EP-DT
Detector Technologies

EP-DT contributions to the CMS Calorimeter Endcap and Tracker upgrades for HL-LHC

Joao Batista Lopes (EP-DT-EO), Marta Krawczyk (EP-DT-TP)

EP-DT group meeting
June 26, 2024

CMS upgrades for HL-LHC

L1-Trigger
https://cds.cern.ch/record/2714892
- Tracks in L1-Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting

Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Active layers:
  Silicon and Scint.+Silicon Photomultiplier
- Absorbers (main components):
  Cu+CuW+Pb and Cu+Stainless Steel

Tracker
https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to η ≈ 3.8

MIP Timing Detector
https://cds.cern.ch/record/2667167
Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

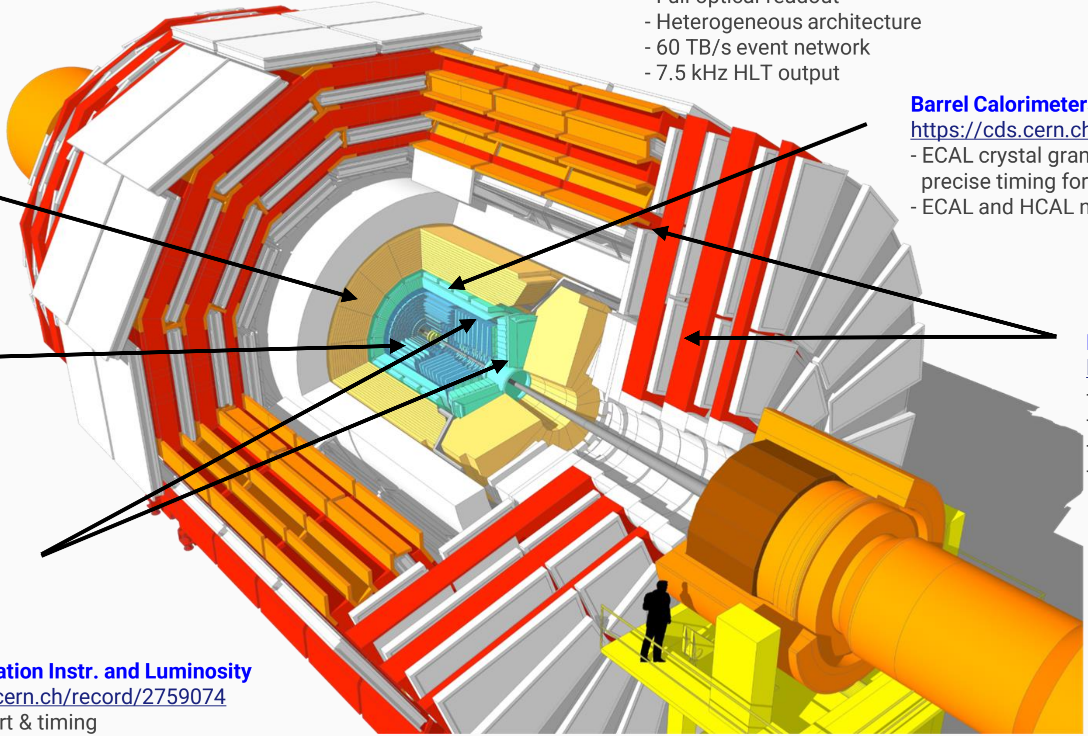
Beam Radiation Instr. and Luminosity
http://cds.cern.ch/record/2759074
- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity: 1% offline, 2% online
- Neutron and mixed-field radiation monitors

DAQ & High-Level Trigger
https://cds.cern.ch/record/2759072
- Full optical readout
- Heterogeneous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η ≈ 3

General services and infrastructure
- Replacement of C_6F_{14} cooling systems by CO_2



CMS detector as of today

DT contributions to CMS upgrades

L1-Trigger

DAQ & High-Level Trigger

Calorimeter Endcap ⟶ **Marta**
- Silicon sensor development
- Radiation hardness qualification
- Quality control of production sensors
- Readout electronics qualification using irradiated sensors
- Reconstruction software

