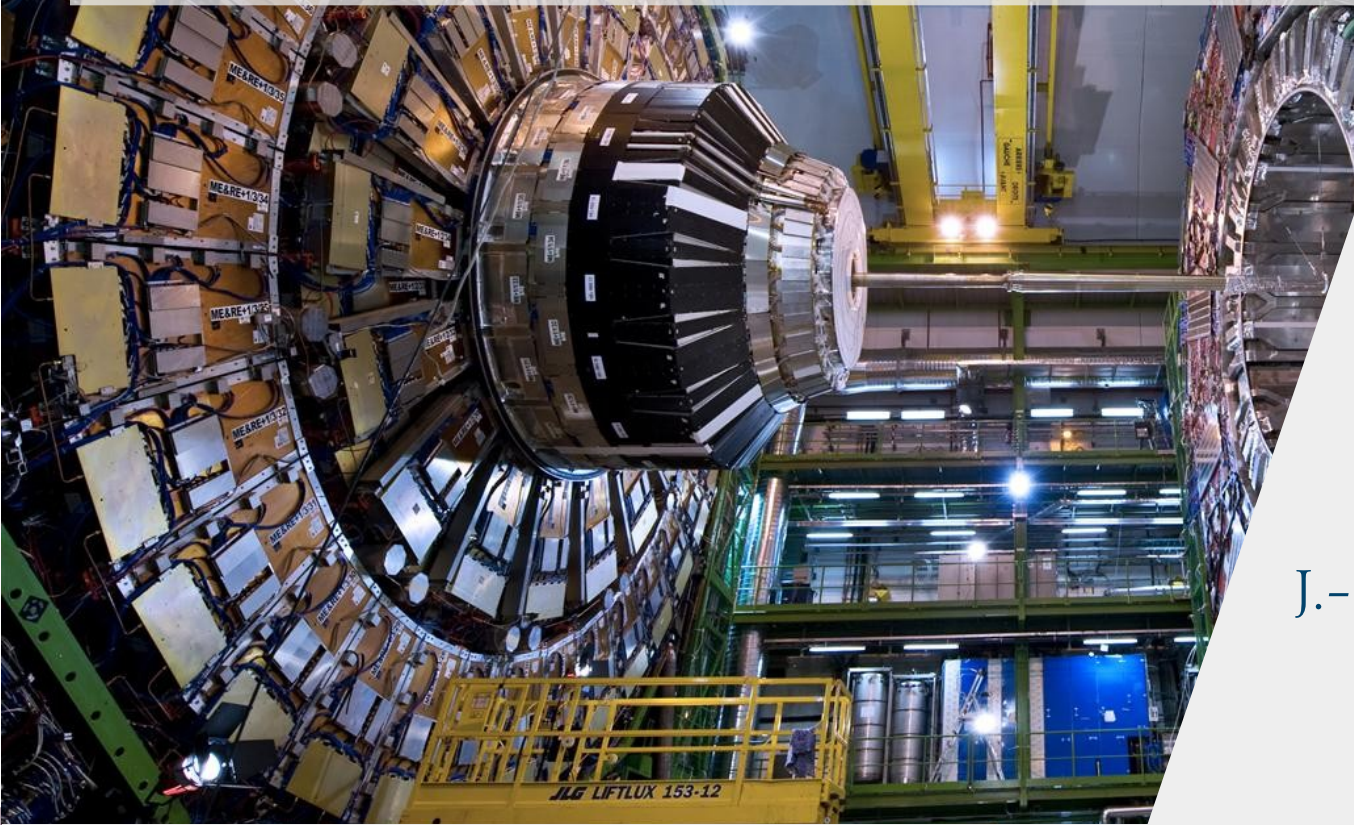
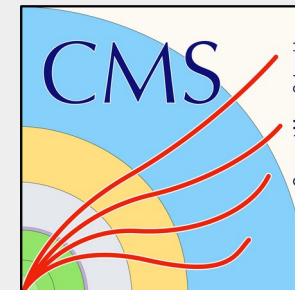


The CMS HGCAL (High Granularity CALorimeter) From Design to Reality



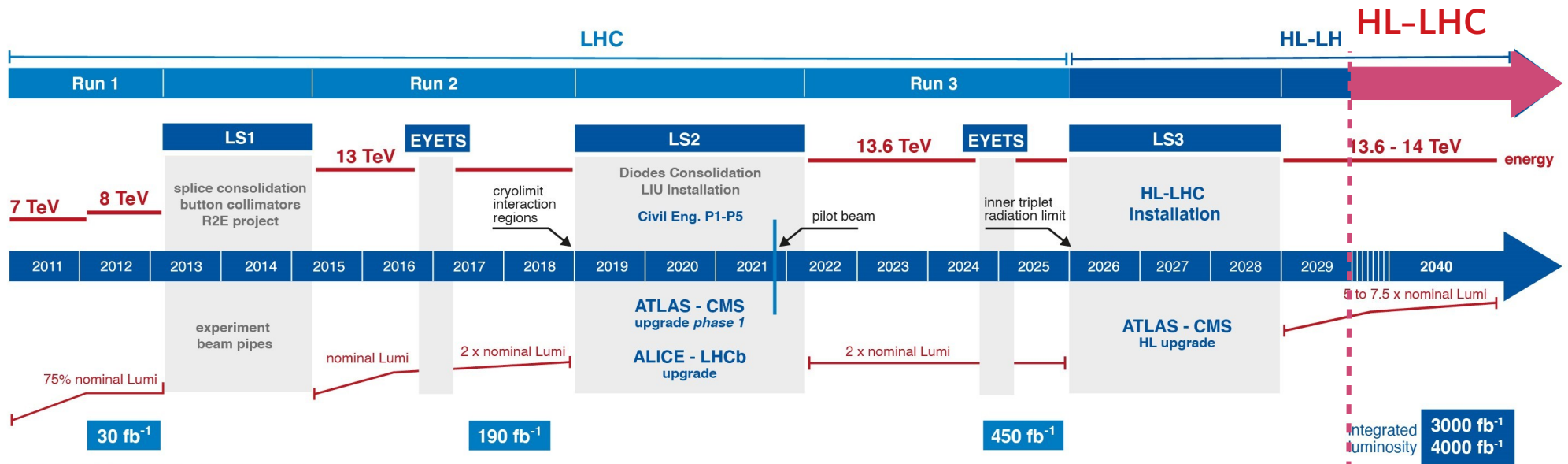
J.-B. Sauvan, on behalf of the
CMS Collaboration
LLR CNRS / École Polytechnique



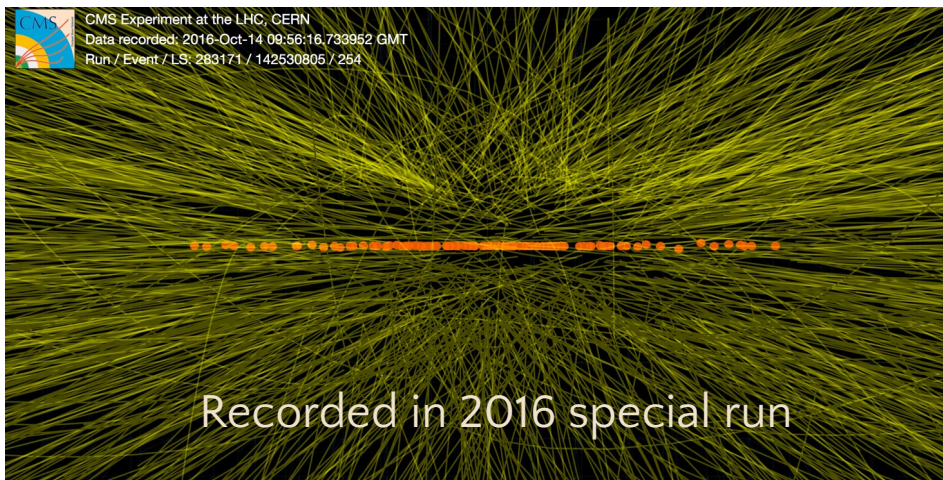
LHC Days in Split
30 September - 4 October 2024
Hotel Amfora, Hvar
Island of Hvar, Croatia




High Luminosity LHC (HL-LHC)




Event with ~130 reconstructed vertices



- 13.6-14 TeV
- 5-7.5 × nominal luminosity
-  140-200 simultaneous (PU) interactions

Why the HGCAL?

- CMS endcap calorimeters must be replaced
-  ECAL crystals and HCAL scintillators suffer from **irreparable damages** after 500fb⁻¹

CMS DETECTOR

Total weight : 14,000 tonnes
 Overall diameter : 15.0 m
 Overall length : 28.7 m
 Magnetic field : 3.8 T

STEEL RETURN YOKE
 12,500 tonnes

SILICON TRACKERS
 Pixel (100x150 μm) ~1m² ~66M channels
 Microstrips (80x180 μm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
 Niobium titanium coil carrying ~18,000A

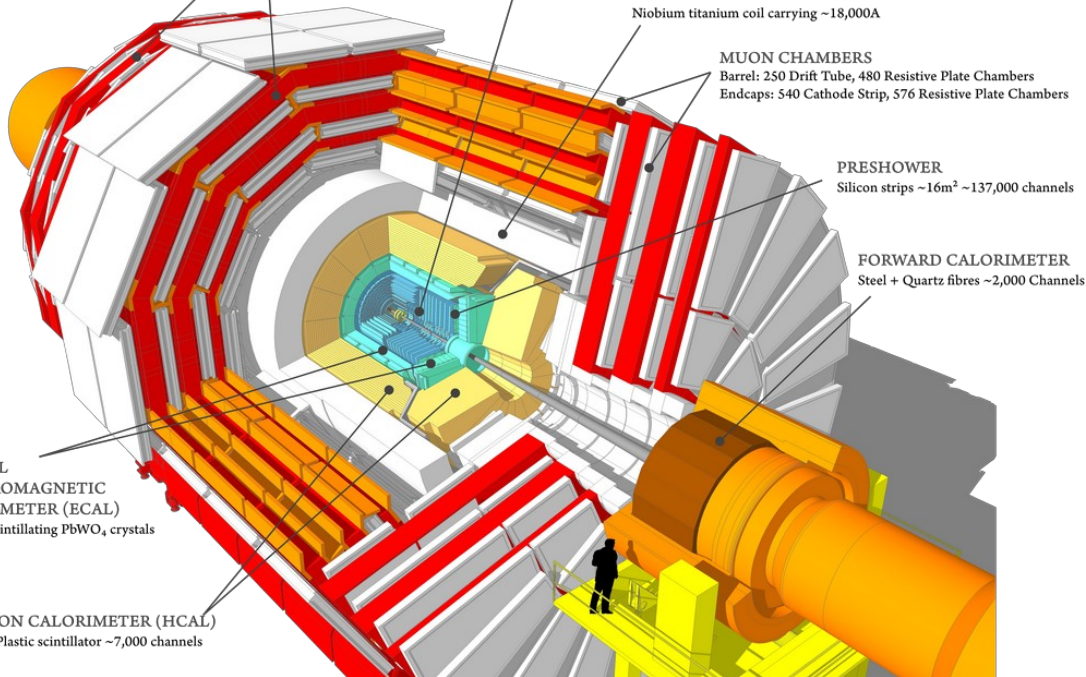
MUON CHAMBERS
 Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
 Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER
 Silicon strips ~16m² ~137,000 channels

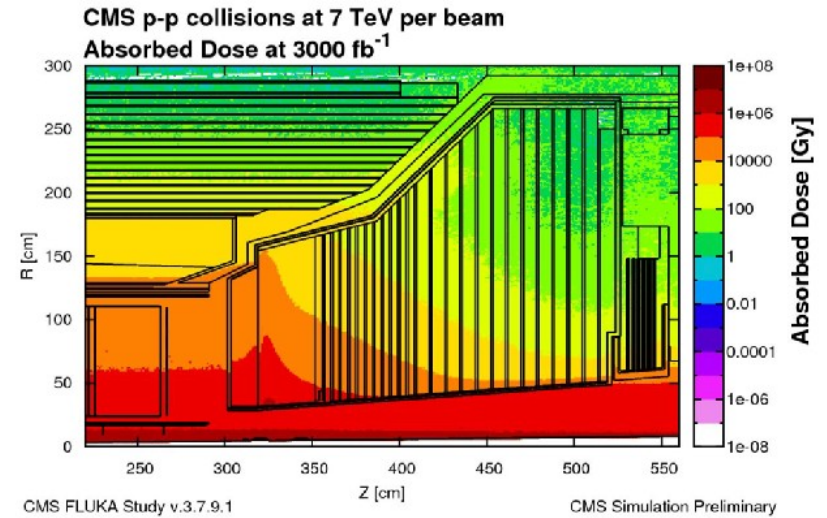
FORWARD CALORIMETER
 Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
 ~76,000 scintillating PbWO₄ crystals

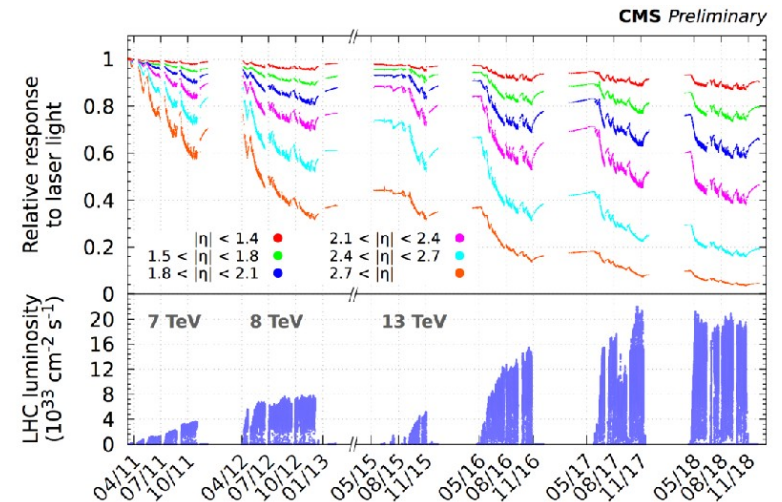
HADRON CALORIMETER (HCAL)
 Brass + Plastic scintillator ~7,000 channels



Absorbed dose at the end of HL-LHC



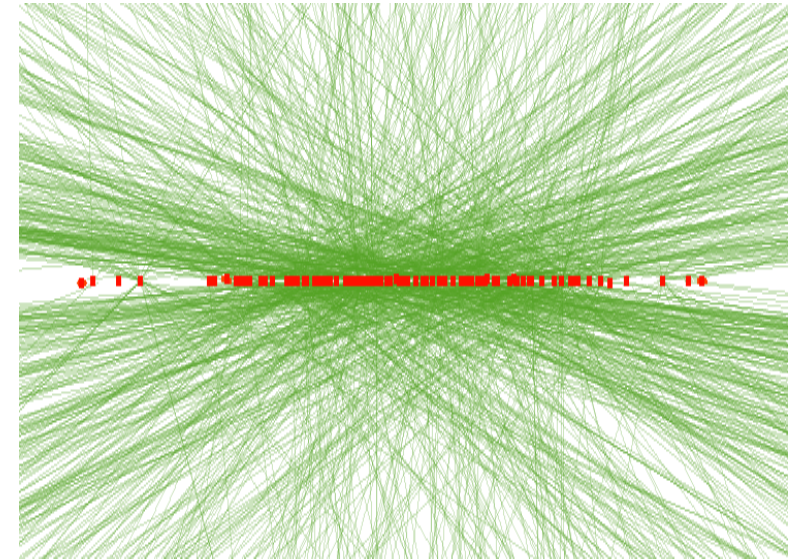
Transparency loss of ECAL crystals



Why the HGCAL?

