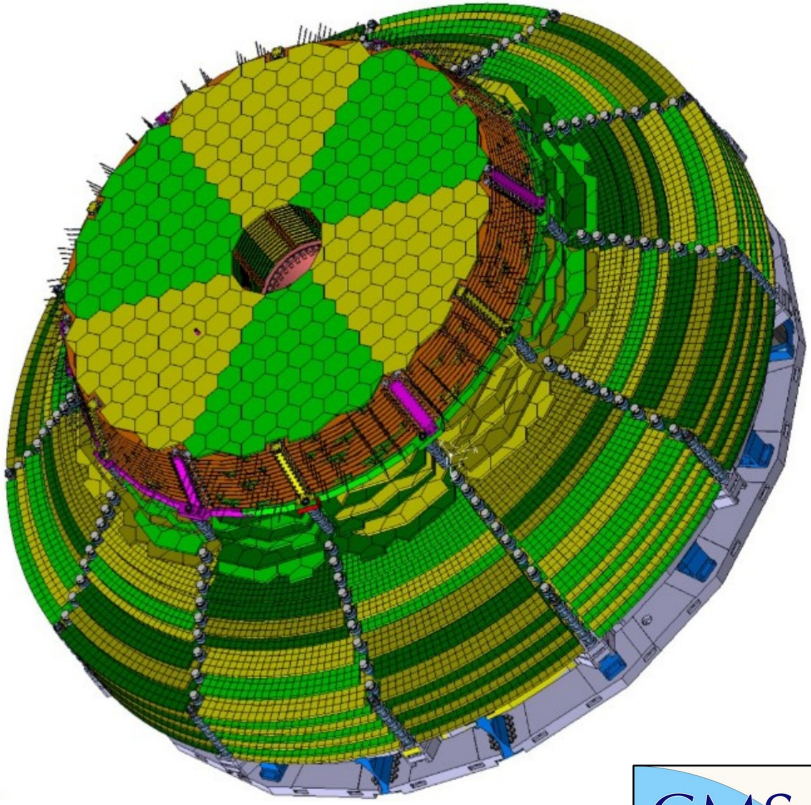
Si & SiPM-on-Tile

in the CMS High-Granular Calorimeter (HGCAL)

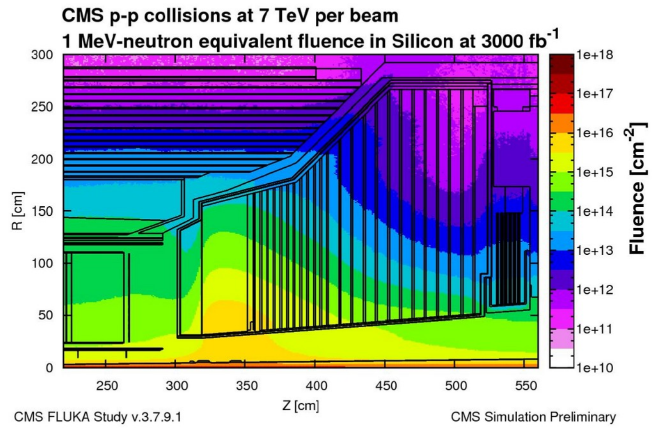


8th FCC physics workshop'25

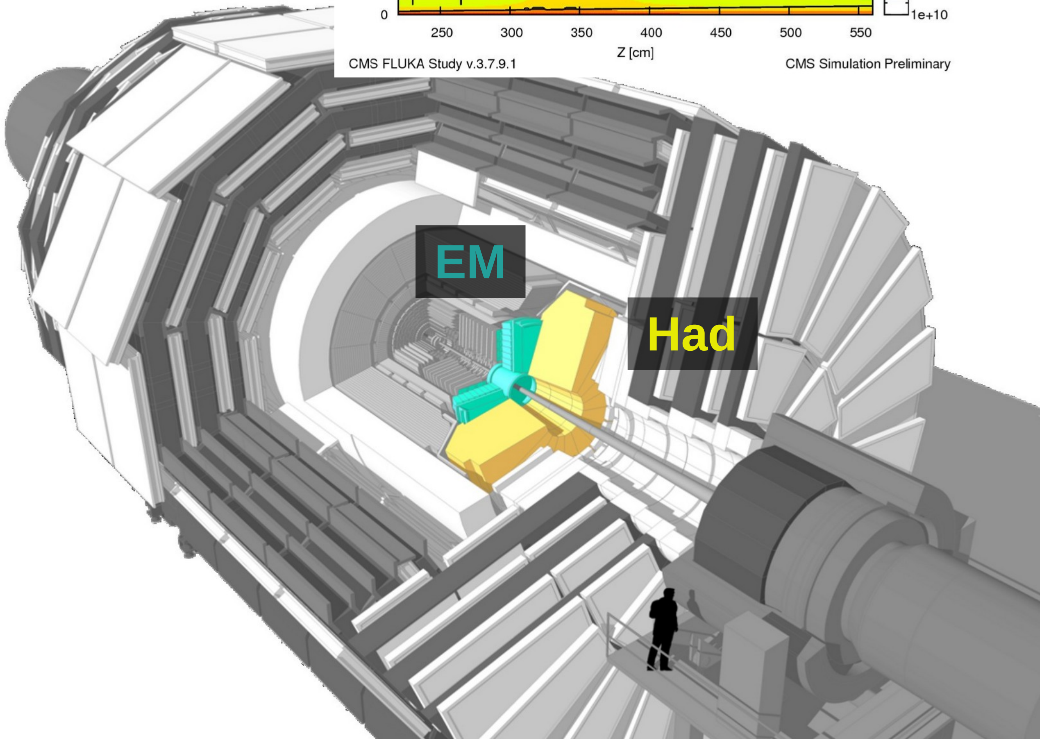
Matthias Komm
on behalf of the CMS Collaboration

Introduction

- HL LHC luminosity will reach $5\text{–}7.5 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  = 4x higher than currently!
- Up to **200 pileup** events expected
- LHC detectors have to be upgraded!

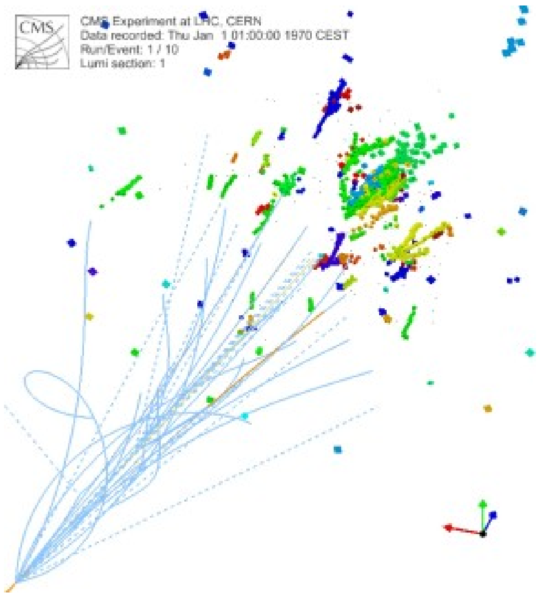


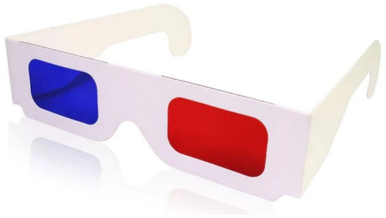
- CMS high granularity calorimeter (HGCAL)
  = **entirely new calorimeter** in both endcaps
  - Covers $1.5 < |\eta| < 3$
  - Electromagnetic & hadron calorimeter parts
  - Finely-segmented & radiation-hard
  - Contributes to event trigger decision

