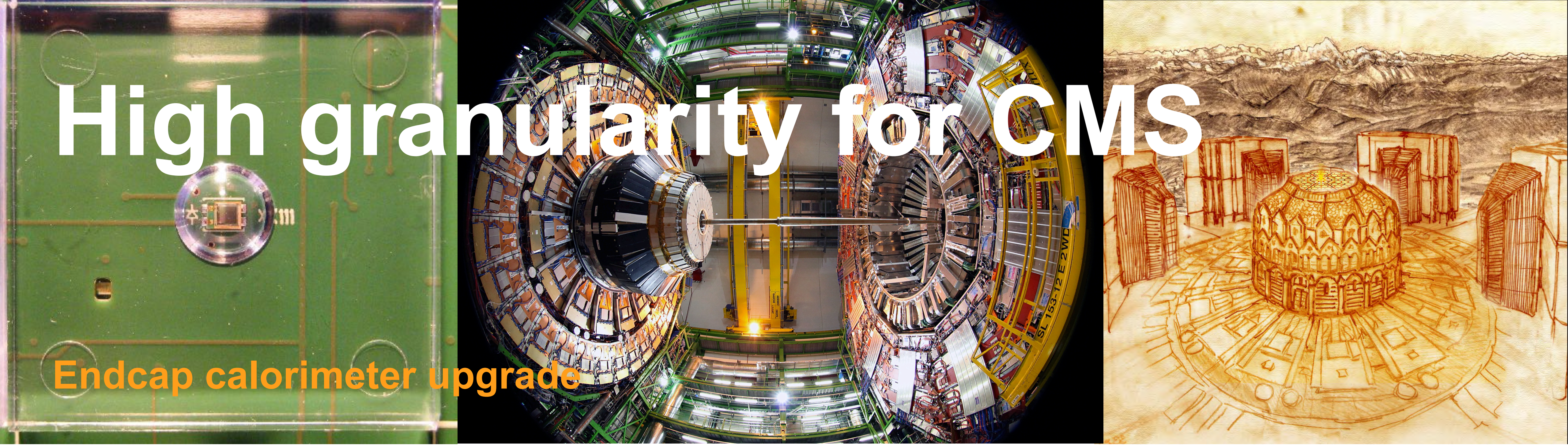
High granularity for CMS



Endcap calorimeter upgrade

Matter and Technologies 4th Annual Meeting

Berlin, June 13, 2018

Felix Sefkow
DESY

Outline

This Talk.

High granularity for LC and LHC

- Particle Flow and pile-up

SiPM-on-tile - technology

- State of the art and on-going work

The HGCAL upgrade of the CMS endcap calorimeter

- Detector design
- New challenges

Outlook

From LC…

Particle Flow Paradigm

Tackle the jet energy challenge.

In e+e- physics every event counts - exclusive reconstruction possible

- Heavy objects - multi-jet final states

W / Z mass splitting dictates required jet energy resolution of 3-4%

- Cannot be archived with classical calorimeters (e.g. ZEUS: 6%)

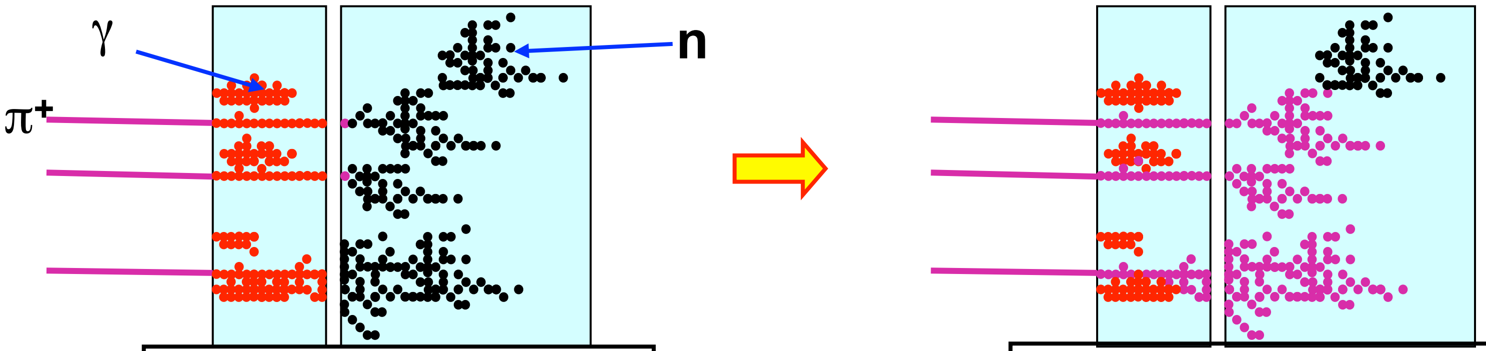
Reconstruct each particle individually and use optimal detector

- 60% charged, 20% photons, 10% neutral hadrons

Requires fine 3D segmentation of and sophisticated software

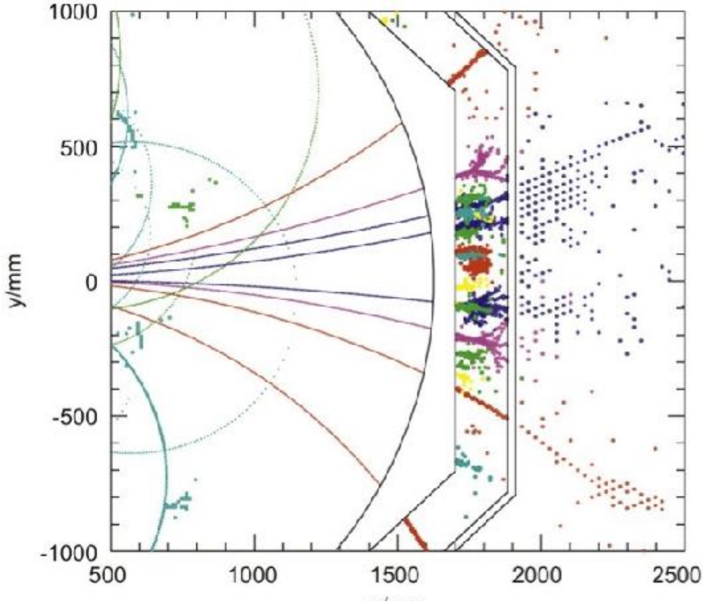
- ECAL few 10 mm², HCAL 1-10 cm² - millions of channels

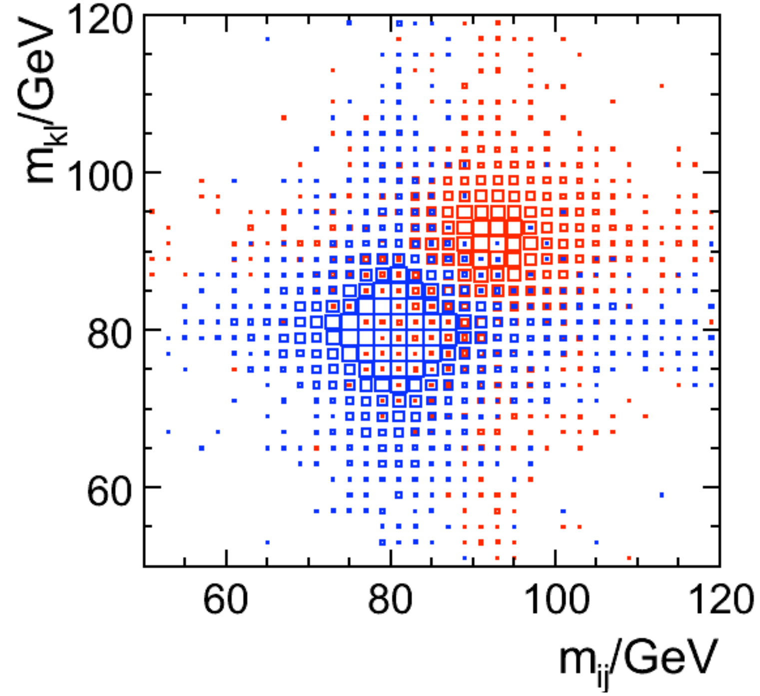
Today all linear collider detector concepts follow particle flow concept



$E_{JET} = E_{ECAL} + E_{HCAL}$

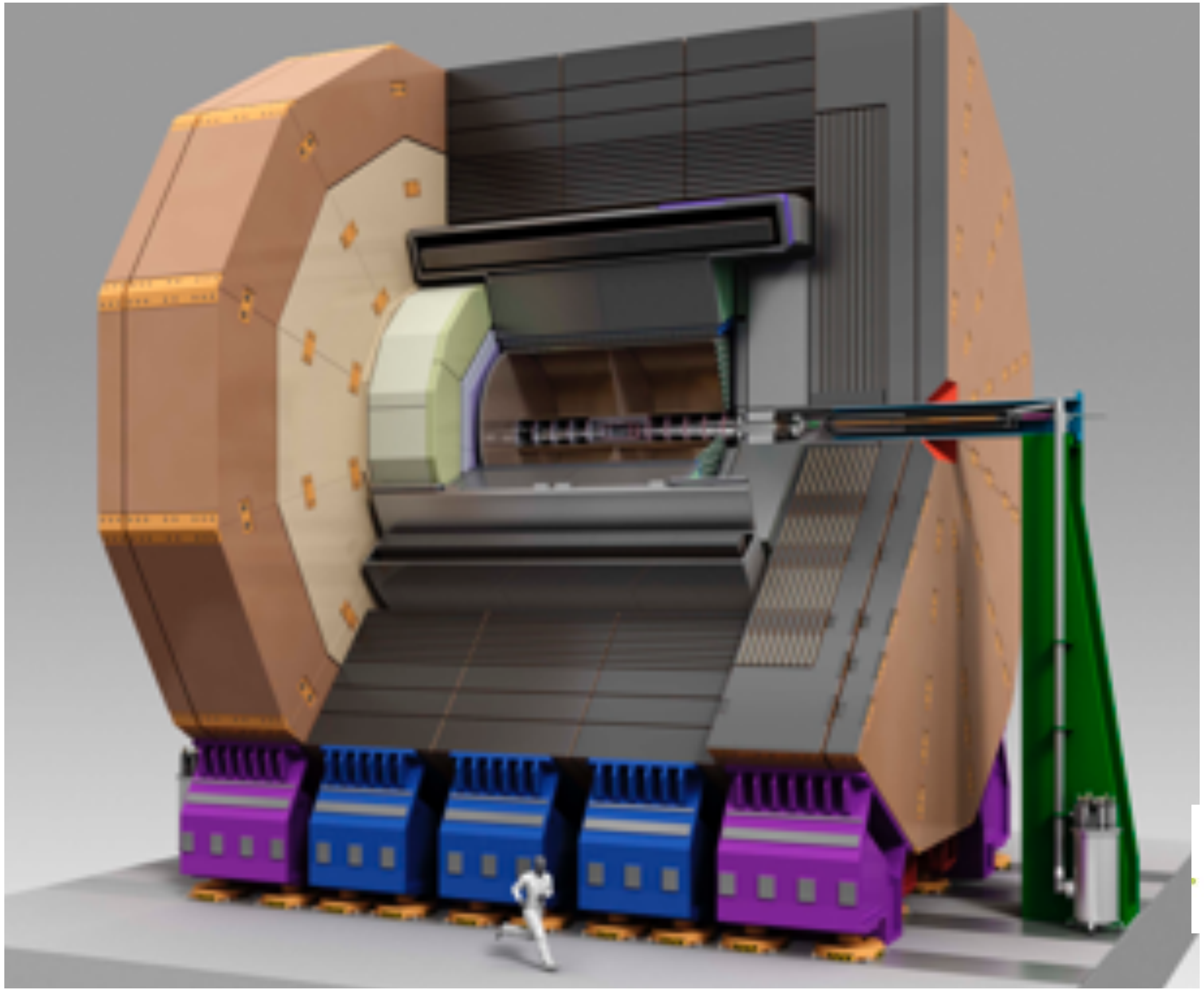
$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

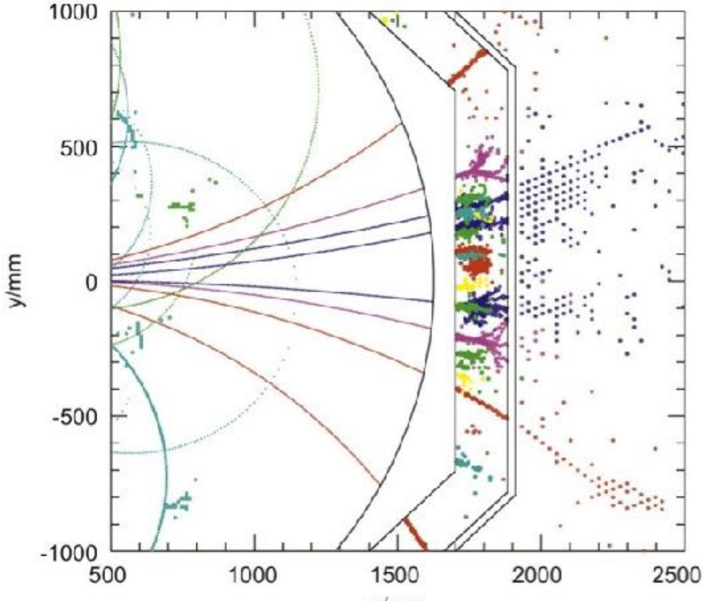


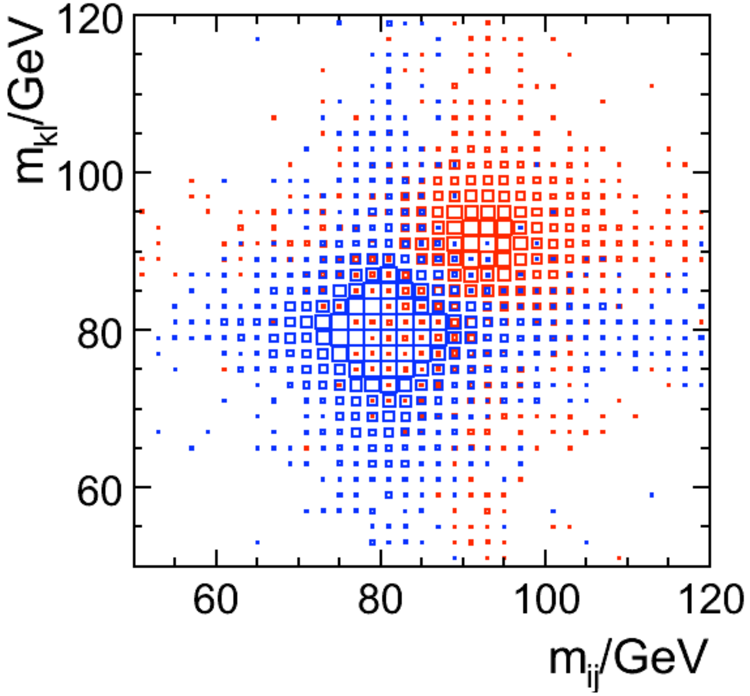


Particle Flow Paradigm

Tackle the jet energy challenge.

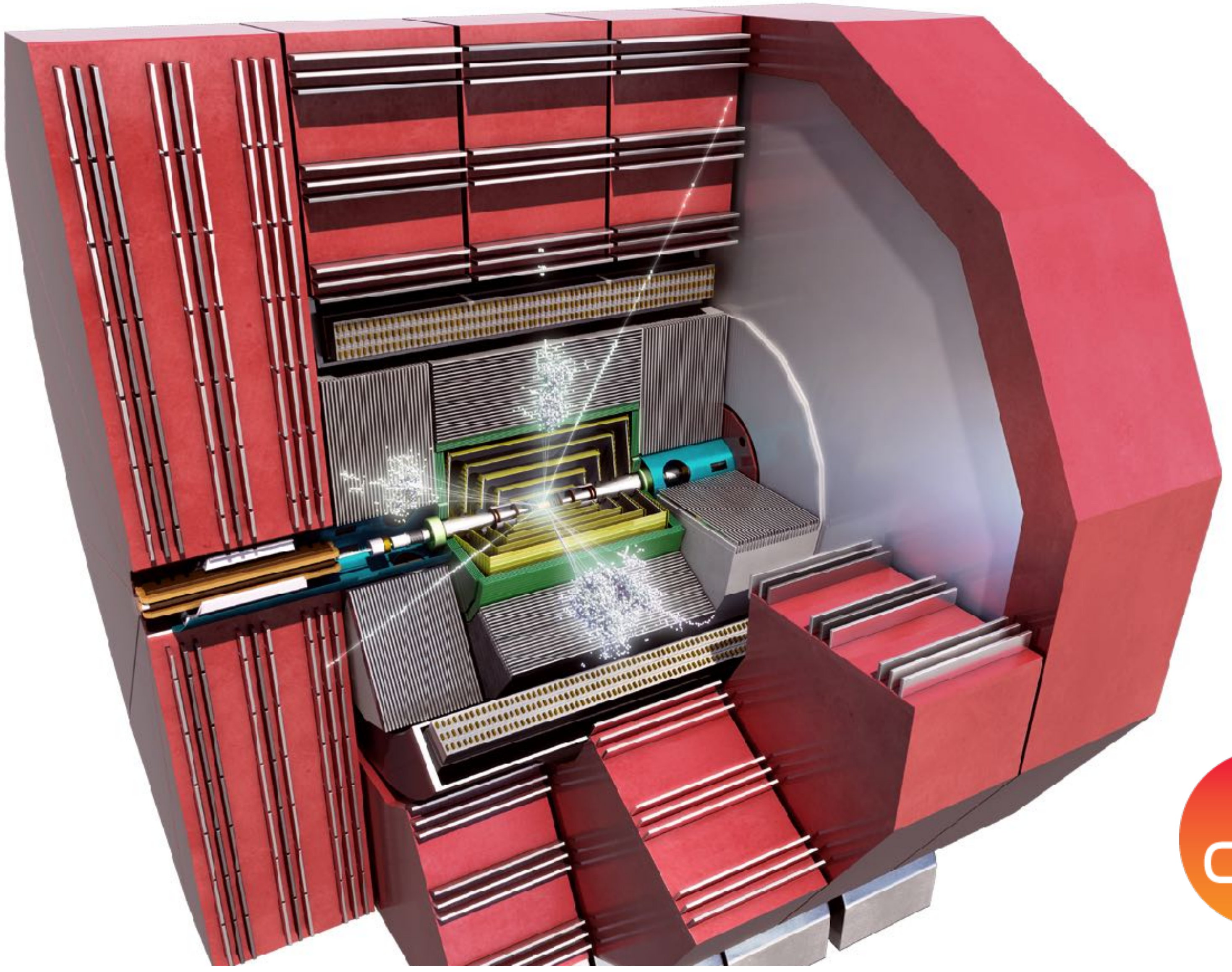


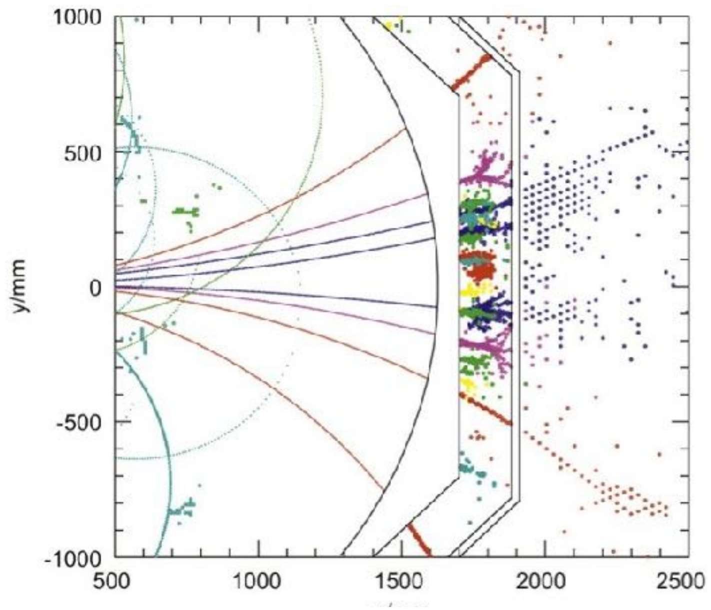


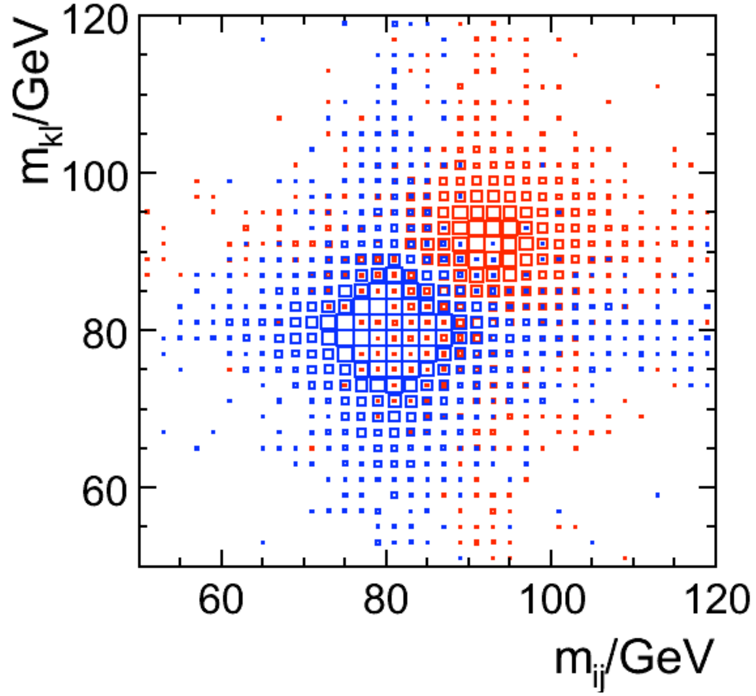


Particle Flow Paradigm

Tackle the jet energy challenge.







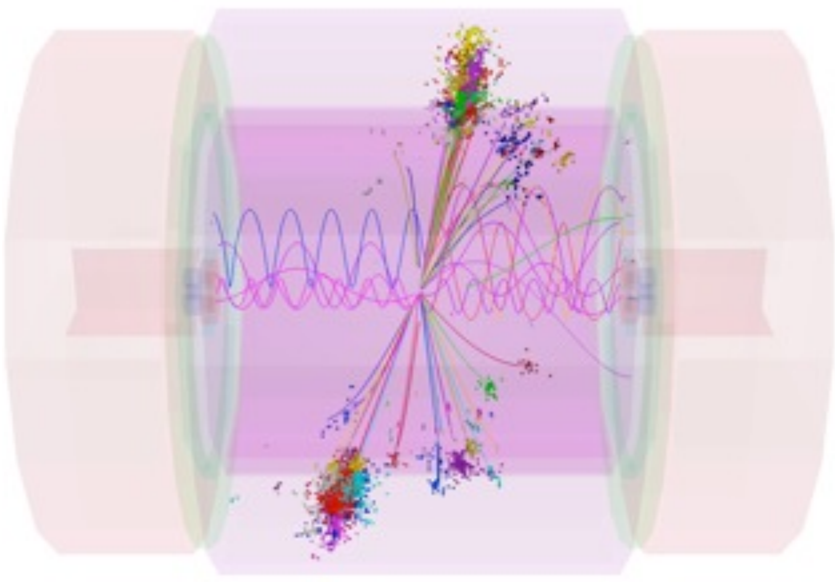
High Granularity and Pile-up

Particle flow with harsher backgrounds.

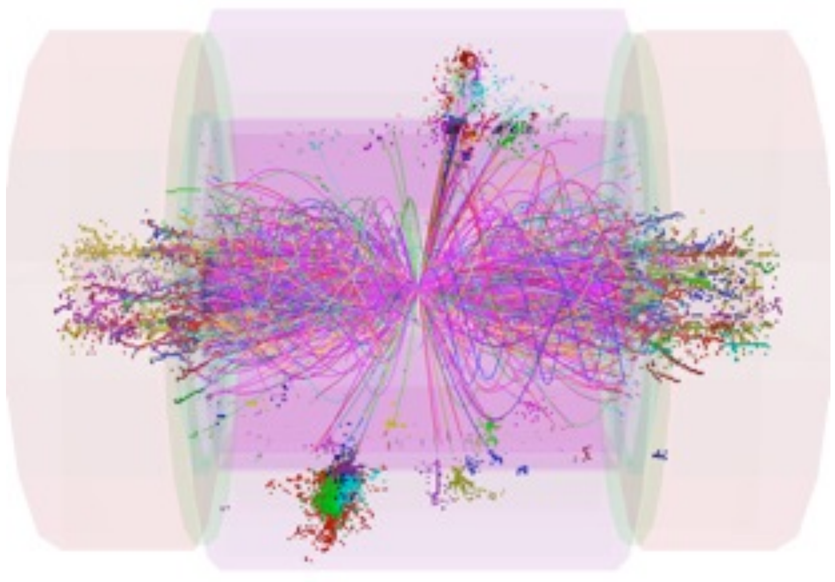
Studied intensively for CLIC: backgrounds from γγ → hadrons and short BX 0.5 ns

- Overlay γγ events from 60 BX, take sub-detector specific integration times, multi-hit capability and time-stamping accuracy into account
- Apply combination of topological, pt and timing cuts on cluster level (sub-ns accuracy)

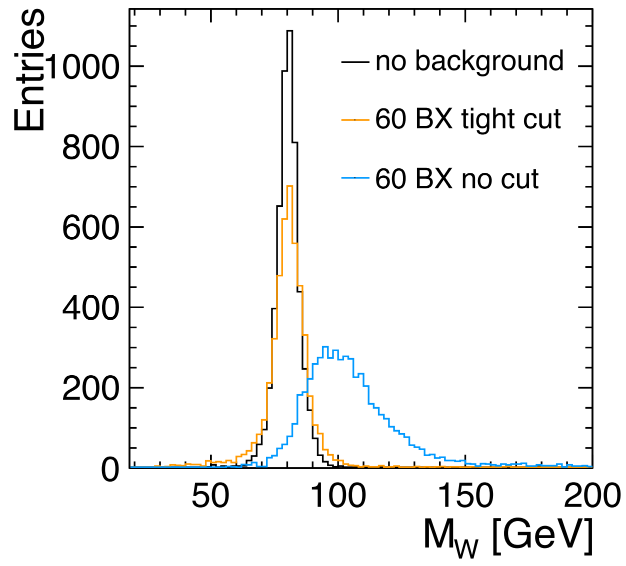
High granularity essential for pile-up rejection capabilities



Z @ 1 TeV



+ 1.4 TeV BG (reconstructed particles)



E_W = 500 GeV

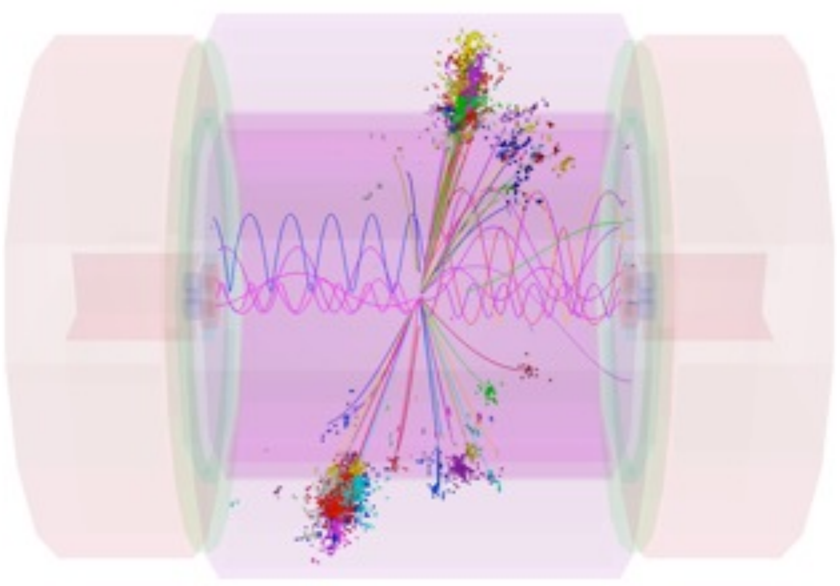
High Granularity and Pile-up

Particle flow with harsher backgrounds.

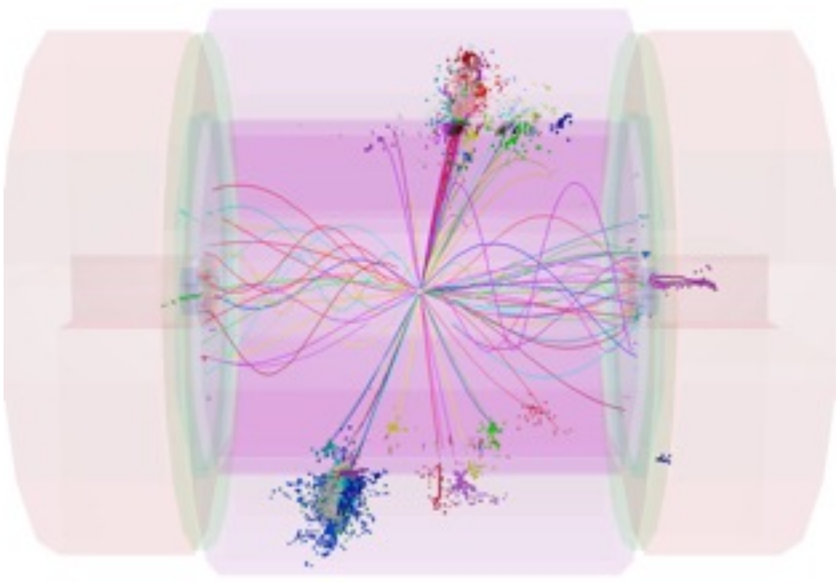
Studied intensively for CLIC: backgrounds from γγ → hadrons and short BX 0.5 ns

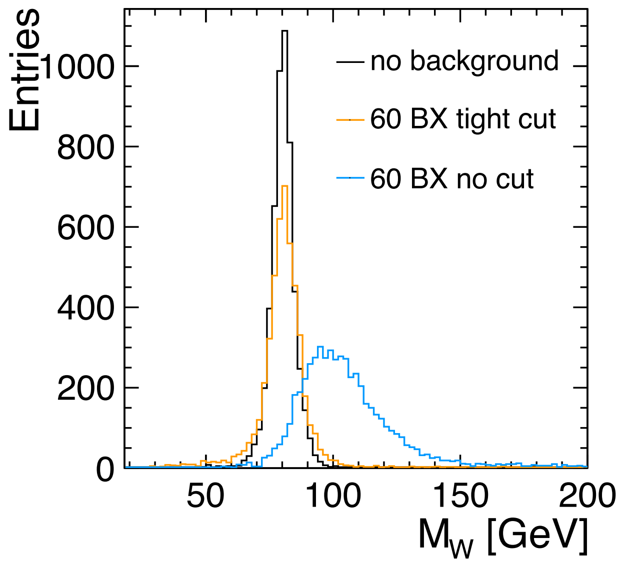
- Overlay γγ events from 60 BX, take sub-detector specific integration times, multi-hit capability and time-stamping accuracy into account
- Apply combination of topological, pt and timing cuts on cluster level (sub-ns accuracy)

High granularity essential for pile-up rejection capabilities



Z @ 1 TeV

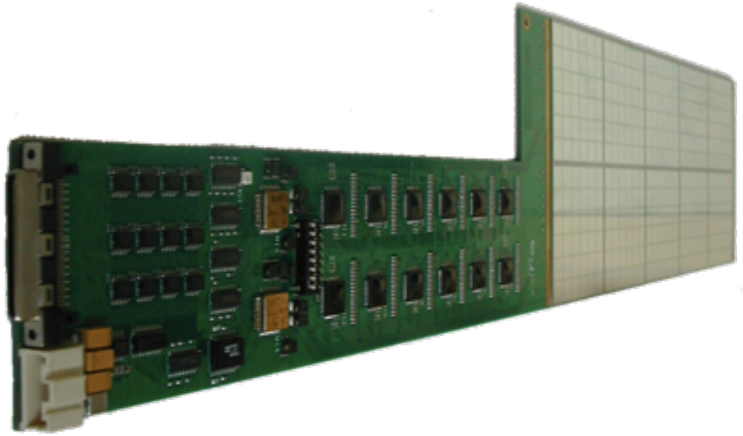




E_W = 500 GeV

Technologies for Highly Granular Calorimeters

Because we can.

