HIGH GRANULARITY CALORIMETERS FOR FUTURE COLLIDERS

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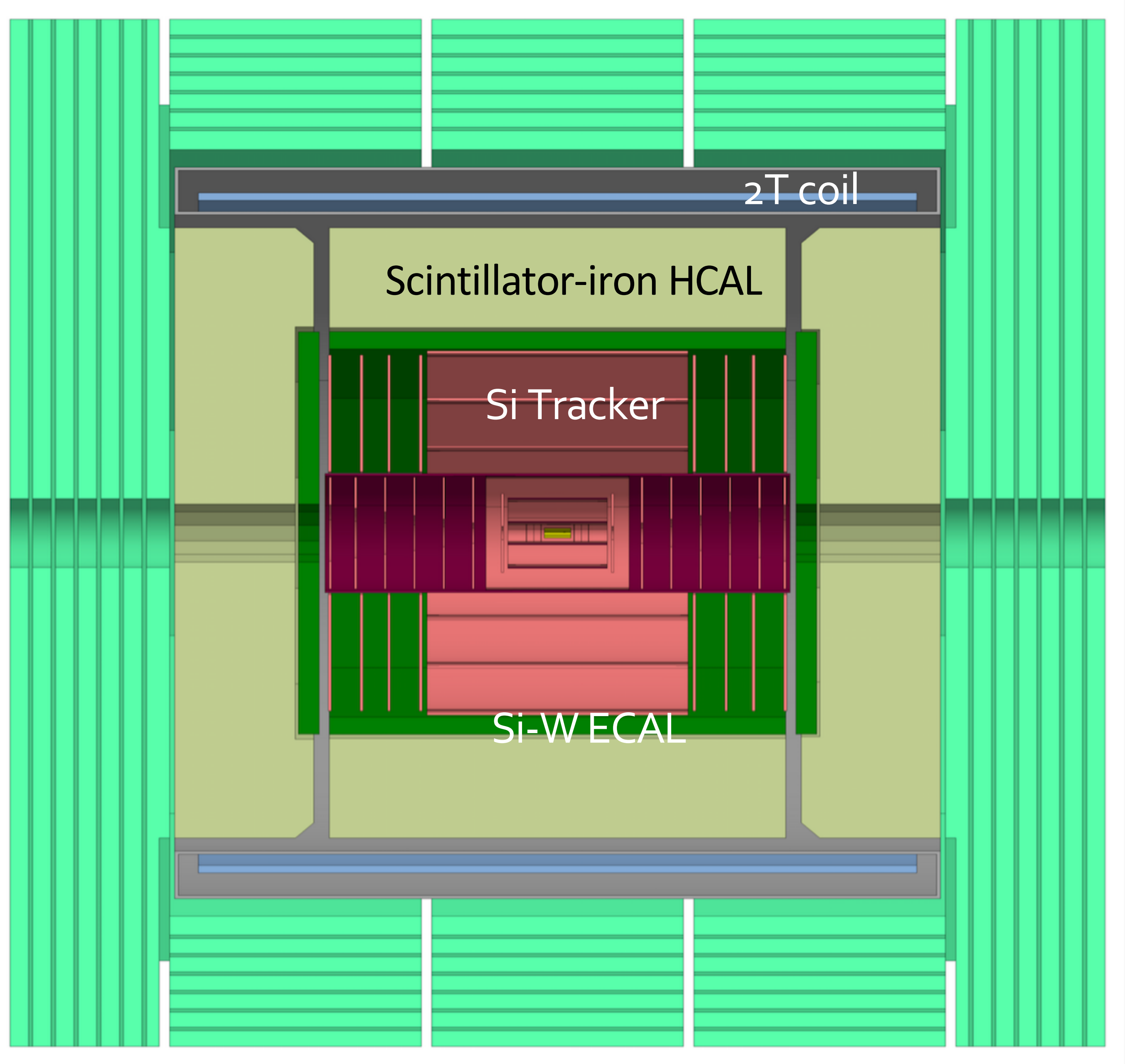
HIGH GRANULARITY CALORIMETRY FOR FUTURE COLLIDERS

- **FCC-ee will be a precision machine:**
  - Posing stringent requirements on particle reconstruction precision
  - Calorimetry – key component of particles' energy measurement



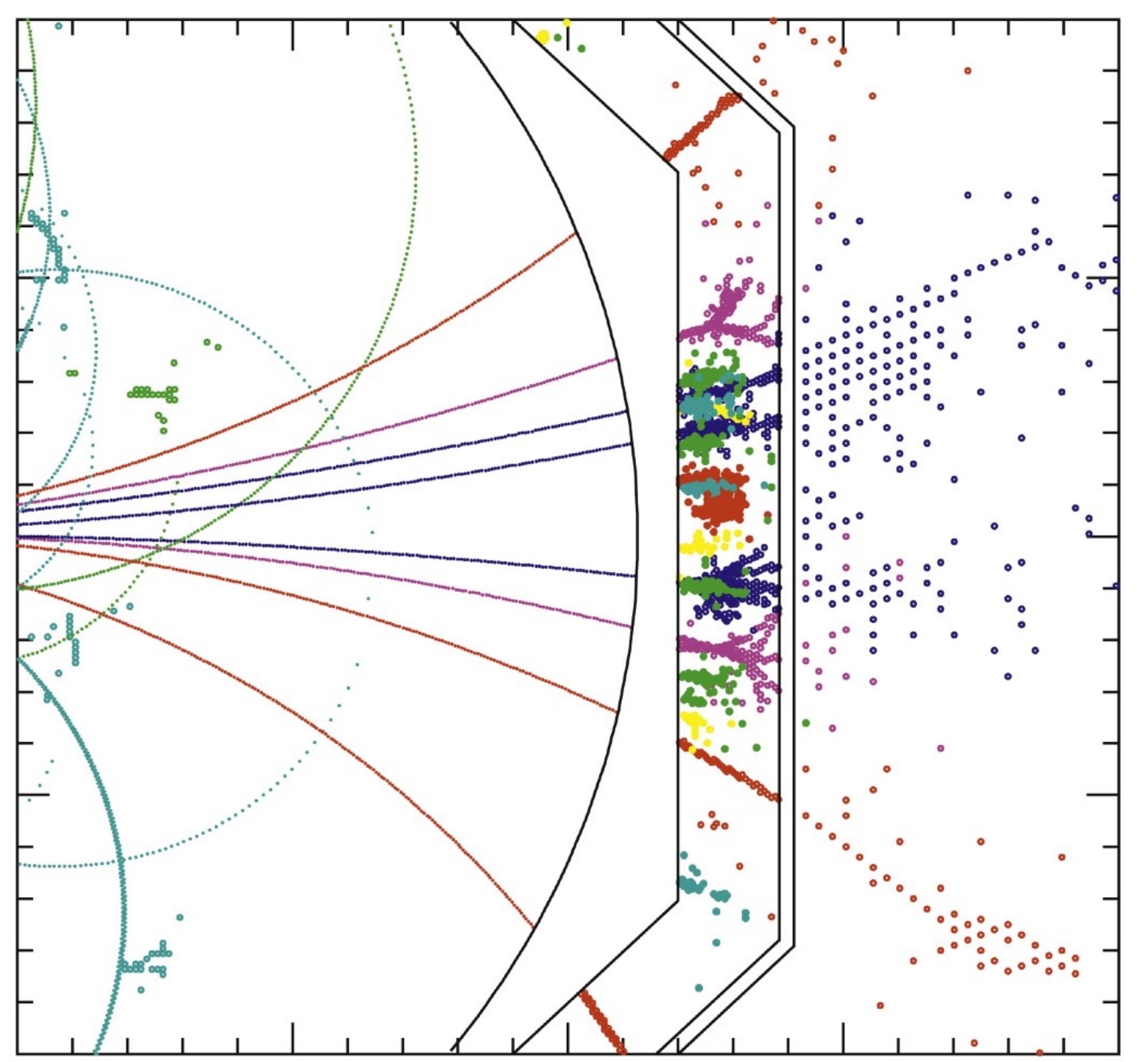
CLD proposal for FCC-ee

- **High granularity calorimeters are perfect candidates for lepton colliders**
  - **Ideal for Particle Flow reconstruction**, enabling imaging of showers, particle separation and identification
  - **Good energy resolution** for single particles and jets
  - **Extensive and successful R&D within the CALICE** collaboration for the ILC, designs adopted for CLIC, HL-LHC and now considered for FCC-ee (CLD, LumiCAL)

CALICE

CALICE: IMAGING CALORIMETRY R&D

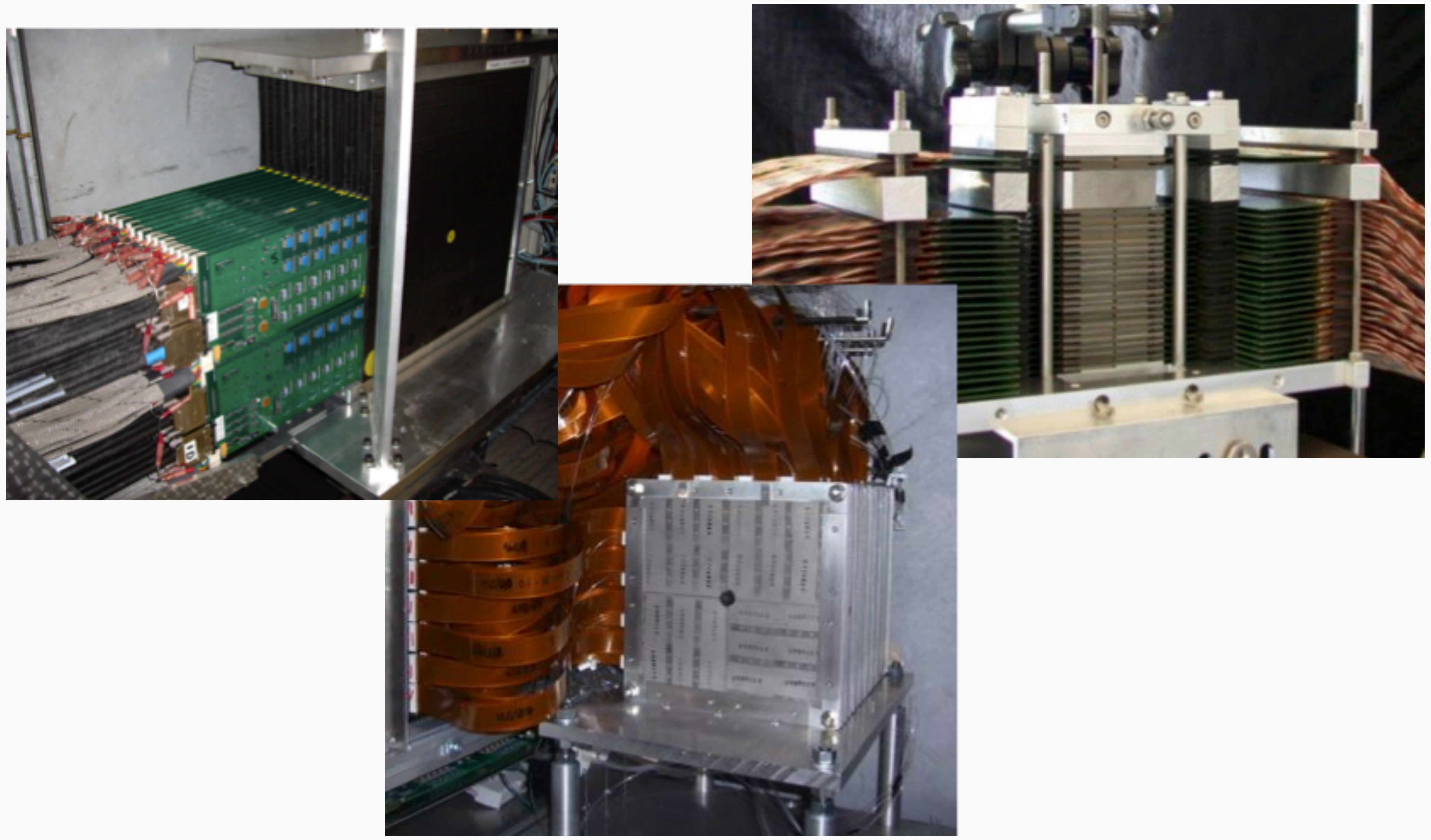
- **CALICE** was formed as a **R&D collaboration for highly granular calorimeters** for future e+e- colliders, **optimised for Particle Flow (PF) reconstruction**
  - **Granularity goals defined by hadronic shower physics:**
  - Segmentation finer than the typical structures in showers R_M/X_0 drive ECAL and HCAL (electromagnetic subshowers)
  - **Large variety of detector technologies and approaches:**
    - Proof-of-principle of detector designs
    - Reconstruction and simulation validation
    - Technological prototyping
    - Application of CALICE technology in other experiments
  - **Large French implication in CALICE since the beginning**: Omega, LAL, LLR, IPNL, CEA, …

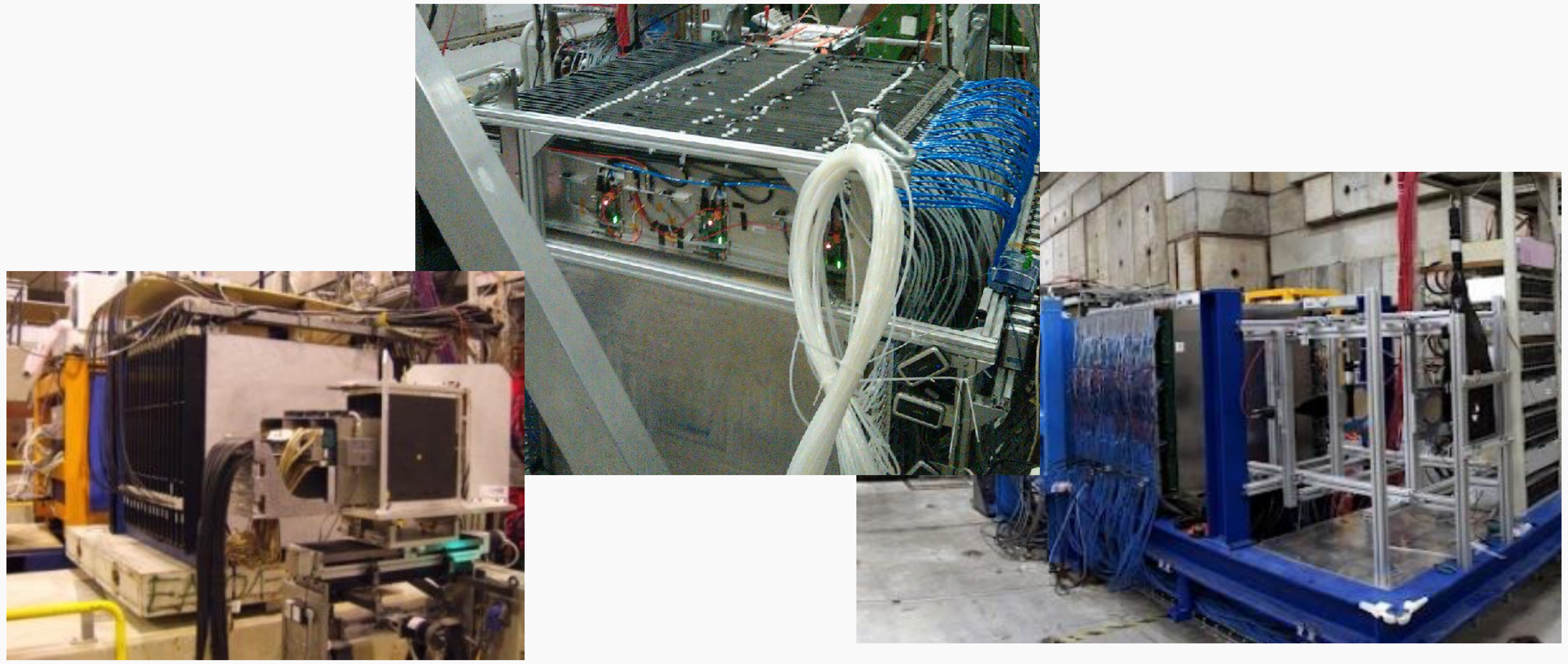


CALICE TECHNOLOGIES

- **Electromagnetic calorimeters:**
  Tungsten/W absorbers
  - Analog: silicon, scintillator/SiPM
  - Digital: MAPS

- **Hadronic calorimeters:**
  Steel and Tungsten absorbers
  - Analog: scintillator/SiPM
  - Semi-digital: RPC
  - Digital: RPC

