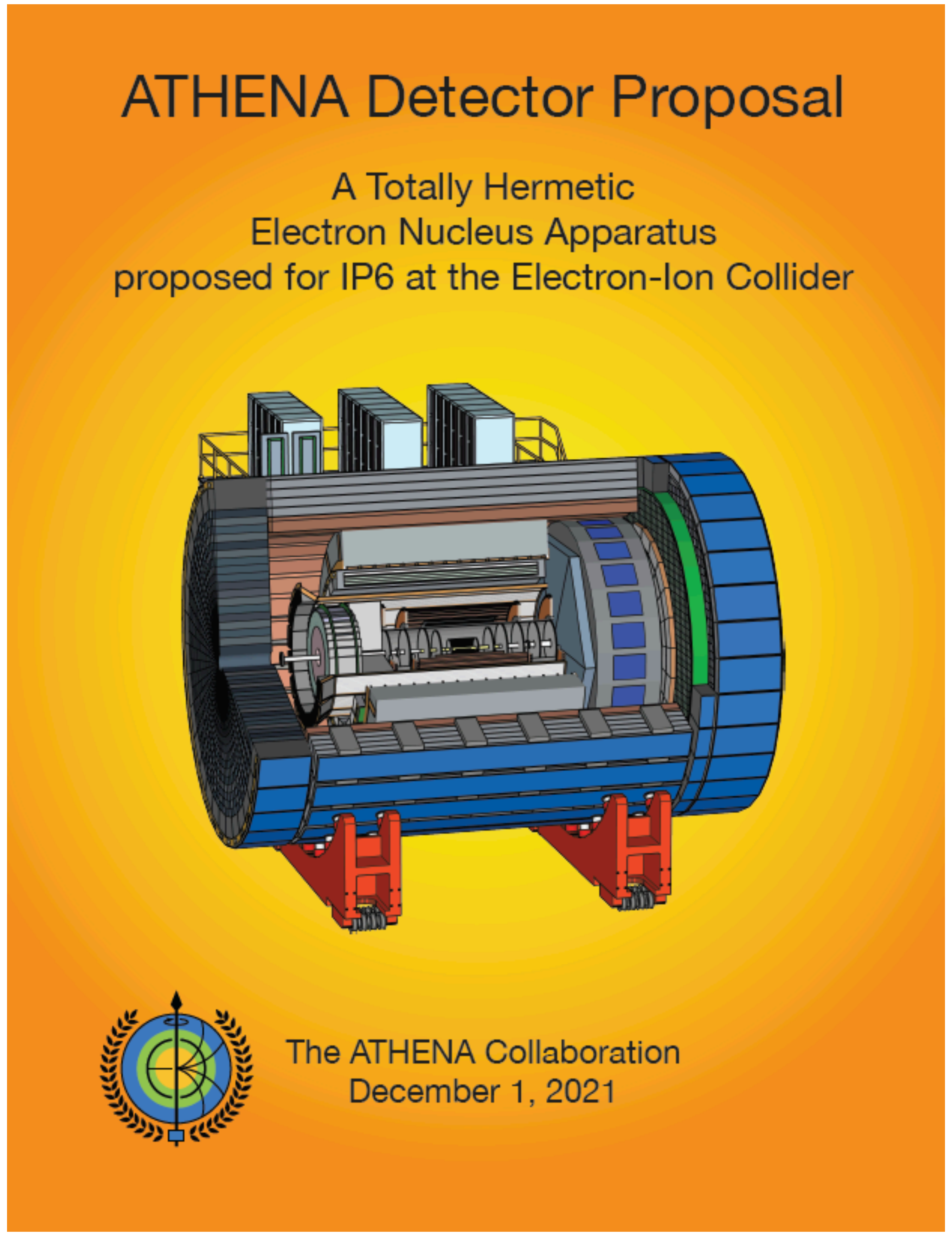
The Global Design of the ATHENA Detector: Concepts, Issues & Choices



Thomas Ullrich
GD/I Meeting
May 16, 2022

BROOKHAVEN NATIONAL LABORATORY

Reminder

- ATHENA Proposal Level Design

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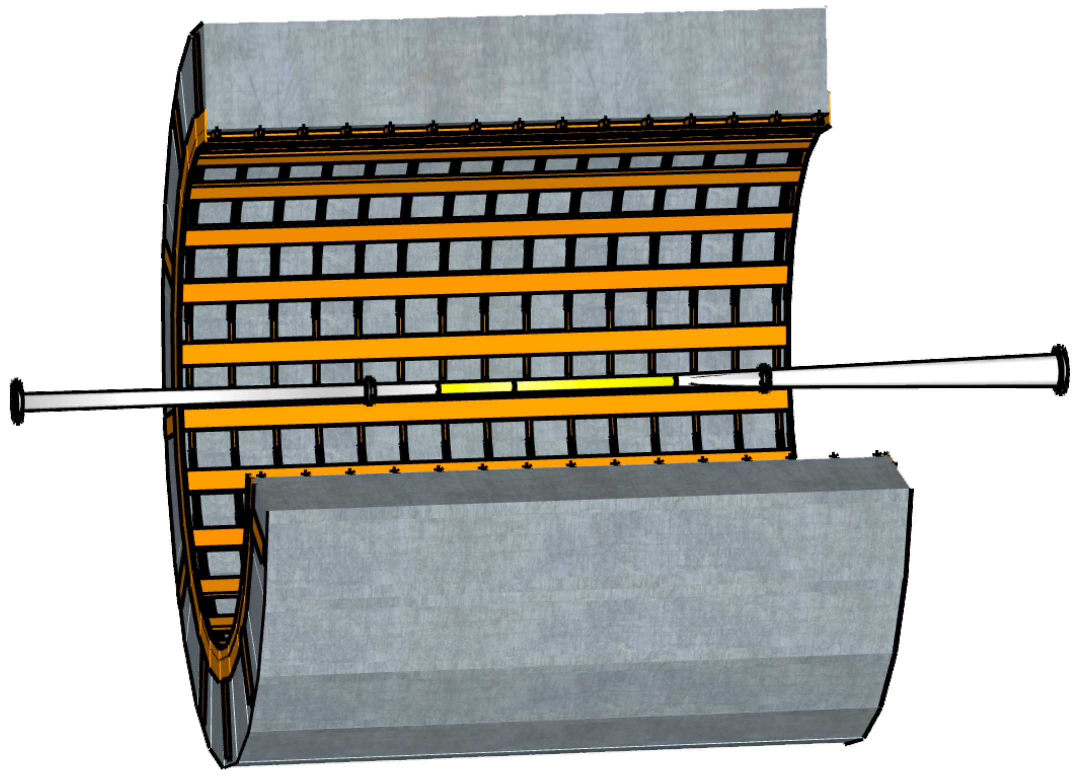
  - Solenoid



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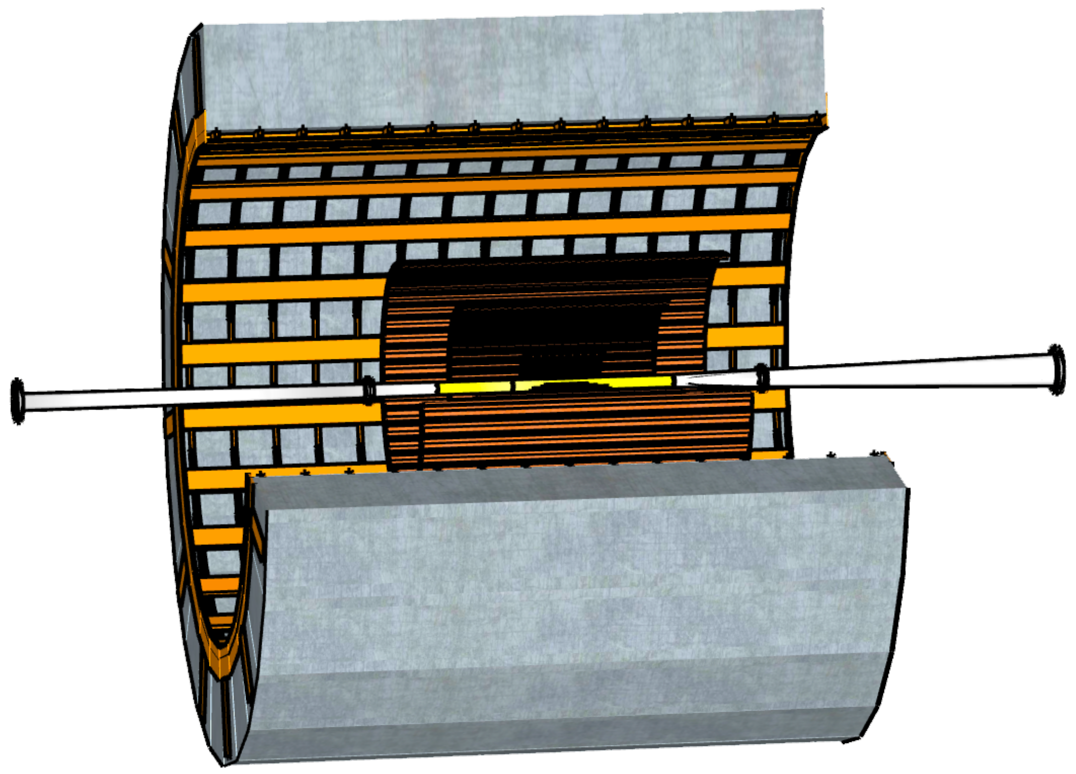
  - Barrel tracking
    - vertex - wafer-scale stitched MAPS
    - inner - MAPS layers
    - outer - cylindrical Micromegas layers



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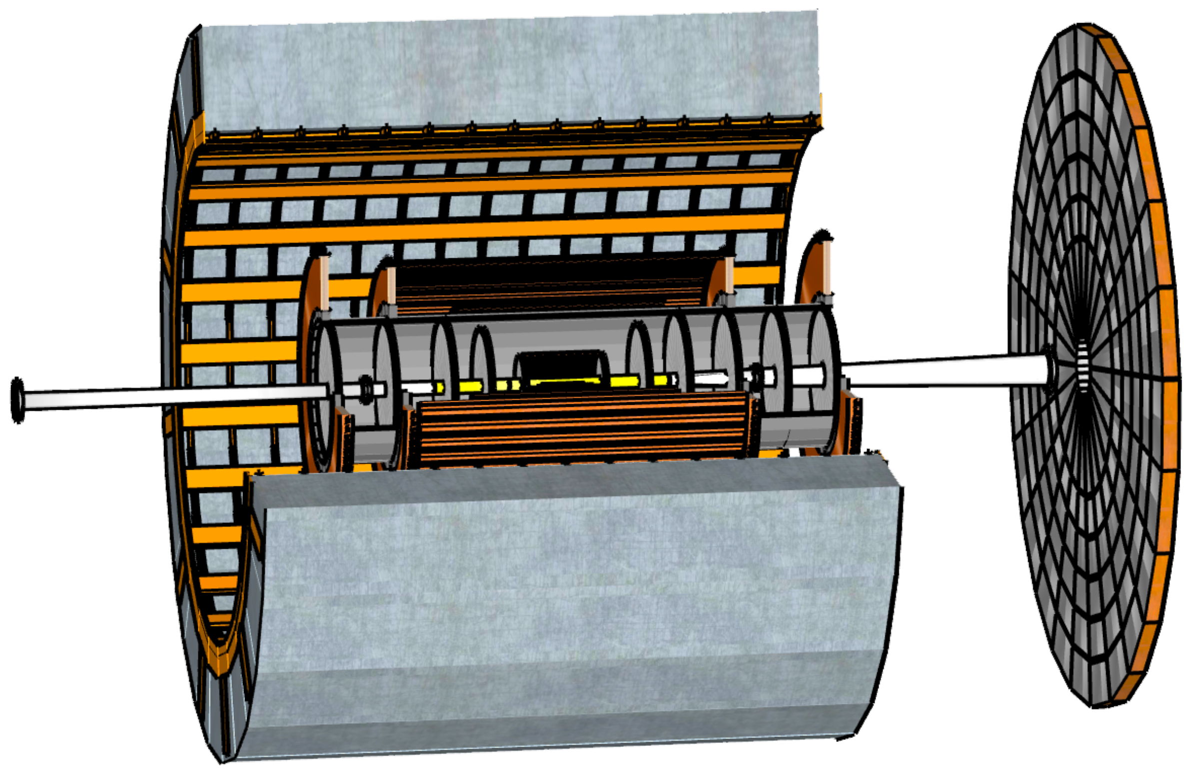
    - MAPS Disks
    - Planar GEMs/μRWell with annular shape
    - μRWell disk



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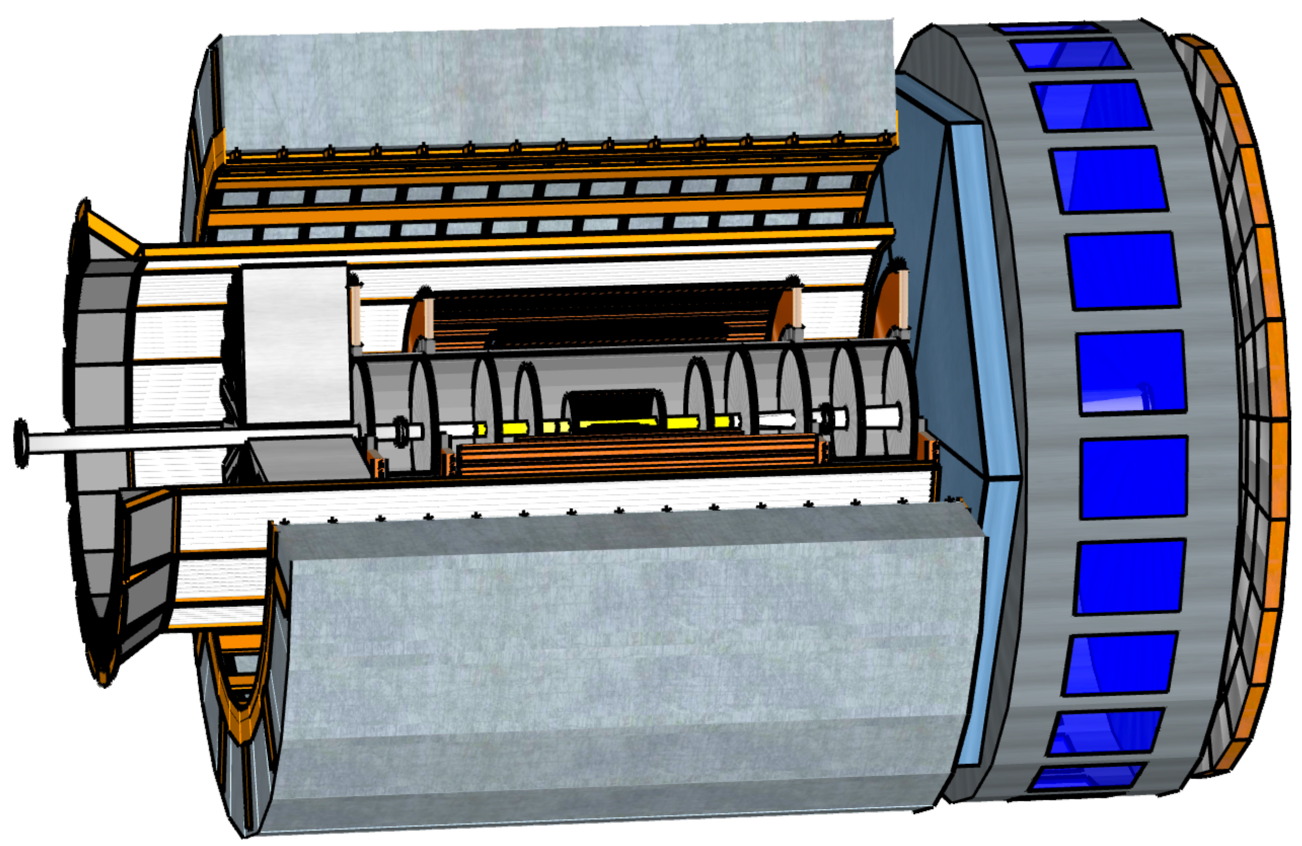
  - Particle Identification
    - dual RICH (aerogel + gas)
    - proximity focussing RICH (aerogel)
    - high-performance DIRC
    - Time-of-Flight with AC-LGAD sensors



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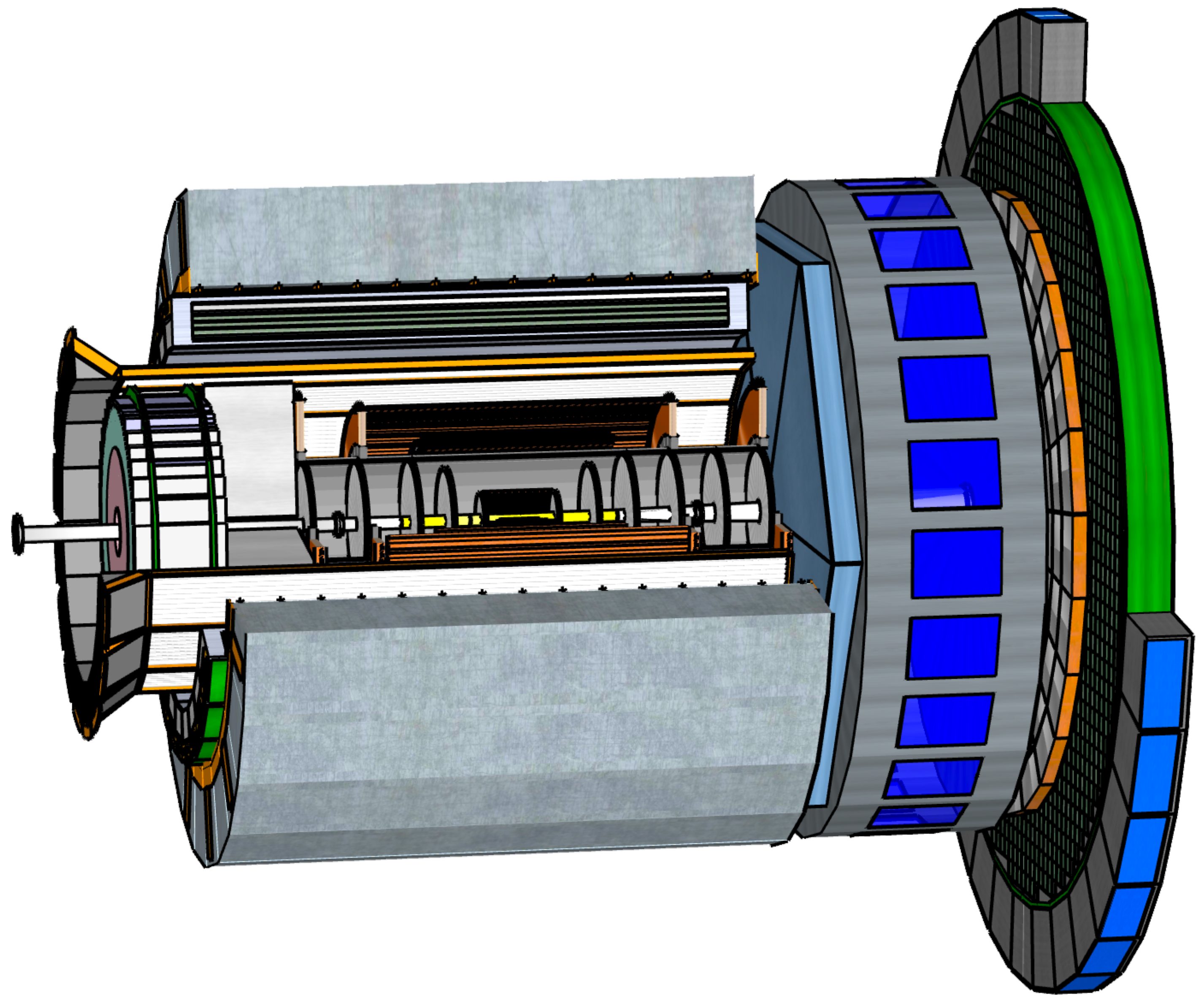
    - forward: W-Powder/Scintillating Fiber
    - backward: $PbWO_4$, SciGlass
    - barrel: Astropix imaging layers & Pb/SciFi layers



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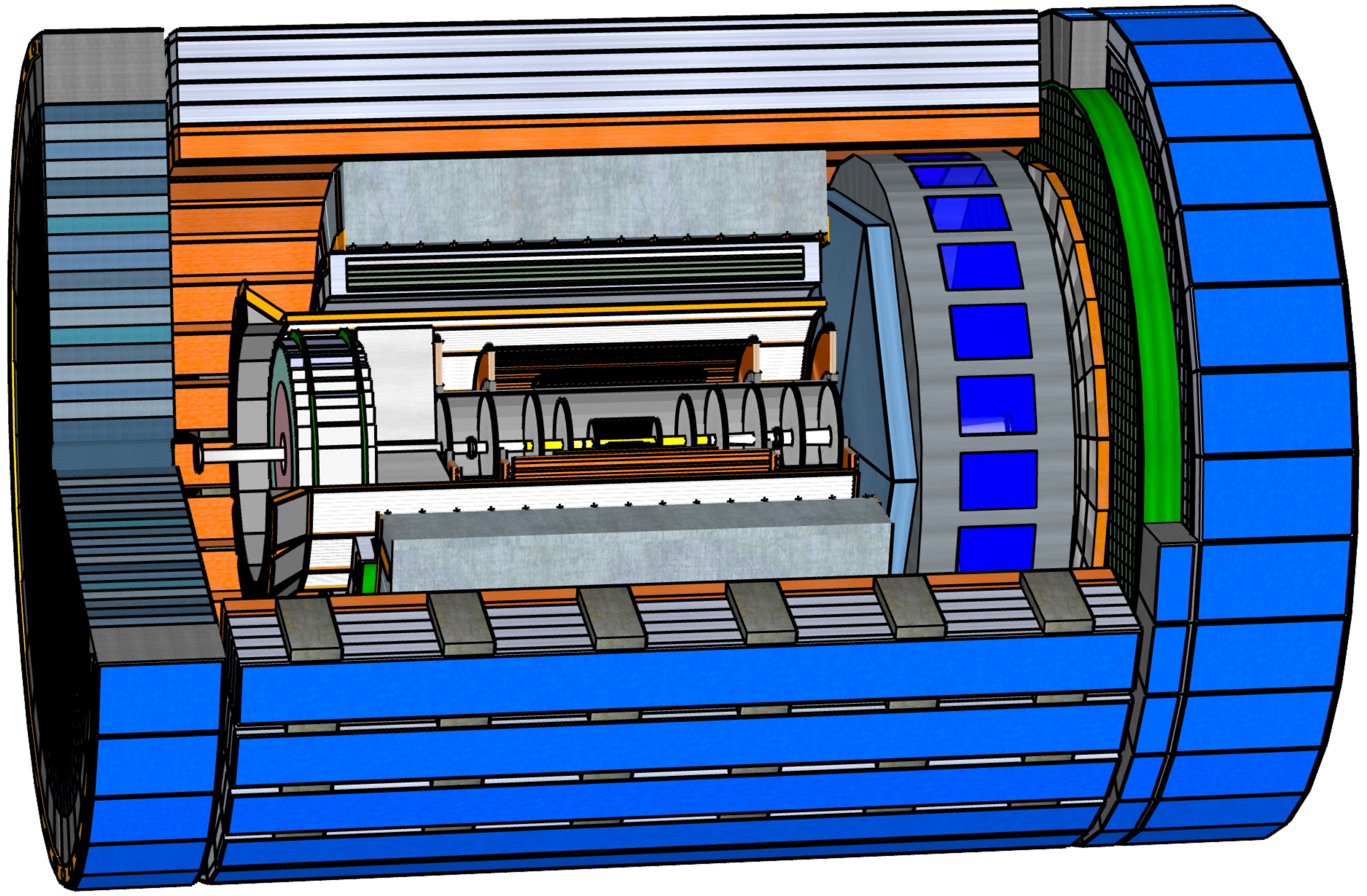
  - Hadron Calorimetry
    - Fe/Sci sandwich



