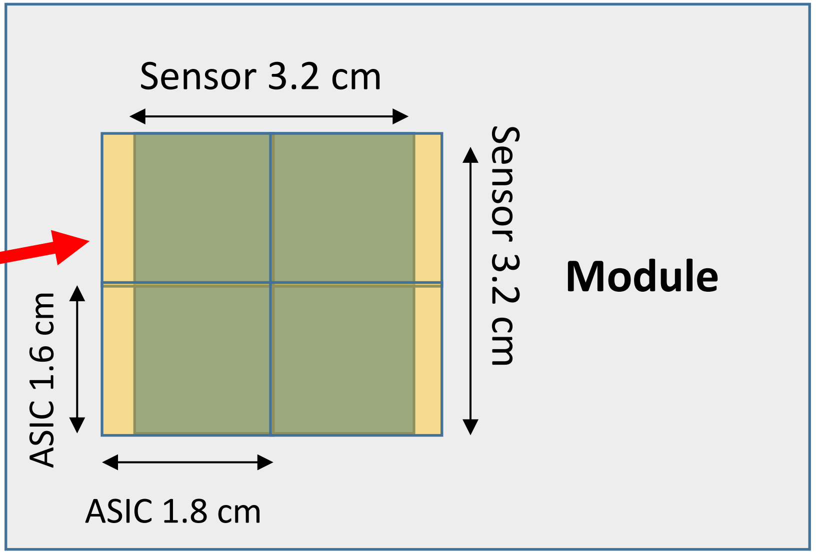
Roman Pots

- 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.



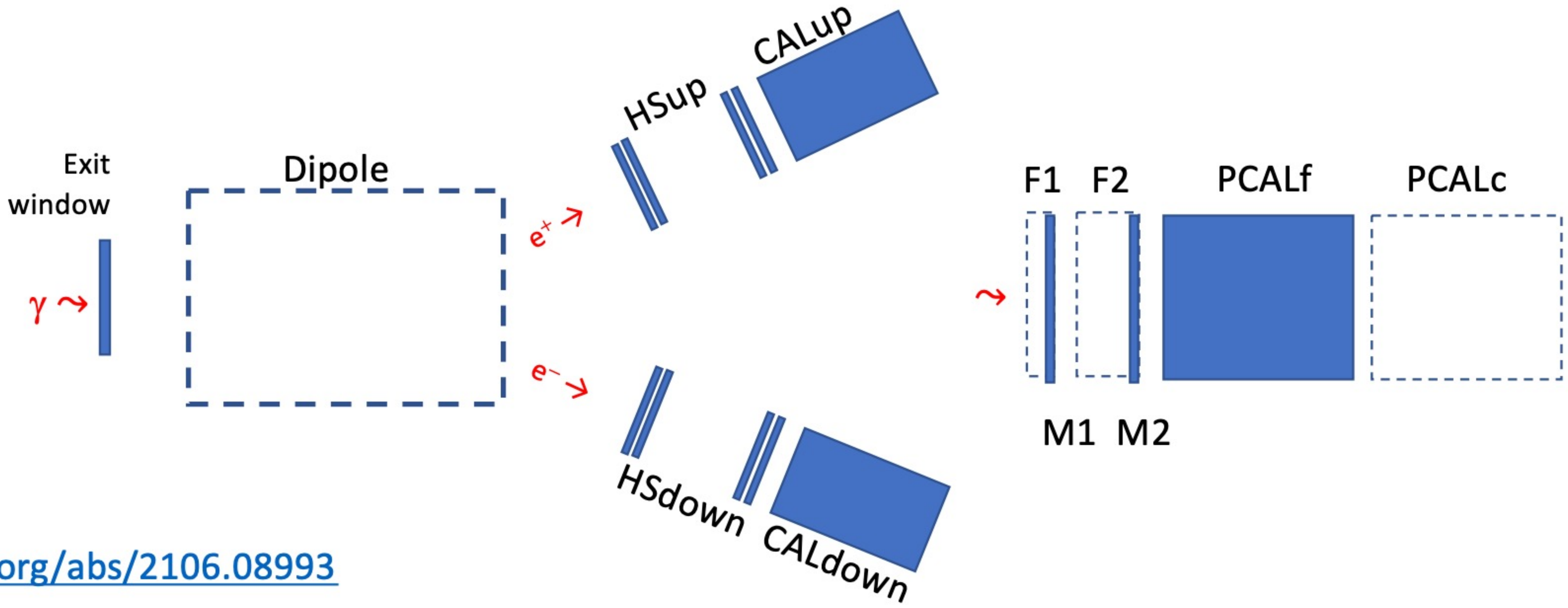


- Current R&D aimed at customizing ASIC readout chip (ALTIROC) for use with AC-LGADs.

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

Luminosity Monitor

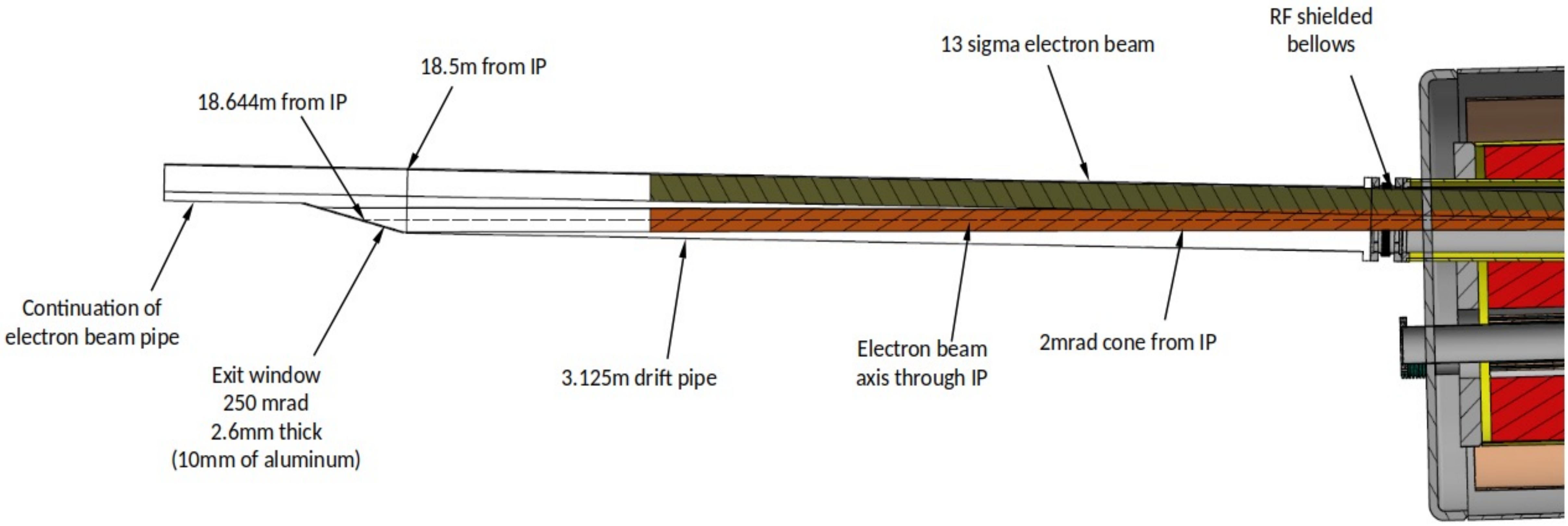
- Must make measurement in challenging environment.
    - High synchrotron radiation, high bremsstrahlung rates (~10 GHz), etc.
- Need ~1% for absolute luminosity measurement, ~10^{-4} for relative luminosity measurement.
- Can make direct photon measurement, or indirect via pair conversion in exit window, 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