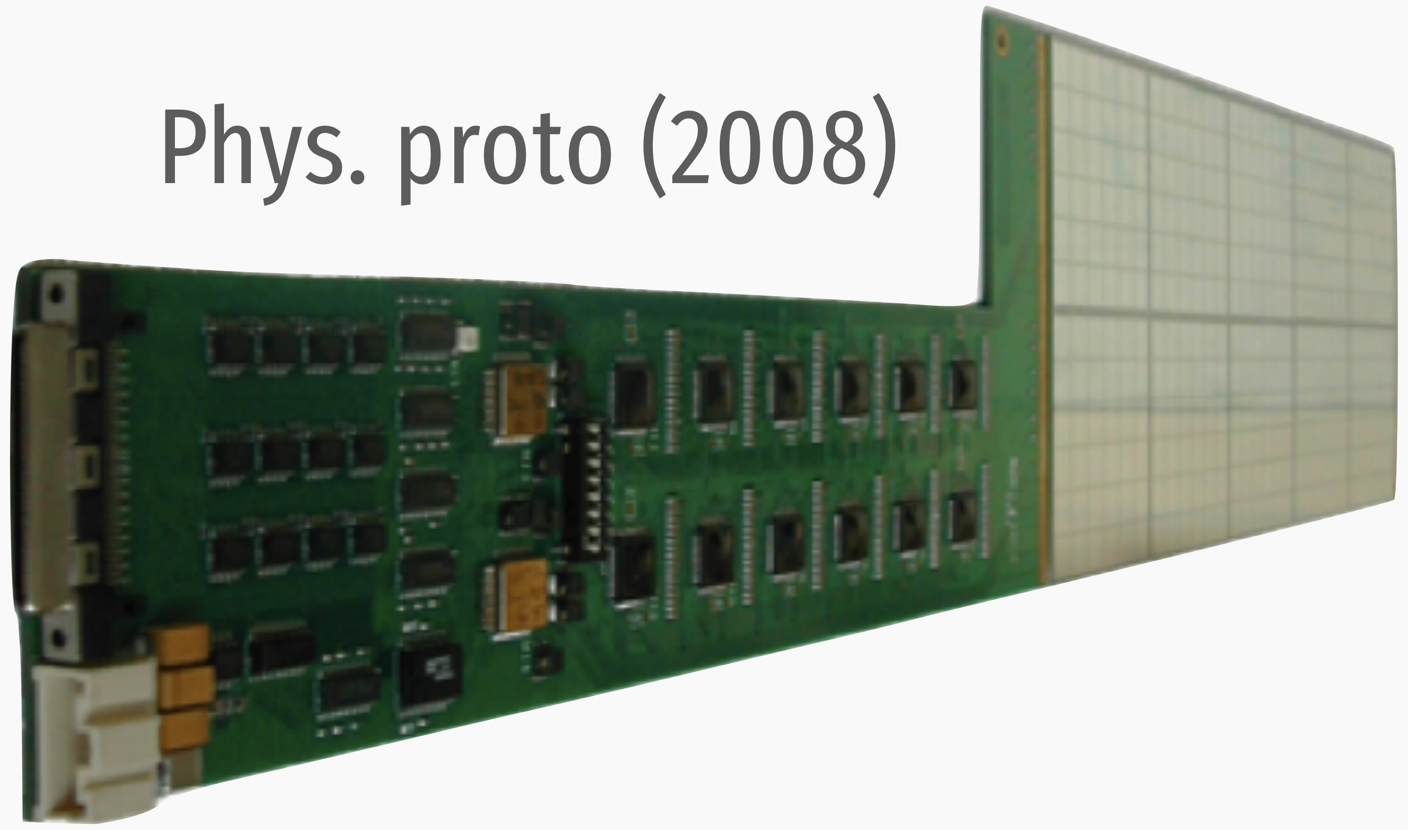


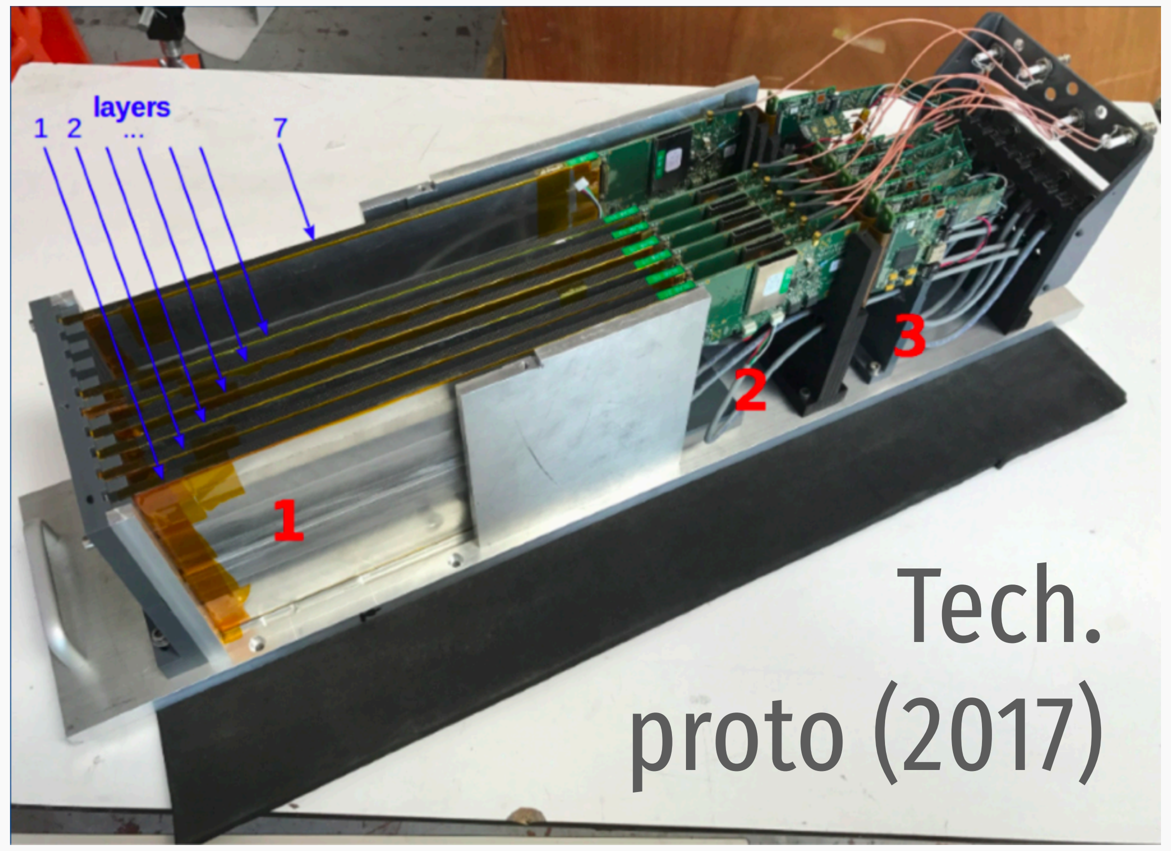


SiW-ECAL Evolution

- SiW-ECAL: baseline ECAL for ILD (ILC) and CLD (FCC-ee)
  - **Optimised for particle separation**, not single particle resolution
  - Physics prototype in 2008, **technological prototype with 5x5 mm² cells in 2017**
  - Work ongoing on detector integration: **“long slab” ~1.5m,** mechanical structure

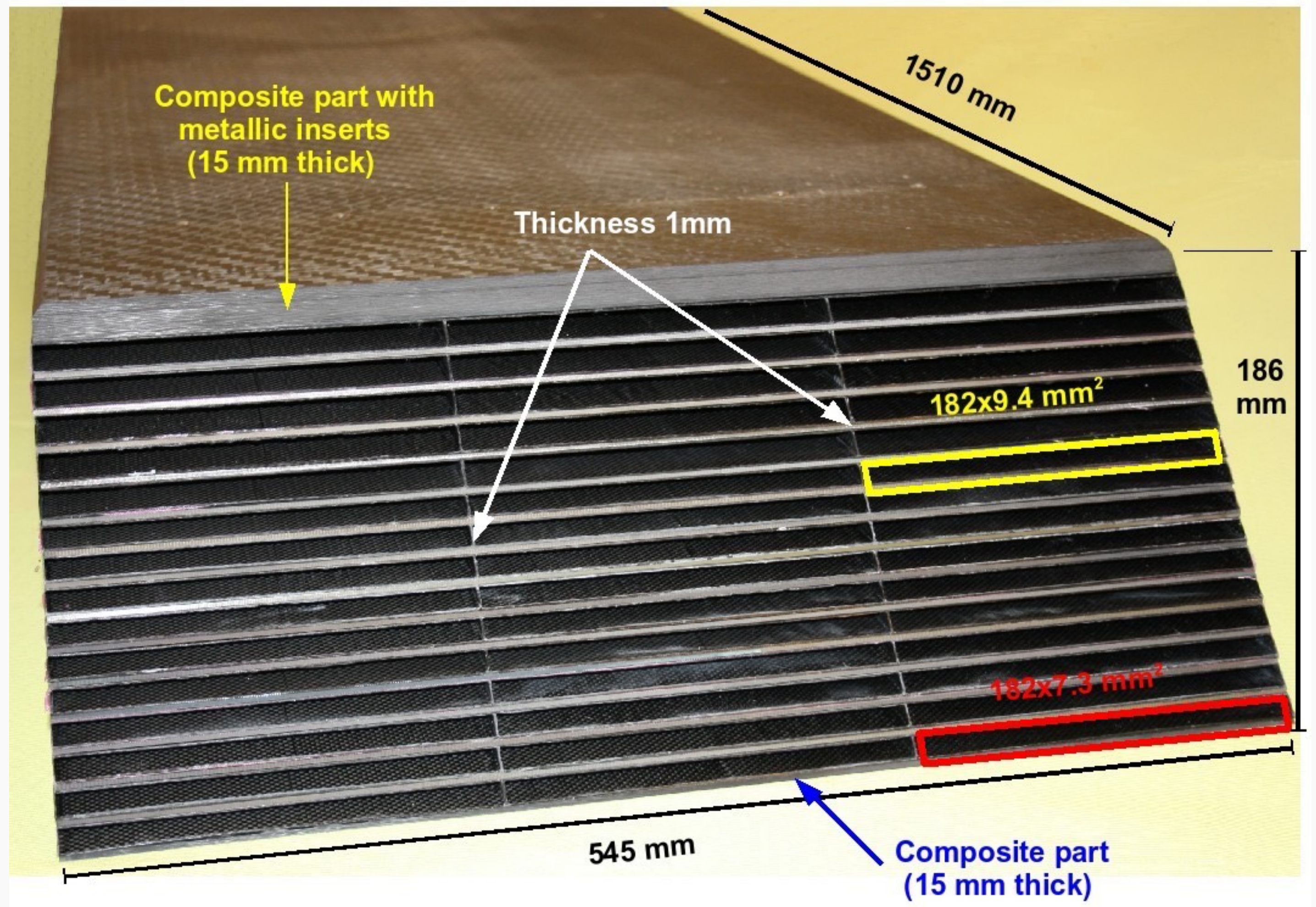
Phys. proto (2008)



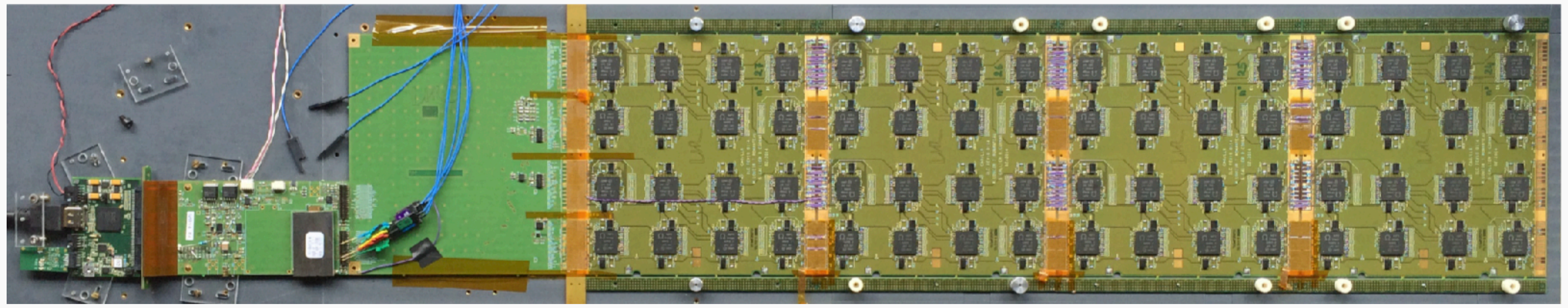


Tech. proto (2017)

Carbon-fibre alveolar structure

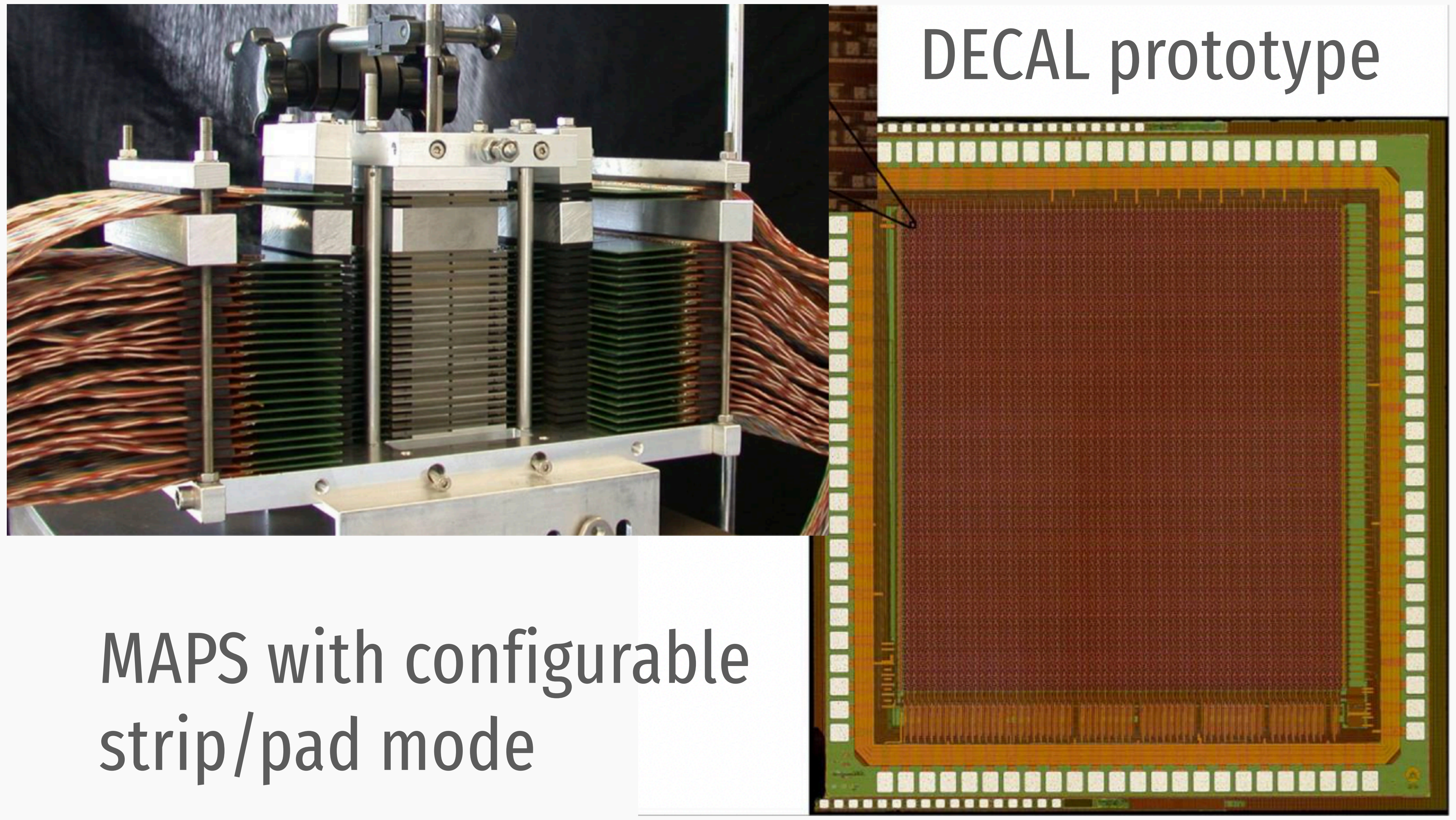


Long slab (2018)