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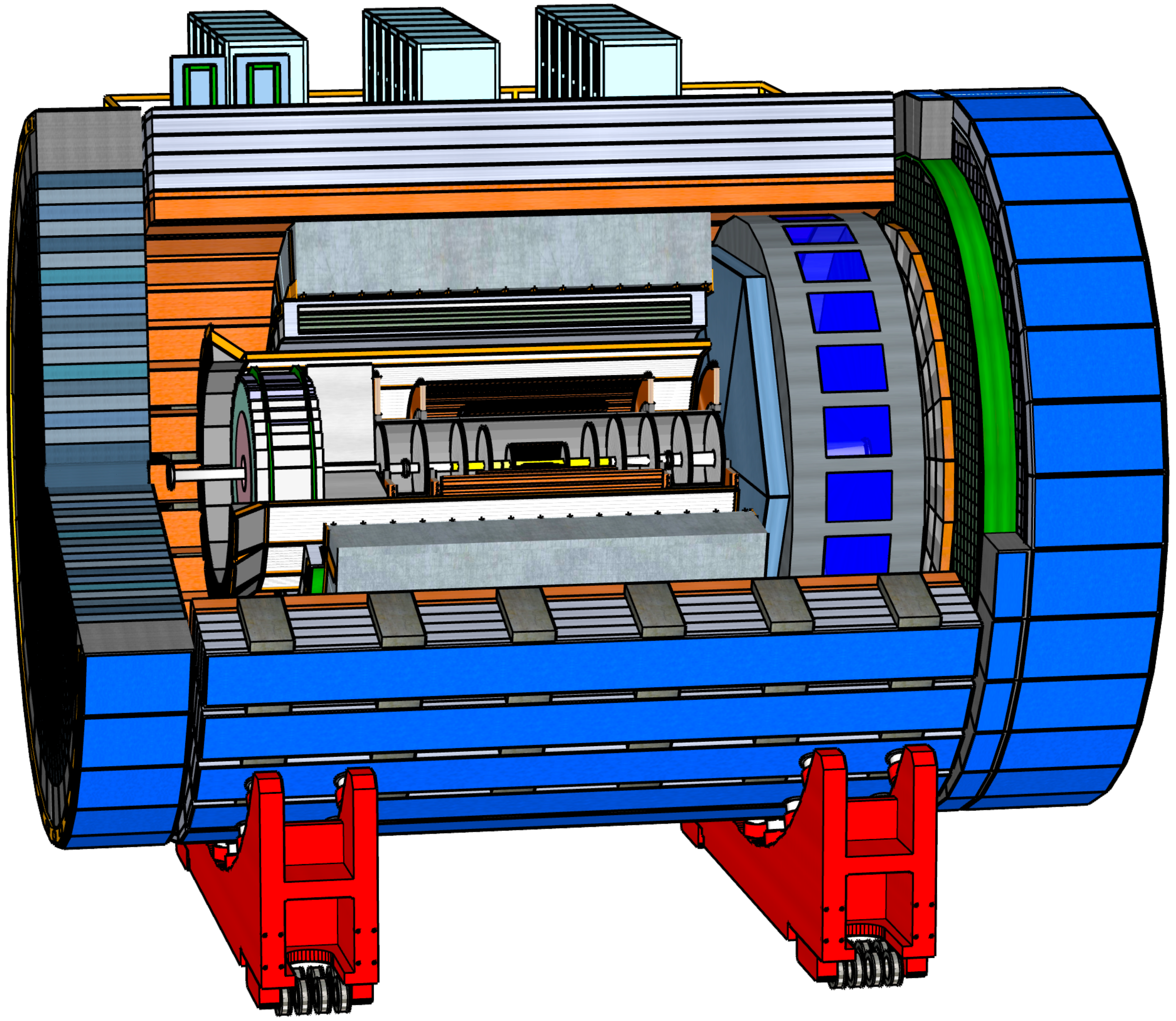
  - Support Structure & Platforms



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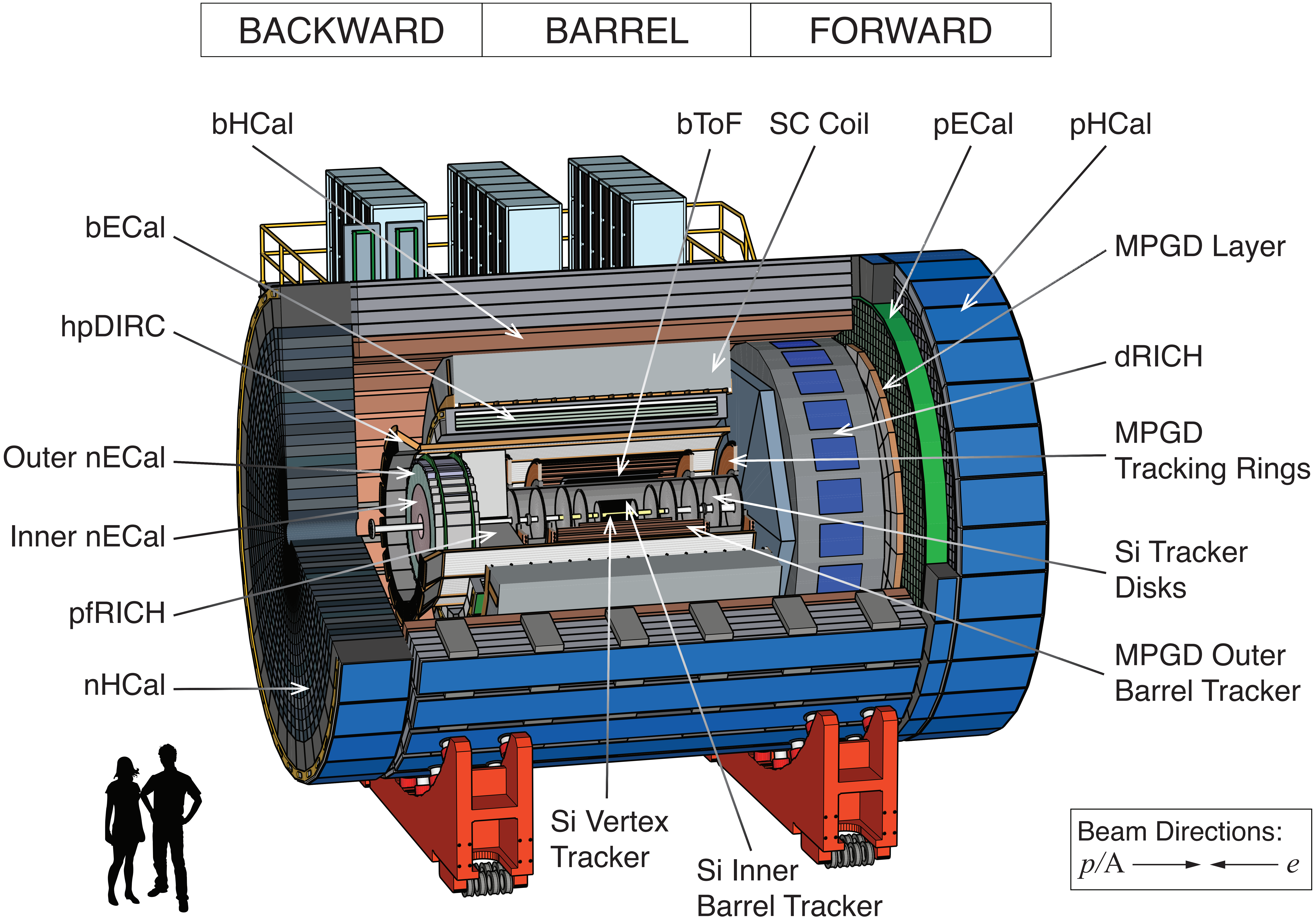
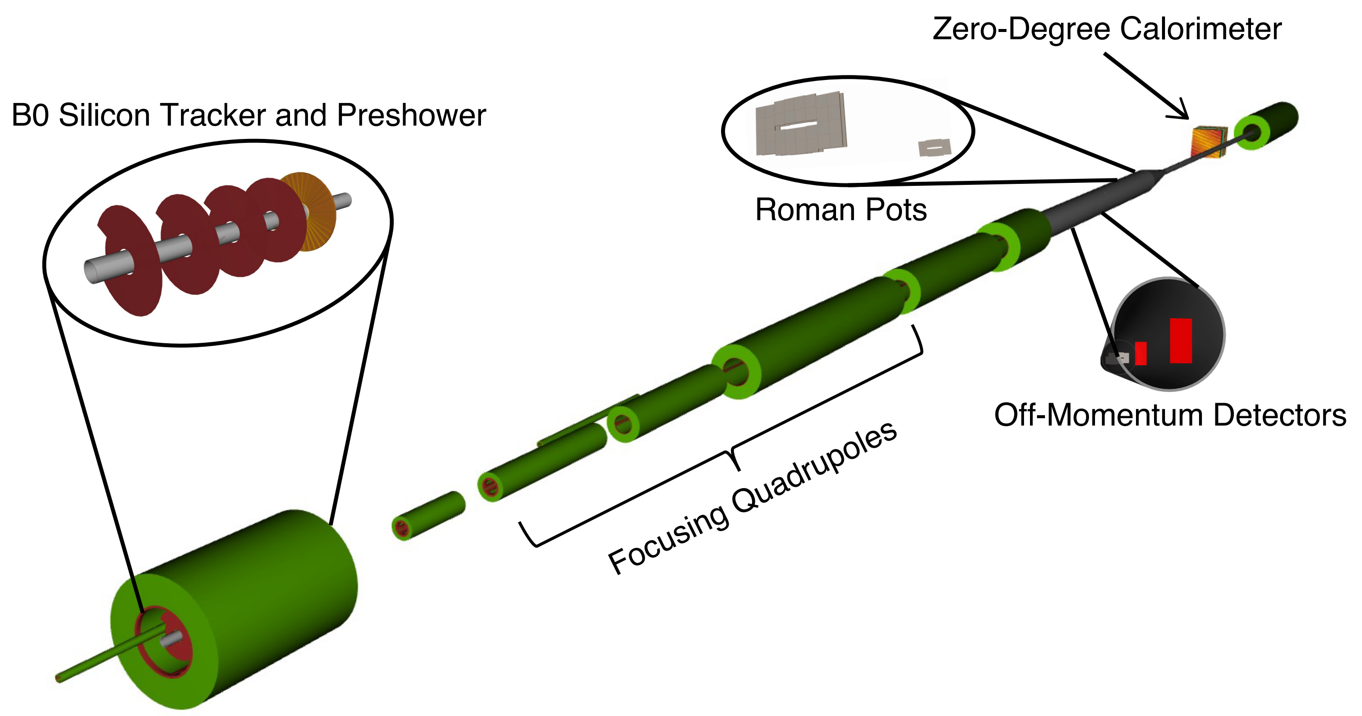

BACKWARD
BARREL
FORWARD
bHCal
bToF
SC Coil
pECal
pHCal
bECal
MPGD Layer
hpDIRC
dRICH
MPGD
Tracking Rings
Outer nECal
Inner nECal
Si Tracker
Disks
pfRICH
MPGD Outer
Barrel Tracker
nHCal
Si Vertex
Tracker
Si Inner
Barrel Tracker
Beam Directions:
p/A
e

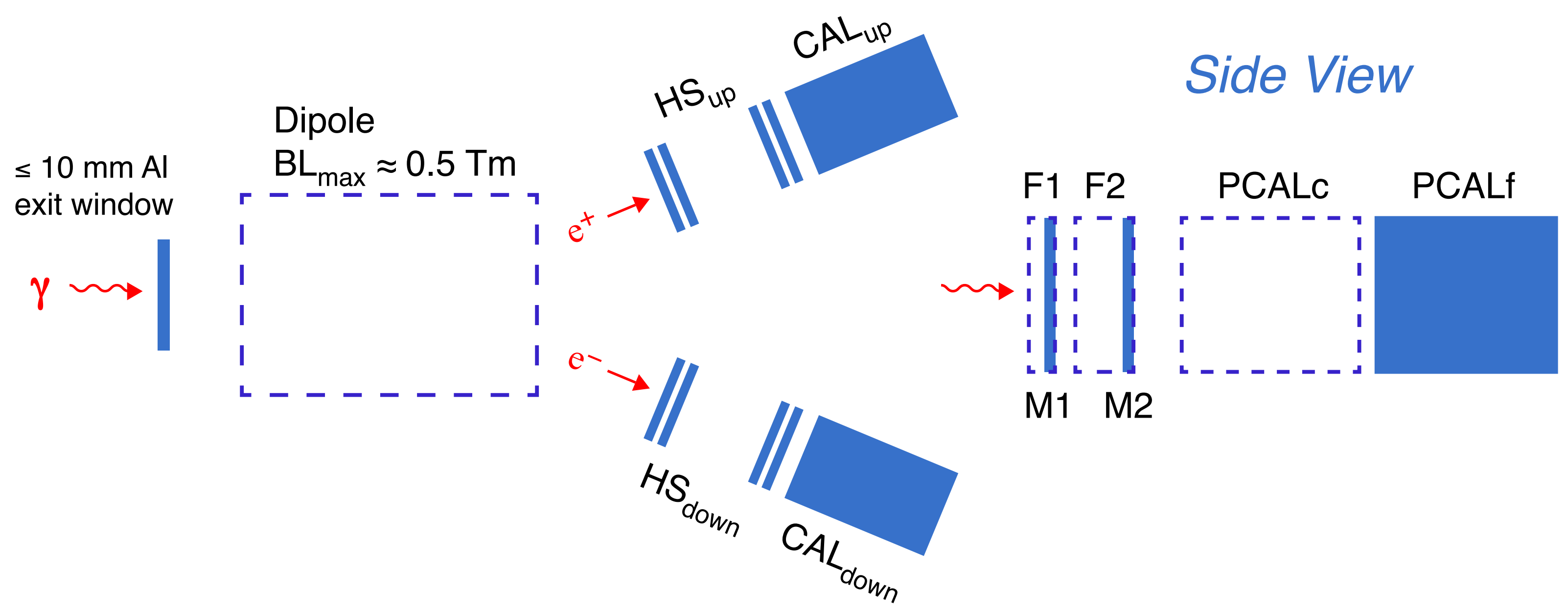
Far Forward/Backward Setup

- In this talk I will focus only on the central detector
- The far-forward and far-backward are very similar in ATHENA and ECCE and the same design ideas and concepts were deployed.
- For a good and detailed summary of the see Alex's talk on the far-forward and Jada's talk in far-backward last Friday (5/13).



far - forward

far - backward



A Solid Base

Tracking Resolution:

Precision term: $$\left.\frac{\sigma_{p_T}}{p_T}\right|_{\text{meas}} = \frac{p_T\ \sigma_{r_{\phi r}}}{0.3\ L^2\ B}\sqrt{\frac{720}{N+5}}$$

MS term: $$\left.\frac{\sigma_{p_T}}{p_T}\right|_{\text{MS}} = \frac{0.05}{L\ B\ \beta}\sqrt{1.43\frac{L}{X_0}}\left[1+0.038\ \log\frac{L}{X_0}\right]$$

where

$\sigma_{r_{\phi r}}$ is point resolution in meter

L is lever arm in meter

B is magnetic field in Tesla

N are number of measurements (hits)

β velocity of particle

X_0 is gas/material density in meter

Track momentum resolution: $$\frac{\sigma_{p_T}}{p_T} = \left.\frac{\sigma_{p_T}}{p_T}\right|_{\text{meas}} \oplus \left.\frac{\sigma_{p_T}}{p_T}\right|_{\text{MS}}$$

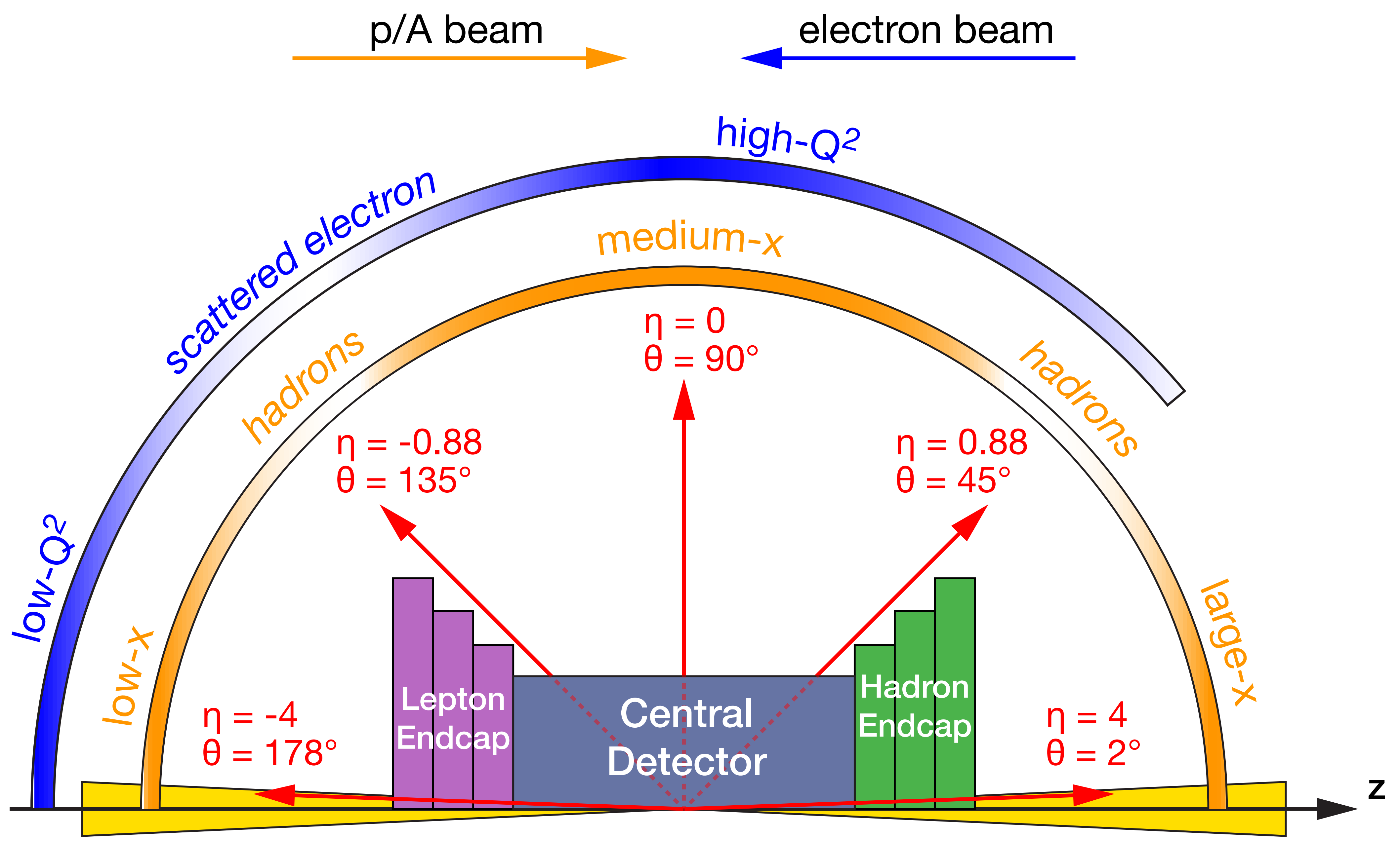
Maximize Resolution:

- N ↑: good but adds material and services
- σ_r ↑: good, but increases channel count & heat, limited by technology
- X_0↓: important but also affects N
- L↑: Good, needs room/space
- B↑: Good, affects photosensors, low-p_T PID

ATHENA's choice:

- Large field (3T) following YR: B↑
- Large magnet bore (max. compatible with IP6): L↑
  - eases for service routing
  - room for future upgrades
  - maximize acceptance

Always Keep in Mind X/X_0 (λ/λ_I) !



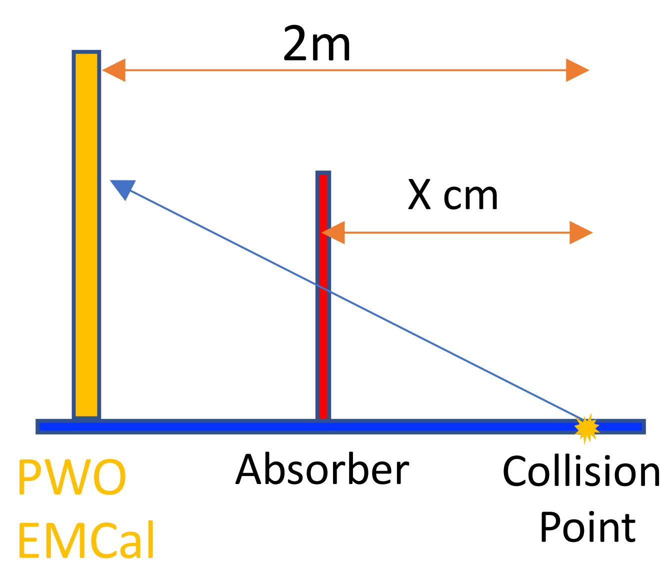
DIS:

- Highest priority has to be the clean detection of the scattered electron in $\eta < 1$
  - high efficiency
  - max. e/h (purity)
    - recall YR req.: 10^3
- Material
  - Multiple scattering
  - radiation/E-loss
  - Absorption

- Fwd and Barrel/Bckwd have different X/X_0 demands
  - Asymmetric tracker configuration OK
  - EMCs are key
    - provide best possible e/h in $-4 < \eta < 1$
    - E (p) determination for $\eta < -3.5$

Sasha's Rule

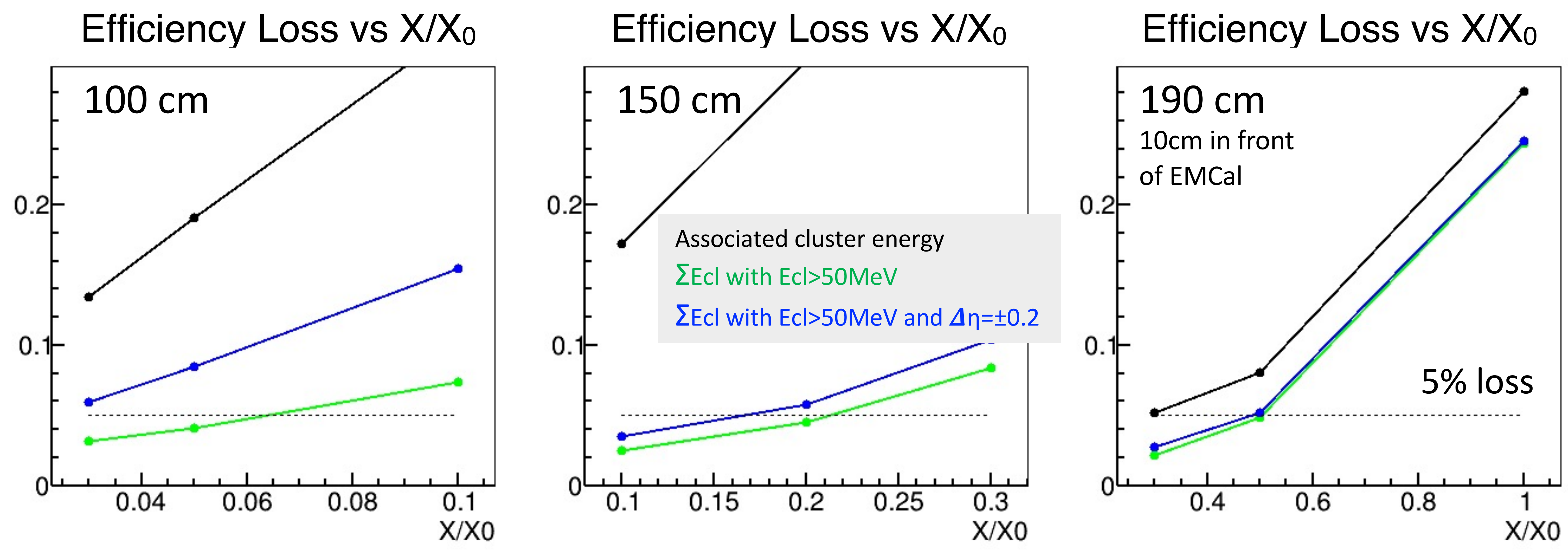
- Alexander Bazilevsky did some simple but extremely useful studies on the effect of material on e measurements in the Endcap EMC. These results guided the design of ATHENA substantially. They especially highlight the importance of the distance of the material from the ECal.
- The key question is how well we can reconstruct/associate the energy related to original electron
  - e-track associated cluster – not enough
  - Need to combine electron cluster with accompanying radiation
  - Need to measure photons to as low energy as possible (down to 20 MeV)
- Impact: For 5% acceptable electron eff. loss, the tolerable material is:
  - ~5%X_0 at <100cm (100 cm from the EMCal)
  - ~20%X_0 at 150cm (50 cm from the EMCal)
  - ~50%X_0 at 190cm (10 cm from the EMCal)