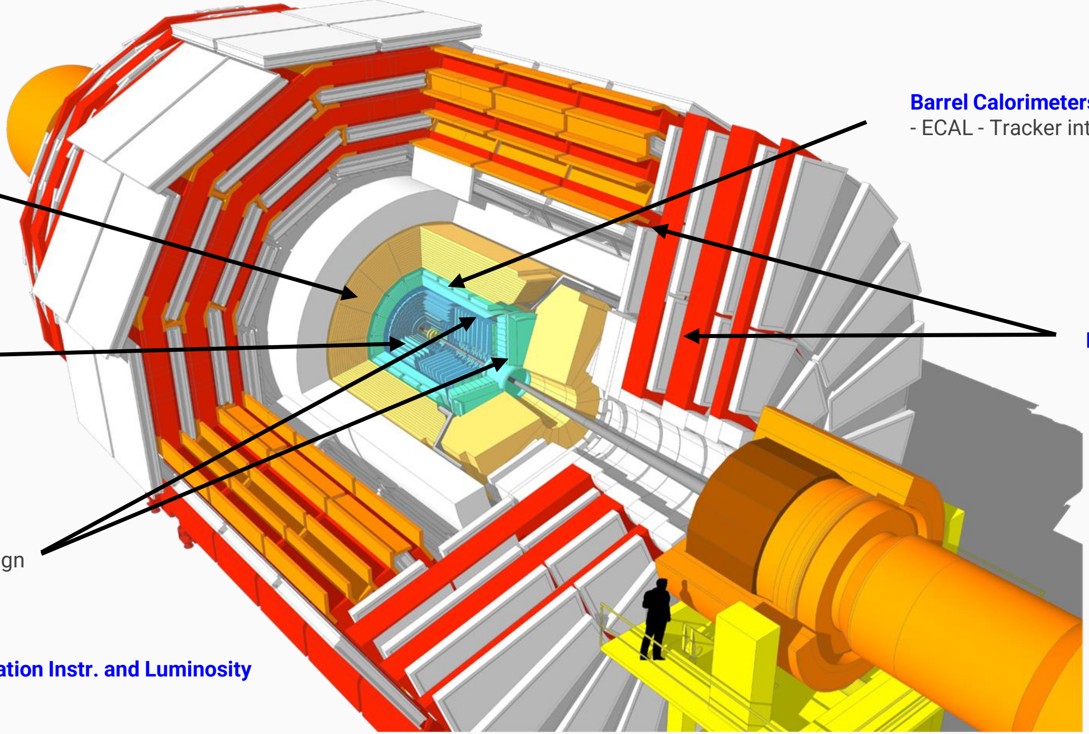
Tracker ⟶ **Joao**

Tracker:
- Design and construction of TBPS and TB2S sub-detectors
- Tracker integration and services design
- Production of heating foils
- Quality control of detector module hybrids

MIP Timing Detector
- Barrel Timing layer - Tracker integration design

Barrel Calorimeters
- ECAL - Tracker integration design

Muon systems



Beam Radiation Instr. and Luminosity

CMS detector as of today

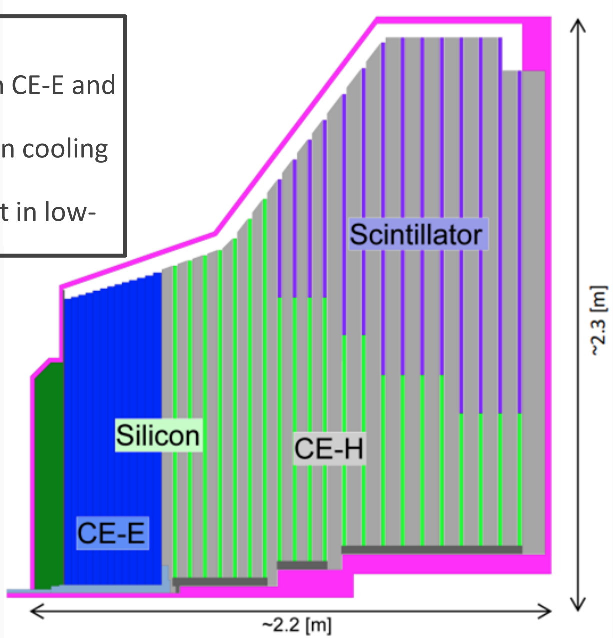
General services and infrastructure
- Design and construction of CO_2 cooling systems for Tracker, Timing Layers and HGCAL
- Upgrade of ECAL thermal controls
- Upgrade of CMS Detector Safety System (DSS)

CE: Calorimeter Endcap - a.k.a. HGCAL

Main parameters:

Active Elements:
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- "Cassettes": multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with on-tile SiPM readout in low-radiation regions of CE-H

Key Parameters:
Coverage: 1.5 < |η| < 3.0
~215 tonnes per endcap
Full system maintained at -35°C
~620m² Si sensors in ~26000 modules
~6M Si channels, 0.6 or 1.2cm² cell size
~370m² of scintillators in ~3700 boards
~240k scint. channels, 4-30cm² cell size
Power at end of HL-LHC: ~125 kW per endcap