DECAL & AHCAL

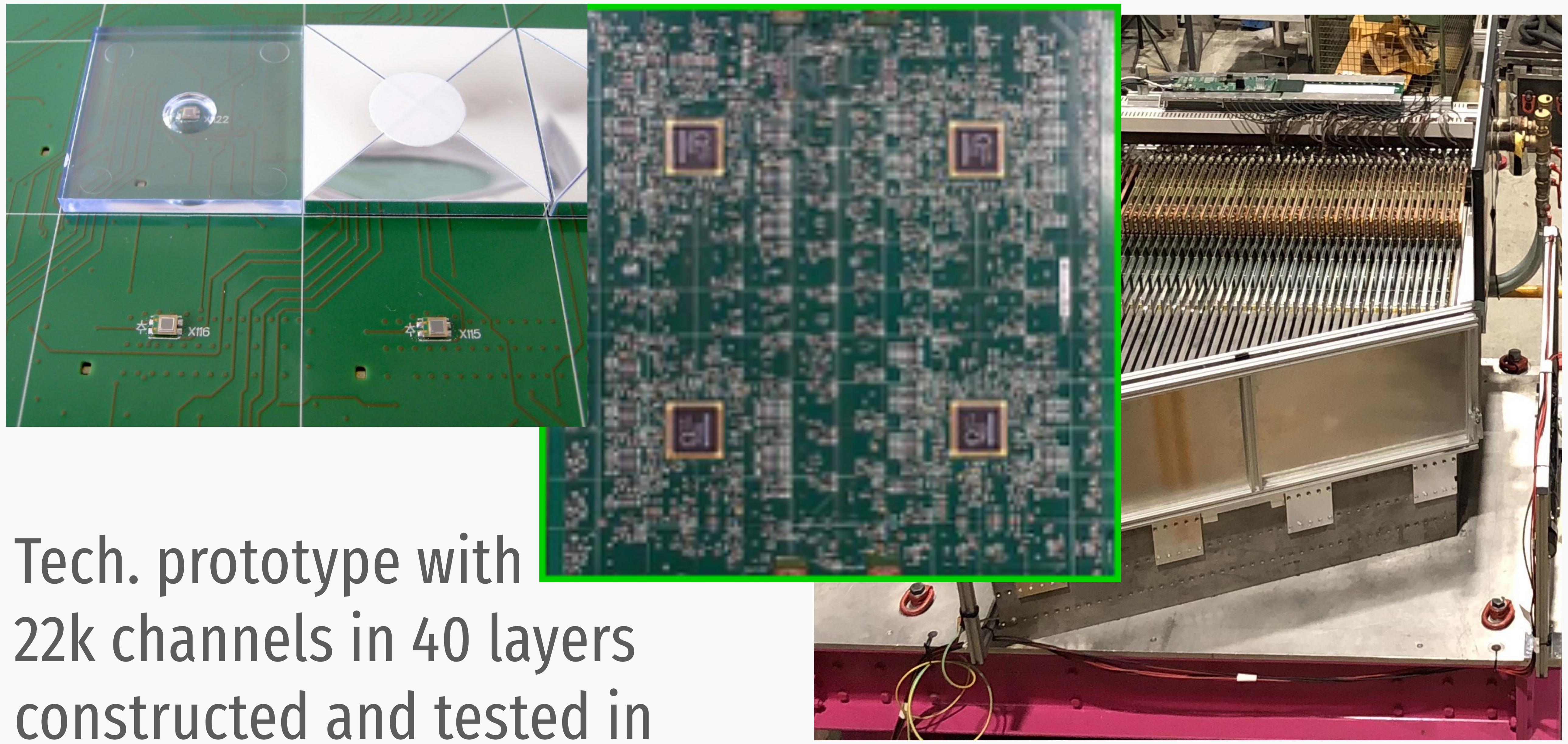
- Digital ECAL (DECAL):
  - Monolithic Active Pixel Sensors (MAPS): highly granular (50um), rad. hard and fast
    - Can be used both in Tracker and CALO
  - Successful prototype with 39M pixels, new sensors and ASIC studied within context of ALICE FoCAL upgrade



DECAL prototype

MAPS with configurable strip/pad mode

- AHCAL: baseline for ILD
  - 3x3cm^2 scintillator tiles with SiPM
  - HCAL Base Unit (HBU): 144 channels/4 ASICs
  - Technological prototype: demonstrate scalability to full detector (8M channels)



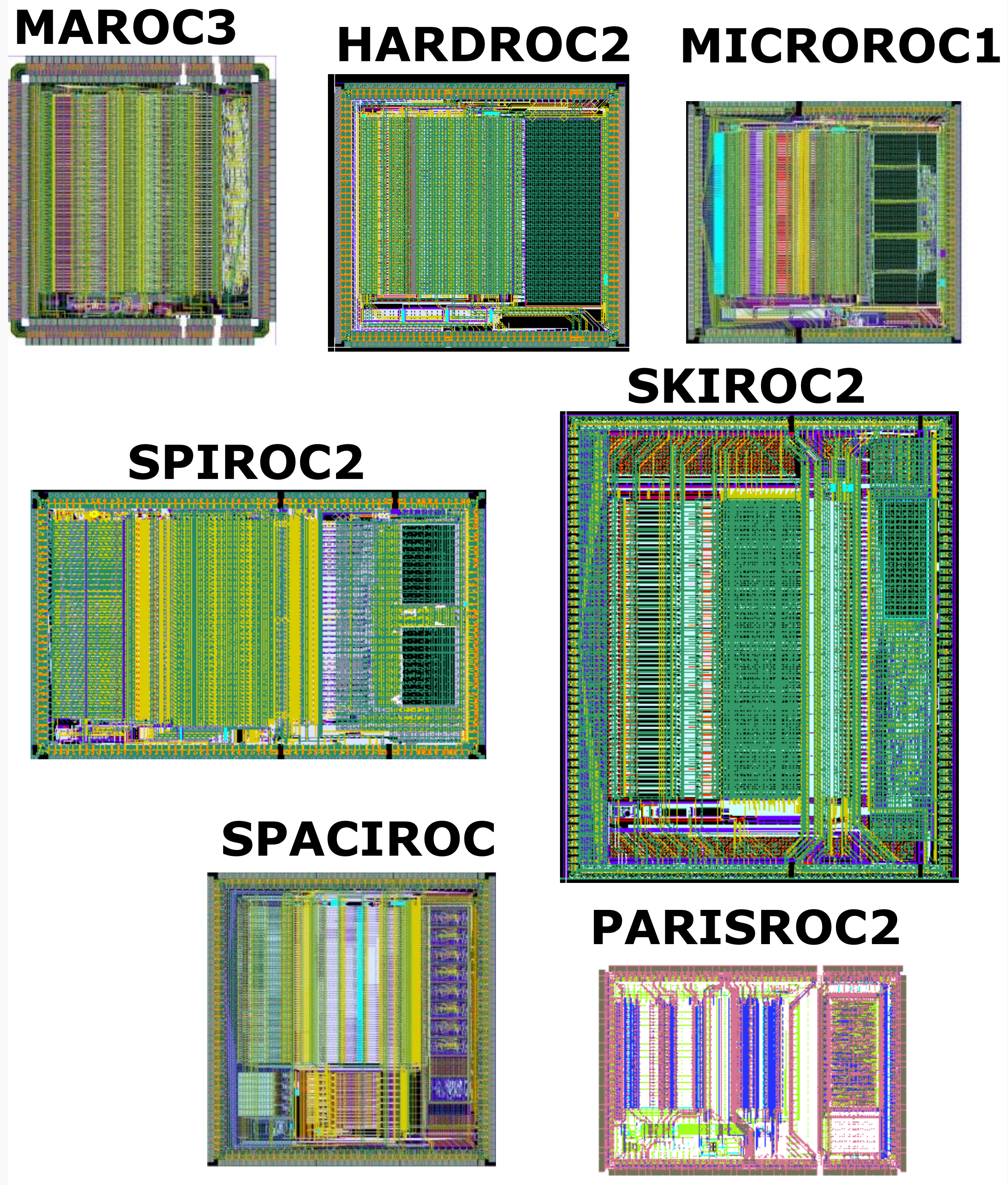
Tech. prototype with 22k channels in 40 layers constructed and tested in 2017-2018

FRONT-END ELECTRONICS

- High granularity calorimeters have very dense and compact design:
  - **Absolute requirement of System-on-Chip ASIC or full integration (CMOS)**
- **ILC bunch structure allows for power-pulsing**, thus no active cooling
  - Alternatives with active cooling being investigated, requires ASIC optimisation

Chip	detector	ch	DR (C)
MAROC	PMT	64	-2f-50p
SPIROC	SiPM	36	+10f-200p
SKIROC	Si	64	+0.3f-10p
HARDROC	RPC	64	-2f-10p
PARISROC	PM	16	-5f-50p
SPACIROC	PMT	64	-5f-15p
MICROROC	μMegas	64	-0.2f-0.5p
PETIROC	SiPM	32	50fC-300pC

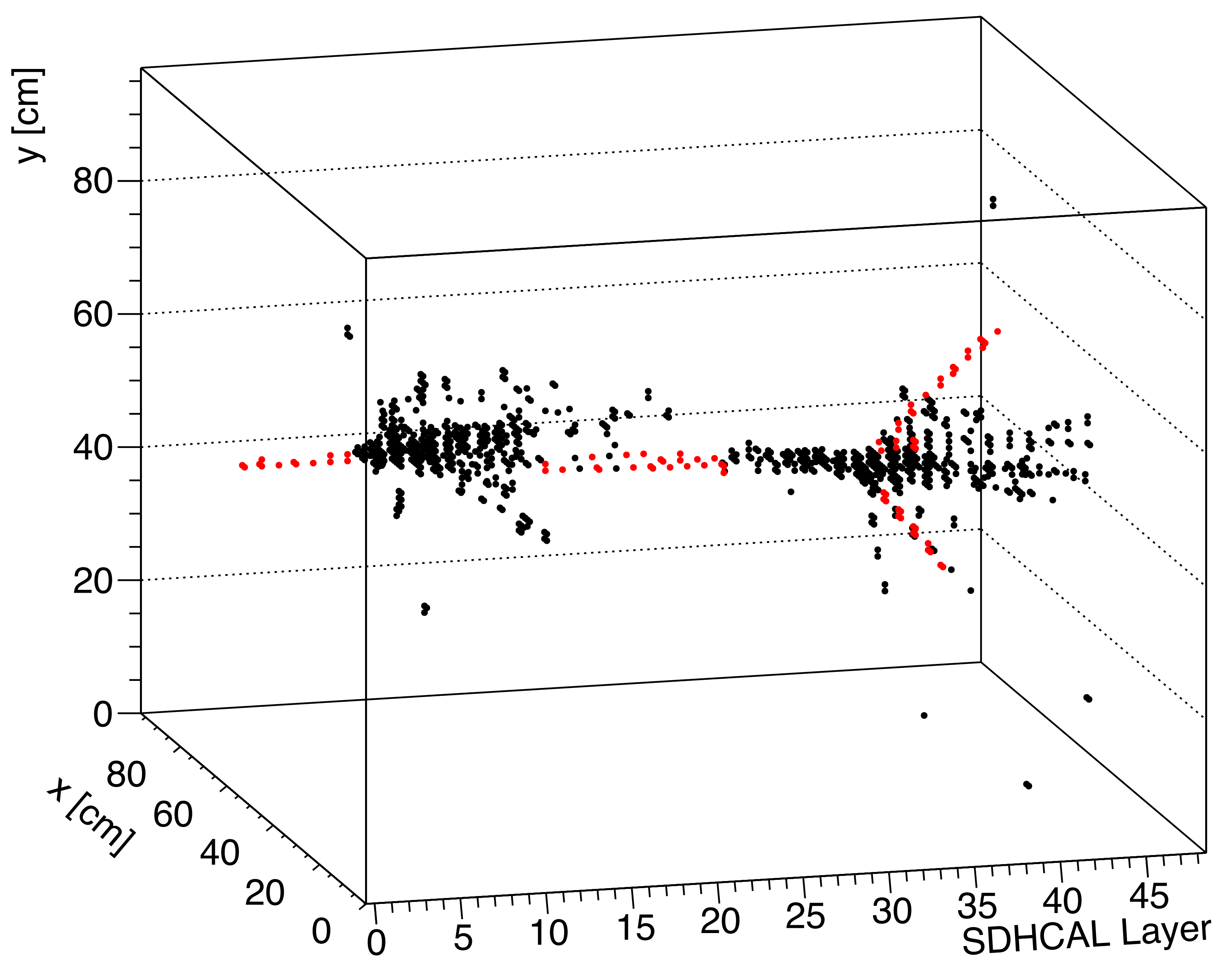
OMEGA ASICS for CALICE



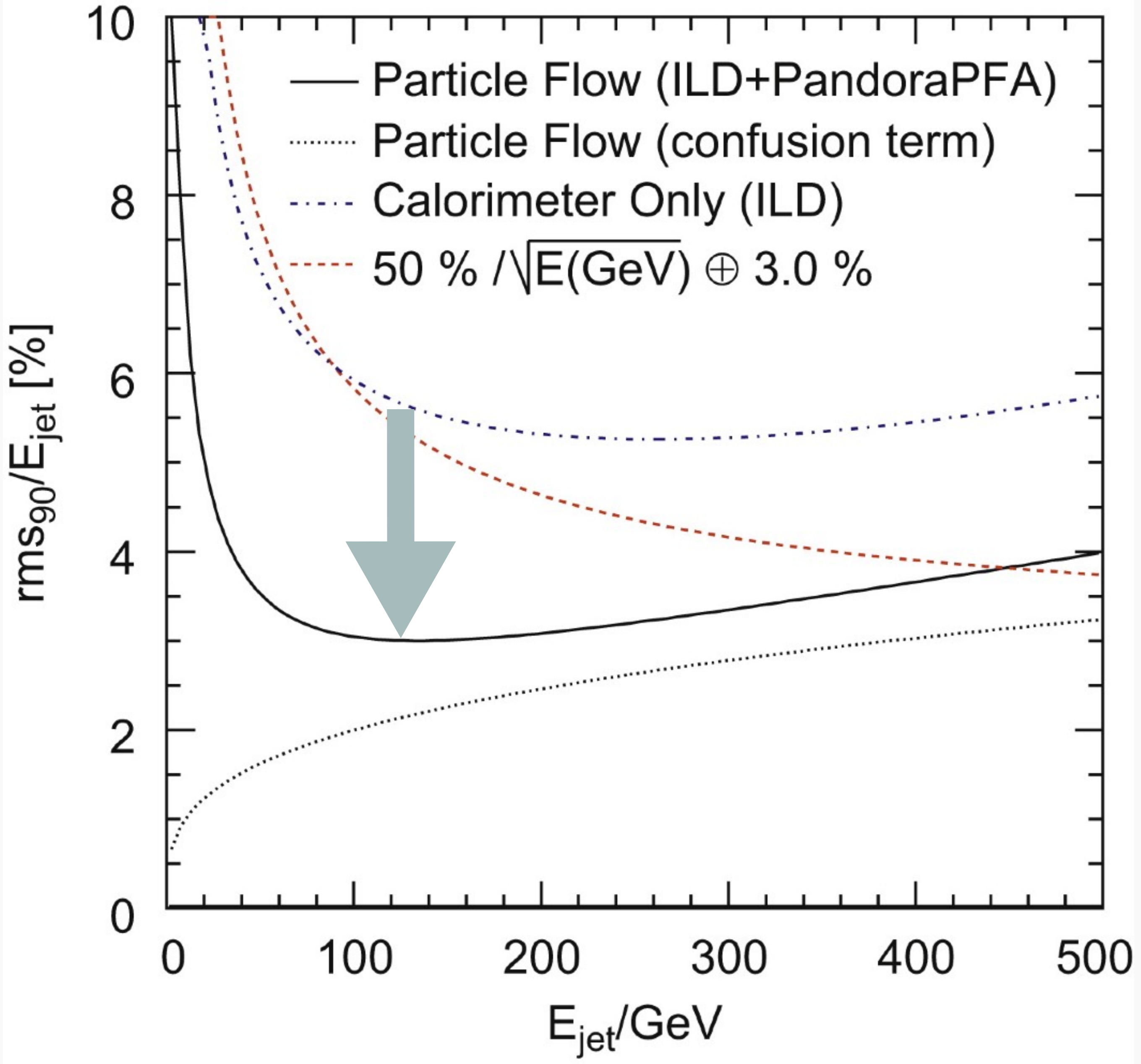
- **Long & fruitful collaboration of CALICE with UMS Omega** (IN2P3/ Ecole Polytechnique)
  - Providing front-end ASICs for most CALICE protos.
  - SiGe 0.35 μm CMOS technology
    - Required to move to 130nm!

PARTICLE FLOW PERFORMANCE

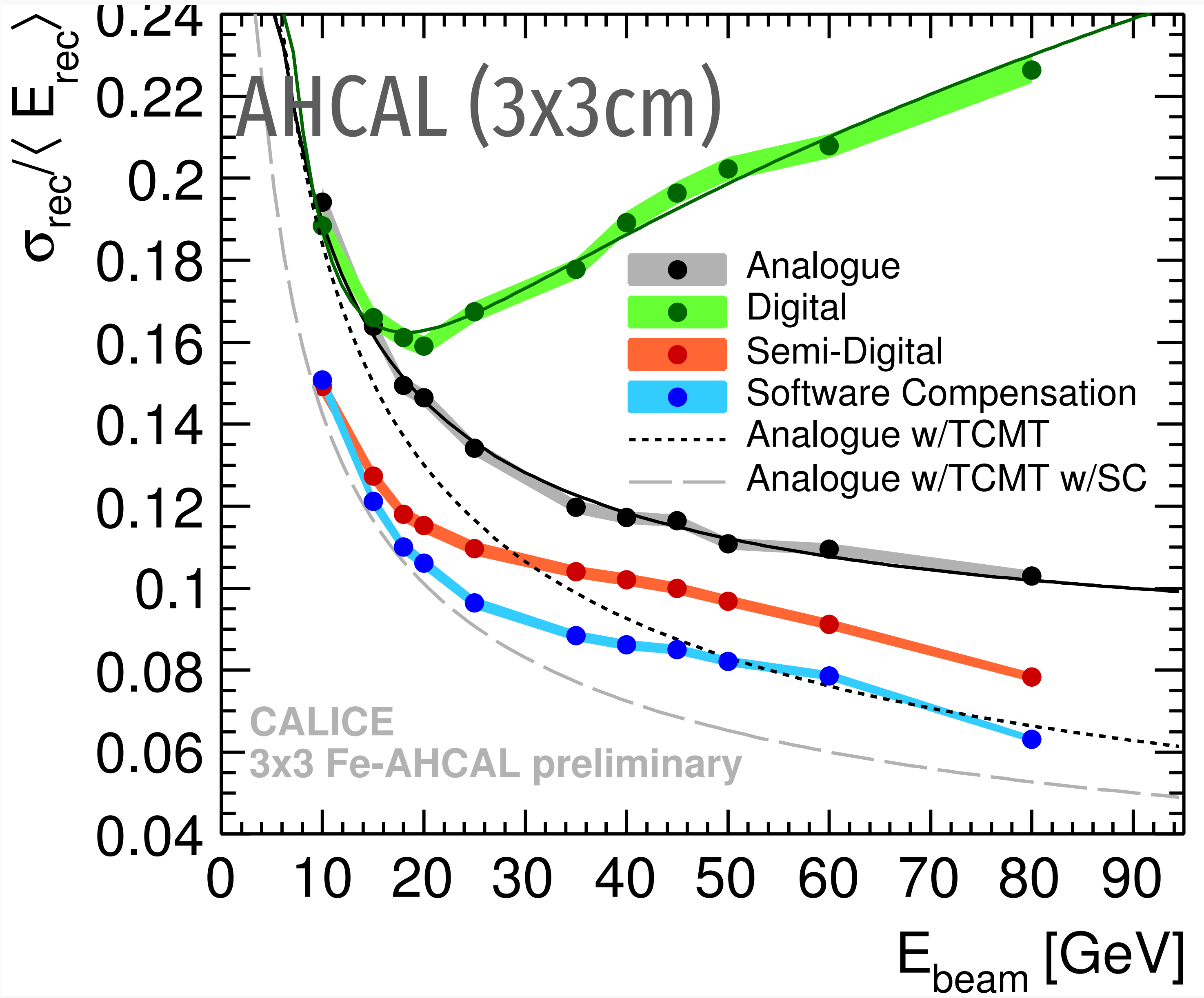
- **Extensive development of particle flow algorithms**
  - Arbor & PandoraPFA packages developed for ILC, but used as well for CMS, CLIC, CEPC and FCC-ee studies
- **Energy reconstruction using software compensation:**
  - Non-compensation of calorimeters (EM≠HAD response) can be circumvented with software compensation methods, based on local energy density (exploiting granularity!)