Eta=-1.5, B=3T, p=1 GeV

The worst case: Highest Bdl, lowest e momentum

Baseline (for no material) subtracted



For 5% eff loss: 3-6% X0 ~20% X0 ~50% X0

All this was confirmed by simulations but it was extremely useful during the conceptual design to have some "rules of thumb" to guide the process

Early Decisions

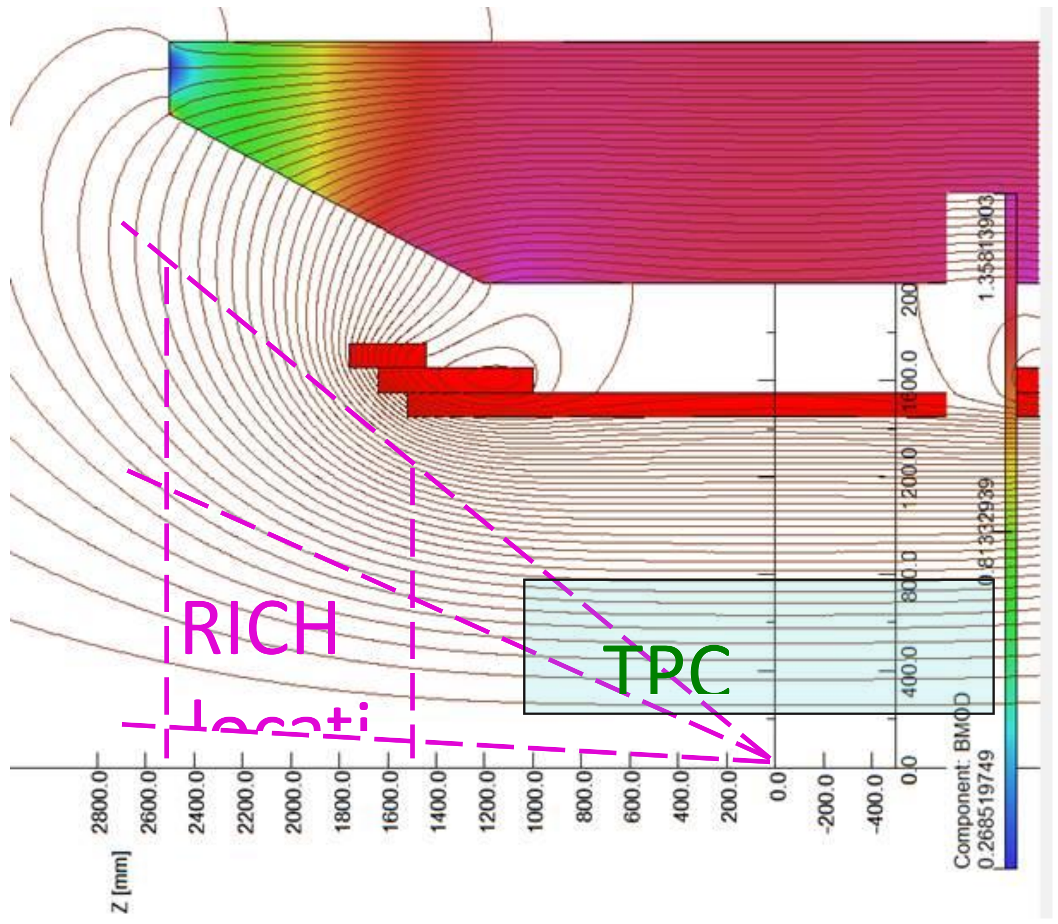
- TPC (baseline YR) was rejected due to large material load in endcaps
  - cons: loss of low-p_T PID, loss of many tracking points
  - replaced by MAPS (not wafer stitched) and MMG layers
- All PID detectors based on Cherenkov effect only
  - dRICH (SiPM readout)
  - mRICH (MCP-PMT)
  - hpDIRC (MCP-PMT) - flipped w.r.t YR expansion volume on lepton side
- HCAL in both endcaps
  - dropping backward HCAL did not save much cost and iron was needed anyway for return yoke
- Routing of central detectors services through slice of $1 < |\eta| < 1.05$
- Naming and numbering detector concepts
  - B-<n>.<m> for barrel <n> system configuration, <m> geometry configuration
  - P-<n>.<m> for p (P = positive η)
  - N-<n>.<m> for backward (N = negative η)
  - Cool codenames from S&C for given combination
- Detector description via DD4HEP

Magnet - Early Decisions

- Engineering at Saclay (Valerio Calvelli) and project support by Renuka Rajput-Ghoshal (JLab)
- Homogenity versus Projectivity
  - Projectivity and homogeneities are inversely proportional
  - Homogenity requirements could be relaxed (compared to YR) since no TPC
  - WG see no big difference between configuration with optimized homogeneity versus configuration with optimized projectivity

Projectivity
[Field lines parallel to particle trajectory]

Important in fwd/bwg region



$$Proj = \frac{B_z \tan\Theta - B_r}{J_E}$$

If $Proj = 0$ everywhere, particles are not deflected from the original trajectory

Homogeneity
[Field lines parallel to main axis]

Flat region: $H_{Flat} = (B_{max}-B_{min})/B_{IP}$

“TPC” Region: $H^2_{TPC} = B_r/B_z$

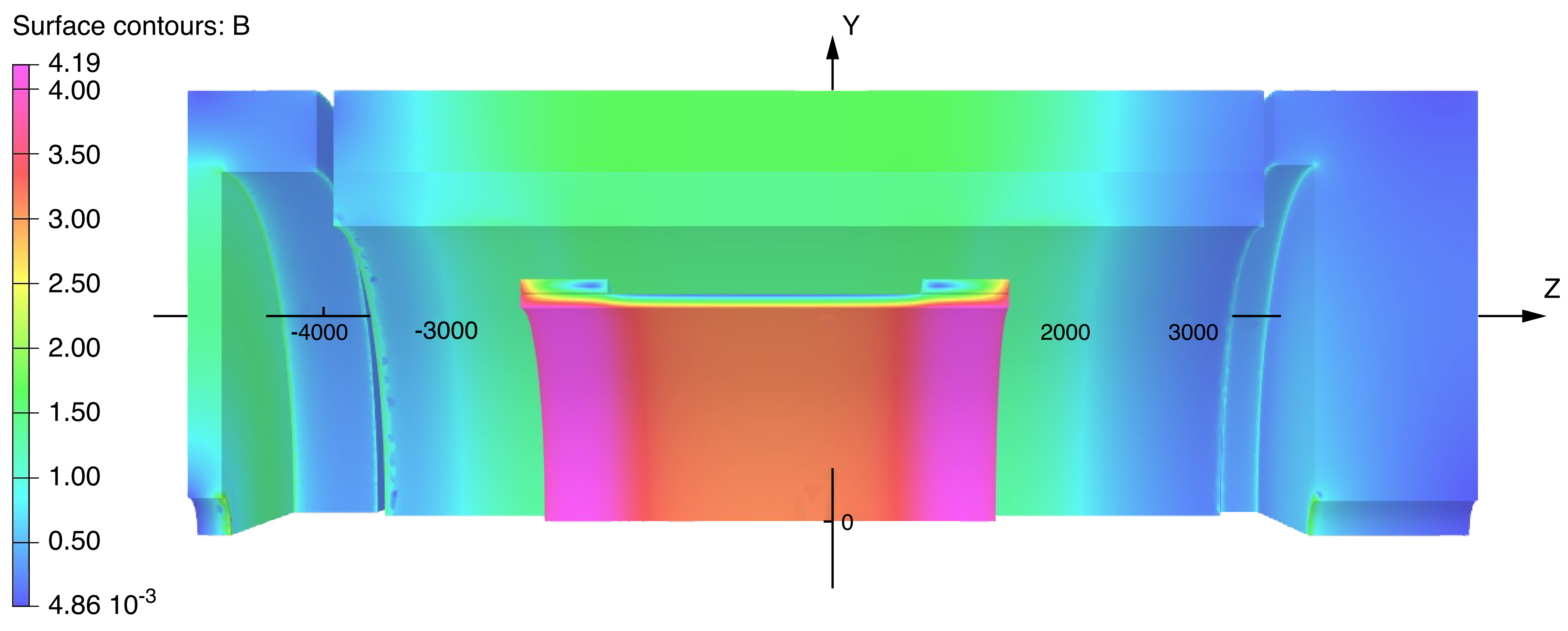
ATHENA Final: homogeneity at 27.5%
projectivity at 10.4% level

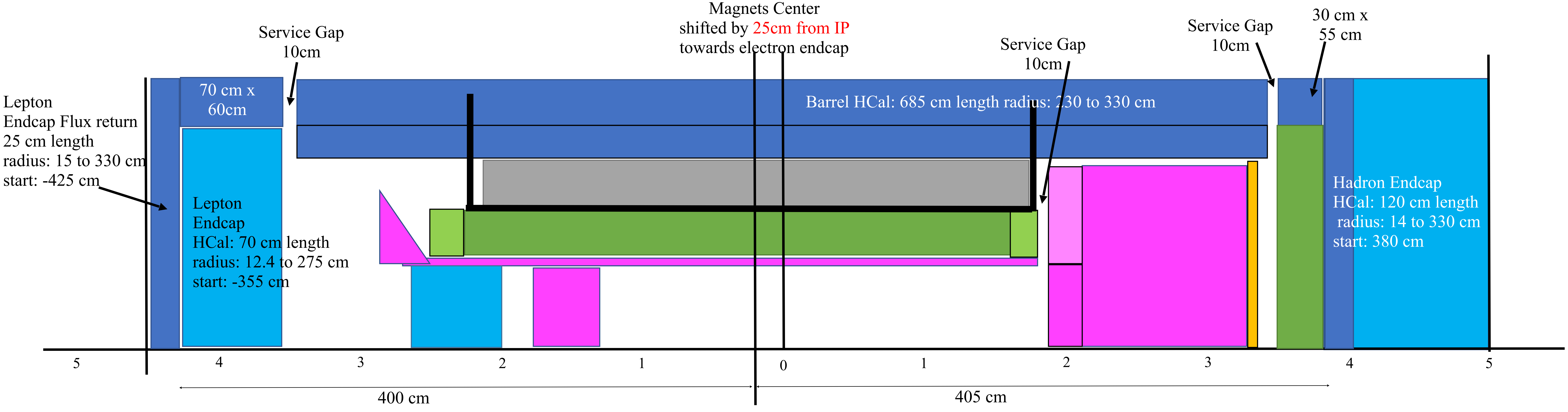
Studies with SIMULIA Opera package

Magnet - Big Step Forward

Shift of Magnet (25 cm):

- novel configuration
- shift the magnet by 25 cm towards the electron endcap
- gives enough space for the dRICH
- get service gaps we need and can support the heavy barrel ECal
- hpDIRC OK with slight increased field at exp. vol.



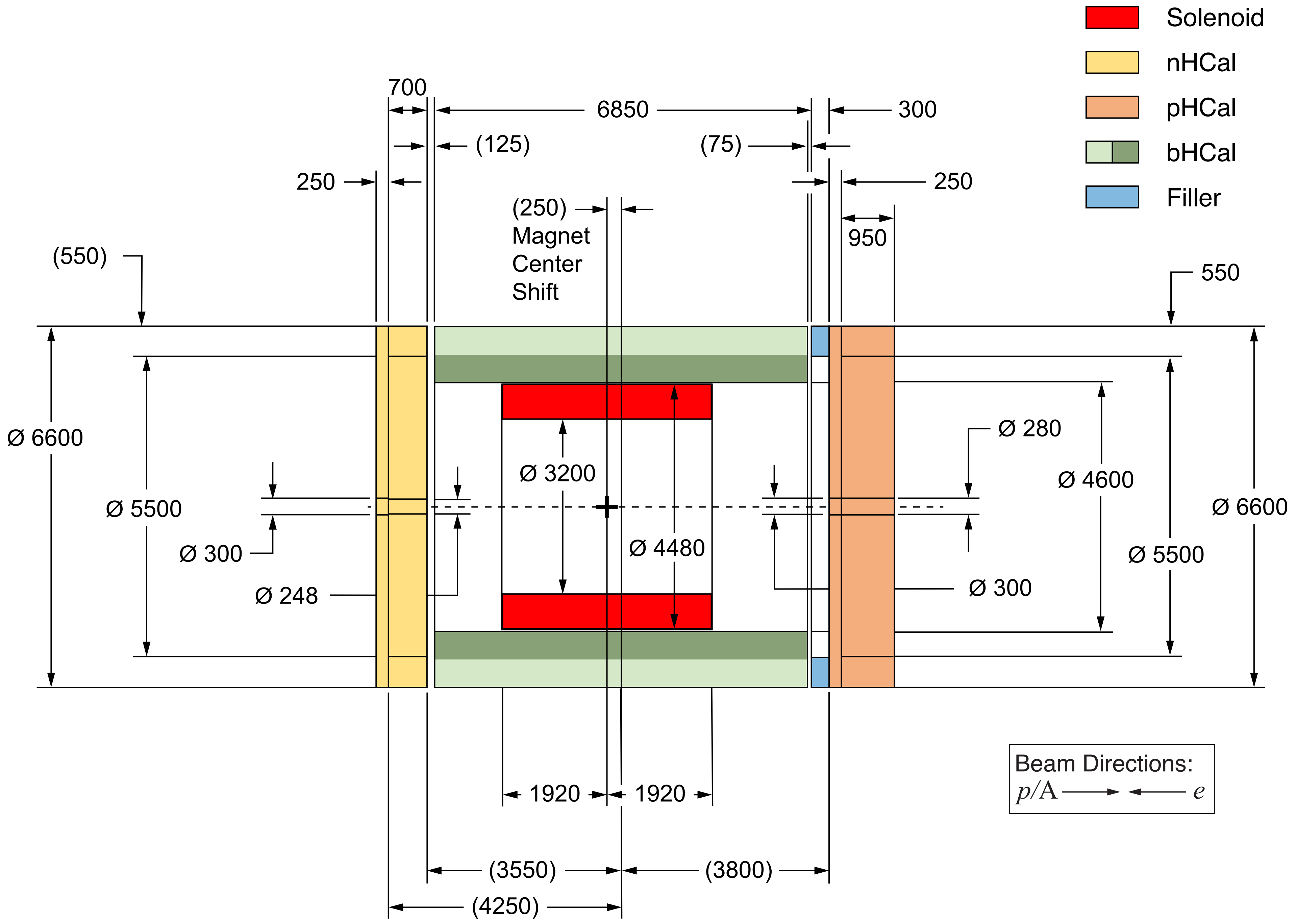


Dark blue indicates steal which is used as flux return, sometimes as part of the detector

Magnet - FINAL

Final Parameters:

- B_{IP} = 3.02 T
- Bore Diameter = 3.2 m
- Length = 3.6 m
- Homogeneity
- Possible operation down to B = 0.5 T

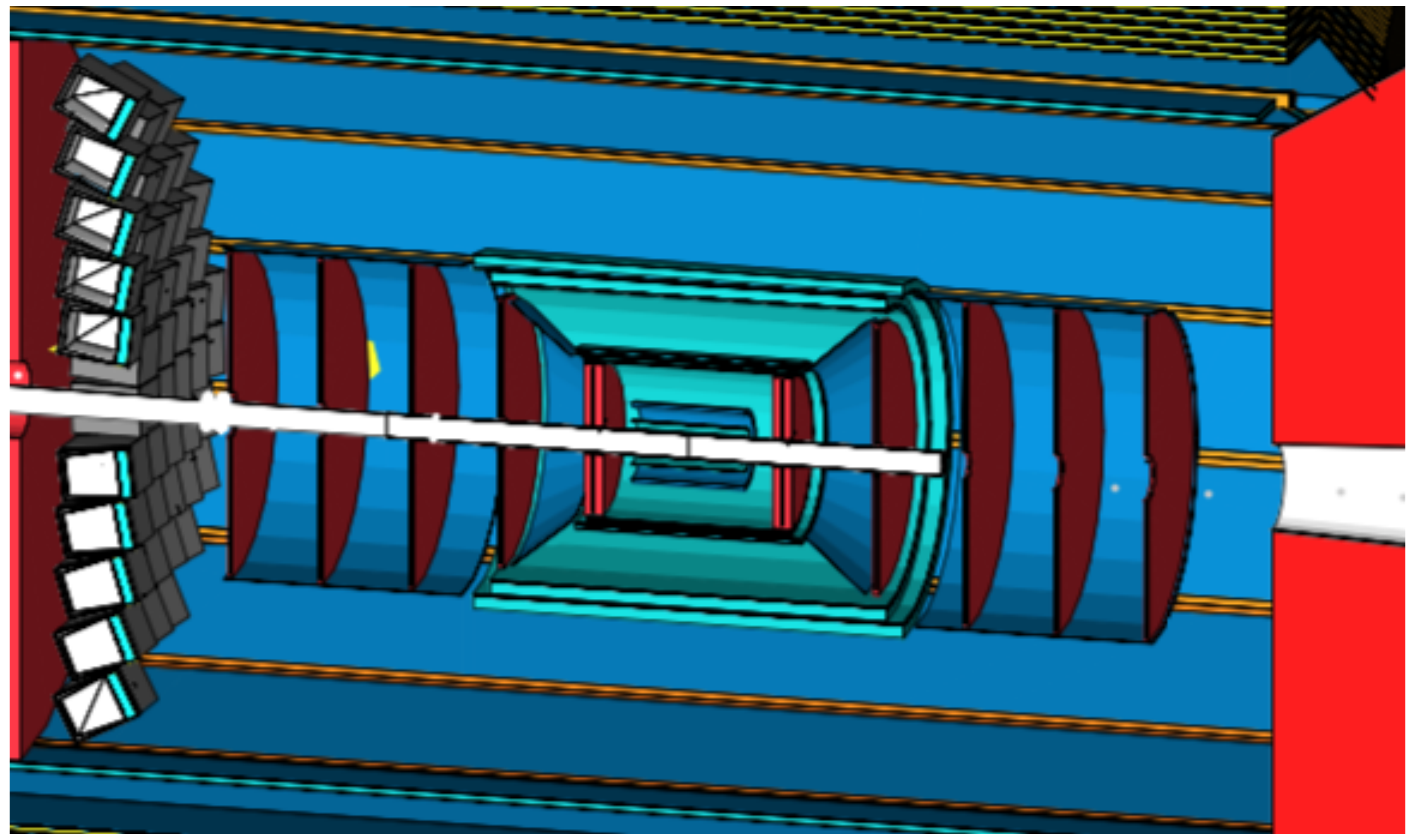


- Flat area in the volume around the beam axis (enough ∫B·dl): homogeneity at 27.5% level
- Projective field in dRICH area (190<z<330 cm; 3.5<θ<25degree) : projective at 10.4% level
- “Light”: material budget in nuclear interaction length ~1.3 λ/λ_I

Tracking - First Steps

- Started with baseline for later comparison
  - B-0.0 = All-Silicon Tracker (no MPGD) + HP-DIRC + …
  - P-0.0 = Si-Disks + GEM Layer + dRICH + …
  - N-0.0 = Si-Disks + GEM Layer + mRICH + …
  - Clear from the beginning that ITS3 sensors are the way to go but *only vertex layers can be wafer-stitched-sensors* (EIC sensor)
    - Big advantage having the EICSC on board
    - Silicon Vertex, 3 layers, 0.05 X/X_0/ layer, $-2.2 < \eta < 2.2$
    - Silicon barrel, 2 layers, 0.55 X/X_0/ layer, $1.05 < \eta < 1.05$
    - F + B disks, initially symmetric, 5 disks, 0.24 X/X_0/ layer
  - Many discussion about disk geometry (cone vs cylinder)
  - Deliberate choice to extend the tracker in z to capture more curvature for forward and backward tracks.

Convener: Laura Gonella, Domenico Elia, Francesco Bossu, Matt Posik

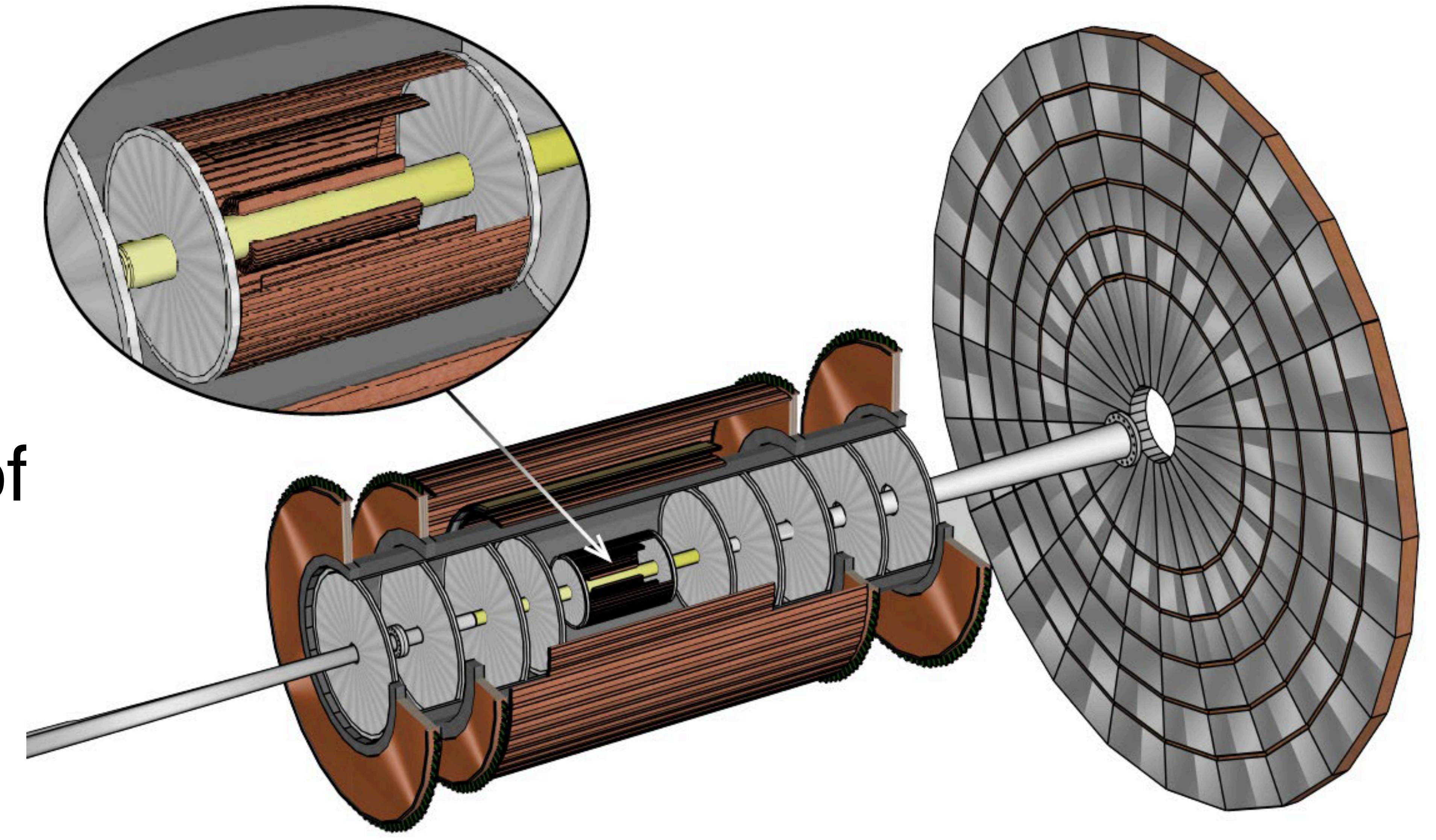


Tracking - Things I Learned from Wise “Trackers”

- An **odd number** of evenly spaced disks tends to capture the sagitta point. As such, it is preferred over an even number of disks.
  - Acceptance edges, both at the inner and outer radii, make it "less straightforward" and that holds also for non equidistant spacing.
  - Was one of the initial conceptual design considerations.
  - The choice for 6 silicon disks in the forward direction was driven by acceptance considerations when more space in z became available;
  - MGPD behind the RICH would be the additional point "to make it odd."

