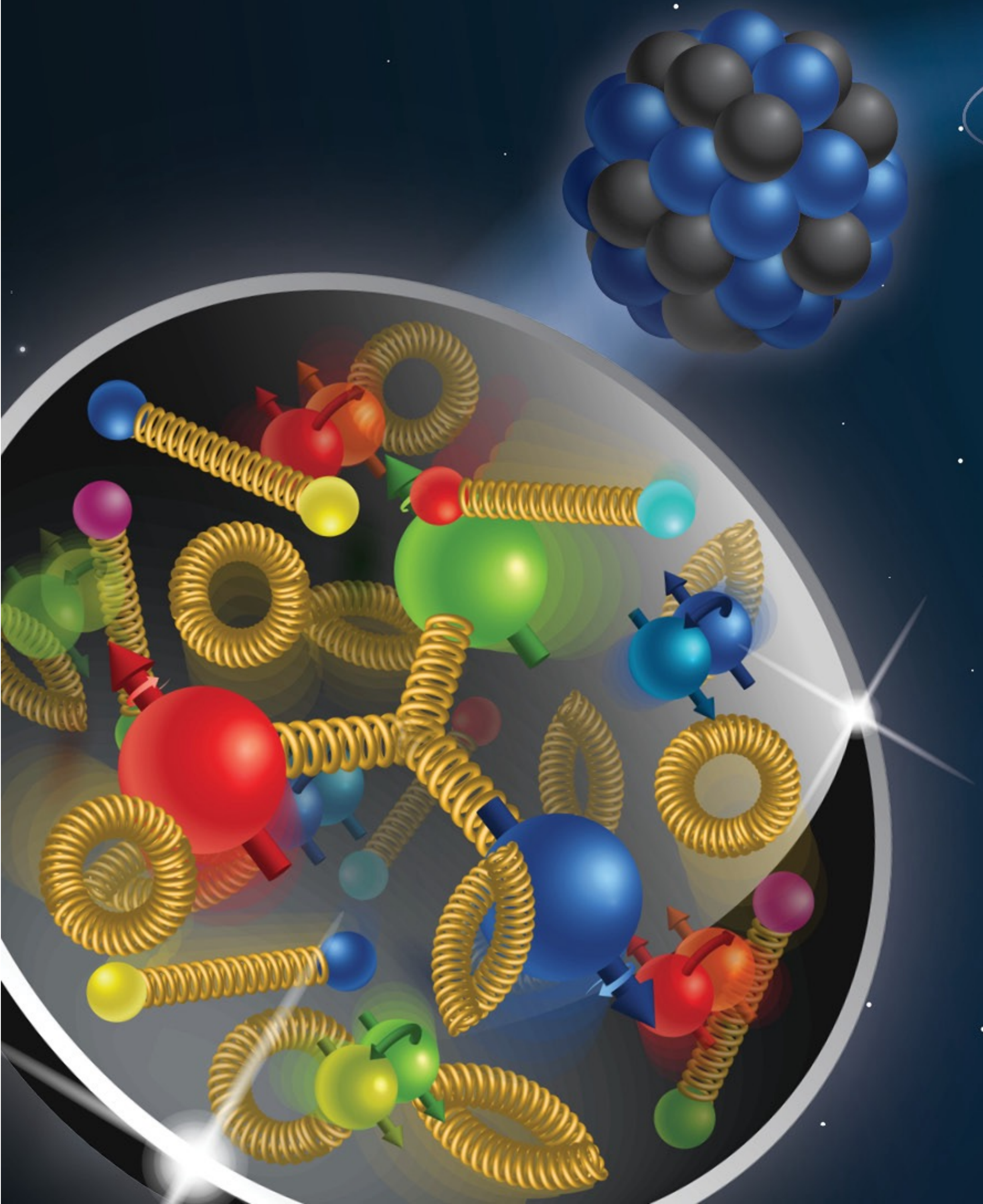


WBS 6.10.06 Hadronic Calorimetry

Alexander Kiselev, BNL

EIC Detector Comprehensive Design Review

August 29-30, 2023

Electron-Ion Collider

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

Outline of the talk

- ➢ Introduction
- ➢ ePIC hadronic calorimeter subsystems
  - ➢ Backward HCal
  - ➢ Barrel HCal
  - ➢ Forward HCal (LFHCal)
- ➢ Summary

Charge items

(1) • Given the detector progress over the last two years and the status of the ePIC detector, are the projected timelines of the Electron-Ion Collider detector feasible? Do there remain significant open detector technology questions?

(2) • Are the requirements for the detector and their flow down sufficiently comprehensive for this stage of the project to complete the design of the various detector technologies?

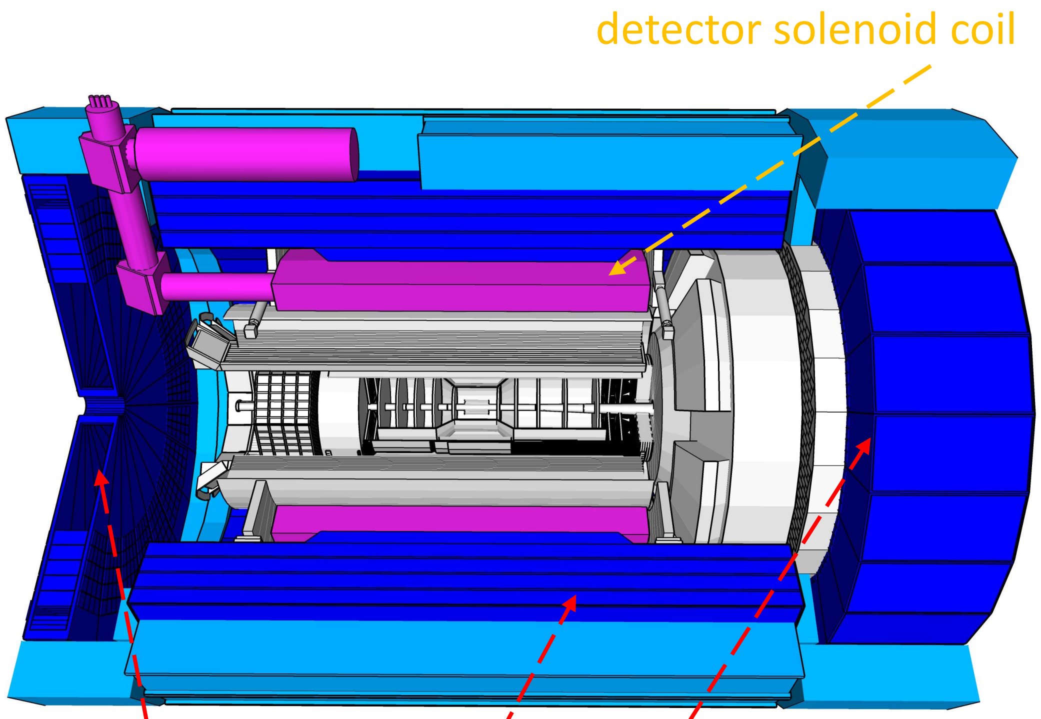
(3) • Are the interfaces between the elements of the design adequately defined for this stage of the project and to proceed with the detector long-lead procurement items?

(4) • Is the design of these long-lead procurement items sufficiently advanced and mature to start procurement in 2024? Are the technical specifications complete?

(5) • Is the projected design maturity of the further detector components likely to be accomplished by the end of 2024 for CD-2 and CD-3?

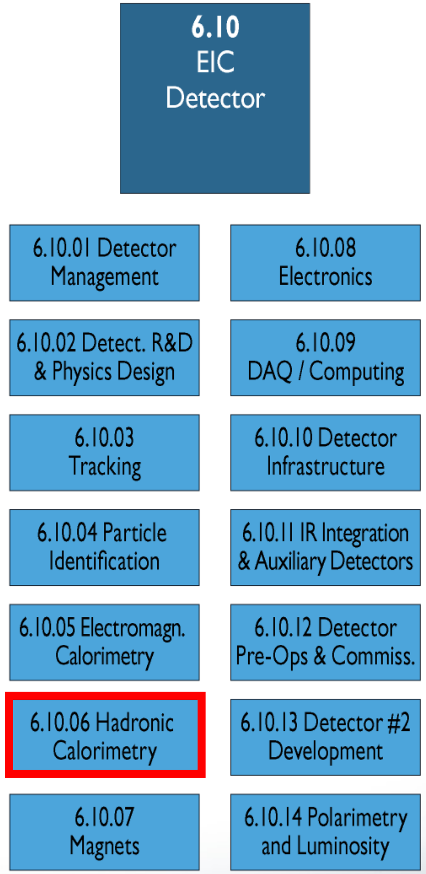
(6) • Is the overall schedule for completion of the design, production, and installation of detector components realistic?

Hadronic Calorimetry of ePIC detector



- Jet energy measurement
  - Tag jets with a neutral component
- DIS kinematics reconstruction
  - Hadronic method

- Solenoid flux return
- Additional capability: muon ID



Barrel HCal	Refurbished sPHENIX barrel calorimeter
Backward HCal	Scintillator recycled from STAR endcap EmCal
Forward HCal	Brand new design

All: sampling sandwich design with a SiPM readout (well understood cost-efficient technology)

Requirements

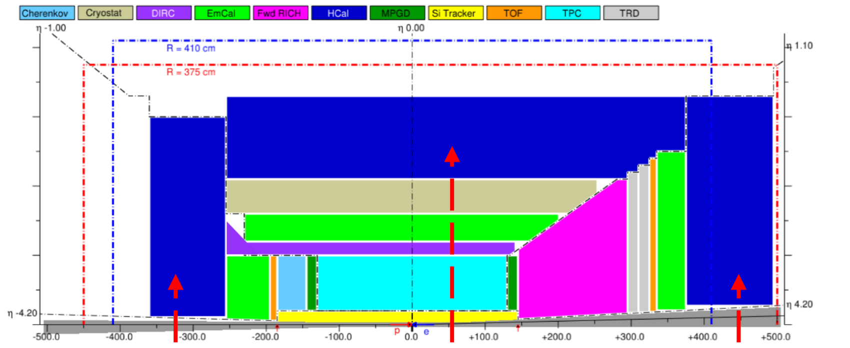
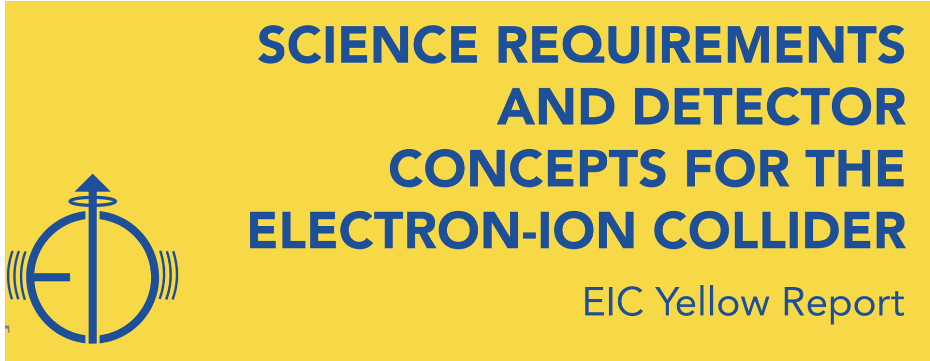


Figure 9.3: A 2D sketch of an EIC detector layout, horizontal cross cut.

Backward | Barrel | Forward



Hadron calorimetry In the mid-rapidity region, the energy resolution of hadron calorimeters is driven by single jet measurements. Neutral hadron isolation could also be important for jet energy scale and resolution. In the forward and backward rapidity region diffractive di-jets need a good hadron energy measurement, with a resolution of the level of $\sigma(E)/E \approx 50\%/\sqrt{E} \oplus 10\%$. The requirement on the constant factor at the highest rapidities is driven by the need for good energy resolution where tracking dies out. A minimum energy threshold of 500 MeV/c was assumed for all the studies performed.

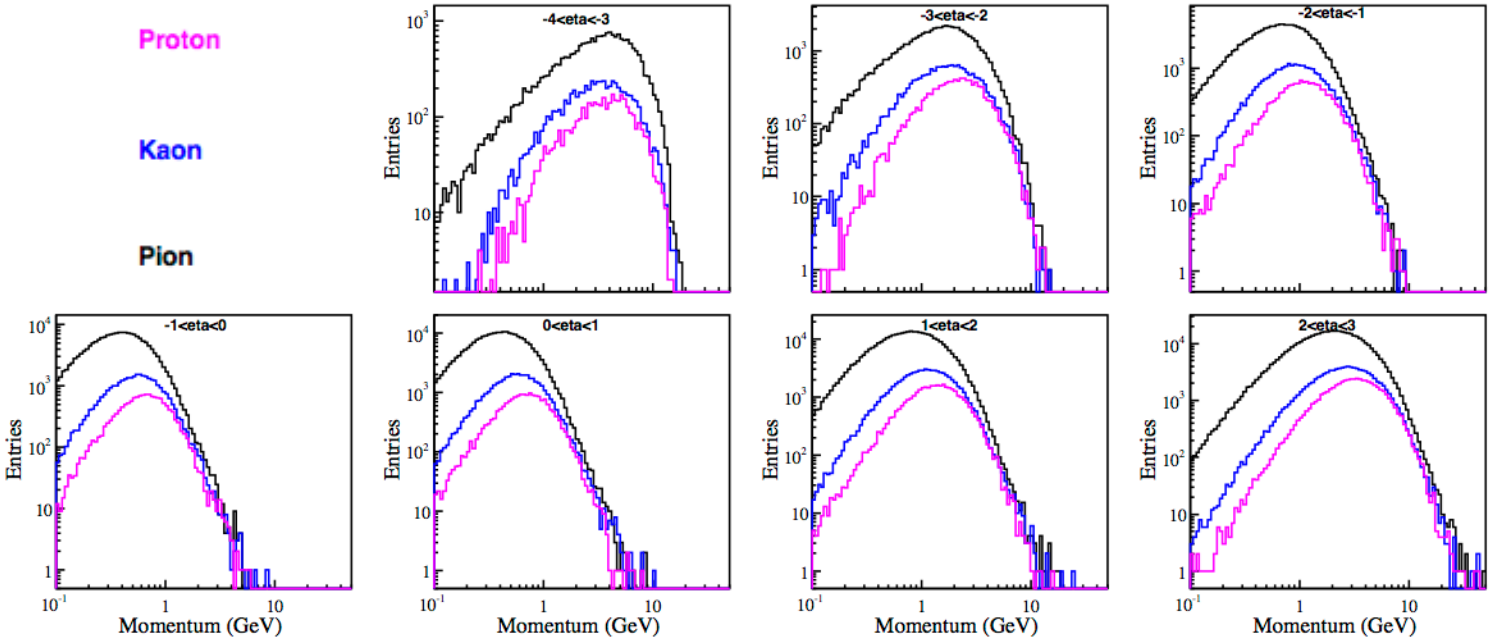
- The layout and most of the requirements for hadronic calorimetry did not change much since the Yellow Report times
  - Energy resolution is driven by the needs of Particle Flow reconstruction, given a full tracker and e/m calorimetry coverage in the same η acceptance
  - Granularity is driven by the needs of neutral cluster isolation and jet substructure measurements

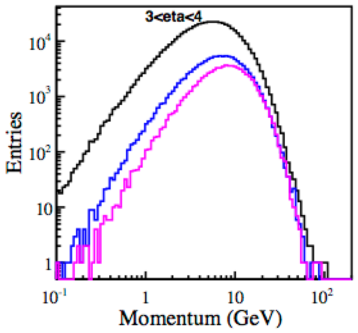
	"Ideal" configuration		Acceptable configuration	
η	σ_E/E, %	E_{min}, MeV	σ_E/E, %	E_{min}, MeV
-3.5 to -1.0	$45/\sqrt{E}+7$	500	$50/\sqrt{E}+10$	500
-1.0 to +1.0	$85/\sqrt{E}+7$	500	$100/\sqrt{E}+10$	500
+1.0 to +3.5	$35/\sqrt{E}$	500	$50/\sqrt{E}+10$	500

Electron-Ion Collider

Hadron momentum spectra

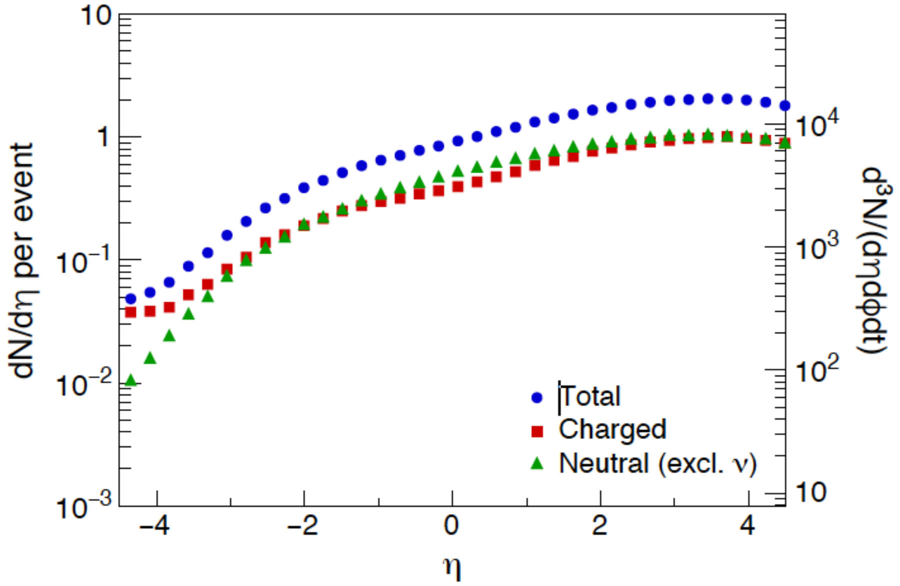
- Yields for a 20 x 250 GeV configuration, $-4 < \eta < 4$