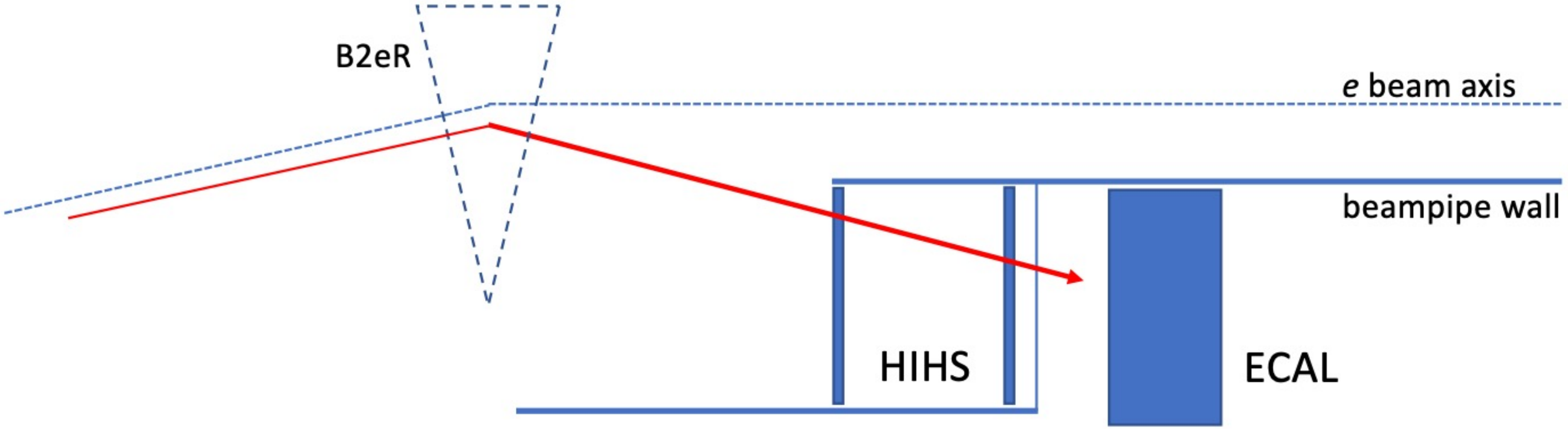
Exit window for luminosity monitor

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



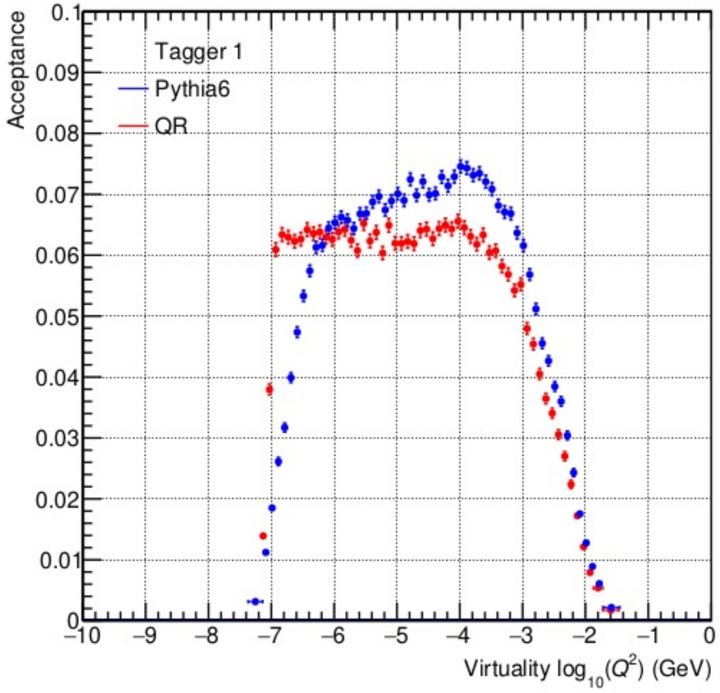
Low-Q^2 Taggers

- 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.