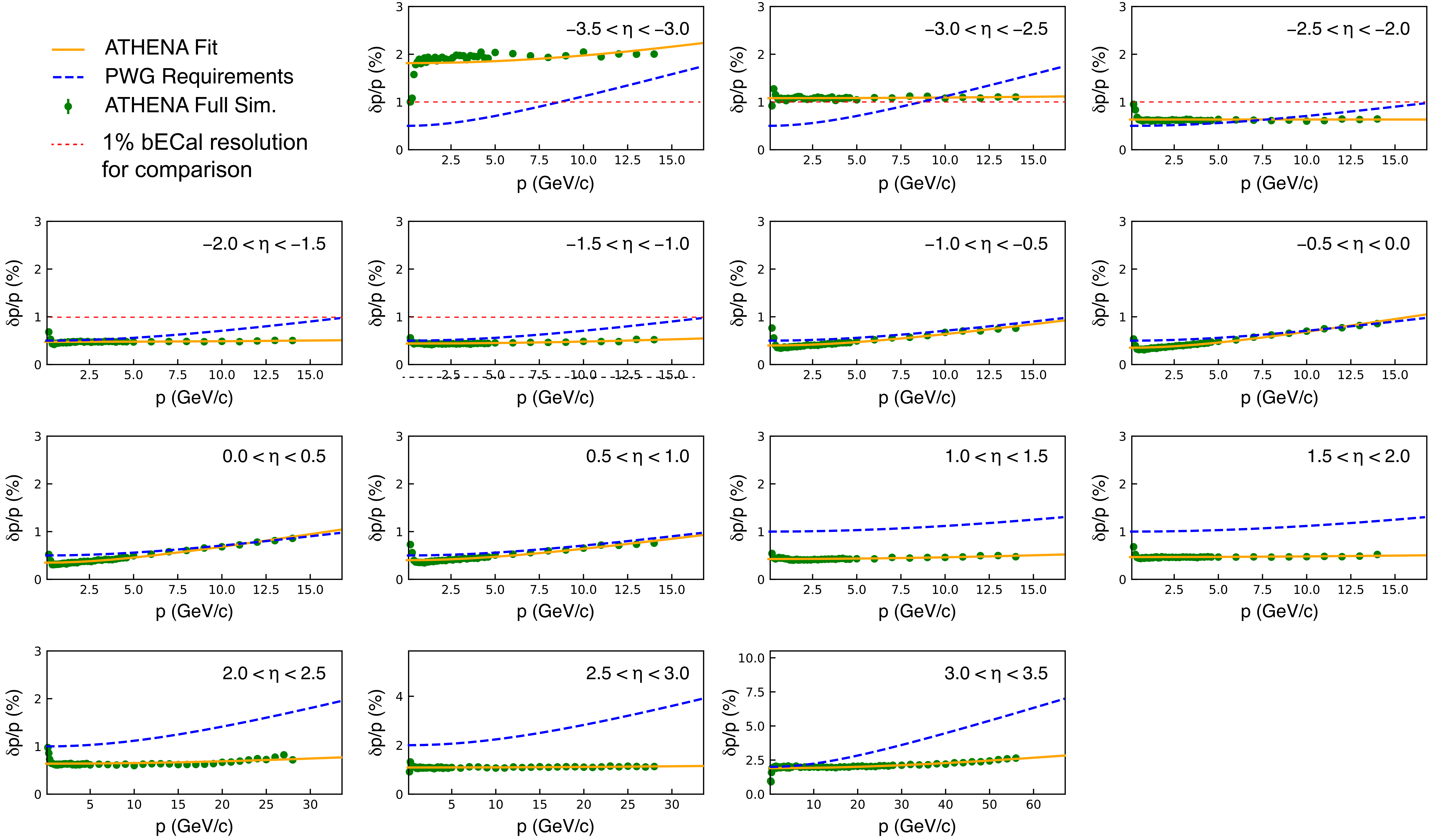
Tracking - Evolution

- Barrel
  - Need for more tracking points (also large L)
  - Solution: 4 layers (2x2) cylindrical Micromegas
    - Proven and understood technology (see CLAS@JLab)
  - 3+2+4+1 = 9 still on the low side
  - Later added 1 layer AC-LGAD + 1st imaging layer (Astropix) of bECal behind hpDIRC ➟ 11 potential tracking points
- Forward
  - 5 → 6 disks
  - Outer disks too large for MAPS alone ➟ MPGD rings
    - lots of discussion among us and with engineers on routing and mounting etc
    - Note: if using all Si the thickness of the disks would have to increase affecting the resolution and X/X_0.
  - Technologies: GEM is safe, μRWell desirable since less materials, easier construction and likely lower cost (needs R&D)
  - Large MPGD disk after dRICH ➟ improve tracking and dRICH reconstruction (MS)



- Backward
  - e-going direction is precious, need to minimize material ➟ only 5 Si-disks + 2 MPGD rings around 2 outer disks

Tracking - Performance & Impact (I)



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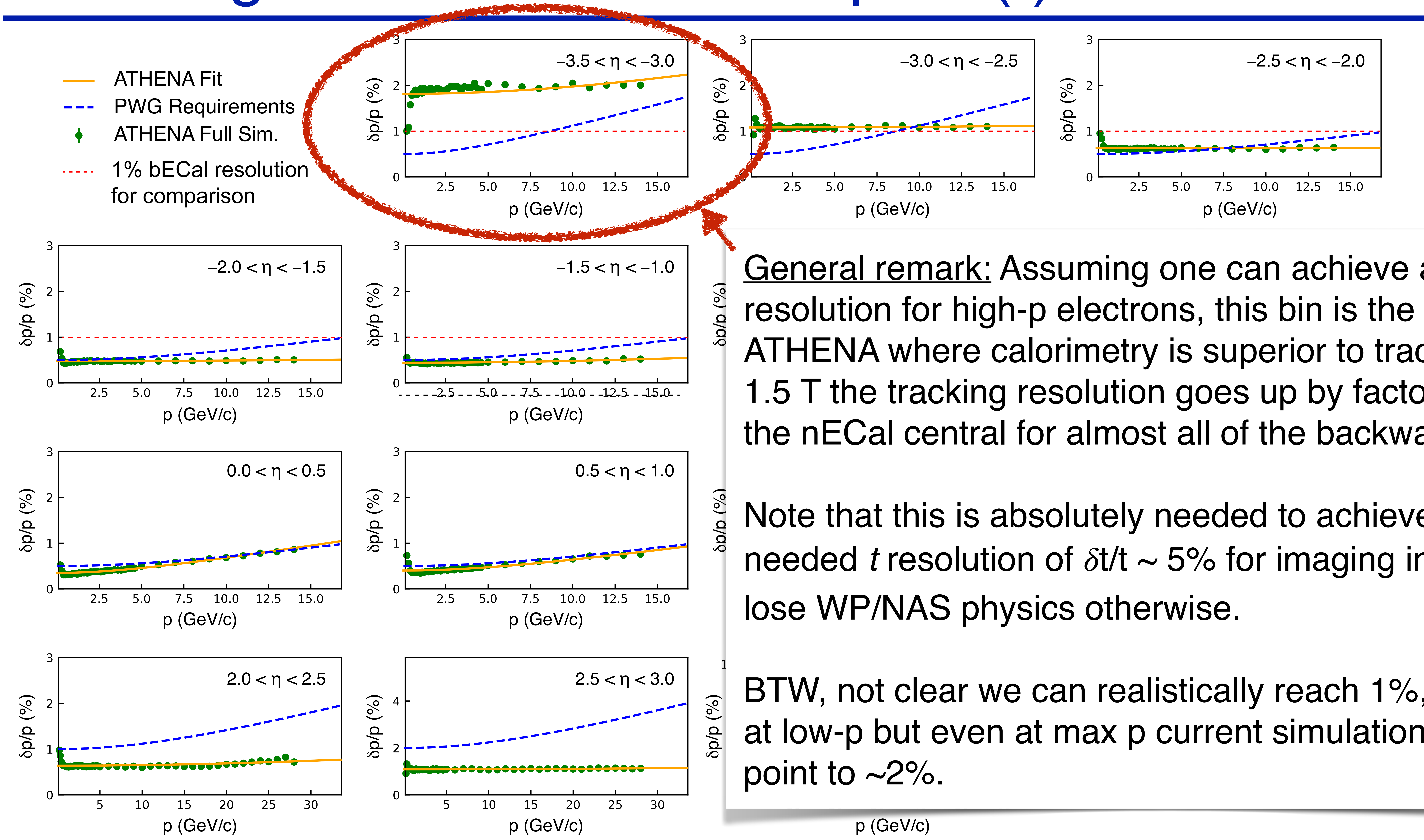
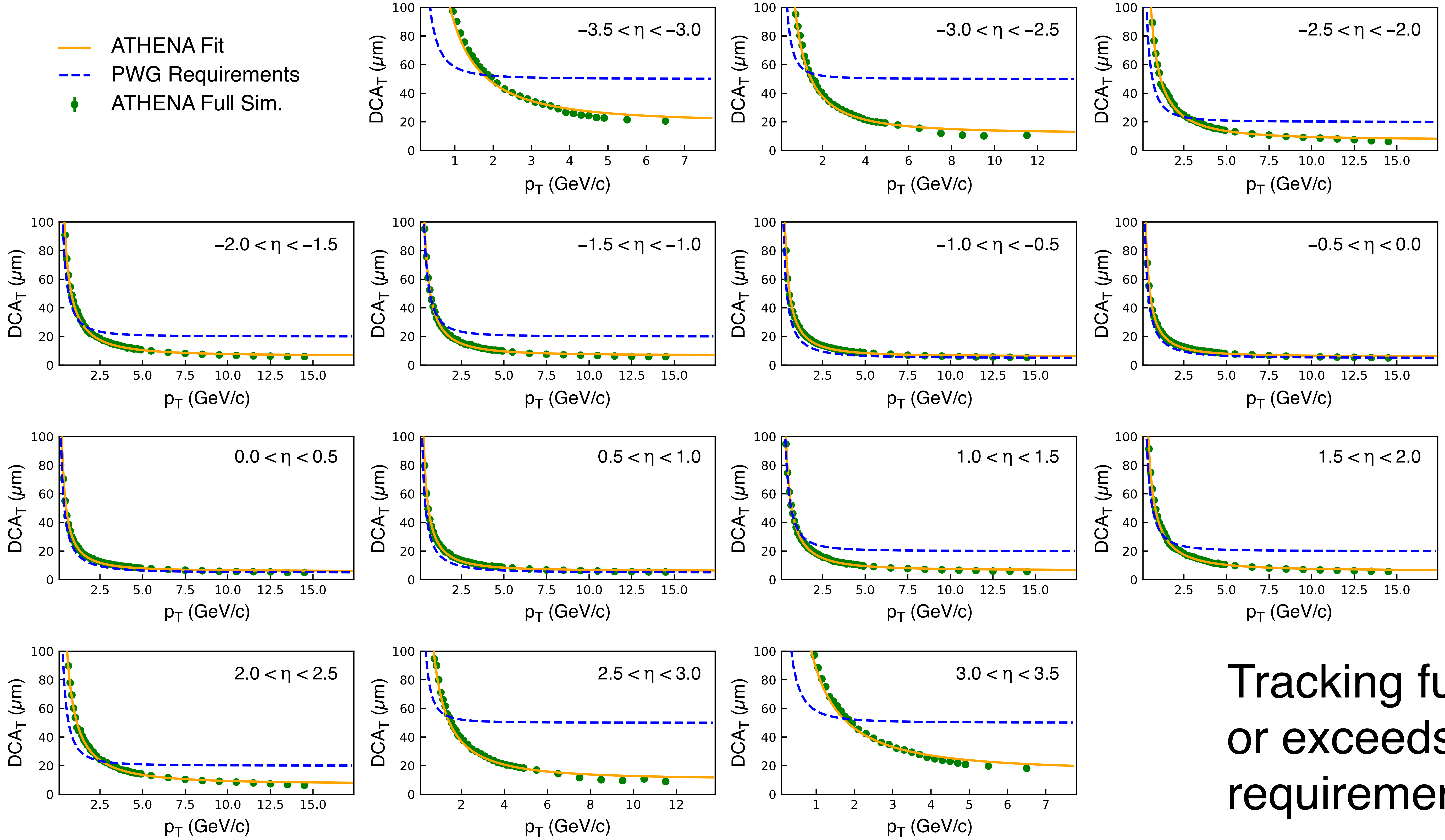


<u>General remark:</u> Assuming one can achieve a 1% resolution for high-p electrons, this bin is the only one in ATHENA where calorimetry is superior to tracking. For 1.5 T the tracking resolution goes up by factor 2 making the nECal central for almost all of the backward range.

Note that this is absolutely needed to achieve the much needed *t* resolution of $\delta t/t \sim 5\%$ for imaging in eA. We lose WP/NAS physics otherwise.

BTW, not clear we can realistically reach 1%, clearly not at low-p but even at max p current simulations rather point to ~2%.

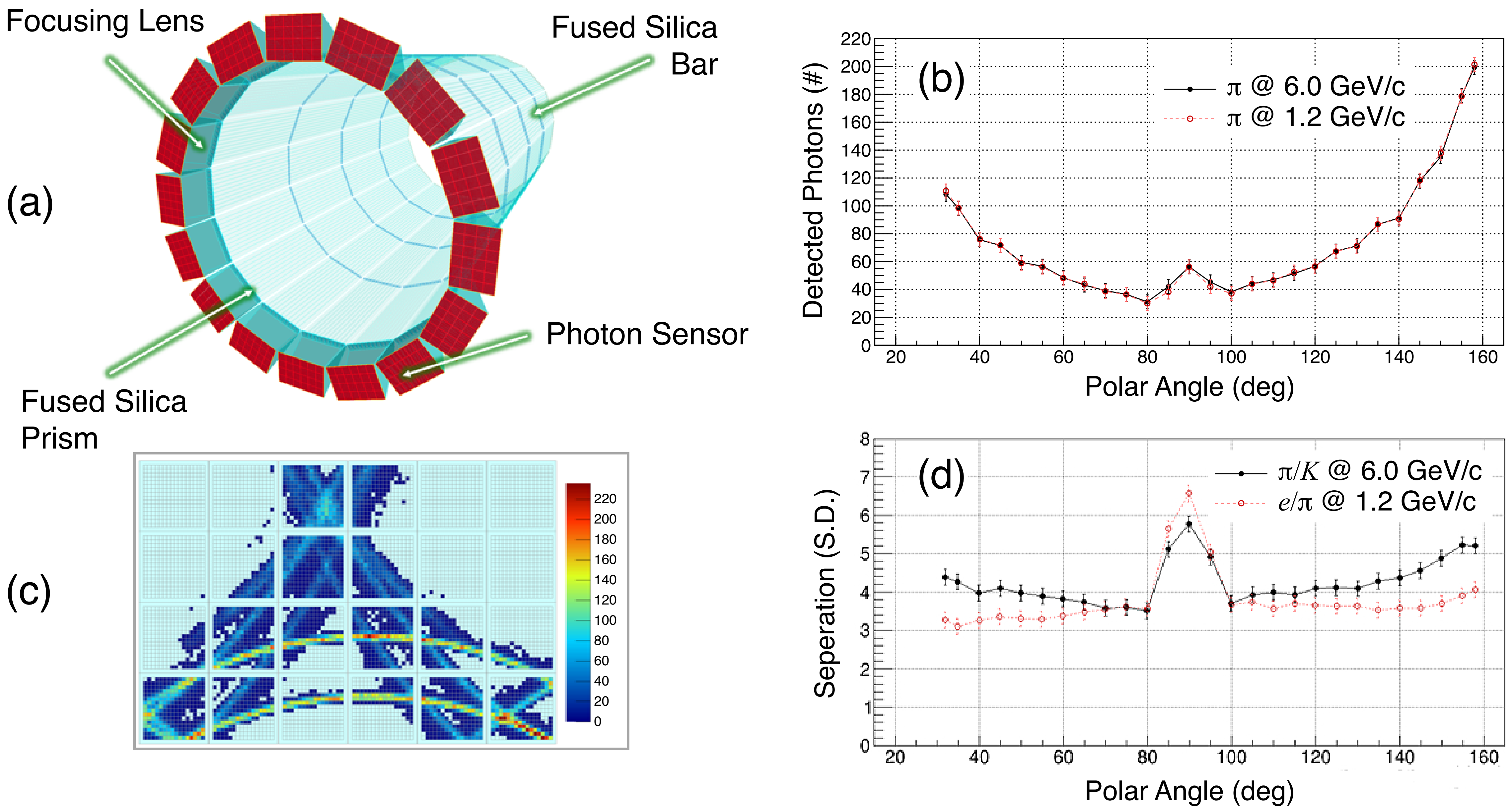
Tracking - Performance & Impact (II)



Tracking fulfills or exceeds requirements

PID - Barrel (I)

- Key detector is hpDIRC
  - Acceptance: $-1.64 < \eta < 1.25$
  - p_T > 0.45 GeV/c @ 3T
  - p < 6.5 (K/π), p < 1.2 (e/π)

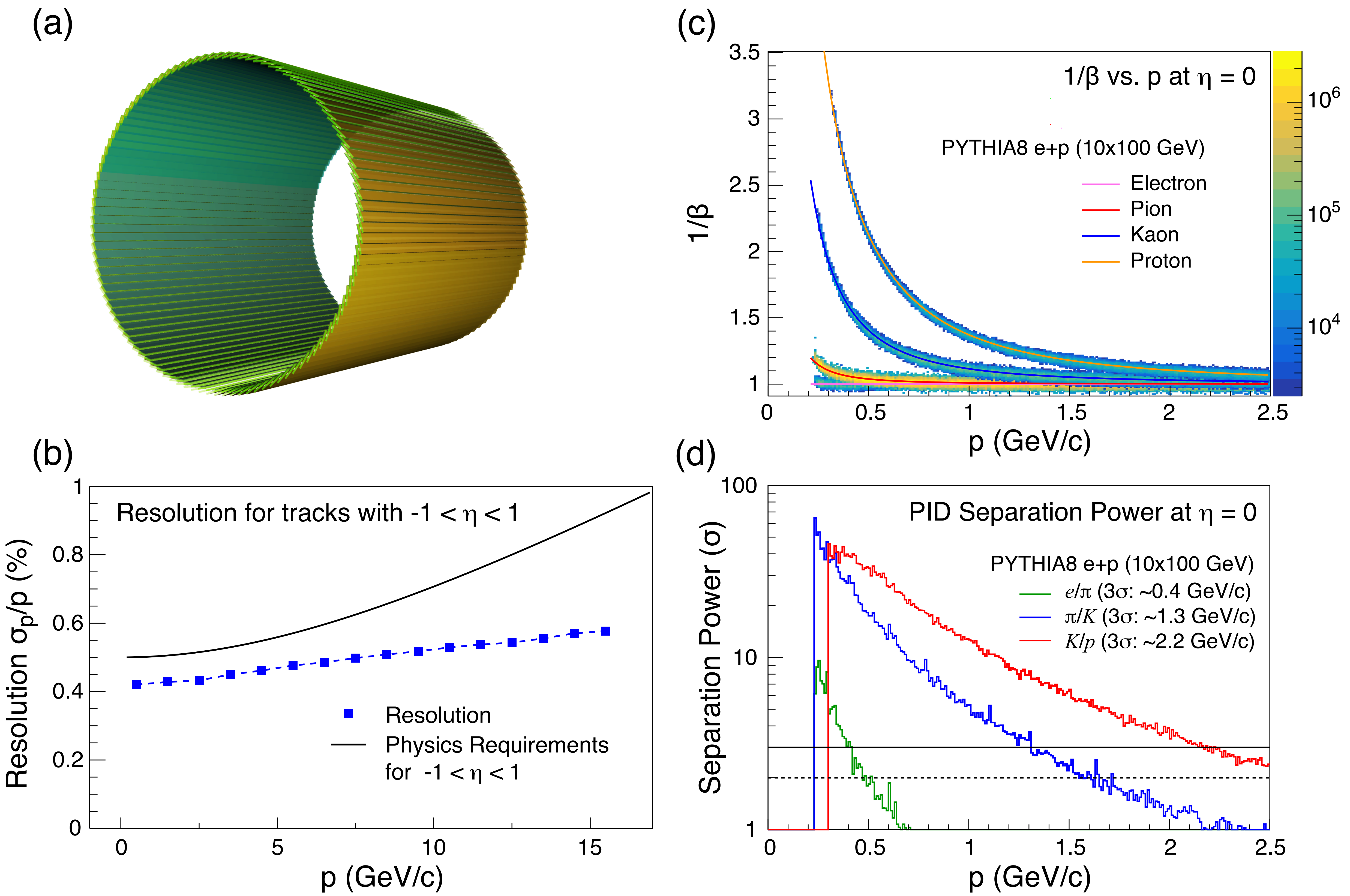


- PID gap below 450 MeV/c since particles do not cross DIRC. Impacts ρ, ϕ reconstruction and possibly charm
  - possibility 1 - run at lower field for short time ➟ sub-optimal, deterioration of overall performance, non-optimal use of run time
  - add ToF detector ➟ our pick
    - requires no degrading of tracking performance
    - has to have low mass to not affect bECal: $X/X_0 \leq 1\%$

Convener: Tom Hemmick, Roberto Preghenella, Franck Geurts

PID - Barrel (II)

- ToF using AC-LGAD
  - A single-layer array of AC-LGAD devices at a radius of 52.5 cm in the ATHENA design provides an effective PID coverage between 0.23 and 1.3 GeV/c for a 3 T field, and an additional spatial hit to supplement the tracking system in the barrel region.
  - AC-LGAD with **strips** to reduce power consumption and thus X/X_0. Estimate is $X/X_0 \sim 1\%$
  - $-1.05 < \eta < 1.05$
  - $p_T > 0.23$ GeV/c @ 3T
  - $p < 1.3$ (K/π), $p < 0.4$ (e/π)
  - Exact position in relation to cyl. MMG has room for optimization
- Discussed alternative: miniTPC/Gridpix



- Critical: AC-LGAD sensor development and especially ASIC
  - Mitigation: no problem if it comes delayed. Impact on physics is moderate especially in the first years.
  - No need to look for alternatives
  - Can always run at lower field if absolutely needed

