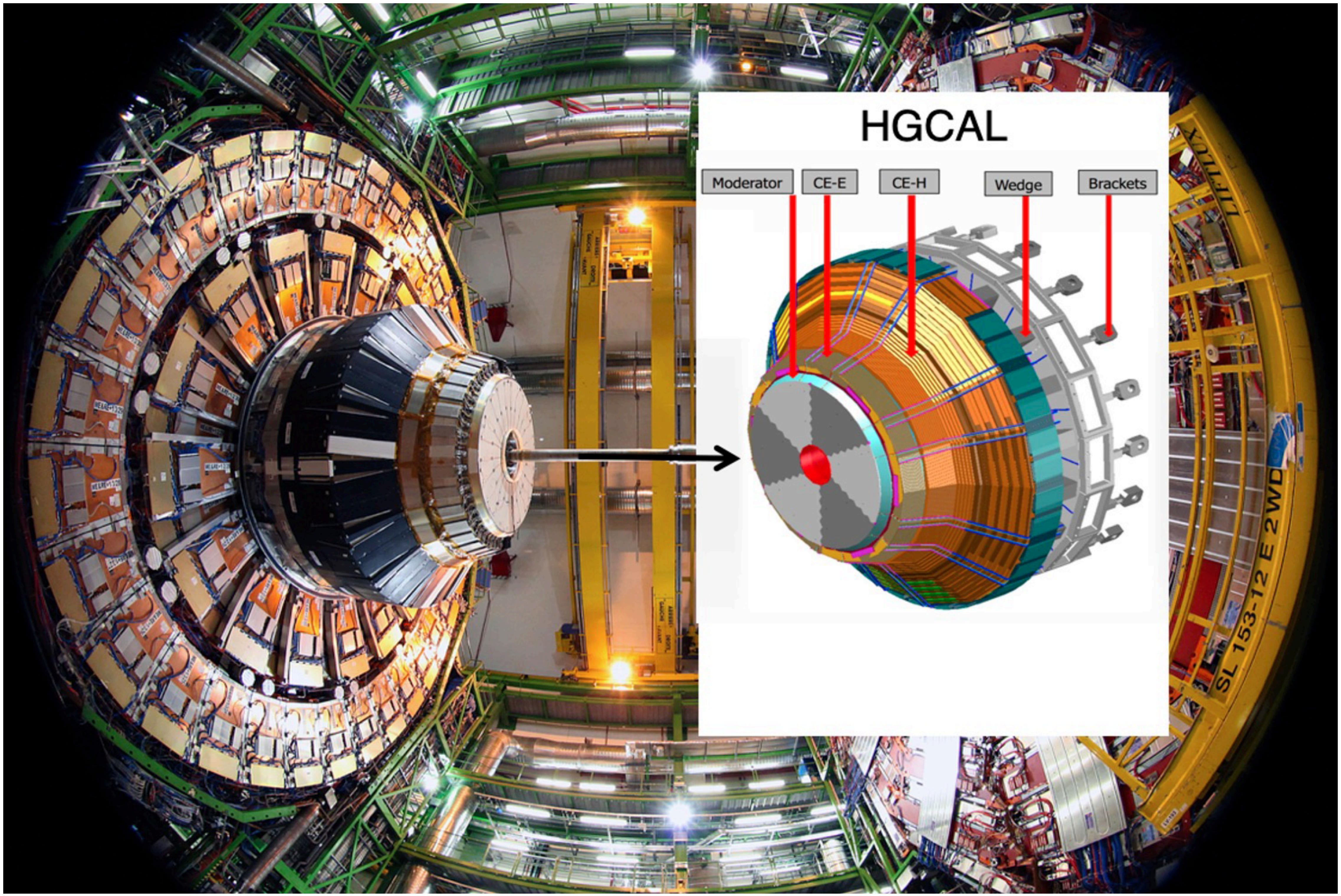
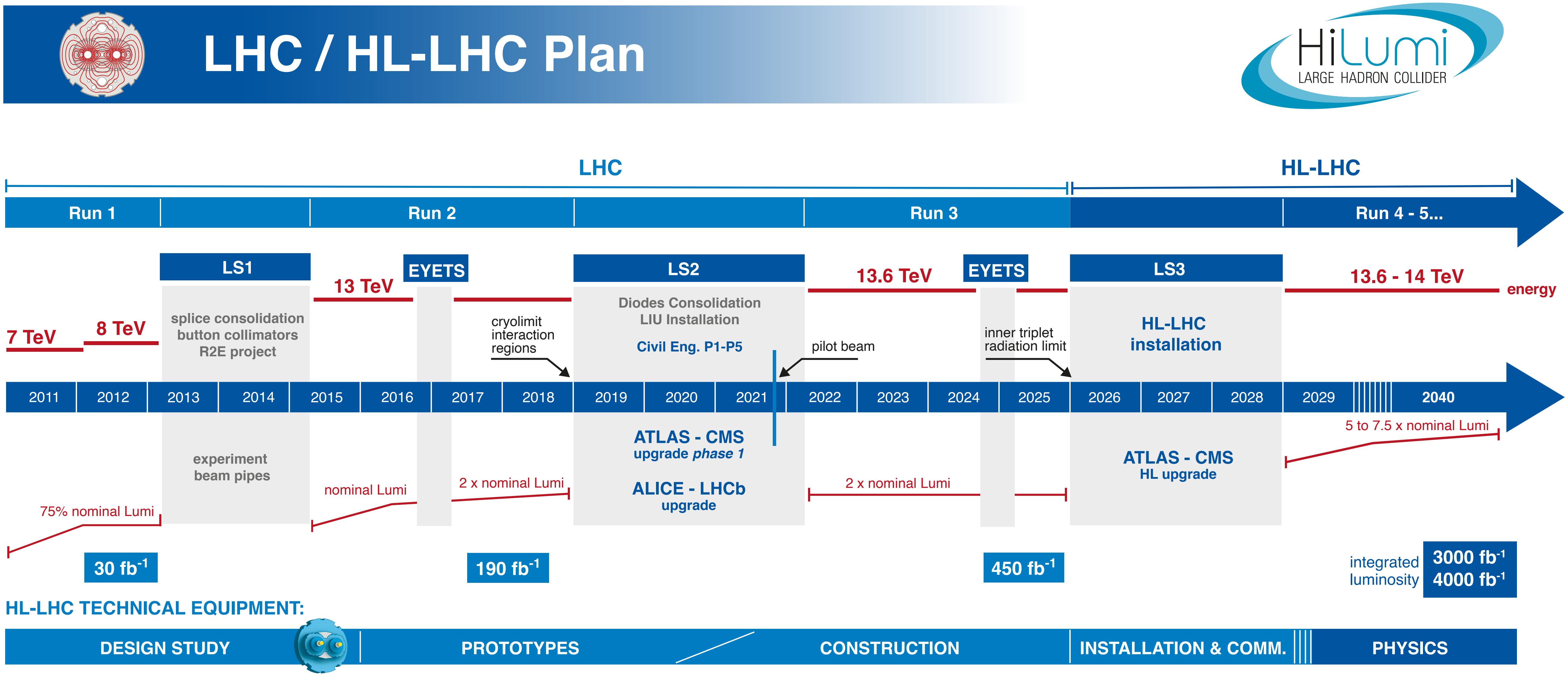
CMS HGCAL

Rong-Shyang Lu
National Taiwan University

Introduction



HL-LHC and Phase-2 Upgrade

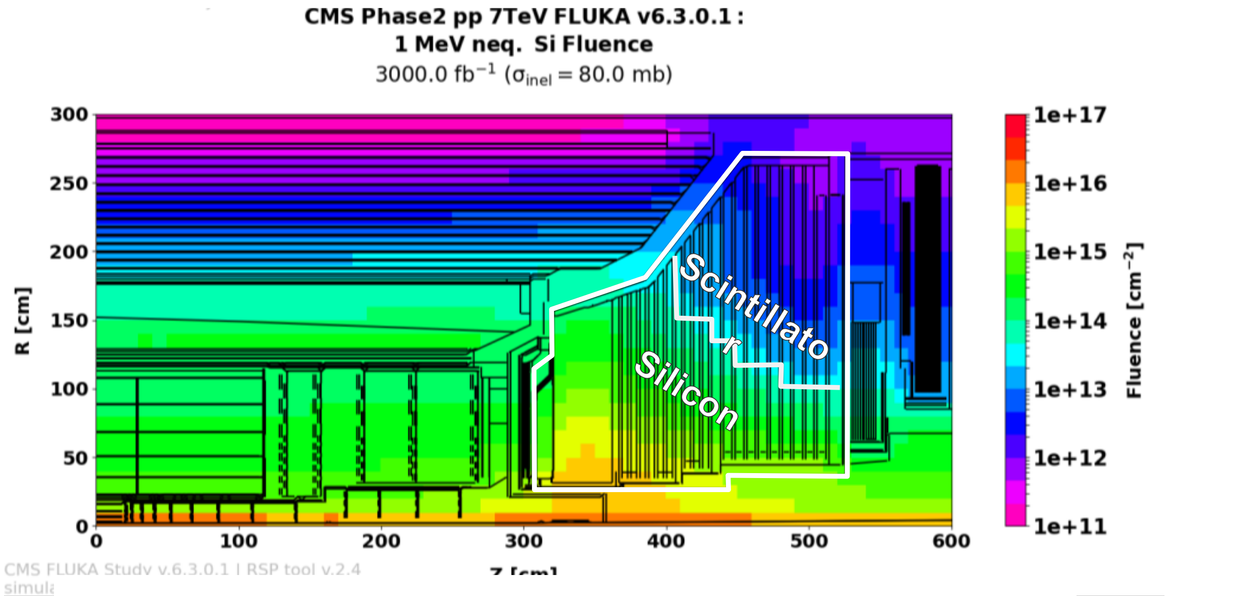


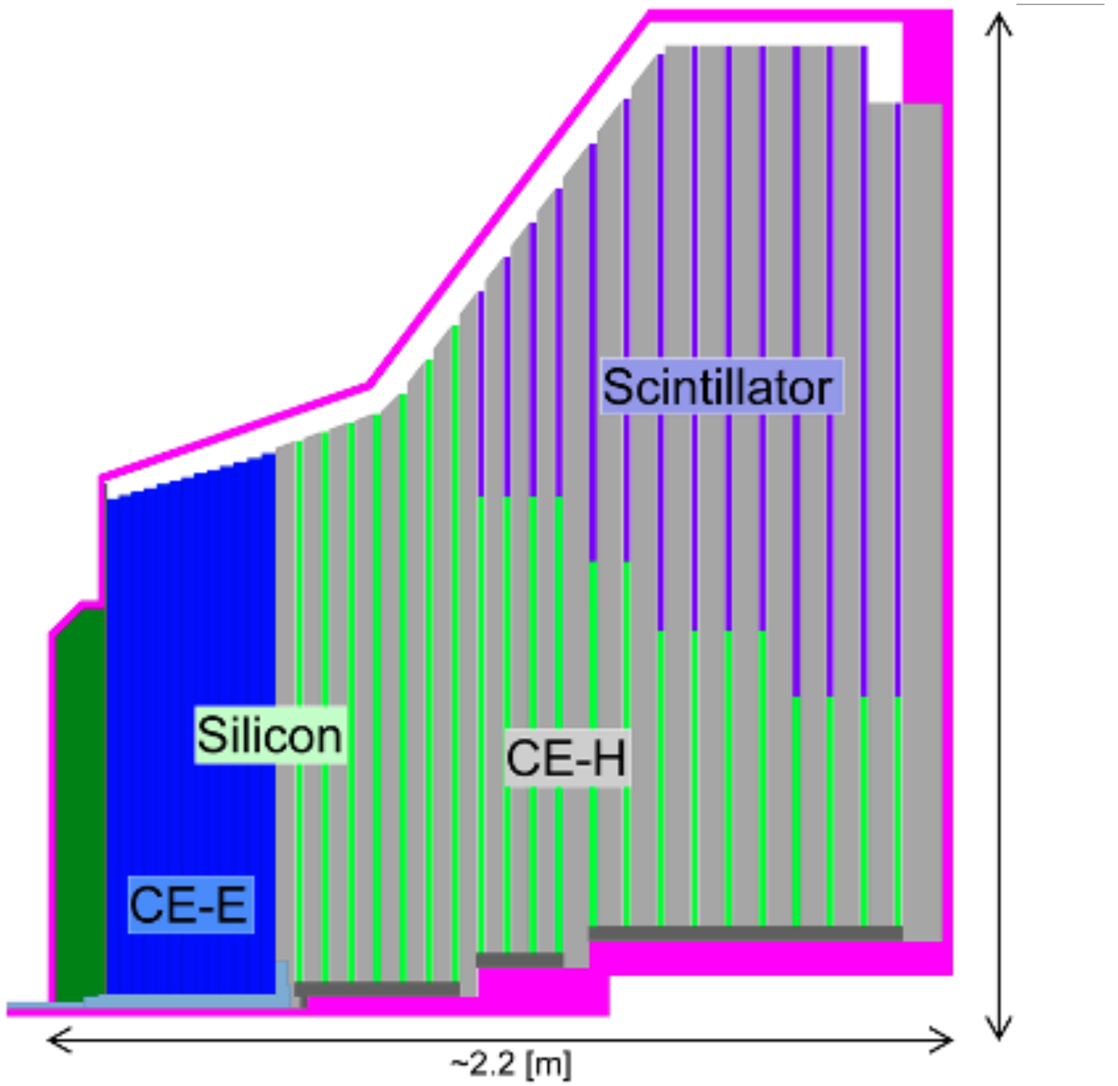
Introduction

Key Parameters:
- HGCAL covers $1.5 < \eta < 3.0$
- **Full system maintained at -30°C**
- **~620 m²** of silicon sensors
- **~370 m²** of scintillators
- ~6M Si channels, 0.5 or 1.2 cm² cell size (*6M*)
  ~280k scint-tile channels ($\eta-\phi$) 4-30 cm²
  - Data readout from all layers
  - Trigger readout from alternate layers in CE-E and all in CE-H
- ~26000 Si modules, 3700 Scintillator modules

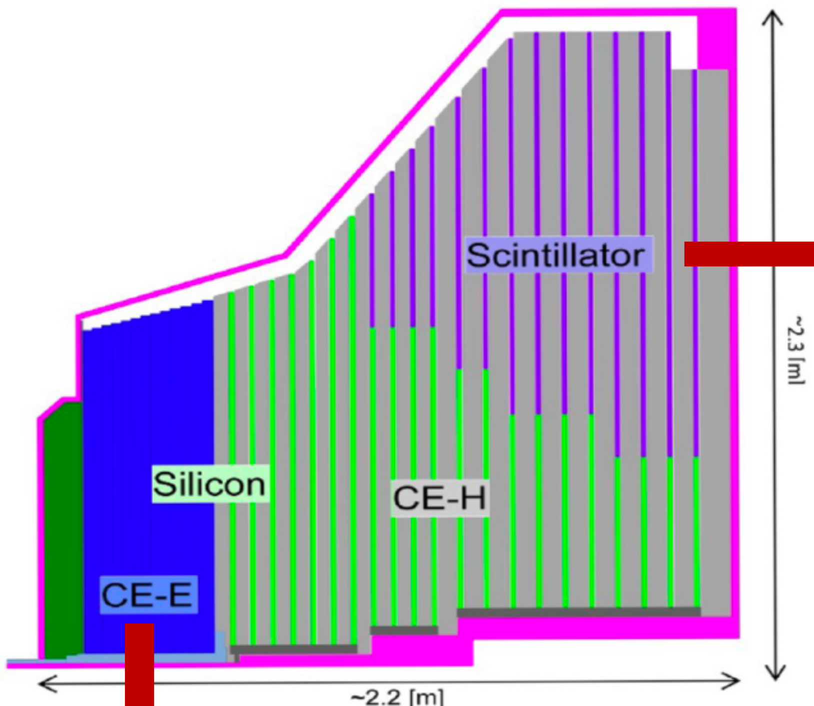
Active Elements:
- Si sensors (full and partial hexagons) in CE-E and high-radiation region of CE-H.
- SiPM-on-Scintillating tiles in low-radiation region of CE-H

Electromagnetic calorimeter (**CE-E**): **Si**, Cu/CuW/Pb absorbers, 26 layers, 27.7 X_0
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 21 layers, 10.0λ (including CE-E)
~220 tonnes per endcap





Active Material



Lower radiation level than silicon sector

Radiation level comparable to pixel tracker

Cell sizes from 4 to 30 cm^2

Tileboard PCB
Hosting the readout chips

Wrapped Scintillating Tile
Reflective foil

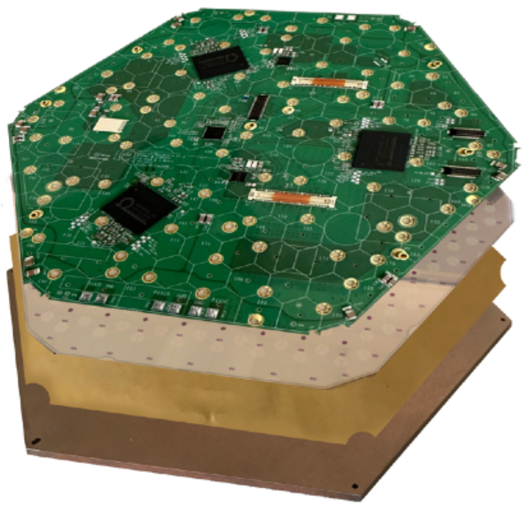
Silicon Photo Multiplier (SiPM)
Calibration with LED