Hadronic shower in SDHCAL



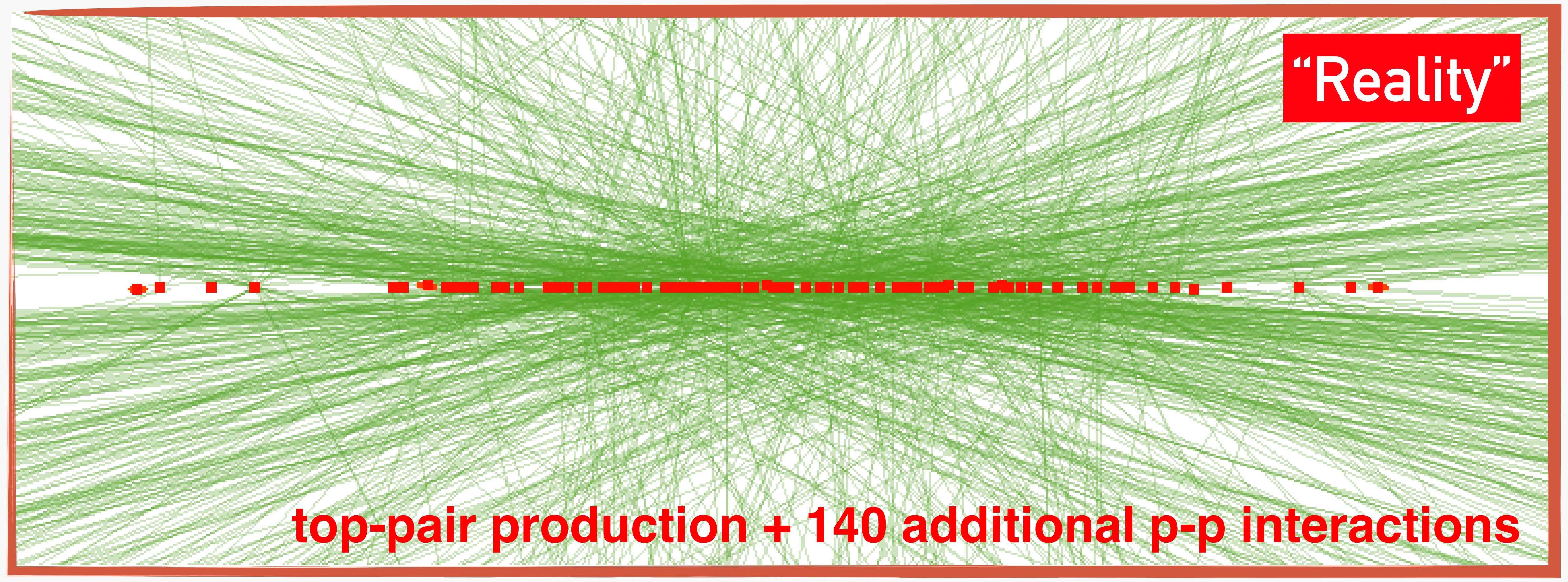
ILD jet energy resolution

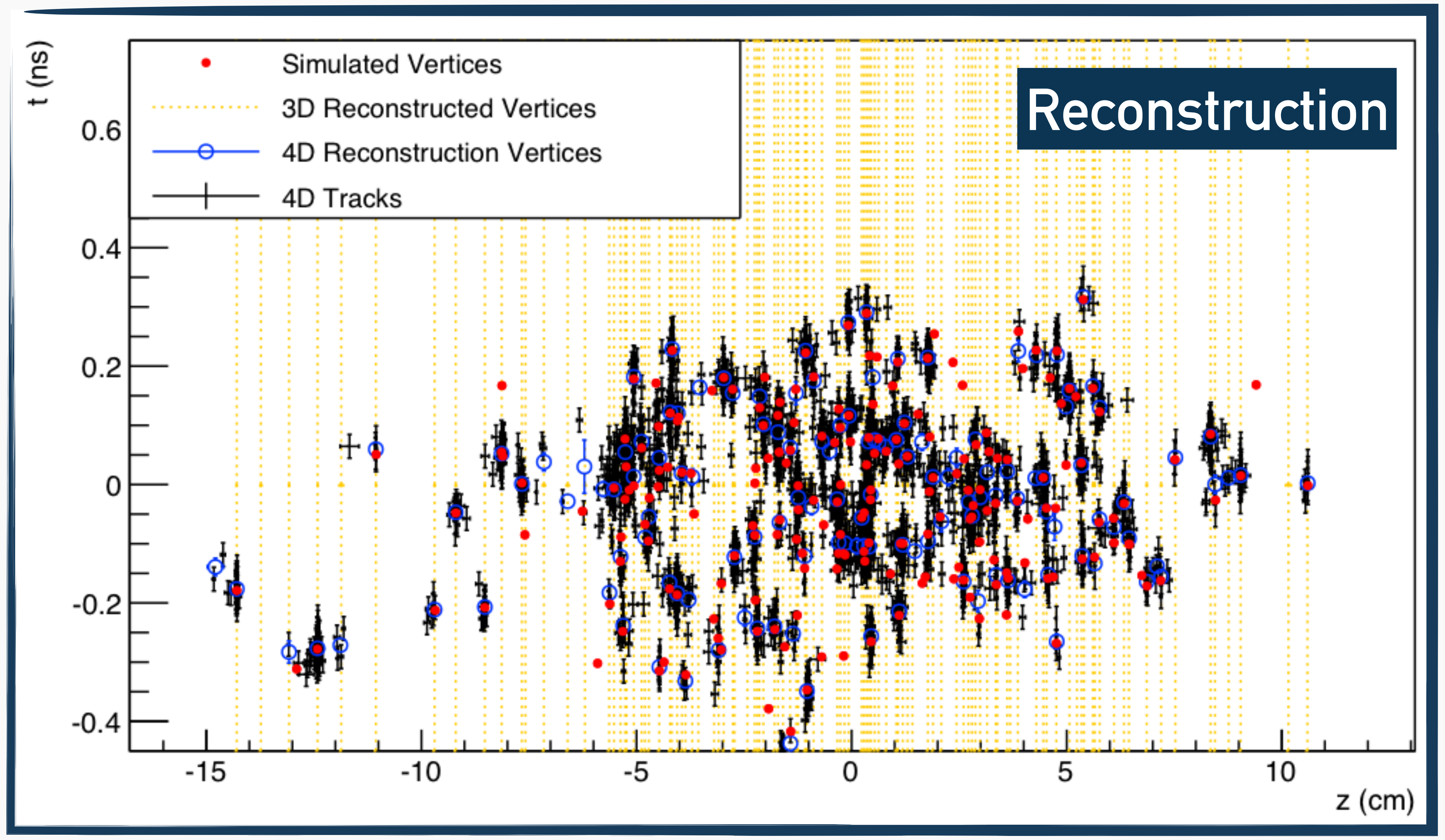


CMS

HIGH GRANULARITY CALORIMETER

GOING 5D FOR HL-LHC





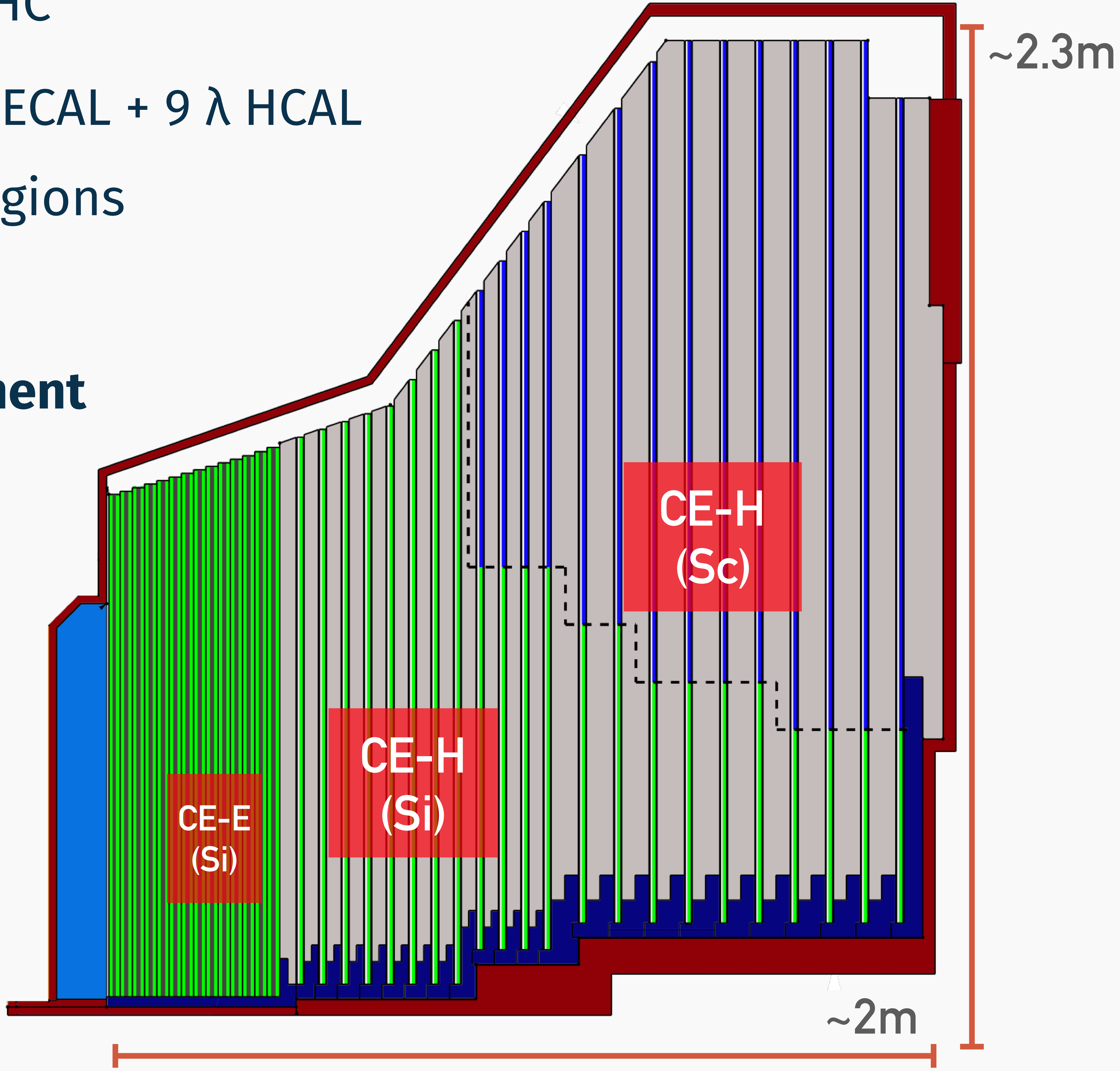
- **Extremely busy interaction region** in the ~140-200 pileup environment
  - Vertices spread in position and time! z: ±50 mm, t: ±150 ps
- Pileup mitigation at new scale needed
  - **Highly-granular** tracking and calorimetry (esp. forward)
  - **Timing measurement** at σ ~ 30 ps
  - ➡ **Going to new dimensions: 5D**

CMS HIGH GRANULARITY CALORIMETER

- **HGCAL:** replacement of current endcap calorimeters for HL-LHC
  - **Inspired by CALICE** concepts: SiW-ECAL and AHCAL: 28 Xo ECAL + 9 λ HCAL
  - Silicon/scintillator detectors in the high/low radiation regions
  - Triggering and reading data of >6M channels at ~1 MHz

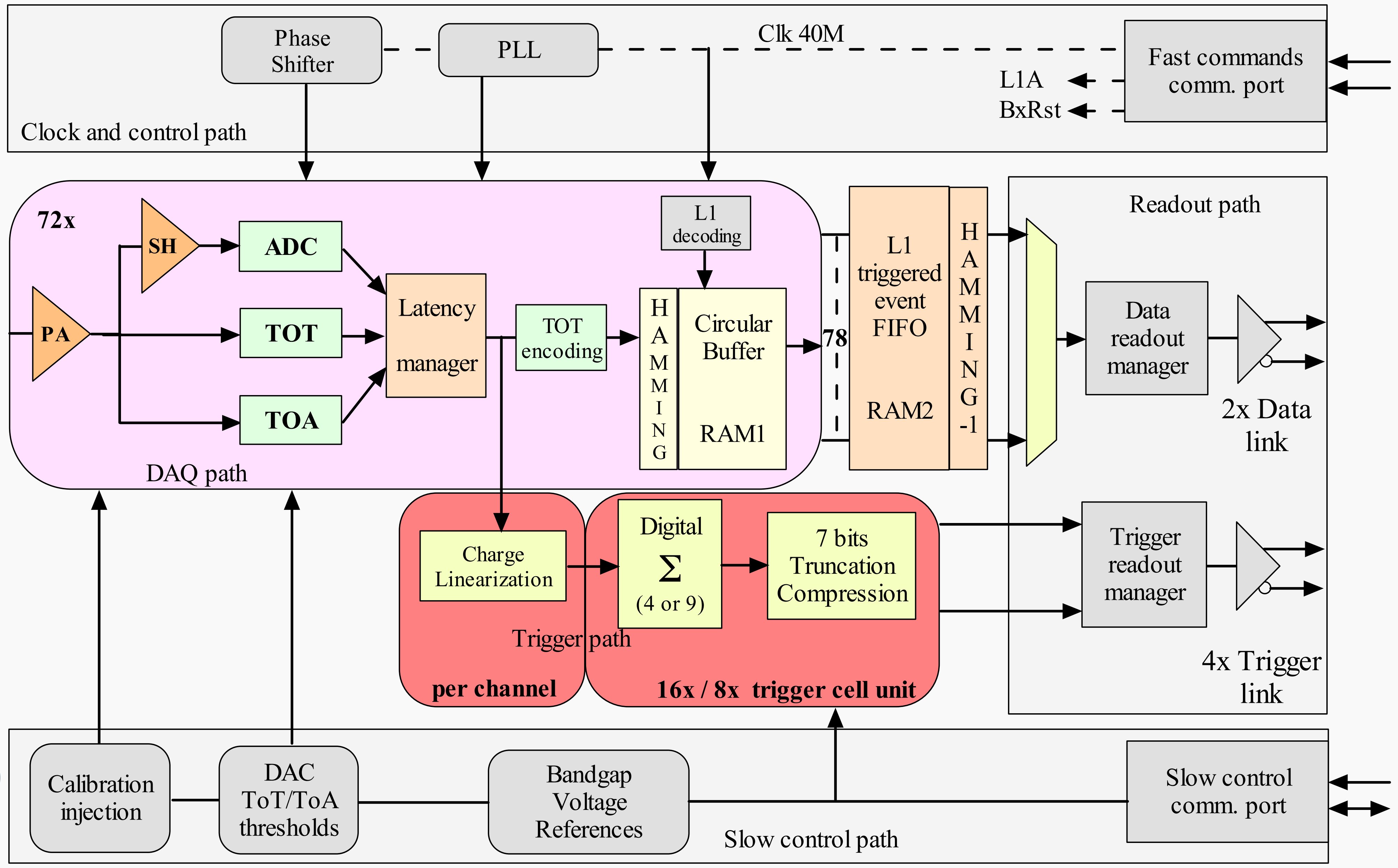
➡ **Particle-flow enabled detector for the busy HL-LHC environment**

Endcap coverage: $1.5 < \lvert\eta\rvert < 3.0$		
Total	Silicon sensors	Scintillator
Area	620 m²	410 m²
Number of modules	29 900	3800
Cell size	0.5 — 1.2 cm²	5 — 30 cm²
N of channels	6 260 000	240 000
Power	Total at end of HL-LHC: 2x125 kW @ -30°C	