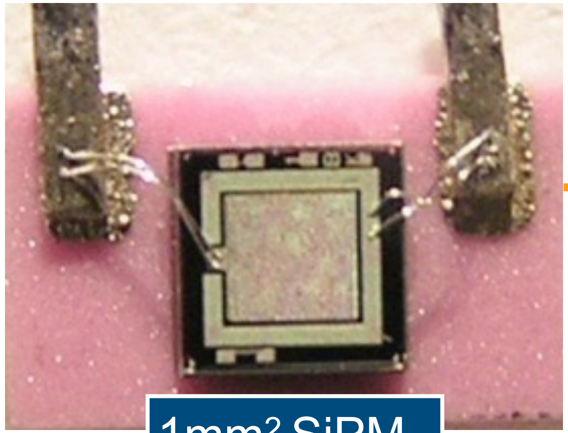


Large area silicon arrays

- silicon calorimetry grows out of the domain of small plug devices

New segmented gas amplification structures (RPC, GEM, µMs)

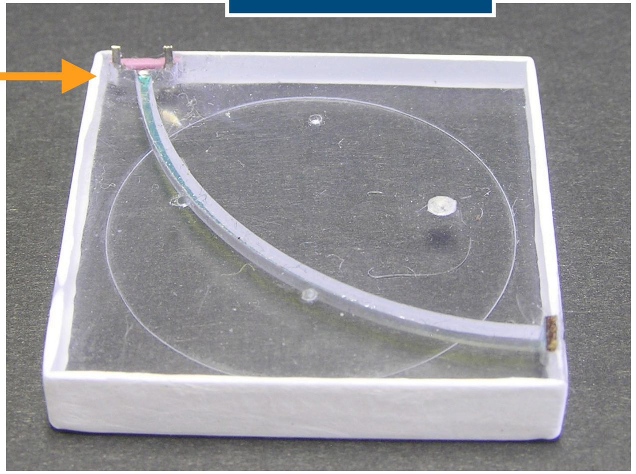
Silicon photomultipliers on scintillator tiles or strips



1mm² SiPM

2004

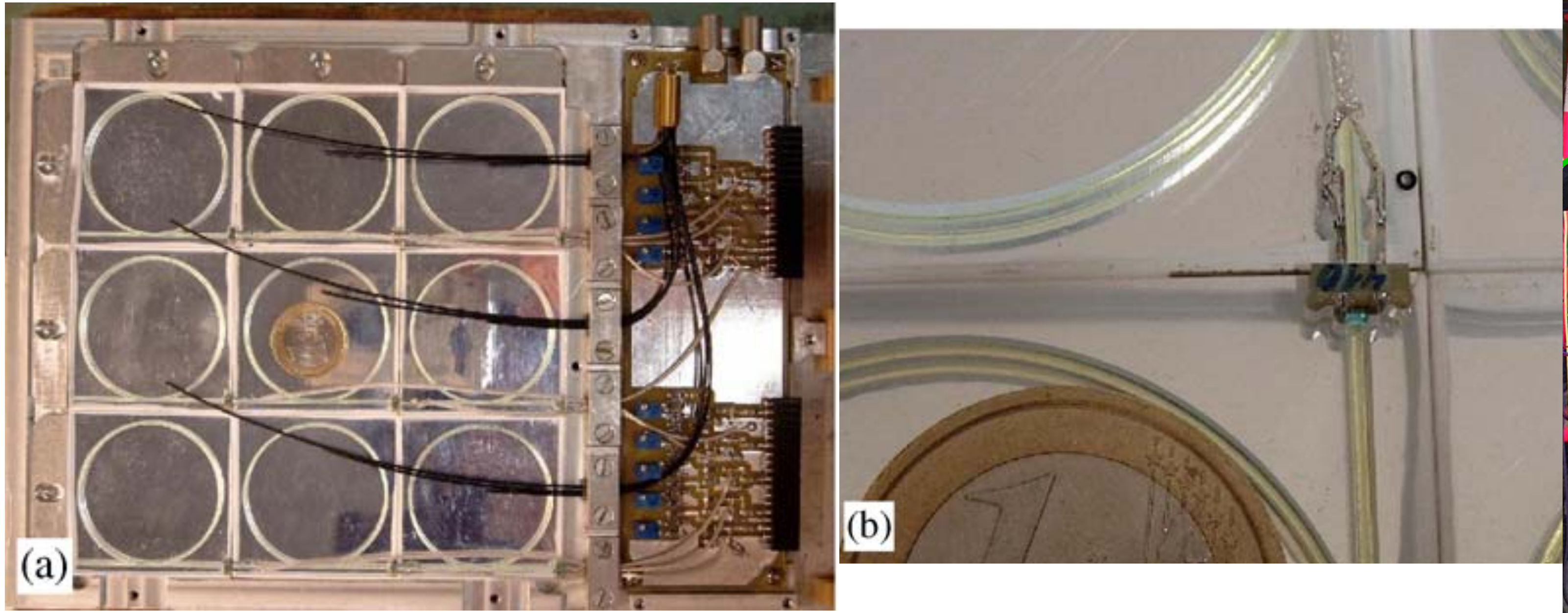
3x3cm² tile



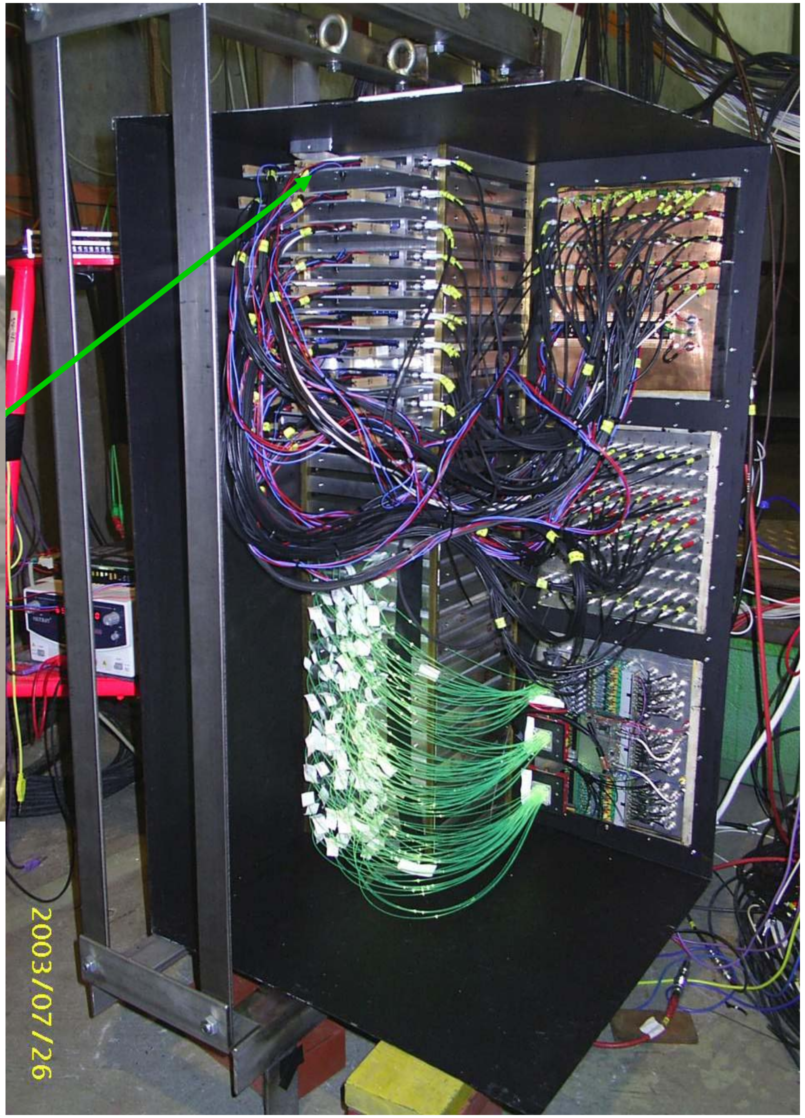
small, B-insensitive, cheap, robust

SiPM-on-Tile Evolution

A long way



2003: MiniCal

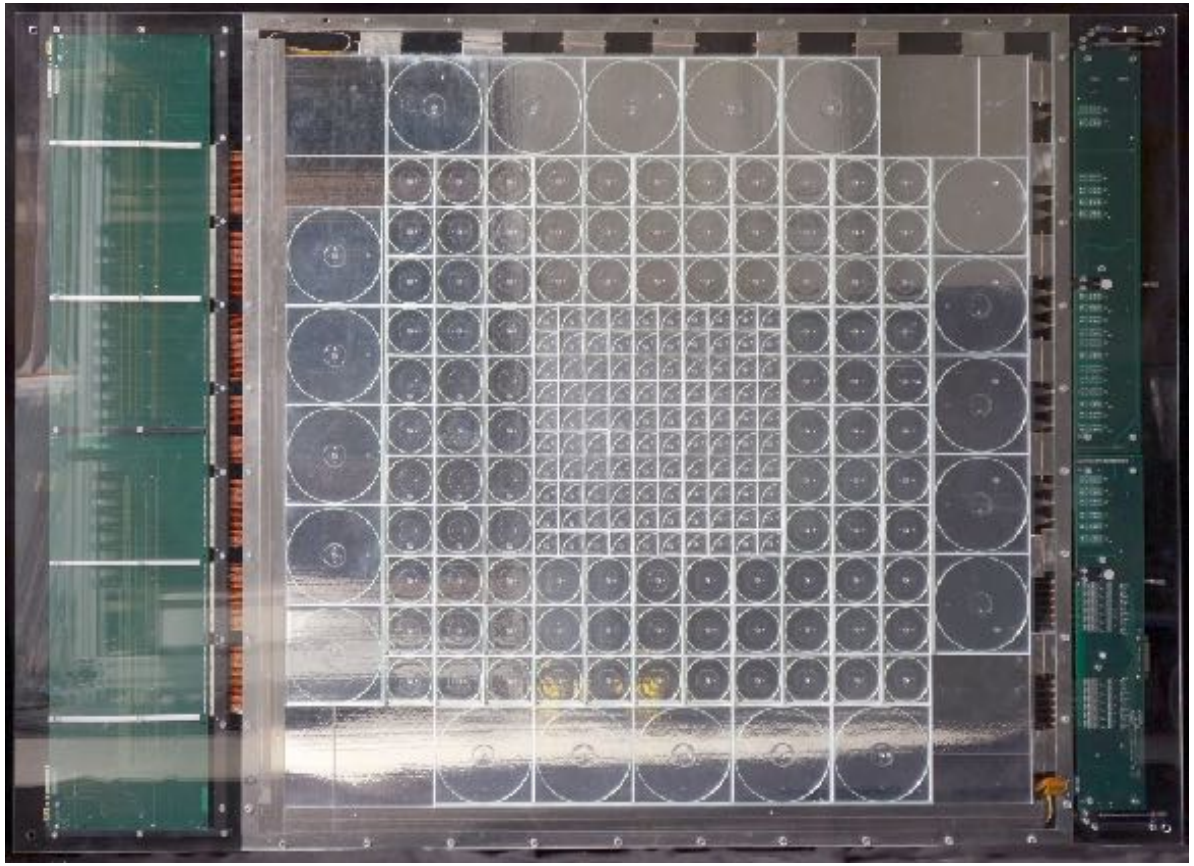


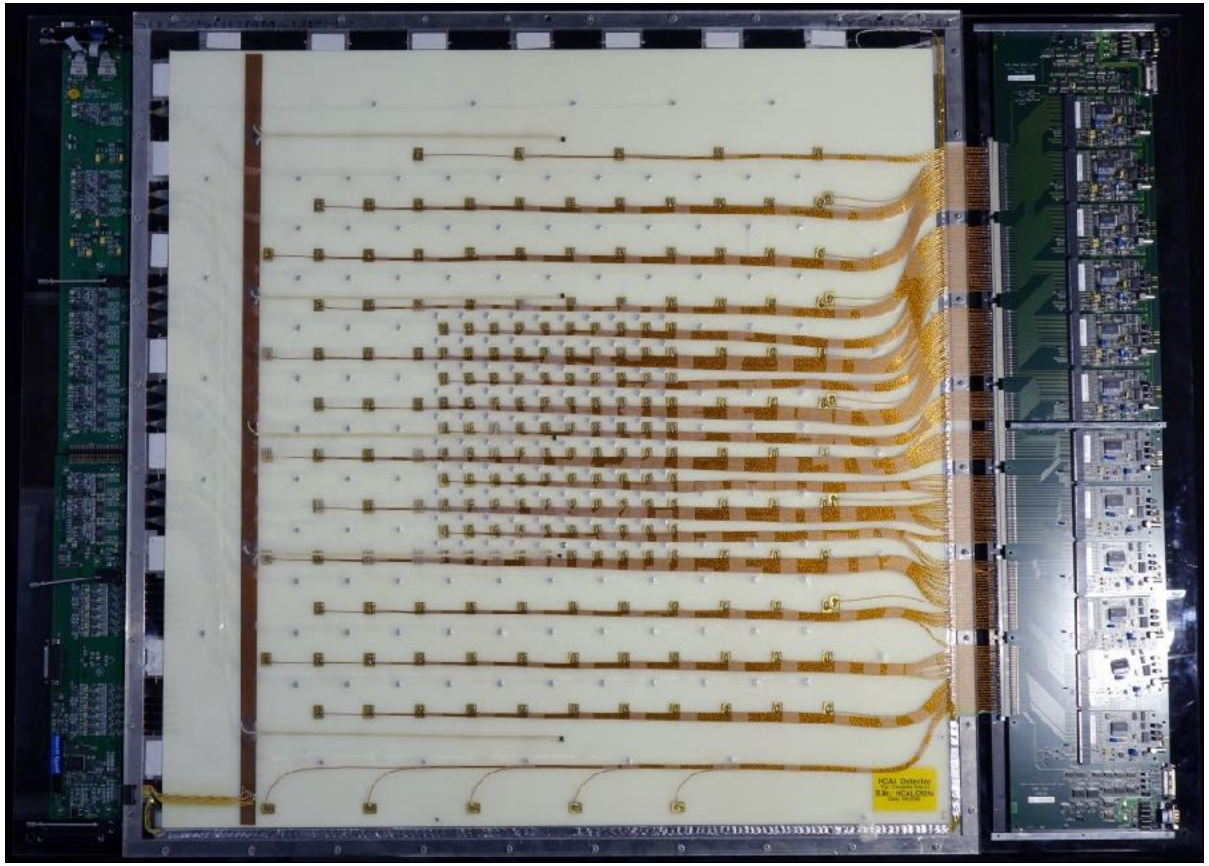
SiPM-on-Tile Evolution

A long way

SiPM-on-Tile Evolution

A long way





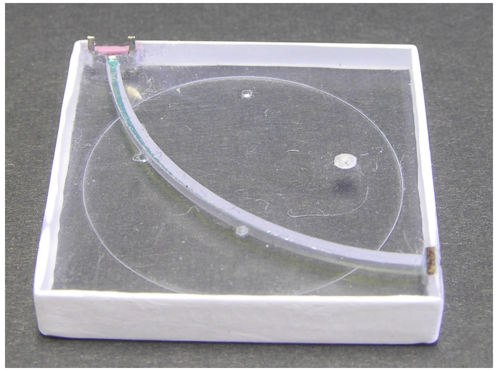
2006: Physics Prototype

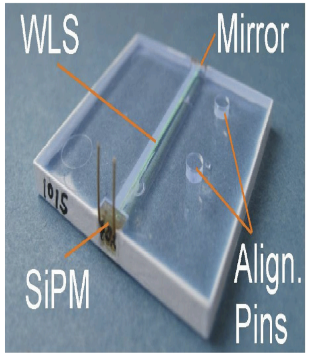
SiPM-on-Tile Evolution

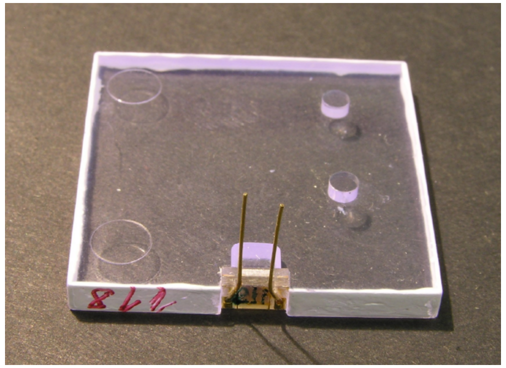
A long way

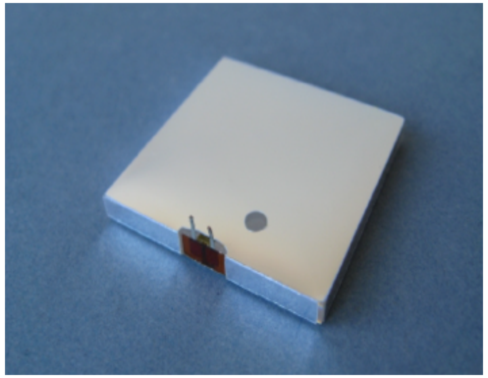
SiPM-on-Tile Evolution

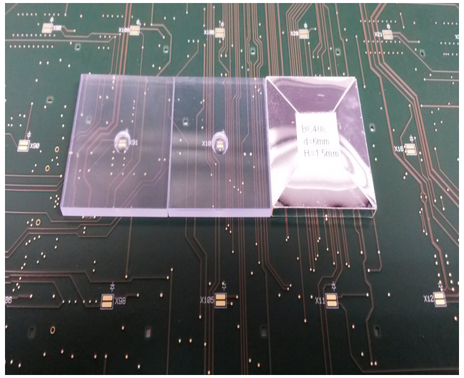
A long way





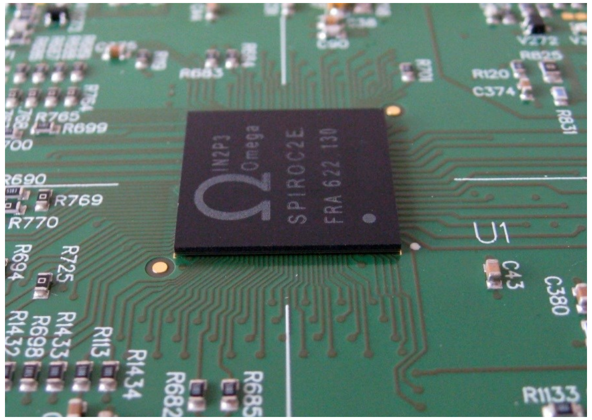


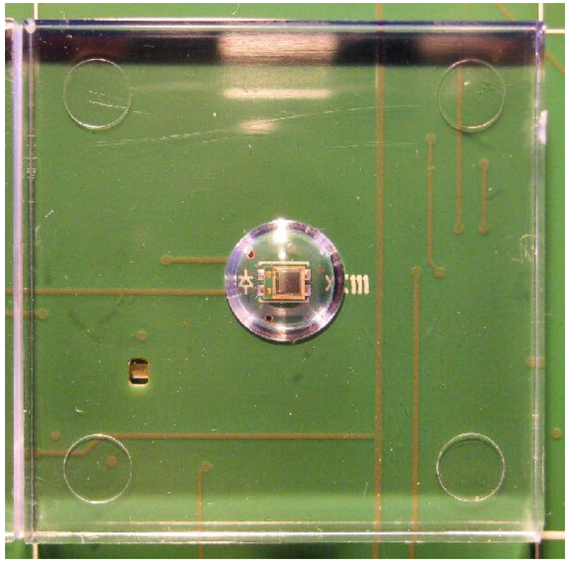


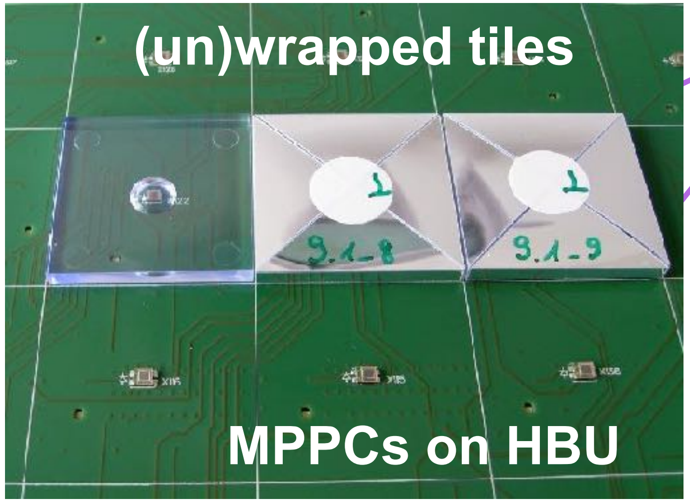


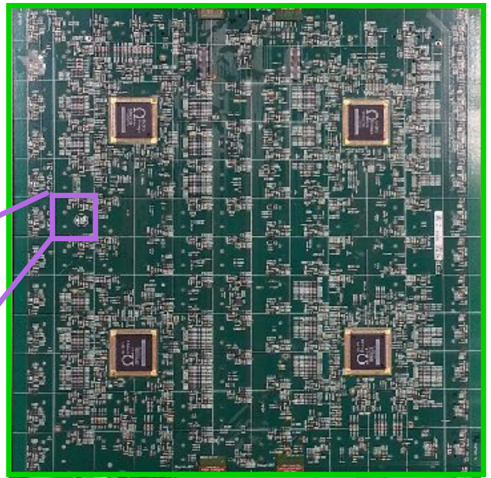
The Next Step: Scalability

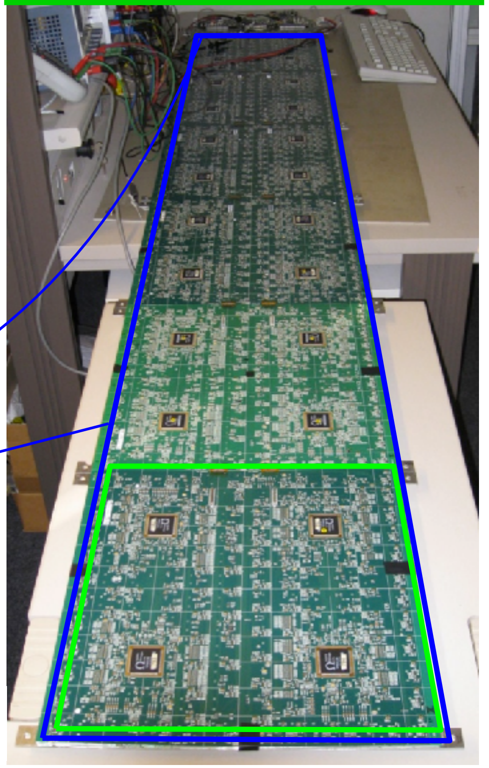
Technological prototypes.

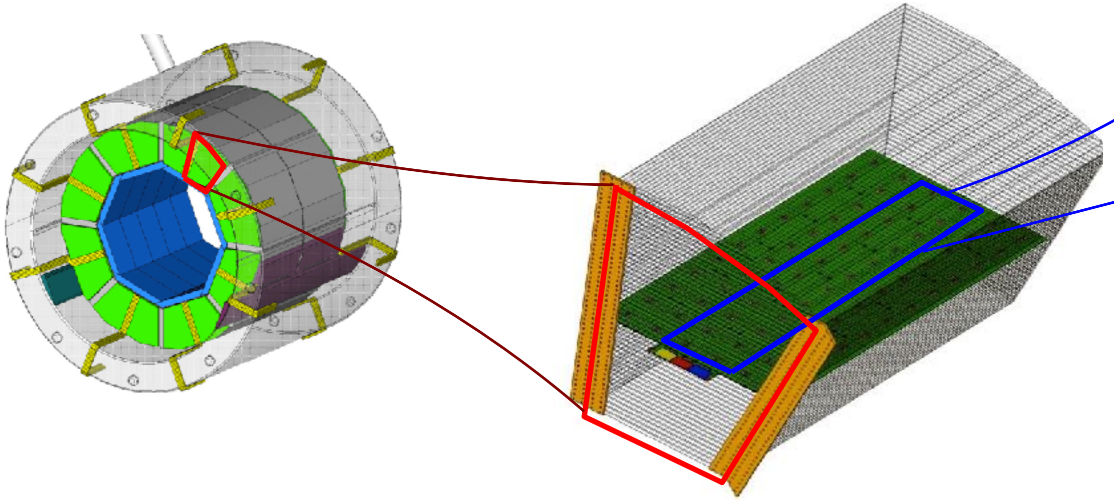








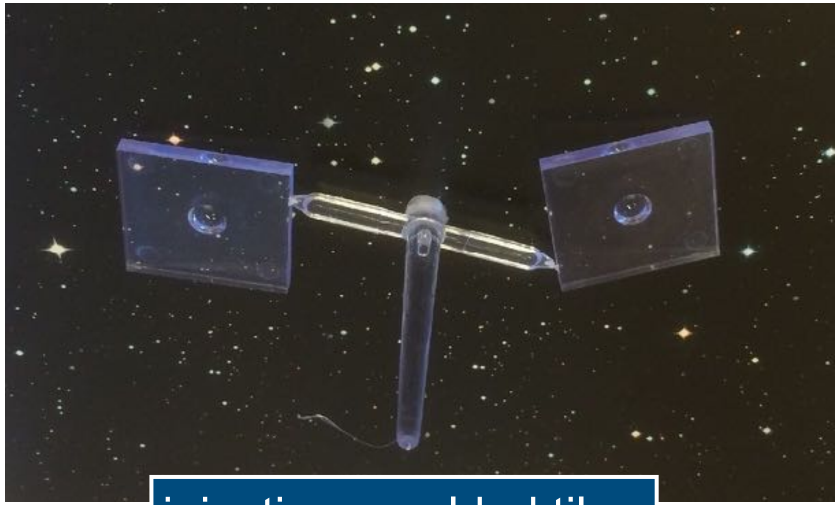




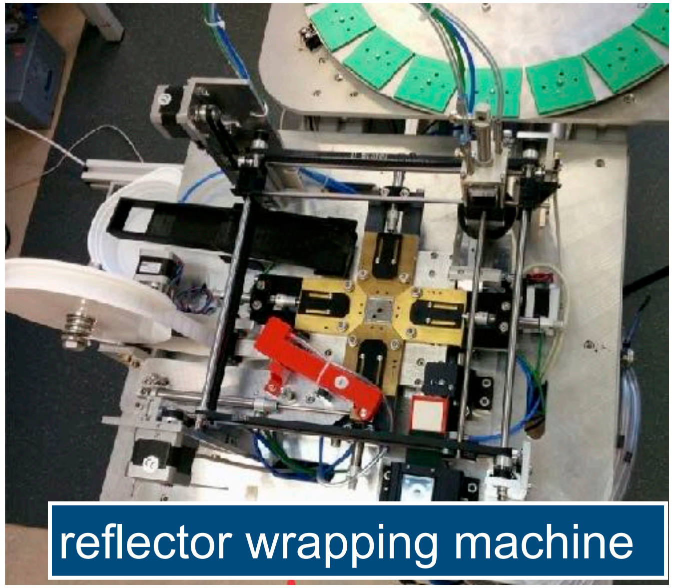
- 1000’s of channels per m^2
- 1000’s of m^2
- must embed electronics and go digital as early as possible
- Integrate SiPMs in read-out board, too

Automated Production and Quality Assurance

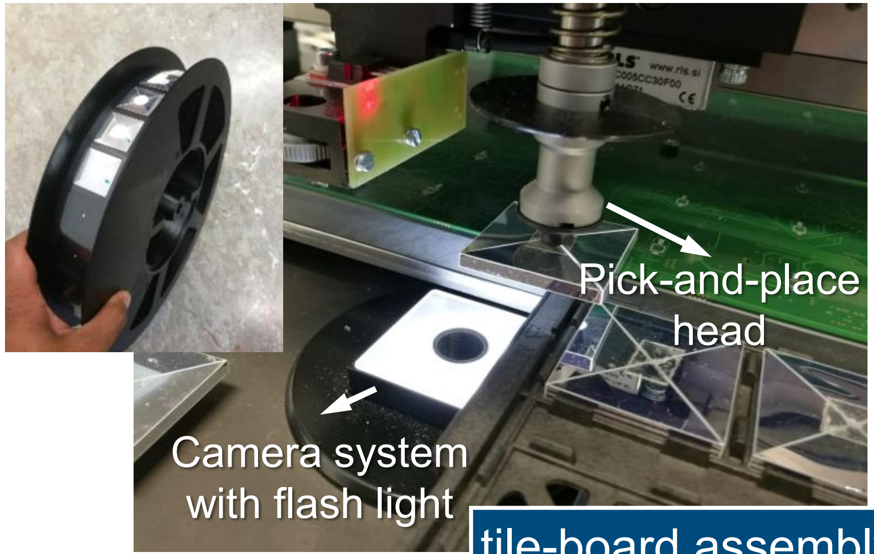
Establishing the concept.



injection-moulded tiles



reflector wrapping machine



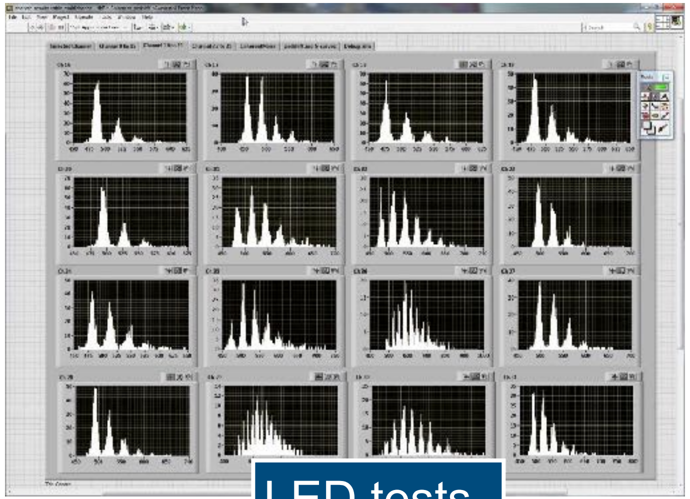
tile-board assembly

In addition test infrastructures:

- Multi-channel SiPM tests
- Automated ASIC tests
- PCB tests using LEDs
- Coscmic tests after tile assembly