Hexaboard PCB
Hosting the readout chips

Silicon Sensor

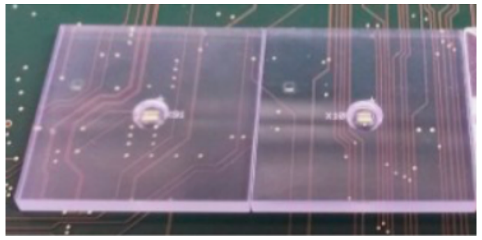
Metalized Kapton Sheet

CuW BasePlate*
Rigidity, contributes to the absorber material

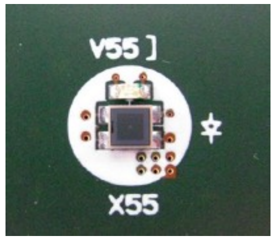


*Carbon fibre baseplate in the hadronic sector

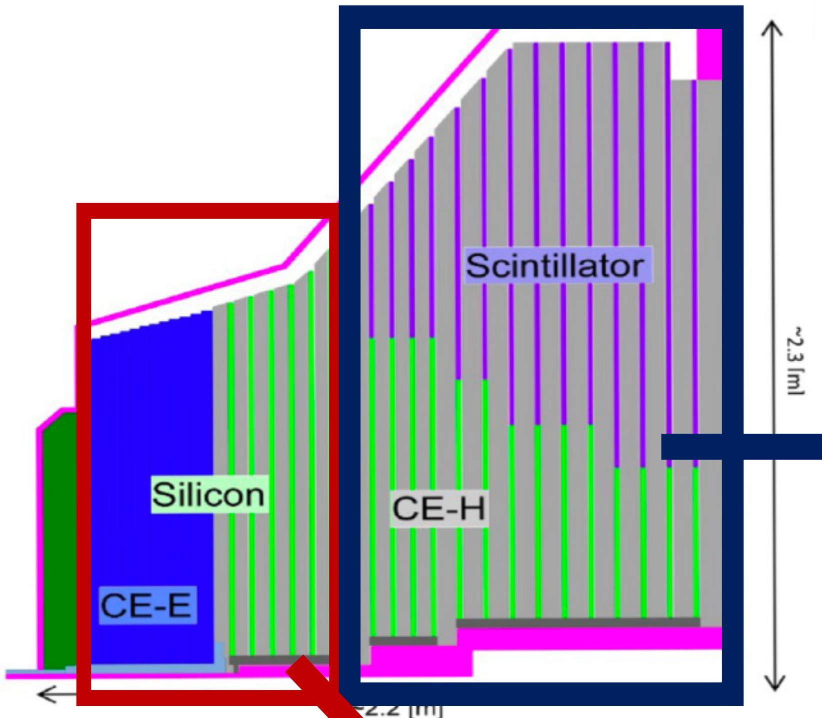
Scintillator

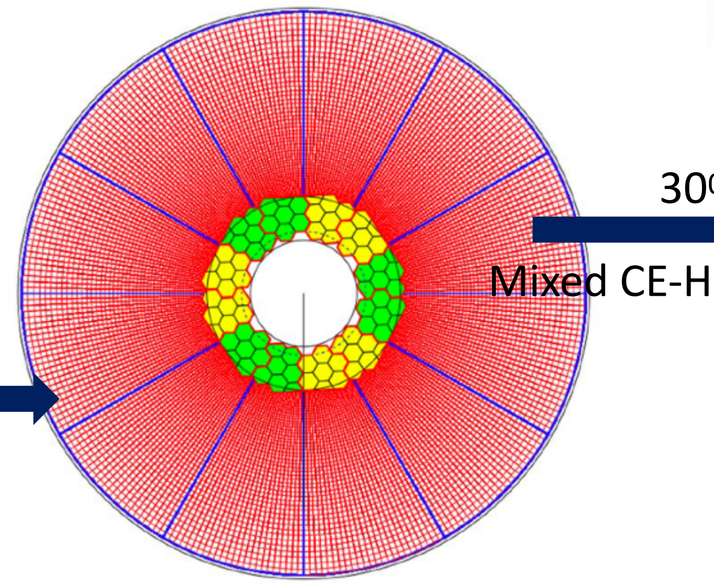


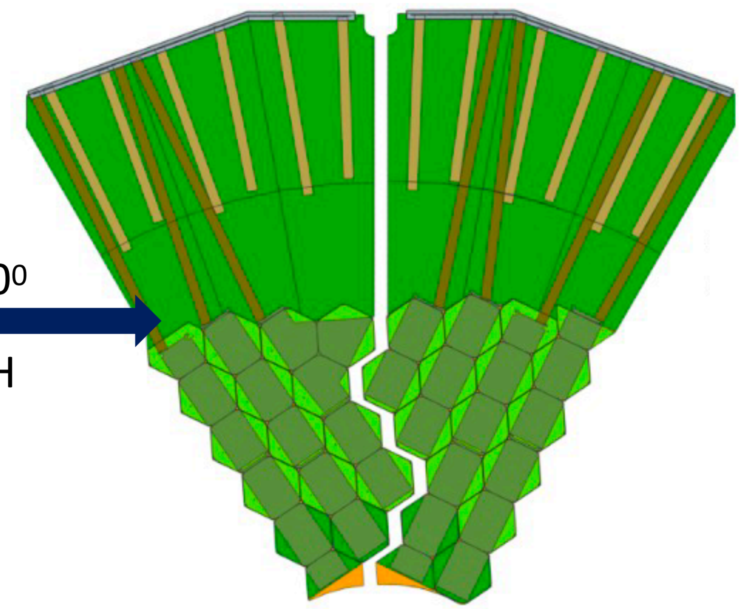
SiPM



Integration : Cassette

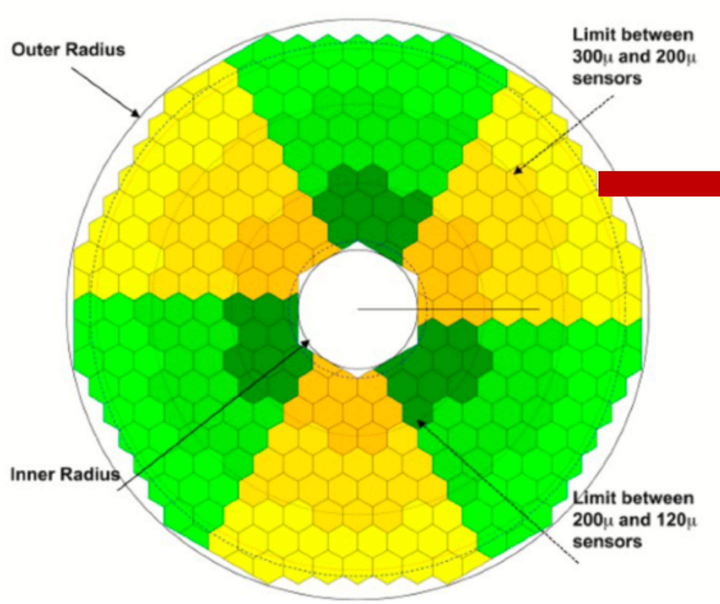


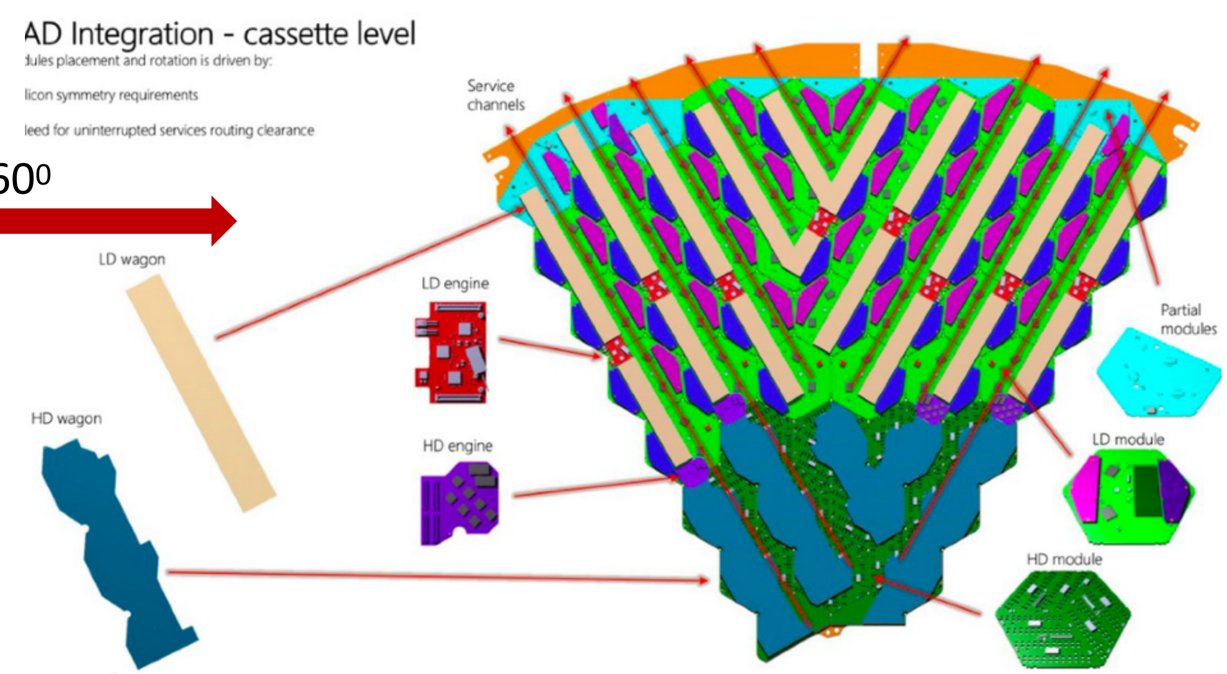




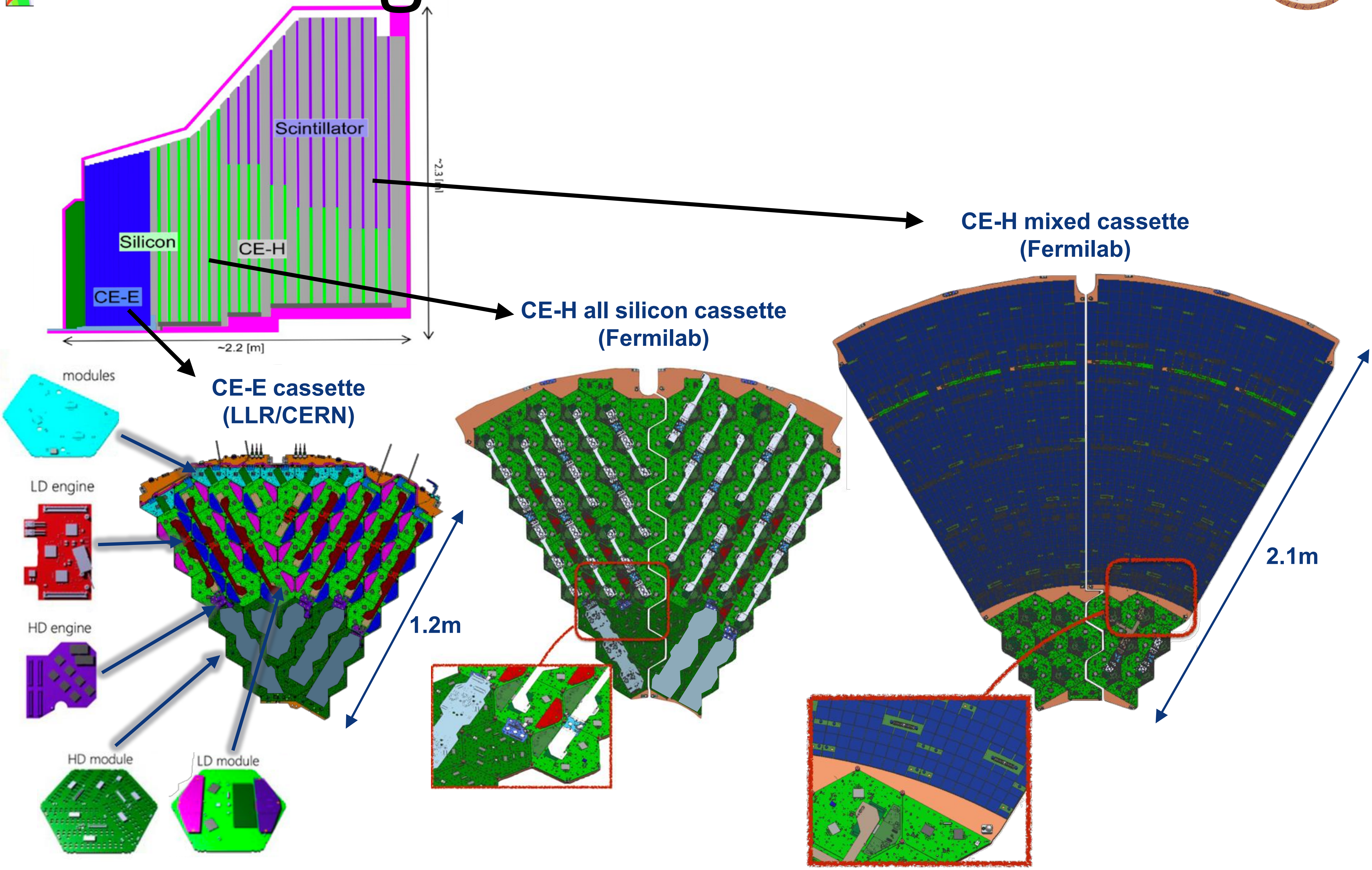
- Integration of modules and auxiliary components
  - Motherboards
  - Wingboards
  - Twinax cables

- Integration of modules and auxiliary components
  - Engines, wagons, DCDC, ECON mezzanines,
  - services