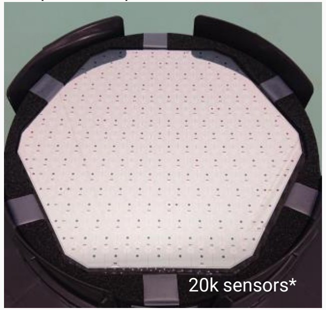
Electromagnetic calorimeter (CE-E): Si, Cu & CuW & Pb absorbers, 26 layers, 27.7 X_0 & ~1.5λ
Hadronic calorimeter (CE-H): Si & scintillator, stainless steel absorbers, 21 layers, ~8.5λ

Project scale and challenges:

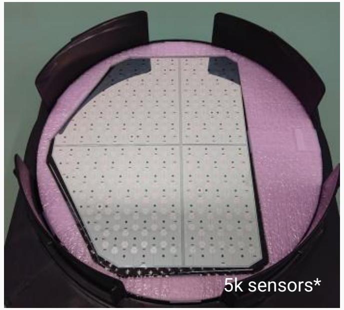
- By far largest approved project based on silicon sensors in HEP
  - → 3x area of ATLAS/CMS trackers
- First imaging calorimeter approved for installation in collider experiment
  - → Pave the way for future collider detectors
- First application of 8” sensors in a detector
  - → Very large and fragile objects
  - → Develop novel production process together with industrial suppliers
    - Need for radiation hardness qualification

620 m^2 of silicon sensors

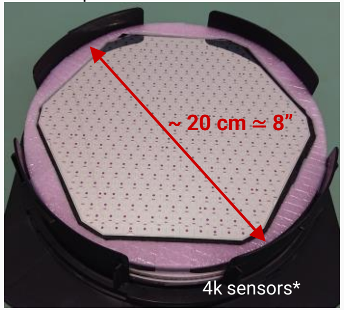
Low-Density sensor
~ 200 cells of 1.1 cm^2 size
300 µm & 200 µm active thickness



Low-Density "Partial sensor" example from "Multi-Geometry" sensor

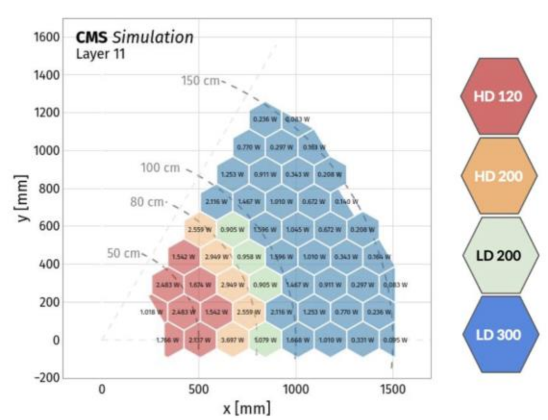


High-Density sensor
~ 450 cells of 0.5 cm^2 size
120 µm active thickness



High-Density "Partial sensor" example from "Multi-Geometry" sensor

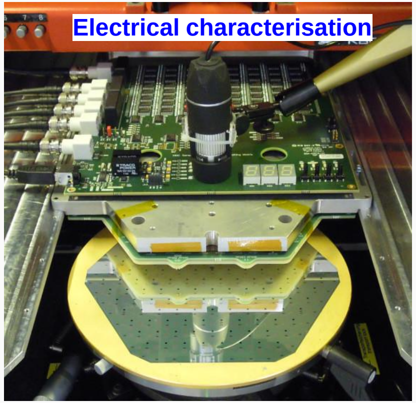
* needed in the final detector



- Hexagonal silicon sensor geometry
  - Largest regular tiling polygon
  - Maximise wafer usage
  - "Partial" sensors to tile border regions
- Thickness and granularity adapted to radiation field
  - Fluence from 10^{14} to 10^{16} n_{eq}/cm^2
- 8-inch wafers
  - Reduces number of modules w.r.t. 6-inch wafers
  - New production process and radiation-hardness qualification
- Planar, DC-coupled, p-type sensor cells
  - p-type more radiation tolerant than n-type sensors
- Sensor producer: Hamamatsu Photonics K. K. (HPK)