- Ability to disentangle simultaneous collisions
- **High granularity**
- **Precise timing** information

140 PU interactions event



CMS DETECTOR

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 Overall diameter : 15.0 m
 Overall length : 28.7 m
 Magnetic field : 3.8 T

STEEL RETURN YOKE
 12,500 tonnes

SILICON TRACKERS
 Pixel (100x150 μm) $\sim 1\text{m}^2 \sim 66\text{M}$ channels
 Microstrips (80x180 μm) $\sim 200\text{m}^2 \sim 9.6\text{M}$ channels

SUPERCONDUCTING SOLENOID
 Niobium titanium coil carrying $\sim 18,000\text{A}$

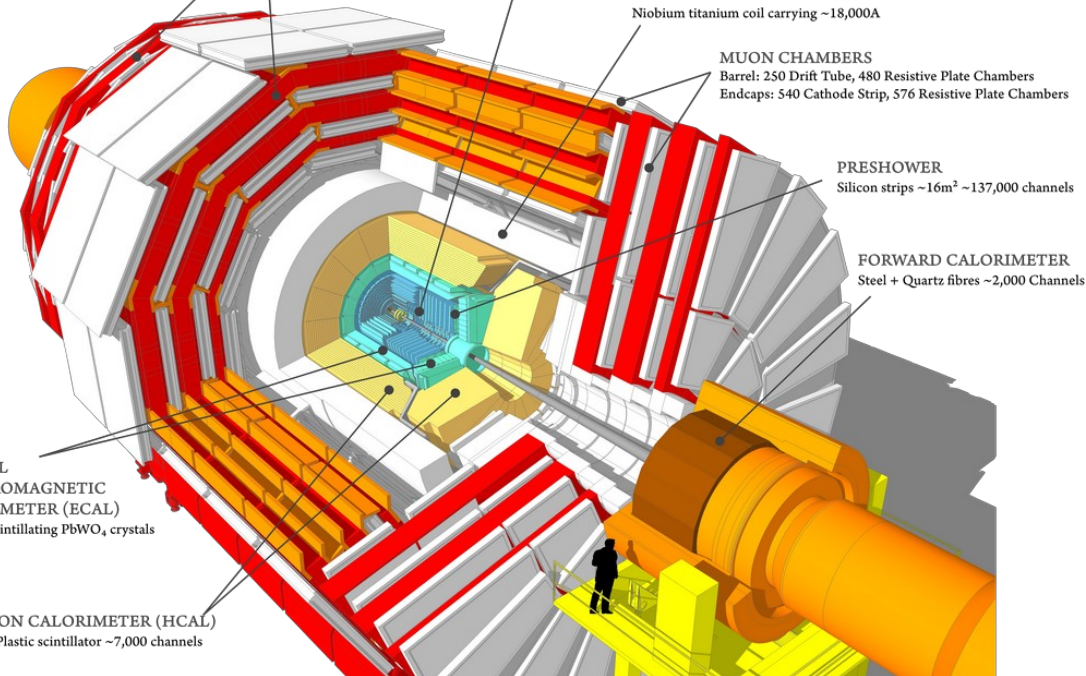
MUON CHAMBERS
 Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
 Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER
 Silicon strips $\sim 16\text{m}^2 \sim 137,000$ channels

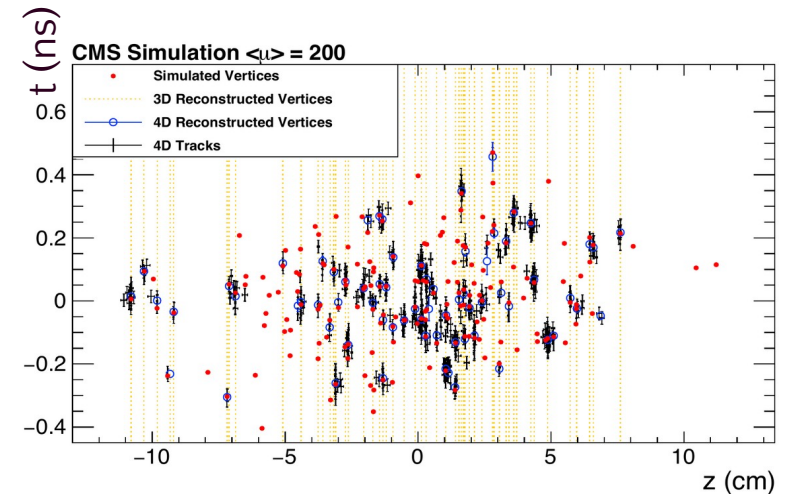
FORWARD CALORIMETER
 Steel + Quartz fibres $\sim 2,000$ Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

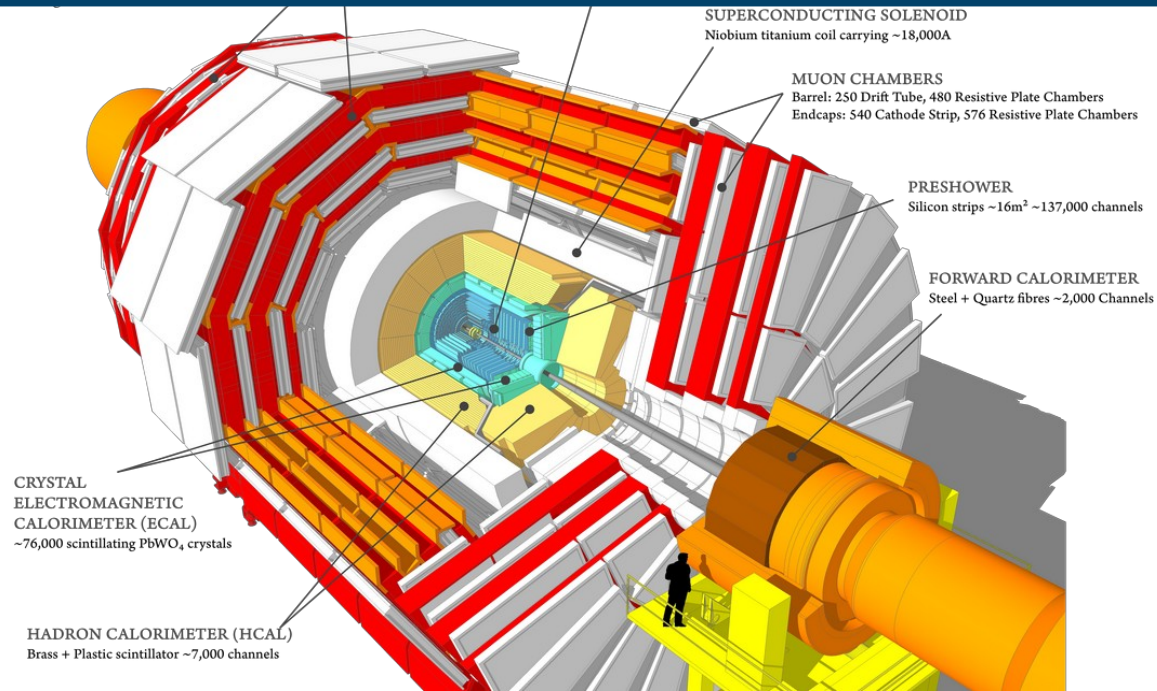
HADRON CALORIMETER (HCAL)
 Brass + Plastic scintillator $\sim 7,000$ channels