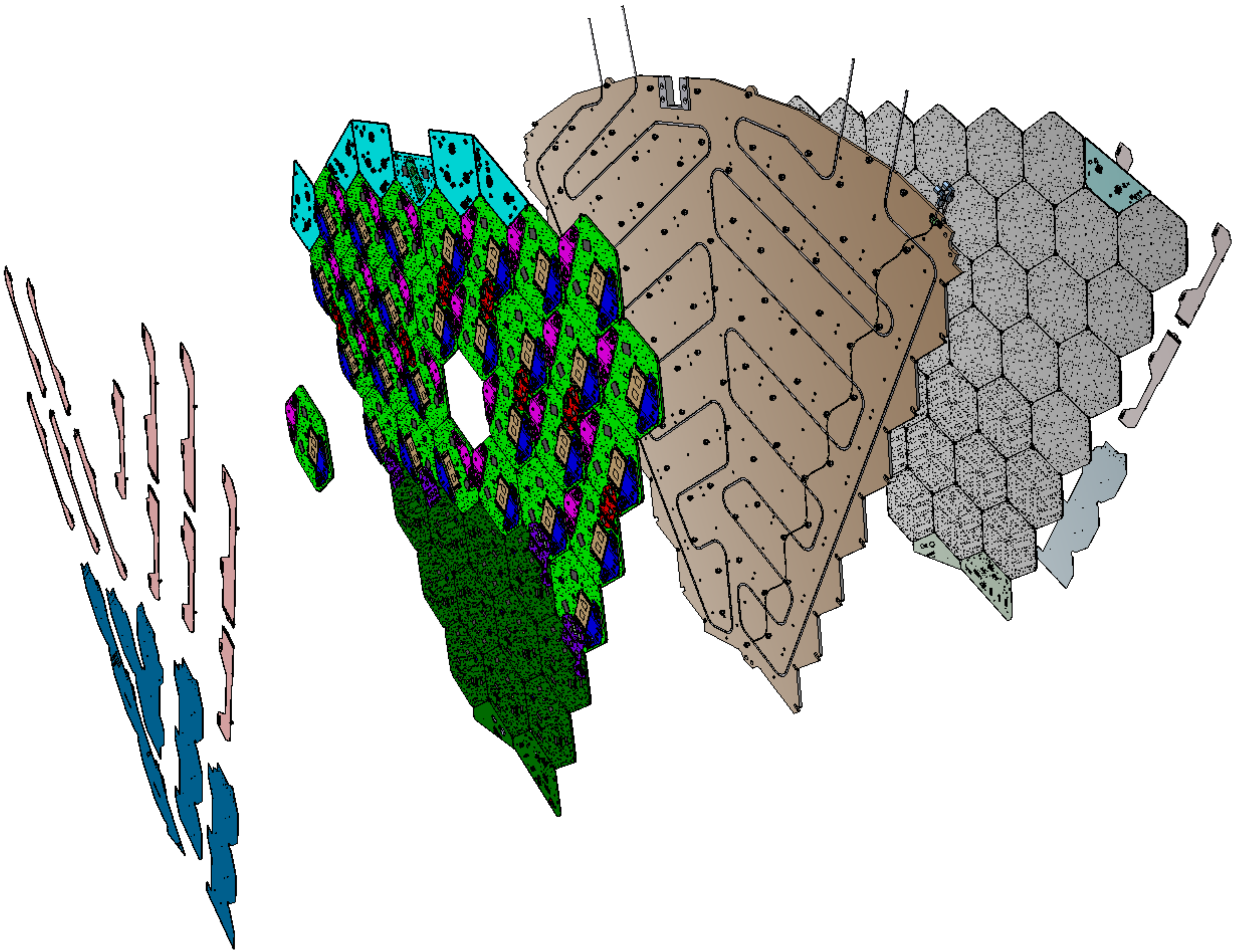




Integration : Cassette

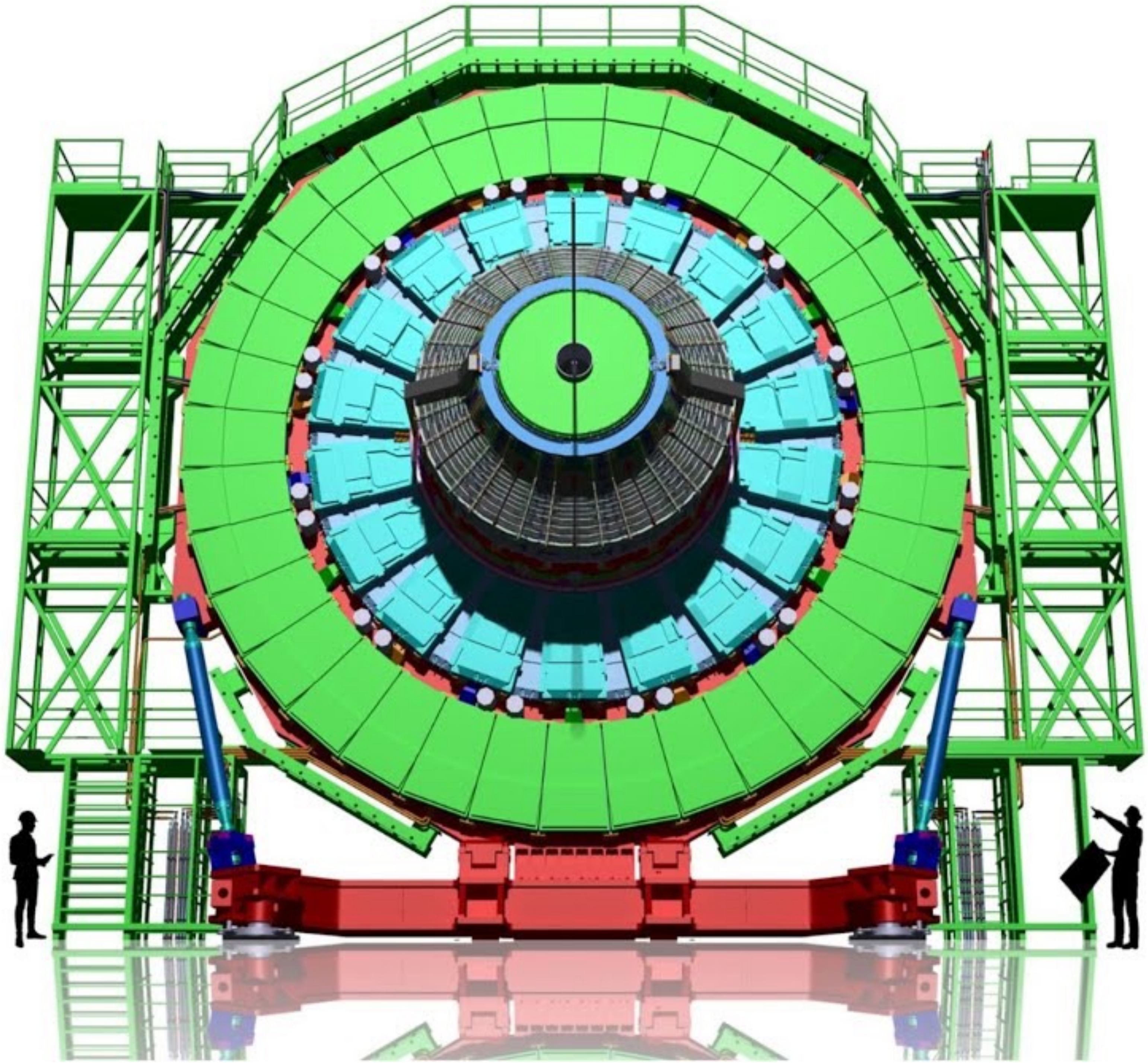


CEE Cassette



Integration Animation

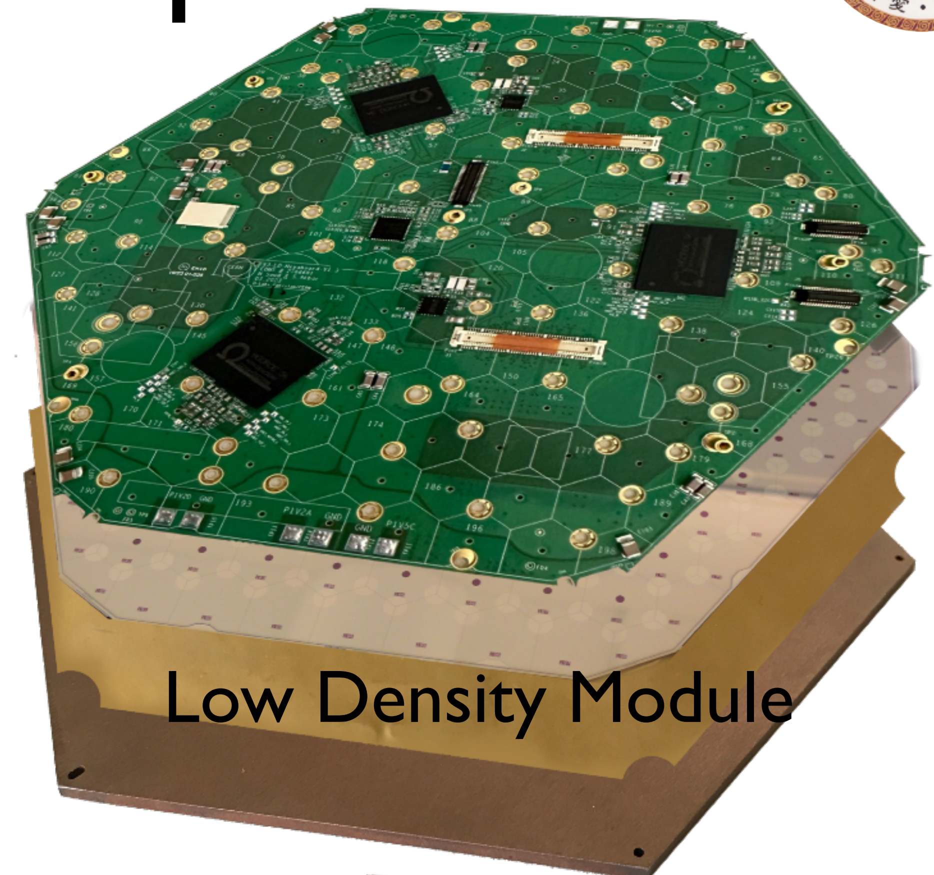
CMS HGCAL *'High Granularity Calorimeter'*

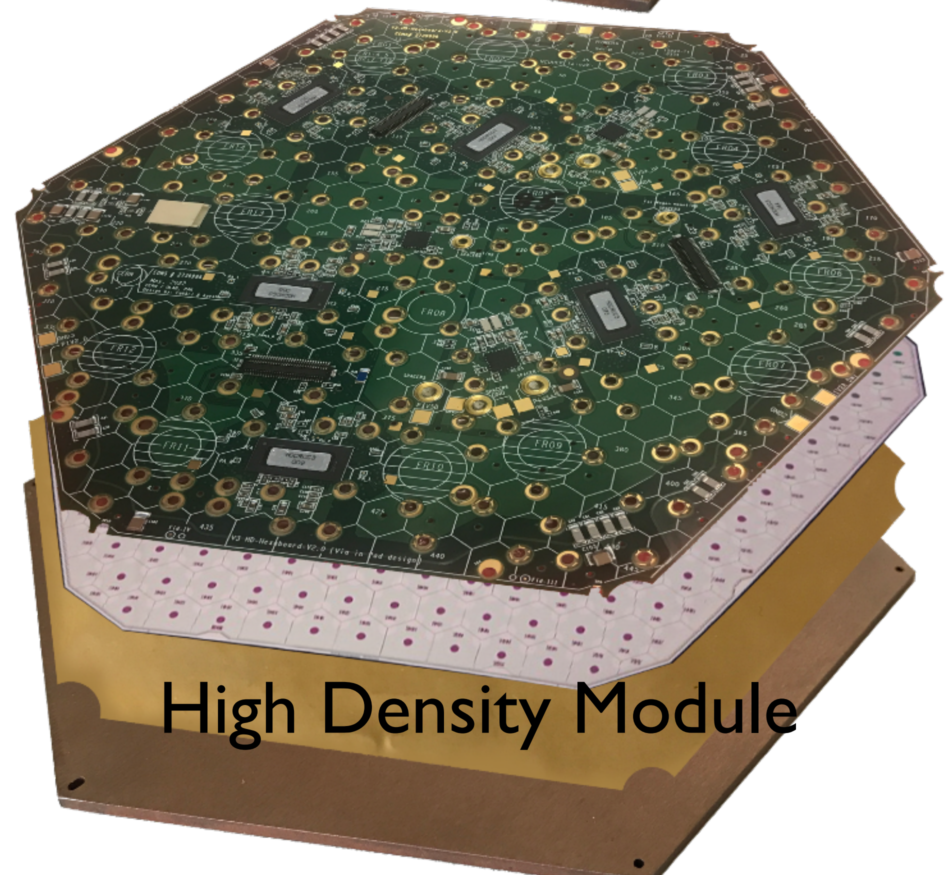


https://youtu.be/5EKumUsYinM

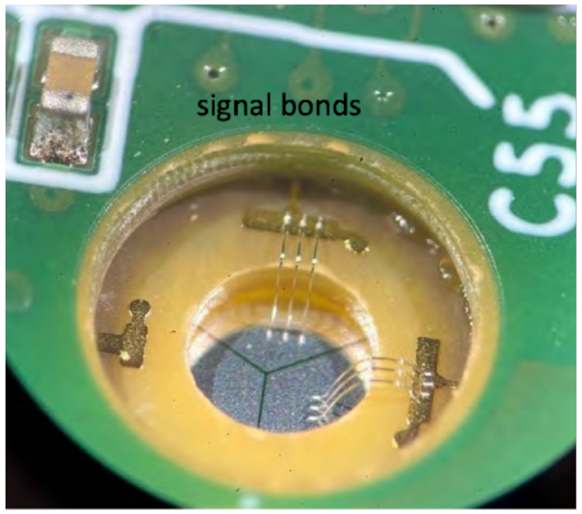
Silicon Module Composition

- Stack of baseplate, sensor, and readout hexaboard. Baseplates are made of CuW in CE-E, carbon fiber in CE-H
- Relative alignment within ~50um achieved with gantry based automated assembly.
- Electrical connections are done with wire-bonds