- π/K/p spectra at a given η look similar, with a π/K ratio ~3
- Barrel and e-endcap: up to ~10 GeV/c
- h-endcap: up to ~100 GeV/c

- Multiplicities



On average at most a few particles per unit of pseudorapidity per event, even at η ~ 4

Backward Hadronic Calorimeter

by L. Kosarzewski (Ohio State University)

Electron-Ion Collider

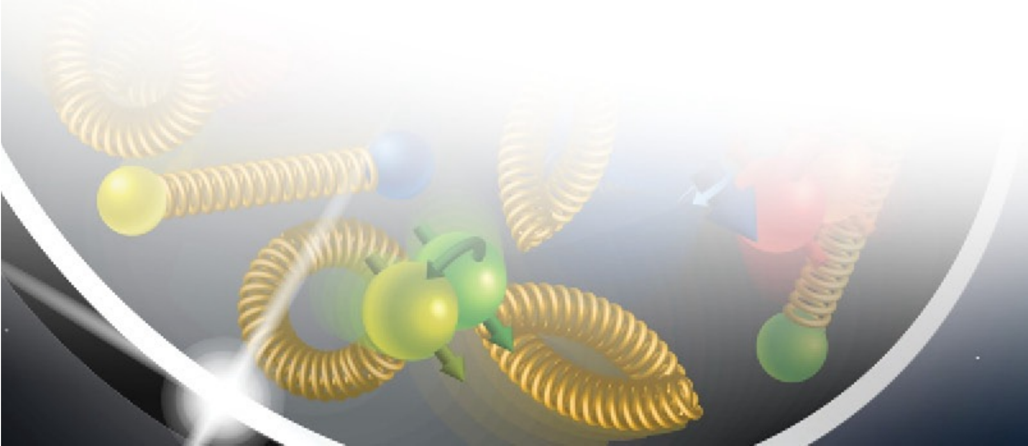
Requirements

GENERAL REQUIREMENTS	
Name	Description
Backward HCAL	
G-DET-HCAL-BCK.1	Backward HCal shall provide functionality of a tail catcher for the high resolution e/m calorimeter in electron identification, as well as for je… Bjork…

- Identification of neutral hadron jets – especially at low **x**
- A KLM–type tail catcher for e/m calorimeter for electron identification

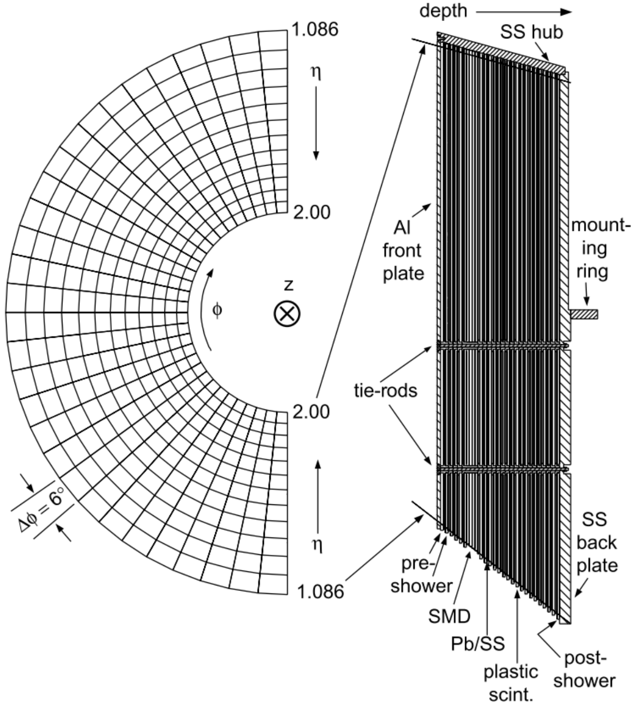
FUNCTIONAL REQUIREMENTS		
Name	Description	Parent
Backward HCAL		
F-DET-HCAL-BCK.1	Shall accommodate the possibility of hadron energy measurements in the range up to few dozens of GeV and pseudorapidity down to -3.5 .	G-DET-HCAL-BCK.1
F-DET-HCAL-BCK.2	Shall accommodate the ability to complement e/m calorimeter by tail catching capability for electron ID purposes, especially below 3-4 GeV/c.	G-DET
F-DET-HCAL-BCK.3	Shall not interfere with the detector solenoid magnetic field	G-DET

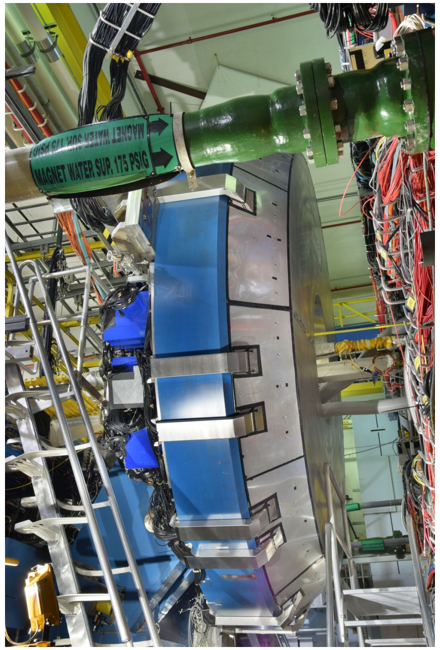
PERFORMANCE REQUIREMENTS		
Name	Description	Parent
Backward HCAL		
P-DET-HCAL-BCK.1	Must provide capability to cover pseudo rapidity range down to at least -3.5.	F-DET-HCAL-BCK.1
P-DET-HCAL-BCK.2	Shall provide capability to have energy resolution s(E)/E ~ 100%/sqrt(E) + a 10% constant term.	F-DET-HCAL-BCK.2
P-DET-HCAL-BCK.3	Should be built of non-magnetic materials	F-DET-HCAL-BCK.3
P-DET-HCAL-BCK.4	Must provide space to have tower depth of 3-4 interaction lengths (together with the e/m PWO crystal calorimeter) in order to suppress longitudinal leakage for relatively small hadron energies in the e-endcap.	F-DET-HCAL-BCK.2

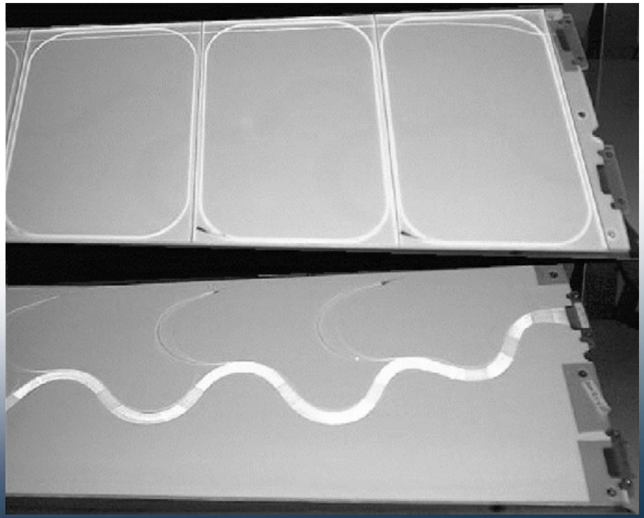


Design based on STAR megatiles

- Design considerations
  - High efficiency for neutron detection
  - Good spatial resolution to distinguish neutral/charged hadrons
- Structure ($2.4\lambda_0$ in total)
  - 10 layers of alternating:
    - 4 cm stainless steel
    - 4 mm plastic scintillator Kuraray SCSN-81 tiles
- Signal readout:
  - Scintillator light guided by WLS fibers
    - 0.83 mm Kuraray Y11-doped 200 ppm fiber
  - SiPM used for light collection
- Extension of acceptance:
  - By adding new tiles in the inner and outer parts
- Absorber decoupled from flux return steel
  - Gives more flexibility with the design
  - Located at z=-3.85 m from the IP





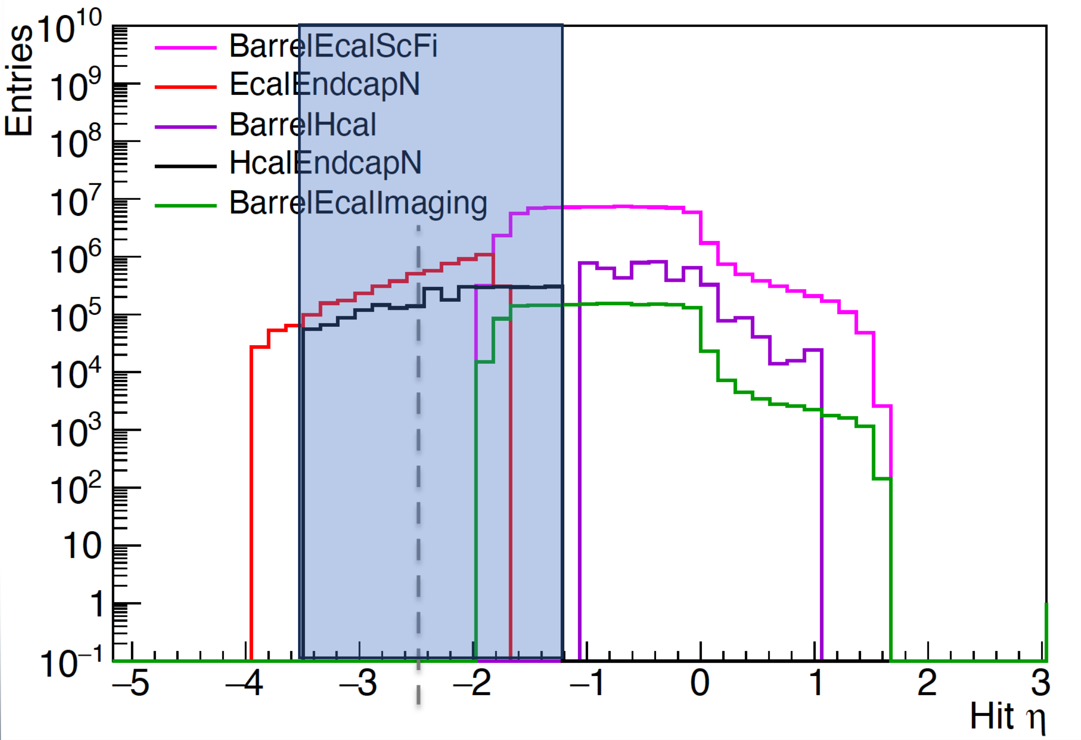


Acceptance

PERFORMANCE REQUIREMENTS		
Name	Description	Parent
Backward HCAL		
P-DET-HCAL-BCK.1	Must provide capability to cover pseudo rapidity range down to at least -3.5.	**F-DET-HCAL-BCK.1**

- STAR scintillator tile geometry:
  - So that each covers the same η range
  - The η coverage changes due to shift in z position
  - STAR EEMC tiles cover $-1.39 < \eta < -2.195$ when placed in the correct position

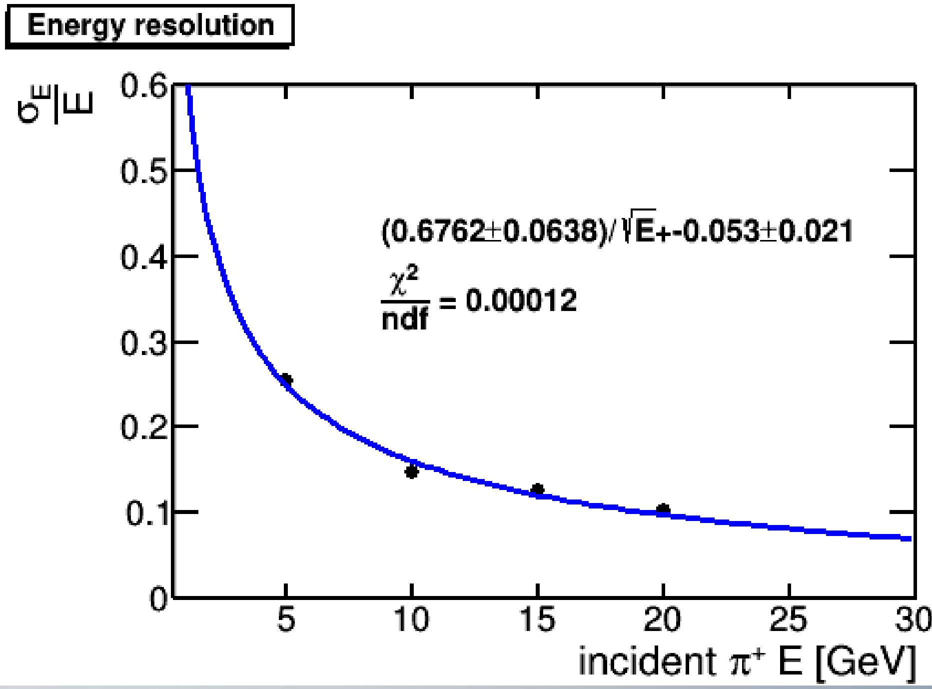
- New tiles added
  - The sizes are kept around ~10 cm
  - Tiles in φ are merged as they approach the beampipe
- Total acceptance:
  - $-3.5 < \eta < -1.27$
  - Requirement satisfied



Energy resolution

PERFORMANCE REQUIREMENTS		
Name	Description	Parent
Backward HCAL		
P-DET-HCAL-BCK.2	Shall provide capability to have energy resolution s(E)/E ~ 100%/sqrt(E) + a 10% constant term.	F-DET-HCAL-BCK.2

- Energy resolution investigated in GEANT
  - Exceeds the requirements

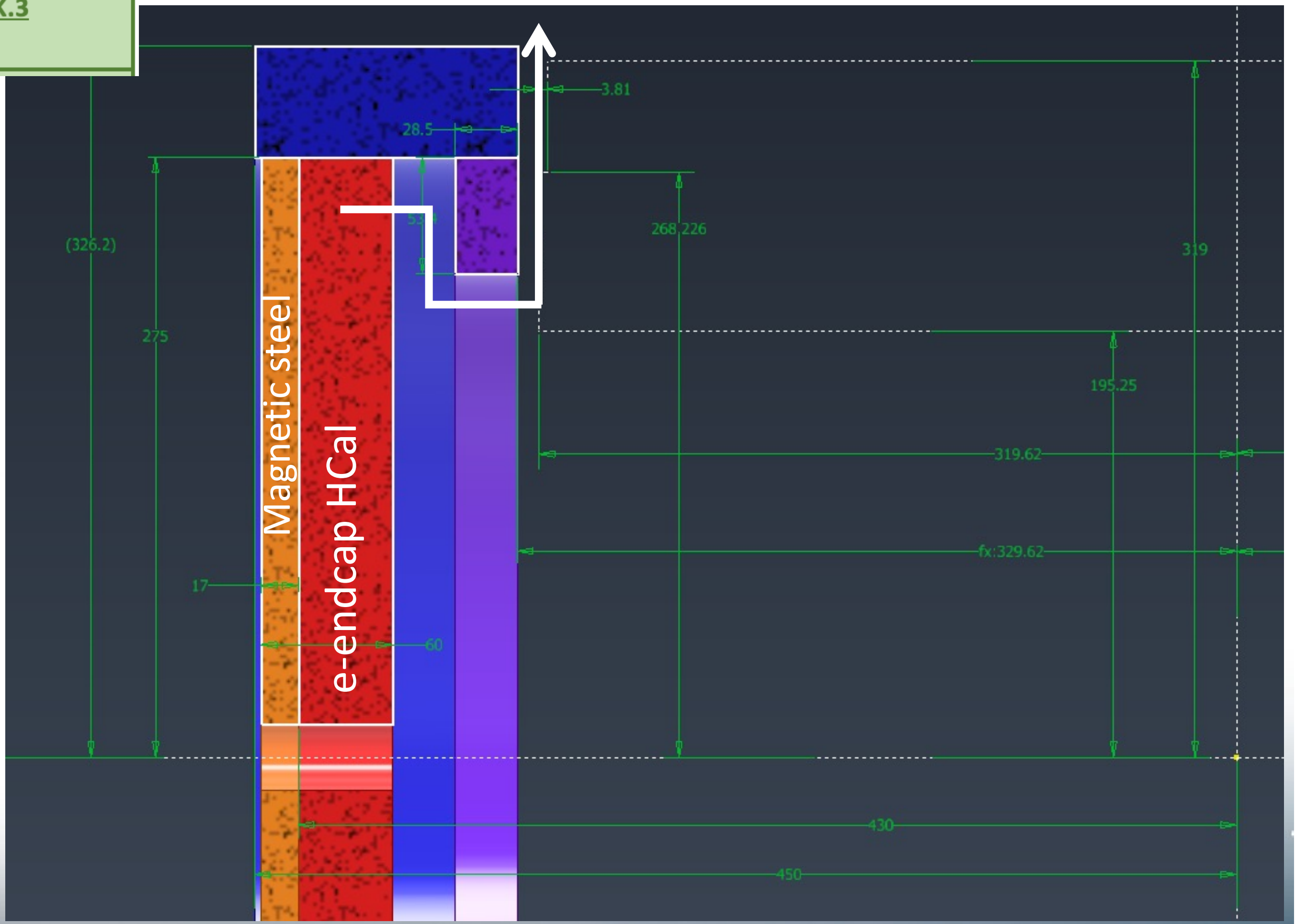


Services & interfaces

PERFORMANCE REQUIREMENTS		
Name	Description	Parent
Backward HCAL		
P-DET-HCAL-BCK.3	Should be built of non-magnetic materials	F-DET-HCAL-BCK.3

- Services
  - 50 V sensor bias cable
    - 60x Multidrop flat ribbon cable
  - Data signal cable
    - 240x 2x1.28 LVDS cable
  - Slow controls cable
    - 600x 1.5 mm cable
- No need for cooling, but temperature monitoring is necessary
- Absorber is stainless steel
  - No interference with the solenoid flux return