AIDA2020

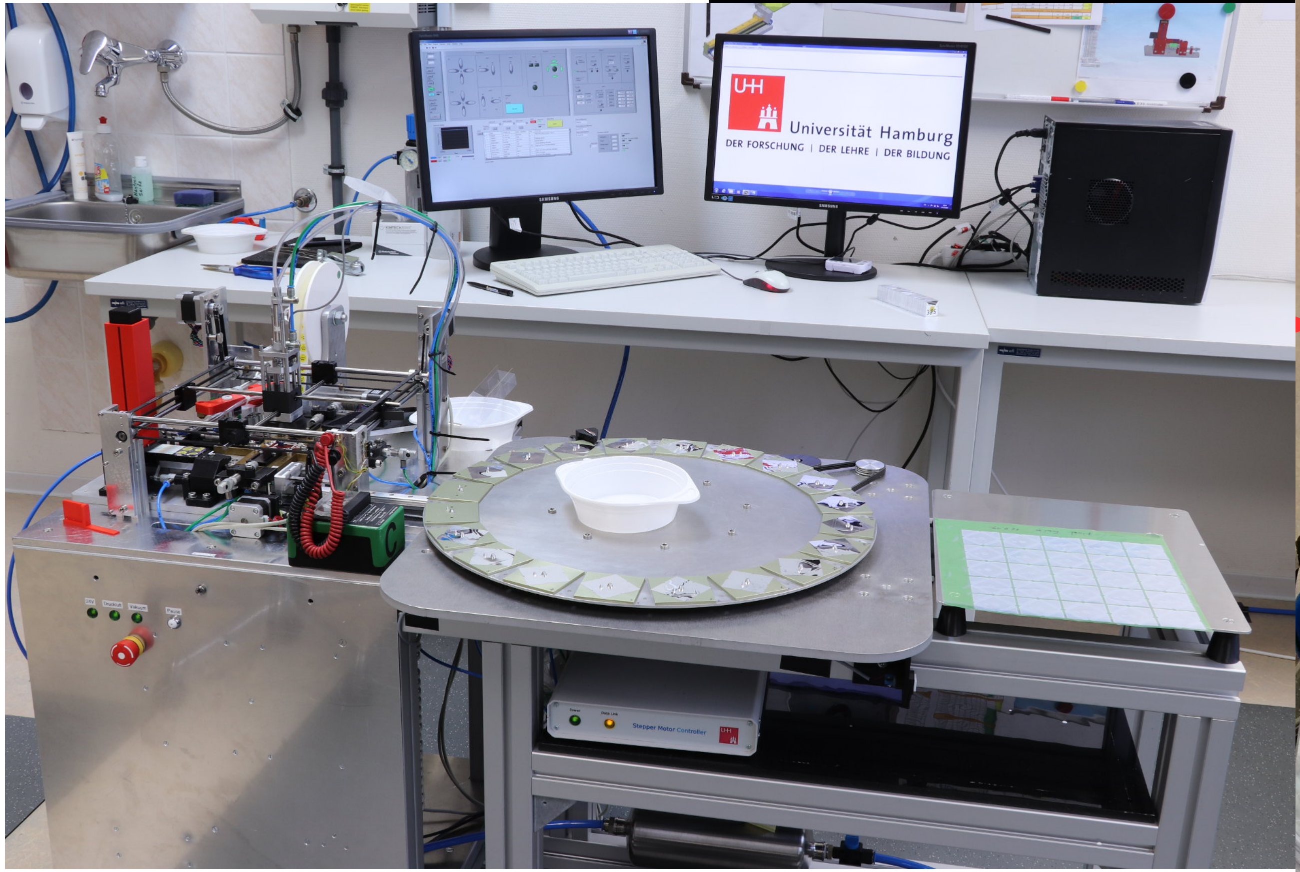
read-out boards

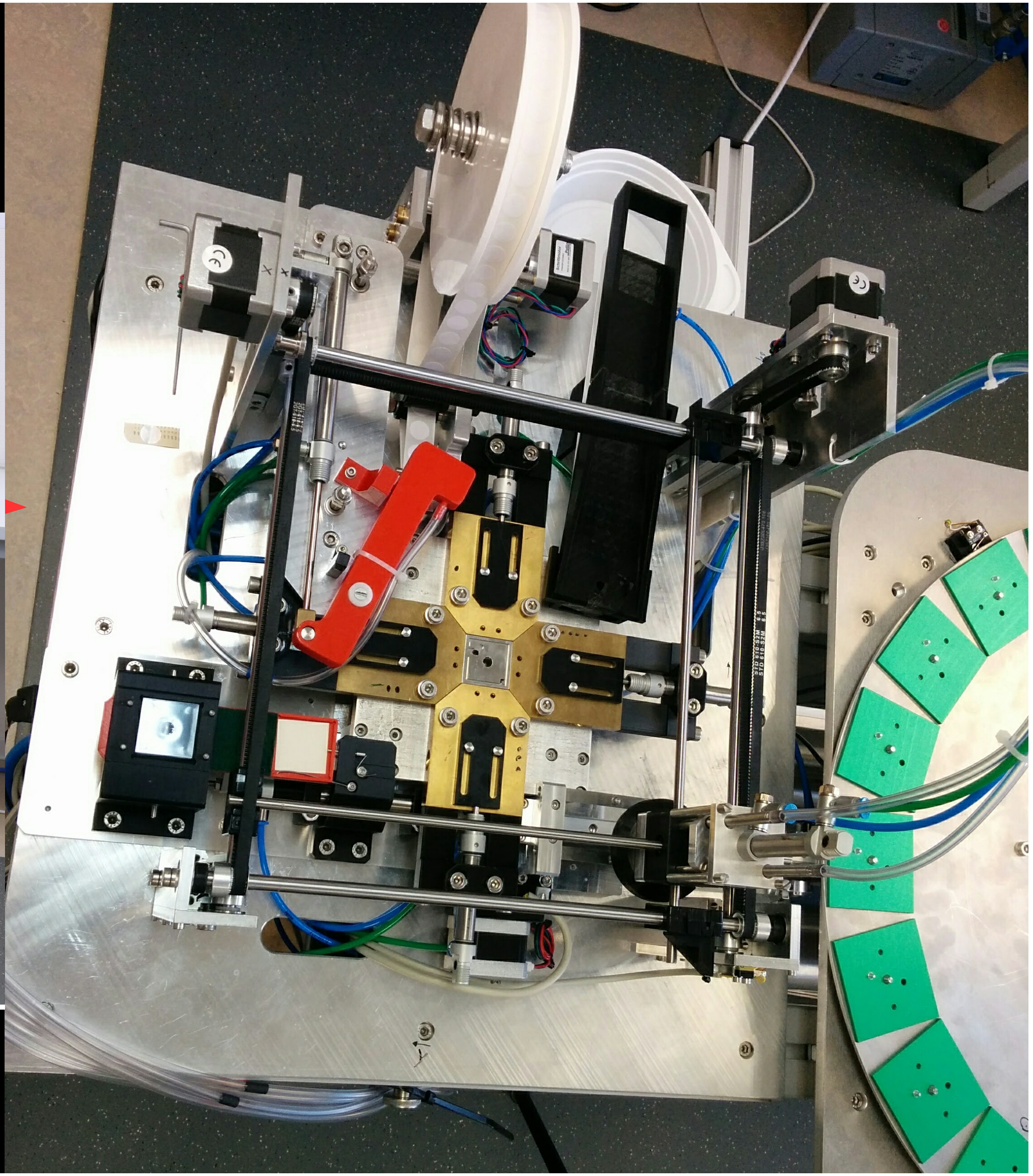


LED tests

Tile Wrapping

Custom-made machine



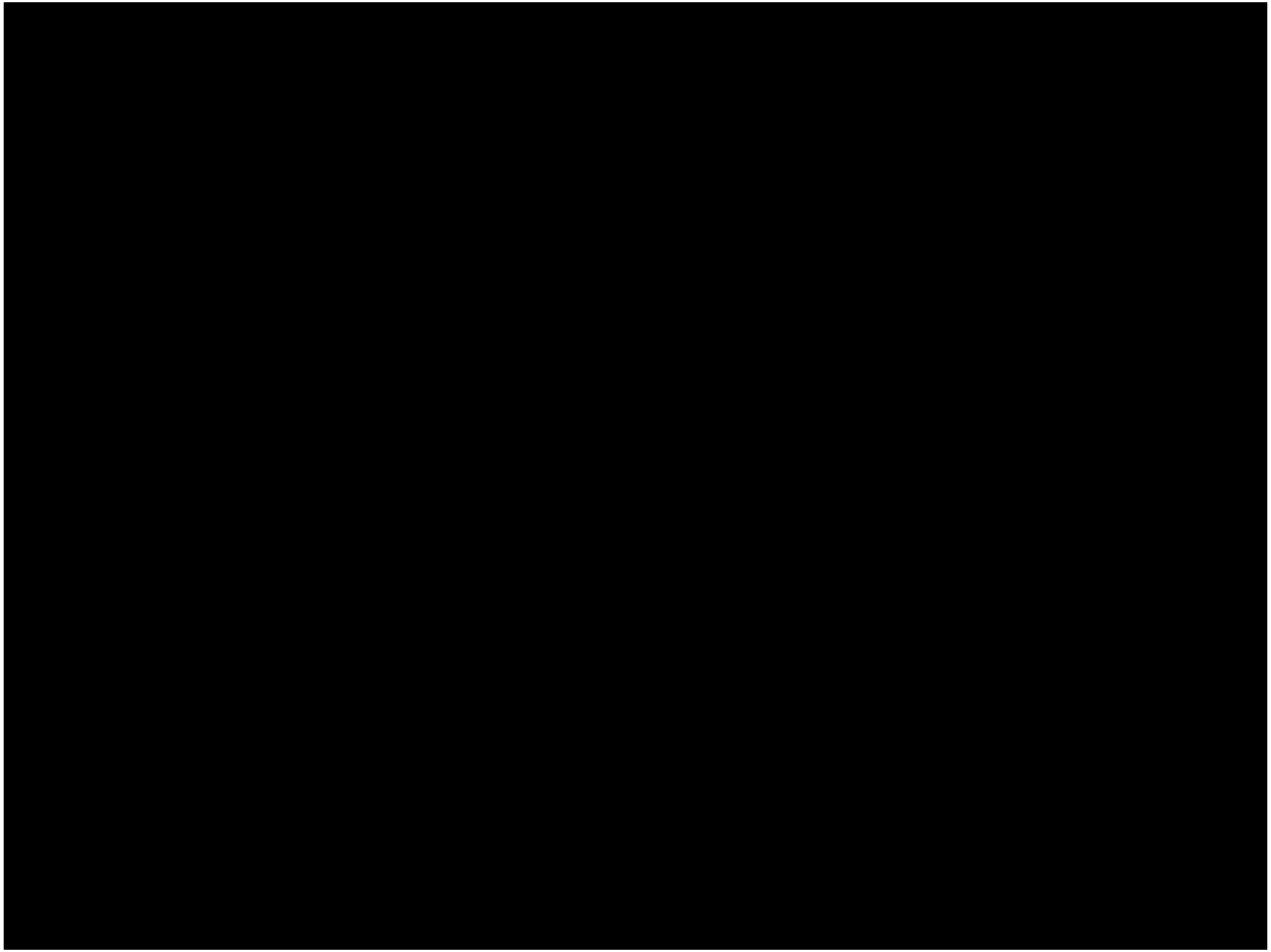


- University of Hamburg

start in October

Tile Wrapping

Custom-made machine

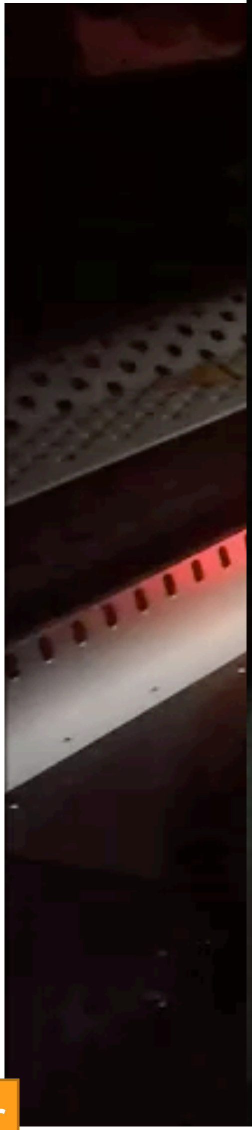


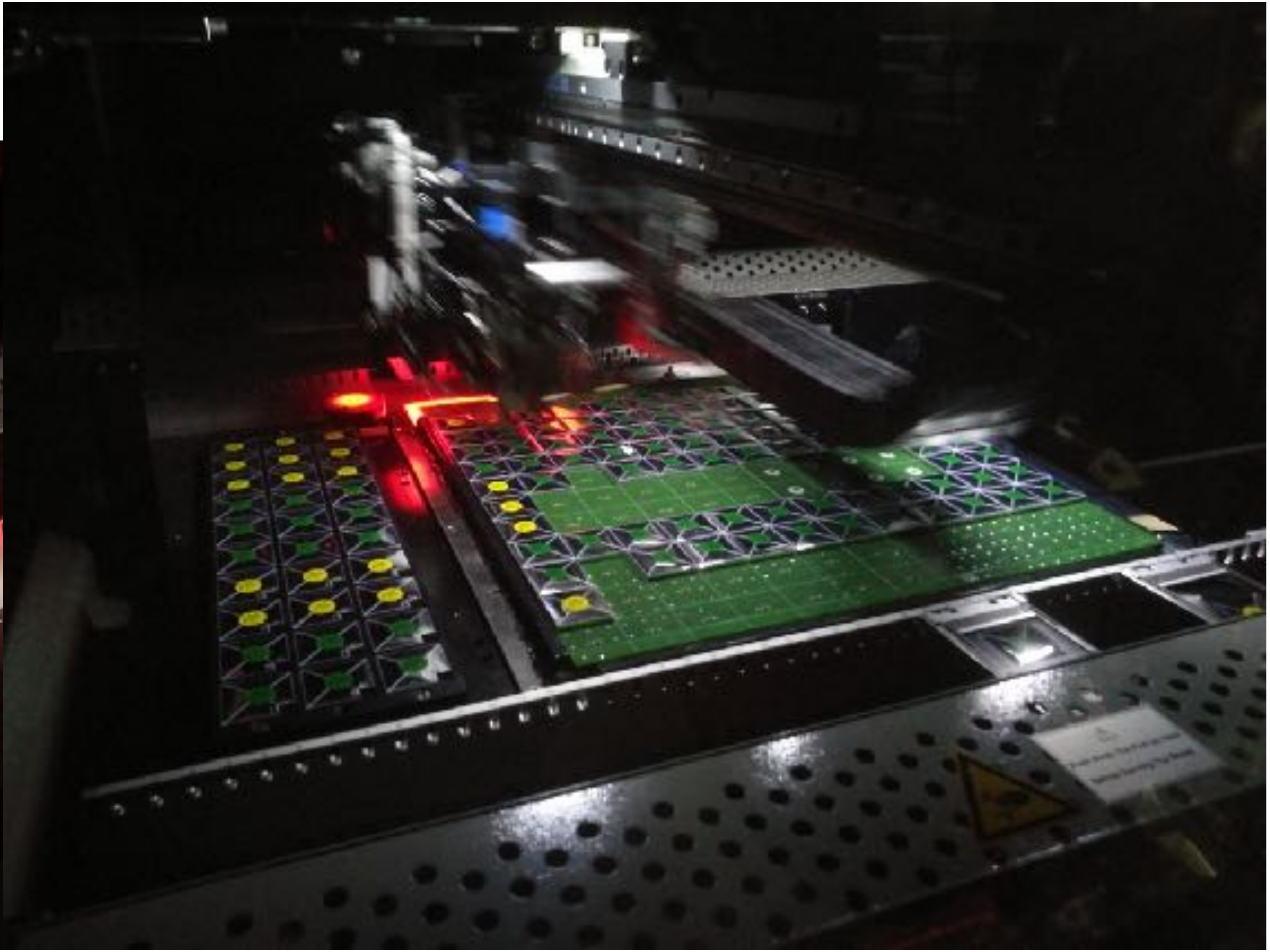
- University of Hamburg

start in October

Pick & Place

Standard Machine



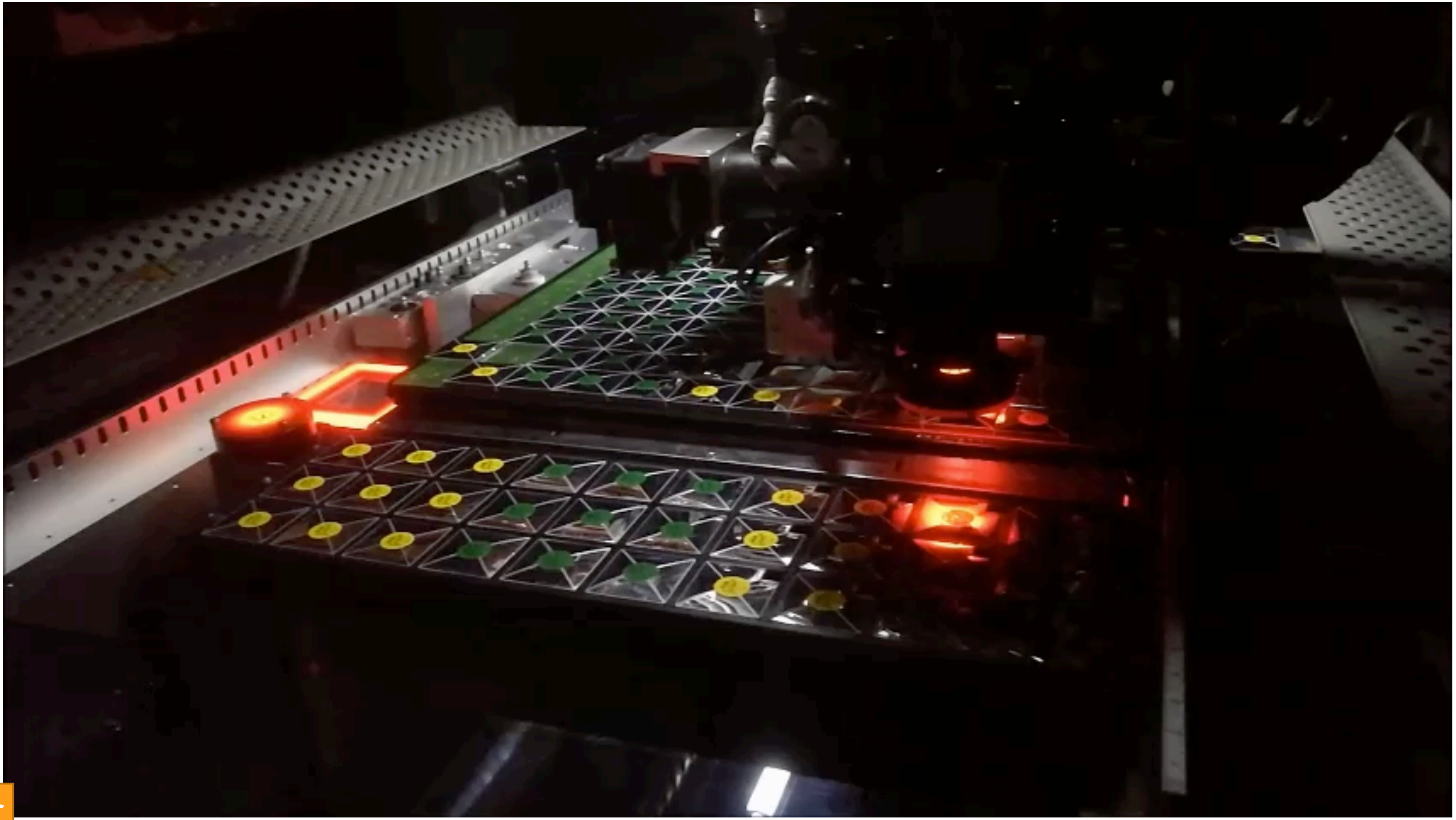


- University of Mainz

start in November

Pick & Place

Standard Machine

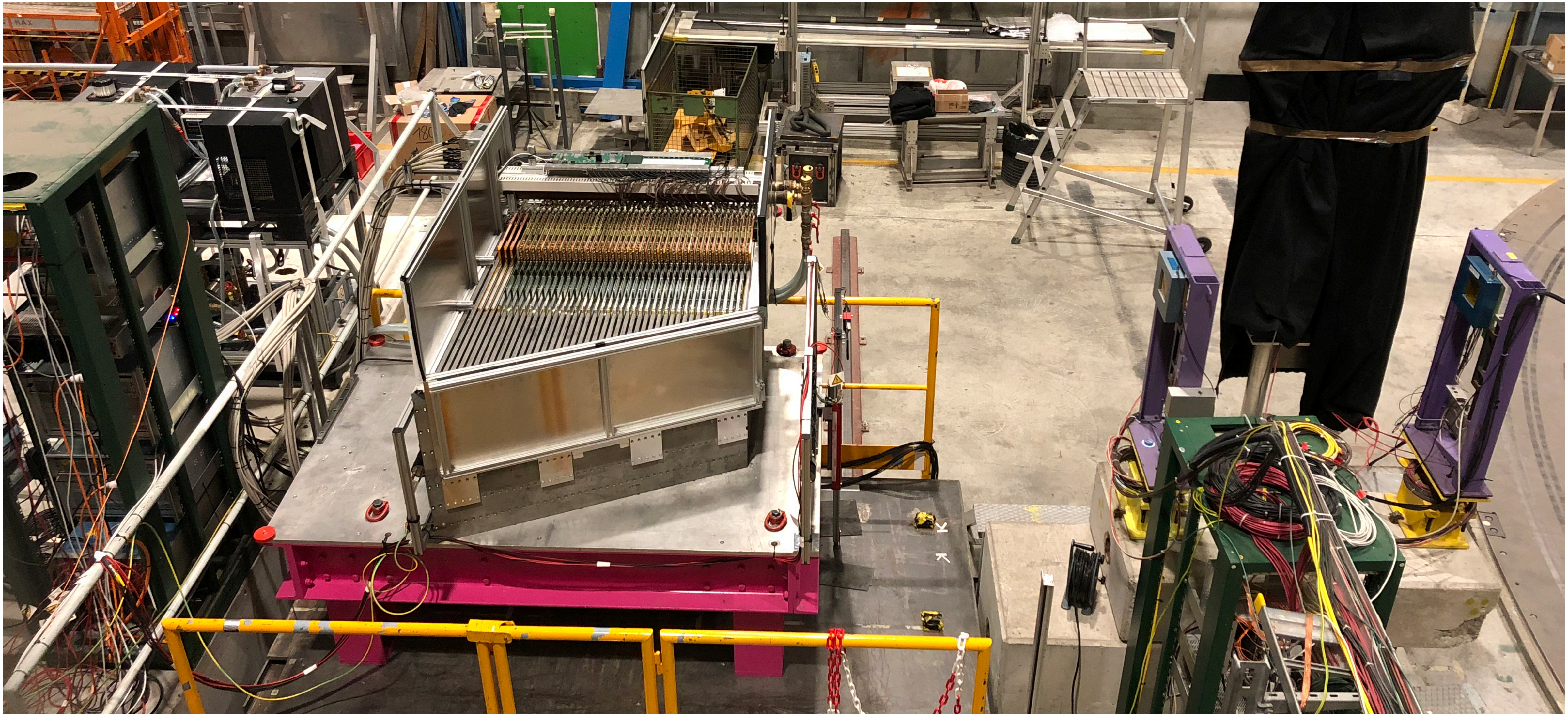


- University of Mainz

start in November

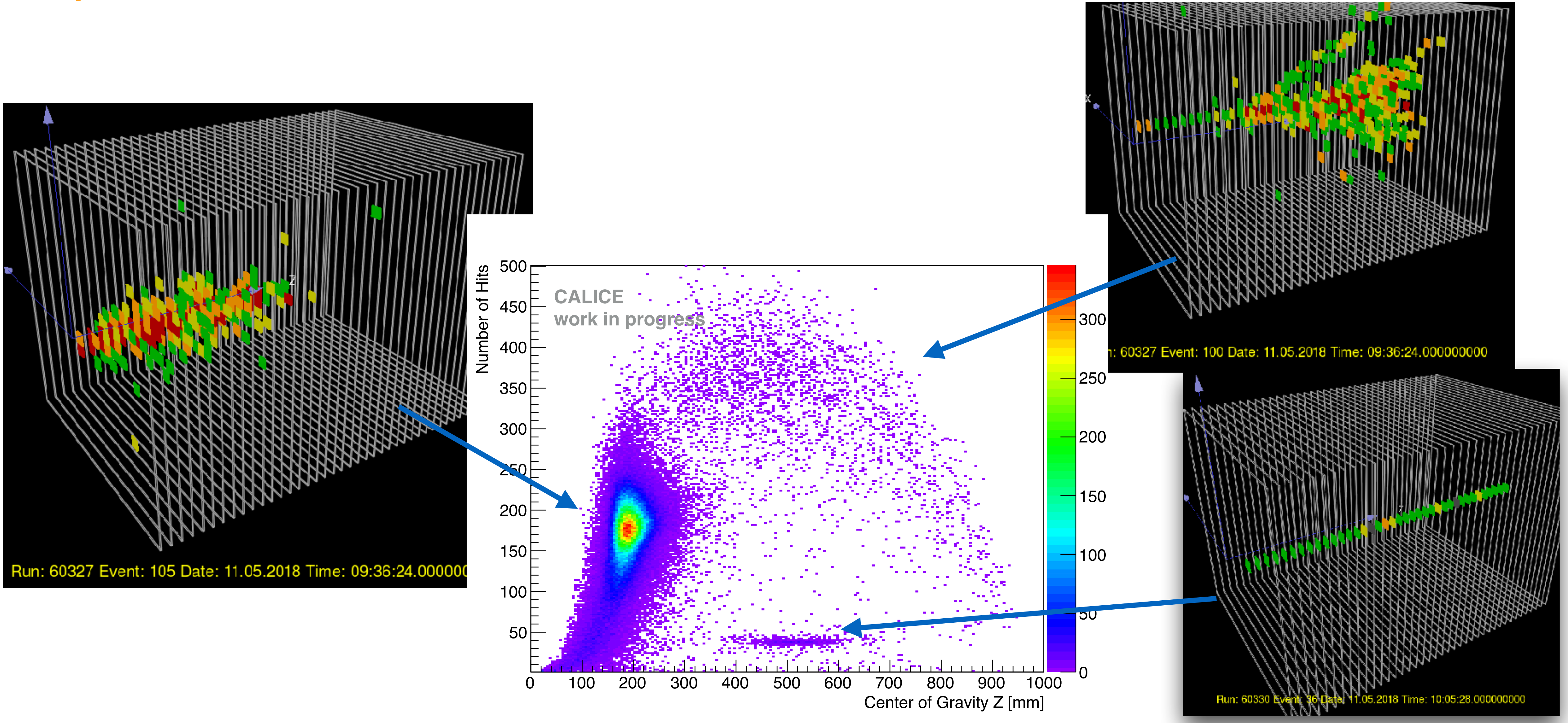
Test beam

May 2918 at CERN SPS



Test beam

May 2918 at CERN SPS



… to LHC

HGCAL Motivation and Timeline

High Granularity Endcap Calorimeter for CMS.

HL-LHC: 300 -> 3000 fb-1 to start end of 2026

- Emphasis moves to vector boson fusion initiated processes
- Narrow and merged jets, isolated objects
- Pile-up: 200 collisions per BX, keep thresholds
- Existing end-cap will be degraded at end of Run 2 (2023)

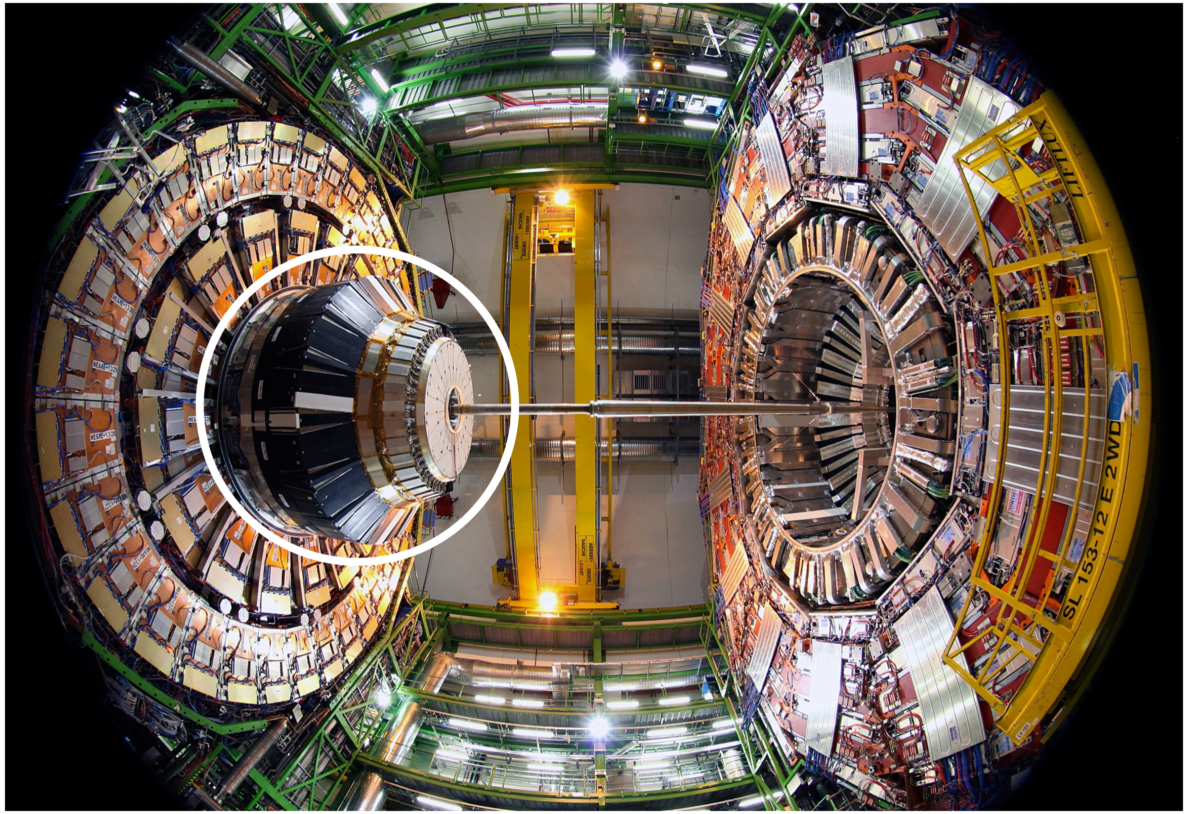
Technical proposal 2015

- Decision plastic scintillator for CE-H: Nov 2016
- Decision SiPM-on-tile Mar 2017

TDR submitted Nov 2017

- LHCC review Feb 2018, approved
- EDR end 2020

Largely building on CALICE developments



HGCAL Motivation and Timeline

High Granularity Endcap Calorimeter for CMS.

HL-LHC: 300 -> 3000 fb-1 to start end of 2026

- Emphasis moves to vector boson fusion initiated processes
- Narrow and merged jets, isolated objects
- Pile-up: 200 collisions per BX, keep thresholds
- Existing end-cap will be degraded at end of Run 2 (2023)

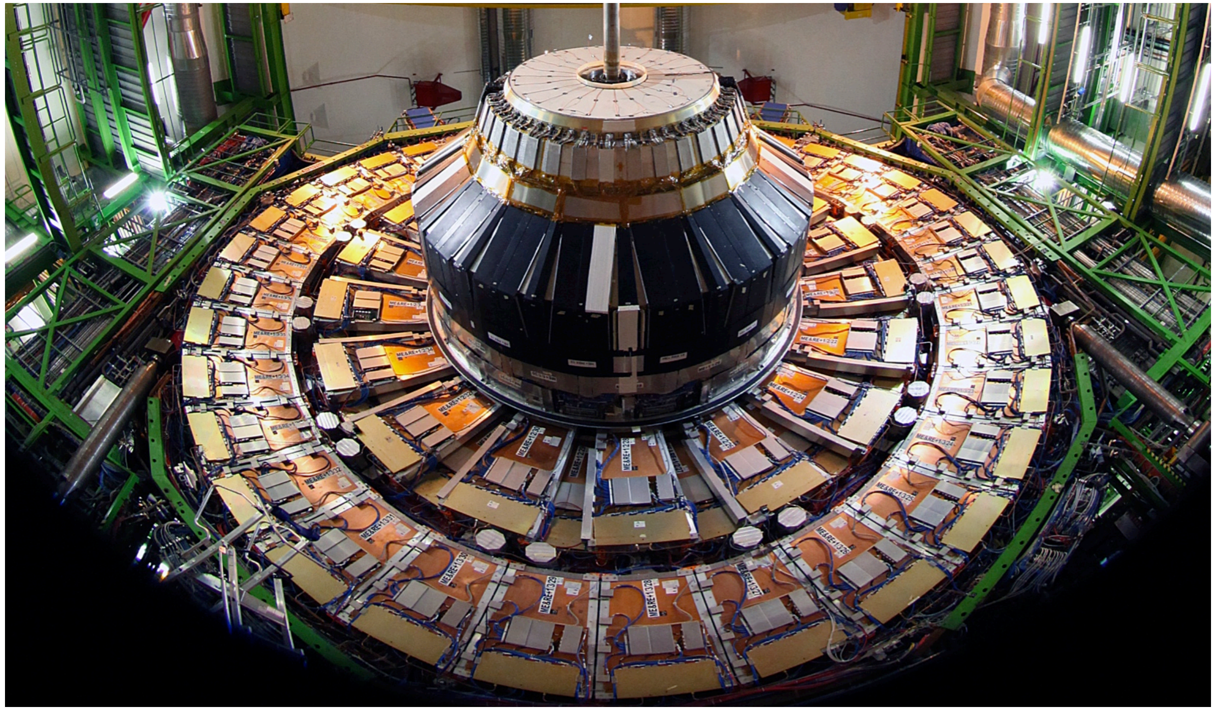
Technical proposal 2015

- Decision plastic scintillator for CE-H: Nov 2016
- Decision SiPM-on-tile Mar 2017

TDR submitted Nov 2017

- LHCC review Feb 2018, approved
- EDR end 2020

Largely building on CALICE developments



HGCAL Motivation and Timeline

High Granularity Endcap Calorimeter for CMS.