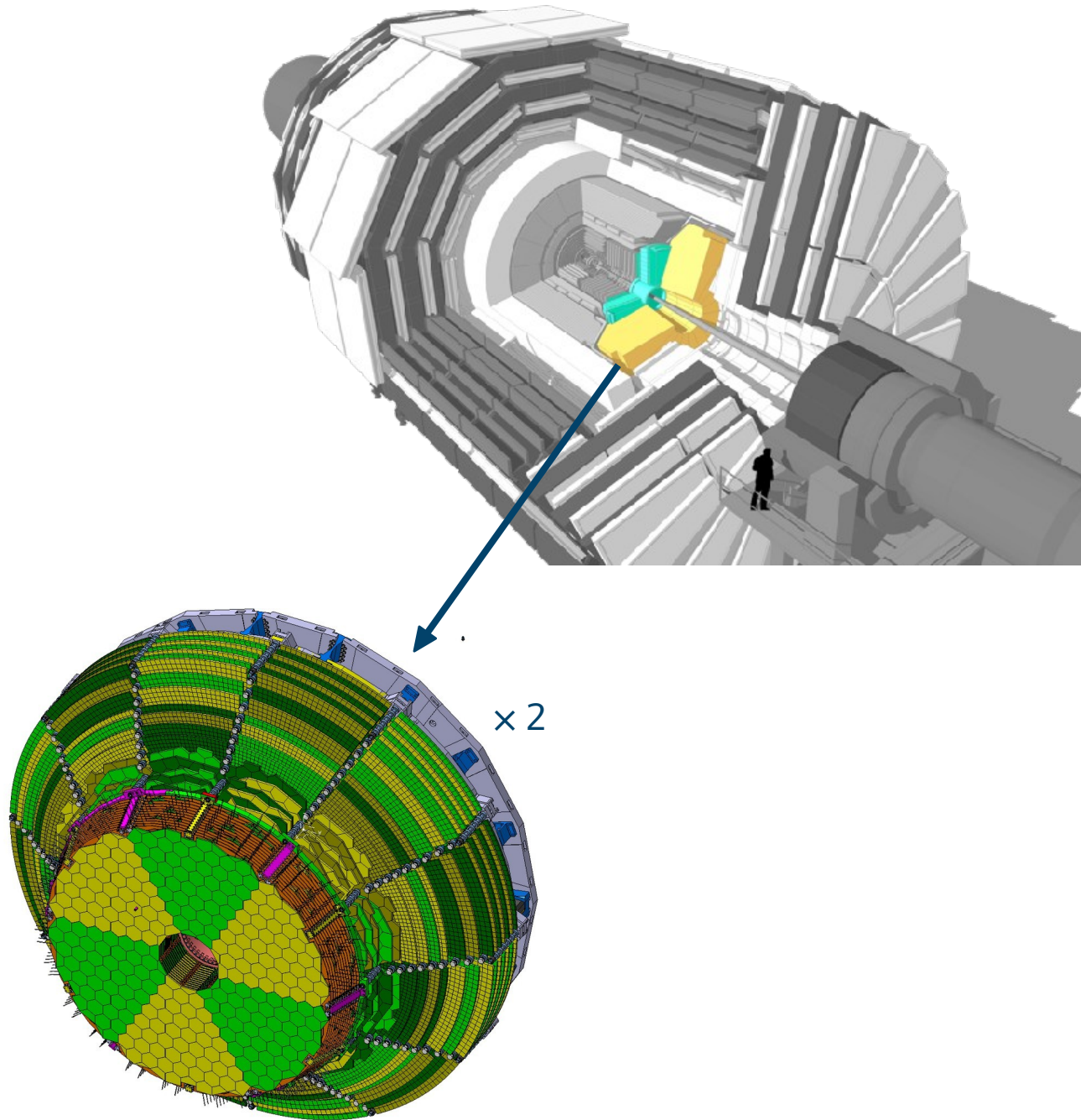
Space-time view of interaction vertices



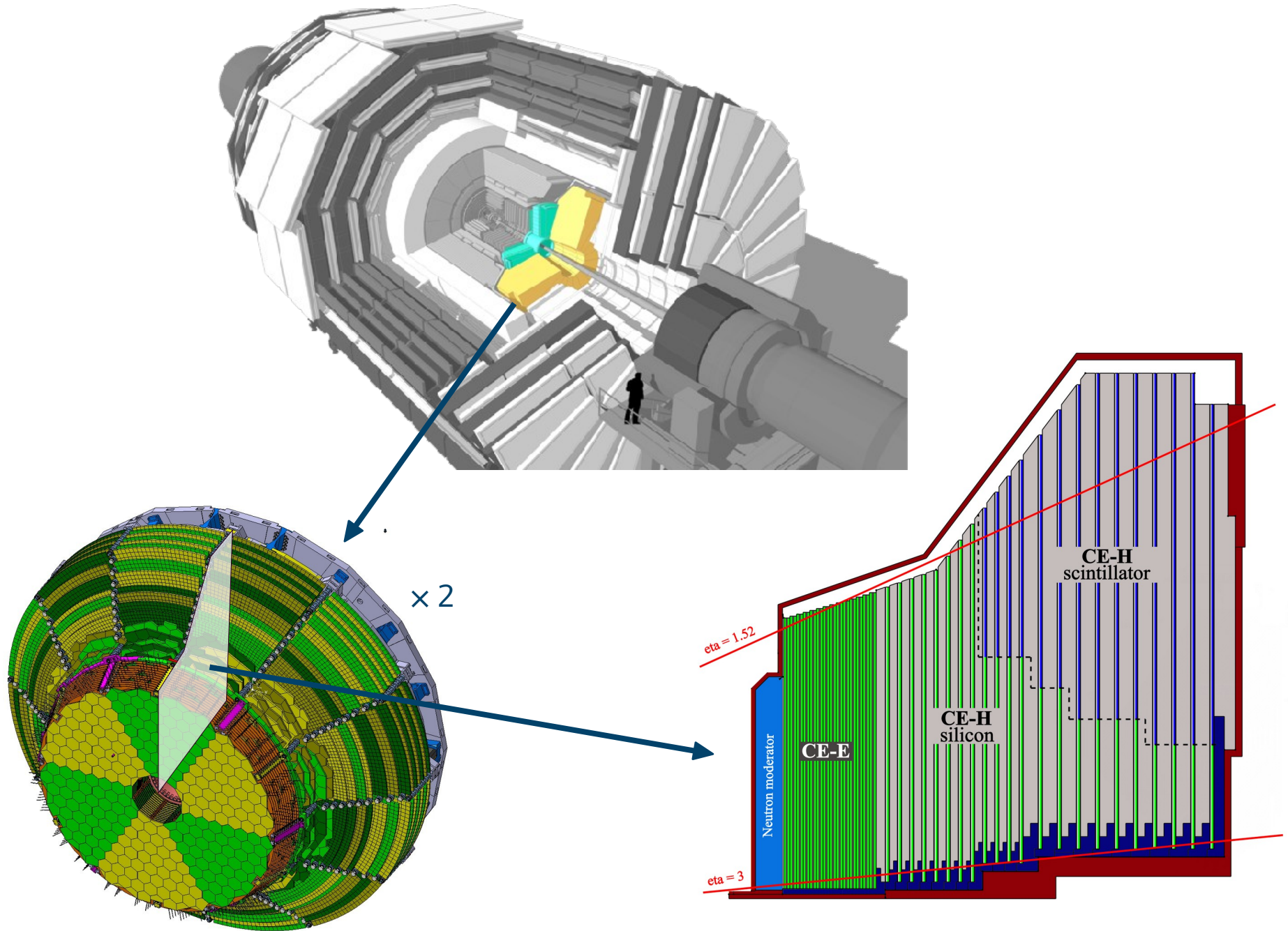
The High Granularity CALorimeter



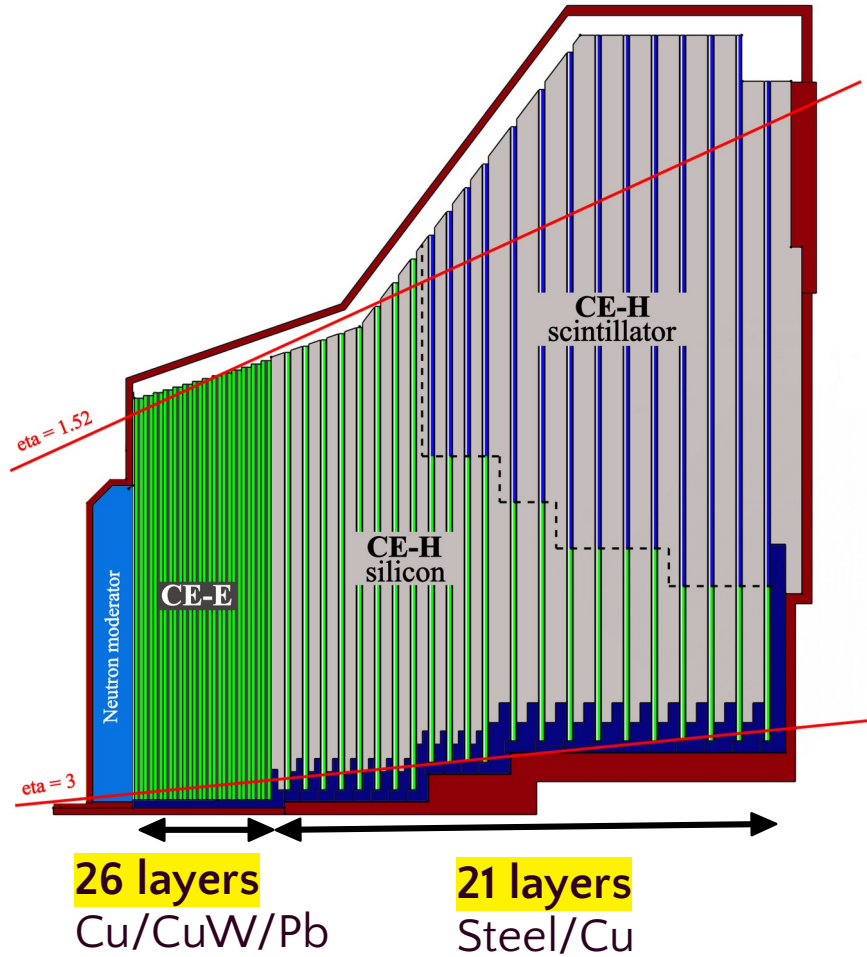
The High Granularity CALorimeter



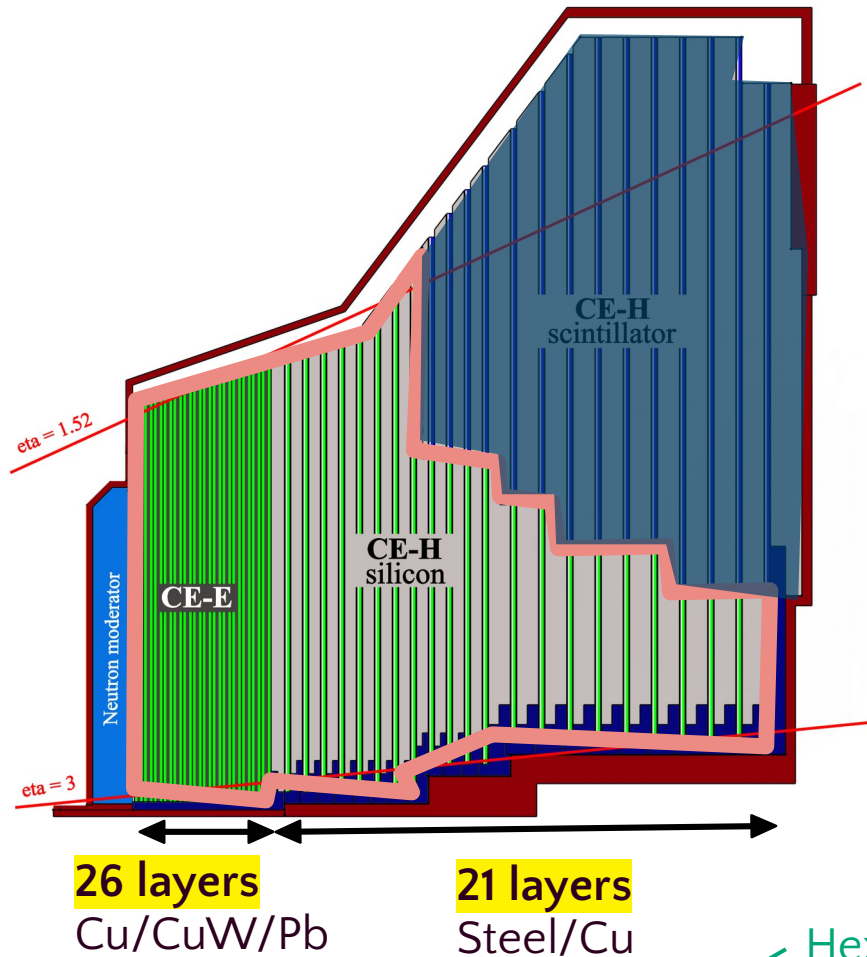
The High Granularity CALorimeter



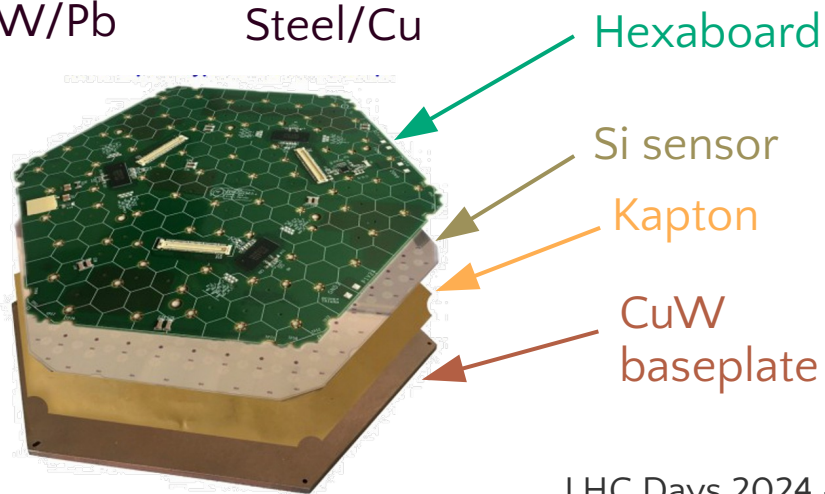
The High Granularity CALorimeter



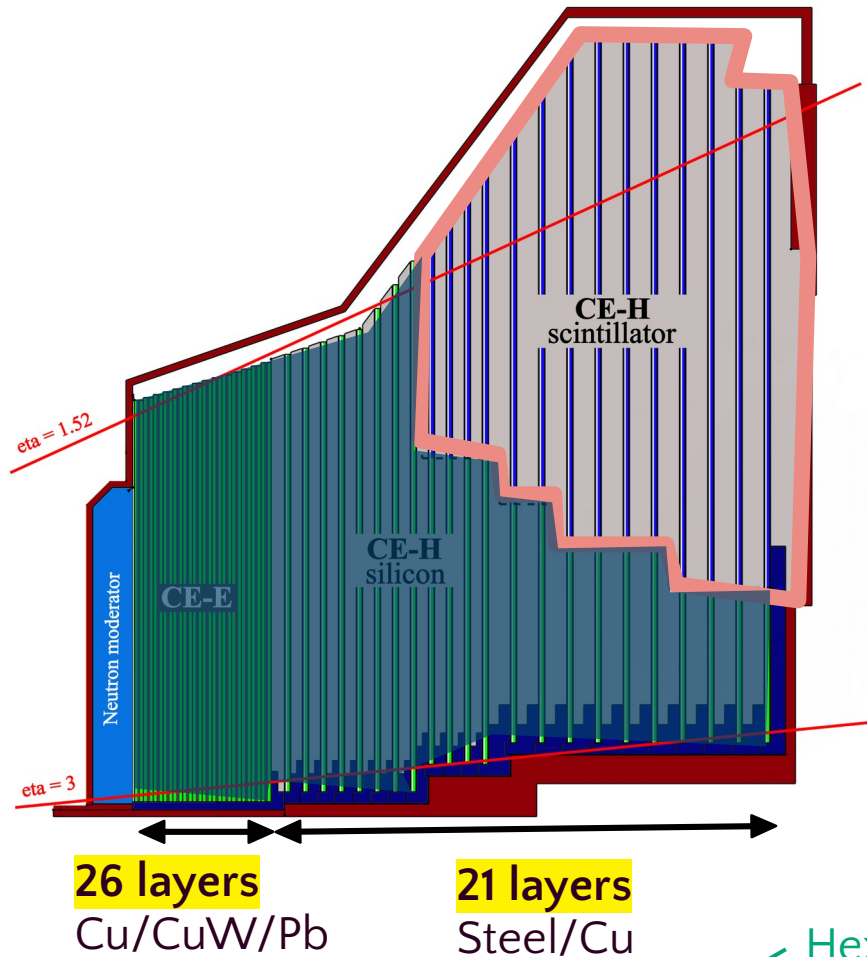
The High Granularity CALorimeter



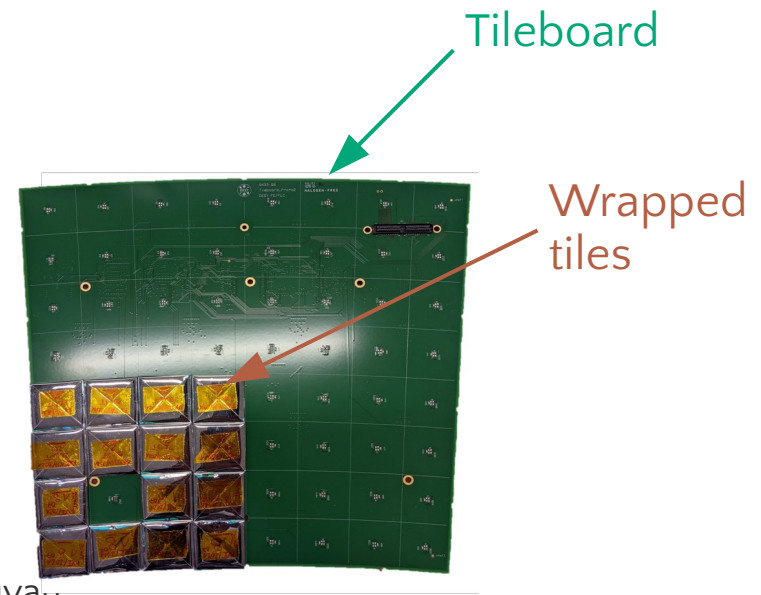
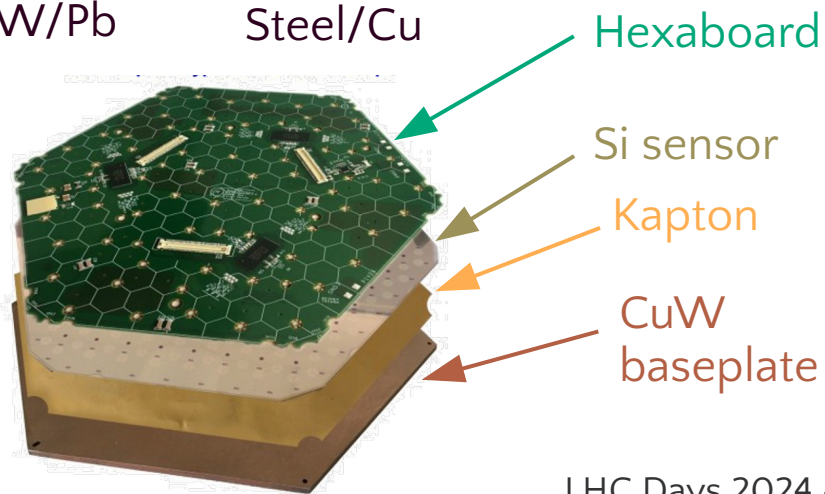
- **Silicon** sensors in high-radiation regions
 - 6M channels
 - Cell size: ~ 0.5 or 1 cm^2



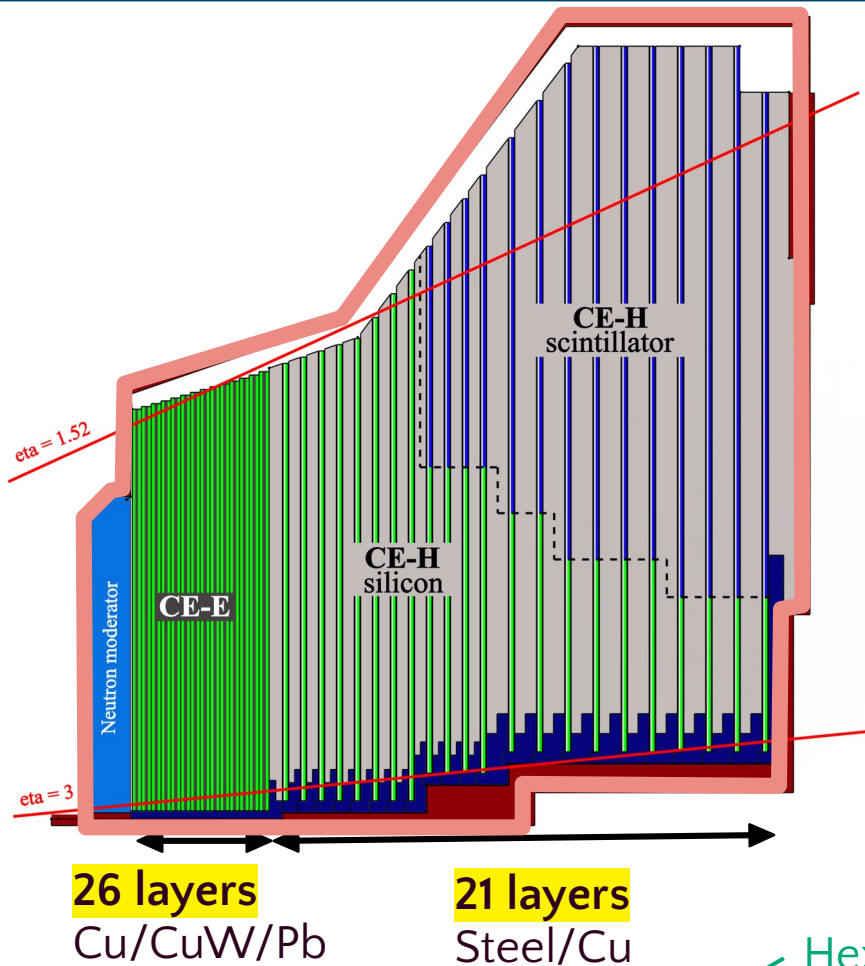
The High Granularity CALorimeter



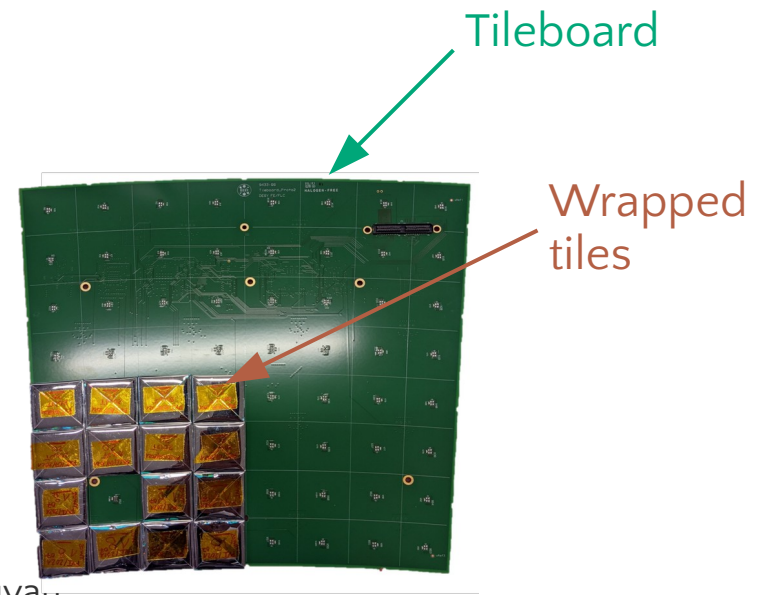
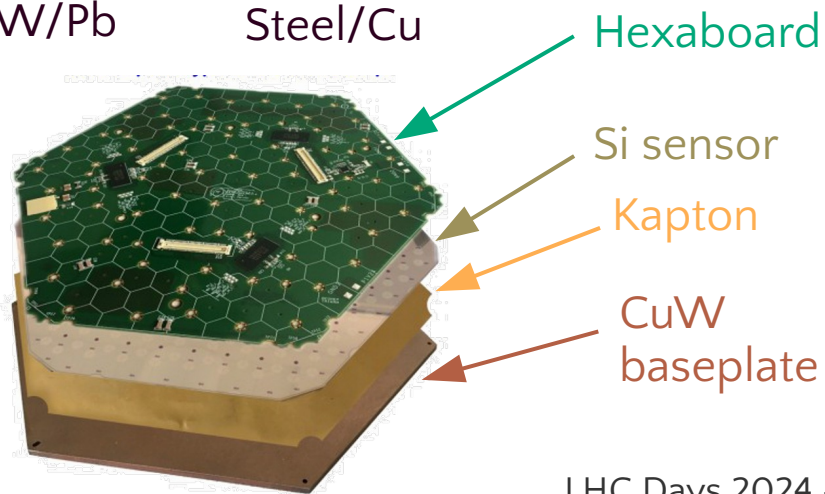
- **Silicon** sensors in high-radiation regions
 - 6M channels
 - Cell size: ~ 0.5 or 1 cm^2
- **Scintillating tiles + on-tile SiPM** in low-radiation area
 - 240k tiles
 - Cell sizes from ~ 4 to 30 cm^2