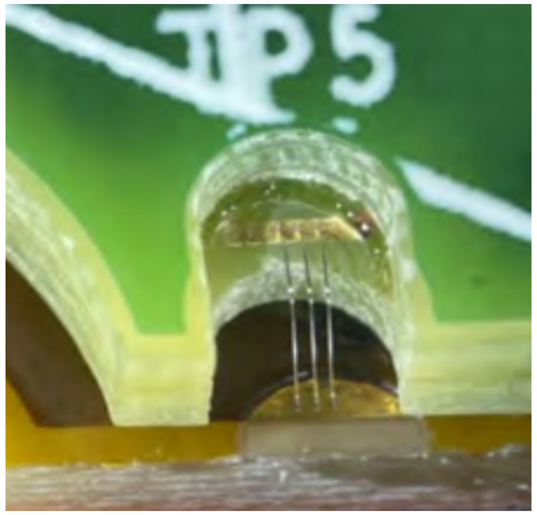




signal bonds



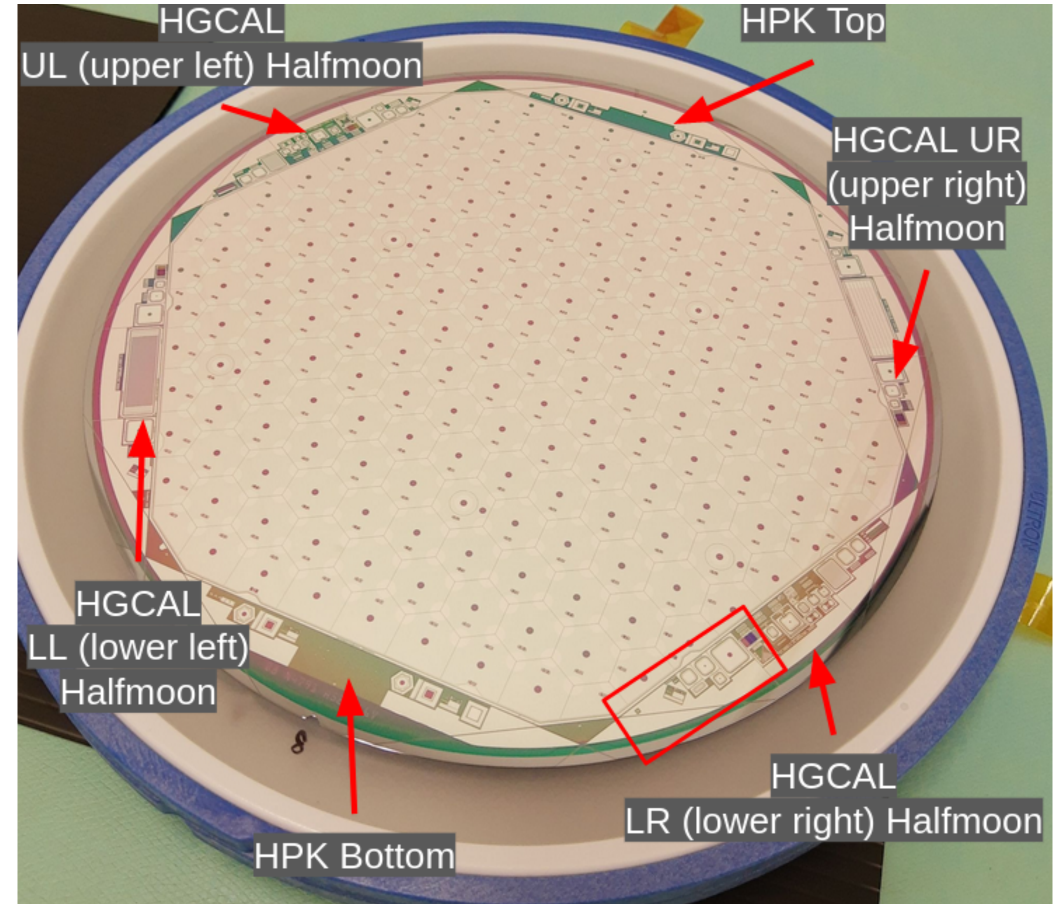
shield bonds



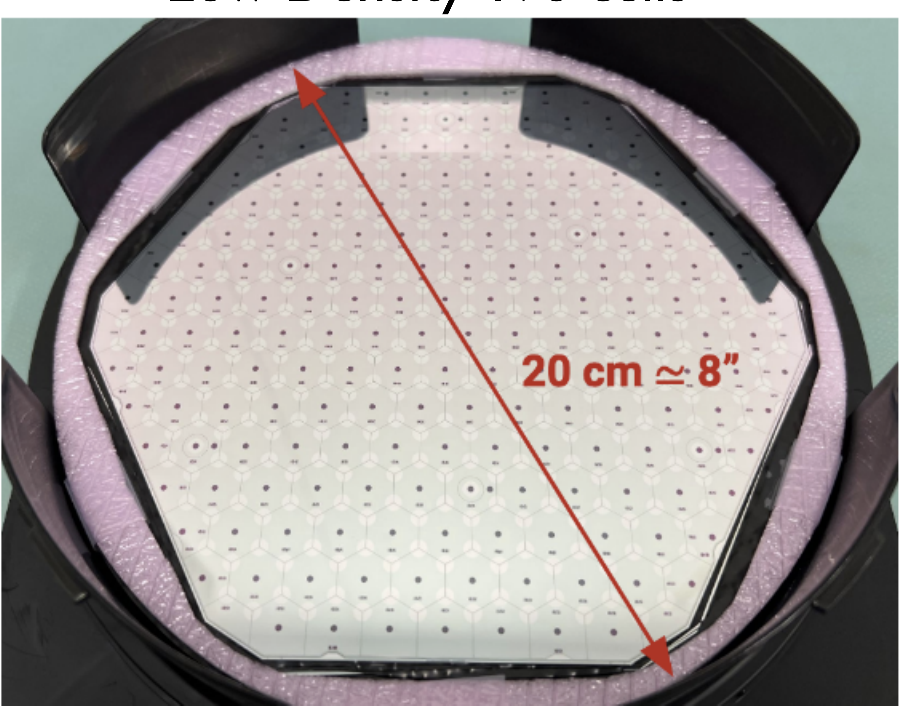
backside HV bonds

Silicon Sensor

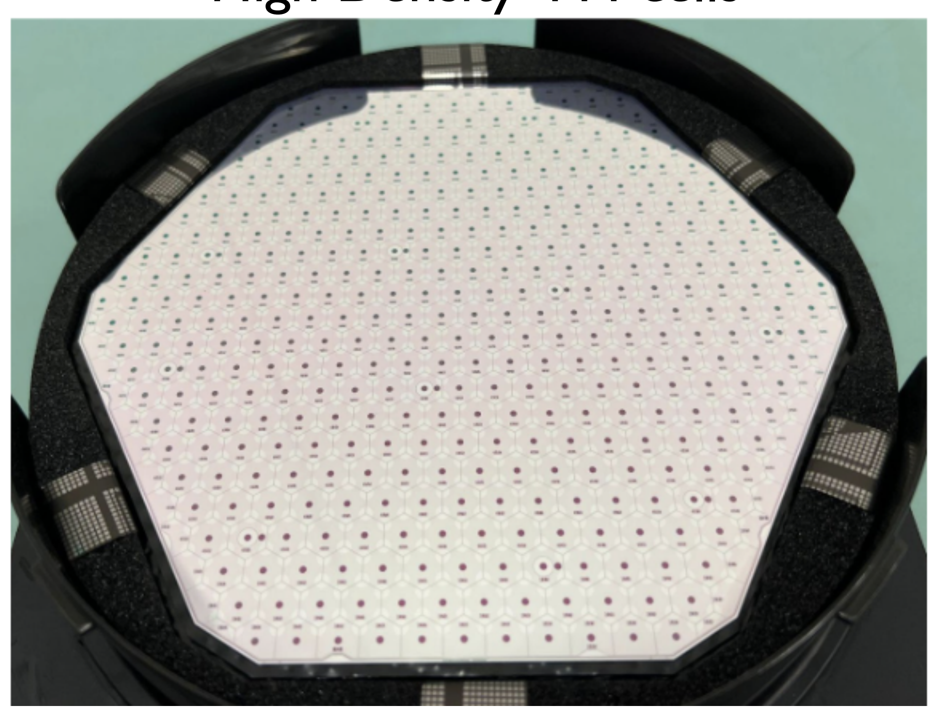
- 8-inch Hamamatsu sensors. Three thickness and technologies, assuming $3\mathrm{ab}^{-1}$ lifetime,
  - ✦ $300\,\mu\mathrm{m}$ (FZ), up to $2\times10^{15}\,\mathrm{n_{eq}/cm^2}$
  - ✦ $200\,\mu\mathrm{m}$ (FZ), up to $5\times10^{15}\,\mathrm{n_{eq}/cm^2}$
  - ✦ $120\,\mu\mathrm{m}$ (EPI) , up to $10\times10^{15}\,\mathrm{n_{eq}/cm^2}$



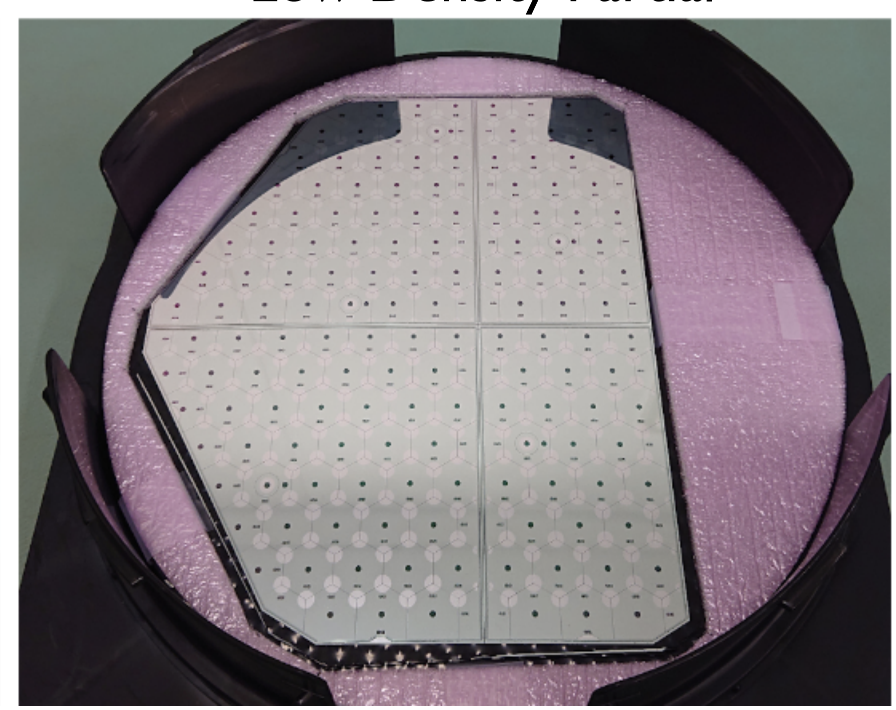
Low Density 198 cells



High Density 444 cells

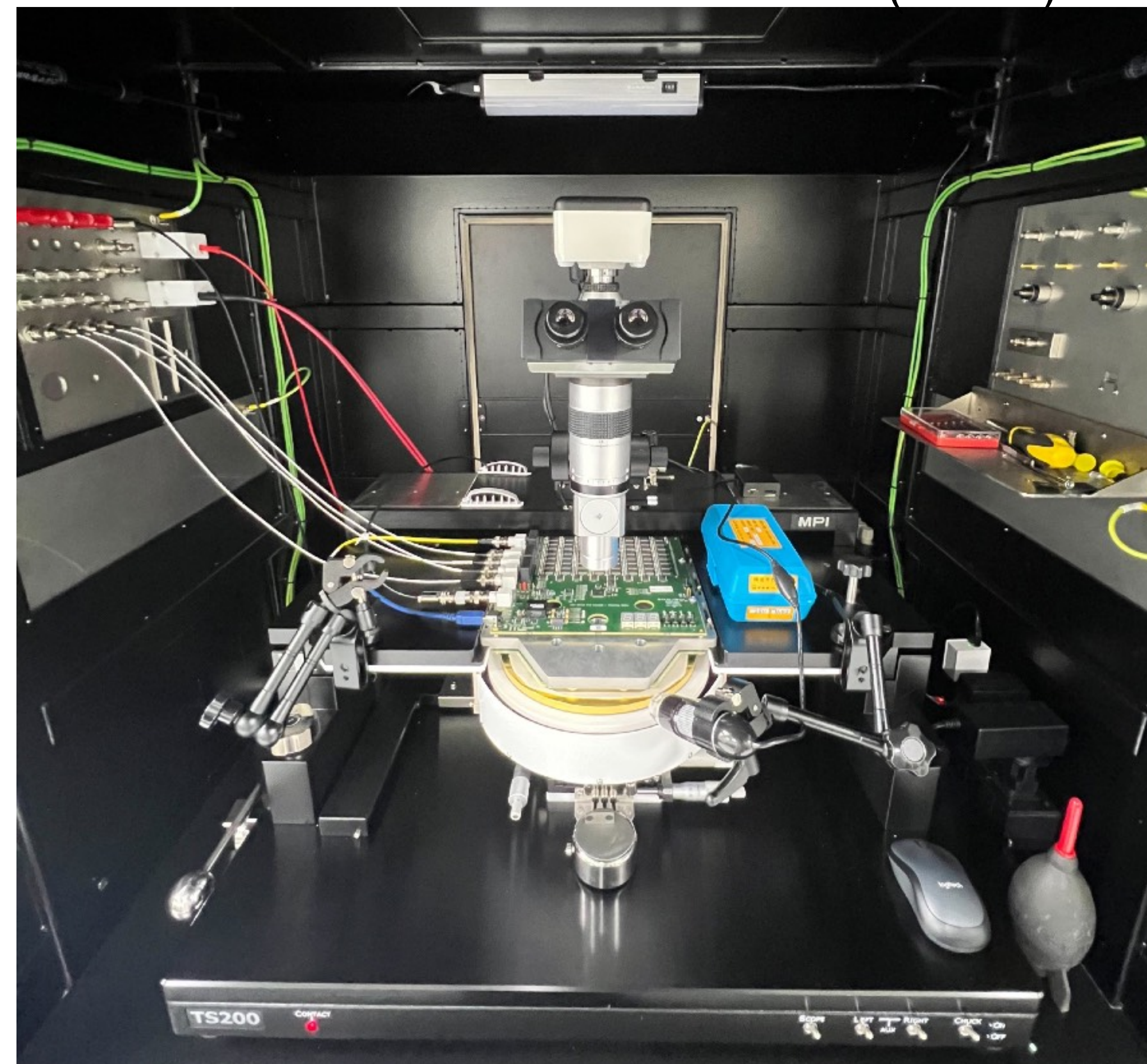


Low Density Partial

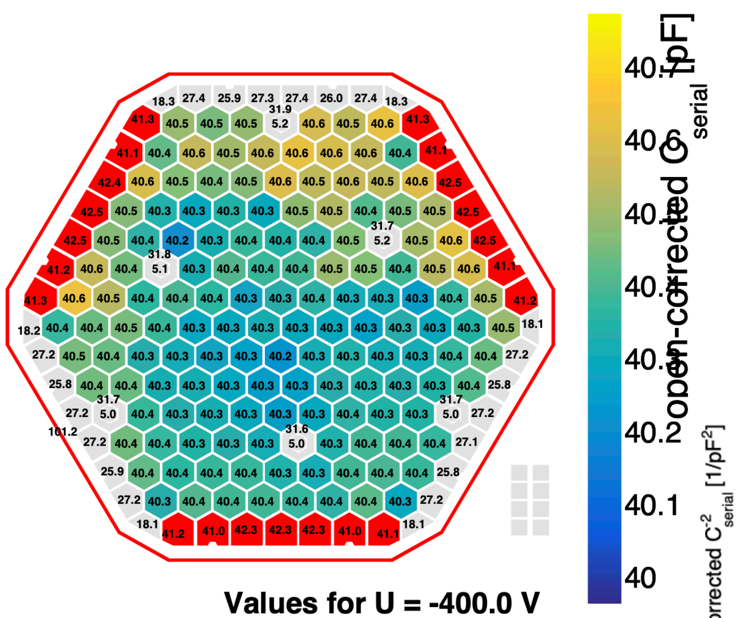


Sensor Qualification Center @NCU

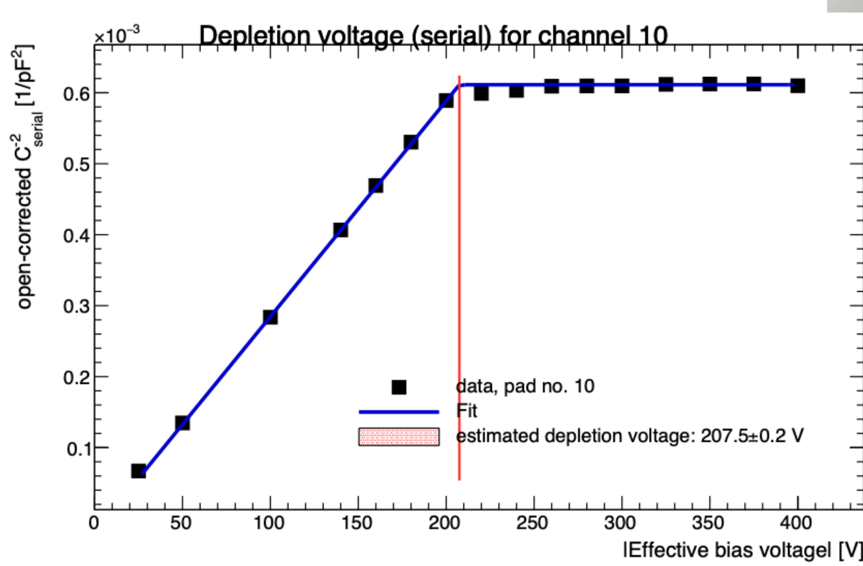
Dr. D. Bhowmik (NCU)



- NCU has set up a cleanroom with probe station and probe card to measure IV and CV for HGCAL LD and HD sensors.
- Goal is to measure 5% of each batch coming to Taiwan.