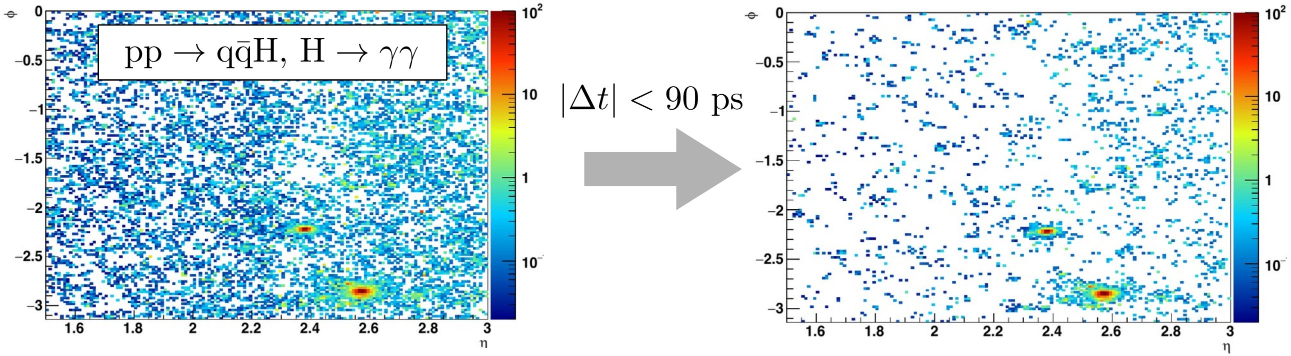


HGCAL records showers in 5D!

- Energy measurement
  - Calibrated using MIP signals
  - Dynamic range: $2\,\mathrm{fC}$–$10\,\mathrm{pC}$
  - Measuring energetic jets: $\mathcal{O}(10k)$ MIPs
- Spatial precision
  - Large number of channels (6M) to resolve shower particles
  - Varying cell sizes: 0.5–$30\,\mathrm{cm}^2$
- Timing precision
  - Important for pileup mitigation
  - Precision: $\mathcal{O}(25\,\mathrm{ps})$ for energetic showers





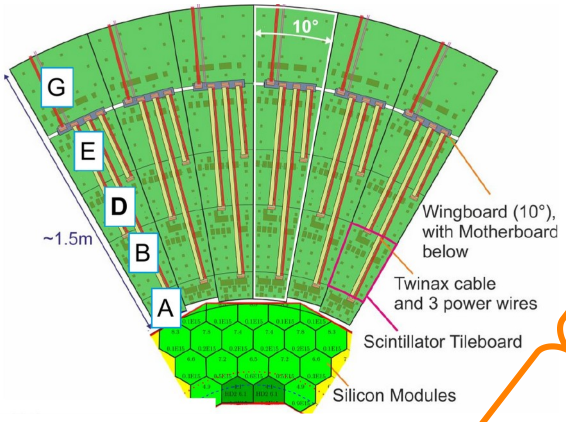


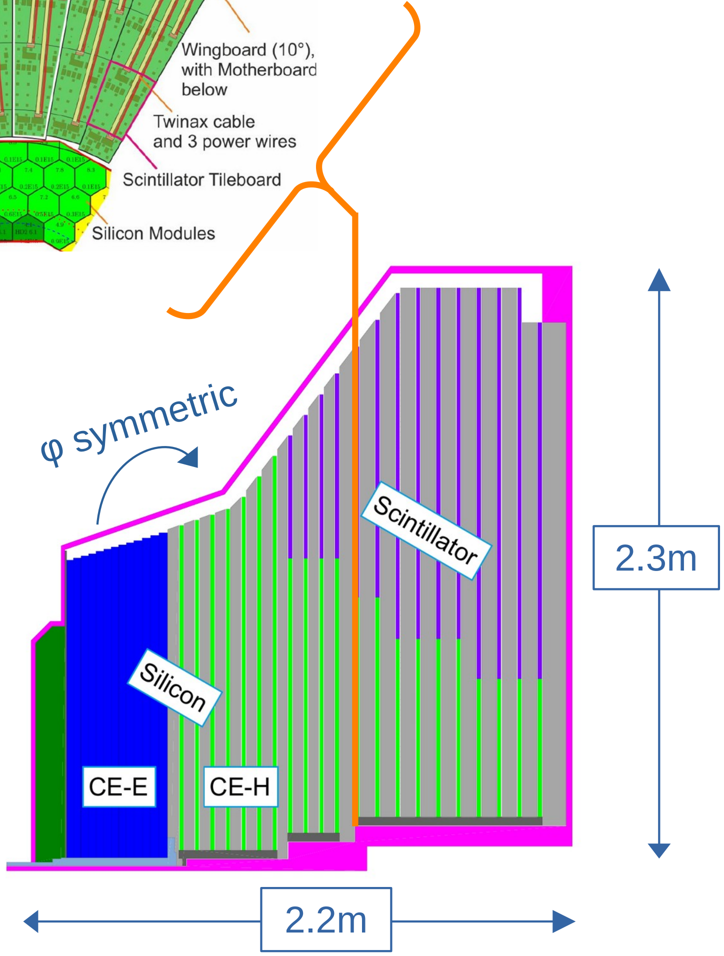
Composition

- CE-E: Electromagnetic calorimeter
  - **Hexagonal silicon modules**
  - Cu, CuW, Pb absorbers, 26 layers ($\approx 28X_0$)

- CE-H: Hadronic calorimeter
  - Hexagonal silicon modules (similar as CE-E)
  - **Scintillator tiles** in regions with lower radiation (< $5 \cdot 10^{13} \mathrm{n/cm}^2$) w/ silicon photomultipliers (SiPMs) for readout
  - Cu/Steel absorbers, 21 layers ($\approx 10\lambda$ including CE-E)

- Key parameters
  - 6M silicon channels from 26k modules (620m^2)
  - 240k SiPM-scintillator channels from 3.7k tileboards (370m^2)
  - Cooled to -30°C using two phase CO_2 cooling
  - 220t per endcap



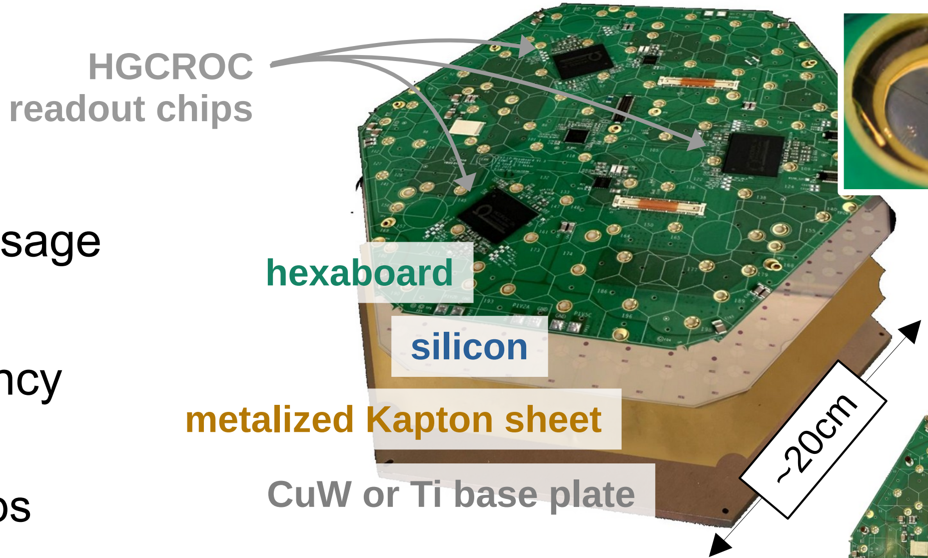


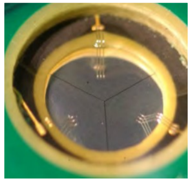
Silicon modules

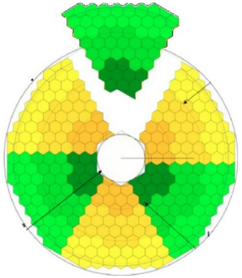
- Hexagonal shape to maximize wafer usage