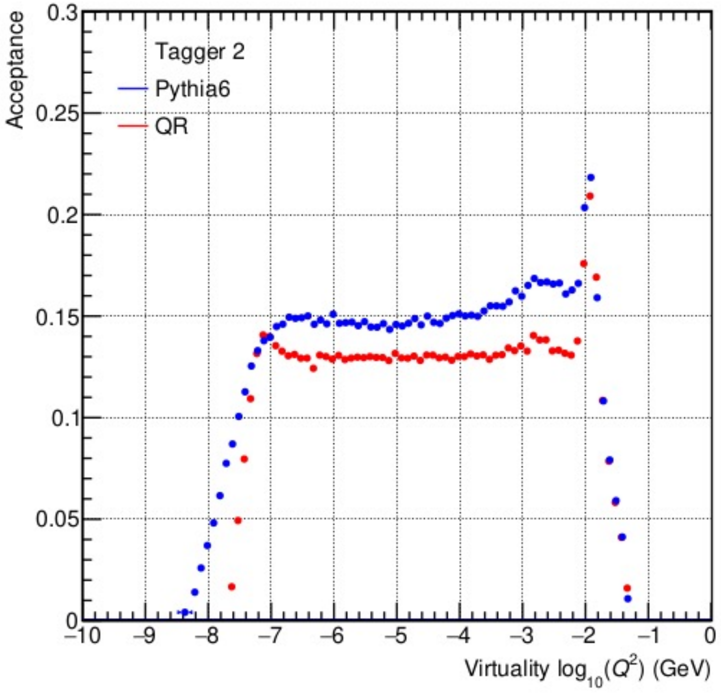


Performance for low-Q2 tagger

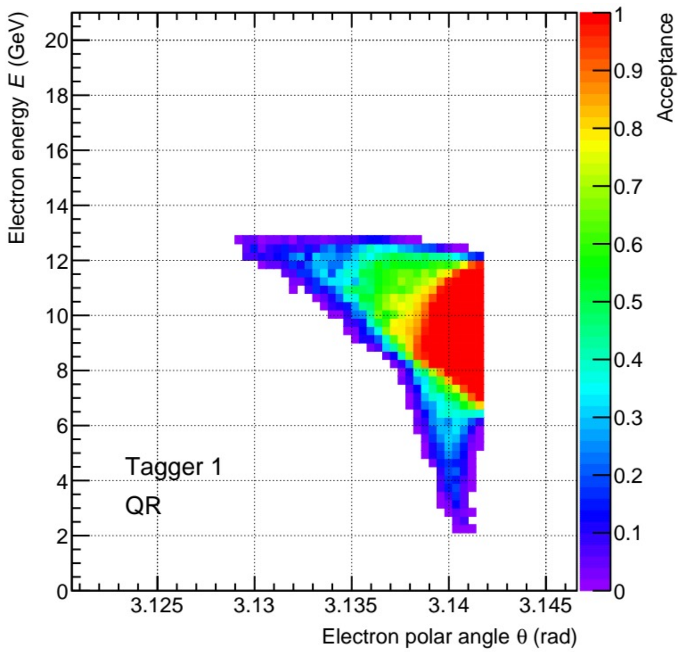
- Tagger 1 and 2 are placed closer (further) from the IP
- Overlap in Q2 acceptance (< 0.1 GeV^2)
- Complementary in electron energy (higher energies reach Tagger 2)
- Consistent for Pythia6 and quasi-real photoproduction (QR)

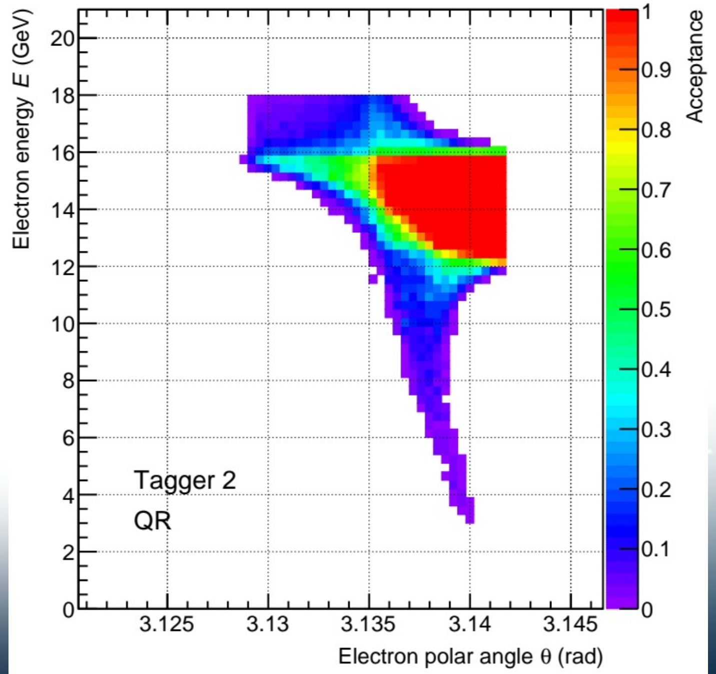


(a) Tagger 1



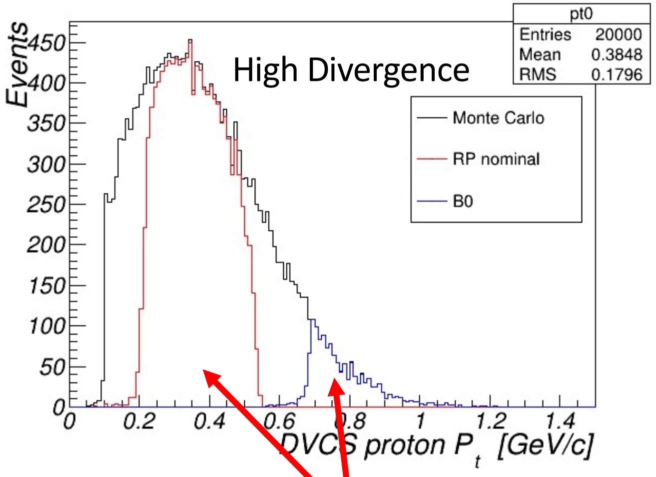
(b) Tagger 2

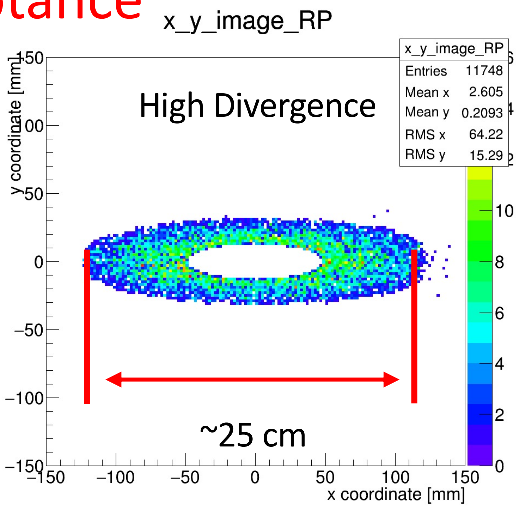


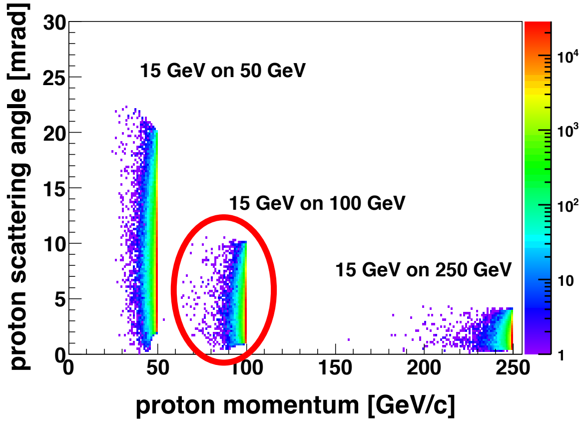


Machine Optics: Roman Pots

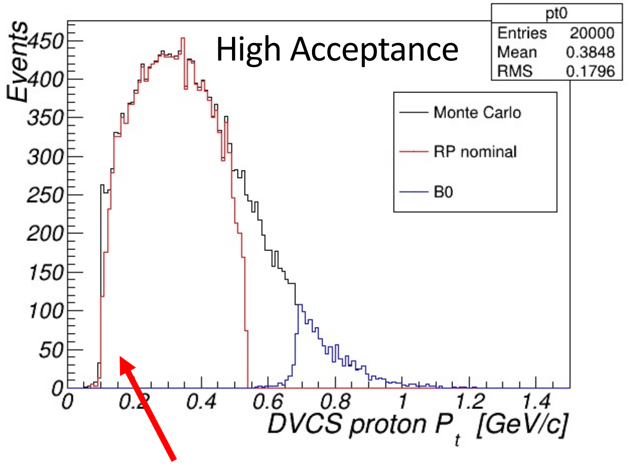
100 GeV DVCS Proton Acceptance

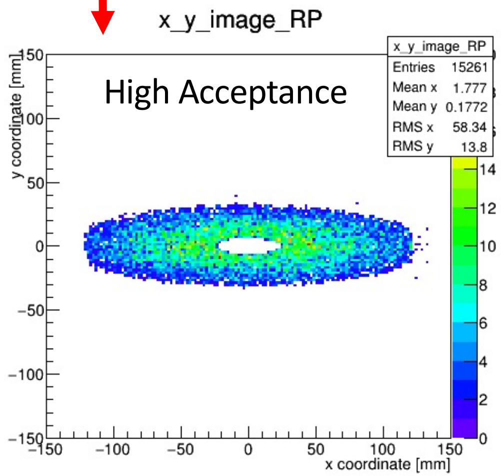






Need both detector systems together here!