HL-LHC: 300 -> 3000 fb-1 to start end of 2026

- Emphasis moves to vector boson fusion initiated processes
- Narrow and merged jets, isolated objects
- Pile-up: 200 collisions per BX, keep thresholds
- Existing end-cap will be degraded at end of Run 2 (2023)

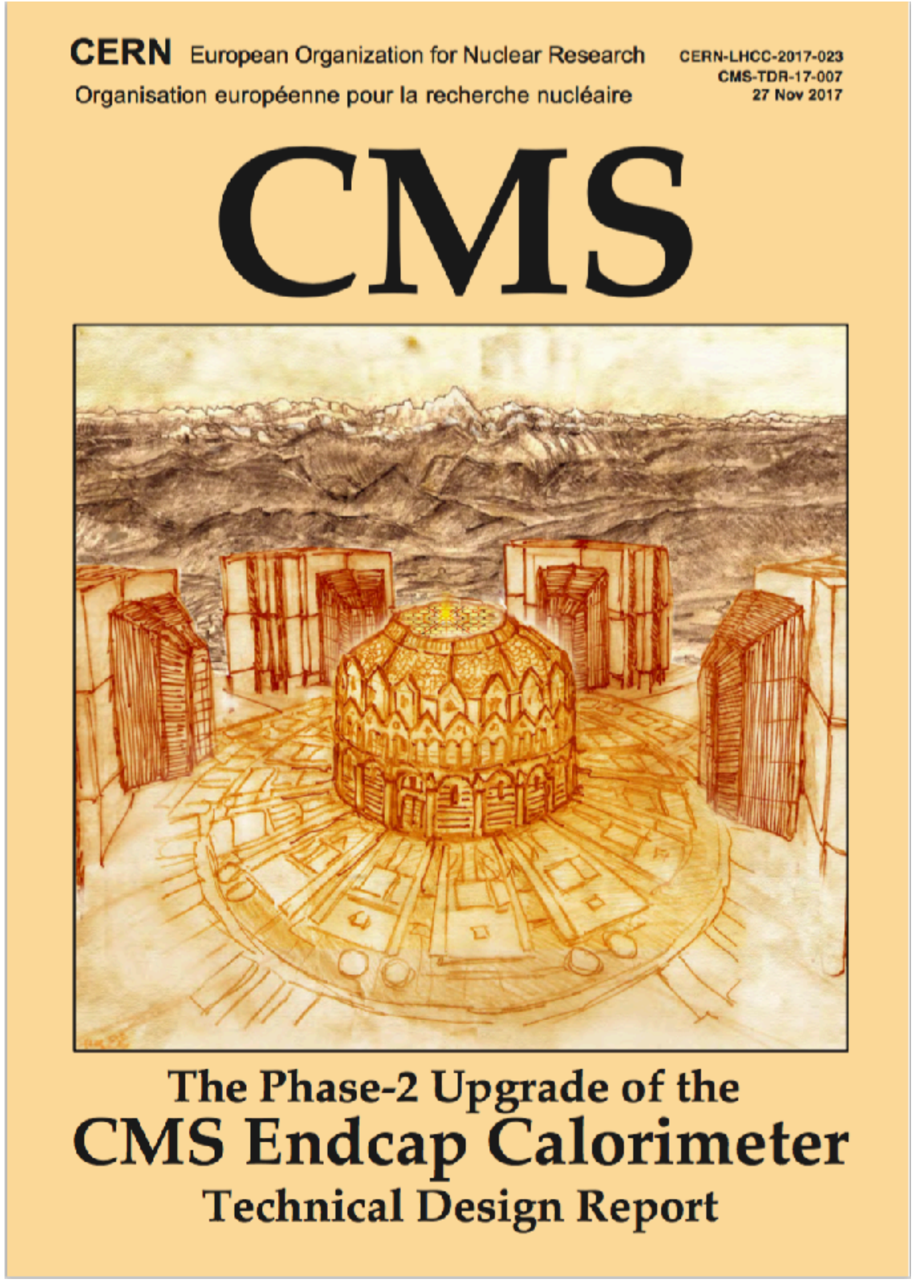
Technical proposal 2015

- Decision plastic scintillator for CE-H: Nov 2016
- Decision SiPM-on-tile Mar 2017

TDR submitted Nov 2017

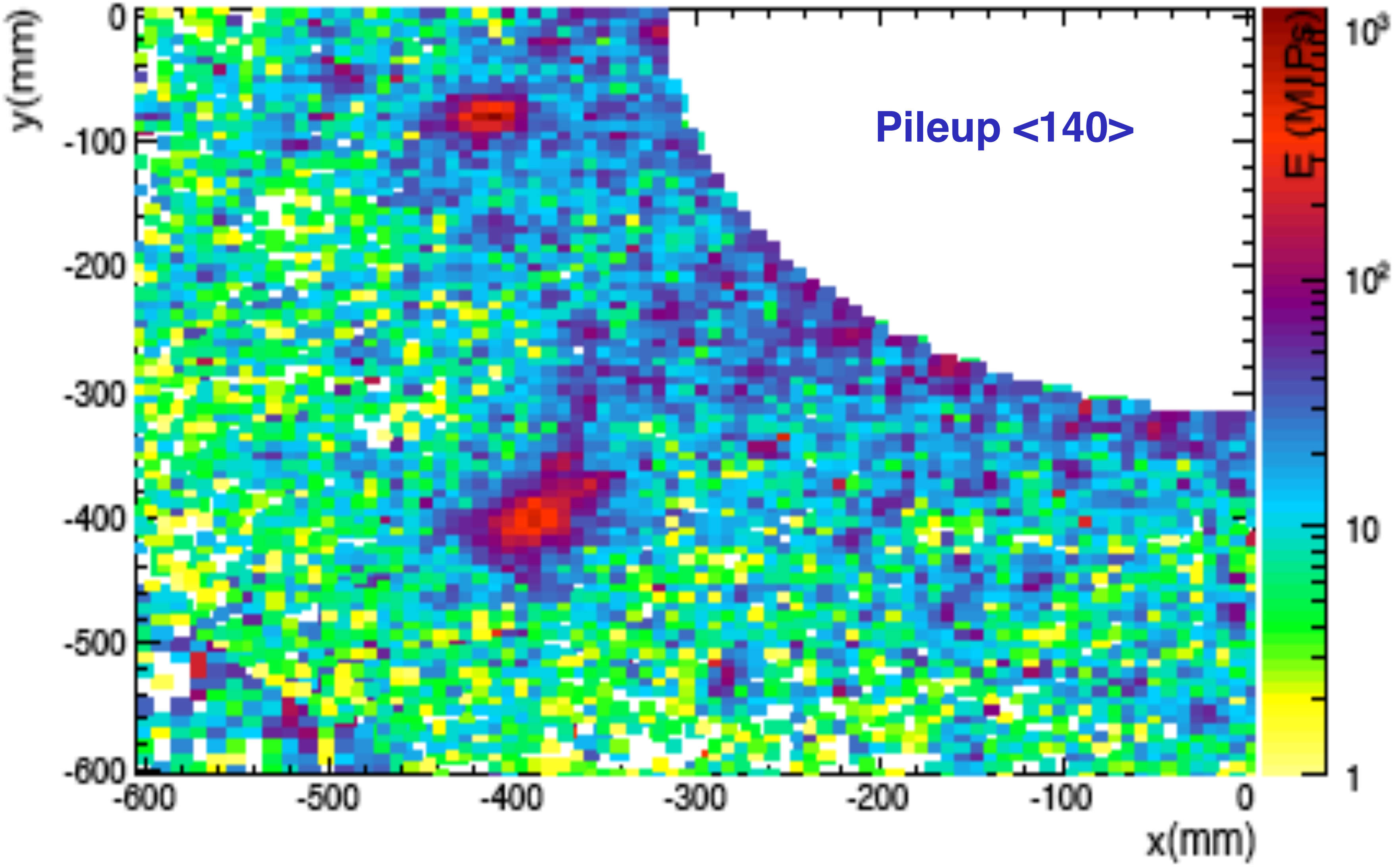
- LHCC review Feb 2018, approved
- EDR end 2020

Largely building on CALICE developments



The Power of High Granularity at the LHC

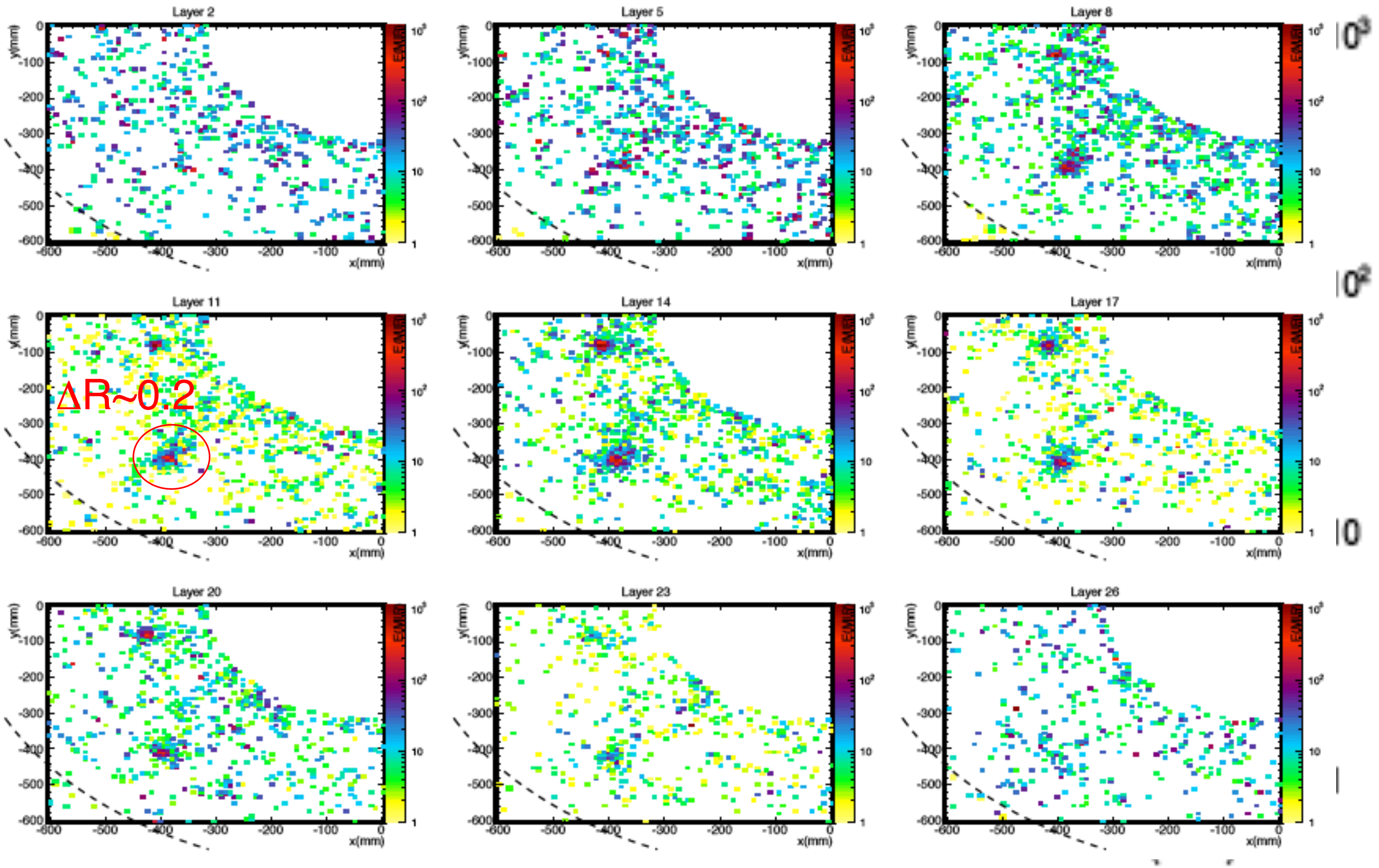
VBF jets + H →γγ: 720 GeV jet, 175 GeV photon



(Next slides) layer by layer development of showers. VBF jet carries 720 GeV (pT = 118 GeV) along with a photon with 175 GeV (pT = 22 GeV). Most of energy in the very narrow VBF jet carried by three particles (two charged pions and one photon) impacting the calorimeter within 1 cm of each other.

The Power of High Granularity at the LHC

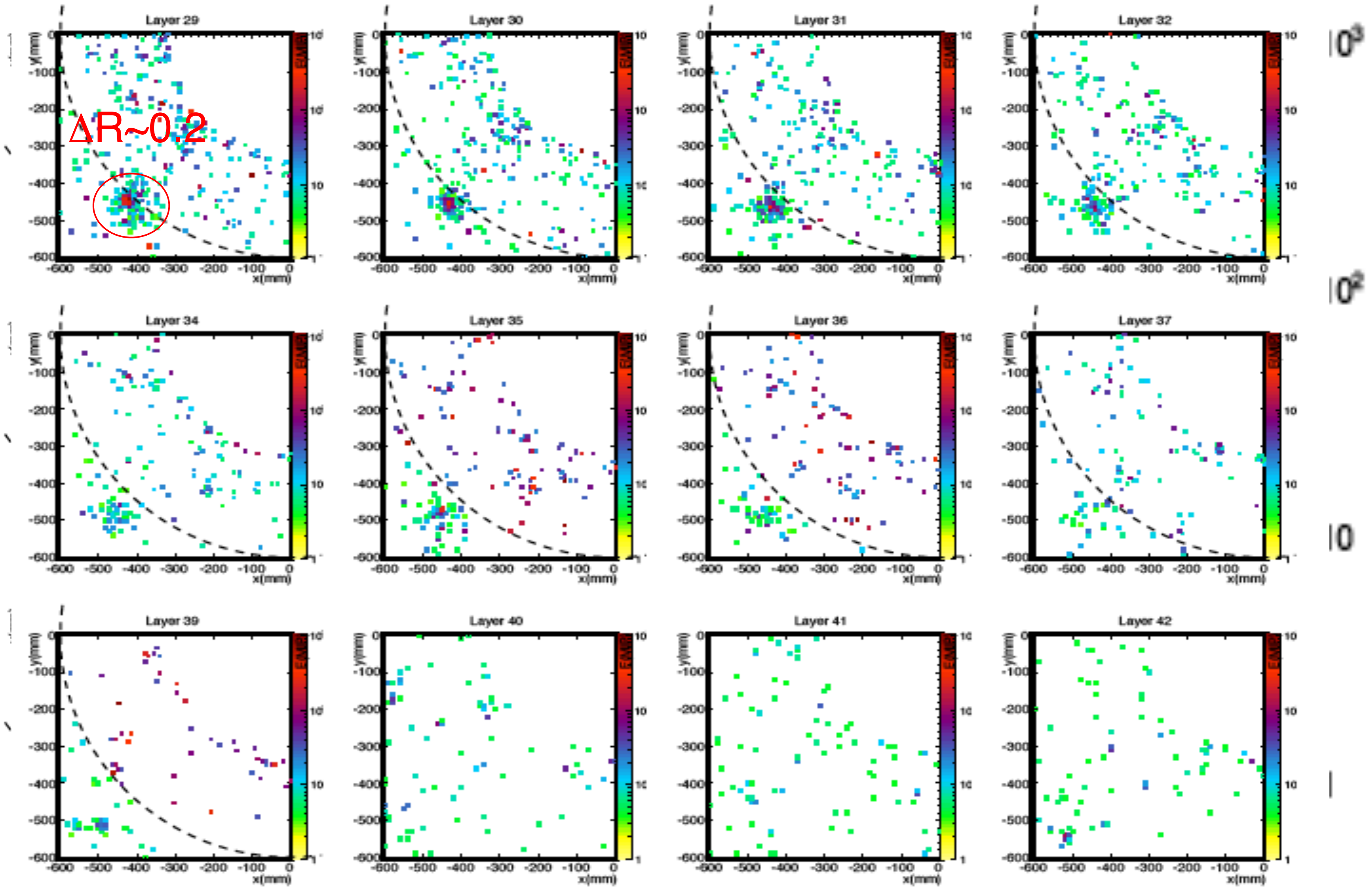
VBF jets + H →γγ: 720 GeV jet, 175 GeV photon



(Next slides) layer by layer development of showers. VBF jet carries 720 GeV (pT = 118 GeV) along with a photon with 175 GeV (pT = 22 GeV). Most of energy in the very narrow VBF jet carried by three particles (two charged pions and one photon) impacting the calorimeter within 1 cm of each other.

The Power of High Granularity at the LHC

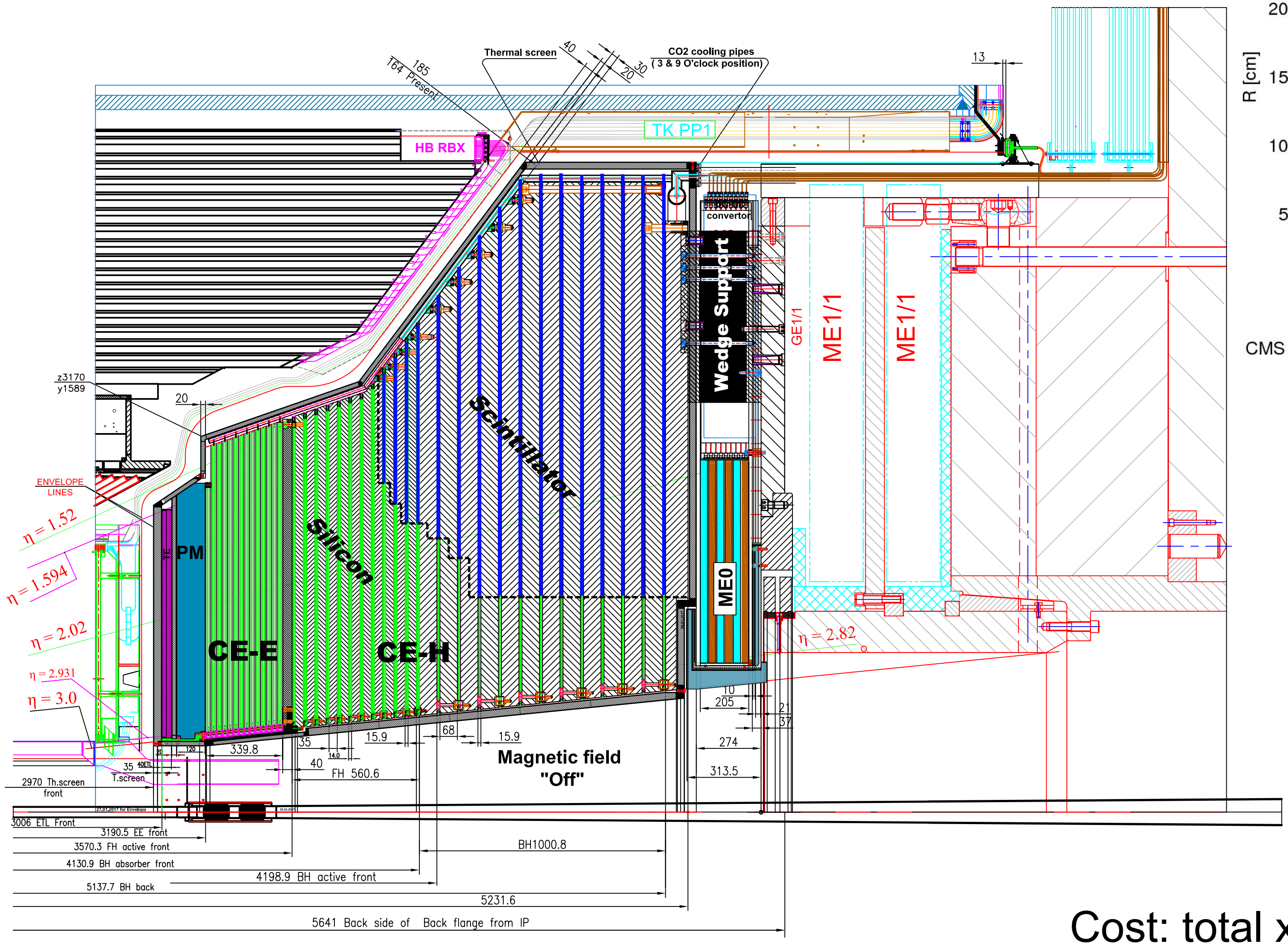
VBF jets + H →γγ: 720 GeV jet, 175 GeV photon

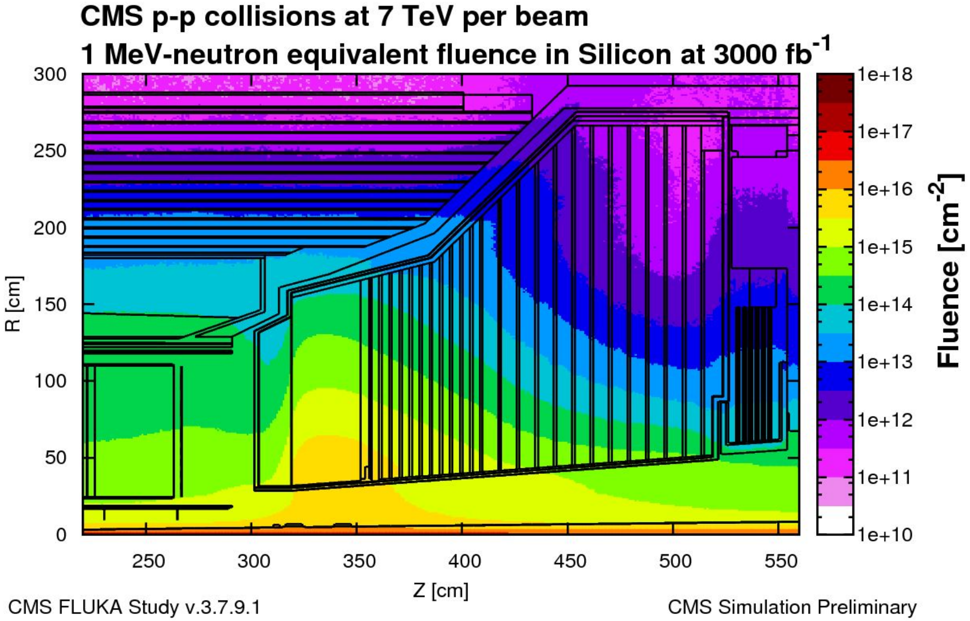


(Next slides) layer by layer development of showers. VBF jet carries 720 GeV (pT = 118 GeV) along with a photon with 175 GeV (pT = 22 GeV). Most of energy in the very narrow VBF jet carried by three particles (two charged pions and one photon) impacting the calorimeter within 1 cm of each other.

HGCAL Layout and Key Numbers

Driven by radiation levels



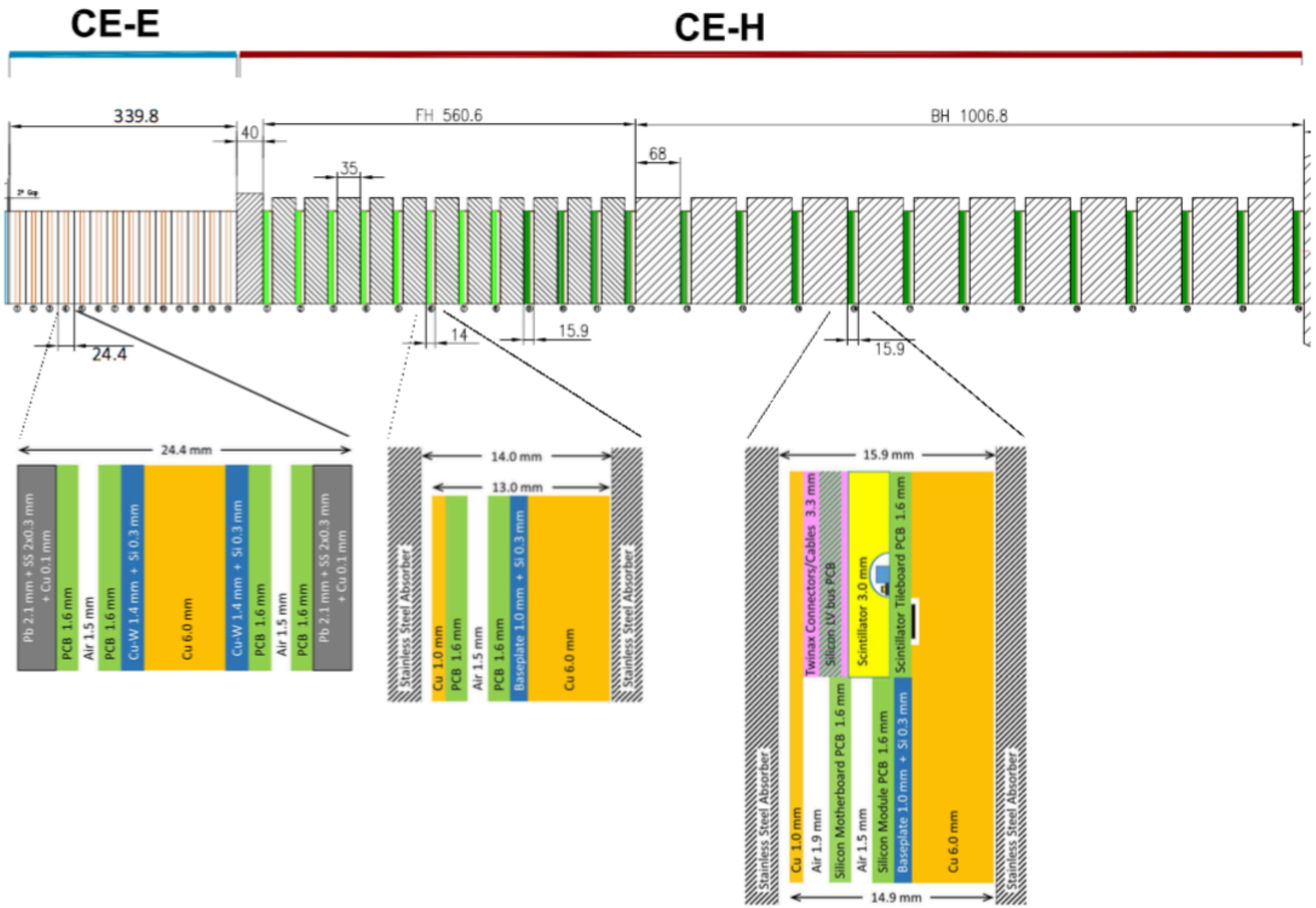


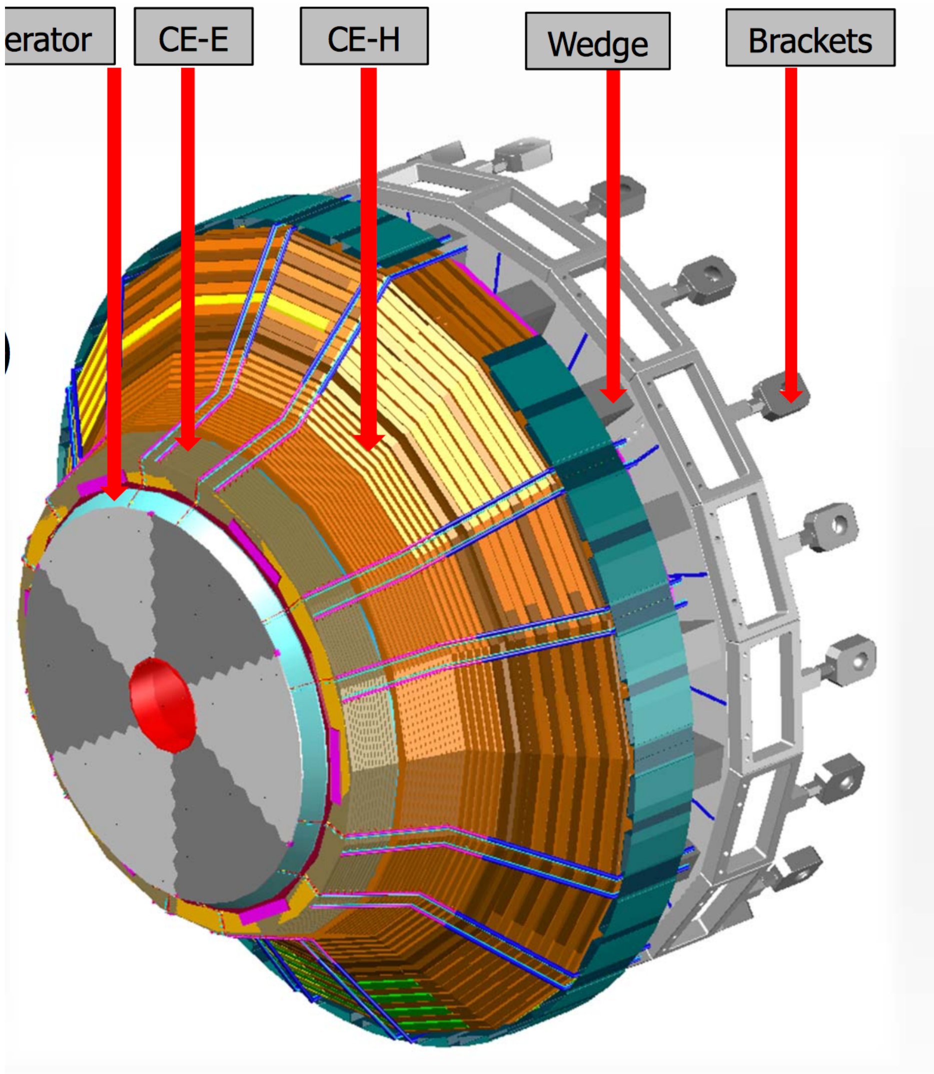
	CE-E	CE-H	
	Si	Si	Scintillator
Area (m^2)	368	215	487
Channels (k)	3916	1939	389
Si modules (Tileboards)	16 008	8868	(3960)
Partial modules	1008	1452	–
Weight (t)	23	205	
Si-only planes	28	8	
Mixed (Si+Scint) planes		16	

Cost: total xM, Scintillator-SiPM Tile Modules yMCHF

Longitudinal Structure

28 silicon, 8 silicon and 16 mixed silicon scintillator layers.

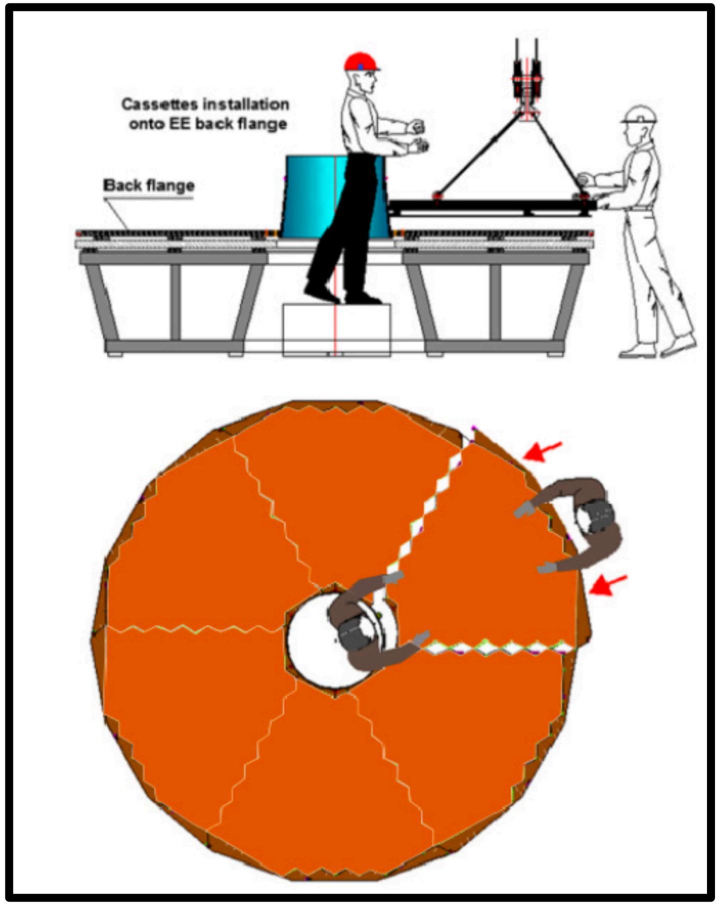




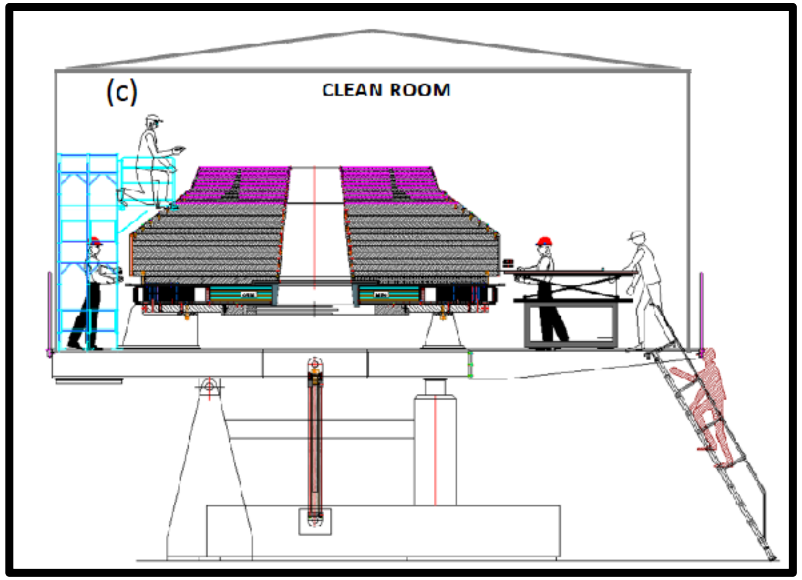
Heavy Engineering

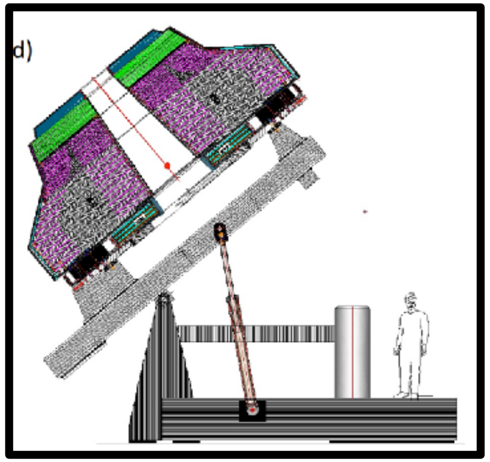
Assembly concepts.