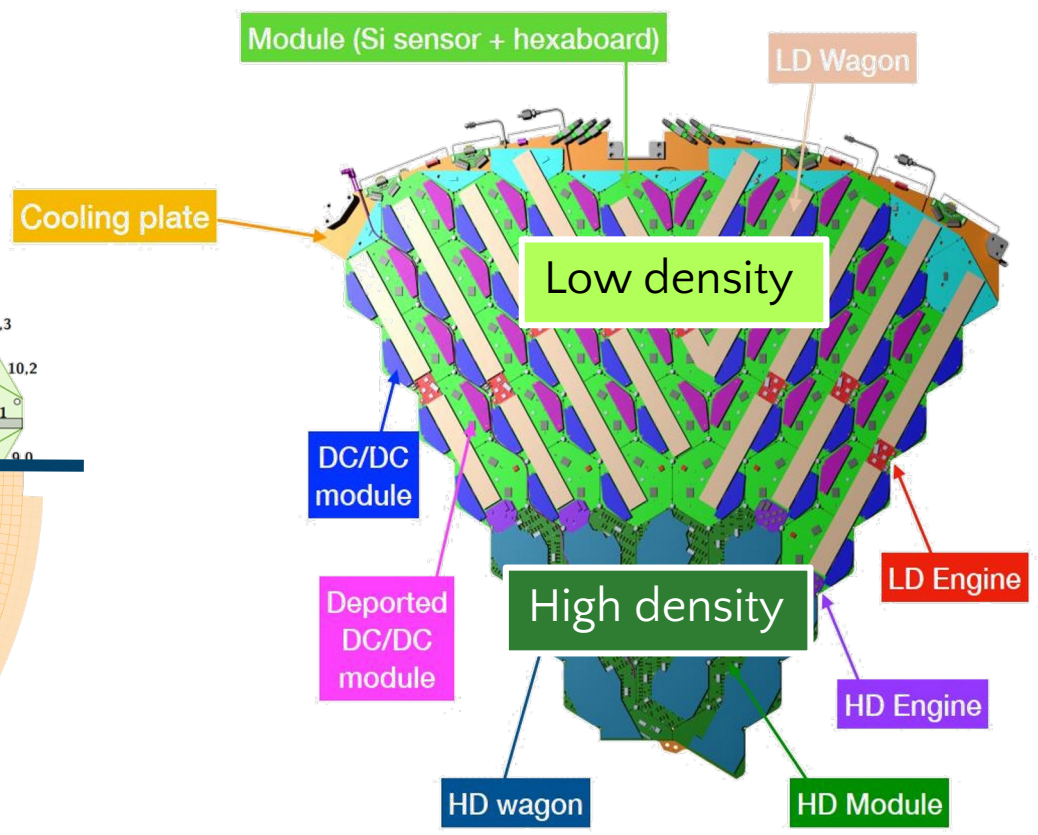
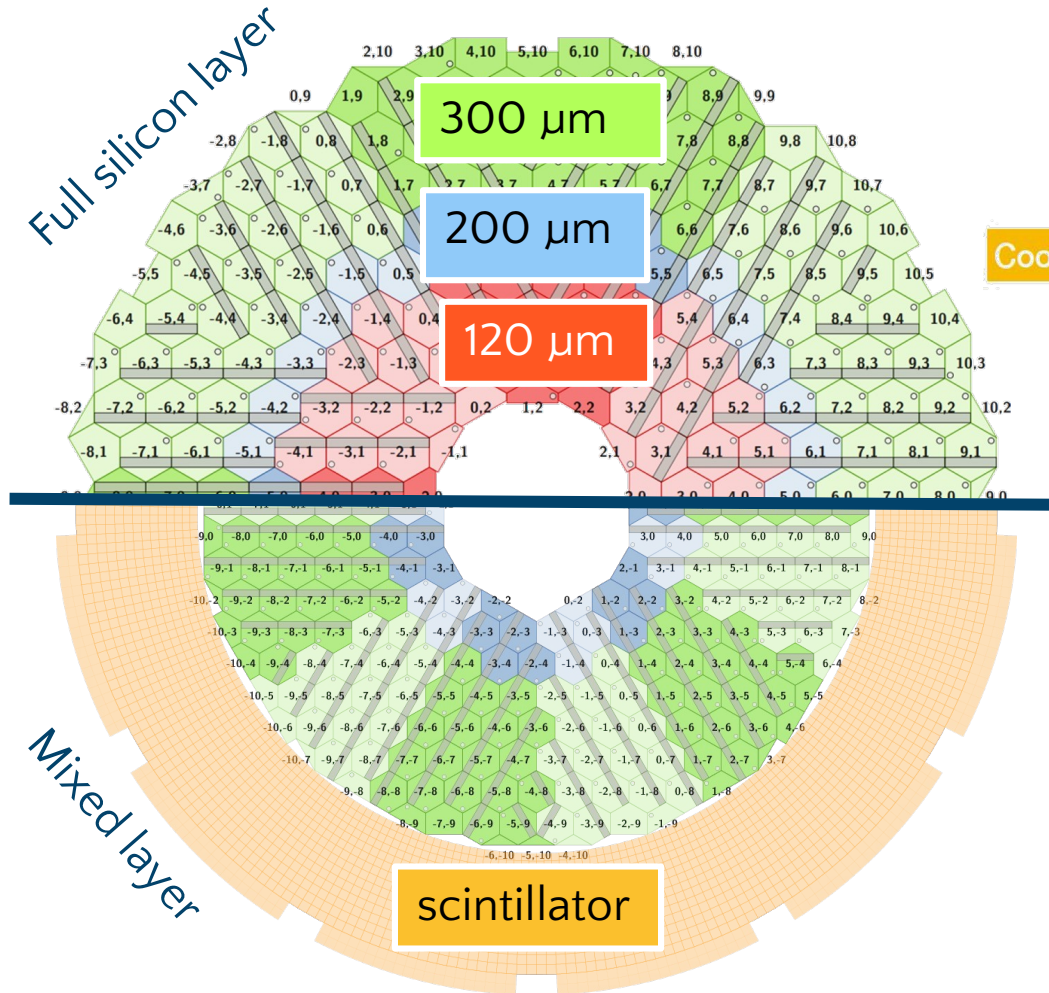
The High Granularity CALorimeter



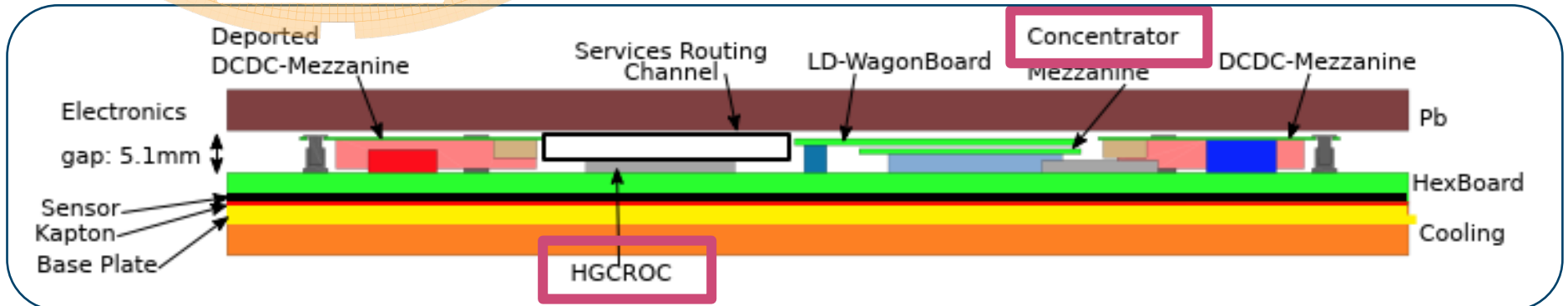
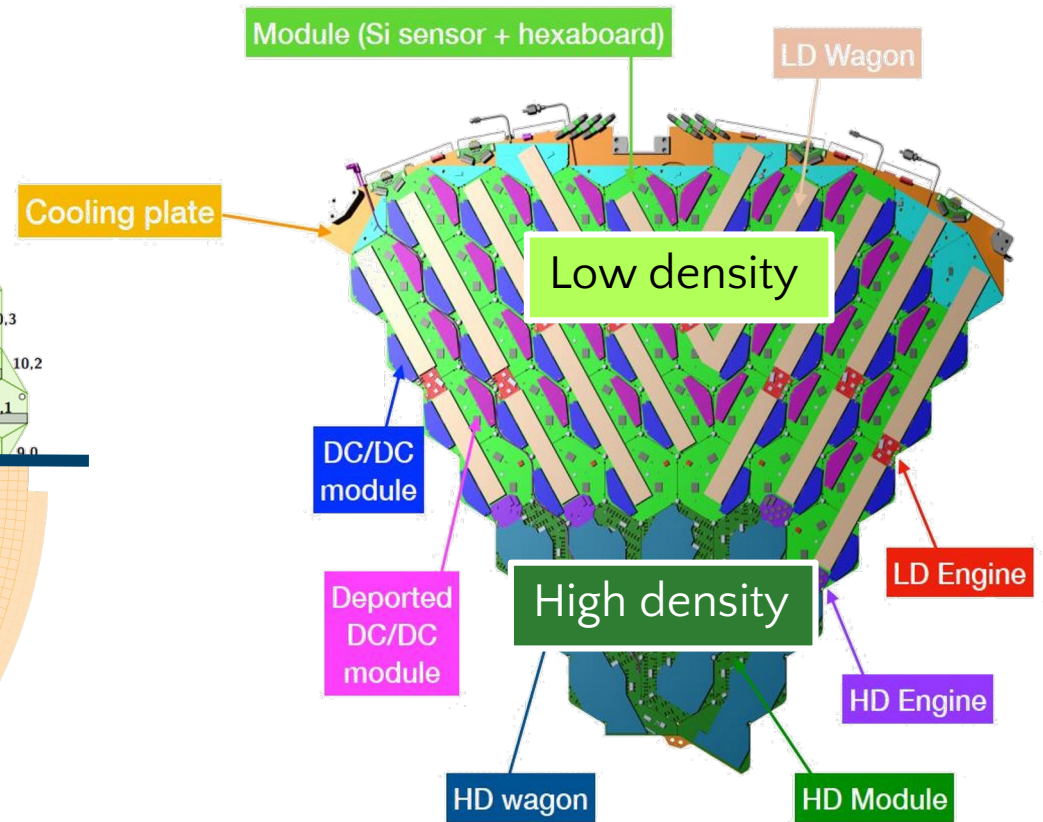
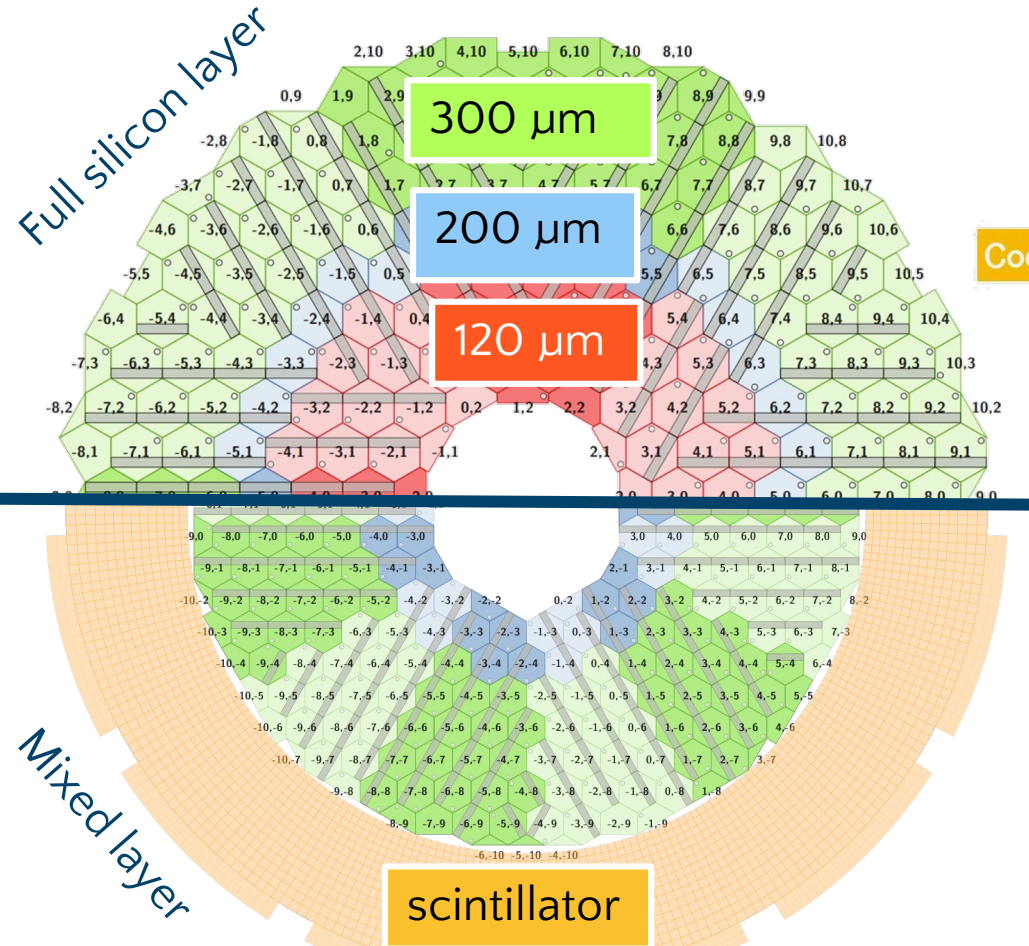
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 - 240k tiles
 - Cell sizes from ~ 4 to 30 cm^2
- Operated at **-35°C**