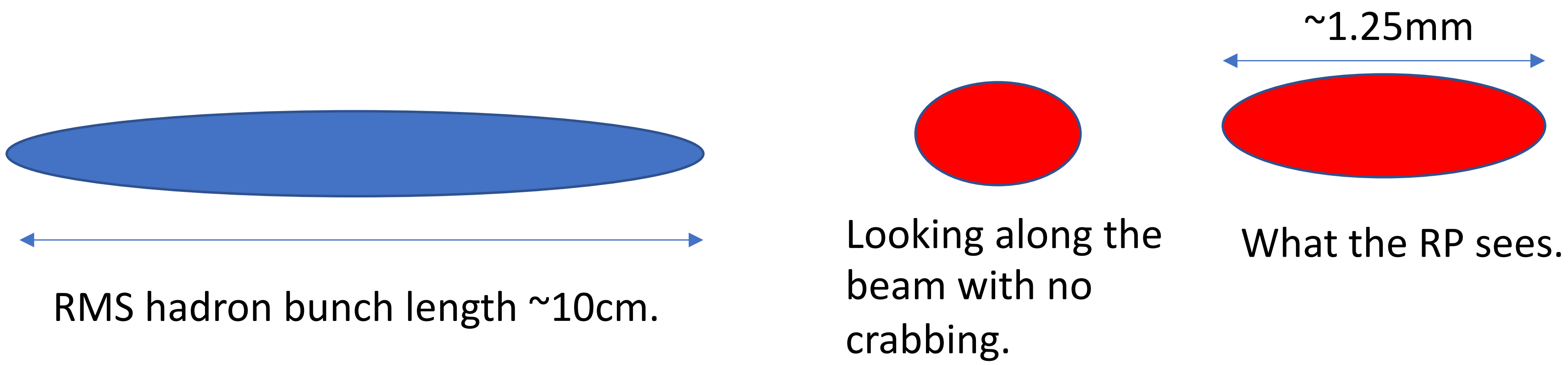




Improves low p_t acceptance.

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?



- 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.

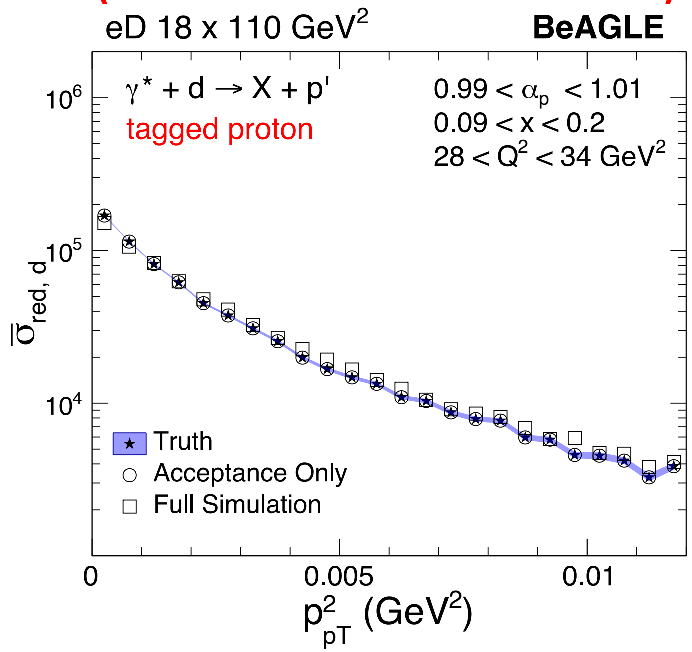
	Ang Div. (HD)	Ang Div. (HA)	Vtx Smear	250um pxl	500um pxl	1.3mm pxl
$\Delta p_{t,total}$ [MeV/c] - 275 GeV	40	28	20	6	11	26
$\Delta p_{t,total}$ [MeV/c] - 100 GeV	22	11	9	9	11	16
$\Delta p_{t,total}$ [MeV/c] - 41 GeV	14	-	10	9	10	12

- **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

Free Neutron F_2 Extraction

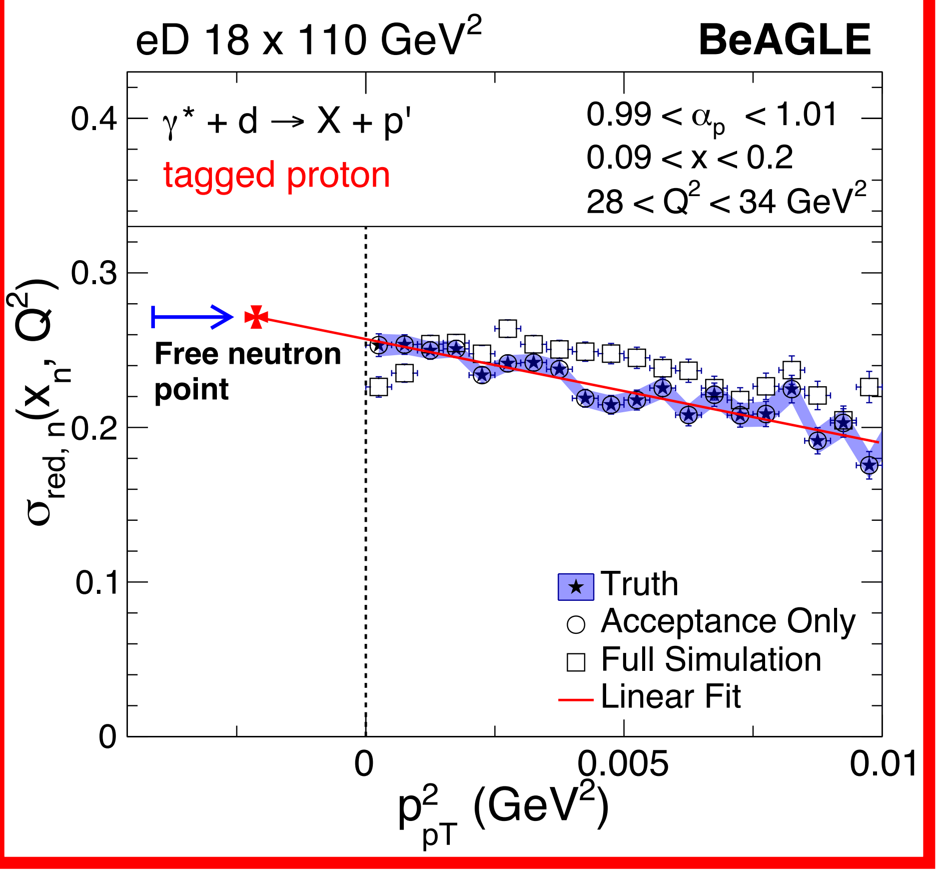
$$\sigma_{red,n}(x,Q^2) = \frac{\sigma_{red,d}}{[2(2\pi)^3]S_d(p_{pT},\alpha_p)}$$