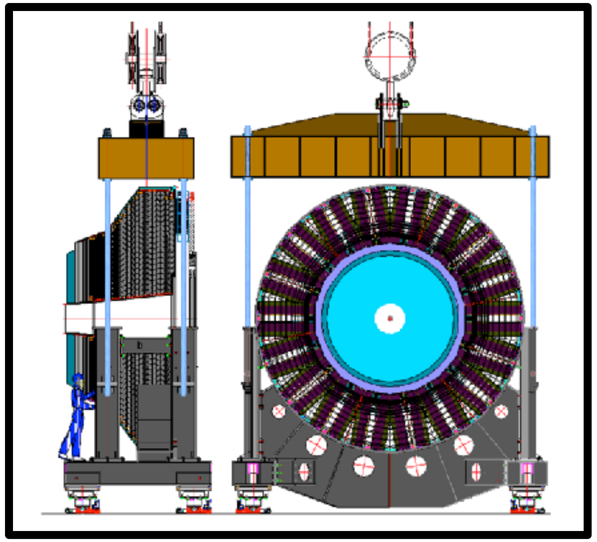
CE-E

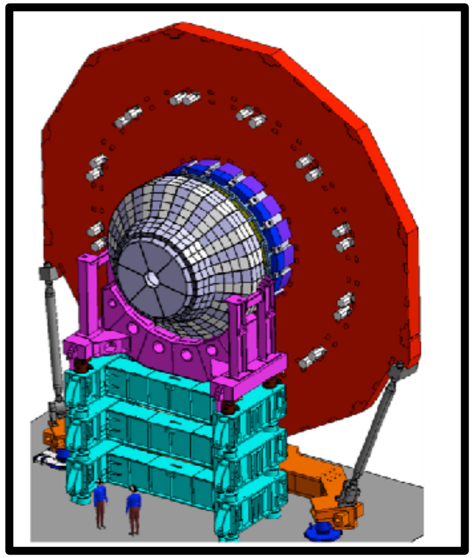


CE-H







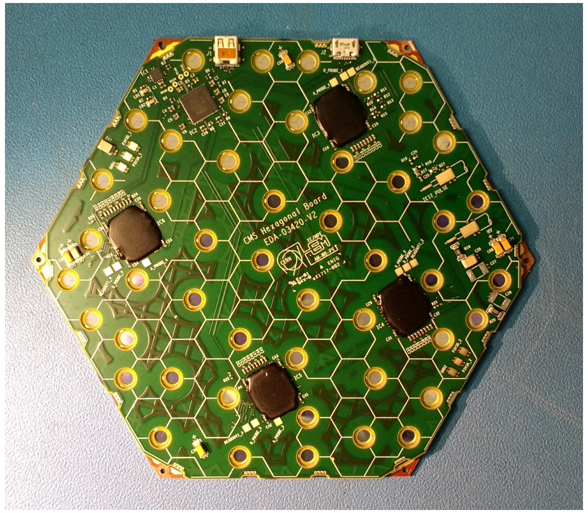


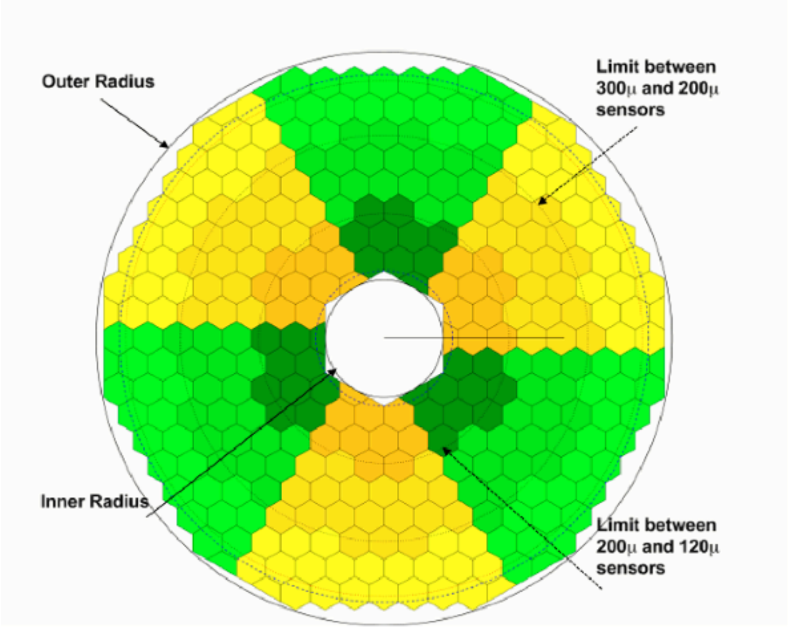
- CE-E: stacking, CE-H: drawers

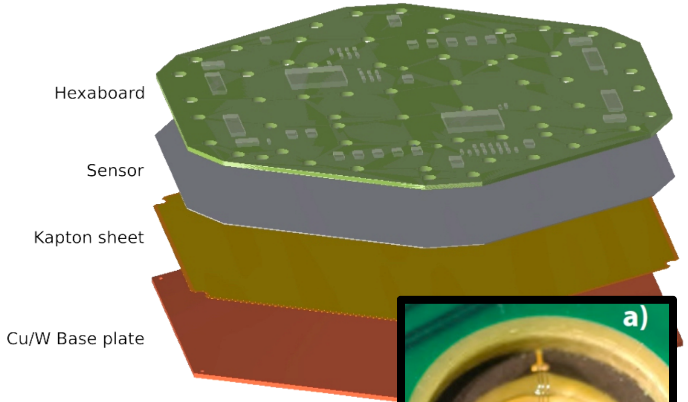
HGCAL Silicon Part

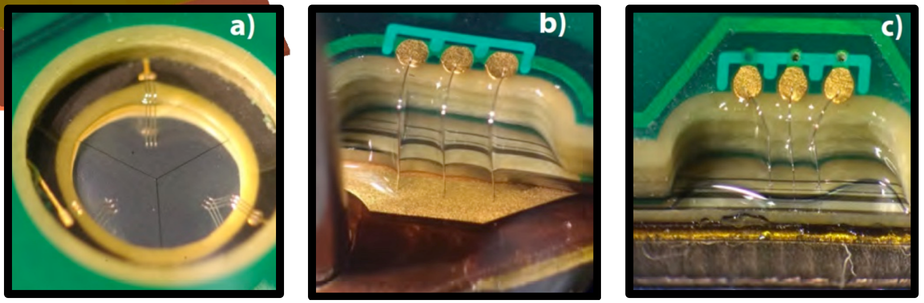
CE and CH

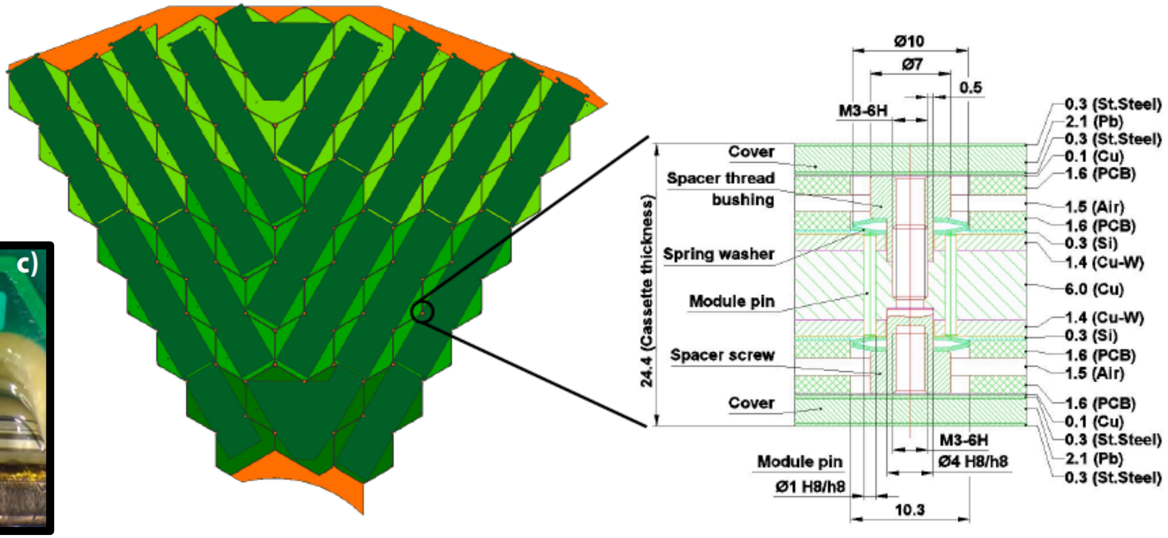
- 8’ wafers (prototypes 6’)
- 3 thicknesses: 120µm, 200µm, 300µm
- 2 cell sizes: 1.18 cm2 and 0.52 cm2
- limited by power and cooling considerations
- 110 kW per end cap
- Motherboards (concentrators integrated)





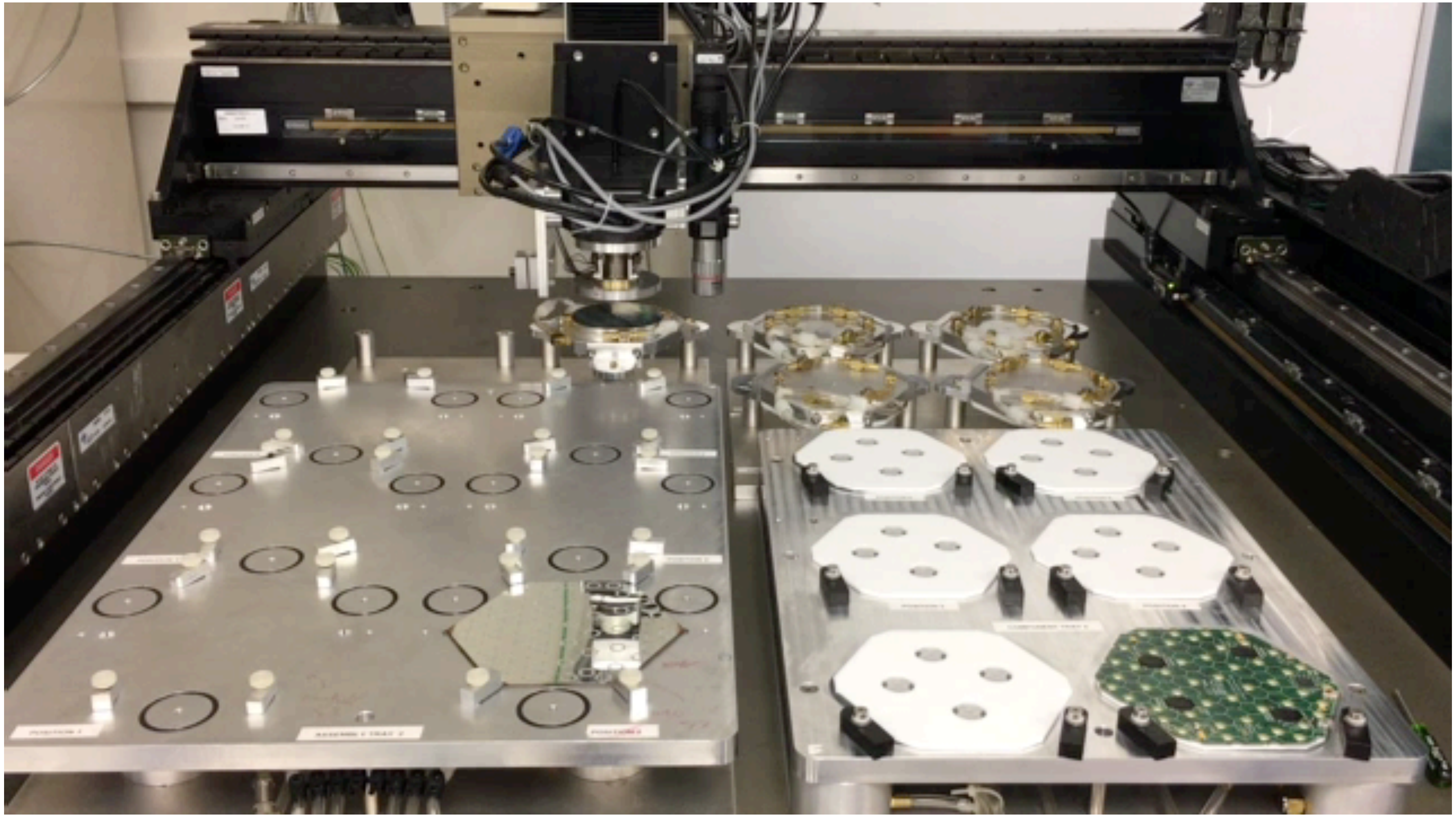






Automated Assembly

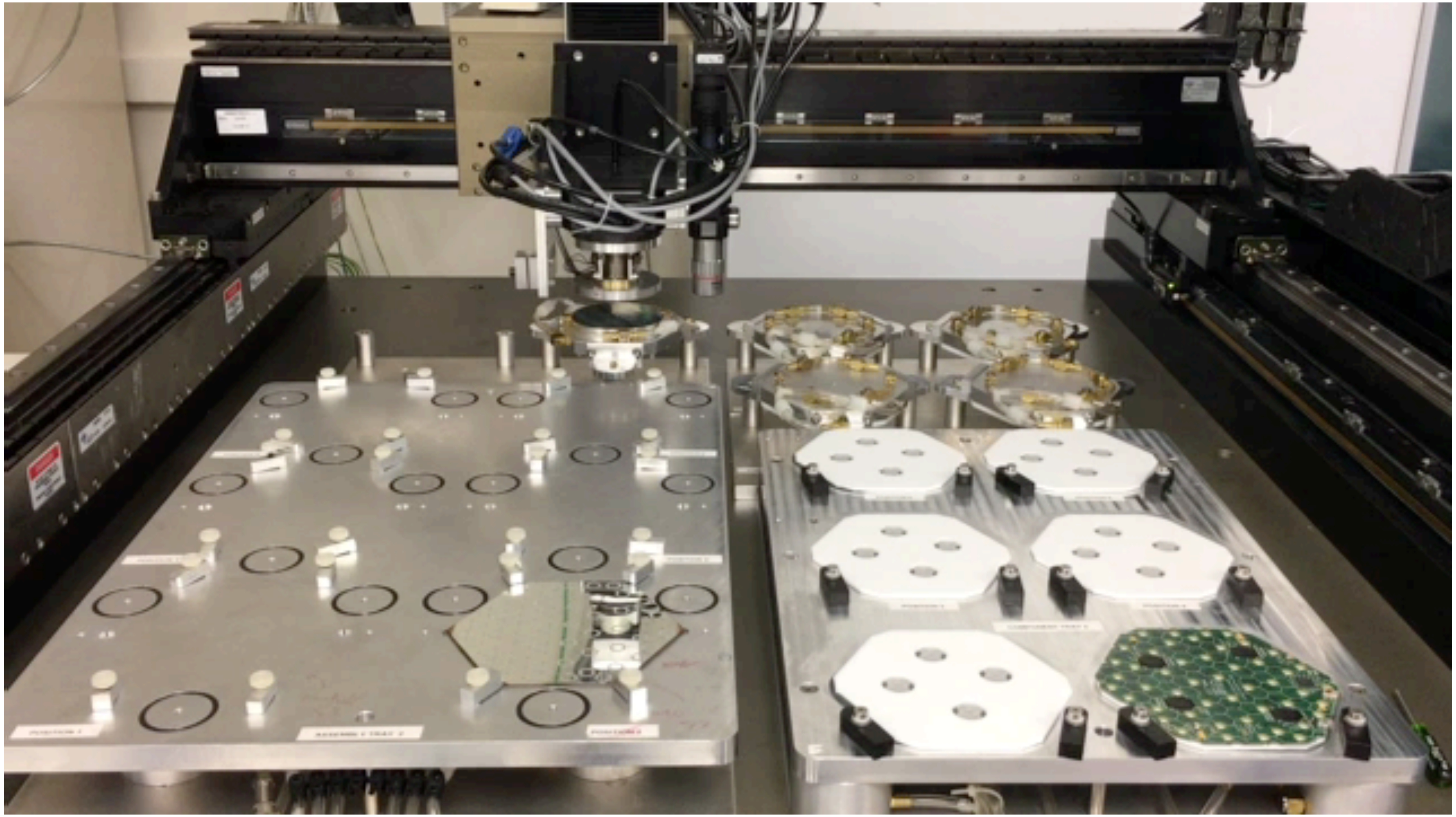
UC Santa Barbara



https://www.dropbox.com/s/sjo5zqitbos2o64/UCSB_IMG_4122.MOV?dl=0

Automated Assembly

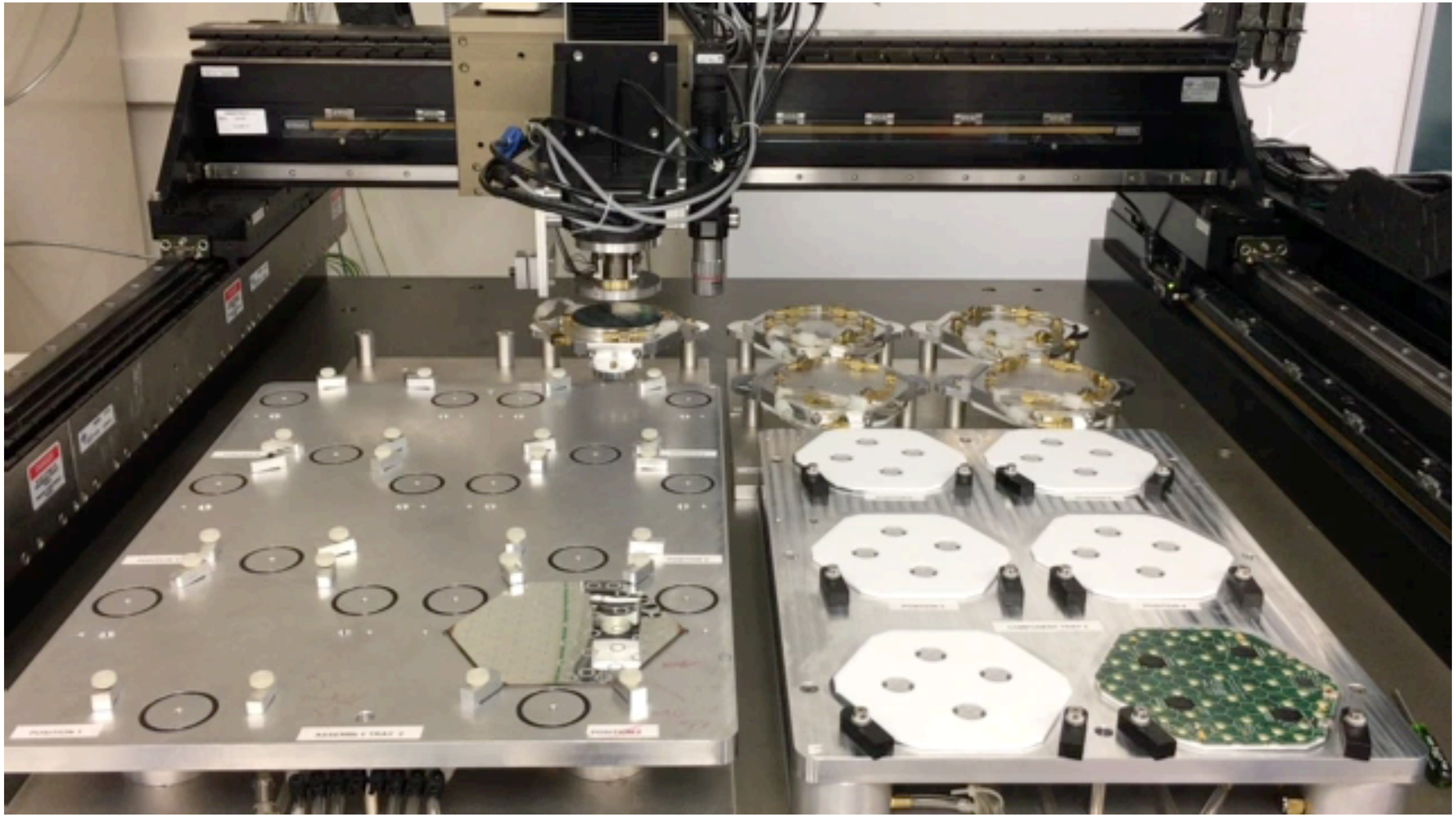
UC Santa Barbara



https://www.dropbox.com/s/sjo5zqitbos2o64/UCSB_IMG_4122.MOV?dl=0

Automated Assembly

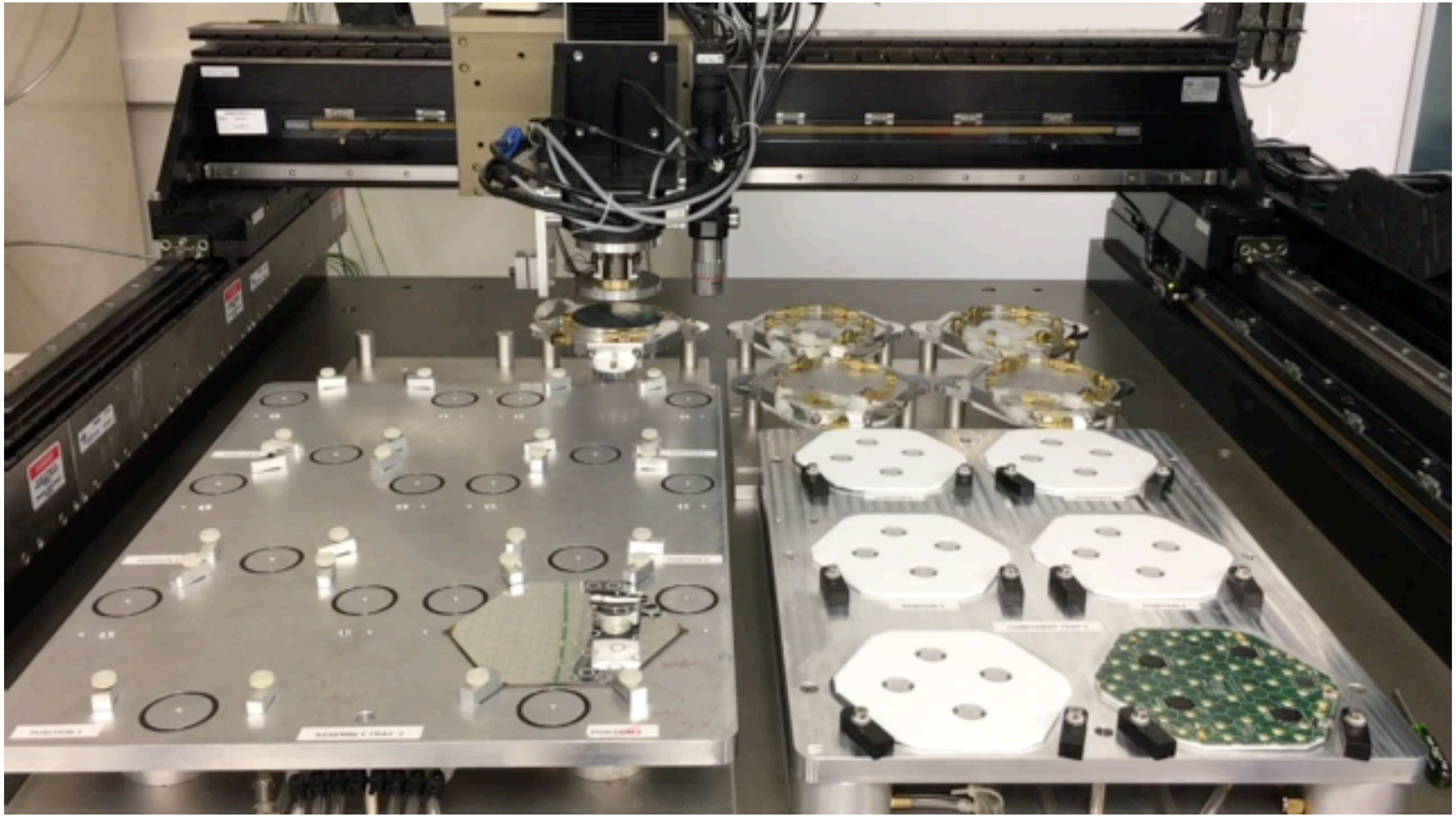
UC Santa Barbara



https://www.dropbox.com/s/sjo5zqitbos2o64/UCSB_IMG_4122.MOV?dl=0

Automated Assembly

UC Santa Barbara

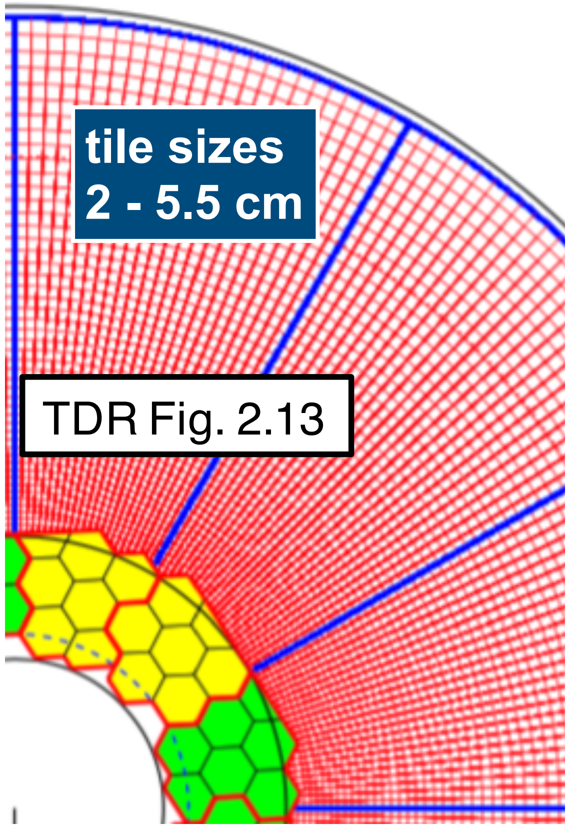


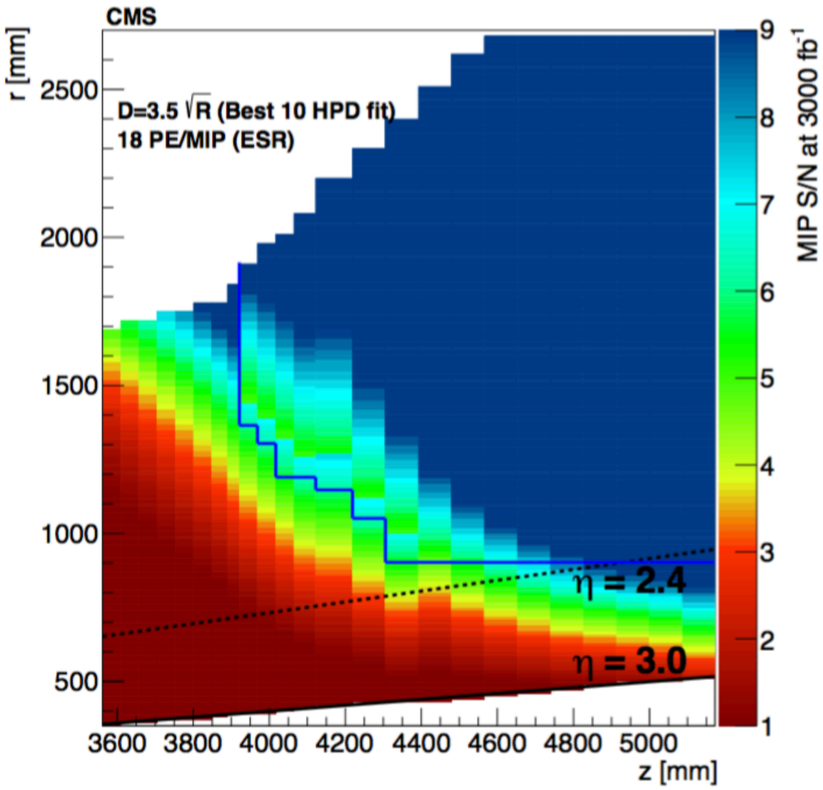
https://www.dropbox.com/s/sjo5zqitbos2o64/UCSB_IMG_4122.MOV?dl=0

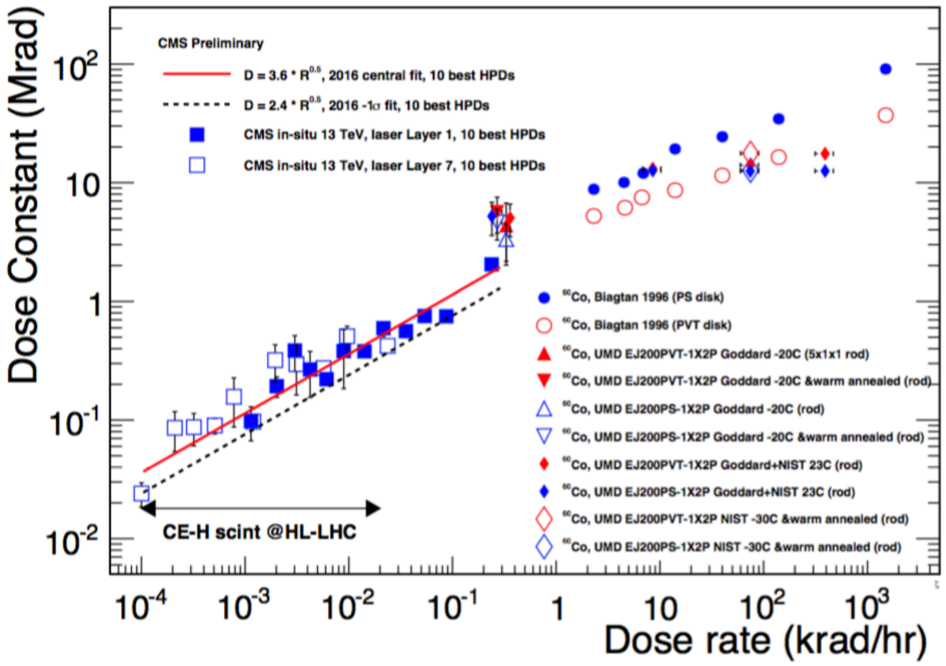
SiPM-on-Tile segmentation

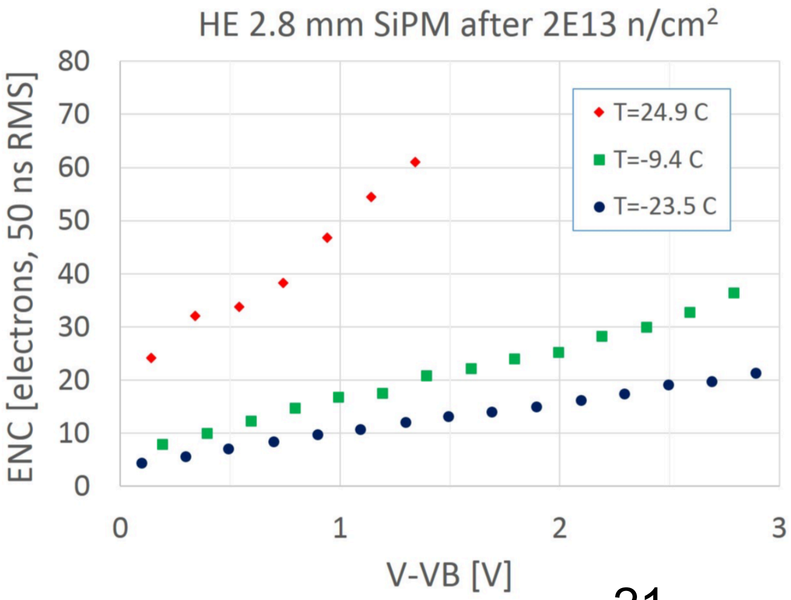
Match radiation levels and trigger geometry

- Higher **dose** (<200 kRad) - smaller tile area - more signal
- Higher **fluency** (<5e14 n/cm²) - larger SiPM area - more S/N