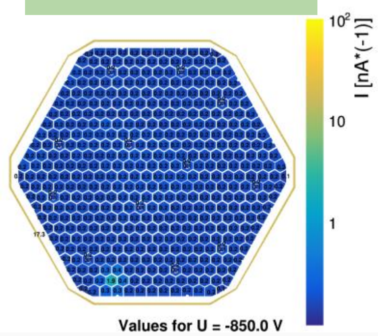
HGCal sensors in production phase

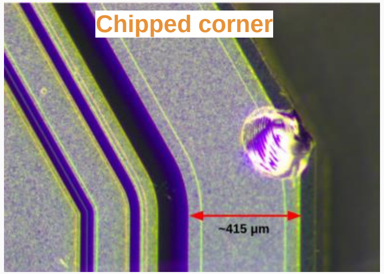
- Production phase from February 2023 to June 2025
  - 53% of all sensors already delivered to CERN
    - 75% already at testing sites (CERN+User, 2 x US, 1 x TW, 1 x CH)
    - 25% still in transit
- Sensor qualification concept
  - 100% of wafers qualified at vendor
  - ~10% of main sensors re-qualified in CMS
    - CERN important player, covering ⅓ of sensors so far
  - ~20% of test structures for process stability tests
- Main sensor quality so far
  - Tested 685 out of 10458 (~7%, goal ~10%)
  - 9 with visible damage
    - Can be detected during optical inspections before module assembly
  - 3 with non-compliant IV result
    - 0.44% of tested sensors (3/685)
    - At 95% CL, defect rate below 1.3%
    - Non-sampled sensors with same failure type covered by spare parts (4%)
  - Findings triggered increase of optical inspection rate to ~50%

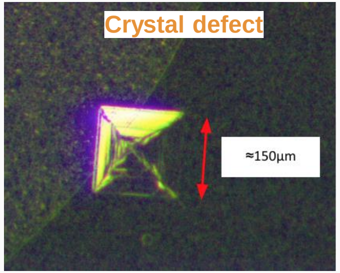


Per-cell leakage current:

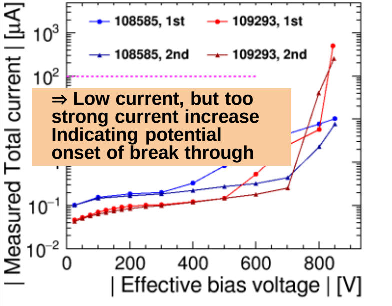
⇒ No high current cells





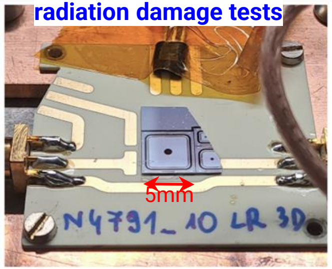


Electrical failure

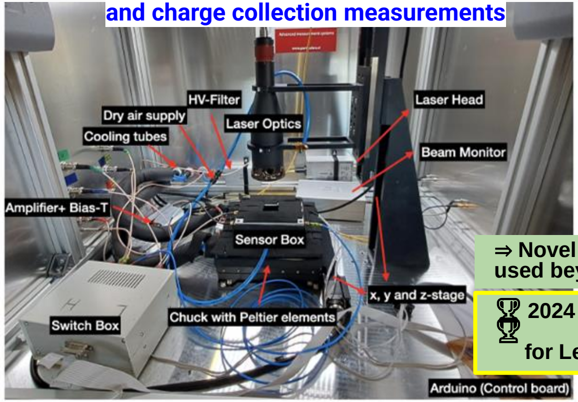


Radiation hardness of silicon sensors: Test structures

Single diode for bulk radiation damage tests



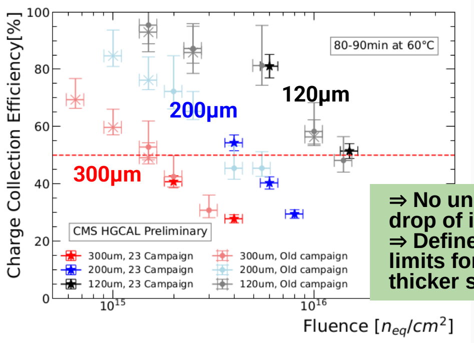
New setup for electrical characterisation and charge collection measurements



⇒ Novel setup to be used beyond HGCAL

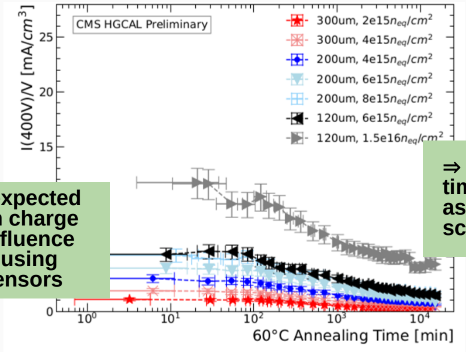
🏆 2024 CMS award for Leena Diehl

Decrease in charge collection efficiency with fluence



⇒ No unexpected drop of in charge
⇒ Define fluence limits for using thicker sensors

Decrease in leakage current after sample warming (annealing)



⇒ Extract annealing time constants used as input for operation scenario (T vs. time)