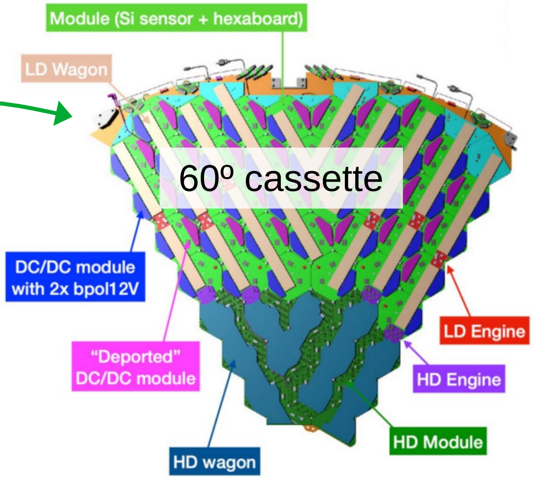
- Two major layouts to equalize occupancy
  - High-density (HD): 432 channels
    $0.5\,\mathrm{cm}^2/\mathrm{pad}$; 6 HGCROC readout chips
  - Low-density (LD): 192 channels
    $1.2\,\mathrm{cm}^2/\mathrm{pad}$; 3 HGCROC readout chips
  - 9 partial layouts for edges

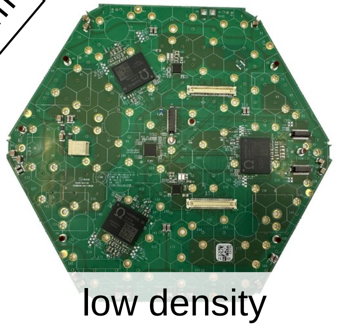
- Complex 6-fold rotational geometry

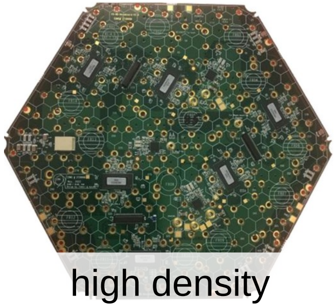








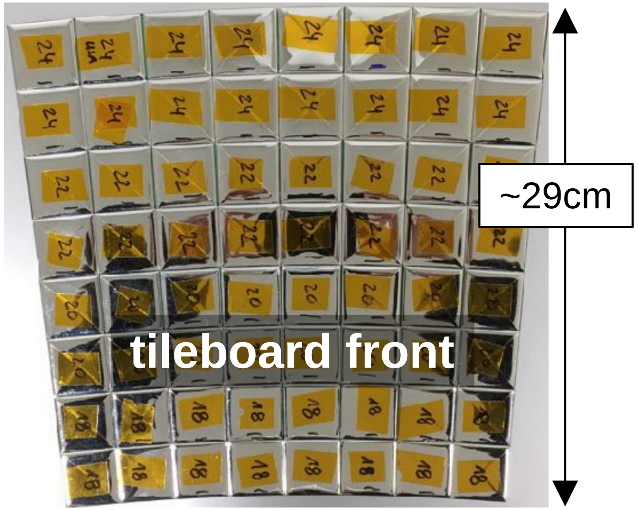




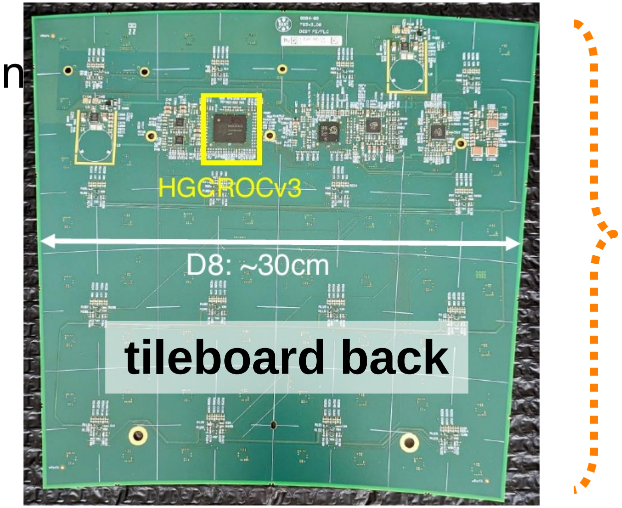
SiPM, Tiles & Boards

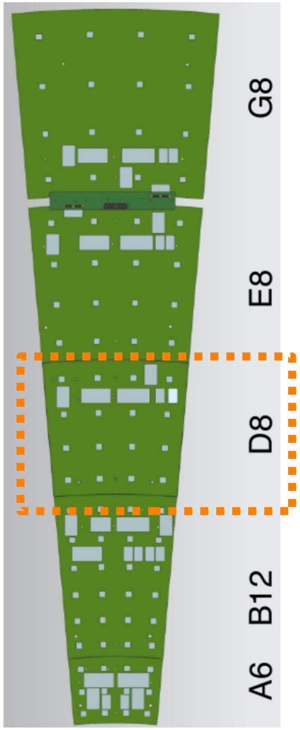
SiPM-on-tile originally developed by CALICE for e^+e^-

- Trapezoidal scintillator tiles (1.25°)
  - Wrapped in reflecting foil
  - 3mm thickness
  - Size increases radially from 2 to 5.5cm
  - Cast/machined or injection-molded
- SiPMs
  - Radiation-tolerant & low dark-rate after irradiation
  - High photon detection efficiency
  - Includes UV-LED system for initial calibration
- Tile boards
  - 8 main geometrical form factors
  - Typically 8 x 8 = 64 tiles/SiPMs per board (requires only 1 HGCROC readout chip)

