Oak Ridge National Laboratory

June 22nd, 2026

LFHCAL CERN Beams Summary

Emily Pottebaum, Friederike Bock, Oskar Hartbrich

U.S. DEPARTMENT of ENERGY

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Preamble

- LFHCAL has concluded its planned beam test program.

- Large parts of this presentation are based on Emily Pottebaum's (Yale) excellent LFHCAL overview plenary talk at CALOR'26

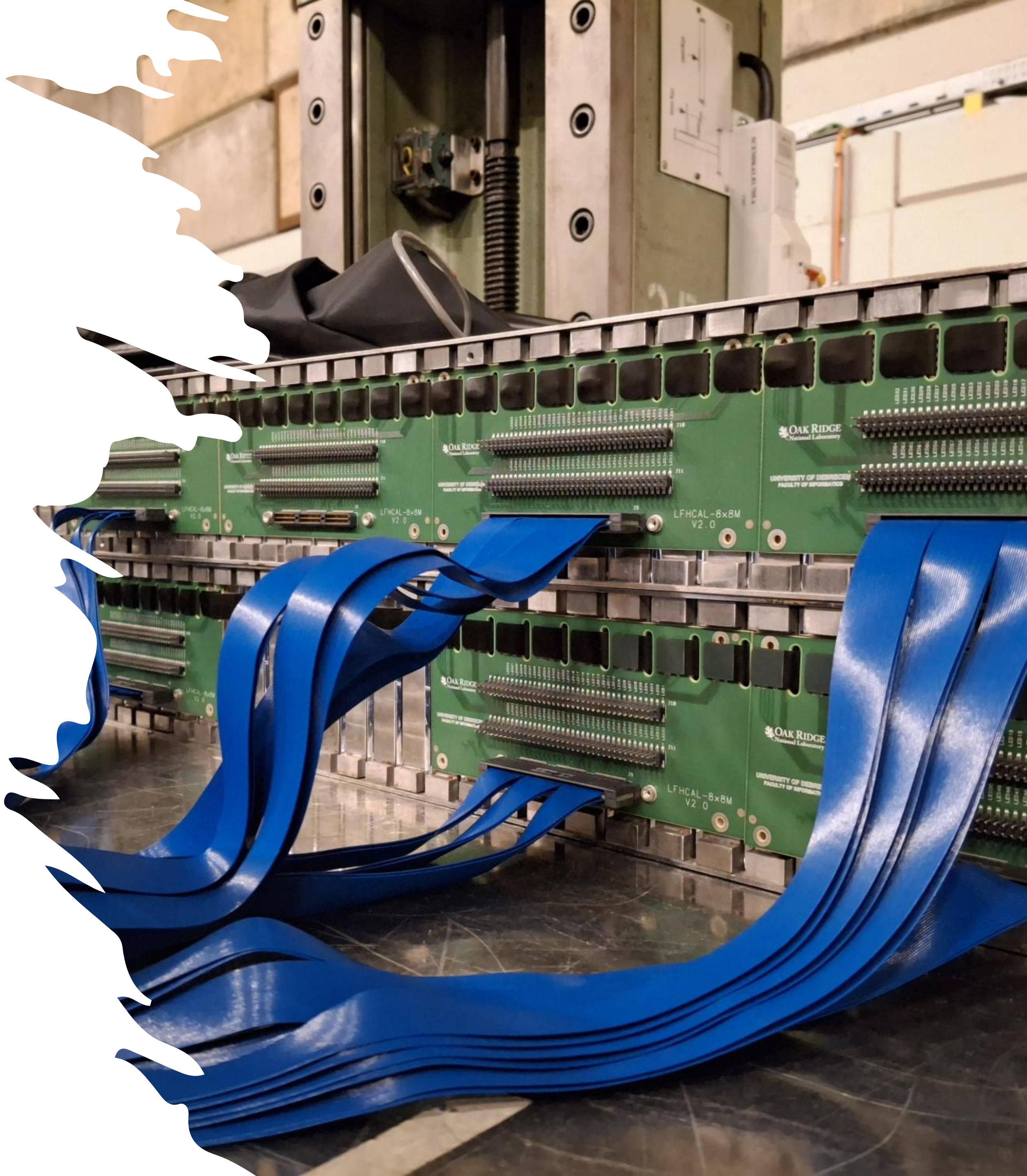
1) The EIC & ePIC

2) The LFHCal

→ QA/QC

→ Test Beams

3) Outlook



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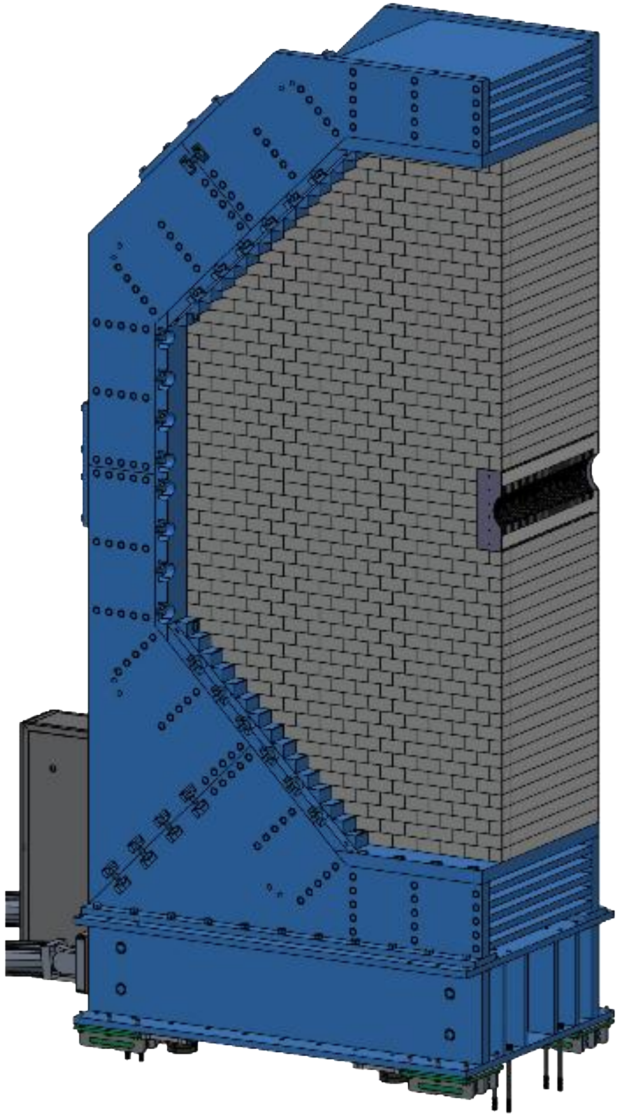
The Longitudinally-segmented Forward HCal

Motivation

- Jet reconstruction (particle flow) at high rapidity where tracking performance falls off
- Study hadronization processes within jets
    - Be able to resolve jet constituents
- Shower containment for high energy particles in dense hadronic environment



Detector subsystem leader:
Friederike Bock, ORNL

Participating institutes:

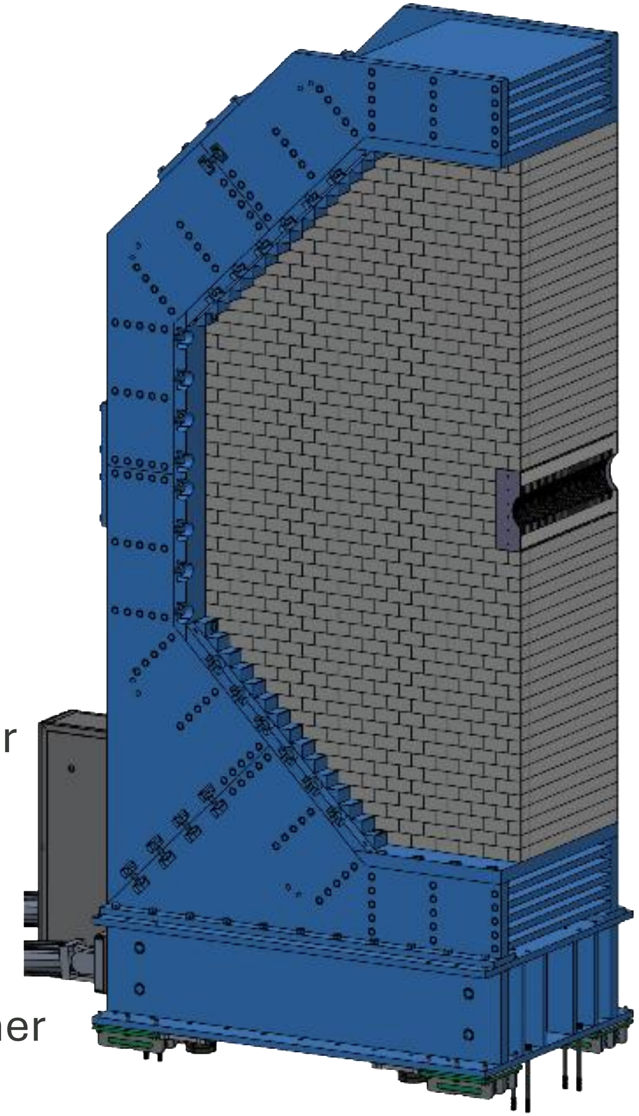
The Longitudinally-segmented Forward HCal

Motivation

- Jet reconstruction (particle flow) at high rapidity where tracking performance falls off
- Study hadronization processes within jets
    - Be able to resolve jet constituents
- Shower containment for high energy particles in dense hadronic environment

Requirements

- Excellent **energy resolution** for hadrons and jets $\sigma(E)/E \sim 50\%/\sqrt{E} \oplus 10\%$ combined with ECal
- Adequate **transverse granularity** that accounts for local particle abundance
  ~ 5x5 cm^2 for $\eta < 2.5$ & 3x3 cm^2 for $2.5 < \eta < 4$
- Sufficient **longitudinal granularity** to identify showers starting at different depths
  → increased segmentation for higher η due to higher particle density



Detector subsystem leader:
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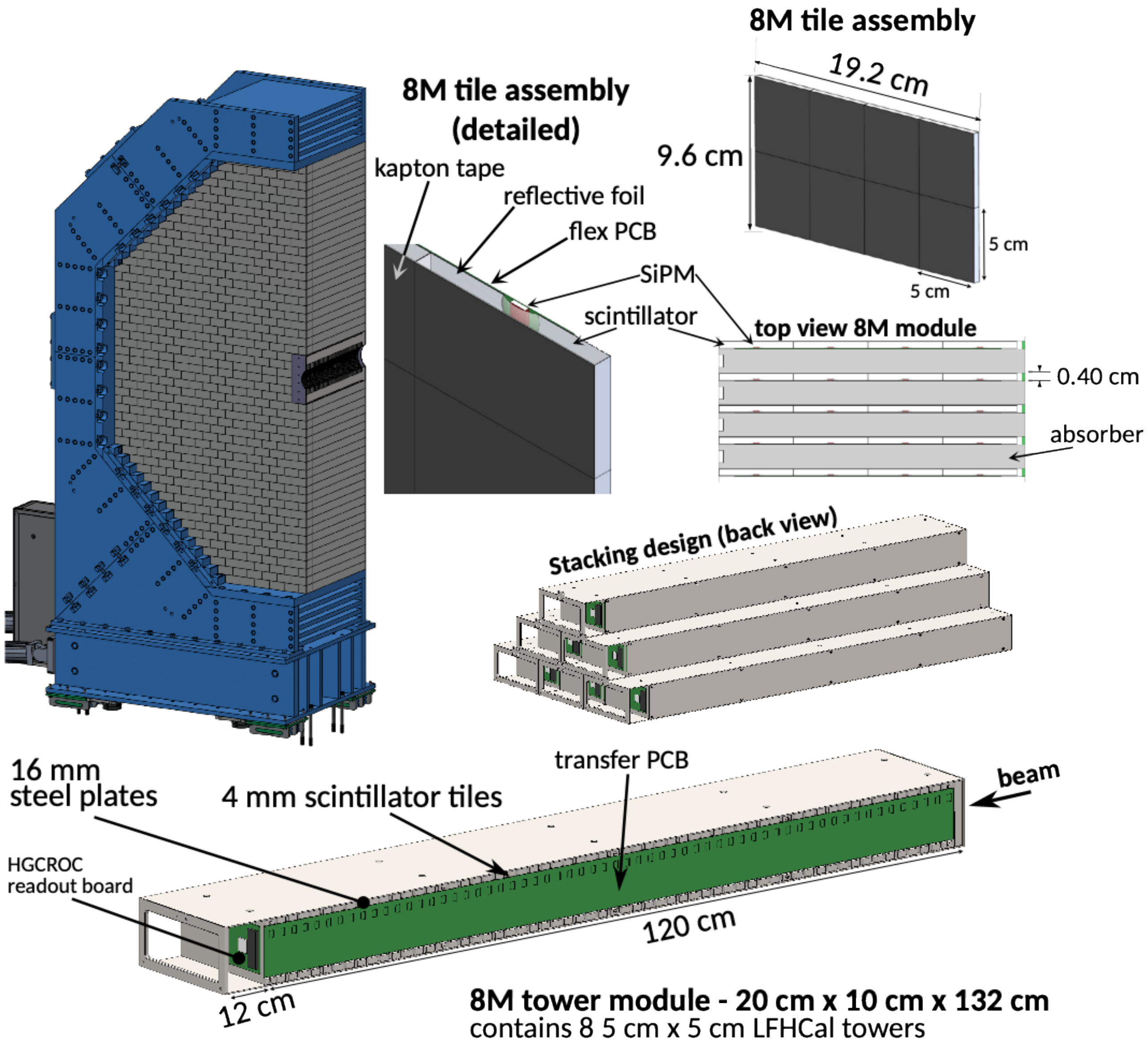
The Longitudinally-segmented Forward HCal