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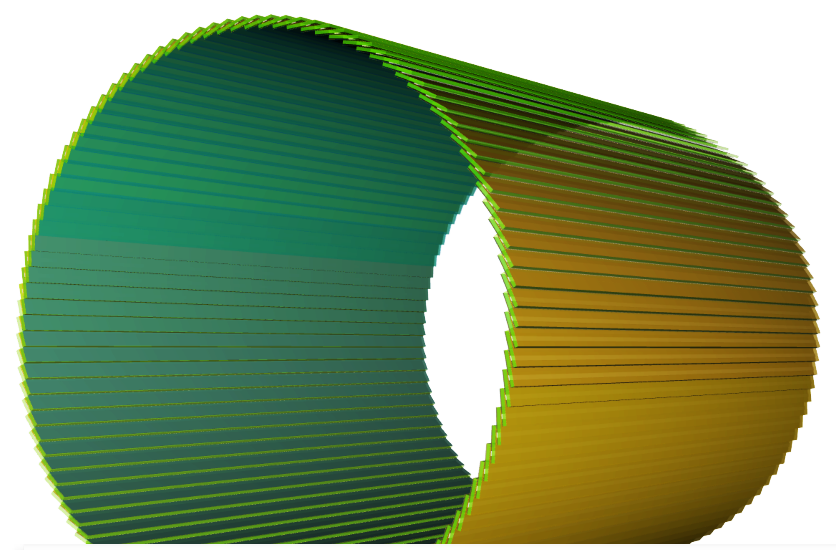
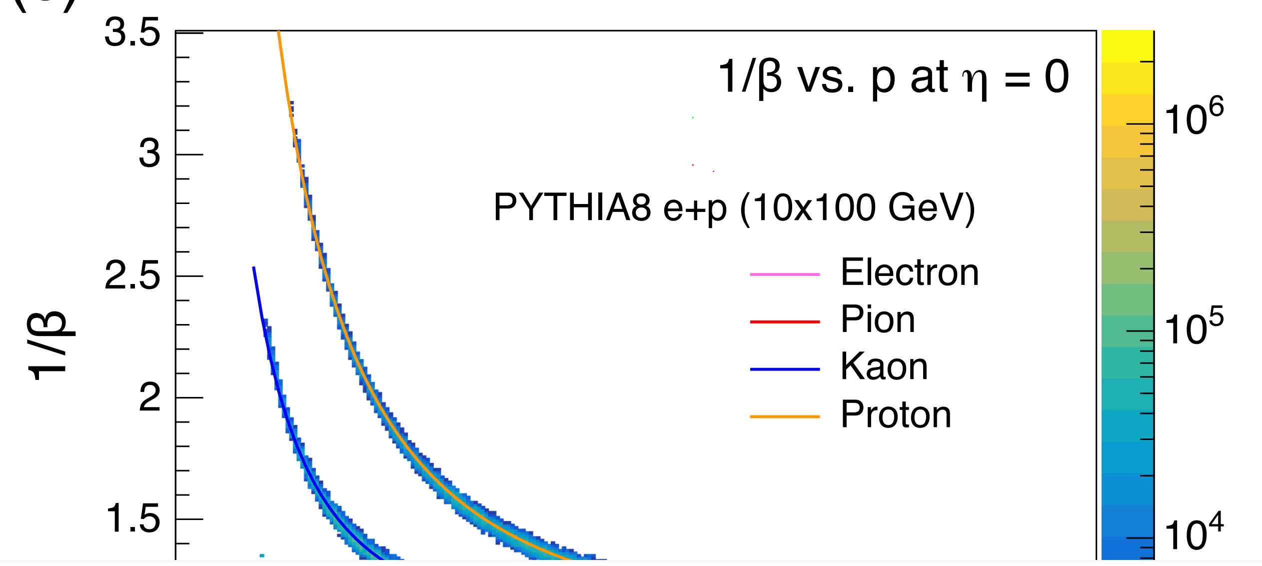
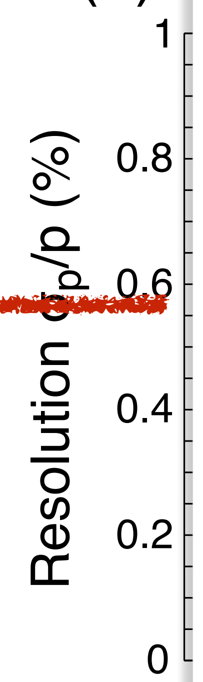
(a)



(c)



(b)



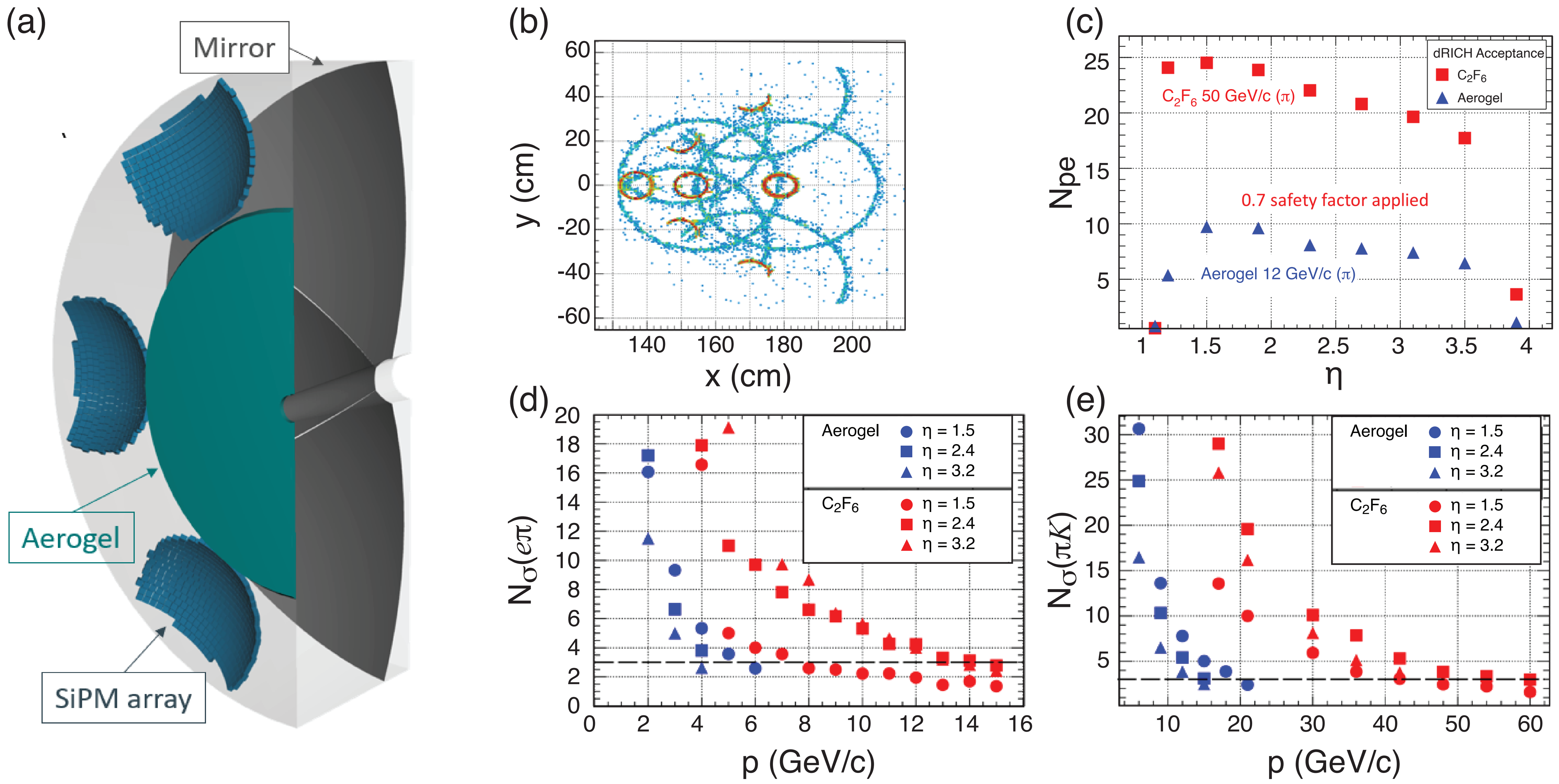
N.B. Achieving 1% was the key development that pushed the bToF into the overall design.

Substantial work by the bToF group to get there. Standard LGADs and even AC-LGADs with “pixels” cannot achieve this.

The number of readout channels per unit area and thus material budget are directly correlated

PID - Forward

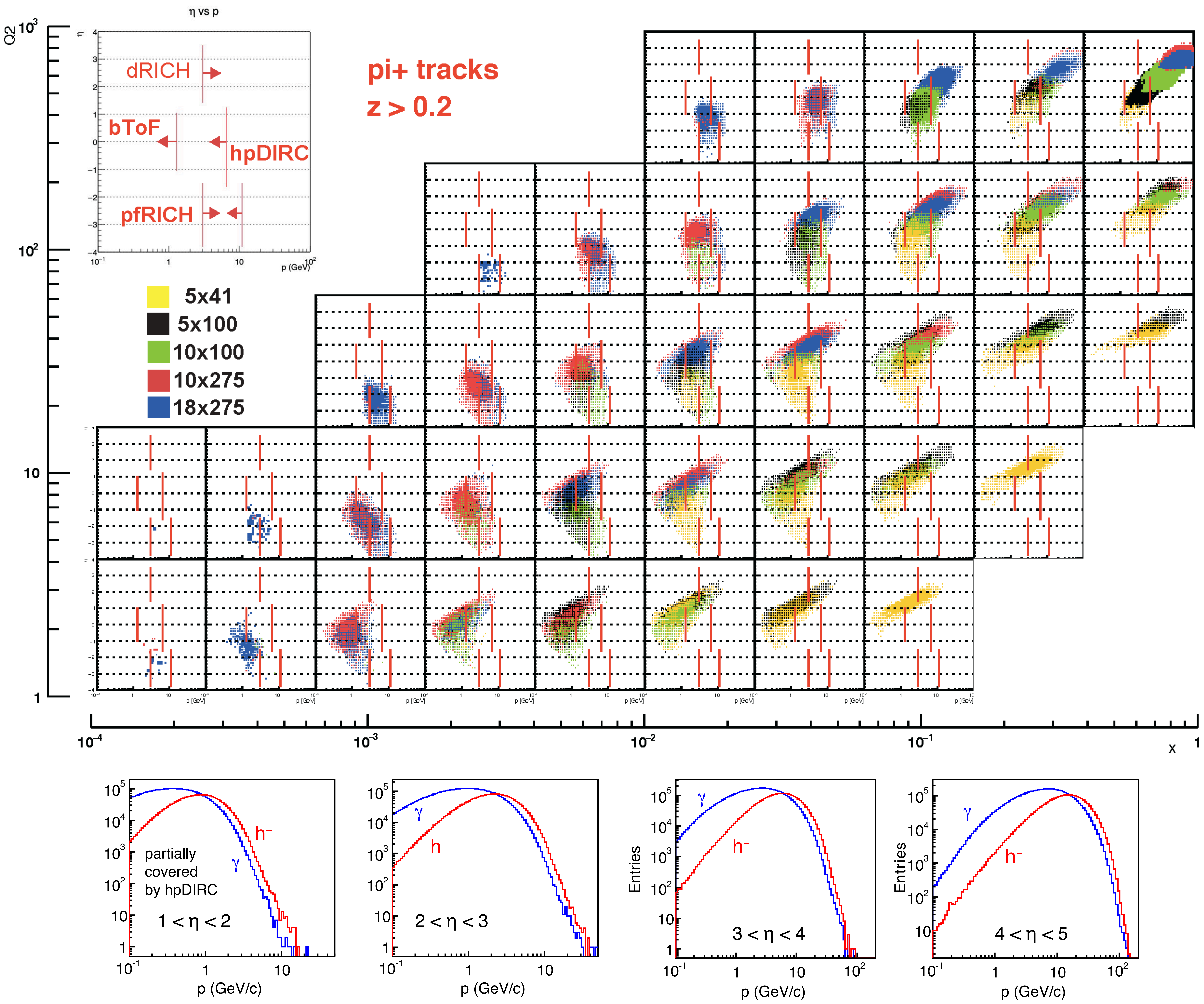
- dRICH is only PID detector in fwd directions
  - $1.2 < \eta < 3.7$
  - $3 < p < 60$ (K/π)
  - $0.85 < p < 15$ (e/π)
- Much effort to optimize position/ dimension (benefitted from 0.25m shift of magnet)



  - Reasonable optics & performance, distortions below 1mrad at small angles
  - 15 cm gap between the sensor plane and the vessel wall
  - “Upgrade space” of 20-25 cm upstream of the vessel
- Lots of studies and discussion if we need PID below the aerogel threshold

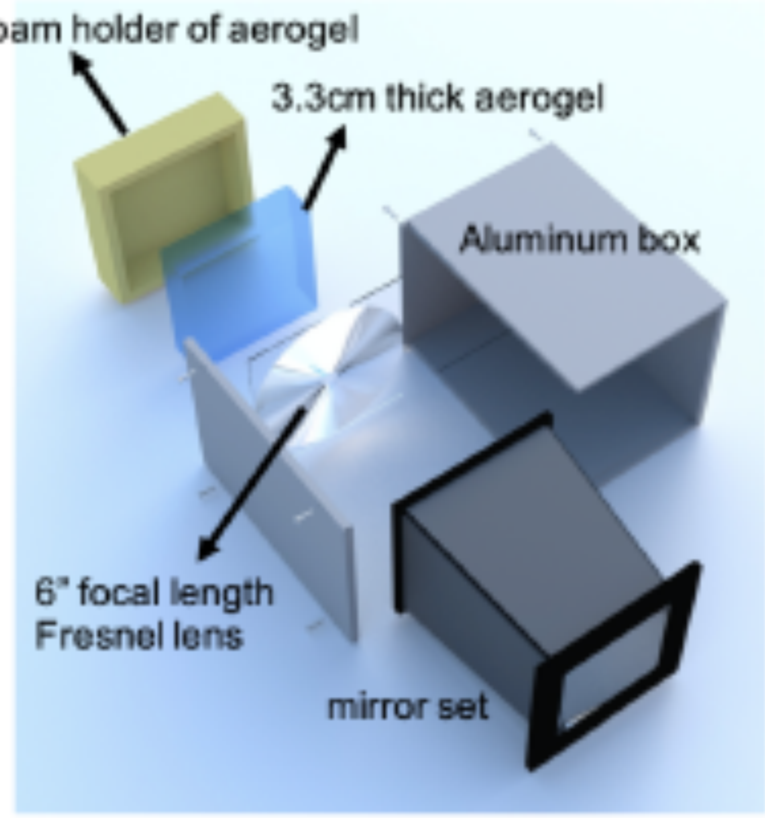
PID - Forward

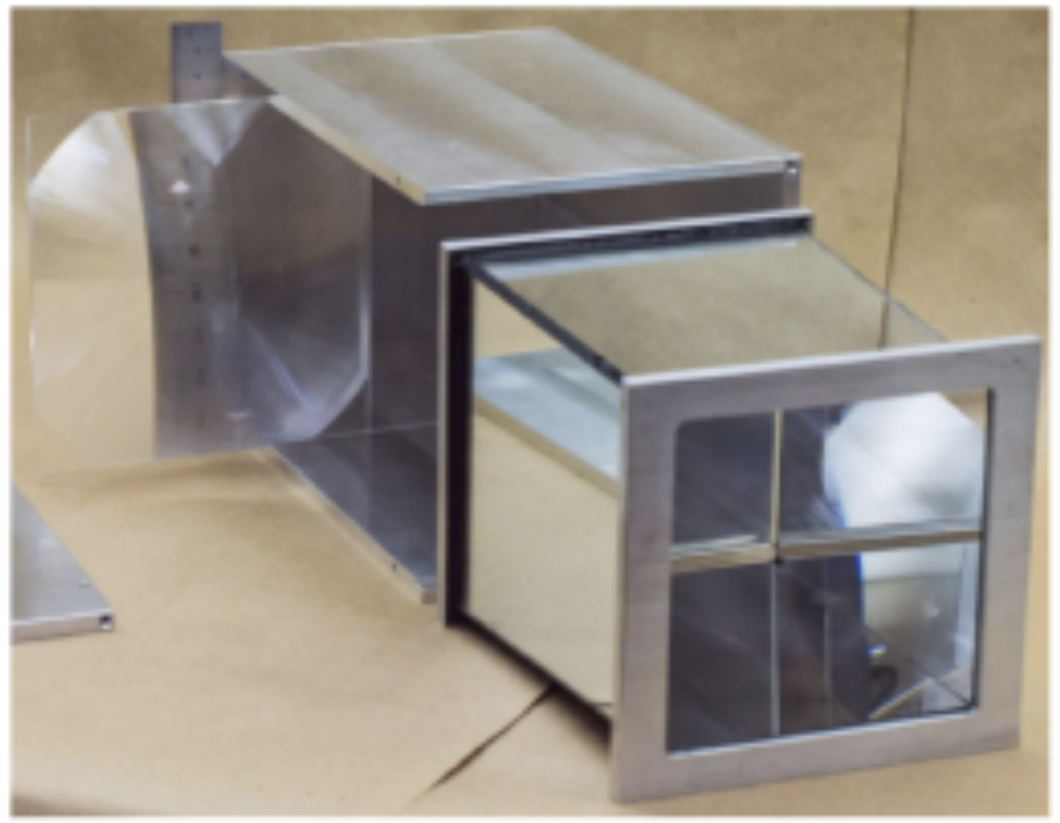
- Many studies in SIDIS WG
  - Example shown π^+
- When taking various beam energies into account and considering the physics/ bucks, ATHENA saw no need to add additional PID to cover momenta below aerosol threshold. Minor physics impact.
- 25 cm room in z for future upgrades if needed.

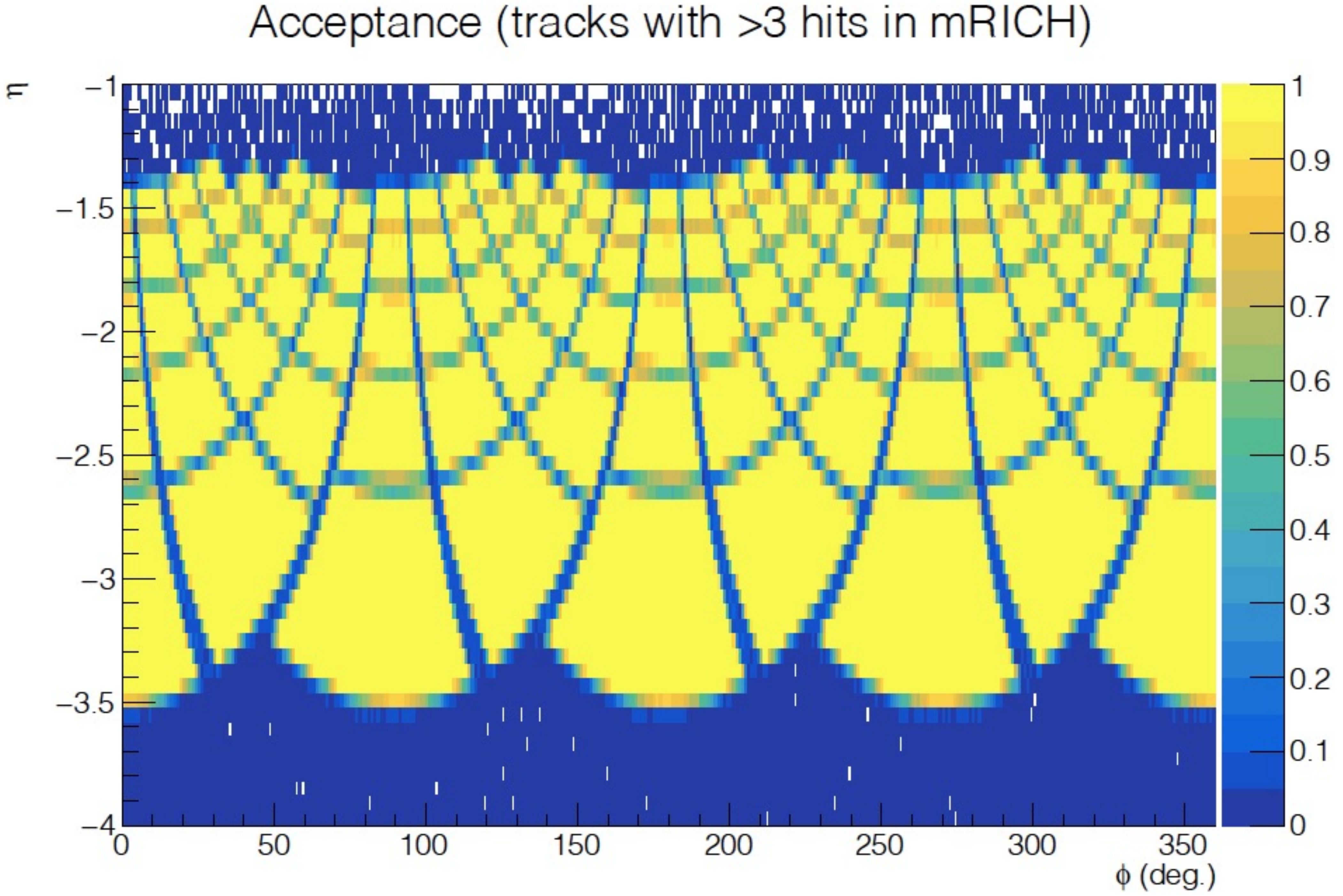


PID - Backwards (I)

- Original PID detector was mRICH (YR)
- Concerns related to
  - support and service (power/gas/signals for each module)
  - X/X_0 already over 10% w/o detailed service and support structure geometry
  - X/X_0 massive for tracks going through frame
  - low acceptance
- mRICH has a lot of nice features that will be fantastic for e.g fixed target experiments or other applications
- ATHENA can make use of available space ➟ proximity focussing RICH

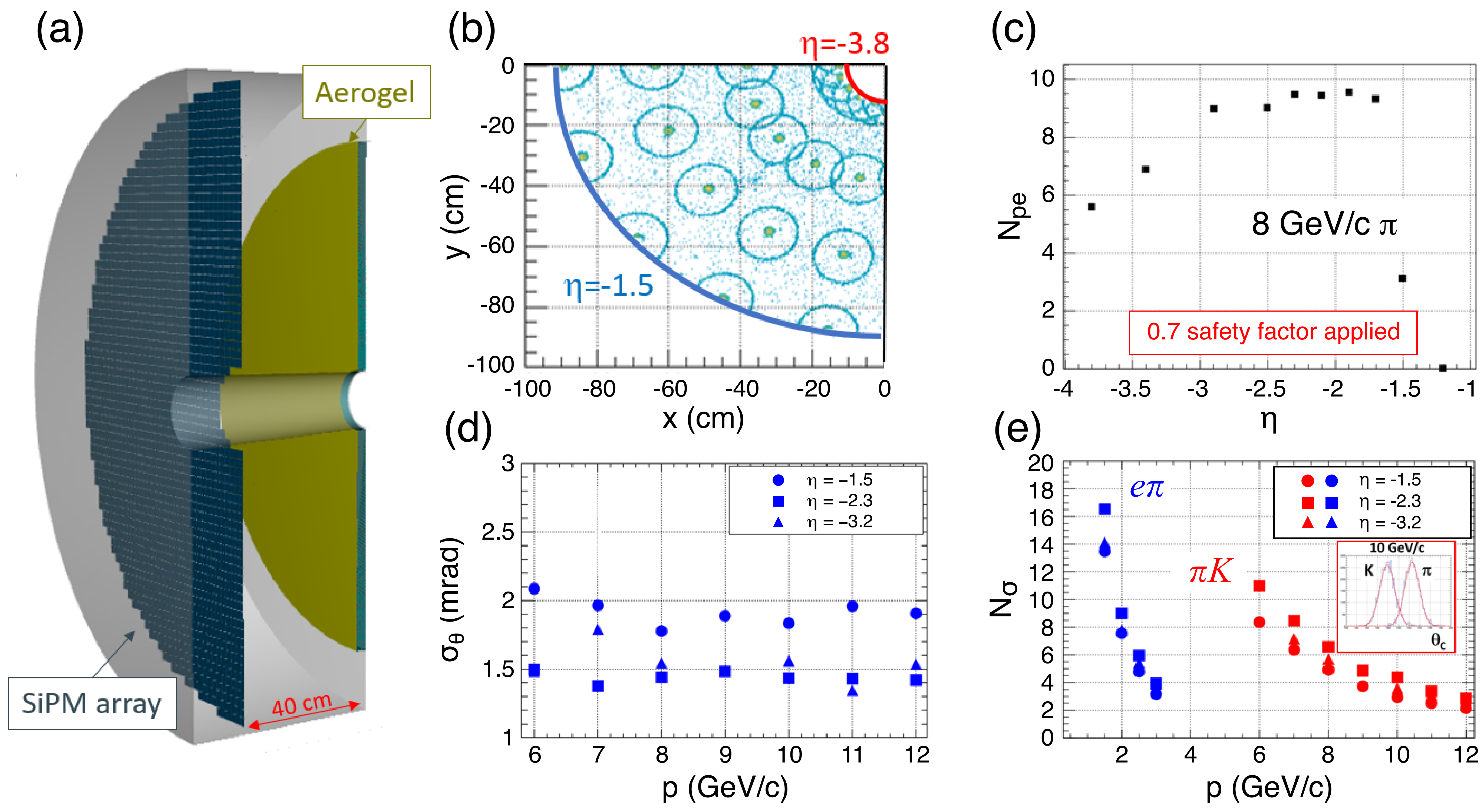






PID - Backwards (II)

- pfRICH
  - aerogel radiator proximity-focusing RICH with a 40 cm proximity gap
  - maximizes acceptance while minimizing material in front of the decal
  - aerogel and photon detector identical to dRICH ➟ minimizes the number of PID technologies
  - $-1.5 > \eta > -3.8$
  - $3 < p < 11$ (K/π)
  - $0.85 < p < 3$ (e/π)
  - allows for pressure vessels (1 bar fluorocarbon → ~3 bar Ar)



N.B: No strong physics case for PID below aerogel threshold identified. If pixelized LAPPD work out this would provide high resolution ToF (and T0) w/o adding material!