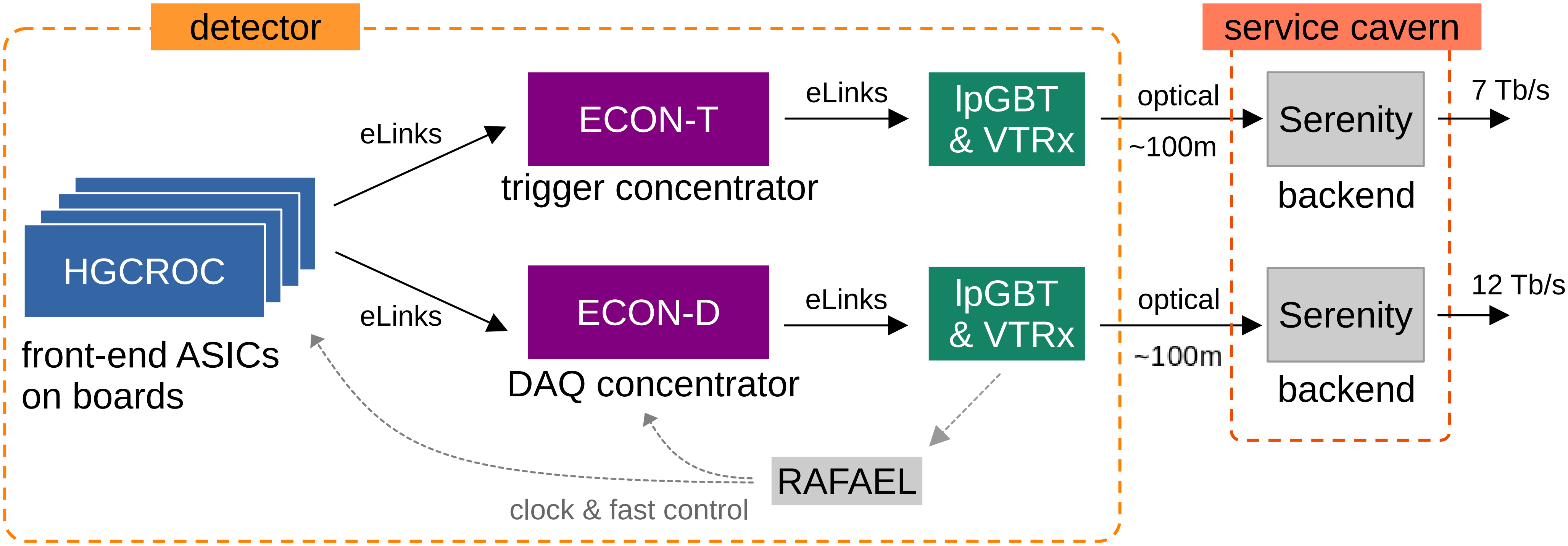


MPPCs





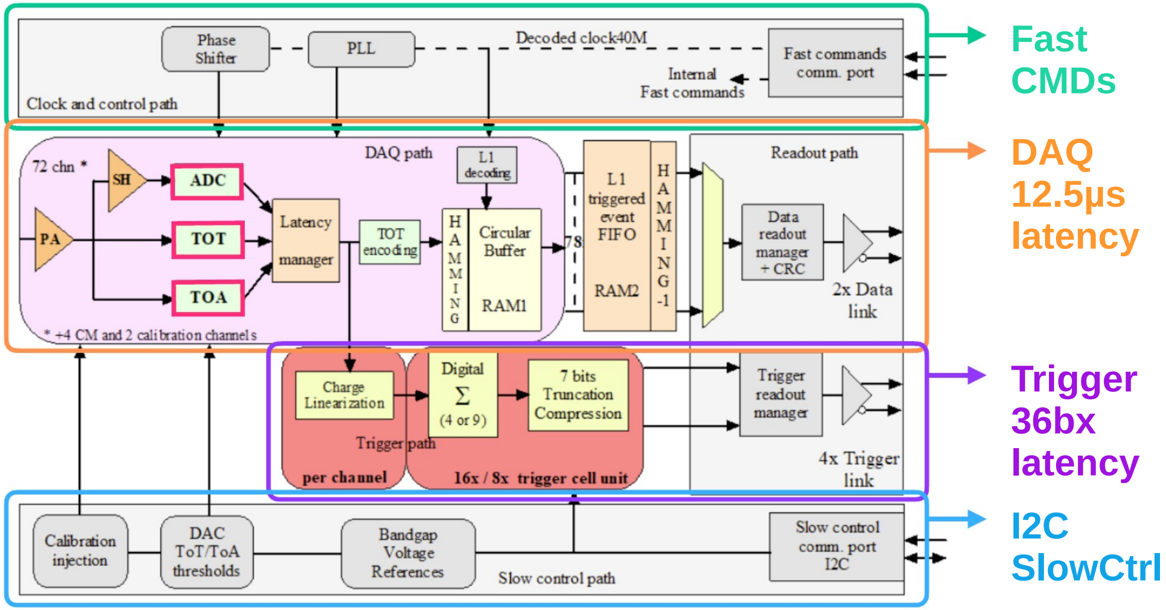
Overview: DAQ & trigger data flow



- Shared readout chain between silicon and SiPM-on-tile modules
- Trigger links continuously readout at 40MHz
- DAQ links read only on positive trigger decision (~750kHz)
- eLinks operate at 1.28 Gb/s; optical links at 10.24 Gb/s; 100 Gb/s data-to-surface links (120x)

HGCROC: Front-end readout ASIC

- Developed by ΩMEGA Microelectronics
- Digitizes charge & time information
- Up to 72 channels in two chip halves
- Chip configured via I2C
- Clock (320MHz) & trigger signals received via fast control
- 3x 10b signals (ADC, TOT & TOA)
- Compute energy sums for trigger decisions (2x2 or 3x3 cell sums)
- Adjustable gain
- Charge injection for calibration
- Outputs: 2 DAQ & 4 trigger eLinks