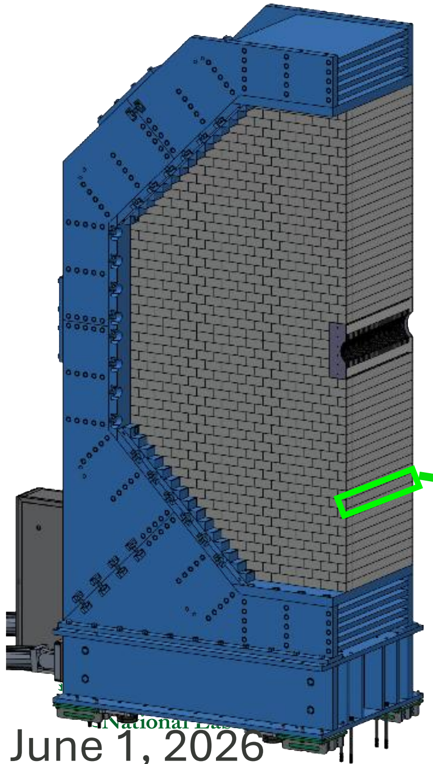
Design

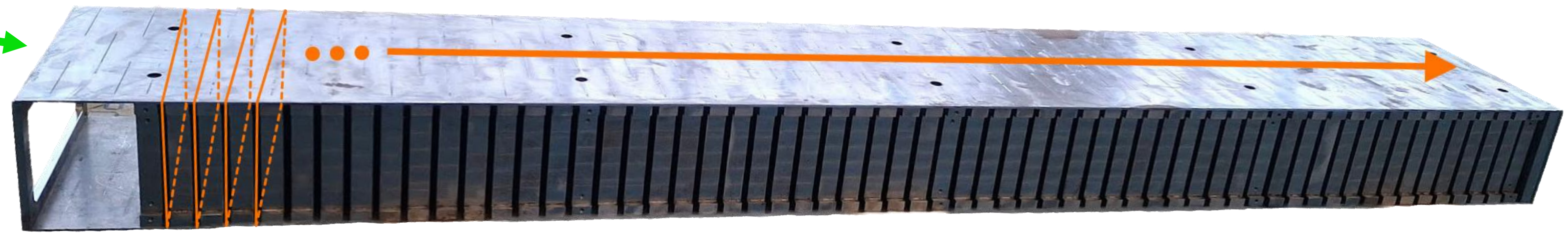
- Longitudinally alternating steel + scintillator SiPM-on-tile design inspired by CALICE AHCal
- Two main parts:
  - High granularity **insert** ($3.5 < \eta < 4.4$) built from two halves surrounding beam pipe
  - LFHCal ($1.2 < \eta < 3.5$) built mostly from “**8M**” modules (+ 4M modules to fill in gaps)
- CALOROC readout, modified version of H2GCROC ASIC developed for CMS HGCAL
  - Streaming (self-triggered) readout
  - Potential dual-ADC readout instead of ADC+TOT



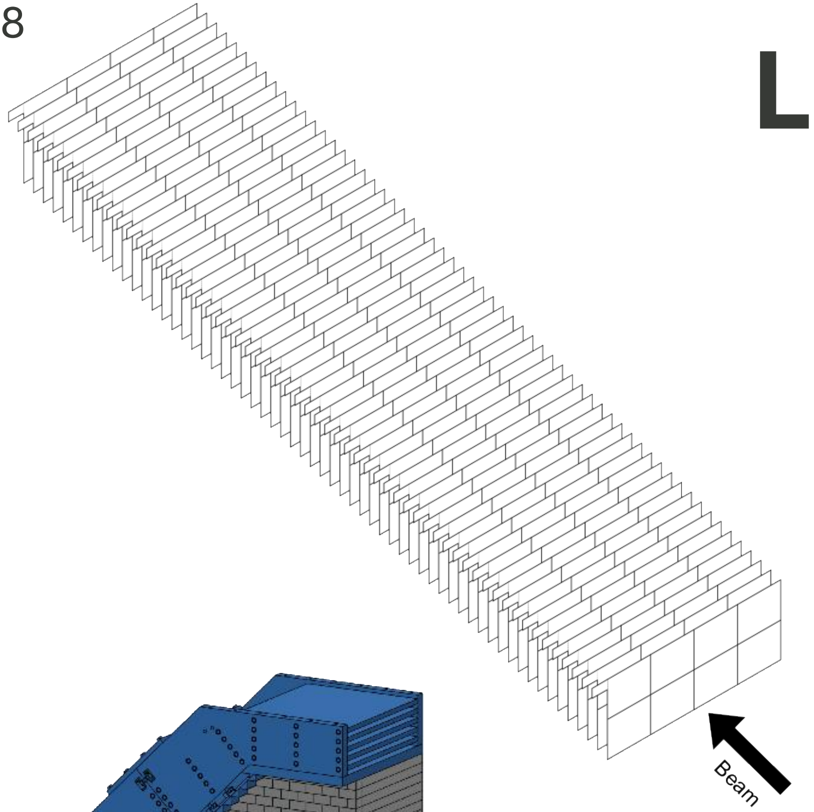
LFHCal 8M Modules

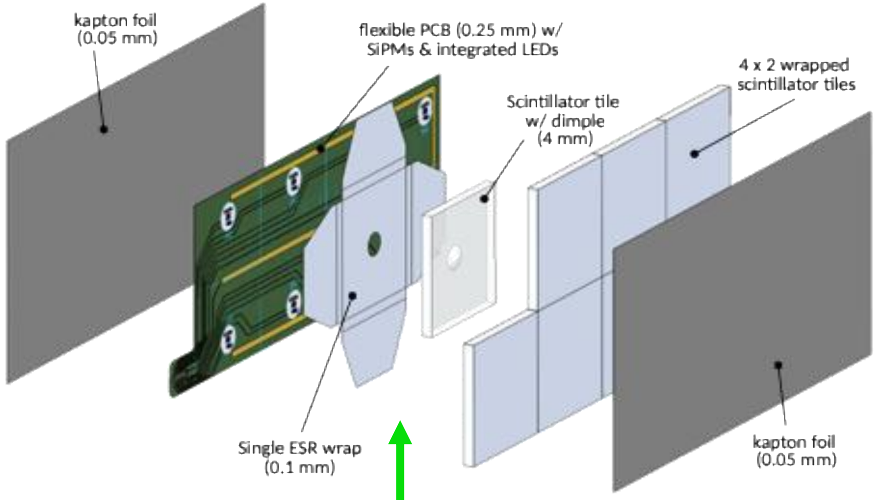
- 10x20x132 cm^3 electron-beam welded steel absorber structure



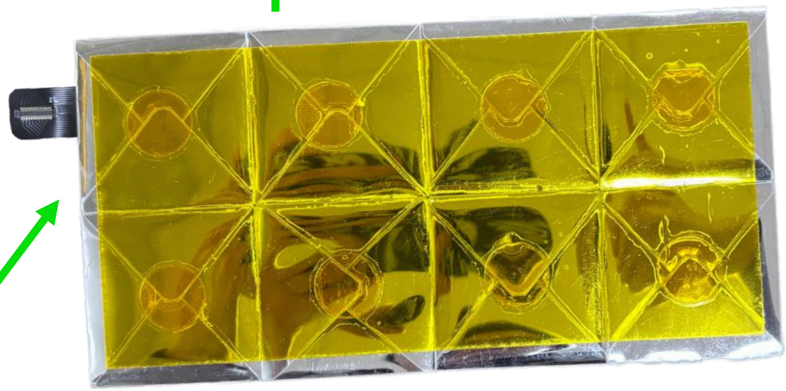


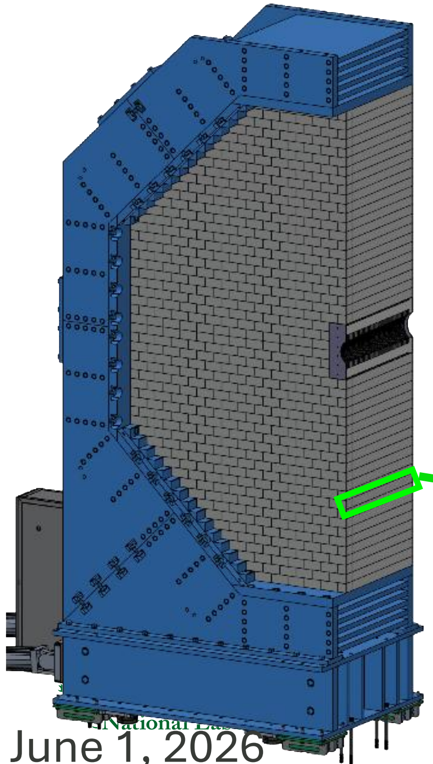
LFHCal 8M Modules

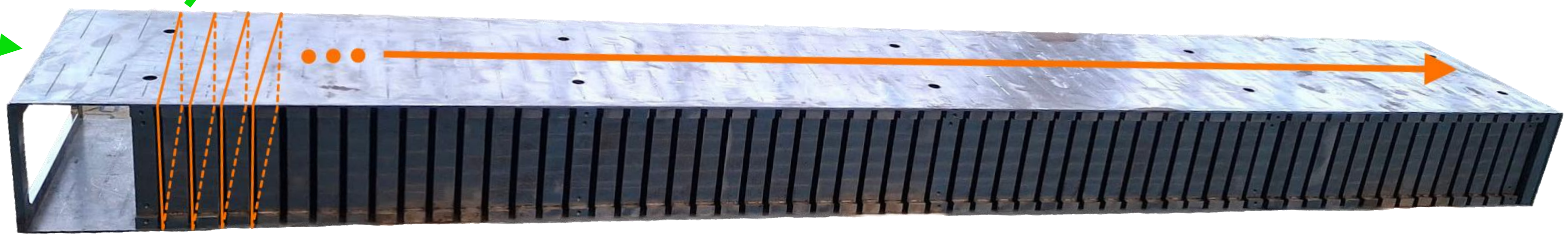




- $10 \times 20 \times 132\ cm^3$ electron-beam welded steel absorber structure
- Interleaved with 60 layers of 4x2 scintillator tile assemblies
  - Inner modules (R<1m) equipped with machined tiles (~83k), outer modules equipped with injection molded tiles (~480k)







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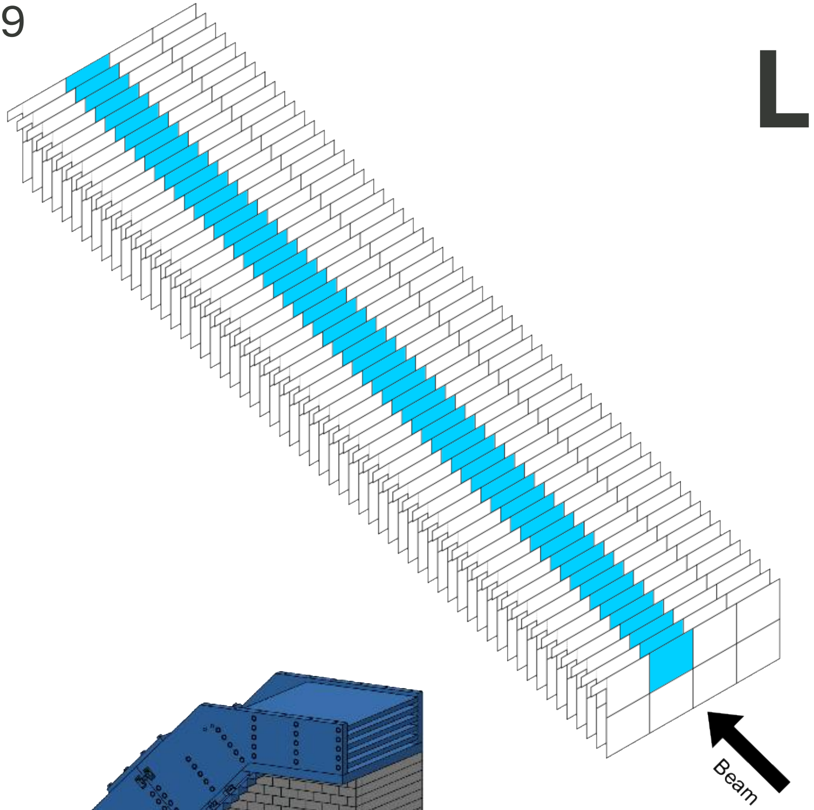