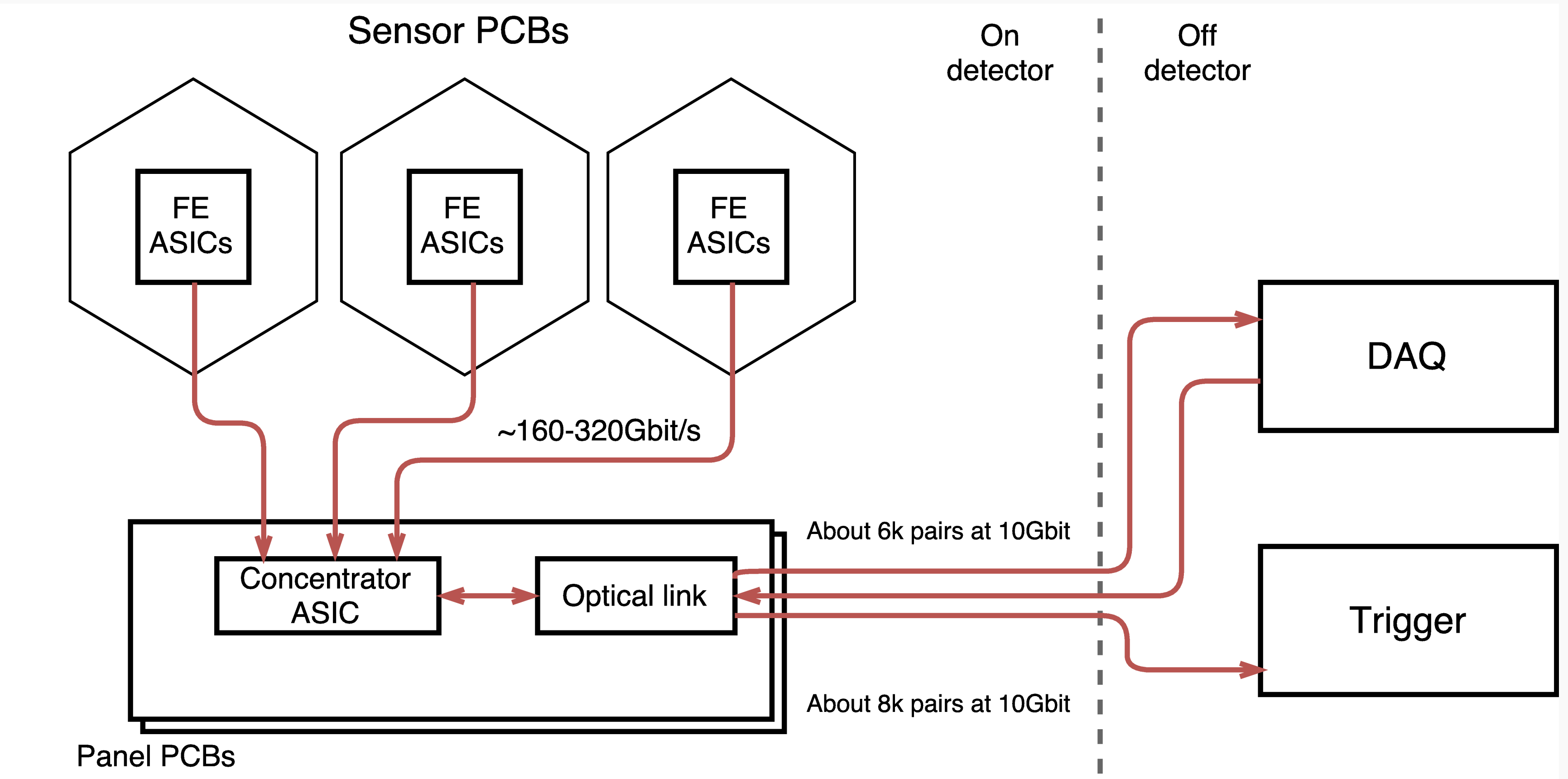


FRONT-END ELECTRONICS

- Challenging front-end electronics requirements: **HGCROC**
  - **System-on-chip:**
    - Large dynamic range (*1-3000MIP*)
    - Low noise (*S/N for MIP sensitivity*)
    - Radiation hard (*200 MRad*) and low power (*<15mW/ch*)
  - Trigger cells formed from 4/9 silicon channels (4 SiPM)
  - Two (four) **1.28 Gb/s links** for the data (trigger primitives)
  - **Design lead by Omega**

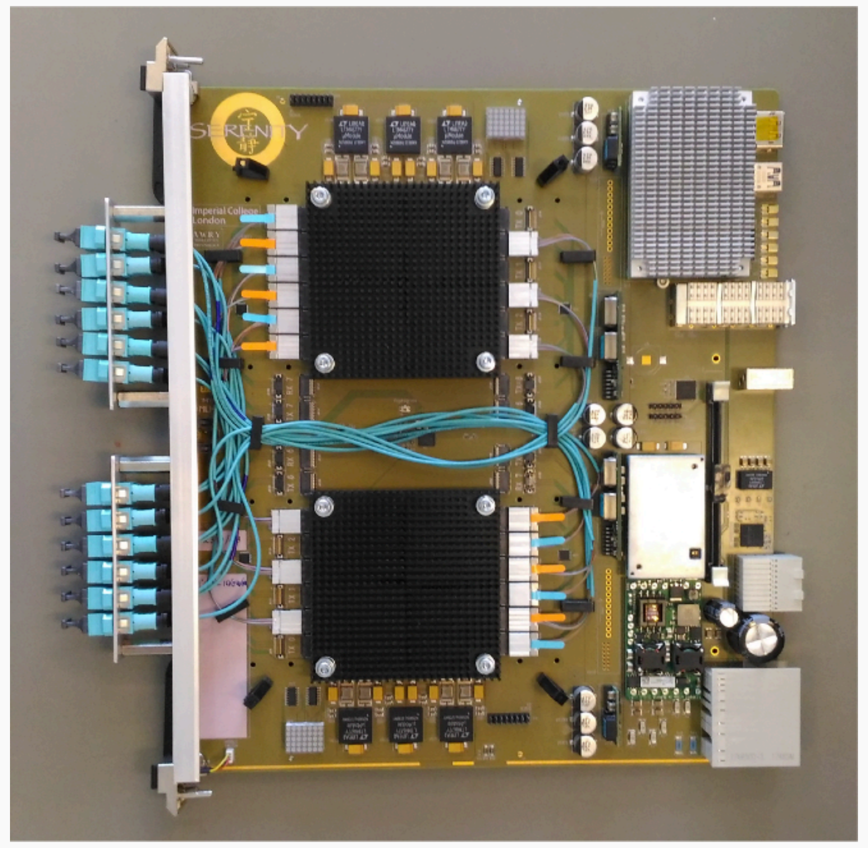


- **Concentrator** needed for data and trigger paths:
  - Select trigger primitives and sent to trigger back-end
  - Zero-suppress data and transmit to DAQ (10 Gb/s links)



HCAL TRIGGER & BACK-END ELECTRONICS

- HGCAL raw trigger data stream will be **~300 TB/s**, L1 rate ~1MHz
- **Significant data reduction required**: multi-step approach
  - Concentrator ASIC and Trigger Primitive generator in the back-end will select and form trigger primitives
- Both DAQ and TPG require boards with high I/O and significant processing power
- Aim to use generic boards developed for the whole CMS trigger and DAQ systems,
  - ATCA format, **~100 I/O links up to 16 or 25 Gbit/s** in and out, Ultrascale(+) FPGA(s)



HGCROC

~300 Tb/s

Front-end

Concentrator

~40 Tb/s

TPG Stage 1

Back-end Trigger primitive generator

~20 Tb/s

TPG Stage 2

~2 Tb/s

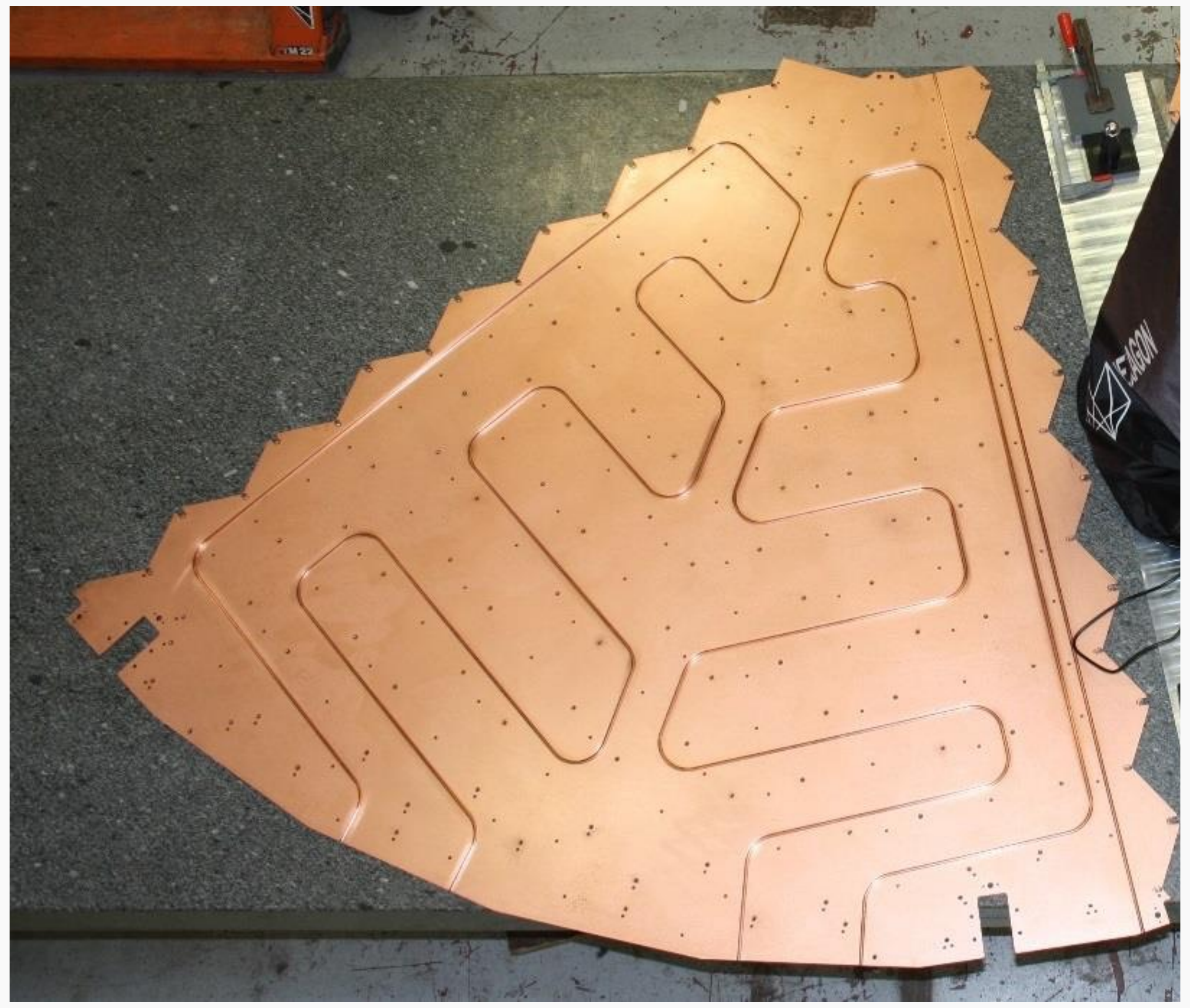
Correlator

CMS Trigger

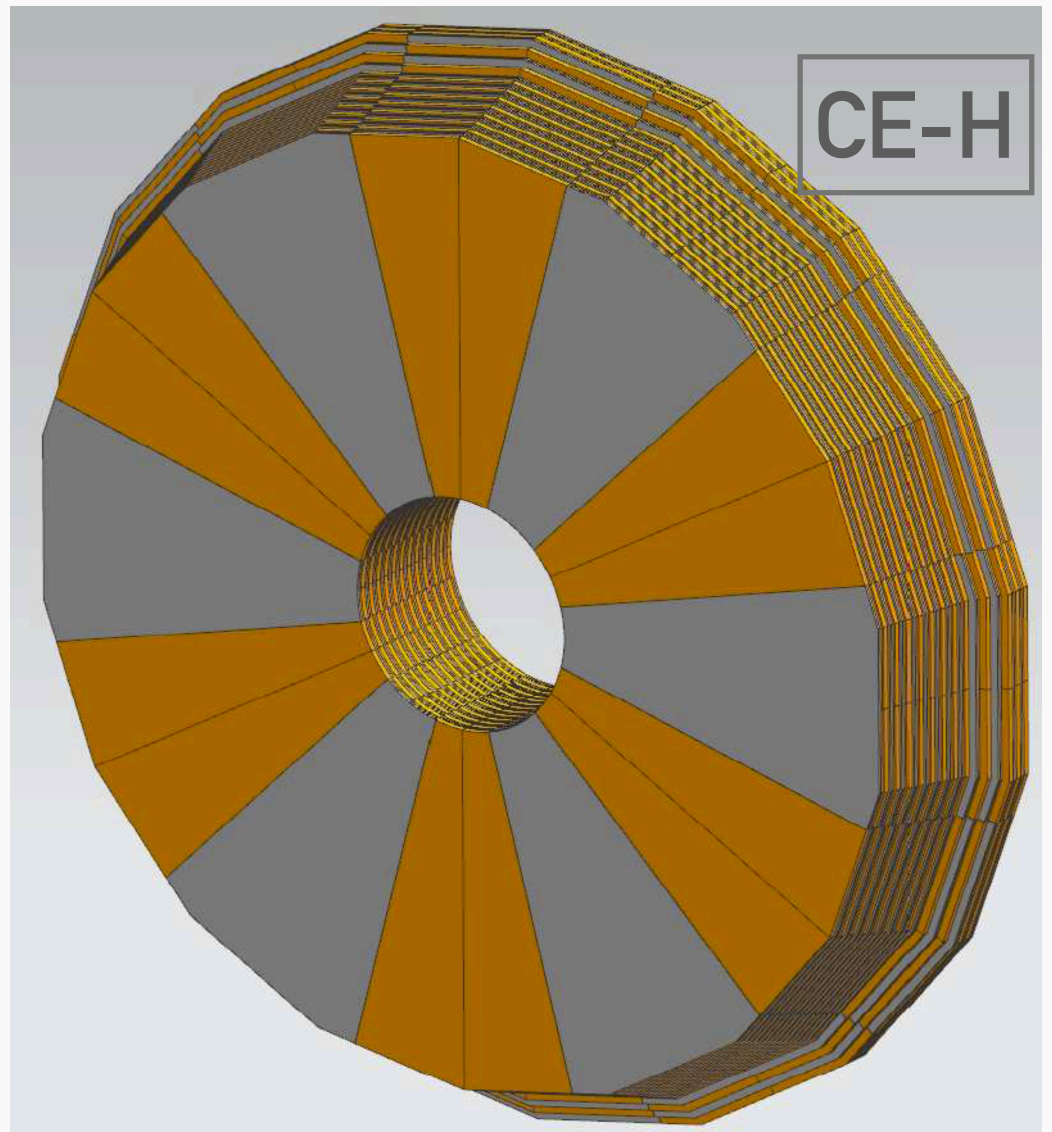
Global trigger

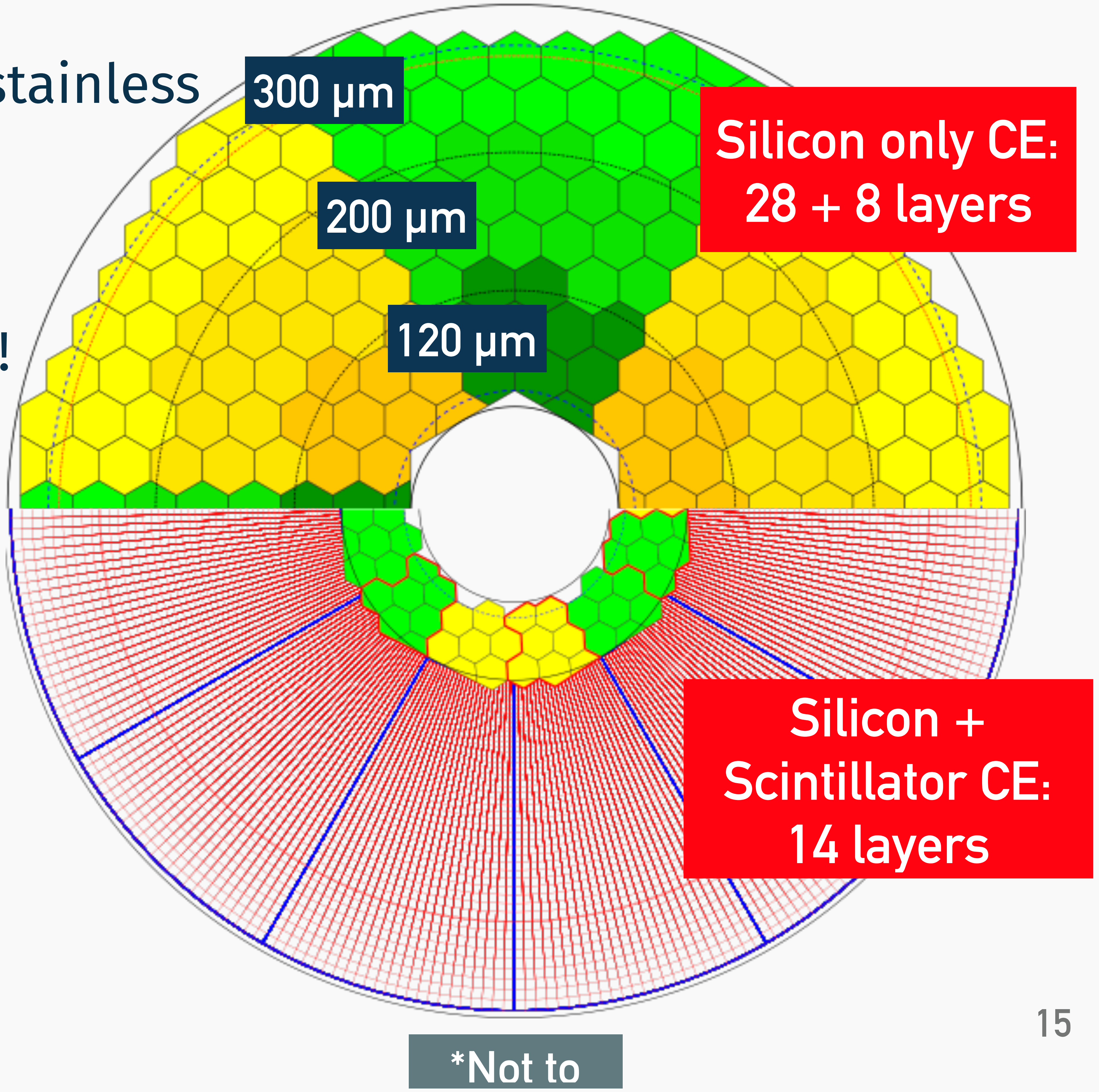
MECHANICS

- Original mechanics of the CE-E was inspired by the ILD design of the SiW-ECAL:
  - Opted for more traditional cassettes as in CE-H due to assembly constraints and flexibility
- **Challenges for compact design with cooling and absorbers**
  - Absorbers: replaced W plates with Pb in CE-E, and brass with stainless steel in CE-H due to cost and manufacturing reasons
  - Removed 2 layers of CE-H due to space constraints
  - **CO2 cooling pipes embedded** within Cu-plates: extensive R&D!

