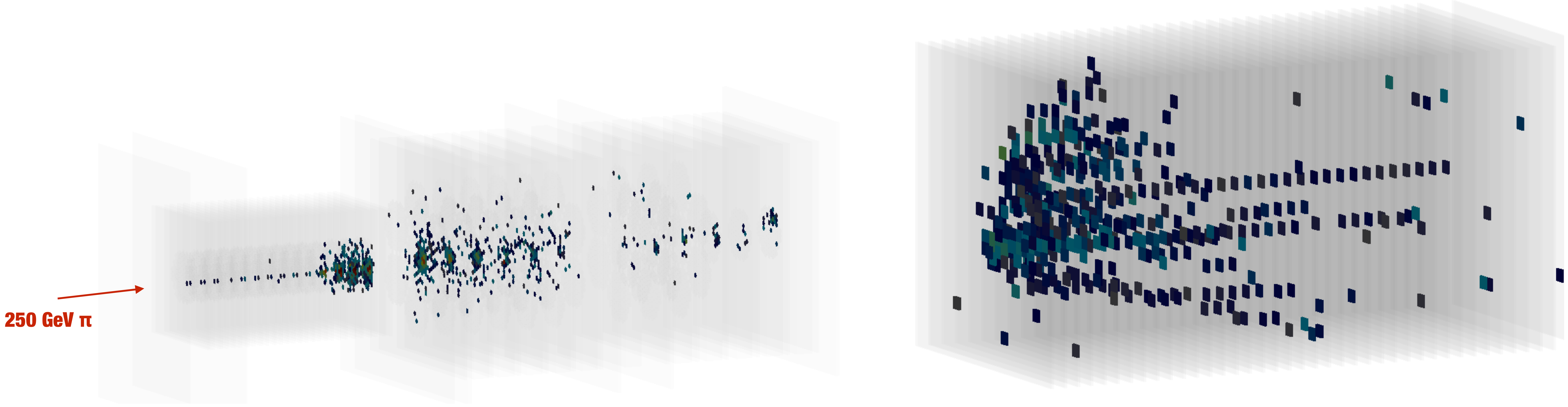
12th Terascale Detector Workshop
12-15 March 2019, Physics Department, TU Dresden

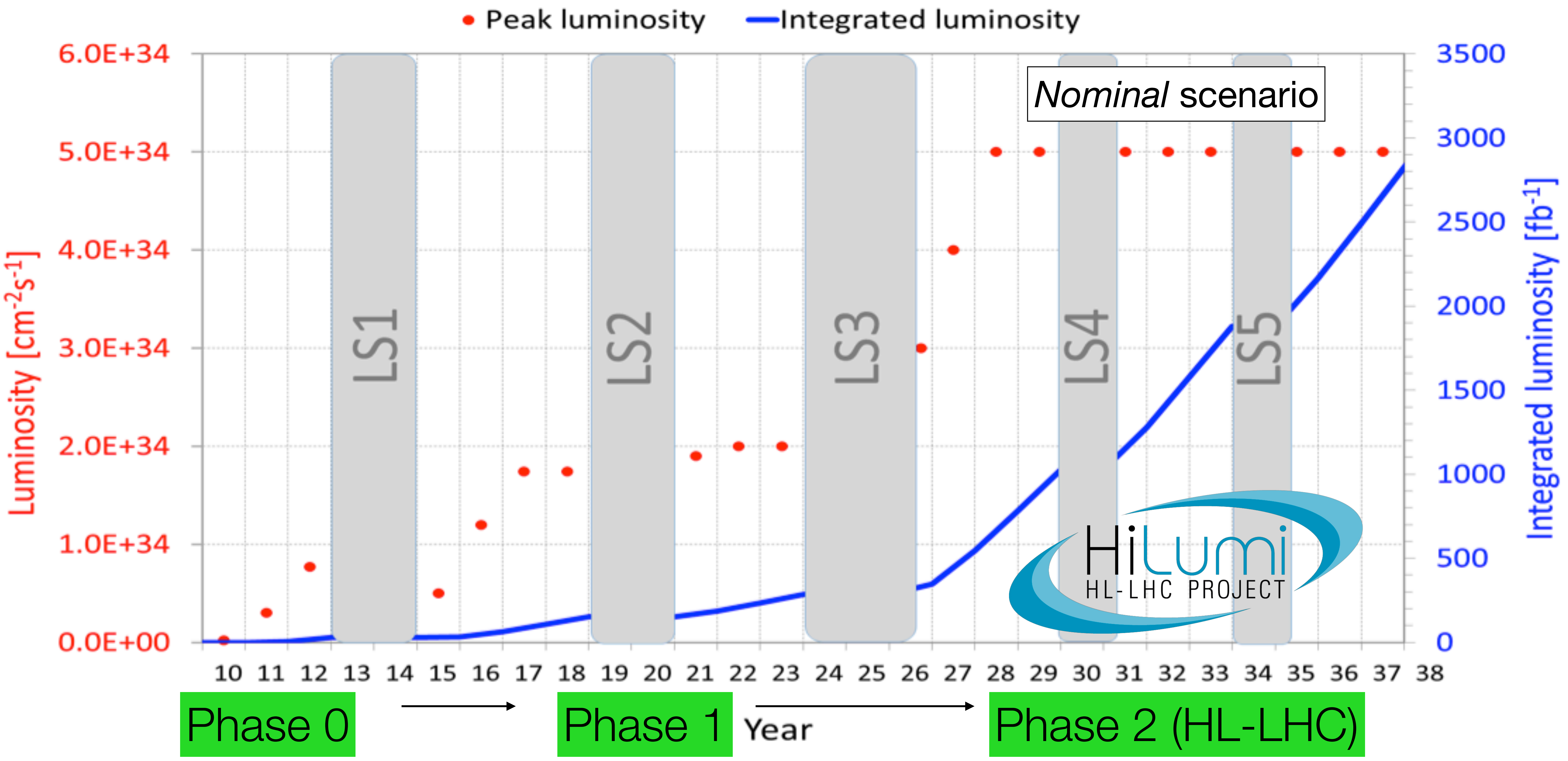
CMS High-Granularity Calorimeter Upgrade (HGCAL)