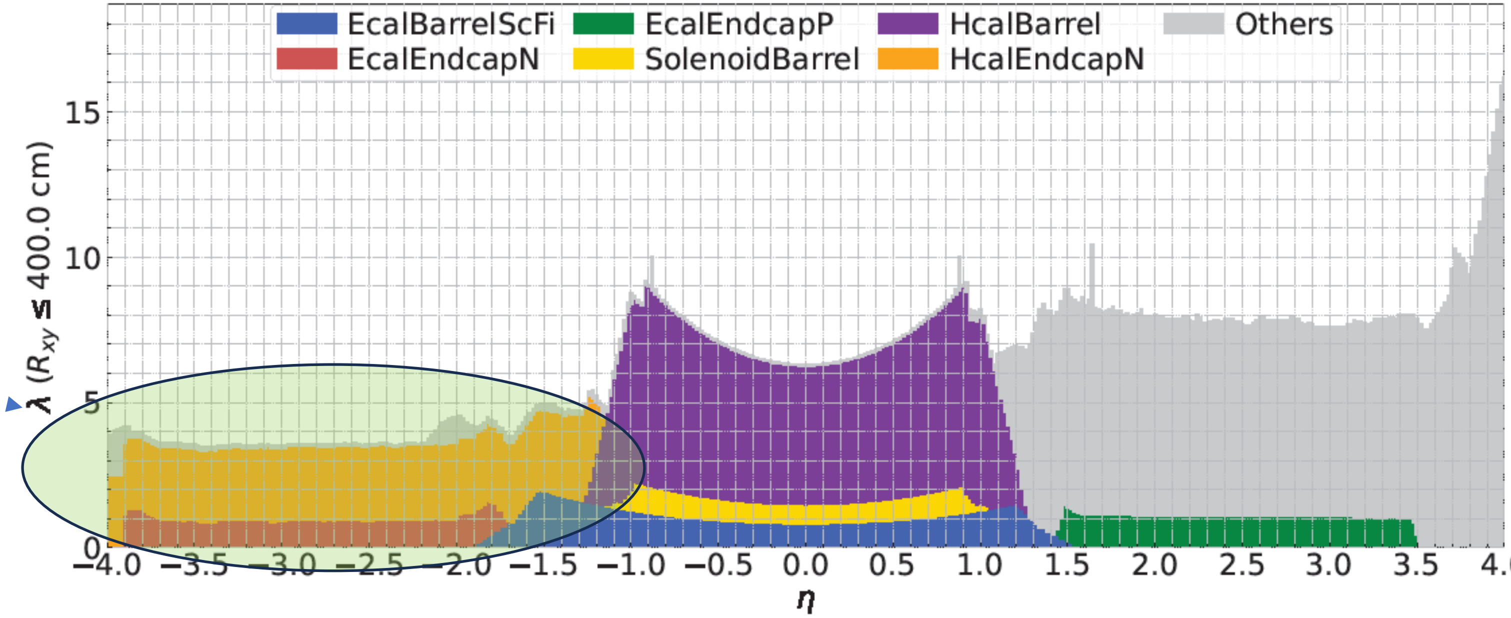
Services path



Nuclear interaction length

PERFORMANCE REQUIREMENTS		
Name	Description	Parent
Backward HCAL		
P-DET-HCAL-BCK.4	Must provide space to have tower depth of 3-4 interaction lengths (together with the e/m PWO crystal calorimeter) in order to suppress longitudinal leakage for relatively small hadron energies in the e-endcap.	F-DET-HCAL-BCK.2

- Thickness of the combined backward Hcal and EMCal $3.4\lambda_0$
  - $2.4\lambda_0$ Hcal
  - $1\lambda_0$ EMCal



Barrel Hadronic Calorimeter

by J. Lajoie (Iowa State University)

Electron-Ion Collider

Requirements

GENERAL REQUIREMENTS	
Name	Description
Barrel HCAL	
G-DET-HCAL-BAR.1	Barrel HCal shall provide adequate functionality for hadronic jet neutral component reconstruction at central rapidities

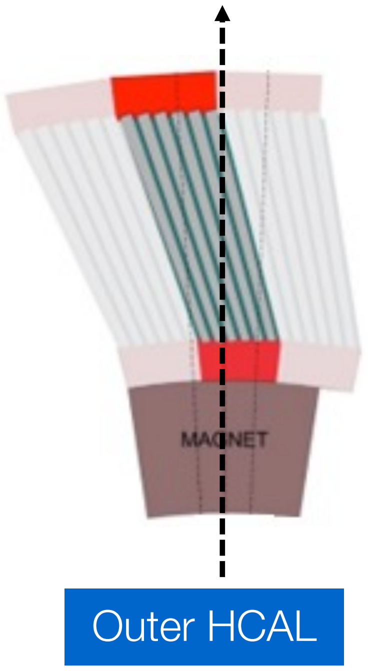
FUNCTIONAL REQUIREMENTS		
Name	Description	Parent
Barrel HCAL		
F-DET-HCAL-BAR.1	Shall be optimized to provide hadron energy measurements at relatively small jet energies (up to few dozens of GeV).	**G-DET-HCAL-BAR.1**

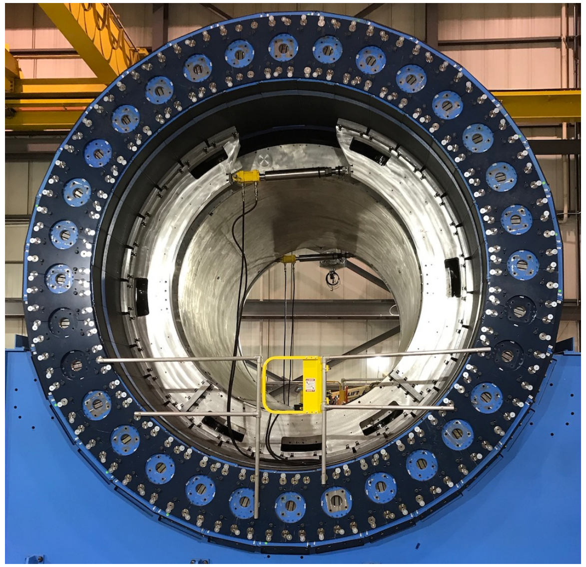
PERFORMANCE REQUIREMENTS		
Name	Description	Parent
Barrel HCAL		
P-DET-HCAL-BAR.1	Should have a moderate energy resolution s(E)/E ~ 100%/sqrt(E) + 10% constant term.	**F-DET-HCAL-BAR.1**
P-DET-HCAL-BAR.2	Must have sufficient granularity in azimuthal and polar angle to resolve neutral clusters.	**F-DET-HCAL-BAR.1**
P-DET-HCAL-BAR.3	Shall have sufficient radial depth to contain medium energy hadronic showers past 2-3 interaction length material of the e/m calorimeter and the solenoid.	**F-DET-HCAL-BAR.1**

- Main goals for barrel HCAL in ePIC:
  - Precise reconstruction of jet energy
    - Jets at the EIC are relatively soft
    - Tracks will provide a better determination of momentum than hadronic calorimetry over most of the kinematic coverage.
    - HCAL provides a measurement of neutral hadrons.
  - Secondary determination of scattered electron kinematics from hadronic remnants
  - Additional capability: Muon identification (MIP)

sPHENIX Barrel Hadronic Calorimeter

Charge questions #1,5





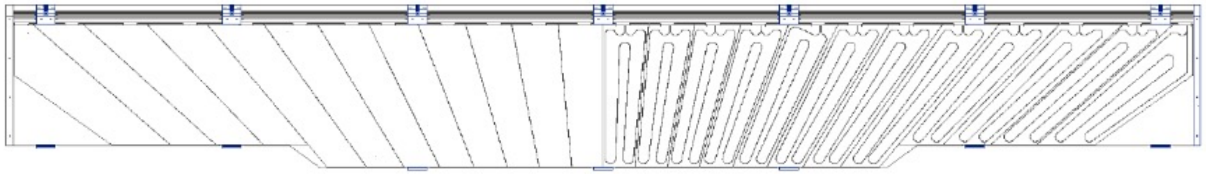
- HCAL steel and scintillating tiles with wavelength shifting fiber
  - **Outer HCal (outside the solenoid)**
  - **Δη x Δϕ ≈ 0.1 x 0.1 (sPHENIX towers)**
  - **1,536 readout channels**
- SiPM Readout
- Repurpose of sPHENIX barrel HCAL

HCAL performance requirements driven by jet physics in ePIC

- Uniform fiducial acceptance $-1<\eta<1$ and $0<\phi<2\pi$
  - Extended coverage $-1.1<\eta<1.1$ to account for jet cone
- Hadronic energy resolution requirement:
  - $\frac{\sigma}{E} < \frac{100\%}{\sqrt{E}}$
  - Gaussian response (limited tails)
- Barrel HCAL created by instrumenting barrel magnetic flux return

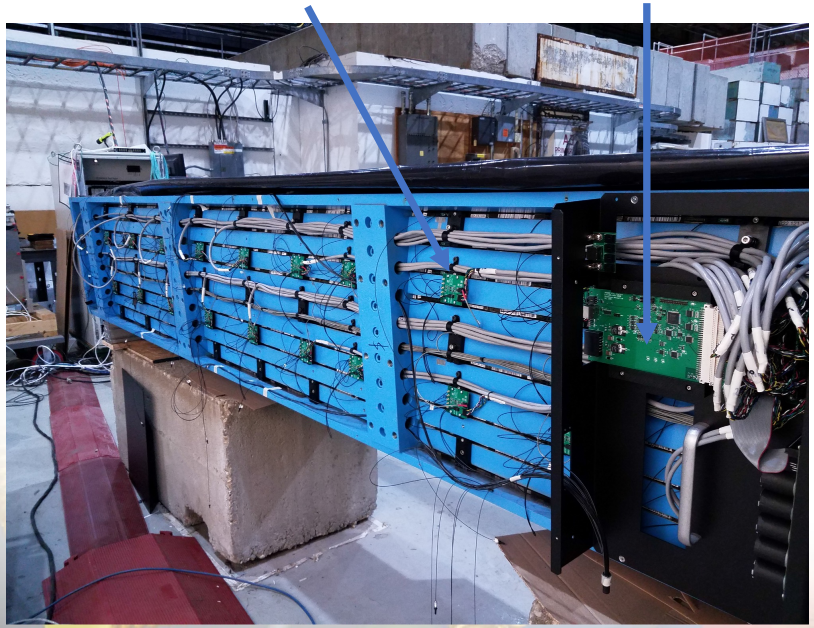
sPHENIX Barrel Hadronic Calorimeter

tiles in sector gap:



Tower preamplifiers

LV/Bias and slow controls.



Assembly Detail:
5 scintillators/tower
48 towers per sector
32 sectors;
1536 channels (7680 SiPMs)

32 sectors - 1.8m inner radius, 2.7m outer radius

Titled-tile design:
10 rows of 7mm scint. tiles (24 tiles per row), 12º tilt angle

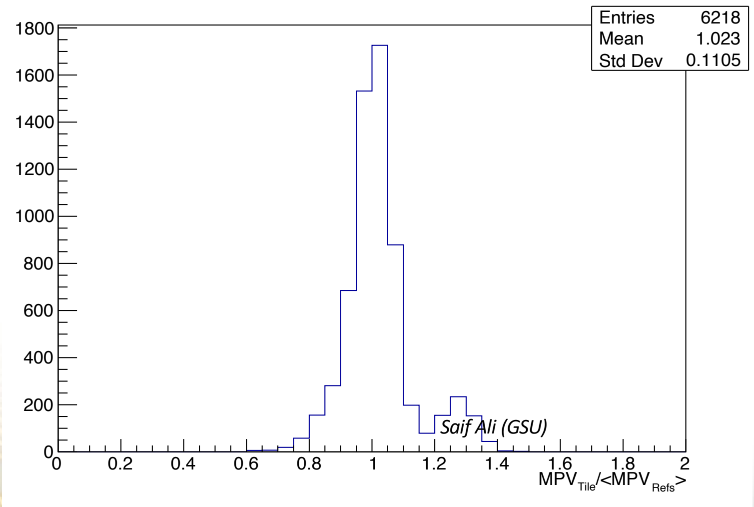
Tapered 1020 steel plates ~26.1mm - ~42.4mm

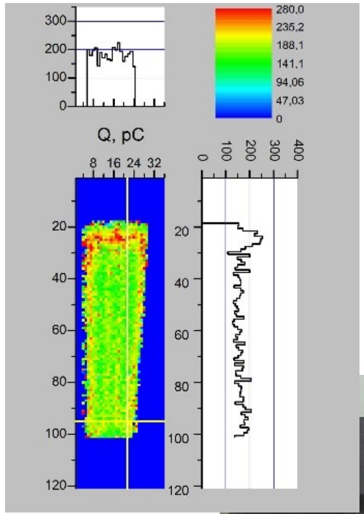
Completed sector is 6.3m long, 13.5 tons

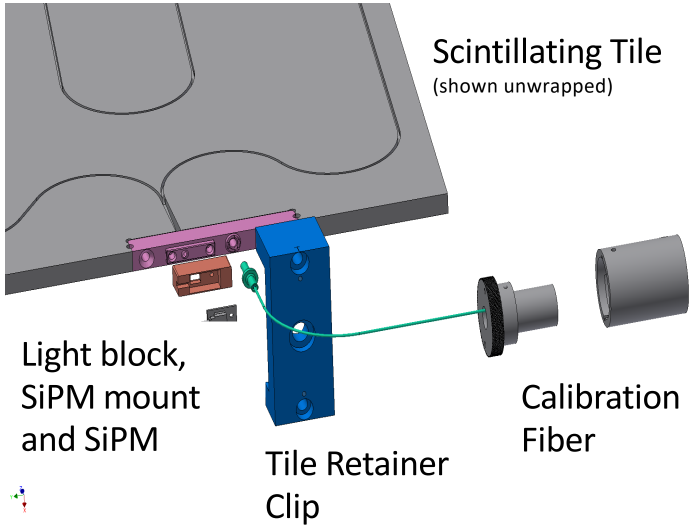
sPHENIX Barrel Hadronic Calorimeter

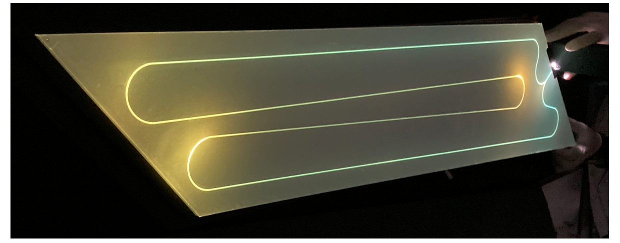
Scintillating tiles are integrated units manufactured by Uniplast. Detailed cosmic ray response maps from MEPHI (Urugan telescope), integrated into sPHENIX simulations

Extensive testing of produced tiles for unform response, results used to sort tiles into a tower with variation <5%









Refurbishment plans

- ➢ sPHENIX barrel HCAL currently has 100% live towers (!!)

- ➢ Do not anticipate significant radiation damage to scintillator
- ➢ Plan to replace SiPMs and readout electronics
  - ➢ Will require removal of scintillating tiles.
  - ➢ Potential to re-measure tile cosmics PR (we should do this)
  - ➢ Opportunity to replace / repair scintillating tiles
  - ➢ Piggy-back on H2GCROC development for forward HCAL
    - ➢ Dual-range ADC/TOT very helpful for MIPs
  - ➢ Replace slow control / monitoring boards as well (LED)
- ➢ Repeat sector-level cosmics calibration

Address by reading out each tile individually rather by summing five tile signals together as in sPHENIX

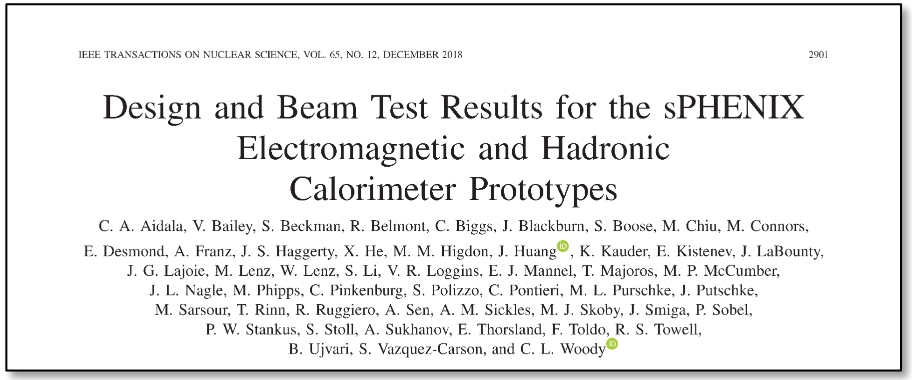
December 2022 Review

- Comments/Concerns
  - Control homogeneity of tiles
  - Consider 1 HGCROC channel/tile to have longitudinal information to distinguish shower from MIP(μ)

Energy resolution

Charge question #2

PERFORMANCE REQUIREMENTS		
Name	Description	Parent
Barrel HCAL		
P-DET-HCAL-BAR.1	Should have a moderate energy resolution s(E)/E ~ 100%/sqrt(E) + 10% constant term.	**F-DET-HCAL-BAR.1**