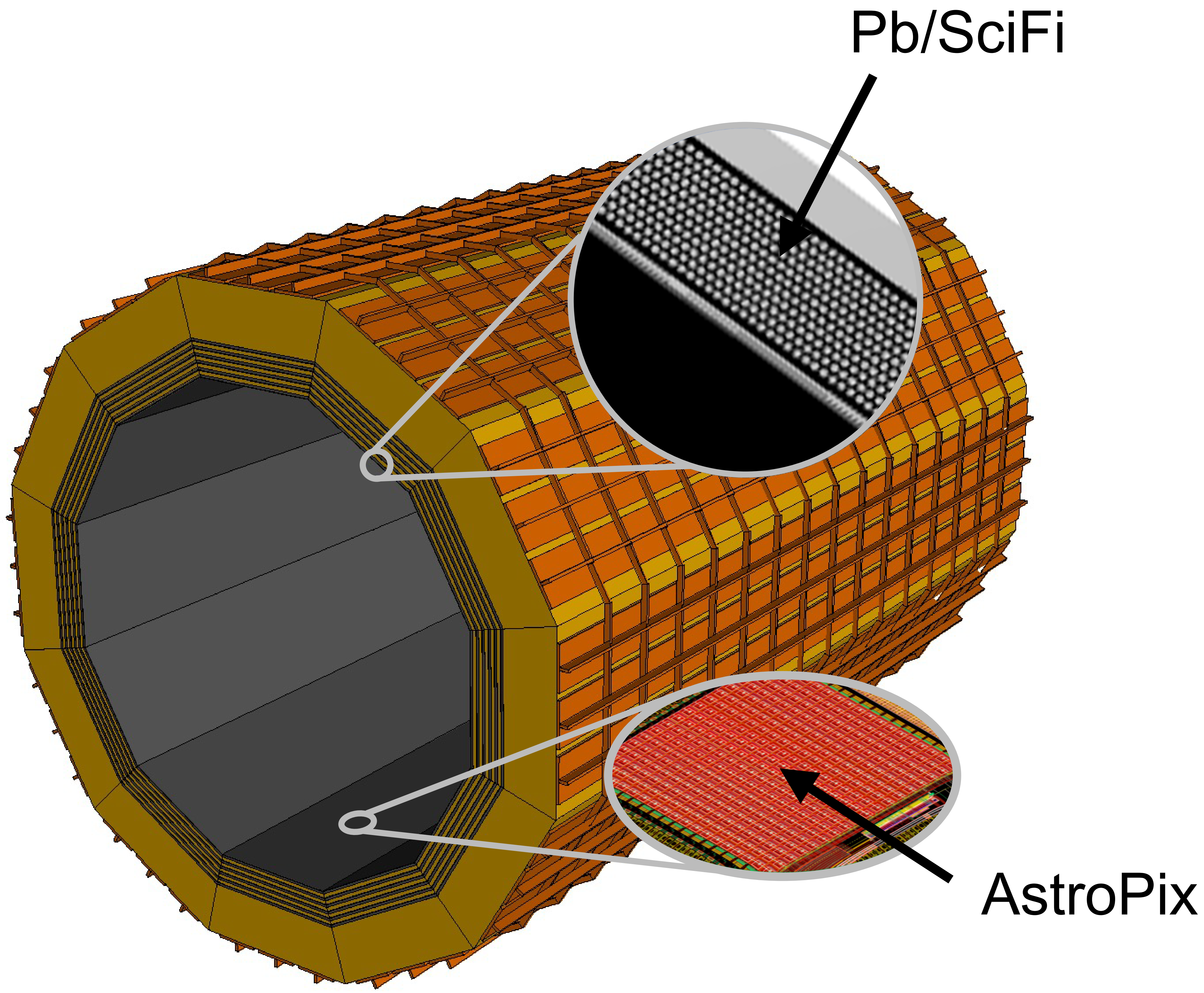
Calorimetry - Barrel (I)

bHCal

- standard Fe/Sci sandwich in $-1.0 < \eta < 1.0$
- outside of magnet cryostat, steel used as flux return

bECal

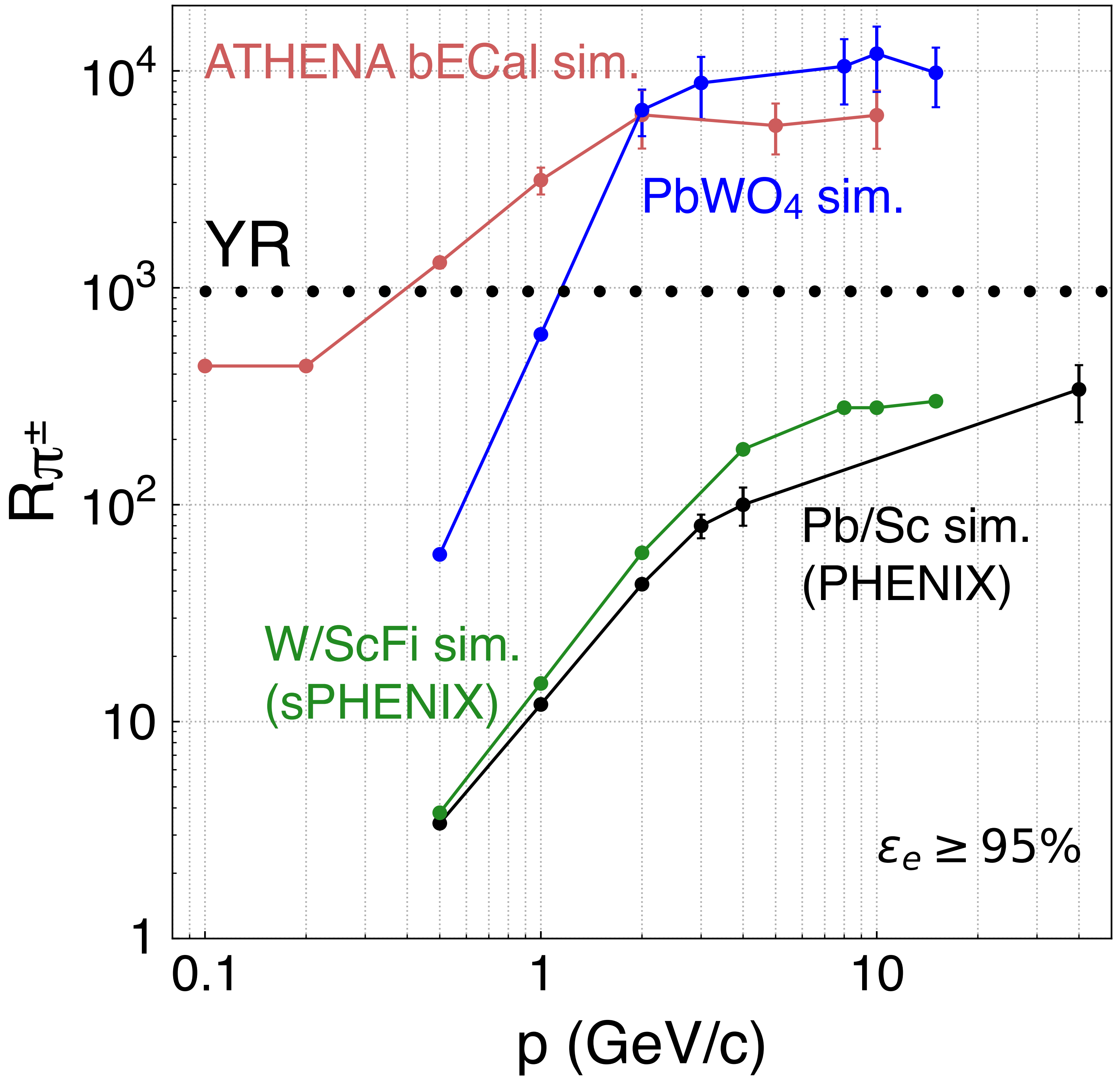
- hybrid: light-collecting calorimetry based on (i) SciFi embedded in Pb and (i) imaging calorimetry based on AstroPix **monolithic** silicon sensors
- imaging of particle showers achieved by 6 layers of silicon sensors interleaved with 5 Pb/SciFi layers, followed by a thick layer of Pb/SciFi calorimeter
- total radiation thickness is 20 X_0.

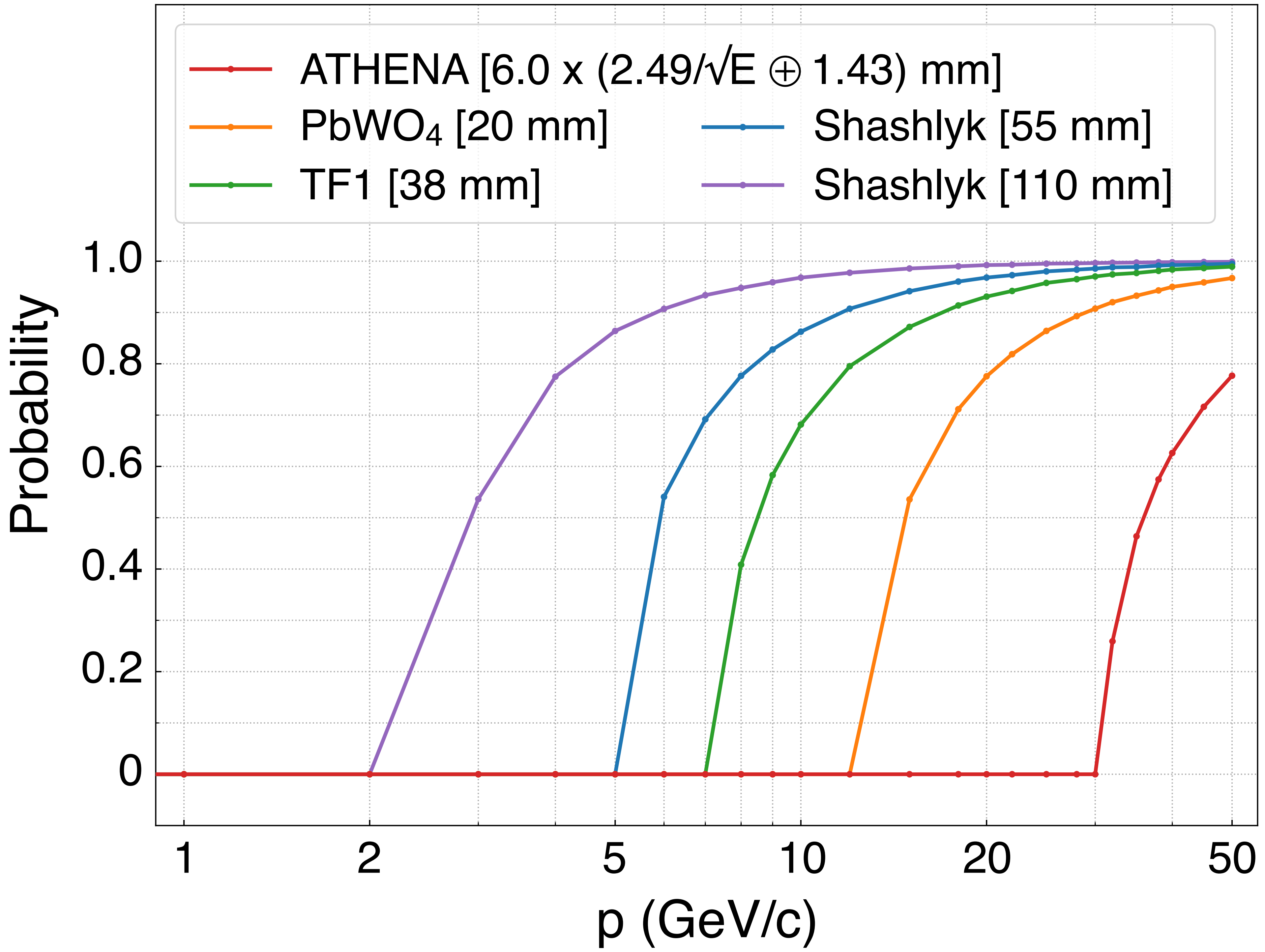


- $-1.5 < \eta < 1.2$
- $5.5\,\% / \sqrt{E} \oplus 1\,\%$

Calorimetry - Barrel (II)

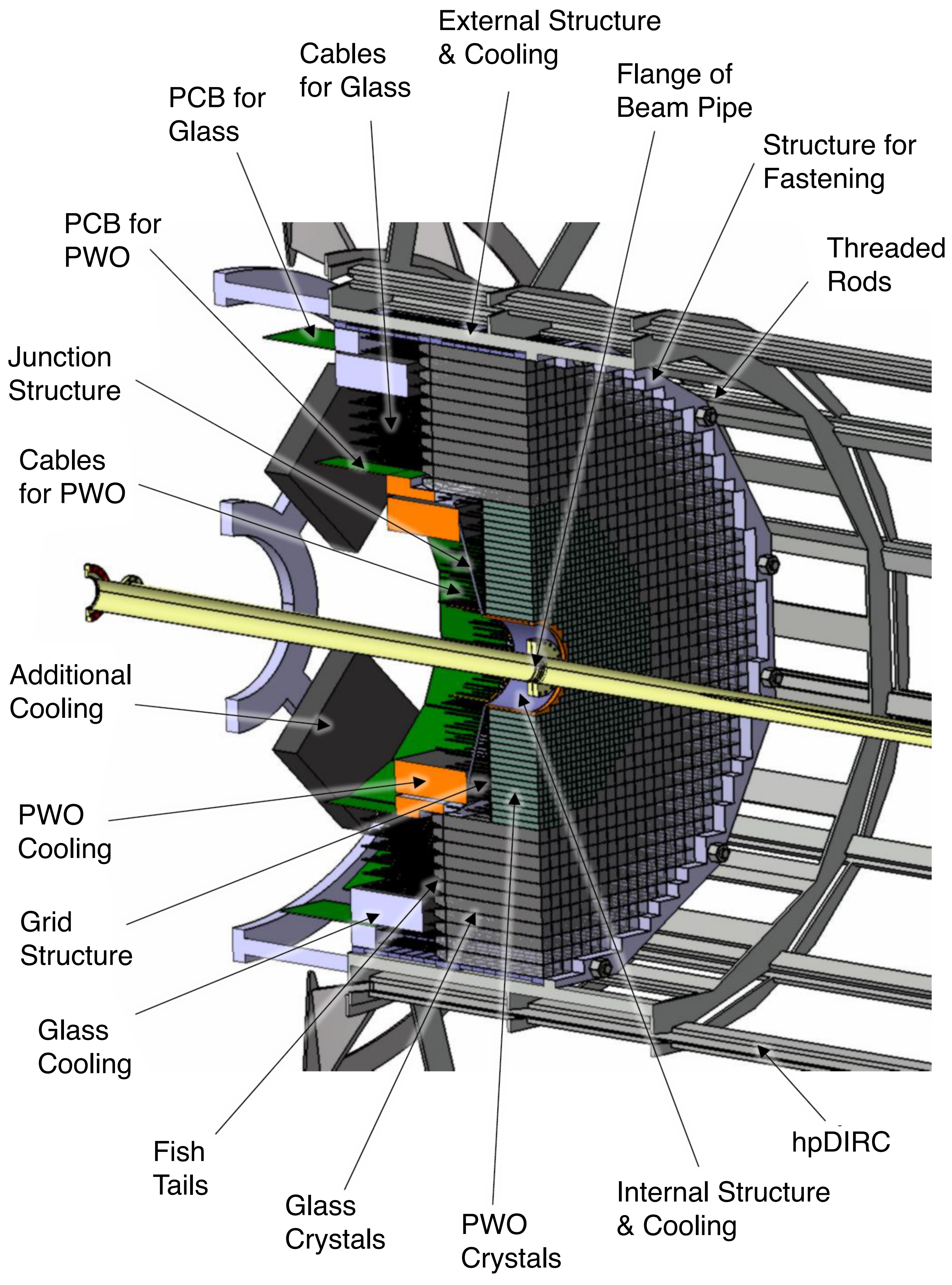
- bECal is sophisticated and expensive but it pays off
  - 1st imaging layer (Astropix) serves as last tracking layer after the hpDIRC - no MPGD necessary
  - Outstanding e/π fulfilling YR requirement of 10^3 for p > 300 MeV/c at $\epsilon_e \geq 95\,\%$
  - Outstanding separation of γ's from π^0



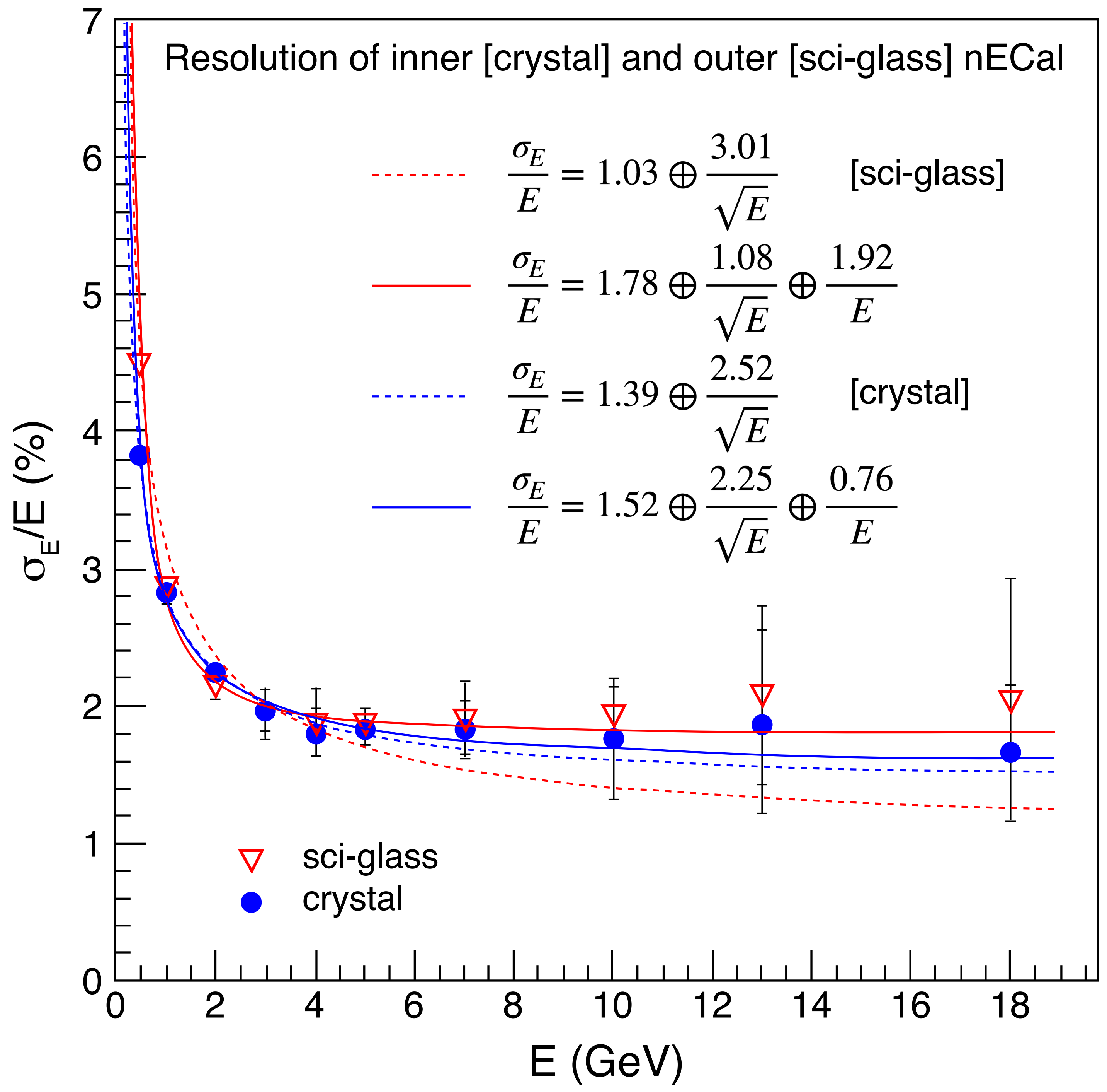


Convener:
Oleg Tsai. Paul Reimer, Vladimir Berdnikov

Calorimetry - Backwards



- nHCal
  - Fe/Sci sandwich, $-1 > \eta > -4$, serves a yoke for return flux as well - Physics → see also Brian's talk in Cal Mtg 5/12
- nECal (EEEMCAL)
  - Inner $PbWO_4$ $-2.3 > \eta > -4.0$, best res. possible (?)
  - Outer SciGlass $-1.5 > \eta > -2.3$, cost effective

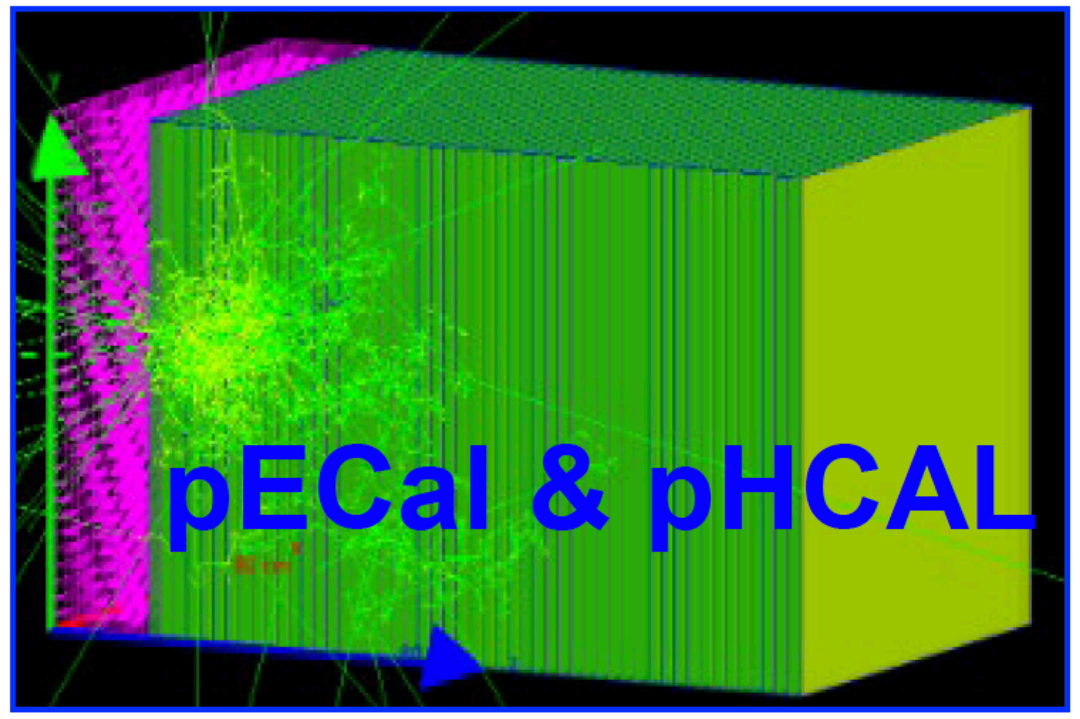


- Note: η < -3 critical region for e+A imaging (t resolution). Interplay between tracking and E resolution matters. Worries about *constant term*! Could turn out to be key for some WP/NAS physics.