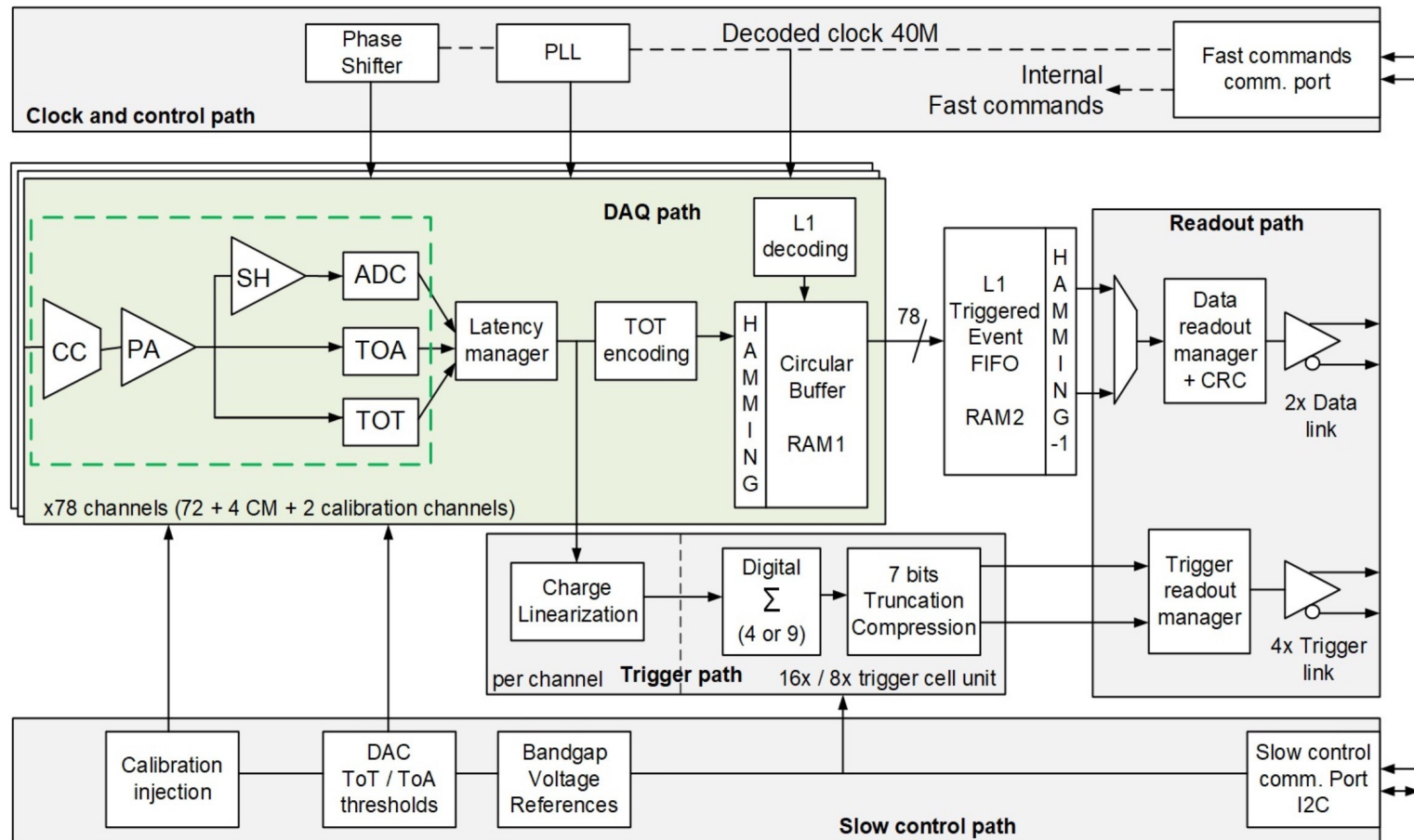
Active layers and front-end electronics





Active layers and front-end electronics

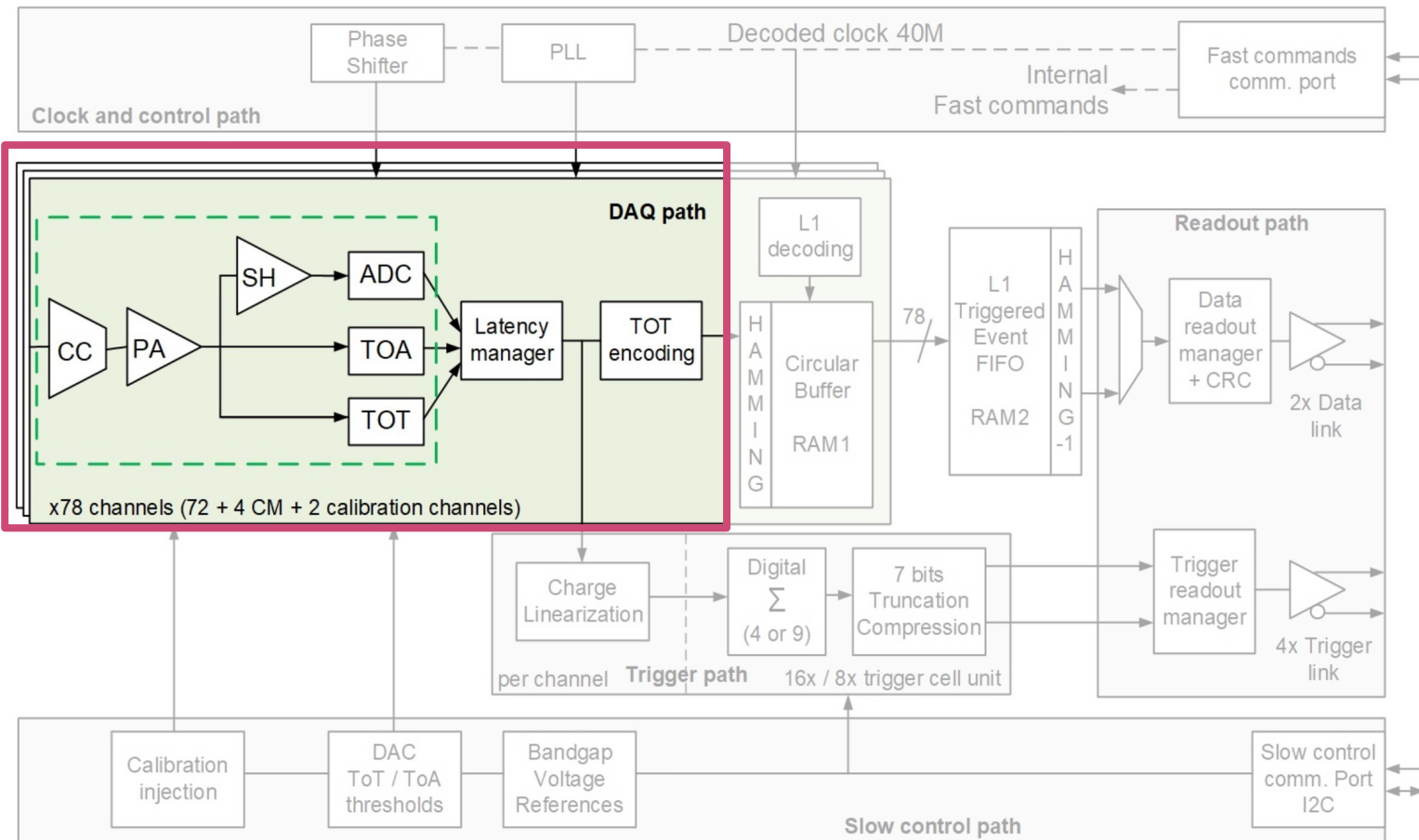


Readout chain: HGCROC



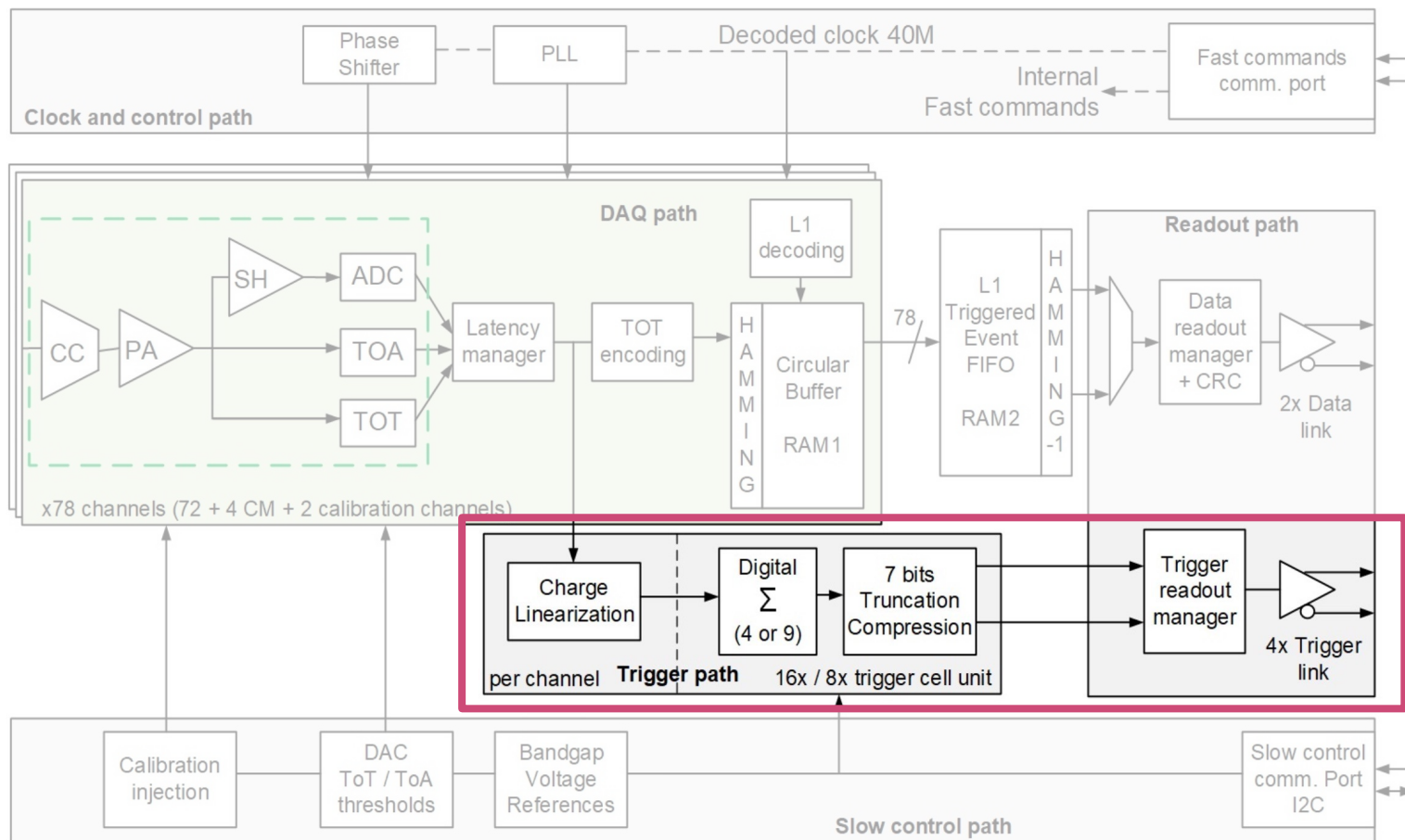
- TSMC 130nm, Analogue and digital parts
-  Wide dynamic range (0.2 fC \rightarrow 10 pC)
-  Fast shaping and precise timing measurement
- 72 channels \rightarrow **3 or 6 HGCROCs per module**

Readout chain: HGCRROC



- Charge / energy measurement
 - **ADC** for small values (typically <100MIP)
 - **ToT** TDC after pre-amplifier saturates
- Time measurement: **ToA** TDC, 25ps LSB

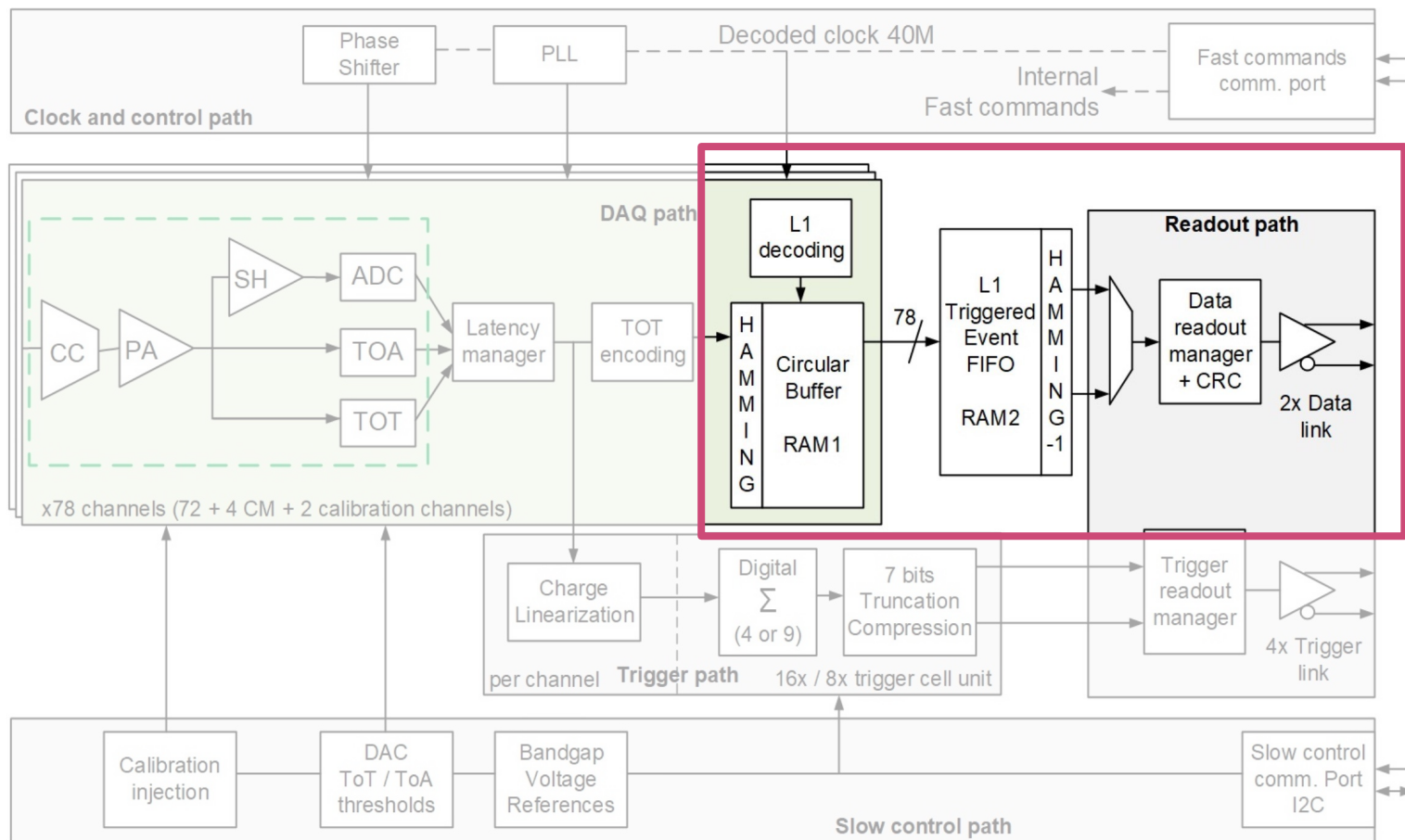
Readout chain: HGCRROC



■ Trigger data @40MHz

- **+** **Sum** of 4 or 9 channels
- **Energy compression** with floating point format

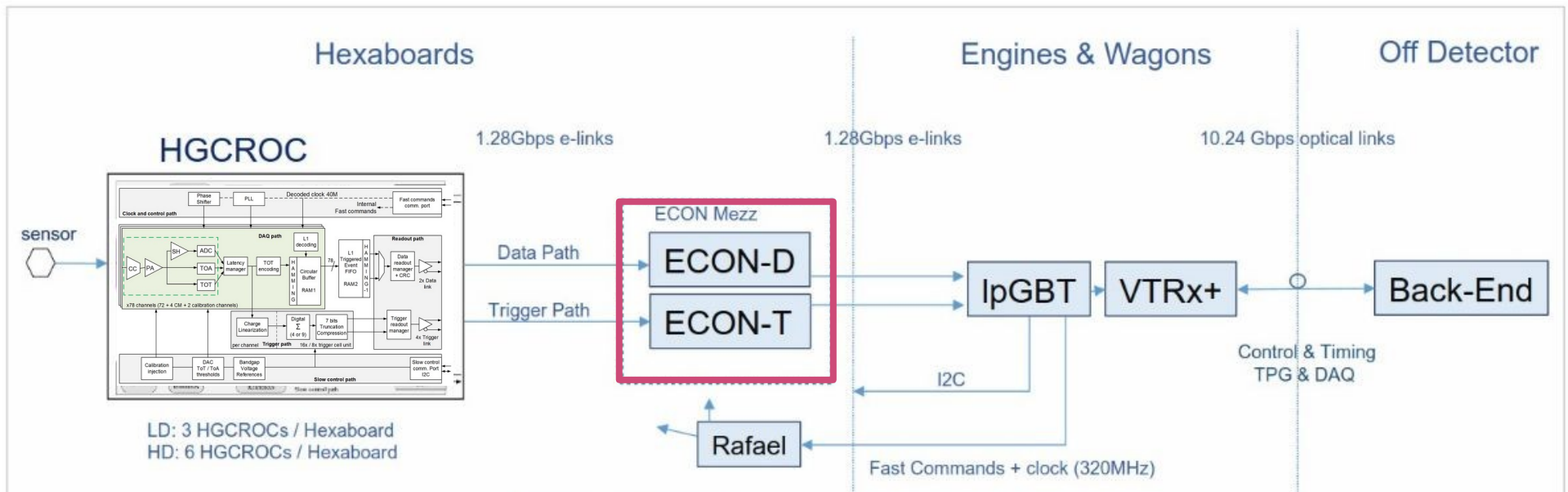
Readout chain: HGCRROC



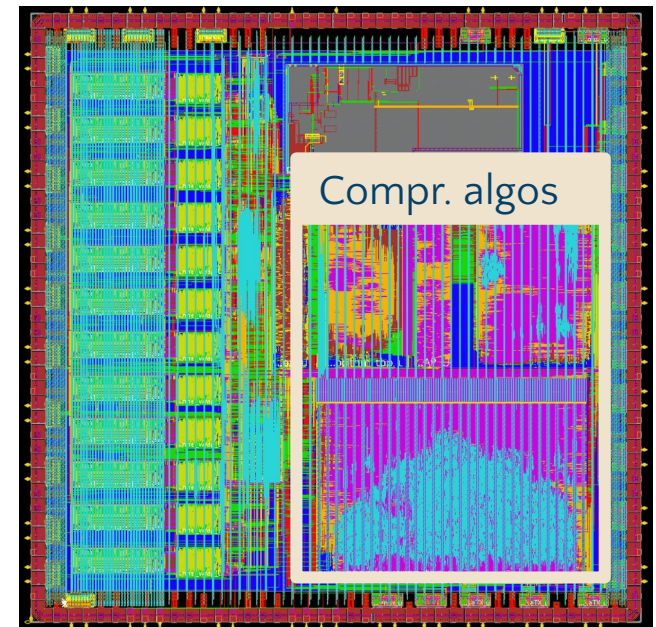
■ DAQ readout

- **Latency** buffers (12.5 μ s)
- **750kHz** average output rate

Readout chain: Concentrators



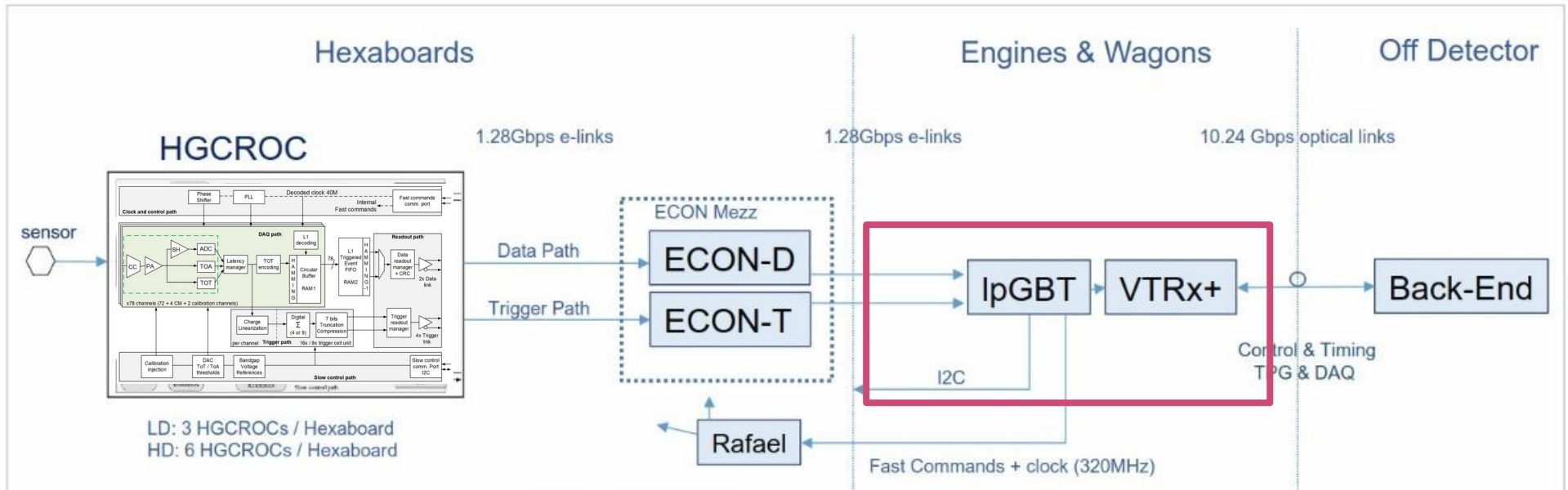
ECON-T



Concentrator chips on mezzanines

- Covering full modules
- ECON-T for trigger data @40MHz, after data **compression algorithms**
- ECON-D for DAQ readout @750kHz (average), **zero-suppressed data**