Challenge:

- Si sensors produced in new 8” process
- Requires validation of radiation hardness of silicon bulk and oxide layer on top

DT team’s contributions:

- Coordinated broad irradiation programmes
  - Neutron irradiation of diodes (bulk)
    - Validate radiation hardness (leakage current increase, charge collection decrease)
    - Get to know how damage changes with heat (annealing)
  - X-ray irradiation of MOS (Metal-Oxide-Silicon) and microstrip sensors (oxide)
    - Improve oxide process together with vendor for production sensors
    - Estimate cross talk between cells
  - Novel systems and software for in-situ and post irradiation testing
  - Deliver new data to scientific community
    - DRD3 presentations [1,2]
    - Publications in preparation

Radiation hardness of silicon sensors: Full sensors

Goal:

- Validate single-diode radiation hardness results for full 8” sensors
    - Study inter-pad and wafer effects

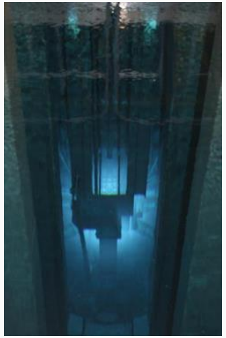
Challenge:

- No existing 8” irradiation facility

DT team’s contribution:

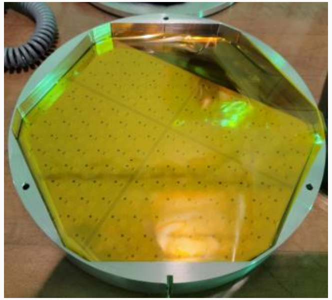
- Validation of new 8” neutron-irradiation facility: Rhode Island Nuclear Science Centre (RINSC)
- Irradiation and measurement campaign covering many sensor variants and fluences (2020–2024)
- Deliver new data to scientific community
    - [JINST publication]
    - [RD50 presentation]
    - [DRD3 presentation]
    - Publication in preparation

RINSC reactor core

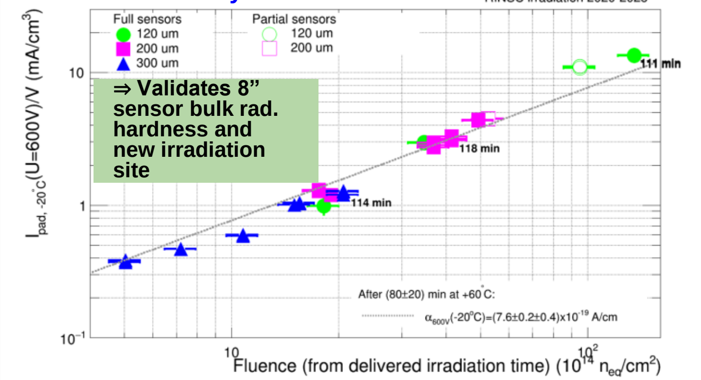


RINSC reactor beam port

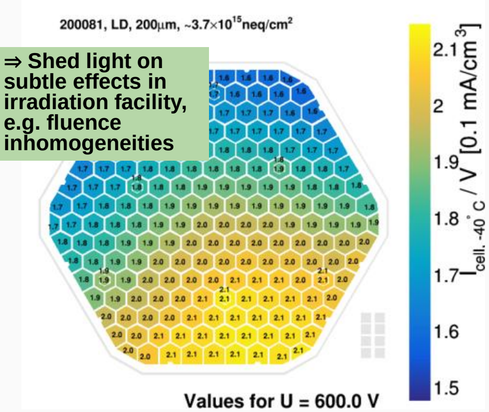
Irradiation holder hosting 8” partial sensors



