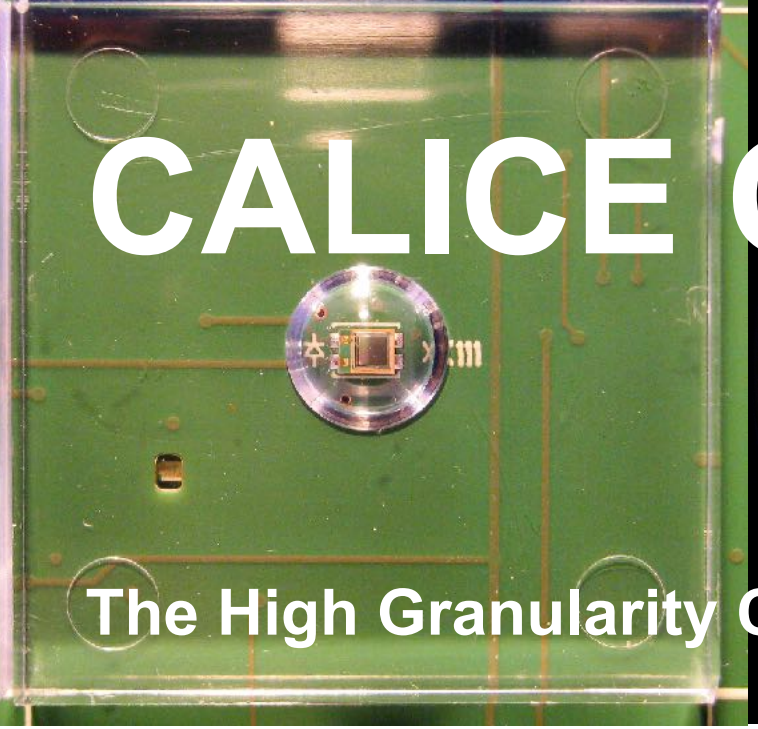
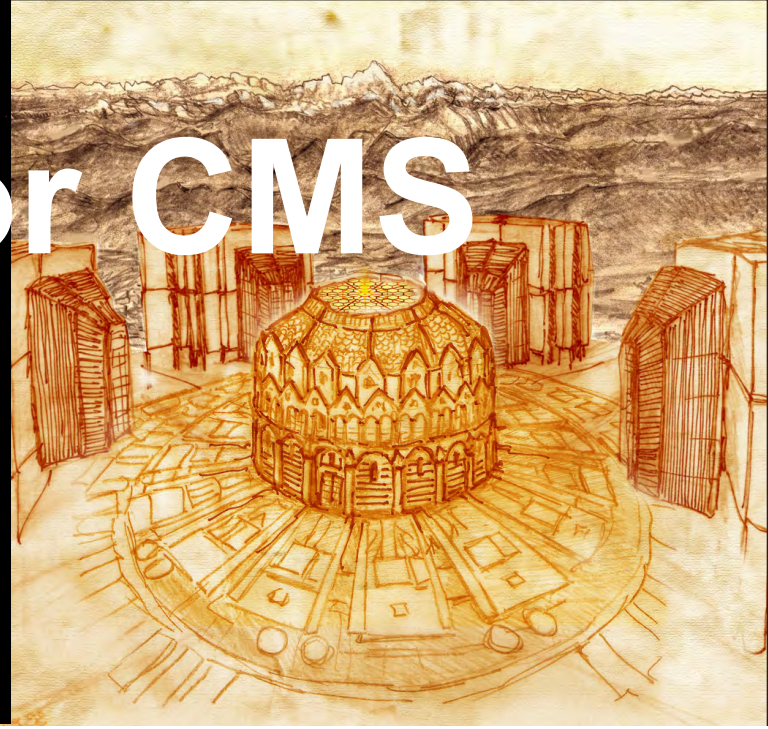




CALICE Calorimetry for CMS

The High Granularity Calorimeter Endcap Upgrade

Joint Instrumentation Seminar

DESY, Hamburg, June 22, 2018

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%)

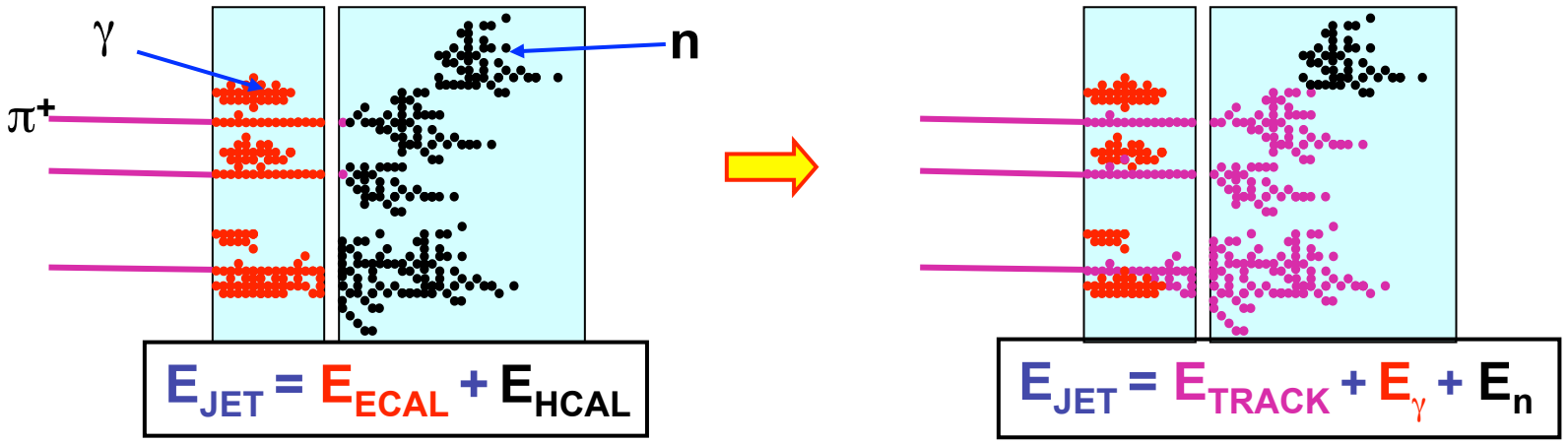
Reconstruct each particle individually and use optimal detector

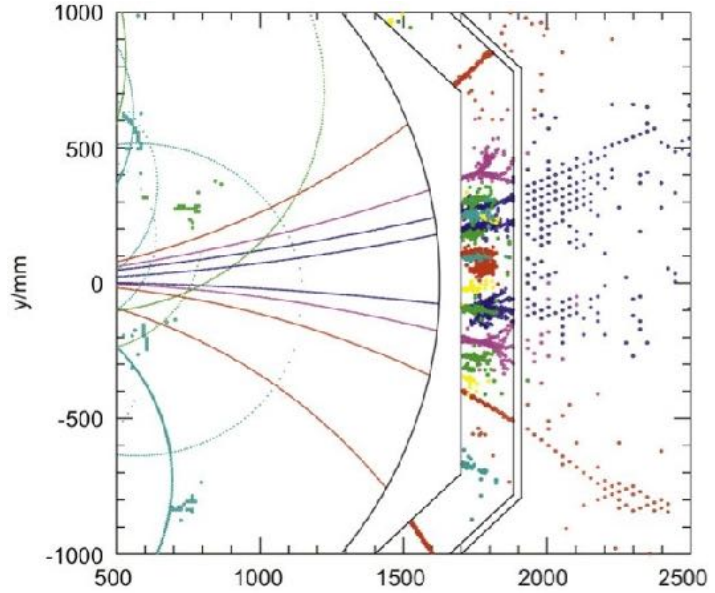
- 60% charged, 20% photons, 10% neutral hadrons

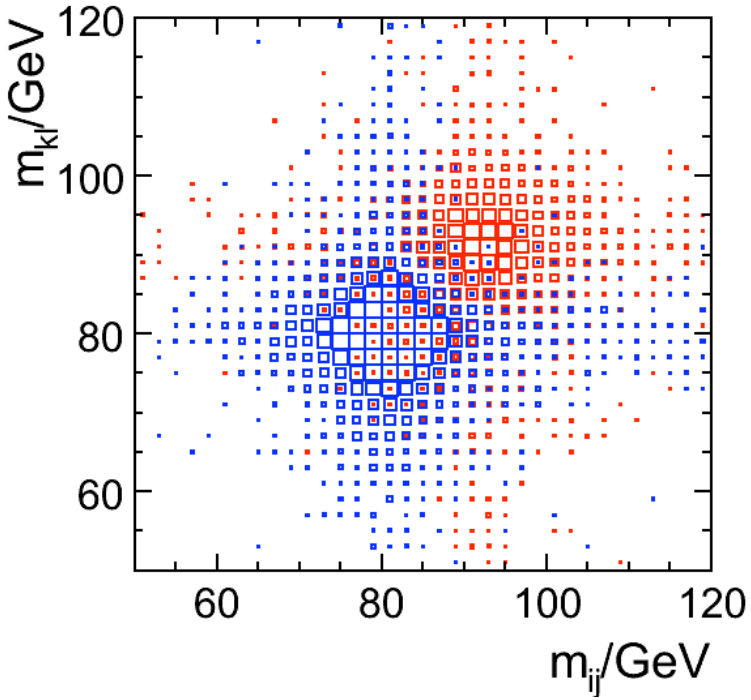
Requires fine 3D segmentation of and sophisticated software

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

Today all linear collider detector concepts follow particle flow concept

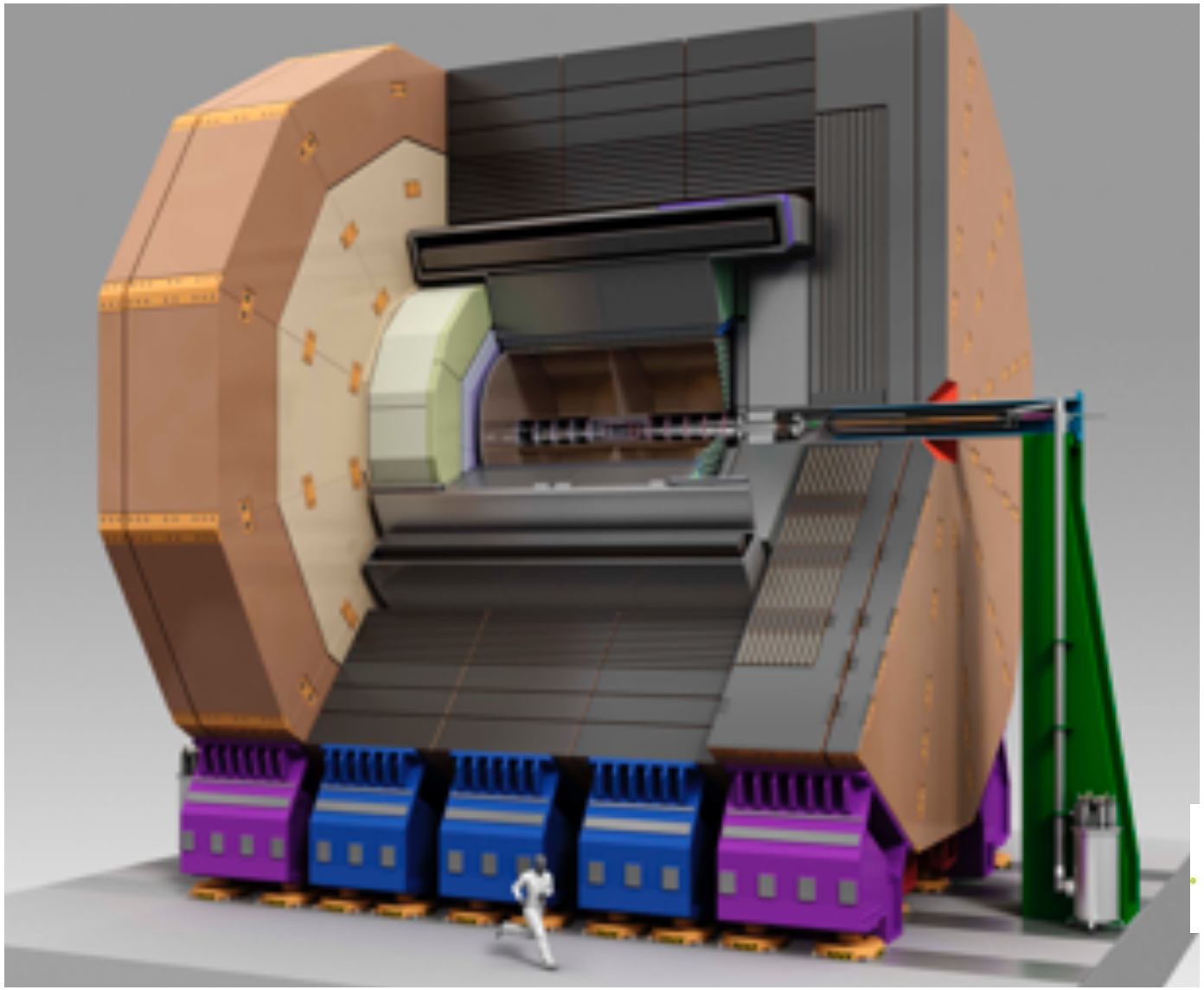


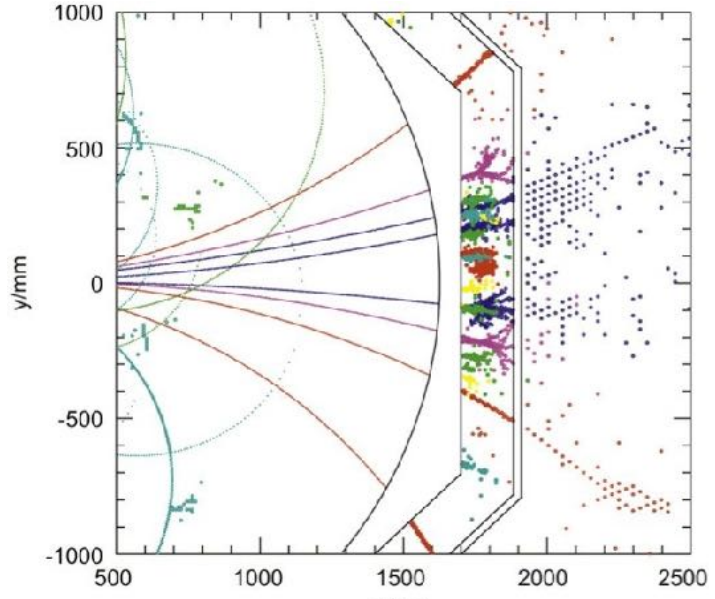


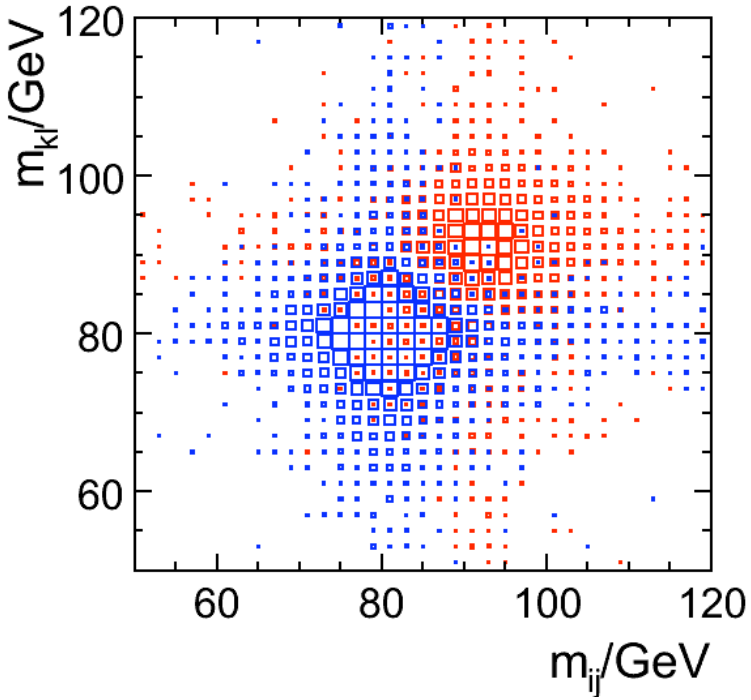


Particle Flow Paradigm

Tackle the jet energy challenge.







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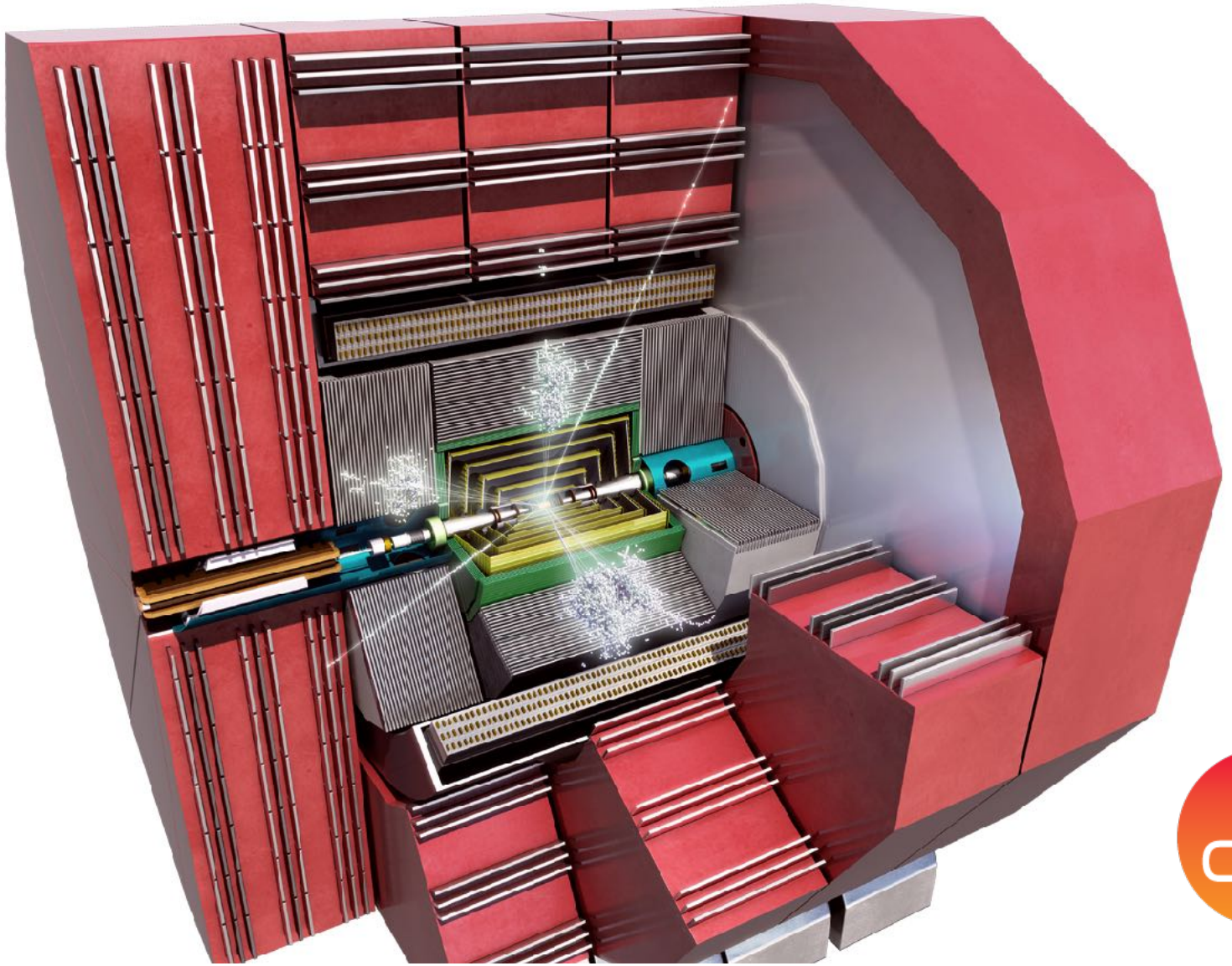
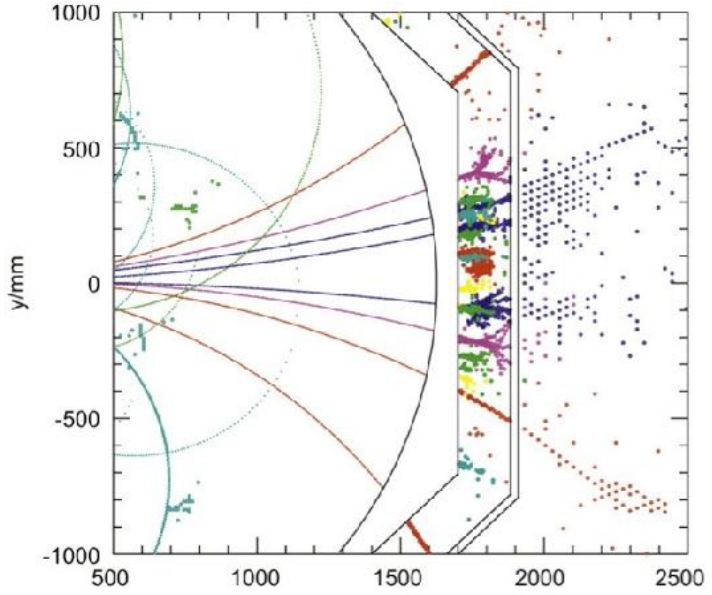
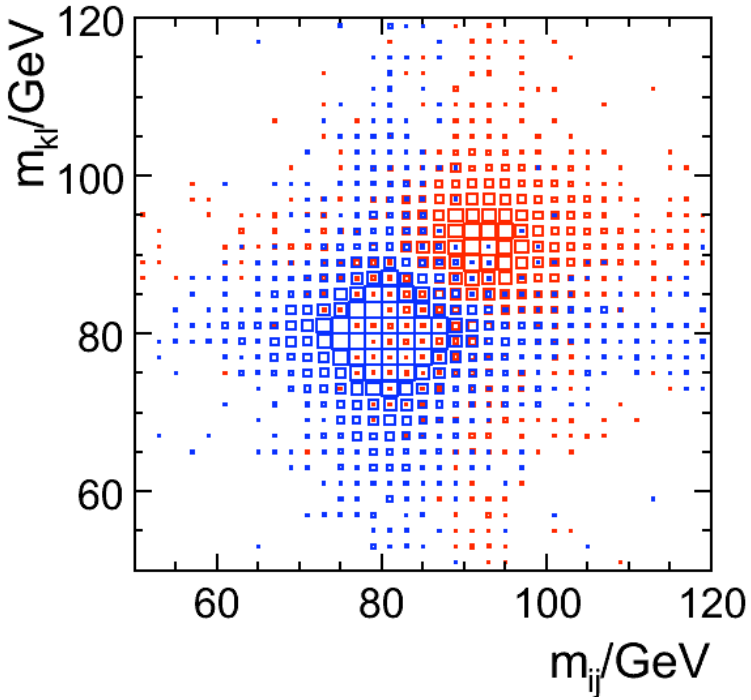






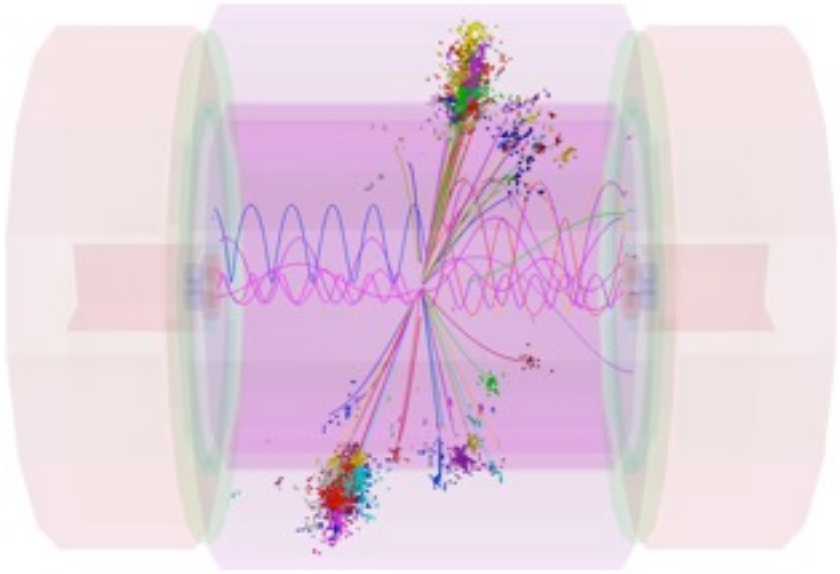
High Granularity and Pile-up

Particle flow with harsher backgrounds.

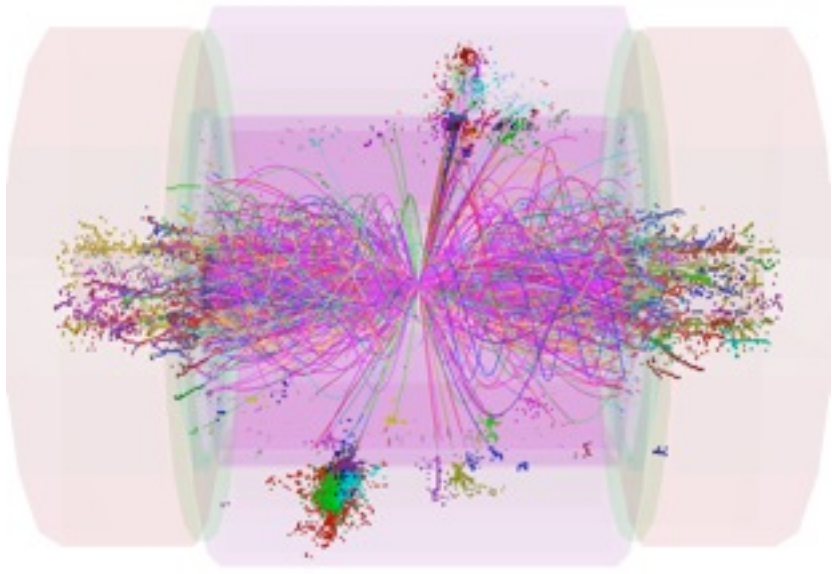
Studied intensively for CLIC: backgrounds from γγ → hadrons and short BX 0.5 ns

- 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)

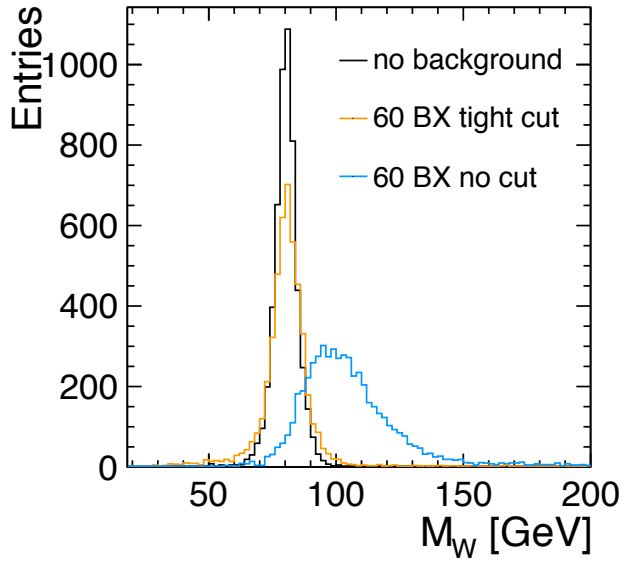
High granularity essential for pile-up rejection capabilities



Z @ 1 TeV



+ 1.4 TeV BG (reconstructed particles)



E_W = 500 GeV

High Granularity and Pile-up

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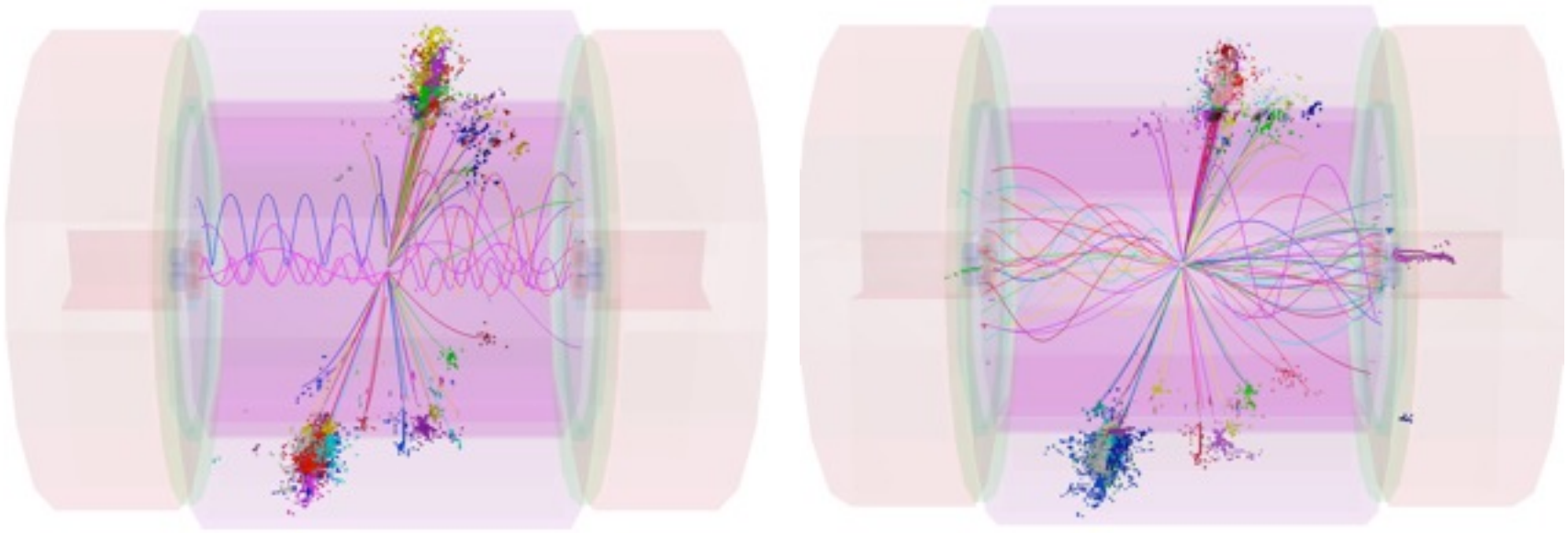

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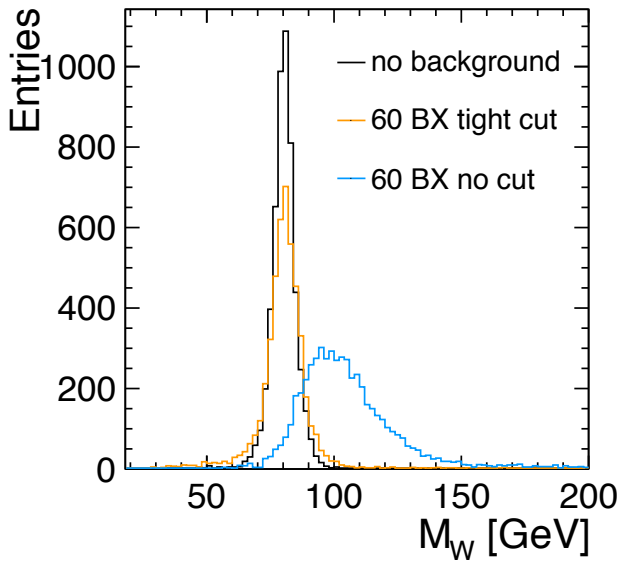


E_W = 500 GeV

Technologies for Highly Granular Calorimeters

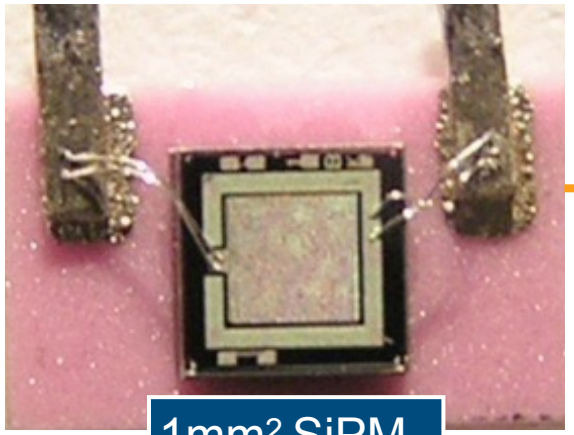
Because we can.

Large area silicon arrays

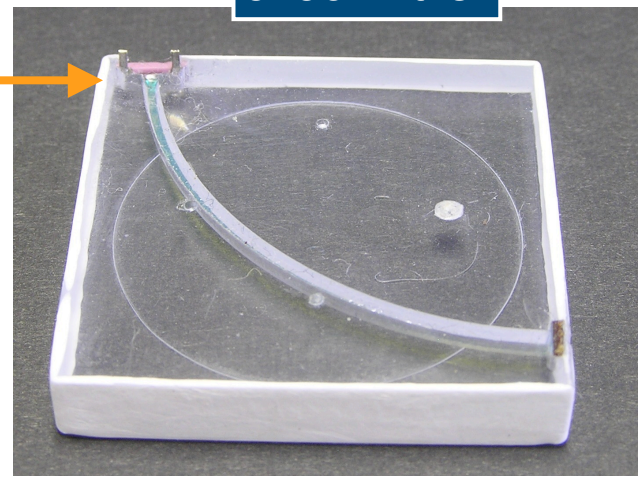
- silicon calorimetry grows out of the domain of small plug devices

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

Silicon photomultipliers on scintillator tiles or strips



1mm² SiPM



3x3cm² tile

2004

small, B-insensitive, cheap, robust

Silicon calorimeters

From H1 to CMS

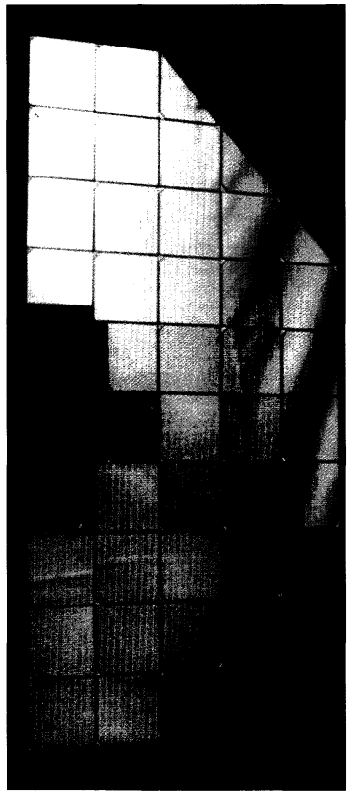
An investigation into the radiation damage of the silicon detectors of the H1-PLUG calorimeter within the HERA environment

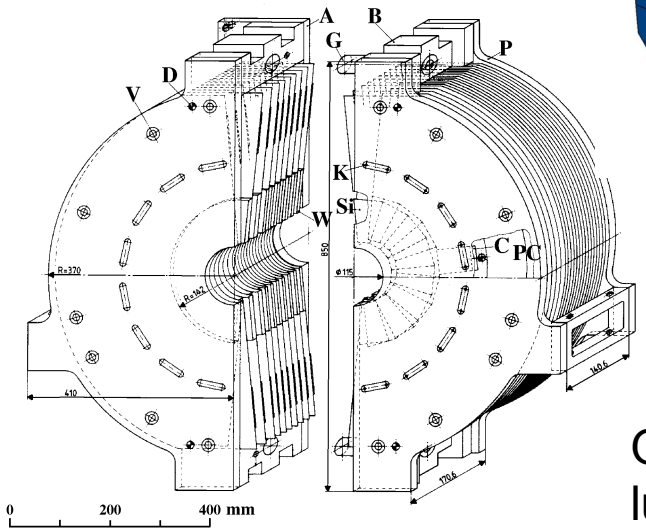
E. Fretwurst[a], W. Hildesheim[b,*], G. Lindstroem[a], M. Seidel[a]

[a] *I. Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany*
[b] *Deutsches Elektronen Synchrotron, Hamburg, Germany*

Received 11 September 1995

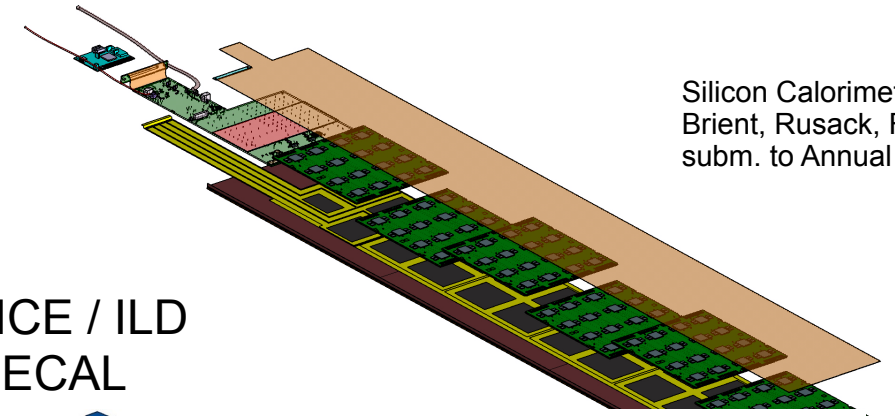
Nuclear Instruments and Methods in Physics Research A 372