(deuteron reduced cross section)



$$\frac{1}{S_d(p_{pT},\alpha_p)[pole]}$$

(inverse pole of deuteron spectral function)



(Active nucleon reduced cross section)

- Resulting dependence on p_{pT}^2 is very weak and the extrapolation can be performed with a 1st-degree polynomial fit.
- Extrapolation only performed for the generator-level distribution.

$$R = 2\alpha_p^2 m_N \Gamma^2 (2-\alpha_p)$$

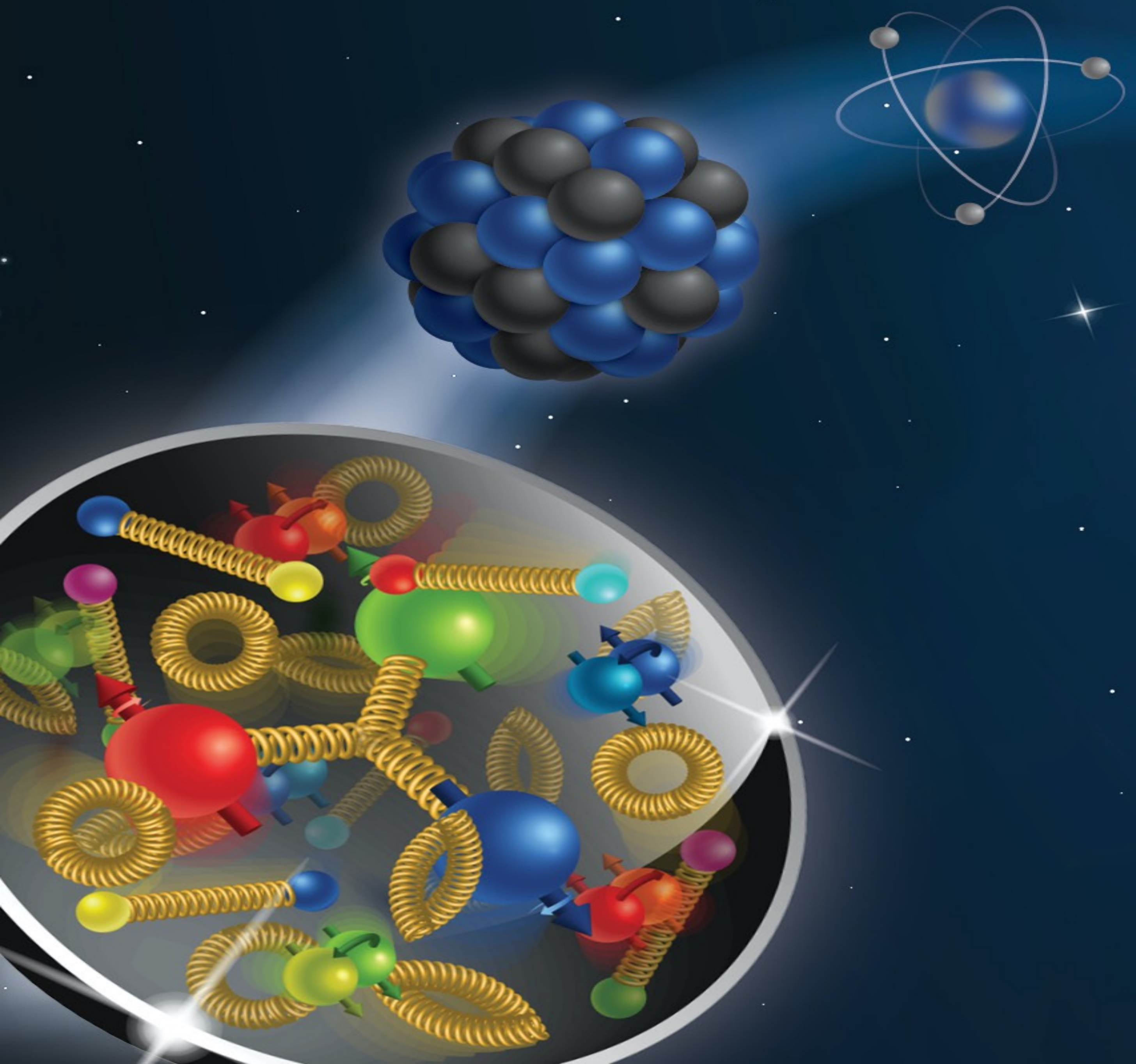
$$a_T^2 = m_N^2 - \alpha_p(2-\alpha_p)\frac{M_d^2}{4}$$