Current density vs. fluence



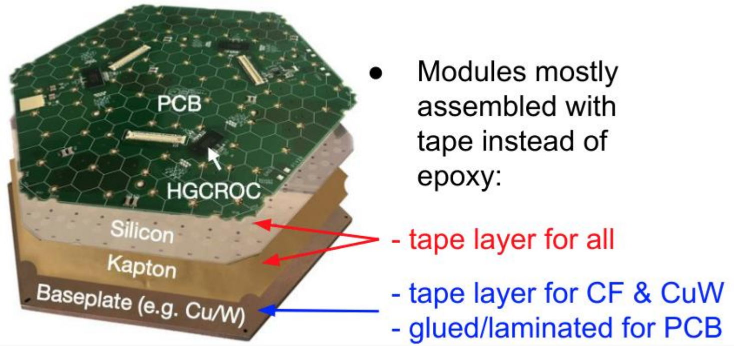
Current density across wafer



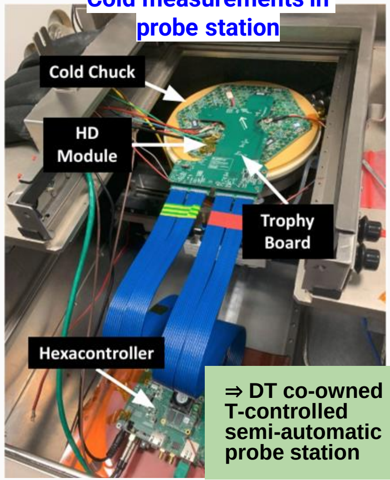
HGCAL silicon modules

- Assembled modules with neutron irradiated sensors
- First usage and validation of leakage current compensation of readout chip (ROC) needed because of DC coupling
  - Leakage current increases with temperature
  - Measure temperature profiles within module
    - Sensitive to heat sources
    - First experimental tests of cooling performance with different base plates
    - CuW better than CF, better than PCB
- Charge measurements
  - Inject charge via infra-red laser
  - Measure cross talk between cells
  - Plan to study charge collection versus fluence
- All test results important input to Procurement Readiness Reviews

Module stack up

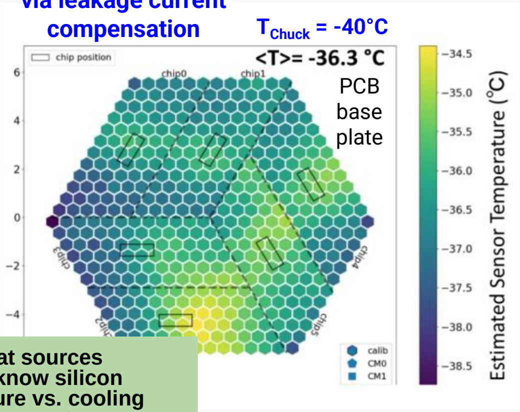


Cold measurements in probe station



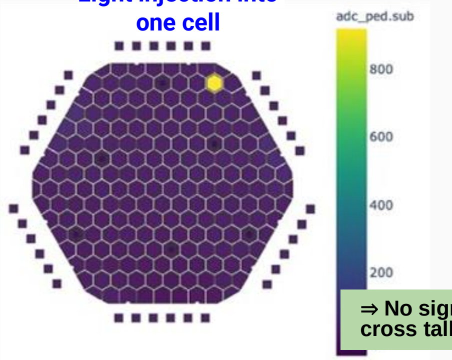
⇒ DT co-owned T-controlled semi-automatic probe station

Temperature estimation via leakage current compensation



⇒ See heat sources
⇒ Get to know silicon temperature vs. cooling system temperature

Light injection into one cell



⇒ No signs of cross talk

HGCAL ingredients and integration steps

- Silicon sensors
- HGCROC
- Hexaboards
- Silicon modules

- Scintillators
- SiPM
- Tileboards
- TileModules

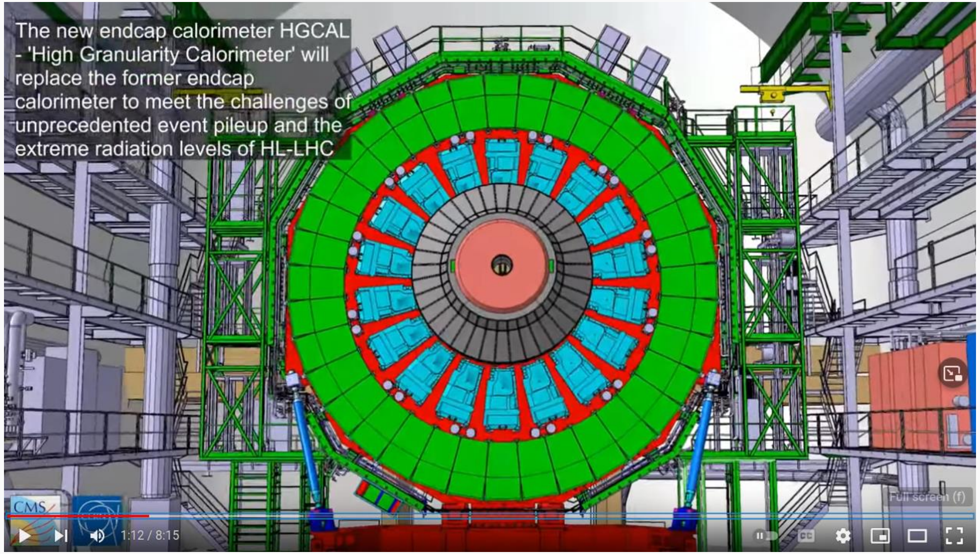
- ECONs
- Frontend Electronics
- Cassettes
- Mechanics