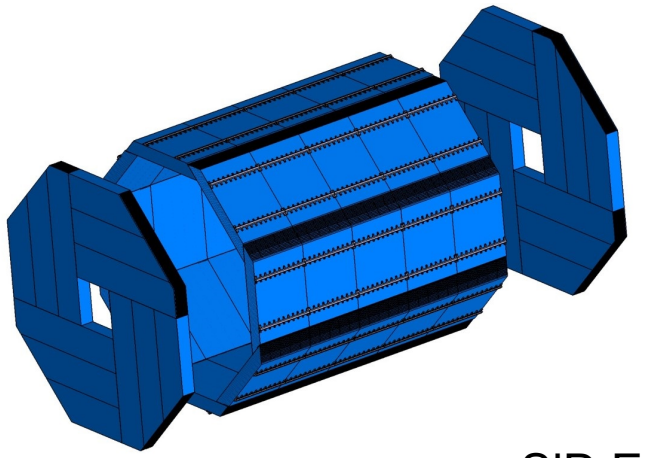


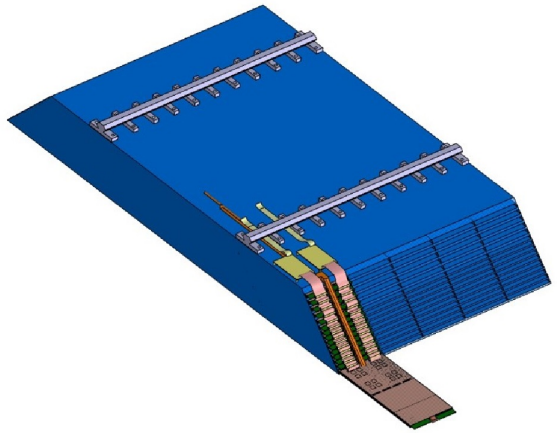
OPAL luminometer

Silicon Calorimeters
Brient, Rusack, FS
subm. to Annual Reviews

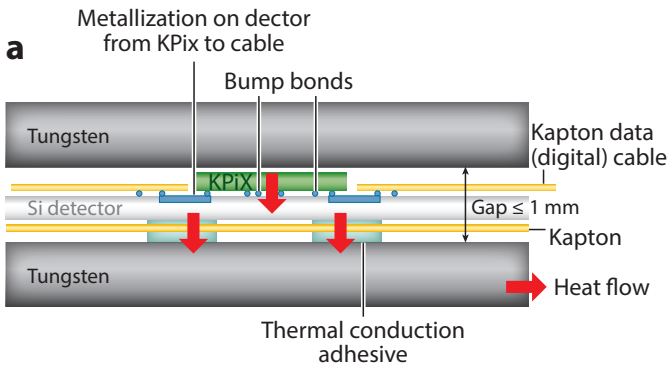


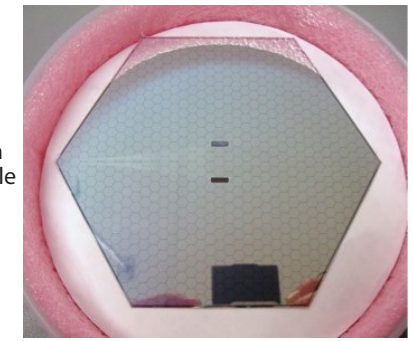
CALICE / ILD
SiW ECAL





SiD ECAL



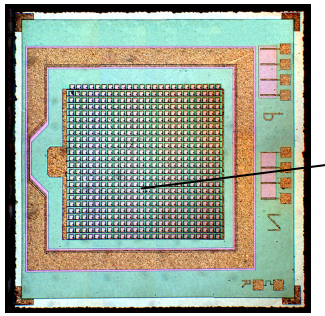


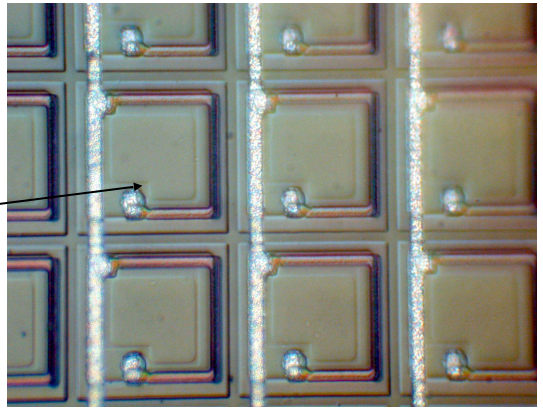
Silicon Photomultipliers

A revolution in optical read-out

Silicon PhotoMultiplier (SiPM)
MEPhI&PULSAR

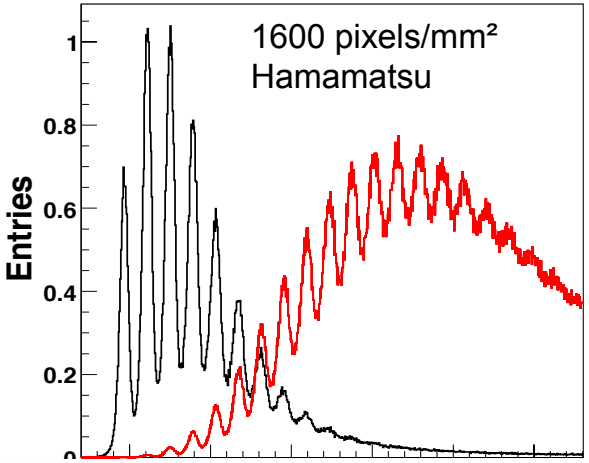
B.Dolgoshein
2002

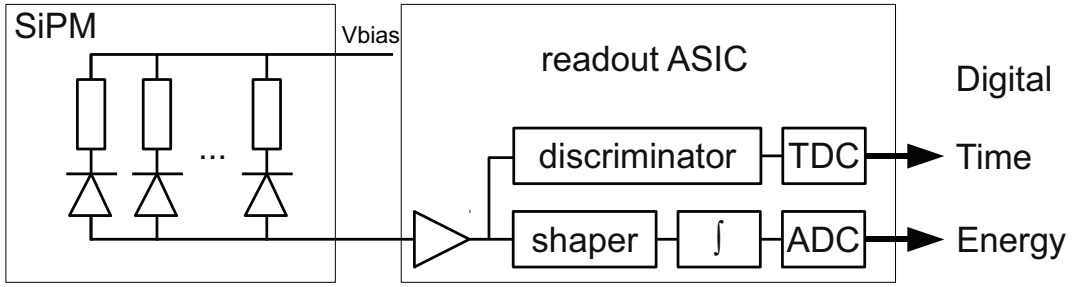




SiPM

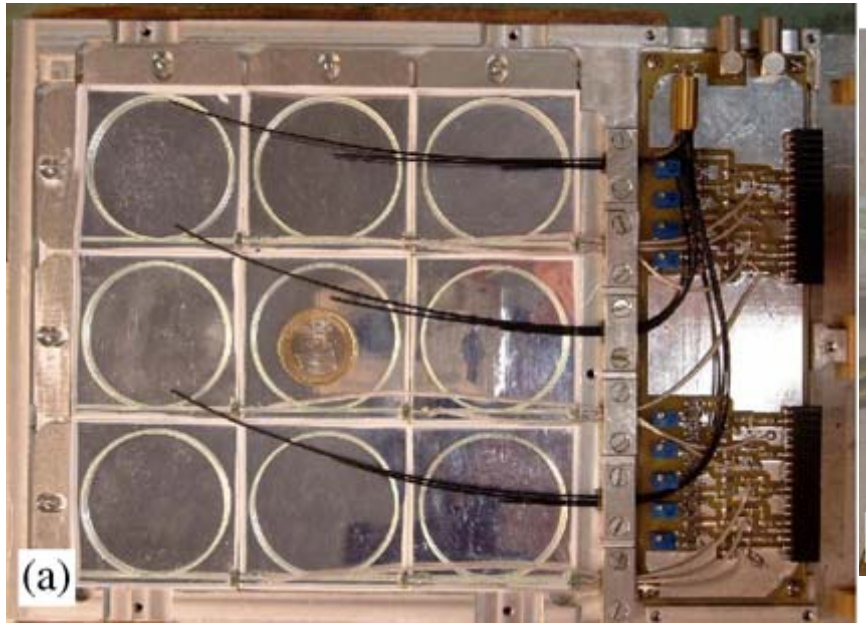
Pixels of the SiPM

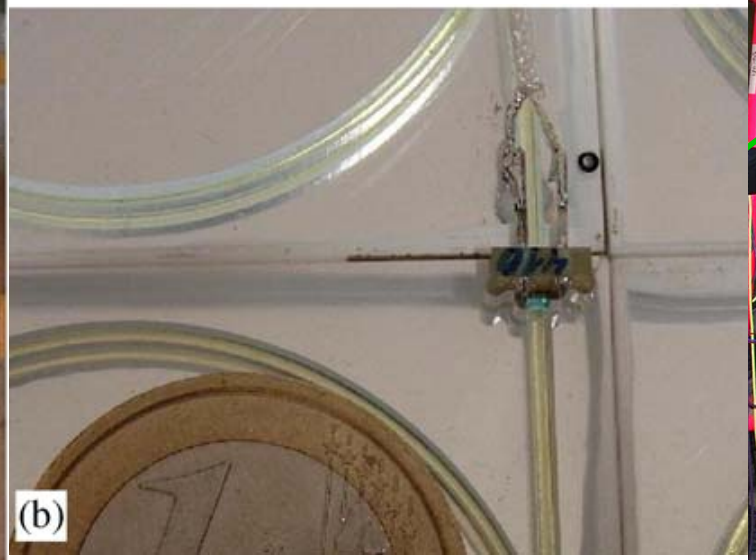




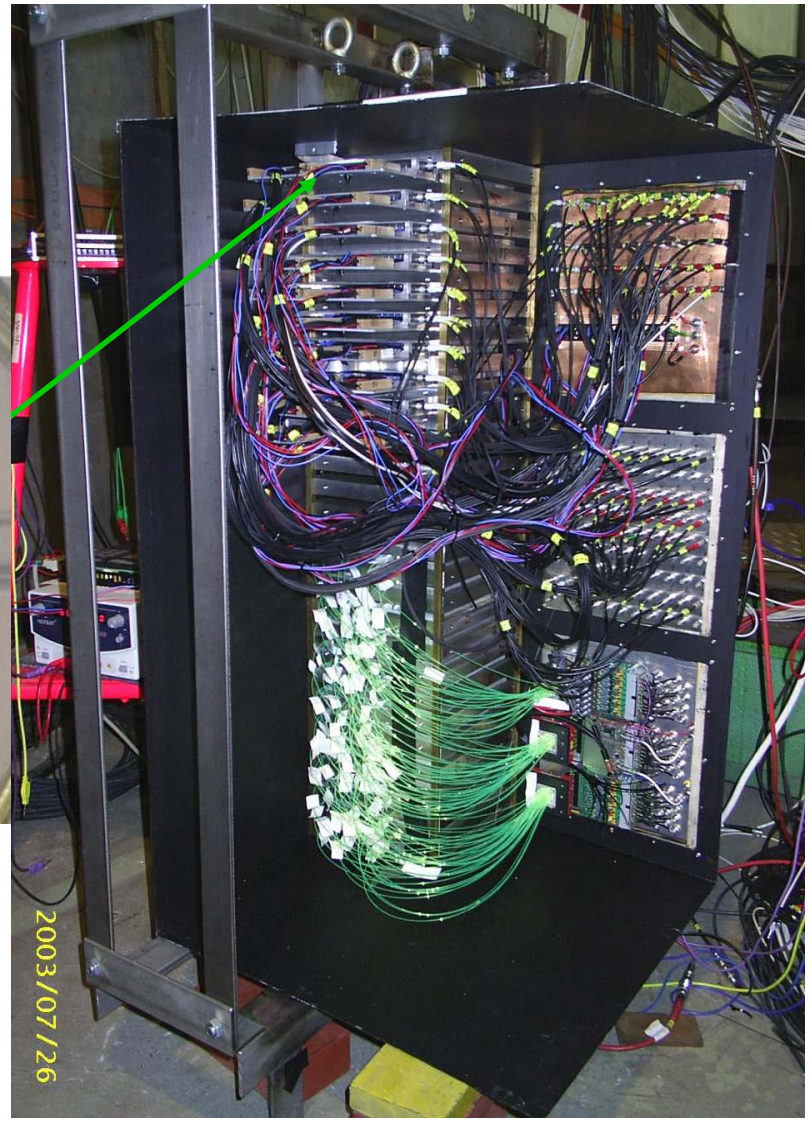
SiPM-on-Tile Evolution

A long way





2003: MiniCal



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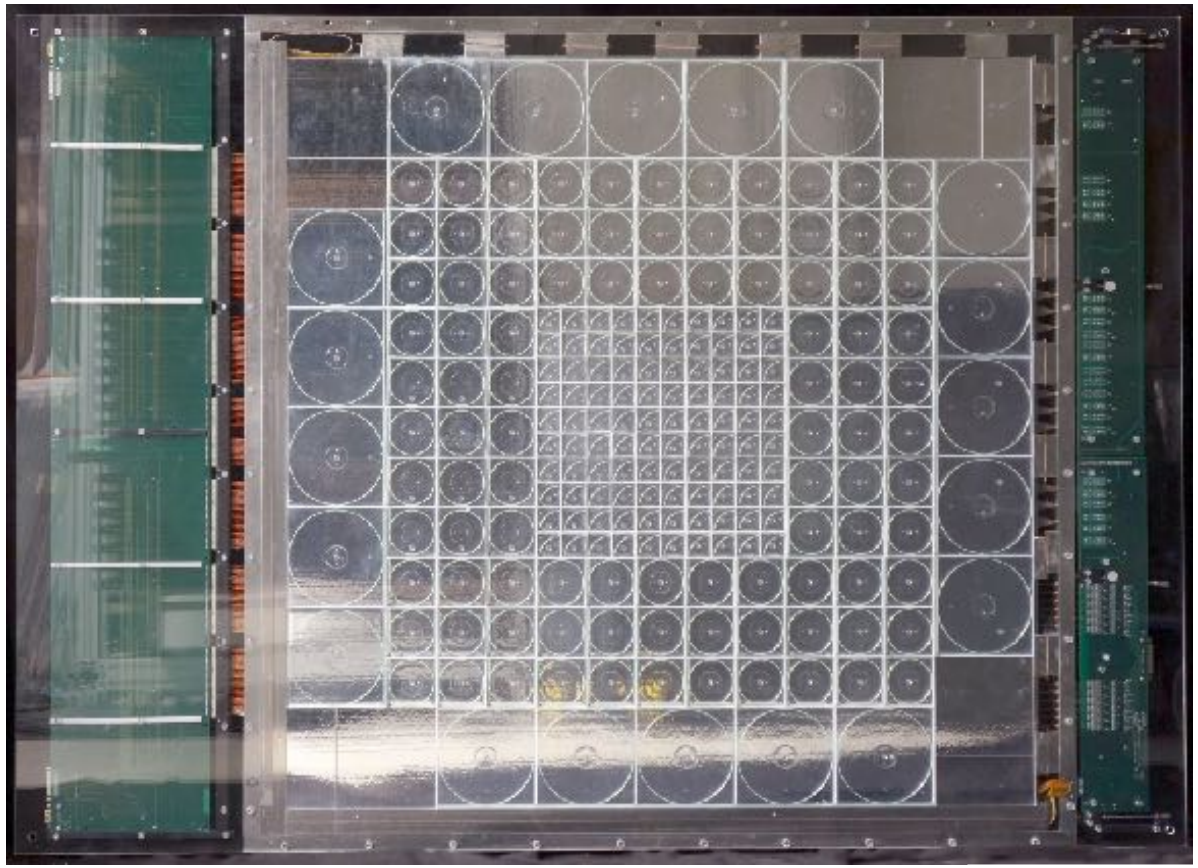
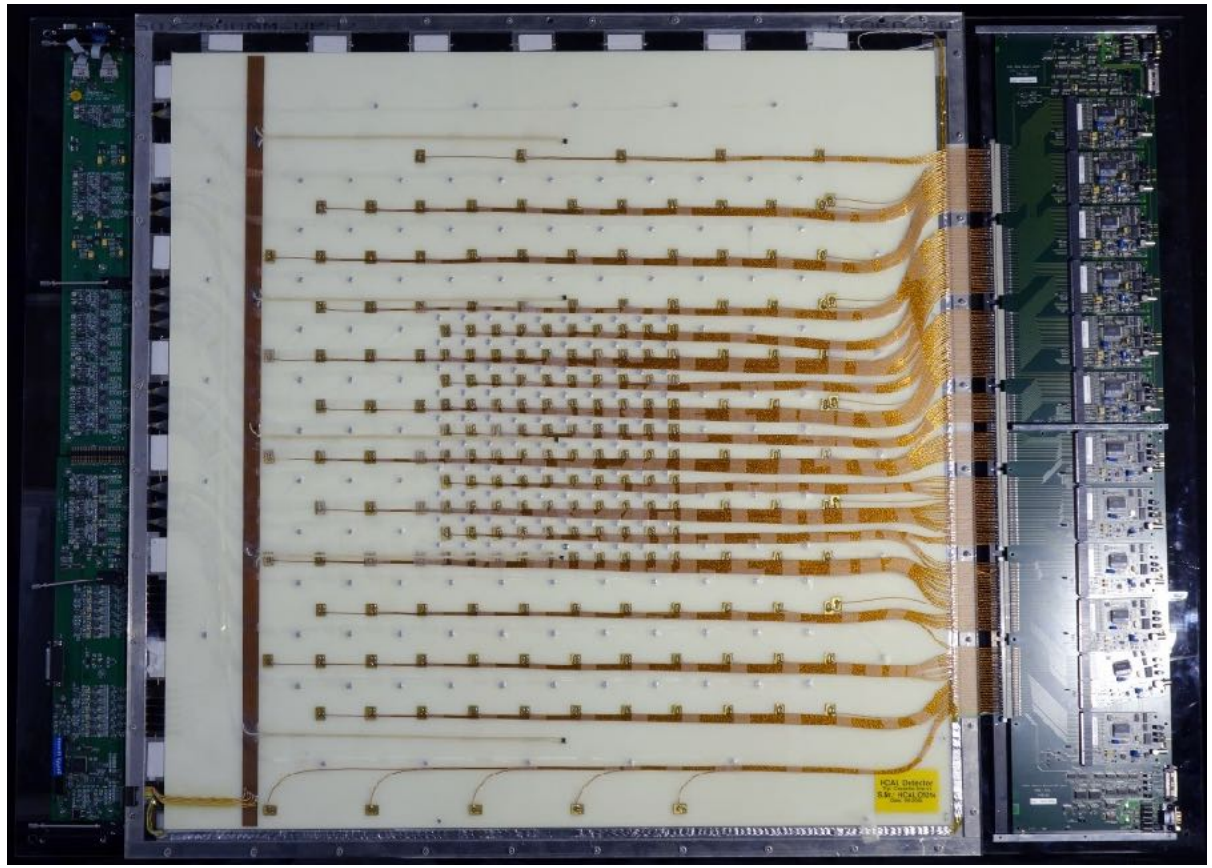
A long way





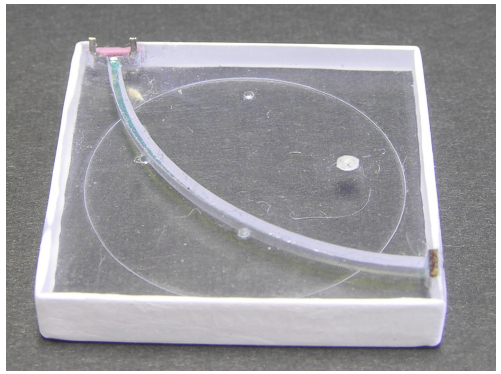
2006: Physics Prototype

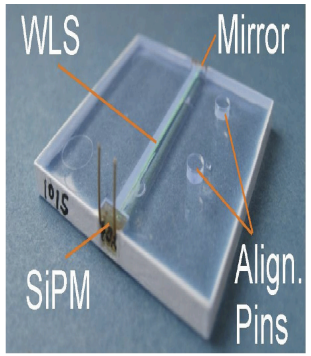
SiPM-on-Tile Evolution

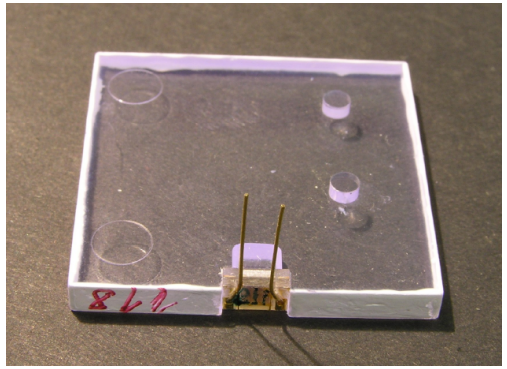
A long way

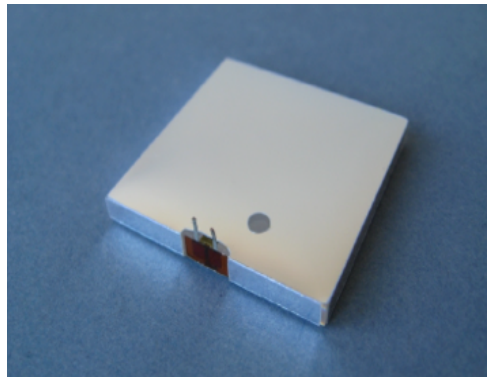
SiPM-on-Tile Evolution

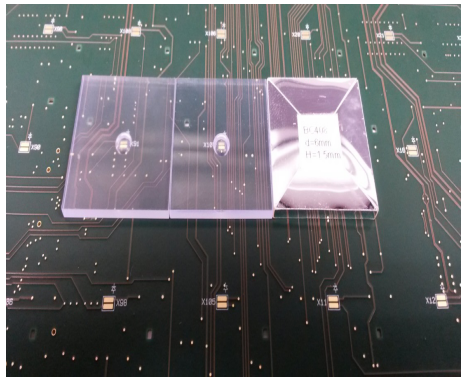
A long way







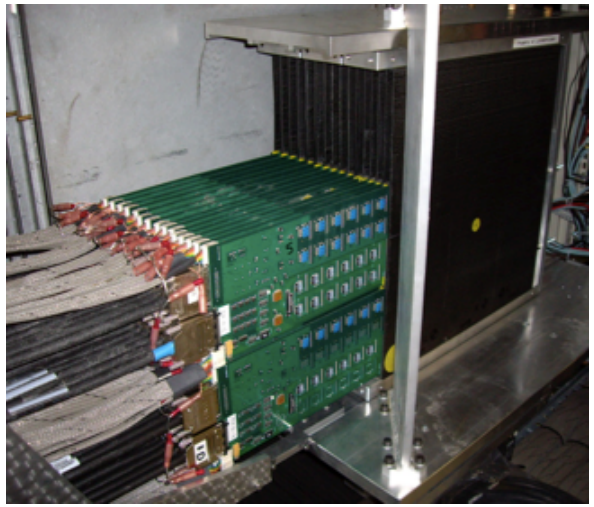




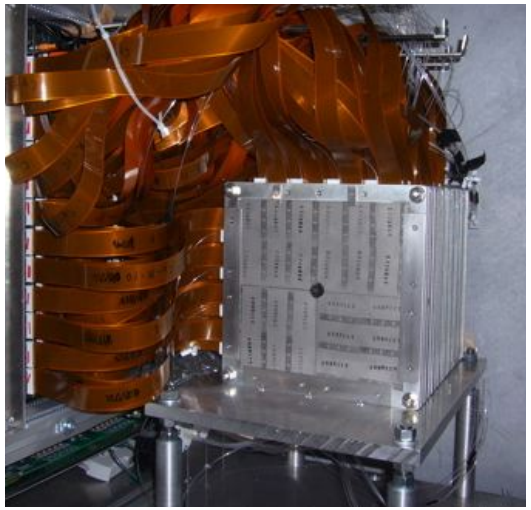
CALICE Test Beam Experiments

Large prototypes, complex systems.

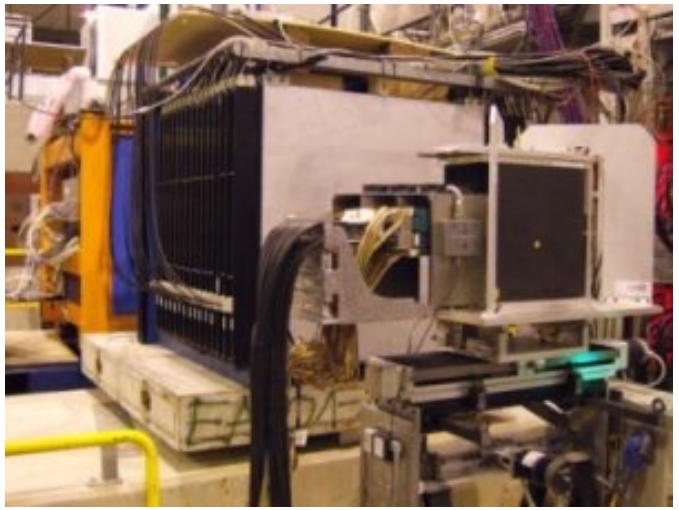
SiW ECAL



ScintW ECAL

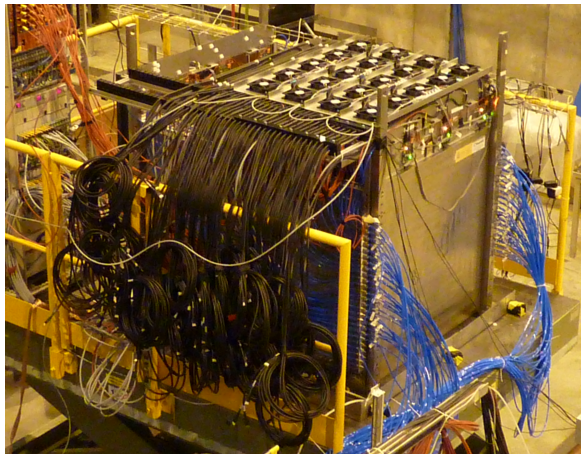


Scint AHCAL, Fe & W



RPC DHCAL, Fe & W

RPC SDHCAL, Fe



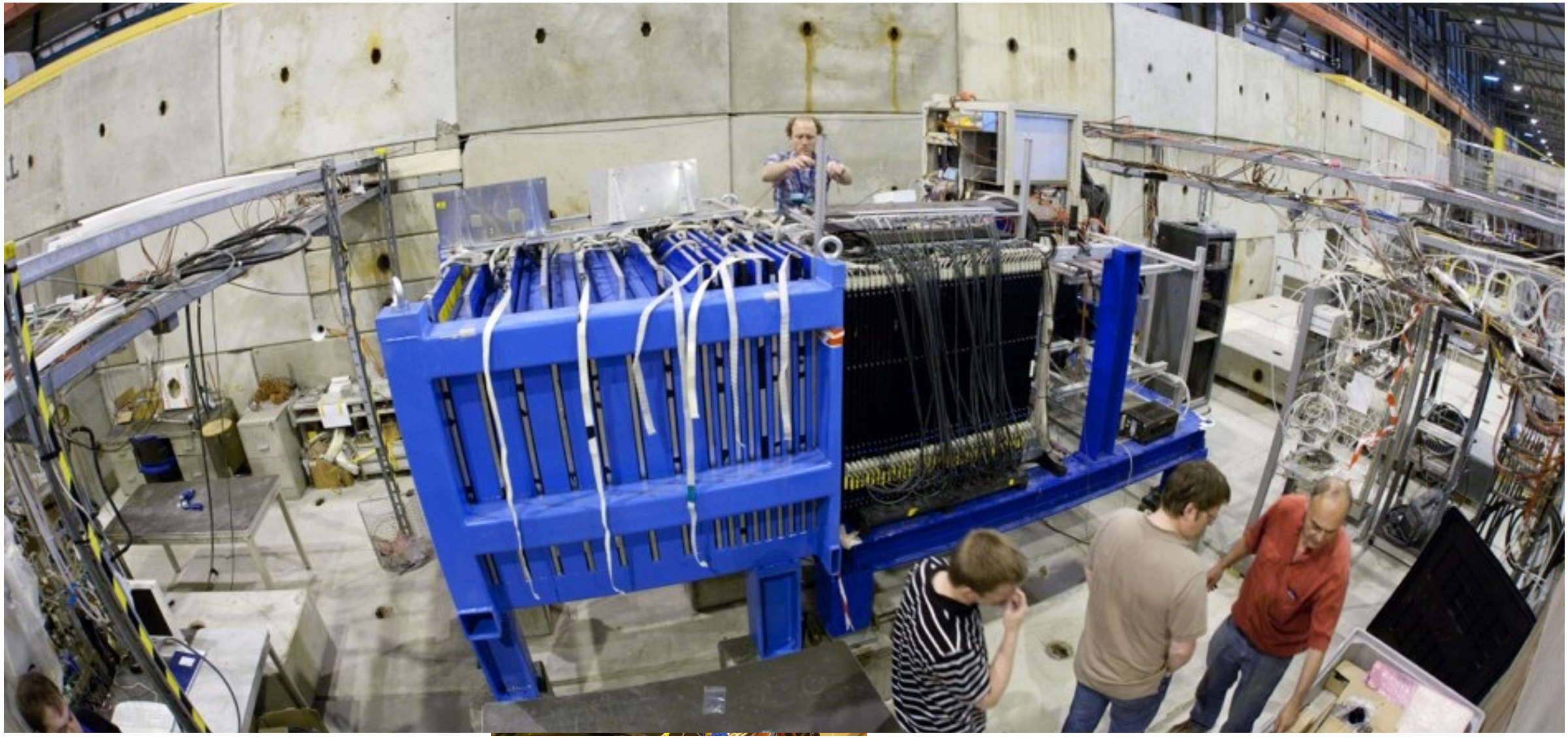
plus tests with small numbers of layers:

- ECAL, AHCAL with integrated electronics

- Micromegas and GEMs

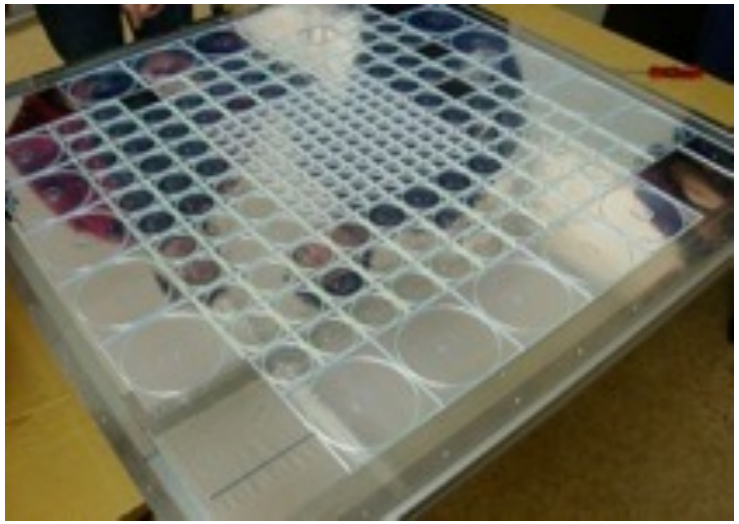
CALICE Test Beam Experiments

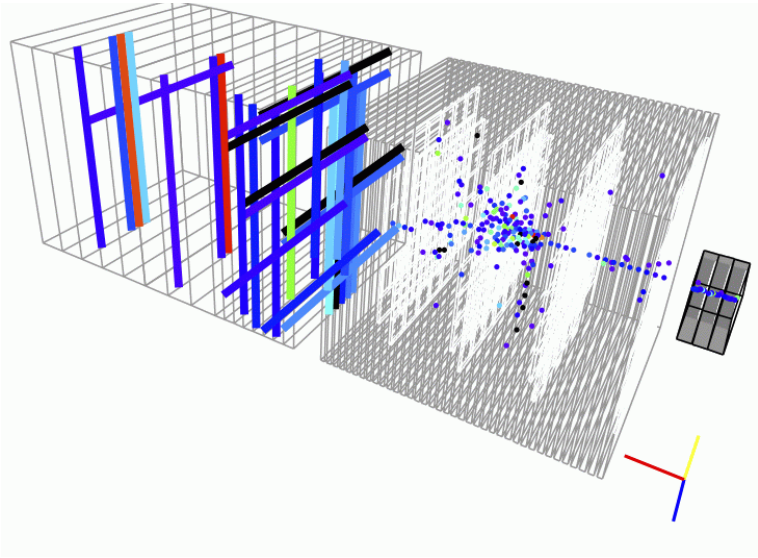
Large prototypes, complex systems.

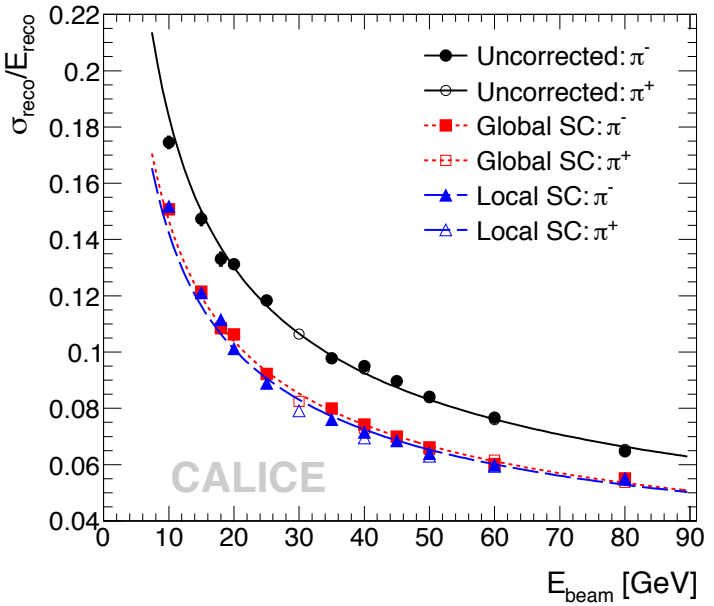


Proof-of-Principle

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

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

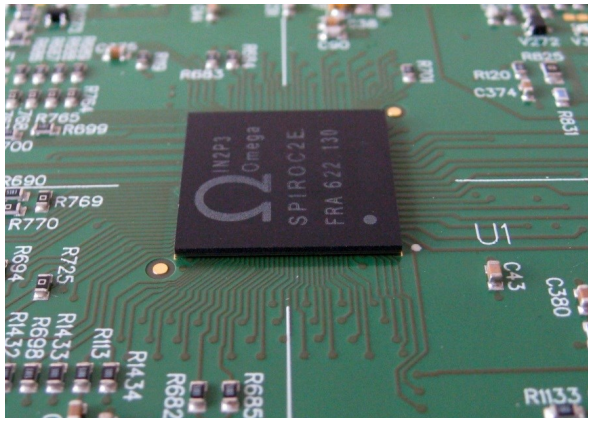
software compensation
now implemented in Particle Flow

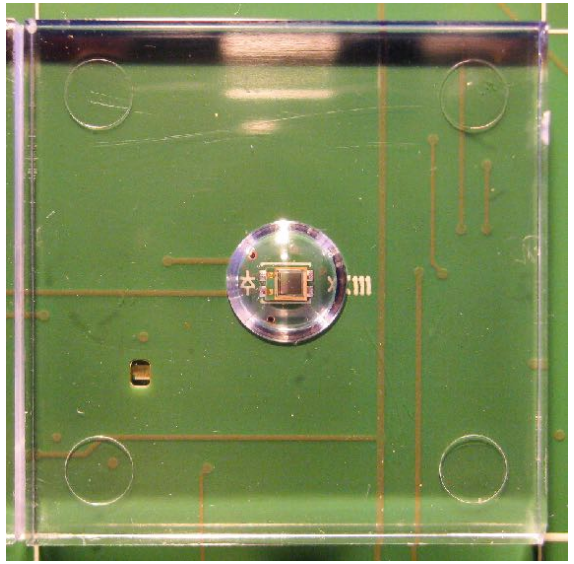
Eur. Phys. J. C77 (2017) 698

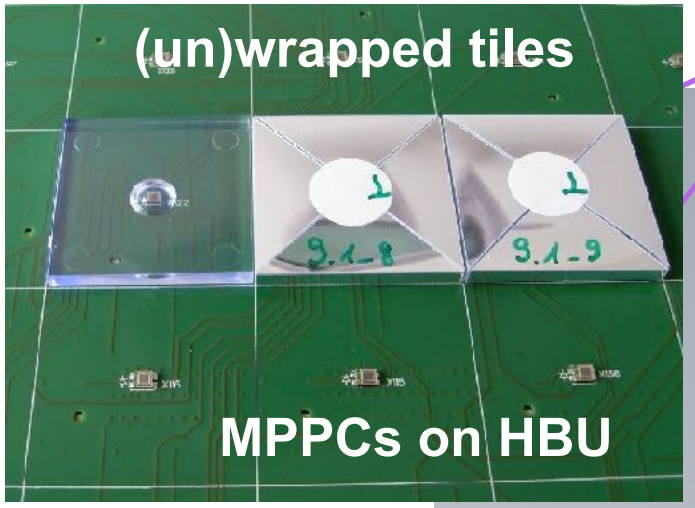
Rev.Mod.Phys. 88 (2016) 015003

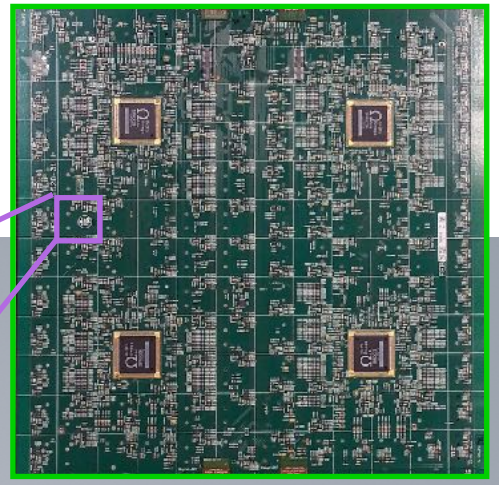
The Next Step: Scalability

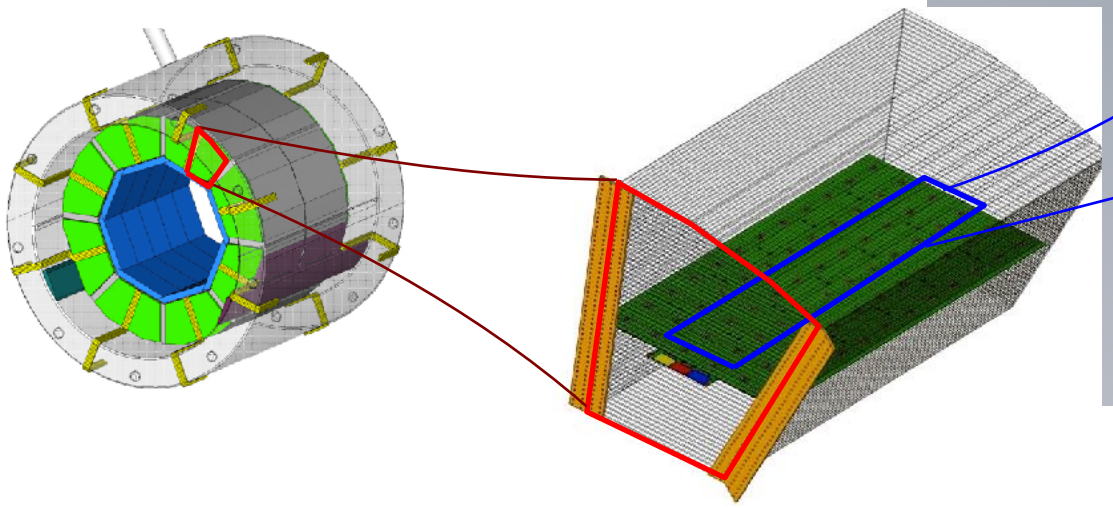
Technological prototypes.

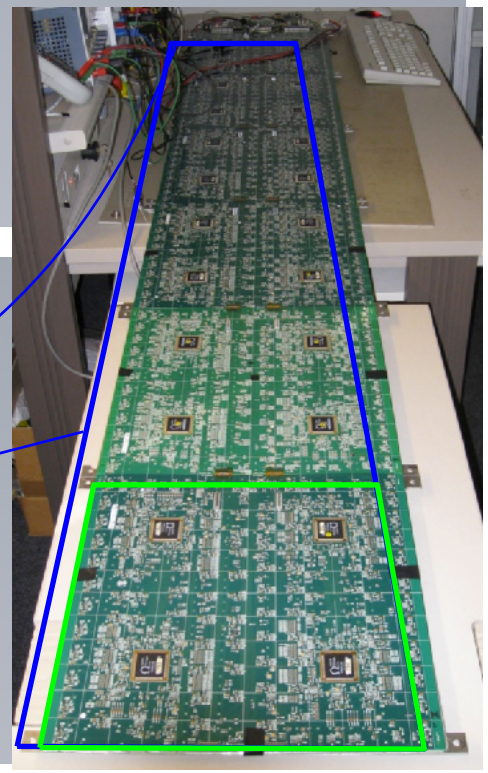










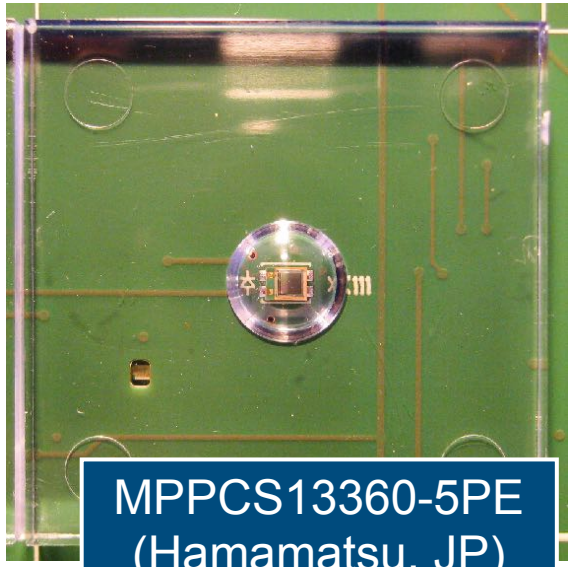


- 1000's of channels per m^2
- 1000's of m^2
- must embed electronics and go digital as early as possible; power pulsing
- Integrate SiPMs in read-out board, too

The Next Step: Scalability

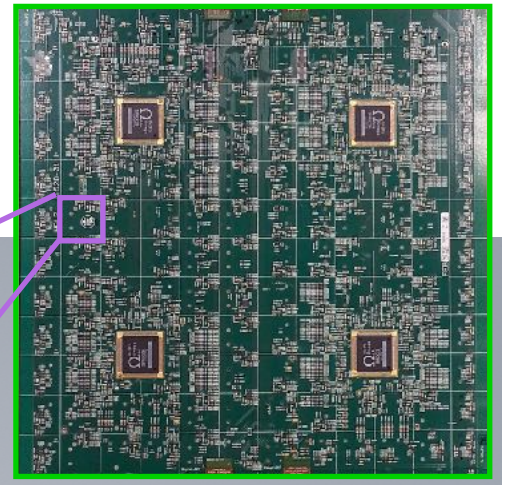
Technological prototypes.

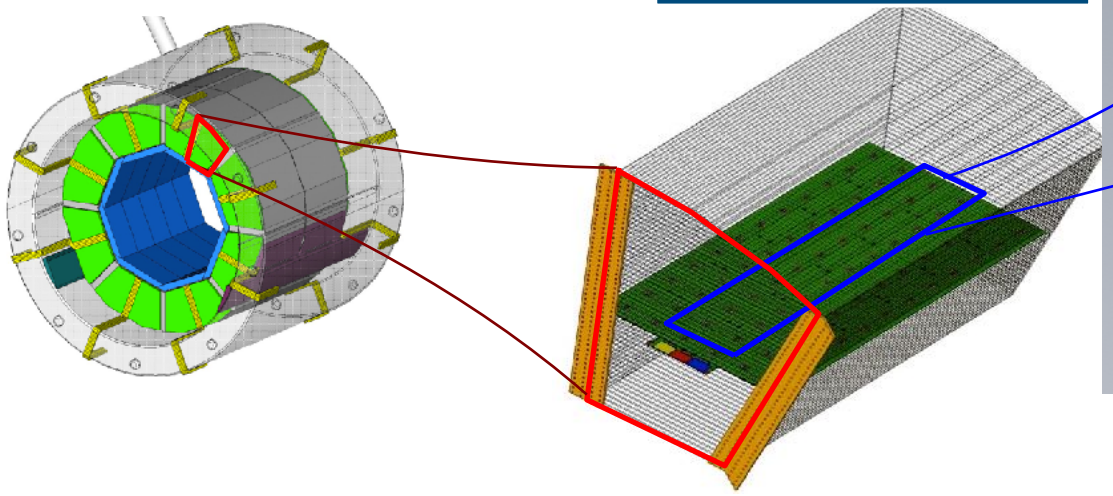
SPIROC2E
(OMEGA, F)

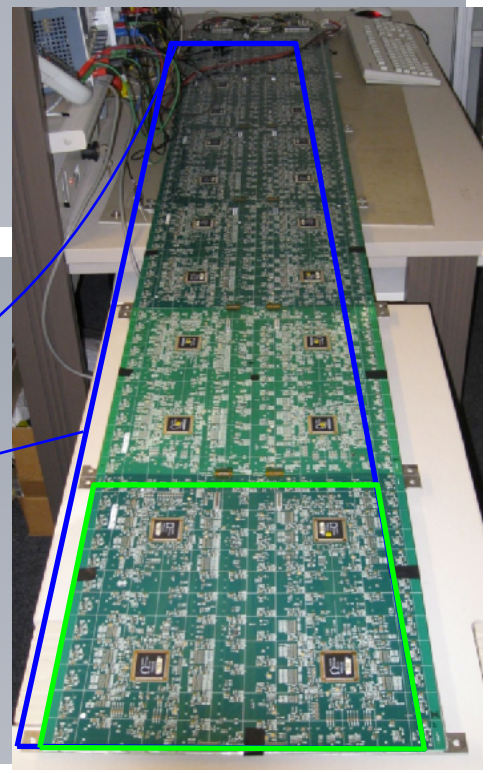


MPPCS13360-5PE
(Hamamatsu, JP)

polystyrene tiles
(Uniplast, RU)
with ESR film







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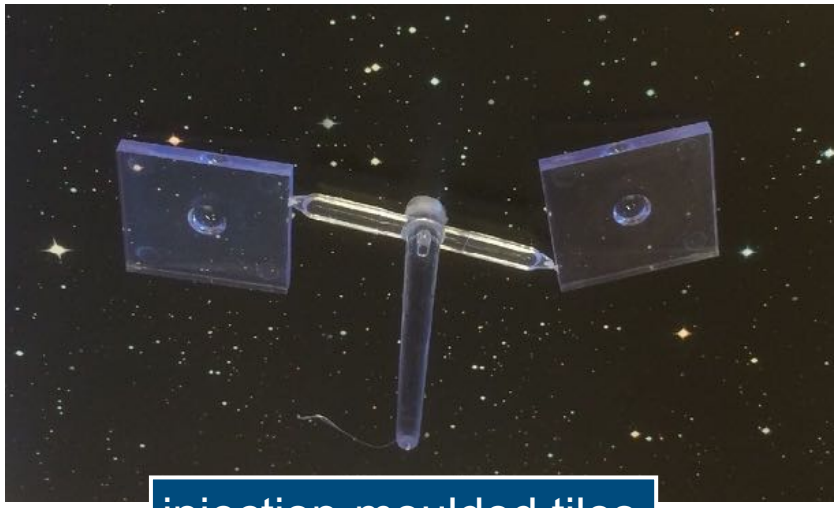
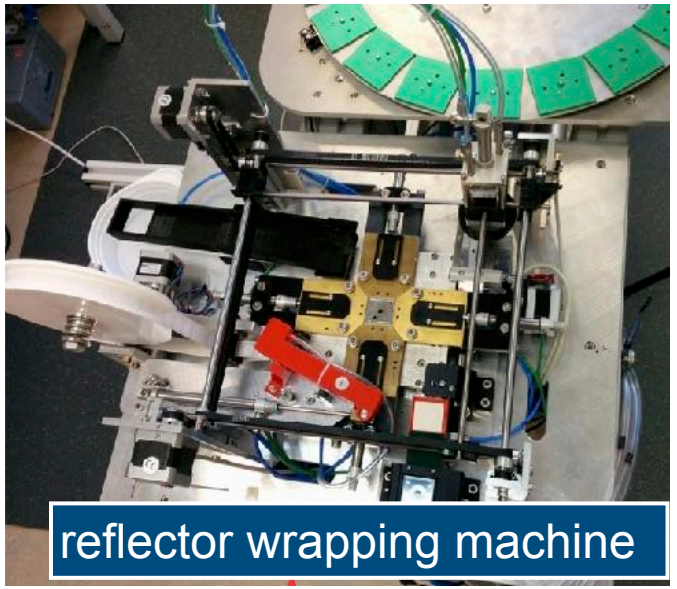
Automated Production and Quality Assurance

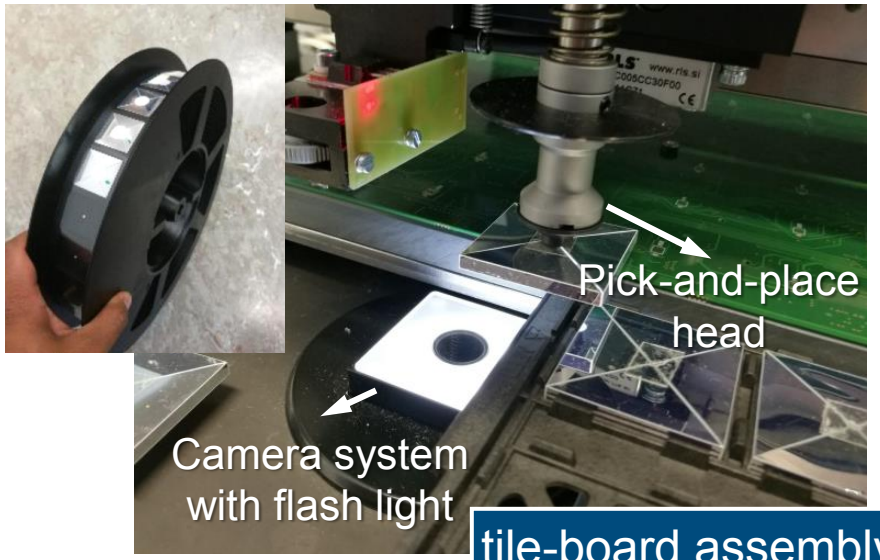
Establishing the concept.



injection-moulded tiles



reflector wrapping machine

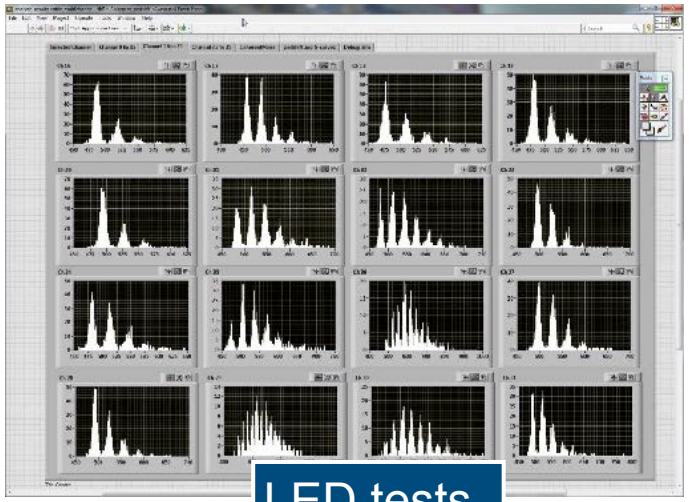


tile-board assembly

In addition test infrastructures:

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

read-out boards

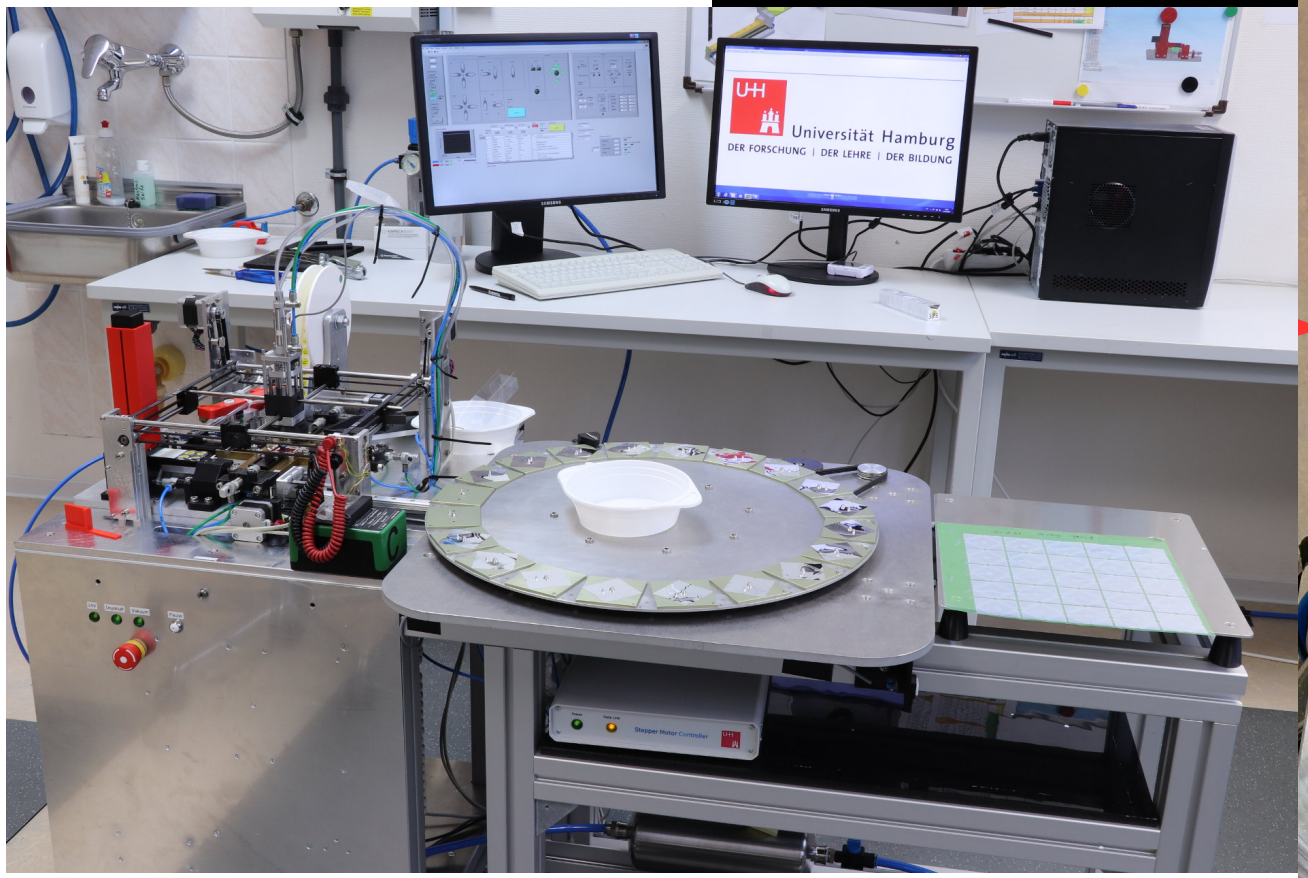


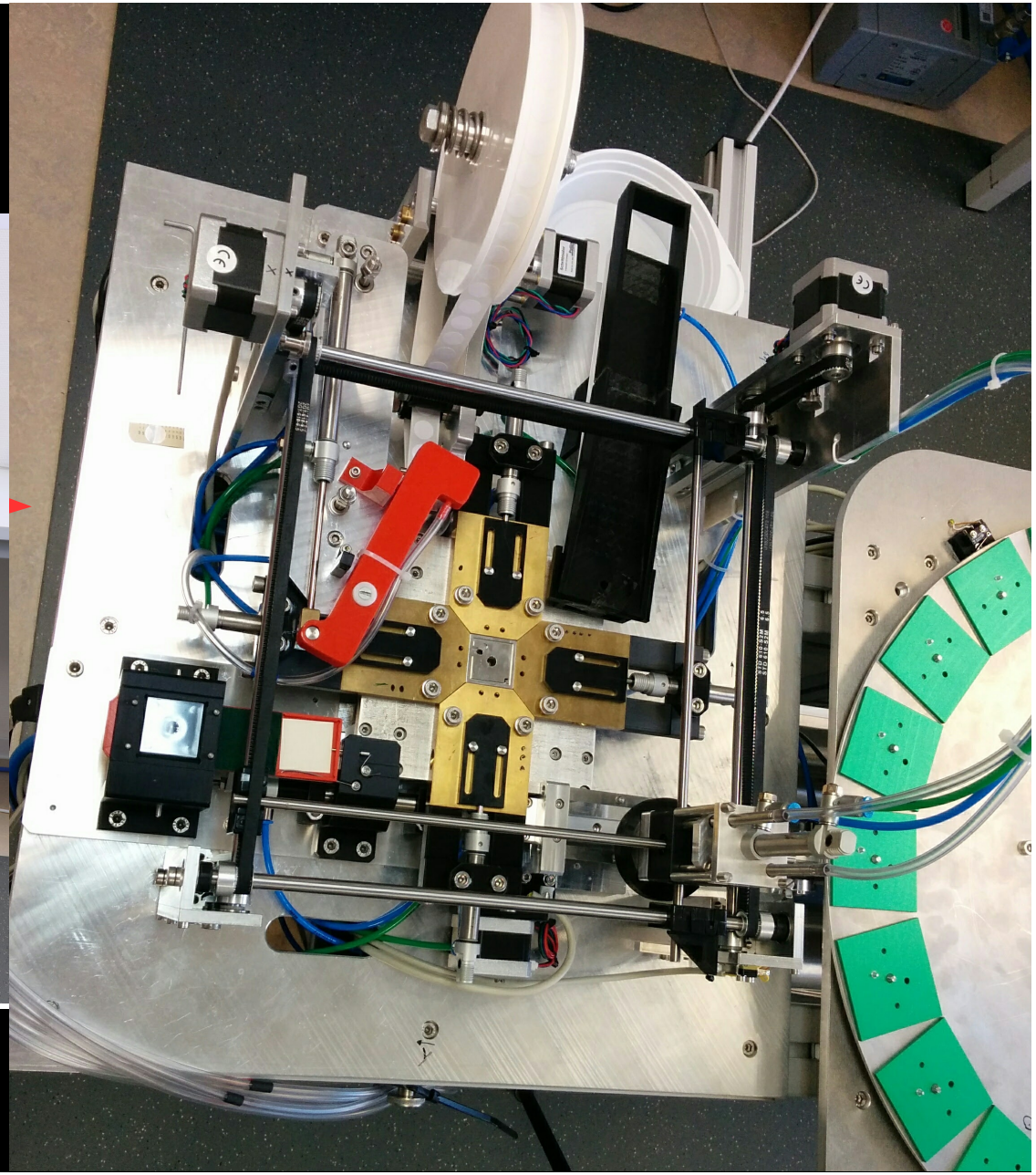
LED tests

AIDA2020

Tile Wrapping

Custom-made machine





- University of Hamburg

start in October

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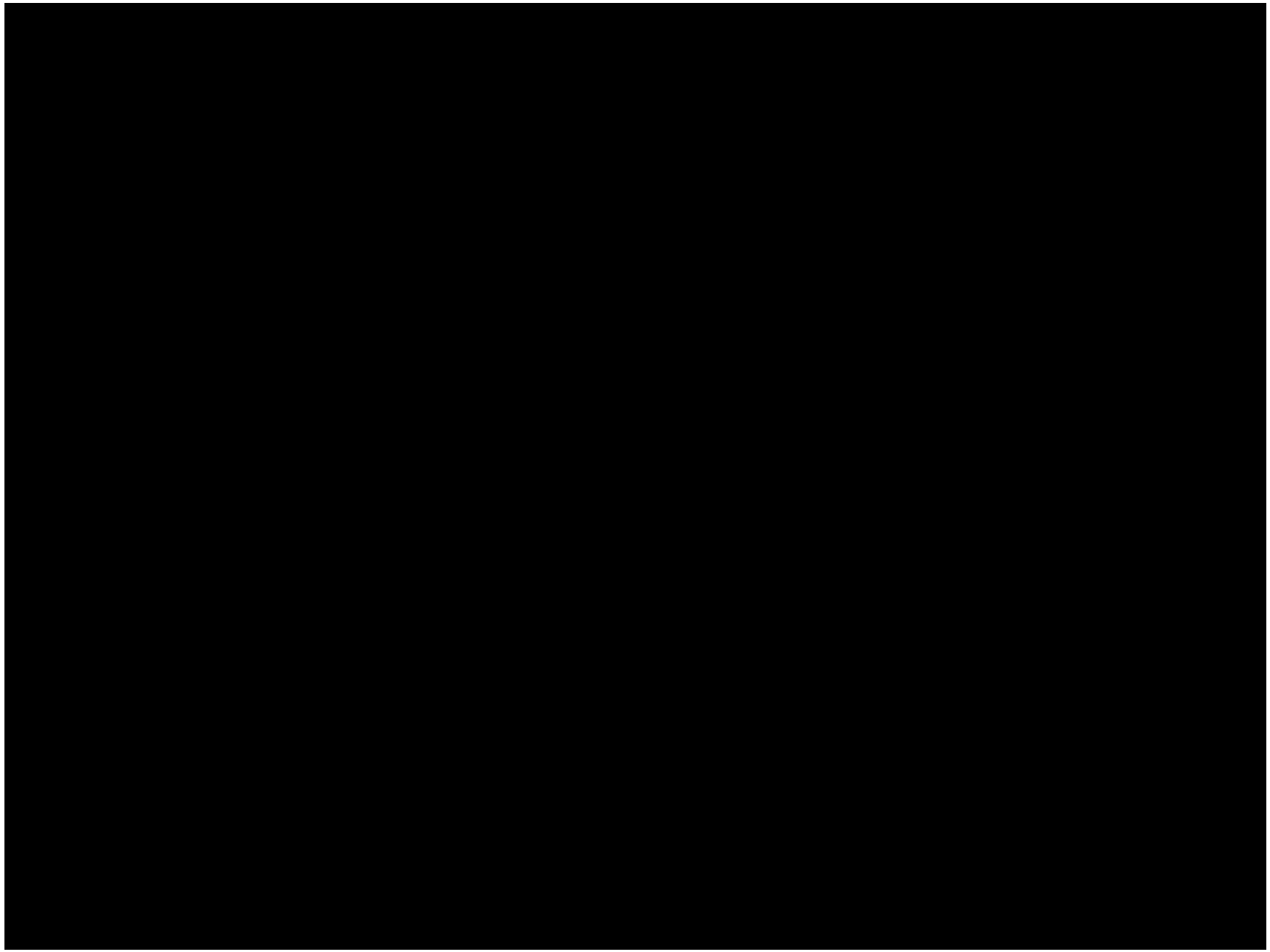