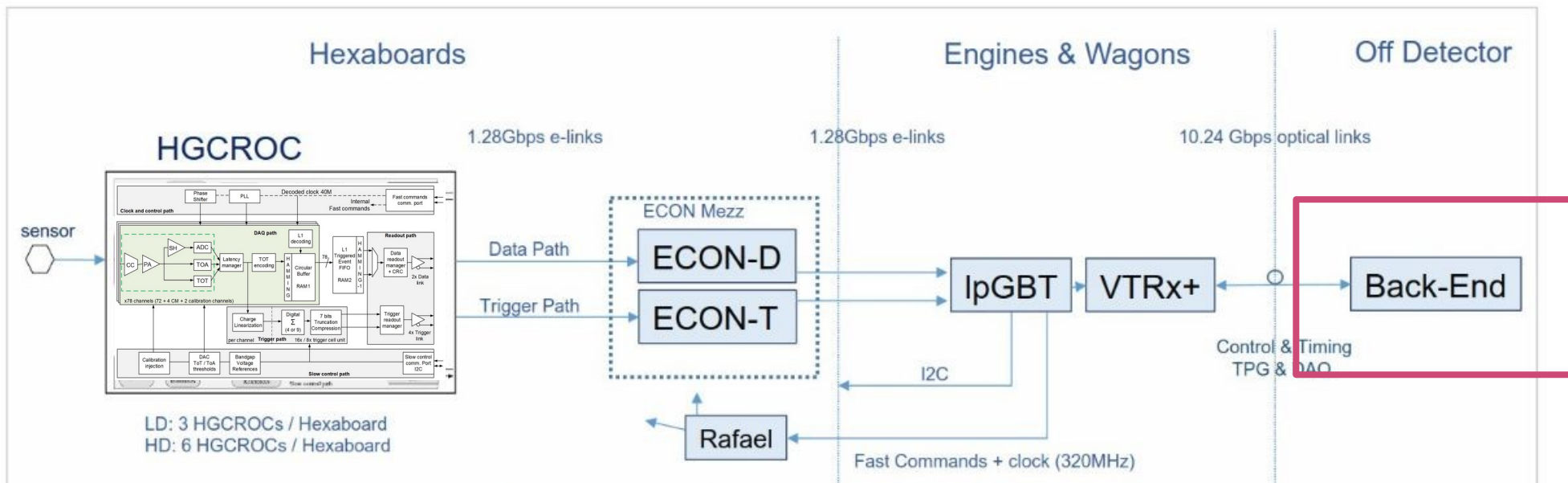
Readout chain: transmission



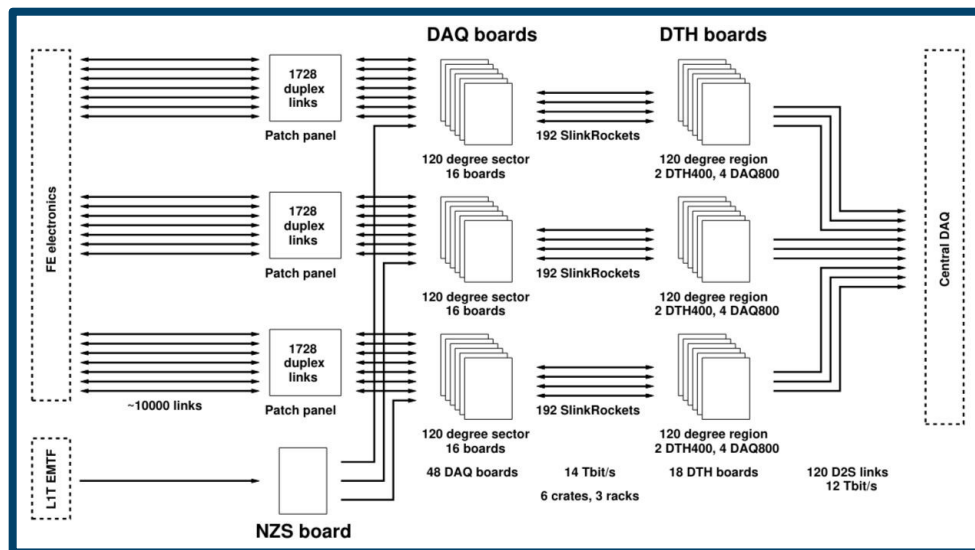
■ Transmission to the Backend electronics

- IpGBT chips & VTRx+ transceivers
- **10.24 Gbps optical links**
- Data transmission + clock, fast commands, slow control