Thorben Quast (CERN / RWTH Aachen)
for the CMS Collaboration



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654168

Starting in 2026 at CERN: High-Luminosity LHC

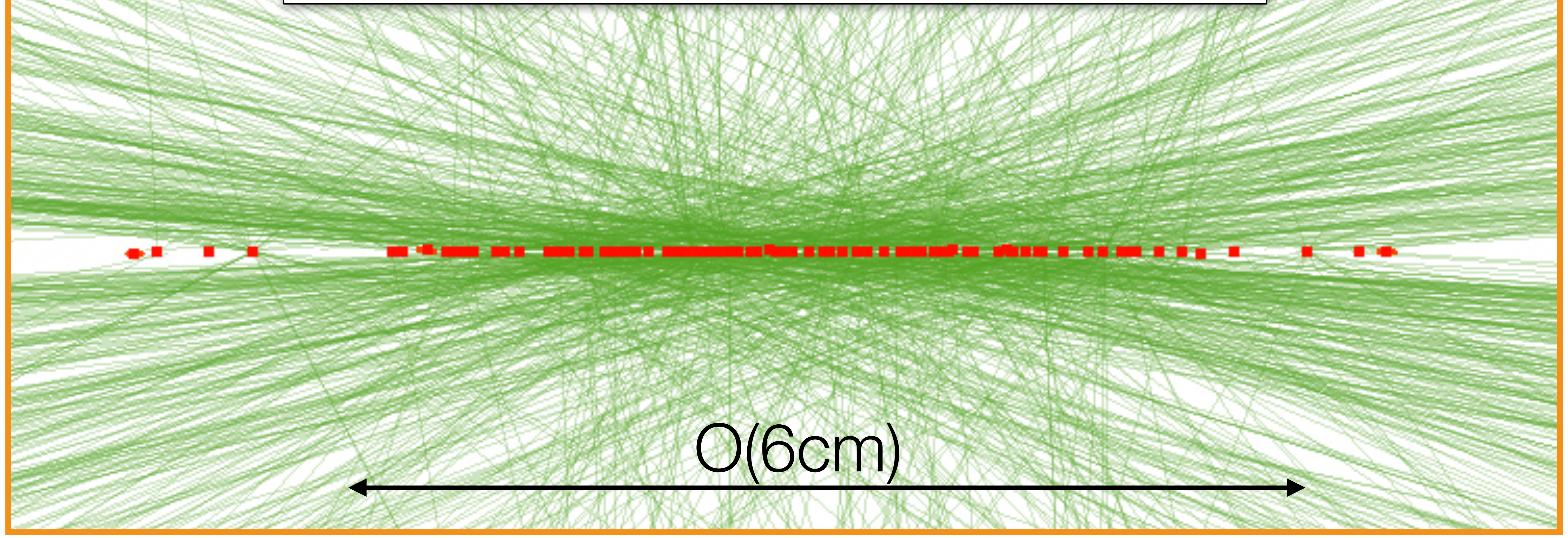


➡**The HL-LHC will provide >5 (x10) instantaneous (integrated) luminosity of LHC**

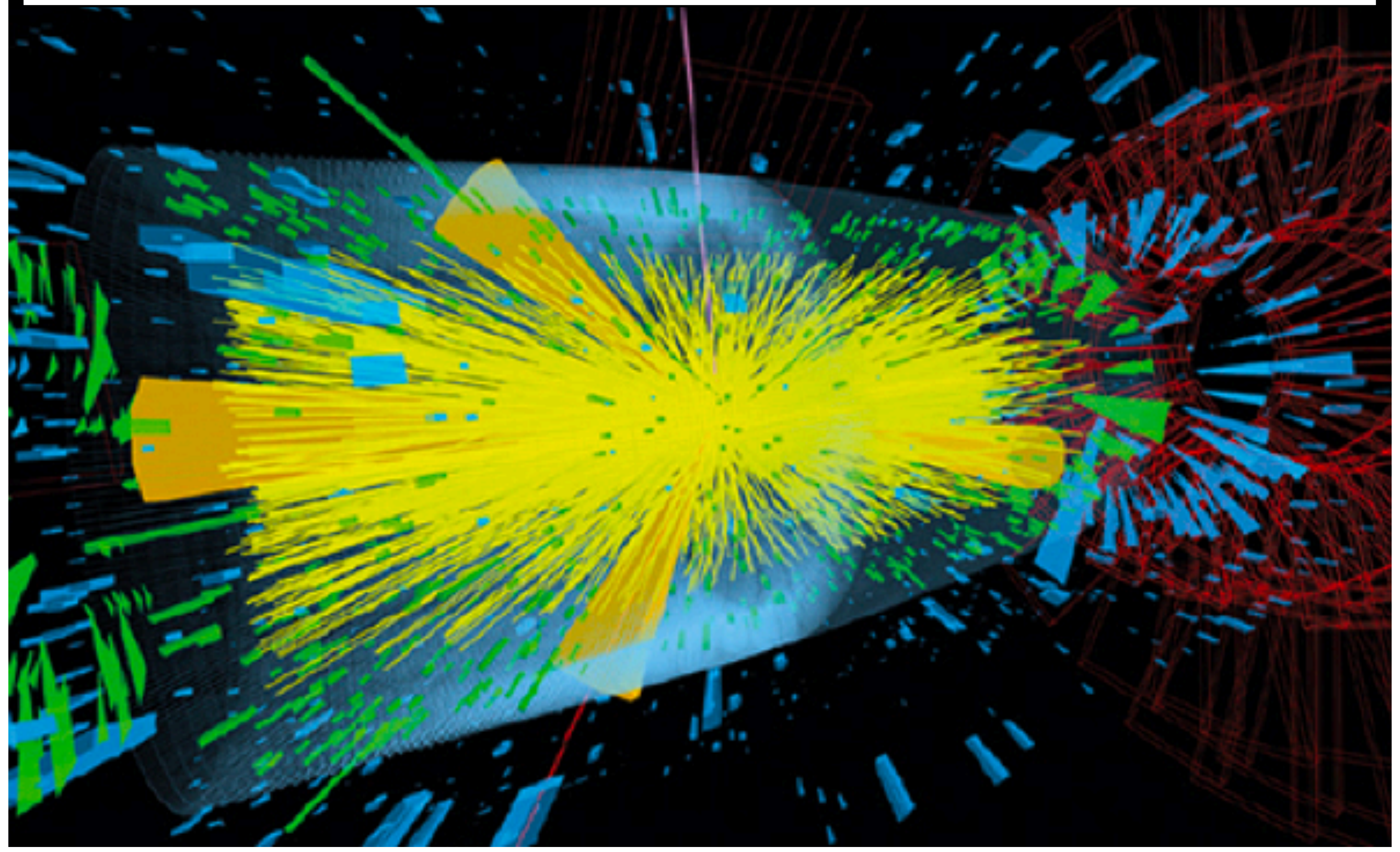
III. Physikalisches Institut
RWTH AACHEN UNIVERSITY
CERN