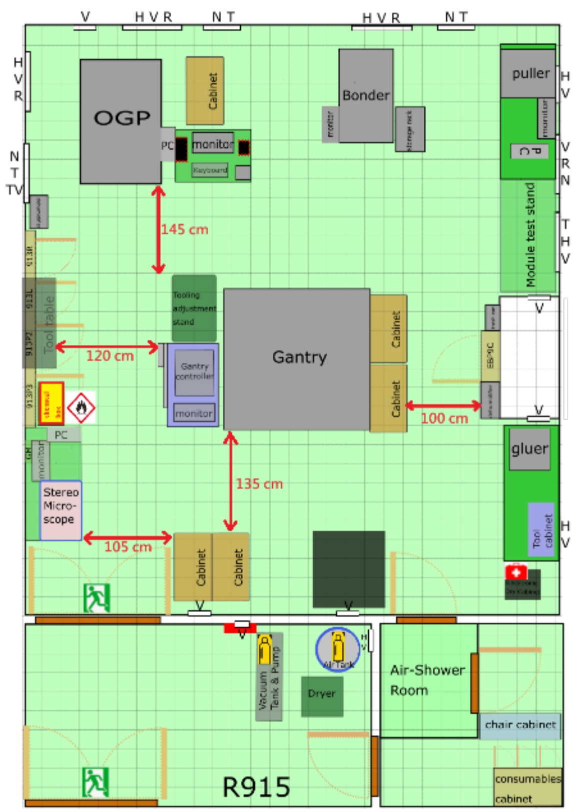


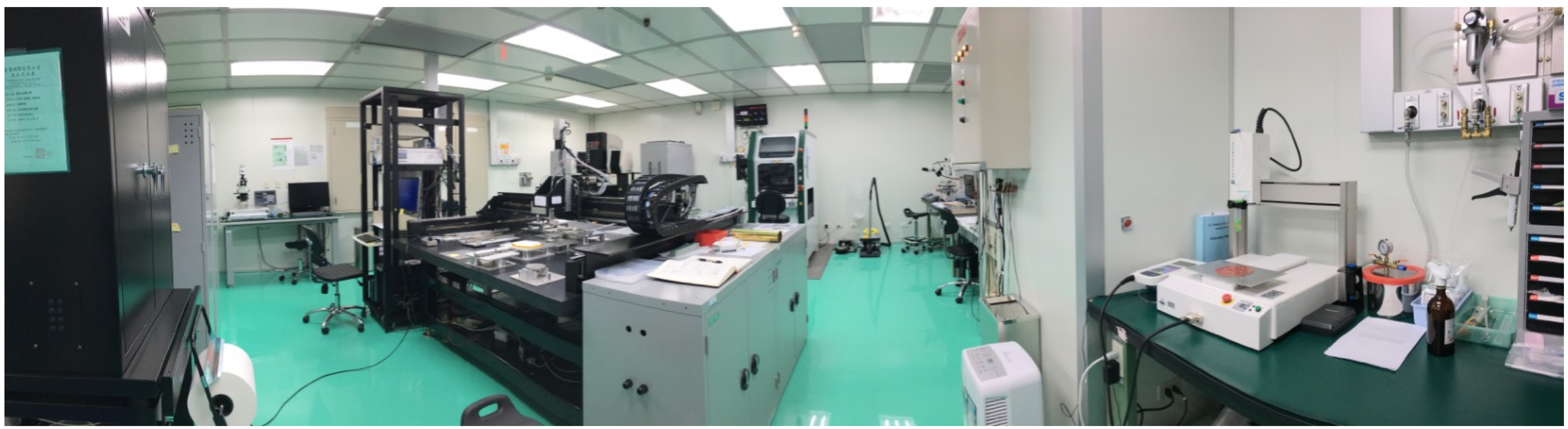
Results of a CV scan

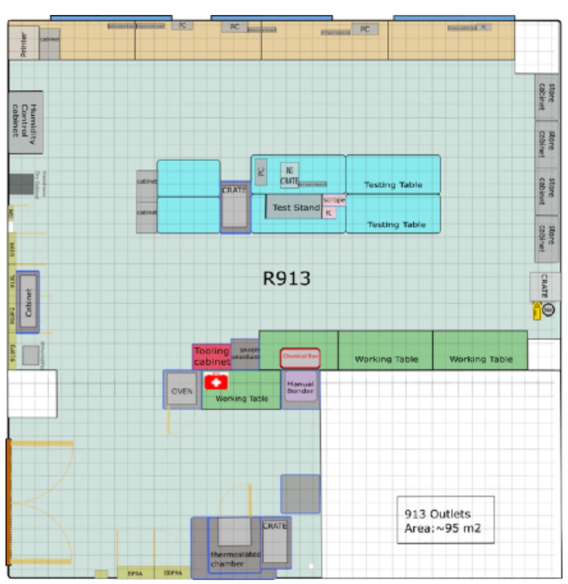


Module Assembly Center @NTU

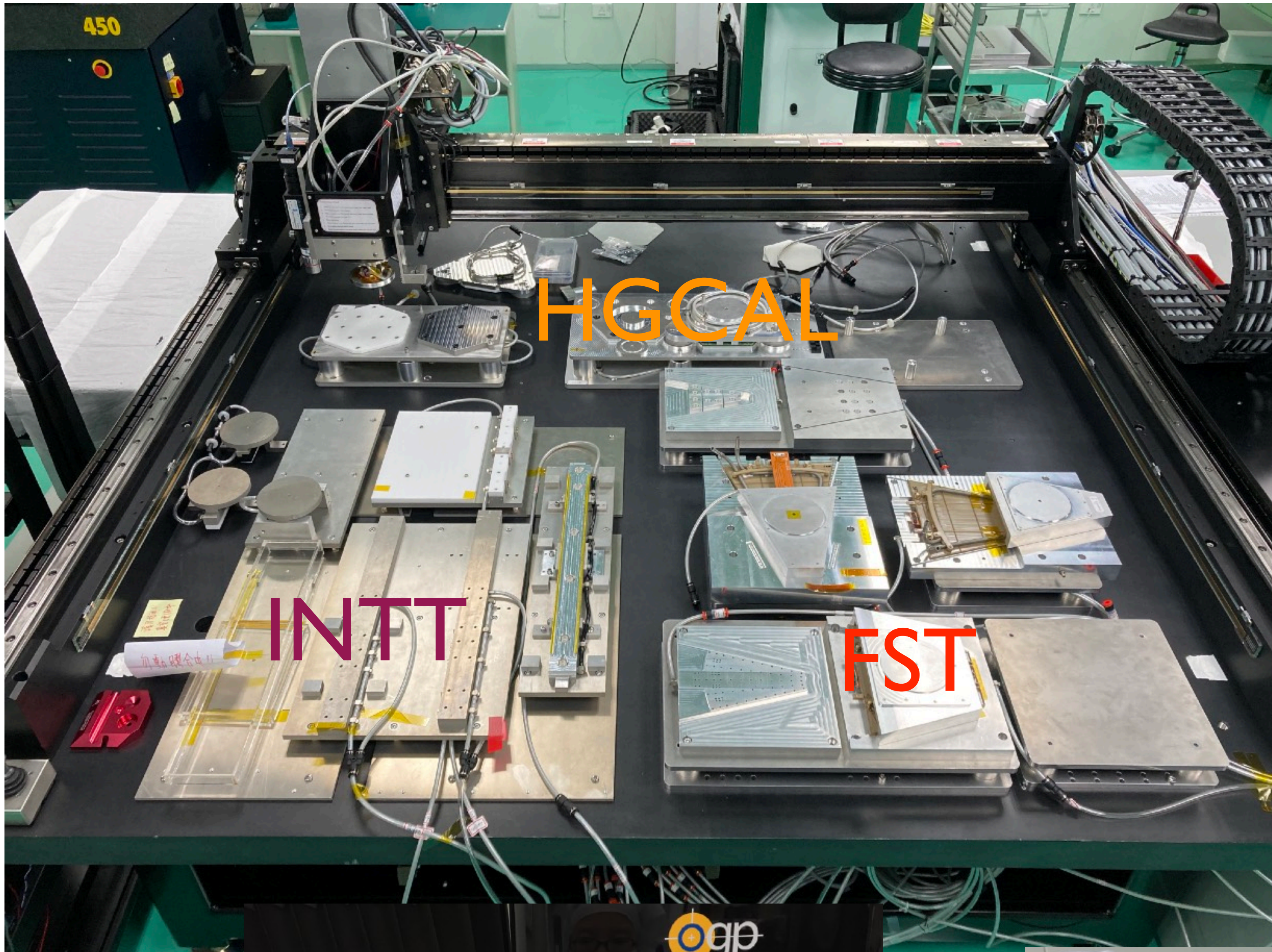
- At NTU, a cleanroom (915) and an electronic lab (913) equip essential silicon detector assembly equipment. An additional room in the basement (B205) for multi-module QC.
- The facility has also contributed to other projects

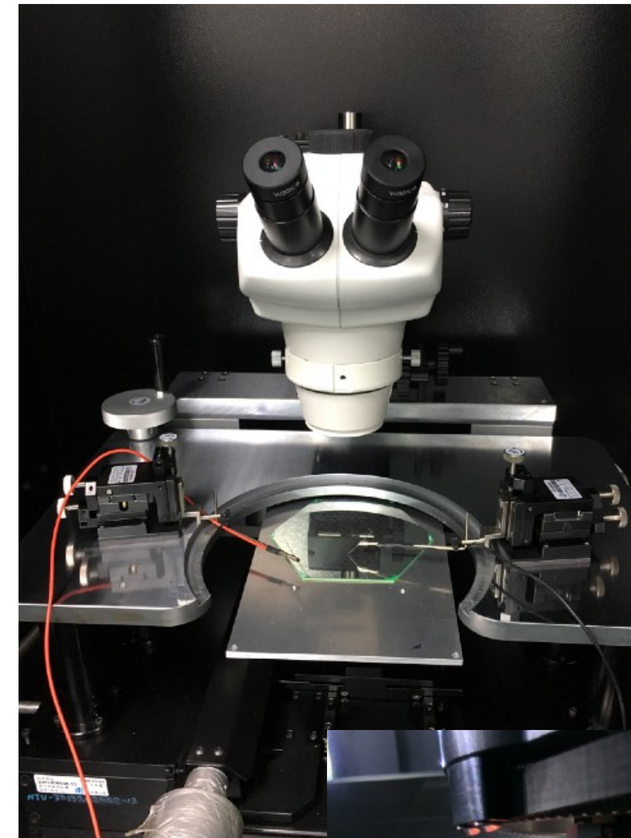


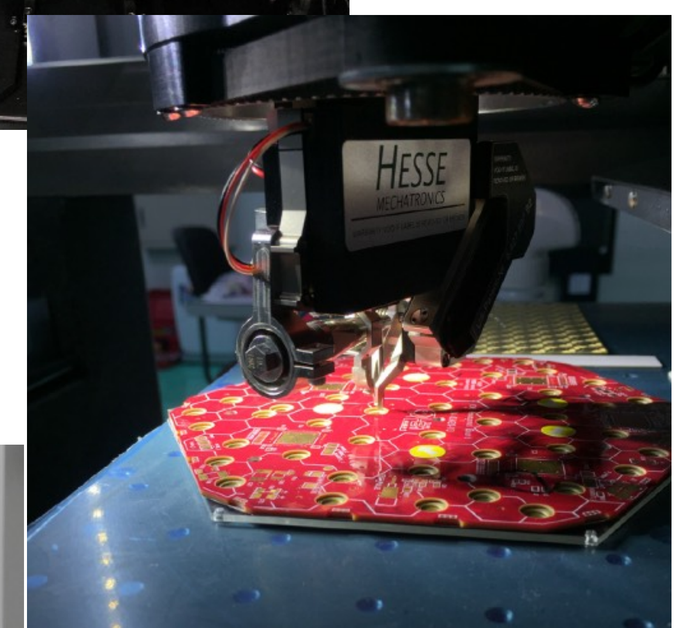


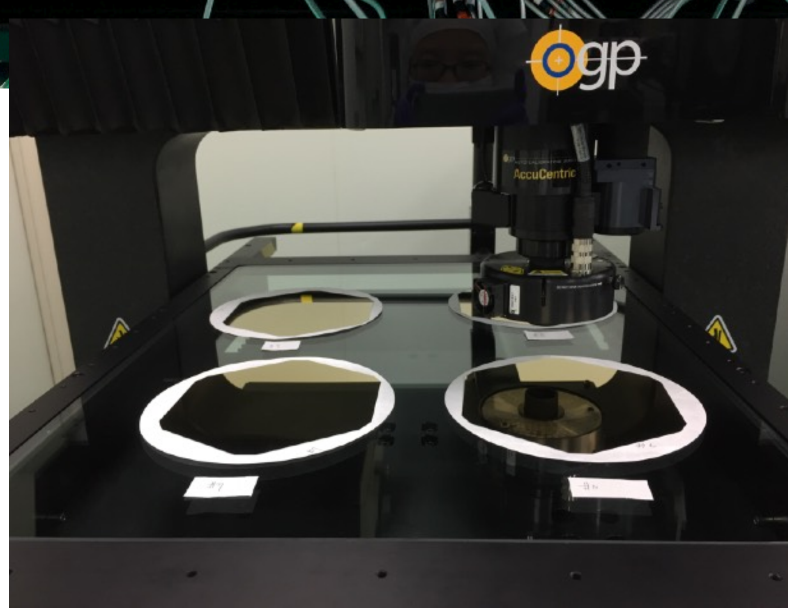


Main equipment









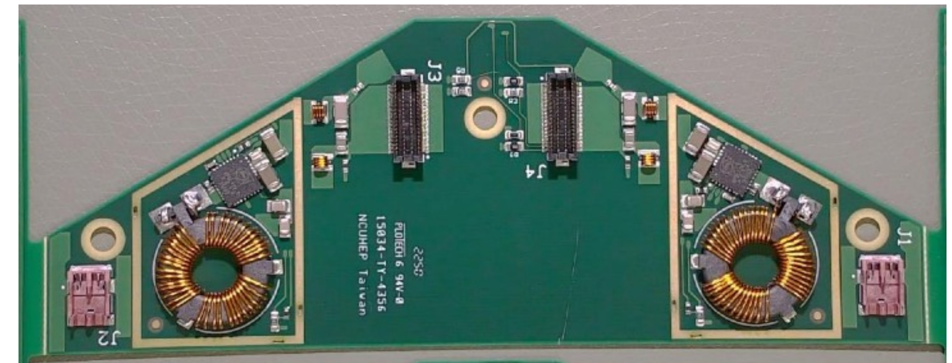
MAC

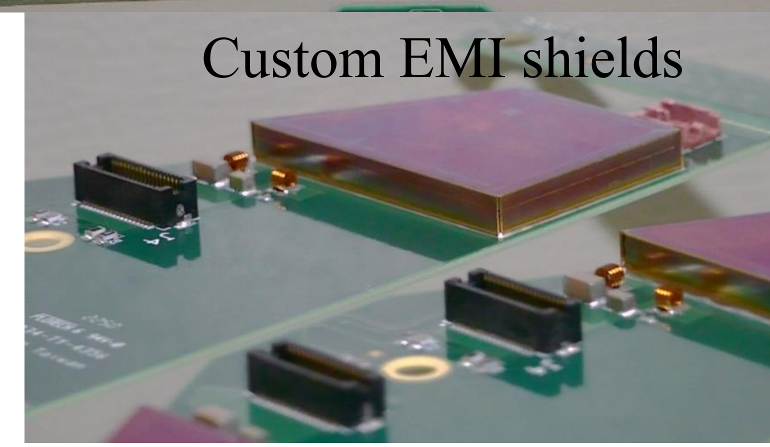
- Automatic gantry operation assembling module layers
- 2 module assembly done in June 13, 2024

DCDC Modules

Dr. Stefano Caregari (NCU)

- The HGCAL dedicated DCDC modules are based on CERN bPOL12V_V6 (TSMC 65nm) ASIC. It converts 10V from PP0 to 1.5V needed for frontend electronics.
- Custom-designed toroidal coils (460nH) and copper shields to fit in the space and radiation tolerance requirement.
- DCDC Mezzanine Pre-Production & Production PCB Fabrication, Assembly & QC will be done in Taiwan



