Far-forward detectors at the Electron-Ion Collider

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On behalf of the EPIC Collaboration

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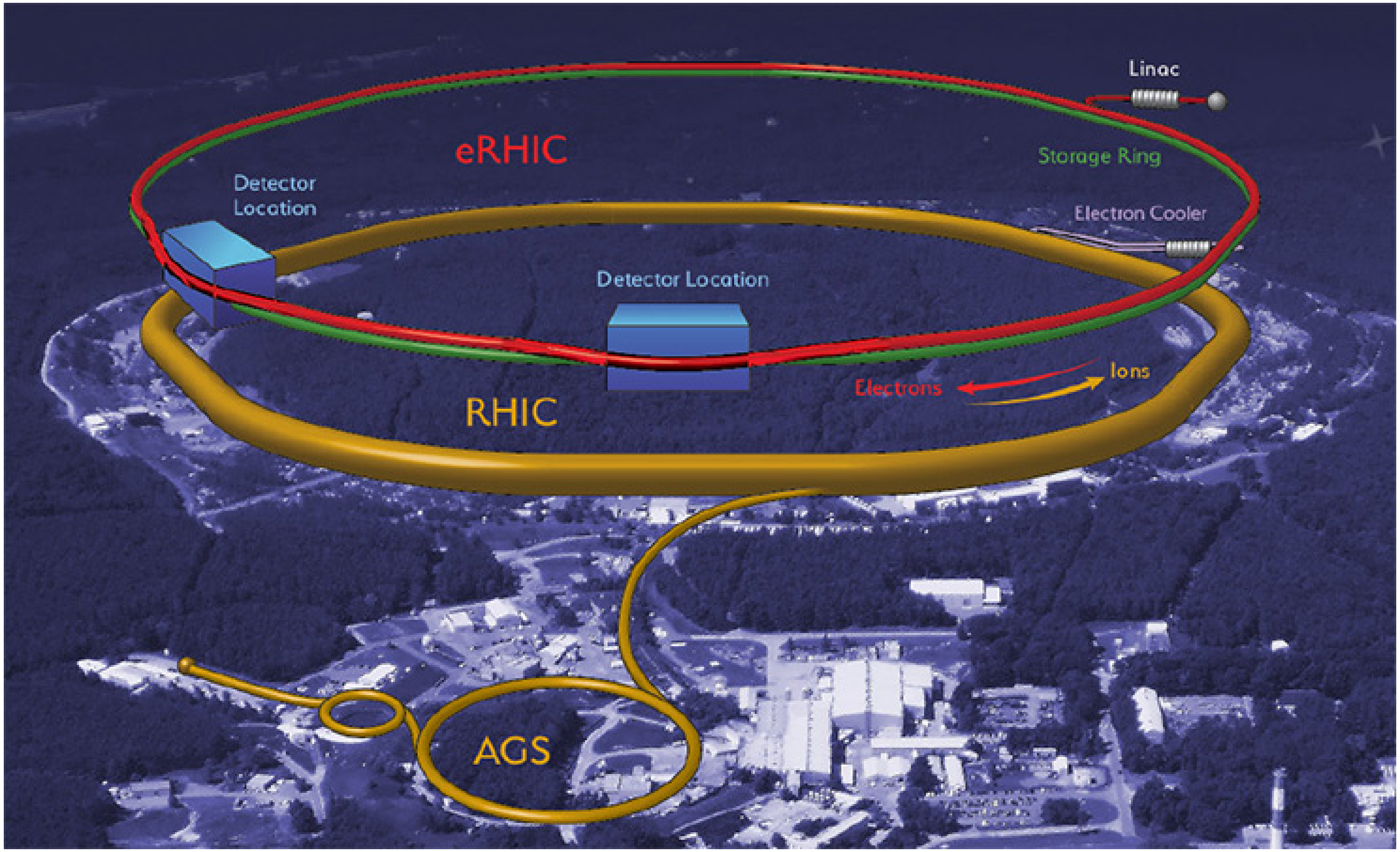
Outline

- Introduction and motivation
- Far Forward Calorimeters
  - B0 Detector
  - ZDC
    - All designs and simulations correspond to the proposed ECCE Detector
- Physics studies examples
- Summary

Electron-Ion Collider

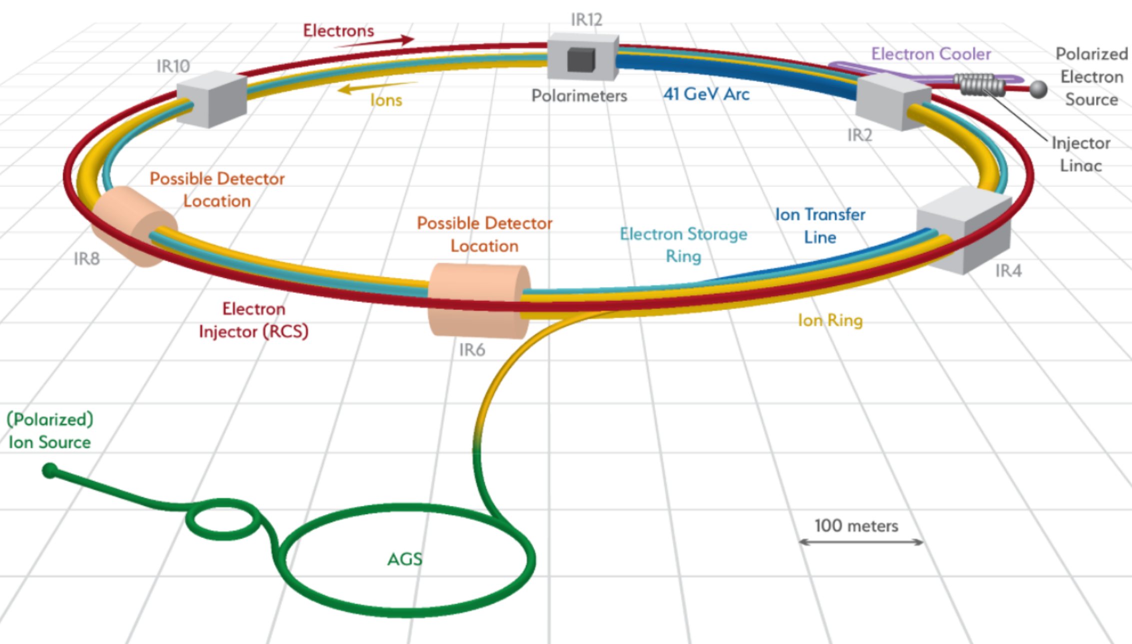
To be build around 2030 at Brookhaven National Laboratory



An EIC can uniquely address three fundamental questions about nucleons – neutrons and protons - and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

EIC Accelerator



EIC will be the first dedicated facility to collide electron with ions (protons) in a wide range of c.m.s. energies.

Moreover, it will allow studies with **highly polarized beams (not possible at HERA)**

E_e: 5 … 18 GeV

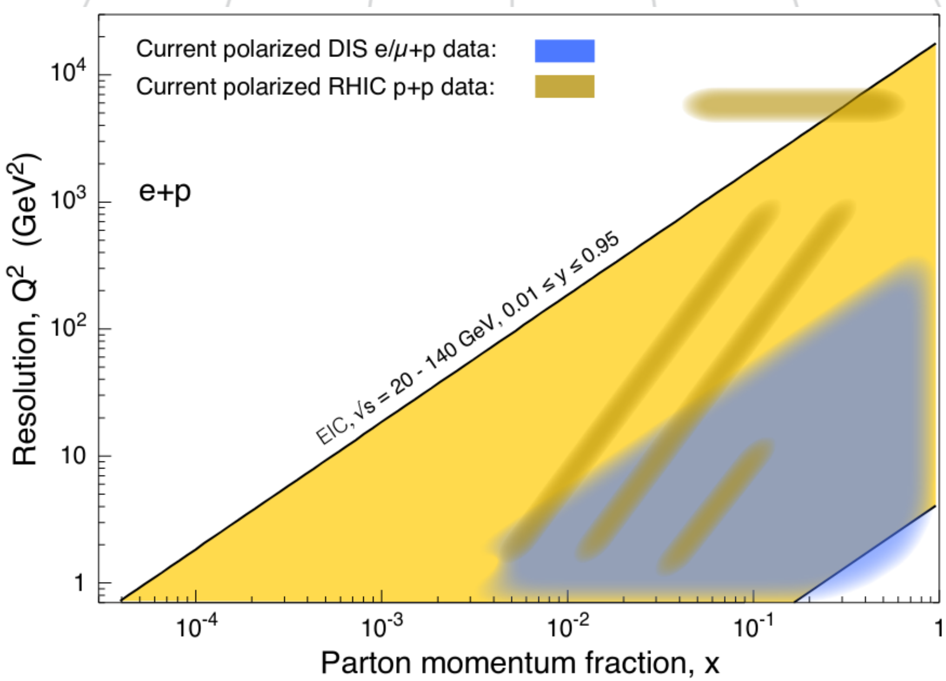
E_p: 41, 100 … 275 GeV

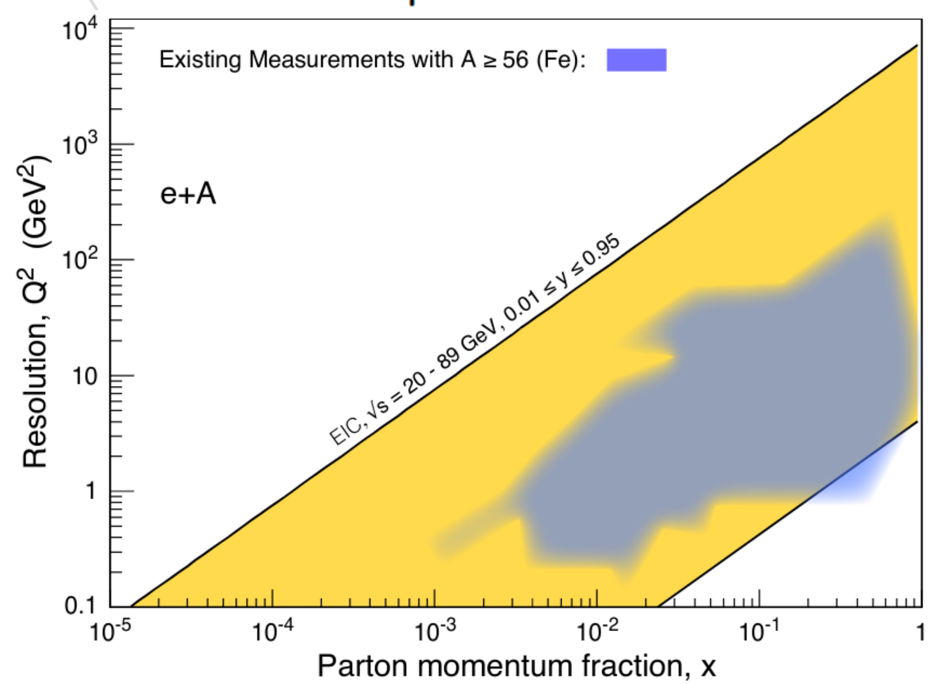
E_{ion}: 41 … 110 GeV/n

Ions: from p to U

Pol (e,p,He, etc): >70%

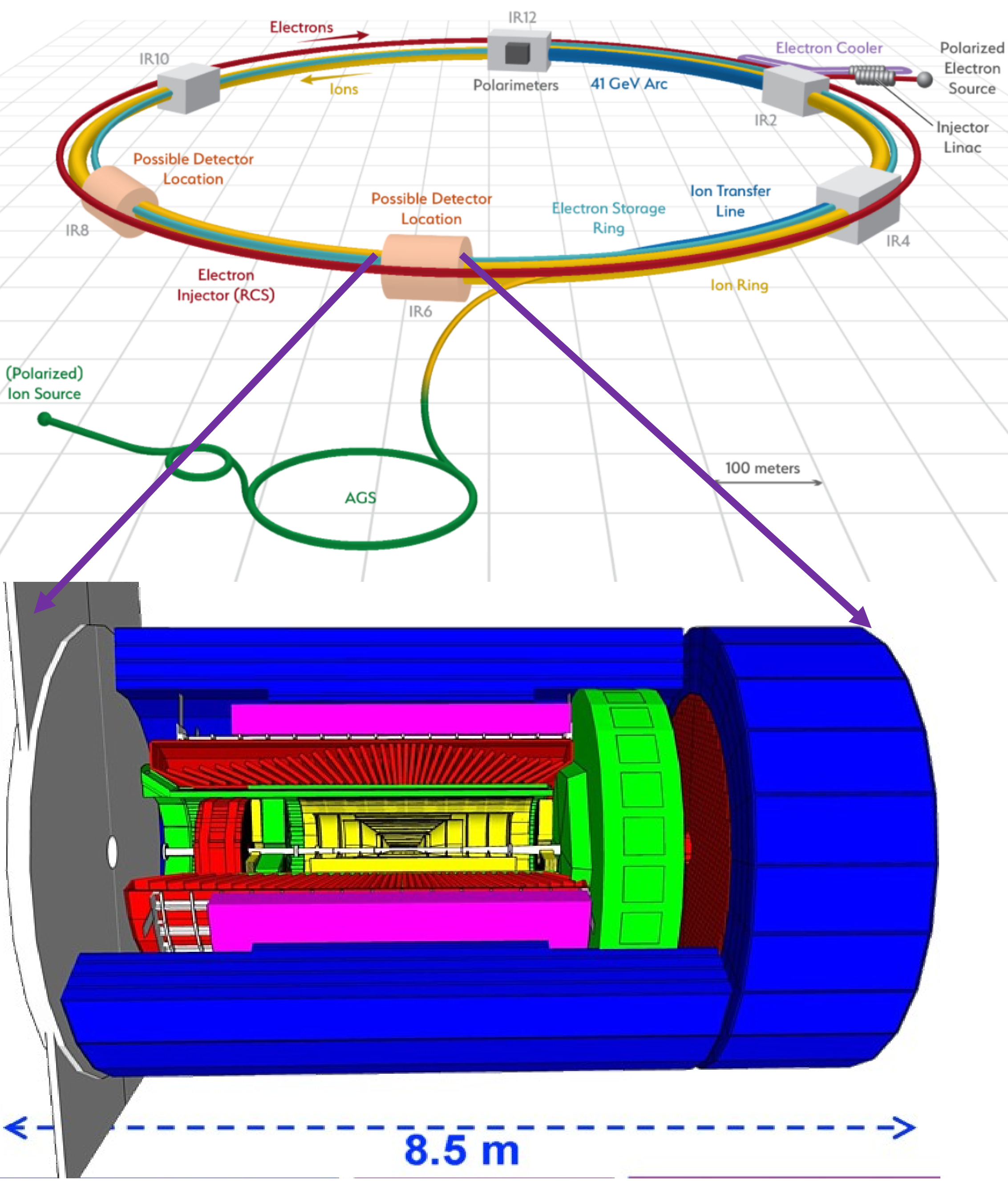
Lum: up to 10^{34} cm^{-2} s^{-1}





Colliding electrons to ions gives access to unexplored kinematic regions with the lowest possible *x* values.