Calorimeter - Forward

pECal & pHCAL

- high resolution, high granularity, compact hadron endcap calorimeter system
- pHCal Hadron Calorimetry Fe/Sci sandwich including a tail-catcher
  - ~ 32% = √E ⊕ 2% in $1 < \eta < 4.0$
  - Longitudinal segmentation achieved by using scintillation tiles with two different time constants, similar to the CALEIDO2 Prototype for the ILC → just two independent readout channels per tower, providing longitudinal information from four segments of the tower
- pECal e/m Calorimetry W-Powder/SciFi calorimeter
  - ~ 11% = √E ⊕ 2% in $1.2 < \eta < 4.0$
- Longitudinal space required for about seven interaction lengths is 150 cm

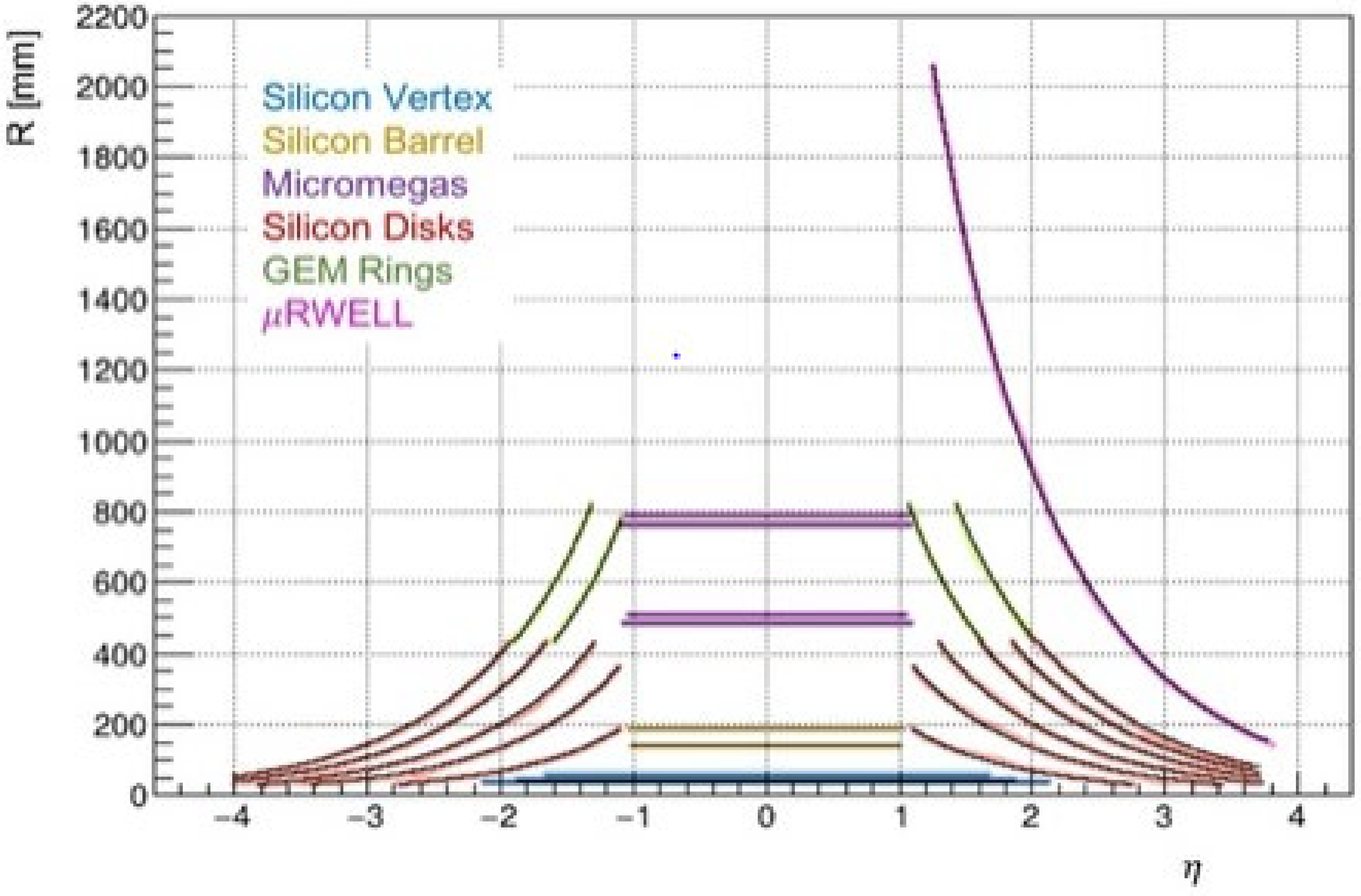


DAQ (Streaming of Course)

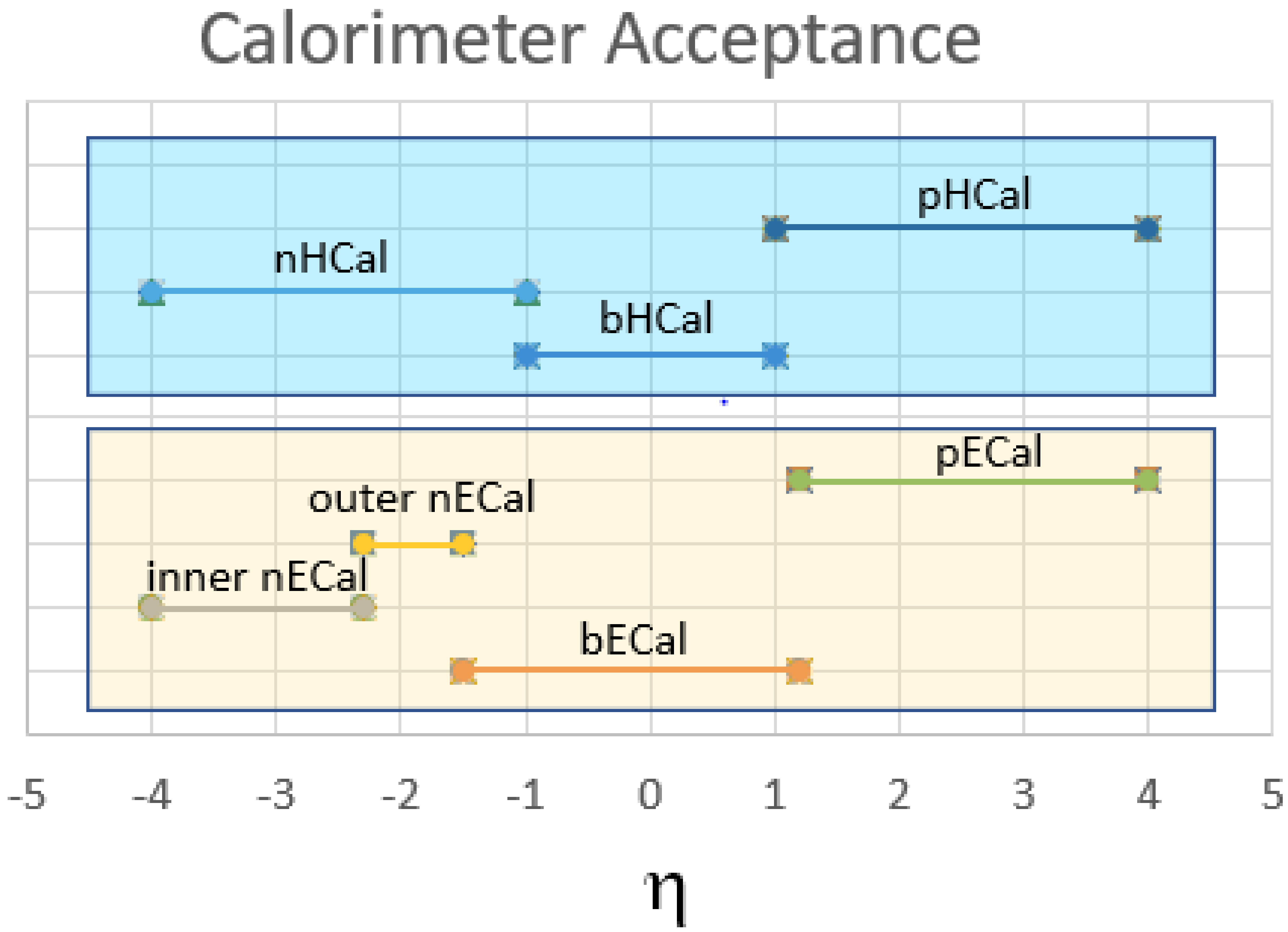
- Thoughts and concerns during design phase (not unique to ATHENA)
  - SiPM detectors sensitive to single photons → very large dark count rates increasing with radiation exposure
  - Many systems have very low fiber utilization! This adds to FELIX cost.
  - Cheaper aggregation scheme
    - ➟ reduce number of FELIX boards by ~x2 freeing ~$2M
    - ➟ need design and construction project for aggregating ~5-10k fibers, which could easily cost O($2M)
  - Understanding/estimate of backgrounds could be key to design of DAQ

Putting It All Together - Overall Acceptance

Tracking



Coverage $-3.8 < \eta < 3.75$



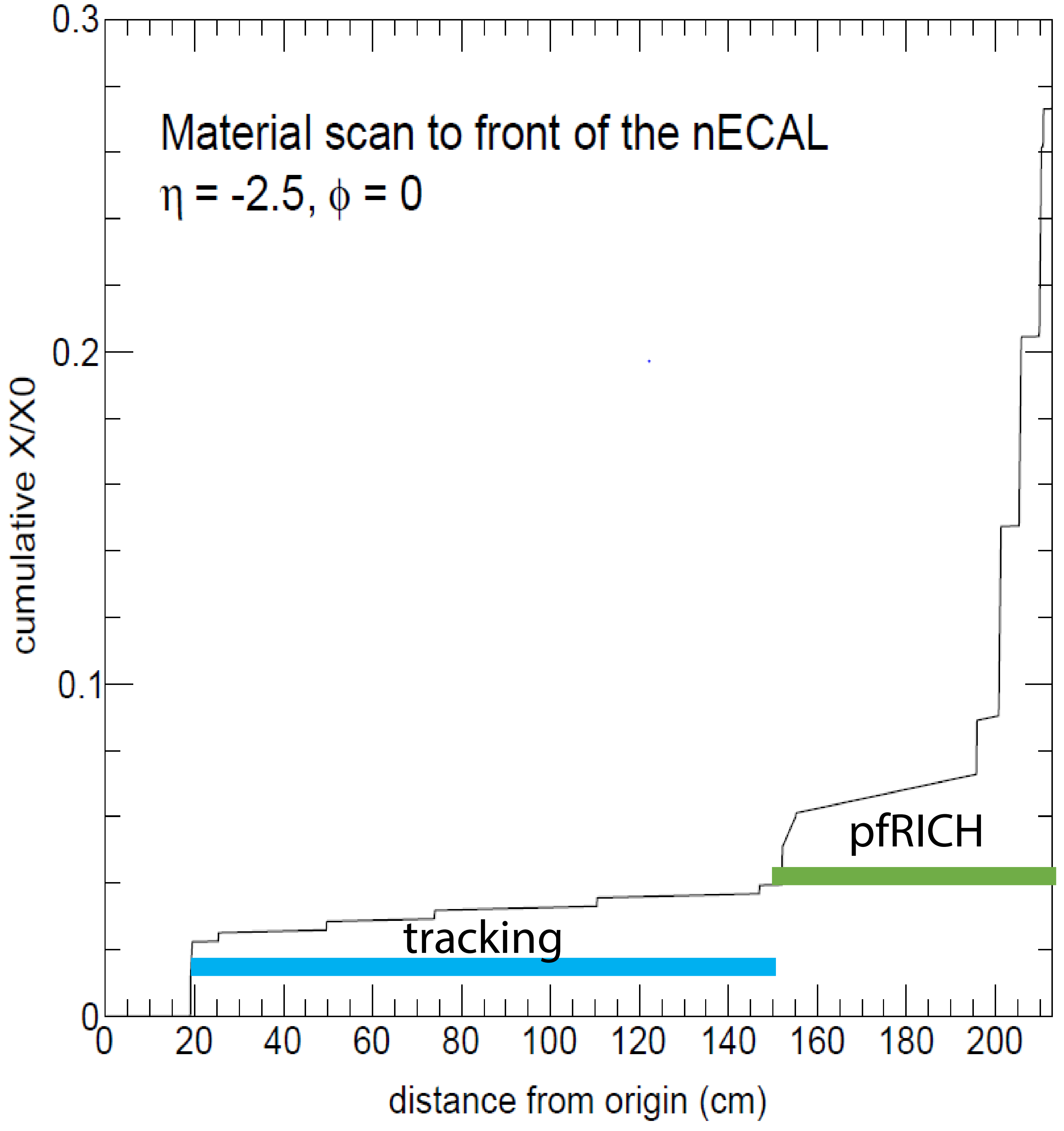
Only small gap in $1 < |\eta| < 1.05$ for services