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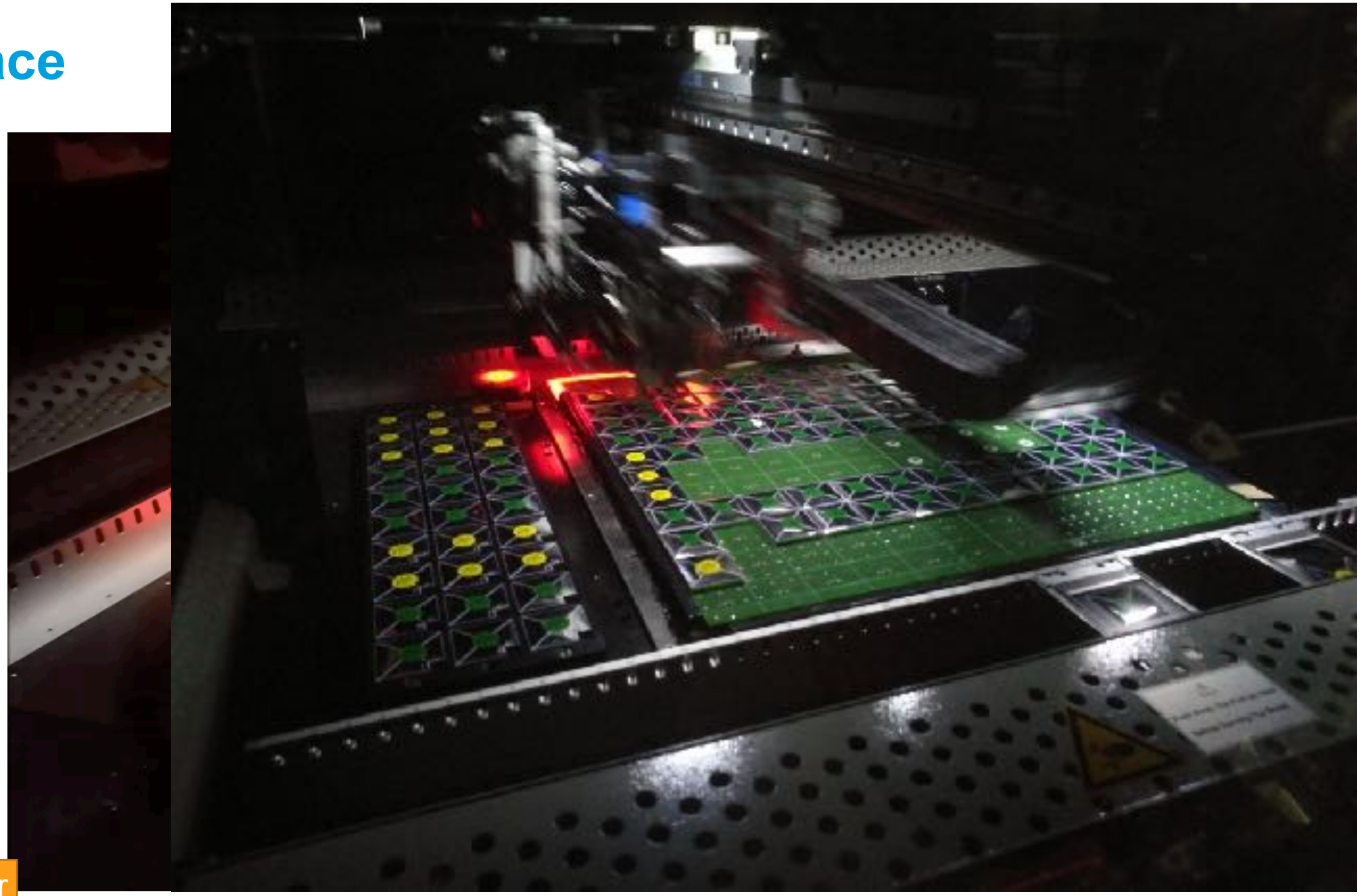
start in October

Pick & Place

Standard Machine



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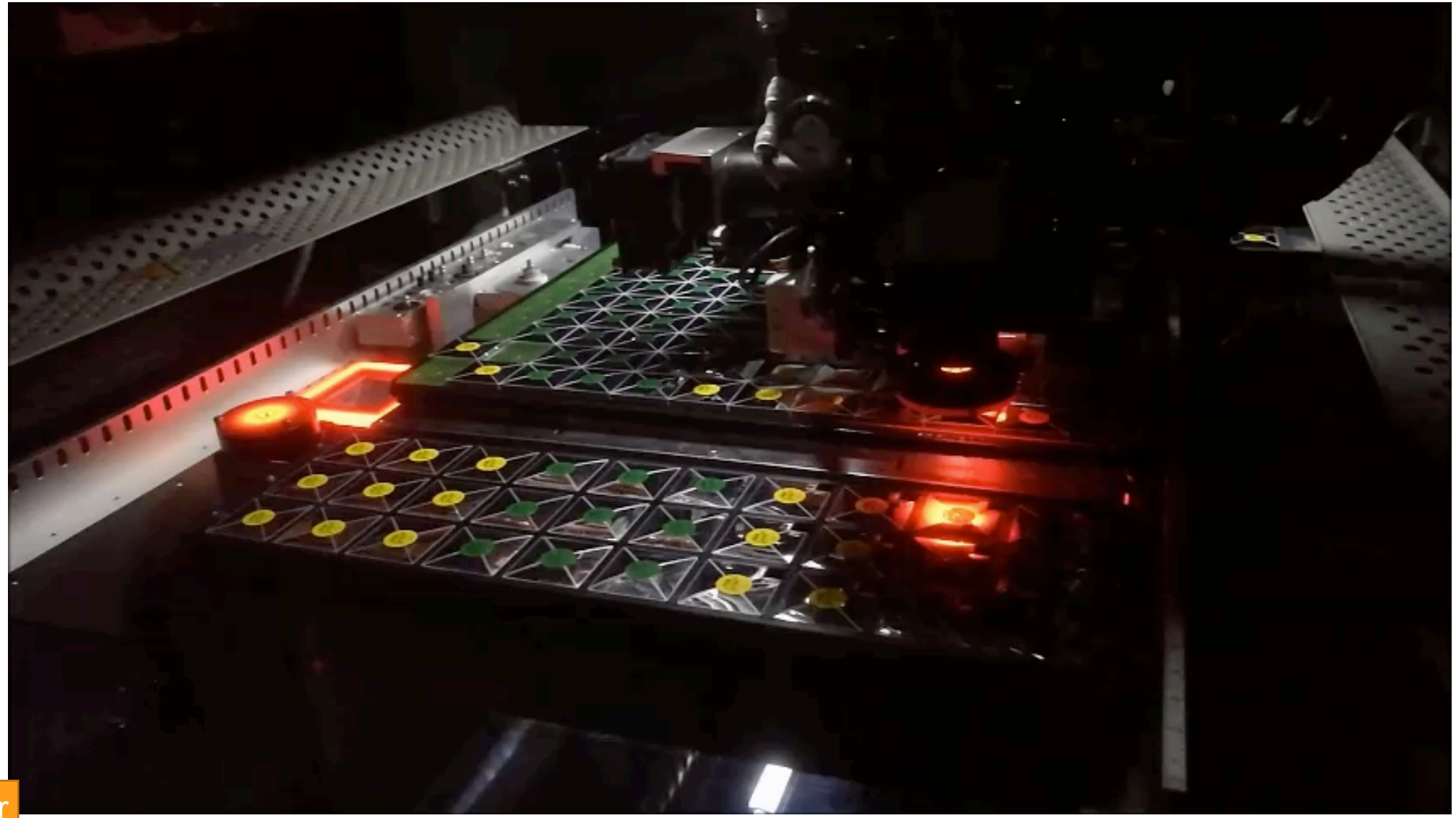

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Quality Assurance

at Each Step

Tiles:

- spot checked for mechanical tolerances
- some deviations affected automatic wrapping

SiPMs:

- spot checked for break-down voltage gain, noise, cross-talk
- all samples passed, excellent uniformity

ASICs:

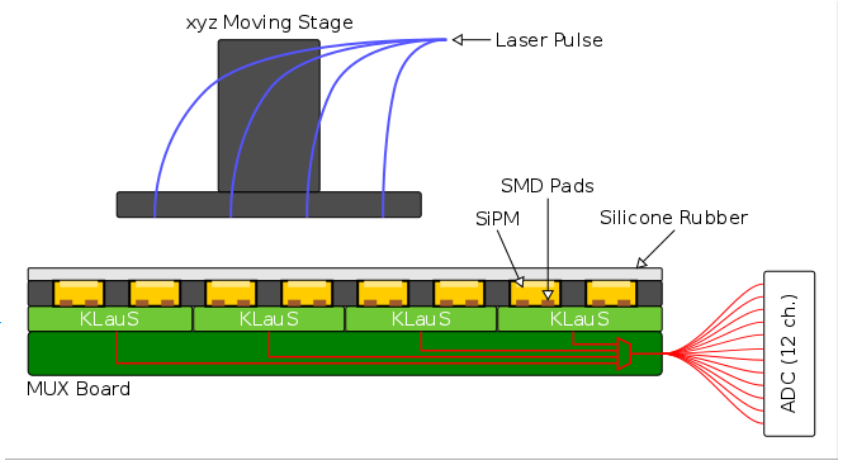
- semi-automated tests on dedicated board, yield ~ 80-90%

HBUs (bare):

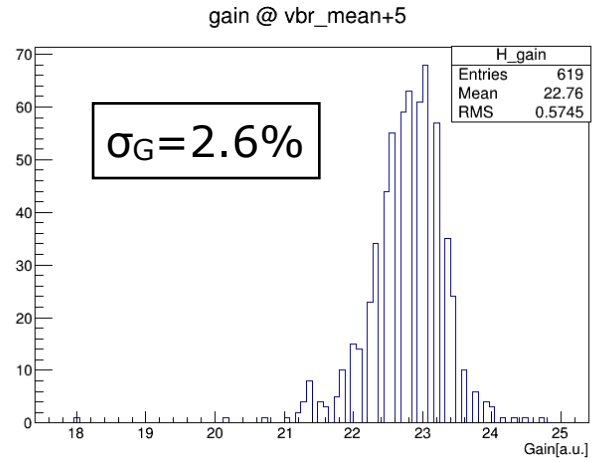
- tested with integrated LED system before mounting tiles (see previous page)
- 158 out of 160 boards OK

HBUs with tiles:

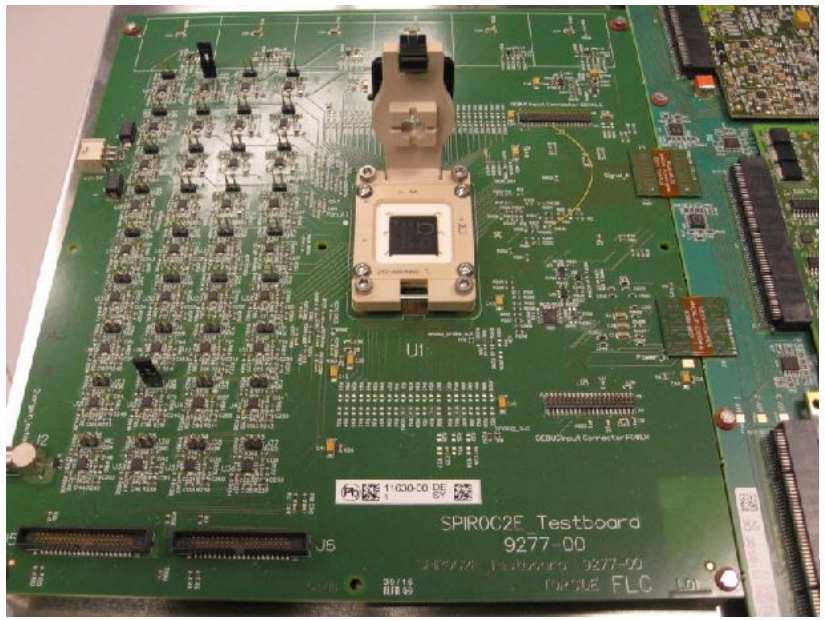
- Cosmics tests
- Most boards: very good light yield uniformity

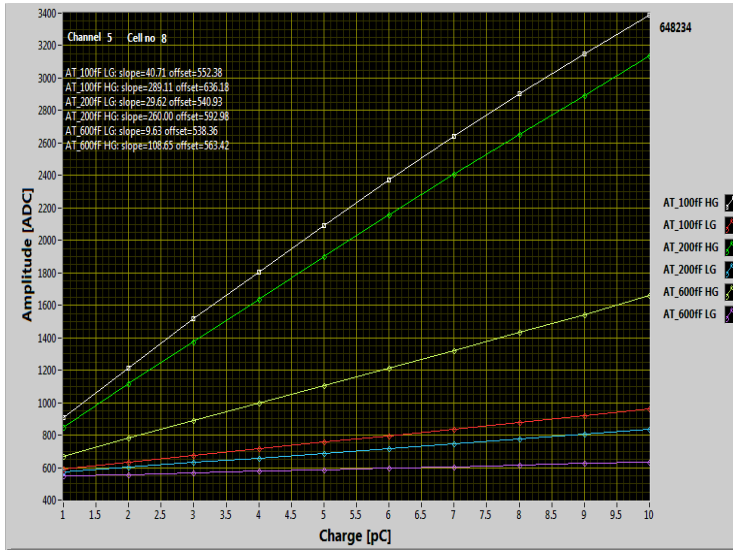


SMD SiPM schematic view



U Heidelberg





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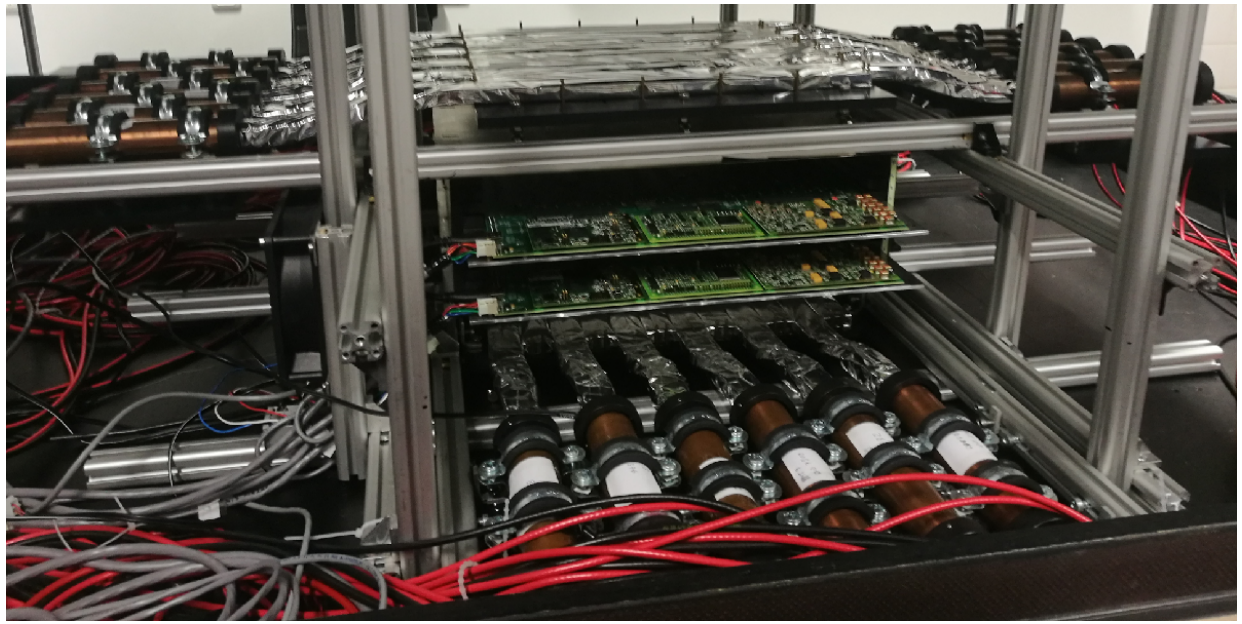
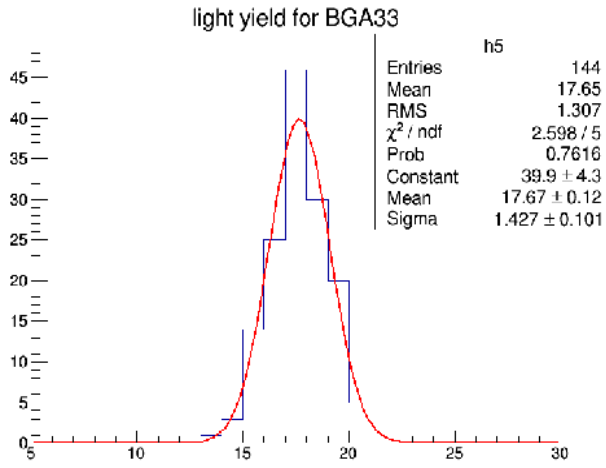
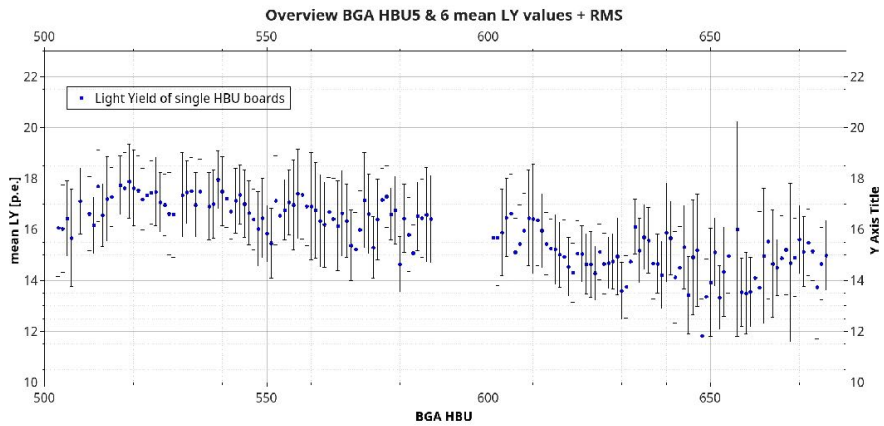






U Mainz

Active Layers: Cosmics and Beam

Cosmics and Beam Tests

Layer integration:

- one set of interface modules serves up to 18 HBUs
  - DIF: DAQ interface, data concentration,
  - CALIB: LED control
  - POWER regulators, distribution, cycling capacitances

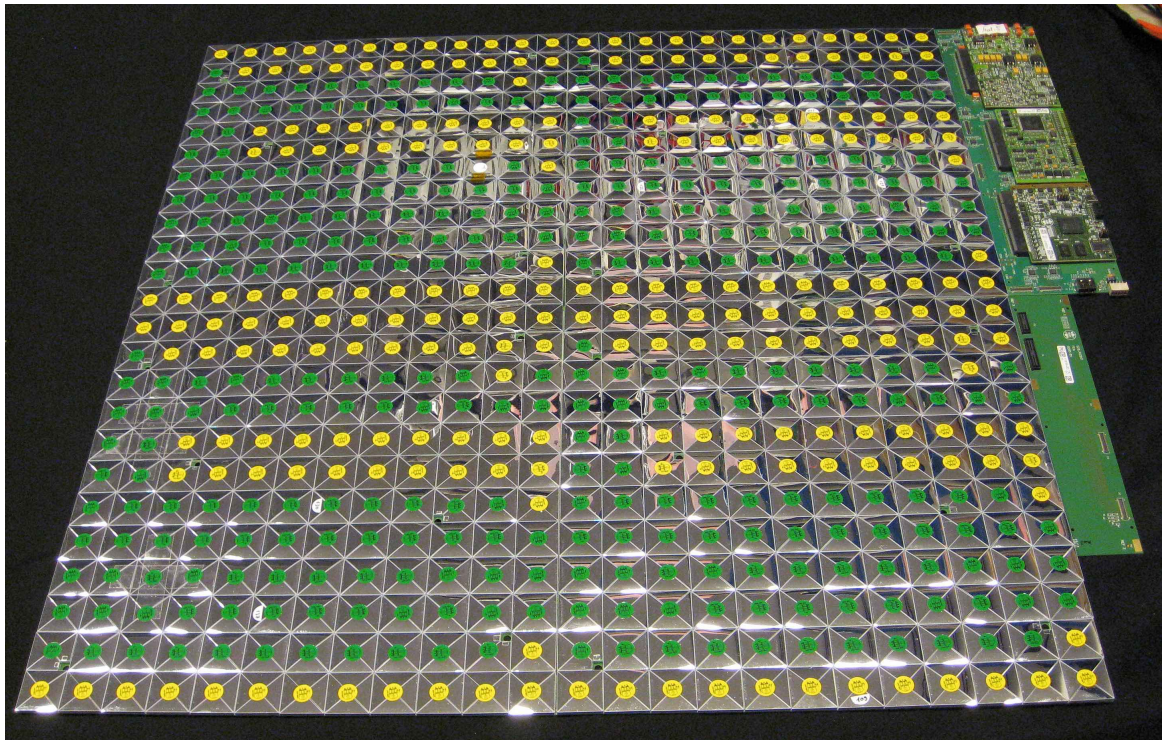
Commissioning with cosmic muons:

- strip hodoscope for central area
- light yield and DAQ stability

Commissioning with DESY electron test beam:

- 5 layers at a time in “air stack"
- automatic scan for all channels
  - movable stage controlled by DAQ
- **initial MIP calibration**
  - active temperature compensation ensures portability

8 dead channels out of 21’888 total



January - March

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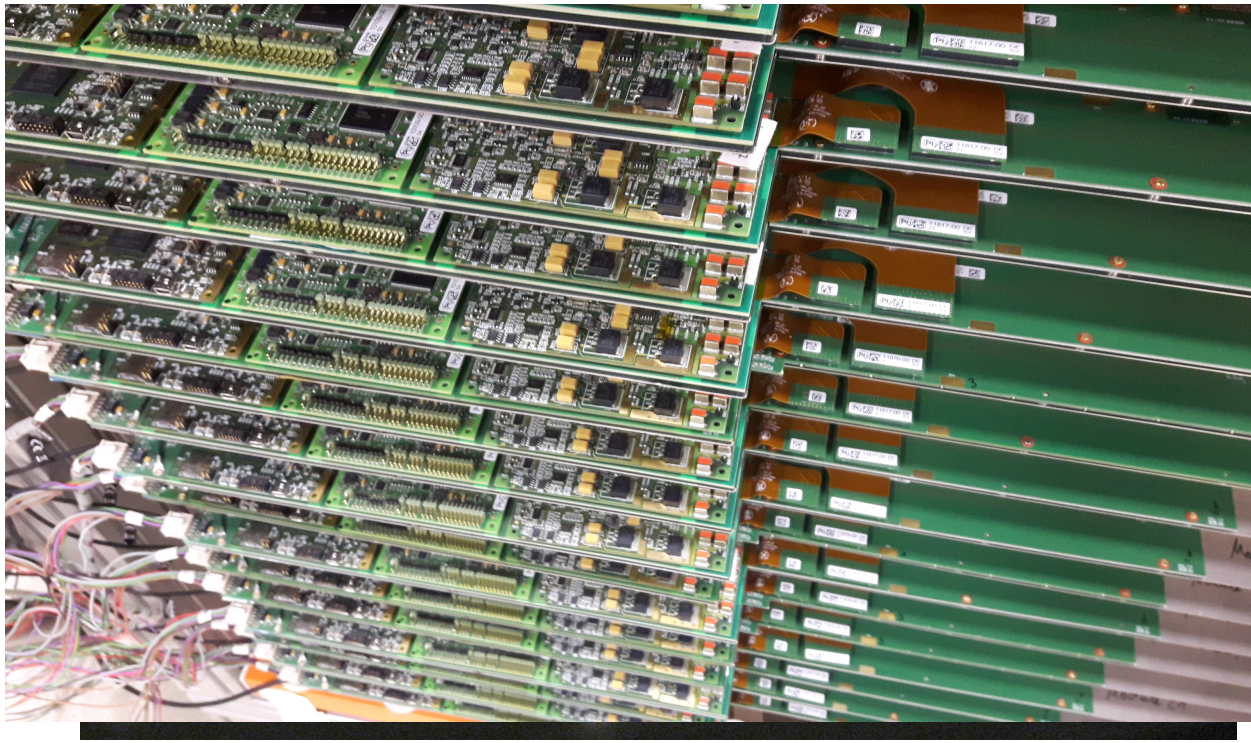

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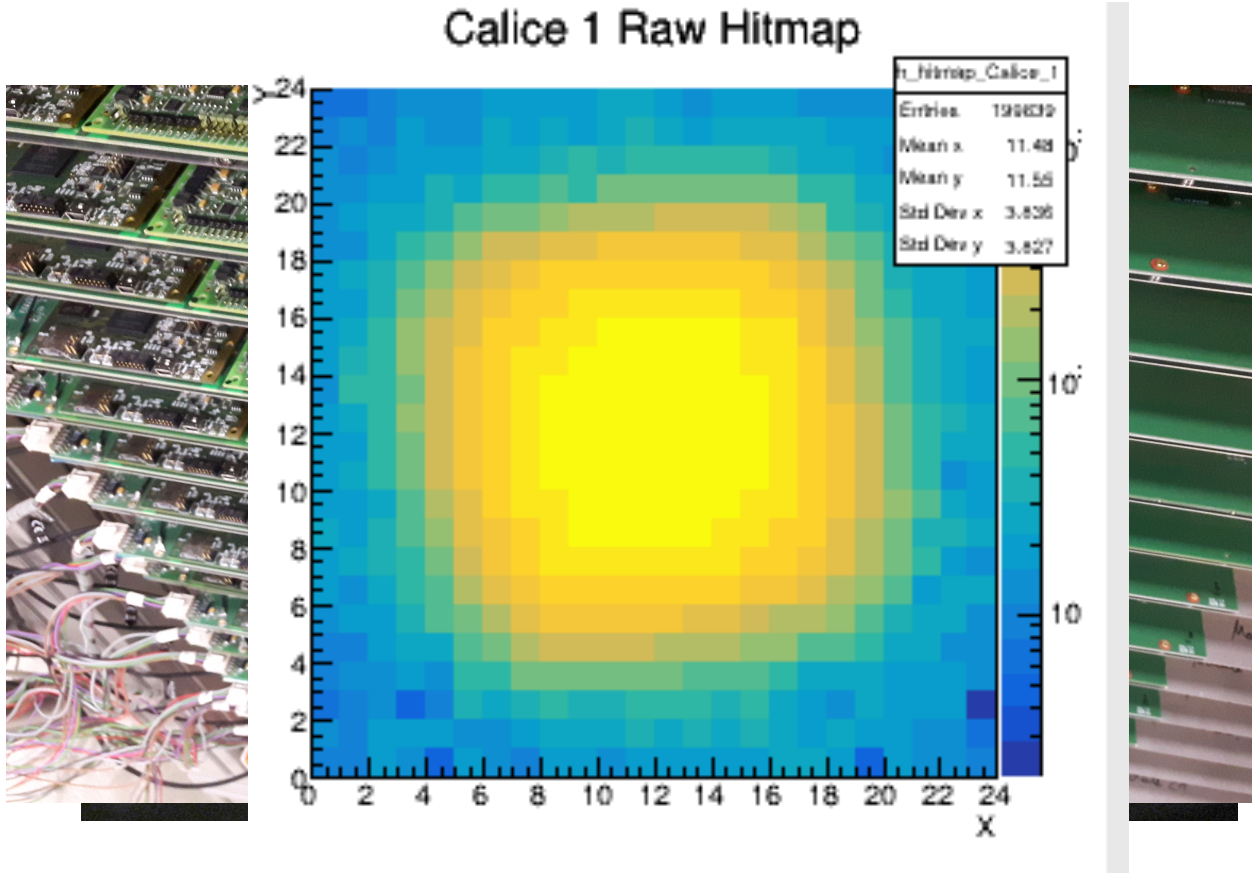

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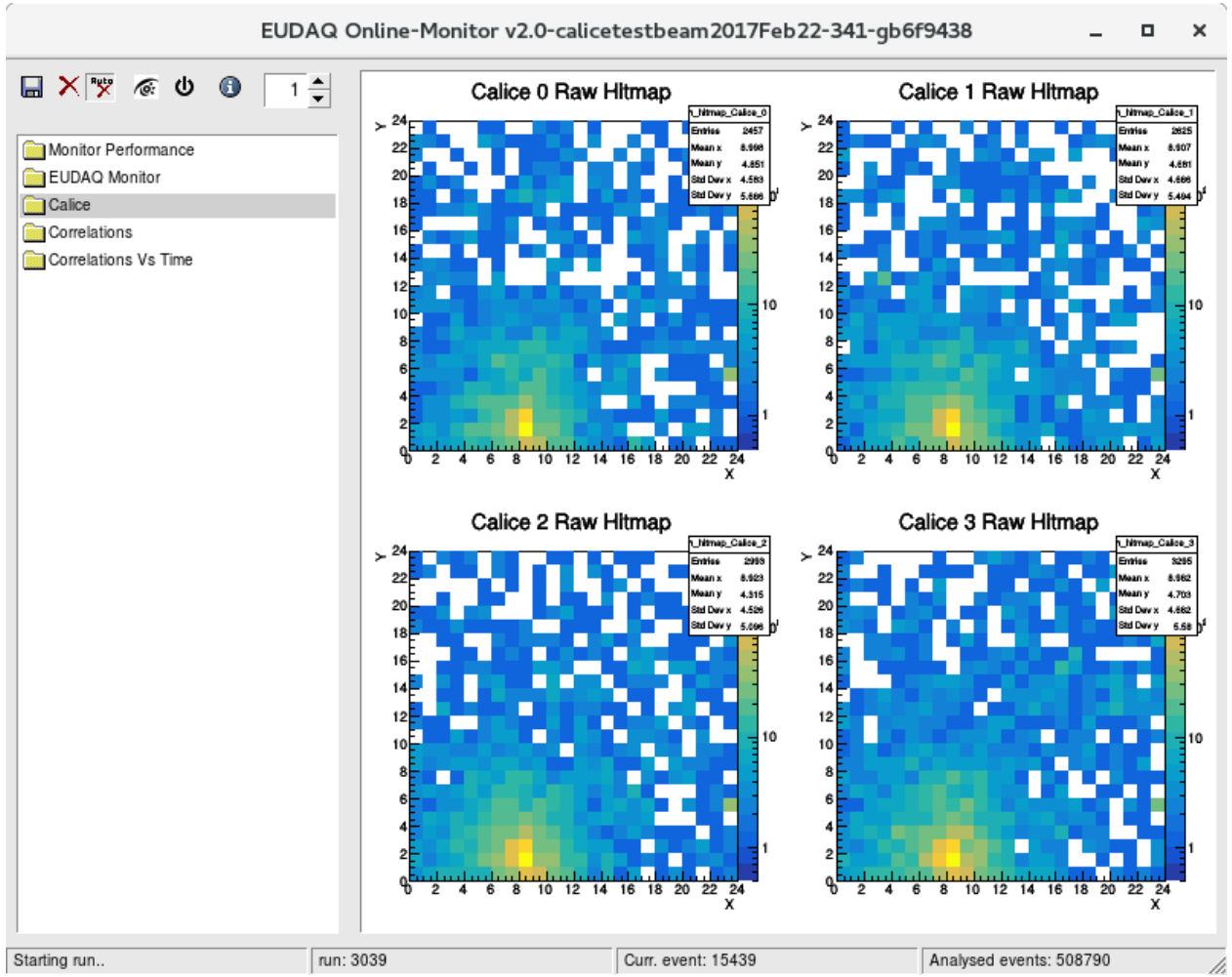

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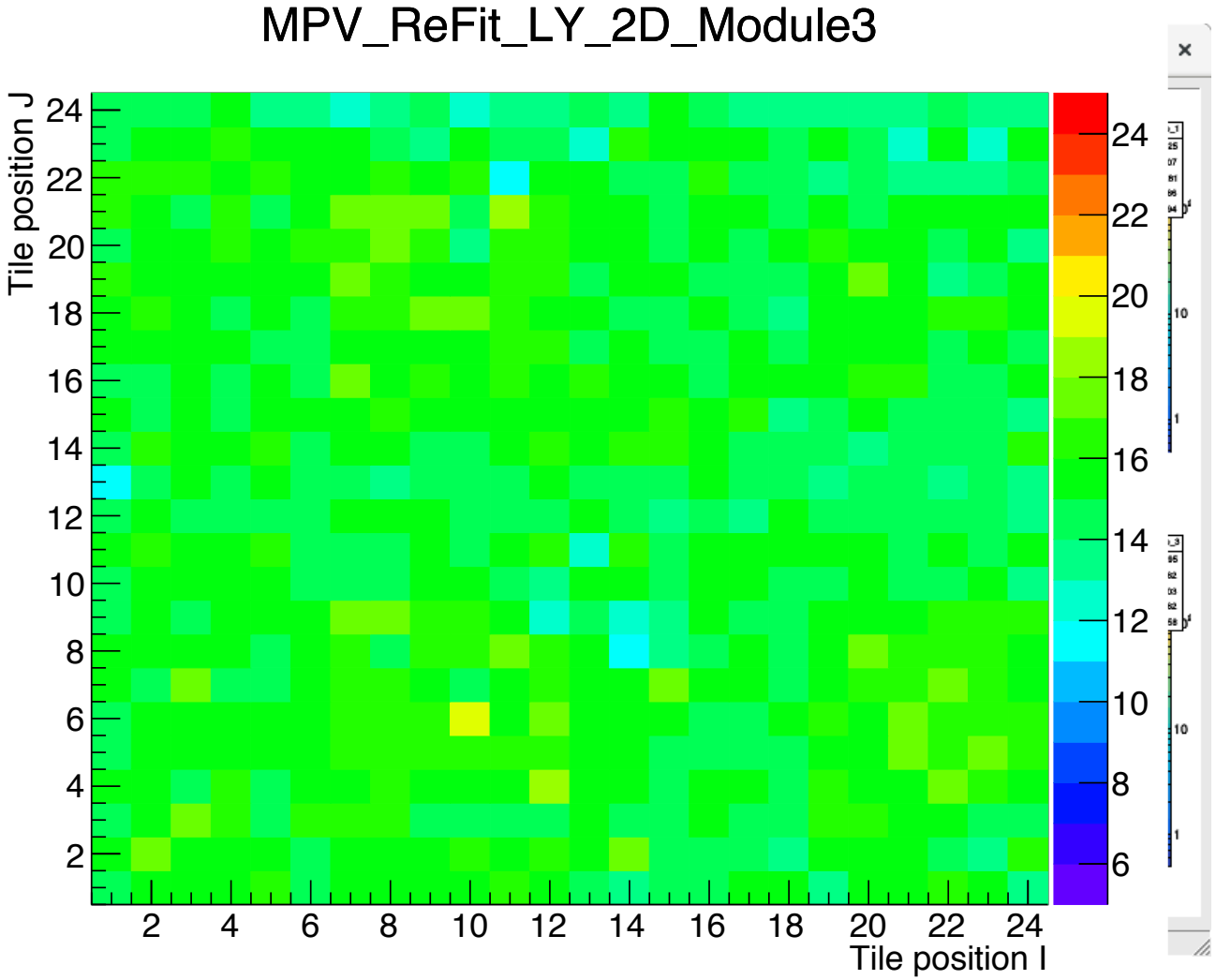

MIP MPV from DESY electrons

Stack integration

and Cosmic Test

Stack services dimensioned for full collider detector module

- Data concentration
  - output via single ethernet line
- Power distribution
  - 3 voltages per layer
- Cooling
  - pipe cross-sections suitable for “leak-less” operation

Commissioning with cosmics

- benefit from self-triggering capabilities
- test the full software chain

April

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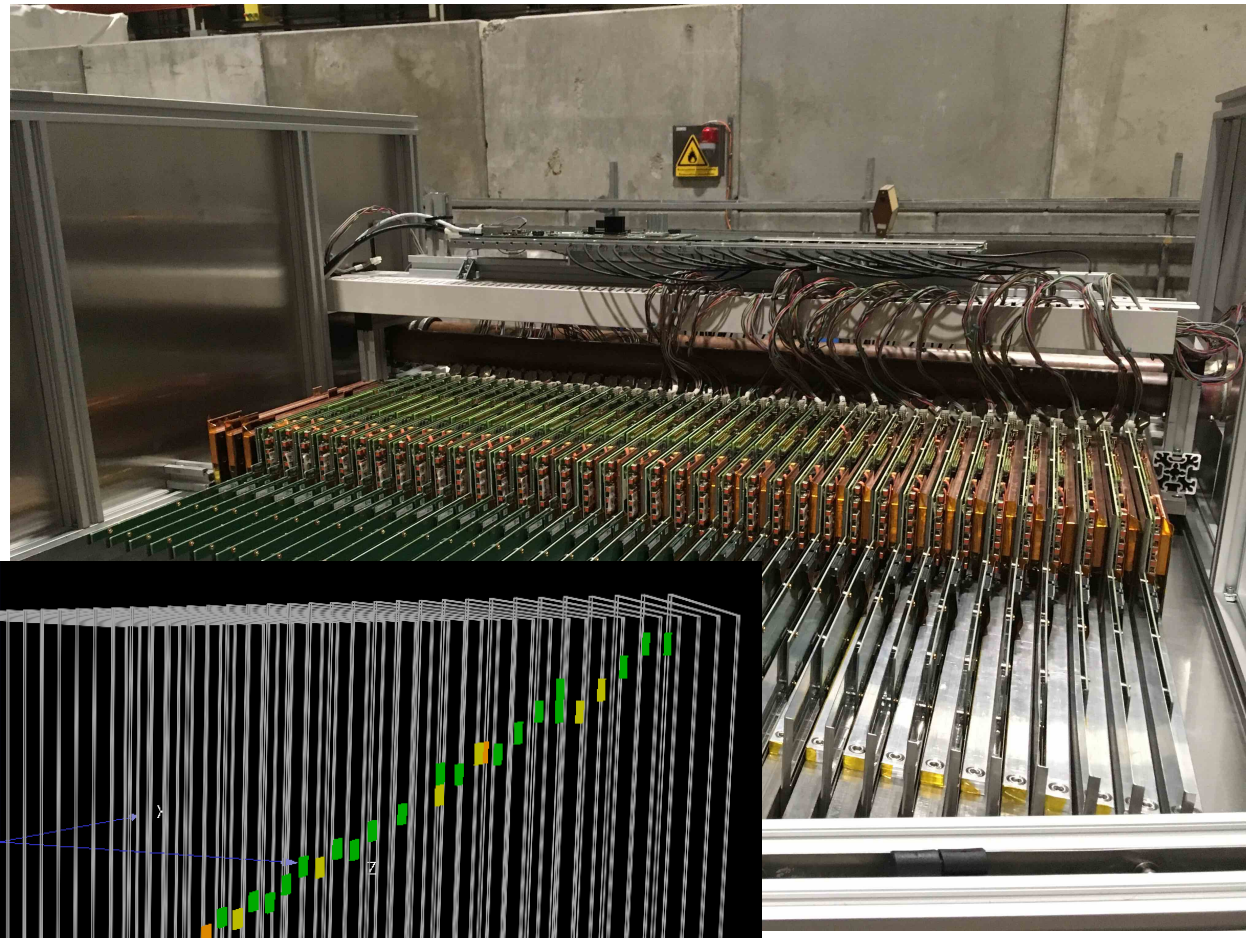

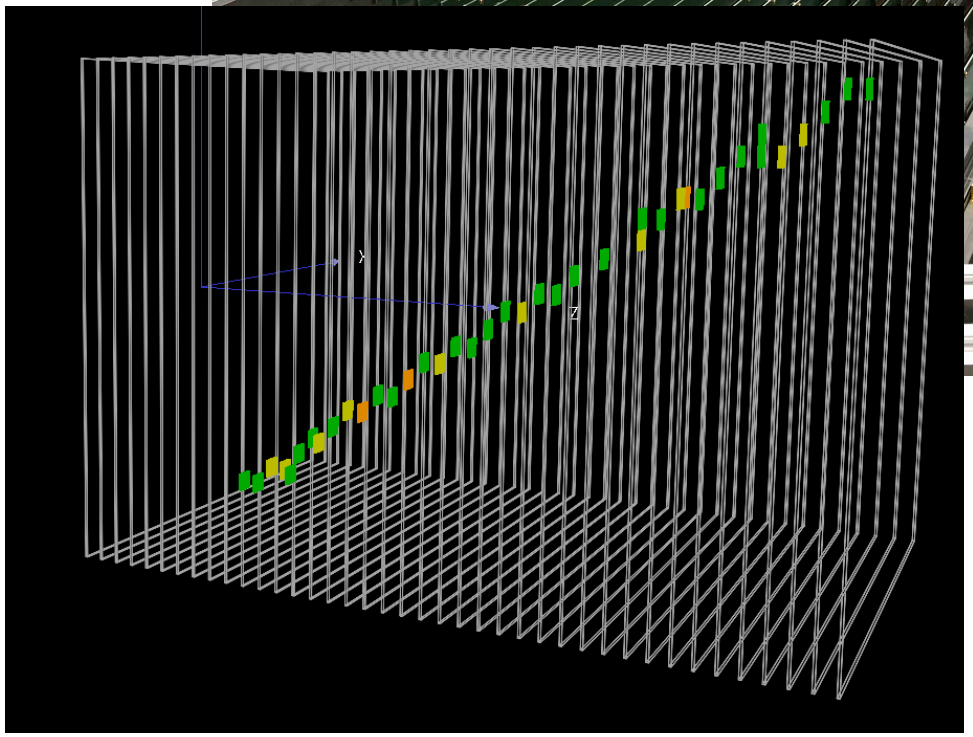

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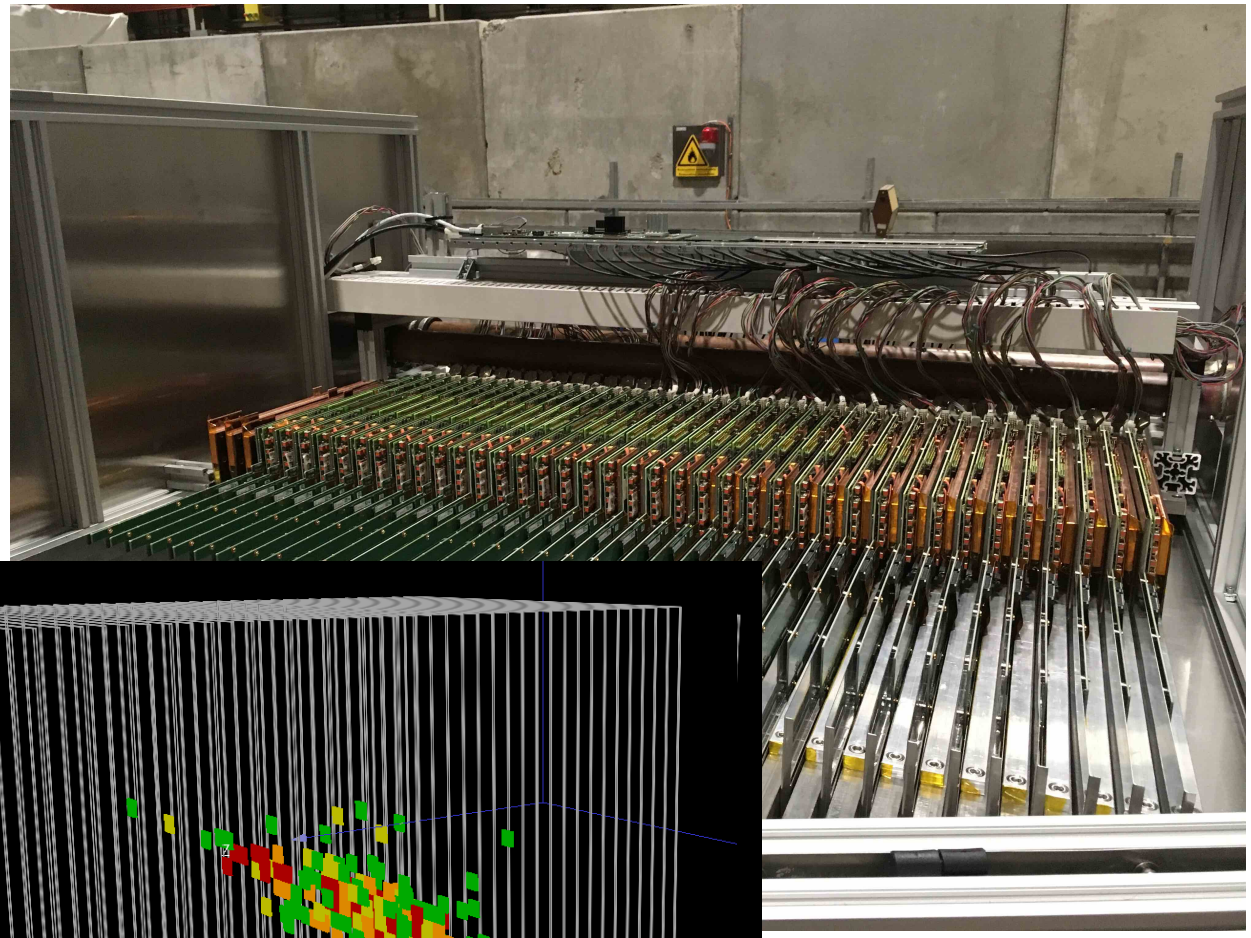