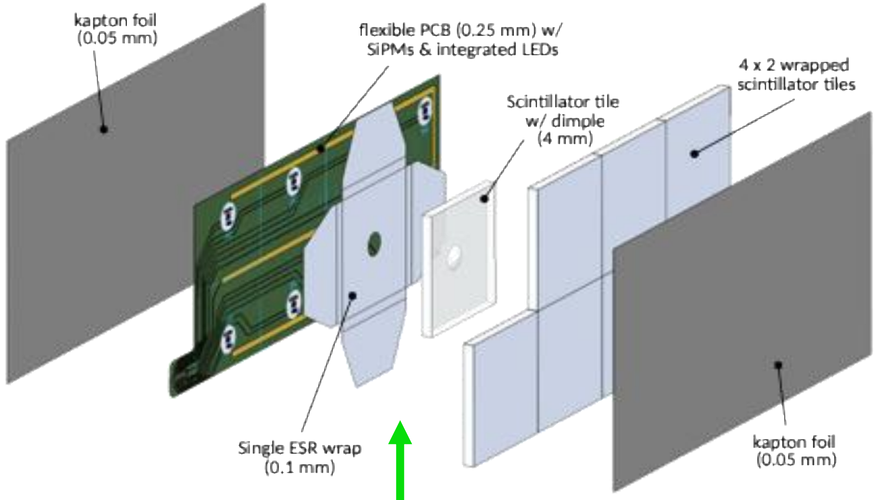

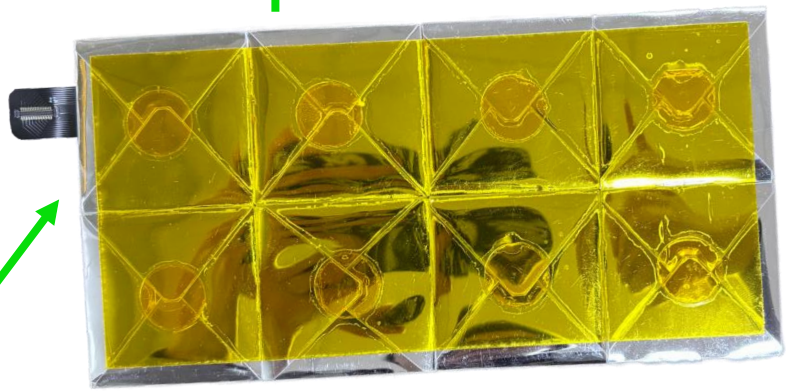

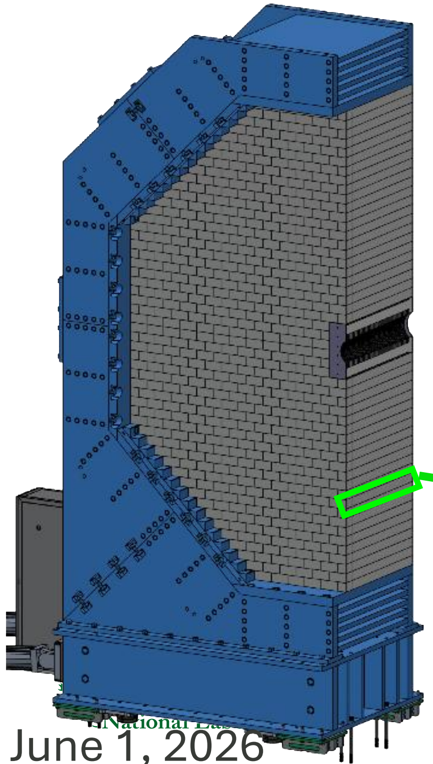

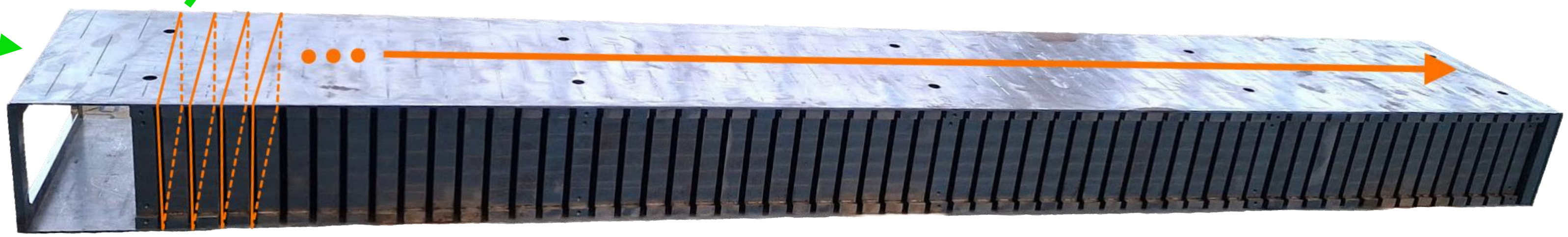

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- Interleaved with 60 layers of 4x2 scintillator tile assemblies
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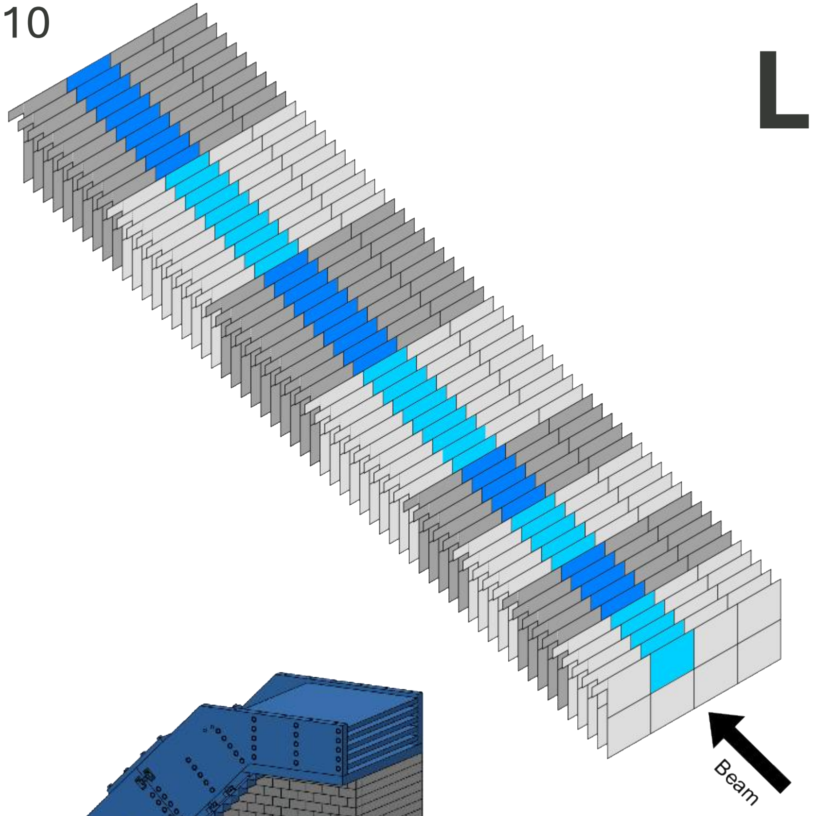
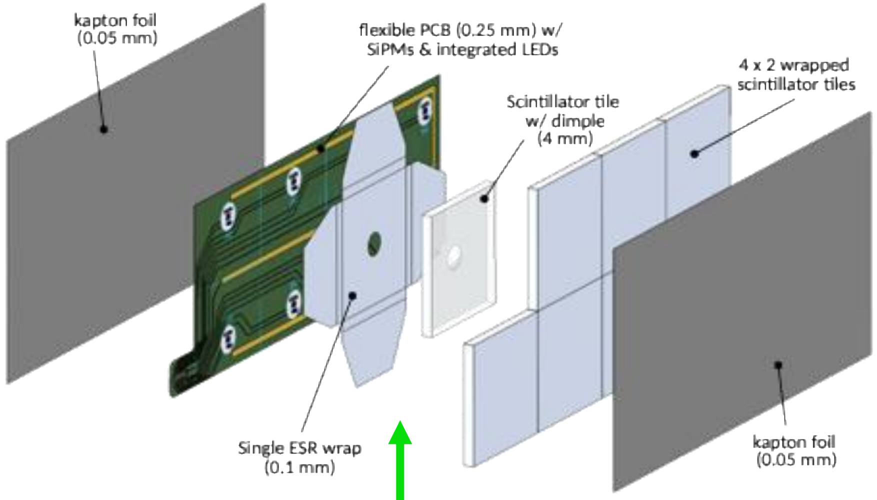
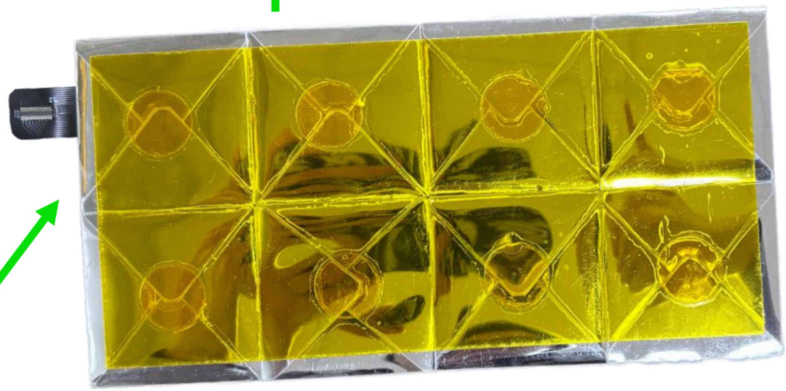
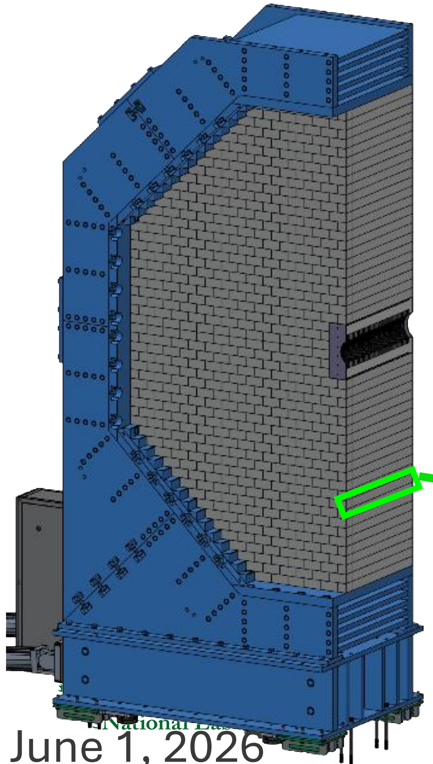
- 8 towers/module, tower transverse size 5x5 cm^2

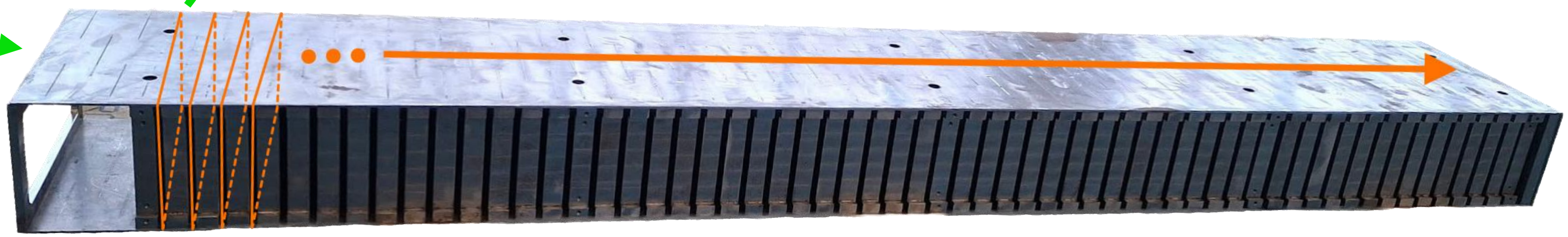
LFHCal 8M Modules











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  - Inner modules (R<1m) equipped with machined tiles (~83k), outer modules equipped with injection molded tiles (~480k)
- 8 towers/module, tower transverse size 5x5 cm^2
- Multiple longitudinally consecutive tiles summed to 8 segments/tower (8 readout channels/segment)