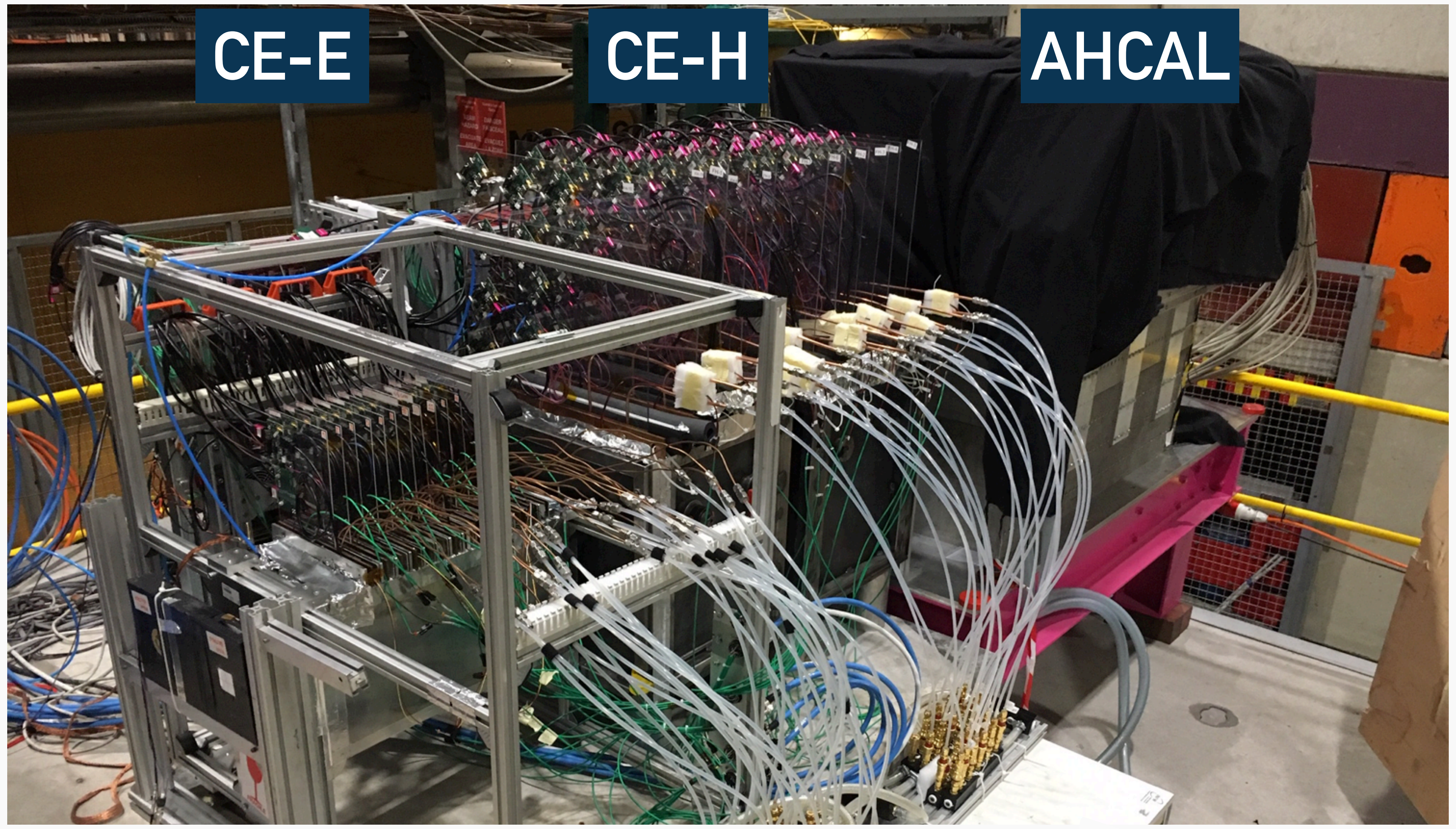


CE-E copper cooling plate

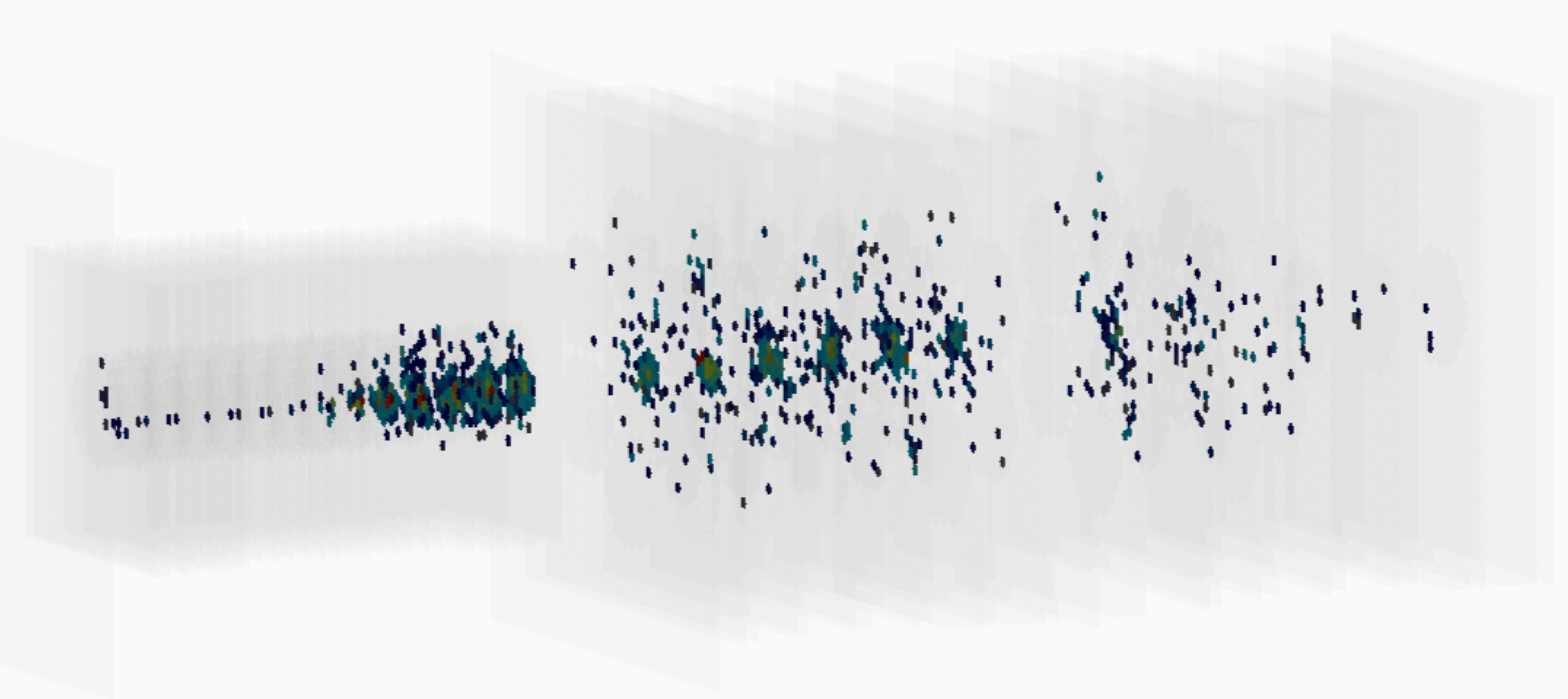




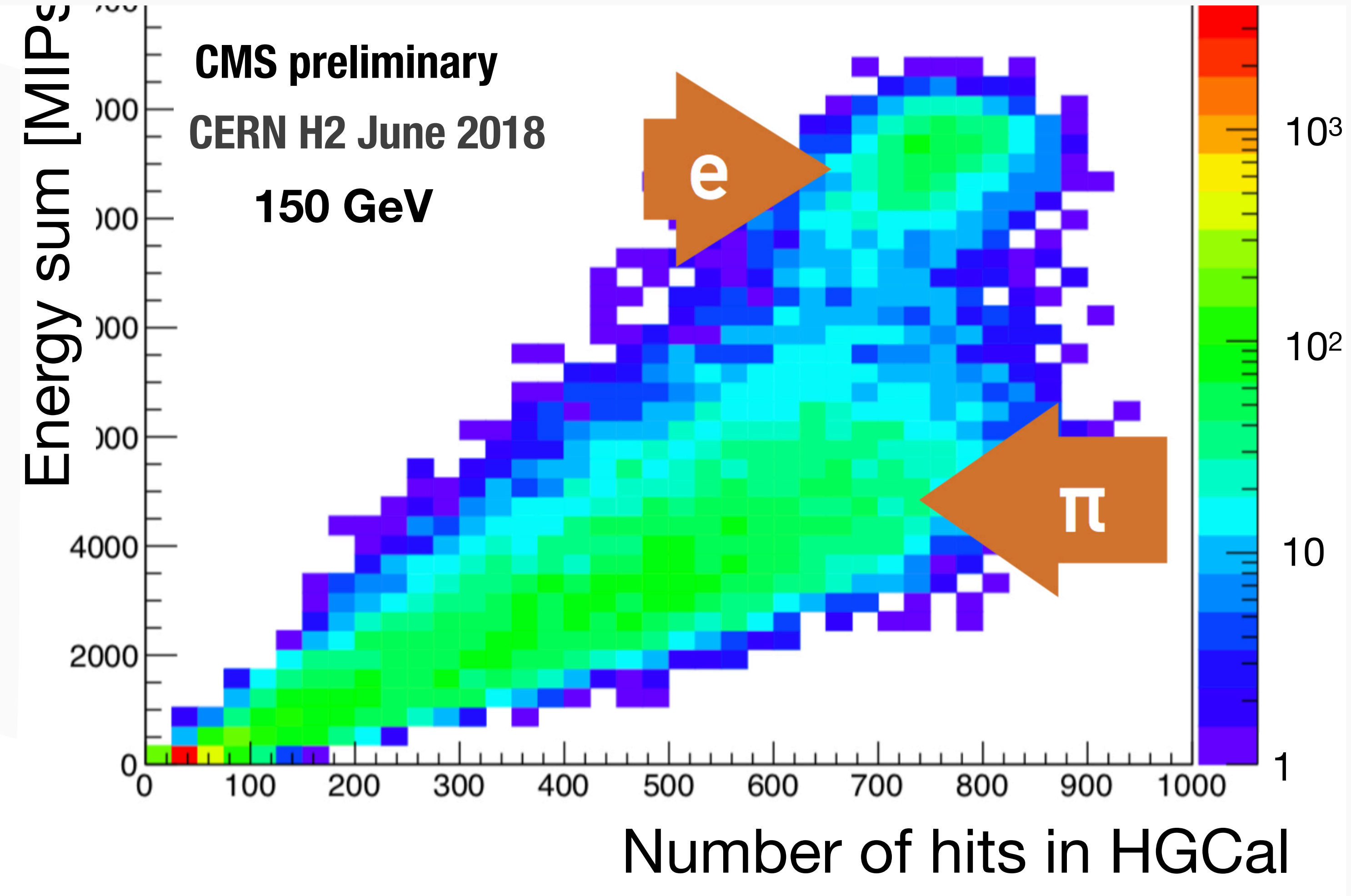
HGCAL PERFORMANCE

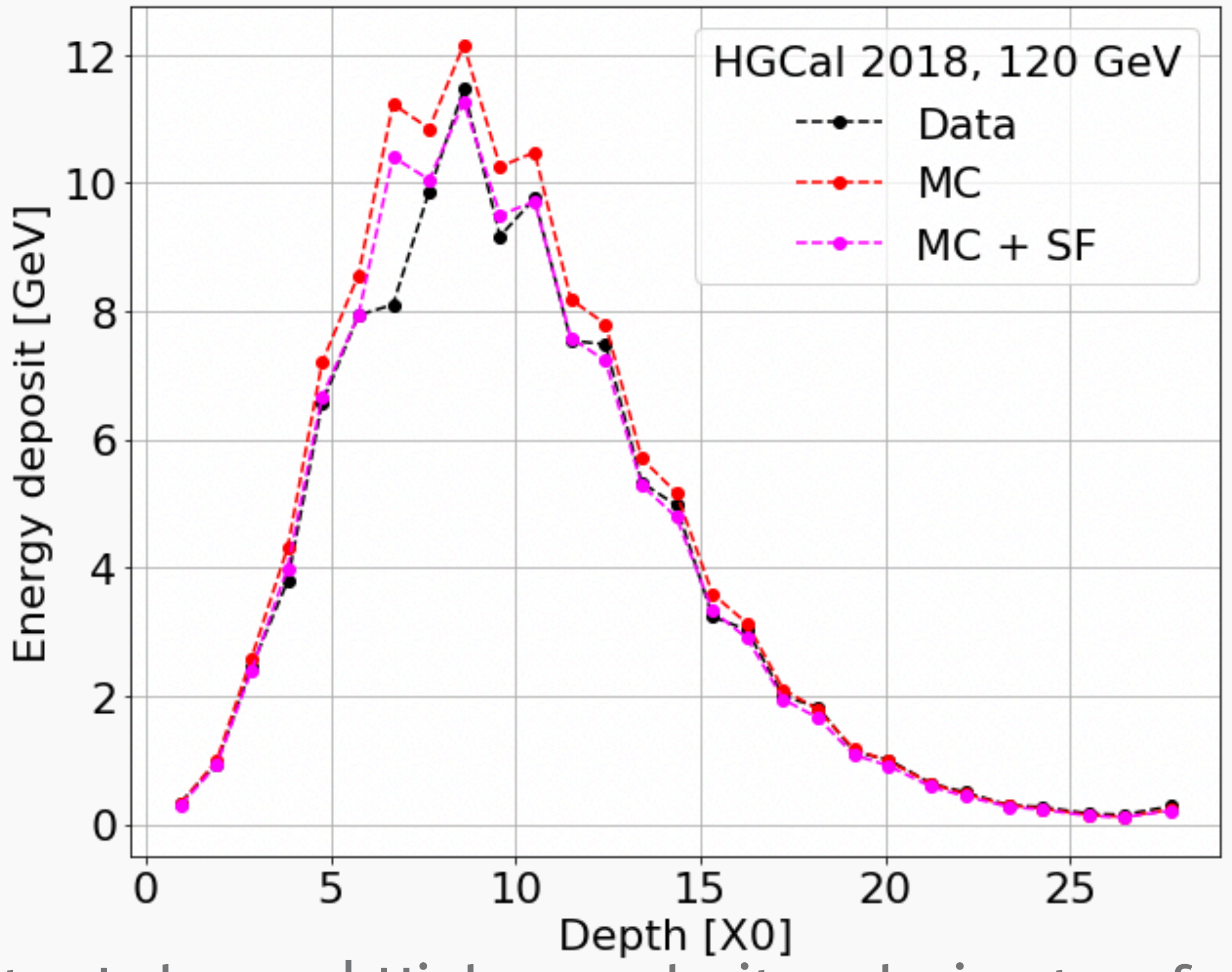


- Several beam test campaigns with prototype sensors, modules and ASICs (based on CALICE chip):
  - **Up to 94 silicon modules, 40 layers** (~50 Xo, 5 λ)
  - Combined running with CALICE AHCAL for CE-H
  - **Validation of electronics performance and calibration**
  - Physics **performance verified and simulation confirmed**
- Extensive **reco. studies also performed with Full simulation!**