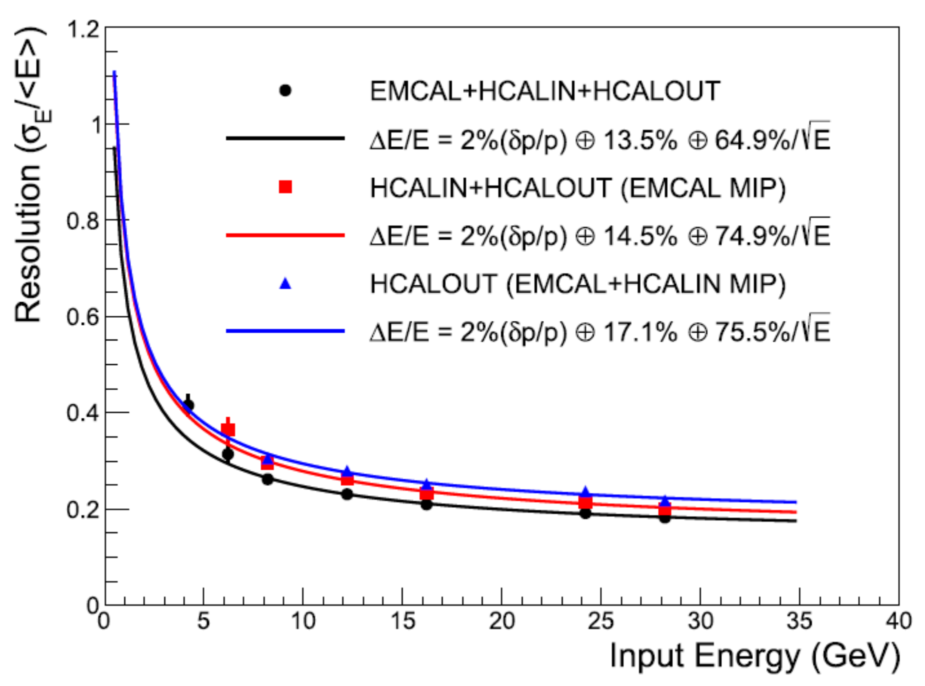

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 65, NO. 12, DECEMBER 2018 2901

Design and Beam Test Results for the sPHENIX Electromagnetic and Hadronic Calorimeter Prototypes

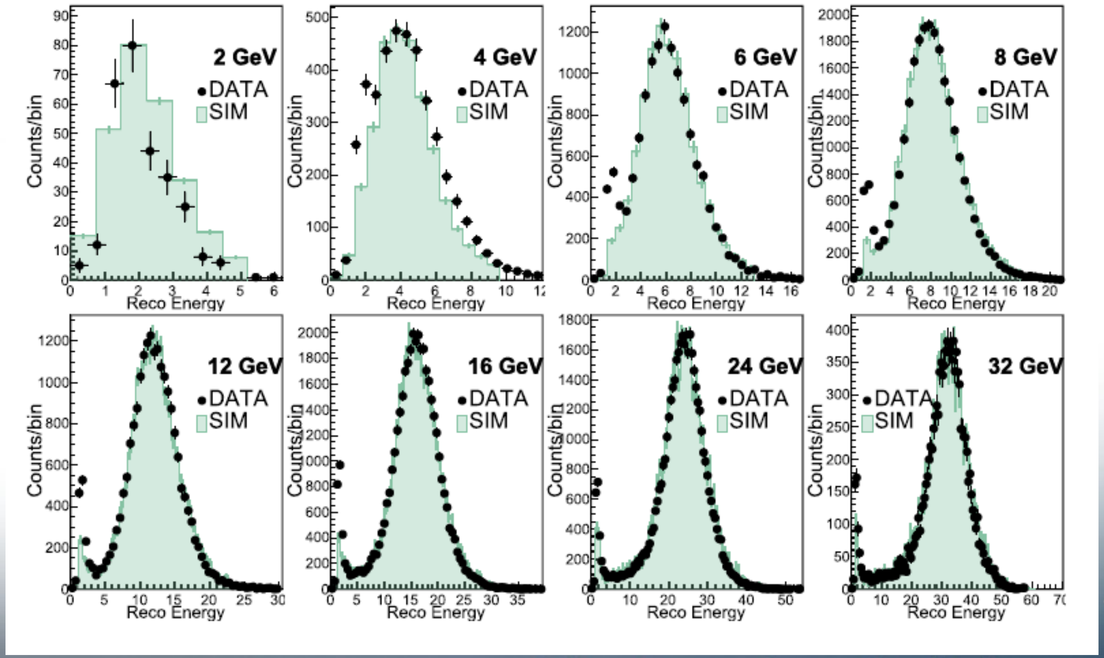
C. A. Aidala, V. Bailey, S. Beckman, R. Belmont, C. Biggs, J. Blackburn, S. Boose, M. Chiu, M. Connors, E. Desmond, A. Franz, J. S. Haggerty, X. He, M. M. Higdon, J. Huang, K. Kauder, E. Kistenev, J. LaBounty, J. G. Lajoie, M. Lenz, W. Lenz, S. Li, V. R. Loggins, J. Mannel, T. Majoros, M. P. McCumber, J. L. Nagle, M. Phipps, C. Pinkenburg, S. Polizzo, C. Pontieri, M. L. Purschke, J. Putschke, M. Sarsour, T. Rinn, R. Ruggiero, A. Sen, A. M. Sickles, M. J. Skoby, J. Smiga, P. Sobel, P. W. Stankus, S. Stoll, A. Sukhanov, E. Thorsland, F. Toldo, R. S. Towell, B. Ujvari, S. Vazquez-Carson, and C. L. Woody

Detailed studies of performance and comparison with simulations done in test beam (T-1044).

Performance of full device will be measured in sPHENIX. We should achieve a reduced constant term due to tighter control on the scintillator variation in a tower for production sectors.



Data vs. Monte-Carlo comparison



Electron-Ion Collider

Granularity

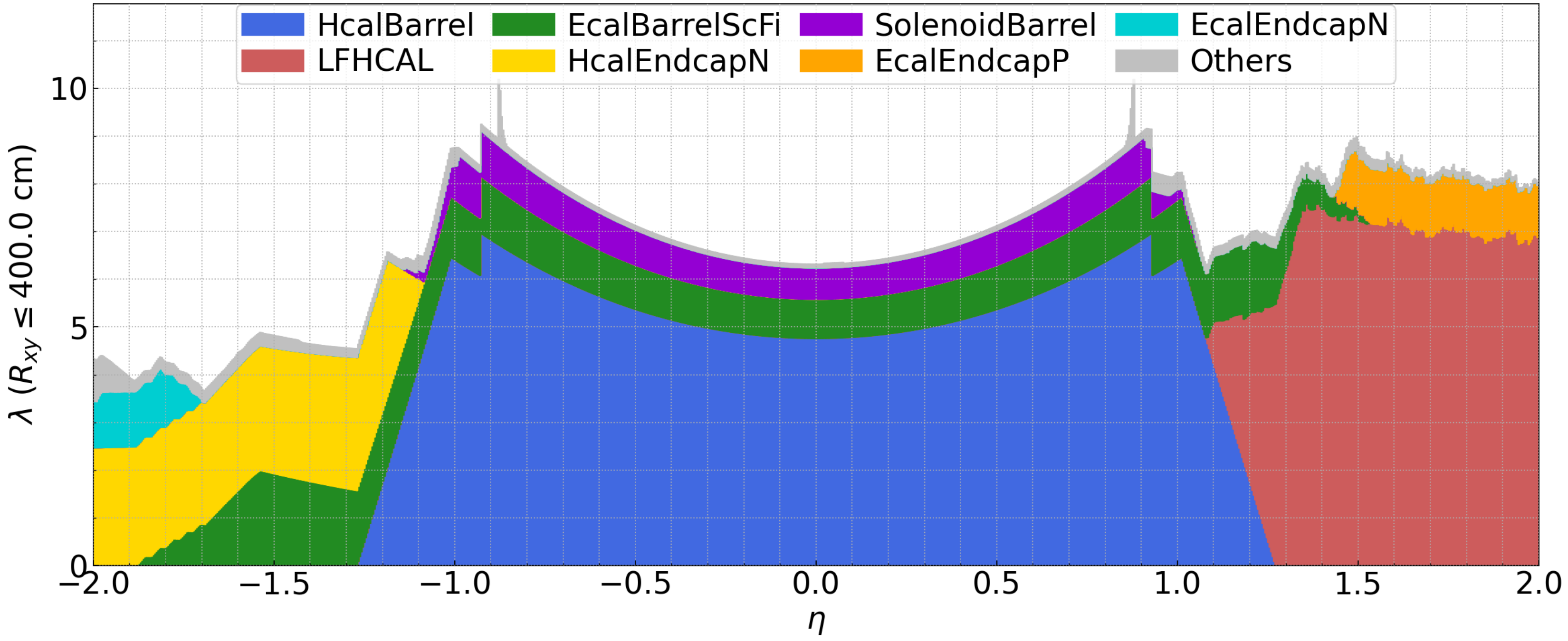
PERFORMANCE REQUIREMENTS		
Name	Description	Parent
Barrel HCAL		
P-DET-HCAL-BAR.2	Must have sufficient granularity in azimuthal and polar angle to resolve neutral clusters.	**F-DET-HCAL-BAR.1**

- The sPHENIX tower readout (5 scintillating tiles) was designed with $\Delta\eta \times \Delta\varphi \approx 0.1 \times 0.1$, smaller than the typical hadronic shower transverse size.
- In ePIC will upgrade the electronics to read out each tile individually.
  - Improved cluster location resolution
  - Possibility to take advantage to depth information.
  - Requires a revised clustering algorithm to incorporate additional information, under development.

Nuclear interaction length

PERFORMANCE REQUIREMENTS		
Name	Description	Parent
Barrel HCAL		
P-DET-HCAL-BAR.3	Shall have sufficient radial depth to contain medium energy hadronic showers past 2-3 interaction length material of the e/m calorimeter and the solenoid.	**F-DET-HCAL-BAR.1**

A material scan from the latest ePIC geometry shows that the barrel HCAL provides > 4*λ_{int} over the depth provided by the barrel EMCal and solenoid.



Forward Hadronic Calorimeter

by F. Bock (Oak Ridge National Lab)

Electron-Ion Collider

Requirements

GENERAL REQUIREMENTS	
Name	Description
ward HCAL	
G-DET-HCAL-FWD.1	Forward HCal shall play a crucial role in jet energy and kinematics reconstruction in the hadron endcap, complementing tracking and e/m calorimetry in the particle flow algorithms, and be consistent with the ePIC detector solenoid design

FUNCTIONAL REQUIREMENTS		
Name	Description	Parent
Forward HCAL		
F-DET-HCAL-FWD.1	Must provide hadron energy measurements up to the highest hadron energies in a 250(p) x 18(e) GeV beam configuration and pseudorapidity up to 3.5, with energy resolution defined by the community Yellow Report and subsequent ePIC simulation studies	**G-DET-HCAL-FWD.1**
F-DET-HCAL-FWD.2	The design must be coupled well with a compensated forward e/m calorimeter for high precision jet energy measurements.	**G-DET-HCAL-FWD.1**
F-DET-HCAL-FWD.3	The calorimeter structure must serve as part of the solenoid flux return	**G-DET-HCAL-FWD.1**

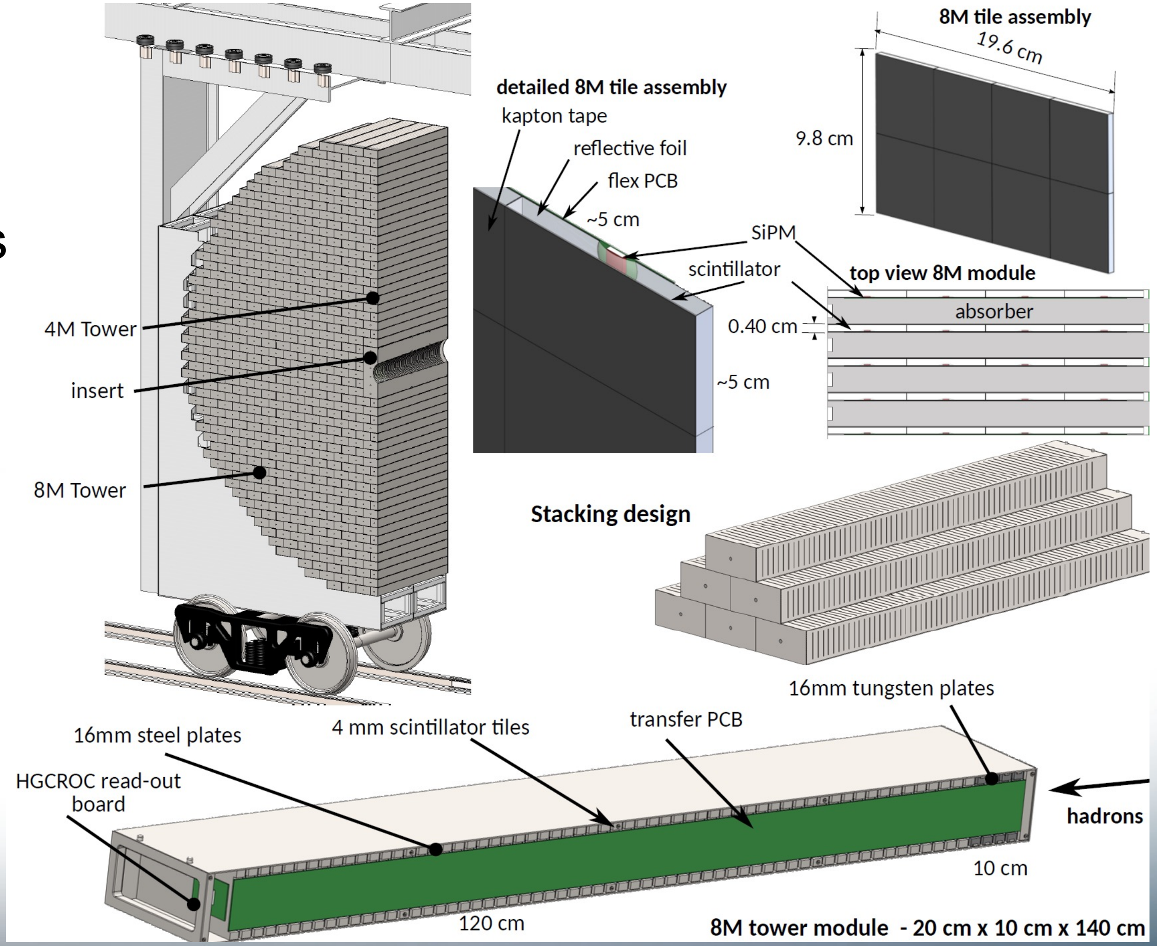
PERFORMANCE REQUIREMENTS		
Name	Description	Parent
Forward HCAL		
P-DET-HCAL-FWD.1	Must cover pseudo rapidity range up to at least 3.5.	**F-DET-HCAL-FWD.1**
P-DET-HCAL-FWD.2	Shall have energy resolution s(E)/E ~ 50%/sqrt(E) + a 10 % constant term.	**F-DET-HCAL-FWD.1**
P-DET-HCAL-FWD.3	Granularity (transverse tower size) should be adequate to resolve deposits from different charged and neutral hadrons taking into account the local abundance, resulting in transverse tower sizes of at least ~5x5 cm^2 for \eta < 2.5 and 3x3 cm^2 for 2.5 < \eta < 4	**F-DET-HCAL-FWD.2**
P-DET-HCAL-FWD.4	Must have tower depth of 6-7 interaction lengths (together with the e/m section) in order to avoid longitudinal leakage for highest energy hadrons at the EIC.	**F-DET-HCAL-FWD.2**
P-DET-HCAL-FWD.5	Granularity (longitudinal tower size) should be adequate to allow for association of showers starting at different depth to the corresponding charged and neutral hadrons. At least 5 longitudinal segments should be read out to determine the shower maximum reliably. For higher rapidity the segmentation should be increased due to the higher particle density	**F-DET-HCAL-FWD.2**
P-DET-HCAL-FWD.6	Calorimeter absorber blocks in the volume allocated for the flux return must be partly built out of a magnetic steel with the permeability defined by the solenoid designers	**F-DET-HCAL-FWD.3**

Design Overview

CALICE AHCal inspired W/Fe-Scintillator calorimeter with SiPM on-tile-readout

Two main parts:

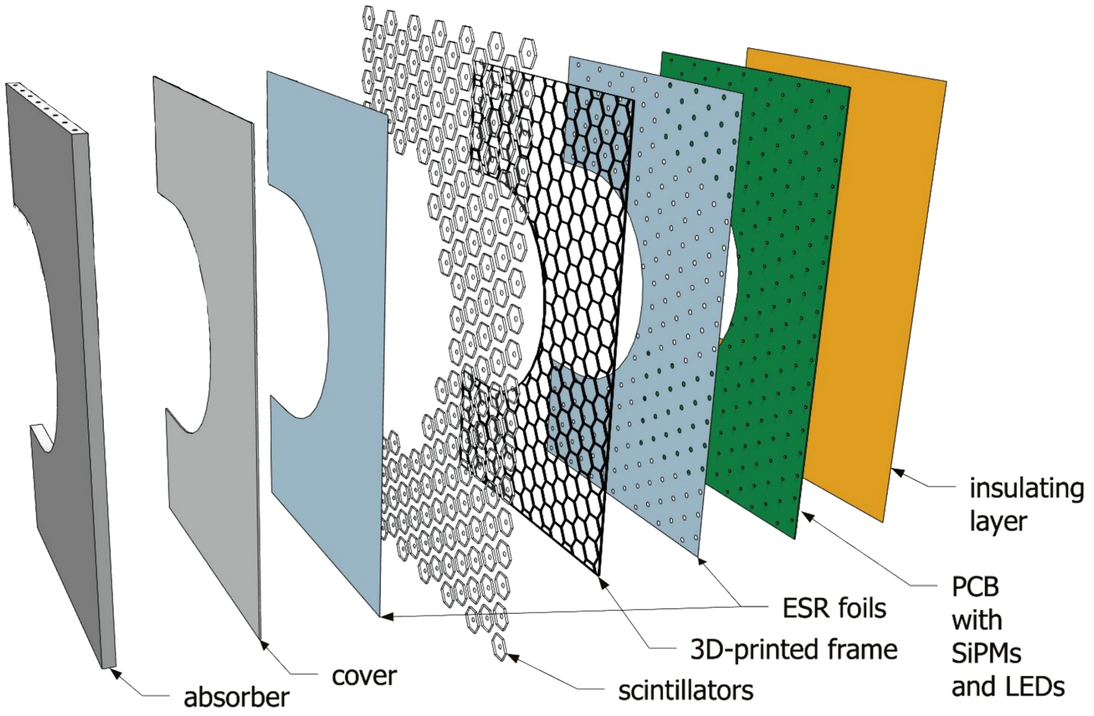
- **LFHCal**:
  - Mostly built out of 10 x 20 x140 cm^3 8M modules
  - 4 layers of tungsten + 61 layers of steel interleaved with scintillator material
  - Transverse tower size 5 x 5 cm^2
  - Multiple consecutive tiles analogously summed to 7 longitudinal segments per tower
- **Insert**:
  - 2 halves surrounding the beam pipe
  - 10 layers of tungsten + 54 layers of steel interleaved with scintillator
  - Hexagonal tiles of 8 cm^2 each read-out separately