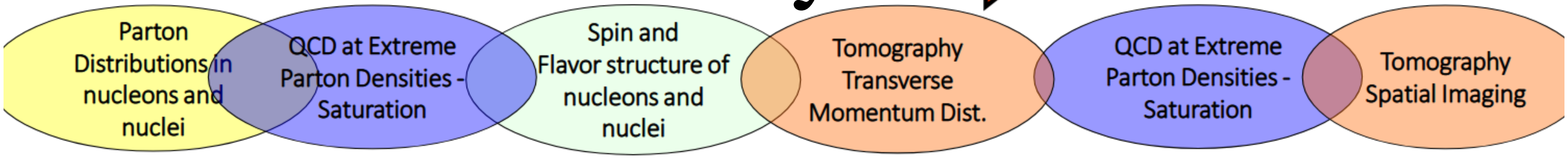
EIC Detector(s)

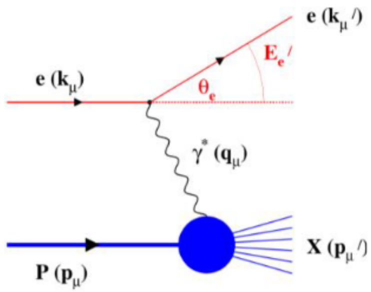


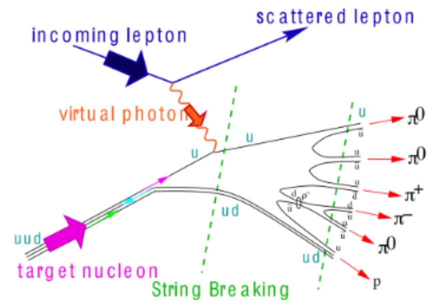
Design optimized to reach 10^{34} $cm^{-2}sec^{-1}$

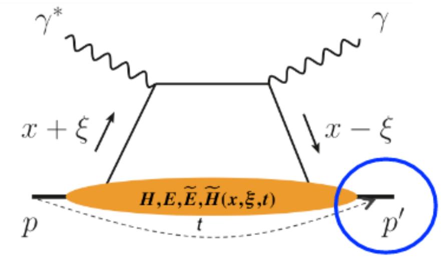
- Reference detector based on the 1.5T BaBar solenoid and ECCE reference design.
- Contains detectors for tracking, PID, and calorimetry.
- Second detector possible, but funding must be raised to support it.

EIC Physics









Inclusive DIS

- measure scattered lepton
- multi-dimensional binning: x, Q^2

→ reach to lowest x, Q^2 impacts Interaction Region design

→ low mass detectors, excellent e/h separation

Semi-inclusive DIS

- measure scattered lepton and hadrons in coincidence
- multi-dimensional binning: x, Q^2, z, p_T, ϕ

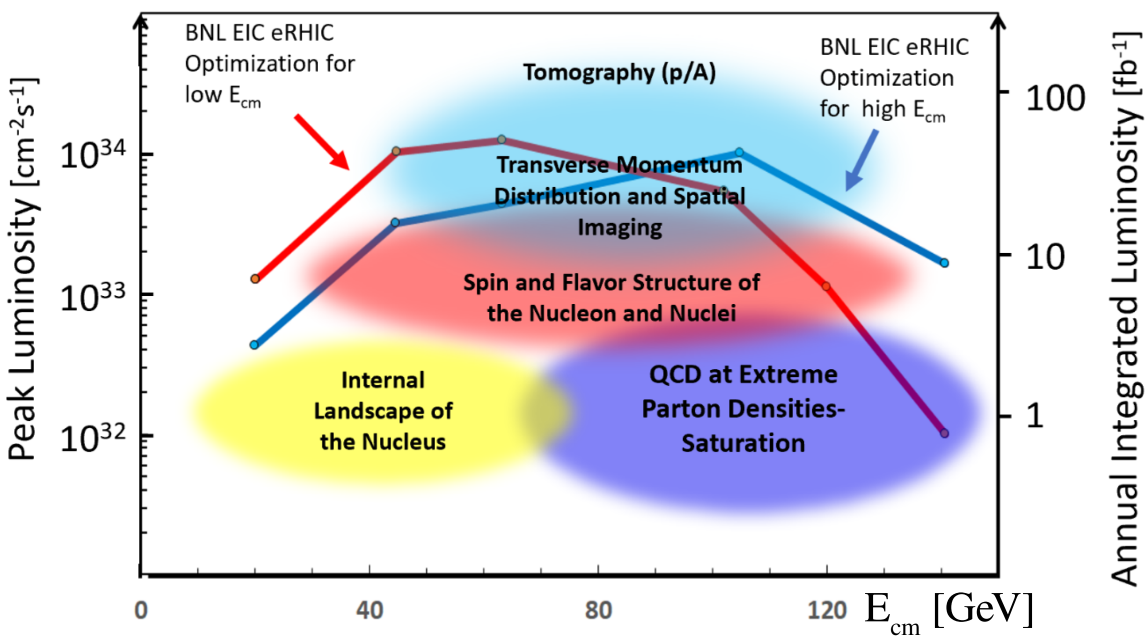
→ particle identification over entire region is critical

Exclusive processes

- measure all particles in event
- multi-dimensional binning: x, Q^2, t, ϕ
- proton p_t: 0.2 - 1.3 GeV

→ cannot be detected in main detector

→ strong impact on Interaction Region design

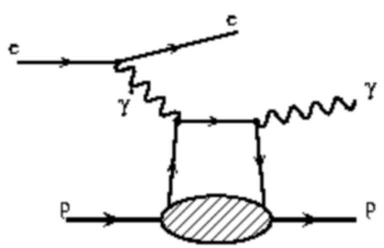


A wide range of the physics processes can be measured at EIC.

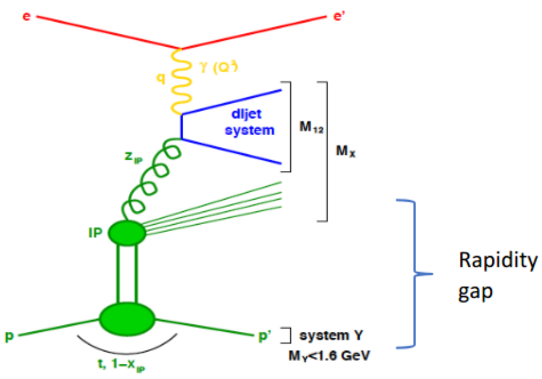
A comprehensive detector with a large rapidity (-4 <η< 4) coverage is essential for these studies.

Far-forward physics at EIC

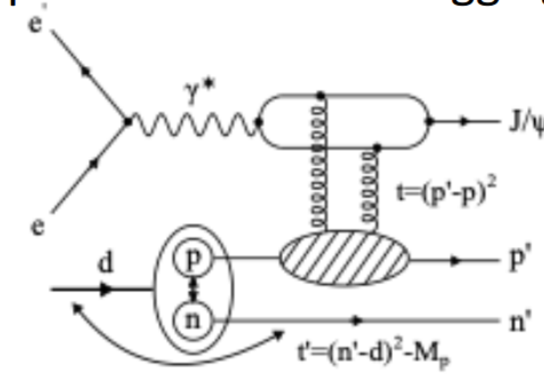
e+p DVCS events with proton tagging.



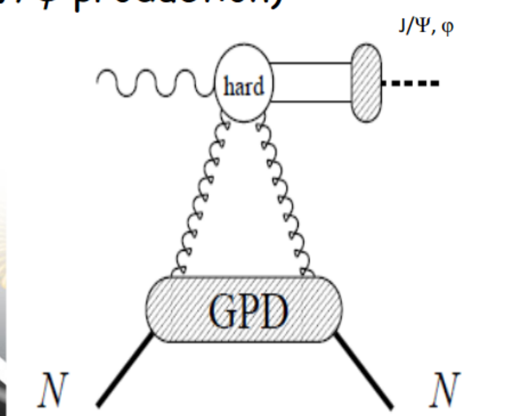
Diffraction



e+d exclusive J/ψ and DIS events with proton or neutron tagging

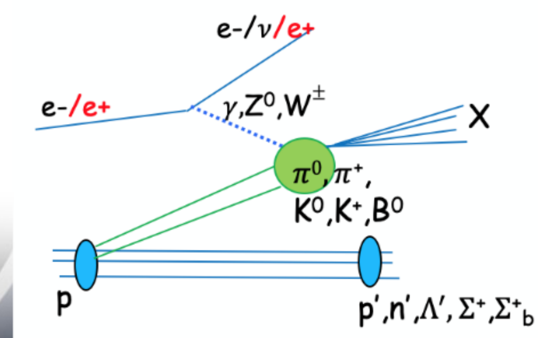


Saturation (coherent/incoherent J/ψ production)



Meson structure:

- with neutron tagging (ep→ (π) →e' n X)
- Lambda decays ($\Lambda \to p\pi^-$ and $\Lambda \to n\pi^0$)



e+He3 with spectator proton tagging.

e+He4 coherent He4 tagging.

e+Au events with neutron tagging to veto breakup and photon acceptance.

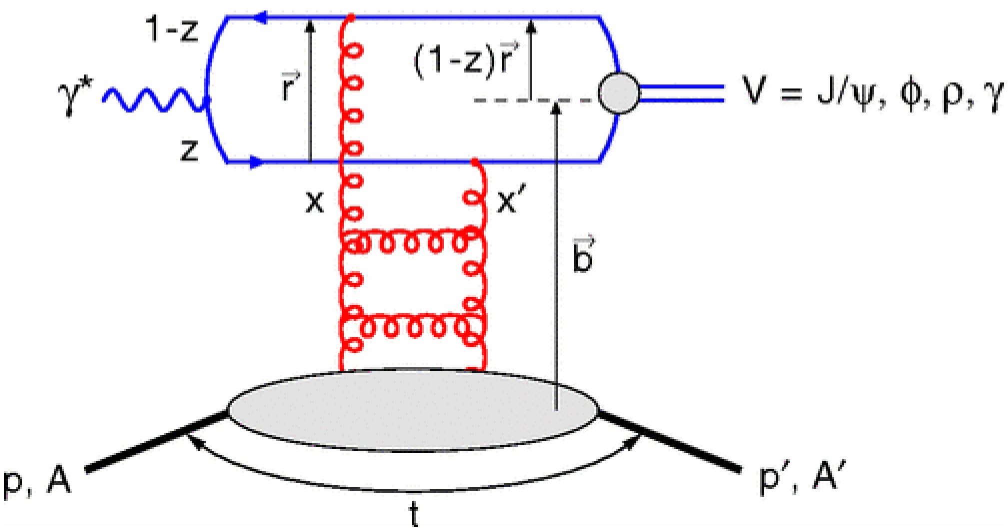
....

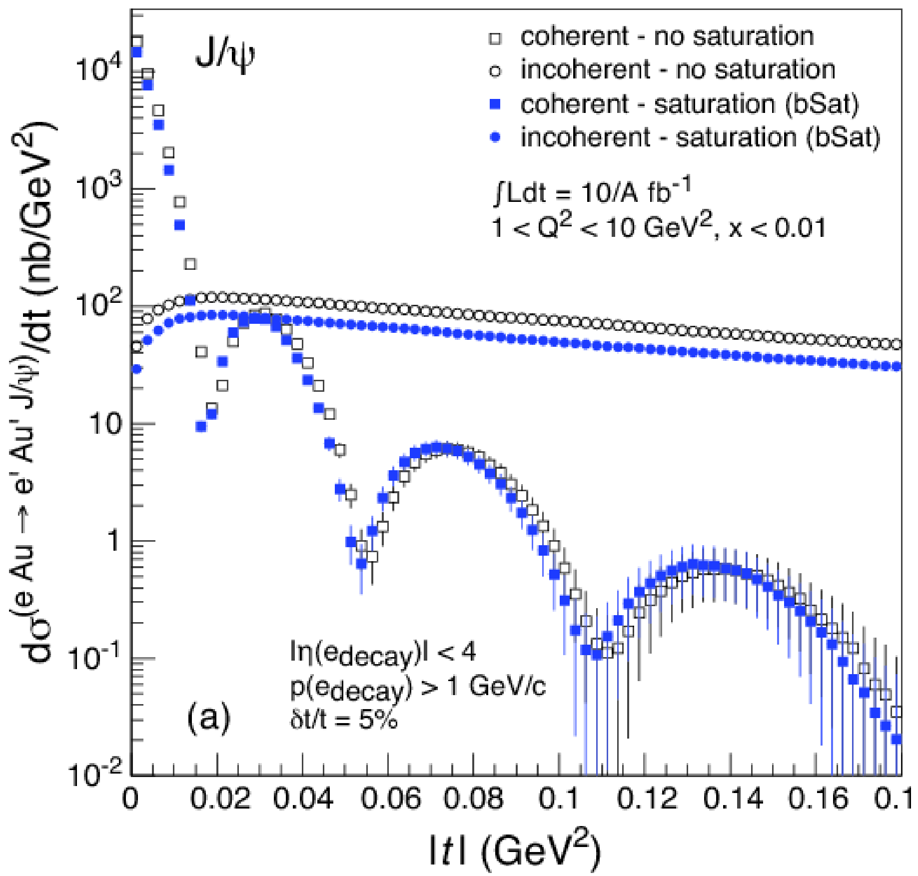
- The various physics channels require tagging of charged hadrons (protons, pions) or neutral particles (neutrons, photons) at very-forward rapidities (**η>4.5**).
- Different final states require different detector subsystem for detection.
- Different collision systems provide unique challenges due to magnetic rigidity difference between beam and final-state particles.
- Placing far-forward detectors uniquely challenging due to presence of machine components, space constraints, apertures, etc

B0 and ZDC applications: Exclusive VM production

Both B0 (*PS or EMCal design*) and ZDC can be used to veto events with forward going photons

T. Toll and T. Ullrich





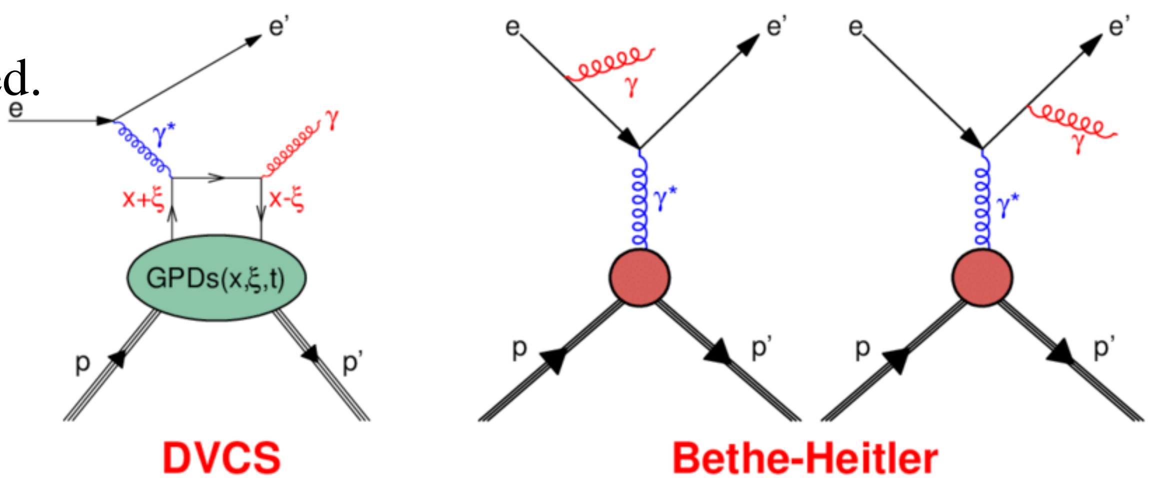
Measurement of the coherent spectrum down to the 3rd diffractive minimum requires rejection of incoherent events.