- Stacking/integration HGCAL side 1
- Stacking/integration HGCAL side 2

- Cold test HGCAL side 1
- Cold test HGCAL side 2

- Silicon sensor activity with strong contributions of DT team is progressing well
  - Production will come to an end in June 2025
- Large interest to join further steps towards completion of HGCAL

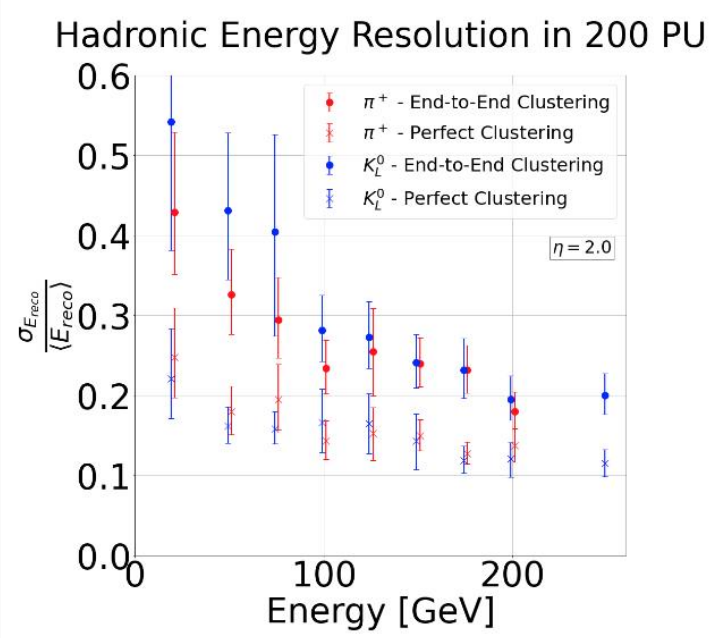
Video: schematic illustration of the detector ingredients and their integration