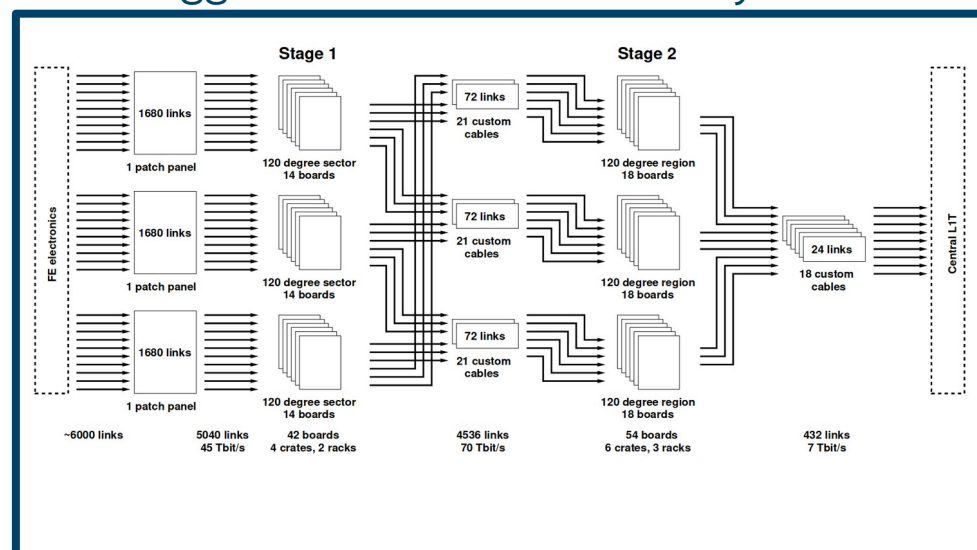
Readout chain: Back-end



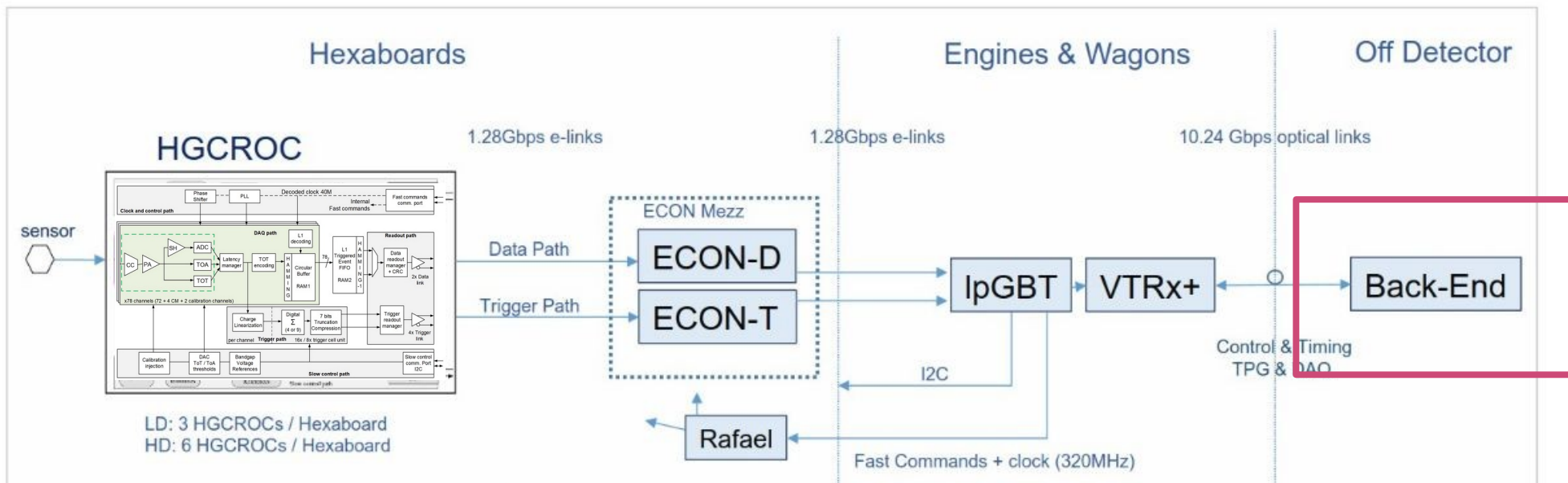
DAQ system



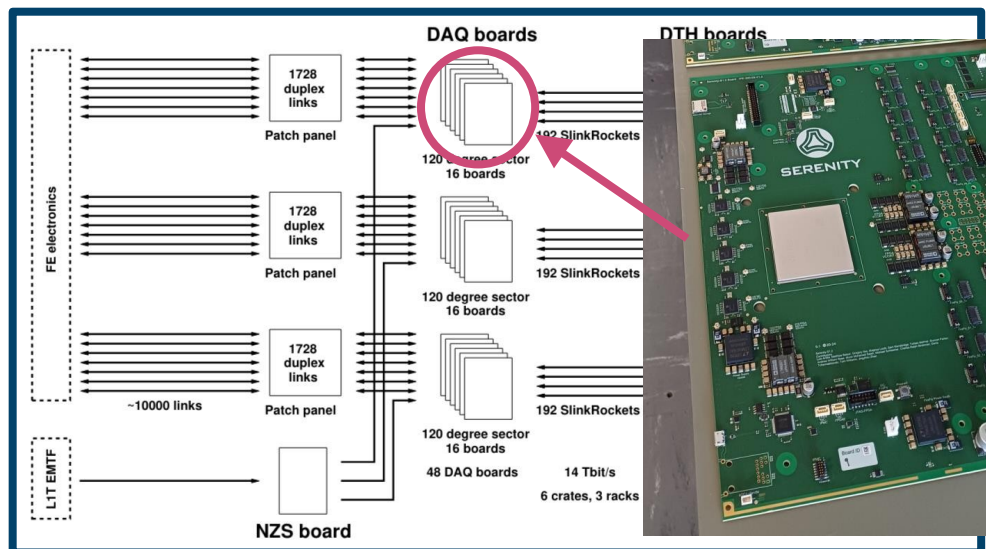
Trigger Primitive Generation system



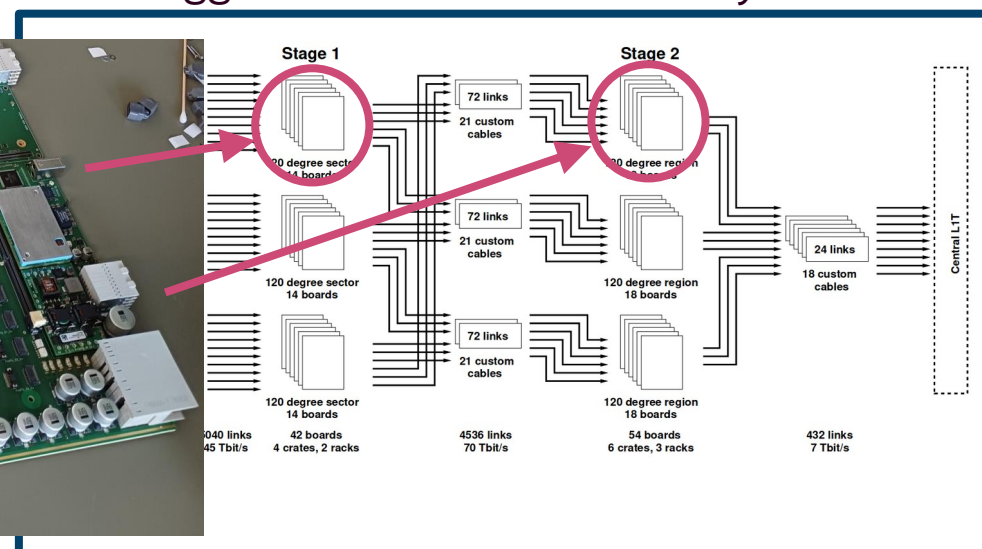
Readout chain: Back-end



DAQ system



Trigger Primitive Generation system

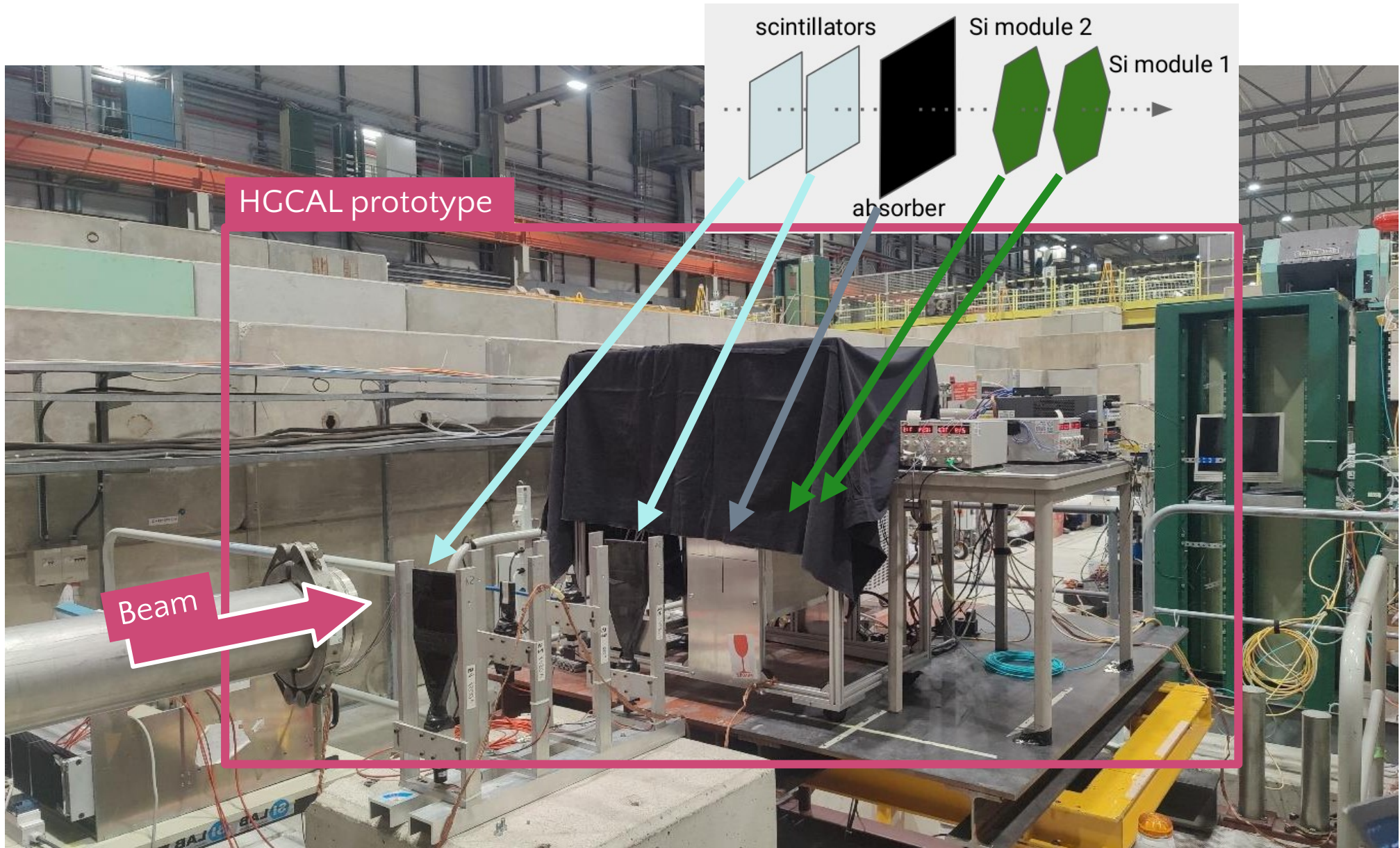


Testing the full chain – 2023 Test Beam campaign

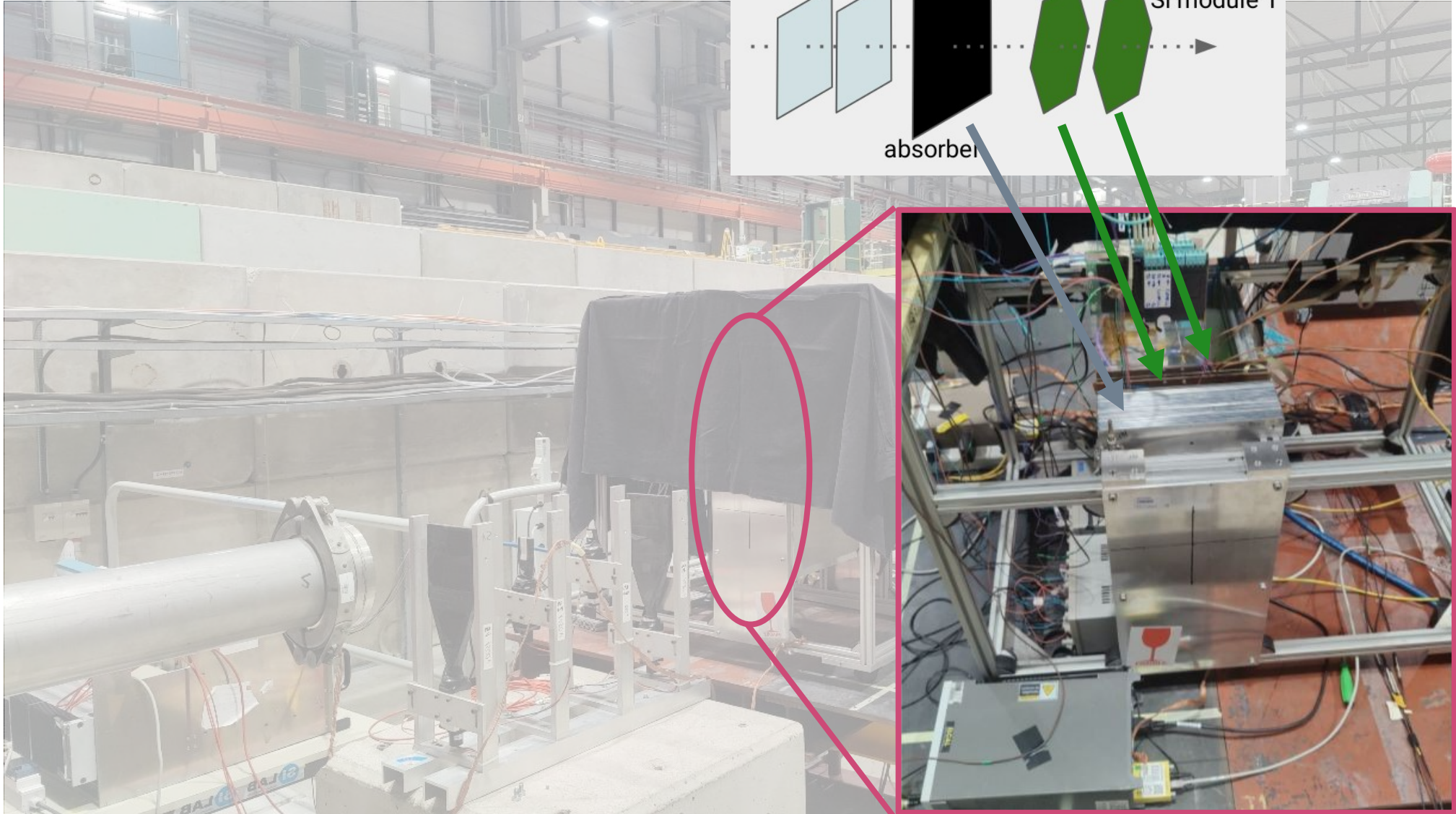
CERN SPS-H4 beam line: pions, muons, electrons



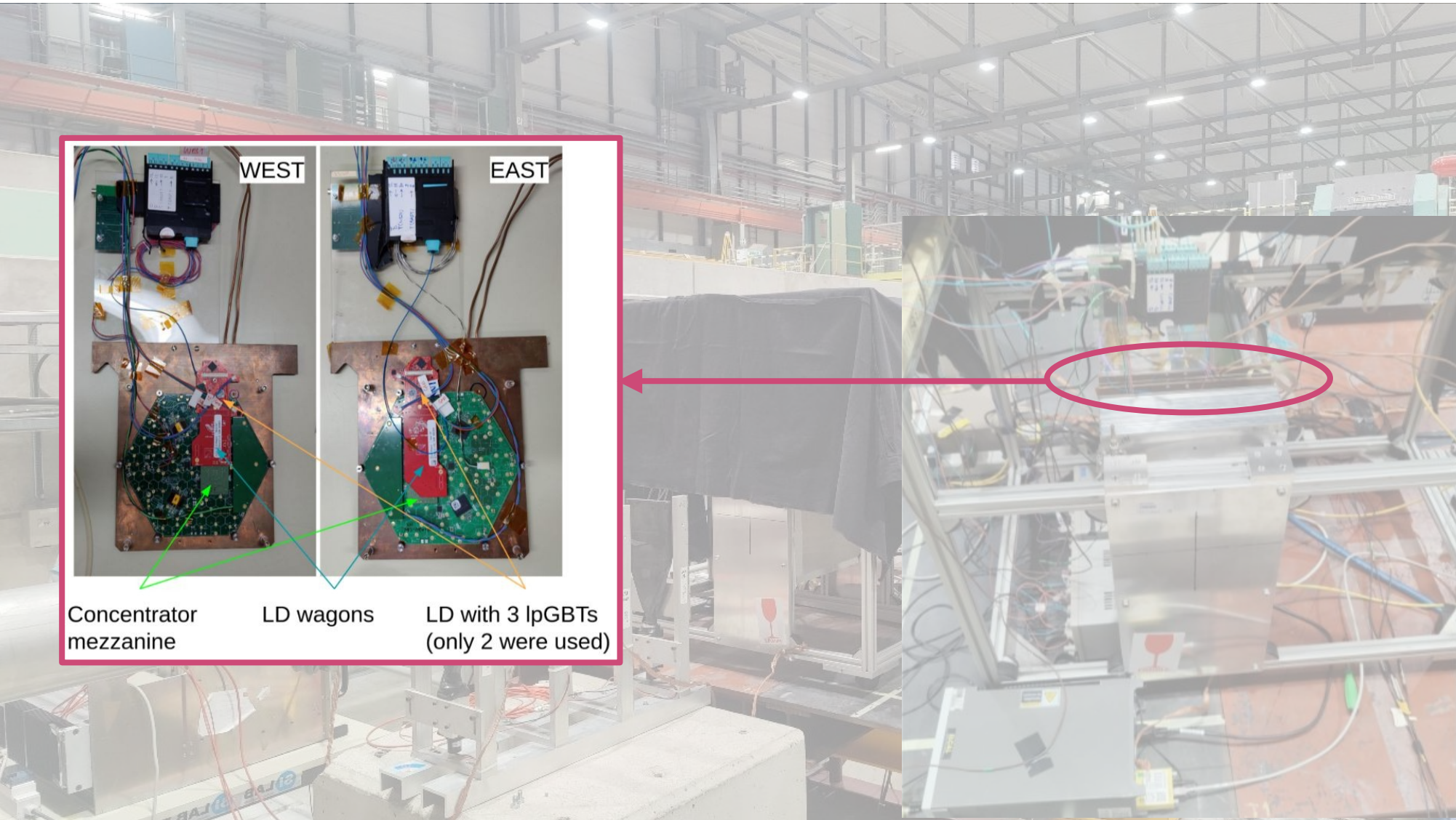
Testing the full chain – 2023 Test Beam campaign



Testing the full chain – 2023 Test Beam campaign



Testing the full chain – 2023 Test Beam campaign

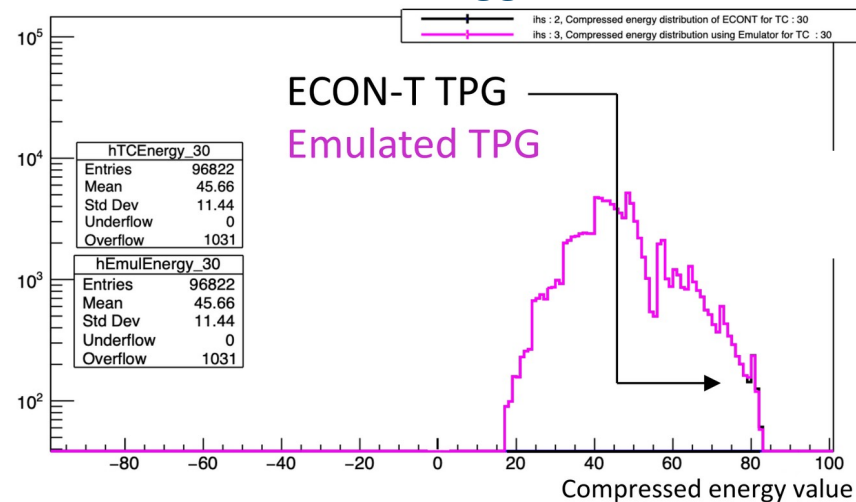


WEST EAST
Concentrator mezzanine LD wagons LD with 3 IpGBTs (only 2 were used)

2023 Test Beam campaign – Selected results

- First test beam with **full vertical readout chain** in place
- Trigger and DAQ path read out **@100kHz**
 - Scintillator and self-trigger
- 2 different ECON-T compression algorithms

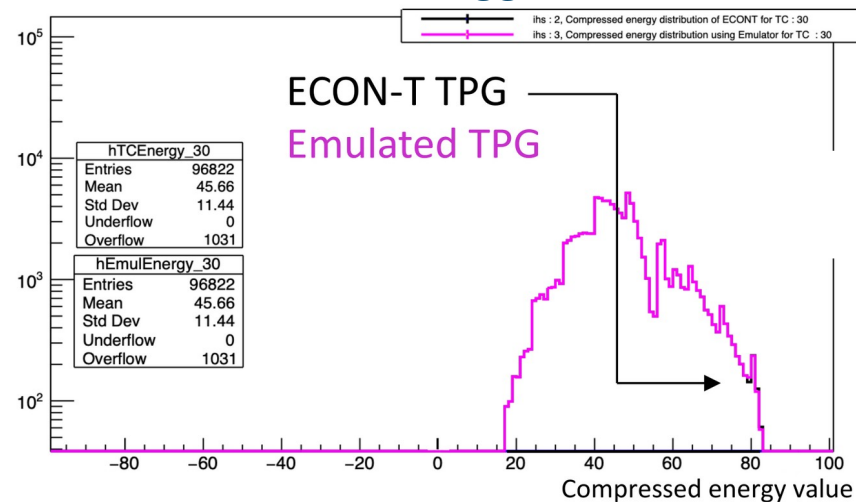
Comparison between acquired and emulated trigger data



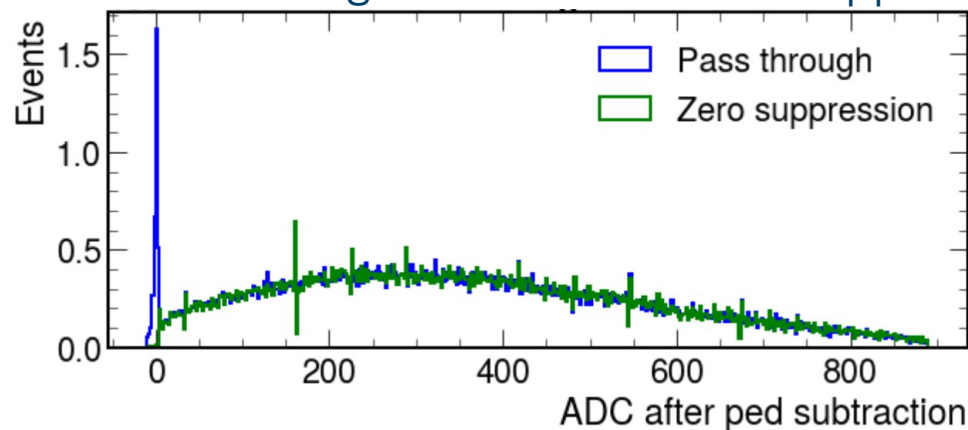
2023 Test Beam campaign – Selected results

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Comparison between acquired and emulated trigger data



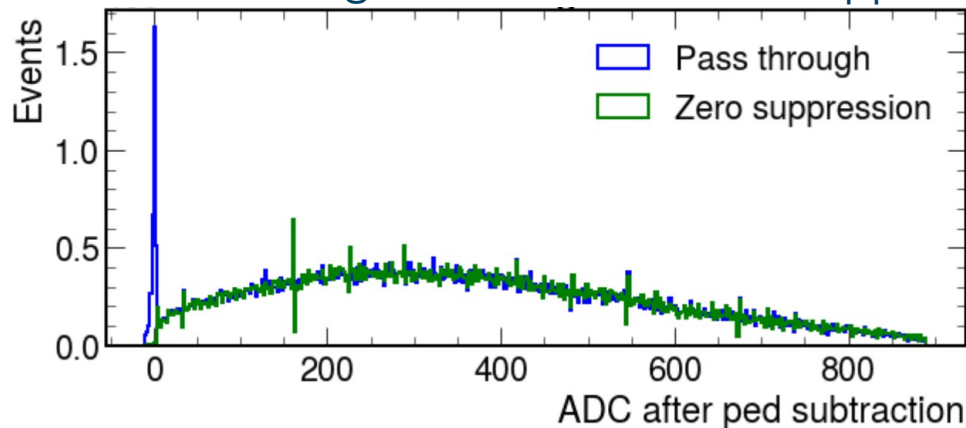
Electron beam signal w/ and w/o zero suppression