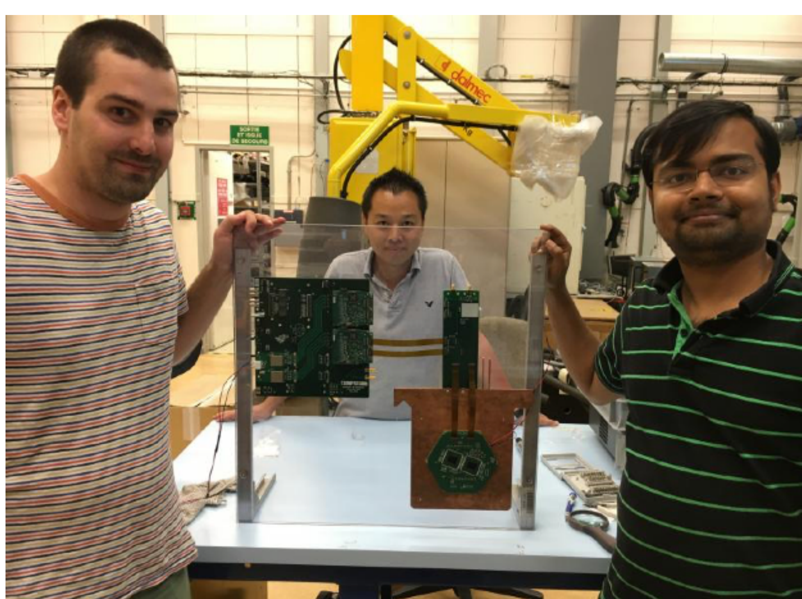


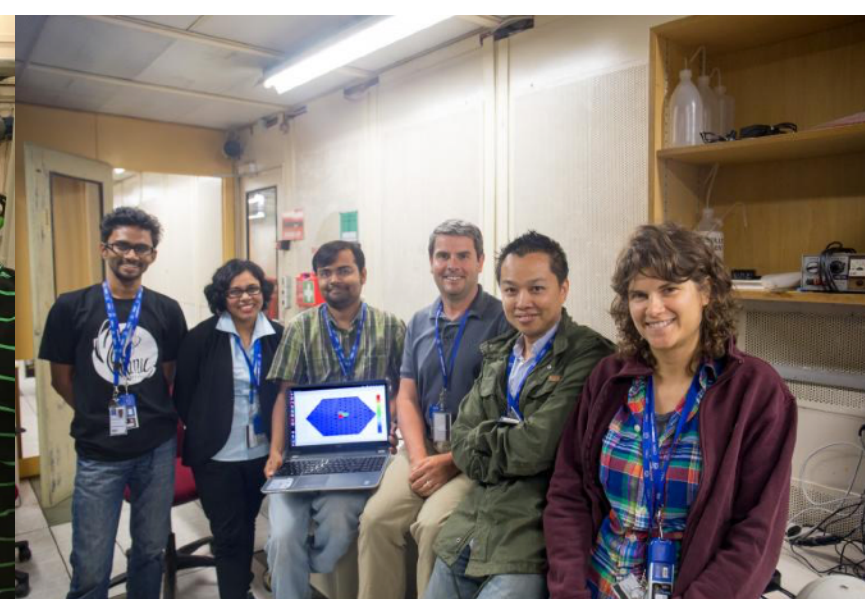
Custom EMI shields

Prototype shield: pure copper foil 0.2mm thick

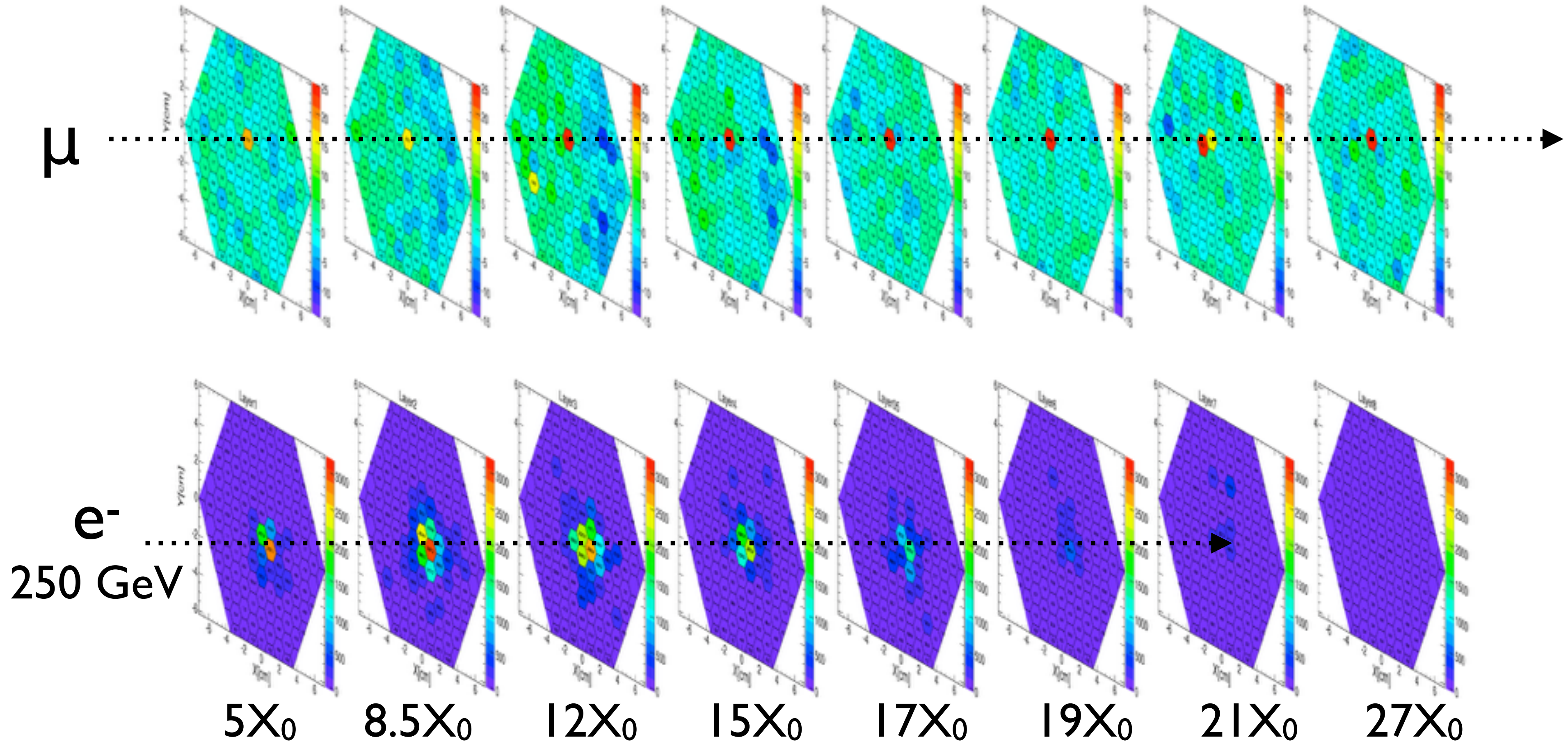
System Test

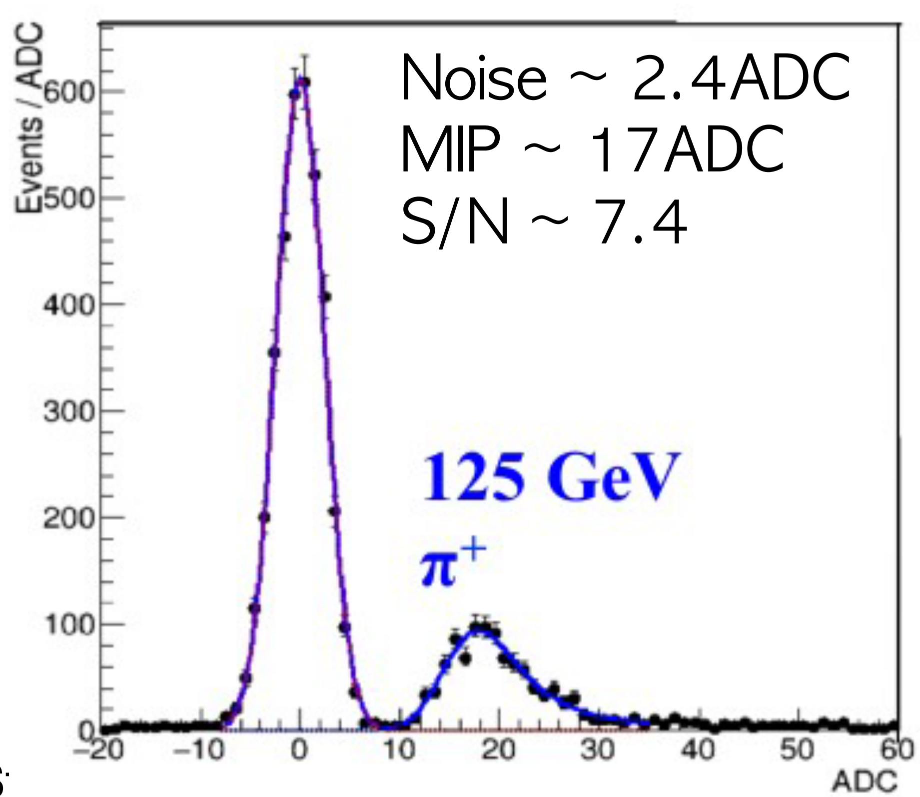
- NTU participated in system test and beam-test exp since 2016. R.-S. Lu and A. Steen were conveners of the system test group.
- In 2016, the 6-inch prototype modules was placed in the beam and measured the electron/pion/muon beams
- Very successful start with many enthusiastic young people participated

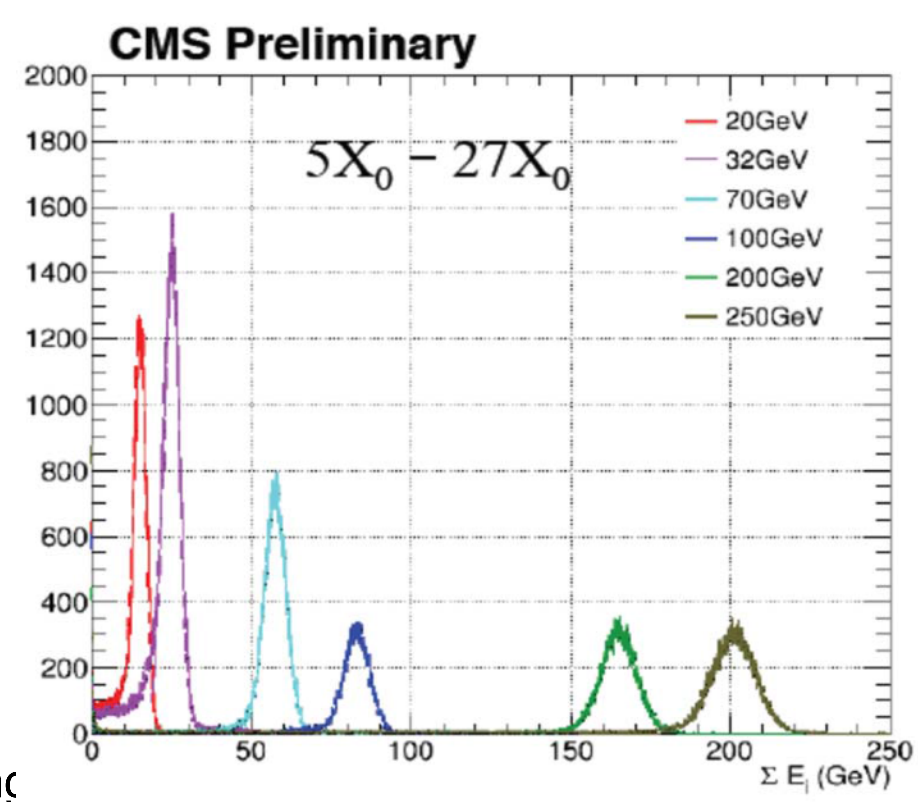




HGCal Prototype Performance

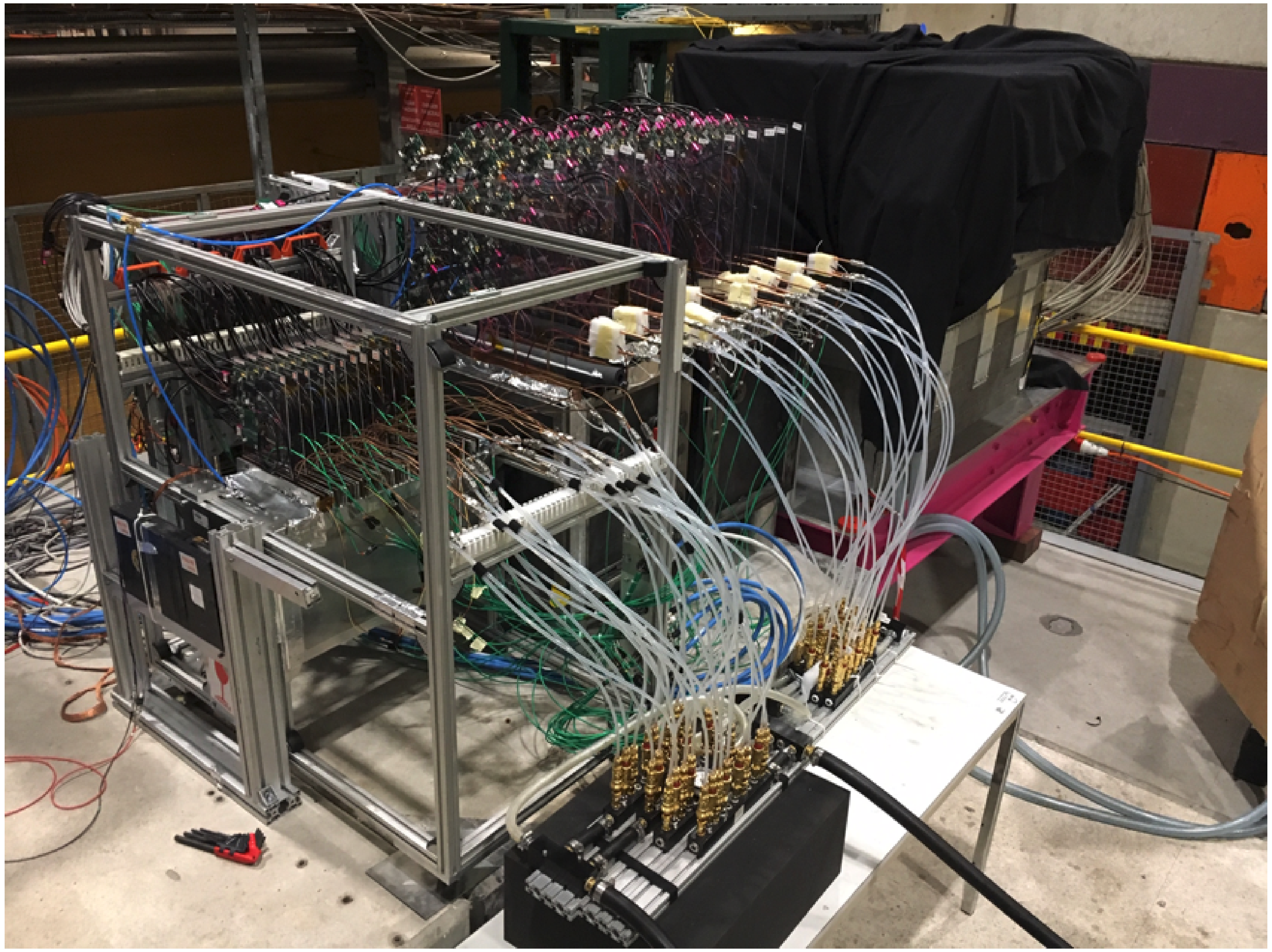


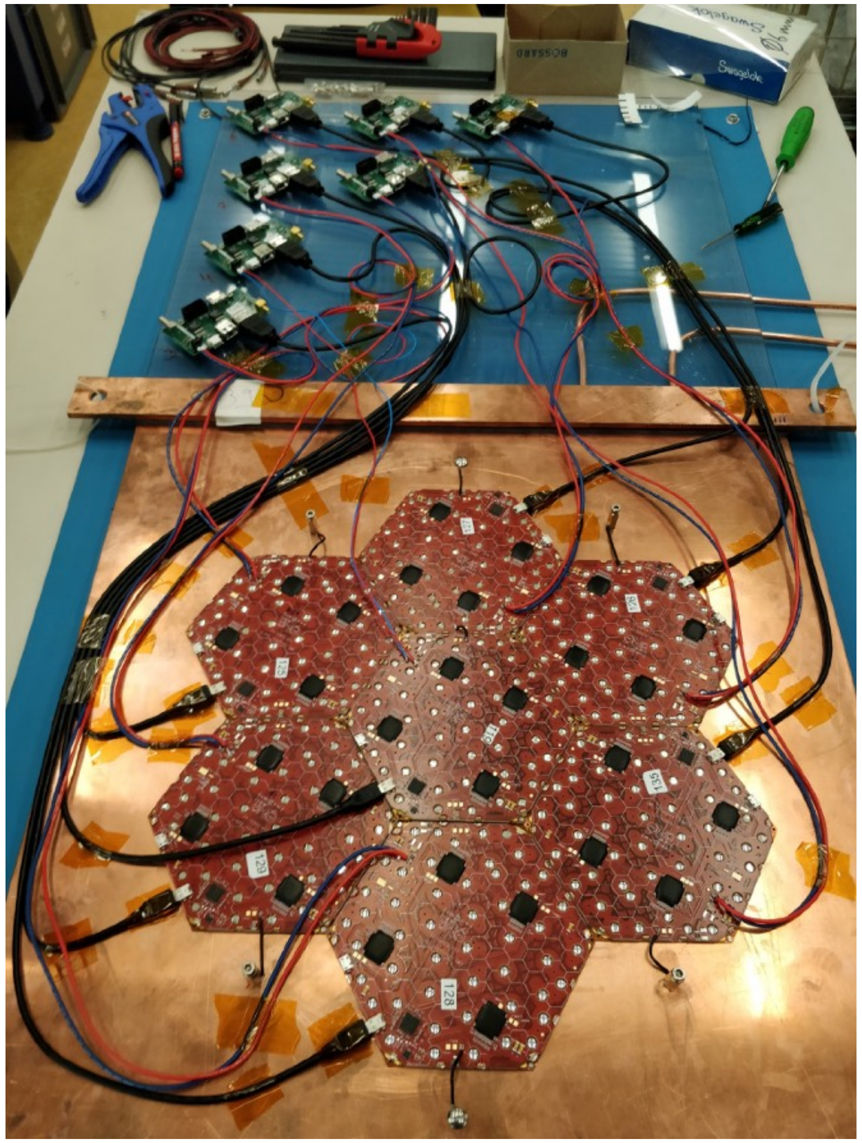




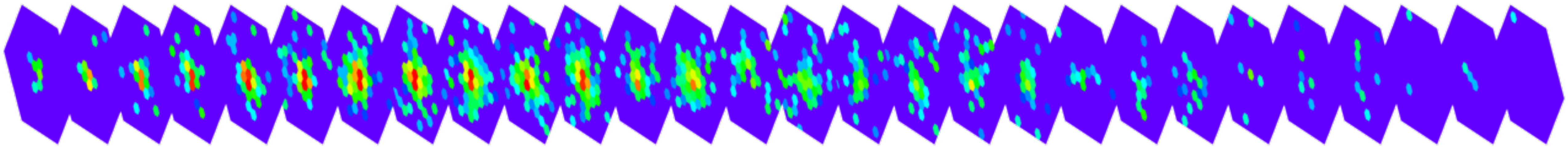
TB setup @H2 beamline at CERN

- In 2018, three detectors similar to HGCAL design were constructed
  - ✦ EE: 28 layers, ~ 1 λ, 26 Xo, single 6" Silicon hex module
  - ✦ FH: 12 layers, ~ 3.1 λ, "daisy" of 7 x 6" Silicon hex modules
  - ✦ BH: ~ 5 λ, CALICE AHCAL prototype