Nuclear breakup in incoherent events produces soft photons (~300 MeV) in the forward direction from the de-excitation of some of the larger nuclear fragments.

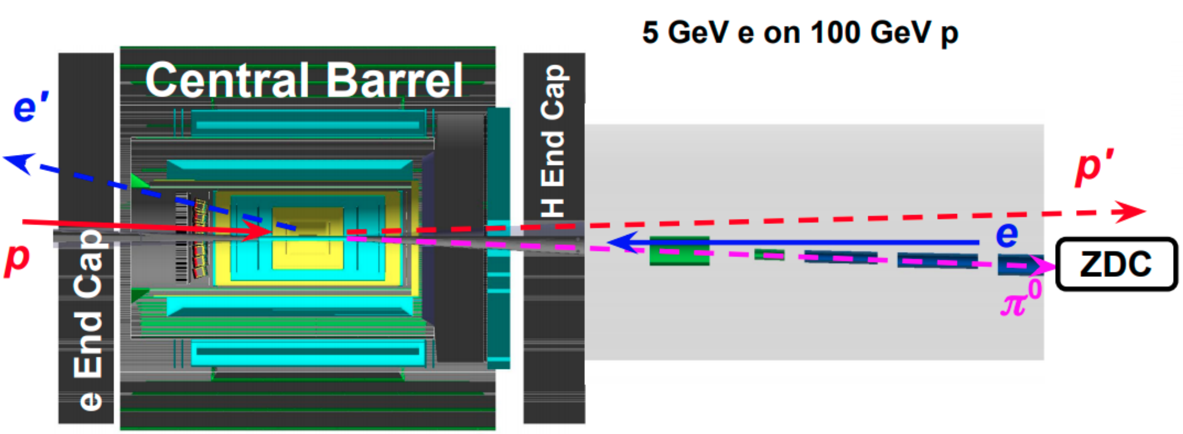
B0 and ZDC applications: u-channel DVCS

- For studies of *u*-Channel (Backward-angle) exclusive electroproduction, need capability to reconstruct photons from decays.
  - Physics beyond the EIC white paper!
- Would require full B0 EMCAL with high granularity and energy resolution.
- Longitudinal space in B0pf magnet limited.
  - Would be a great candidate for an upgrade or for IP8!

Deeply Virtual Compton Scattering



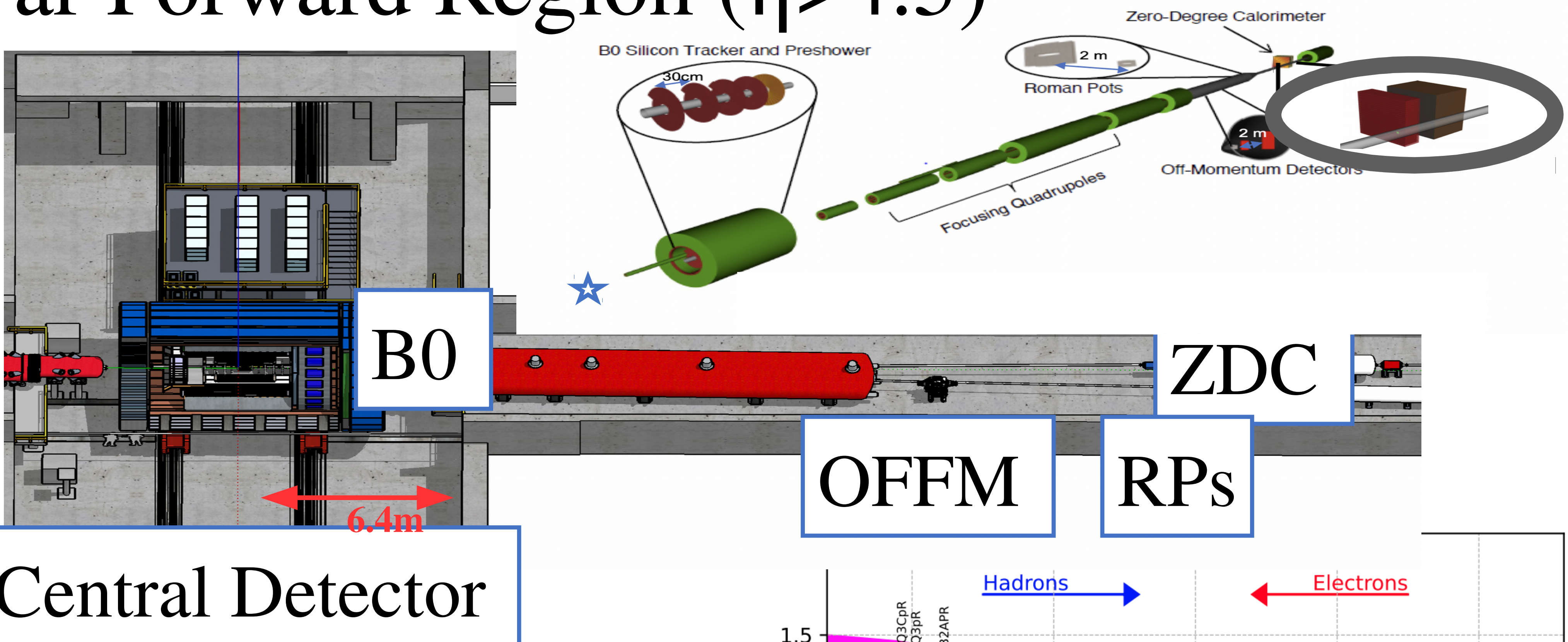
u-Channel Meson Production Setup

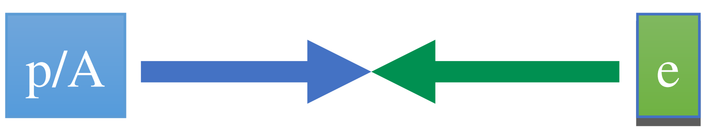


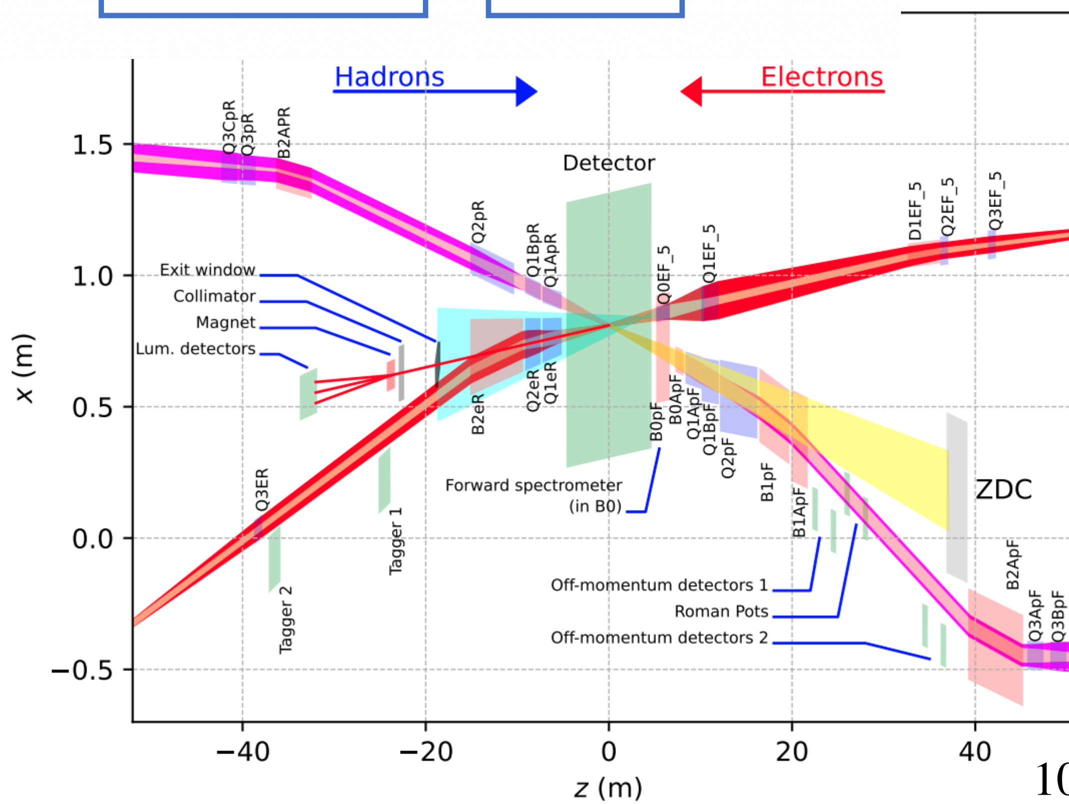
GPD: It is extracted predominantly based in the forward angle observables.

TDA: meson-nucleon Transition Distribution Amplitude (TDA) only accessible through backward (u-channel) meson production

Far Forward Region (η>4.5)

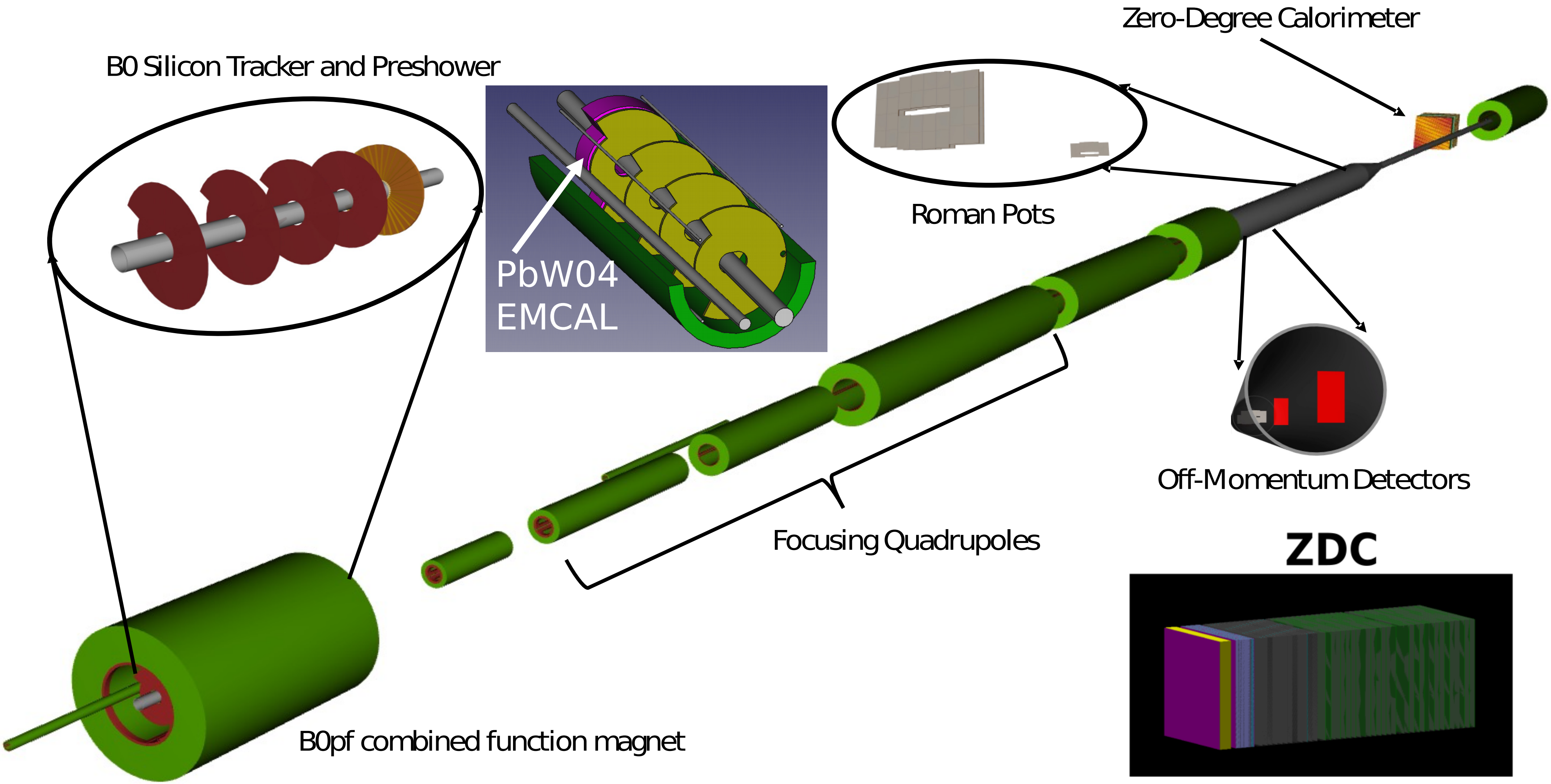






- Central detector spans 9 meters and is machine-component free.
- Hadron-going and electron-going directions fully instrumented.
- Hadron and electron beam cross with an angle of 25mrad.