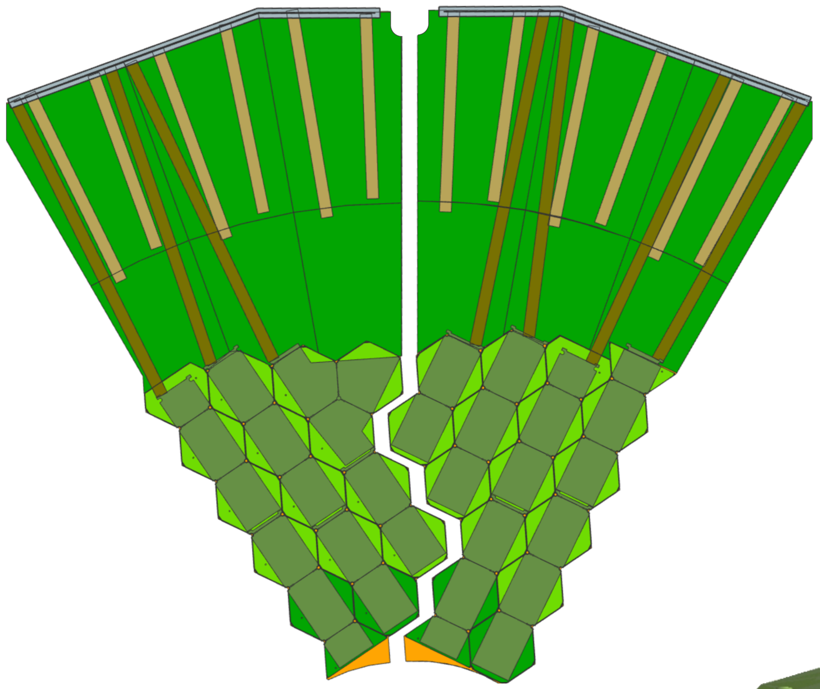


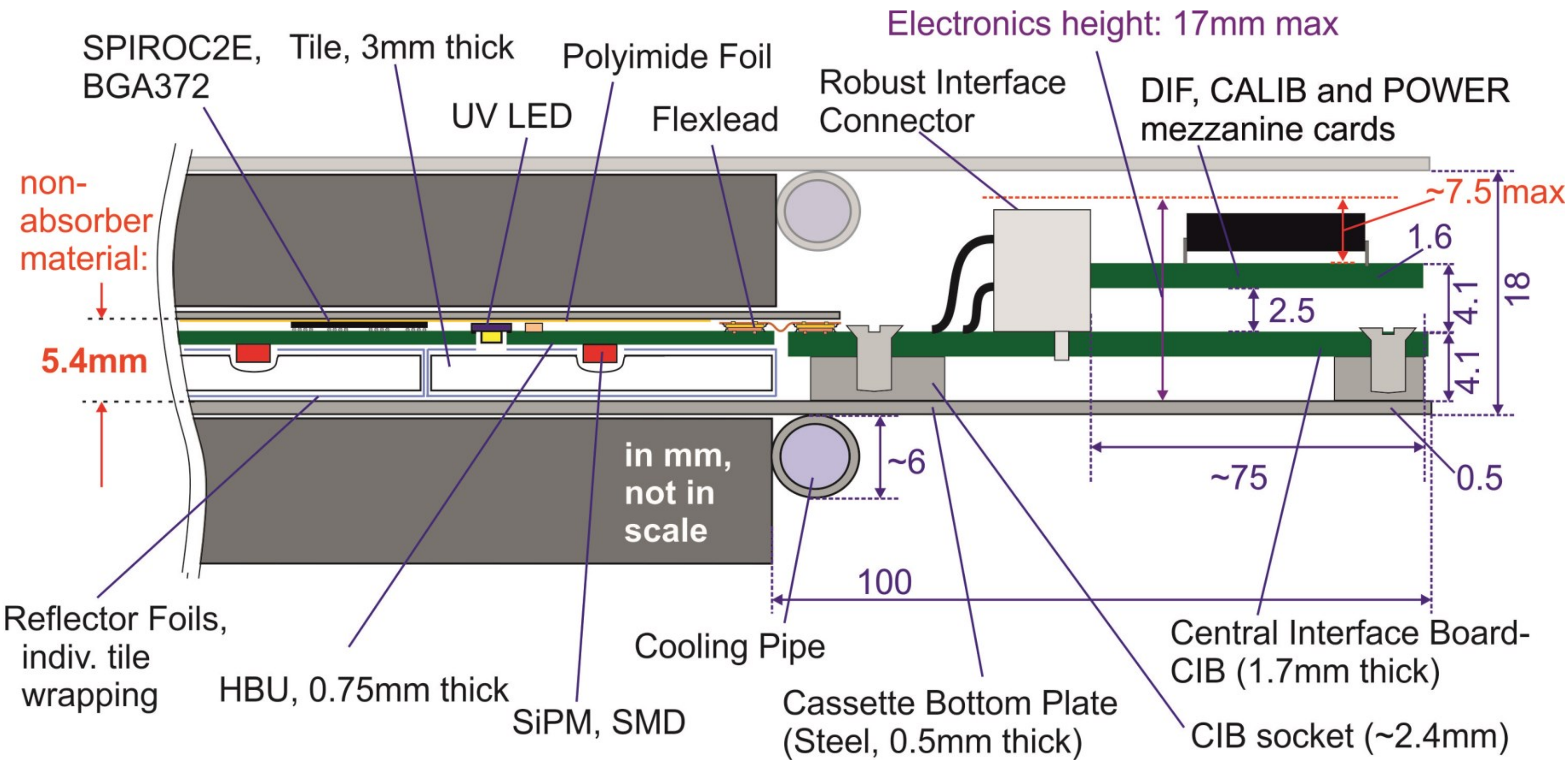


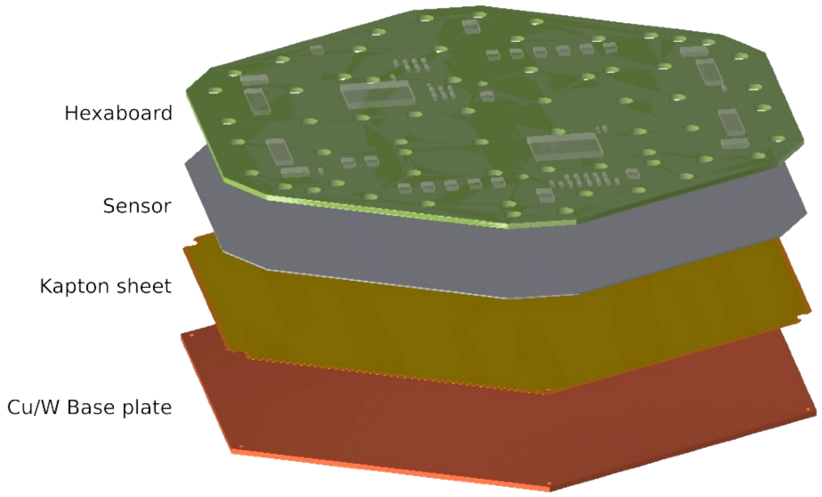


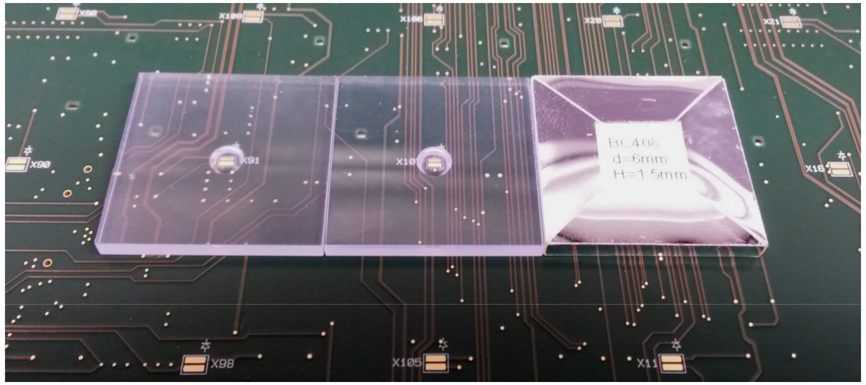
HGCAL active layers

Mixed cassettes





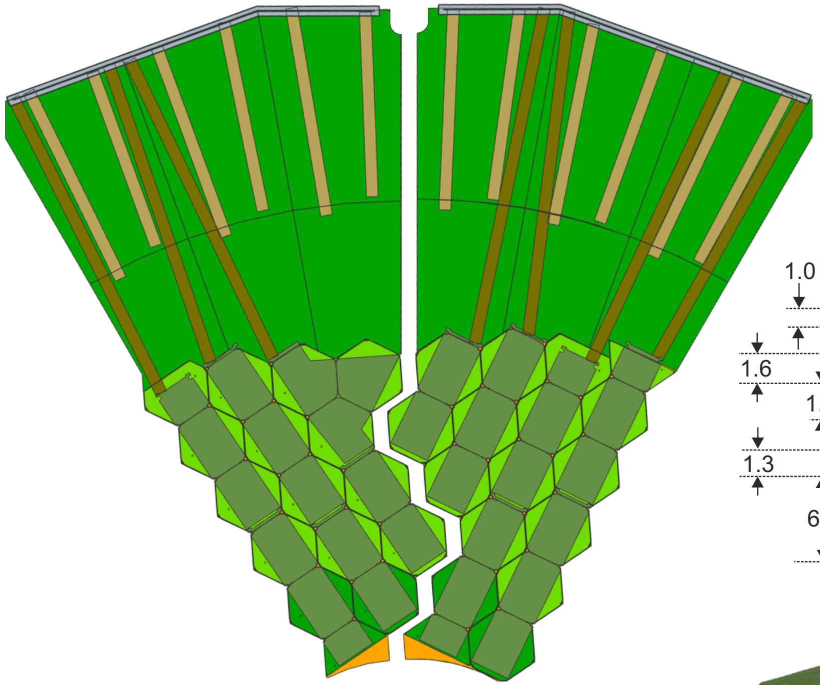


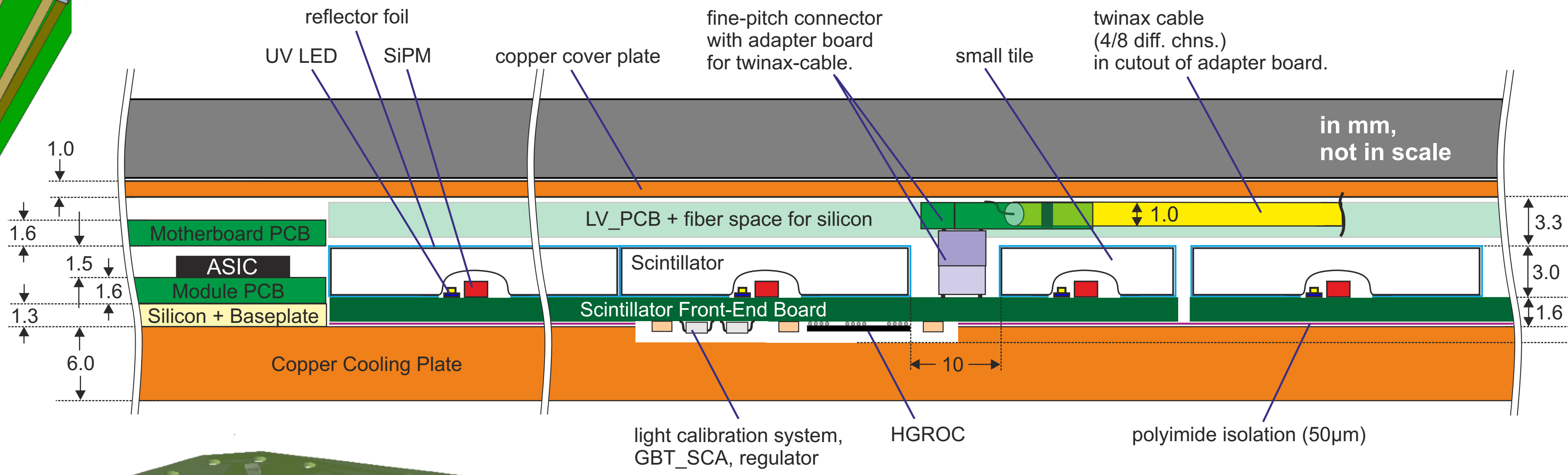


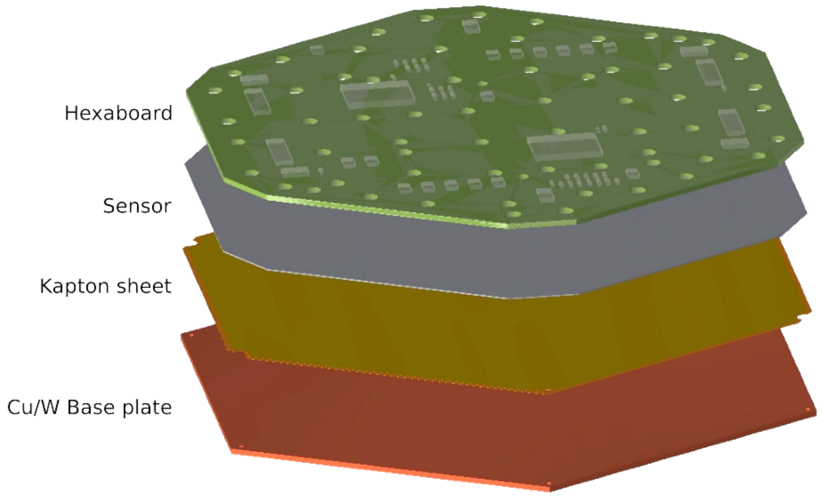
tile sizes 2 cm - 5.5 cm

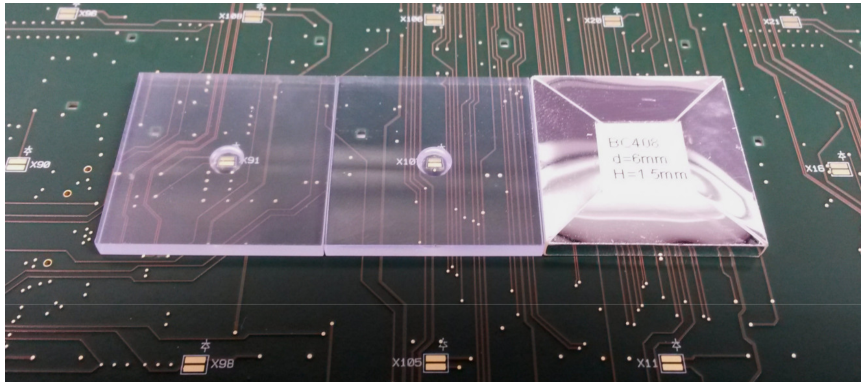
HGCAL active layers

Mixed cassettes





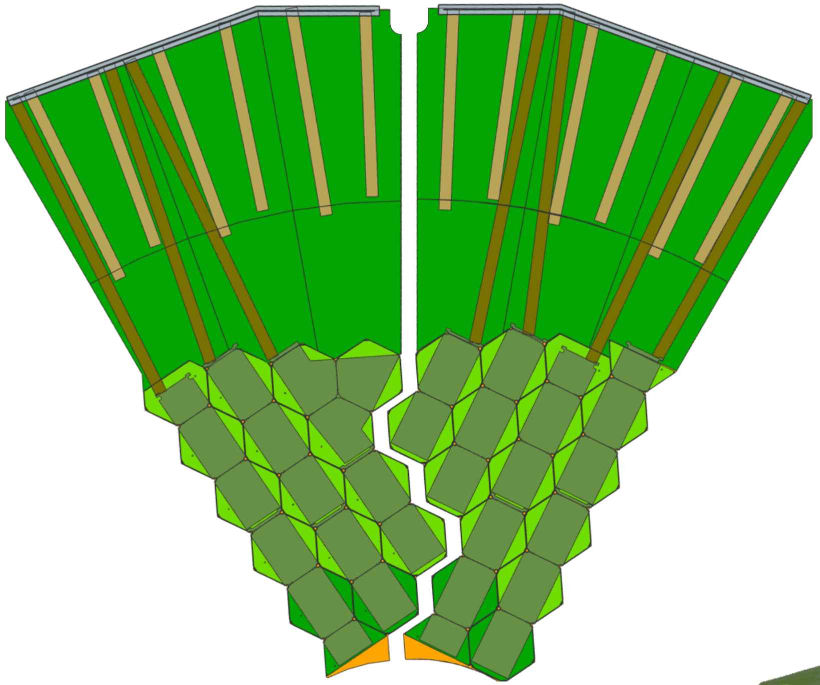


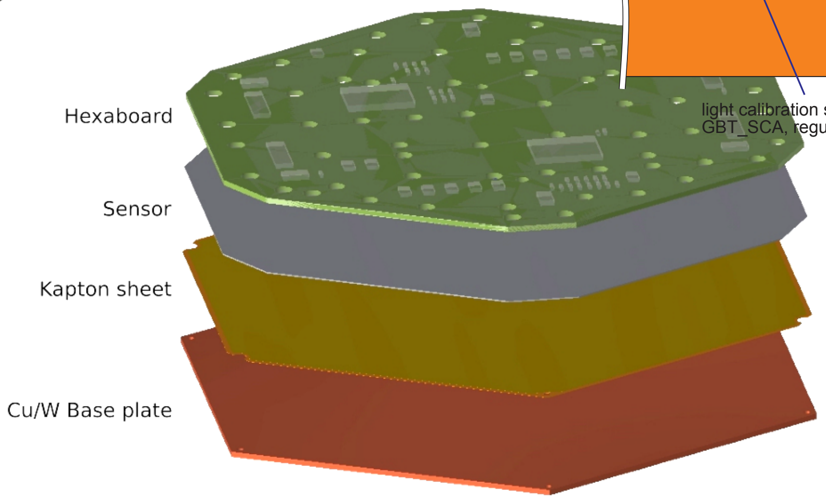


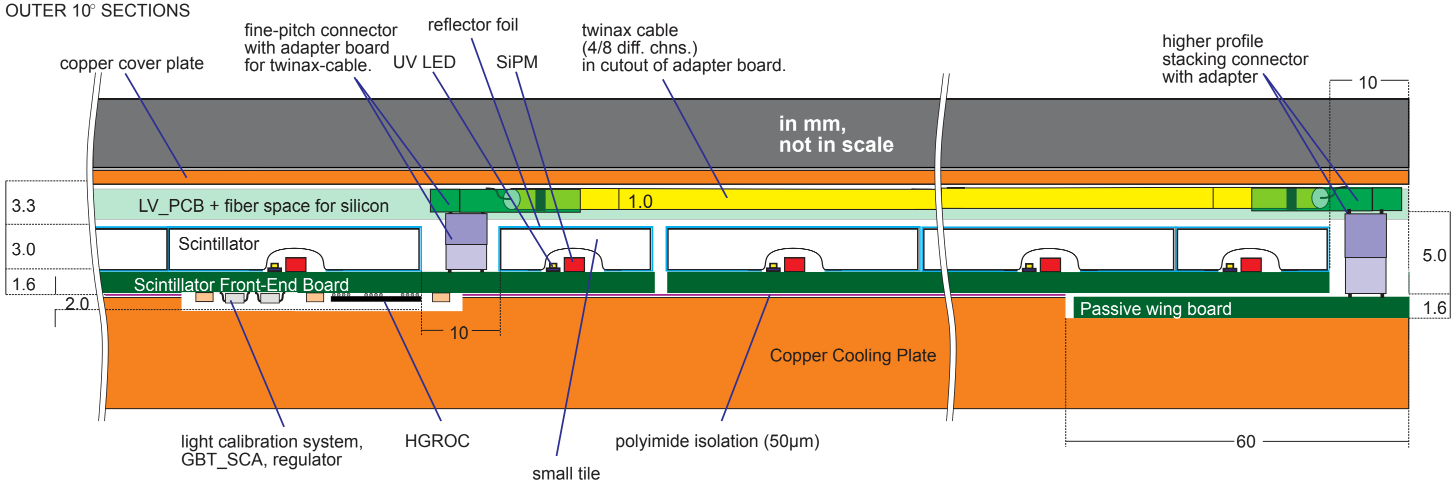
tile sizes 2 cm - 5.5 cm

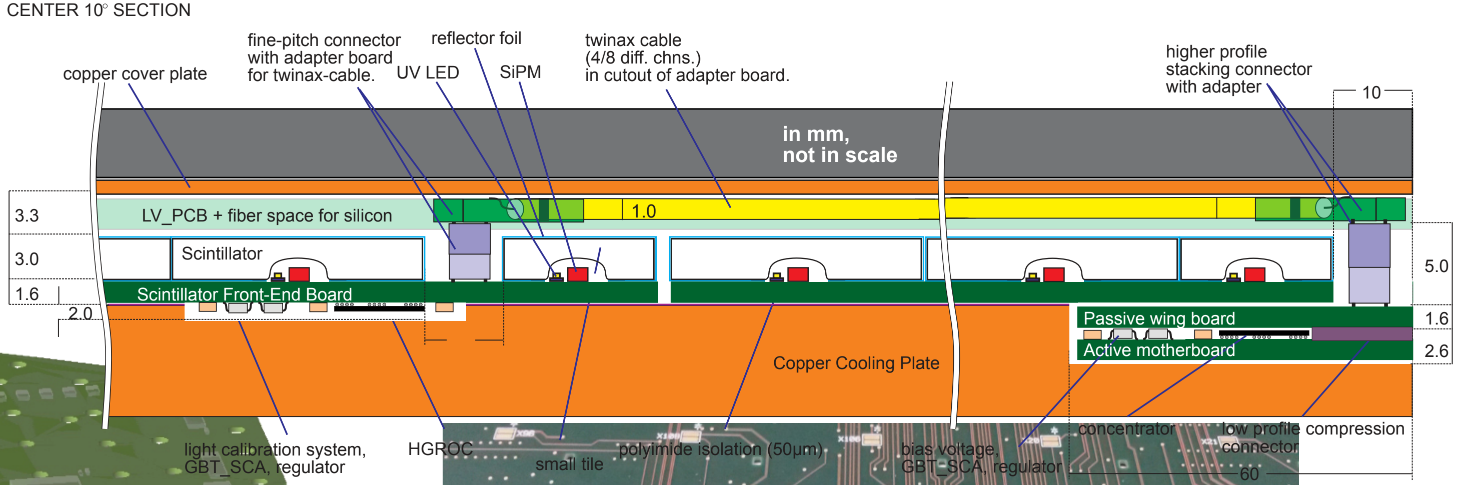
HGCAL active layers

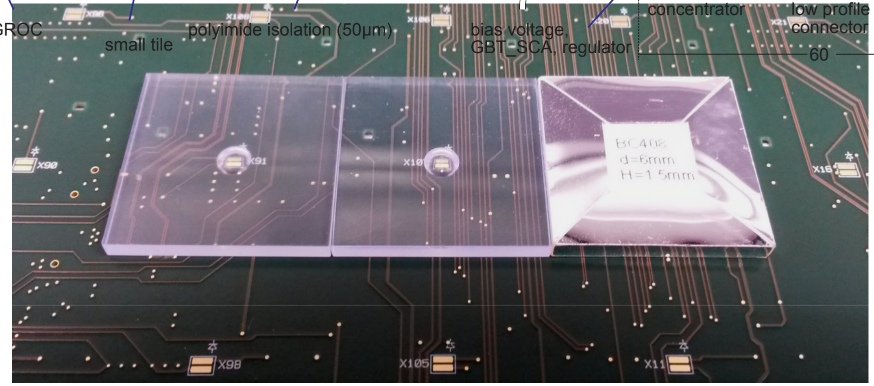
Mixed cassettes











tile sizes 2 cm - 5.5 cm

HGCAL tile-modules

The DESY part.

Tile-boards = HBUs

- only 6 different types (assuming we can cut them)

Tile-modules = tile-boards + scintillator

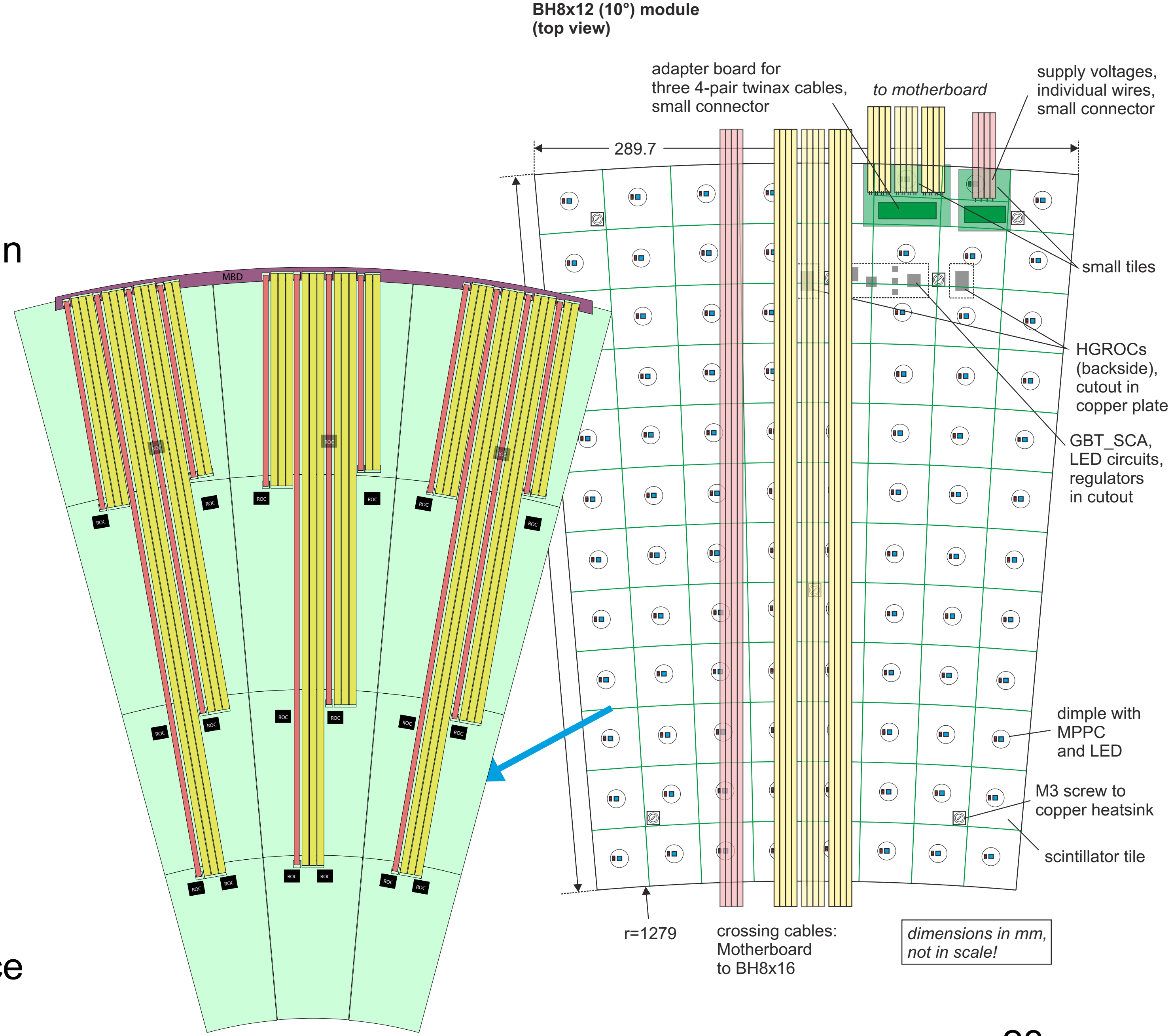
- individual tiles for larger sizes
- mega-tiles for smaller sizes

New technical challenges

- high-speed data transfer
  - 2x 1GB/s / ASIC
- Cooling of SiPMs through PCB
- Thermo-mechanical issues +- 40 ^{o}C
- Rad-hard components

Basic R&D:

- scintillator and SiPM radiation tolerance



HGCAL tile-modules

The DESY part.

Tile-boards = HBUs

- only 6 different types (assuming we can cut them)

Tile-modules = tile-boards + scintillator

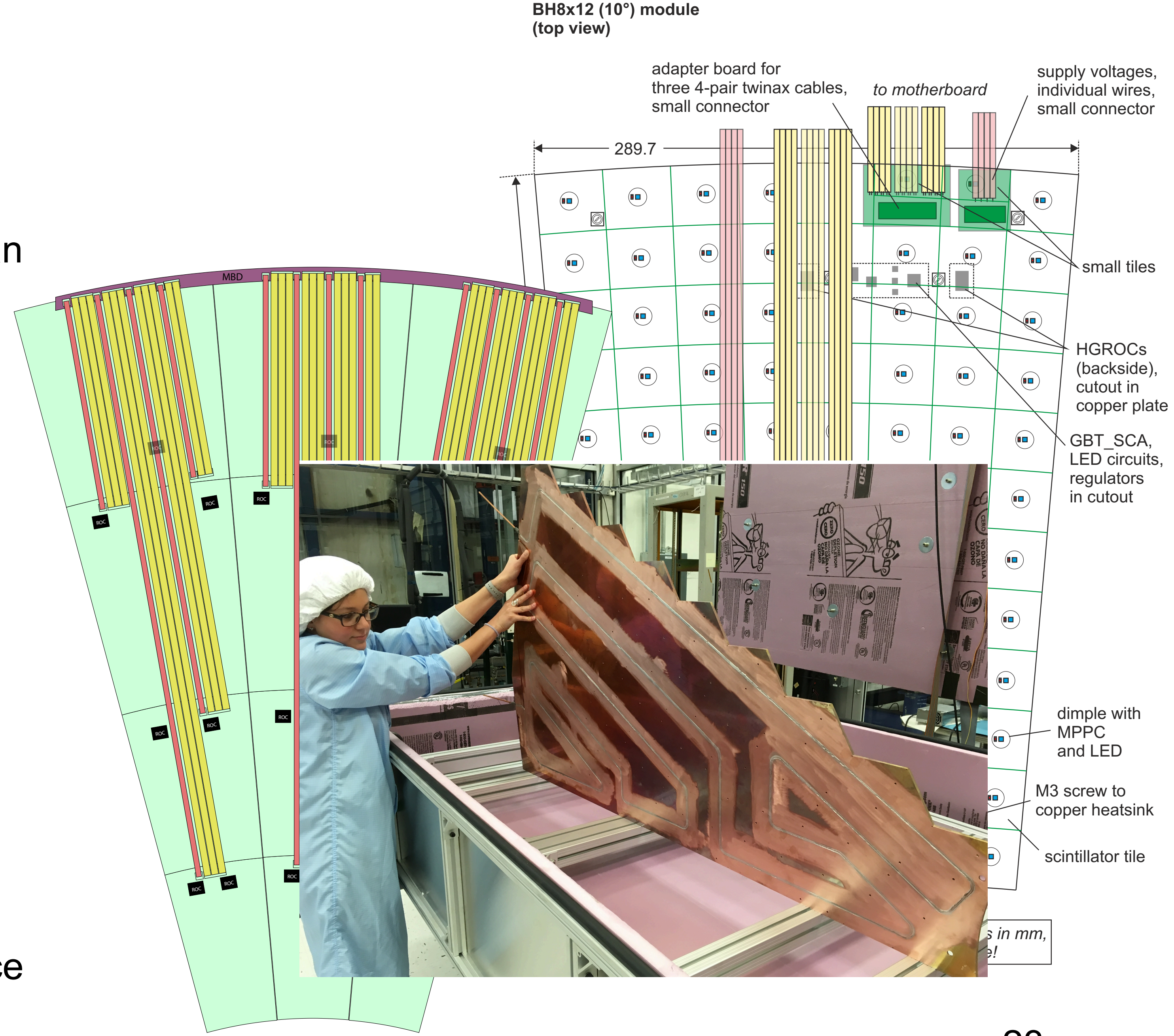
- individual tiles for larger sizes
- mega-tiles for smaller sizes

New technical challenges

- high-speed data transfer
  - 2x 1GB/s / ASIC
- Cooling of SiPMs through PCB
- Thermo-mechanical issues +- 40 ^{o}C
- Rad-hard components

Basic R&D:

- scintillator and SiPM radiation tolerance

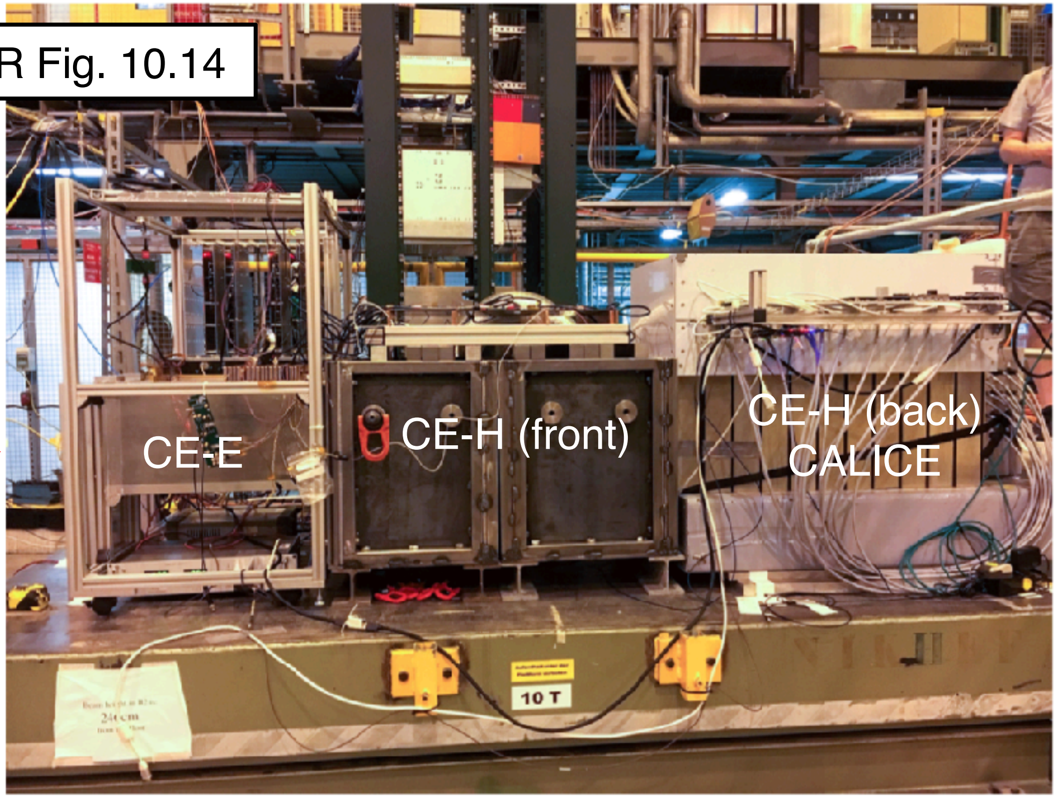


CALICE CMS Common Test Beam

AHCAL prototype as Backing Hadron calorimeter

TDR Fig. 10.14

e, π, μ beam



- Common DAQ: EUDAQ

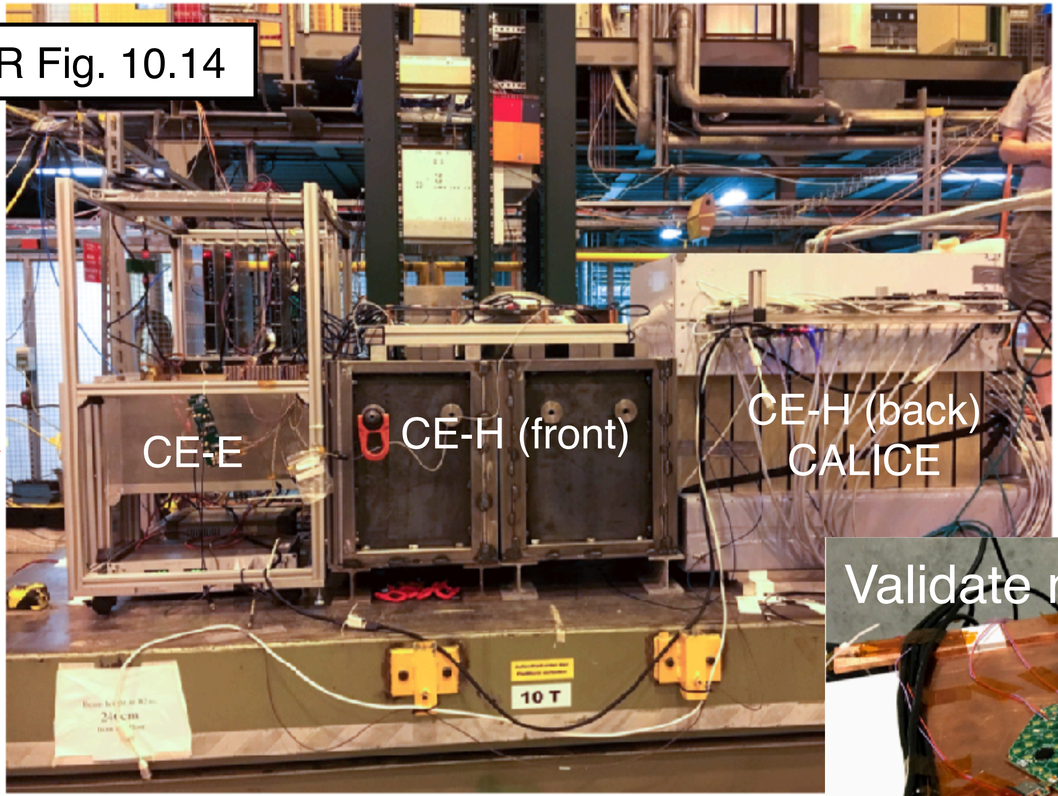
AIDA2020

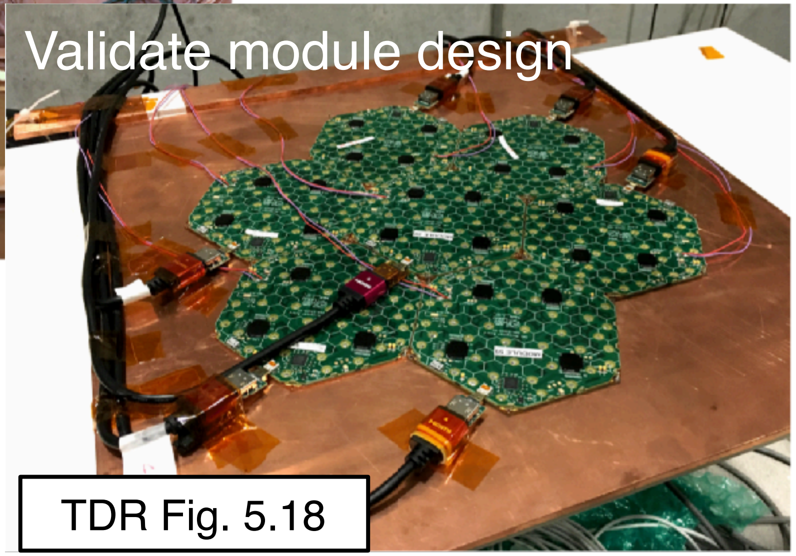
CALICE CMS Common Test Beam

AHCAL prototype as Backing Hadron calorimeter

TDR Fig. 10.14

e, π, μ
beam





TDR Fig. 5.18

- Common DAQ: EUDAQ

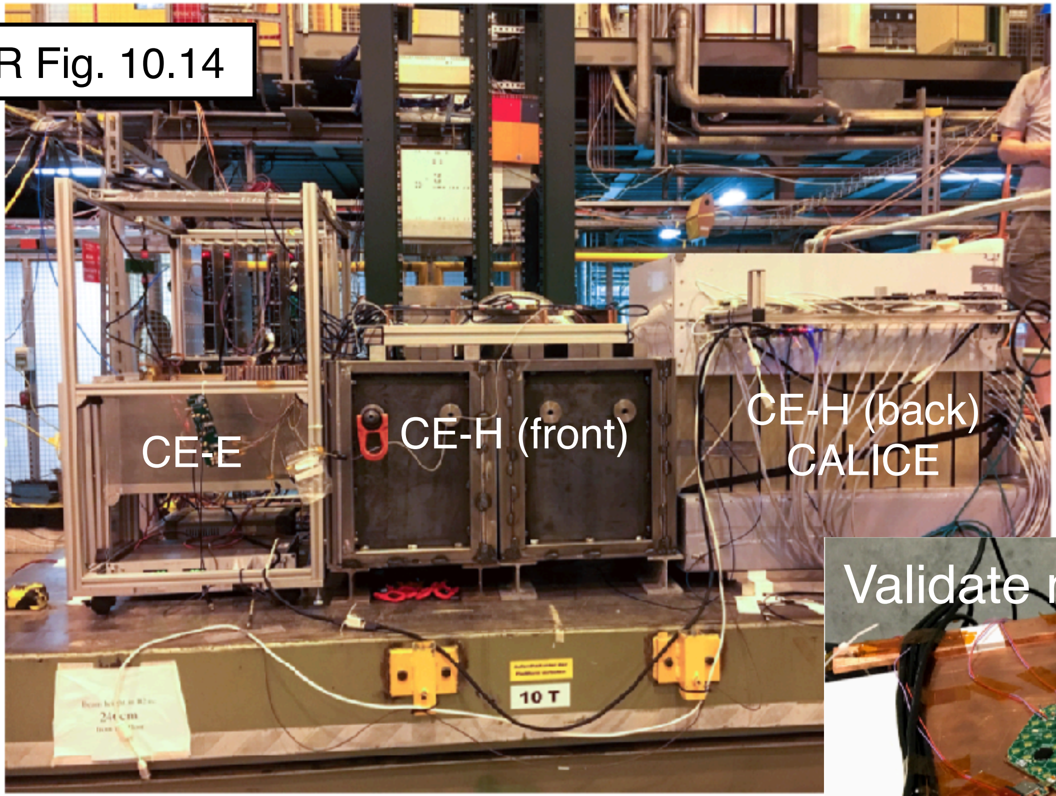
AIDA2020

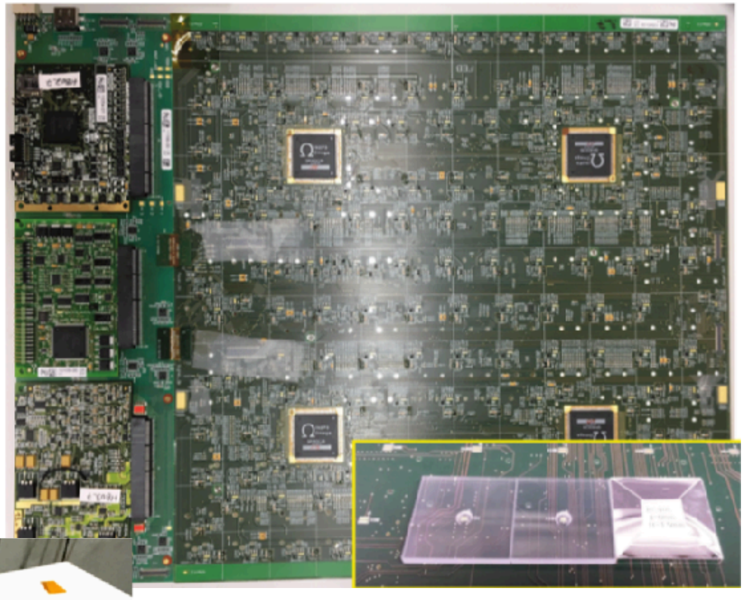
CALICE CMS Common Test Beam

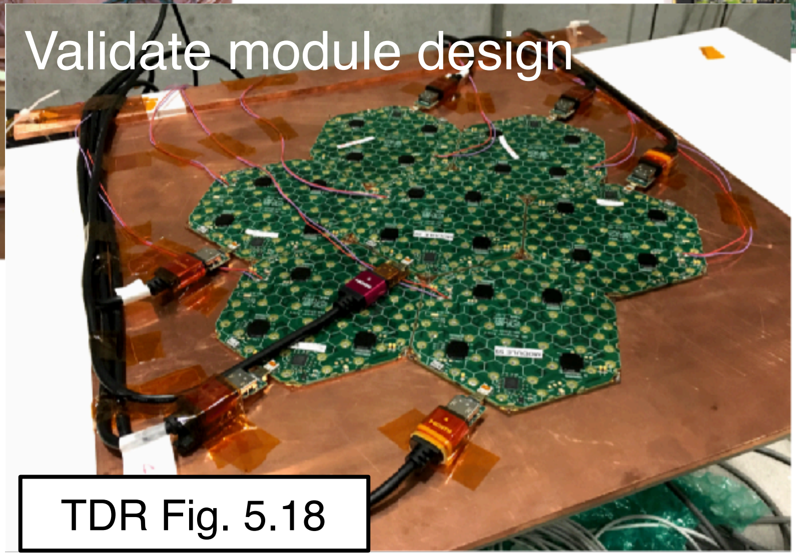
AHCAL prototype as Backing Hadron calorimeter

TDR Fig. 10.14

e, π, μ
beam







TDR Fig. 5.18

- Common DAQ: EUDAQ

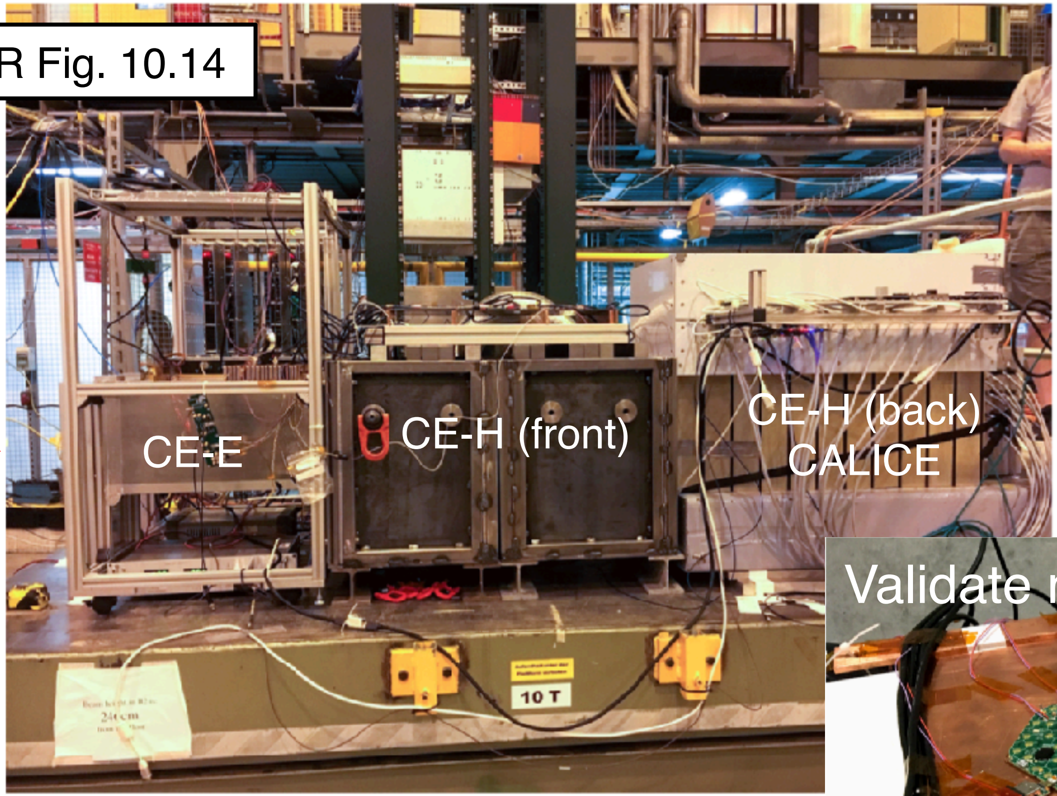
AIDA 2020

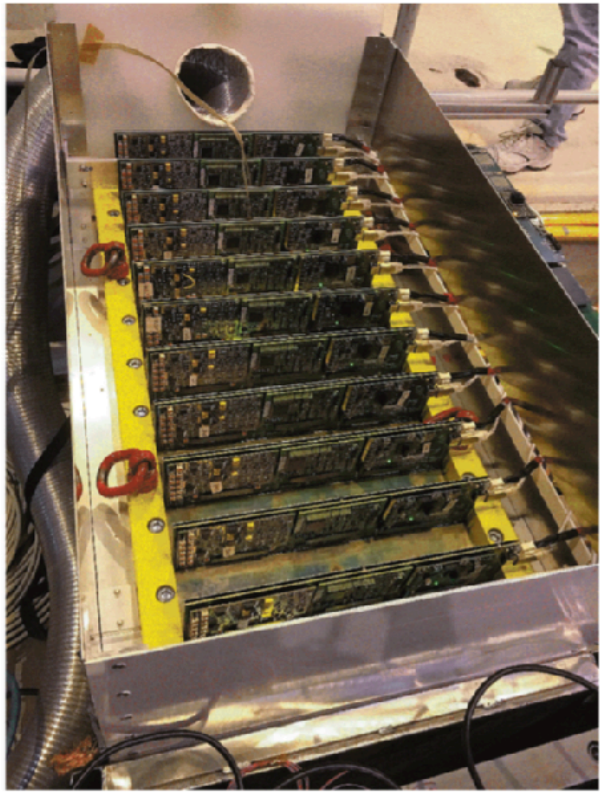
CALICE CMS Common Test Beam

AHCAL prototype as Backing Hadron calorimeter

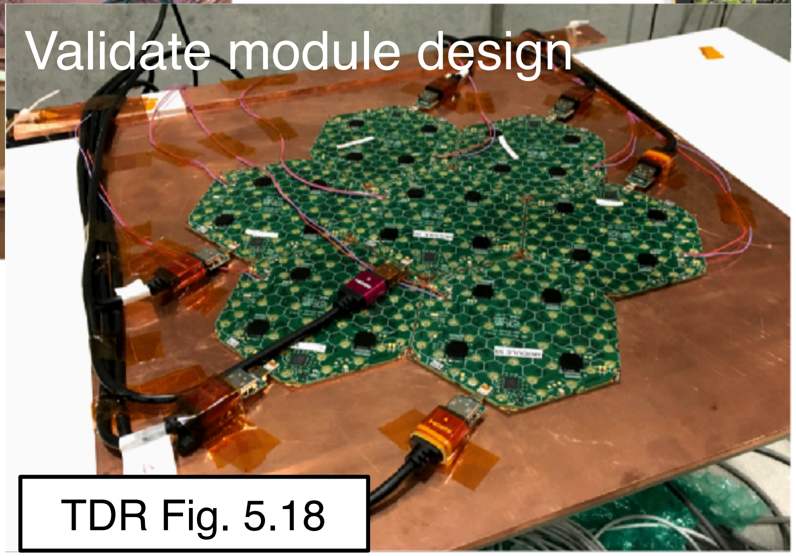
TDR Fig. 10.14

e, π, μ
beam





TDR Fig. 10.12



TDR Fig. 5.18

- Common DAQ: EUDAQ

AIDA2020

Summary

No conclusion.

CALICE SiPM-on-tile HCAL design largely adopted for HL-LHC upgrade of CMS endcap calorimeter.

- 20 x CALICE, 1/20 x CLICdet - and many new challenges

DESY contributes to R&D for the SiPM-on-tile modules.

Exciting to connect LC and LHC expertise.

Breathtaking progress to TDR, EDR, construction.

Rewarding for both sides - absolutely.

Back-up

Detector Requirements for LC and LHC

Accelerator environment.

Compared to LHC, LC radiation tolerance and bandwidth requirements are benign

Precision requirements are more demanding for LC:

- 2x for jet energies, 10x for track momenta, 5-10x for material budgets, 2x for strip and pixel dimensions

At LC, bunch train structure allows power cycled operation (~1%)

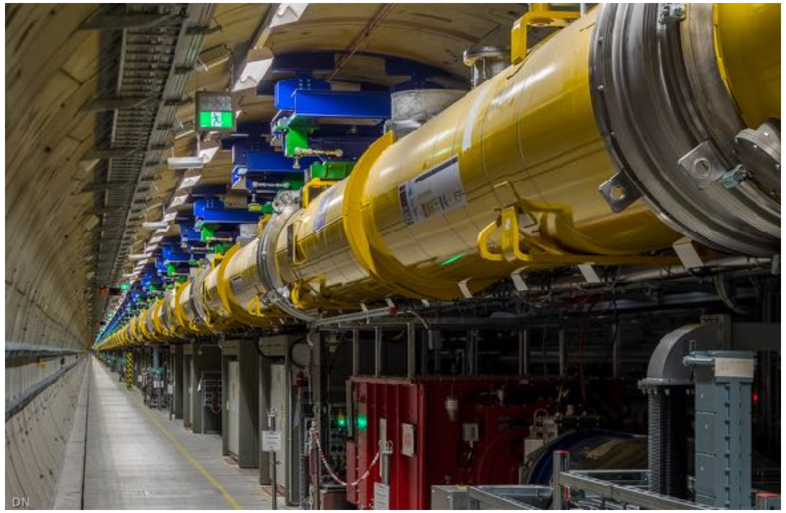
- simplifies powering and cooling: thinner trackers, denser calorimeters

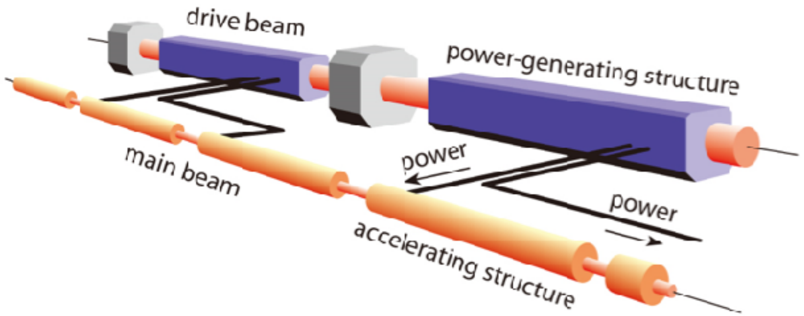
Backgrounds from beamstrahlung and hadronic 2-photon interactions

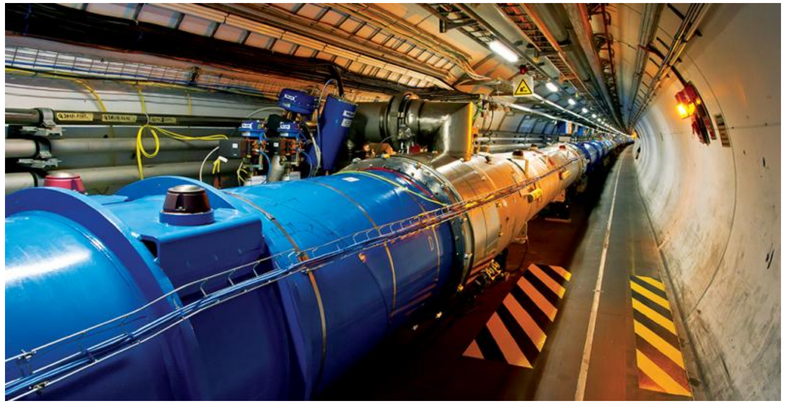
- more relevant for CLIC, higher E and smaller beam spot (5x1nm^2)
- somewhat higher emphasis on fine granularity and precise timing

Shifted focus and unwanted long time span led to development of new detector concepts up to TDR readiness level

- Imaging calorimeters
- Other examples: MAPS / ALICE ITS, ….



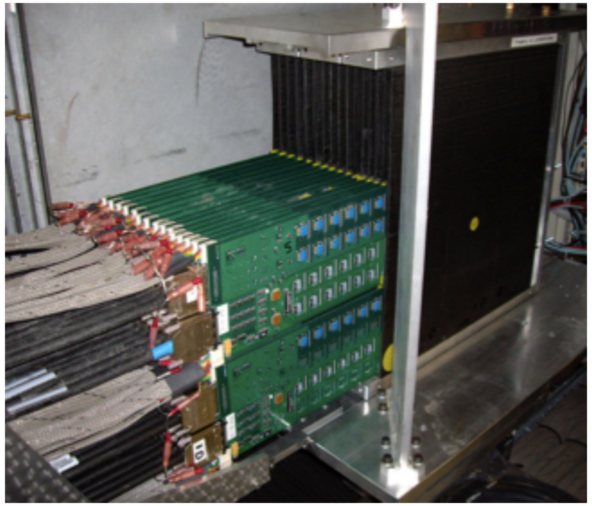




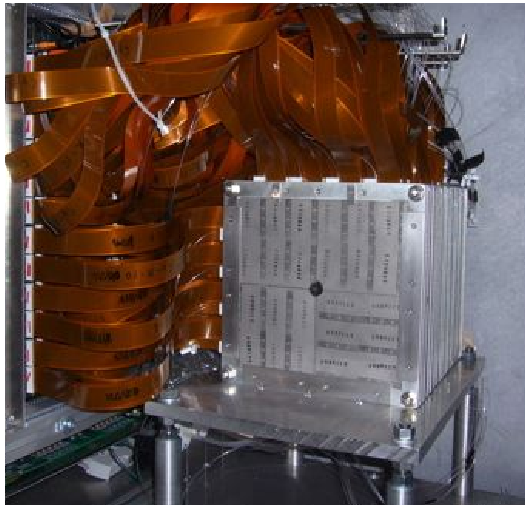
CALICE Test Beam Experiments

Large prototypes, complex systems.

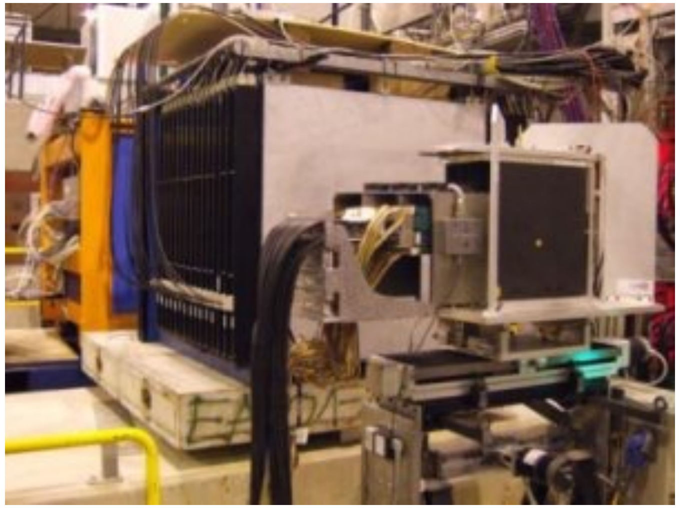
SiW ECAL



ScintW ECAL

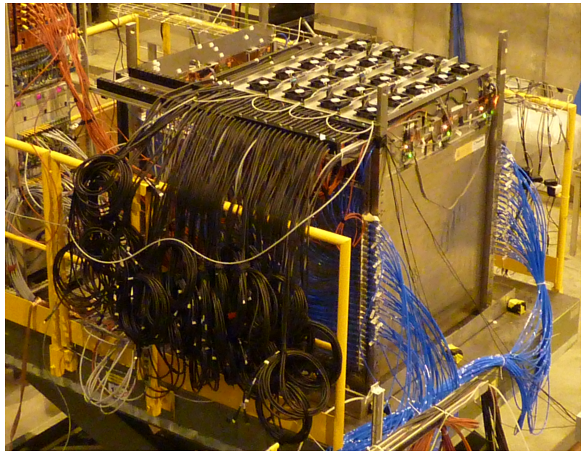


Scint AHCAL, Fe & W



RPC DHCAL, Fe & W

RPC SDHCAL, Fe



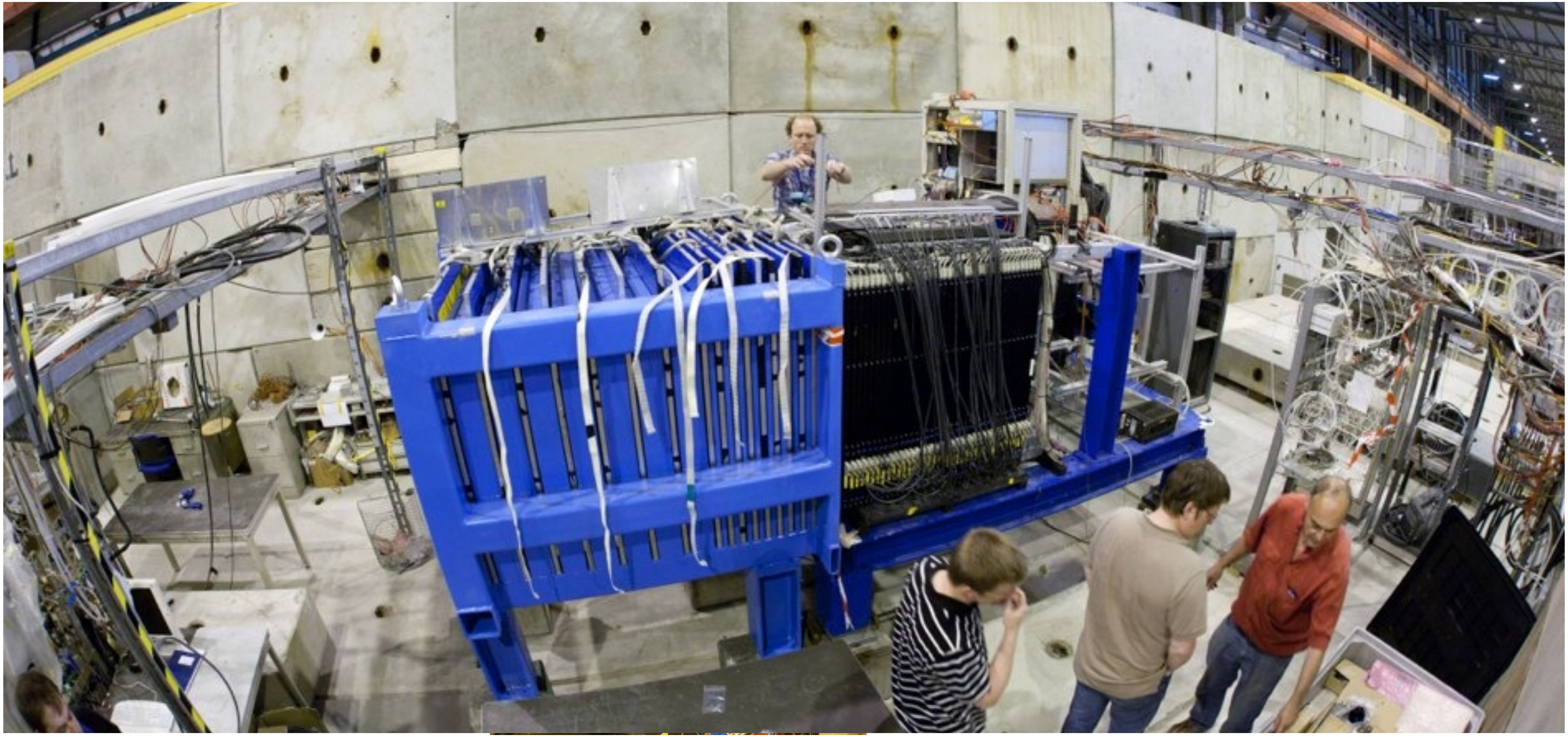
plus tests with small numbers of layers:

- ECAL, AHCAL with integrated electronics

- Micromegas and GEMs

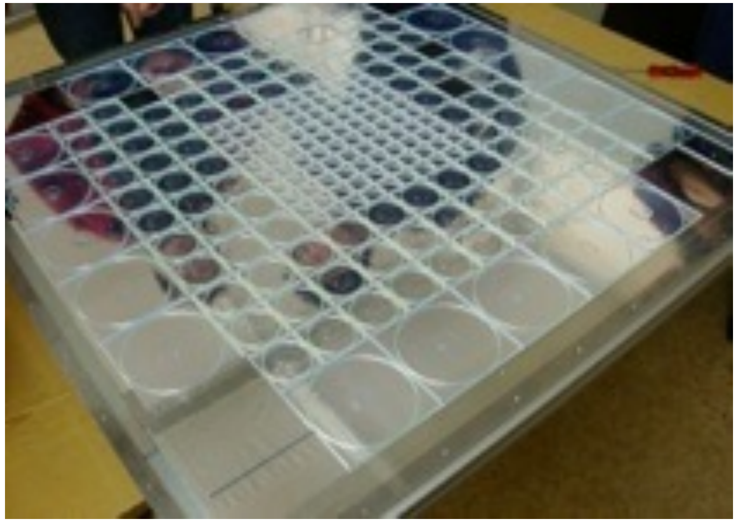
CALICE Test Beam Experiments

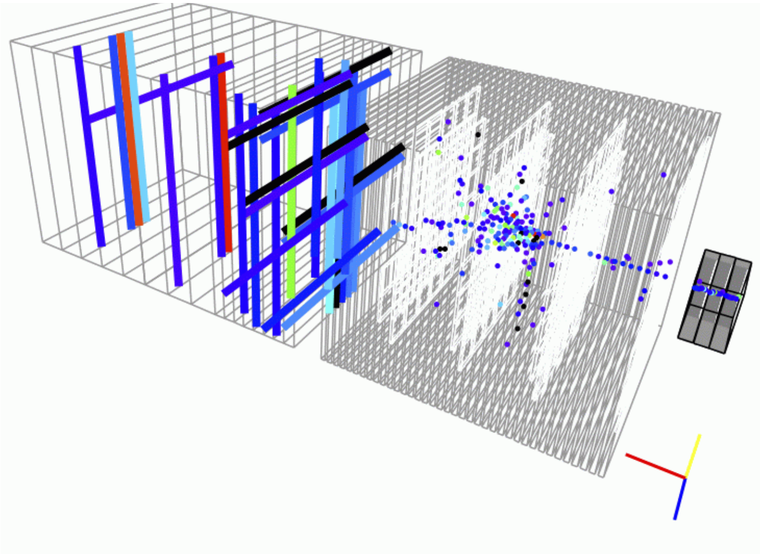
Large prototypes, complex systems.

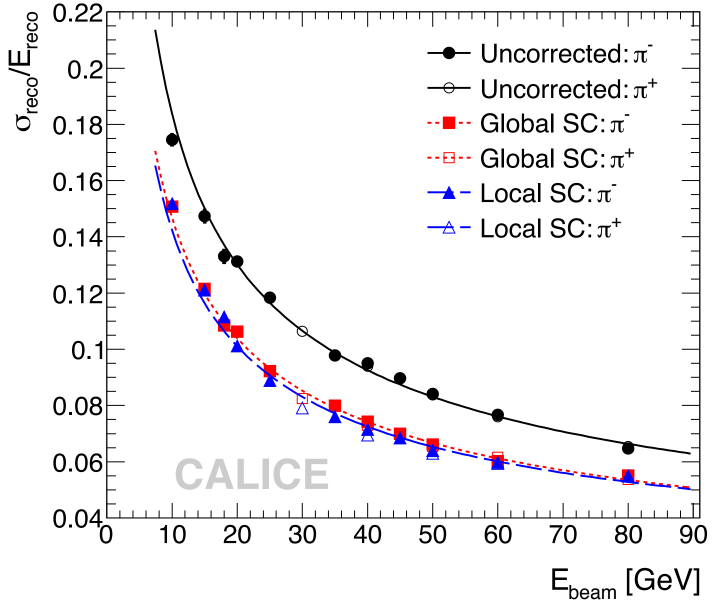


Proof-of-Principle

Validation of performances, simulations and algorithms.