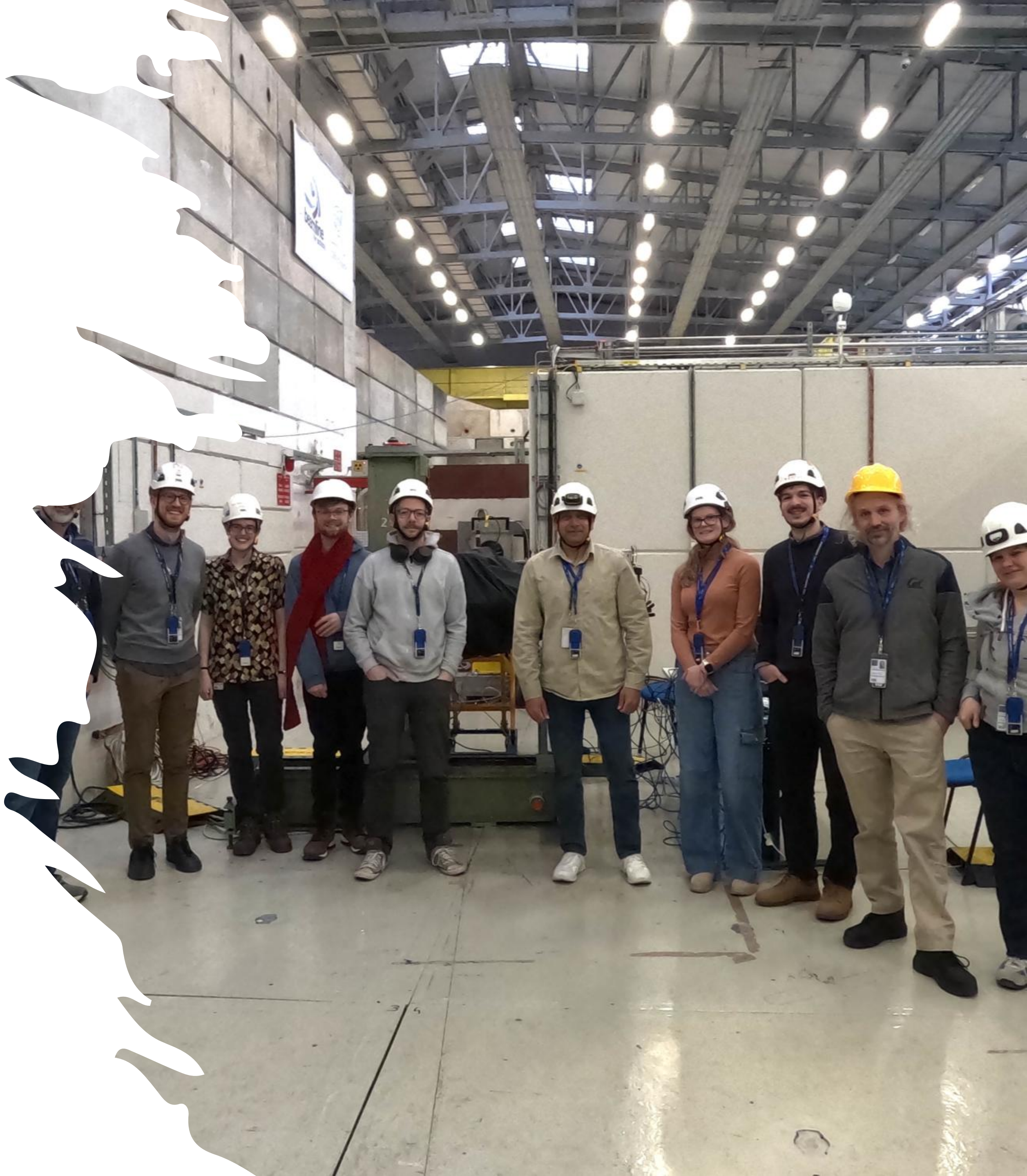
The EIC & ePIC

The LFHCal

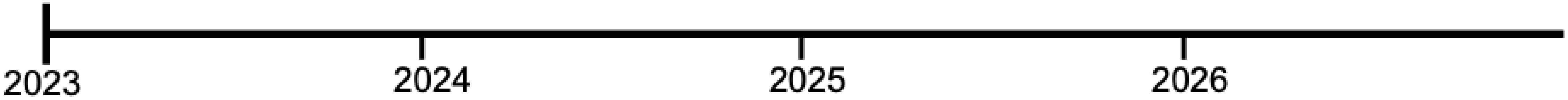
→ QA/QC

→ Test Beams

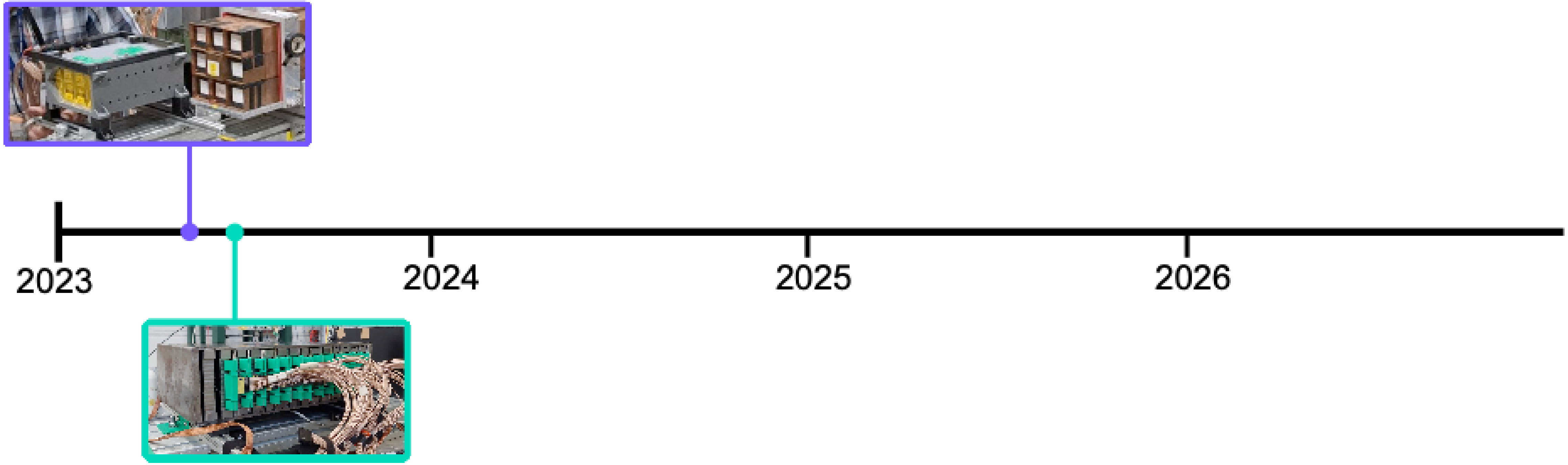
Outlook



Test beam campaigns



Location: CERN SPS H4
Setup: 8 scint. layers, no absorber layers
Readout: CAEN DT5202
Goal: SiPM & tile characterization



Location: CERN PS T09
Setup: 4 layers W,
10 steel + scint.
Readout: CAEN DT5202
Goal: Shower profile, absorber studies

Location: CERN SPS H4
Setup: 8 scint. layers, no absorber layers
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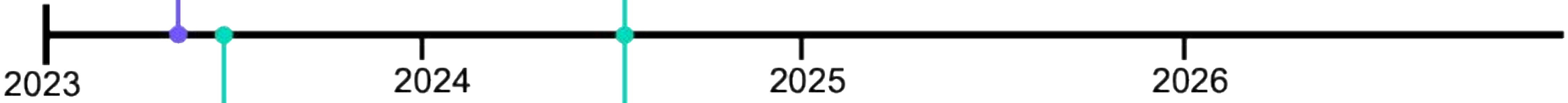
Location: CERN PS T09
Setup: Single 8M module (original 1.4m design)
Readout 1: CAEN DT5202



Location: CERN PS T09
Setup: 4 layers W, 10 steel + scint.
Readout: CAEN DT5202
Goal: Shower profile, absorber studies

(cont.)
Readout 2: H2GCROC
Goal: Test full module, hadron & electron E res, understand H2GCROC

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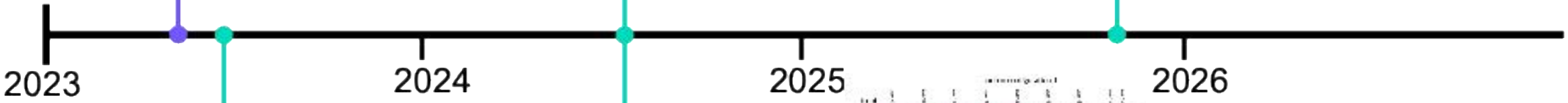

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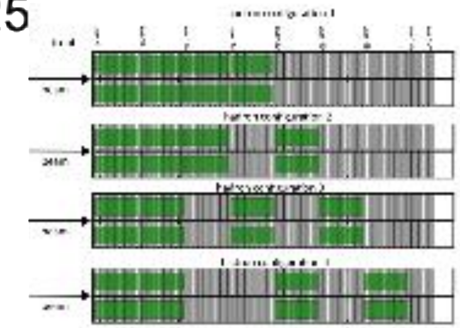
Location: CERN PS T09
Setup: 2 stacked 8M modules (current 1.32m design)



(cont.)
Readout: H2GCROC
Goal: Longitudinal shower development, electron E res

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Setup: 8 scint. layers, no absorber layers
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2023

2024

Location: CERN PS T09
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(cont.)
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2025

Location: CERN PS T09
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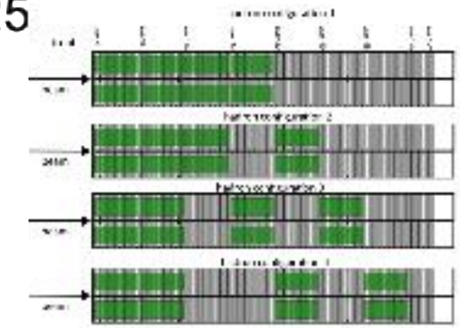

(cont.)
Readout: H2GCROC
Goal: Longitudinal shower development, electron E res

2026

Location: CERN PS T10
Setup: 2 stacked 8Ms, 60 layers each, summing PCBs
Readout: H2GCROC
Goal: PCB validation, shower dev

Location: CERN SPS H2
Setup: 3x2 stacked 60-layer 8Ms, summing PCBs
Readout: H2GCROC
Goal: Assess leakage, resolution studies

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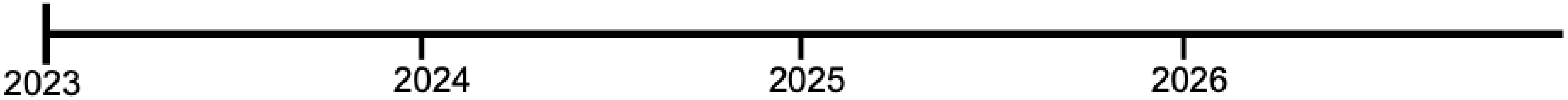
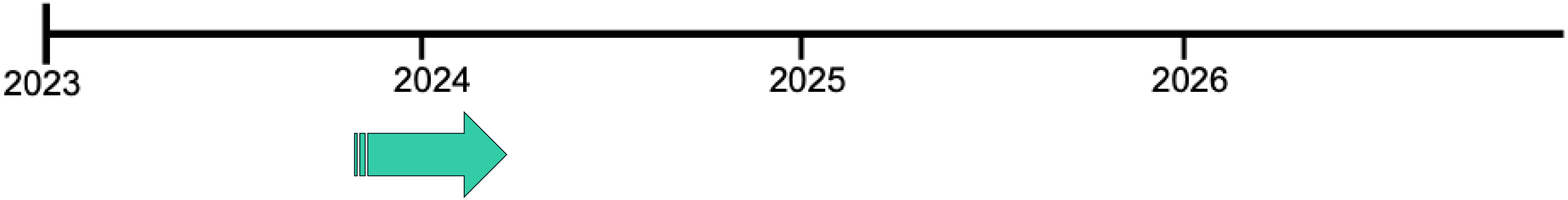
Informing design one test beam at a time