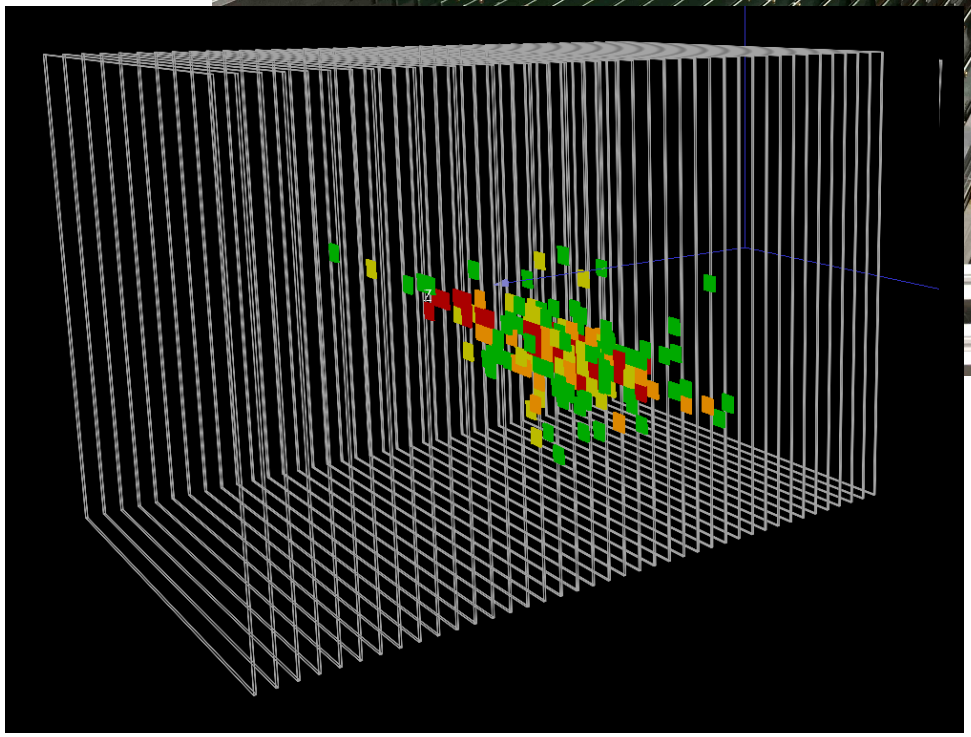

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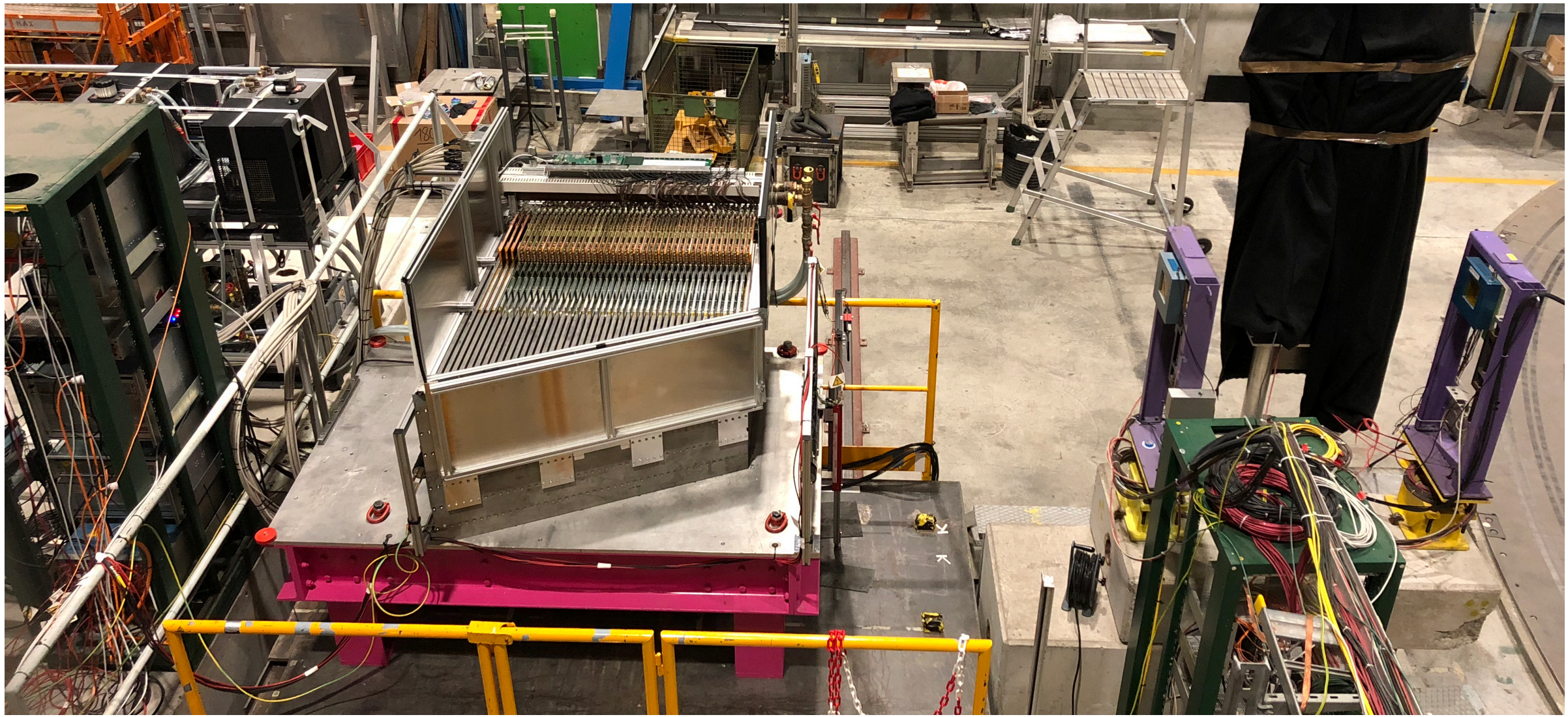
Test beam

May 2018 at CERN SPS



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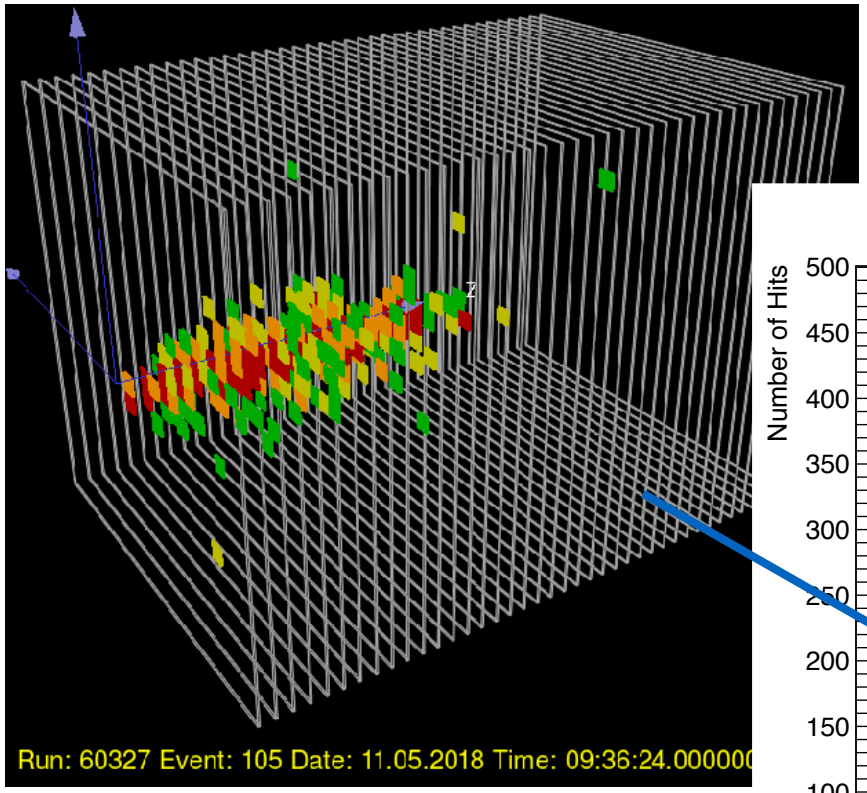
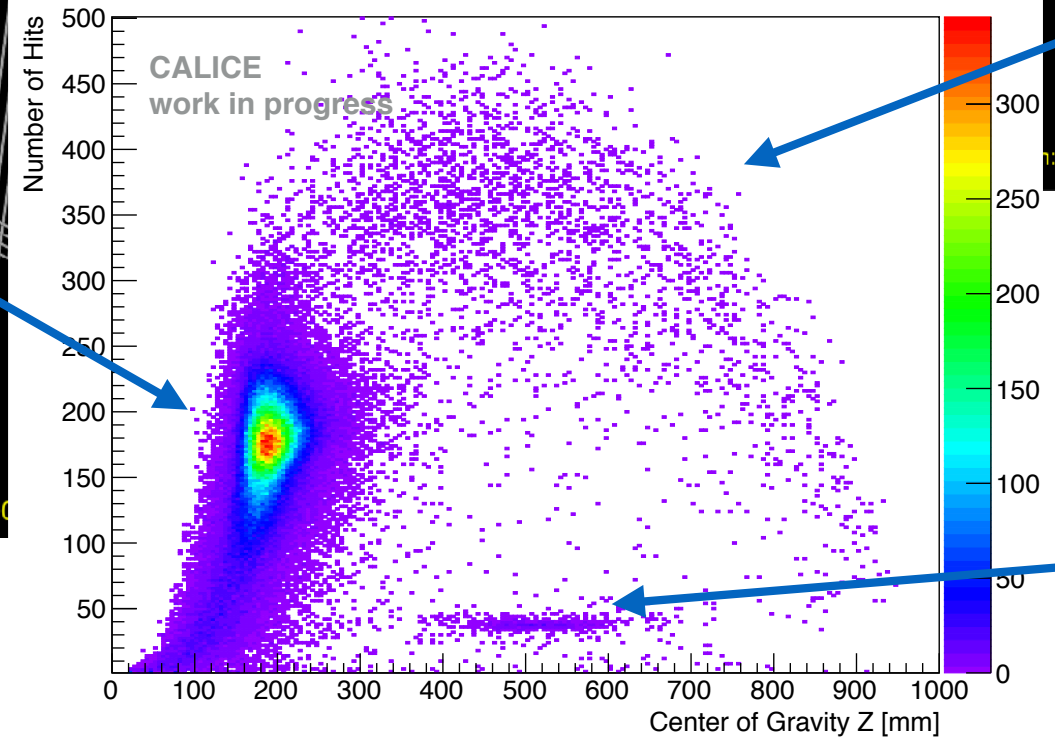
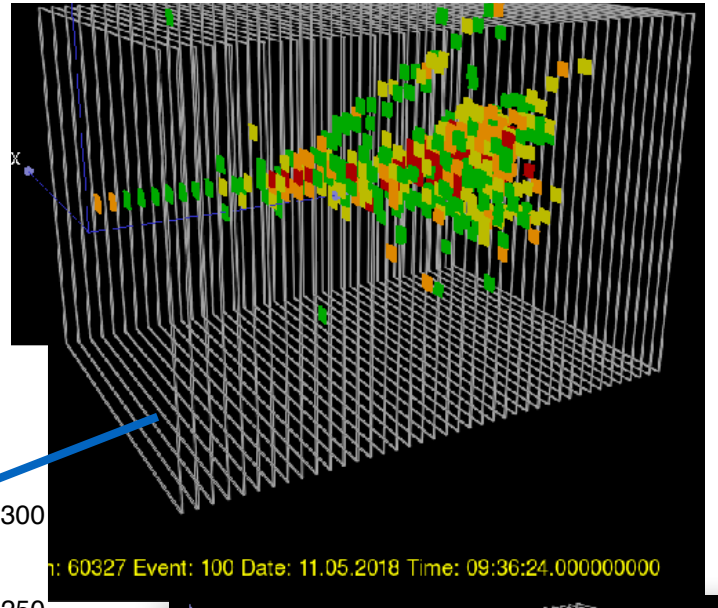
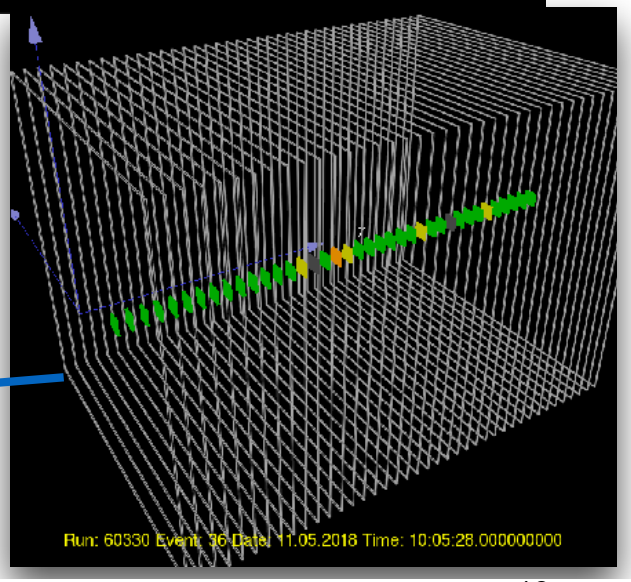




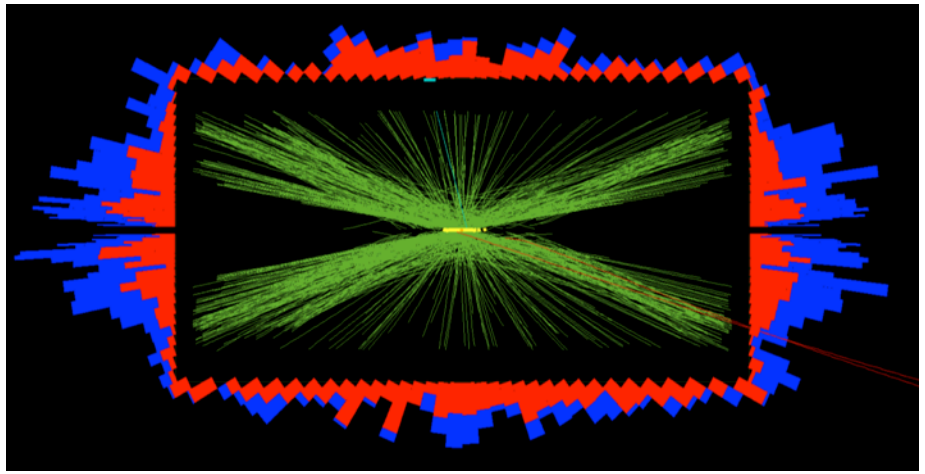




… to LHC

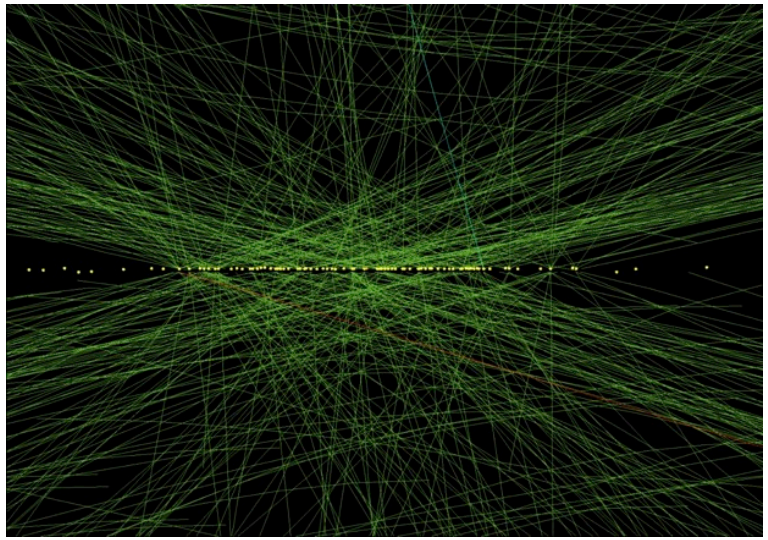
Pile-up and Radiation Damage

From sunny beaches to squalls and breaking seas



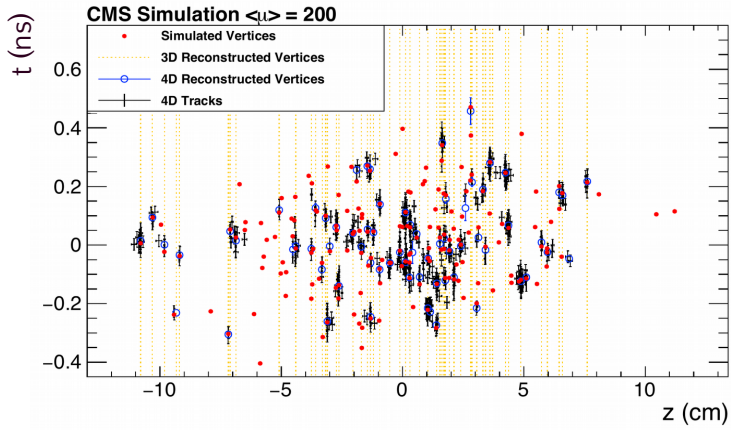
At HL-LHC expect 1 40-200 pile-up

~1x1016 1 MeV neq cm-2 @ 3ab-1 and up to 2 MGy absorbed dose in endcap calorimeters

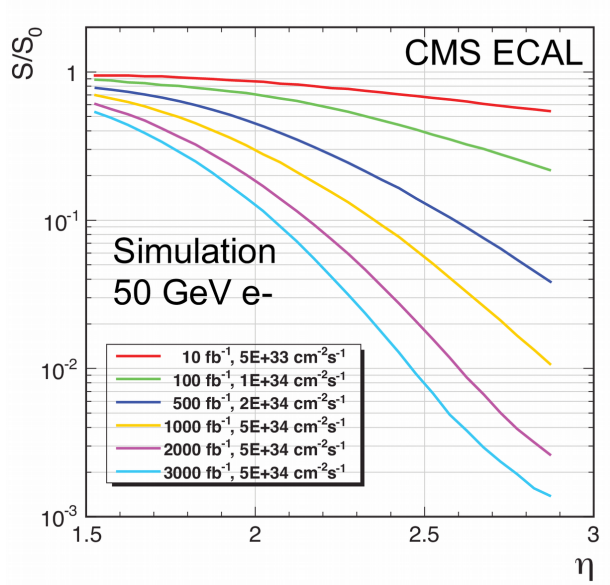


Need 10-30 ps timing resolution

Space-time view of the vertices



Relative response of the existing ECAL endcaps



J-B Sauvan

- Constant term grows to 10%
- The clock is ticking…

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

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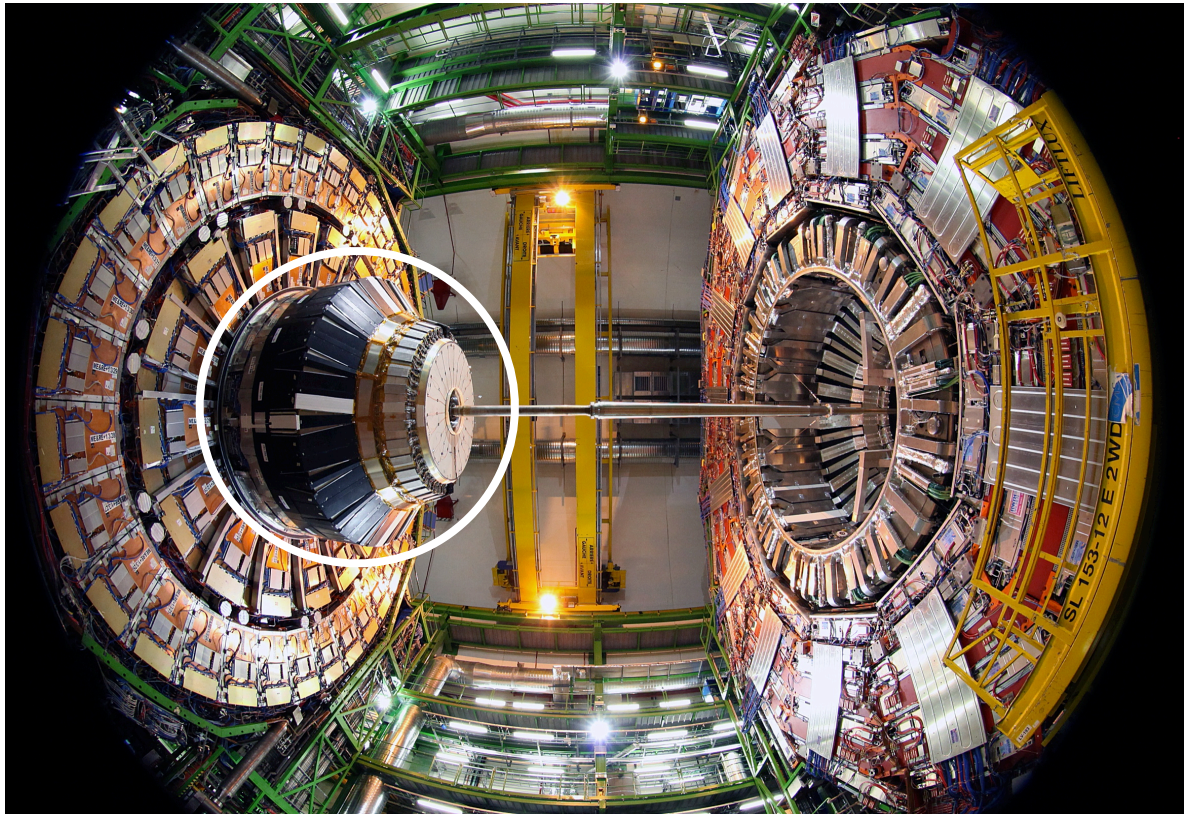
Largely building on CALICE developments



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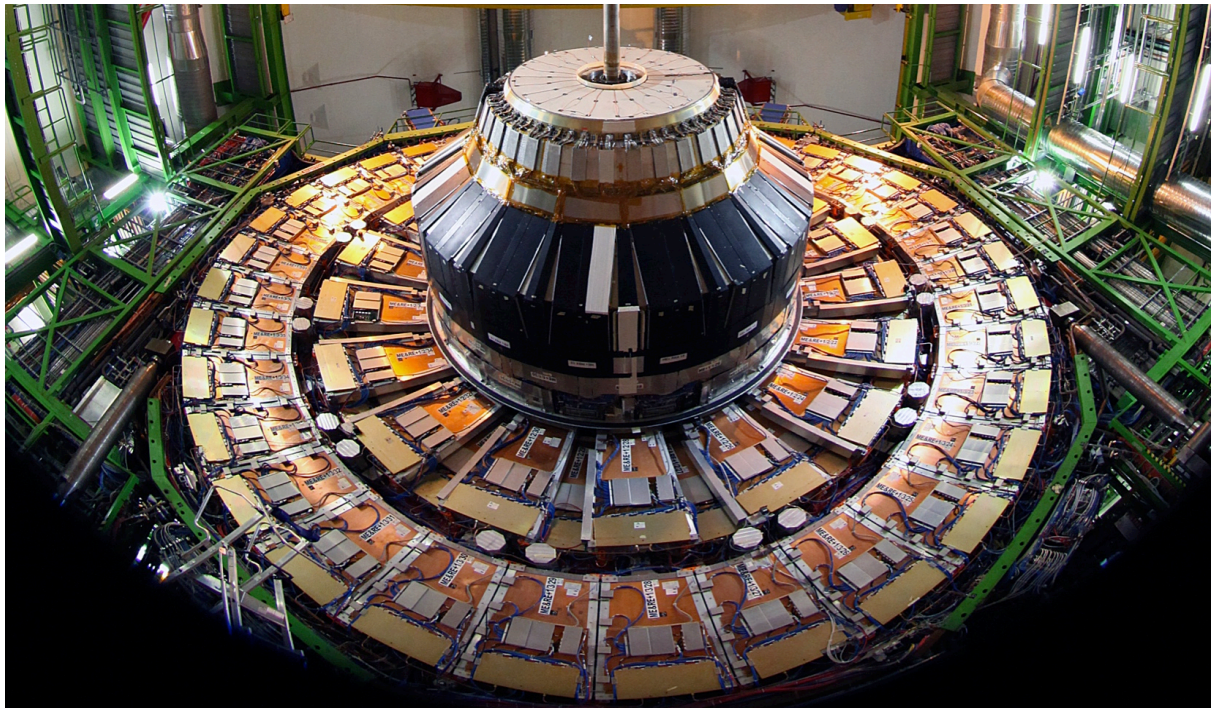

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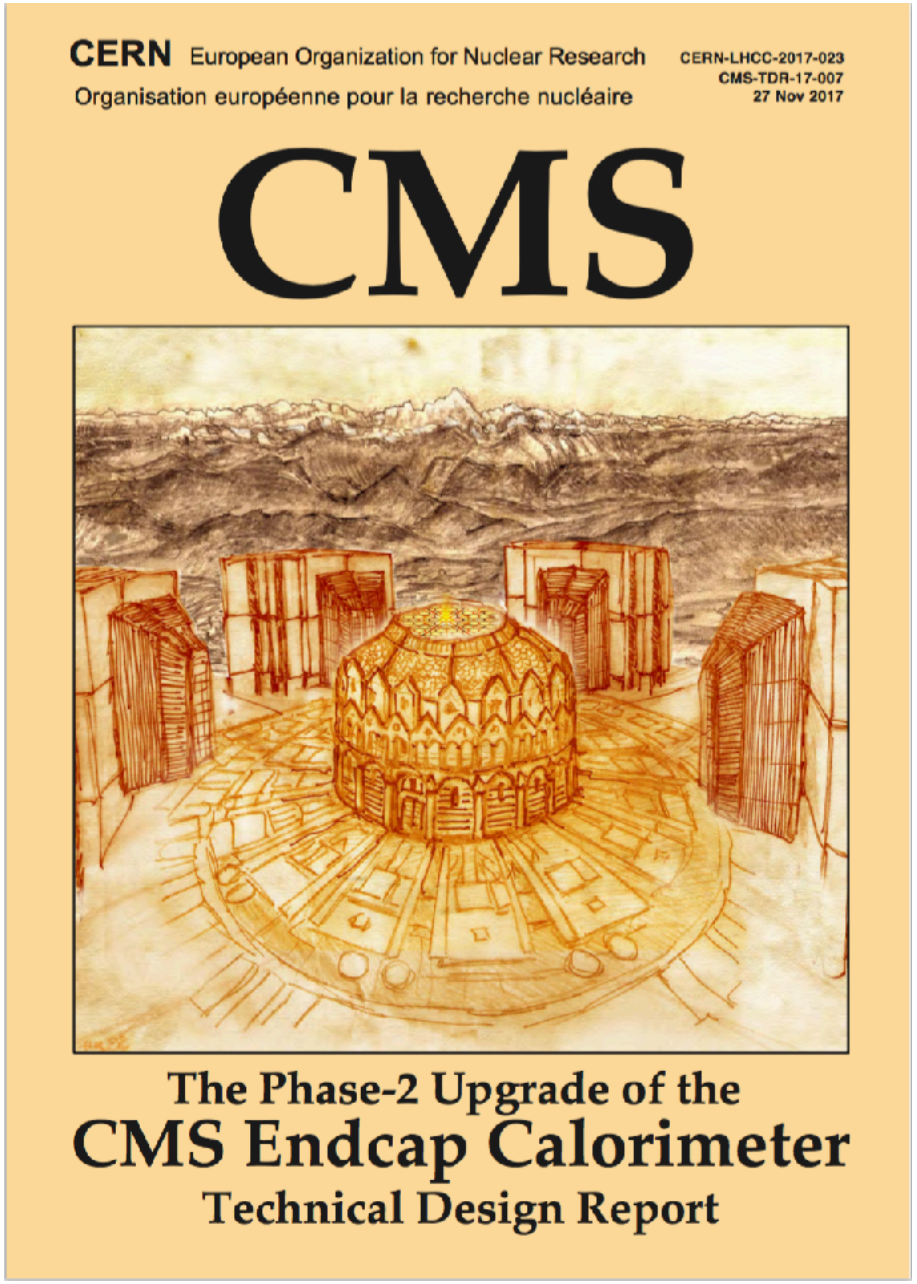
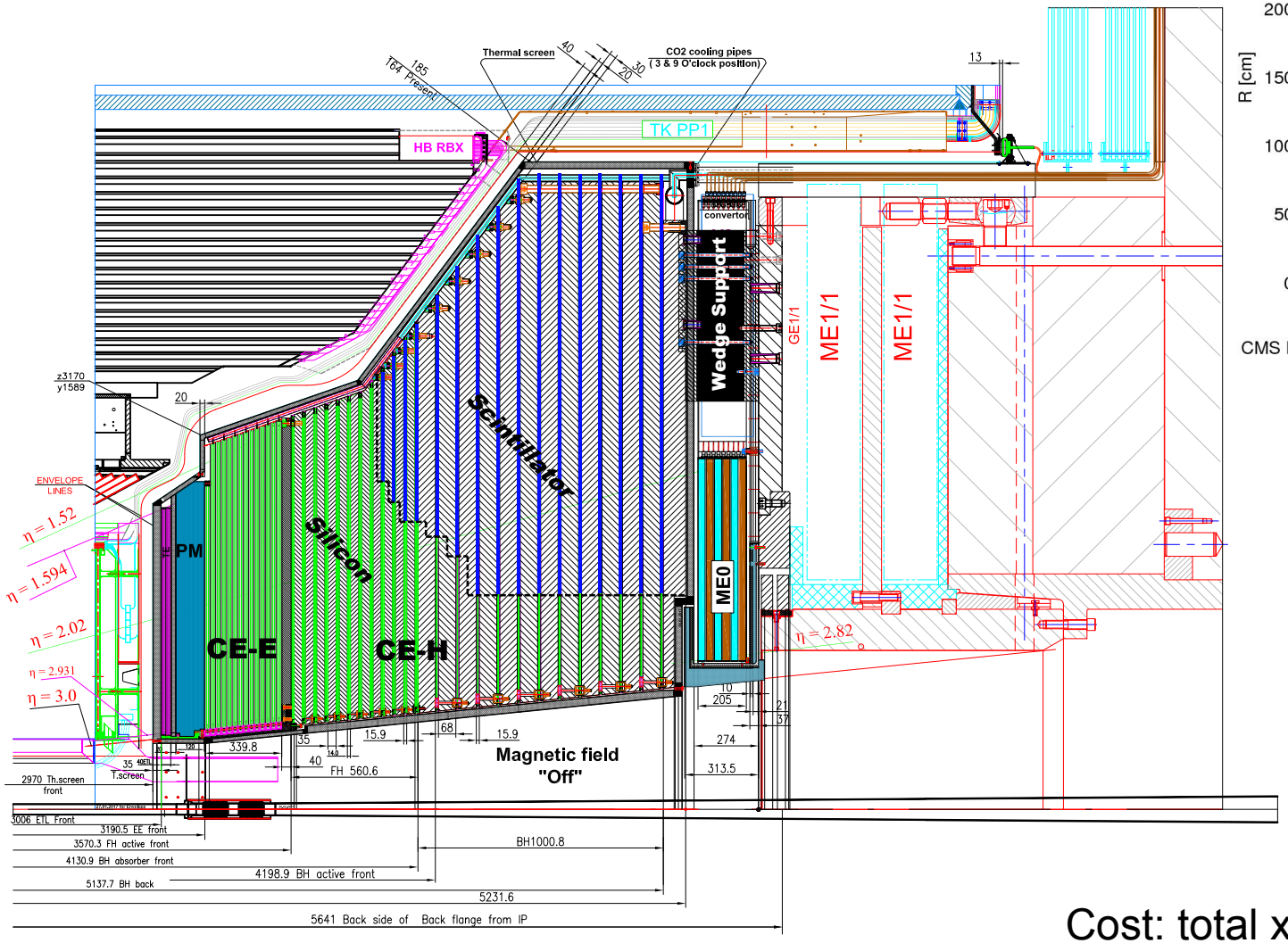
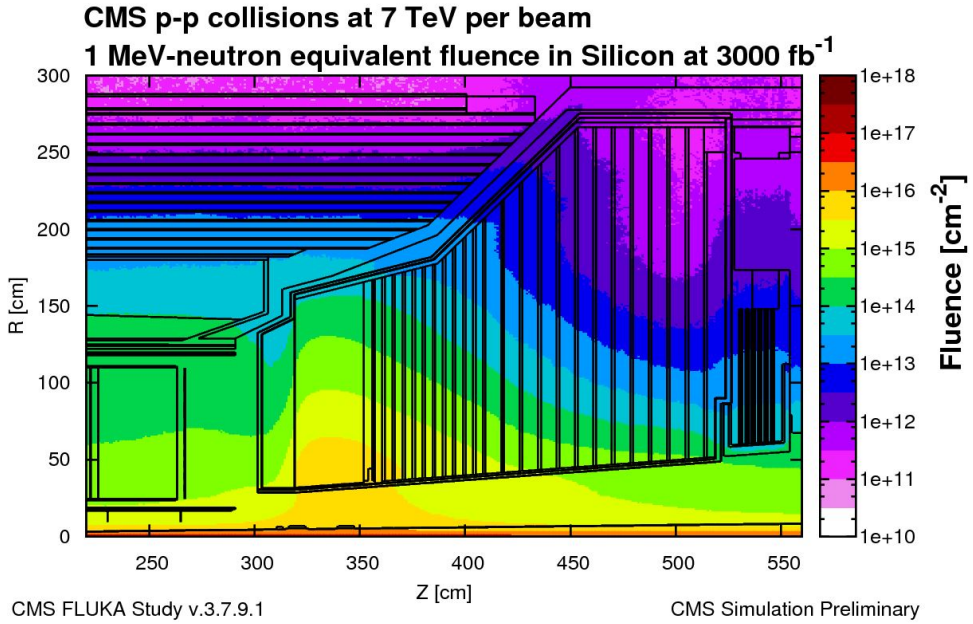


HGCAL Layout and Key Numbers

Driven by radiation levels





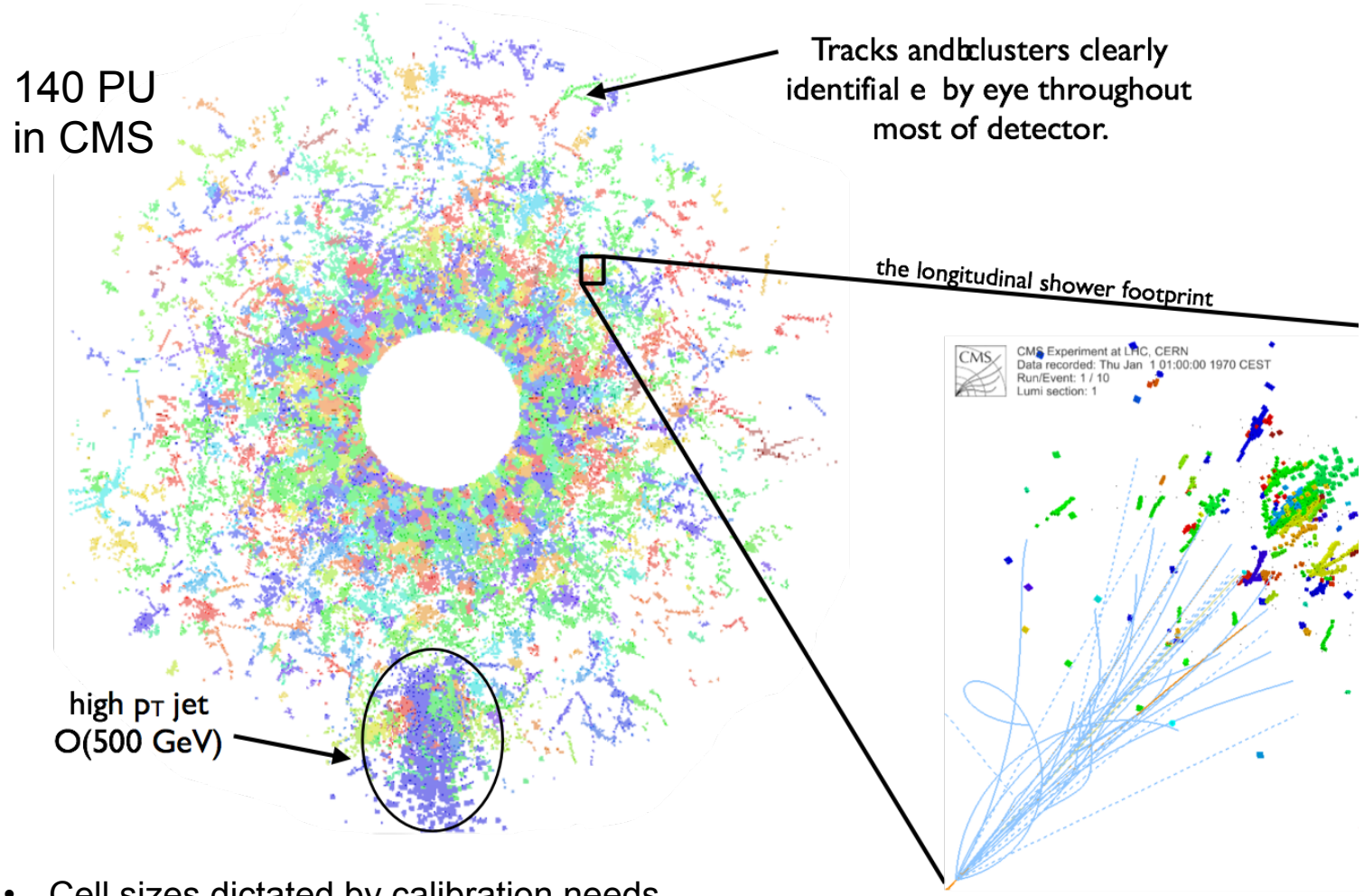
	CE-E	CE-H	
	Si	Si	Scintillator
Area (m^2)	368	215	487
Channels (k)	3916	1939	389
Si modules (Tileboards)	16 008	8868	(3960)
Partial modules	1008	1452	–
Weight (t)	23	205	
Si-only planes	28	8	
Mixed (Si+Scint) planes		16	

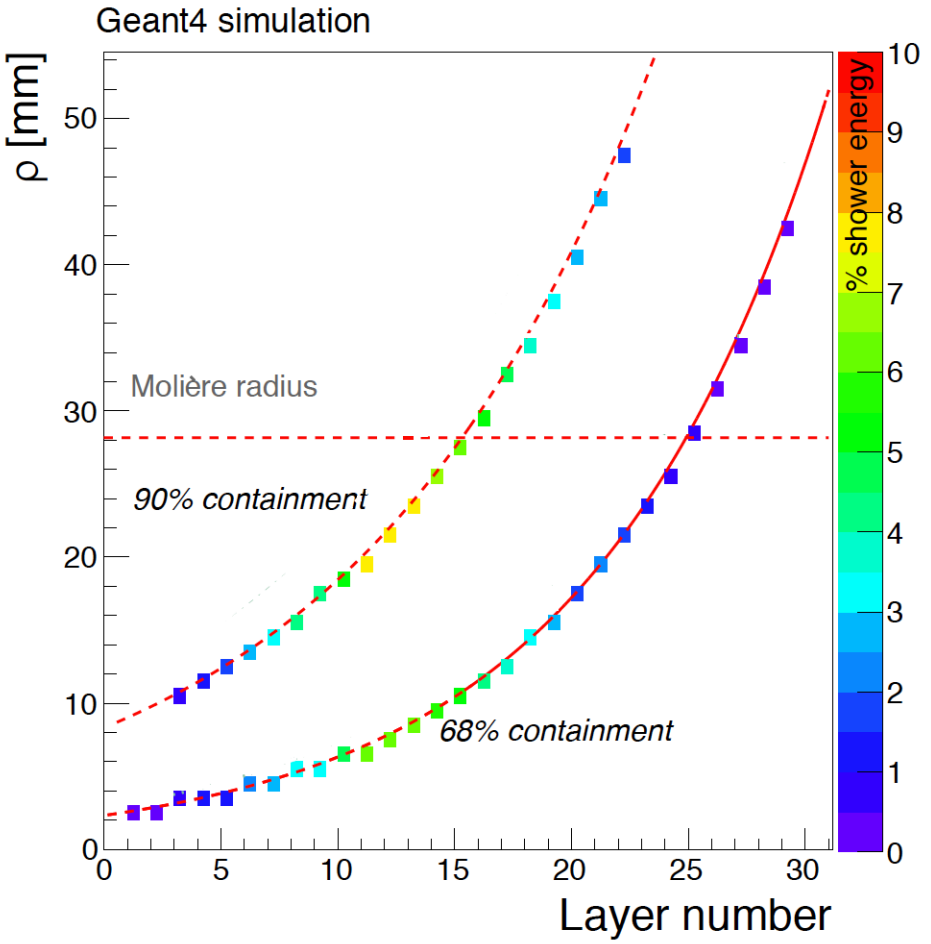
Cooling power @ -35 °C: 300 kW

Cost: total x, Scintillator-SiPM Tile Modules y MCHF

Case for High Granularity

Physics, and Calibration



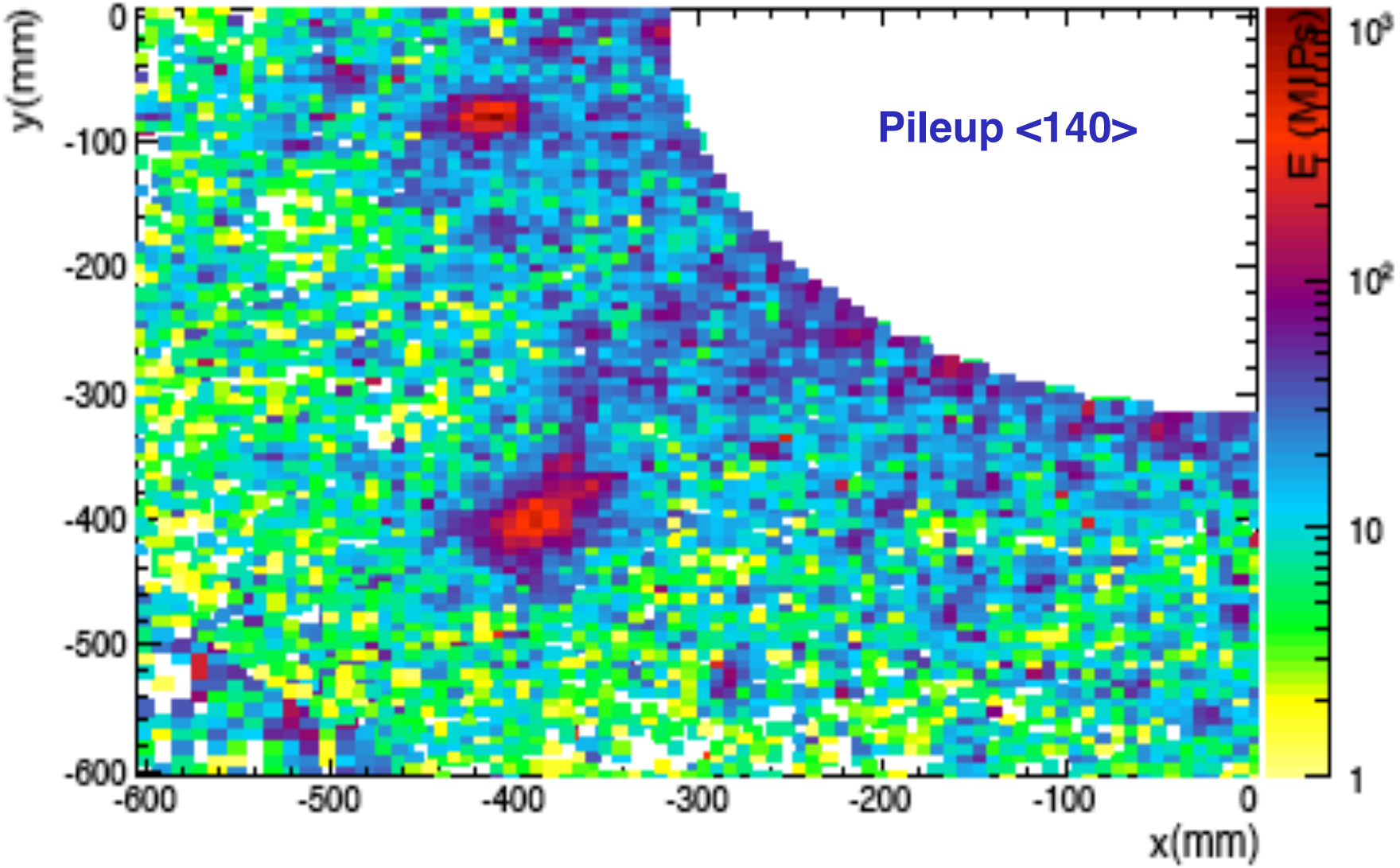


- Cell sizes dictated by calibration needs
- Silicon: small capacitance and noise, scintillator: high light yield

- Molière radius 28mm
- but showers in early stage much smaller

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.