EIC Far-Forward region



Detector	(x,z) Position [m]	Dimensions	θ [mrad]	Notes	Acceptance
ZDC	(-0.96, 37.5)	(60cm, 60cm, 1.62m)	$\theta < 5.5$	$\sim$4.0 mrad at $\phi = \pi$	η > 6.0
Roman Pots (2 stations)	(-0.83, 26.0) (-0.92, 28.0)	(30cm, 10cm)	$0.0 < \theta < 5.5$	10 σ cut.	η > 6.0
Off-Momentum Detector	(-1.62, 34.5), (-1.71, 36.5)	(50cm, 35cm)	$0.0 < \theta < 5.0$	$0.4 < x_L < 0.6$	η > 6.0
B0 Trackers and Calorimeter	(x = -0.15, 5.8 < z < 7.0)	(32cm, 38m)	$6.0 < \theta < 22.5$	$\sim$20 mrad at ϕ=0	4.6 > η > 5.9

Challenges to B0 tracking and calorimeter systems

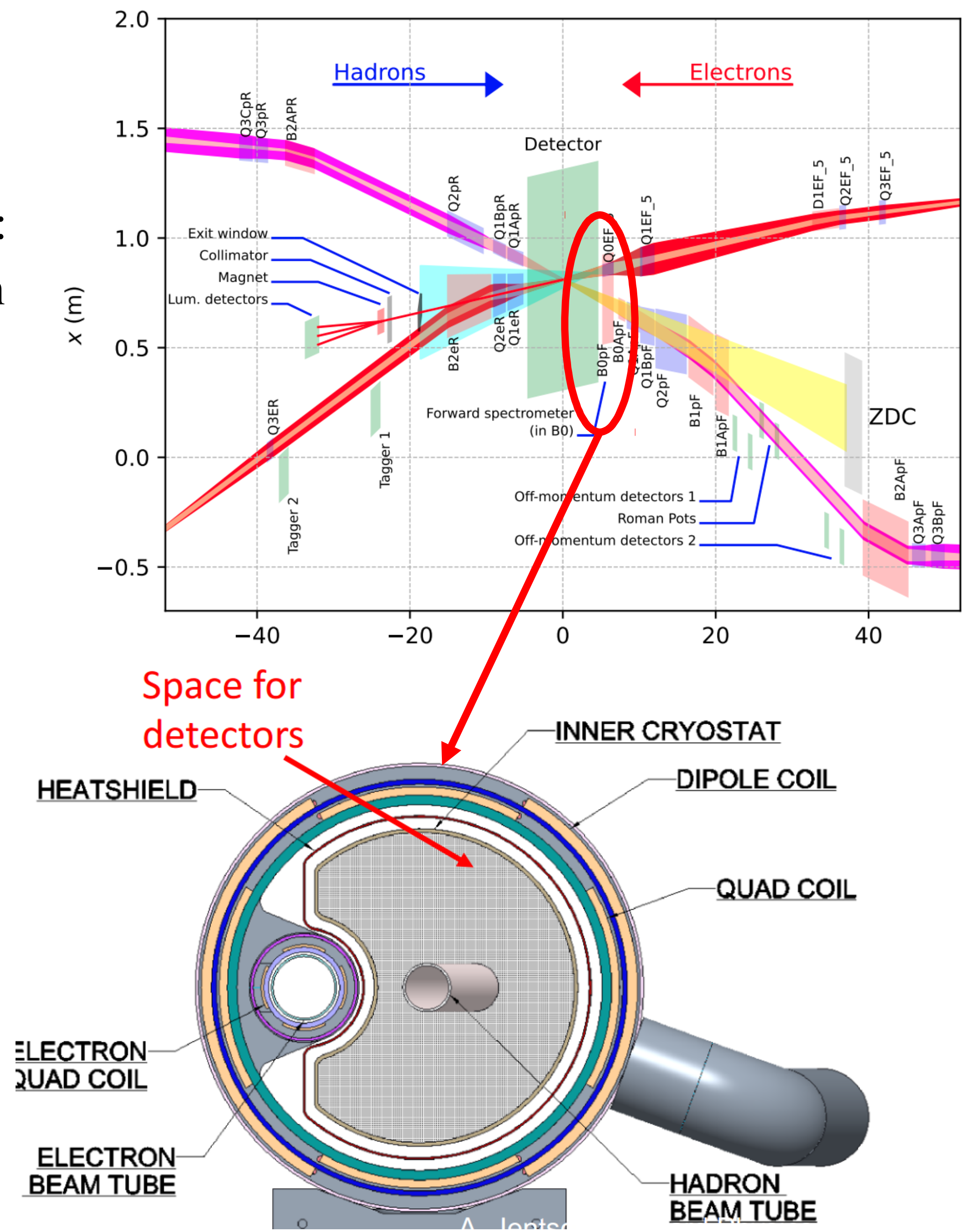
1. Both B0 detectors are located inside a **20 cm** radius magnet

2. The B0 is the most challenging EIC magnet: it needs to provide both field for the proton/ion beam and no field for the electron beam, in limited space.

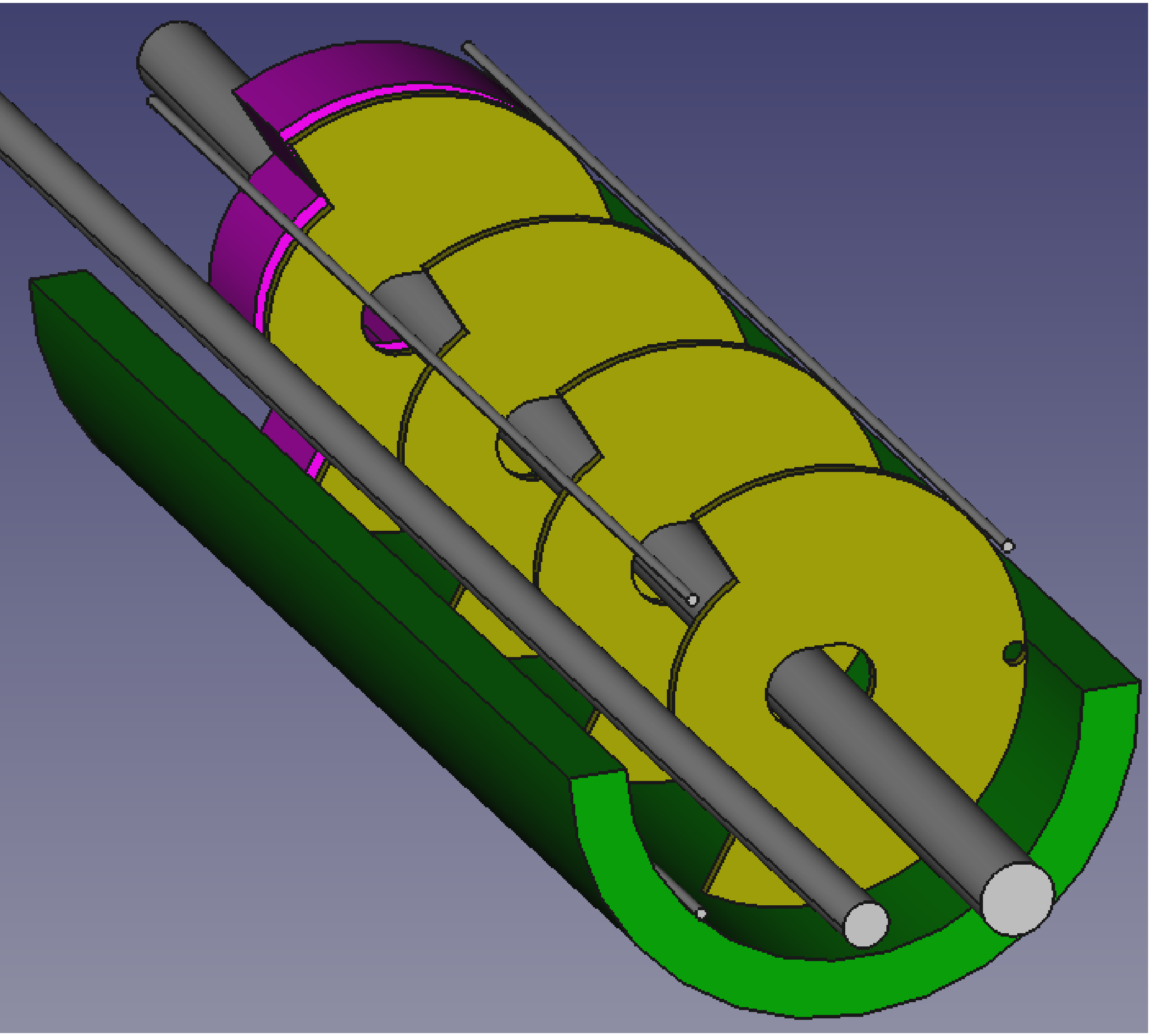
3. The acceptance along z changes due to the crossing angle (25mrad) as the B0 is aligned with the electron beam.

4. Access only possible from IP side, and no access from the hadron downstream side as that region is integrated with the cold mass.

5. High radiation environment.



B0 tracker and calorimeter design



Four Si tracking planes occupy 1m of 120cm
2mm of Cu after each tracking layer to model cooling and readout

They are followed by 10cm $PbW0_4$ Calorimeter 2*2cm granularity

7cm at the back of the Calorimeter are assumed for its readout

Oval shape of the cut off for the hadron beam:

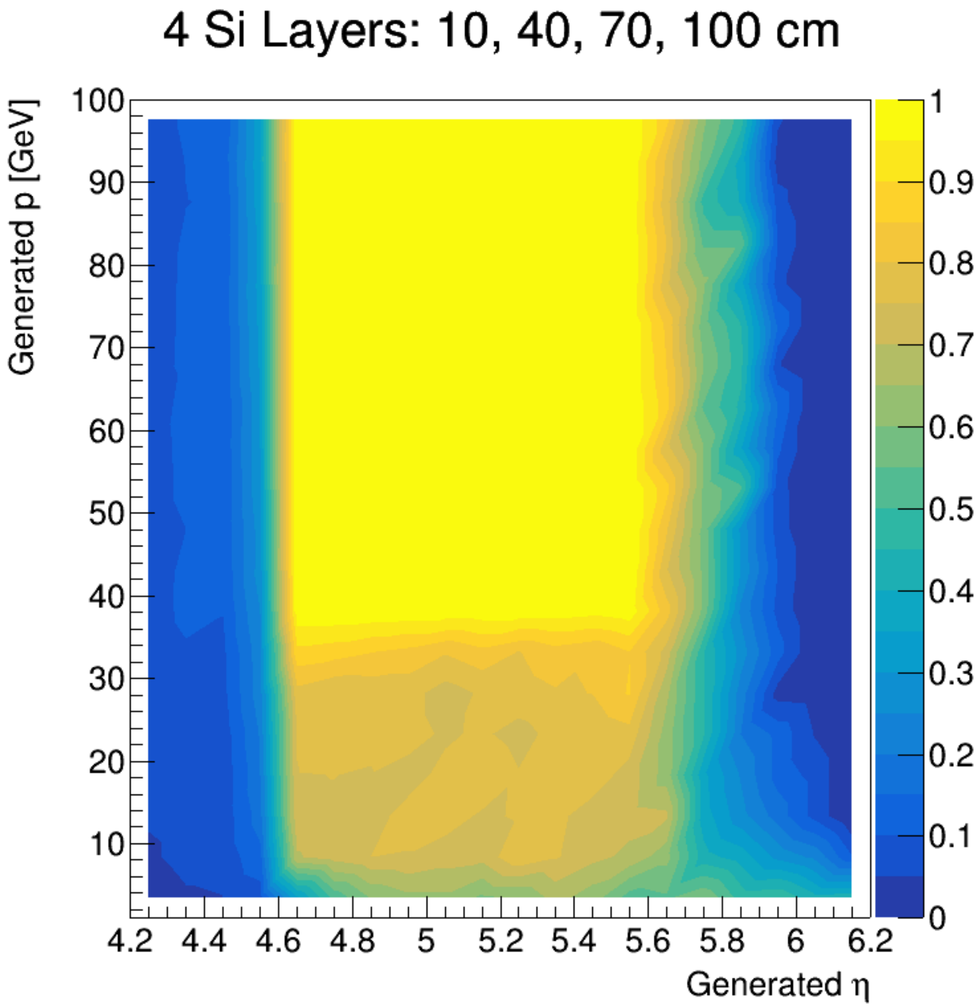
- Account for the 25mrad crossing angle
- Allows to increase the acceptance at large η

Geant4 Simulation:

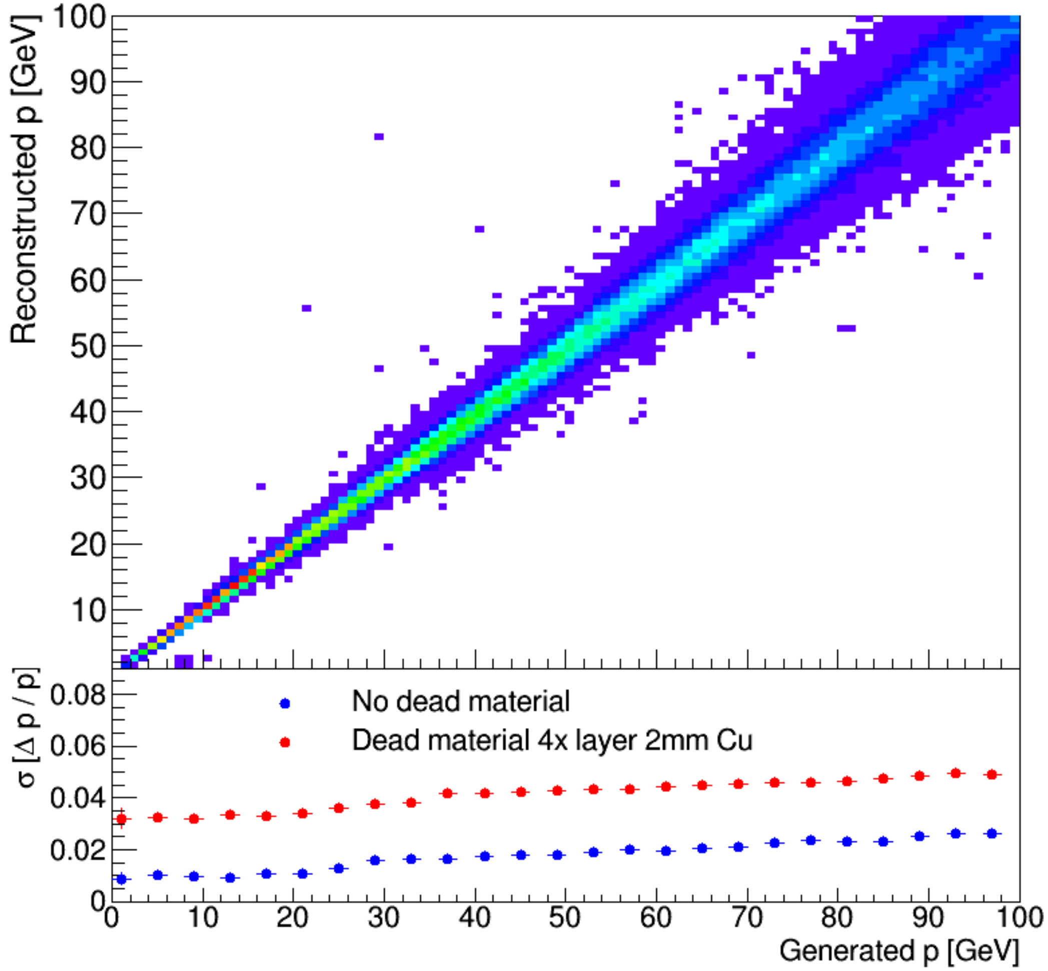
- Charged particle reconstruction and photon tagging.
  - Precise tracking (~10µm spatial resolution).
  - Fast timing for background rejection and to remove crab smearing (~35ps).
  - Photon detection (tagging or full reco).