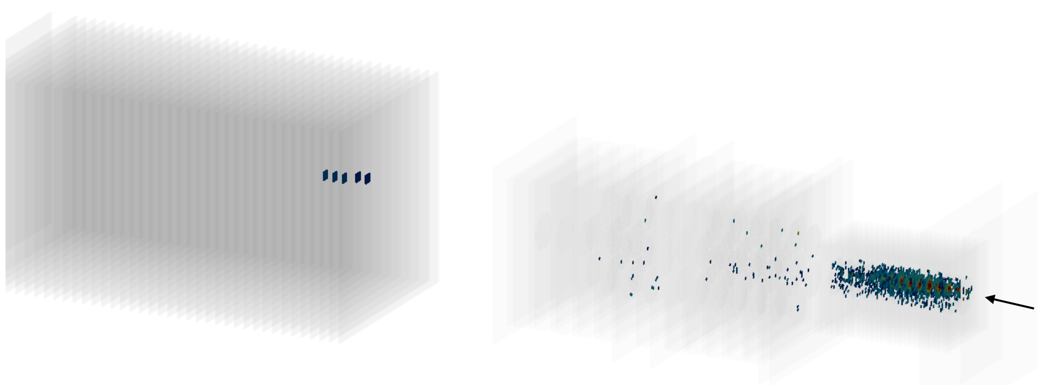


Some Results

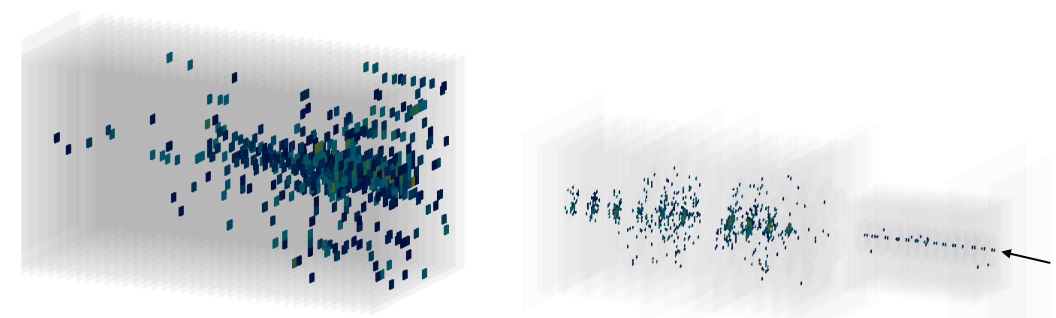


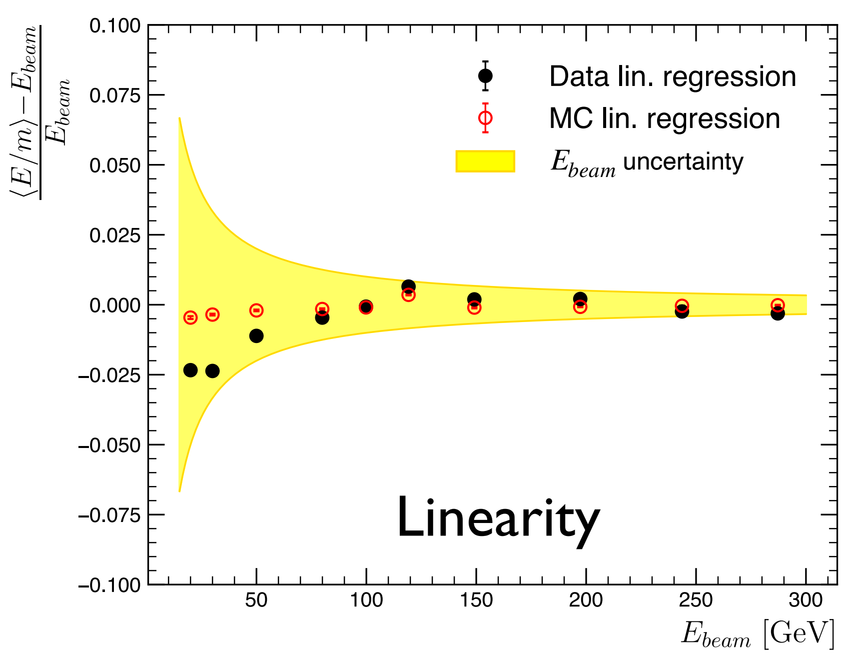
80 GeV electron: 14 double sided layers with 6” Si modules

Run 517, event 101

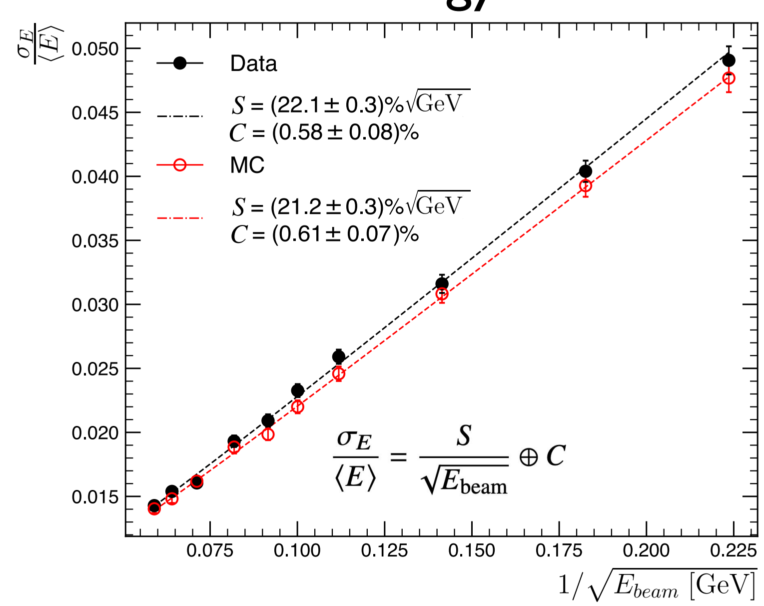


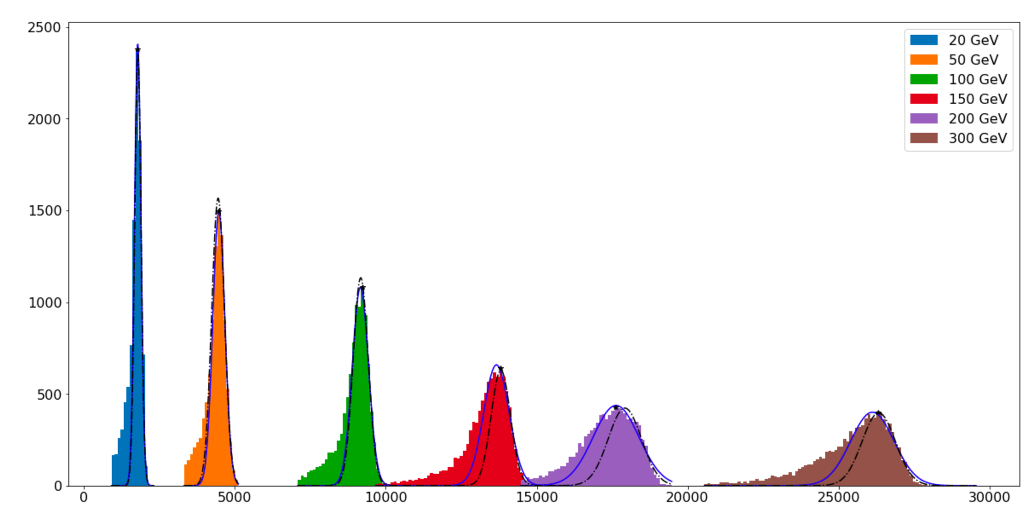
Run 517, event 2





Relative energy resolution





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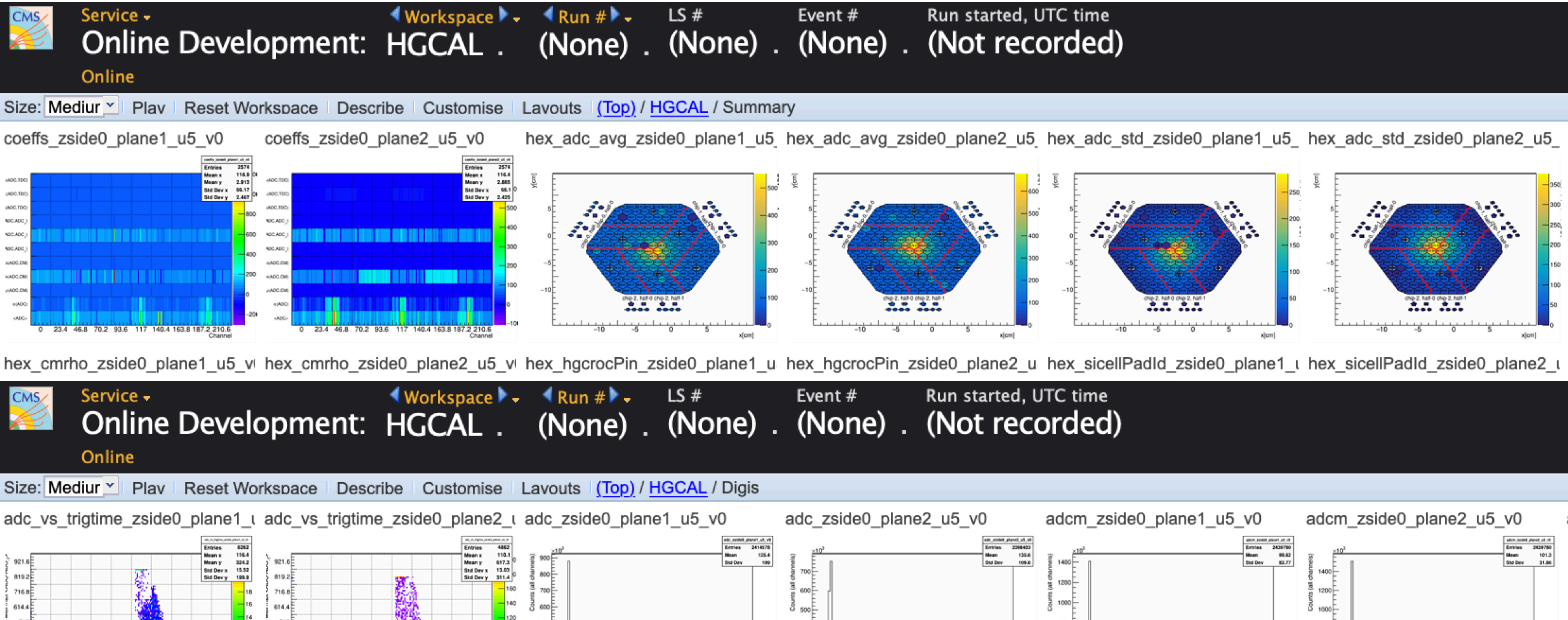
DOI 10.1088/1748-0221/17/05/P05022

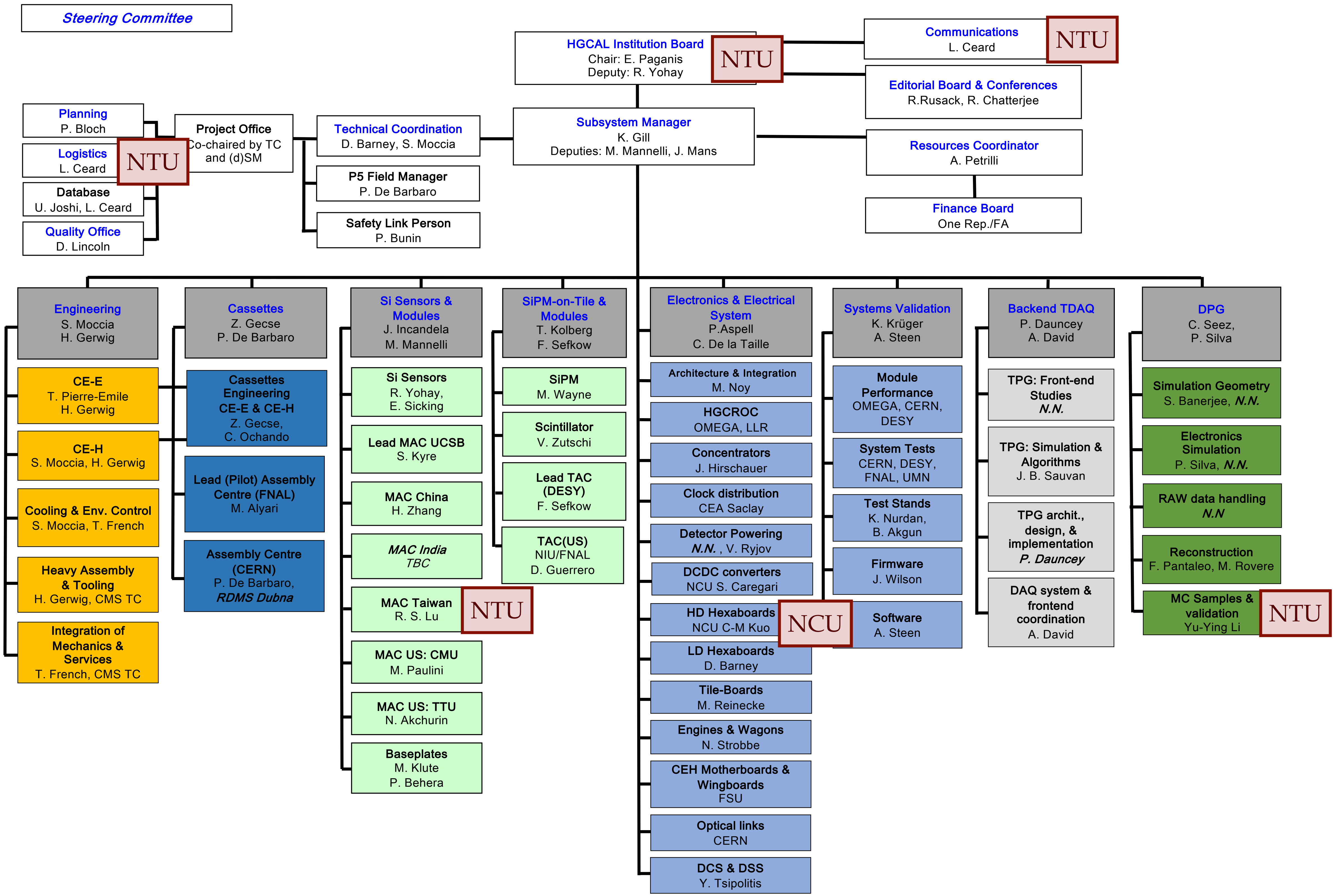
Stathes Paganis was the editor of the paper

DPG

- Dr. YuWei Kao was involved in the HGCAL raw data handling tasks with a realistic data processing chain established in a CMSSW branch. (RAW → DIGI → RECO → DQM / Nano)
- Also, implemented level-0 calibration algorithms in Alpaka modules for heterogeneous computing.
- Initiated HGCAL DQM with polygonal DQM monitor elements implemented. A DQM GUI was built for the 2023 beam test activities.



HGCAL Organization Chart



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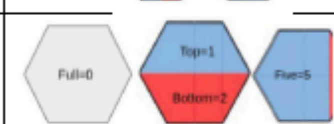
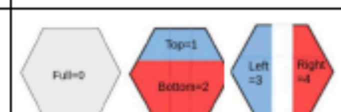
Summary

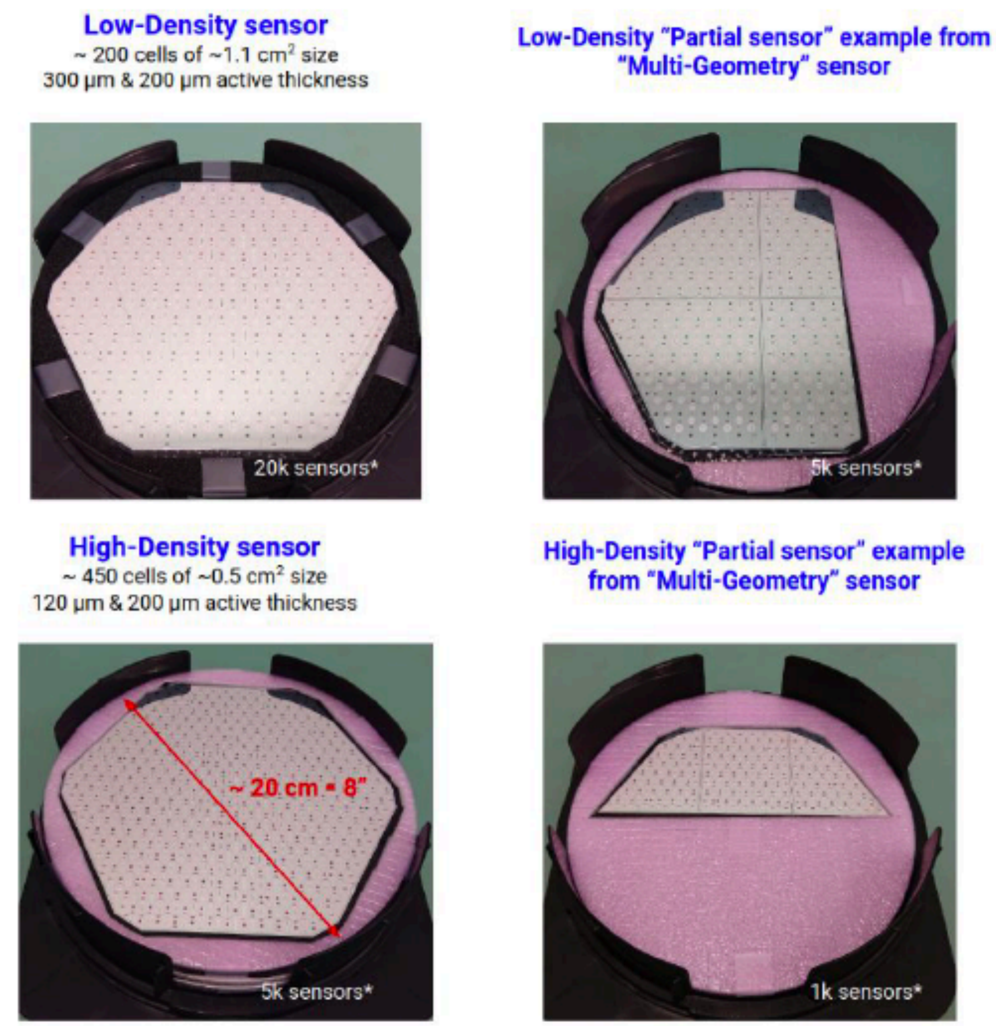
- NTU and NCU teams actively participate in the HGCAL project, ranging from sensor SQC, MAC, system test, Cassette assembly, DPG, and management.
- On CERN site, Dr. Ludivine Ceard (NTU) contributes on Logistics, Dr. Dimitra Tsionou (NTU) on Cassette, and Dr. Debabrata Bhowmik (NCU) on sensor SQC group.
- We also have frequent communication and collaboration with the IHEP HGCAL team.