$$S_d(p_{pT},\alpha_p)[pole] = \frac{R}{\left(p_{pT}^2 + a_T^2\right)^2}$$

$R = residue\ of\ spectral\ function$

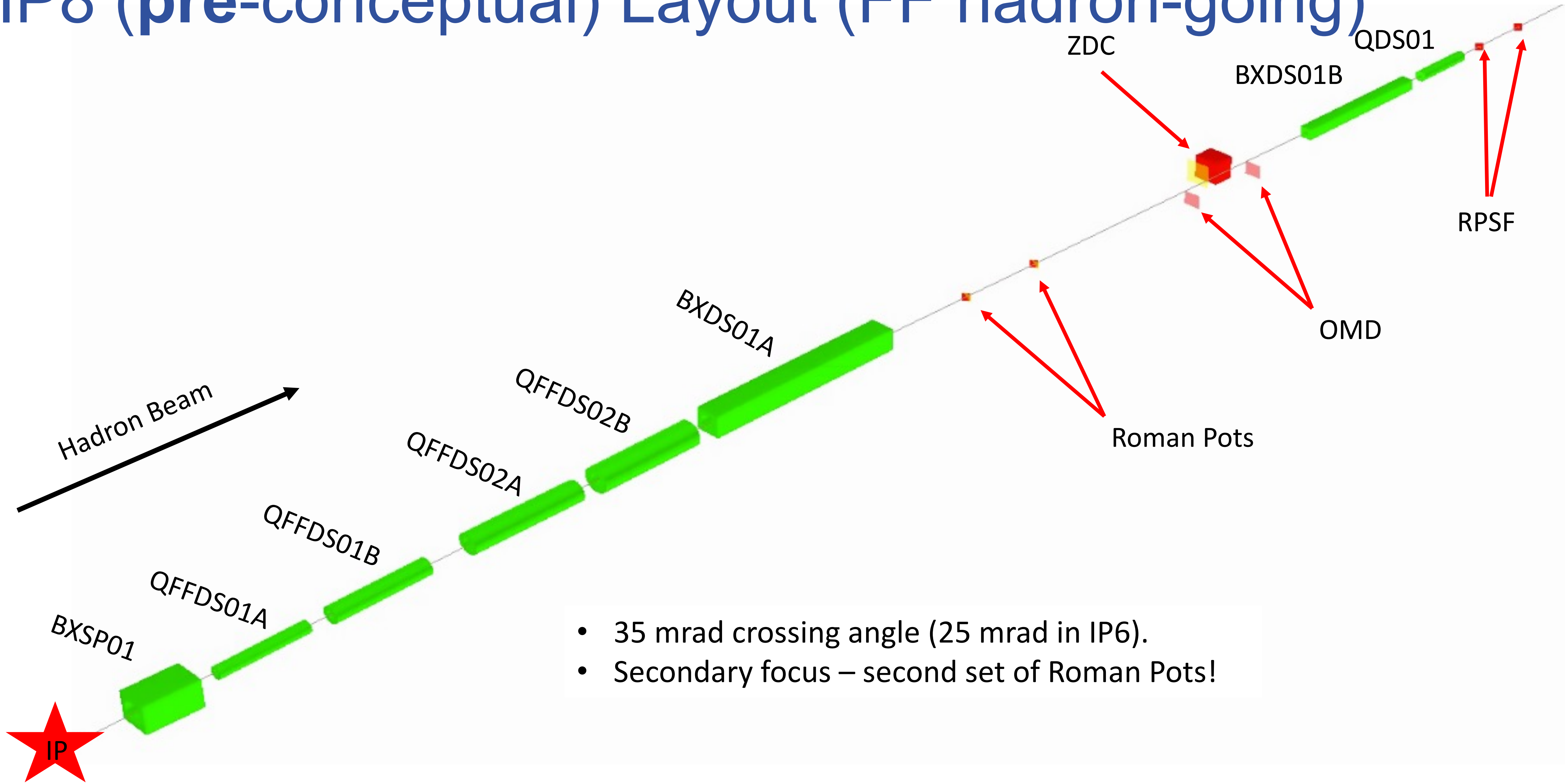
$a_T^2 = position\ of\ pole$

https://arxiv.org/abs/2108.08314
Submitted to Physical Review C



What about IP8?

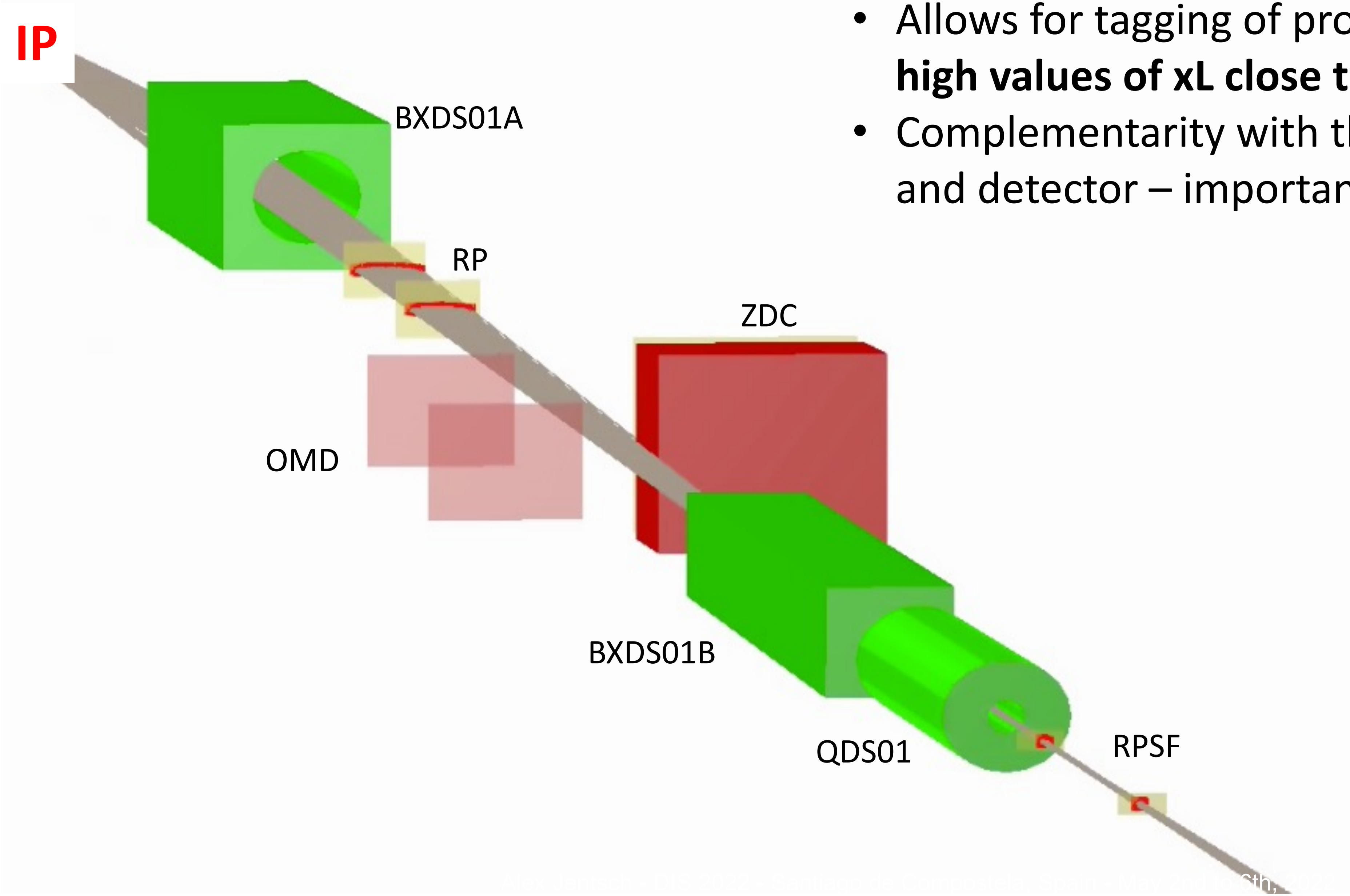
IP8 (**pre**-conceptual) Layout (FF hadron-going)