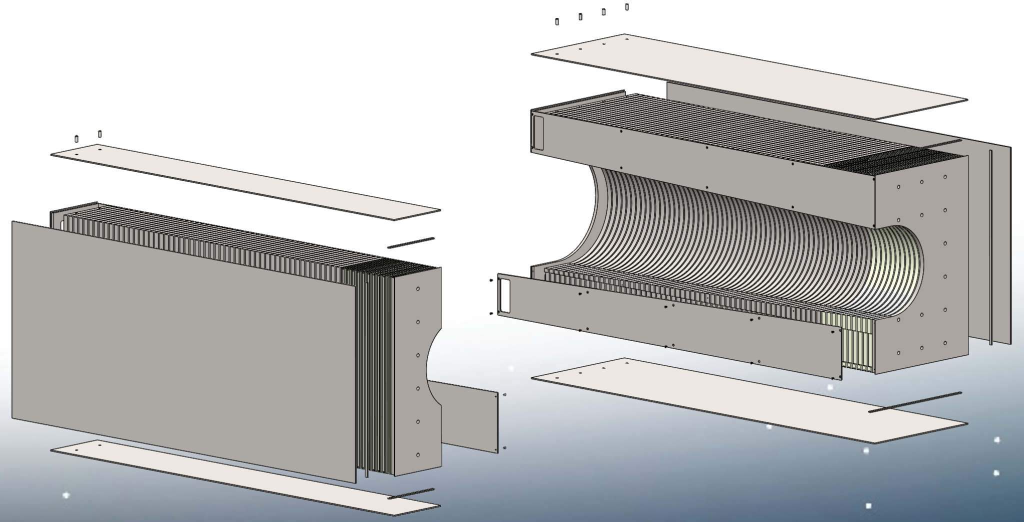


Insert at high η

Higher energy and higher particle density require increased granularity and depth

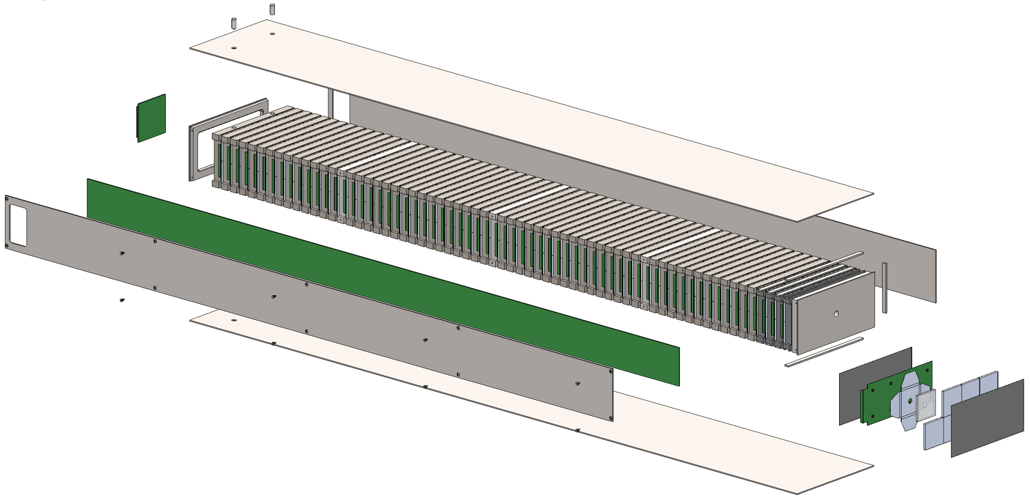
- Acceptance: $2.7 < \eta < 3.8$
- Interaction length: 7.5 λ/λ_0
- Similar sampling structure as LFHCal
- 10 layers of tungsten, 55 layers of steel
- 360 hexagonal tiles with SiPMs per layer, staggered positions in different layers
- Maximum η coverage with minimum dead area in combination with LFHCal

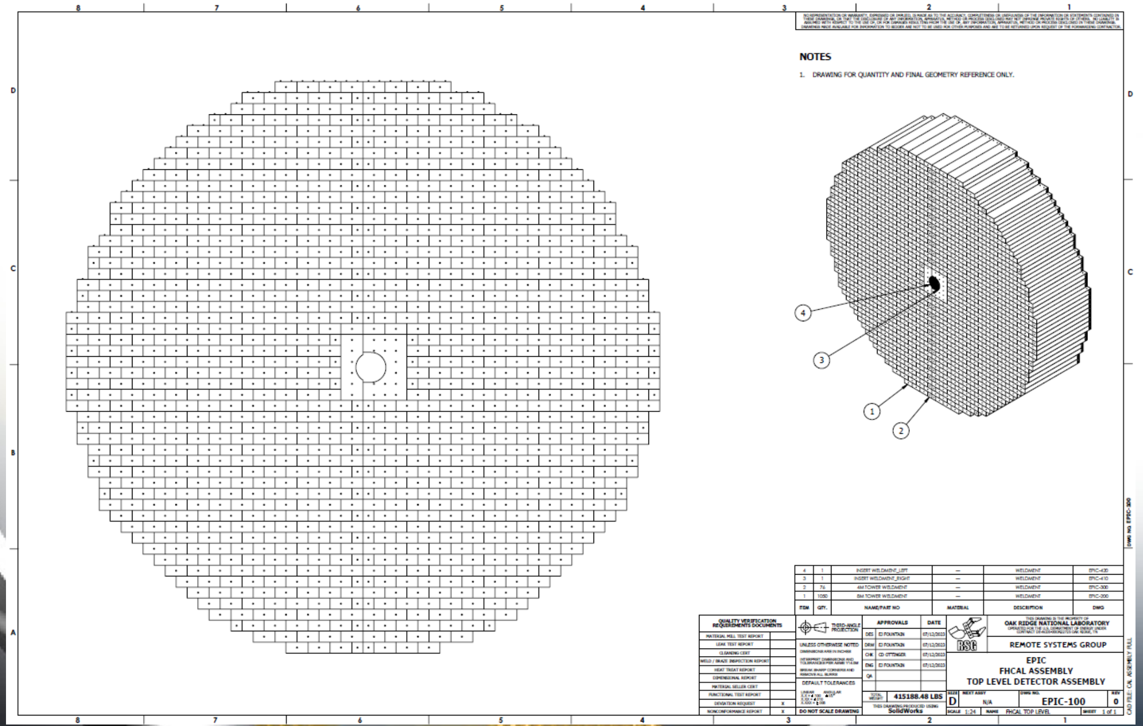


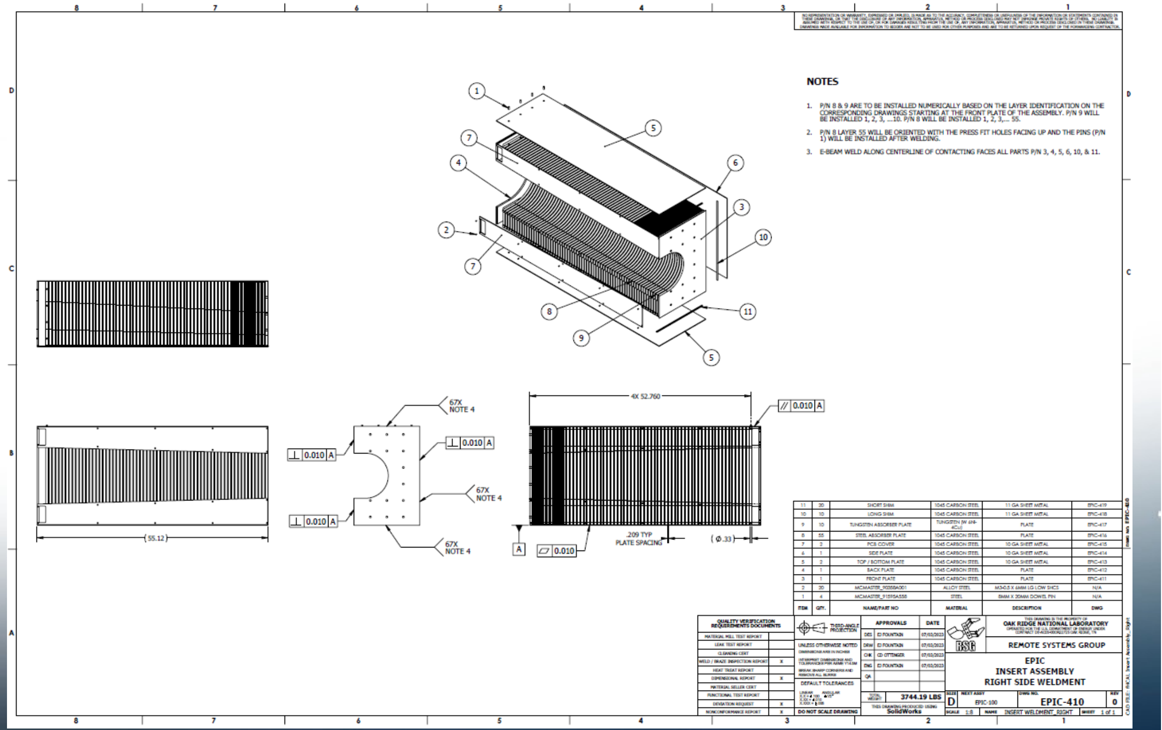


LFHCal module and assembly

- A full set of mechanical drawings exists
- 1050 8M + 76 4M modules stacked to create half shells of LFHCal with insert in the middle





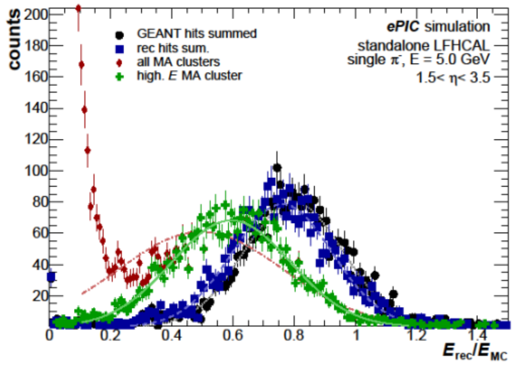


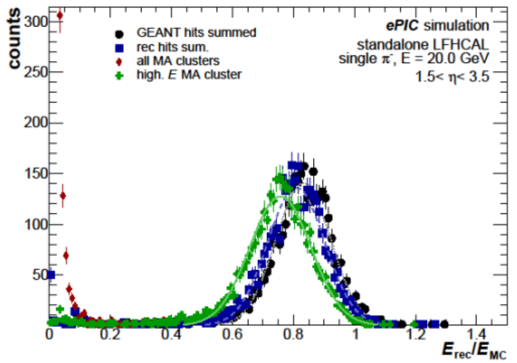
Energy resolution

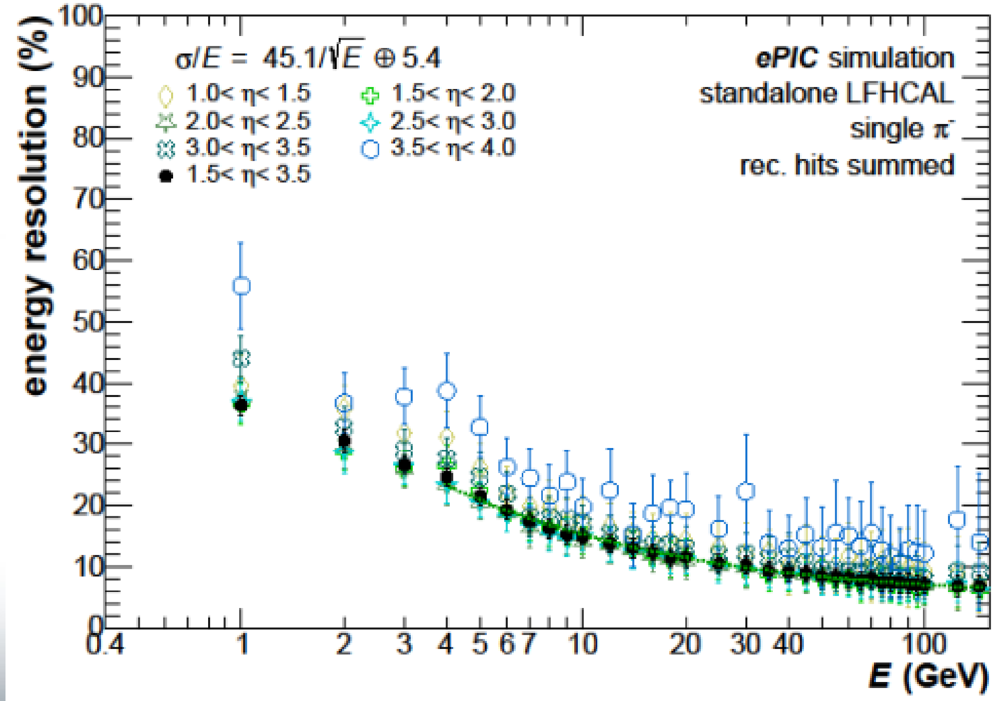
Charge question #2

PERFORMANCE REQUIREMENTS		
Name	Description	Parent
Forward HCAL		
P-DET-HCAL-FWD.2	Shall have energy resolution s(E)/E ~ 50%/sqrt(E) + a 10 % constant term.	**F-DET-HCAL-FWD.1**

- Full LFHCal geometry implemented in ePIC software stack
- First version of full reconstruction chain & cluster finding algorithm implemented
- Standalone detector performance shows very mild η dependence in very forward acceptance where insert is going to be installed







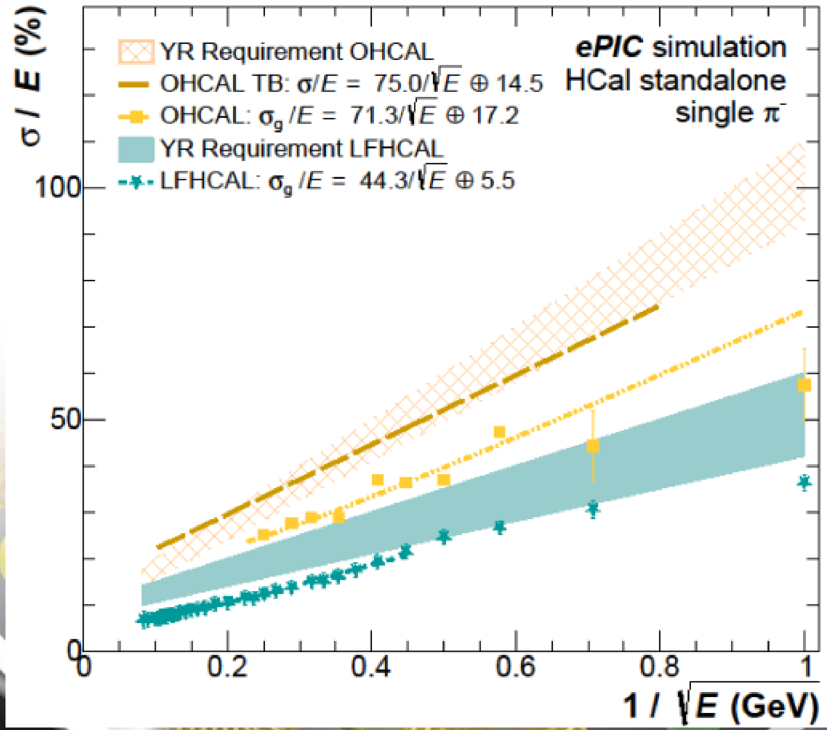
Electron-Ion Collider

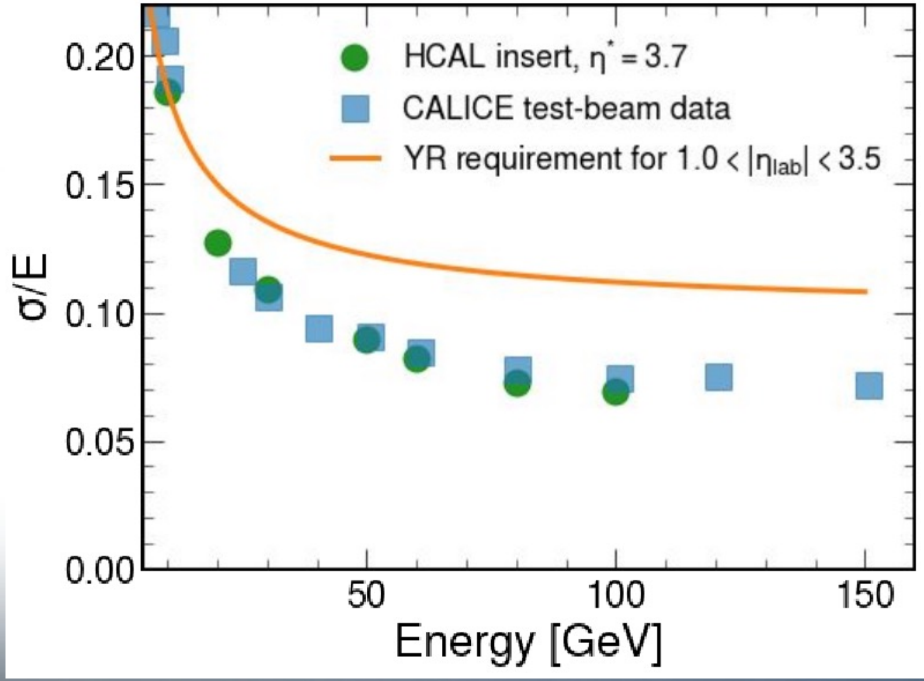
Energy resolution

Charge question #2

PERFORMANCE REQUIREMENTS		
Name	Description	Parent
Forward HCAL		
P-DET-HCAL-FWD.2	Shall have energy resolution s(E)/E ~ 50%/sqrt(E) + a 10 % constant term.	**F-DET-HCAL-FWD.1**