LHC —> HL-LHC: More activity in the CMS detector

HL-LHC: O(140) p-p collisions in one bunch crossing



HL-LHC: A lot of activity in the CMS detector



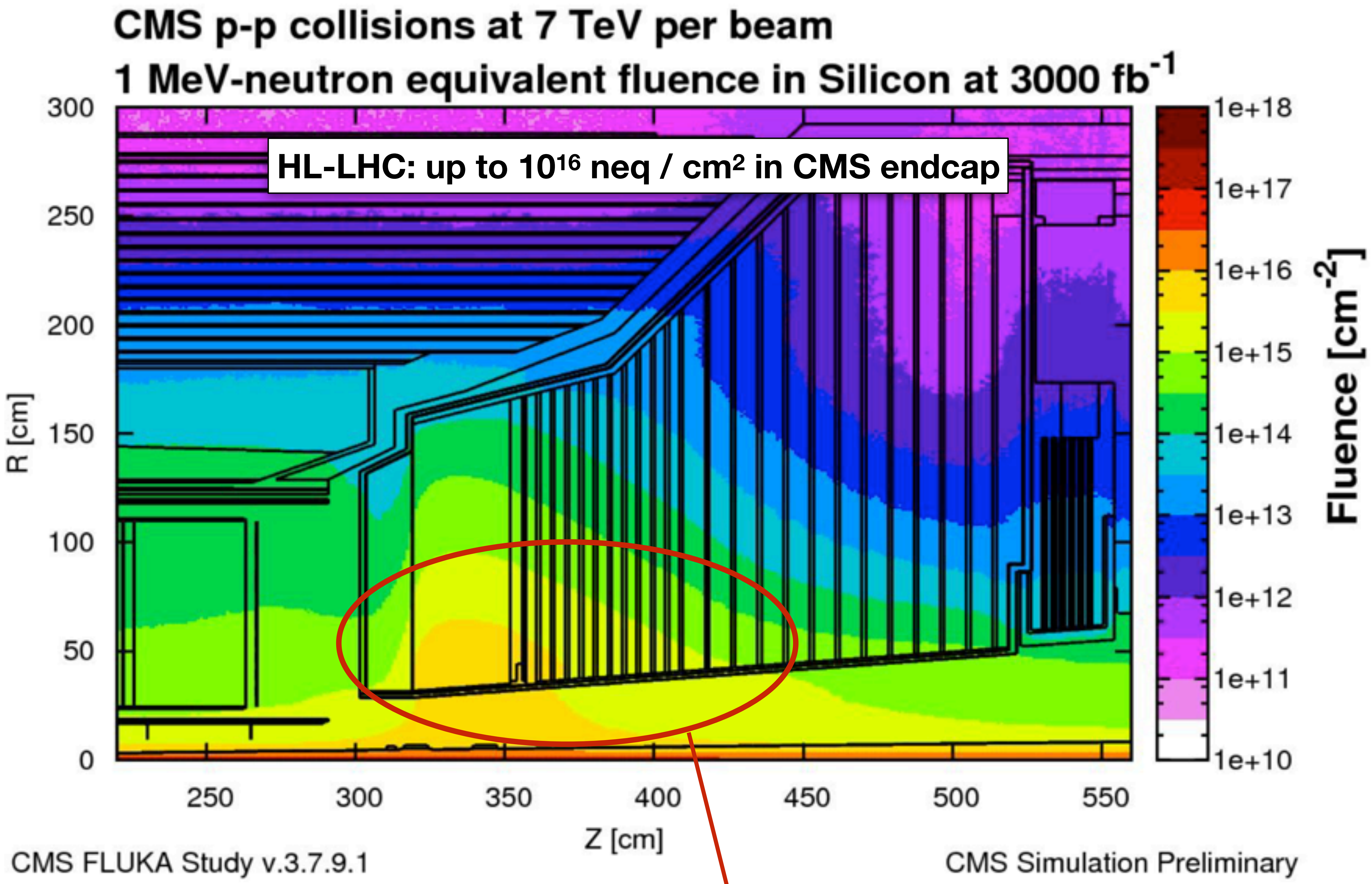
Nominal 5E34 luminosity
"Ultimate" 7.5E34 luminosity