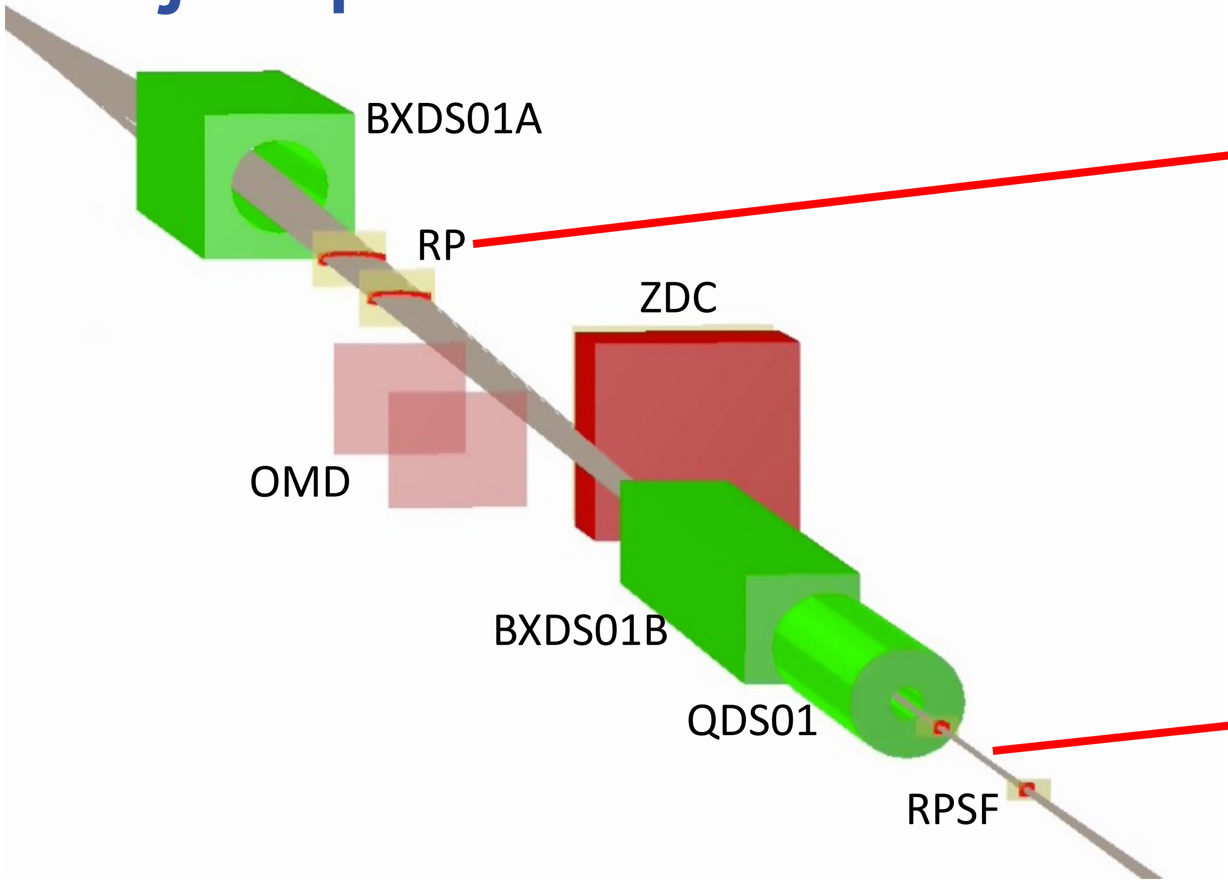
- 35 mrad crossing angle (25 mrad in IP6).
- Secondary focus – second set of Roman Pots!

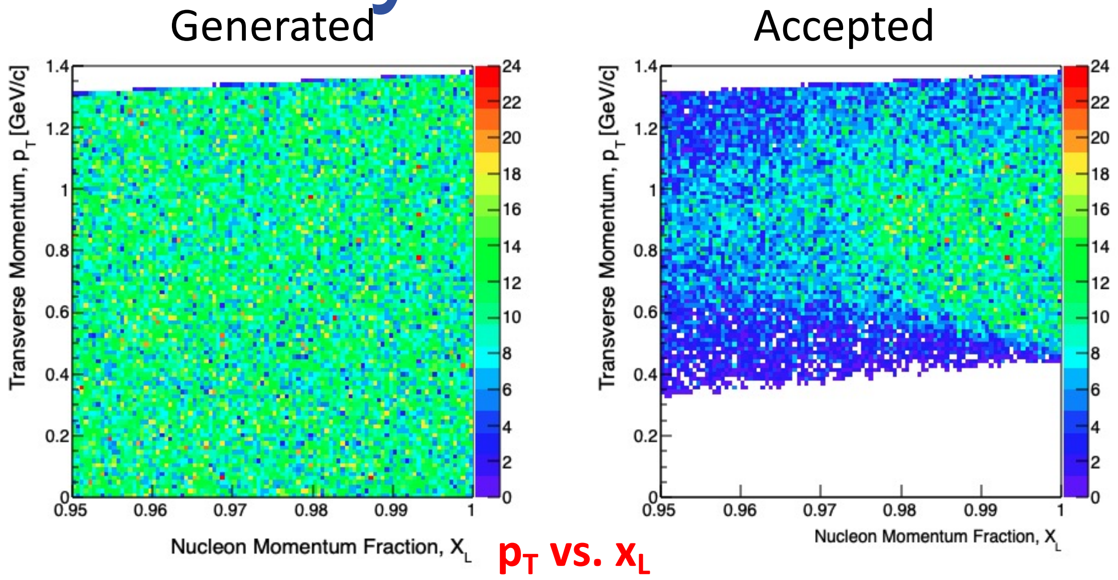
Major potential benefit: Secondary Focus

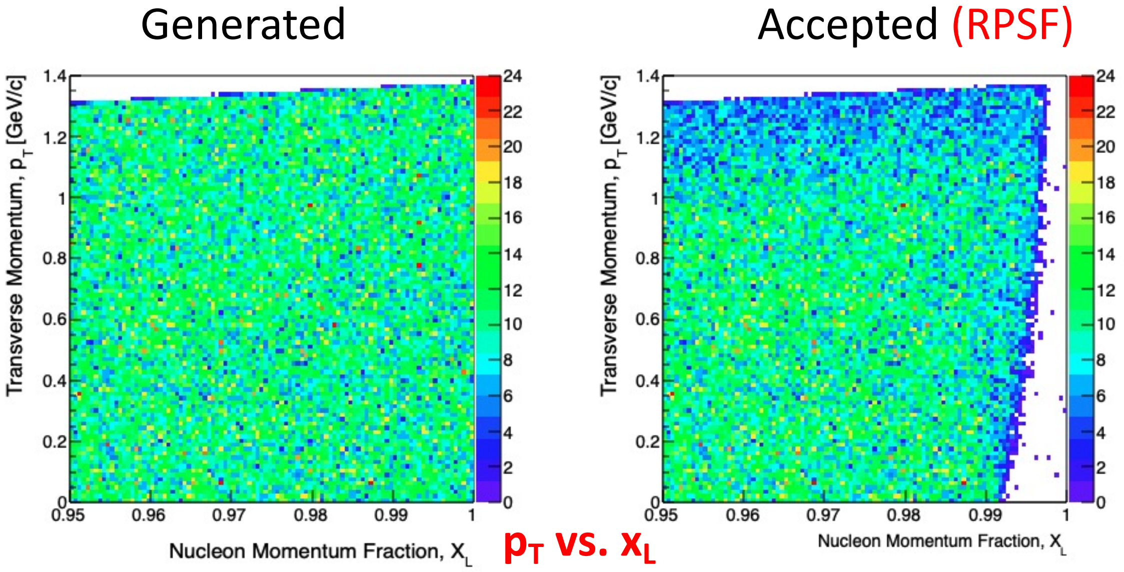
- Allows for tagging of protons and nuclei at very **high values of xL close to one** (pT ~ 0).
- Complementarity with the IP6 configuration and detector – important for the EIC!