B0 tracker

Acceptance



Resolution

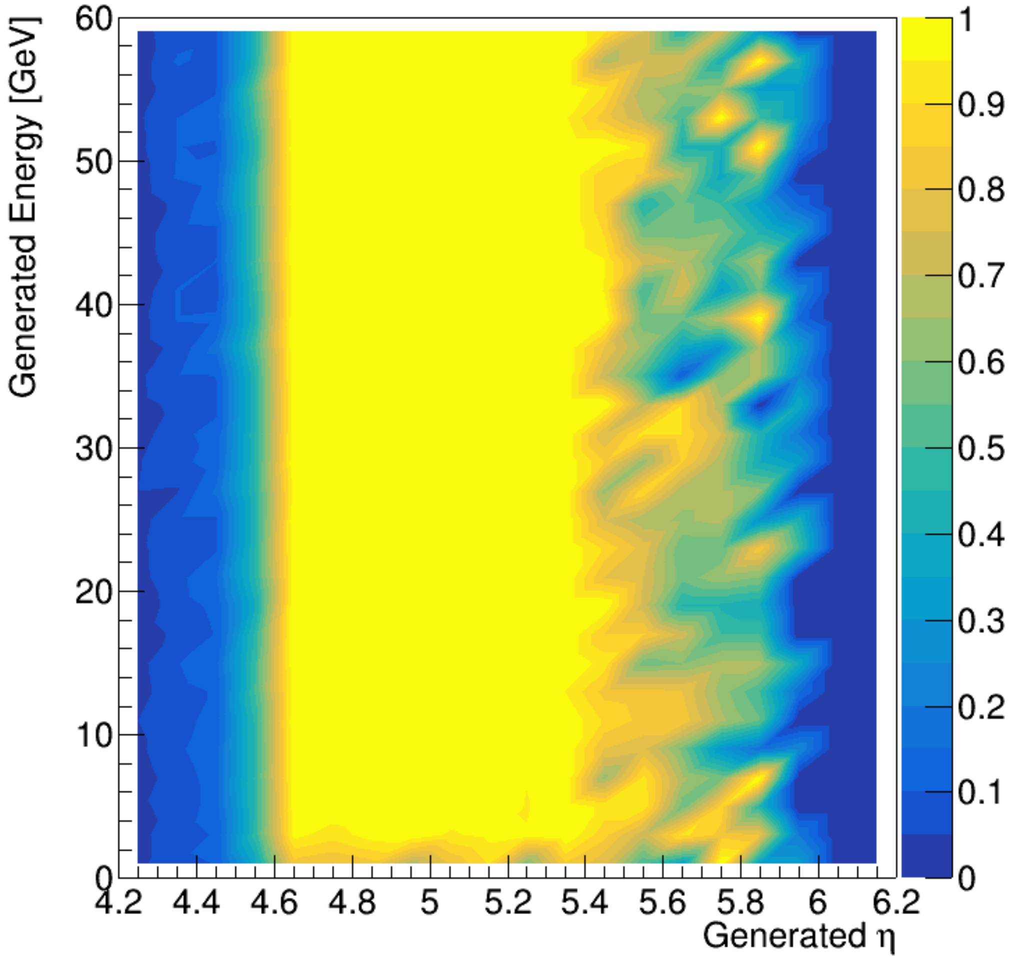


The achieved resolution is below **5%** for all p_T in the realistic design assuming 2mm dead layers for readout

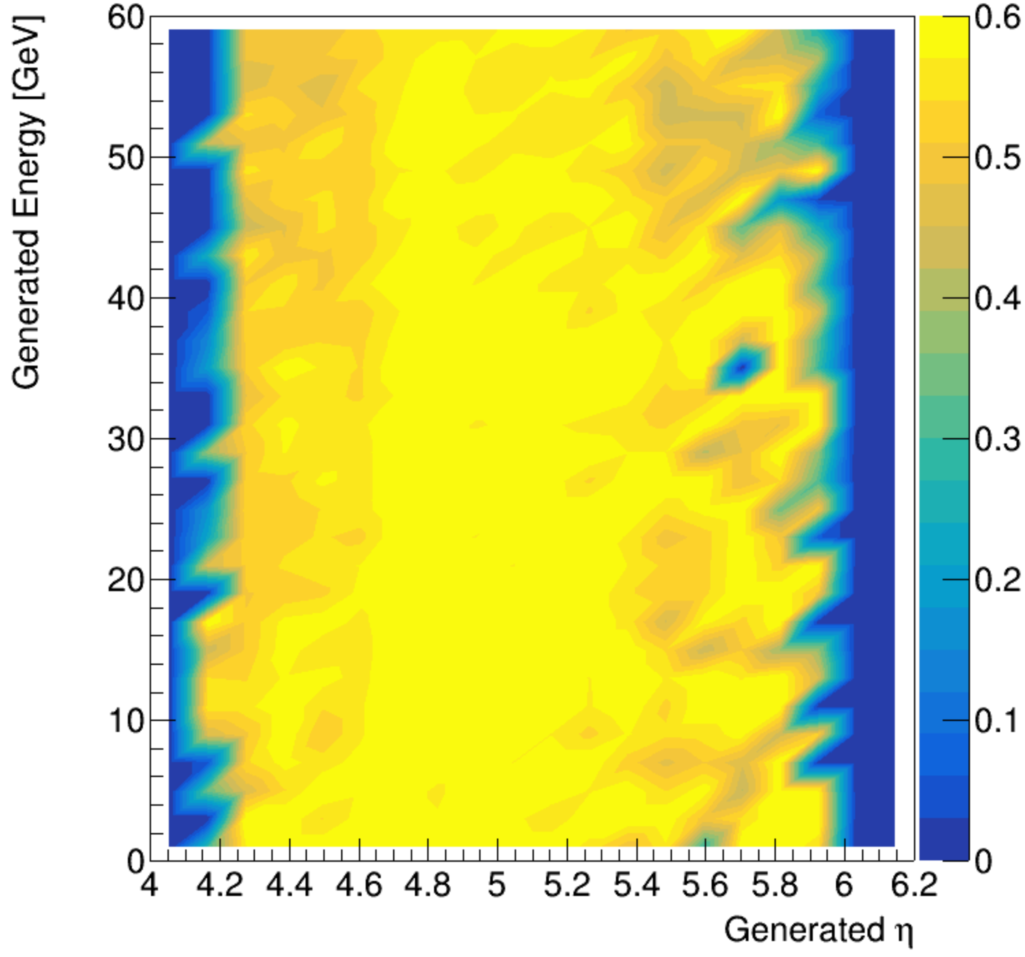
A. Bylinkin et. al [2208.14575]

B0 calorimeter

Acceptance

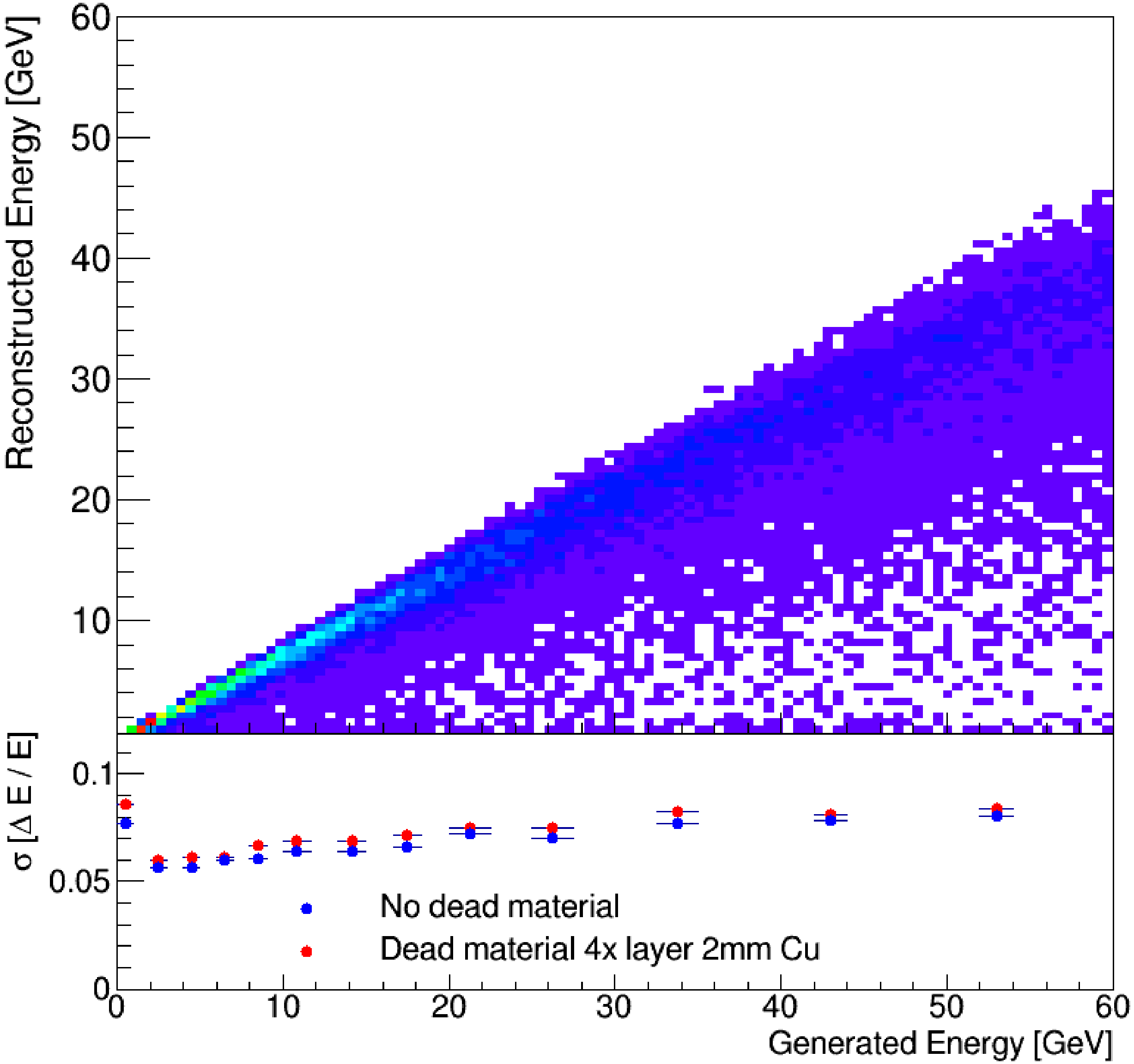


Reconstructed / Generated Energy

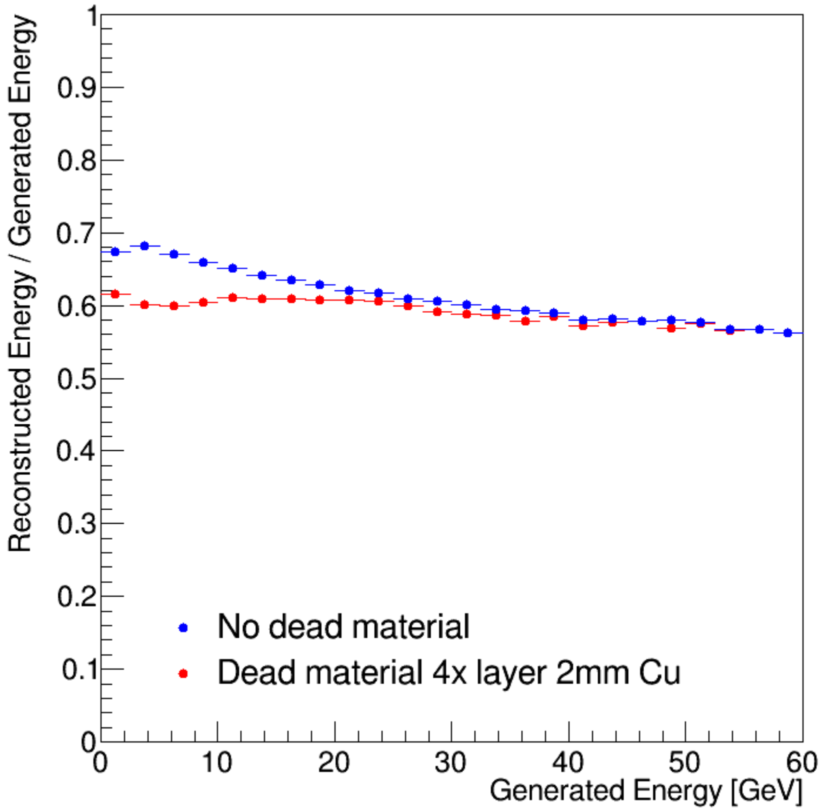


A. Bylinkin et. al [2208.14575]

B0 calorimeter resolution



Effect of the presence of dead material (for cooling and readout) after each tracking plane is estimated.

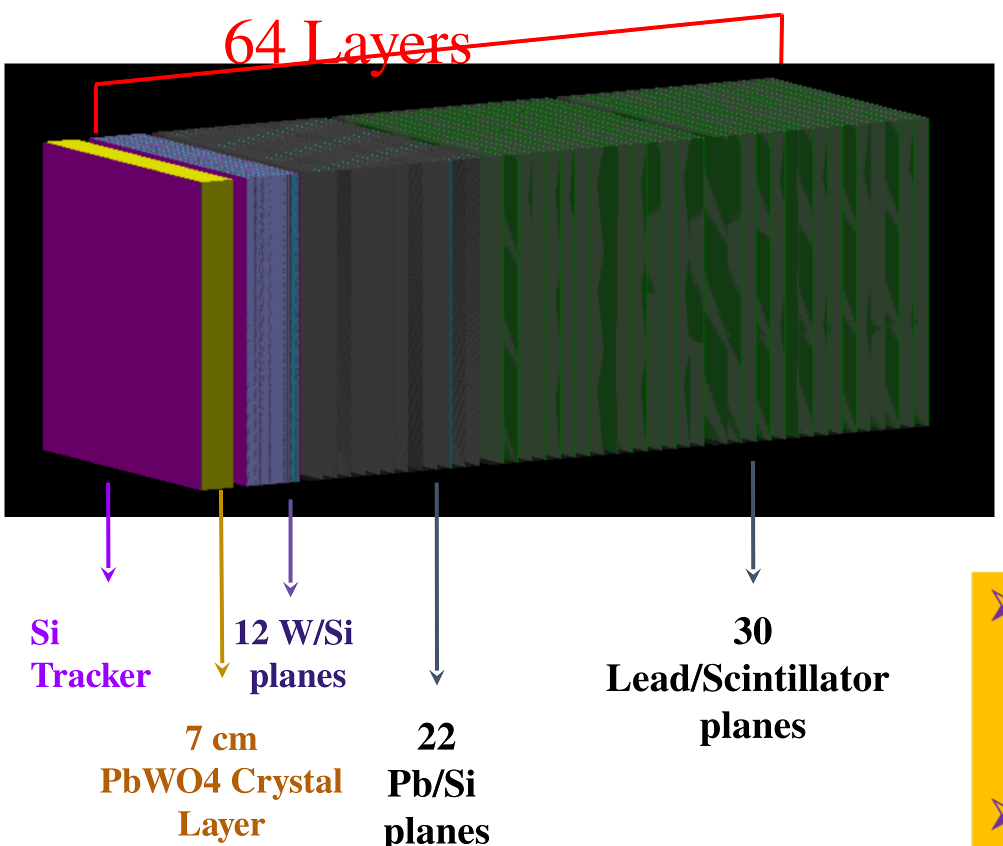


The photon energy resolution is found to be below 7% for the studied kinematic region.