Pile-up

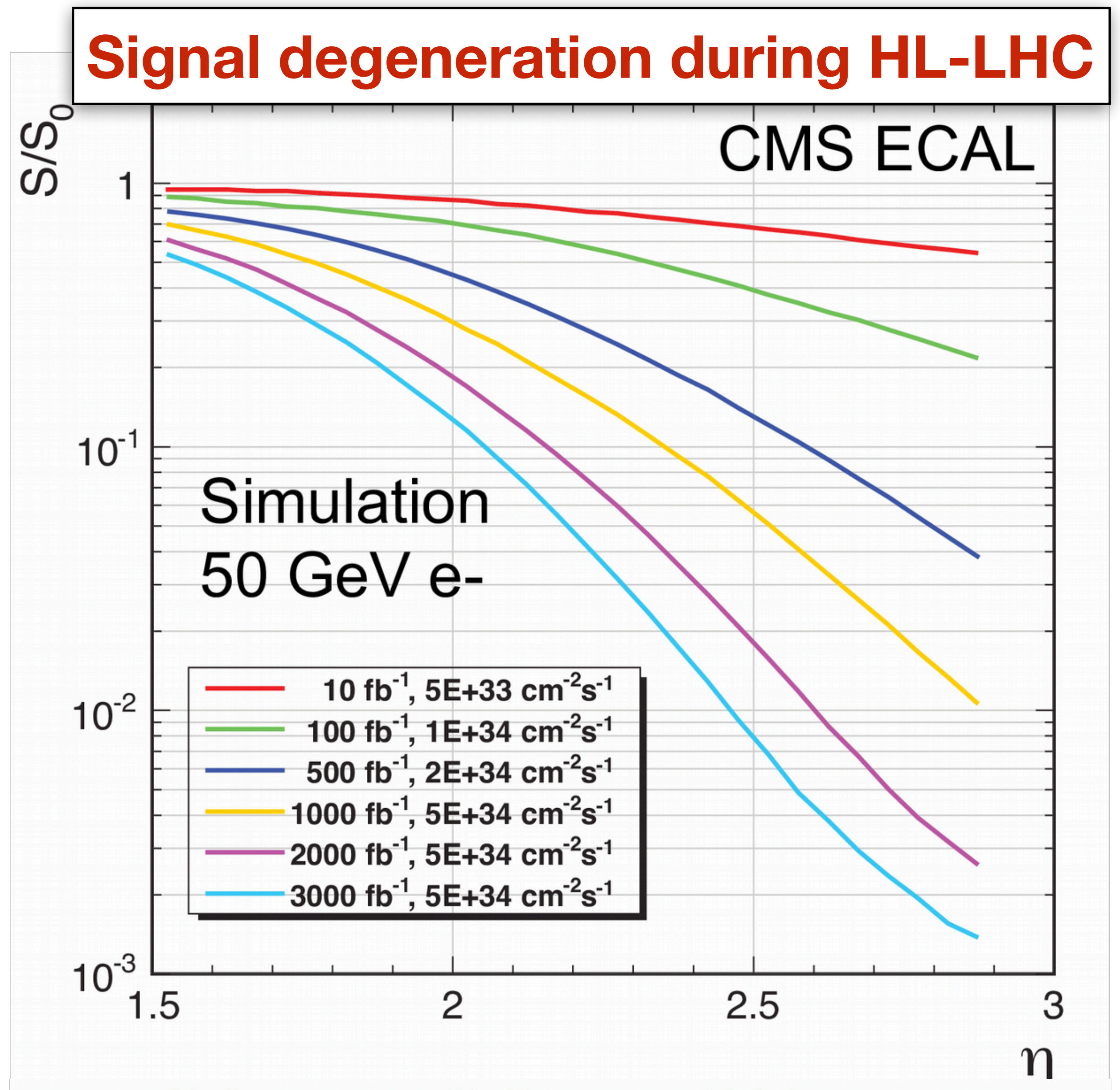
- **140 - 200 collisions** per bunch crossing >> **3-4x** larger than in run 2
  - spread over few centimeters
  - spread over O(200) ps