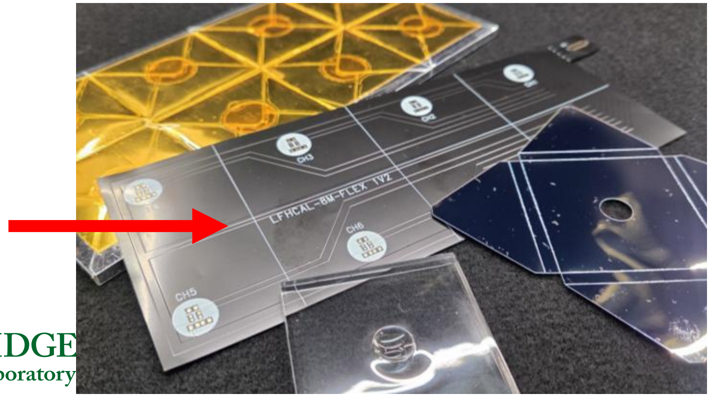


Informing design one test beam at a time

- ✓ Wrapping effective to prevent light leakage
- ✓ Negligible cross-talk



Flex board design optimization



Informing design one test beam at a time

- ✓ Wrapping effective to prevent light leakage
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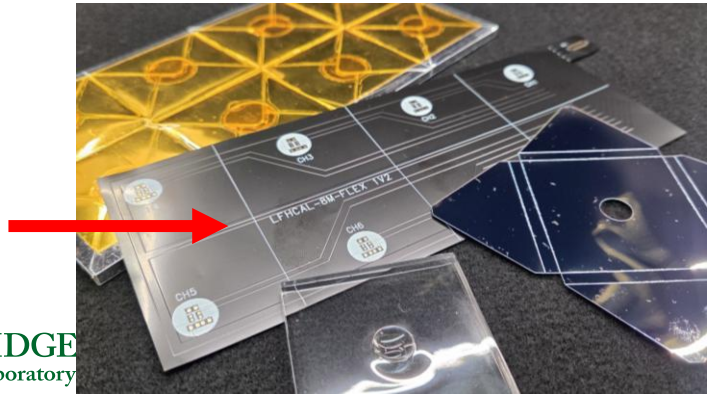
- ✓ First test of fully populated module
- ✓ H2GCROC readout validation

2023 2024 2025 2026

Flex board design optimization



Firmware upgrades:
- Improved chip synchronization
- New UDP data format

Informing design one test beam at a time

- ✓ Wrapping effective to prevent light leakage
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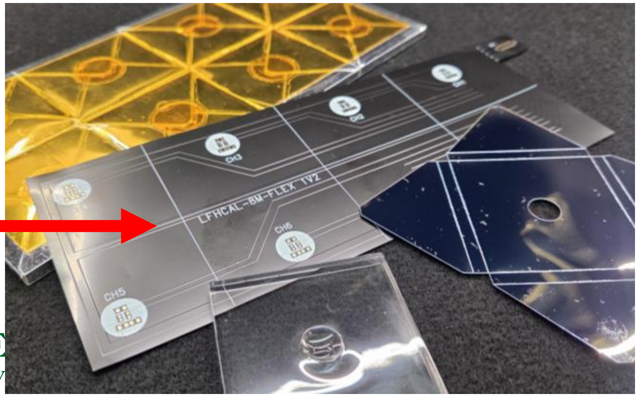
- ✓ First test of fully populated module
- ✓ H2GCROC readout validation

- ✓ Test of E-beam welded structure
- ✓ Two-module setup

2023 2024 2025 2026

Flex board design optimization



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- New UDP data format

Flex cable connector (between transfer & readout board) design optimization

Informing design one test beam at a time

- ✓ Wrapping effective to prevent light leakage
- ✓ Negligible cross-talk

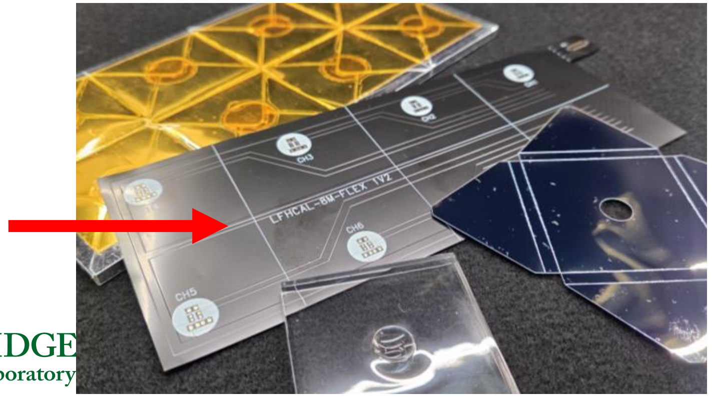
- ✓ First test of fully populated module
- ✓ H2GCROC readout validation

- ✓ Test of E-beam welded structure
- ✓ Two-module setup

- ✓ Summing board validation
- ✓ Long signal transfer board validation
- ✓ Six-module setup
- ✓ Close to final design

2023 — 2024 — 2025 — 2026

Flex board design optimization



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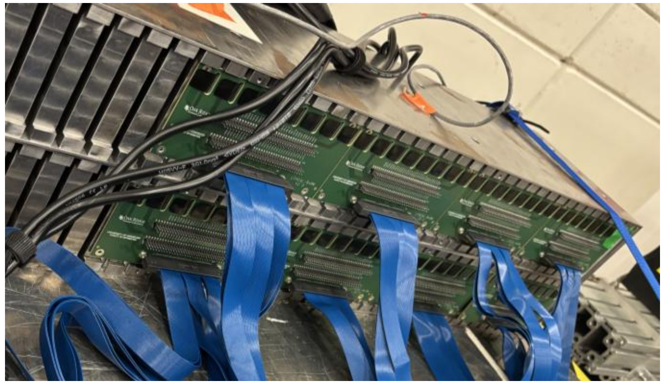
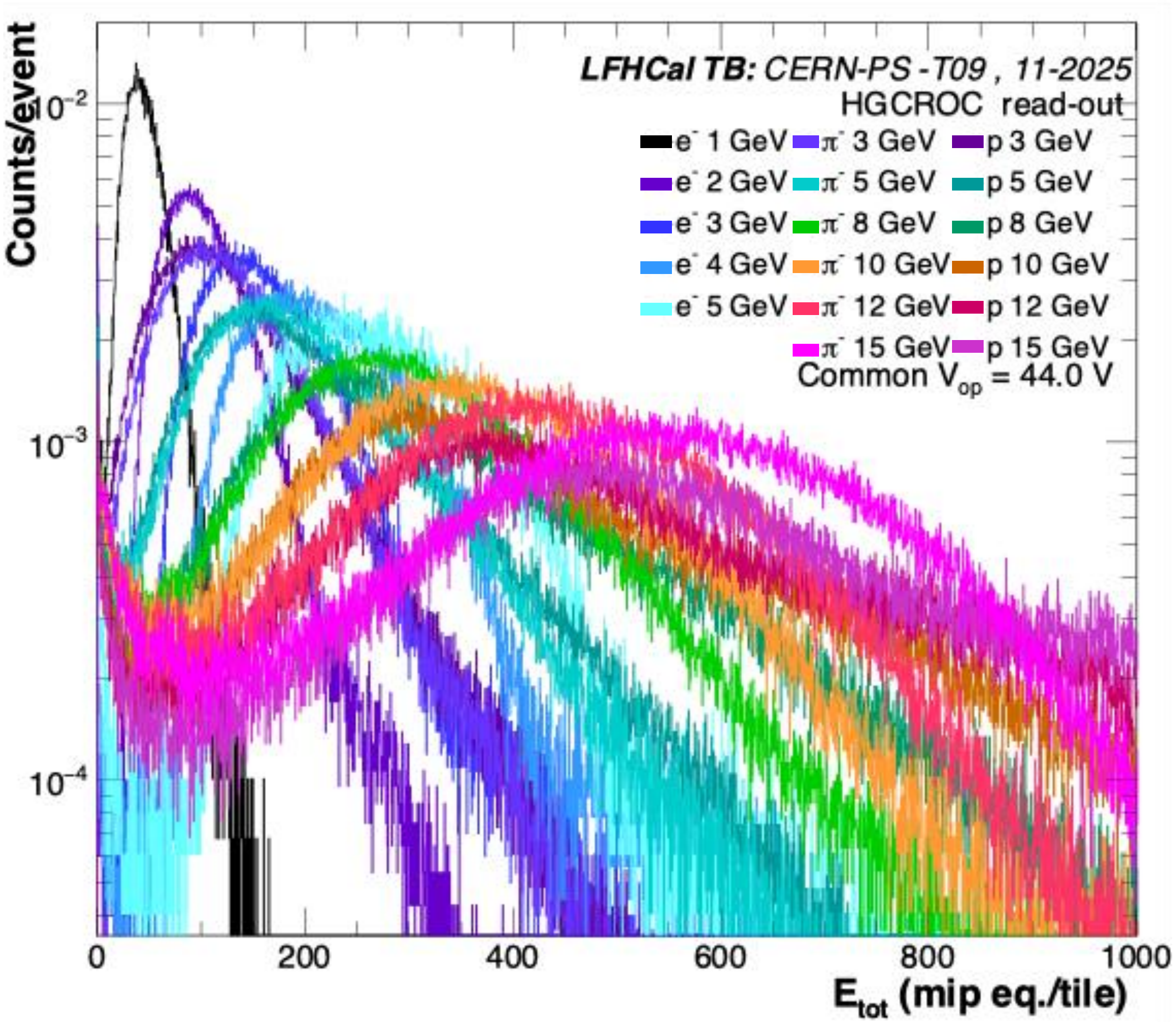
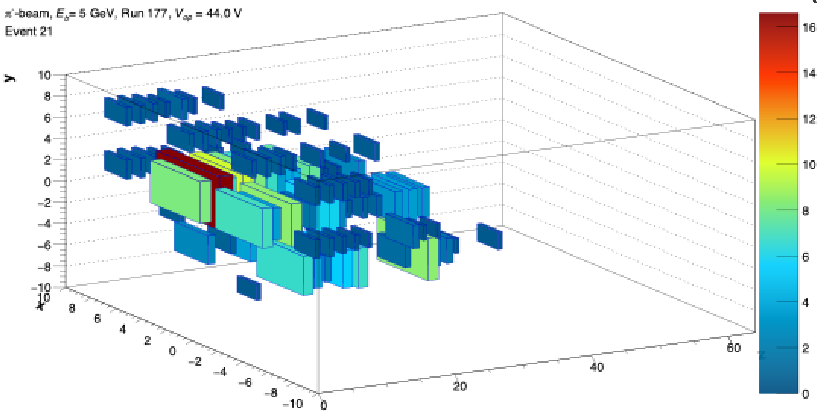
Test beam campaigns: Initial 2025 results



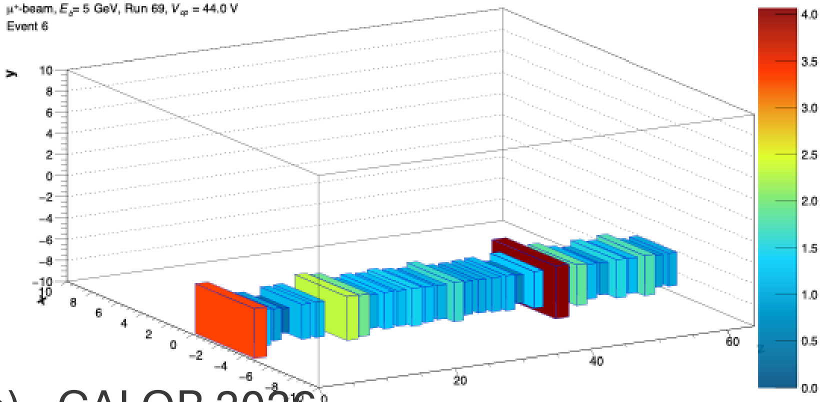
Goals:
- Electron/positron energy resolution
- Longitudinal hadronic shower profile



E (mip eq/tile)