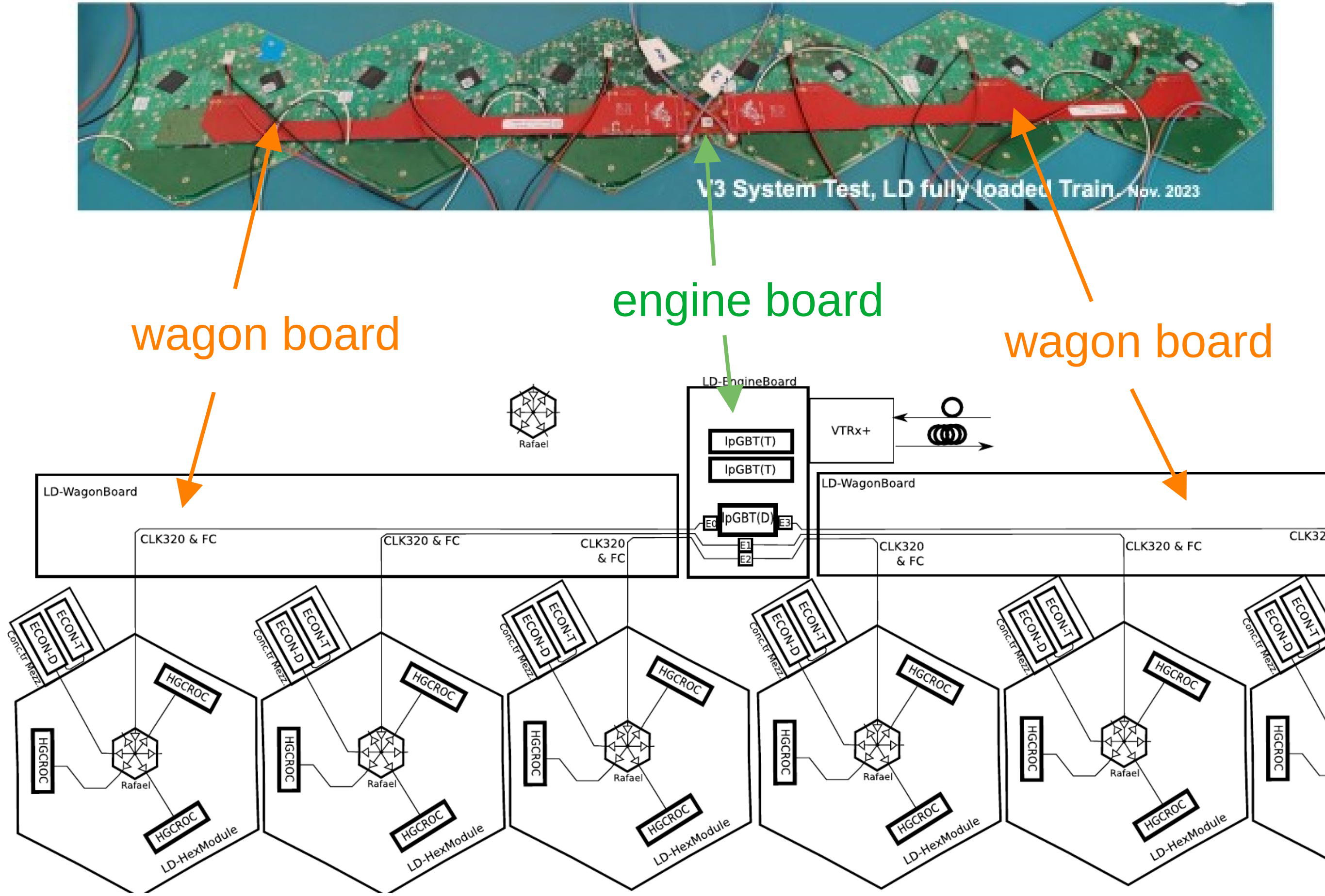
Engines & Wagons for silicon modules

- Modular design

- Passive (LD)/active (HD) **wagon board** connects 1–3 modules
- various shapes as needed

- **Engine board** connects 2 wagon boards
- single design for all

- **Concentrators** (ECONs) apply zero-supression & compress DAQ/trigger data



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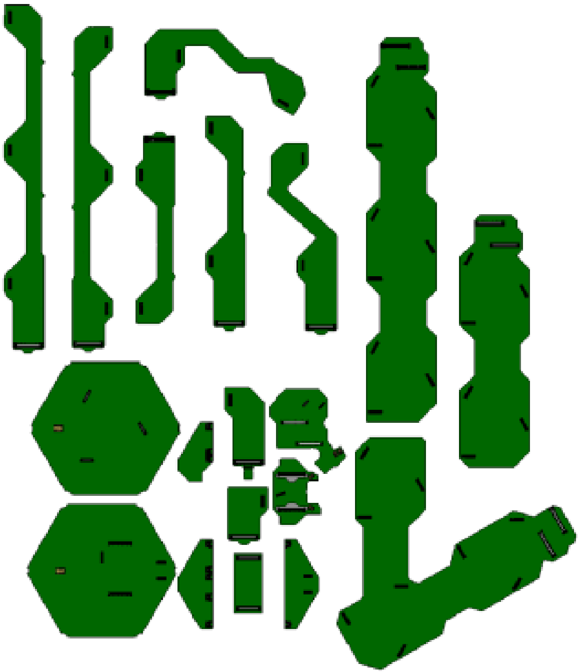
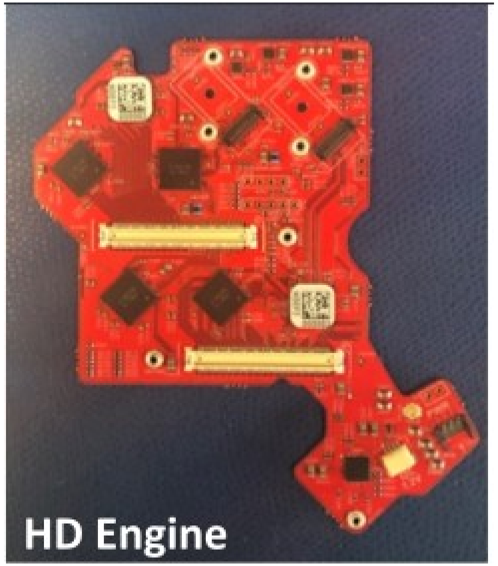
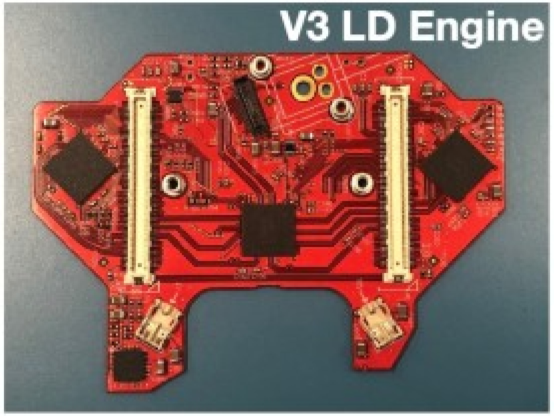
complex PCB designs