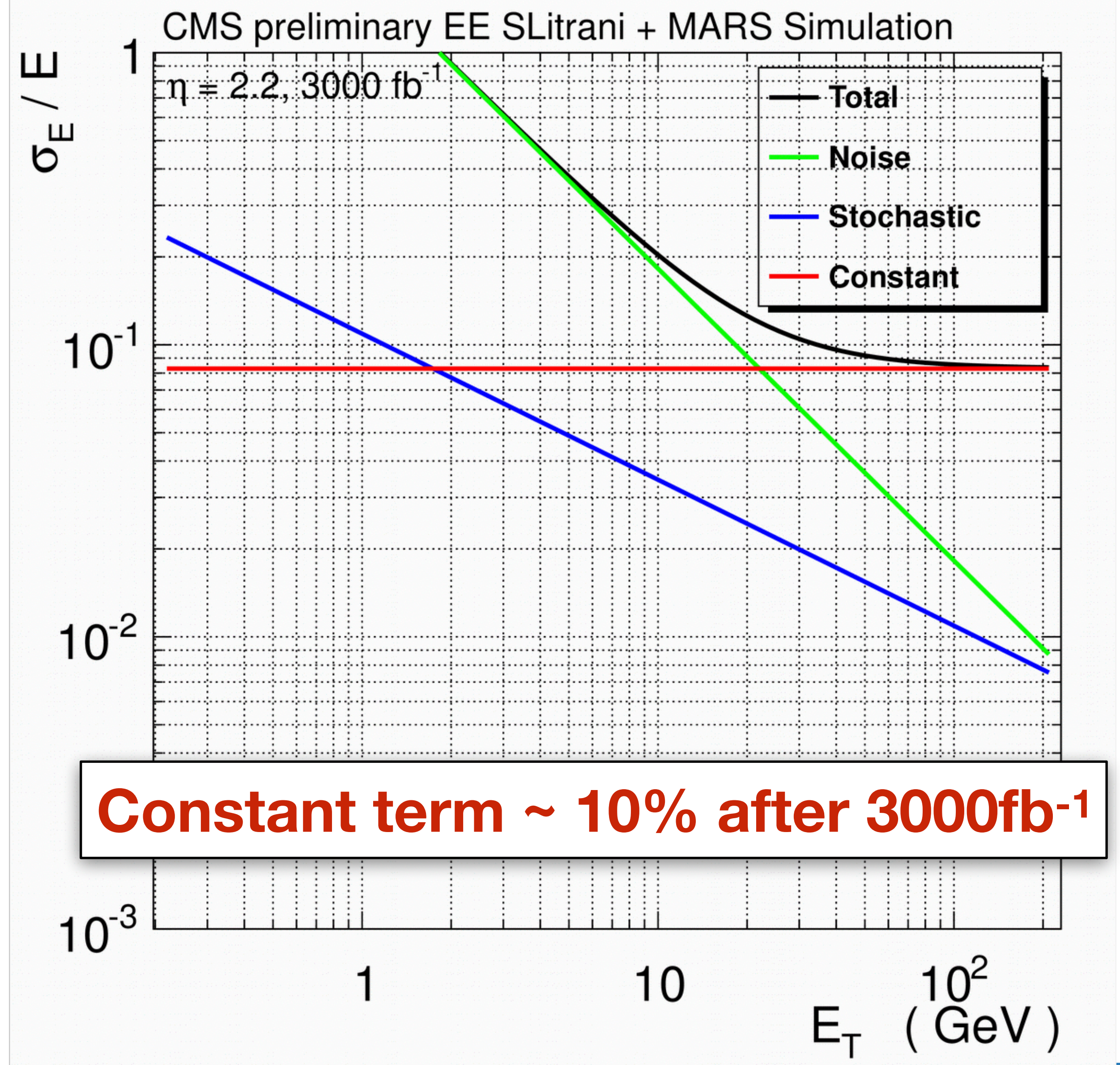
LHC —> HL-LHC: Increased radiation level

Current CMS detectors designed for end of run 3 ($300 fb^{-1}$).



Example: Current CMS ECAL





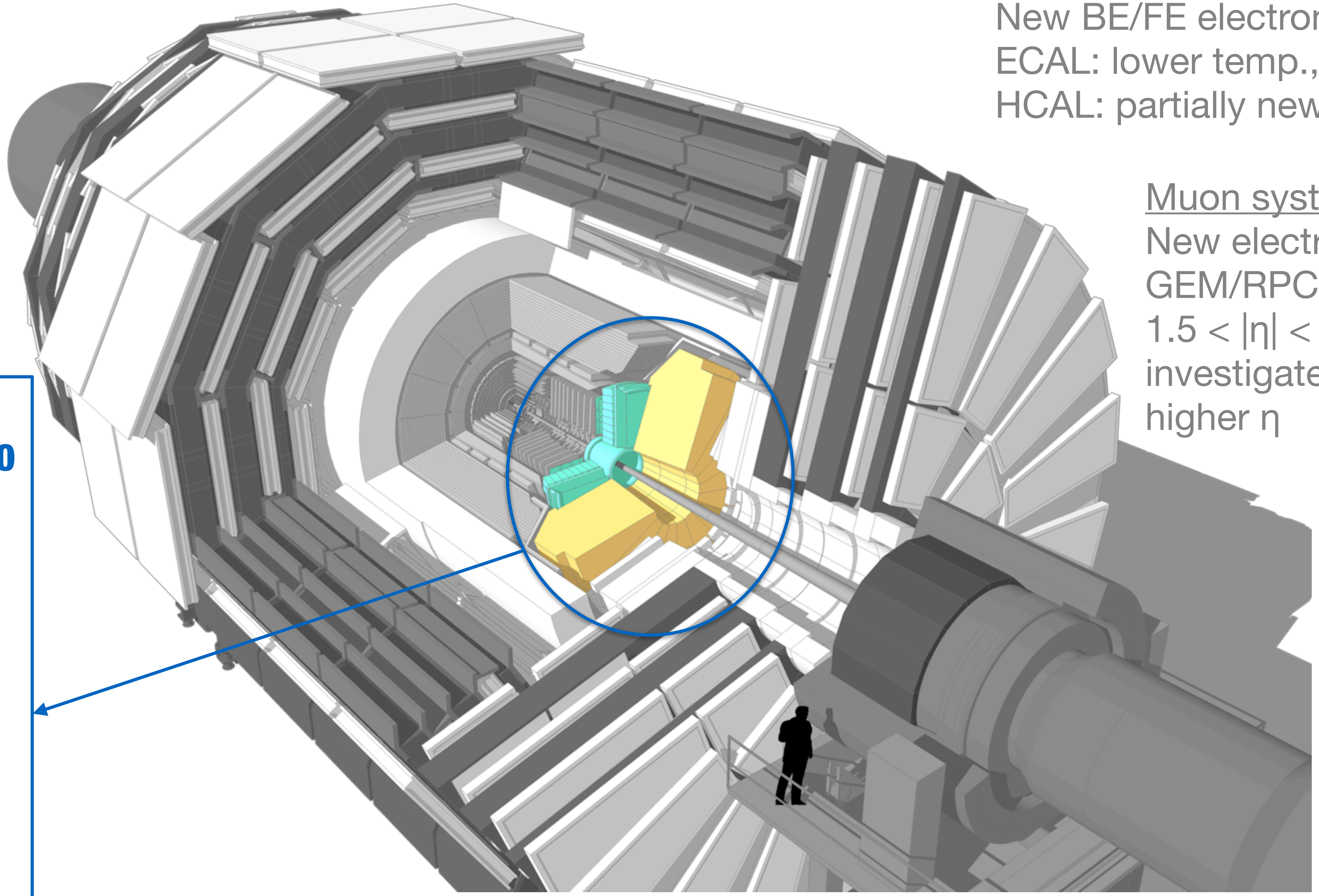
➡**ECAL crystals & HCAL scintillators would suffer from irreparable radiation damage during HL-LHC.**