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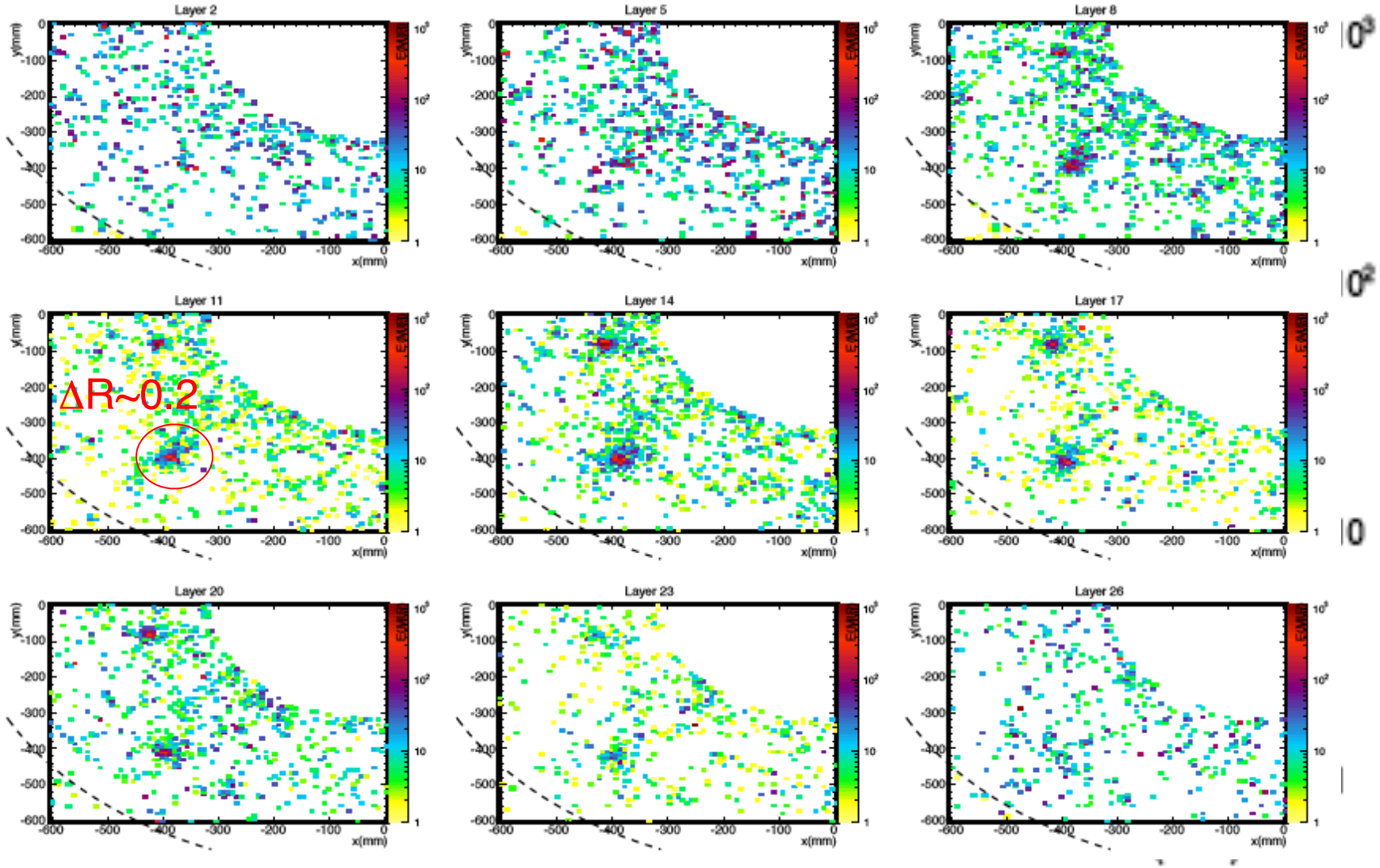

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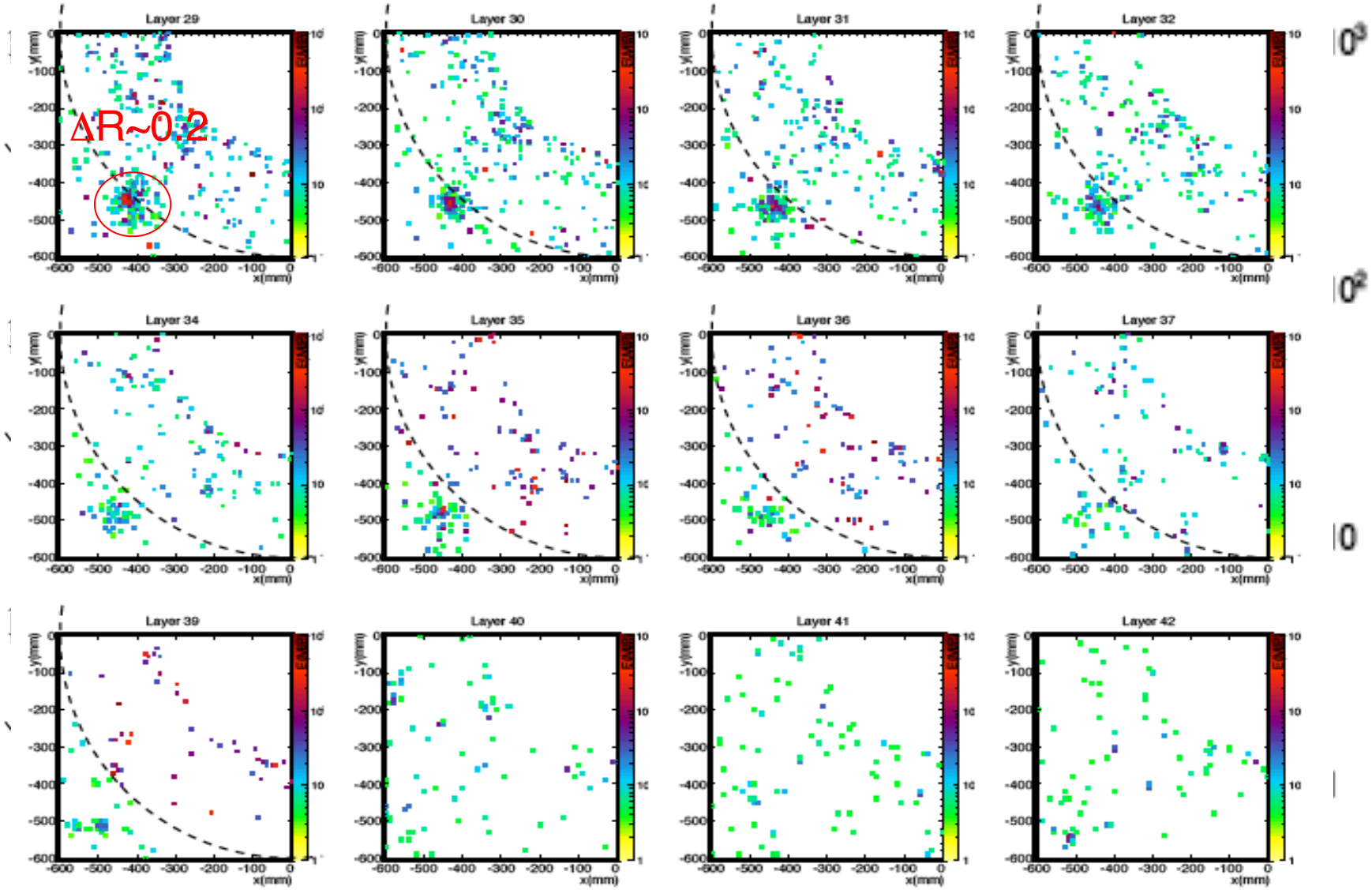

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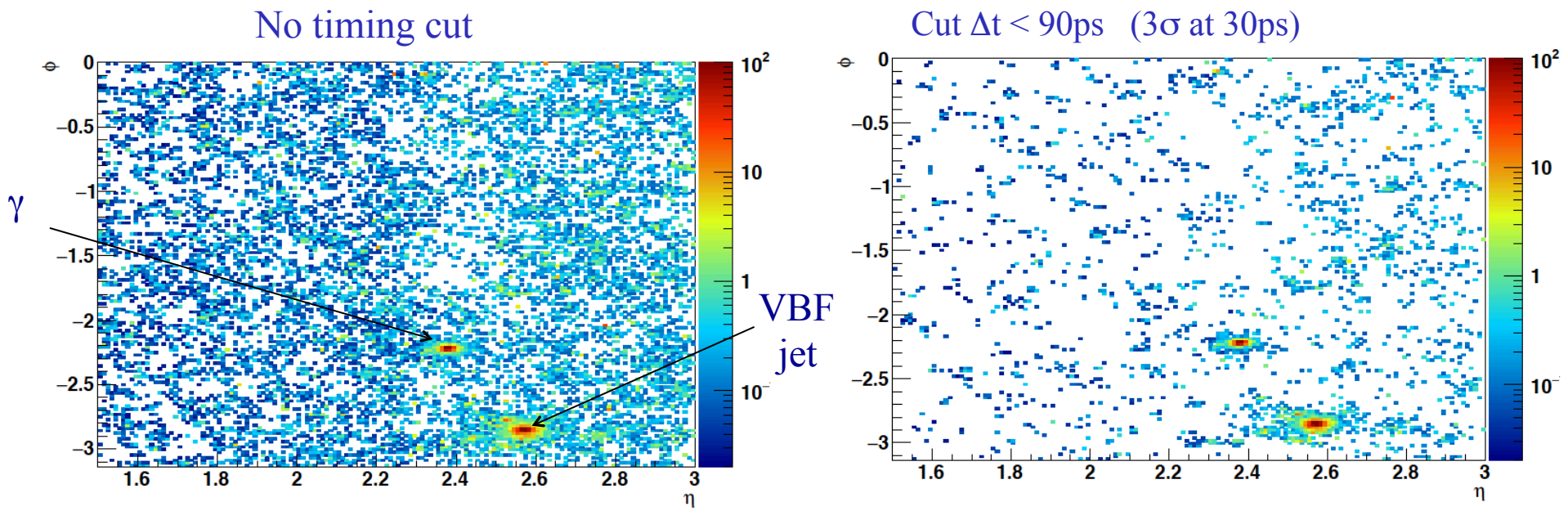
Pile-up rejection

Granularity and timing: a 5D detector

Possible due to the choice of CE sampling parameters and electronics

VBF (H→γγ) event with one photon and one VBF jet in the same quadrant,

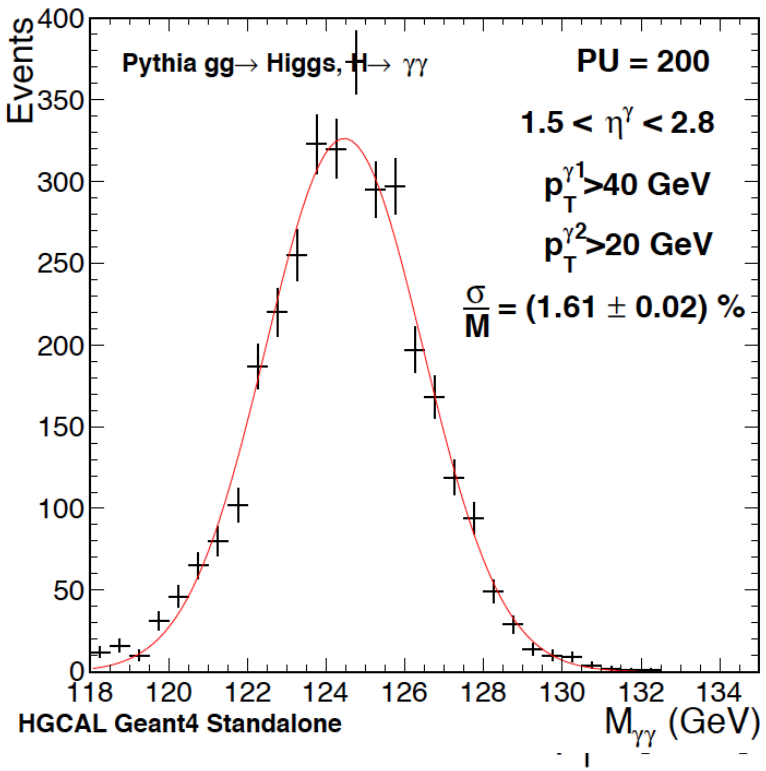


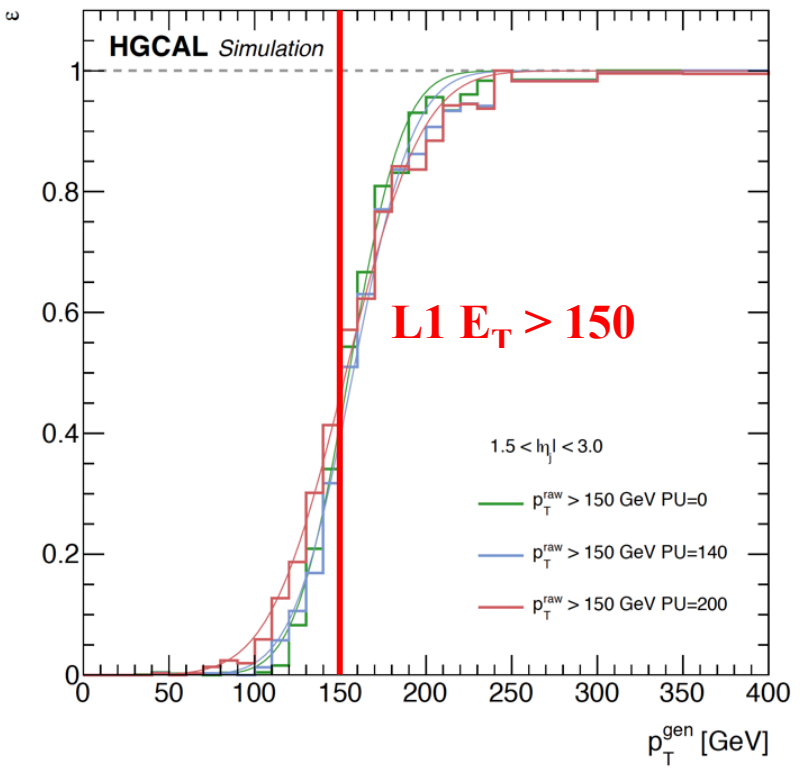
Plots show cells with Q > 12fC (~3.5 MIPs @300μm - threshold for timing measurement) projected to the front face of the endcap calorimeter.
Concept: identify high-energy clusters, then make timing cut to retain hits of interest

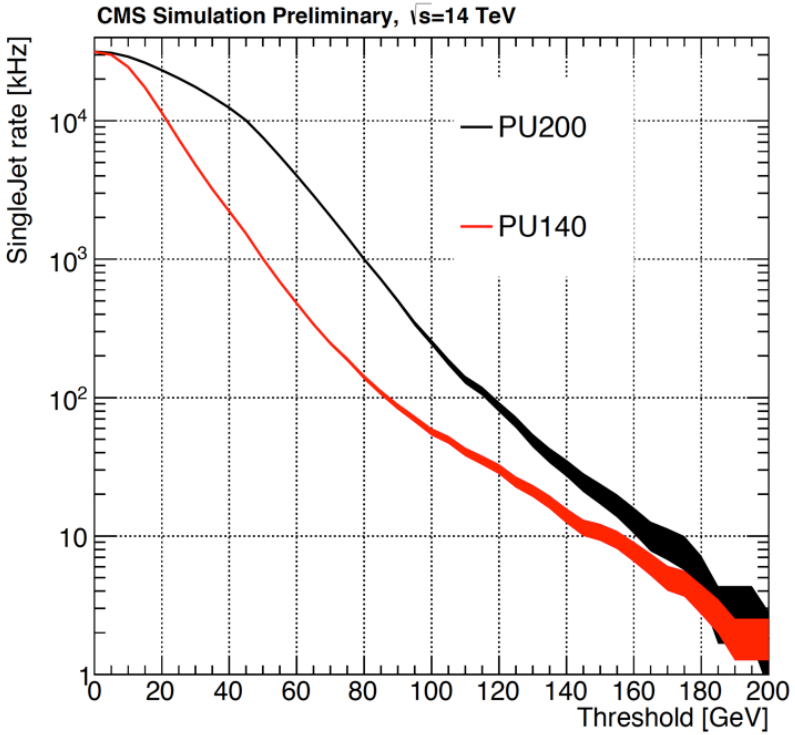
D.Barney

Trigger and Reconstruction Performance

Exploit dense core of objects







- Energy resolution insensitive to pile-up
- stochastic term 24…31 %

- Jet trigger efficiency quite insensitive to pile-up
- Jet rate ~10 kHz before isolation and track matching

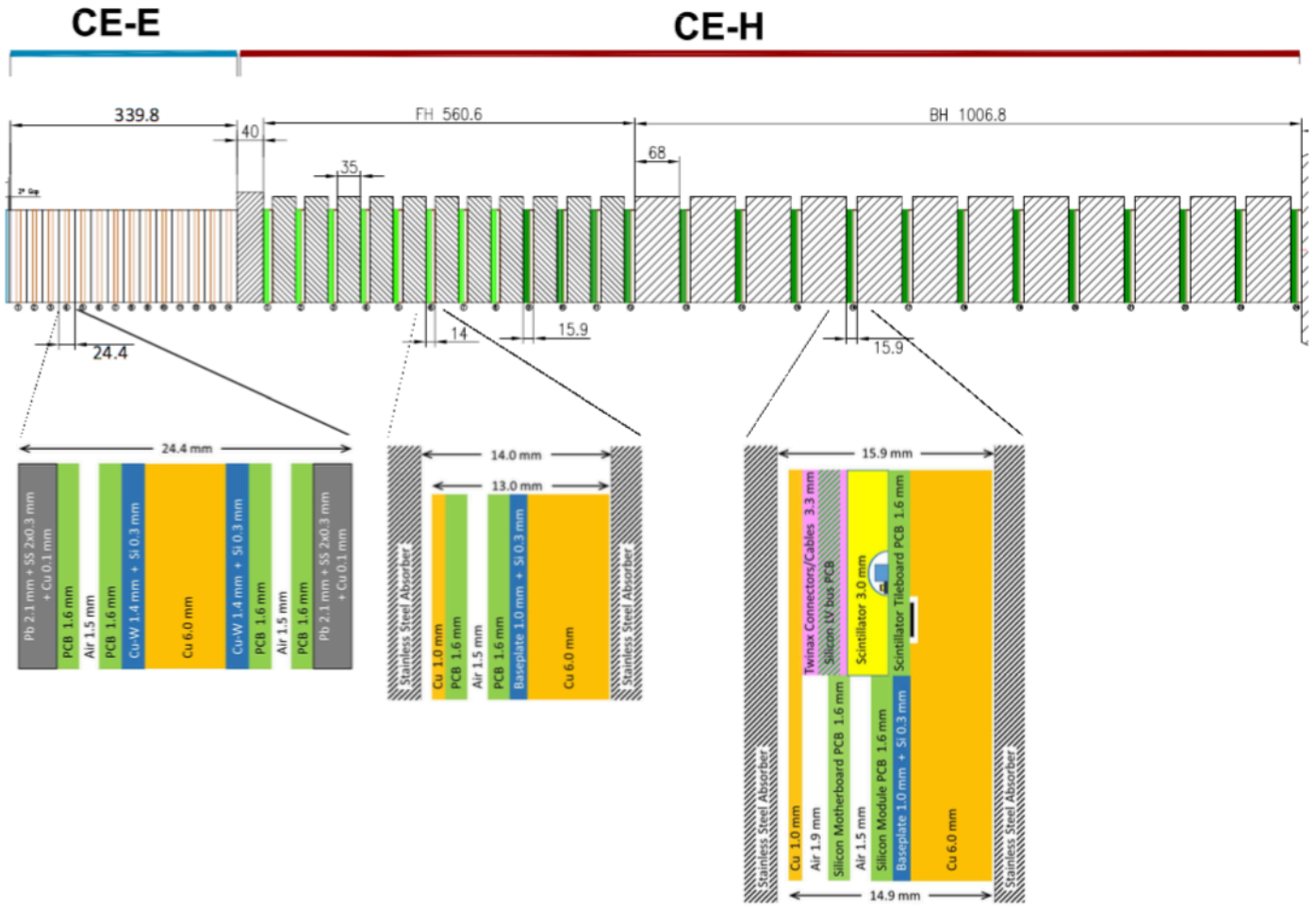
Challenges

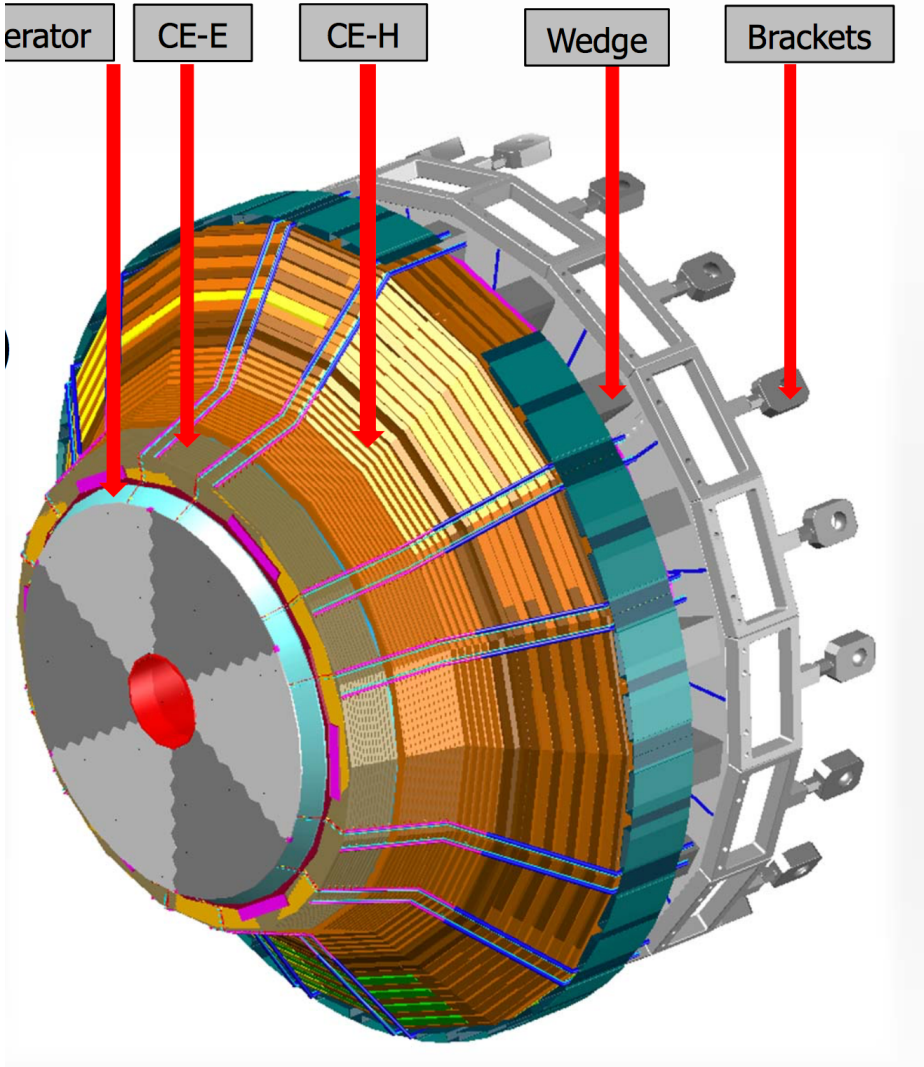
“There are no show-stoppers; it is all just engineering”

“HGCAL is perhaps the most challenging
engineering project ever undertaken in particle physics”

Longitudinal Structure

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

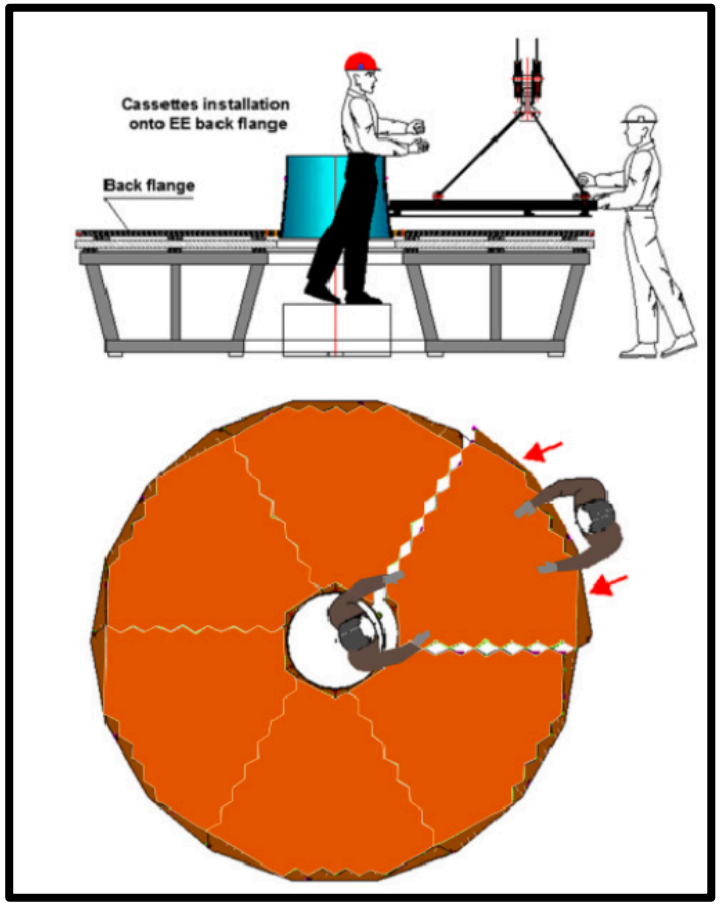




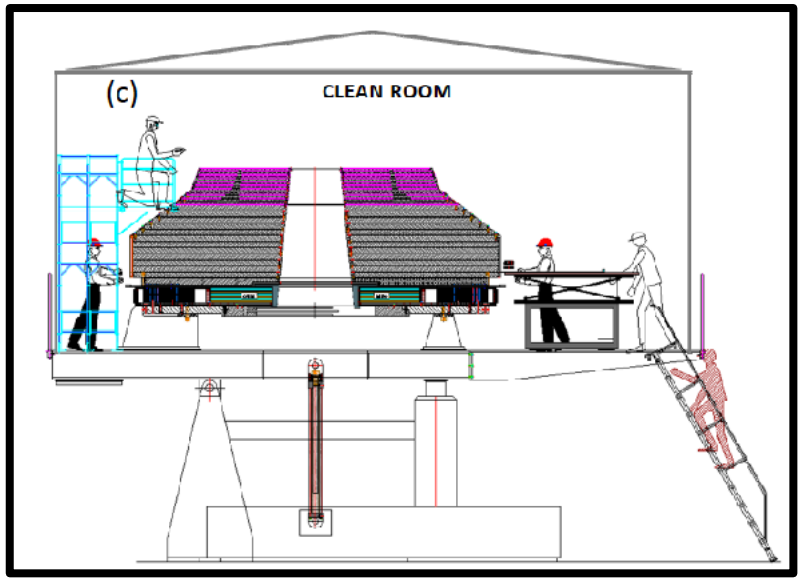
Heavy Engineering

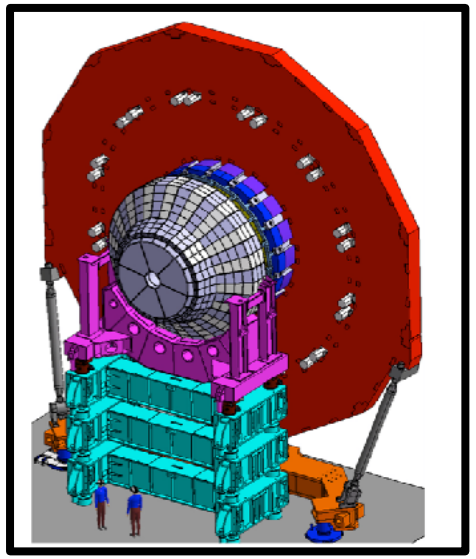
Assembly concepts.

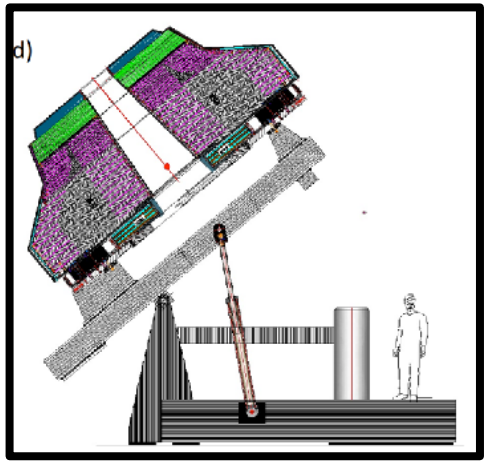
CE-E

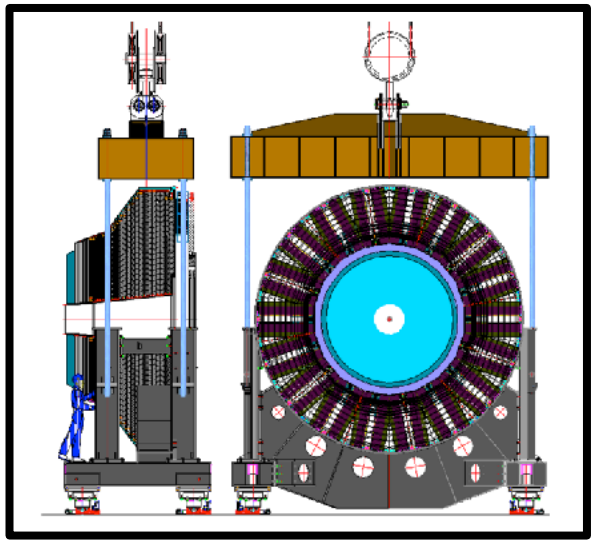


CE-H







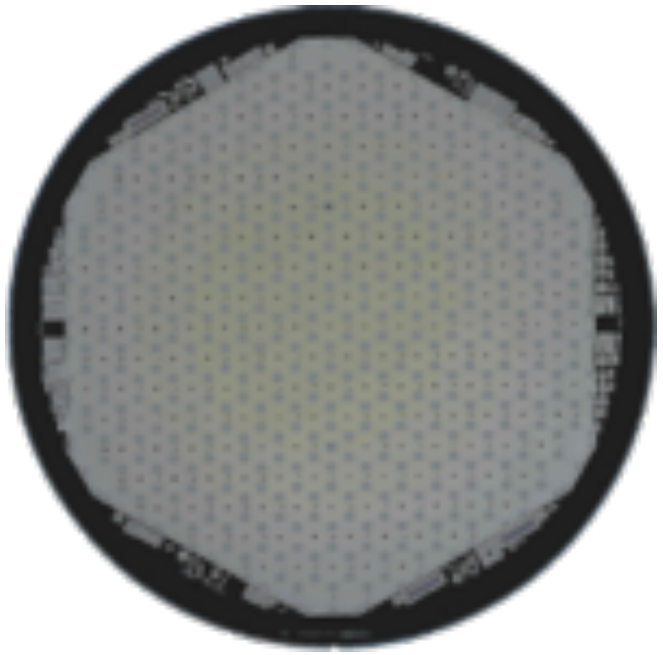


- CE-E: stacking, CE-H: drawers
- Structure cantilevered from yoke

Silicon sensors

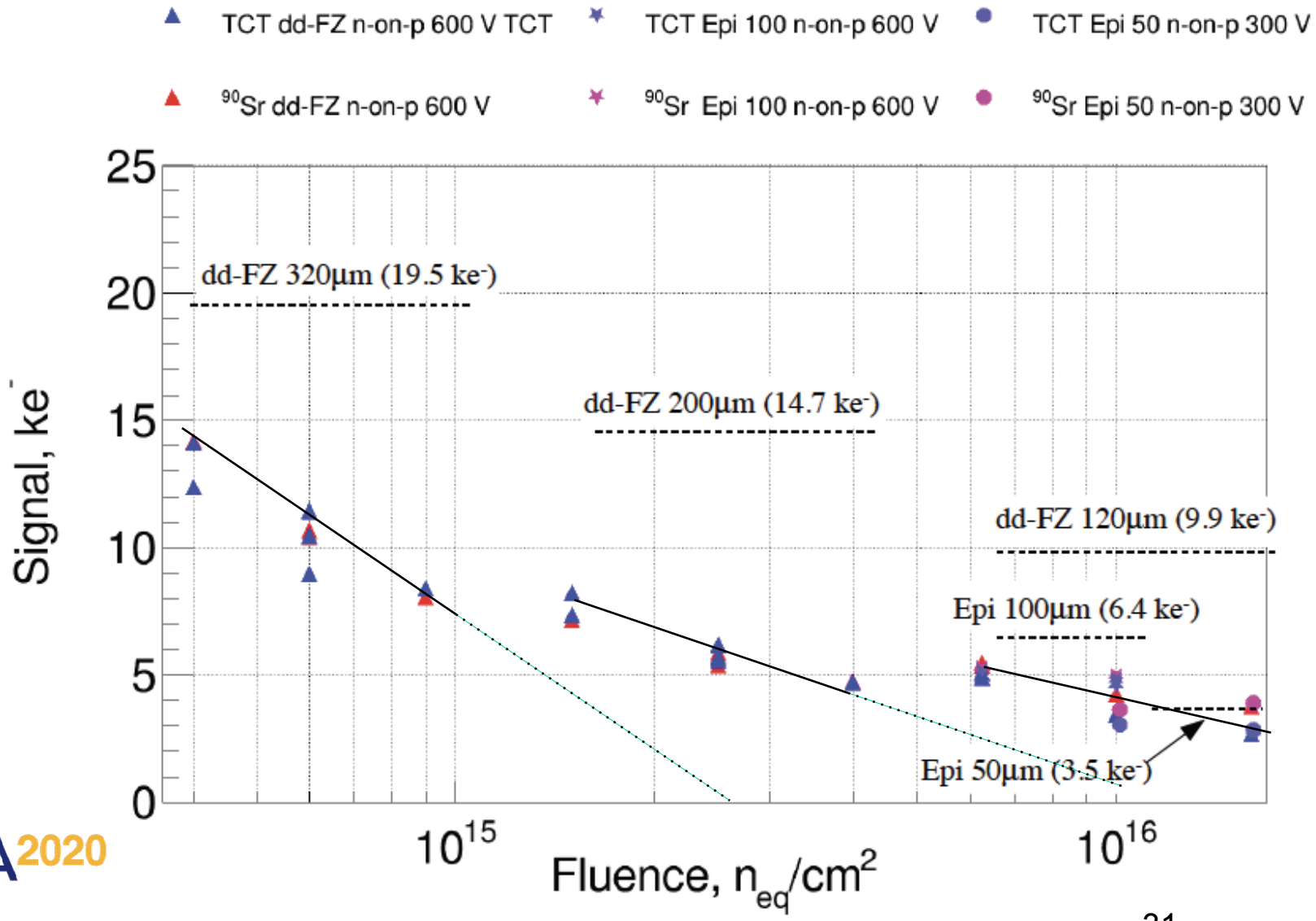
600 m2

- Thinner sensors in more irradiated areas
- Work towards 8 inch wafers with Japanese and European industry



8'' prototype from Infineon

AIDA2020



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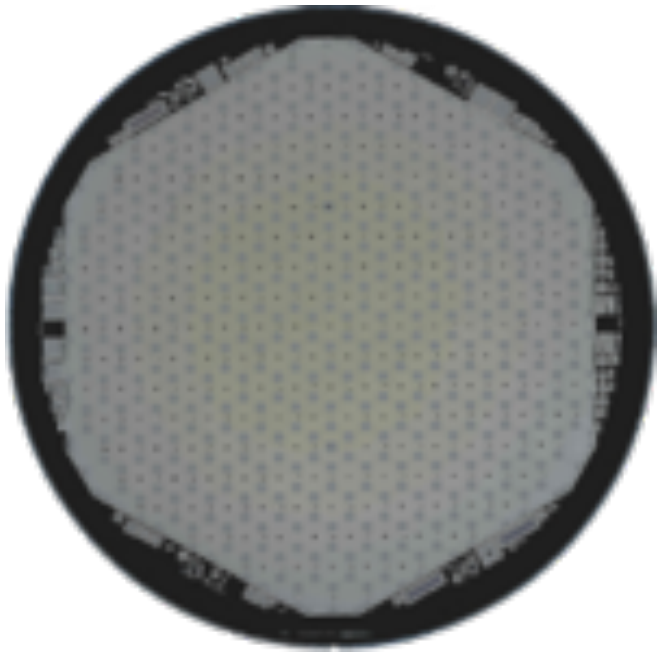

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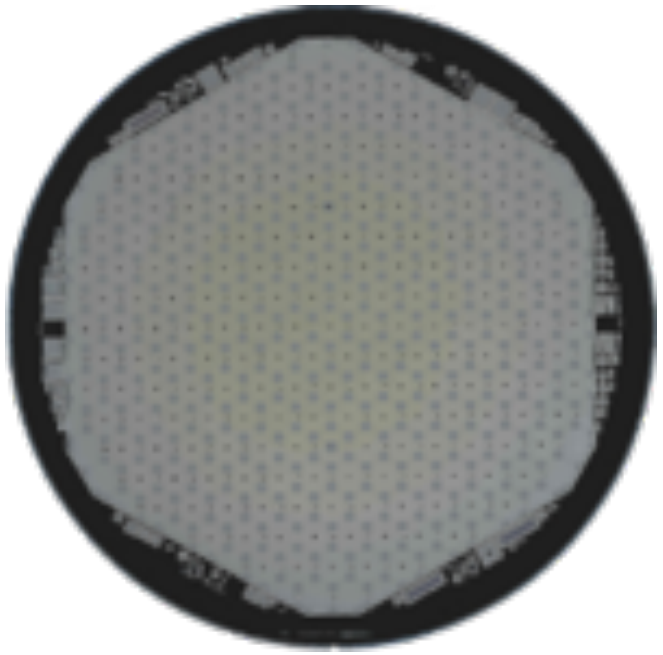
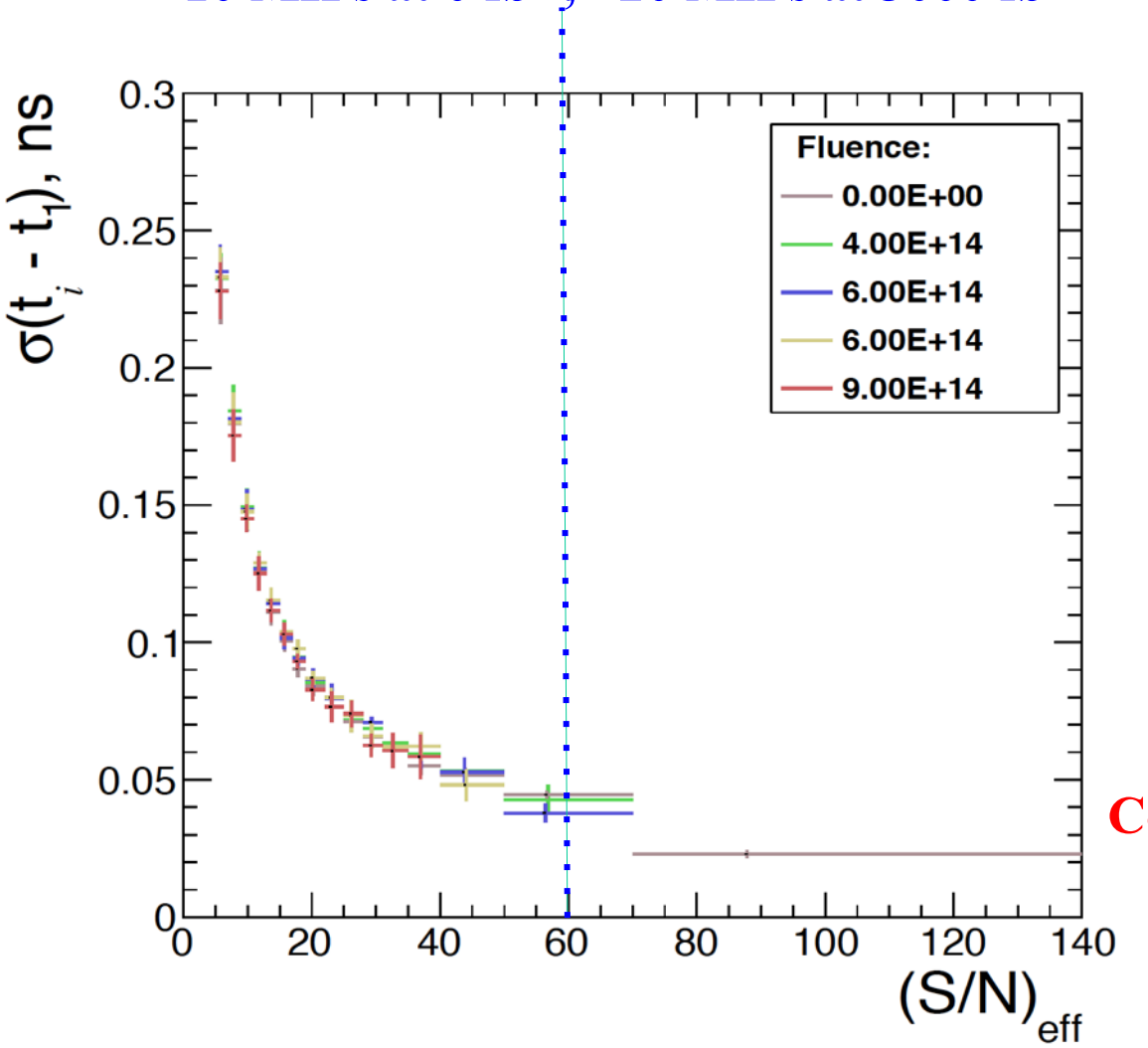


8'' prototype from Infineon

~10 MIPs at 0 fb^{-1}; ~20 MIPs at 3000 fb^{-1}

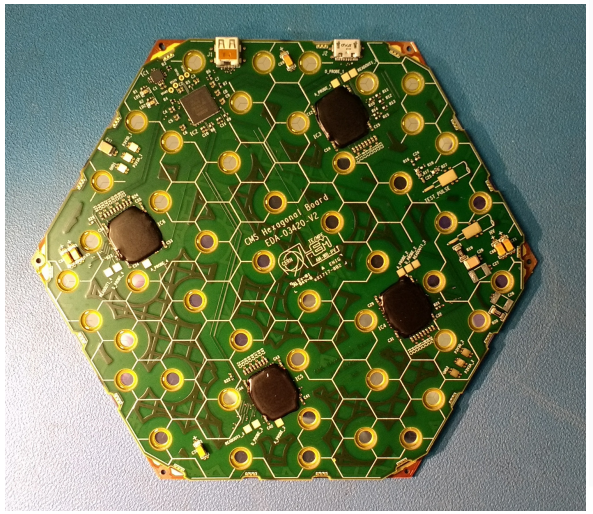


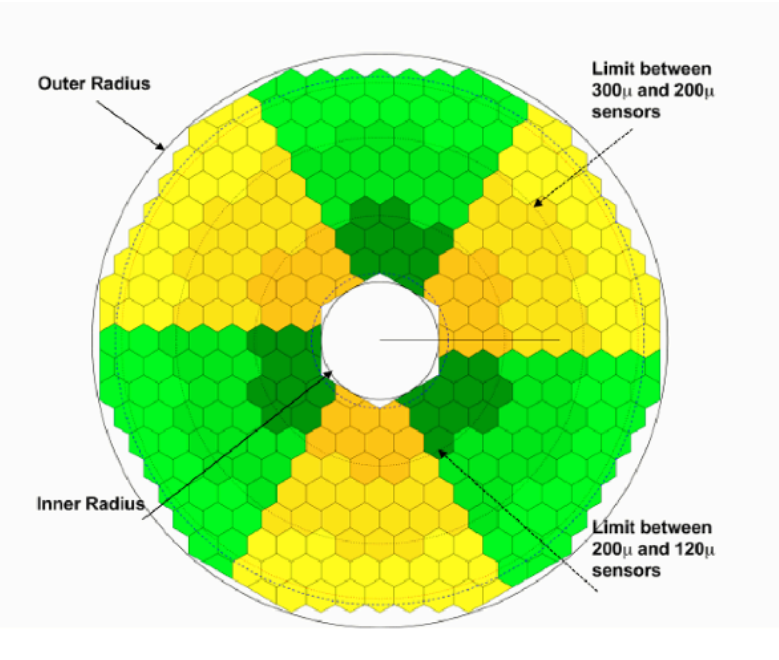
Constant term ~20ps

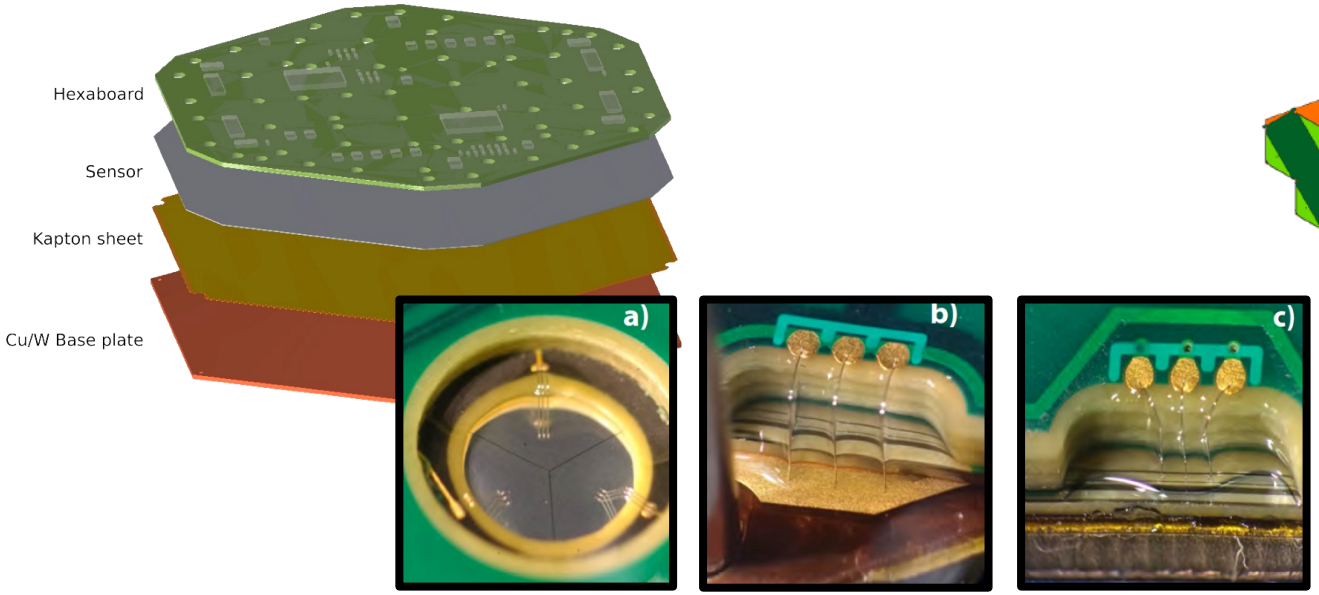
HGCAL Silicon Part

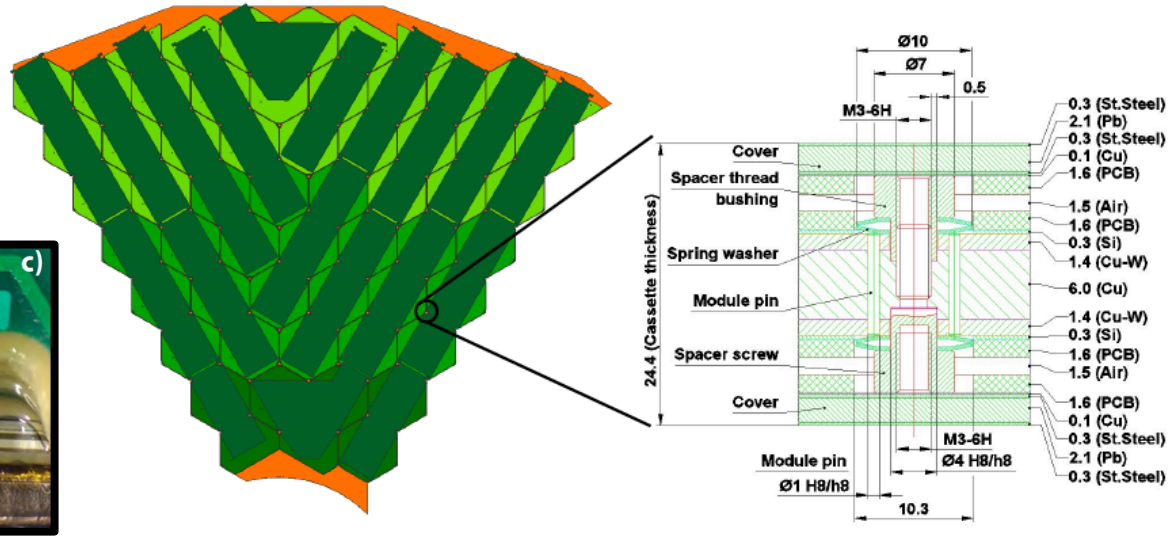
CE and CH

- 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)