- Standalone resolution for both LFHCal and insert surpasses Yellow Report requirement for the respective region



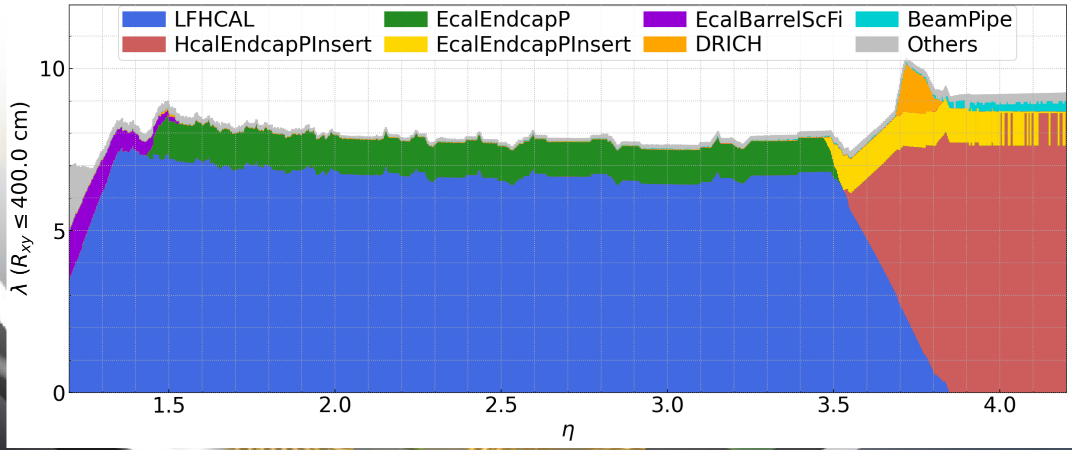


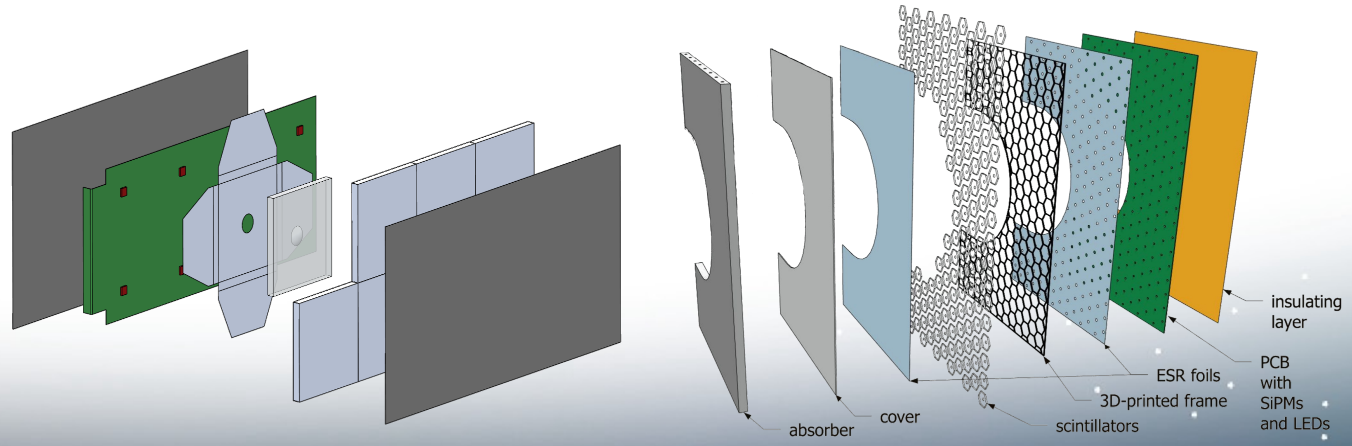
Granularity & nuclear interaction length

Charge question #2

PERFORMANCE REQUIREMENTS		
Name	Description	Parent
Forward HCAL		
P-DET-HCAL-FWD.3	Granularity (transverse tower size) should be adequate to resolve deposits from different charged and neutral hadrons taking into account the local abundance, resulting in transverse tower sizes of at least ~5x5 cm^2 for \eta < 2.5 and 3x3 cm^2 for 2.5 < \eta < 4	F-DET-HCAL-FWD.2
P-DET-HCAL-FWD.4	Must have tower depth of 6-7 interaction lengths (together with the e/m section) in order to avoid longitudinal leakage for highest energy hadrons at the EIC.	F-DET-HCAL-FWD.2
P-DET-HCAL-FWD.5	Granularity (longitudinal tower size) should be adequate to allow for association of showers starting at different depth to the corresponding charged and neutral hadrons. At least 5 longitudinal segments should be read out to determine the shower maximum reliably. For higher rapidity the segmentation should be increased due to the higher particle density	F-DET-HCAL-FWD.2

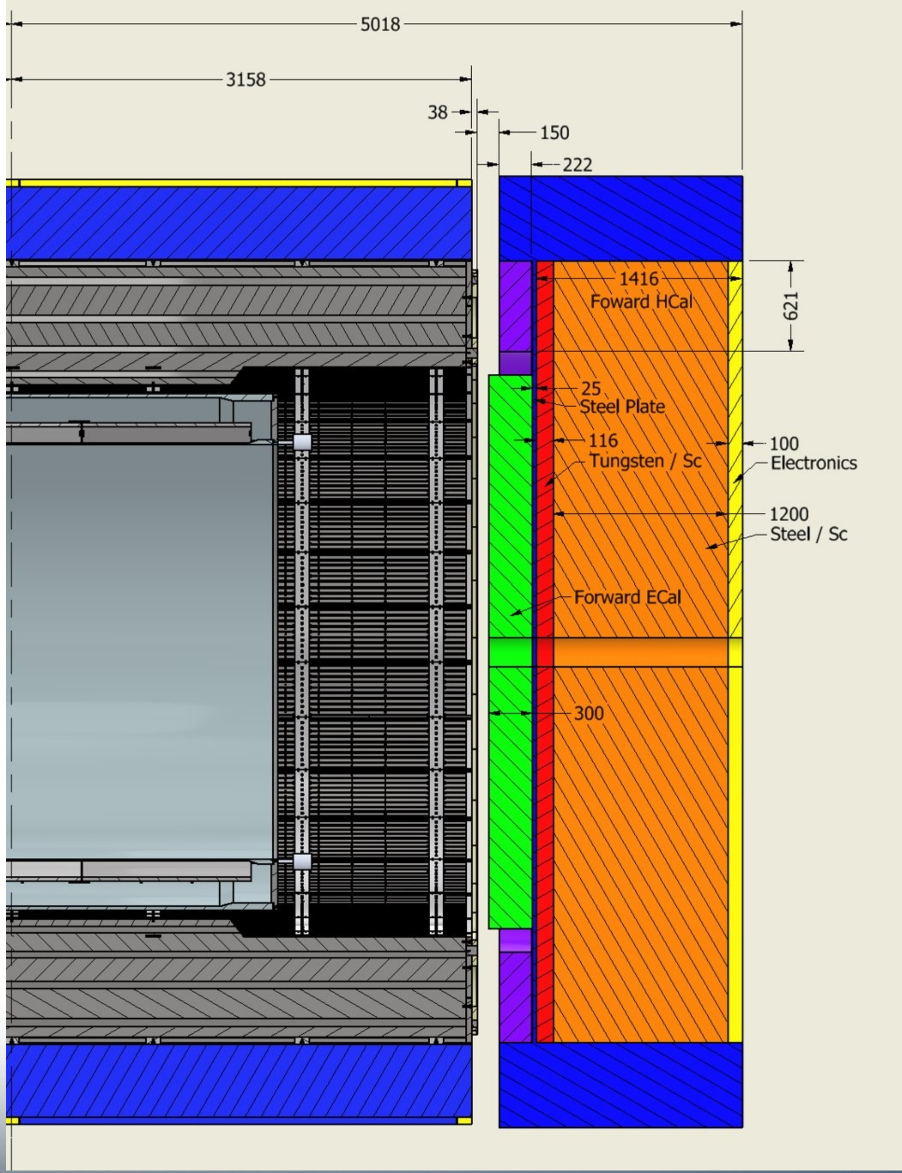
- Interaction length: LFHCal 6.5 λ/λ_0 & insert 7.5 λ/λ_0
- Transverse tower size: square tiles 5x5 cm^2 for LFHCal & hexagonal tiles of 8cm^2 for insert
- Longitudinal segmentation: 7 segments for LFHCal & 65 layers for insert





Flux return requirement

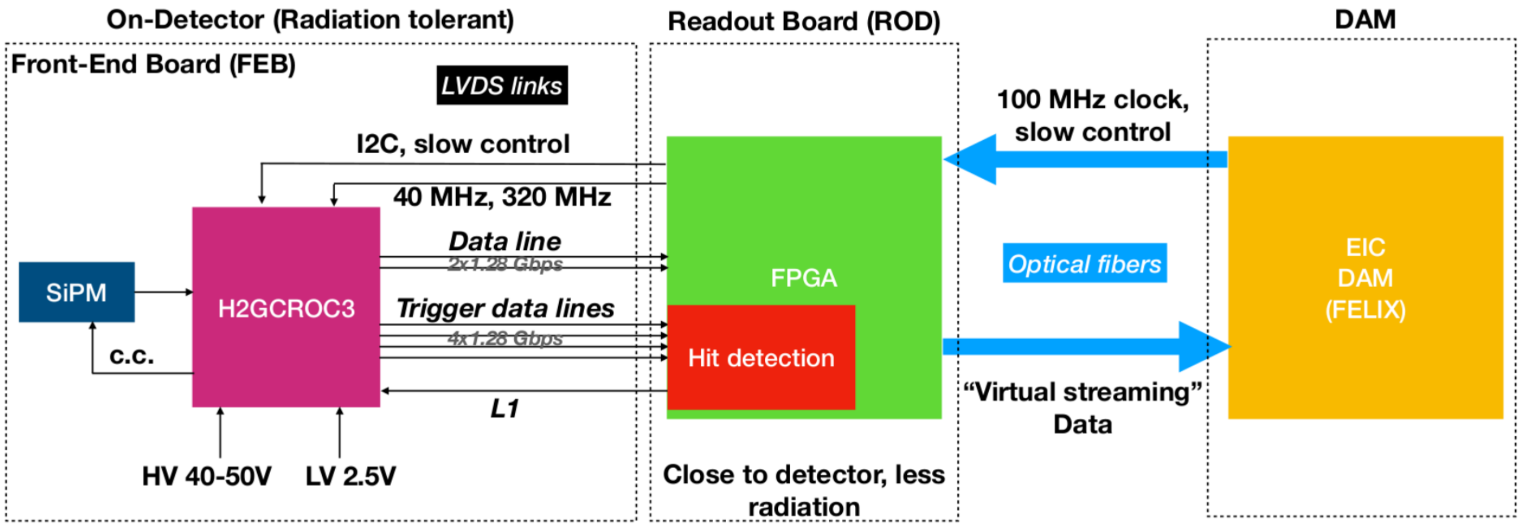
PERFORMANCE REQUIREMENTS		
Name	Description	Parent
Forward HCAL		
P-DET-HCAL-FWD.6	Calorimeter absorber blocks in the volume allocated for the flux return must be partly built out of a magnetic steel with the permeability defined by the solenoid designers	F-DET-HCAL-FWD.3

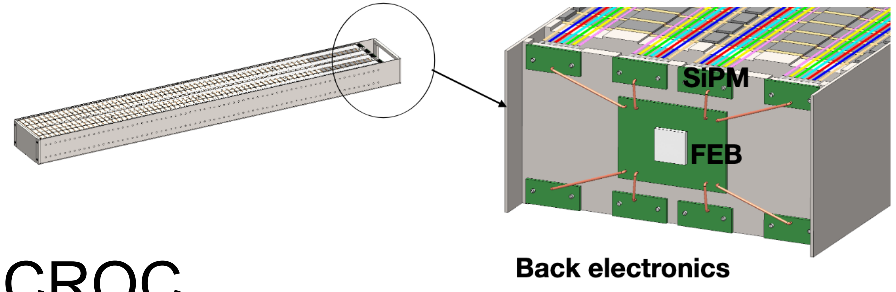


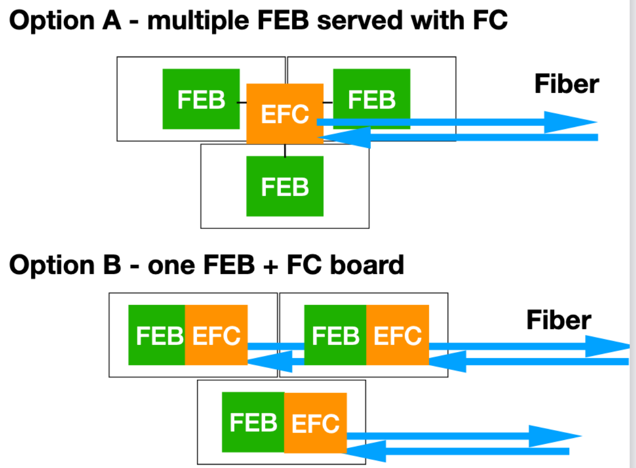
- Absorber structure consistent of:
  - LFHCal: 4 cm steel + 4 layers of 1.52 cm tungsten + 60 layers of 1.52 cm steel
  - Insert: 4 cm steel + 10 layers of 1.52 cm tungsten + 55 layers of 1.52 cm steel
- 1045 Carbon steel used as main flux return

These are all Long Lead Procurement items, as well as the SiPMs

Electronics







- An adaptation of CMS H2GCROC
  - Will be used for all three ePIC HCal subsystems

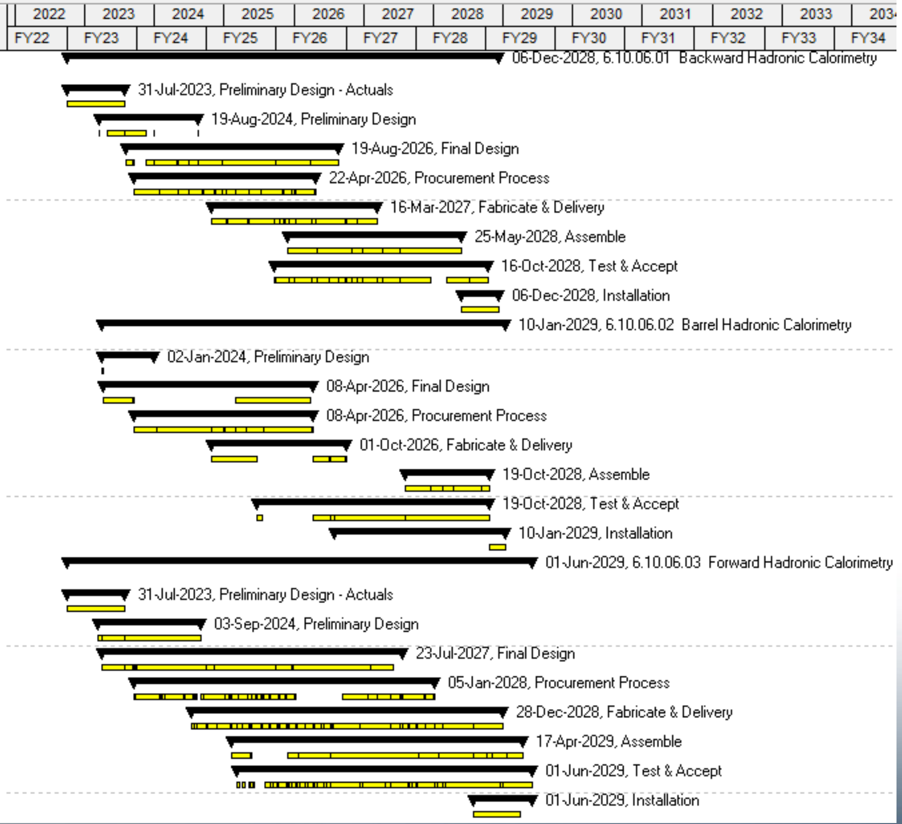
Schedule

- PDR and FDR dates are defined for all HCal subsystems

- All three should be installation ready on time:
  - Barrel: early 2029 for solenoid installation and low current tests
  - Forward: Fall 2029 for a full field test
  - Backward: later in 2030