300 GeV pion starting showering in CE-E





SUMMARY

SUMMARY

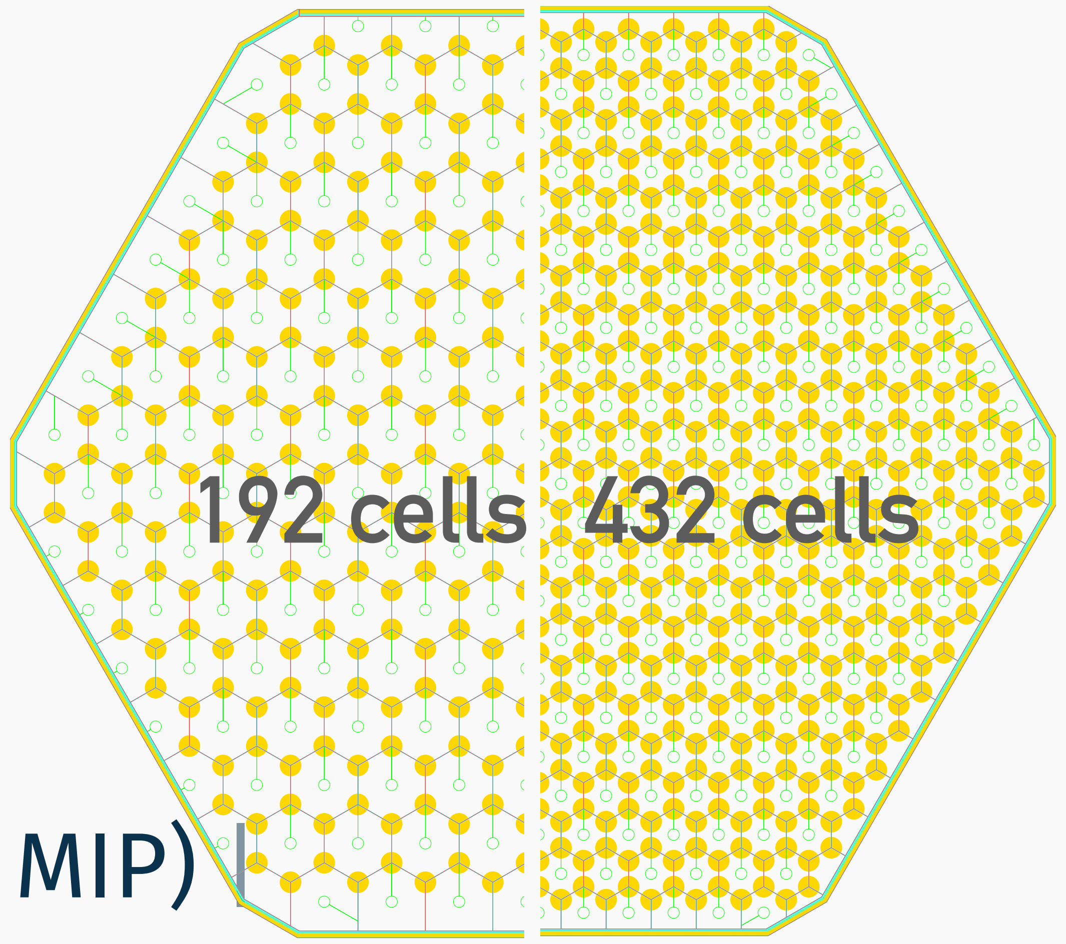
- Plethora of **high granular calorimeters studied within CALICE** for future e± machines
  - **Many French groups involved** and very experienced with this technology
  - Technologies being considered for future e+e- colliders: ILC, CLIC, CEPC and FCC-ee studies
  - CMS **HGCAL inspired by SiW-ECAL and AHCAL** technology, but extensively **adapted for HL-LHC**
    - Fast readout, radiation hardness, ps-level timing, active cooling...
- **High granularity calorimeters are well prepared for future machines!**

	SDHCAL	AHCAL	DECAL	SiW-ECAL	HGCAL
Energy meas.	Semi-digital	Bi-gain	MAPS	Bi-gain	Gain & TOT
Pileup	–	–	–	– (+in Lumi)	+
Power pulsing	+	+	+/–	+	–
Active Cooling	–	–	–	–	+
Trigger	Self	Self	Self	Self	1MHz L1
Timing	–	O(ns)	–	O(ns)	O(50ps)

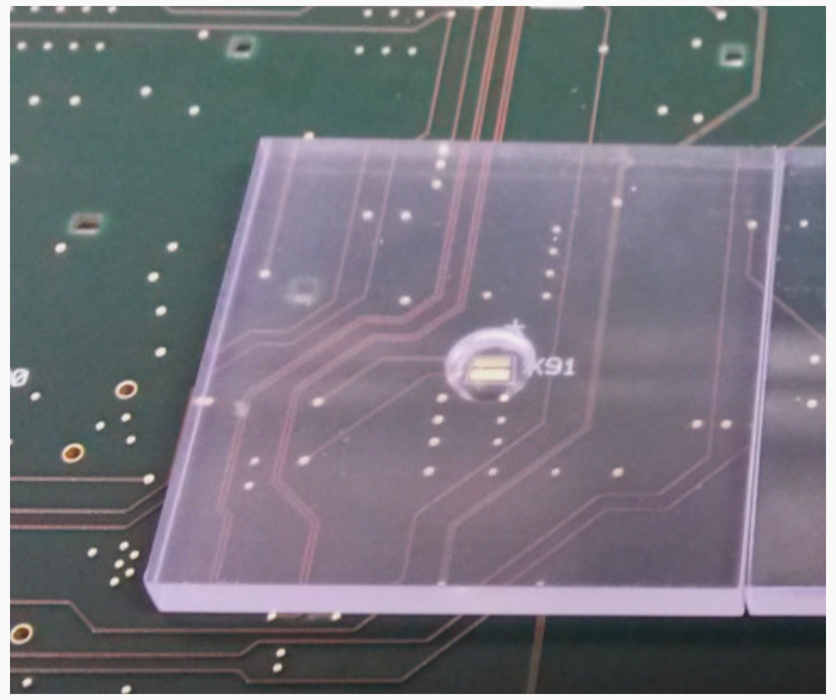
BACKUP

KEY INGREDIENTS OF HGCAL

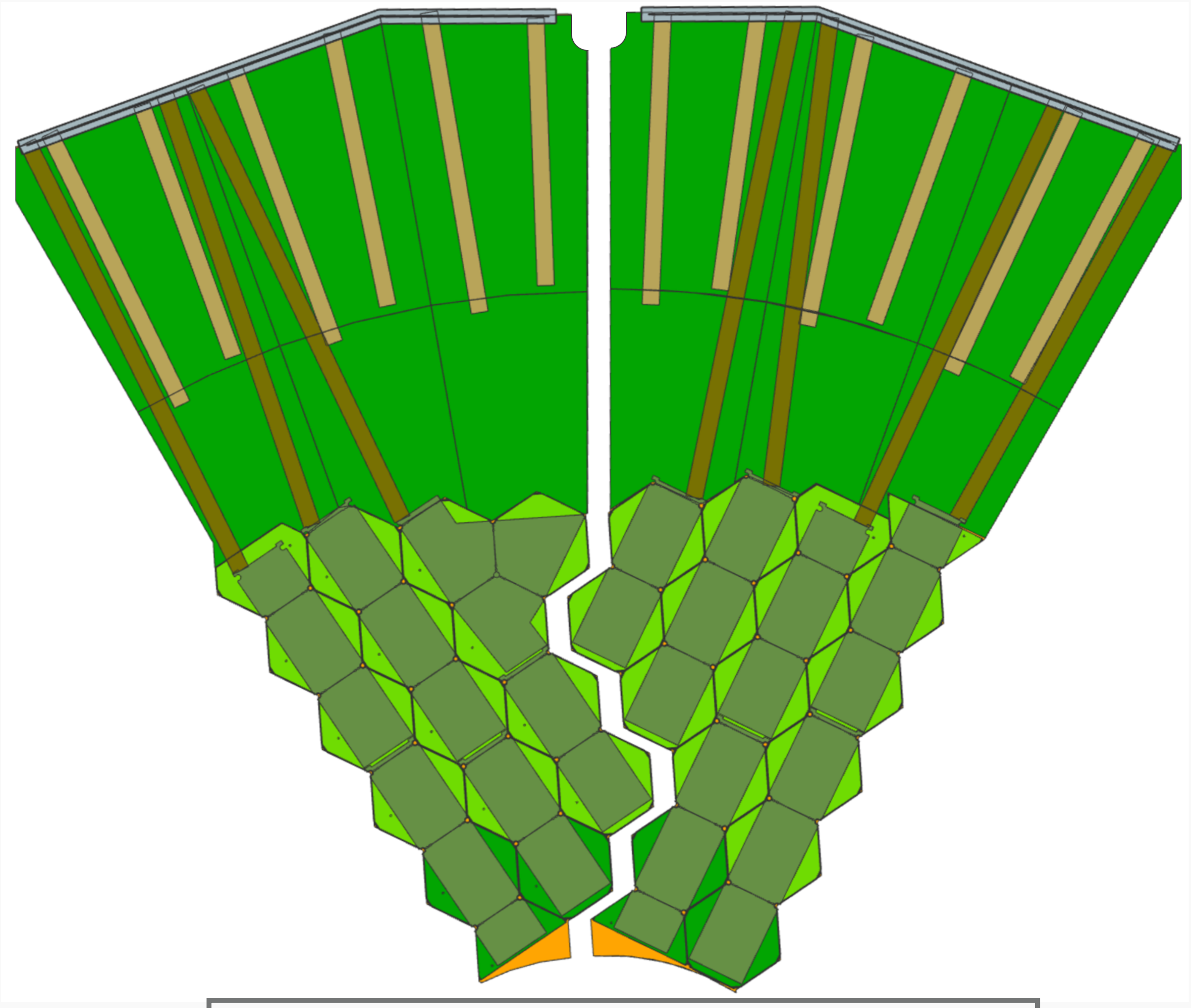
- Active elements:
  - 8” hexagonal silicon wafers p/n-type | thickness: 120/200/300 um | 192/432 cells | HV bias up to 1kV
  - SiPM-on-tile scintillator readout (à la CALICE AHCAL)
- Electronics:
  - Front-End ASIC: rad. hard | low noise | high dynamic range (1-1000 MIP) | timing measurement | < 15 mW/ch consumption
    - High range with low power due to time-over-threshold (TOT)
    - Time-of-arrival (TOA) method with time precision of 20 ps
  - Trigger data from ASICs (300 TB/s) fed through concentrators to the back-end system (2 TB/s) in multi-stage approach
- Engineering:
  - $30^{o}/60^{o}$ cassettes tiled with hexagonal silicon modules and partially mixed with scintillator tile boards
  - Full detector volume cooled to -30^{o}C



Silicon sensors



SiPM-on-tile (AHCAL)



Si+Sci mixed cassette

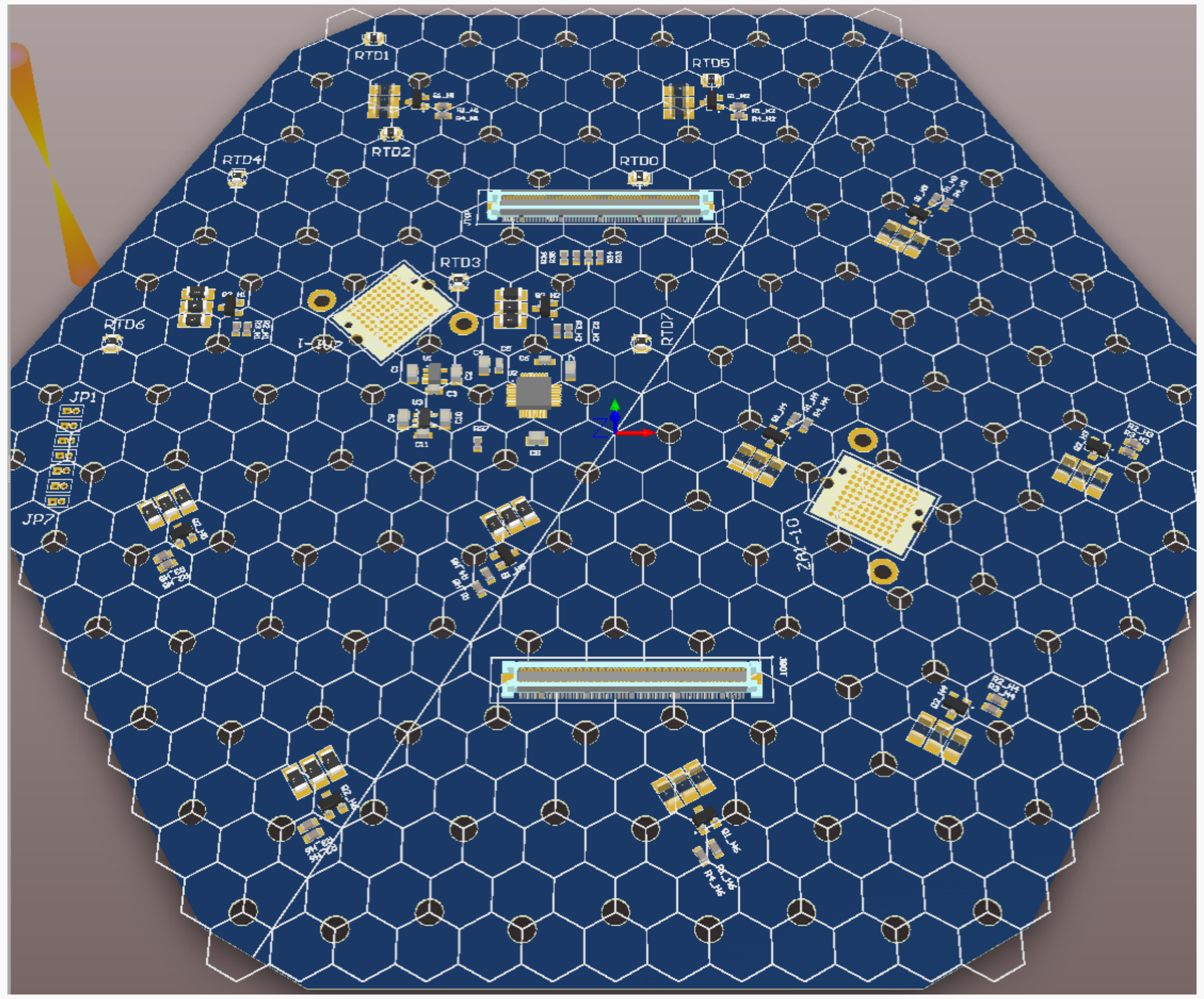
FRONT-END ELECTRONICS

- Detector modules with 2 PCBs <u>< 6mm thick</u>:

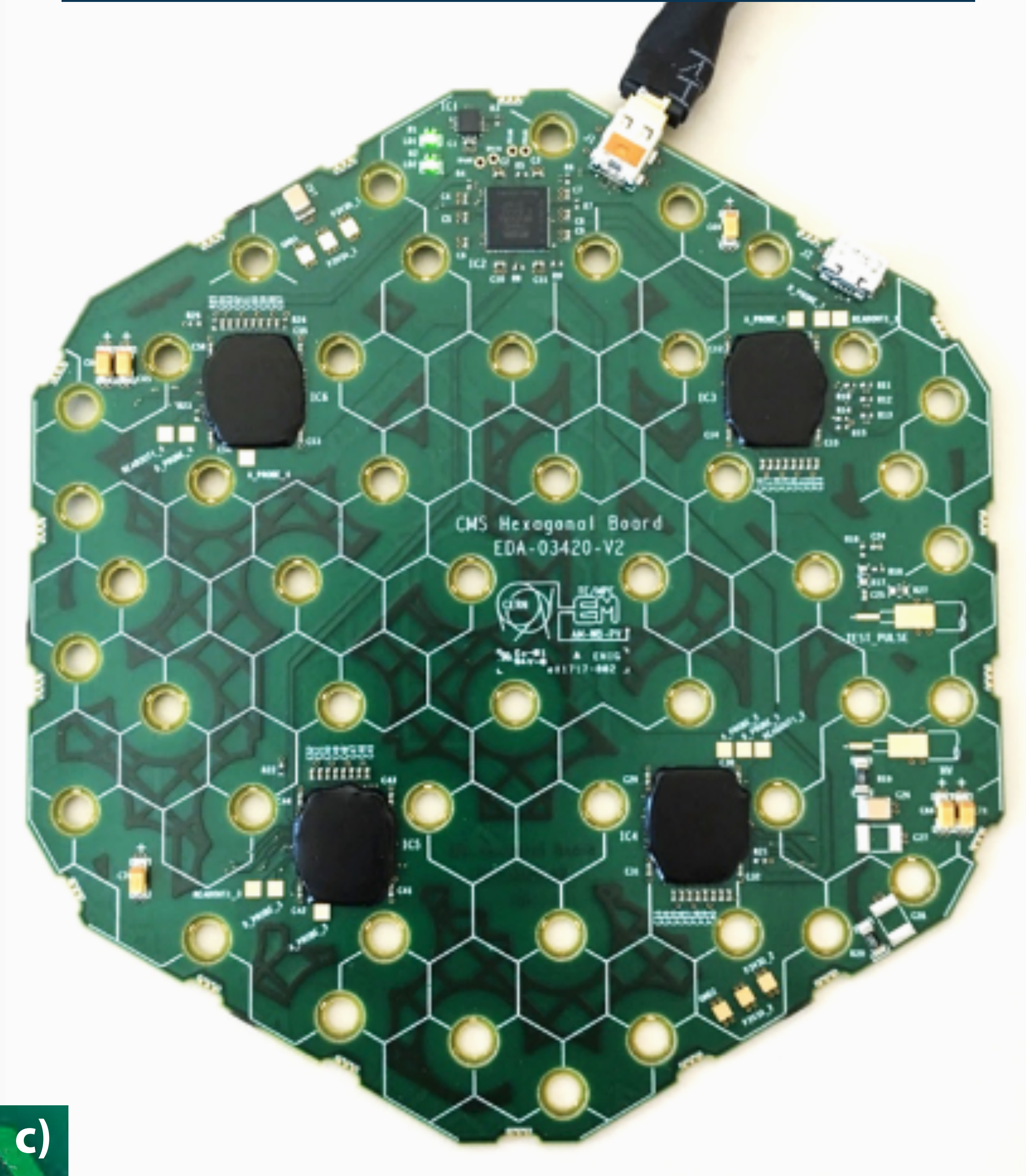
  1. PCB: “hexaboard”
     Wire-bonds to Si-sensor
     and very-FE ASICs
  2. PCB: Motherboard for
     powering, data concentration,
     trigger generation and
     bi-directional communication