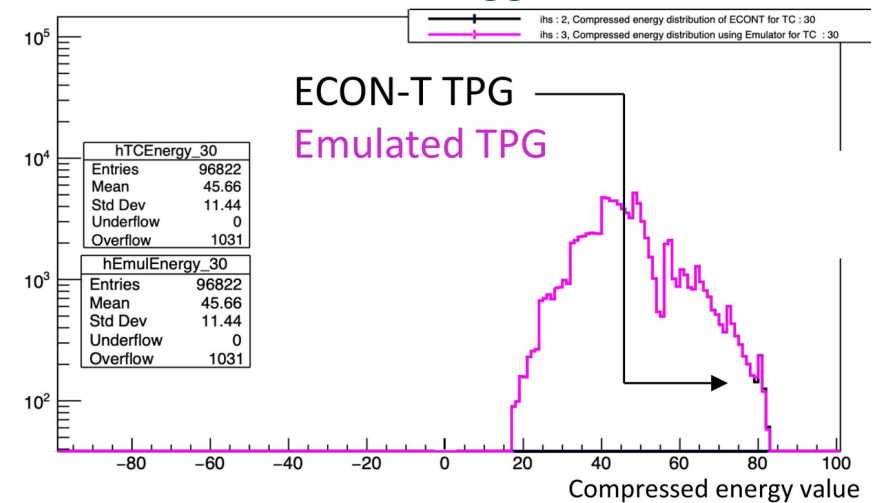
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- 2 different ECON-T compression algorithms
- ECON-D zero-suppression & passthrough modes
- Good S/N within expectation

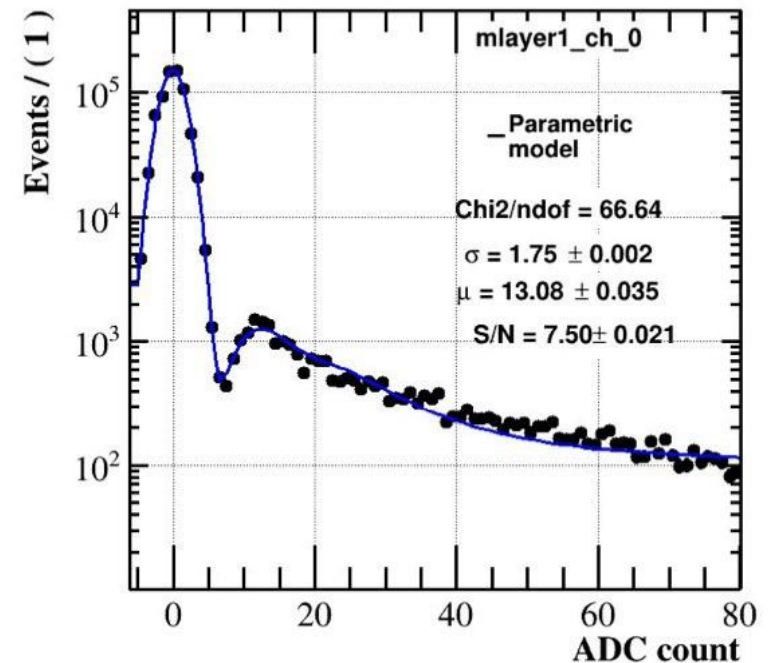
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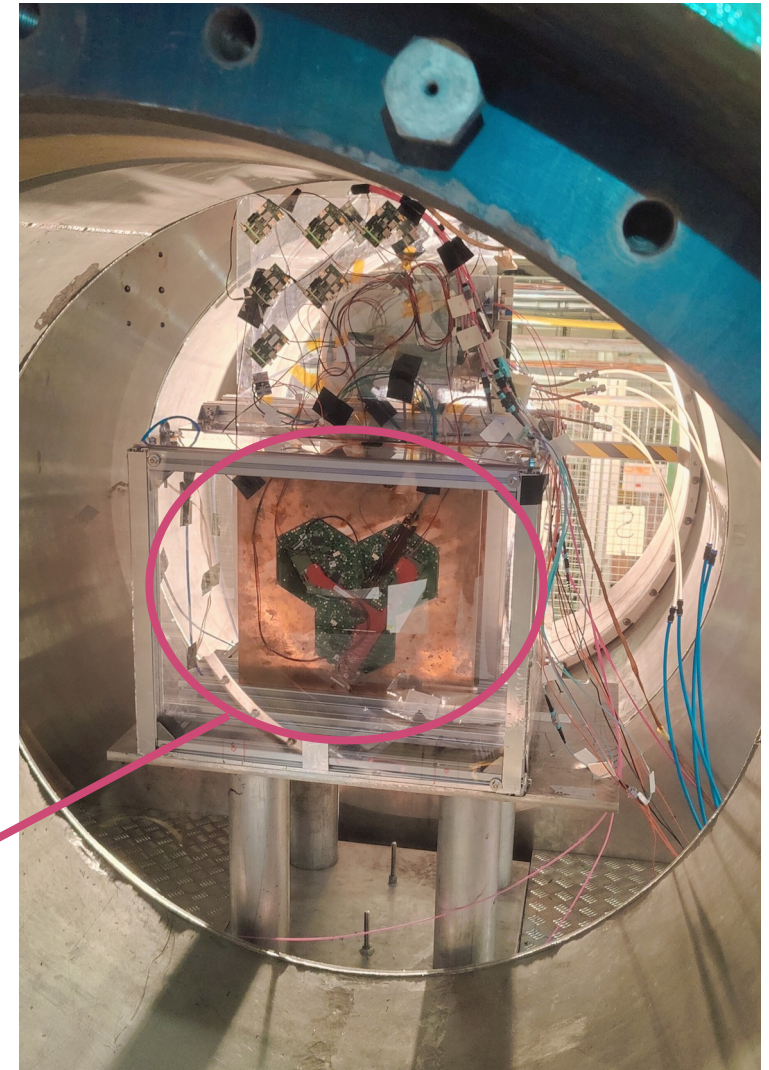
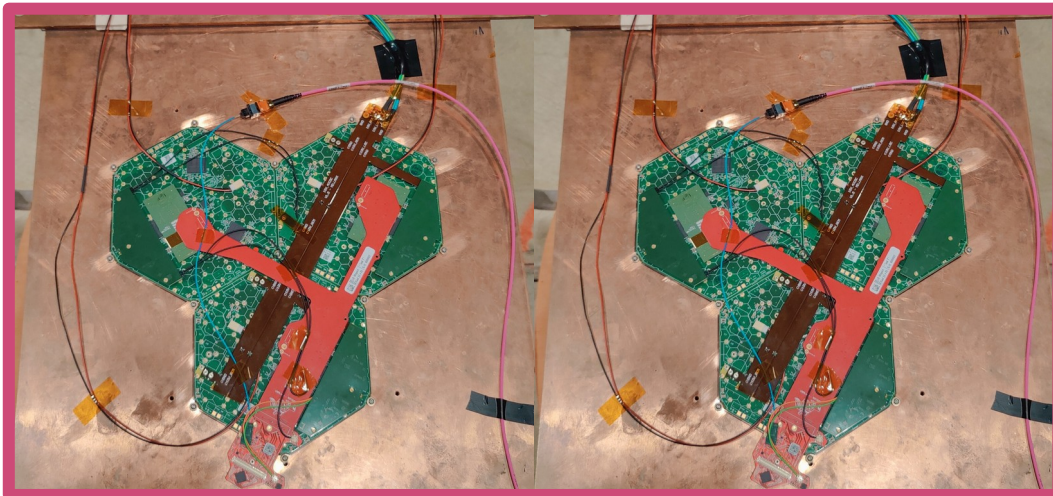


MIP signal from muon beam




Summer 2024 Test beam campaign

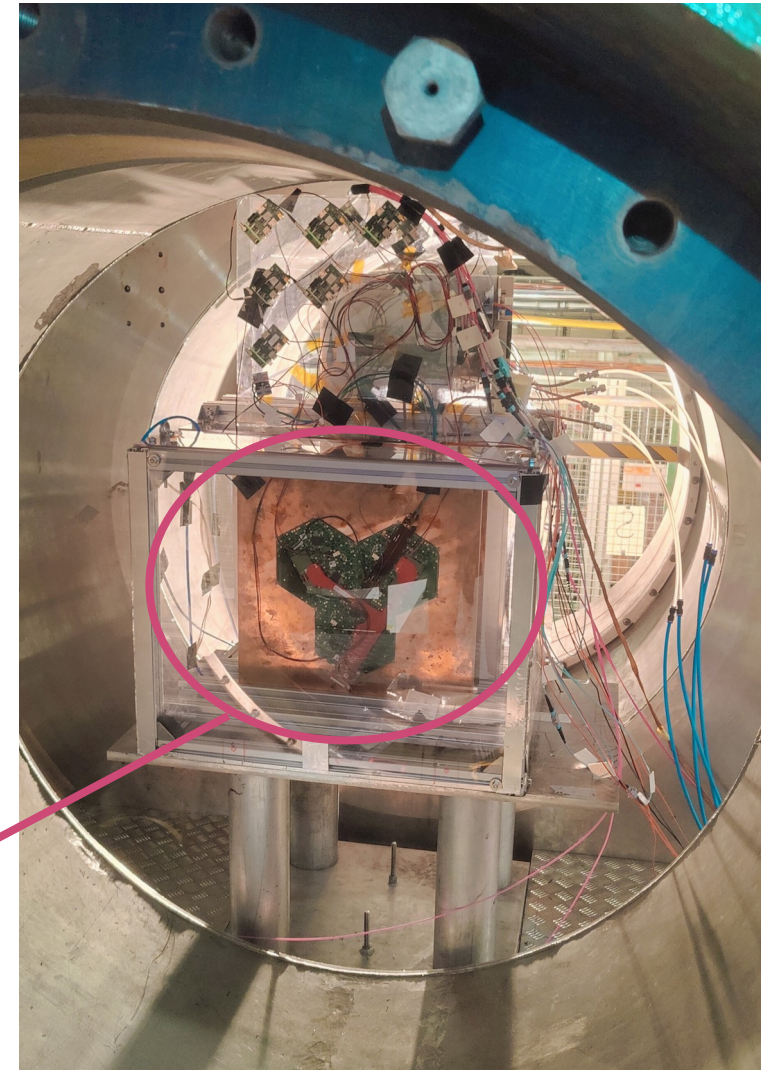
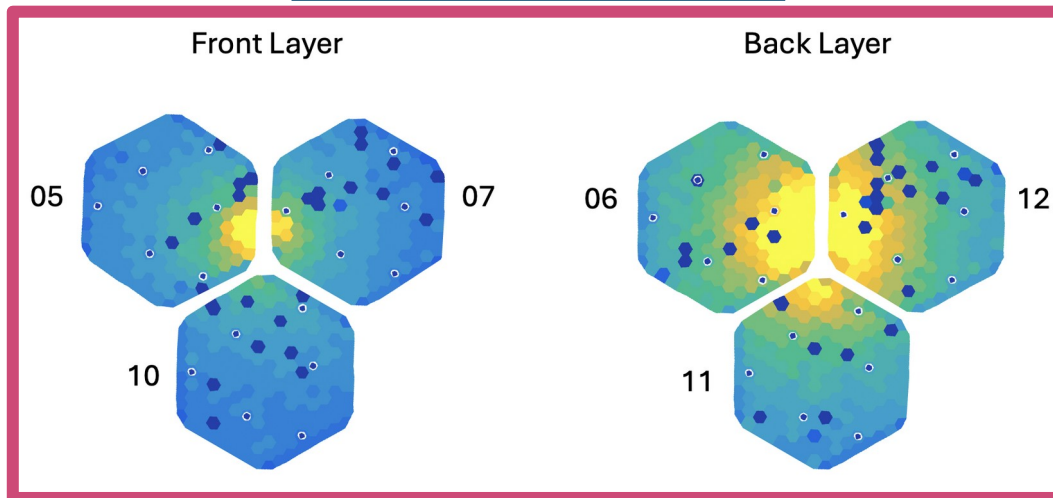
- SPS-H2 beam line
 - muon & electron beams
- **Larger scale system** compared to last year
 - 2 silicon layers w/ 3 modules
 - 2 scintillator tileboards
 - Readout at ~200kHz, and 750kHz tests
-  Operations in **magnetic field** up to 3T



Summer 2024 Test beam campaign

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Standard deviation of ADC counts w/
200 GeV electron beam



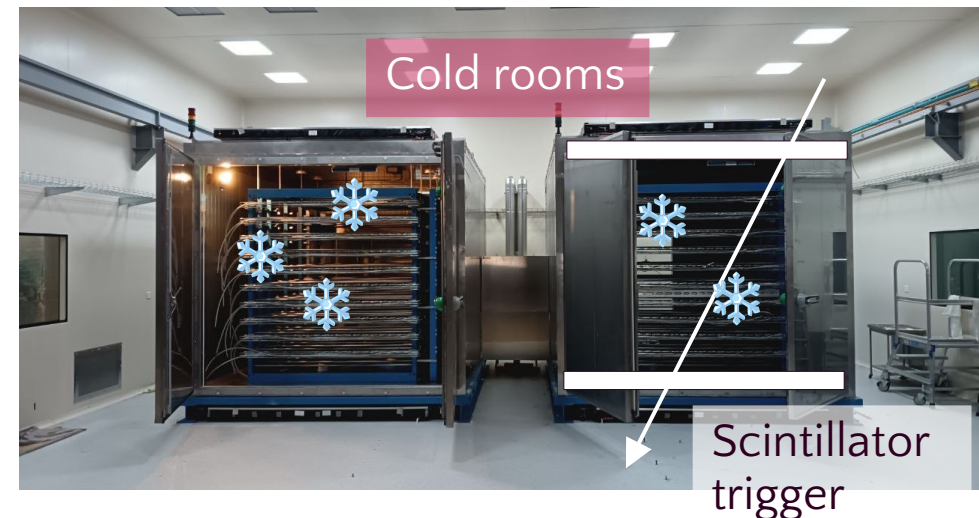
Cassette assembly & testing preparation

- Test beams with full readout chain = first step towards cassette testing
- **Pre-production** cassette assembly schedule in **Jan.-May 2025**
- Ongoing preparation of cassette assembly centers

Fermilab site



CERN site



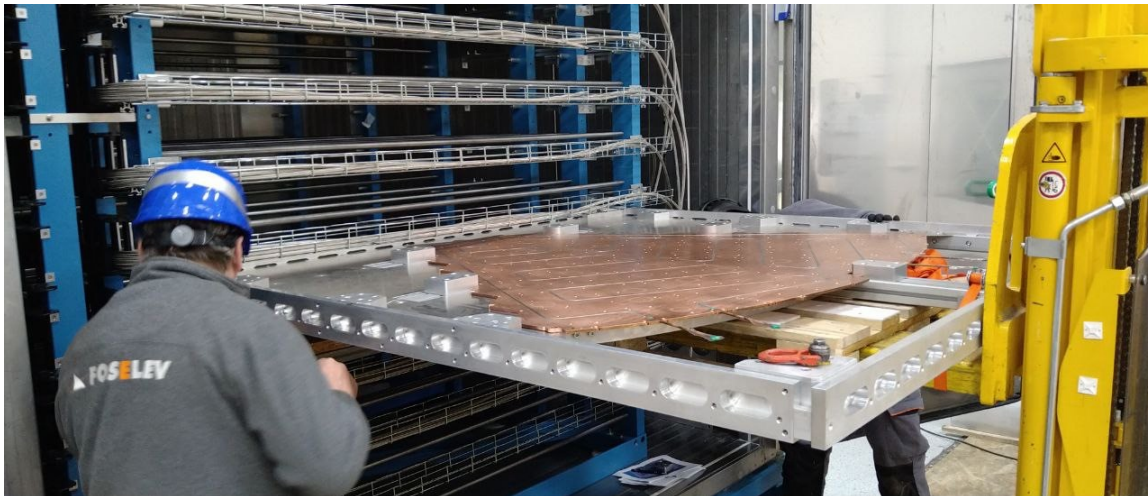
Cassette assembly & testing preparation

- Test beams with full readout chain = first step towards cassette testing
- **Pre-production** cassette assembly schedule in **Jan.-May 2025**
- Ongoing preparation of cassette assembly centers
- Checking components integration, connectivity, assembly process

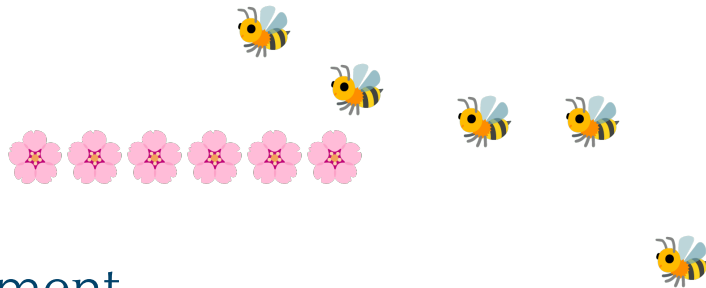
Assembled CE-E cassette mockup



CE-E proto cooling plate inserted in cold box



Outlook: the HGCAL blossom



- Pivotal moment
- Designs becoming reality
- Production ramping up on all fronts
- Assembly of detector structures starting