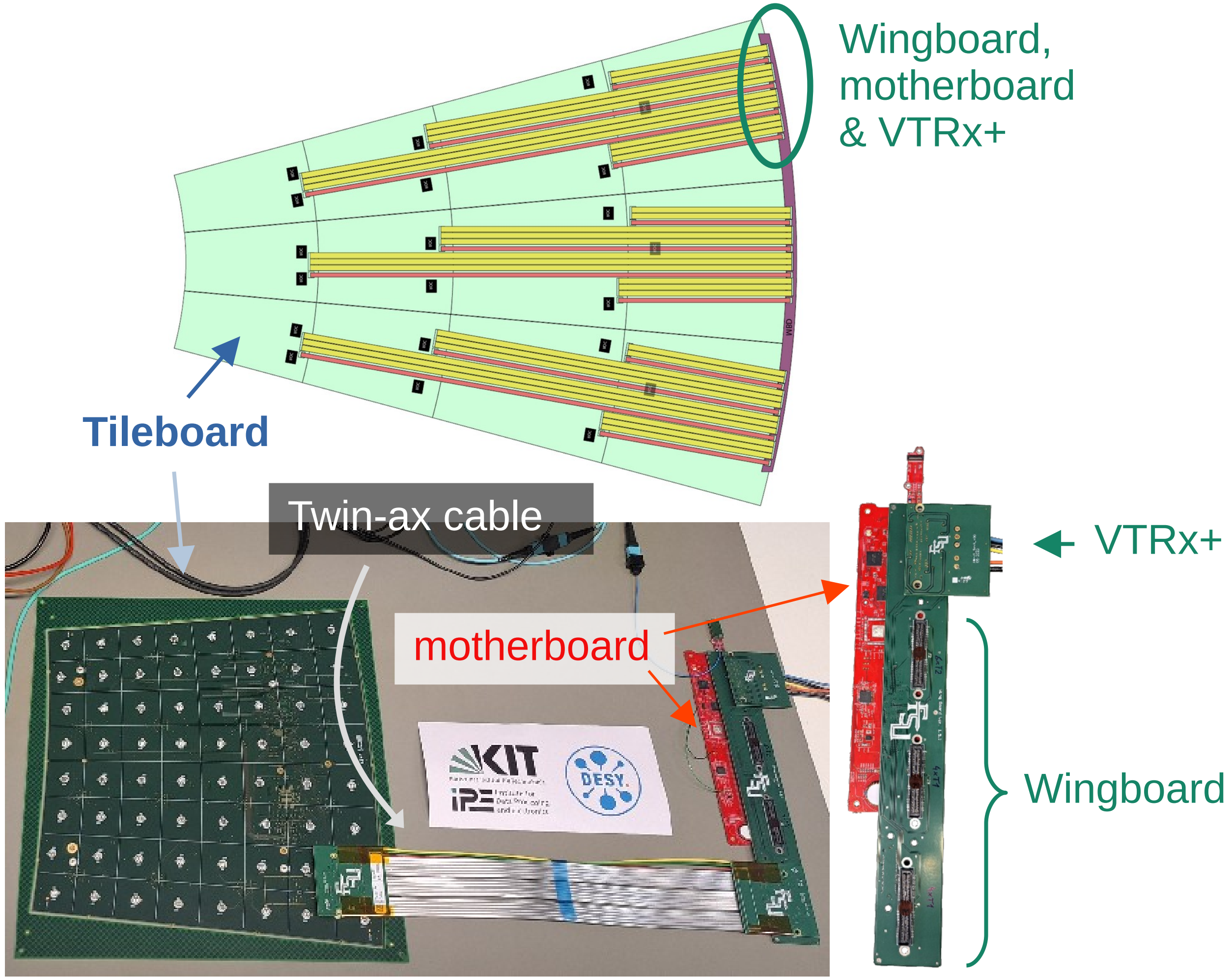






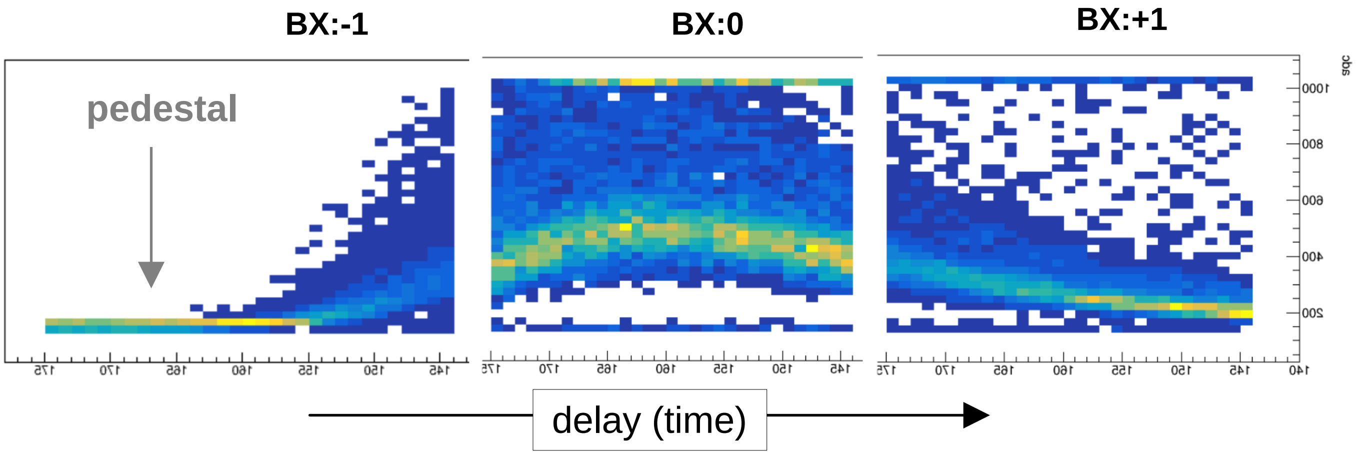
Wingboard & Motherboard for tilemodules

- Passive wingboard connects to 5 tileboards radially via Twin-ax cables
- Motherboard with concentrators (ECONs)
- Optical link via VTRx+ to backend (Serenity)

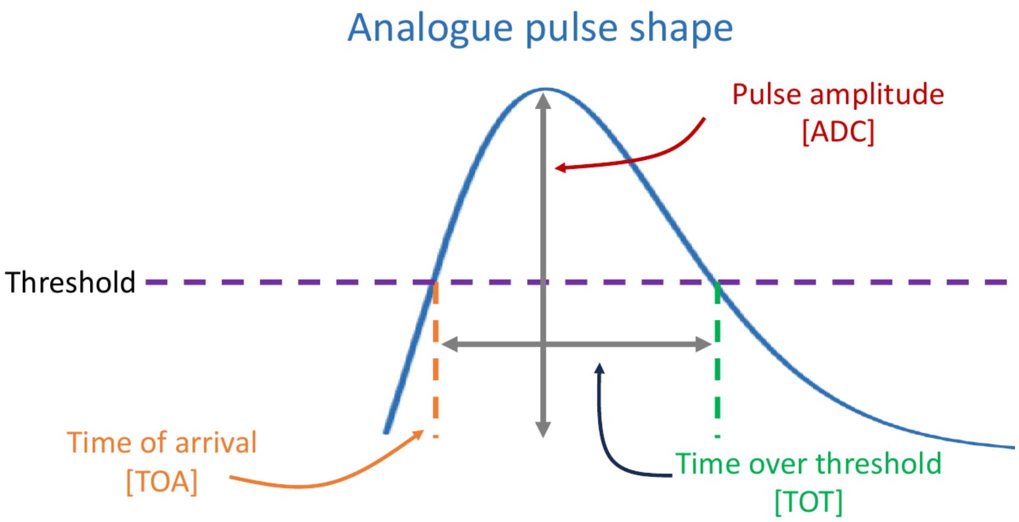


SiPM module during testbeam

- MIP pulse shape
  - Here: read out time stamp from beam trigger system
  - MIP signal visible across 3 bunch crossings

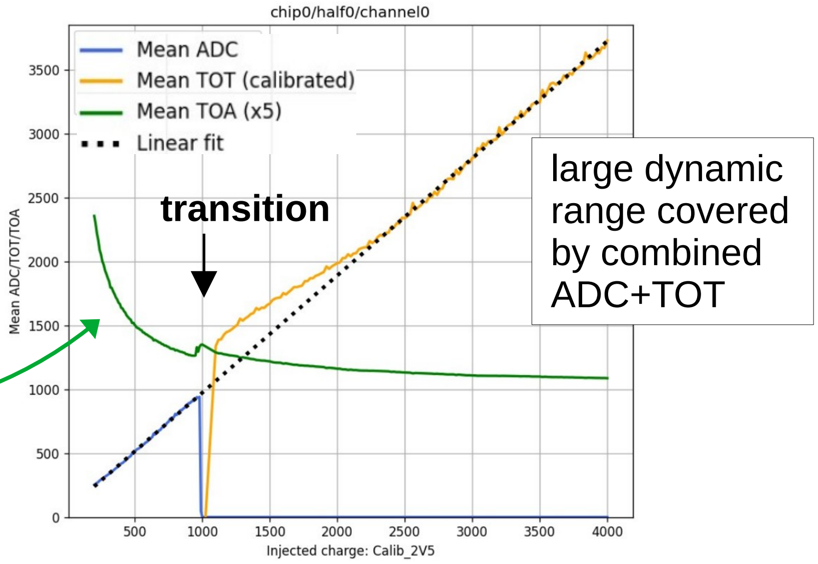


- Dynamic range
  - Read ADC at max. pulse when signal is **small** (~10 MIPs)
  - **Higher** signals covered by time-over-threshold (TOT)
  - ADC at previous bunch crossing read out for pedestal subtraction