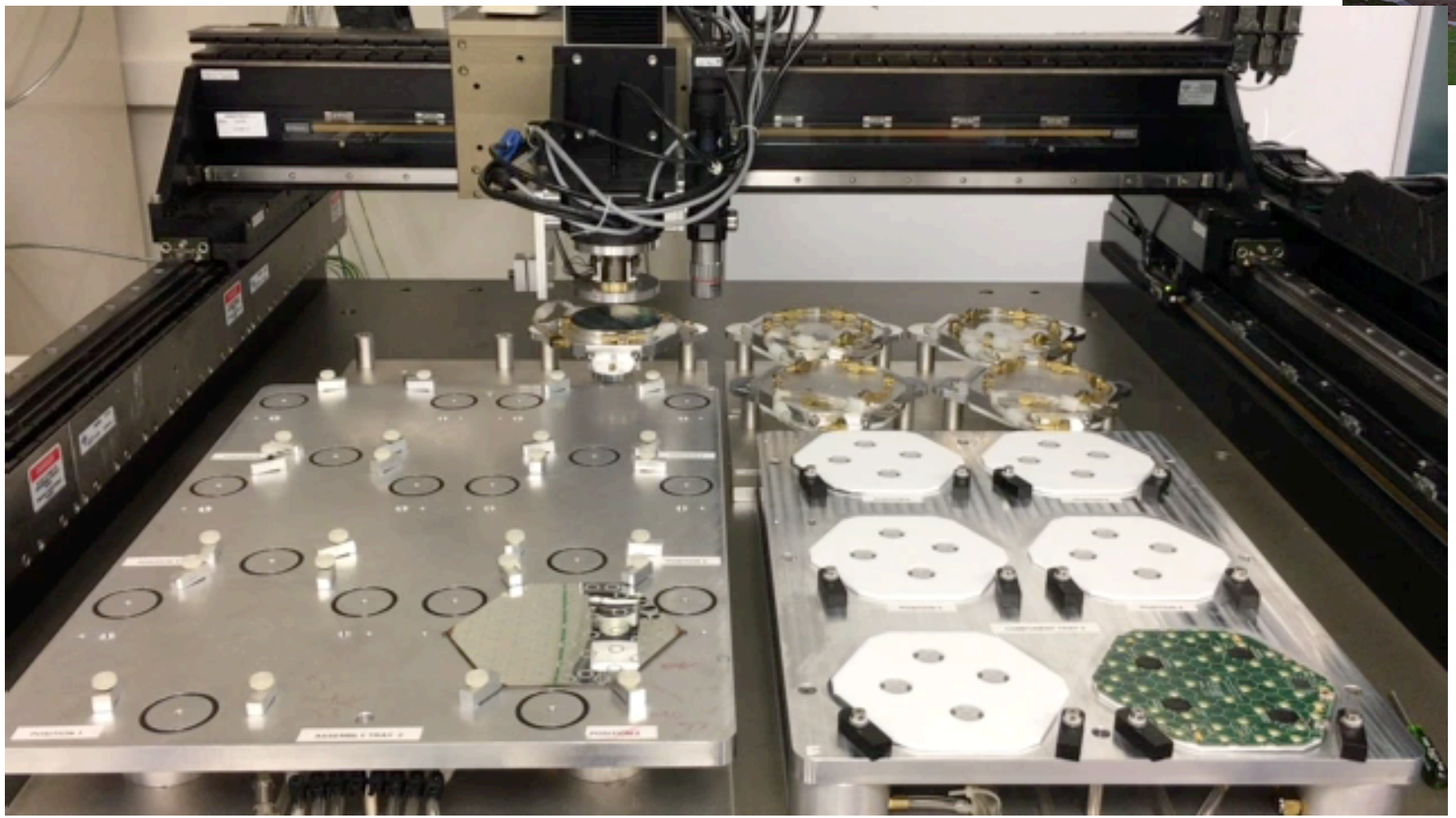






Automated Assembly

UC Santa Barbara



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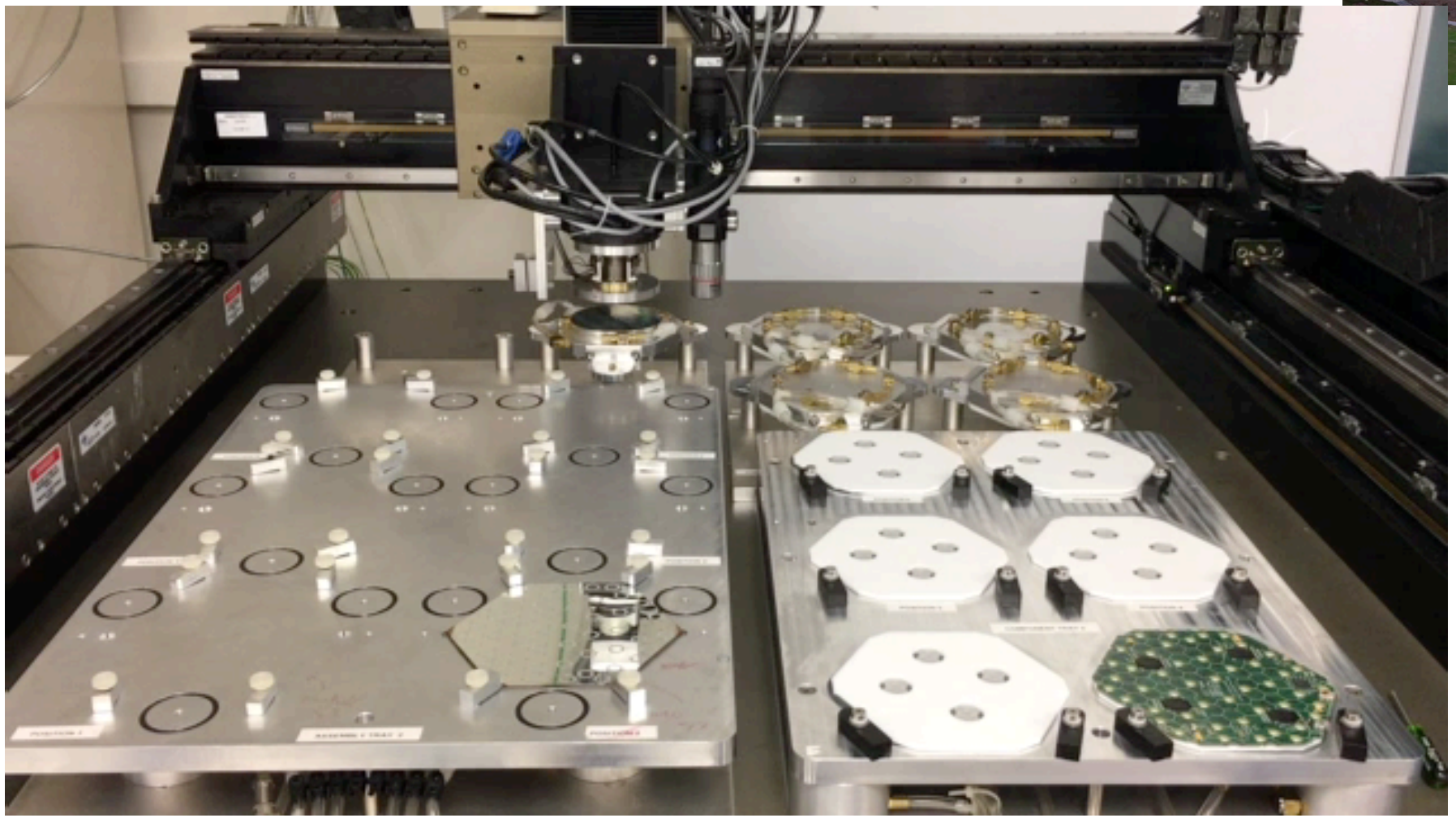
Automated Assembly

UC Santa Barbara



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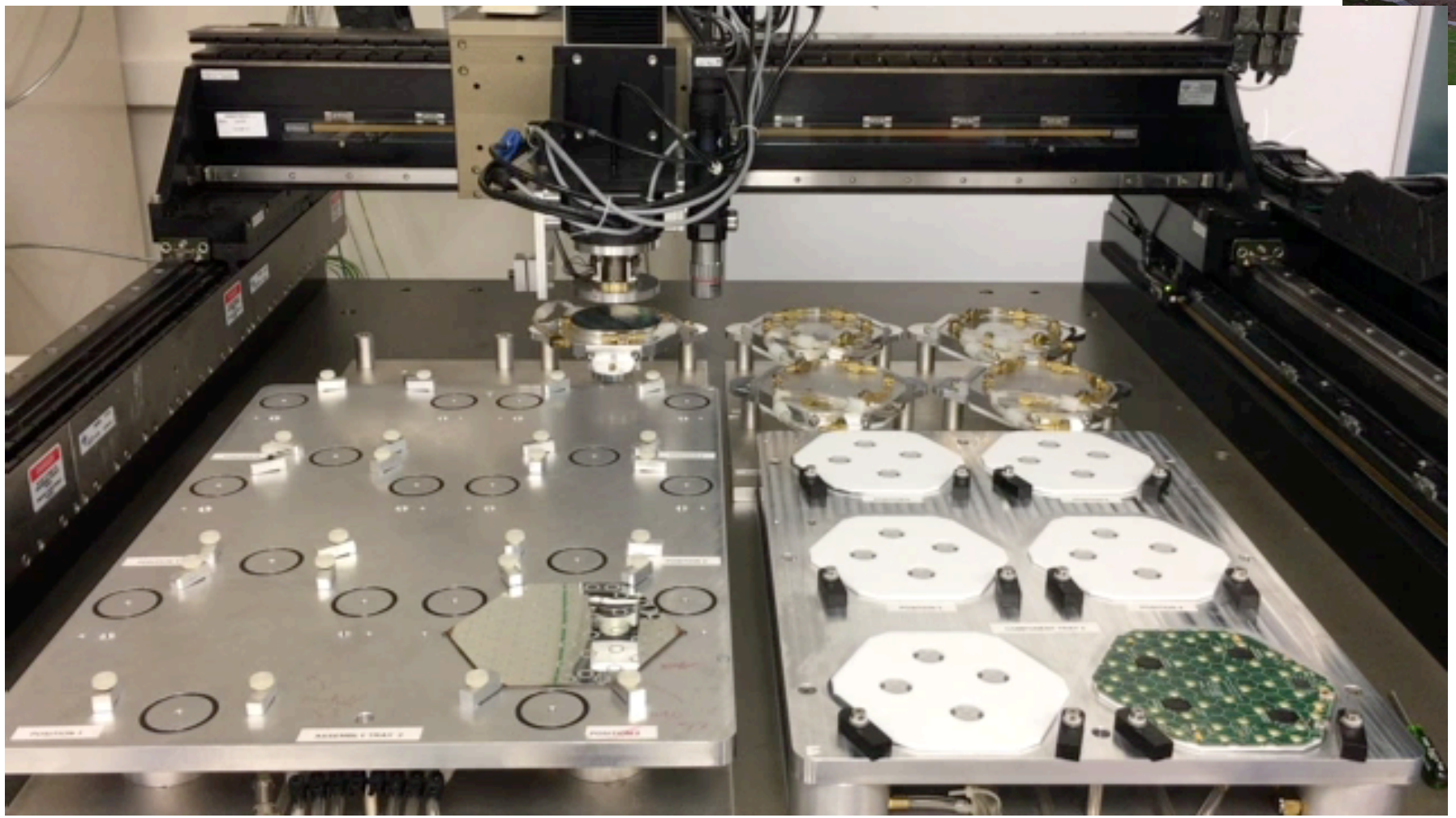

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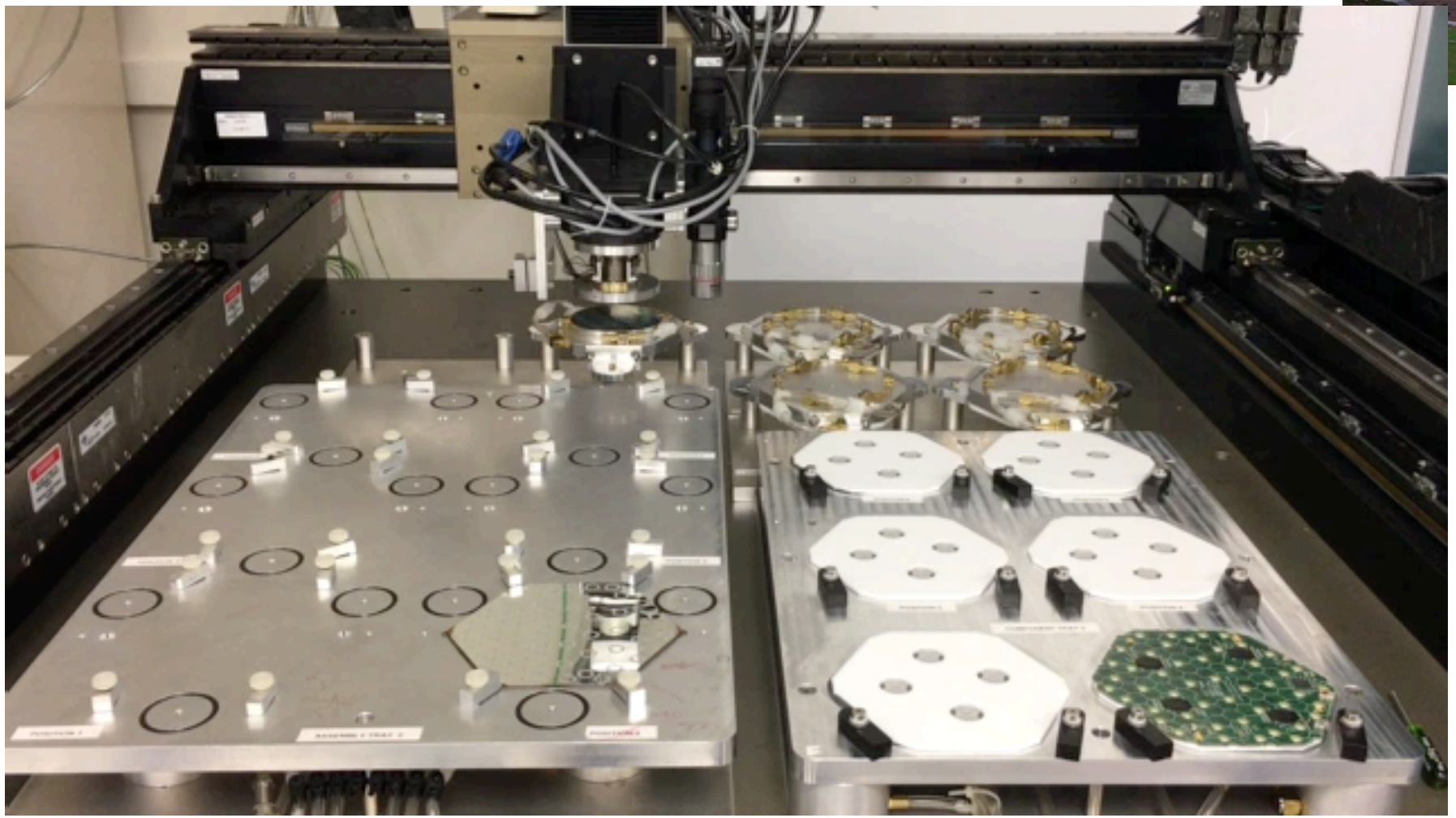

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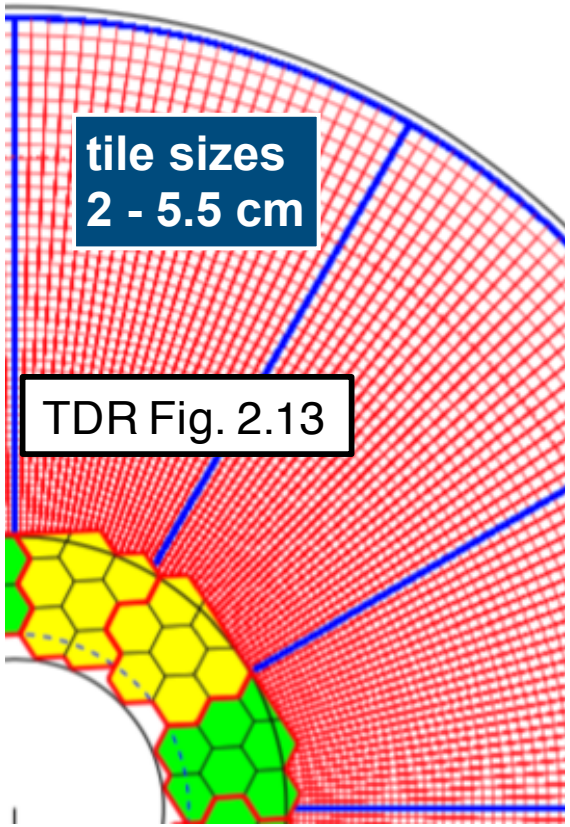
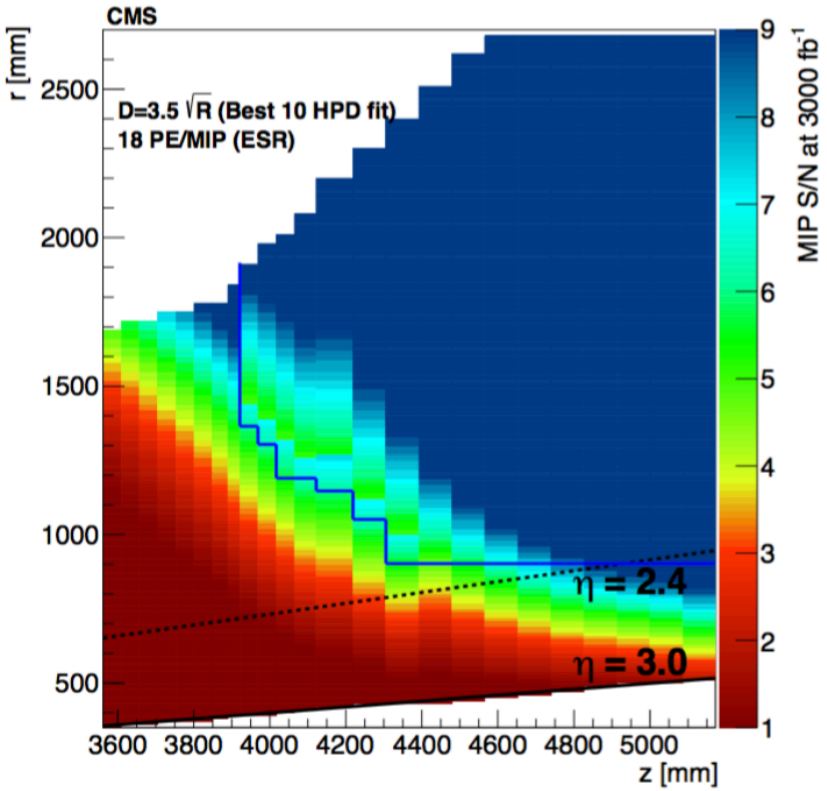
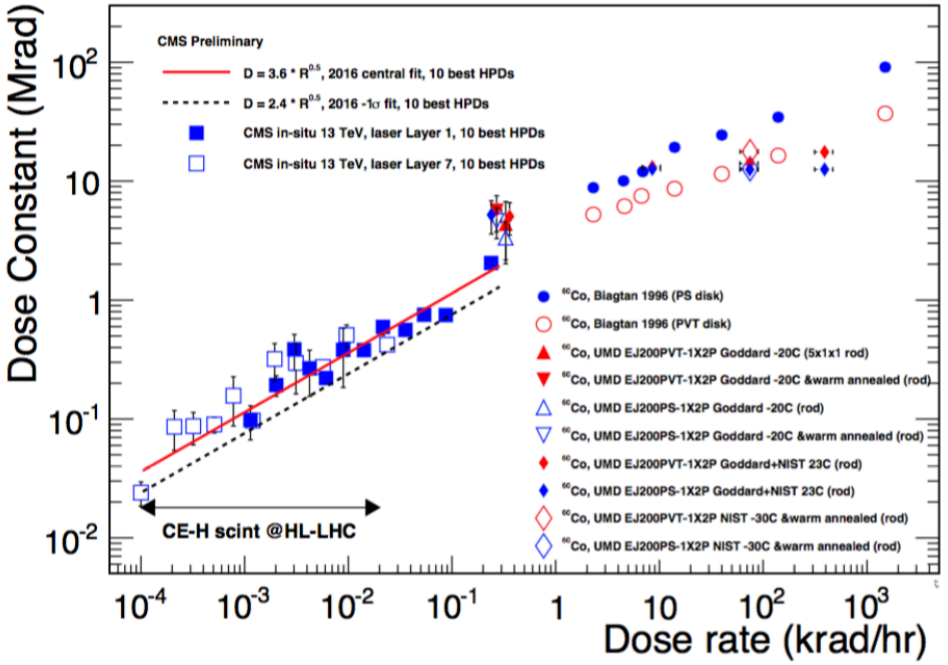
SiPM-on-Tile segmentation

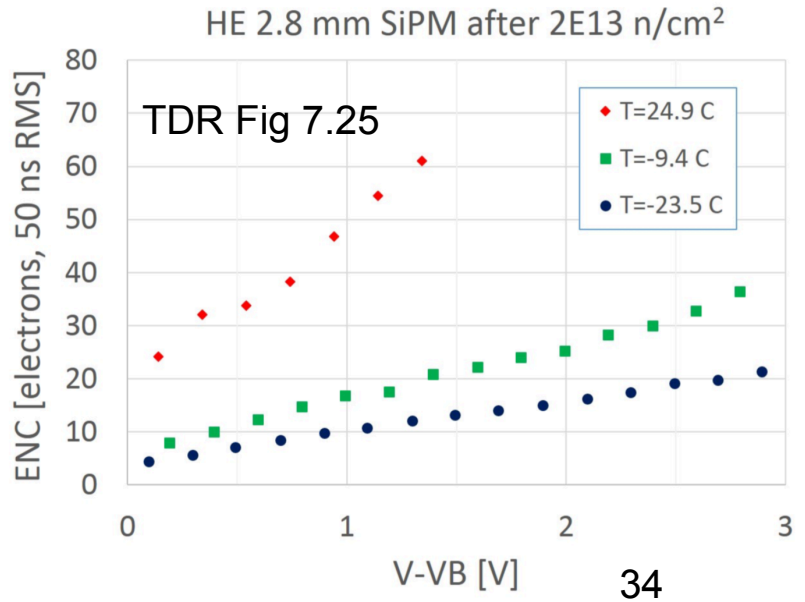
Match radiation levels and trigger geometry

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





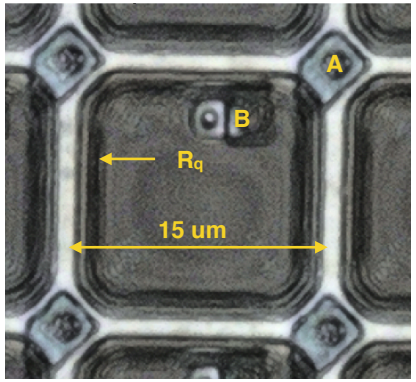


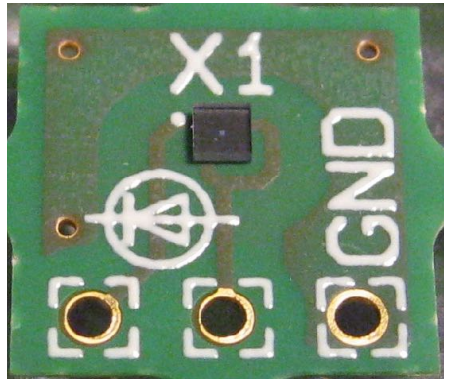


Irradiated SiPMs

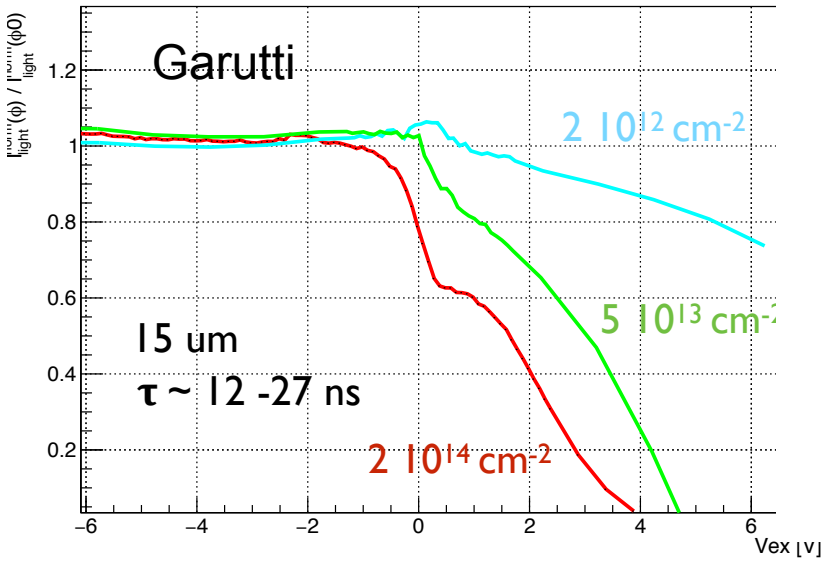
Pushing the limits

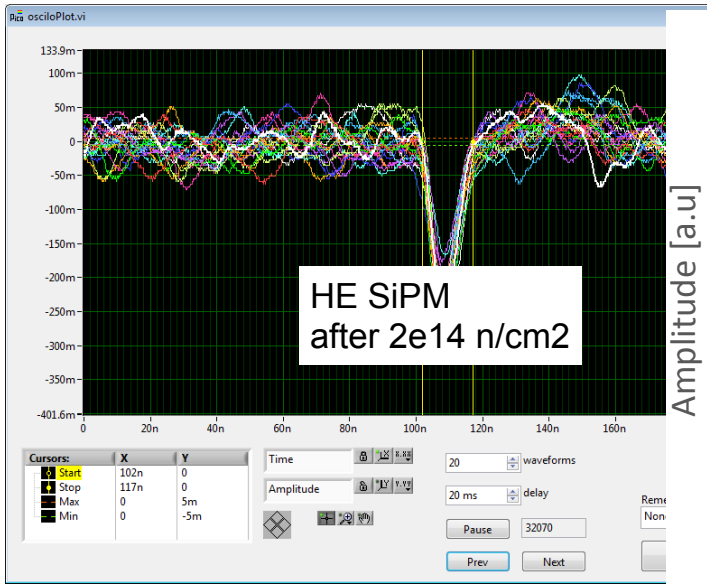
- Characterisation is a challenge in itself
- Several groups, several manufacturers
- After irradiation dark rates go up to GHz range
  - PDE reduction due to noise occupancy
  - baseline shifts, self-heating
  - cooling, bias protection

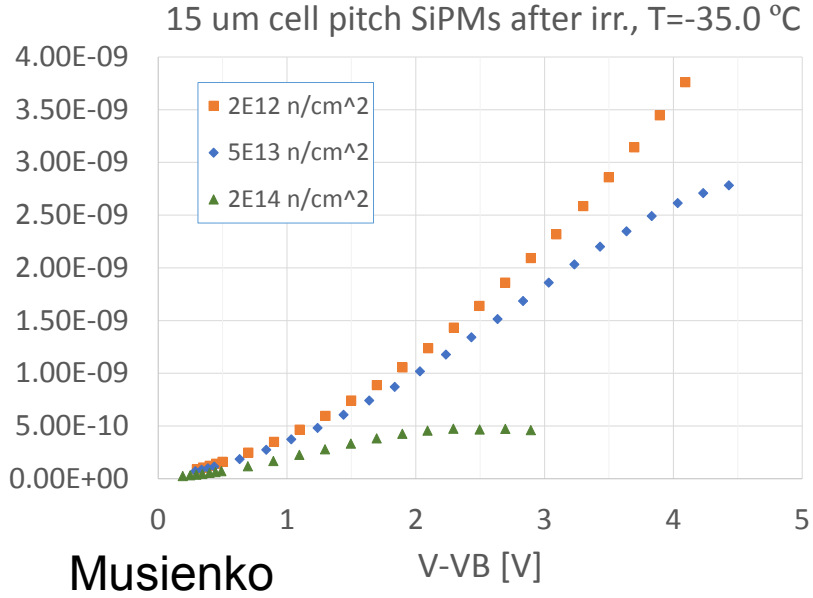




T=-30 °C, U=66.0 V, dVB=2.39 V, PDE(450 nm)=24 %, ENF=1.1, $<N_{photons}>$=340 ==> $<N_{pe}>$~81

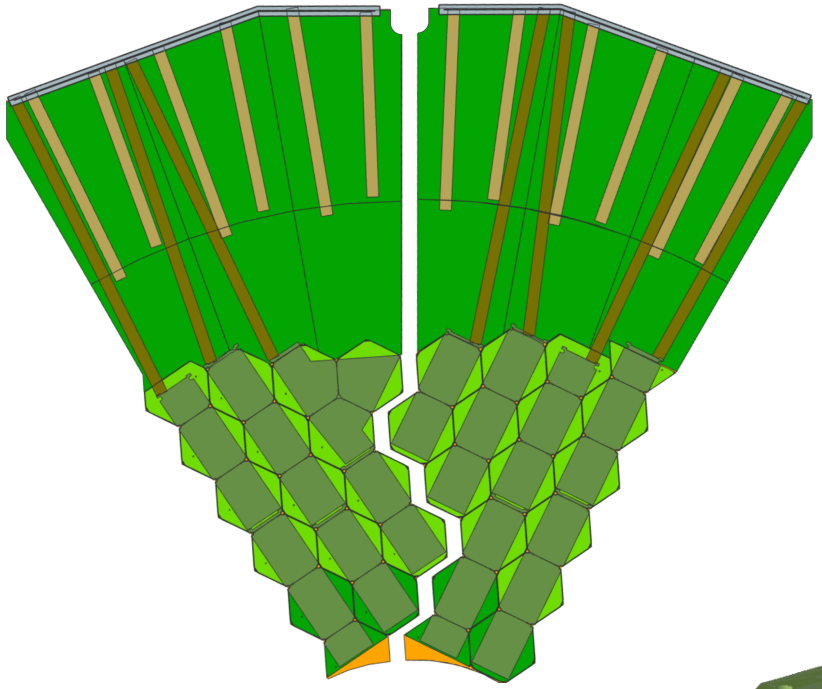


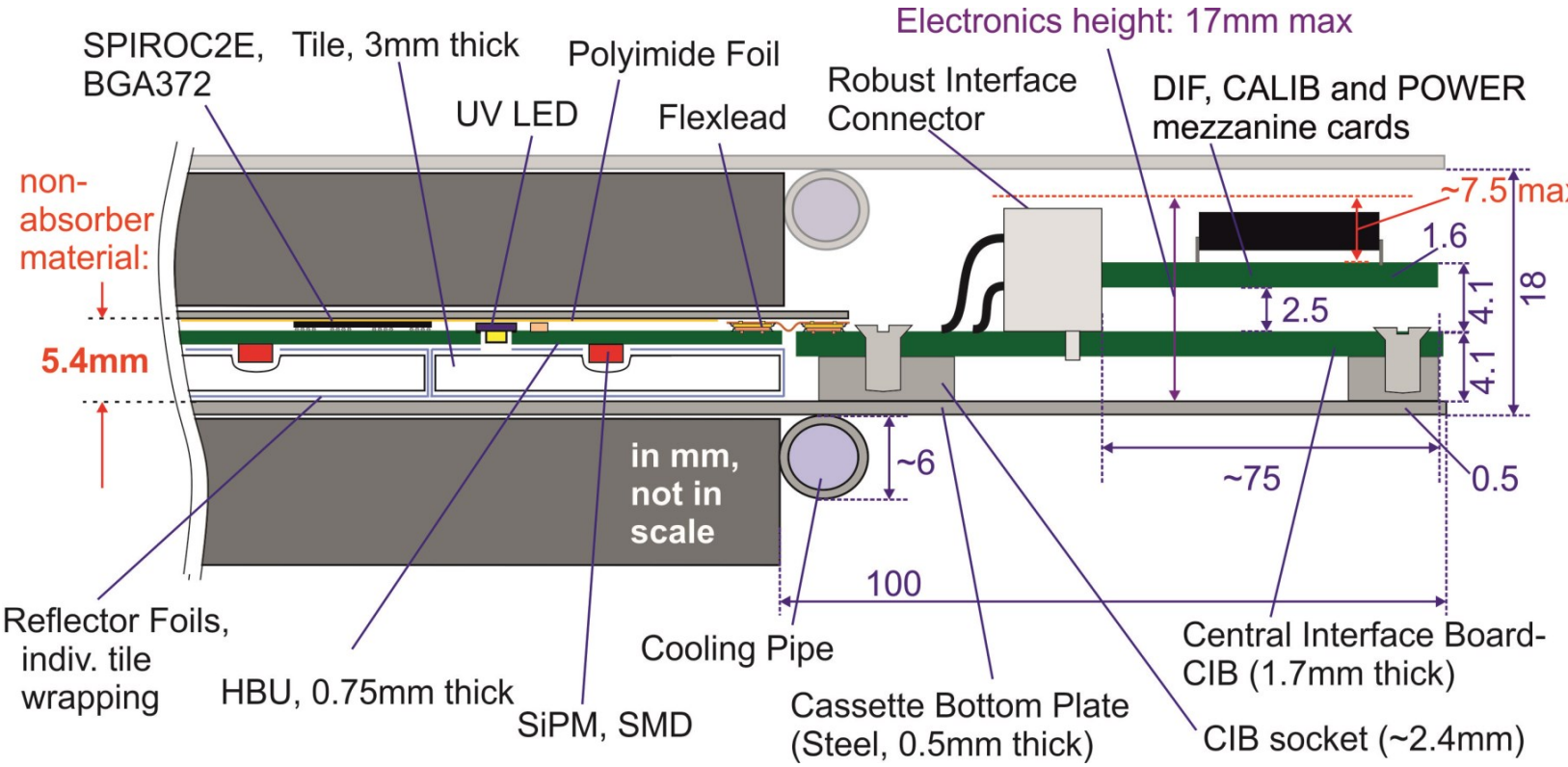


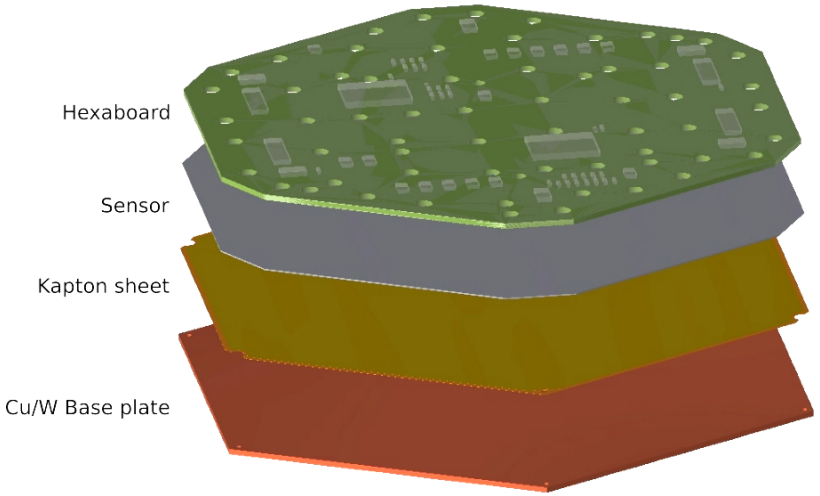


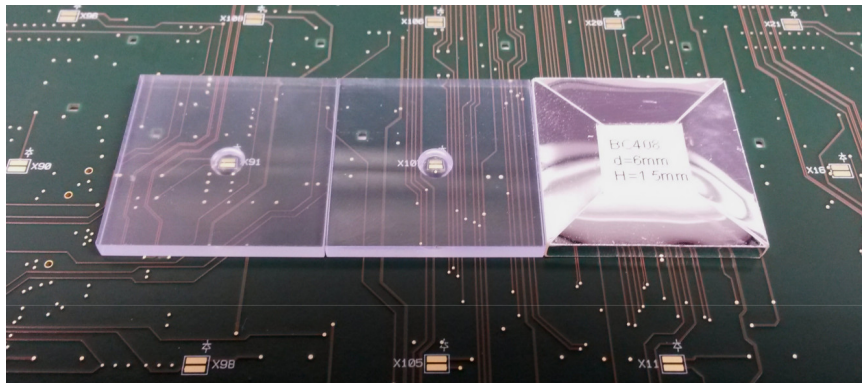
HGCAL active layers

Mixed cassettes





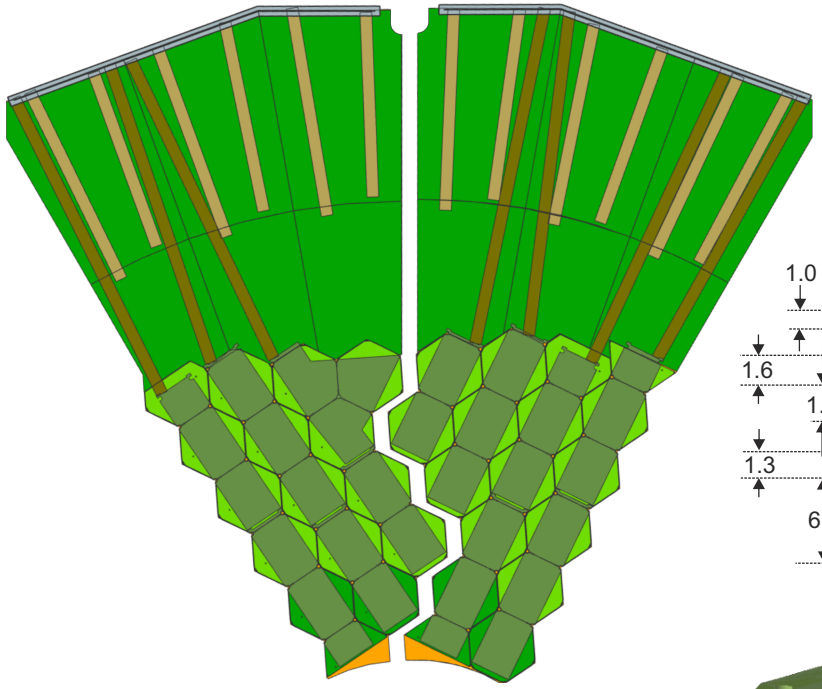


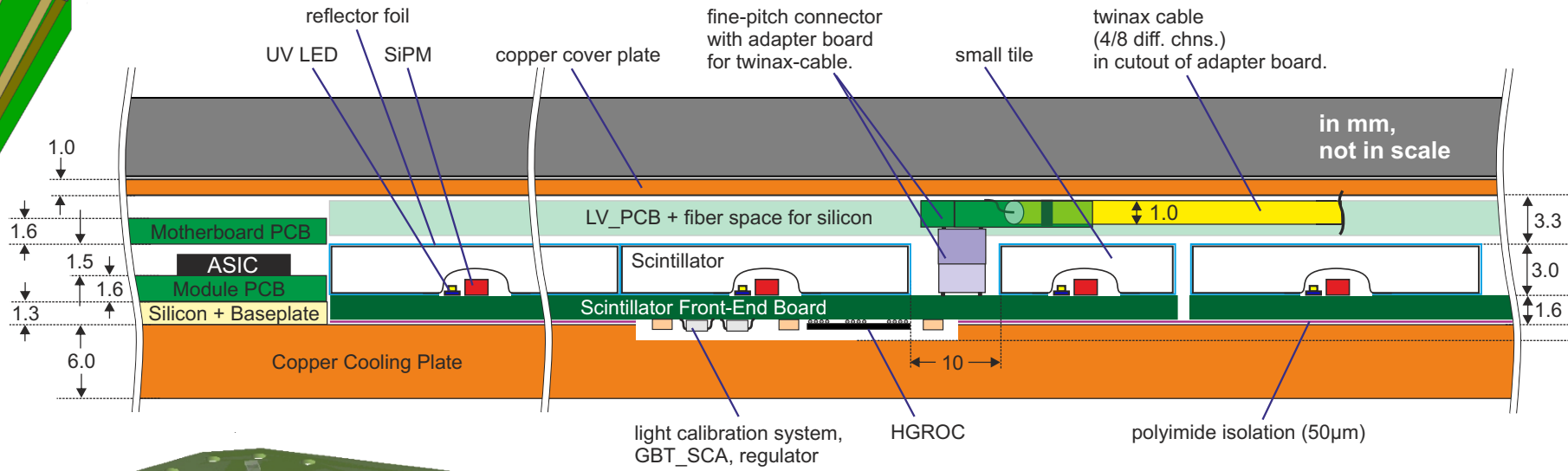


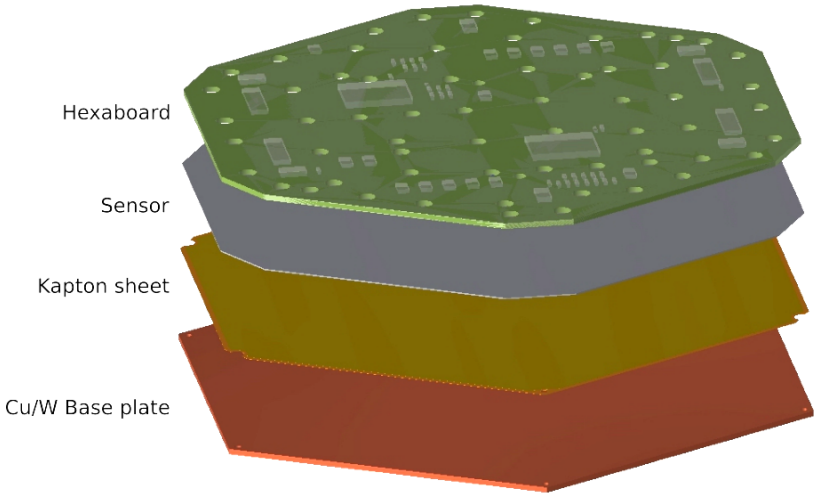
tile sizes 2 cm - 5.5 cm

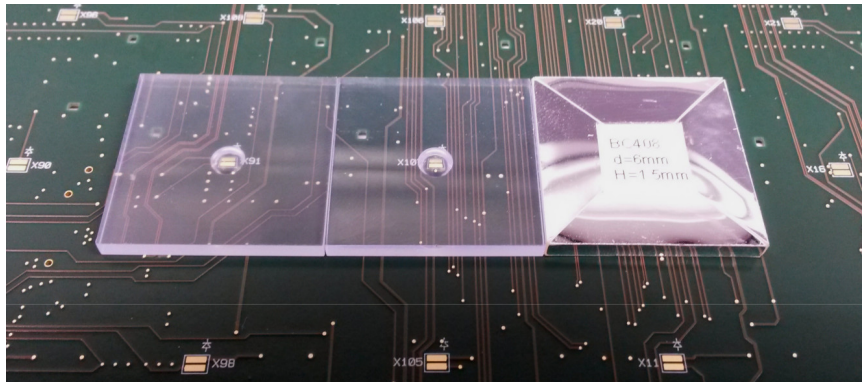
HGCAL active layers

Mixed cassettes









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HGCAL active layers

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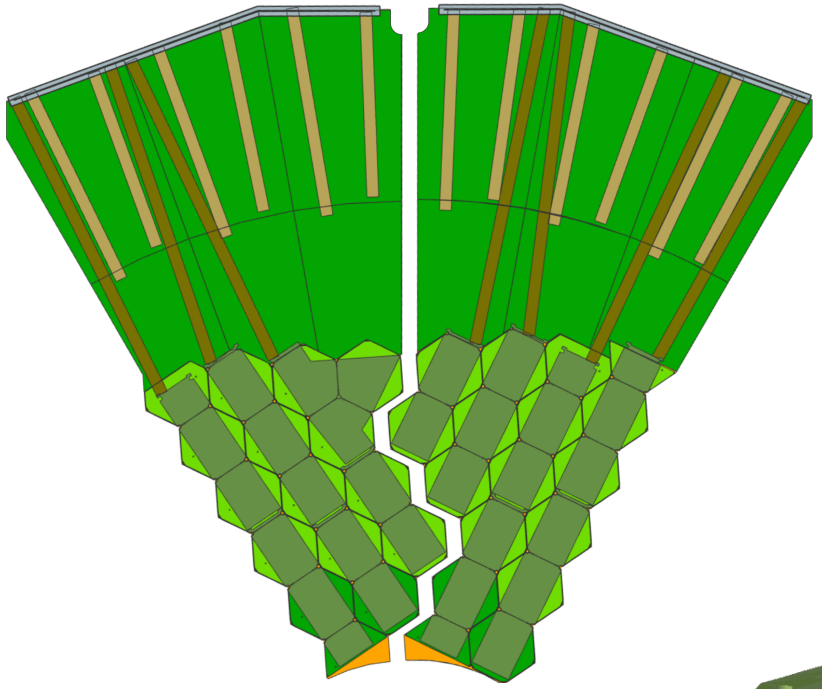
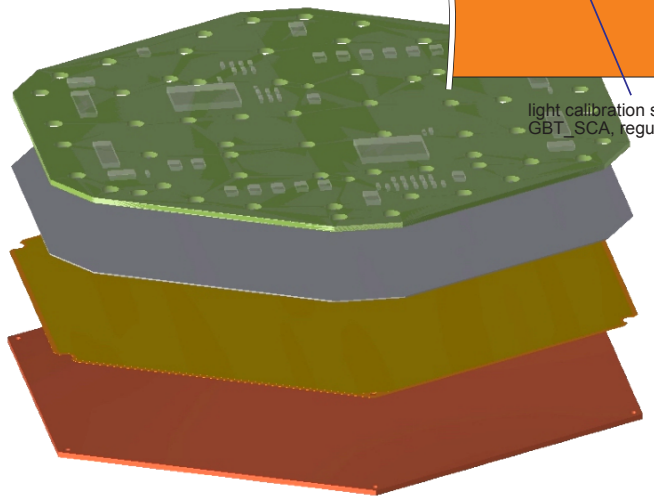
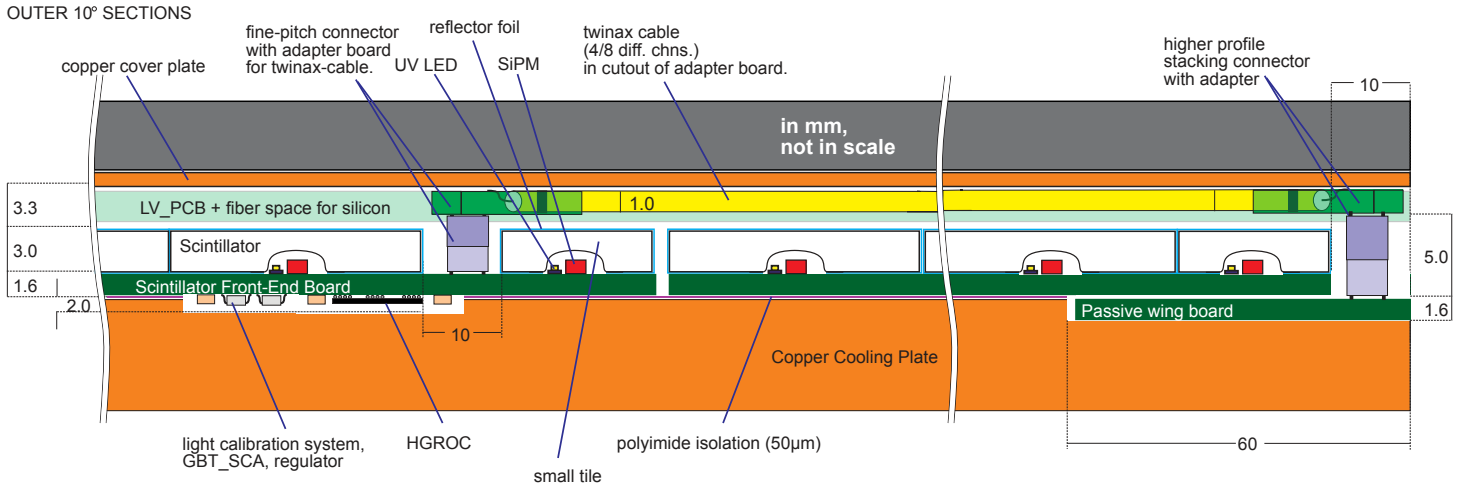
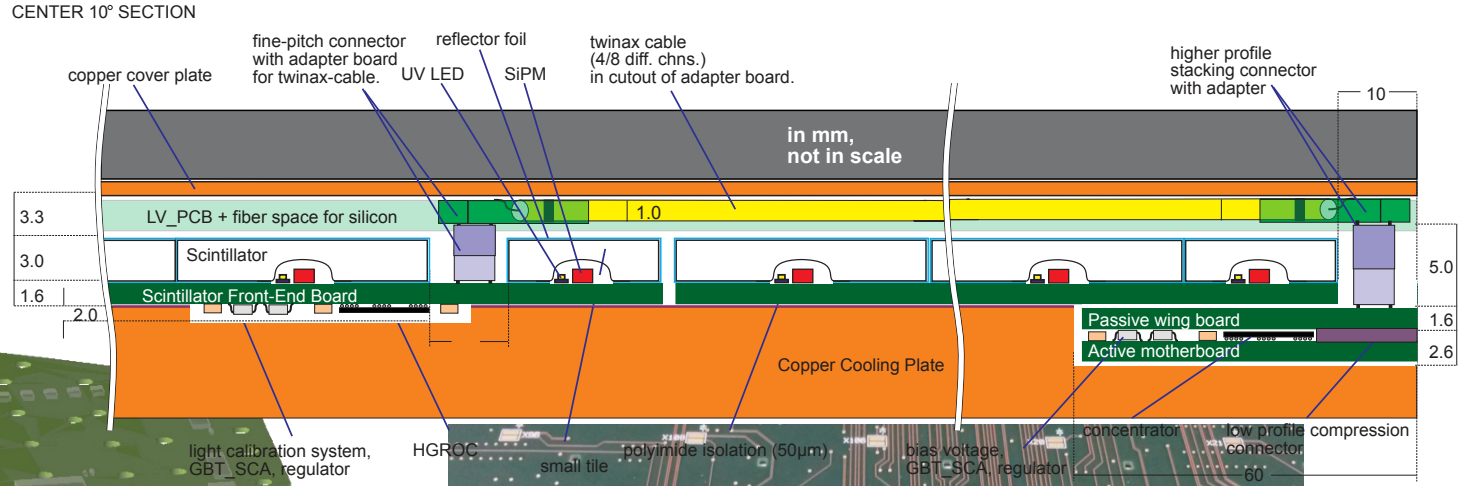
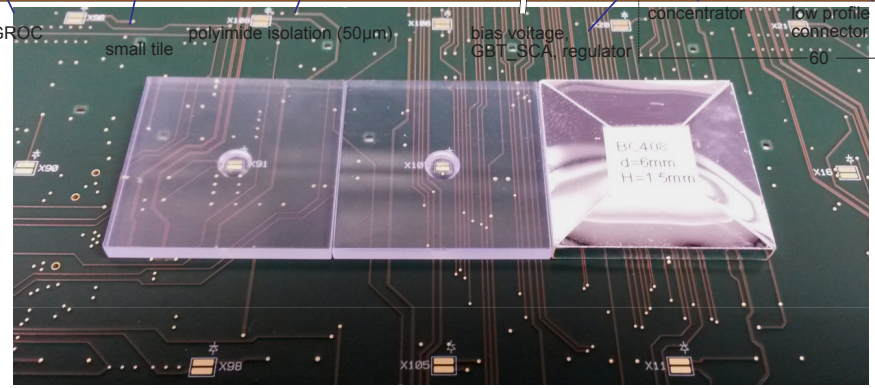










tile sizes 2 cm - 5.5 cm

HGCAL tile-modules

The DESY part.