Extra Slides

Sensor overview

- Silicon sensors from 8-inch wafers
  - Planar, DC coupled, p type, common p-stop
  - Two production processes: Floatzone (FZ) and epitaxial (epi)
  - 120 / 200 / 300 µm, low and high granularity (LD, HD)
  - Hexagonal **full sensors**
  - **Partial sensors** cut from multi-geometry wafers

Thickness [µm]	Main cell size [cm^2]	Main cell capacitance [pF]	Maximal fluence [n_{eq}/cm^2]	Variants	Bulk process
300	1.25	44	1.7e15		FZ
200	1.25	65	3.0e15		FZ
200	0.56	30	5.0e15		FZ
120	0.56	48	1.0e16		epi



* needed in the final detector

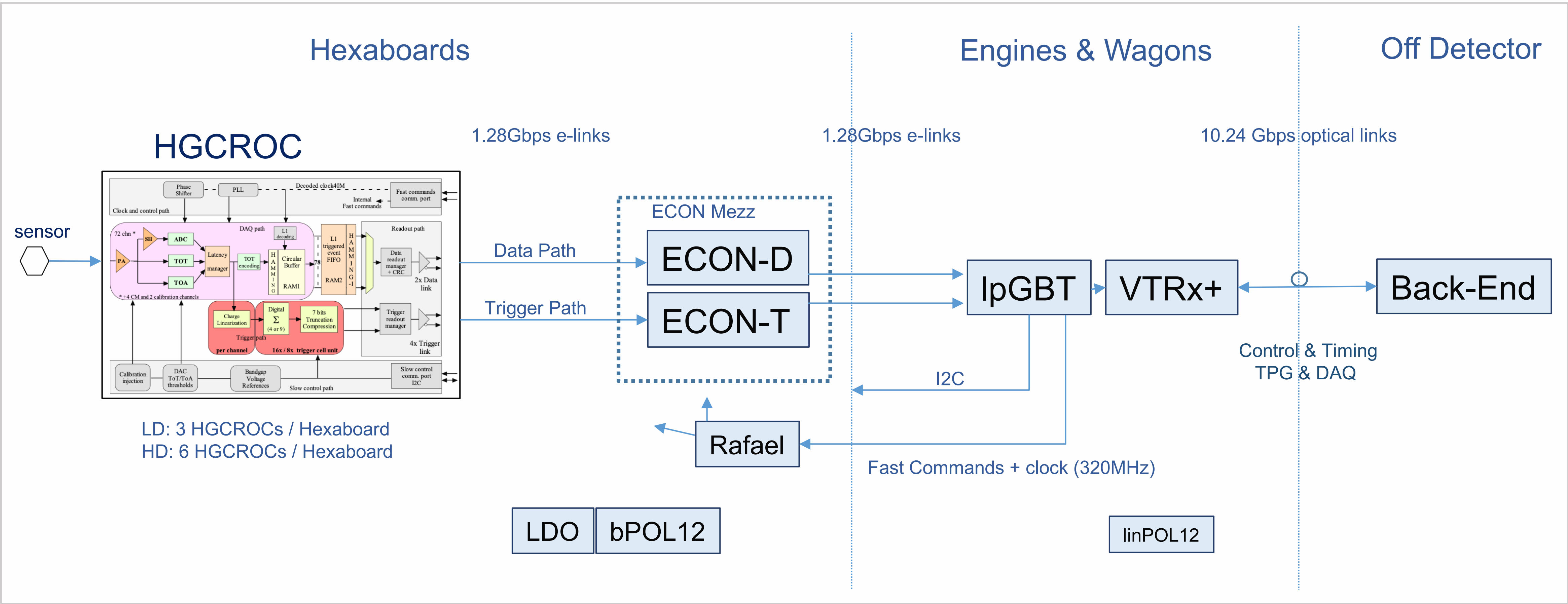
SQC status & summary (status April 5)

	HPK	CERN	FSU	IHEP	NCU	TTU	CMS total
		CMS HGCAL SQC sites					
Delivered	11515	2703	1523	75	2790	2246	9337
In transit (@ April 1)	-	1022	1156	0	0	0	2178
Tested	11515	194	94	4	122	149	563
Testing ratio	100%	7.2%	6.2%	5.3%	4.4%	6.6%	6.0%
Rejected (damage)	0	2	0	0	0	3	5
Rejected (IV)	0	2	0	0	1	1	4

➜ 9 sensors rejected:
- 5 with visible damage
  - Can be detected during optical inspections before module assembly
- 4 with non-compliant IV result
  - **0.7%** of tested sensors (4/571)
  - At 95% CL, defect rate below 1.8%
  - Non-sampled sensors with same failure type covered by spare parts

- Further increase optical inspection
  - Full optical inspection of frontside + backside inspection by eye of all tested sensors
  - Up to 11 additional sensors per batch (≤25): frontside inspection by eye for significant scratches/ chipped corners
  - Enrich sample of sensors in electrical tests with optically flawed sensors
- Further increase throughput of electrical tests
  - Reduced IV voltage steps
  - CV measurements for only ~10 cells across sensor for homogeneity tests (all cells in overnight measurements

HGCAL Electronics – Main components and signal flow.

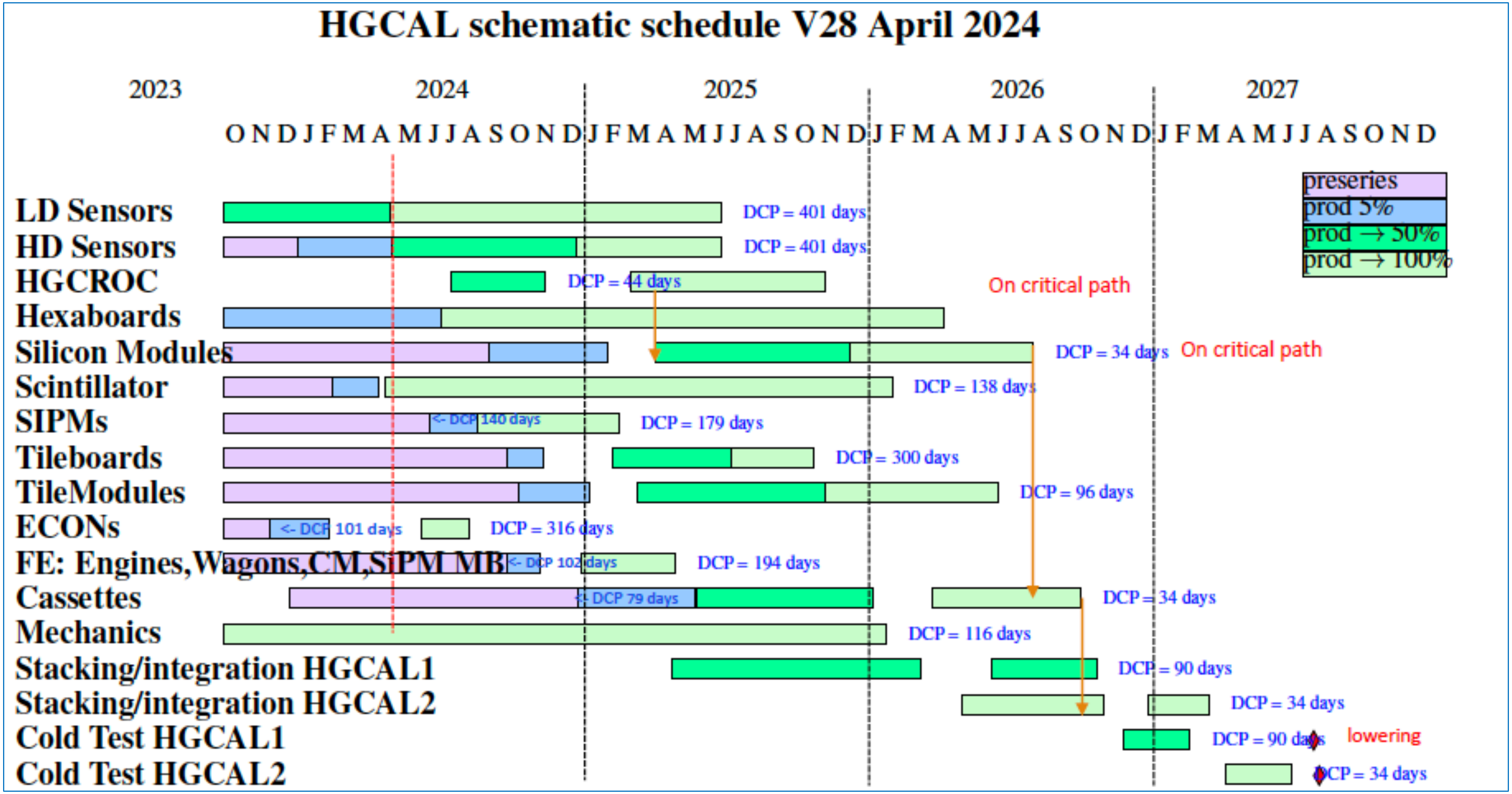


ASIC developments: HGCROC, ECON-T/D, LDO & Rafael

Generic components: lpGBT, VTRx+, bPOL12V, linPOL

These are hosted on pcbs: Hexaboards, Engines & Wagons (CE-E/H) & Tileboards (CE-H)

Note: The figure above is for the Si region.
The scintillator region is very similar. It uses a different version of HGCROC ie. HGC2ROC and also uses the SCA for Slow Control and ALDO for SiPM biasing.

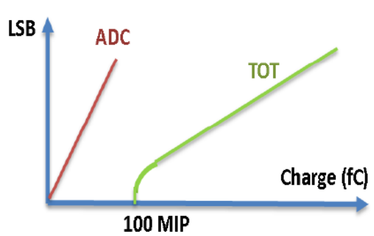

HGCAL schematic schedule V28 April 2024
2023
2024
2025
2026
2027
O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
preseries
prod 5%
prod → 50%
prod → 100%
LD Sensors
DCP = 401 days
HD Sensors
DCP = 401 days
HGCROC
DCP = 44 days
On critical path
Hexaboards
Silicon Modules
DCP = 34 days
On critical path
Scintillator
DCP = 138 days
SIPMs
<- DCP 140 days
DCP = 179 days
Tileboards
DCP = 300 days
TileModules
DCP = 96 days
ECONs
<- DCP 101 days
DCP = 316 days
FE: Engines,Wagons,CM,SiPM MB
<- DCP 102 days
DCP = 194 days
Cassettes
<- DCP 79 days
DCP = 34 days
Mechanics
DCP = 116 days
Stacking/integration HGCAL1
DCP = 90 days
Stacking/integration HGCAL2
DCP = 34 days
Cold Test HGCAL1
DCP = 90 days
lowering
Cold Test HGCAL2
DCP = 34 days

HGCROC Architecture specifications (TDR)

Analog
72 active channels
+2 for calibration
+4 for Common Mode

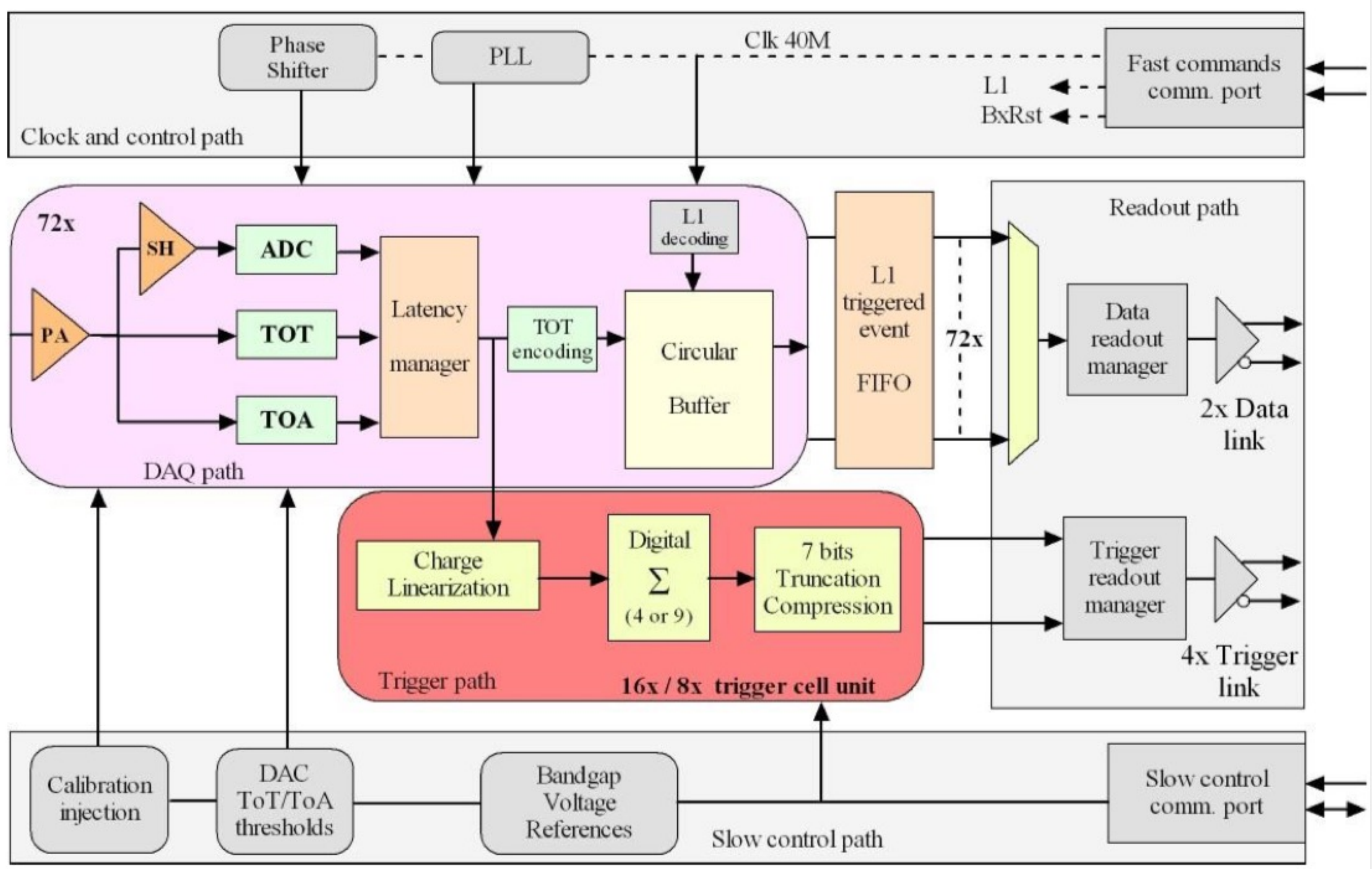
Dynamic Range ~0.2fC to 10pC
ENC < 2500e (Cd=65pF)
Peaking Time ~20ns
Linearity <1%

Energy Measurement
ADC 10b SAR
range 0 > 100fC (150fC)
TOT range 100fC > 10pC
TOT bin size 2.5fC



10b TDC , >12fC
lsb 25ps, 25ns full range

2 HGCROC versions:
Different preamps optimised
for Si & SiPM readout



Comm port
320MHz clock
Reception of T1 fast commands
From lpGBT

Data Readout Path
Data packets after LV1A
LV1A latency up to 12.5us
2 slvs outputs @ 1.28Gbps

Trigger readout Path
Trigger primitives
max latency of 36bx
4 slvs outputs @ 1.28Gbps

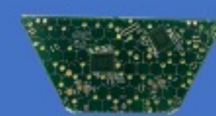
Slow Control
Programmable registers
I2C protocol
Connected to SCA

Monitoring
Monitoring of DACs and
essential bias voltages to SCA

5/14/24 P. Aspell CMS HGCAL 58

Hexaboards – LD HB PCB pre-production status

PCBs look very good so far; 44 Full Hexaboards assembled with HGCROC3b just before Easter

	 Full	 Half top	 Half bottom	 Five	 Semi left	 Semi right
Needed	17604	816	780	1248	276	264
Prototyping status	Prototyped OK	Pre-production = prototyping	Pre-production = prototyping	Pre-production = prototyping	Prototyped OK	Prototyped OK
Pre-production Launched 2023	920 (600 HiQ + 320 µpack)	40	40	70	30	30
Pre-production # received & inspection status	720 (600+120) remainder shipped on 5/4/24) **100+44 inspected: 142 accepted**	Shipped on 6/4/24	Shipped on 6/4/24	70 **20 inspected: 19 accepted**	30 **12 inspected: 11 accepted**	30 **8 inspected: 8 accepted**
Pre-production assembly status	44 (24+20) assembled 28/3/24 Further 156 to be assembled in summer; remainder a bit later (limited by ASICs)	First 10 to be assembled in May; remainder in summer	First 10 to be assembled in April/May; remainder in summer	First 15 to be assembled in April/May; remainder in summer	First 10 to be assembled in April/May; remainder in summer	First 10 to be assembled in April/May; remainder in summer

5/14/24 P. Aspell CMS HGCAL 27