Layout: EIC - L2 by Stage | Filter All: No Actuals, WBS: 6.10.XX

Activity ID	Activity Name	Original Duration	Start	Finish	Total Float
6.10.06.01	Backward Hadronic Calorimetry	1543	03-Oct-2022	06-Dec-2028	540
	Preliminary Design - Actuals	206	03-Oct-2022	31-Jul-2023	540
	Preliminary Design	356	20-Mar-2023	19-Aug-2024	1013
	Final Design	759	03-Aug-2023	19-Aug-2026	538
	Procurement Process	647	15-Sep-2023	22-Apr-2026	599
	Fabricate & Delivery	590	29-Oct-2024	16-Mar-2027	969
	Assemble	620	02-Dec-2025	25-May-2028	669
	Test & Accept	765	19-Sep-2025	16-Oct-2028	572
	Installation	131	26-May-2028	06-Dec-2028	538
6.10.06.02	Barrel Hadronic Calorimetry	1436	05-Apr-2023	10-Jan-2029	351
	Preliminary Design	185	05-Apr-2023	02-Jan-2024	1043
	Final Design	746	11-Apr-2023	08-Apr-2026	602
	Procurement Process	637	15-Sep-2023	08-Apr-2026	602
	Fabricate & Delivery	480	29-Oct-2024	01-Oct-2026	542
	Assemble	300	09-Aug-2027	19-Oct-2028	351
	Test & Accept	828	25-Jun-2025	19-Oct-2028	351
	Installation	605	04-Aug-2026	10-Jan-2029	351
6.10.06.03	Forward Hadronic Calorimetry	1665	03-Oct-2022	01-Jun-2029	418
	Preliminary Design - Actuals	206	03-Oct-2022	31-Jul-2023	417
	Preliminary Design	372	10-Mar-2023	03-Sep-2024	486
	Final Design	1074	03-Apr-2023	23-Jul-2027	756
	Procurement Process	1070	15-Sep-2023	05-Jan-2028	727
	Fabricate & Delivery	1111	12-Jul-2024	28-Dec-2028	523
	Assemble	1042	11-Feb-2025	17-Apr-2029	448
	Test & Accept	1056	10-Mar-2025	01-Jun-2029	416
	Installation	209	01-Aug-2028	01-Jun-2029	416



Summary

(1) Technological challenges for all three HCal subsystems are solved

(2) Detector requirements are fully defined

(3) The barrel HCal schedule is driven by the low current test of the detector solenoid, and the forward HCal provides a flux return for the magnet

(4) Detector design is sufficiently advanced to fully define specifications of the SiPMs for all three HCal subsystems, and detailed drawings exist for the forward HCal

(5) Design has evolved sufficiently to project a 90% maturity in 1.5 years (by CD-3)

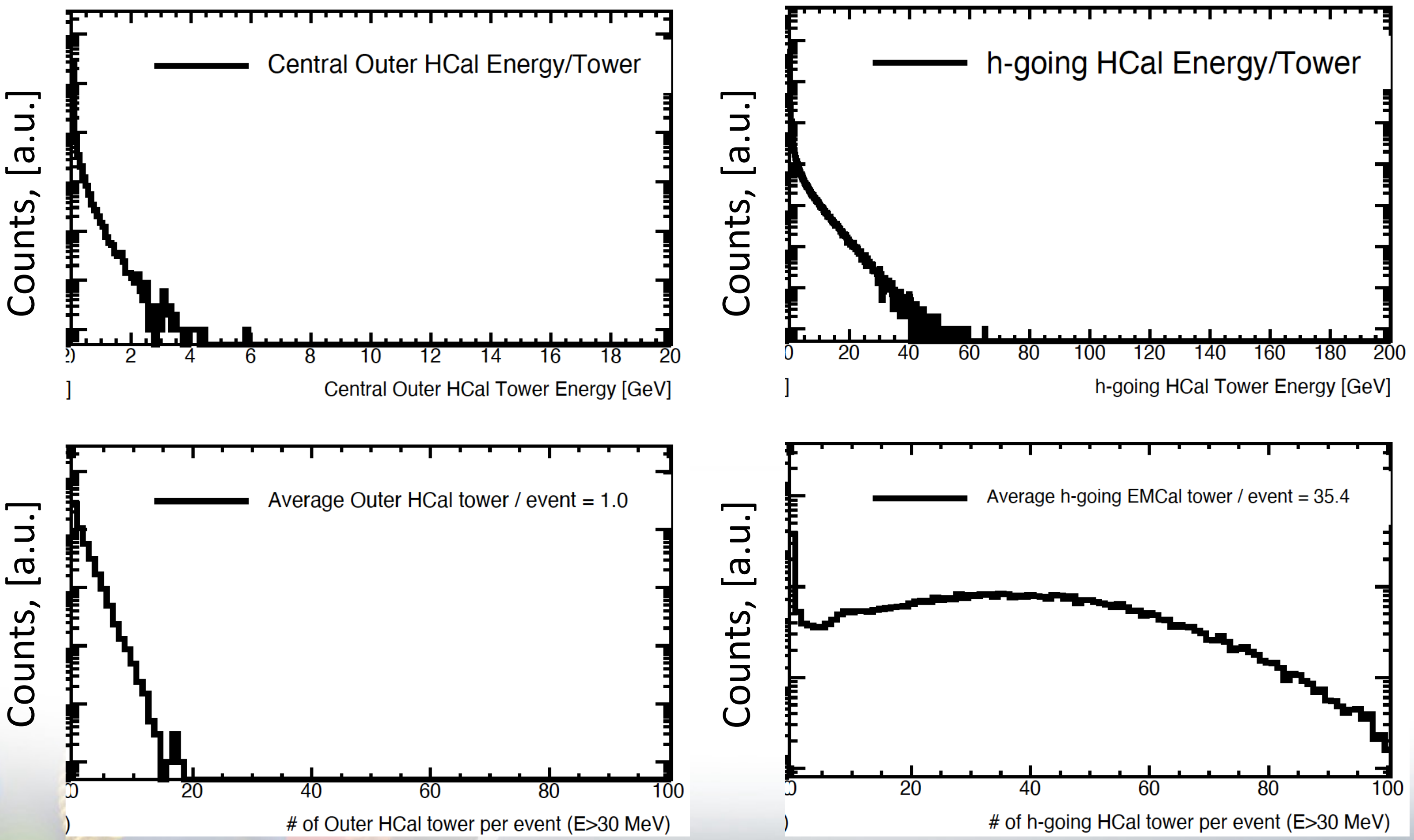
- e-endcap HCal is of a “simple” design with rather modest requirements
- barrel HCal will be a proven to work sPHENIX calorimeter
- h-endcap HCal design and assembly procedure are at the design drawing stage

(6) Schedule has a sufficient float to have both barrel and forward HCal subsystems installed in 2029 when they are needed to perform the solenoid installation & magnetic field tests. Backward HCal can be installed later in 2030.

Backup

Occupancy

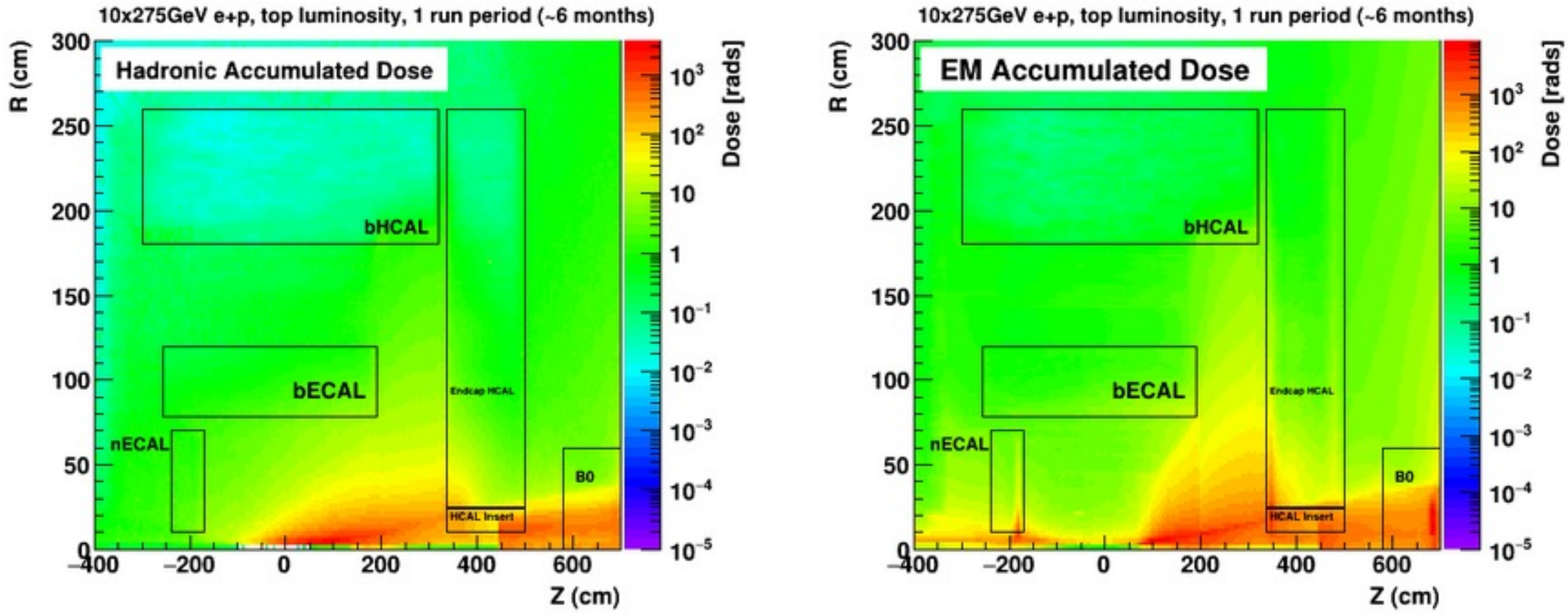
barrel forward endcap



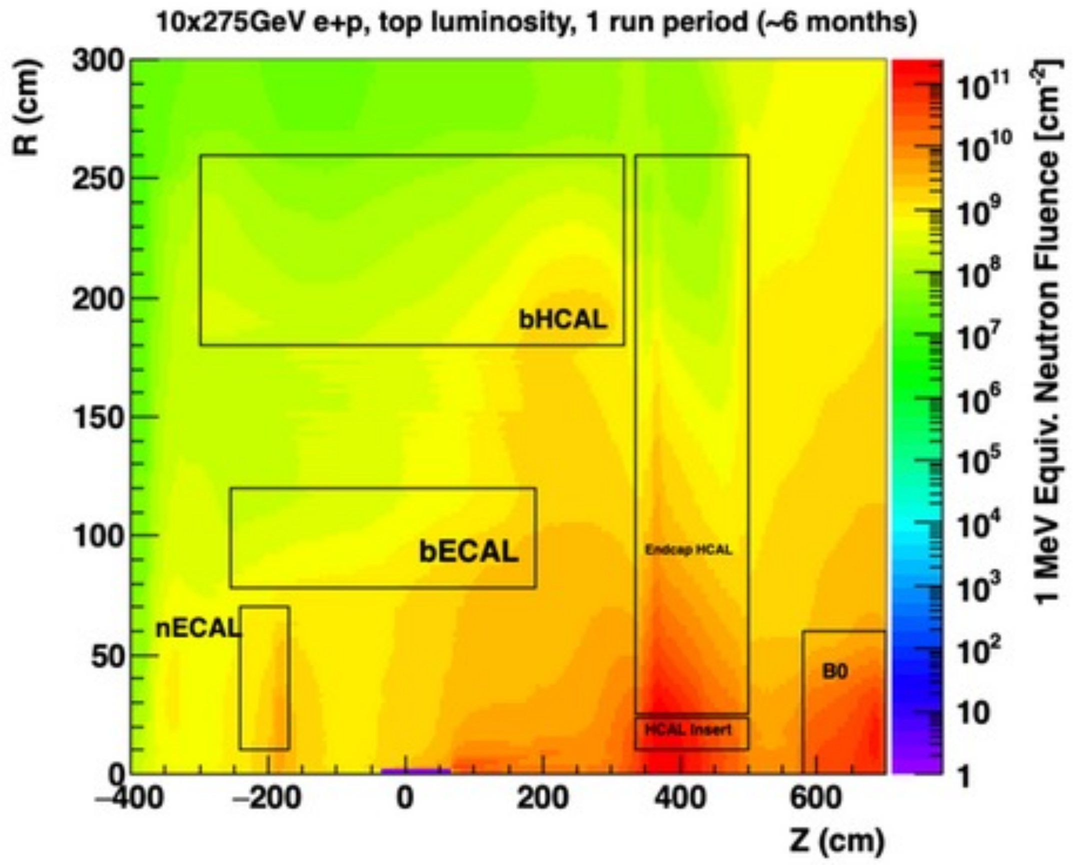
- Typically, few towers hit per event, few GeV energy deposit per tower, except for the rare high energy jets in the forward endcap

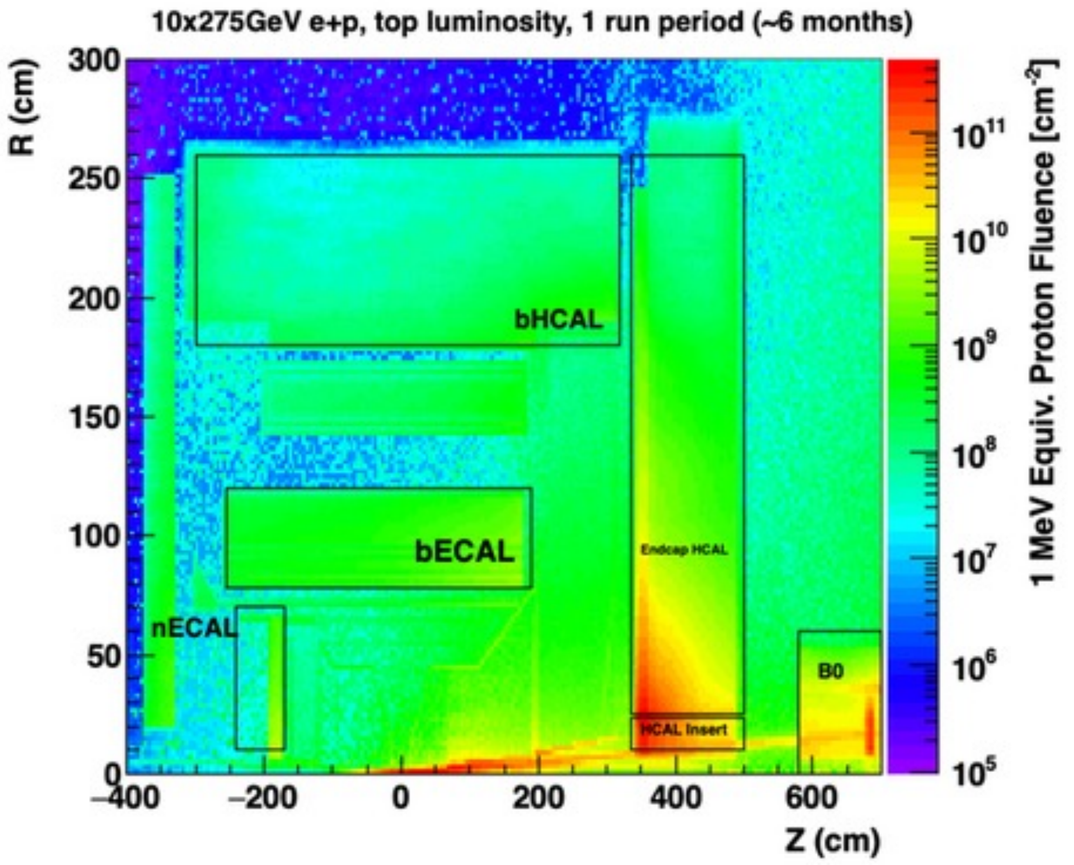
Electron-Ion Collider

Accumulated dose



Proton and neutron fluence



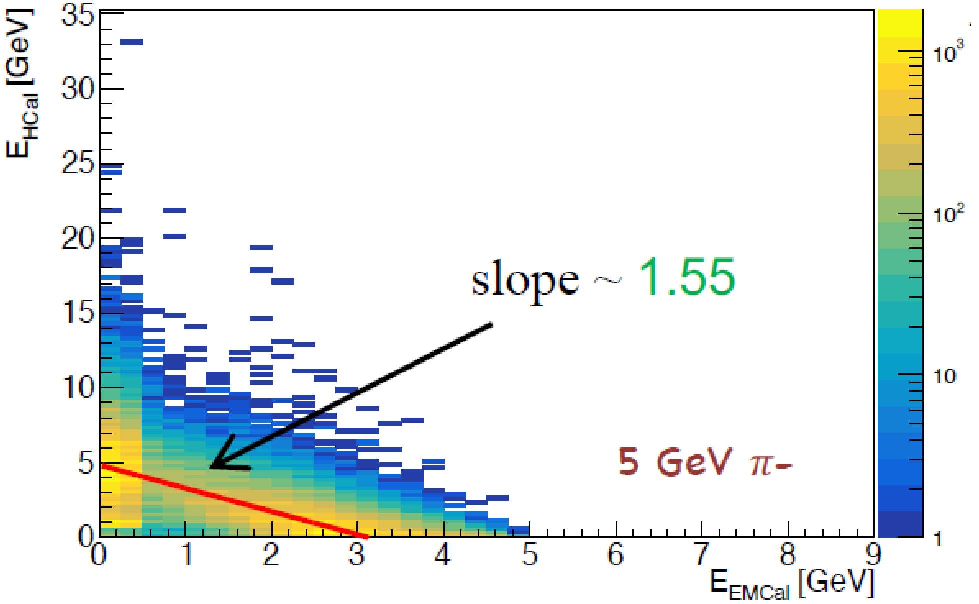


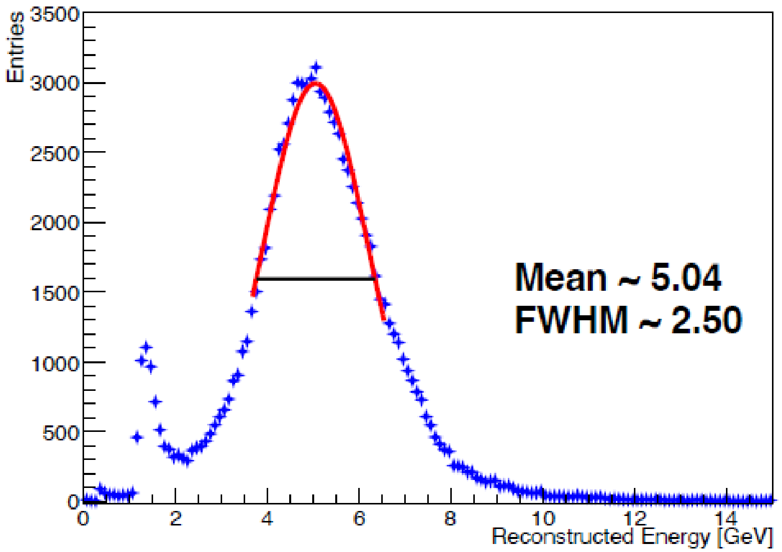
Replacement SiPM Specifications

Barrel Hadronic Calorimeter

Parameter	Specification	Notes
Active Area	3mm x 3mm	
Pixel Size	15 micron	
Package Type	surface mount	
Peak Sensitivity	~460 nm	
PDE	~25%	
Gain	~2 x 10^5	
DCR	1kHz typical/2kHz max	
Temperature coefficient of Vop	<60 mV/C	
Direct crosstalk probability	<1%	from S14160-3015PS, not specified for S12572-015P
Terminal capacity	~500pF	
Packing granularity	N/A	
Vop variation within a tray	+/-0.1V	sPHENIX was +/- 0.04, 0.1V is from Hamamatsu quote, should be OK
Recharge Time	N/A	probably should have a spec here, but not sure from datasheets?
Fill Factor	~50%	yields approximately 40k pixels
Protective Layer	Silicone or epoxy resin (n=~1.55)	this probably doesn't need to be a spec for oHCAL?
	NB: Specifications set to match sPHENIX - Hamamatsu S12572-015P	
	Crosschecked against datasheet for Hamamatsu S14160-3015PS	