Tile-boards = HBUs

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

Tile-modules = tile-boards + scintillator

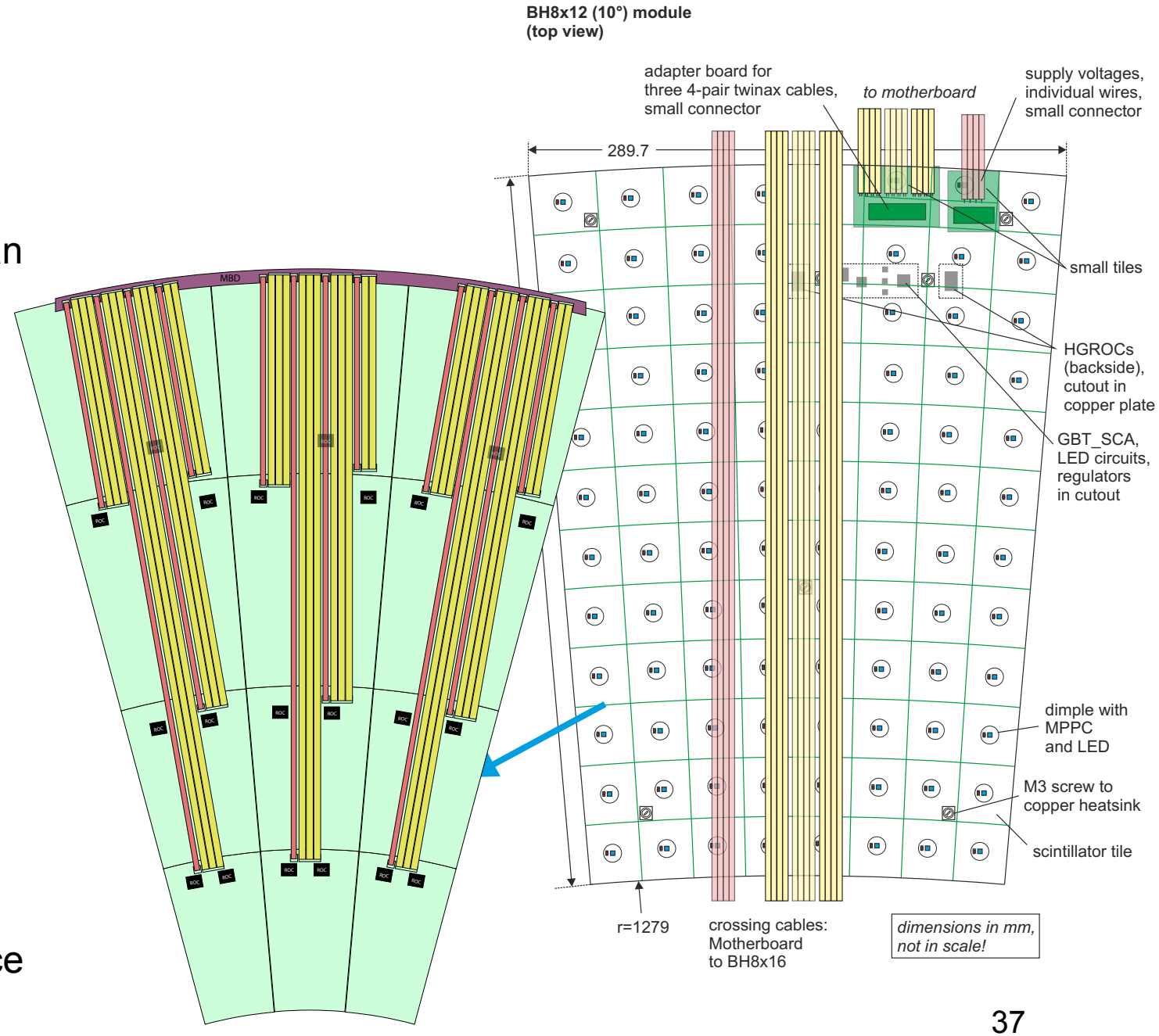
- individual tiles for larger sizes
- mega-tiles for smaller sizes

New technical challenges

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

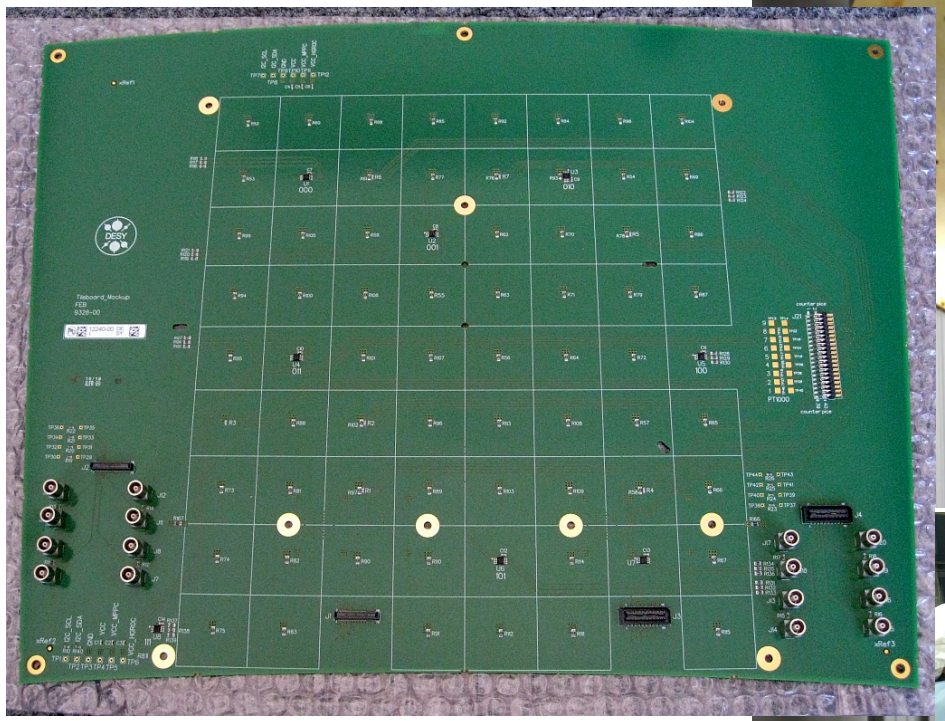
Basic R&D:

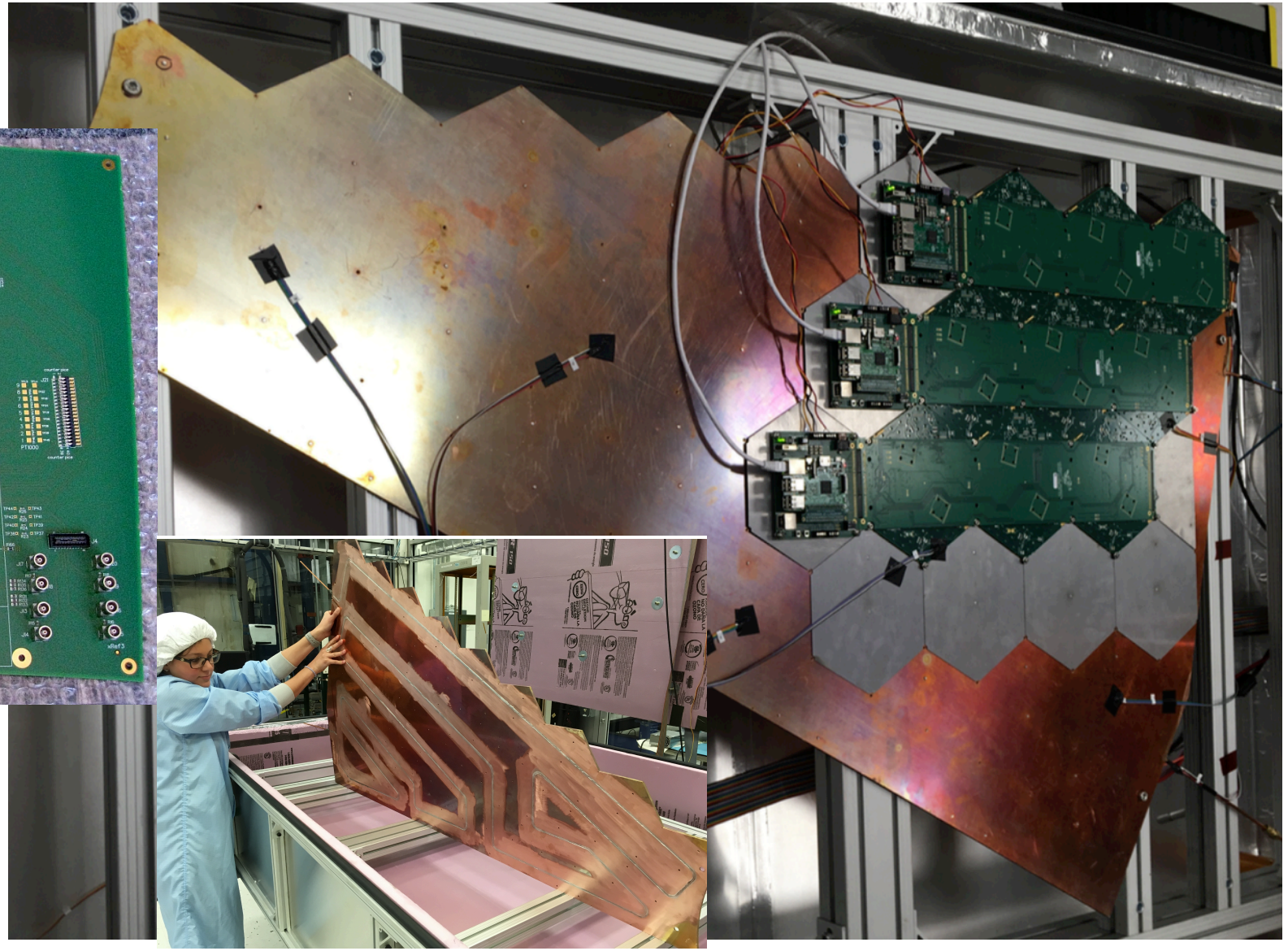
- scintillator and SiPM radiation tolerance



Mixed Cassette Mockup

Effort at Fermilab



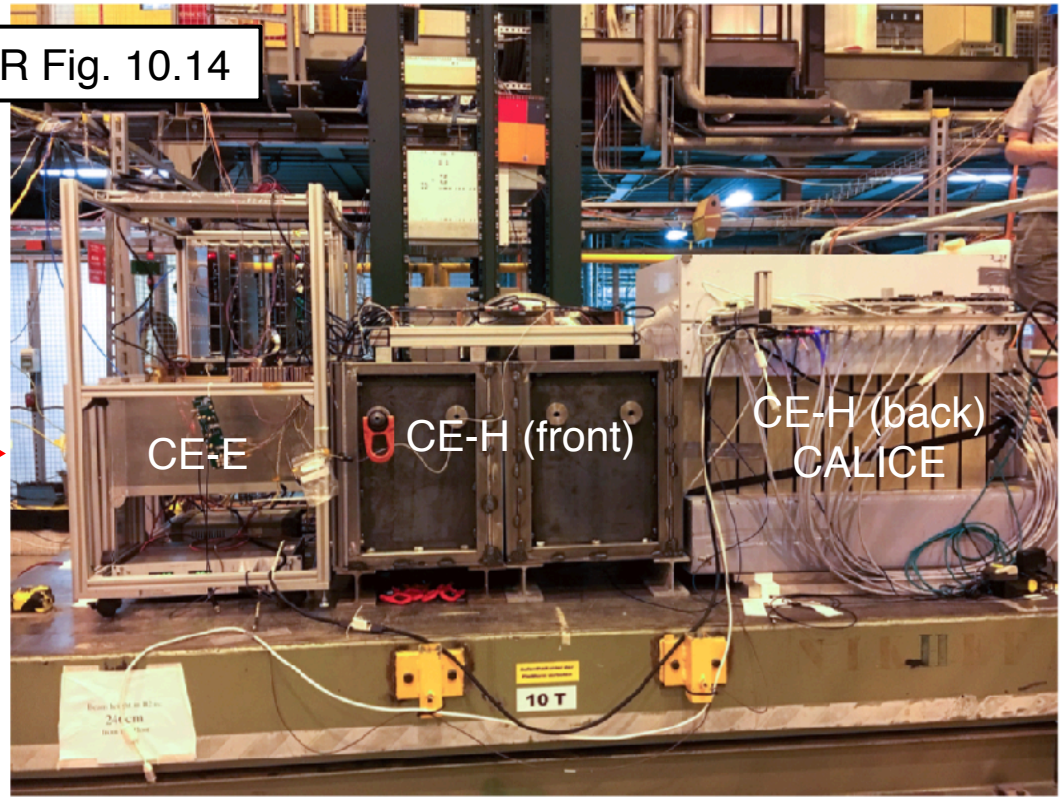


- Thermal mock-up board to study SiPM cooling
- Single-board studies at DESY under preparation, too

CALICE CMS Common Test Beam

AHCAL prototype as Backing Hadron calorimeter (2017)

TDR Fig. 10.14



- Common DAQ: EUDAQ

AIDA2020

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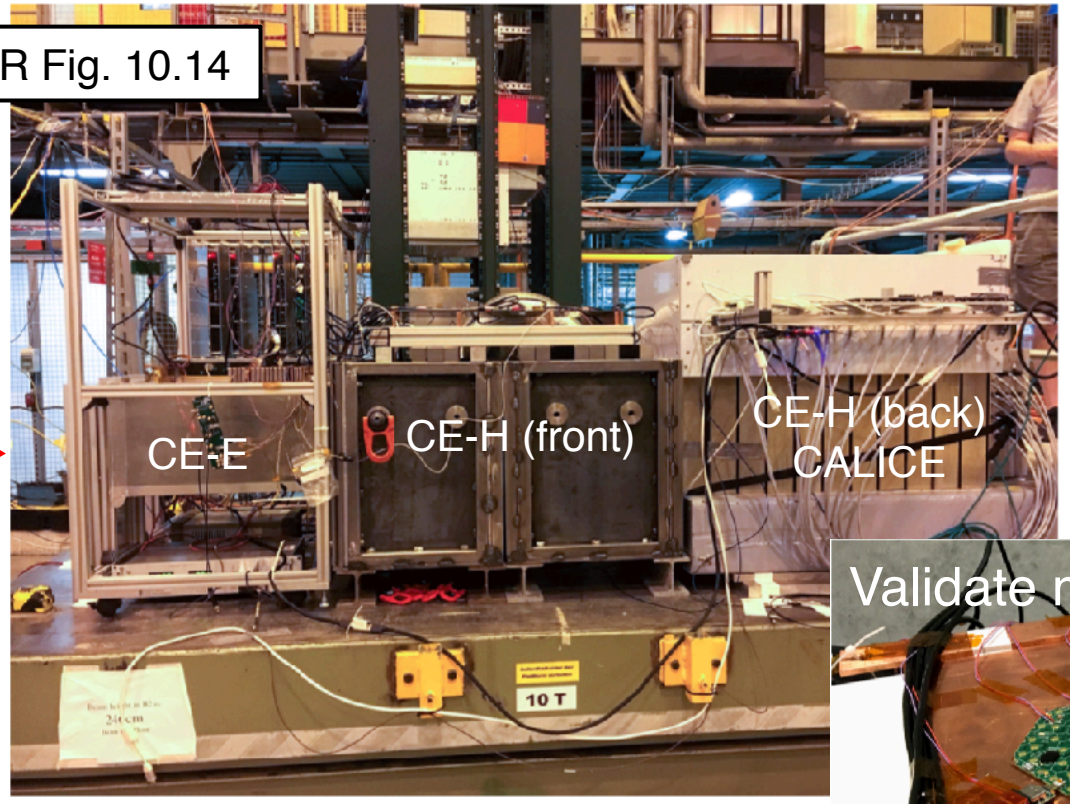
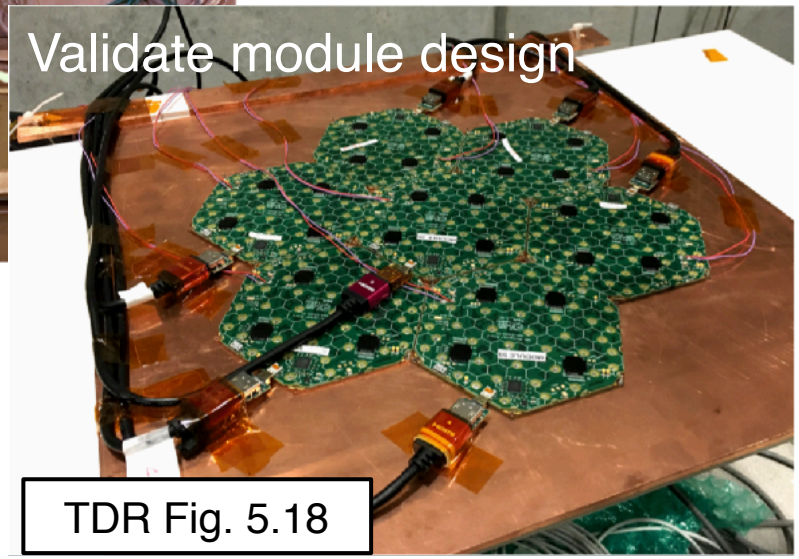
AHCAL prototype as Backing Hadron calorimeter (2017)

TDR Fig. 10.14





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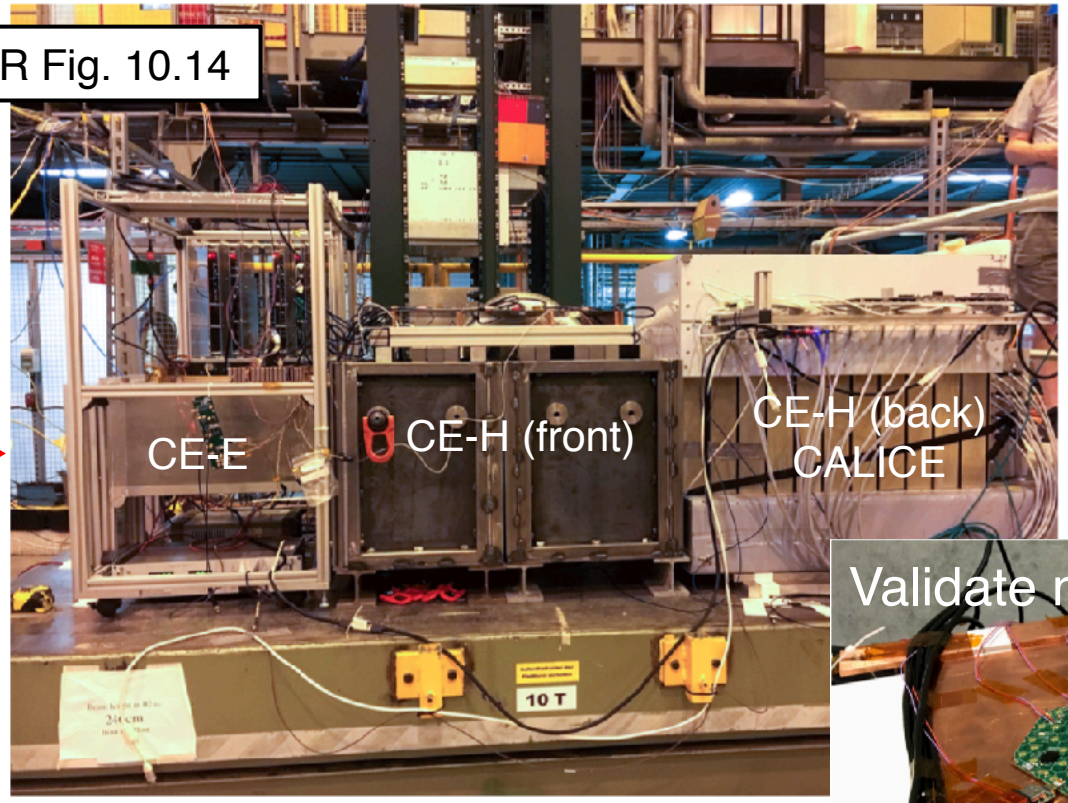

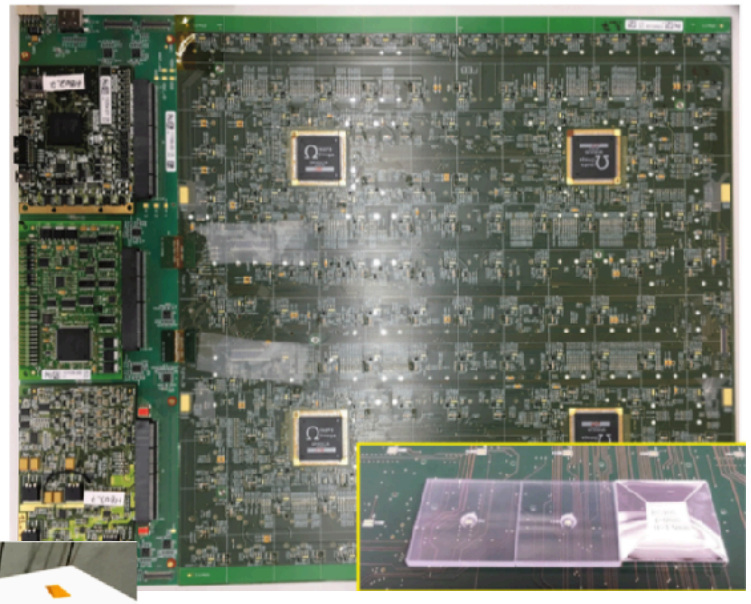

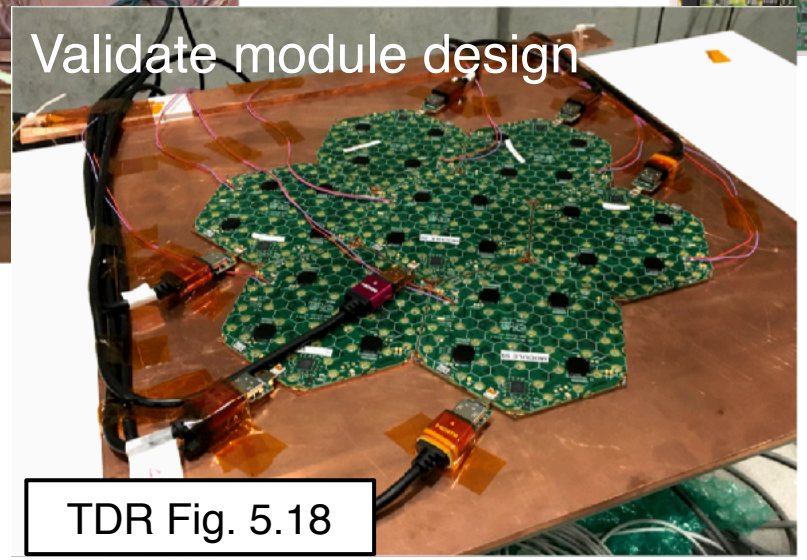

TDR Fig. 5.18

- Common DAQ: EUDAQ

AIDA2020

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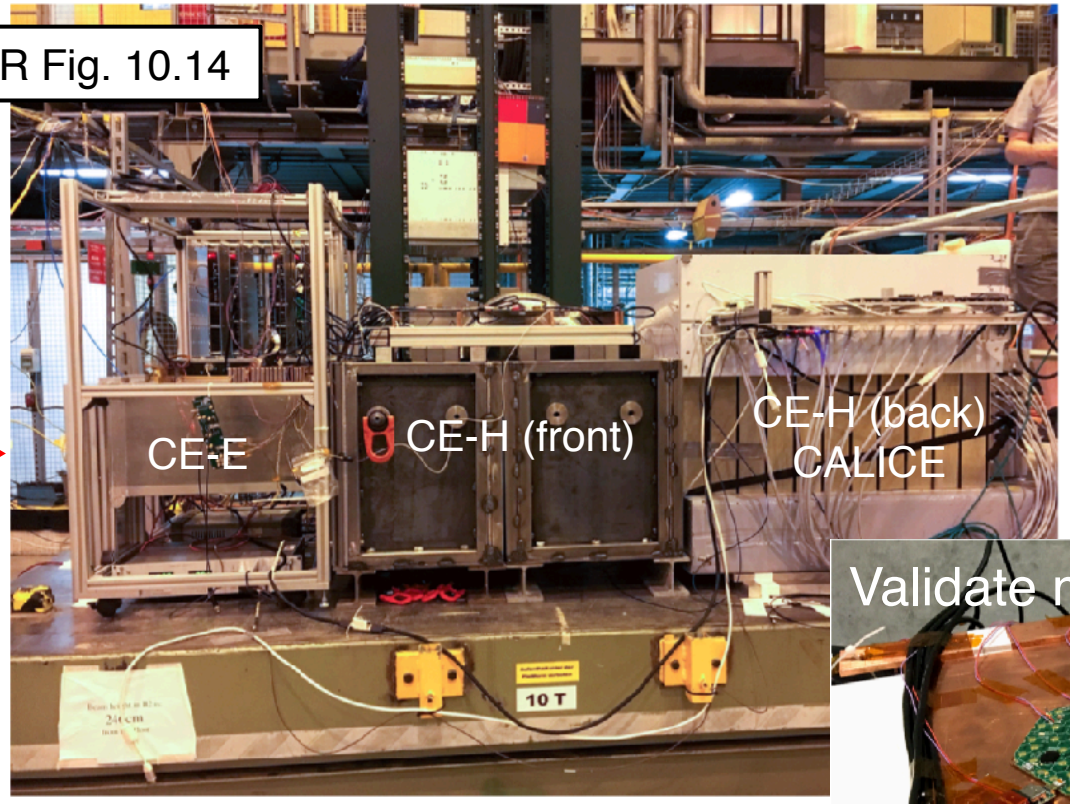
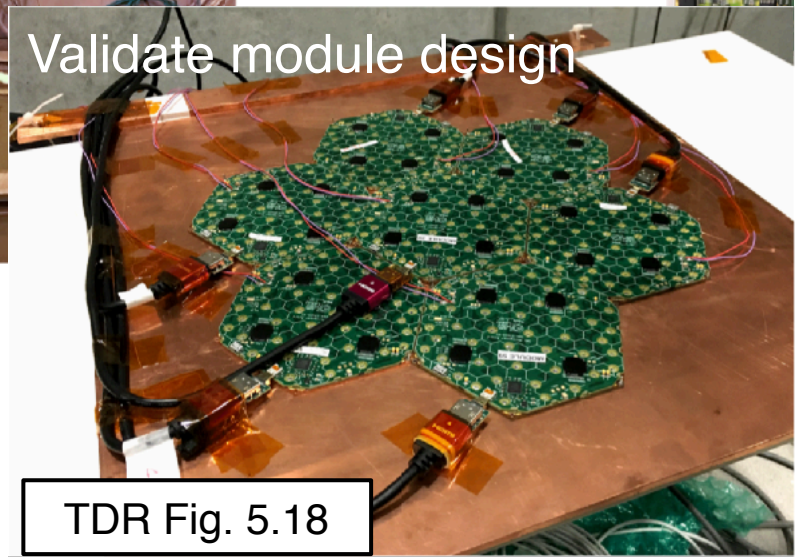
AHCAL prototype as Backing Hadron calorimeter (2017)

TDR Fig. 10.14



Validate module design



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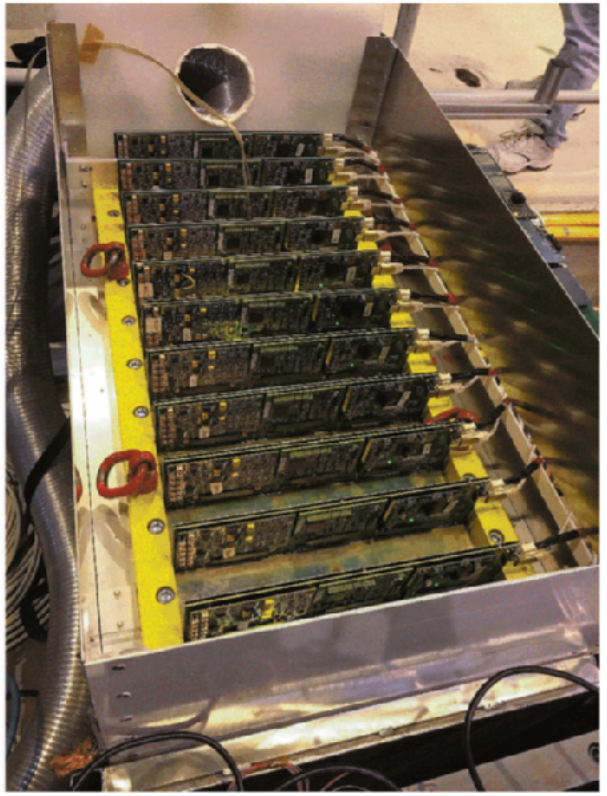


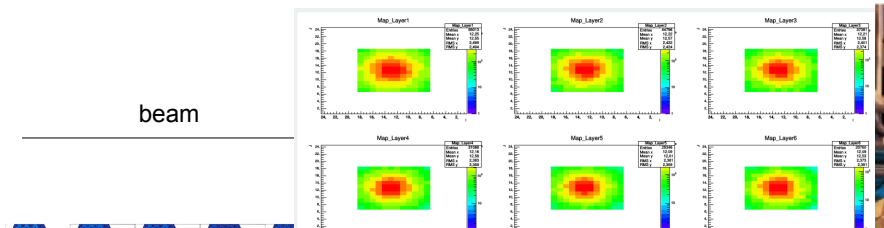
TDR Fig. 10.12

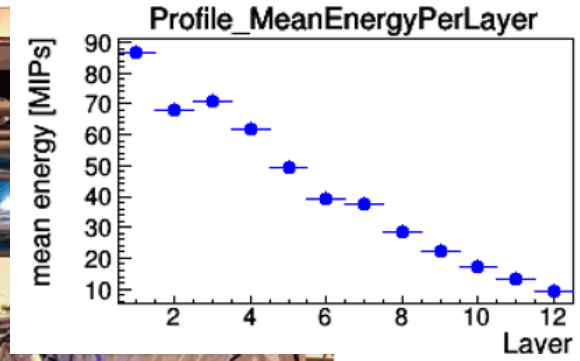
- Common DAQ: EUDAQ

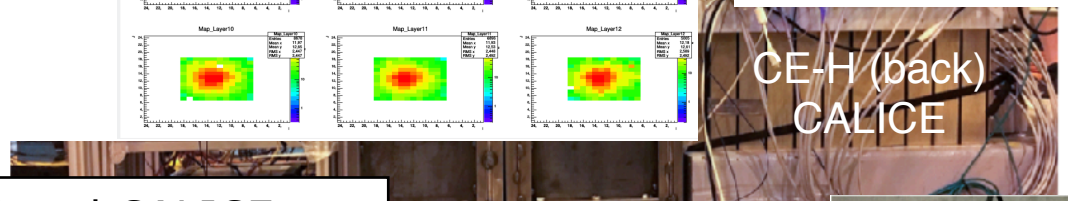
AIDA2020

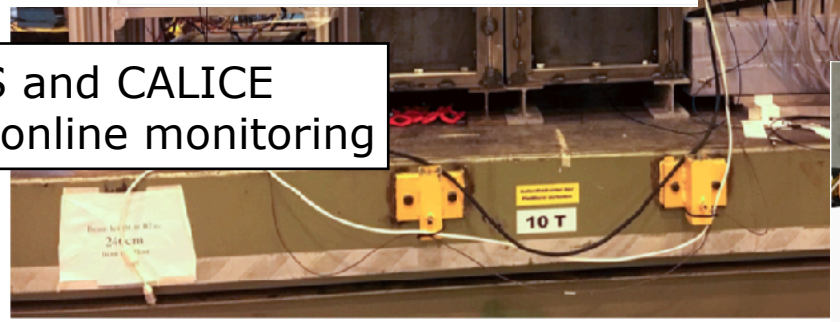
CALICE CMS Common Test Beam

AHCAL prototype as Backing Hadron calorimeter (2017)

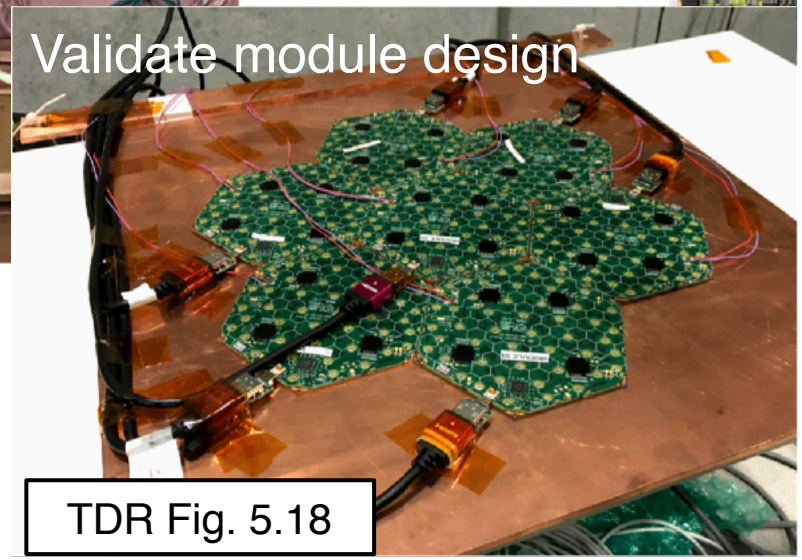








CMS and CALICE
(quasi-) online monitoring



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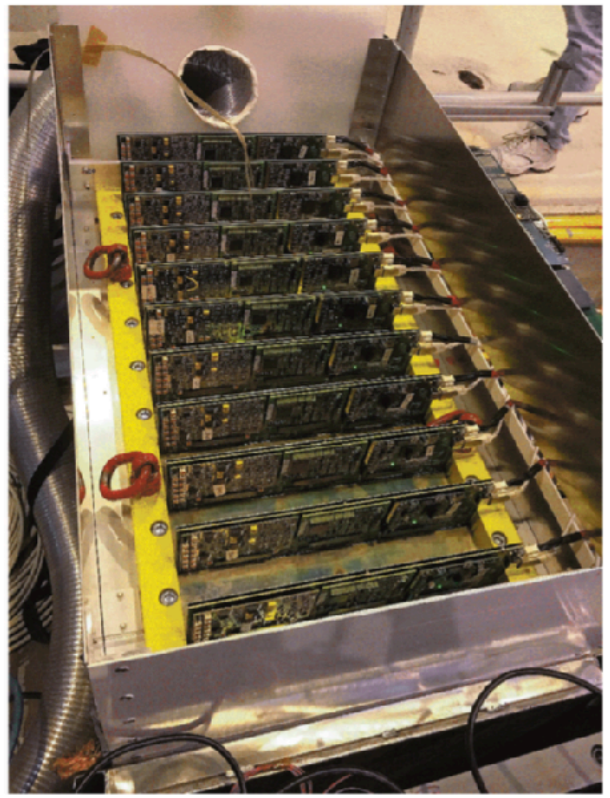


TDR Fig. 10.12

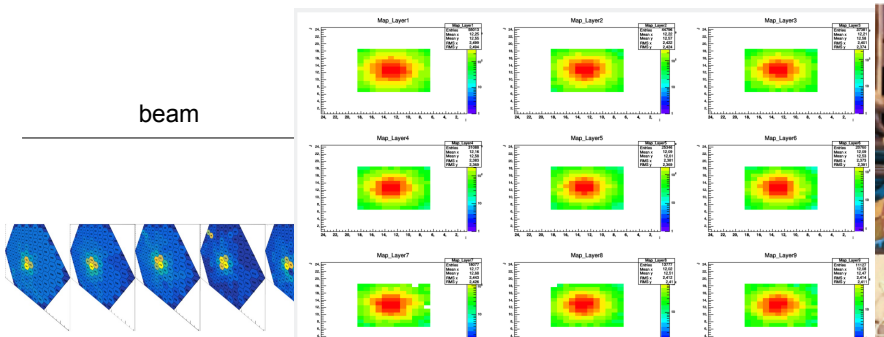
- Common DAQ: EUDAQ

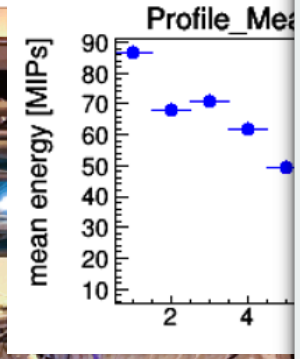
AIDA2020

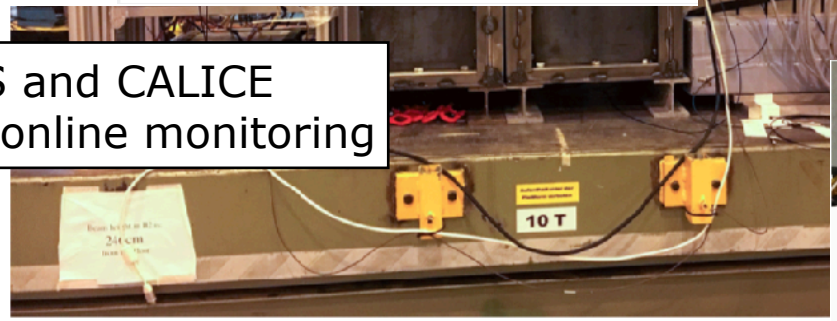
CALICE CMS Common Test Beam

AHCAL prototype as Backing Hadron calorimeter (2017)

MIP signals from track segments in 300 GeV pion shower



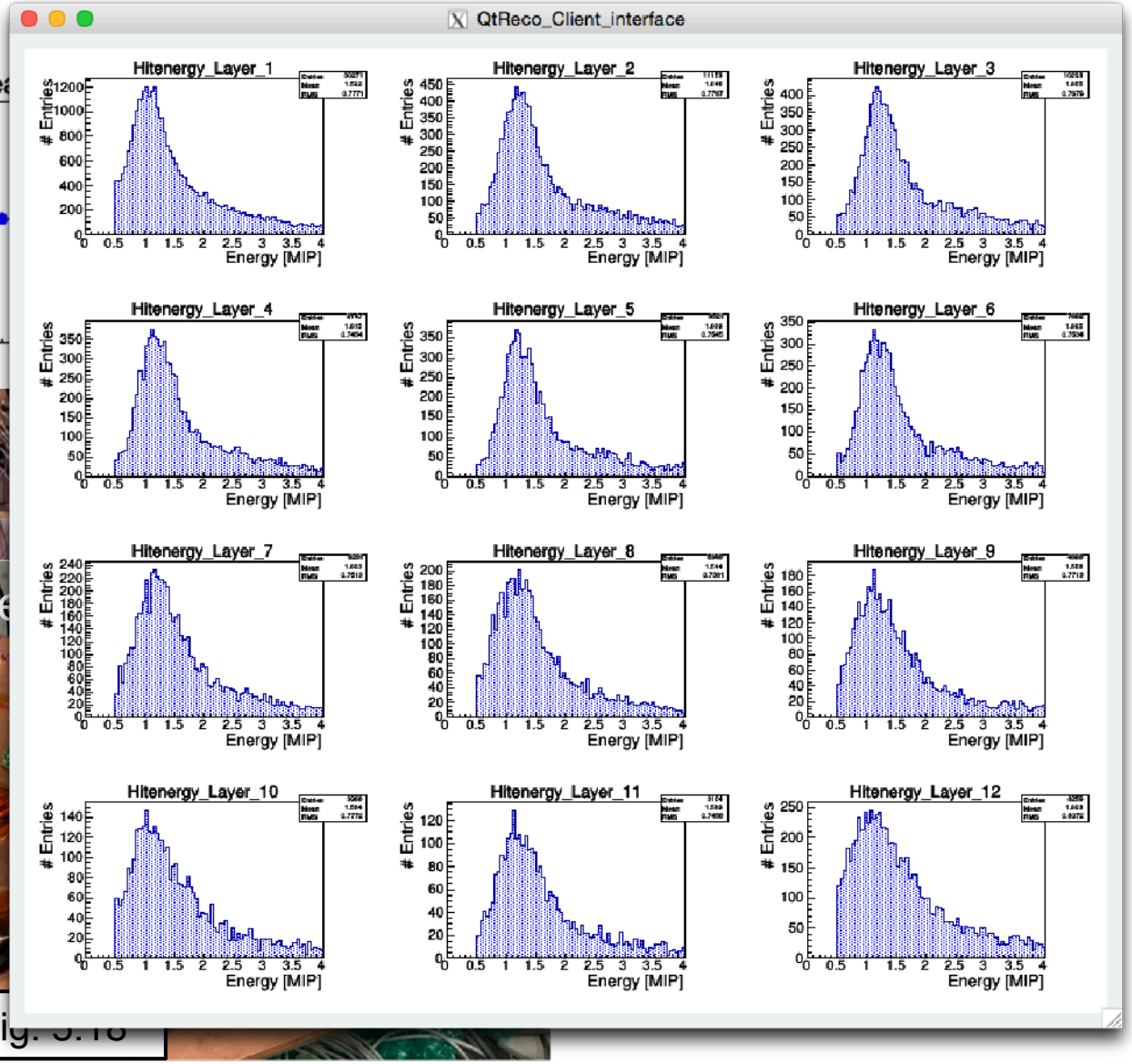




CE-H (back)
CALICE

Validate

CMS and CALICE
(quasi-) online monitoring



- Common DAQ: EUDAQ

AIDA2020

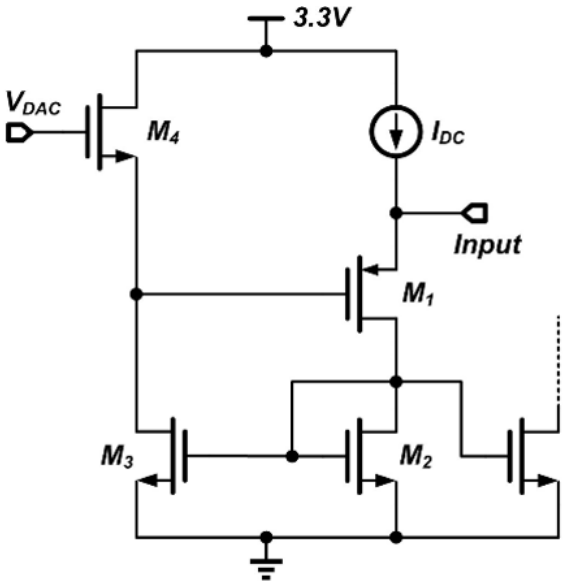
TDR Fig. 5.18

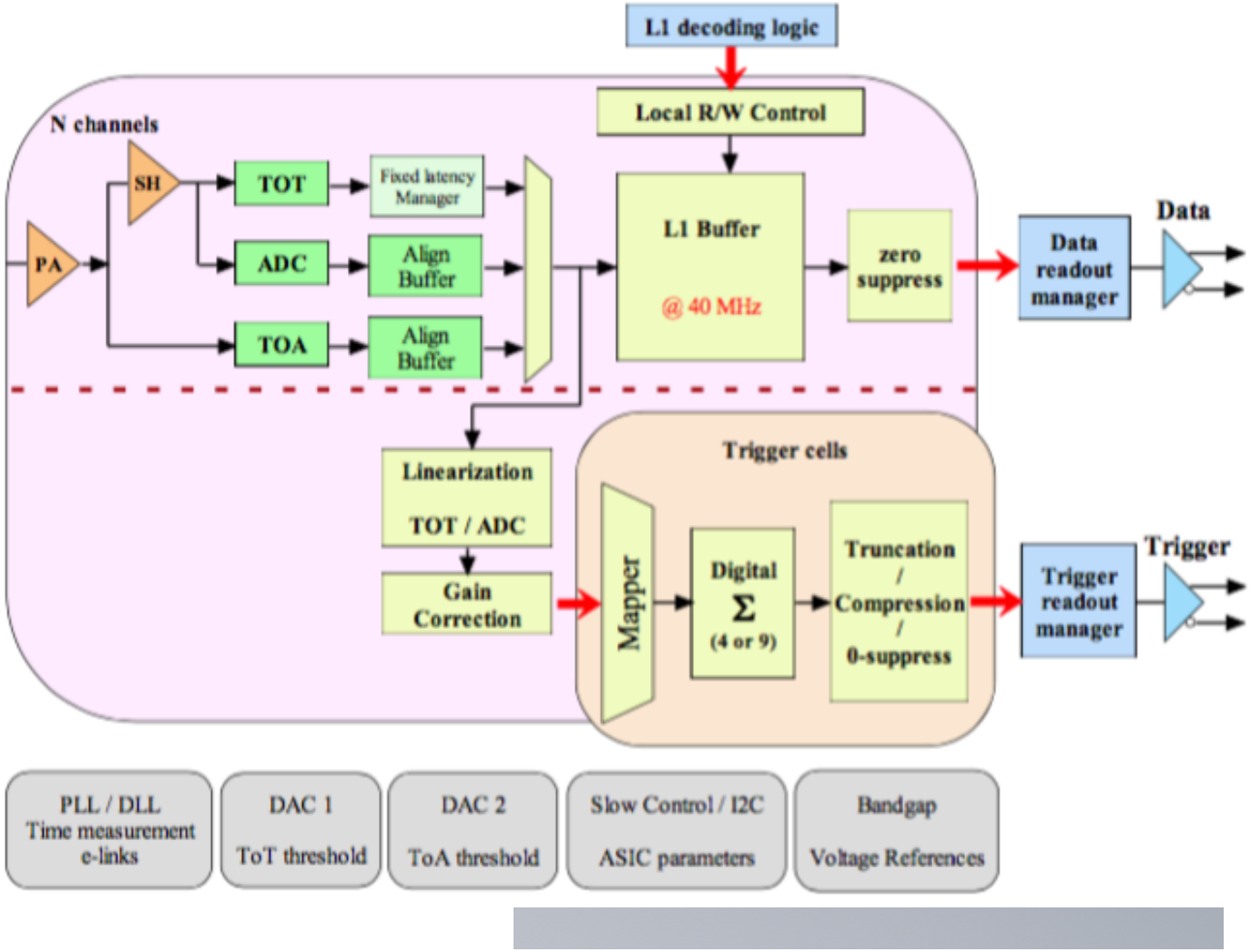
Read-out electronics

Front-end based on CALICE developments

HGCROC derived from 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)