➡CMS will replace its endcap calorimeters for HL-LHC

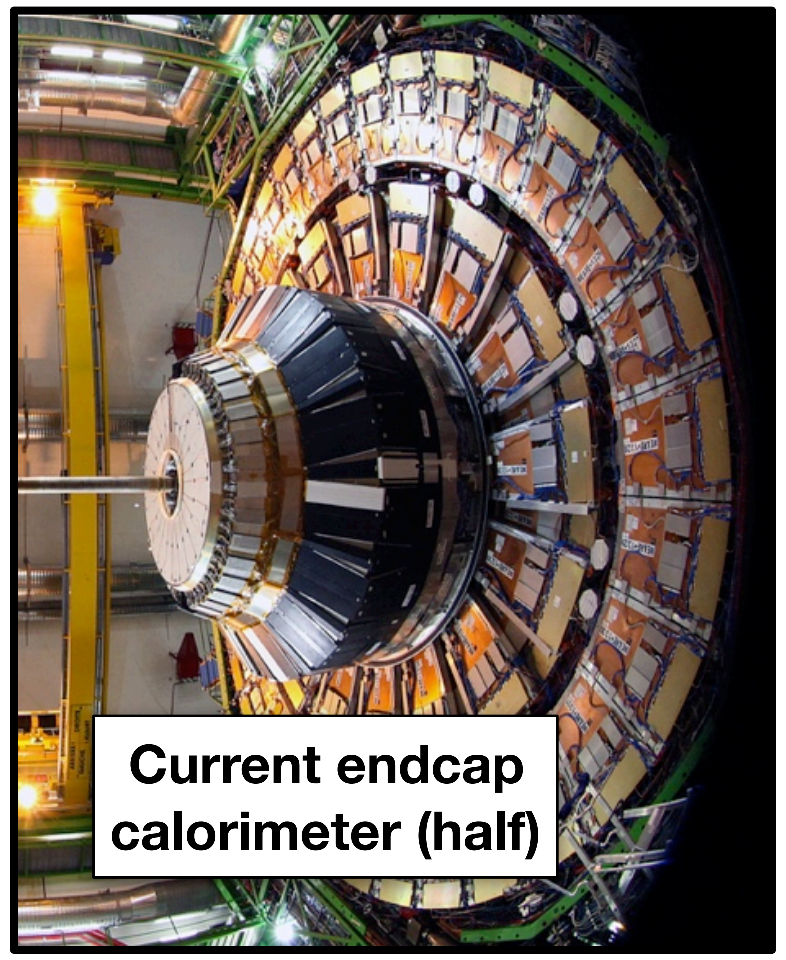
Tracker:
Radiation tolerant,
high granularity,
less materials, tracks in
hardware trigger (L1),
coverage up to |η| = 3.8

Barrel Calorimeter:
New BE/FE electronics,
ECAL: lower temp.,
HCAL: partially new scintillator

Muon system:
New electronics
GEM/RPC coverage in
1.5 < |η| < 2.4,
investigate muon tagging at
higher η



Endcap calorimeters:
Coverage 1.5 < lηl < 3.0
…



Current endcap
calorimeter (half)

Endcap calorimeter upgrade proposal

CALICE - inspired idea

An all-new 'imaging' calorimeter with unprecedented readout granularity that offers robustness and good performance through the full HL-LHC operational lifetime.

Requirements

Radiation tolerance

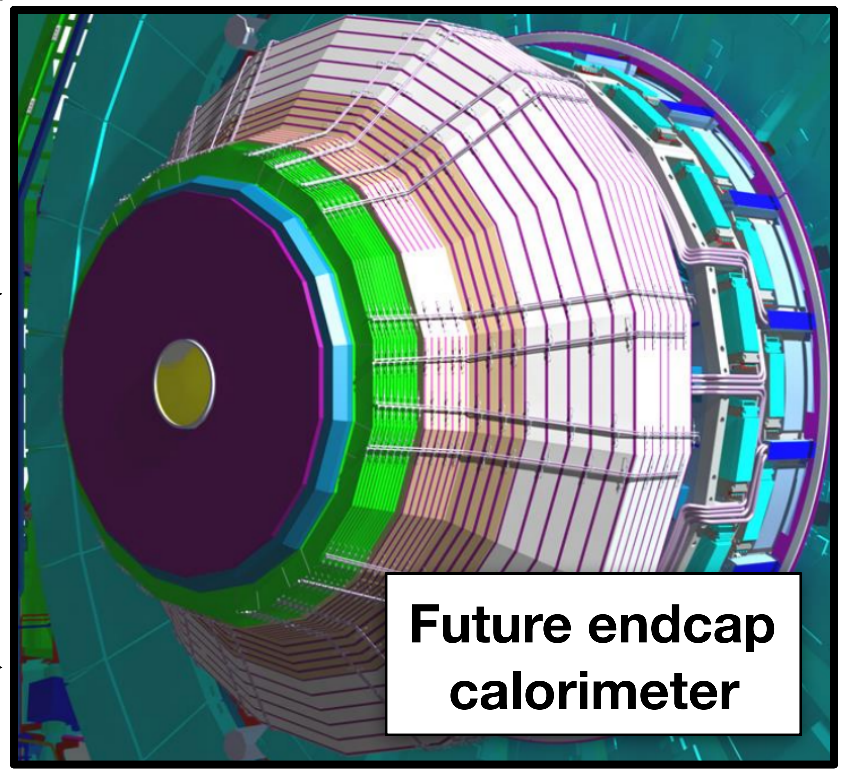
fully preserving the energy resolution after 3000 fb^{-1}