Coverage $-4.0 < \eta < 4.0$

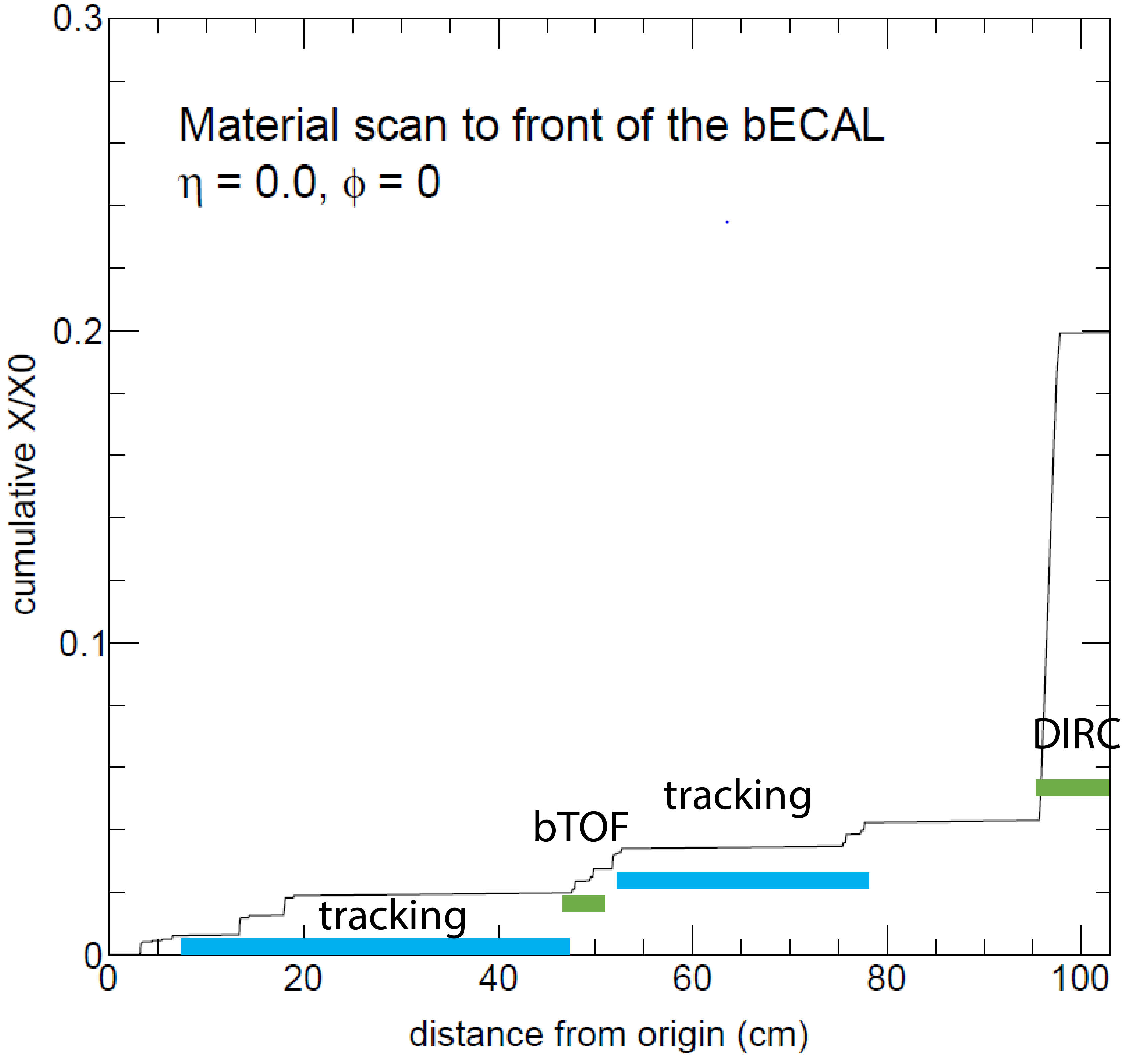
Putting It All Together - Material

Material budget in front of ECals

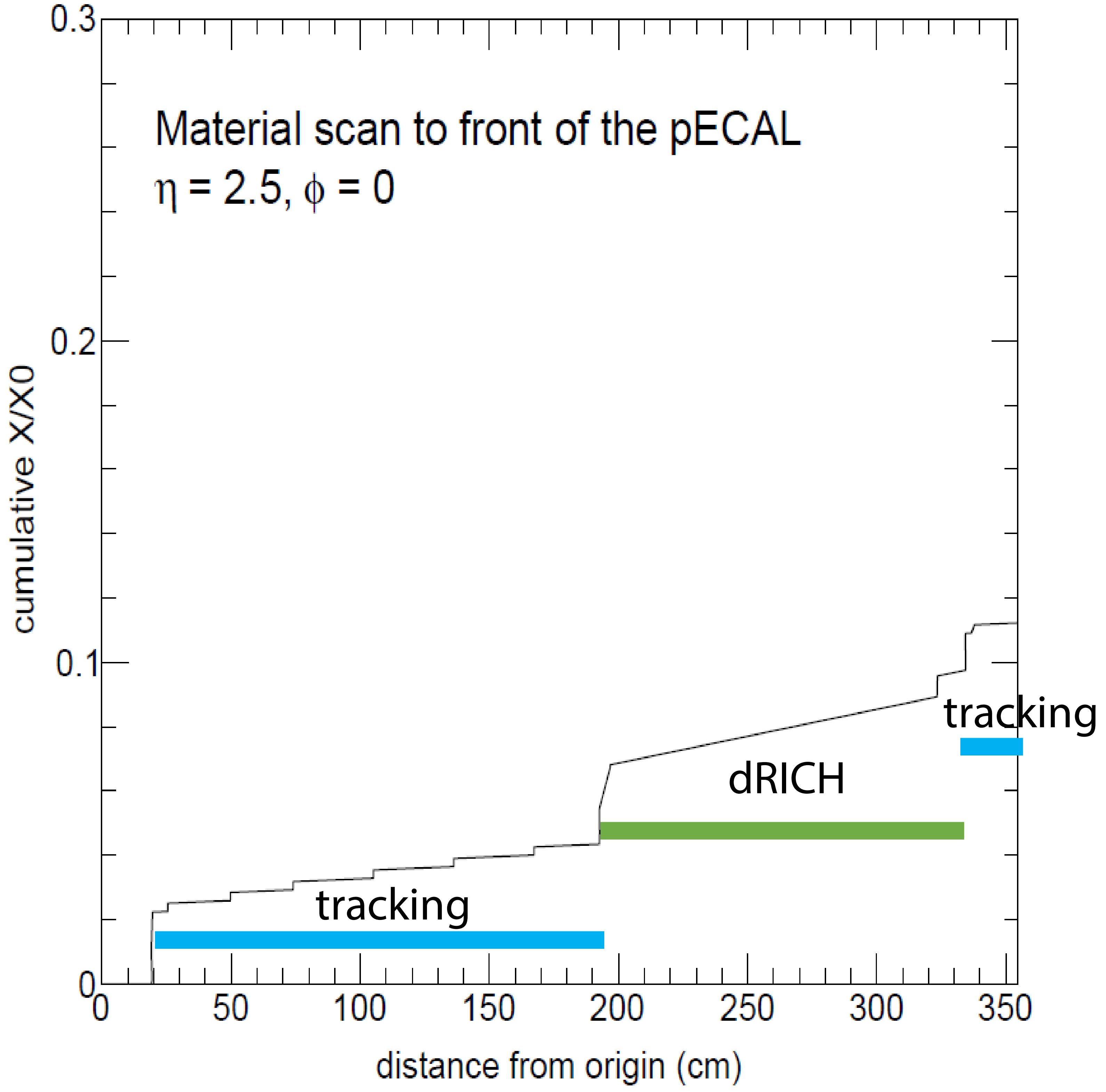
Backward endcap



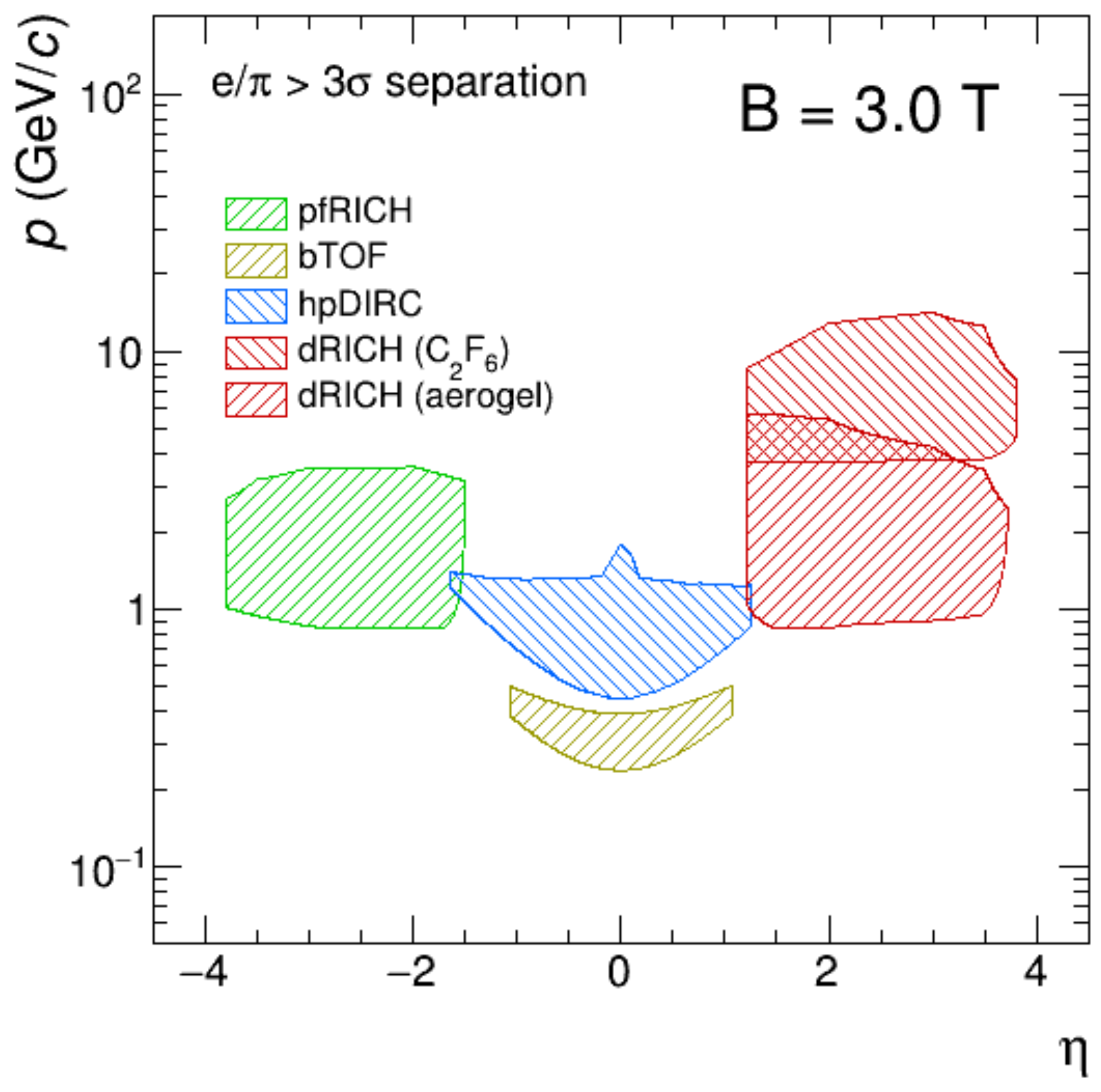
Barrel

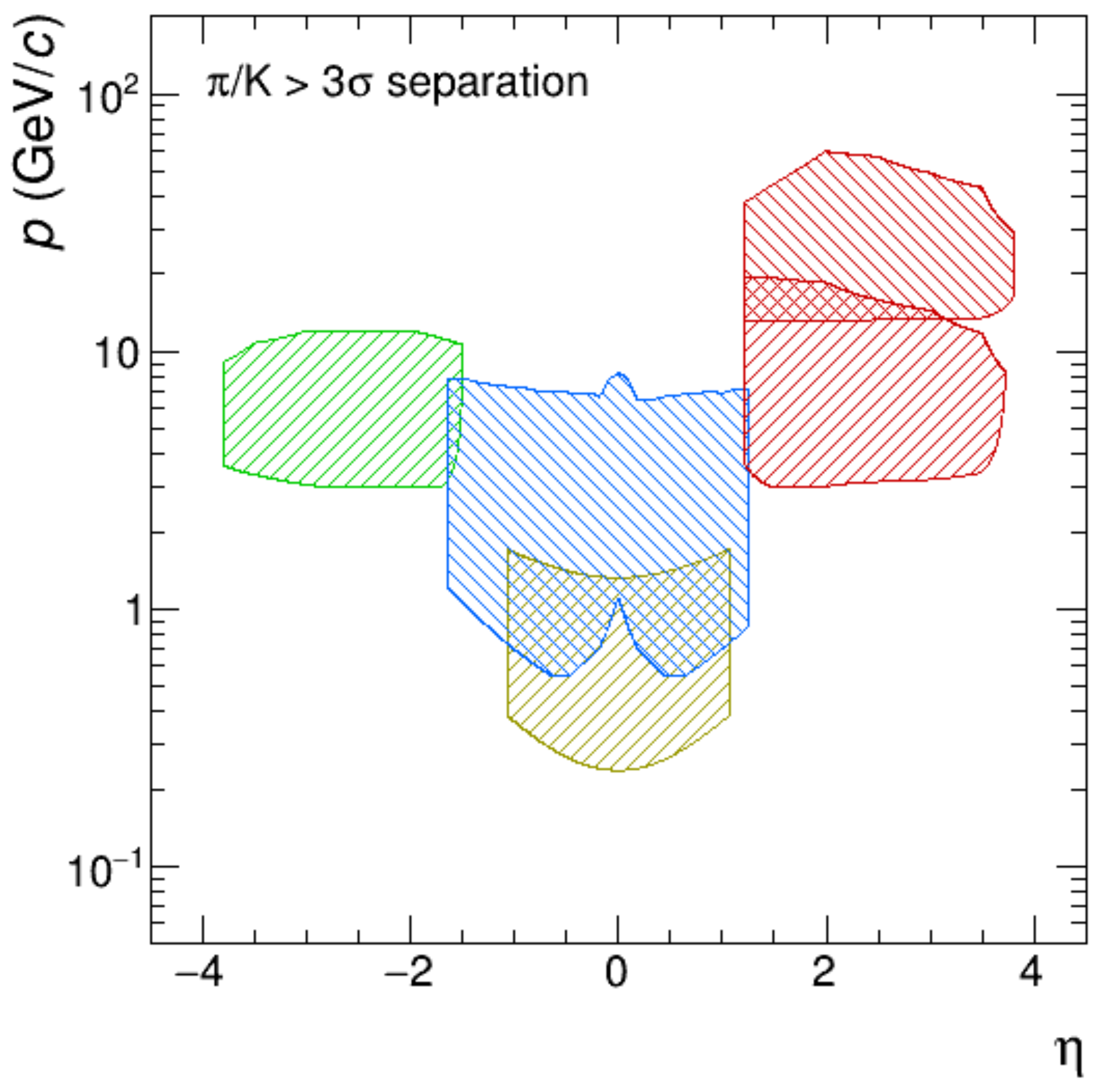


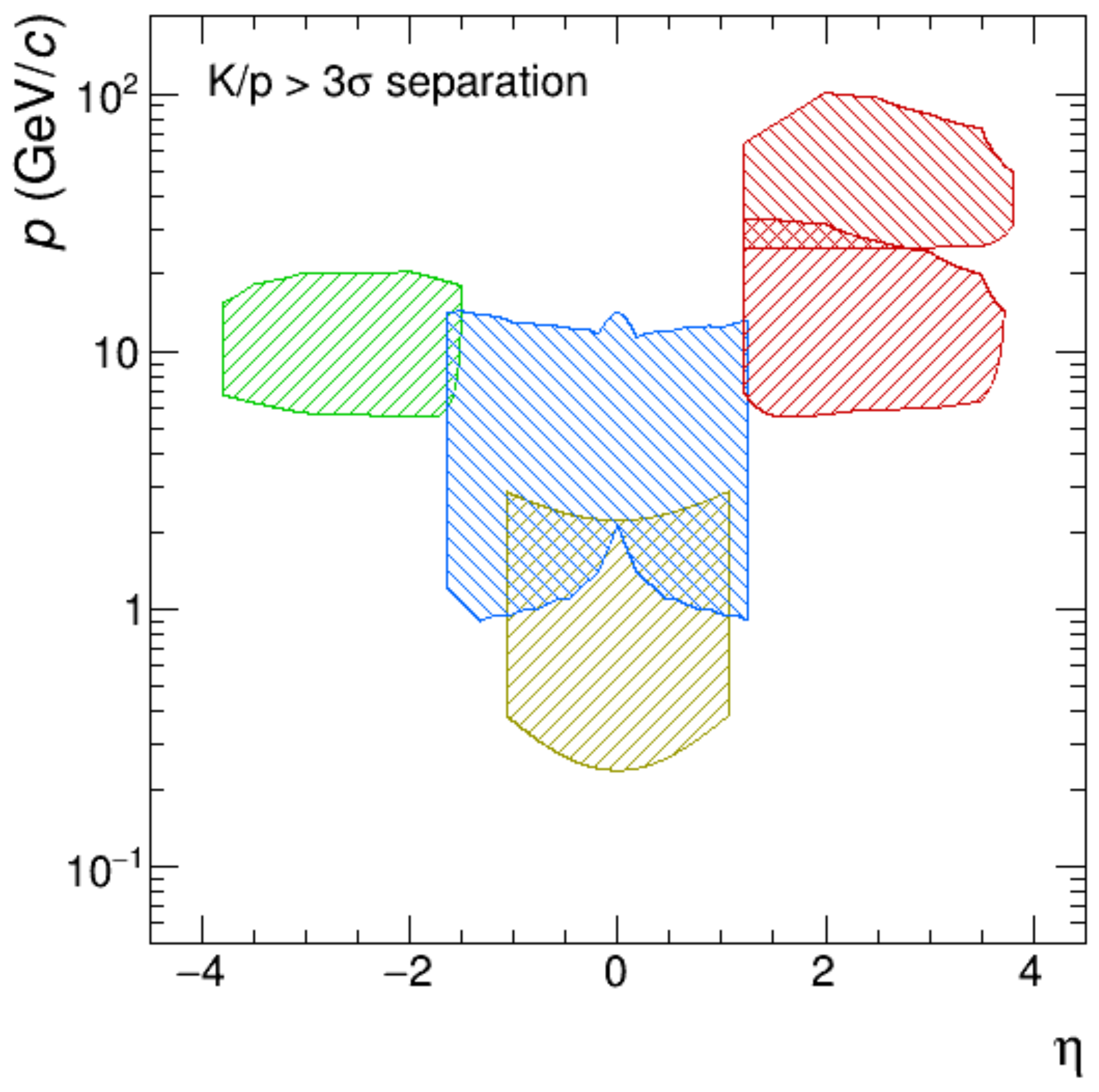
Forward endcap



Putting It All Together - PID

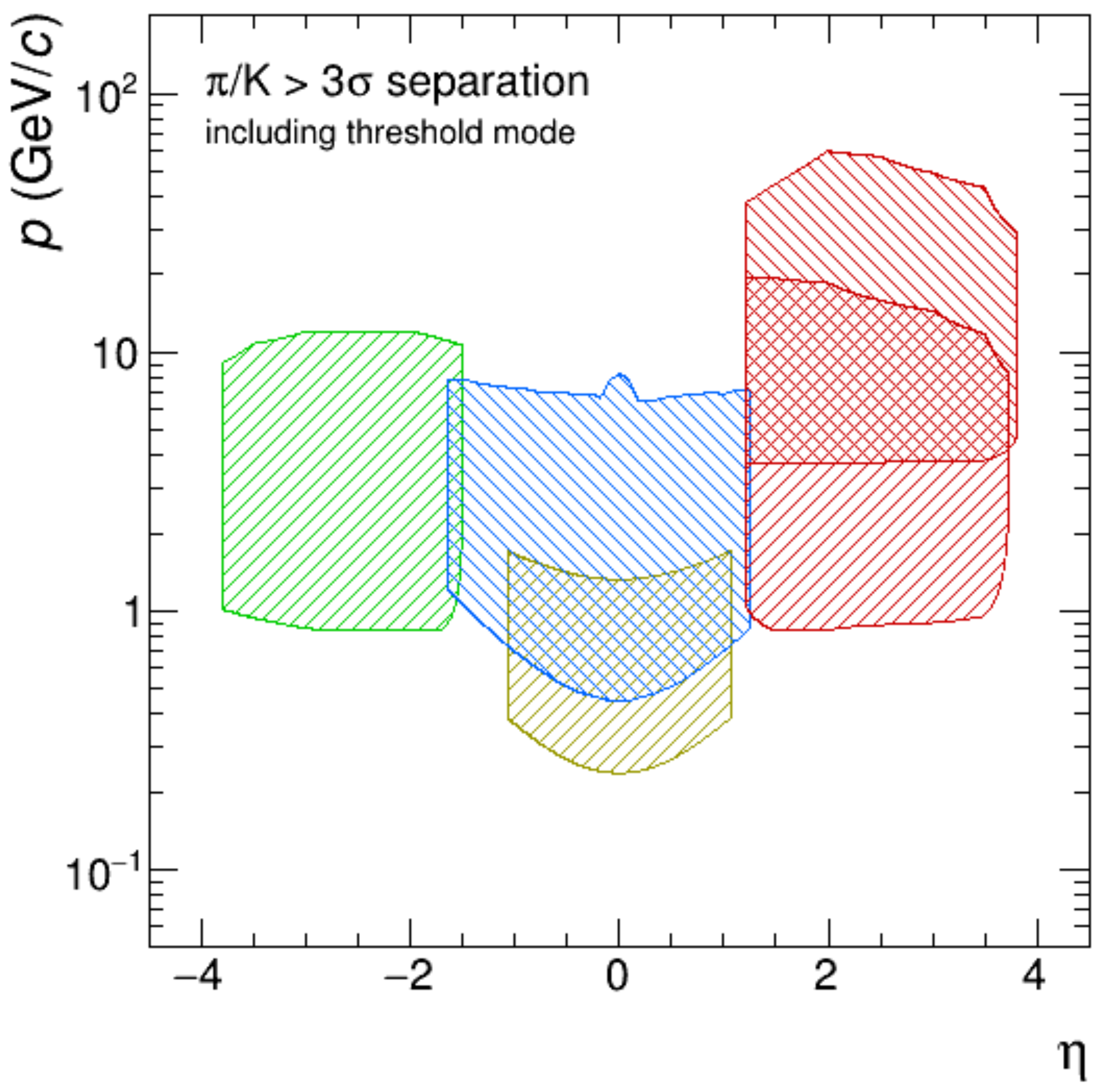






- Regions where PID subsystems can perform e/π, π/K and K/p with better than 3-σ separation. The low-p part is either determined by the p_T acceptance due to magnetic field or by the Cherenkov emission threshold for effective PID. For DIRC and RICH detectors, the separation region is defined for "full mode" operation, namely when both particles can be positively identified

- RICH detectors can also provide PID information exploiting the "threshold RICH" mode operation. This mode can be utilized when at least the lightest particle is above threshold

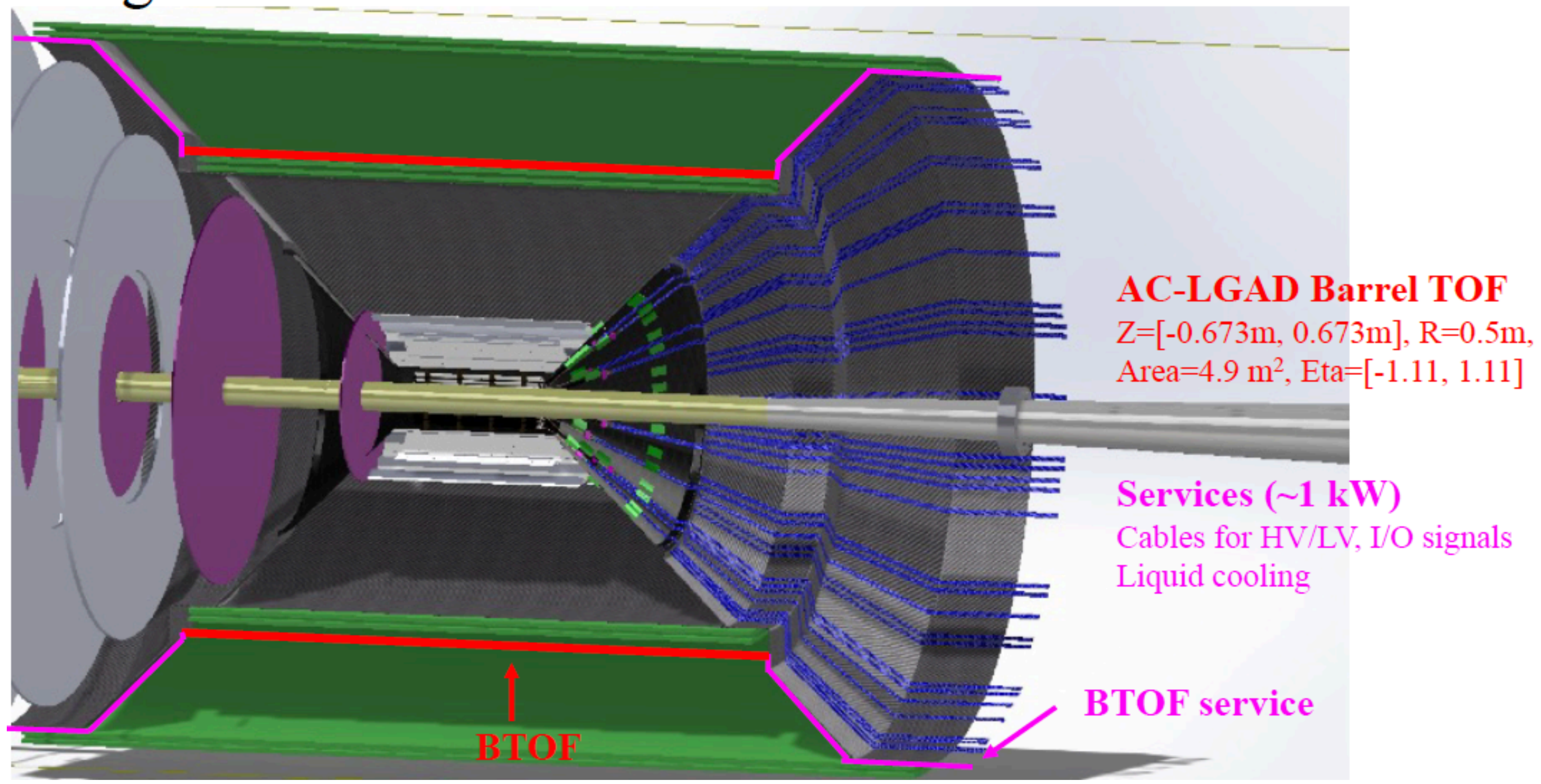


Putting It All Together - Services

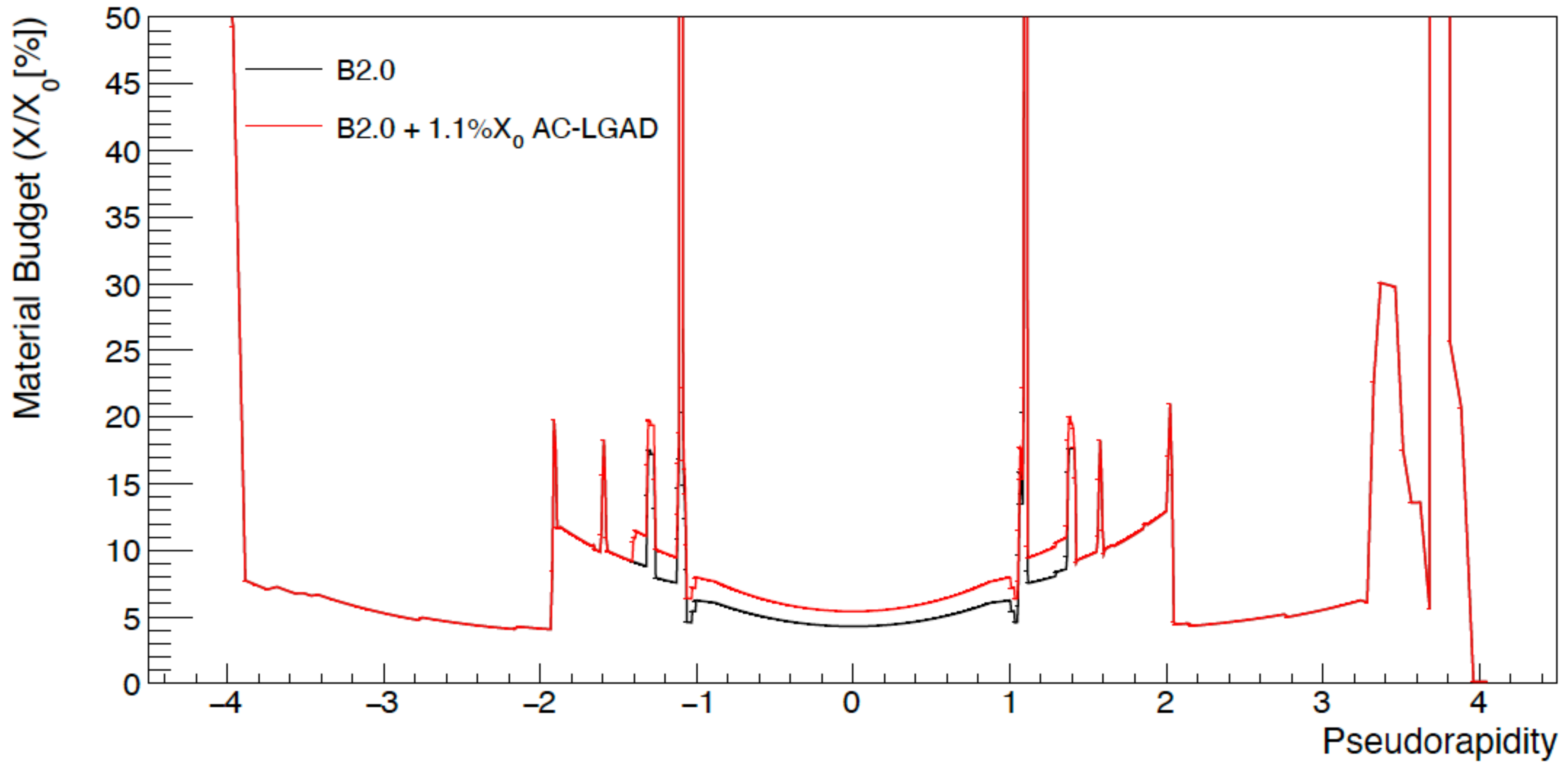
- All general systems had meetings with project engineers to establish the service routing and support structure
- Achieved integration of support structures and detector services that minimize gaps

Example: bToF (AC-LGAD) verification and integration analysis

Integration of BTOF into ATHENA



ATHENA Tracker Baseline 2.0 - Material Scan



Putting It All Together - Accessibility of Systems

- ATHENA requirement: **All** detector systems are accessible during an annual maintenance period.
  - requires to roll the detector from its in-beam location into the assembly hall at IP-6
- Detector systems accessible in beam location
  - needs to open endcap calorimeters (timeframe 2+ hours)
  - Lepton Endcap: hadron and electromagnetic calorimeter
  - Barrel: Hadron Calorimeter, DIRC, restricted access to Pb/SciFi ECal-electronics
  - Hadron Endcap: hadron and electromagnetic calorimeter, GEM-Tracker behind dRICH
  - Other systems: Read-Out electronics (fADCs, TDCs, …) , DAQ, timing system, HV, LV, gas-systems
- Detector systems accessible only in assembly hall
  - timeframe ~1 week on top of the rolling out/in
  - Lepton Endcap: pfRICH
  - Barrel: Si-tracker (barrel and disks), bToF, MicroMega-Tracker and MPGD-rings, full access to Pb/SciFi ECal
  - Hadron Endcap: dRICH

Last Slide

- At the proposal release level ATHENA was in a quite mature state
- The pros of a 3T field were pretty well exploited, cons were mitigated by careful placement of RICH sensors and the AC-LGAD
- Except for a small gap, hermeticity was achieved for tracking and full hermeticity was achieved for calorimeter
- PID covers wide range in barrel but could not find strong physics motivation for fwd and bckwd region below the aerogel threshold (~2 GeV)
- Close contact with project and engineers helped substantially in getting the infrastructure on its way

- Key in the design process was
  - that it was science driven
  - impressive expert level with lots of experience in WG
  - close contact between different WG
  - coordination and sometimes hard decisions by the GD/I
  - Friendly and collegial atmosphere