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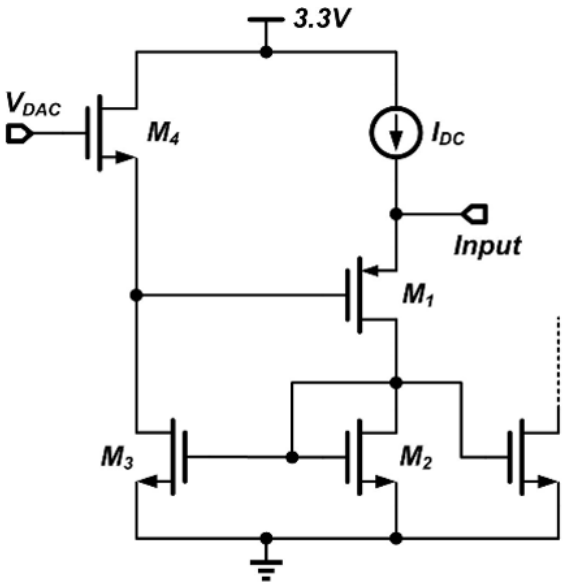

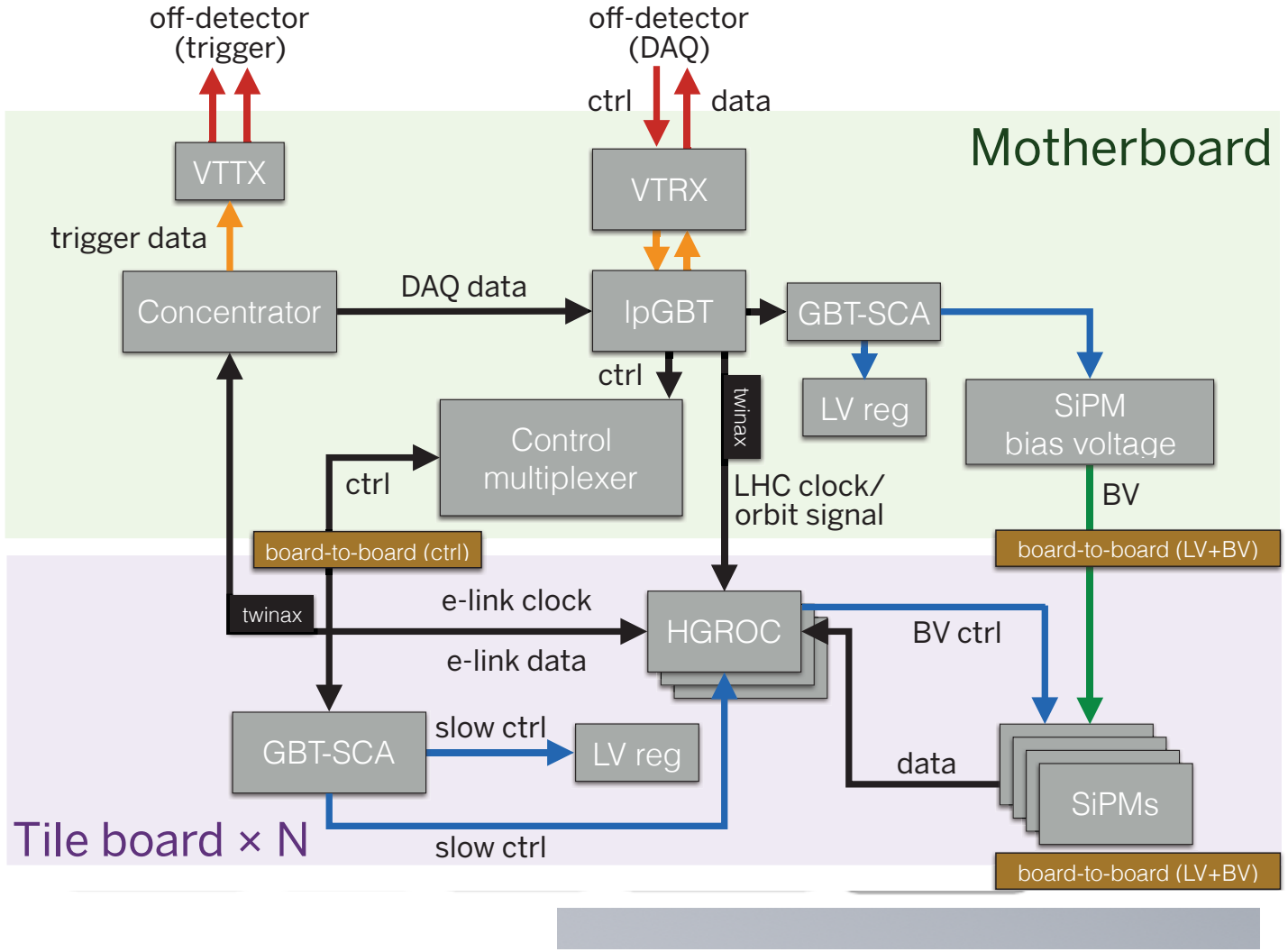

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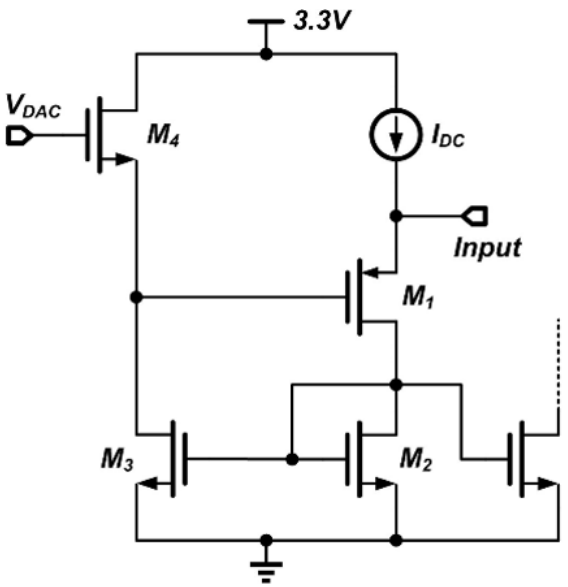
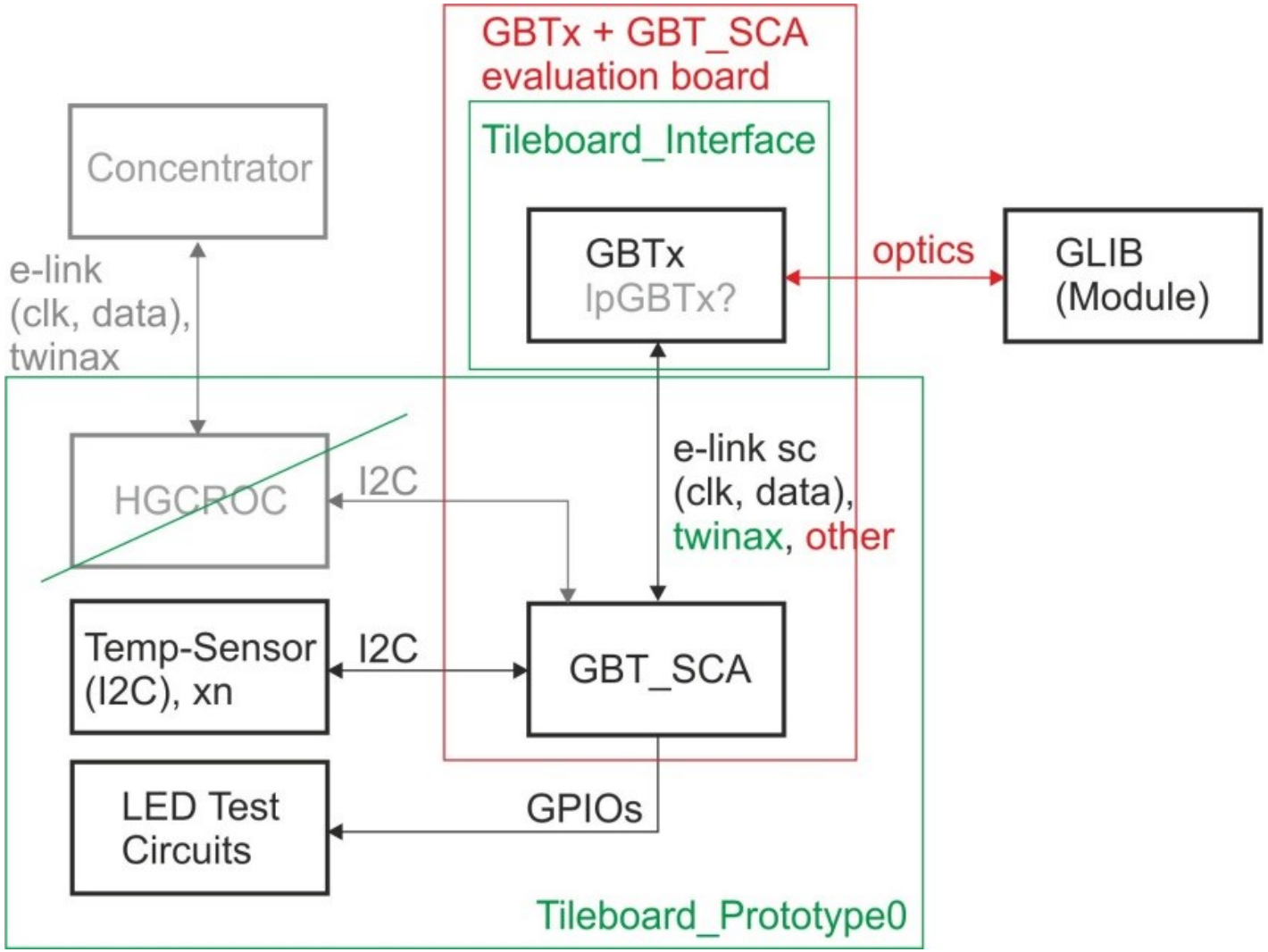
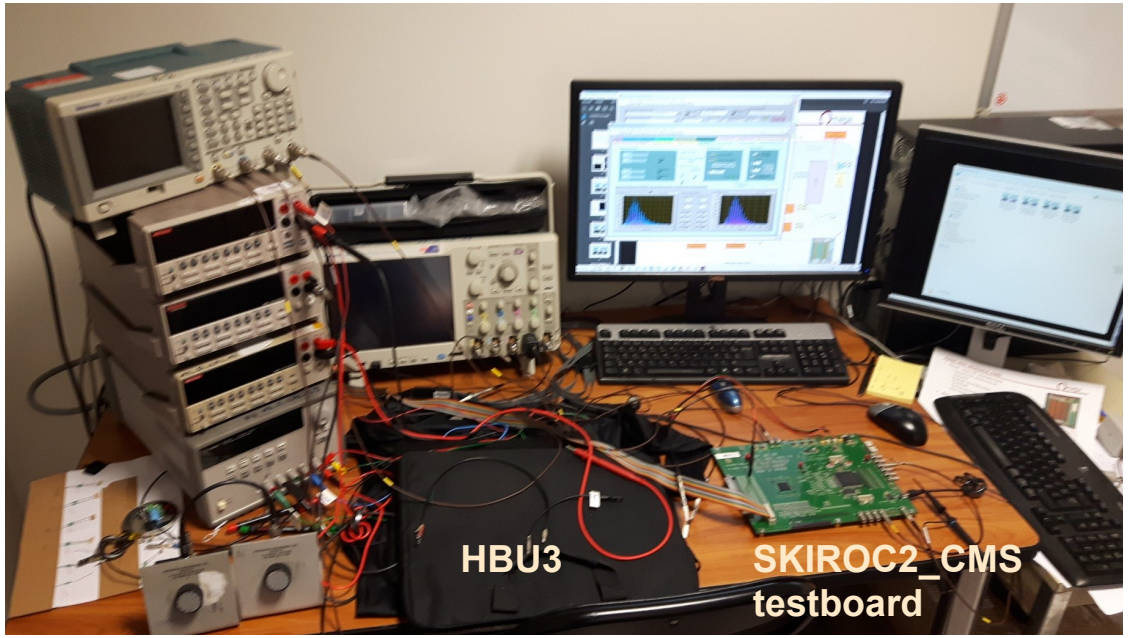
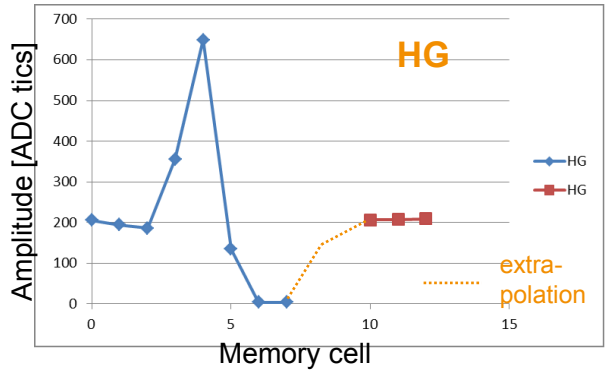


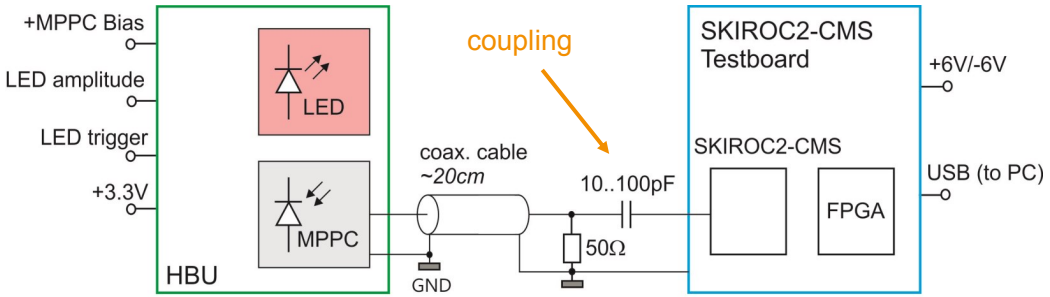


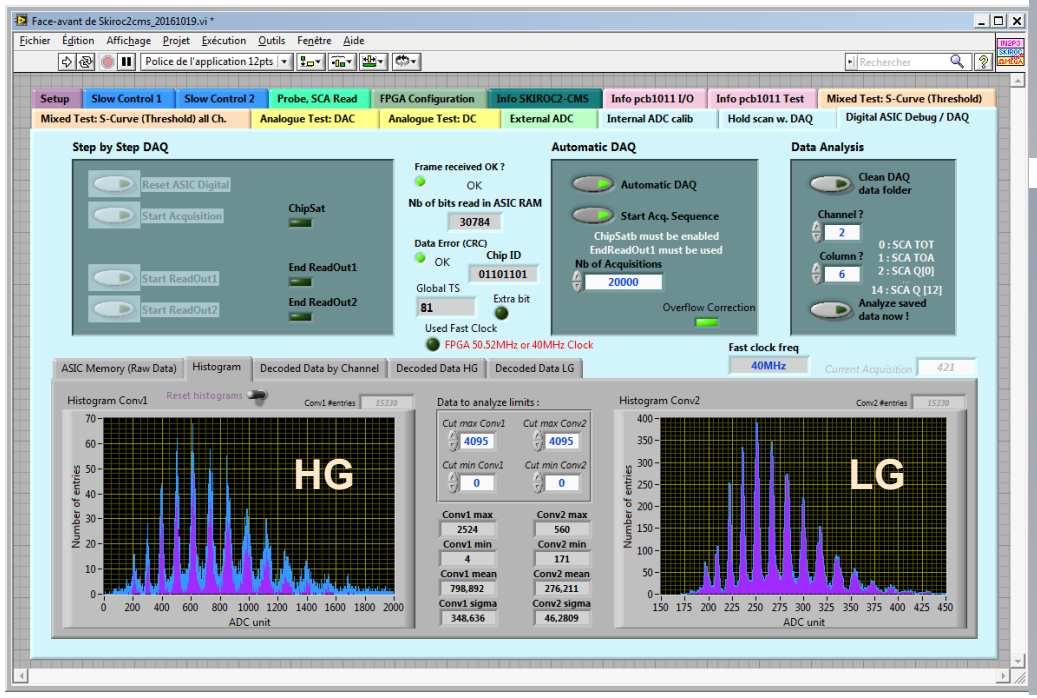
First steps

SiPMs read out CMS style







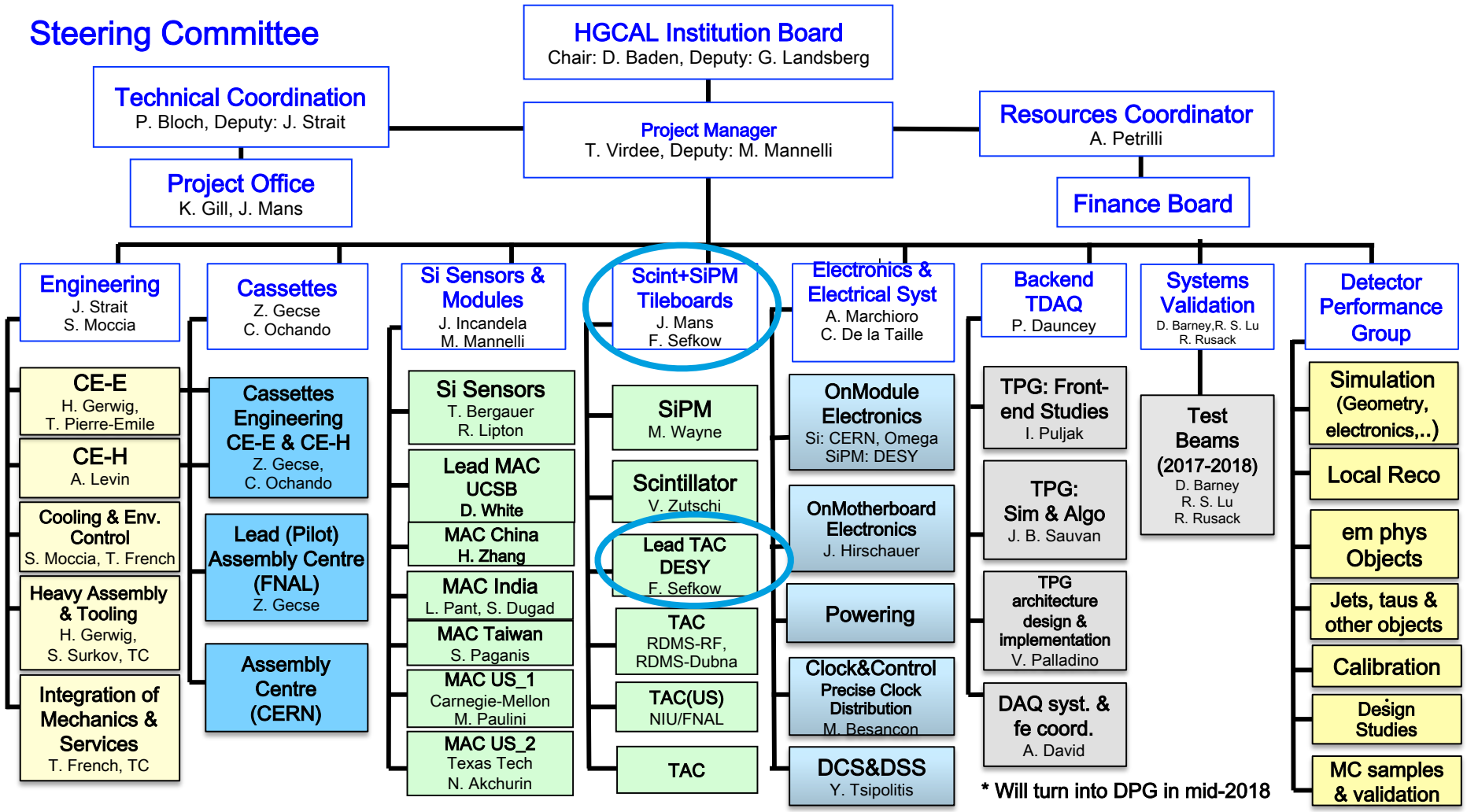


M.Reinecke (DESY), S. Callier (OMEGA)

HGCAL organisation

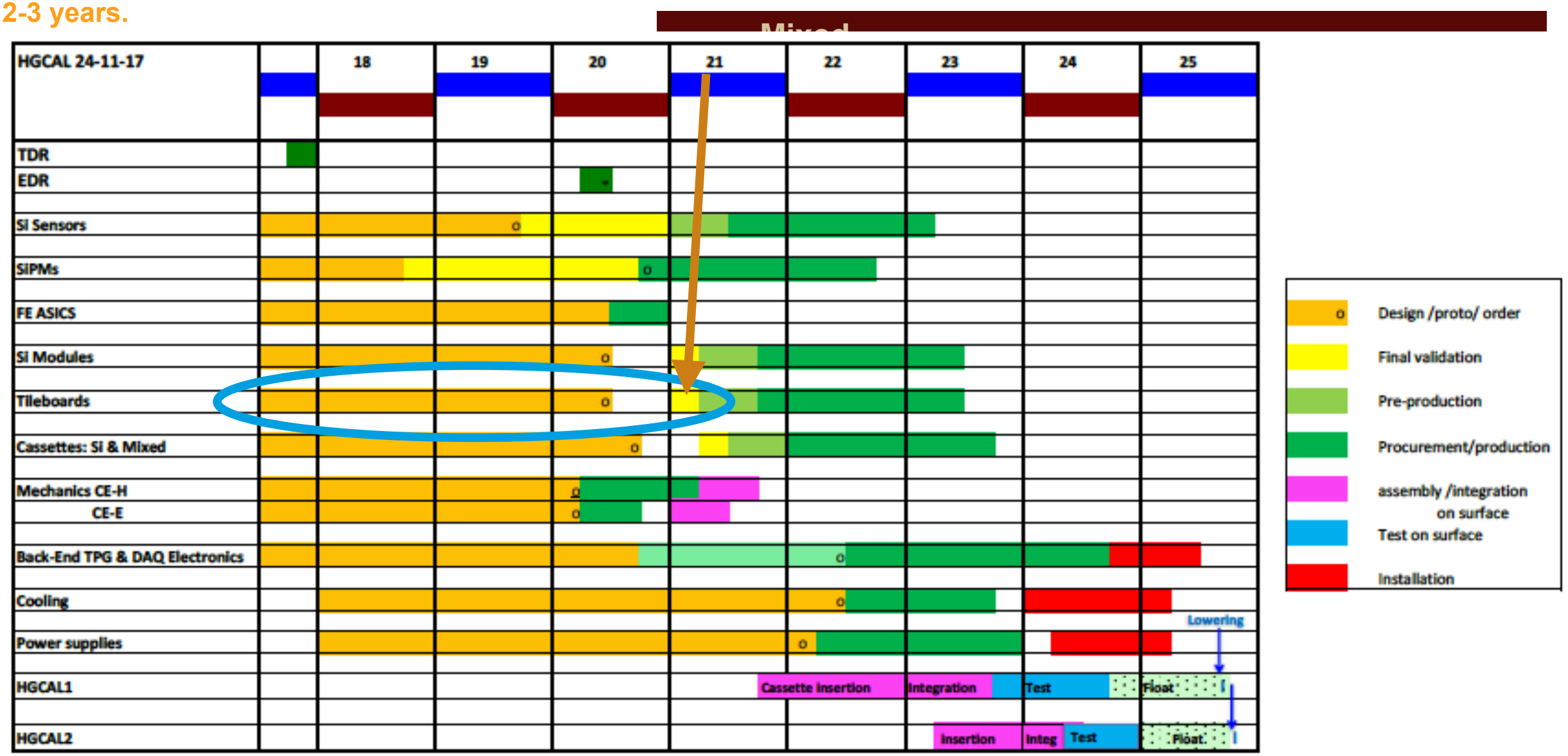
The pople

- 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),
  - LLR engineers



HGCAL scintillator R&D plan

2-3 years.



HGCAL scintillator R&D plan

2-3 years.

	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

Summary

No conclusion.

CMS High Granularity Calorimeter upgrade taking up momentum after approval of TDR.

Strongly buying on CMS silicon tracking and LC calorimeter experience.

CALICE SiPM-on-tile HCAL design largely adopted.

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

Exciting to connect LC and LHC expertise.

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%)

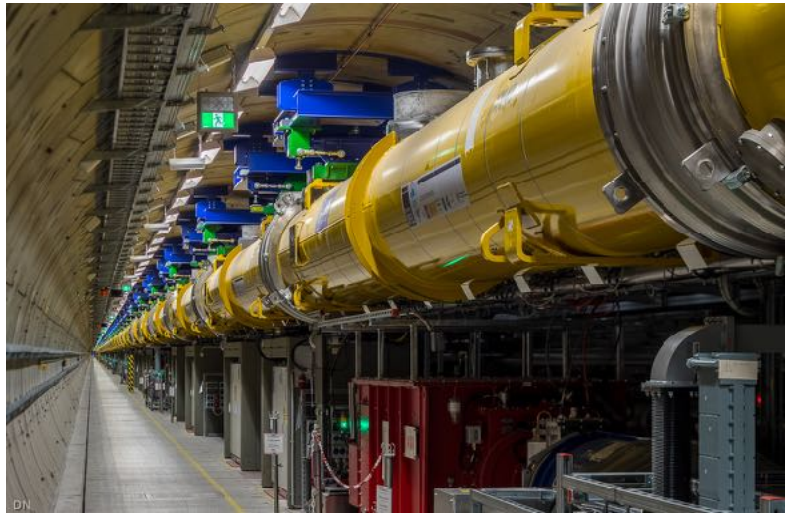
- simplifies powering and cooling: thinner trackers, denser calorimeters

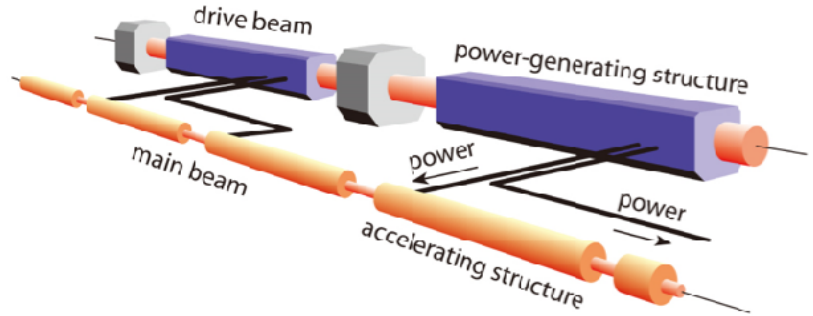
Backgrounds from beamstrahlung and hadronic 2-photon interactions

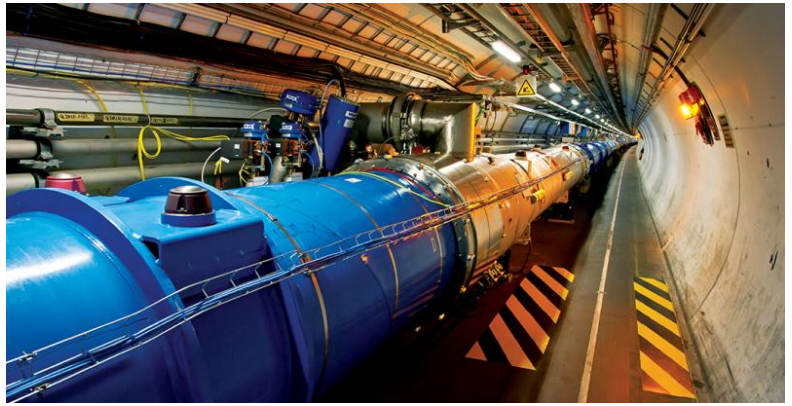
- more relevant for CLIC, higher E and smaller beam spot ($5x1nm^2$)
- somewhat higher emphasis on fine granularity and precise timing

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, ….

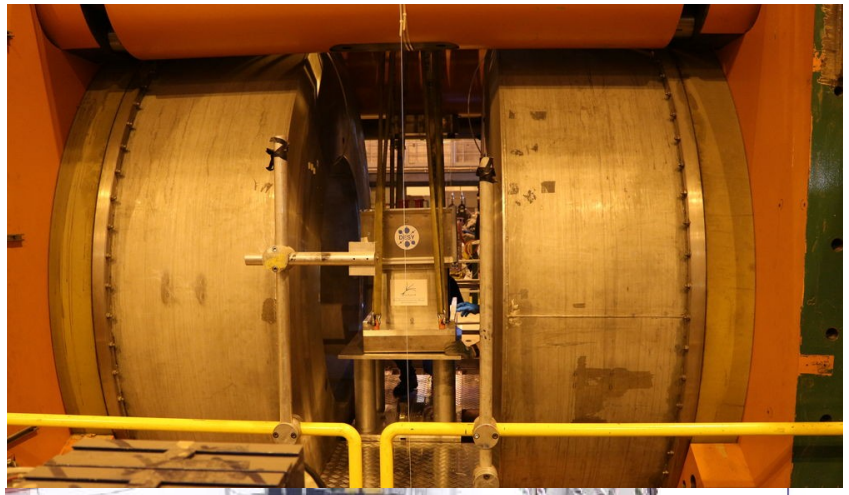


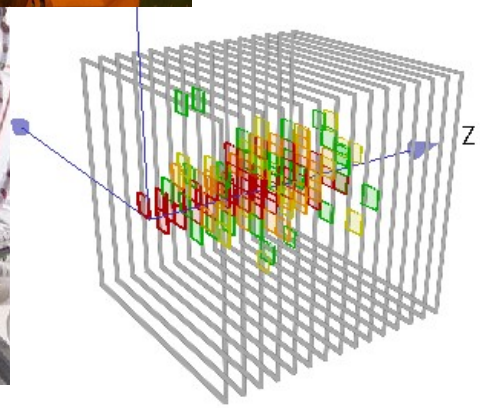


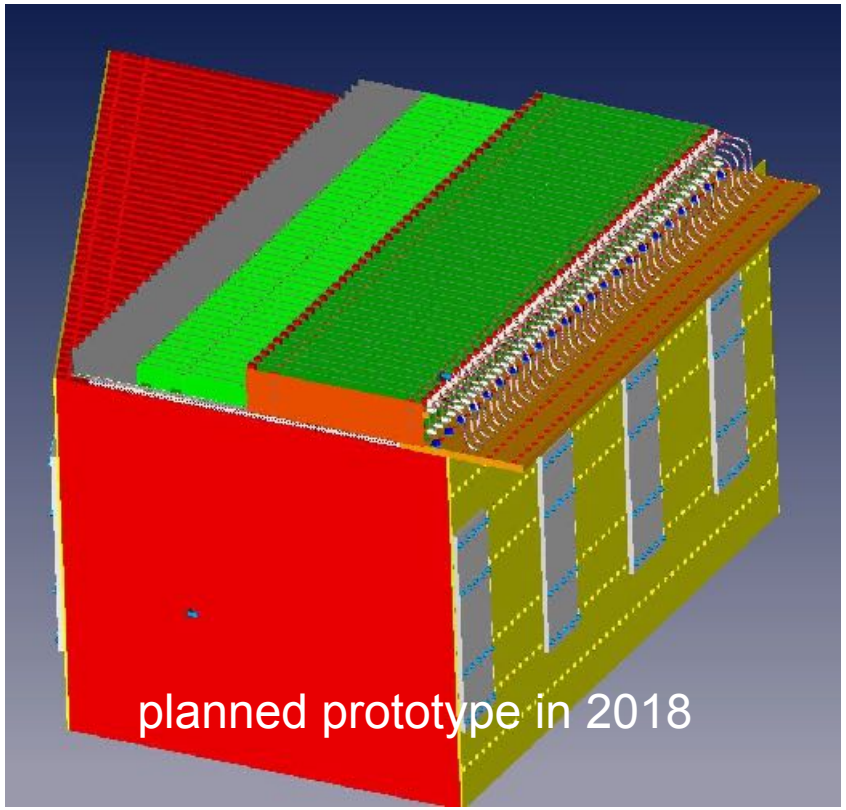


New Prototypes

`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

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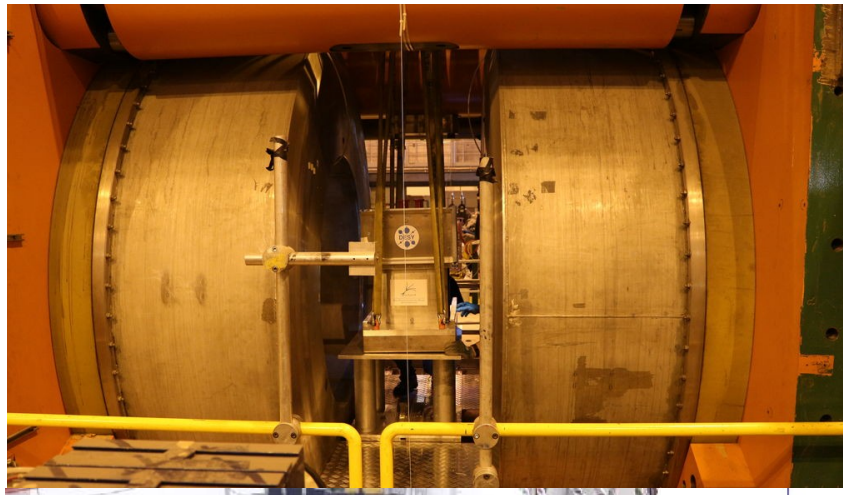

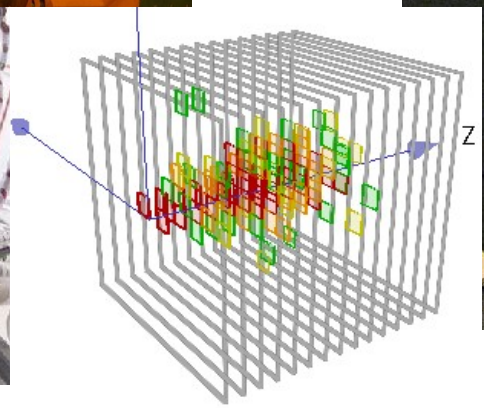

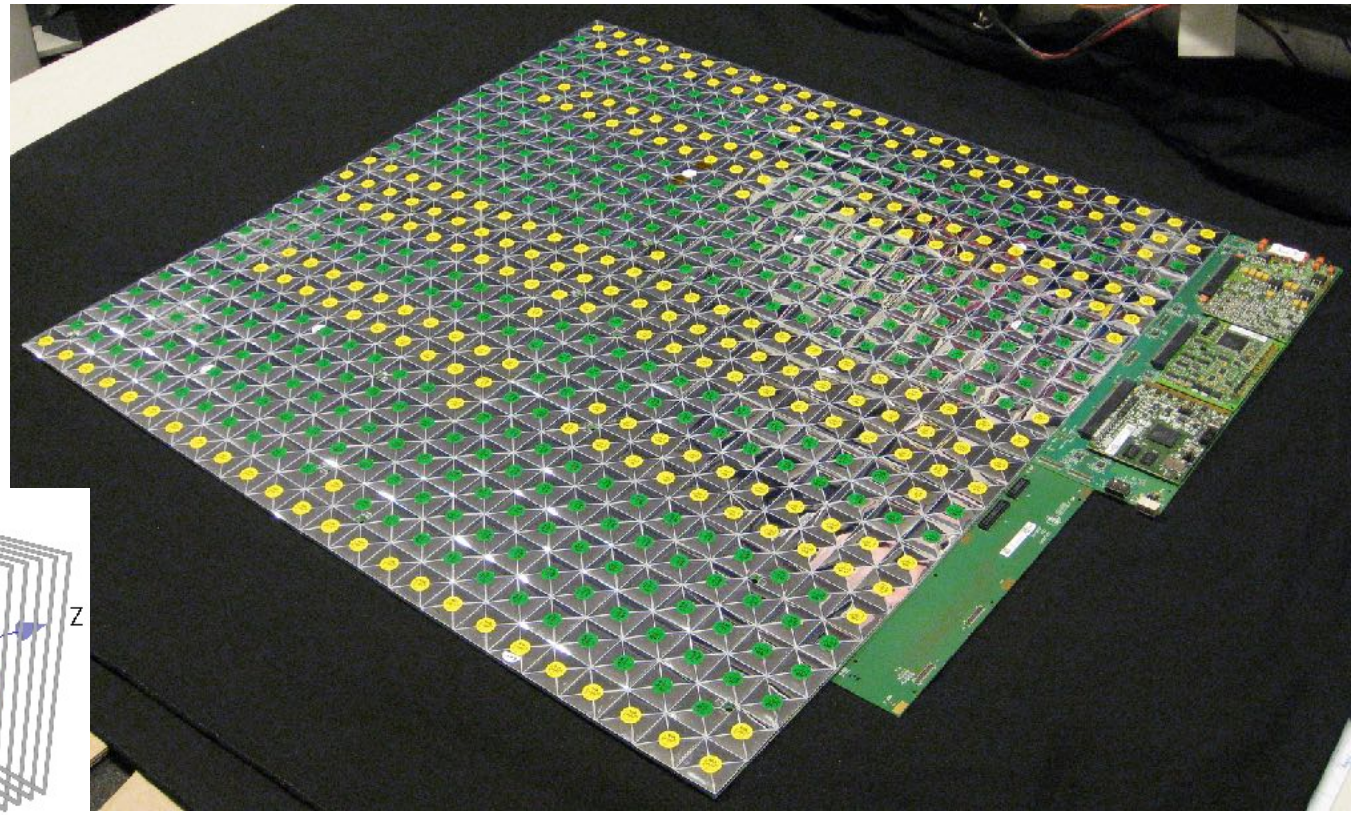

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DESY tasks

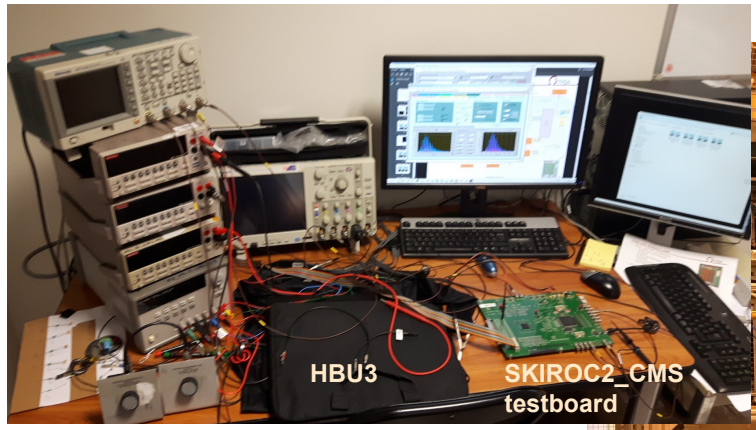
2017 - 2020

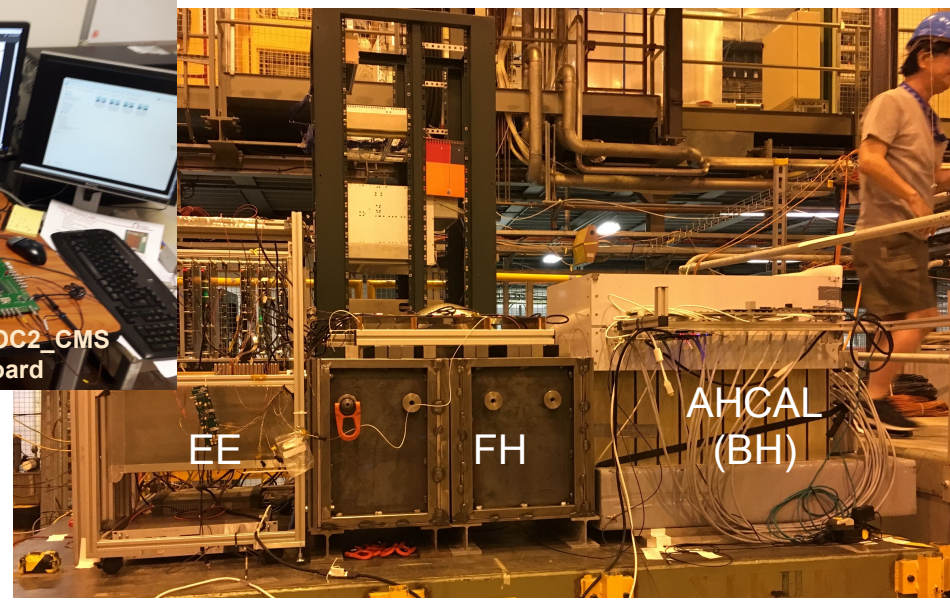
DESY commitments:

- 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





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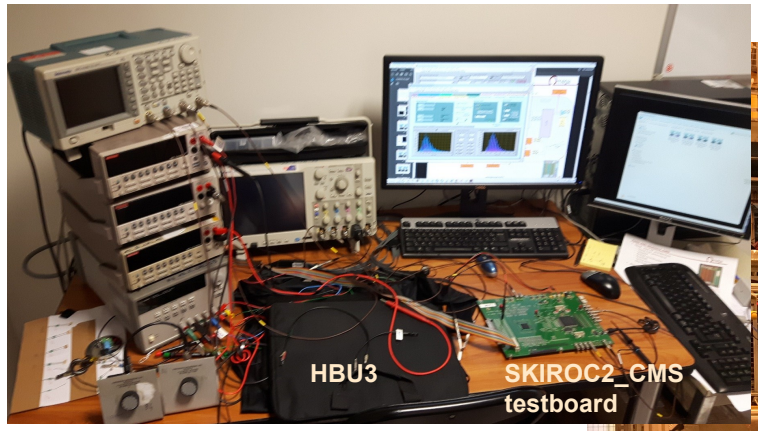
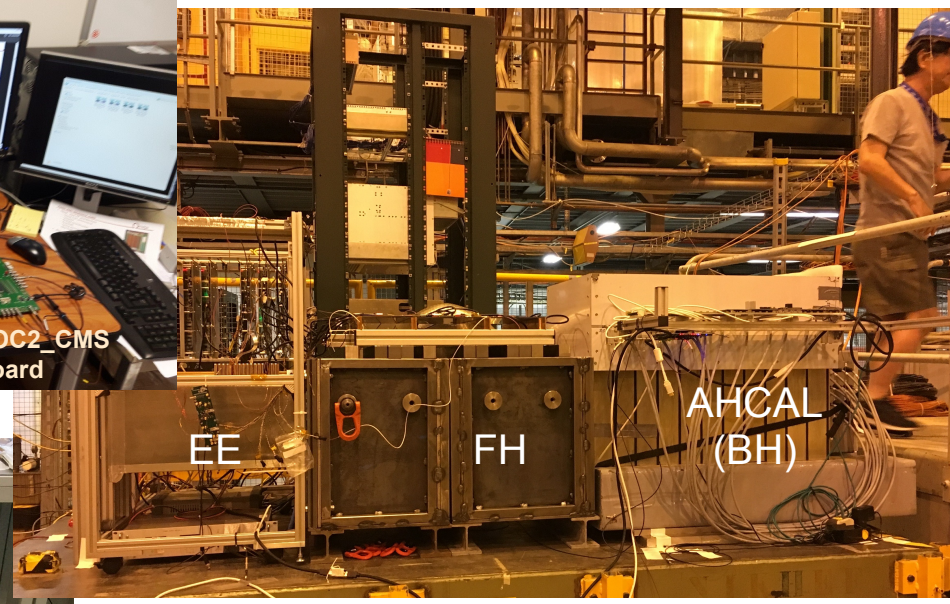
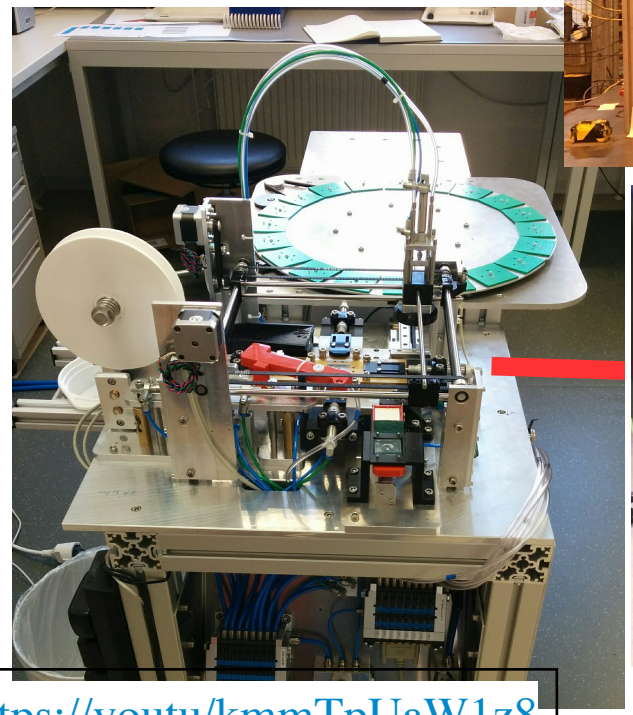
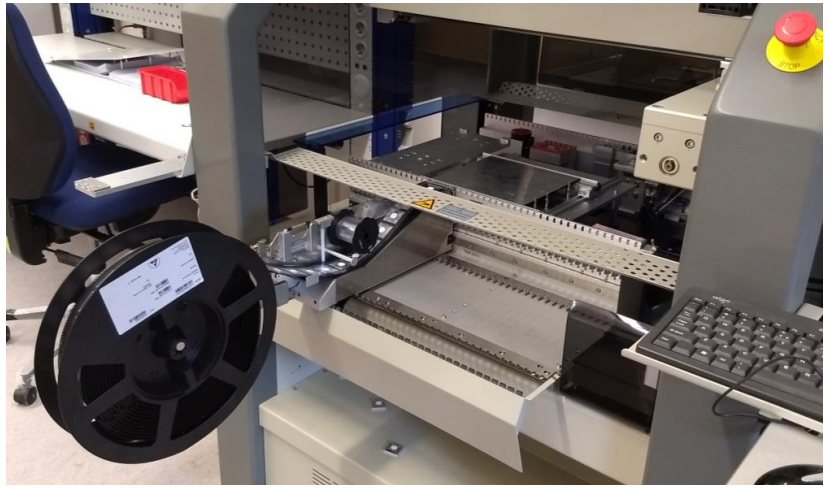
- Validate interplay SiPM - HGCROC
- Develop & characterise tile-board prototypes
  - electronically
  - thermo-mechanically
- Establish assembly & QC sequence
  - Build on CALICE achievements and develop further
  - Electronics and mechanical engineering support
- Coordination









https://youtu/kmmTpUaW1z8