Dense calorimeter

preserve lateral compactness of showers

Fine lateral granularity

two shower separation + observation of narrow jets, minimise pileup contributions in energy & timing measurements



Fine longitudinal granularity

fine sampling of the shower: good energy resolution, pattern recognition, pile-up discrimination, …

Precision time measurement

high energy showers for pile-up rejection, primary vertex identification

Contribute to L1 (Hardware) trigger

CMS High-Granularity Calorimeter (HGCAL)

TDR 2018

HGCAL = Sampling calorimeter

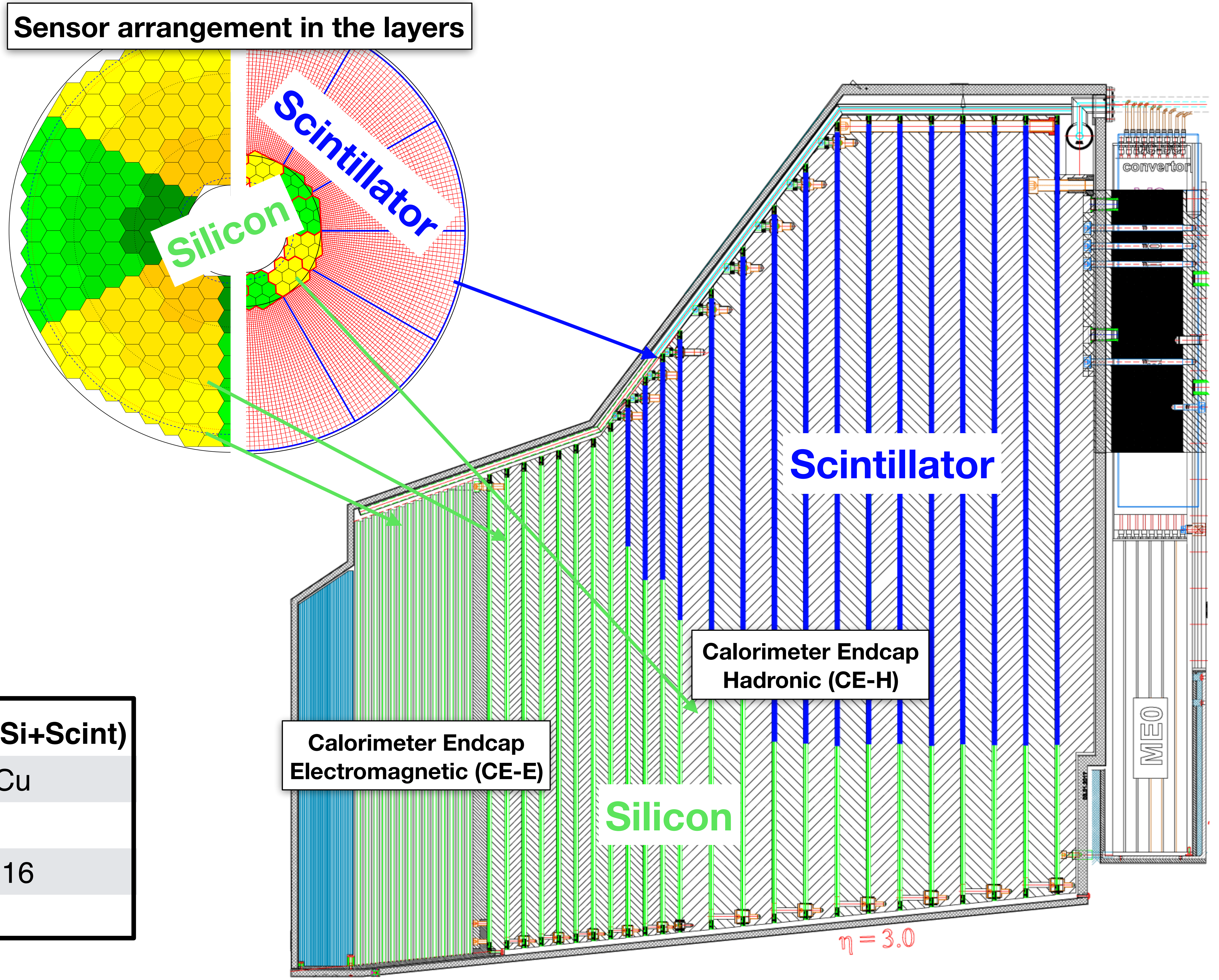
Active material

- Silicon sensors in CE-E and high radiation regions of CE-H
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H

Both endcaps	Silicon	Scintillators
Area	600m^2	500m^2
#Modules	27000	4000
Channel size	0.5 - 1 cm^2	4-30 cm^2
#Channels	6 M	400 k
Op. temp.	-30 ° C	-30 ° C