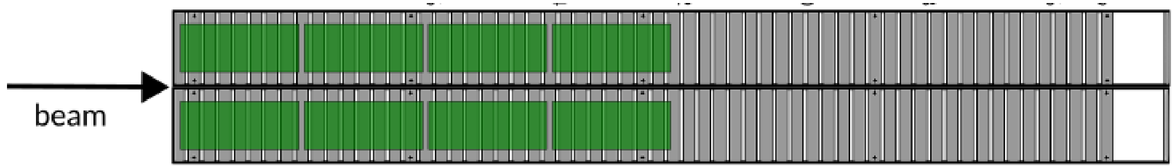
π- beam 5 GeV

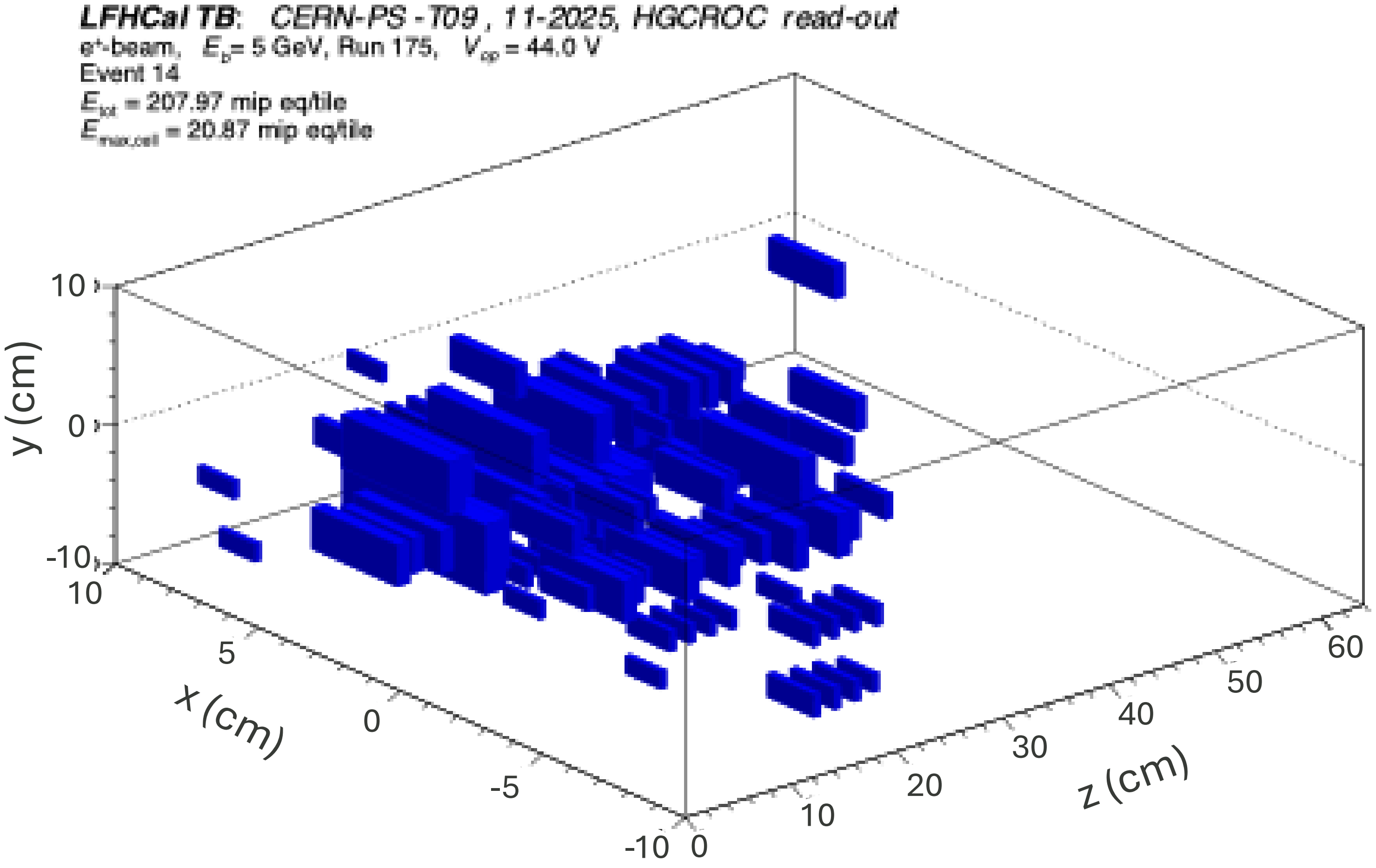


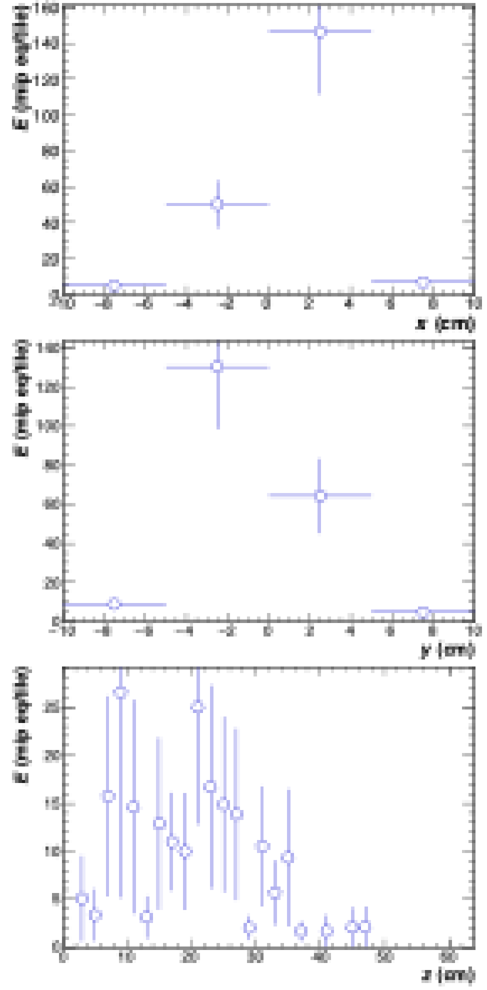
μ+ beam 5 GeV

Test beam campaigns: Initial 2025 results

Goal: electron energy resolution



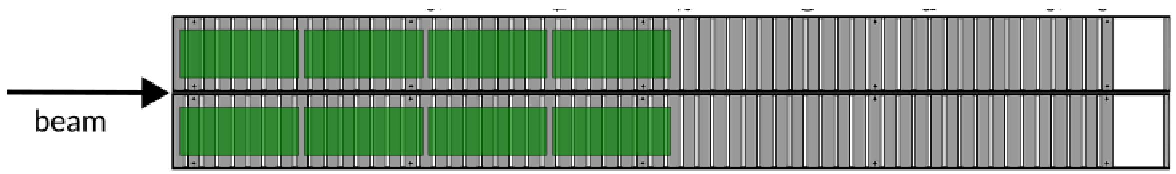


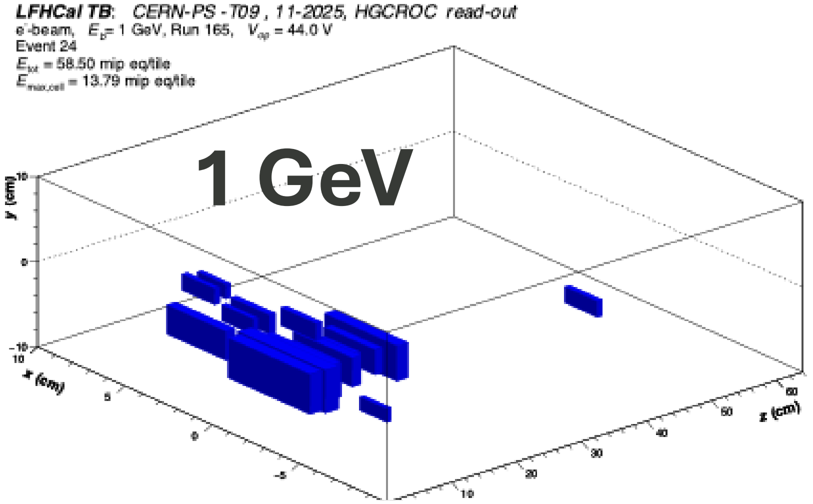


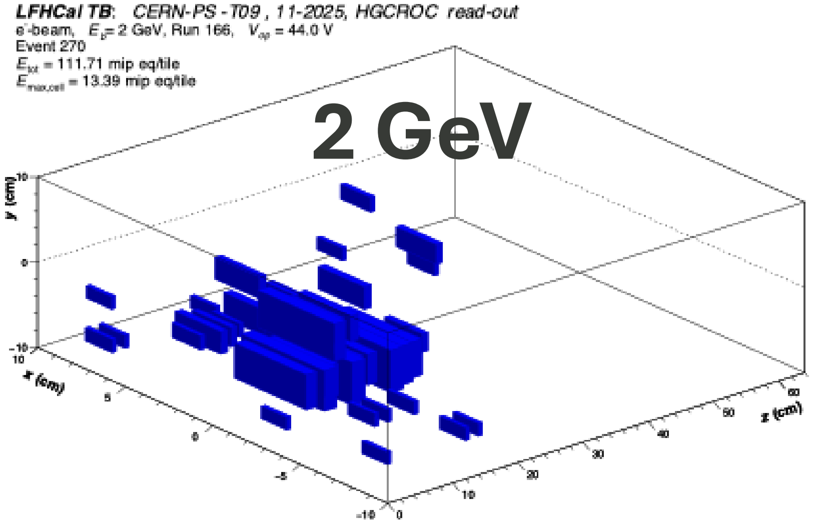
e+ beam
5 GeV

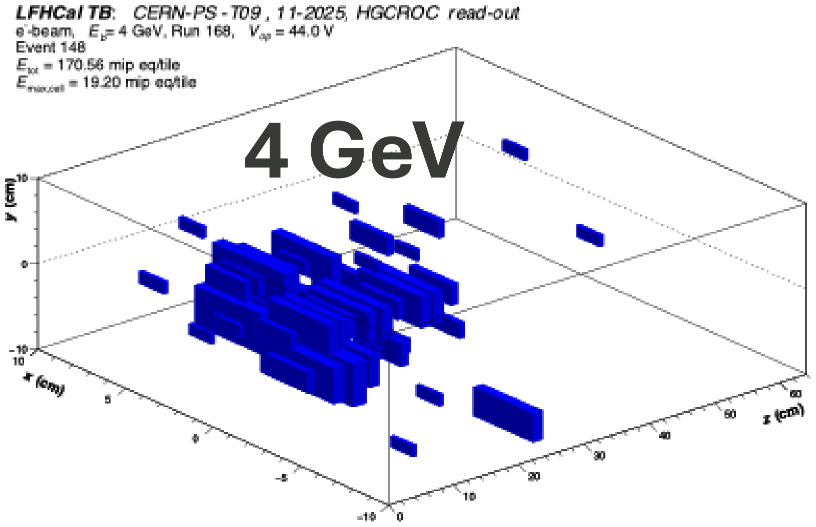
Test beam campaigns: Initial 2025 results