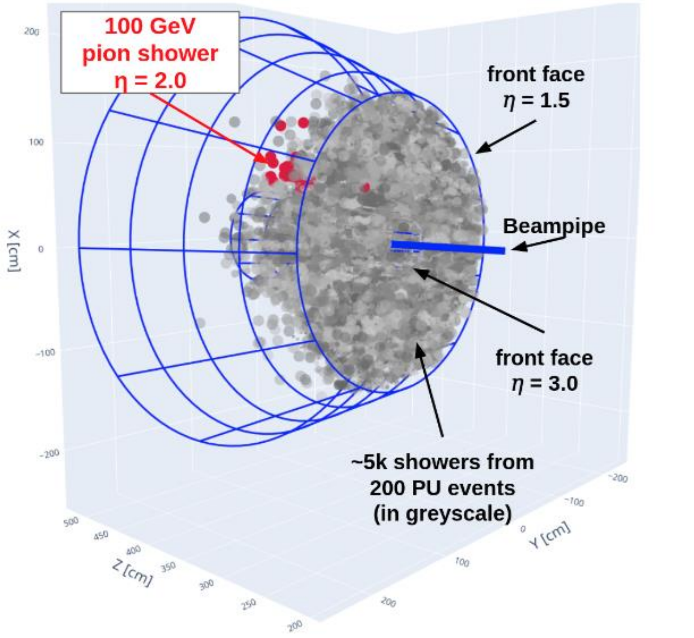


Backup

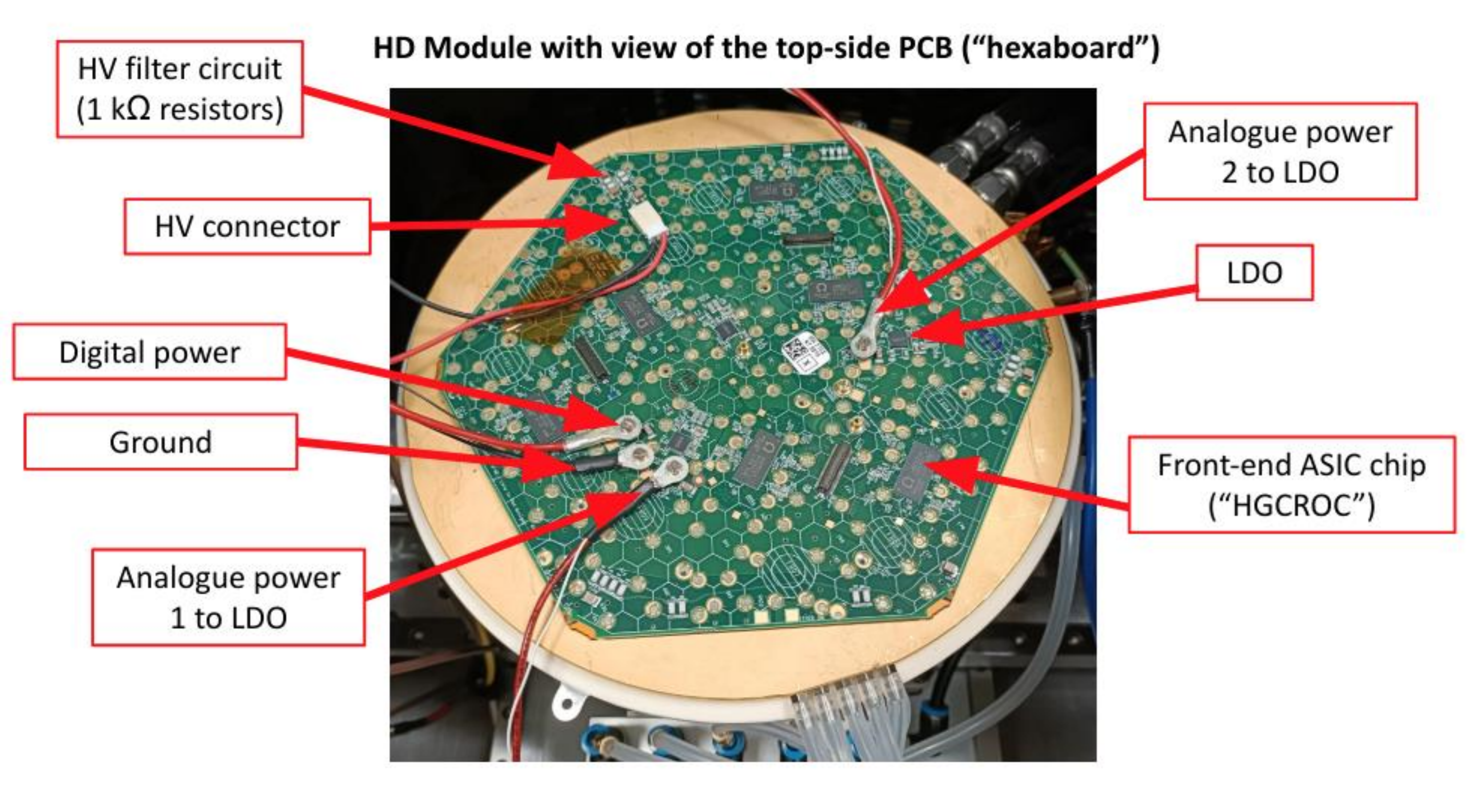
Reconstruction of simulated HGCAL-like data

- ML4Reco (Machine Learning for Reconstruction) project
  - End-to-end machine-learning aided reconstruction of simulated HGCAL-like data
  - First full end-to-end reconstruction chain including particle-flow reconstruction
    - Example results: Energy resolution for hadronic showers in events with 200 pile-up events





HGCAL modules: Details



Team members

- **EP-DT:** Eva Sicking, Leena Diehl, Pablo Alvarez Dominguez (ETH Zürich), Oliwia Kałuzińska (KIT Karlsruhe(DE)), Marta Krawczyk, Natalya Gerassyova (Al-Farabi Kazakh National University (KAZ)), Philipp Zehetner (Ludwig Maximilians Universitat (DE))
- Collaborations for work areas:
  - **HGCAL sensor production quality assurance:**
    - EP-CMG: Ankita Mehta, Filip Moortgat, Pedro Silva, David Walter
    - Users: Wesley Terrill (Carnegie-Mellon (US)), Buse Duran (Istanbul U. (TR)), Kerem Cankocak & Gizem Gul Dincer (Istanbul Technical U. (TR)), Ram Sharma & Xiaonan Hou (IHEP Beijing (CN))
  - **Radiation hardness of silicon sensors (Test structures):**
    - EP-CMG: Matteo Defranchis, David Walter
  - **Radiation hardness of silicon sensors (Full sensors):**
    - Brown University (US): Bjorn Burkle, Ulrich Heintz, Nick Hinton, Daniel Li, Meenakshi Narain, Nikolas Pervan, Eric Spencer, Catherine Tiley, Philipp Wagenknecht
    - Many former team members (campaign since 2020)
  - **HGCAL silicon modules:**
    - EP-CMG: Ankita Mehta, Fabio Monti, Pedro Silva
    - Users: Buse Duran (Istanbul University (TR)), Ram Krishna Sharma (IHEP Beijing (CN)), Wesley Terrill (Carnegie-Mellon University (US))