nHCal Calibration – energy sharing





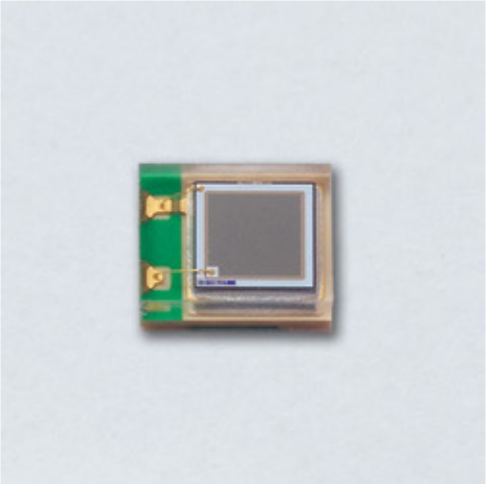
$$E_{reco} = 1.55 * E_{EMCal} + E_{HCal}$$

Fitted a linear function to E_{HCal} vs. E_{EMCal} histogram to extract the energy sharing parameters

* $E_{Hcal}/f \equiv E_{HCal}$

Study by Subhadip Pal

SiPMs

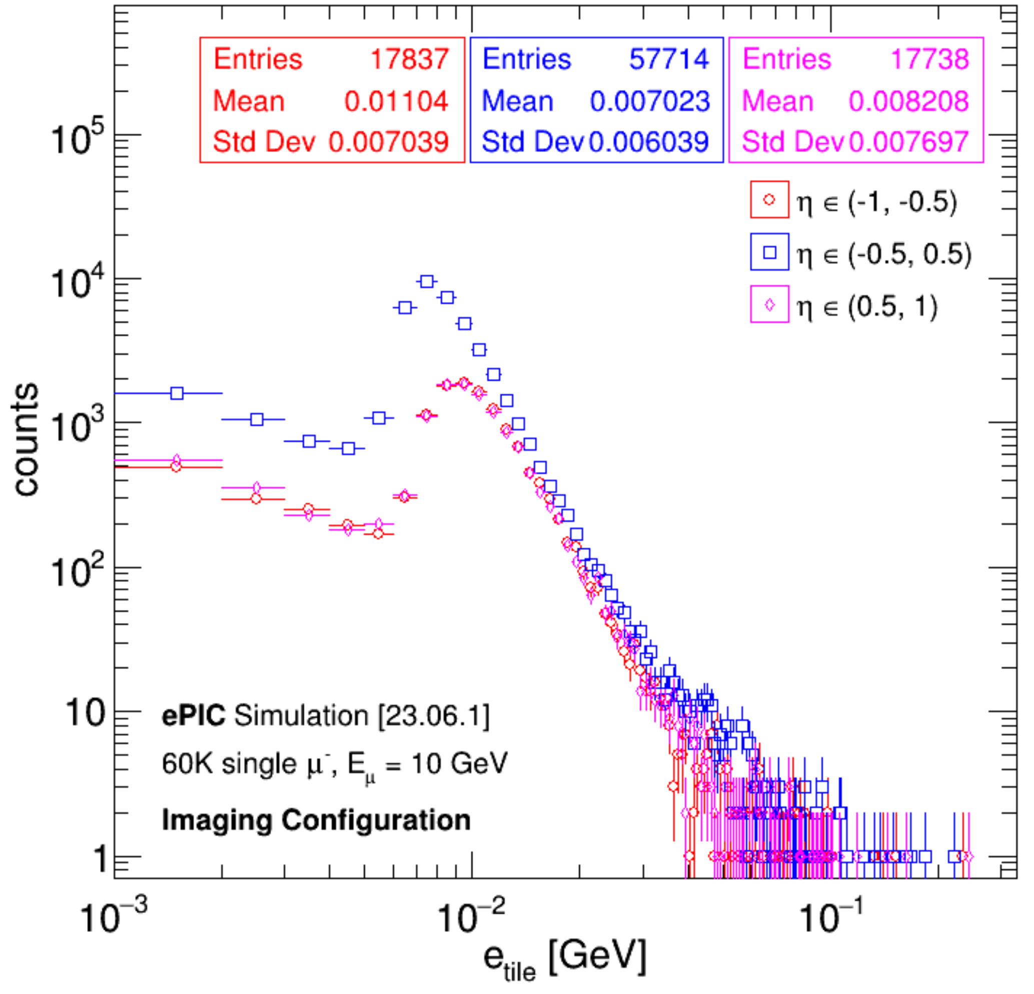


- Candidate SiPM:
  - S14160-1315PS 1.3x1.3 mm^2 15 μm pixel by Hamamatsu
    - https://www.hamamatsu.com/eu/en/product/optical-sensors/mppc/mppc_mppc-array/S14160-1315PS.html
- Fibers to be glued to the SiPMs
- Specifications:

Backward Hadronic Calorimeter

Parameter	Specification	Notes
Active Area	1.3 x 1.3 mm^2	S14160-1315PS - most likely? All values taken from it's specs - none determined from design yet
Pixel Size	15 µm	
Package Type	Surface mount?	12 SiPMs to be mounted on the same FEE board
Peak Sensitivity	460 nm	
PDE	32%	
Gain	3.6x10^5	
DCR	typ=120, max 360	
Temperature coefficient of Vop	34 mV/C	
Direct crosstalk probability	<1%	
Terminal capacity	100 pF	
Packing granularity		
Vop variation within a tray	+/-0.1 V	
Recharge Time		
Fill Factor		
Protective Layer		

Muons in Simulation



Single muon peak in simulations is at 0.01 GeV/tile

This corresponds to:

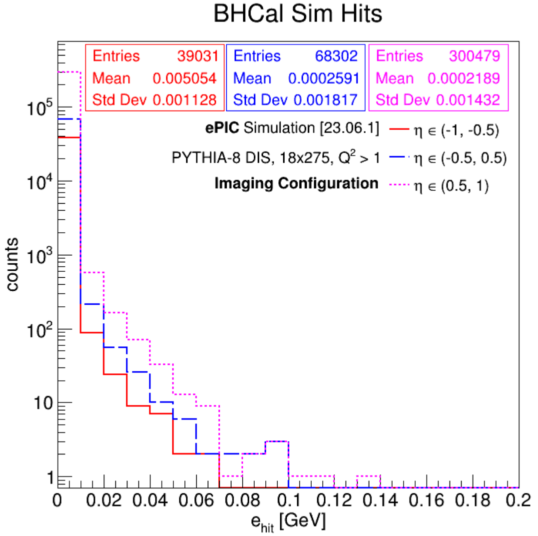
0.01 GeV * 3200 pixels/GeV * (0.32/0.25) = 41 pixels

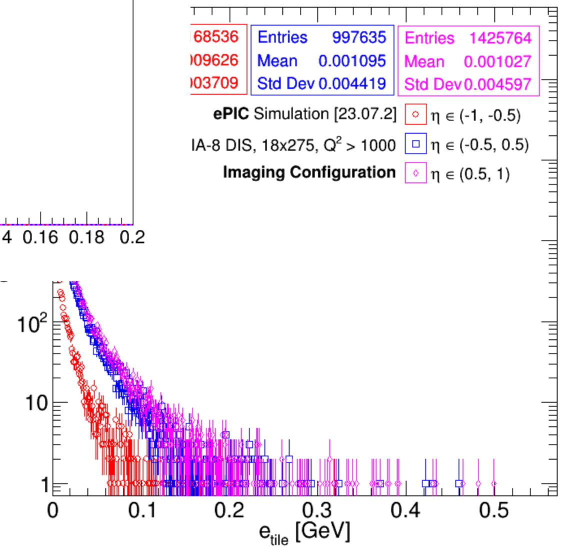
(The conversion comes from sPHENIX test beam results and a correction for the improved photon efficiency of the new SiPM.)

Will need to be careful with noise to make sure the MIP peak is not swamped. With a lower limit of 20 pixels (5MeV per tower) we should still be substantially above the SiPM noise.

(May be able to add additional incoherent noise mitigation by adding scintillators.)

Readout Requirements – Dynamic Range





This is the distribution of energy deposited in the scintillating tiles (*visible* energy) in an ePIC simulation of 18x275 GeV DIS events. The regions are split in rapidity, and the higher overall energy deposition at positive rapidity is visible.

0.5 (1.0) GeV of energy deposited in the tile corresponds to ~2050 (4100) SiPM pixels firing. Single muon requirement sets lower limit at ~20 pixels

ePIC plans to use the Hamamatsu S14160-3015PS SiPM, operated at ~3.6x10^5 gain (about 4V over breakdown, or ~42V). The terminal capacitance of the S14160-3015PS is 530pF at V_{op}. Therefore, the junction capacitance is

$$C_J = \frac{C_T}{N_{pix}} = \frac{530pF}{39984} = 13\text{fF}$$

This gives a single pixel charge output of $Q = C_J \Delta V$ = 13fF x 4V = 52fC

Combined with the dynamic range of fired pixels (20-4100) this means the charge range we would see is 1.0 – 213 pC. Of course, we would want more resolution in the lower range from the HGCROC ADC and then resolution at higher amplitudes from the TOT.

The H2GCROC3 expected range is 1-16pC (ADC), 16-320pC (TOT)

The barrel HCAL will have sufficient dynamic range to cover MIPs up through full energy jets.

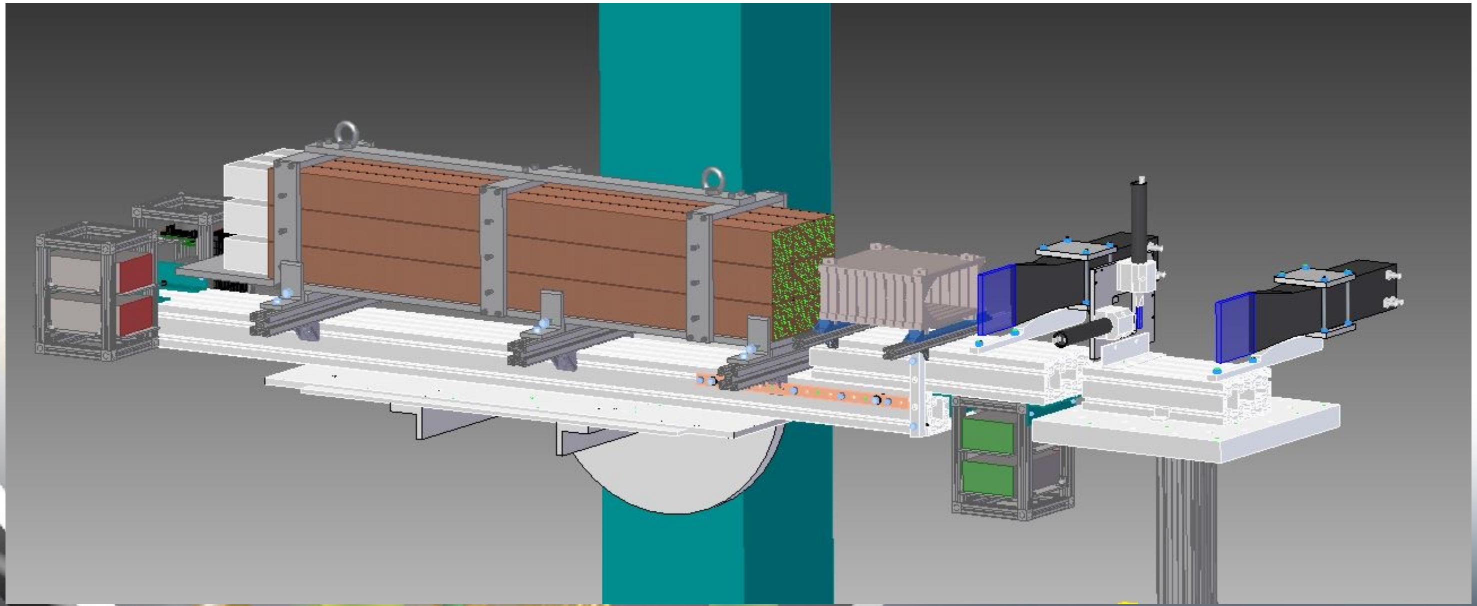
LFHCal in Numbers

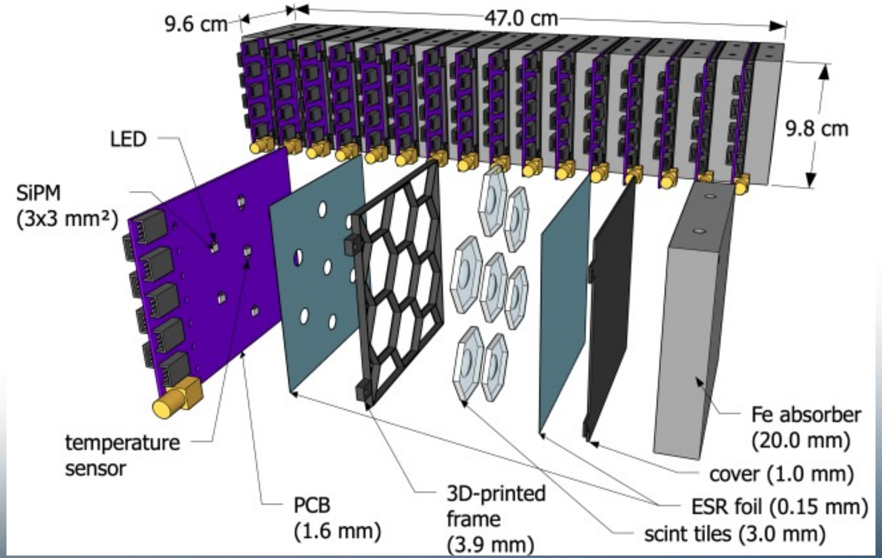
- Acceptance: $1.2 < \eta < 2.8$
- Interaction length: 6.5 λ / λ_0
- Inner modules (R < 1m) equipped with machined scintillator tiles & 3mm SiPMs
- Outer modules equipped with injection molded tiles & 1.3mm SiPMs
- 565,760 SiPMs, 60,928 read-out channels

parameter	**LFHCal**
inner x, y	60 cm
outer radius (envelope)	270 cm
η acceptance	$1.2 < \eta < 3.5$
tower information	
x, y	5 cm
z (active depth)	130 cm
z read-out	10 cm
# scintillator plates	65 (0.4 cm each)
# absorber sheets	61 (1.52 cm steel)
	4 (1.52 cm tungsten)
interaction lengths	6.5 λ/λ_0
Sampling fraction f	0.035
# towers	8704
# modules	
8M	1050
4M	76
# read-out channels	7 x 8704 = 60,928

Next test beam plans for LFHCal & insert

- LFHCal:
  - Sept 23' CERN-SPS: Tile testing w/o absorber structure to measure light yield of machined tiles
  - Oct 23' CERN-PS: Mini-8M-module test for conceptual test of individual components and first shower profile measurements
- Insert:
  - Oct 23': SiPM radiation tests
  - Spring 24' Jlab: Validation of refined construction methods for insert





Long Lead Procurement specifications

- SiPM models defined for all three HCal subsystems & quotes are actual
- Quotes for LFHCAL steel and tungsten are available and match the design drawings

LEADING EDGE METALS & ALLOYS INC

Leading Edge Metals and Alloys, Inc.
22916 Lockness Ave.
Torrance, CA 90501
Phone: (877) 455-5362 Fax: (310) 225-4604
Website: www.leadingedgemetals.com

June 02, 2023
6:31:19PM
Page 1 of 3

Quotation No. 12563

To
OAK RIDGE NATIONAL LABORATORY
1 BETHEL VALLEY ROAD
OAK RIDGE, TN 37830

Ship To
OAK RIDGE NATIONAL LABORATORY
1 BETHEL VALLEY ROAD
OAK RIDGE, TN 37830
Phone: 8655760308

ATTN: Friederike