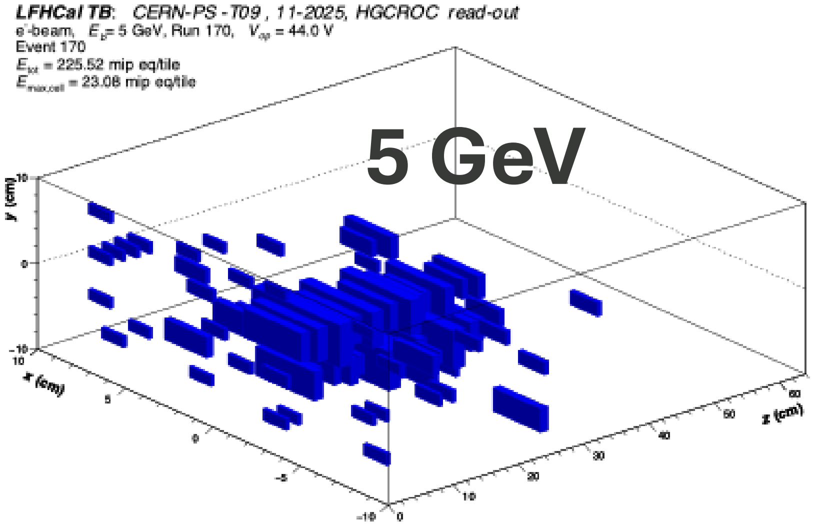
Goal: electron energy resolution





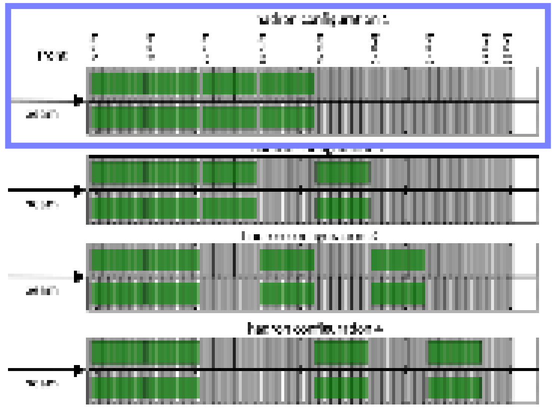






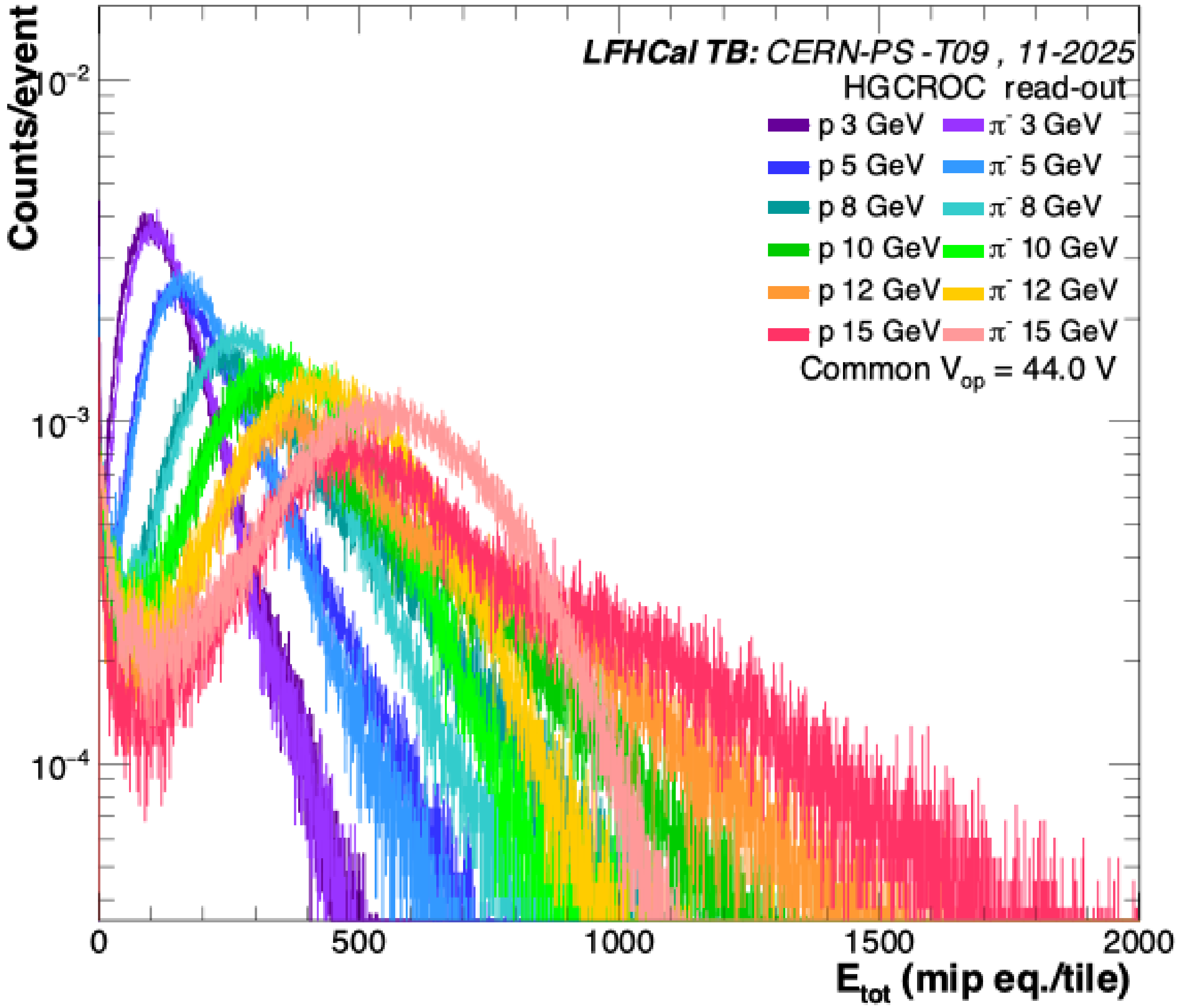
e- beams

Test beam campaigns: Initial 2025 results

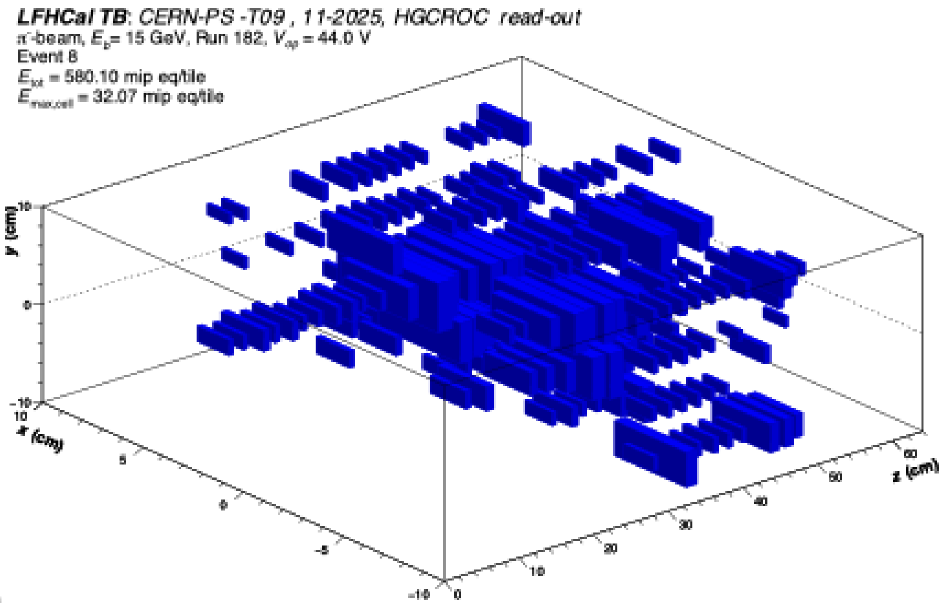


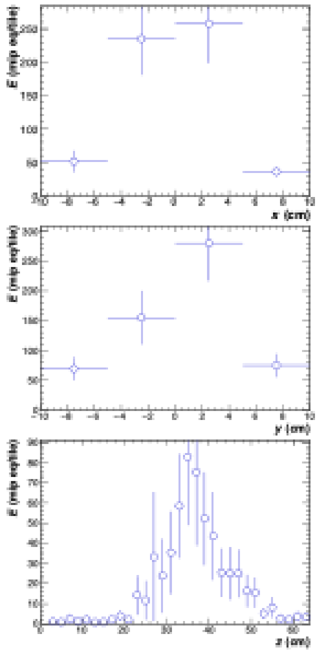
data on this slide taken in configuration 1

Goal: longitudinal hadronic shower profile dev.



15 GeV π- beam

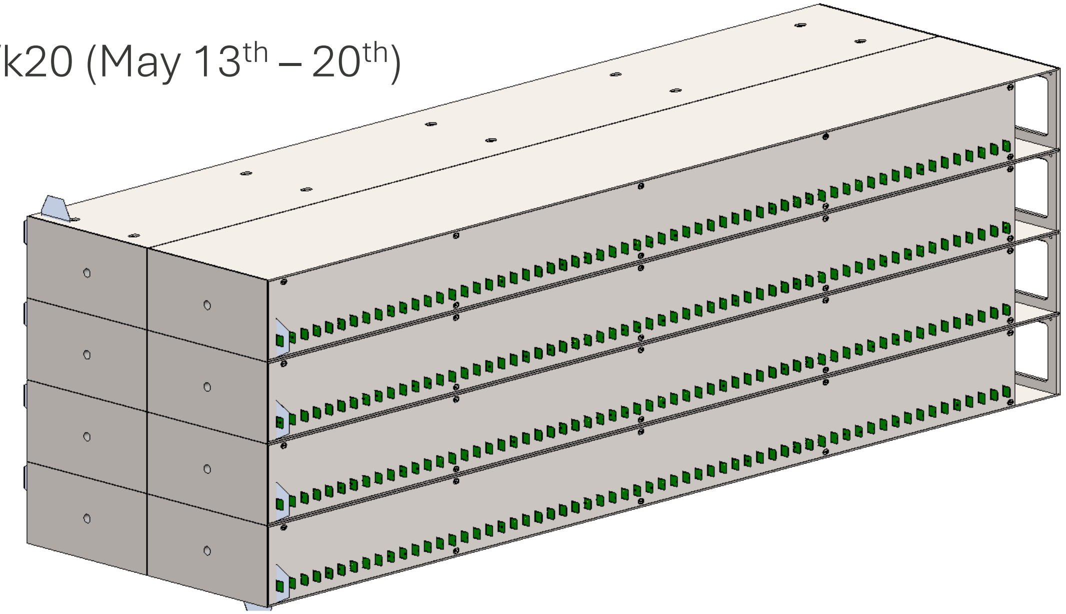


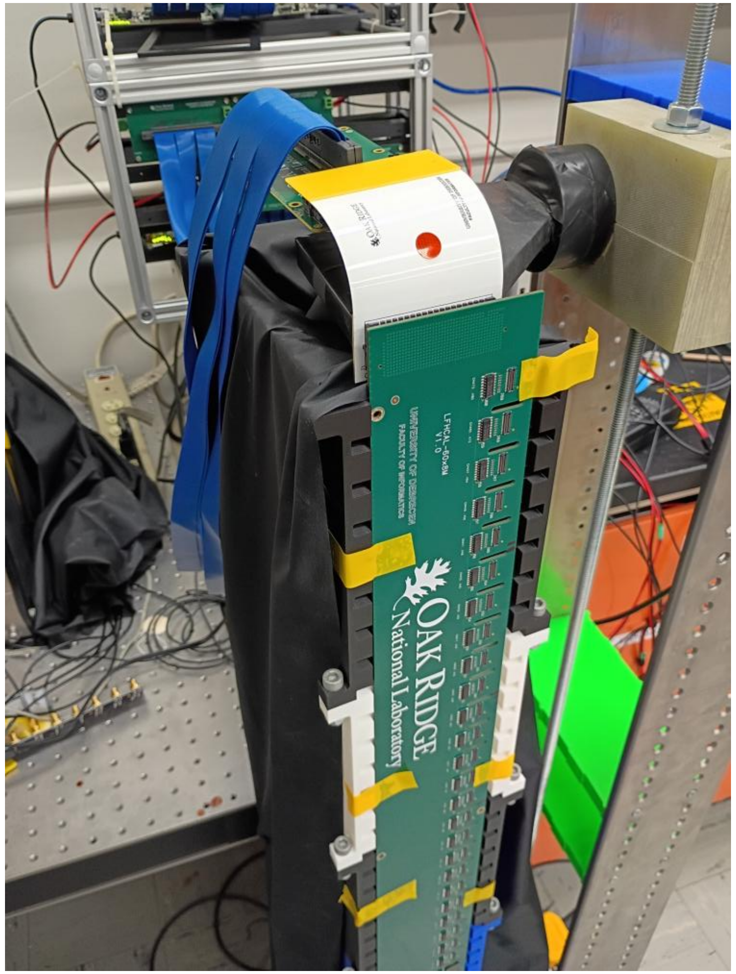


LFHCAL 2026 CERN Beams

- "final" mechanics, "final" electronics up to readout ASIC
  - Final scintillator layers + flex PCBs
  - Final long PCB design