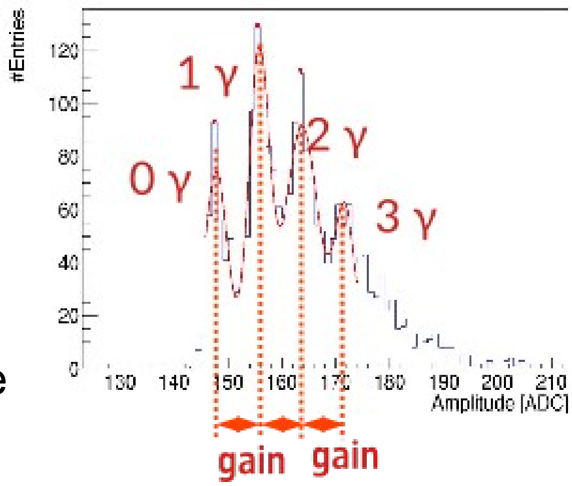
ADC, TOT & TOA

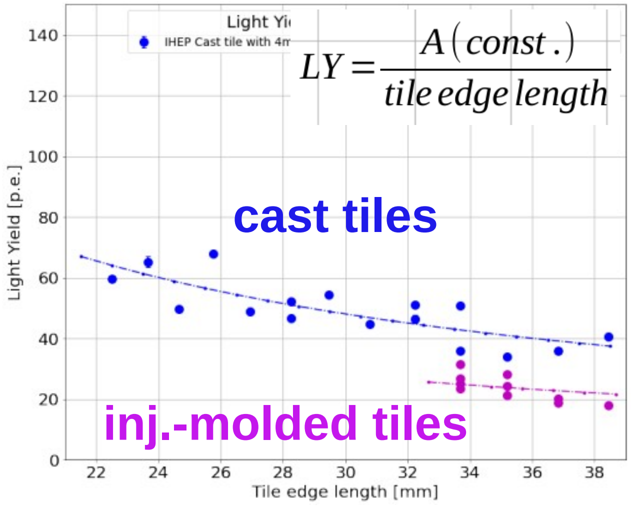
- Calibration
  - Align pedestal levels
  - HGCROC charge injection to define **ADC**/**TOT** transitions
  - Time walk visible in **TOA**



- Measuring scintillator light yield
  - Use LED system within SiPMs
  - Measure single pixel spectra
  - Proportional to MIP height / gain
  - Only possible at high gain (x12)
  - Provides only initial calibration; impossible when irradiated
  - Alternative setup with Sr90 source (spot sampling during production)

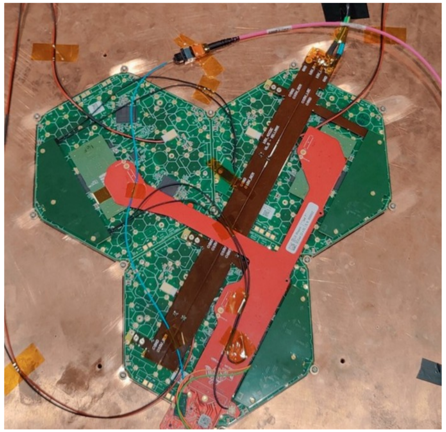
single pixel spectrum (SPS)

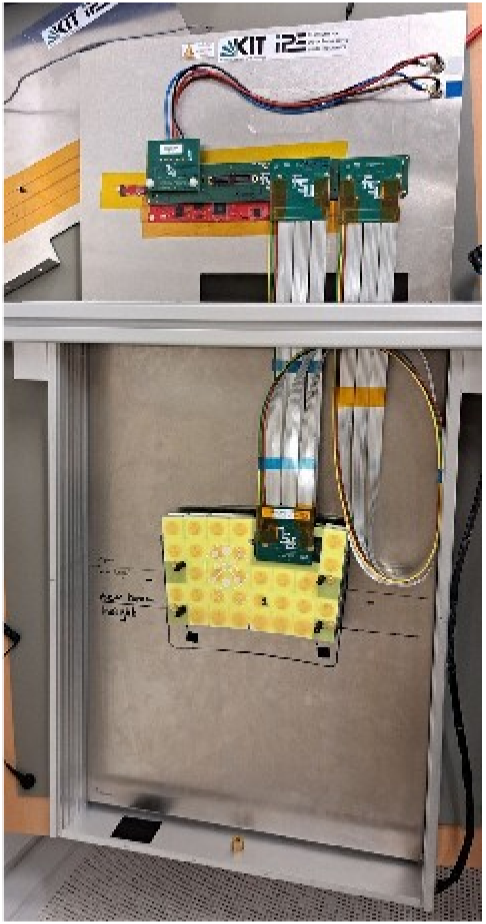




Readout chain in action

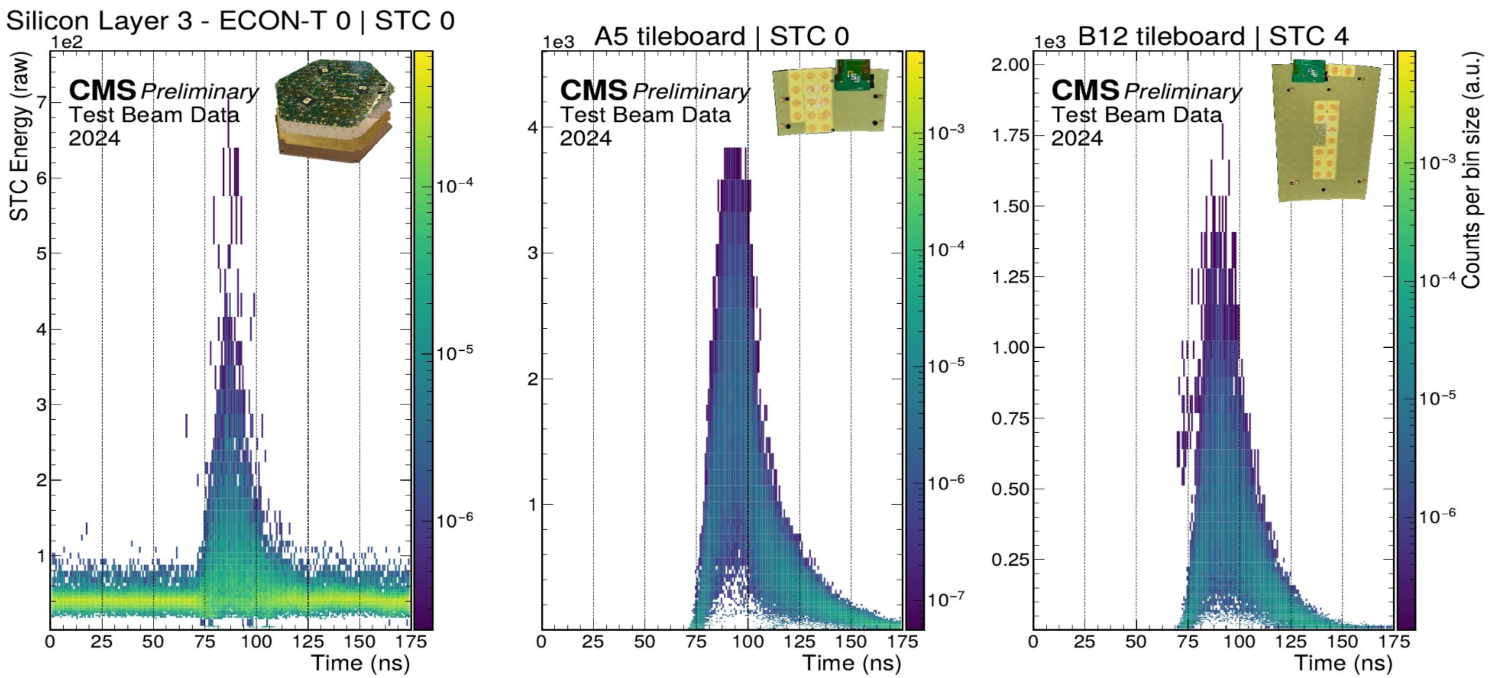
- SPS-H2 testbeams in Summer'24 (120 – 200 GeV muon & electrons)
- Setup
  - 2 layers of silicon layers with 3 modules
  - 2 tileboards
  - Separate readout systems for silicon & tileboards; later combined