- 38 layers, 7608 channels - first large-scale application of SiPMs
  - 6 years of data taking at DESY, CERN, Fermilab
- 12 journal papers (from SiPM-on-tile phototype alone)
  - resolution for electrons and hadrons, shower shapes and shower separation, different particle types and absorber materials,…
- All CALICE results
  - https://twiki.cern.ch/twiki/bin/view/CALICE/CalicePapers

$\sigma/E = 45.1\%/\sqrt{E} \oplus 1.7\% \oplus 0.18/E$

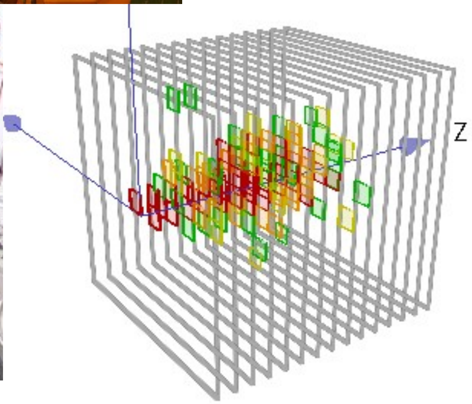
software compensation
now implemented in Particle Flow

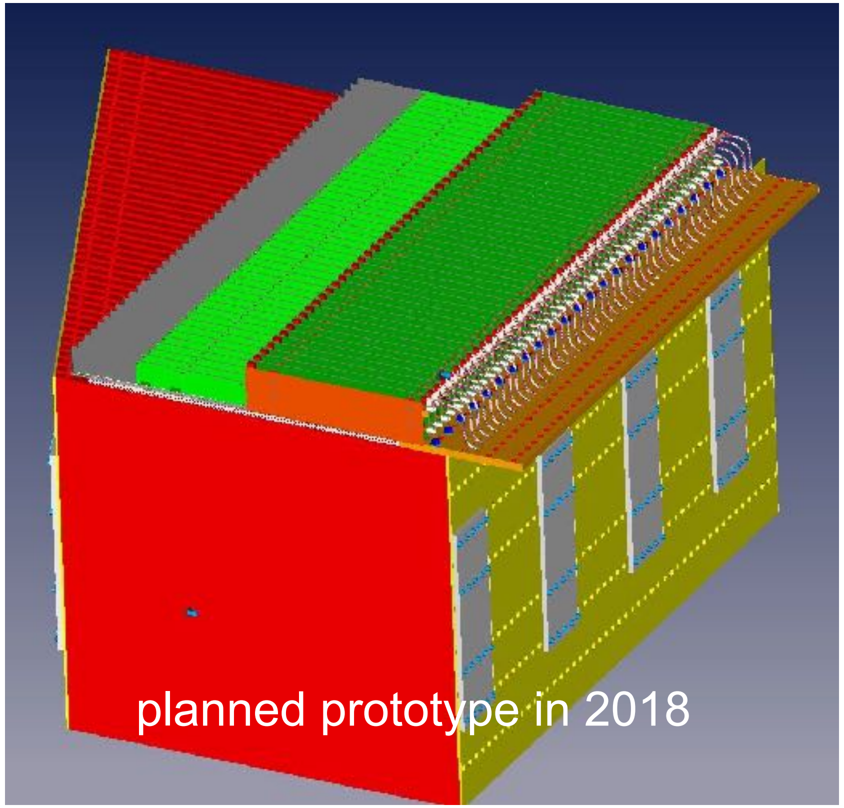
Eur. Phys. J. C77 (2017) 698

Rev.Mod.Phys. 88 (2016) 015003

New Prototypes

`New beam tests





Small stacks tested with electrons

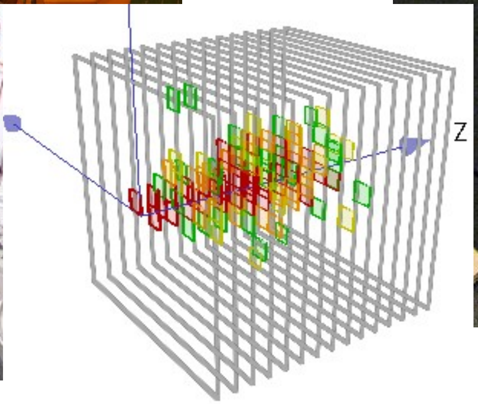
- B field compatibility
- Active temperature compensation

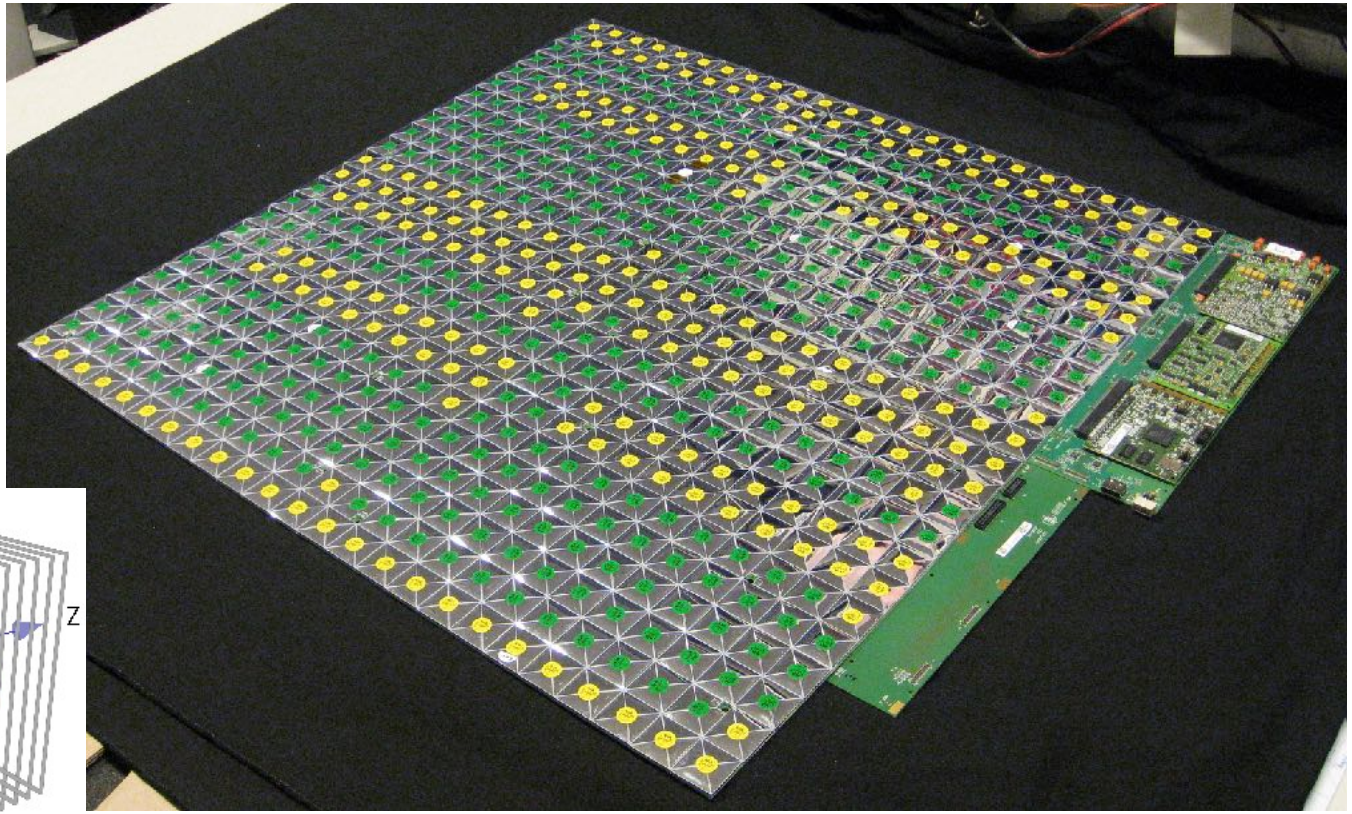
Big HCAL prototype under construction for beam in May + June

- 40 layers, 160 boards, 640 ASICs, 23’000 SiPMs
- Running at full speed - readiness review in April

New Prototypes

`New beam tests





Small stacks tested with electrons

- B field compatibility
- Active temperature compensation

Big HCAL prototype under construction for beam in May + June

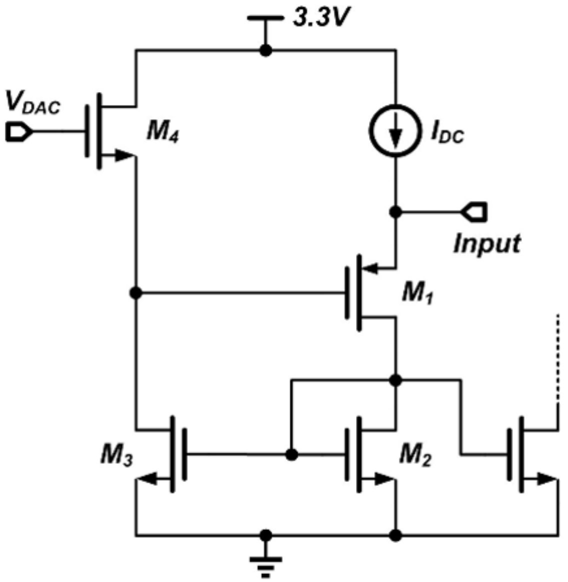
- 40 layers, 160 boards, 640 ASICs, 23’000 SiPMs
- Running at full speed - readiness review in April

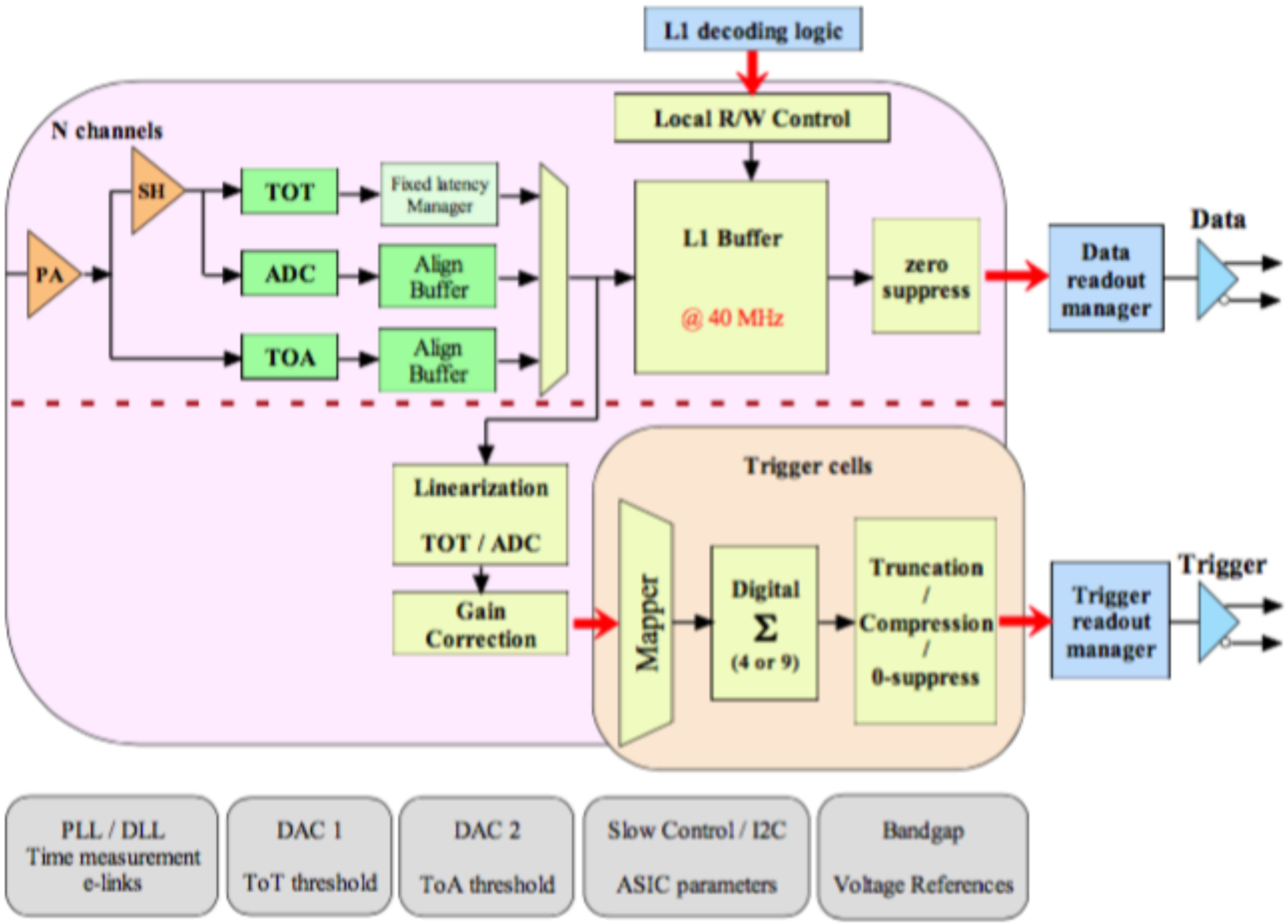
Read-out electronics

Front-end based on CALICE developments

HGCROC based on SKIROC and SPIROC

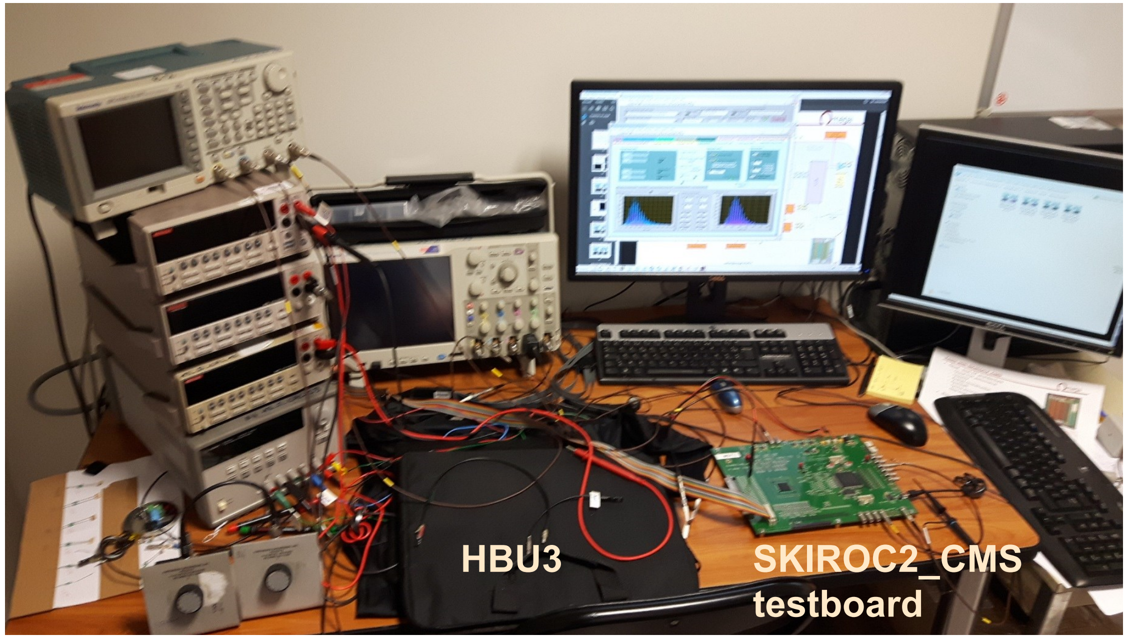
- 1 GB/s data, 1GB/s trigger output
- ADC, TDC, ToA and ToT
- ToT not compatible with AC coupling
- Analoge input stage using current conveyor a la KLauS (Heidelberg)

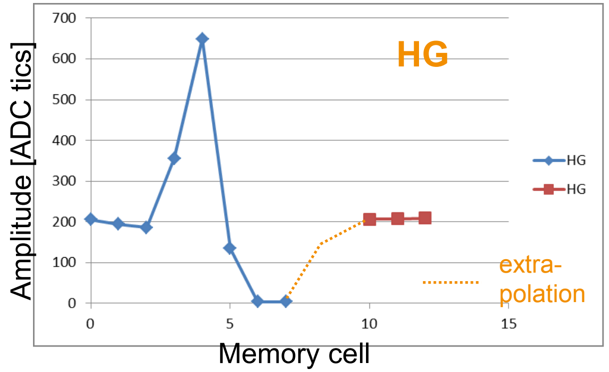


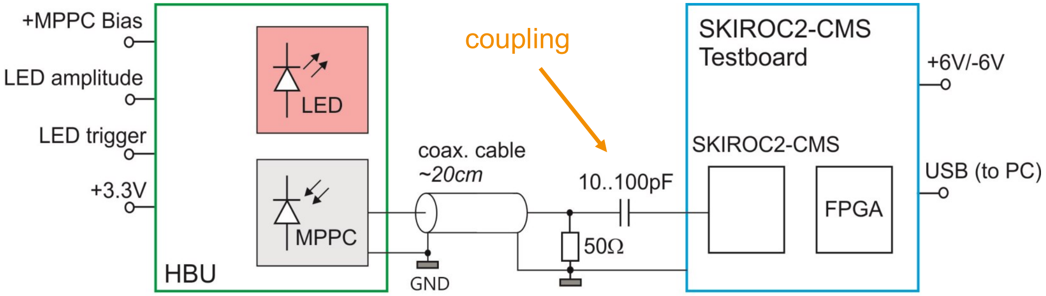


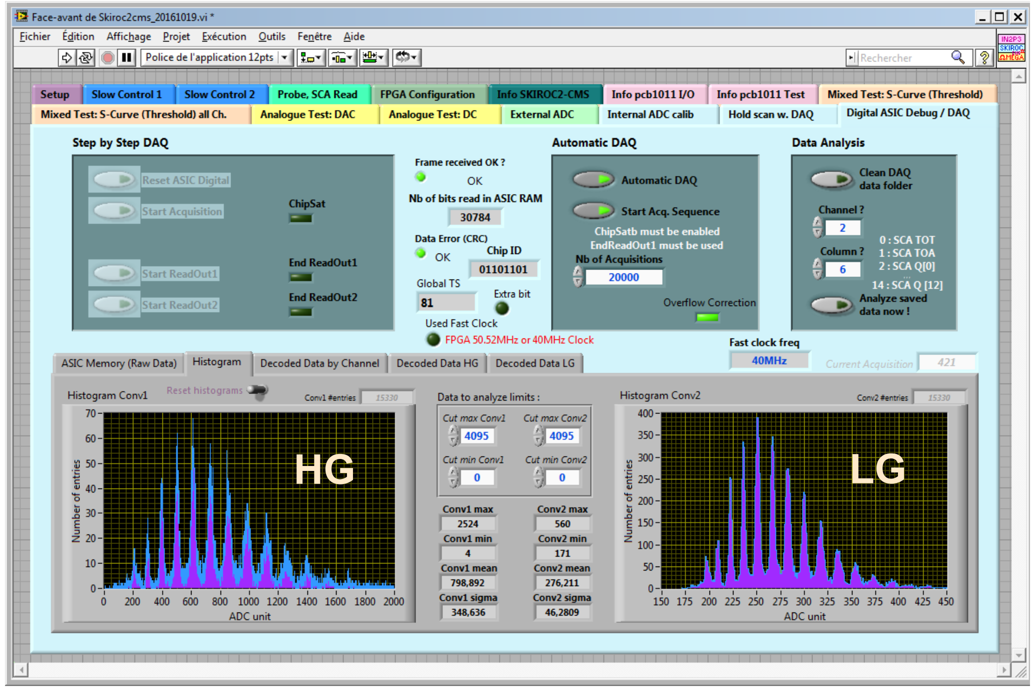
First steps

Test SiPM read-out with CMS-style ASIC







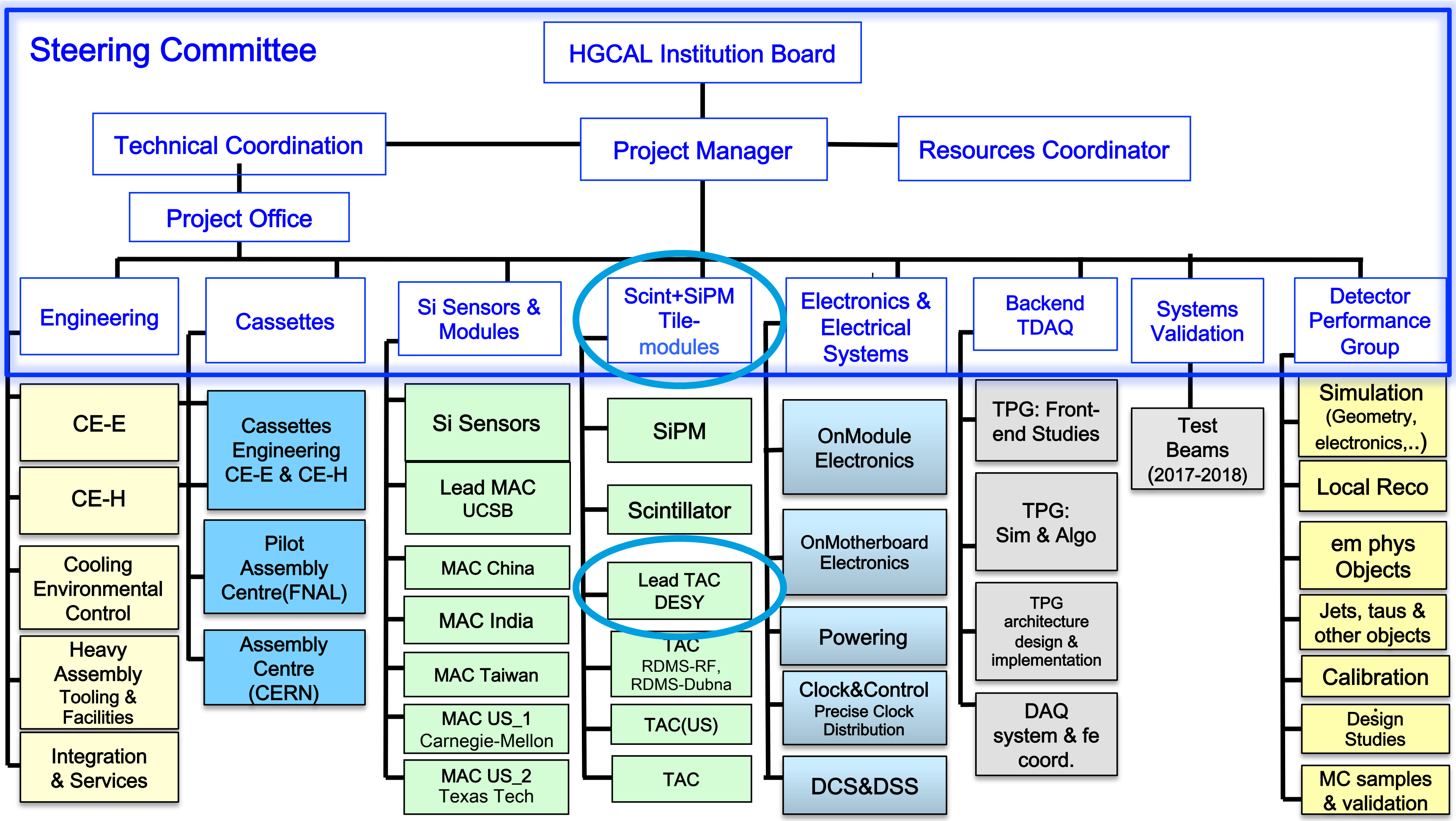


M.Reinecke (DESY), S. Callier (OMEGA)

HGCAL organisation

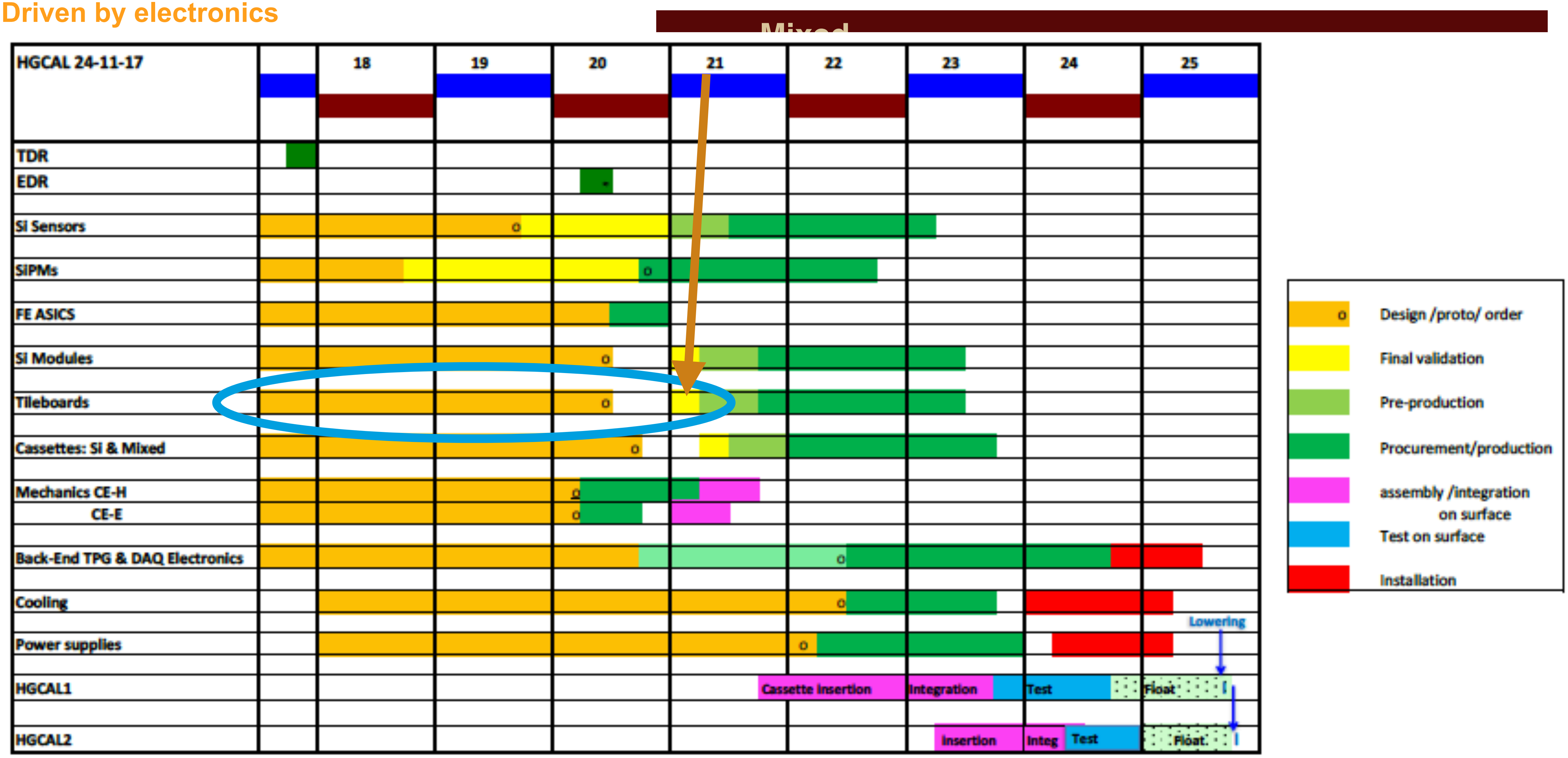
The pople

- The main groups:
  - CERN, Fermilab + US, Imperial, LLR, Russia
- CALICE people:
  - C. de La Taille et al., (ASICs),
  - P.Dauncey (Trigger),
  - V.Zutshi (scintillators)
  - M.Danilov, E.Popova, (E.Garutti) (SiPMs),
  - E.Sicking (sensor tests),
  - LLR engineers



HGCAL scintillator R&D plan

Driven by electronics



HGCAL scintillator R&D plan

Driven by electronics

	Mixed mockup	Prototype 1	Prototype 2
Ready	Jun ‘18	May ‘19	Mar ‘20
HGCROC [tested]	dummy resistor	DV1 [Dec ’18]	DV2 [Oct ’19]
Layers	BH3	one Si-only, one mixed	4 types
Readout	module tester	FPGA	concentrator ASIC [V2]
Tileboard	dummy, 4 sizes	realistic w/ GBT-SCA	actual
SiPM	—	rad-hard candidate	actual
Scintillator	candidate megatile, candidate tile	candidate megatile, candidate tile	actual
Motherboard	power, BV, connectors	“real” w/ FPGA lpGBT if available	actual

DESY tasks

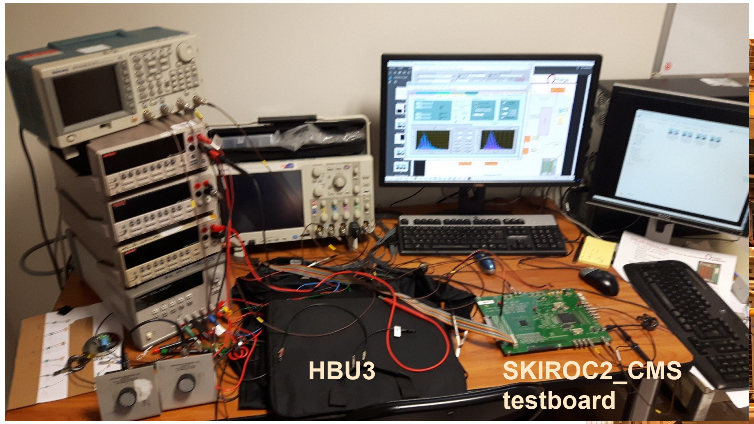
2017 - 2020

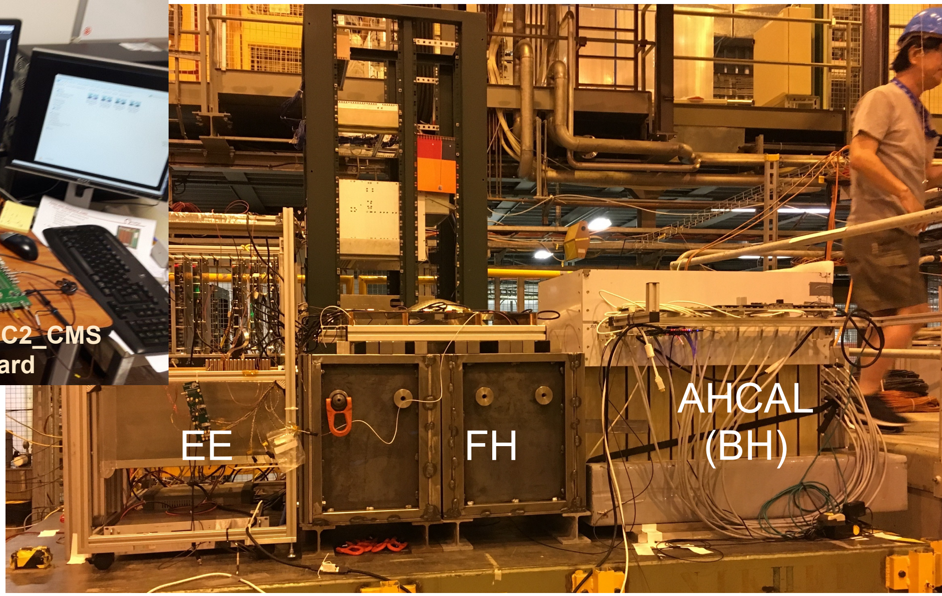
DESY commitments:

- limited to R&D
- tile-bords development, lead assembly centre

DESY Tasks

- Test beam with existing prototypes
- Validate interplay SiPM - HGCROC
- Develop & characterise tile-board prototypes
  - electronically
  - thermo-mechanically
- Establish assembly & QC sequence
  - Build on CALICE achievements and develop further
  - Electronics and mechanical engineering support
- Coordination





DESY tasks

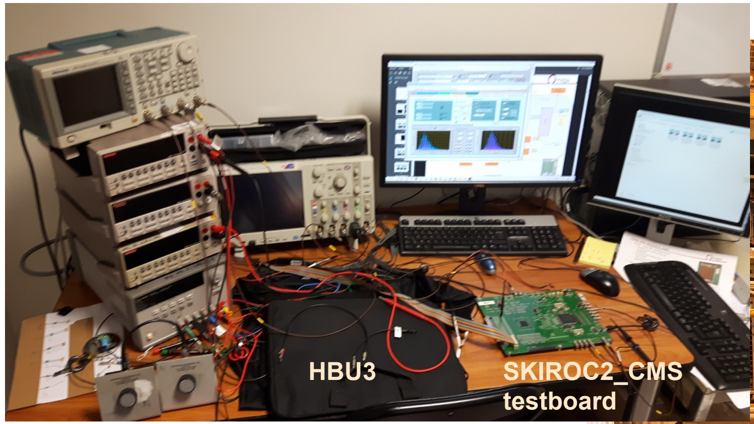
2017 - 2020

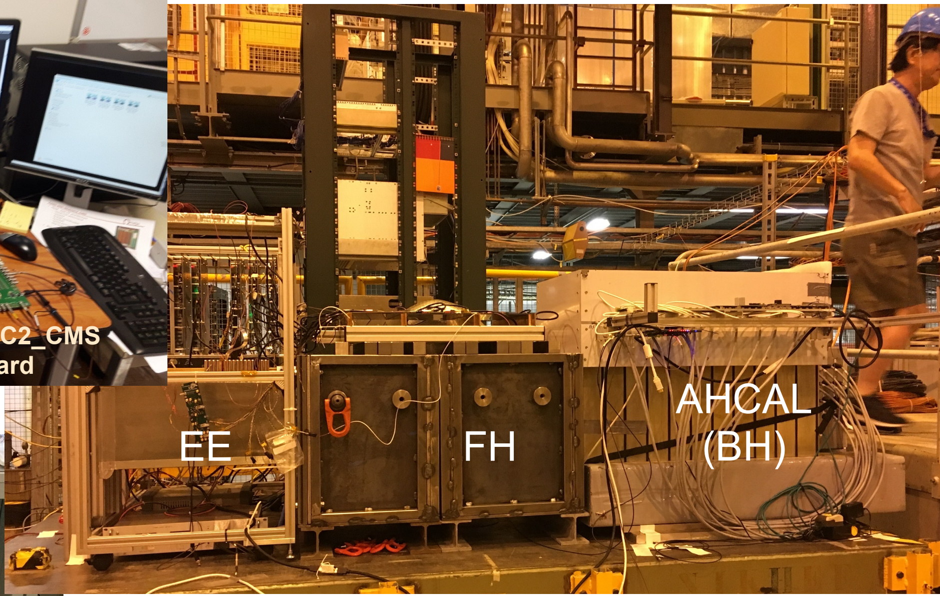
DESY commitments:

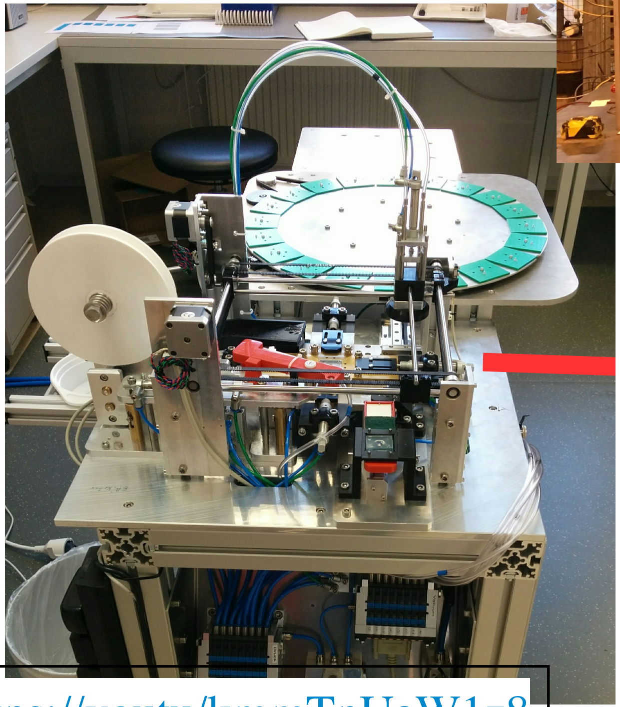
- limited to R&D
- tile-bords development, lead assembly centre

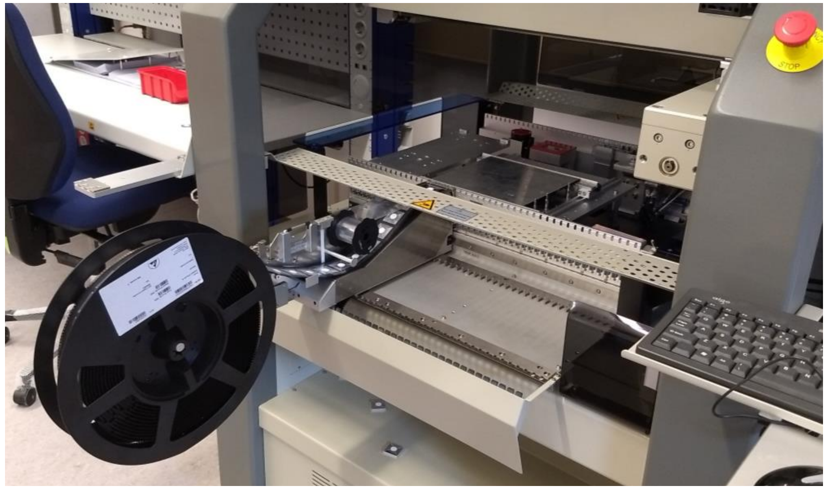
DESY Tasks

- Test beam with existing prototypes
- Validate interplay SiPM - HGCROC
- Develop & characterise tile-board prototypes
    - electronically
    - thermo-mechanically
- Establish assembly & QC sequence
    - Build on CALICE achievements and develop further
    - Electronics and mechanical engineering support
- Coordination









https://youtu/kmmTpUaW1z8