A. Bylinkin et. al [2208.14575]

Zero Degree Calorimeter

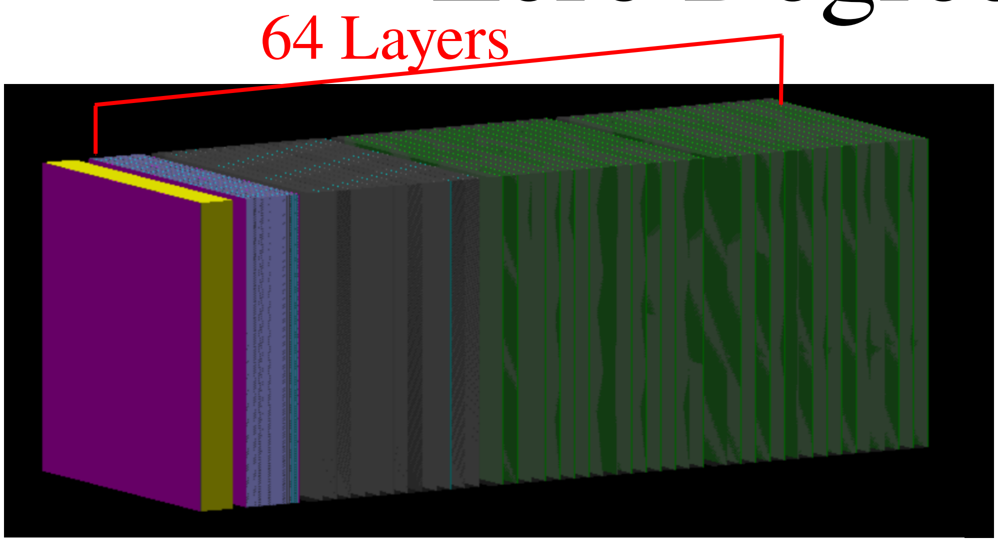
- High resolution HCAL + EMCAL for detecting neutral forward-going particles (neutrons and photons)
  - HCAL requires $\frac{\Delta E}{E} \sim \frac{50\%}{\sqrt{E}} \oplus 5\,\%$ and $\sigma_\theta \sim \frac{3\text{ mrad}}{\sqrt{E}}$, or better.
  - ALICE FoCal assumptions used for studies thus far (EIC R&D group started last summer).
  - Acceptance limited by bore of magnet where the neutron/photon cone exits ($0.0 < \theta < 4.5$ mrad).

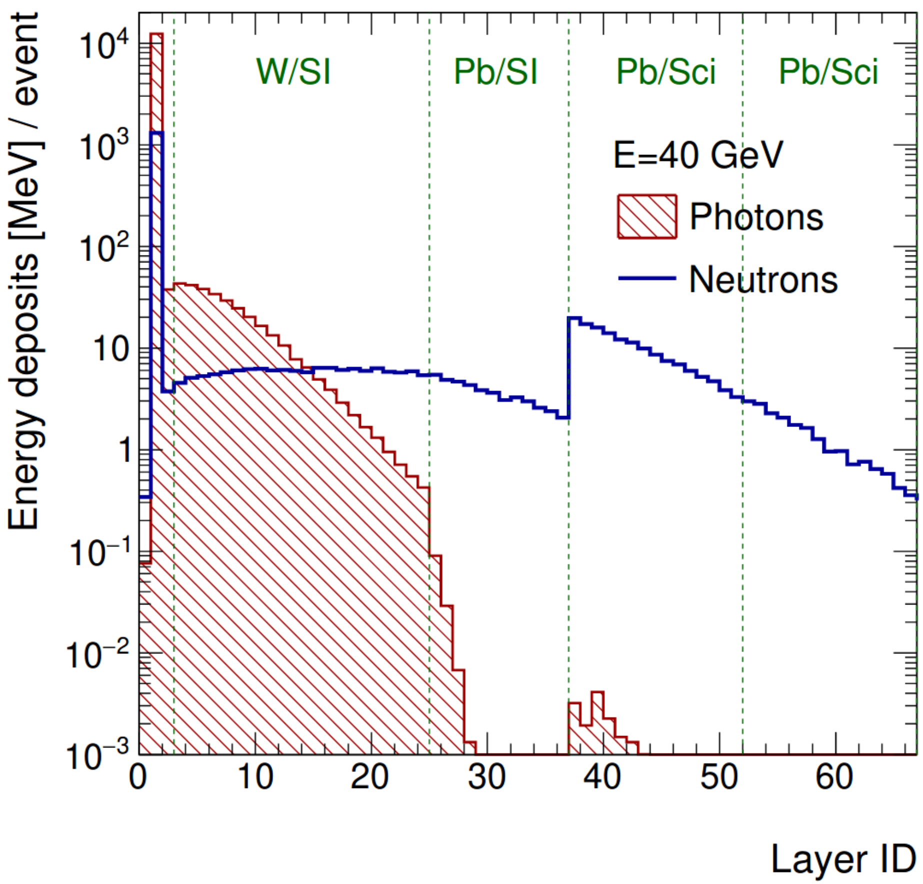


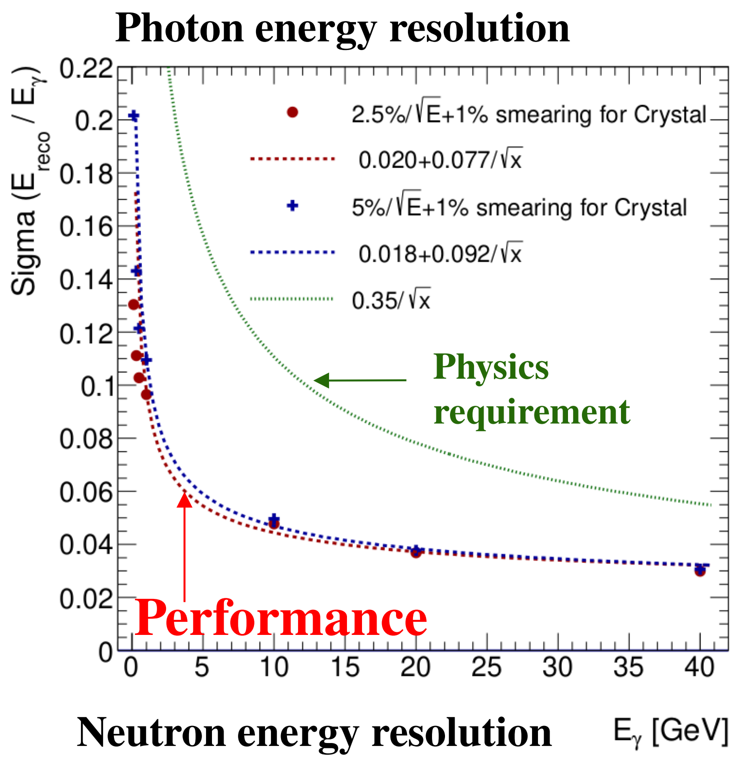
- Zero Degree Calorimeter (improved ALICE design):
  - Dimension: 60 cm x 60 cm x 168 cm
  - 30 m from IR
  - Detect spectator nucleon
  - Acceptance: +4.5 mrad, -5.5mrad
  - Position resolution ~1.3mm at 40 GeV
  - Full reconstruction of photons (EMCAL) and neutrons (HCAL)

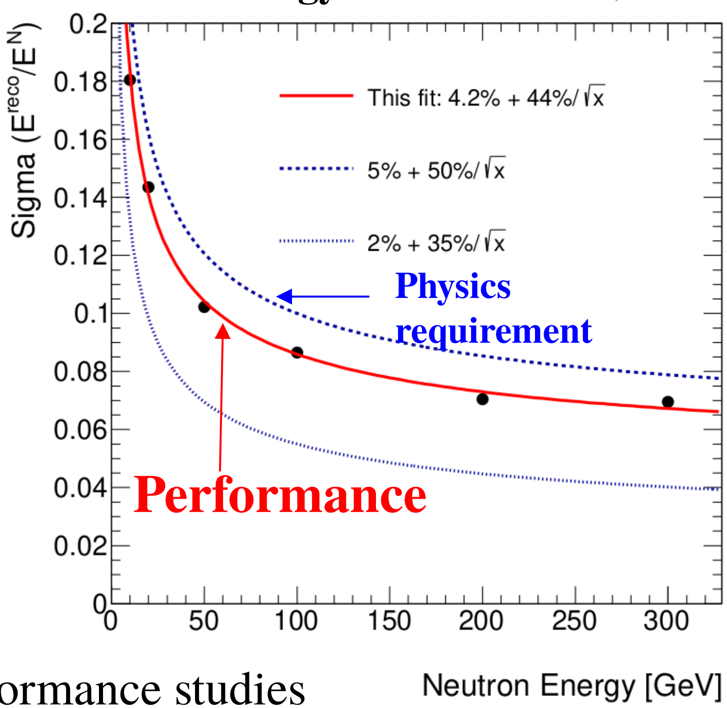
- Sufficient calorimeter depth (radiation lengths, X_0 for photons/electrons; nuclear interaction lengths, λ_I for neutrons/hadrons)
  - Required for good energy resolution.
- Granularity needed for proper reconstruction of shower.
  - Finding the center of the shower needed to provide angular resolution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

Zero Degree Calorimeter



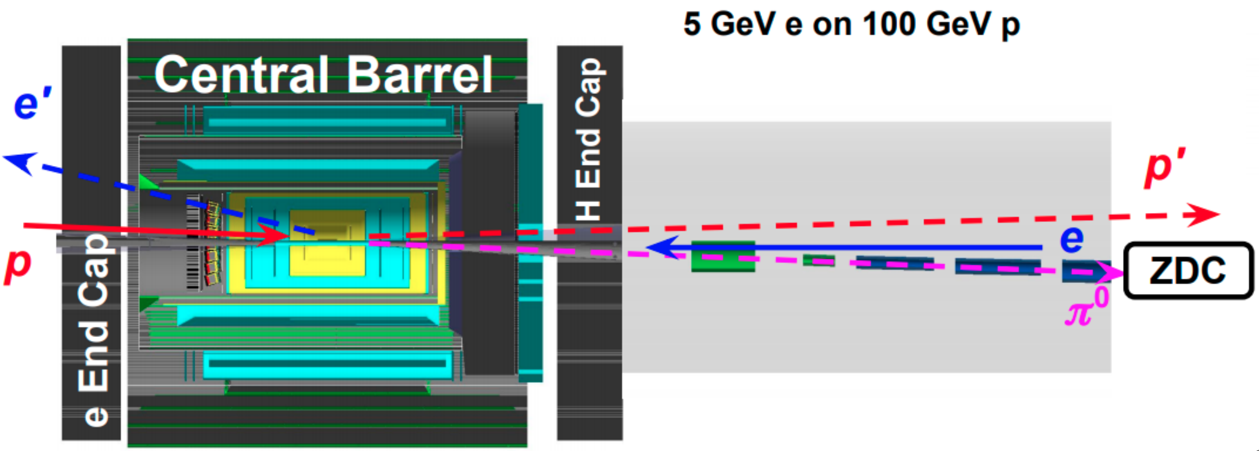


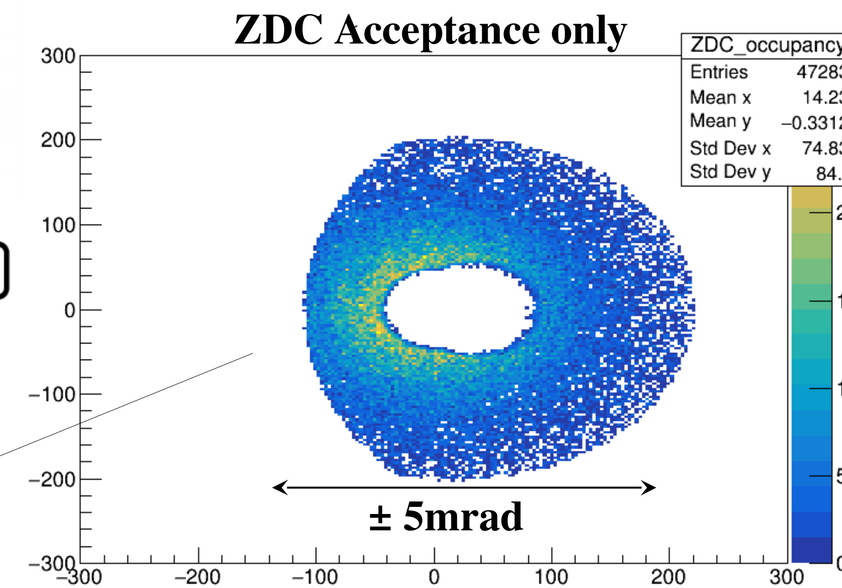


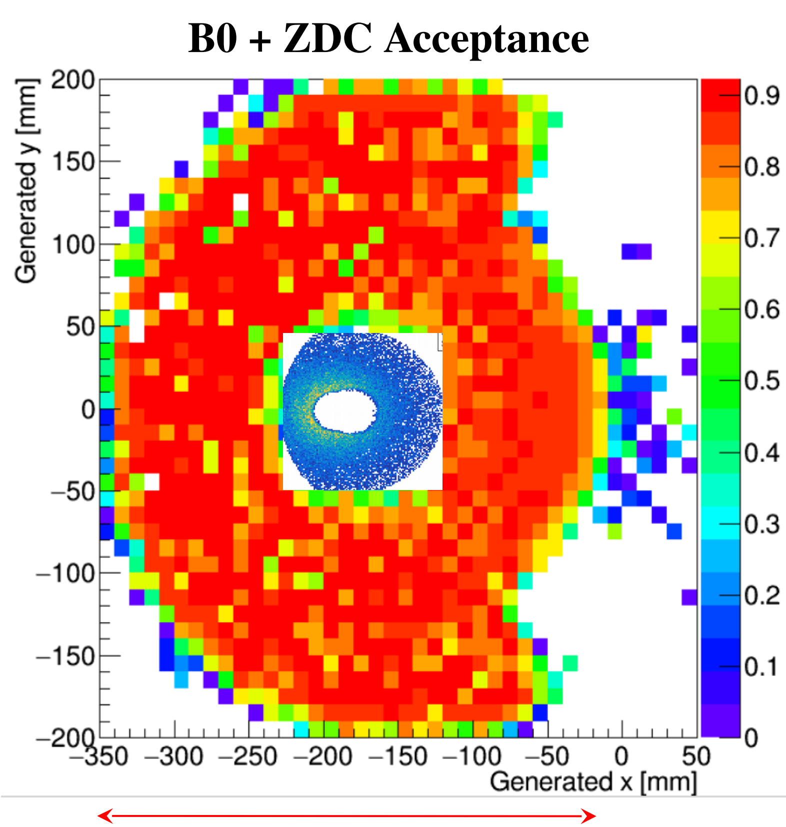


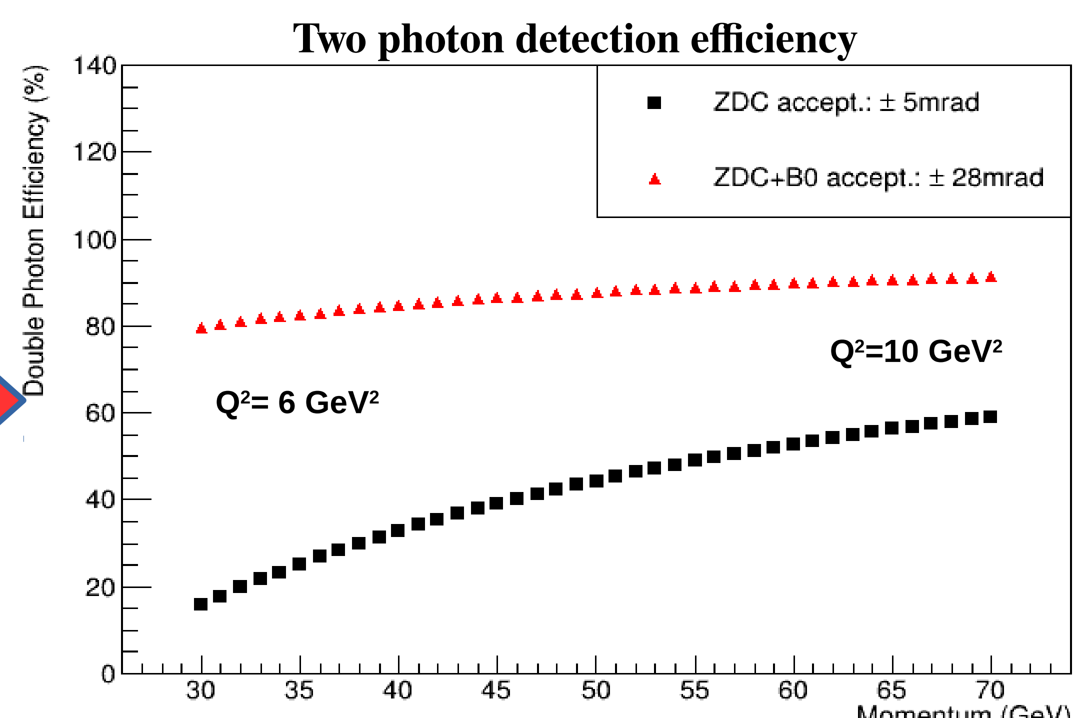
[2208.14575] *Beam pipe effects are not included in performance studies

u-channel DVCS: B0 and ZDC performance









Enhanced acceptance and resolution with B0 and ZDC calorimeters combined.