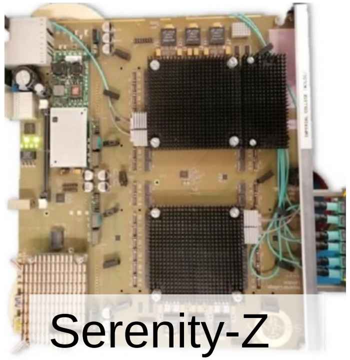




Results

- First readout of trigger data stream from combined silicon + tileboard system
- Using Serenity-Z1.2 VU7P as “mini” backend

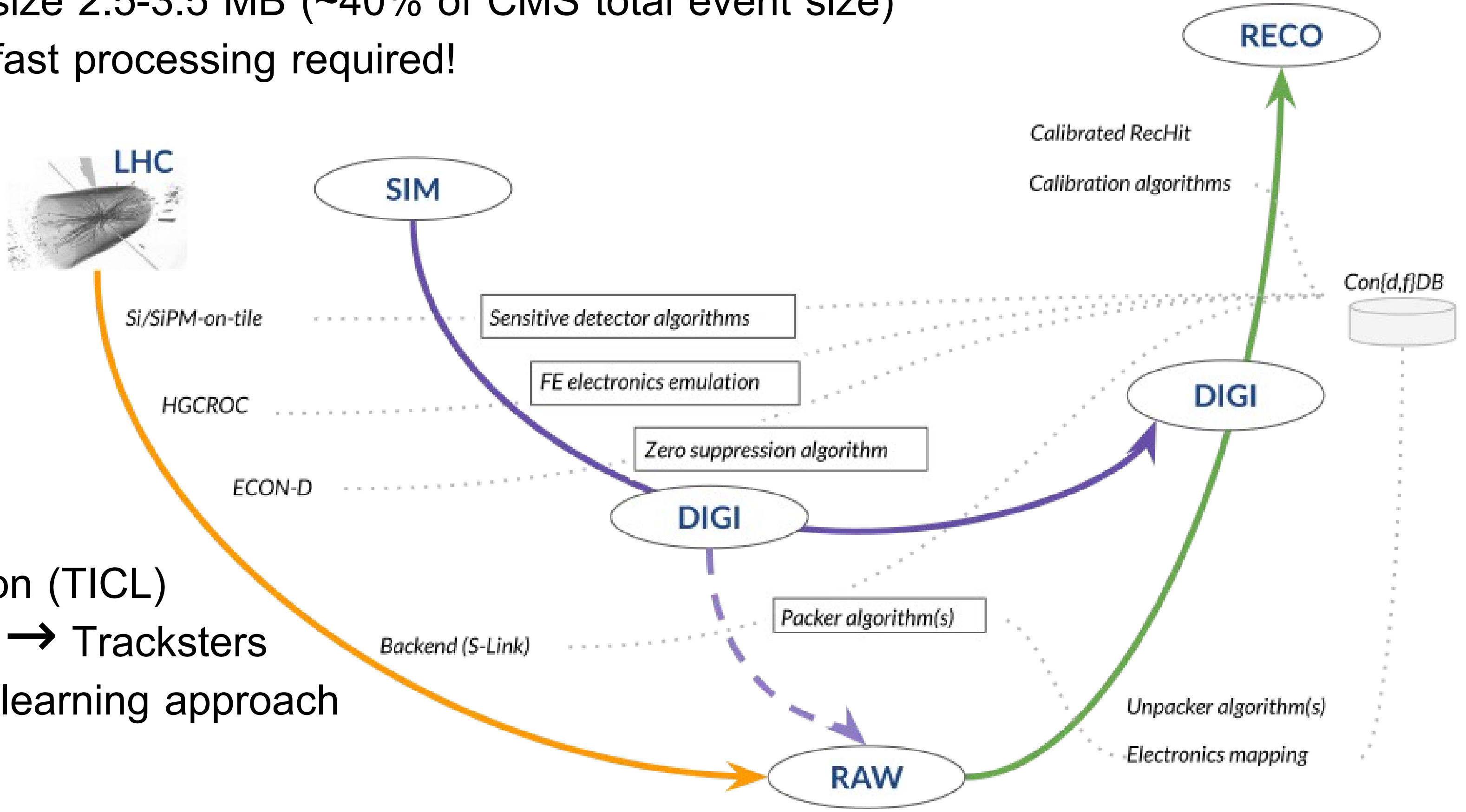




- Plan to switch to Serenity-S1.2 VU9P soon
- Stable operation also in 3T magnetic field (3 field orientation tested)

After backend: HGCAL offline software

- Total HGCAL event size 2.5-3.5 MB (~40% of CMS total event size)
- Clever algorithms & fast processing required!



- Raw data unpacking in ~40ms
- First-level calibration exploits GPUs

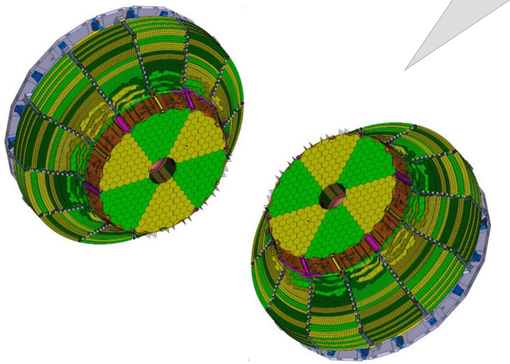
- Iterative reconstruction (TICL) RecHits → Clusters → Tracksters
- End-to-end machine learning approach investigated as well

Production at scale

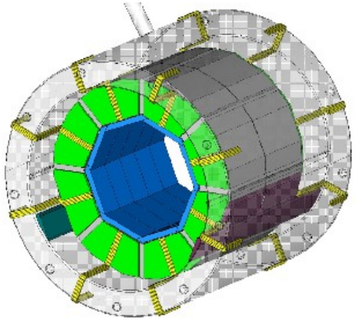
- High channel count = a challenge on all levels
  - Production, test, calibration, software, management
  - Each step requires high degree of automation
  - 2’000 boards to be produced at one site

<u>From AHCAL to HGCAL</u>
x4 faster tile wrapping (4/min)
x10 faster mounting (4 → 40/day)

CALICE AHCAL
prototype
22’000 SiPMs



CMS HGCAL
2 endcaps
240’000 SiPMs



CLD/ILD HCAL
barrel only
4’000’000 SiPMs

Summary

- HGCAL
  - New CMS calorimeter for HL LHC upgrade
  - High granularity: 6M channels
  - 5D showers: energy, position, timing
  - Trigger (40MHz) & DAQ (750kHz) data stream
- Two technologies
  - Silicon & SiPM-on-tile modules
- Data readout chain
  - Common readout ASIC
  - Common readout chain
  - Common testsystems

  } Successfully tested in SPS testbeam!
- Status & plans
  - Moving to mass production in 2025
  - Installation in 2028
  - Operation in 2030 for at least 10 years