Major potential benefit: Secondary Focus



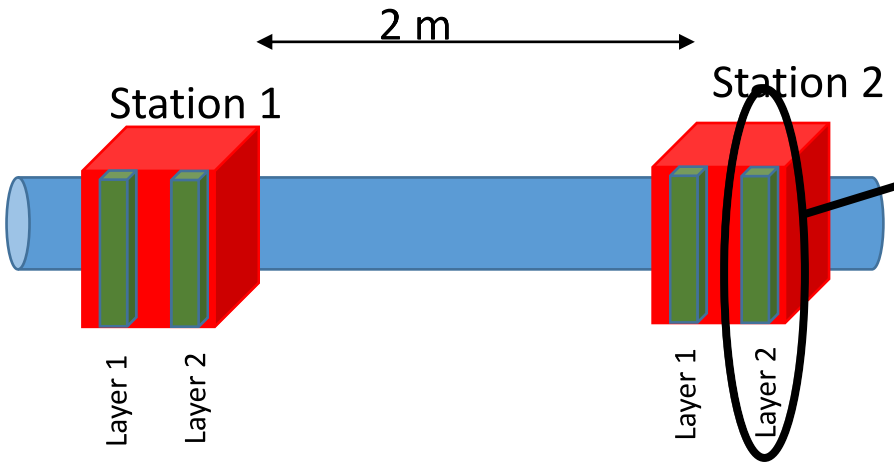


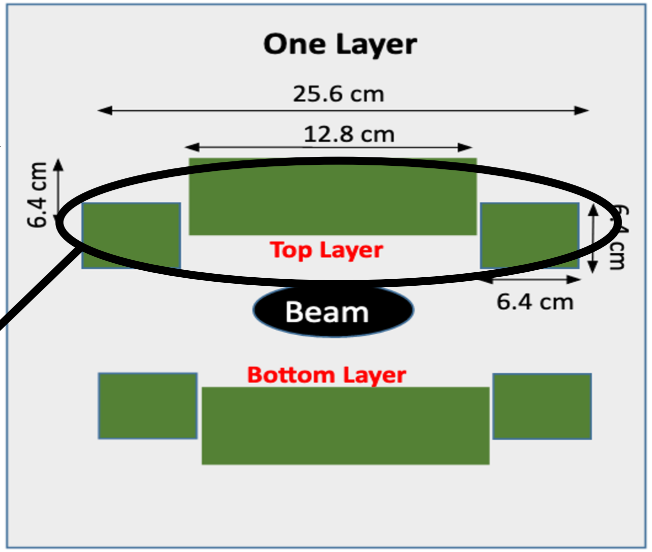


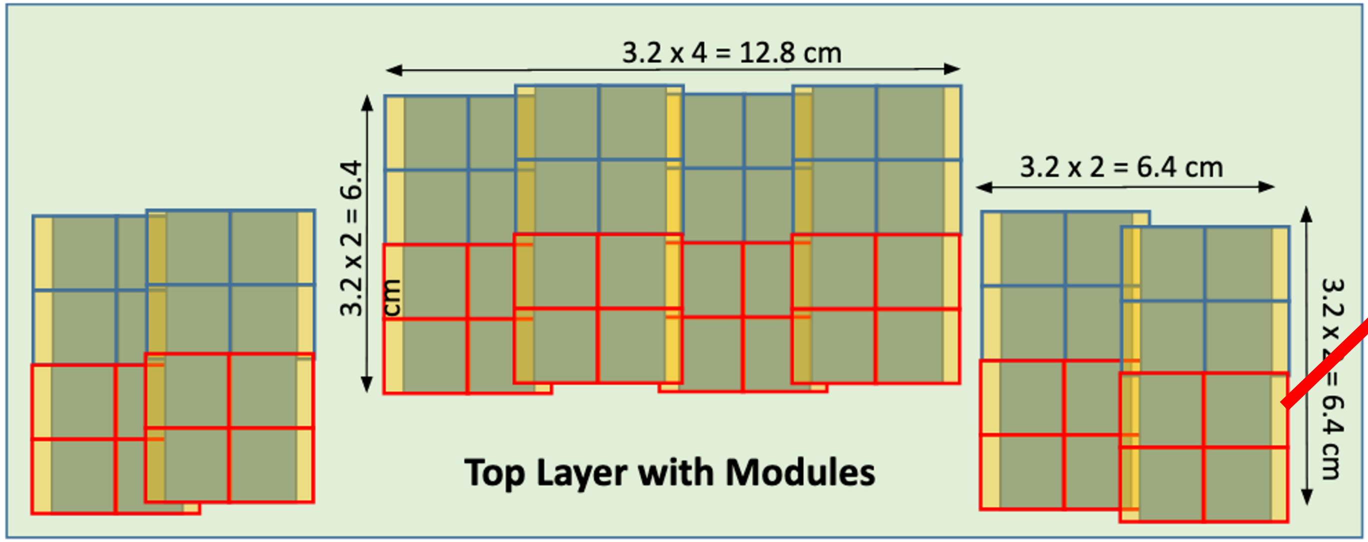
$$x_L = \frac{p_{z,particle}}{p_{beam}}$$

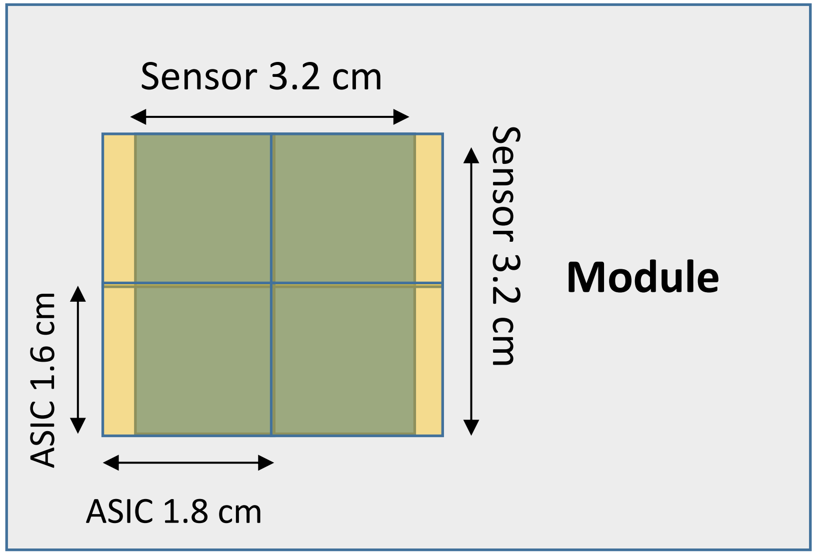
Roman Pots @ the EIC

- 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.