Summary

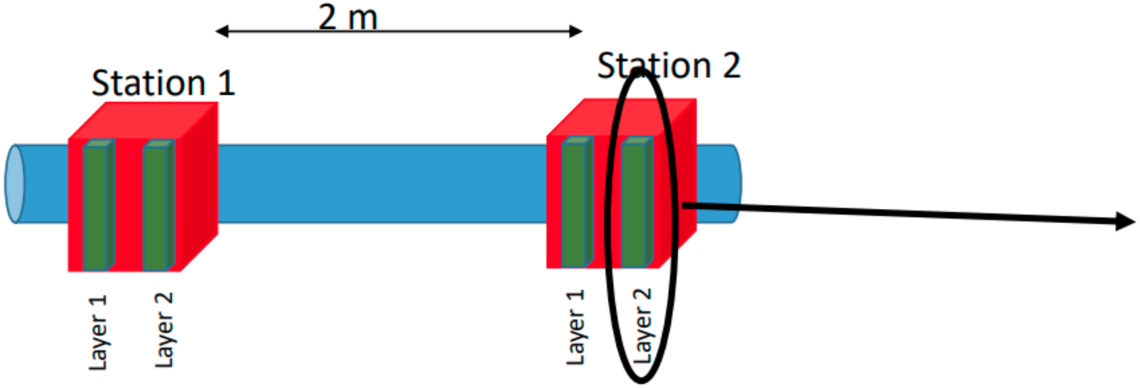
- EIC is a great facility to study diffraction and low-x physics
- Detectors in the Far Forward region are important for various physics processes.
- Combined usage of B0 and ZDC detectors significantly increases the photon detection efficiency.
- Detecting photons in this region is essential for the measurements of **u-DVCS** and **coherent VM** production.

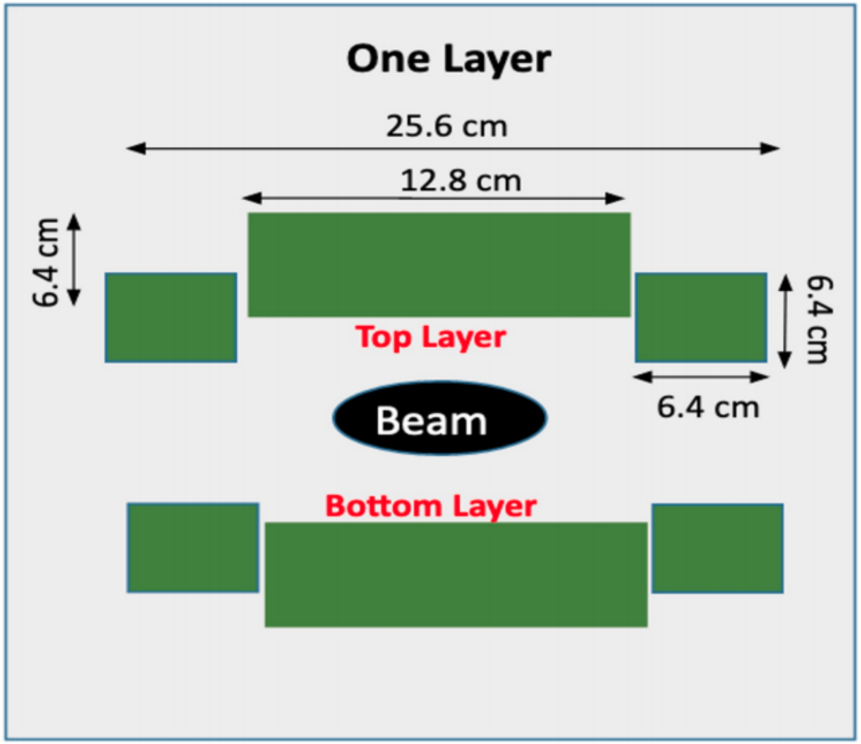
Thank you very much for your attention!

Backup Slides

Far-Forward Spectrometers

Roman "Pots" @ the EIC

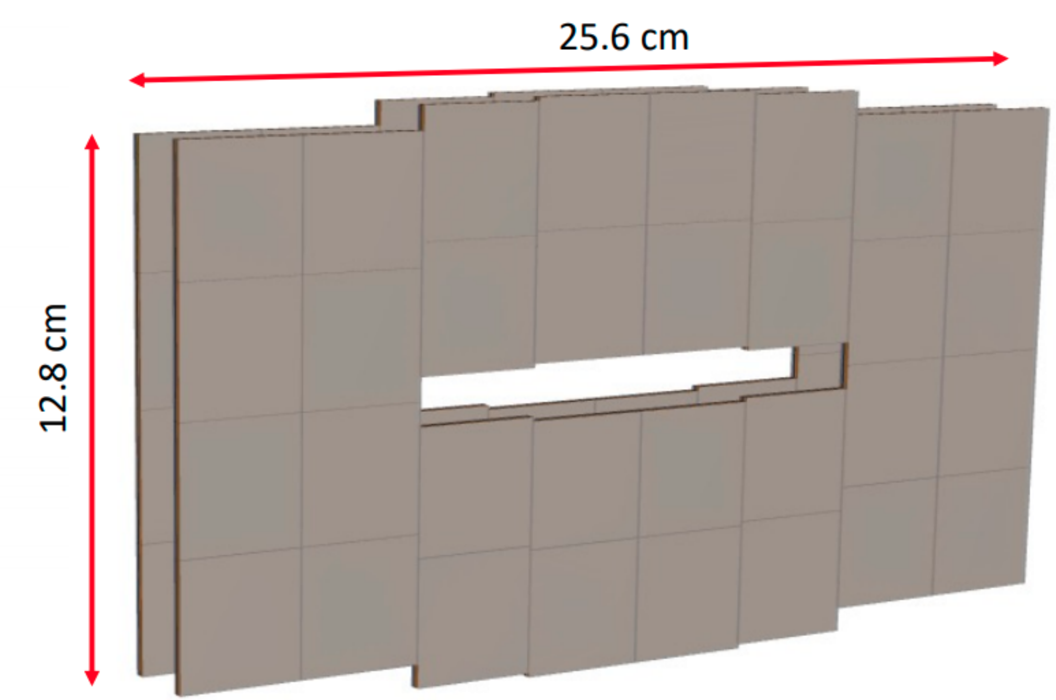




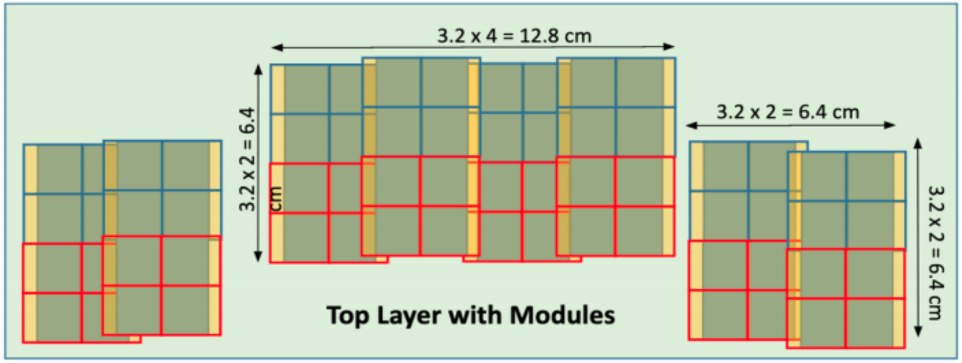
- Two stations, separated by 2 meters, each with two layers (minimum) of silicon detectors.
- Silicon detectors placed directly into machine vacuum!
  - Allows maximal geometric coverage!
- Need space for detector insertion tooling and support structure.

Far-Forward Spectrometers

Roman “Pots” @ the EIC



DD4HEP Simulation



- **Two main options**
  - 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.

DVCS simulations

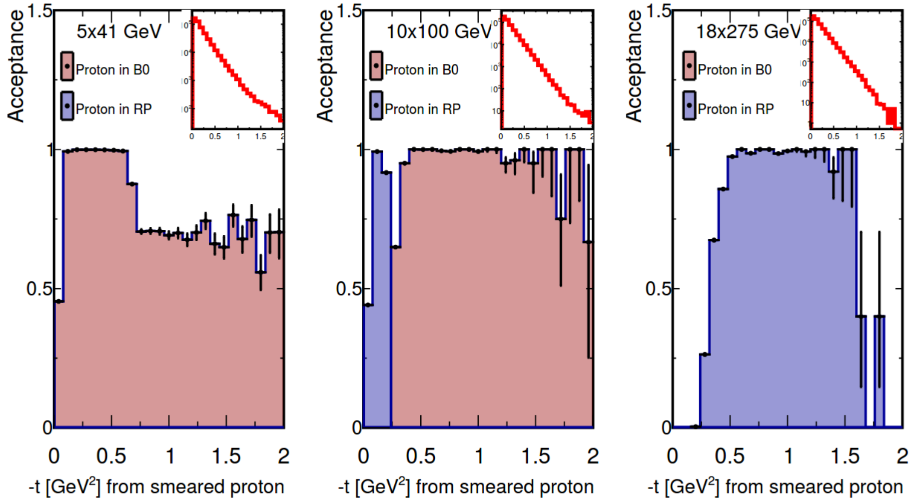
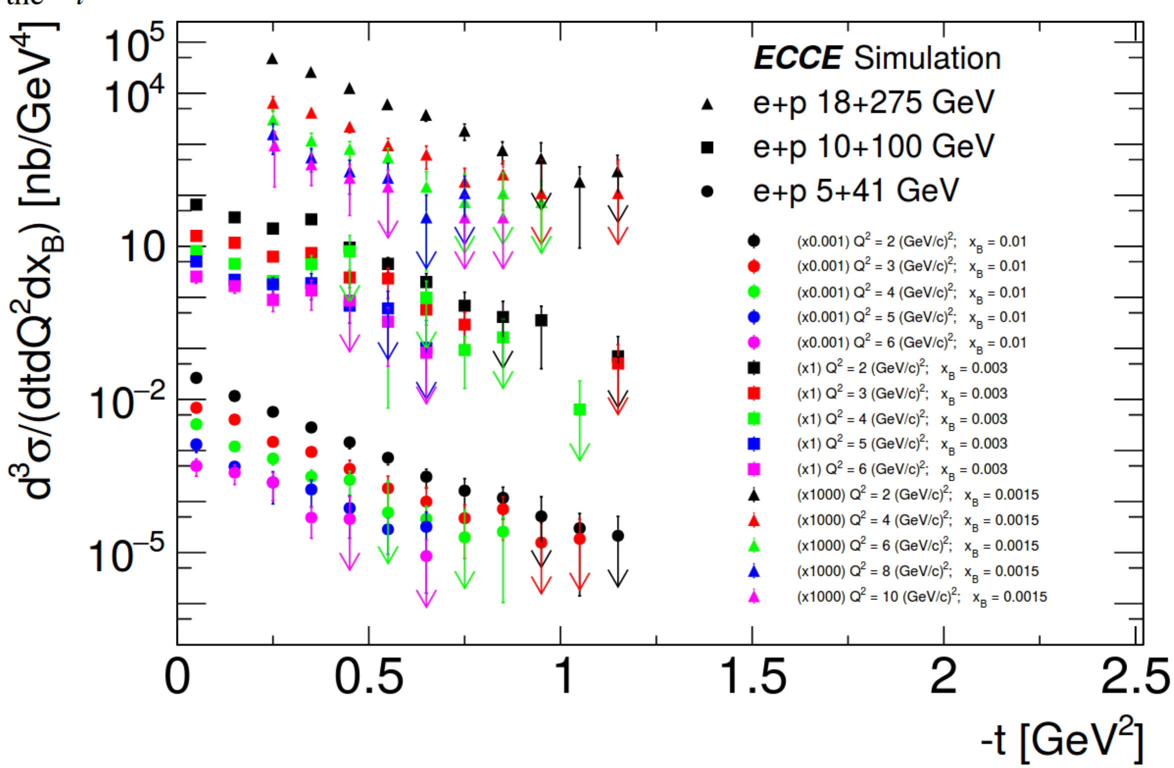