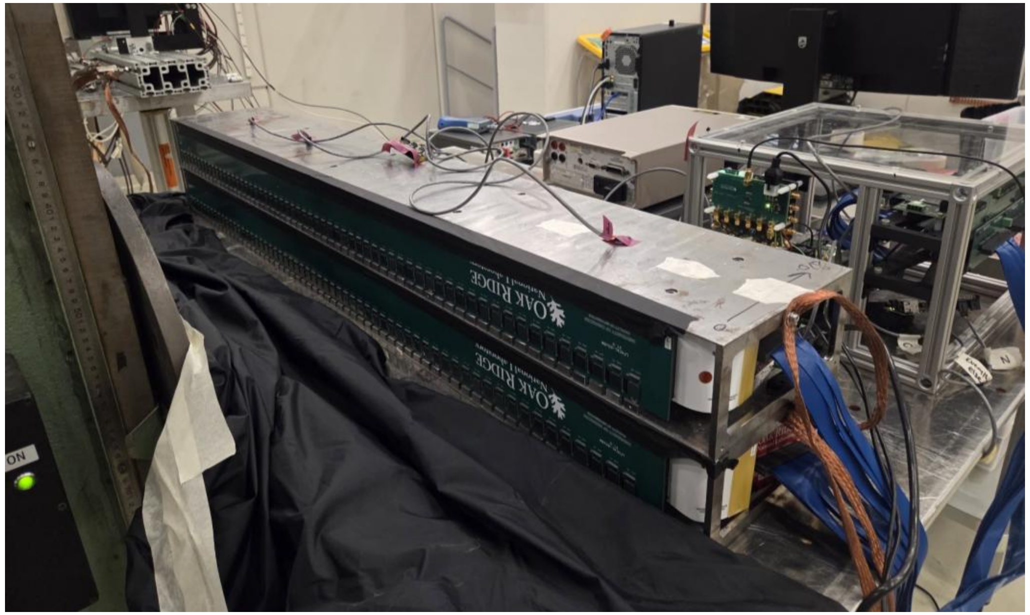
- 1 week of CERN PS: Wk15 (April 8th – 15th)
- 1 week of CERN SPS: Wk20 (May 13th – 20th)





LFHCAL @ PS April 2026

- Additional long PCBs did not arrive in time
  -> only two full modules
    - Still largely contains up to 10GeV showers
- Hadron beams 1-10GeV
    - Different summing configurations
    - Different preamplifier tunings
- Lots of muon calibration runs
- 70M triggers total



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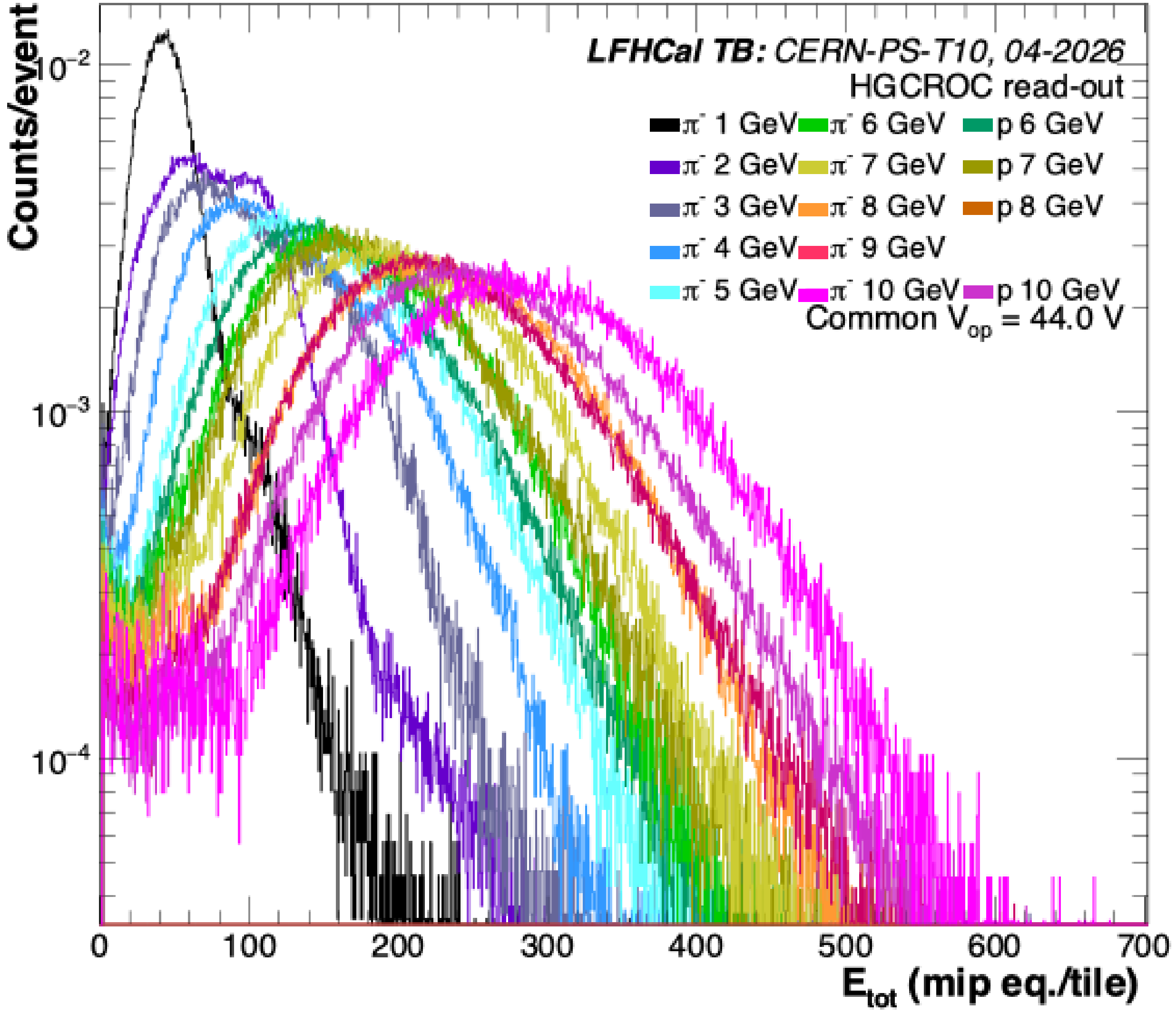
LFHCAL @ SPS May 2026

- Six long PCBs available in total -> 2x3 module stack
- Hadron/electron beams 20-350GeV
  - Both summing configurations
  - Different preamplifier tunings
- Lots of muon calibration runs
- ~100M triggers total
- Overall the 2026 CERN campaigns were very successful
  - Met all data dating goals.

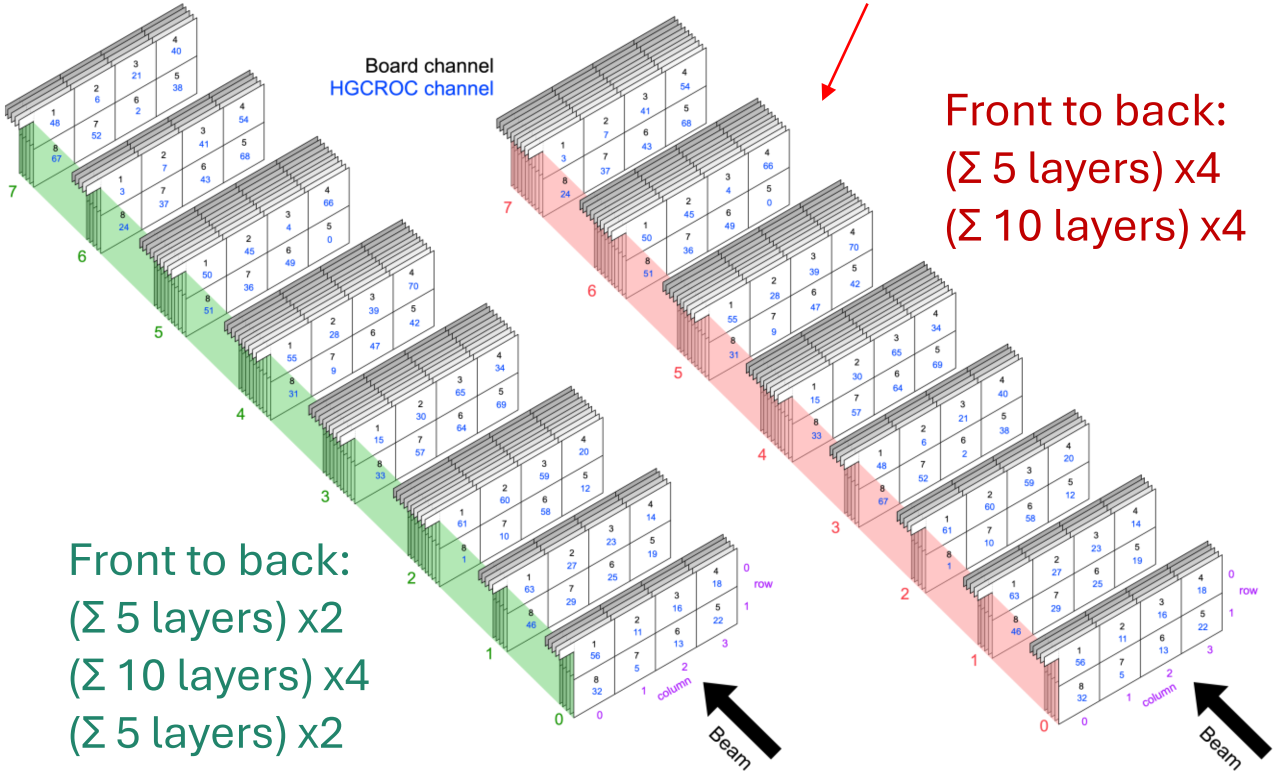
OAK RIDGE National Laboratory

Test beam campaigns:
Very initial 2026 results



Goals:
- Summing board validation
- Longitudinal shower development

Tested 2 summing configs
(data in plot taken with version on the right)



Front to back:
(Σ 5 layers) x2
(Σ 10 layers) x4
(Σ 5 layers) x2

Front to back:
(Σ 5 layers) x4
(Σ 10 layers) x4

Publication plans

- Two publications for ePIC special issue in NIM:
    - Design and construction of the LFHCAL
    - Beam test performance of LFHCAL prototypes

- We now have a comprehensive LFHCAL beam test data set.
    - From full readout granularity to different summing schemes
    - From single modules to 6 module stack
    - From 1GeV to 350GeV electrons, hadrons and a lot of muons

- Interested in joining the analysis efforts? Get in touch with Fredi or Oskar and/or join the weekly LFHCAL TB meeting
    - https://friederikebock.gitbook.io/epiclfhcaltb-ana

With many thanks to the many many contributors:

- ORNL: Fredi Bock, Ewa Glimos, Oskar Hartbrich, Norbert Novitzky
- UTK: Thibor Bernardon, Everett Hagen, Aidan Hill, Droc Nash
- Yale: Ananya Ray, Iris Ponce, Prakhar Garg, Ryan Hamilton, Isaac Mooney, Emily Pottebaum
- Vanderbilt: McKenna Sleeth, Andi Mankoli, Andrew Tamis, Preston White, Logan Hissong
- Debrezen: Miklos Czeller, Gabor Nagy, Gabor David
- Valparaiso: Adam Gibson, Paul Nord, Leah Shafer, Ari Tanner
- Prague University: Alexander Godal, Jana Demjancukova, David Kapukchyan
- Kansas: Nicola Minafra, Tommaso Isidori
- MSU: Bill Lee, Preet Mann
- Archita Dash (Muenster), Nico Strangmann (Frankfurt), Charlotte van Hulse, Tristan Protzmann (Lehigh), Shihai Jia (Copenhagen), Ton van der Brink (Nikhef), Vincent Andrieux (Urbana-Champaign, Mainz), Bobae Kim (ANL), Peter Steinberg (BNL), Kottavai Chandrasekaran (GSU), Sam Corey (OSU), Maciej Czarnynoga (Warsaw), Sushrut Karmarkar (Purdue)

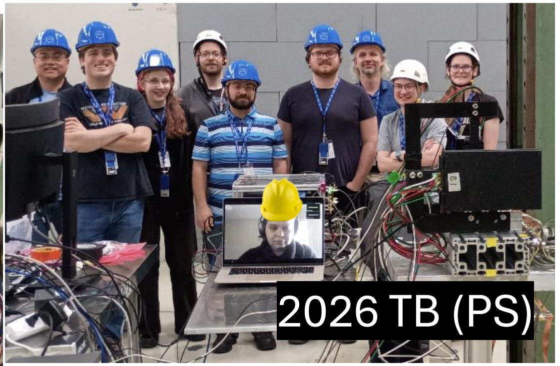
The LFHCal is real!

Outlook

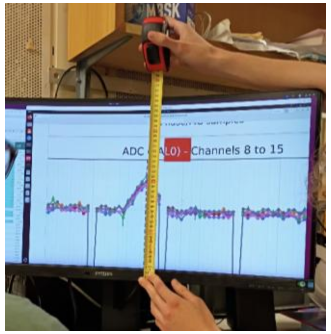
- Next steps: finish processing 2025 & 2026 test beam data, measure longitudinal profiles, energy resolutions as possible
- Final LFHCAL design review planned later in 2026
- Currently have ~340k SiPMs, will receive 650 8M modules starting end of 2026


2025 TB


2023 TB (PS)


2026 TB (PS)


Tile QA at MSU




Tile assembly


2026 TB (SPS)


Loading 8M modules


Building a dark box