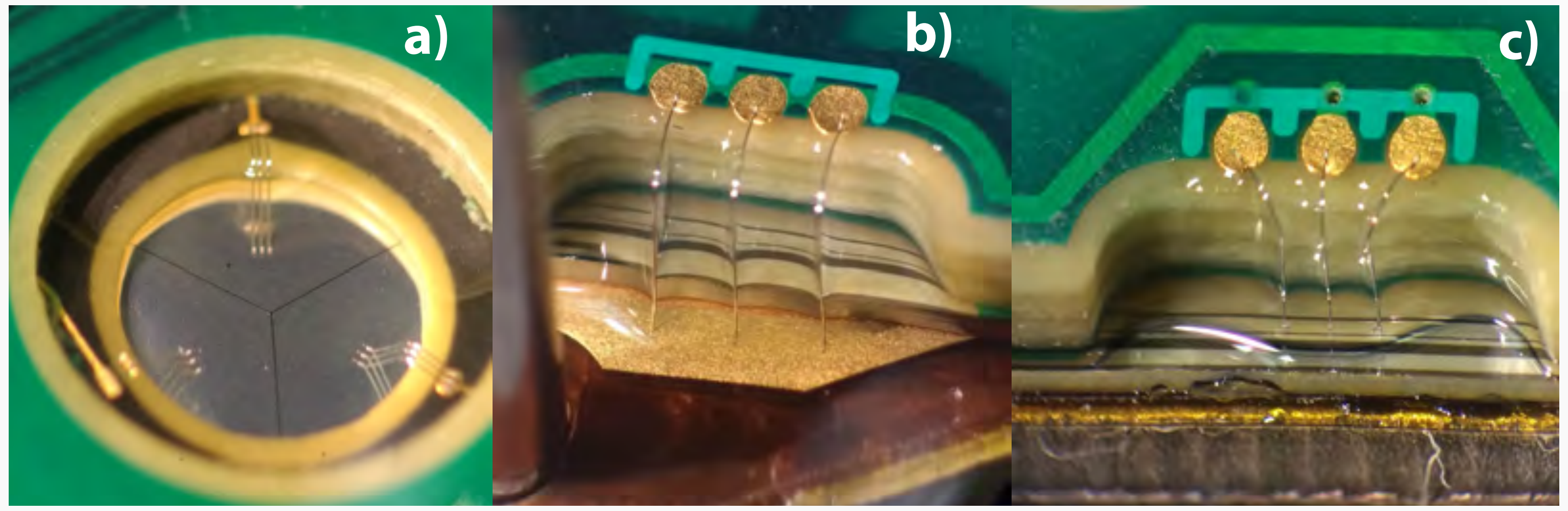
- Trigger/data transfer:
  low-power GBT links (lpGBT)

Hexaboard design for HGCROC



Hexaboard PCB for Test Beam





Wire-bonds from Silicon to 1. PCB

FRONT-END ELECTRONICS

- Detector modules with 2 PCBs <u>< 6mm thick</u>:
  1. PCB: “hexaboard”
     Wire-bonds to Si-sensor and very-FE ASICs
  2. PCB: Motherboard for powering, data concentration, trigger generation and bi-directional communication
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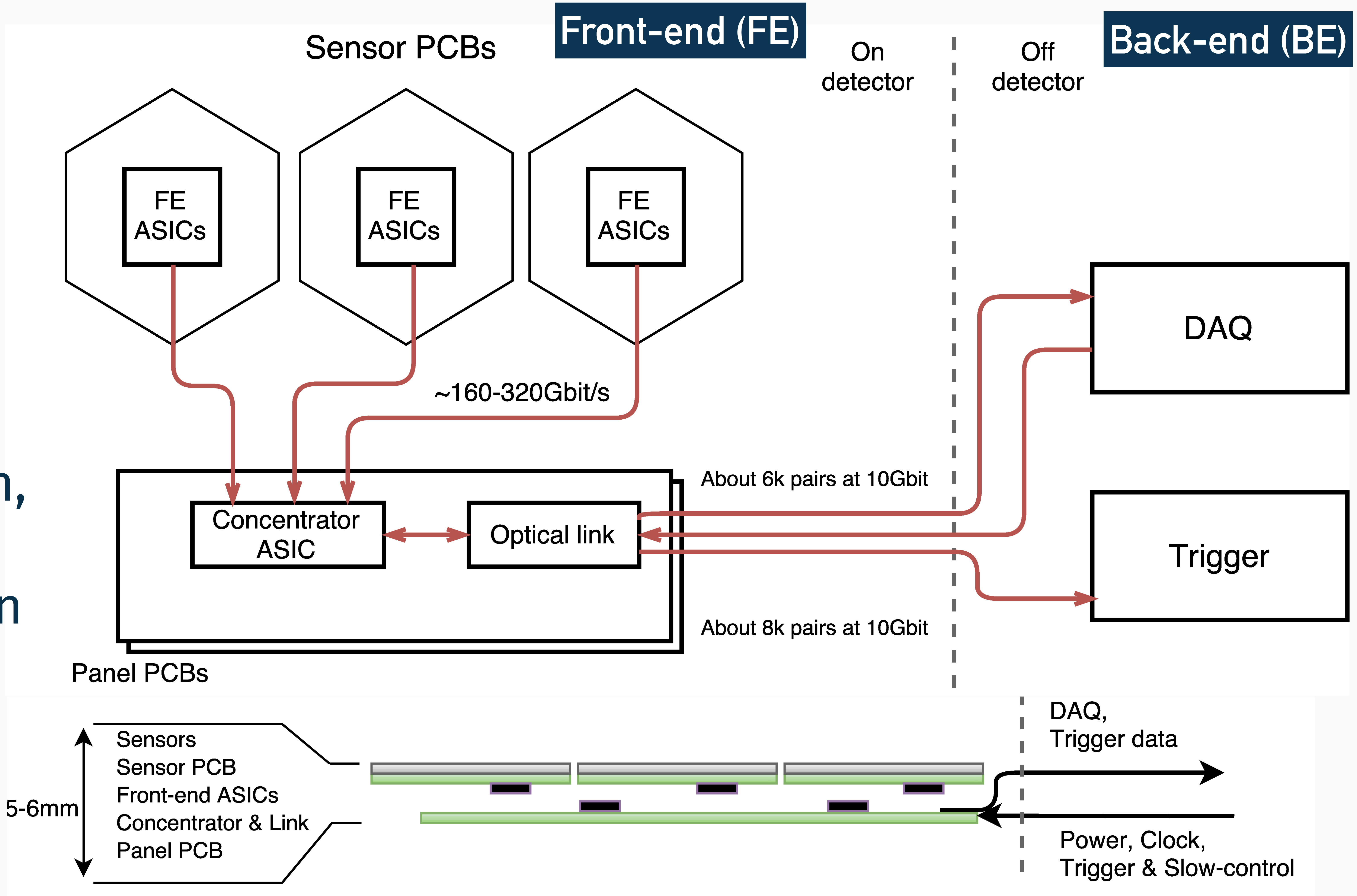
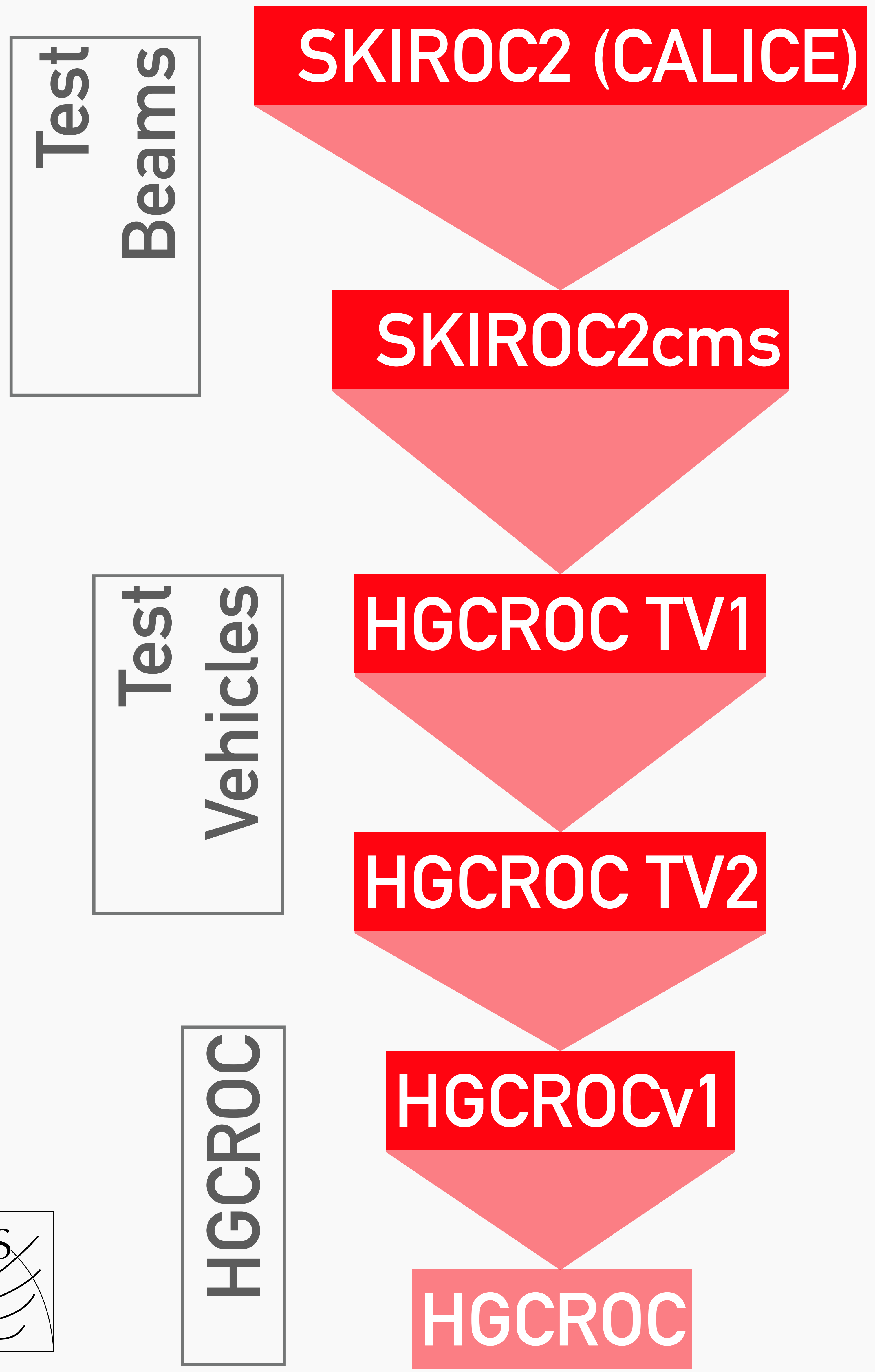


HGCAL ASIC EVOLUTION: FROM SKIROC TO HGCROC



- SKIROC2:
  - ASIC used by CALICE in the SiW ECAL
  - Dedicated 64 channel Si-detector readout ASIC, SiGe 350 nm
- SKIROC2cms: *submitted and received in 1Q of 2016*
  - Modification for test beams with CMS-like running conditions
  - 40 MHz clock and sampling, Gain + ToA + ToT
- Test Vehicle 1: *submitted in May 2016, received in August 2016*
  - First HGCROC test vehicle in CMOS 130 nm architecture
  - Dedicated to preamplifier studies
- Test Vehicle 2: *submitted in December 2016, received in May 2017*
  - Dedicated to analog channel study for TDR
- HGCROCv1: *submitted in July 2017, expected in October 2017*
  - All analog and mixed blocks; many simplified digital blocks

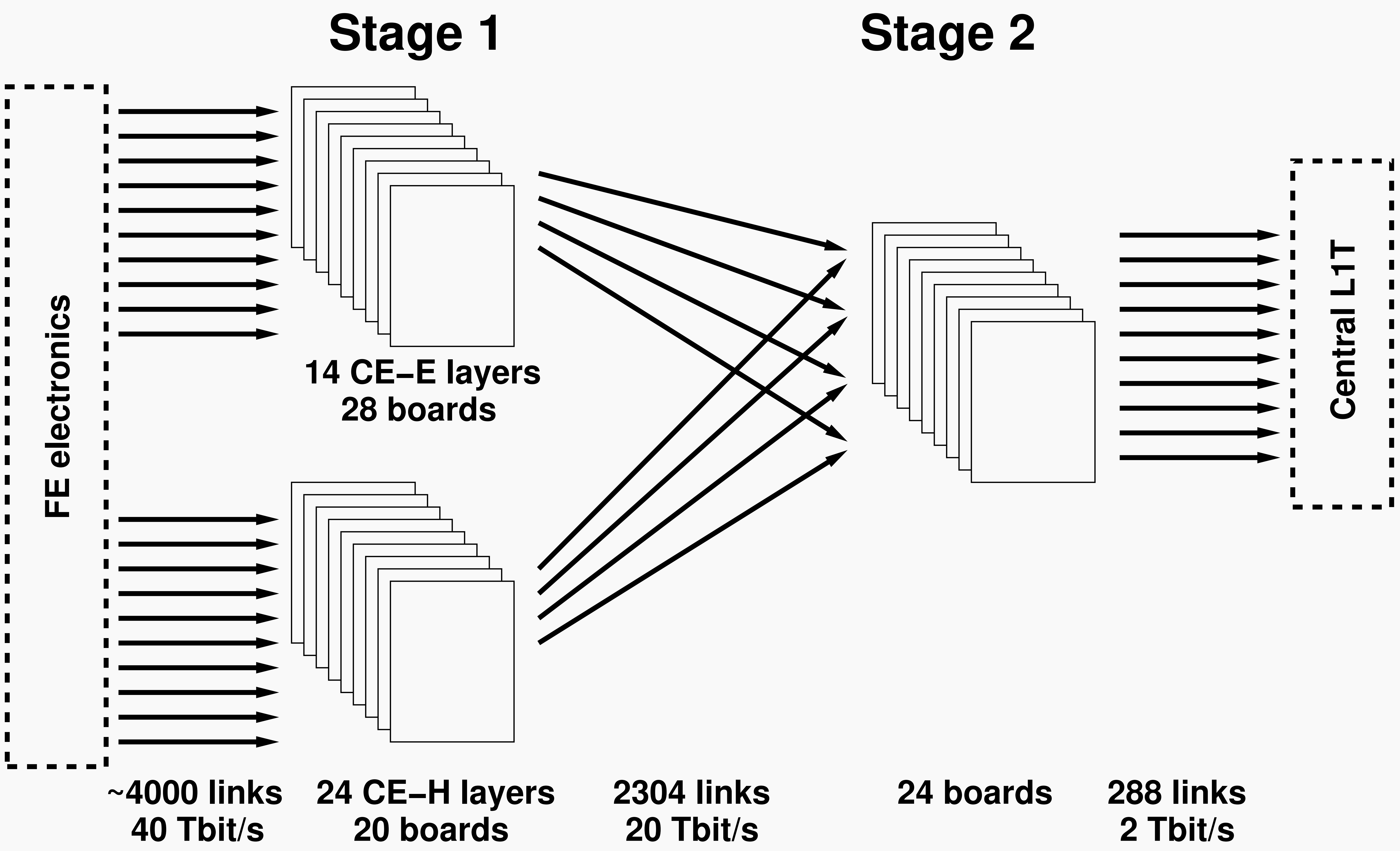
➡ **Final HGCROC submission by mid 2019!**

HGCAL TRIGGER FLOW

Front-end	HGCROC	Resolution and granularity reduction, formation of trigger cells (TC)
	~300 Tb/s	
	Concentrator	Selects fraction of trigger cells (threshold or fixed number of highest energy TC)
	~40 Tb/s	
Back-end Trigger primitive generator	TPG Stage 1	Dynamical 2D clustering of trigger cells per layer
	~20 Tb/s	
	TPG Stage 2	Formation of 3D clusters — trigger primitives (TP)
	~2 Tb/s	
CMS Trigger	Correlator	L1 trigger correlator with input from track trigger
	Global trigger	Central CMS L1 trigger

BACK-END: TRIGGER PRIMITIVE GENERATOR

- Stage 1:
  - Dynamical clustering based on the Nearest Neighbour TCs generates **2D clusters** in each trigger layer
- Stage 2:
  - Creation of **3D-clusters** exploiting the longitudinal development of the shower using the projected position of each 2D cluster to identify its direction



- The Stage 1 –> Stage 2 data transmission is **x24 time-multiplexed** in order for all data from one endcap to be processed by one single FPGA