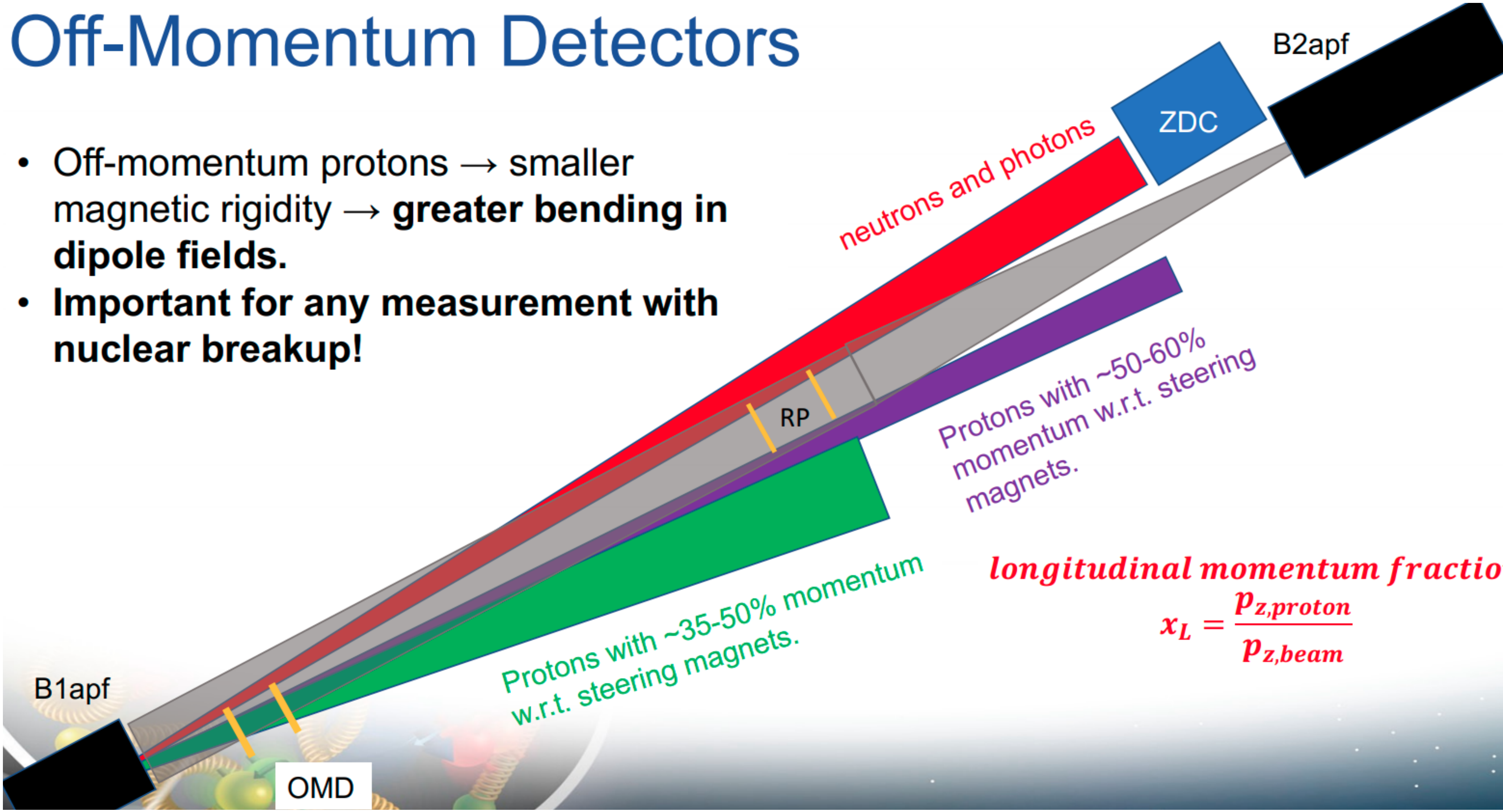
Figure 32: Acceptance for DVCS protons as a function of $-t$ in the far-forward detectors for different beam energy configurations. The inserts show the $-t$ distributions of generated events.



Far-Forward Spectrometers

Off-Momentum Detectors

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

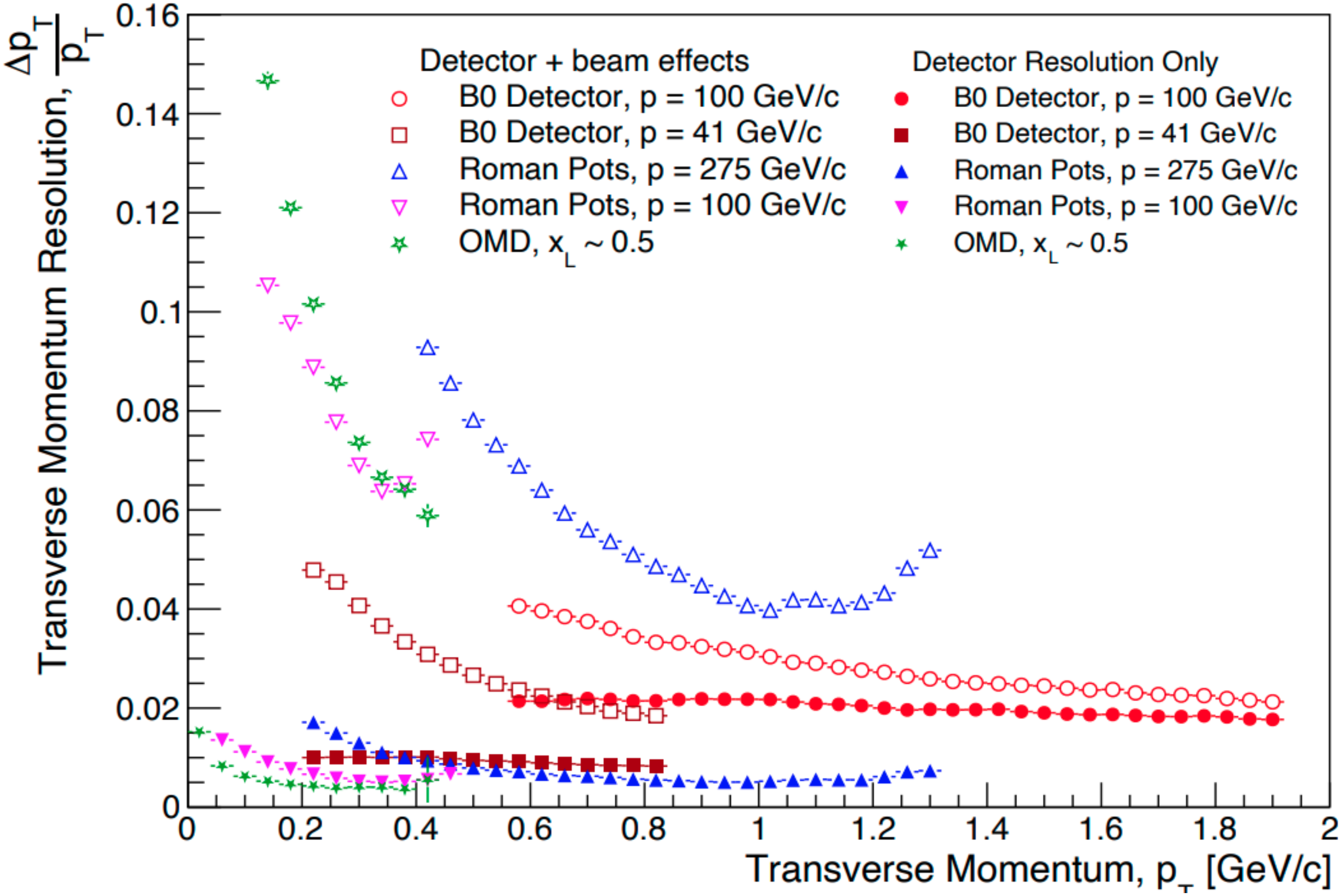


longitudinal momentum fraction

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

Far-Forward Spectrometers

Summary of Detector Performance (Trackers)

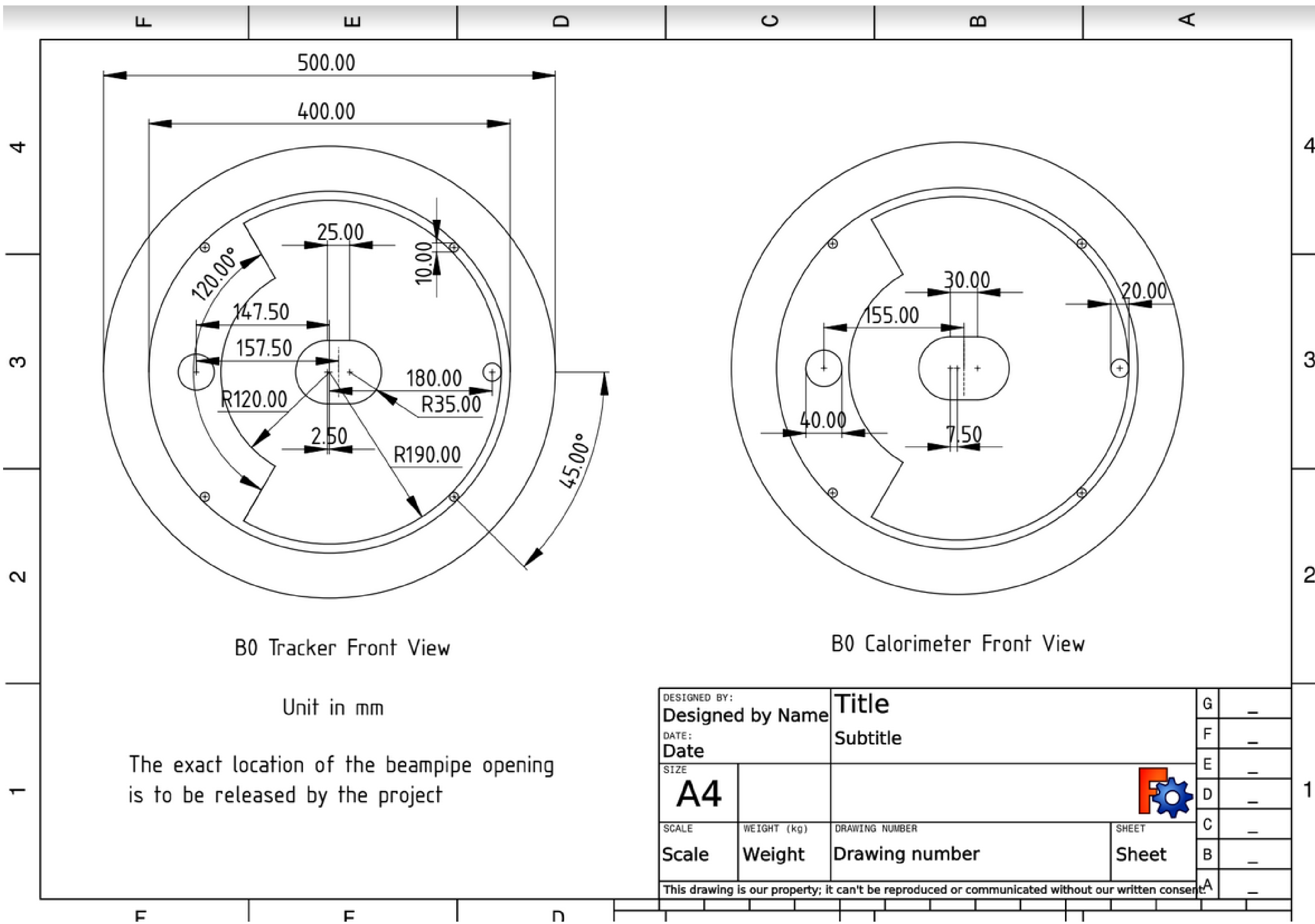


- All beam effects included!
  - Angular divergence.
  - Crossing angle.
  - Crab rotation/vertex smearing.

Beam effects the dominant source of momentum smearing!

*Based on ATHENA design and simulations

B0 Design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B0 Tracker Front View
B0 Calorimeter Front View
Unit in mm
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is to be released by the project
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Designed by Name
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Date
SIZE
A4
Title
Subtitle
SCALE
Scale
WEIGHT (kg)
Weight
DRAWING NUMBER
Drawing number
SHEET
Sheet
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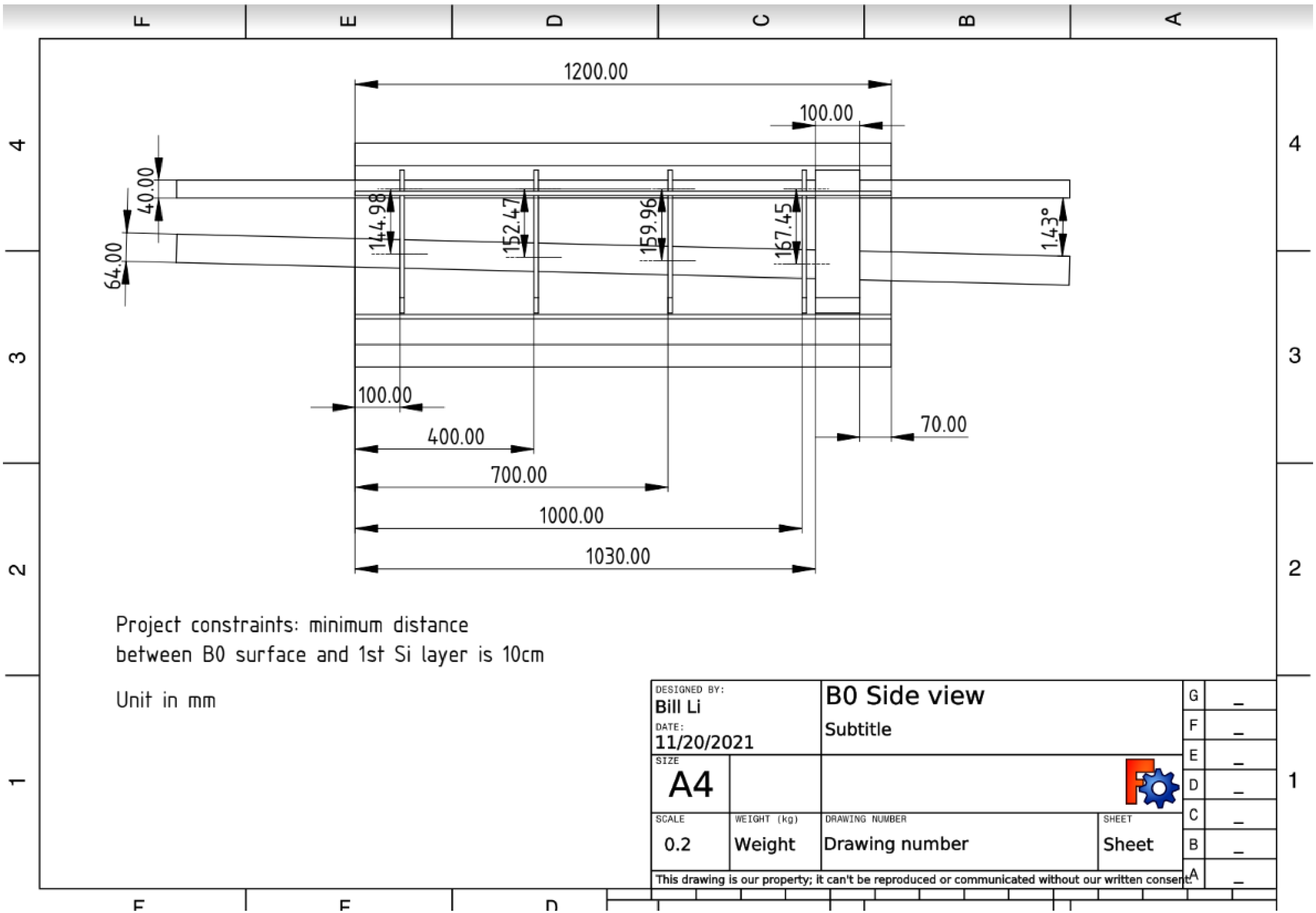
G
F
E
D
C
B
A

B0 Design


F
E
D
C
B
A
4
3
2
1
1200.00
100.00
40.00
64.00
144.98
152.47
159.96
167.45
1.43°
100.00
400.00
700.00
1000.00
1030.00
70.00
Project constraints: minimum distance
between B0 surface and 1st Si layer is 10cm
Unit in mm
DESIGNED BY:
Bill Li
DATE:
11/20/2021
B0 Side view
Subtitle
SIZE
A4
SCALE
0.2
WEIGHT (kg)
Weight
DRAWING NUMBER
Drawing number
SHEET
Sheet
G
F
E
D
C
B
A
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