Passive material

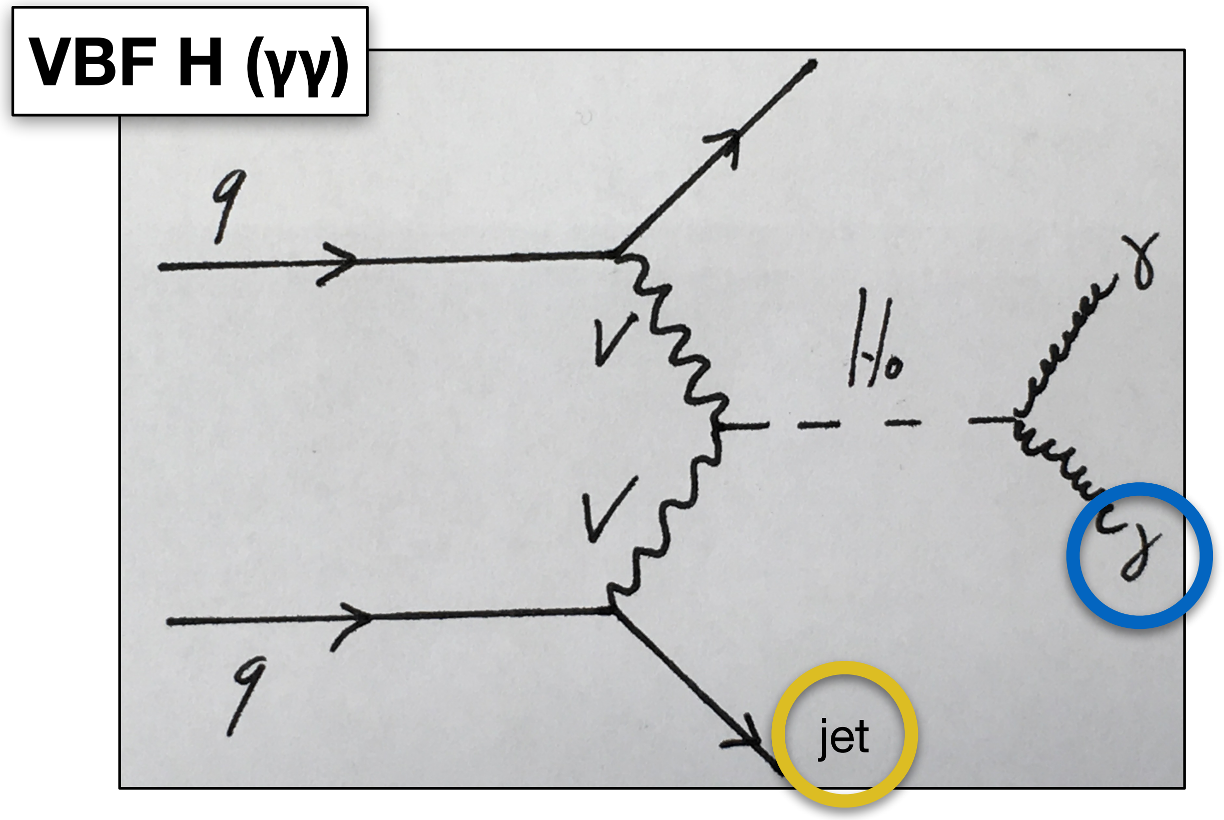
Per endcap	CE-E	CE-H (Si)	CE-H (Si+Scint)
Absorber	Pb, CuW, Cu	Stainless steel, Cu	
Depth	26 X_0, 1.5 λ	9 λ	
Layers	28	8	16
Weight	23t	205 t	



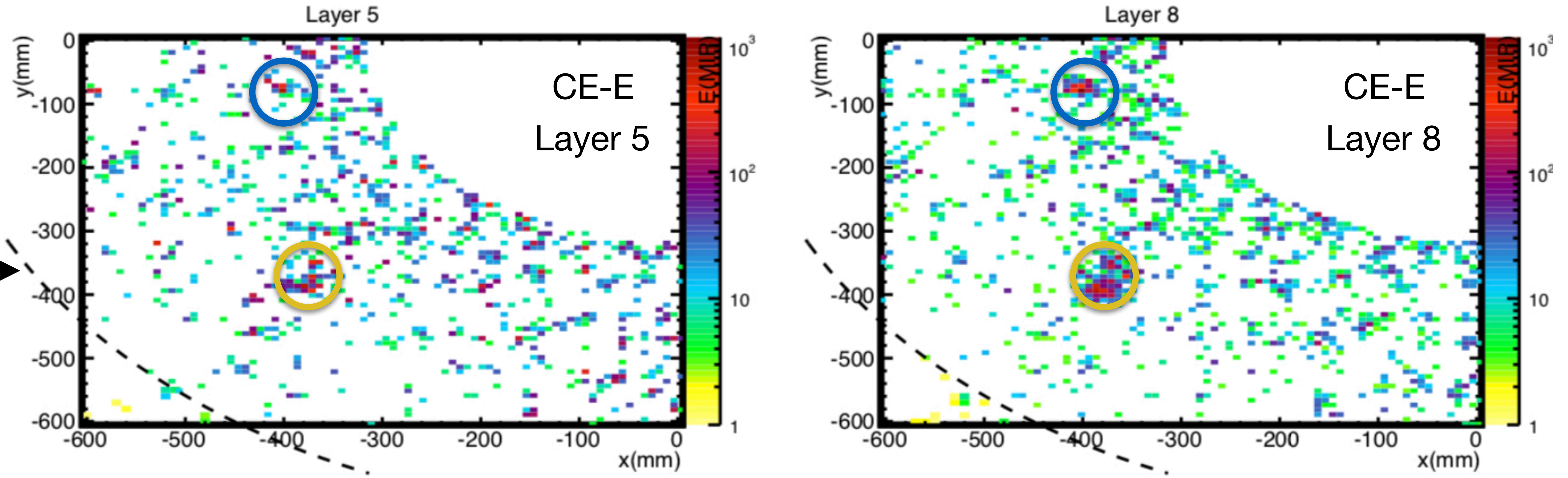
III. Physikalisches Institut
RWTH AACHEN UNIVERSITY

HGCal = 3D imaging calorimeter

Simulated VBF H (γγ) signatures in the granular endcap calorimeter



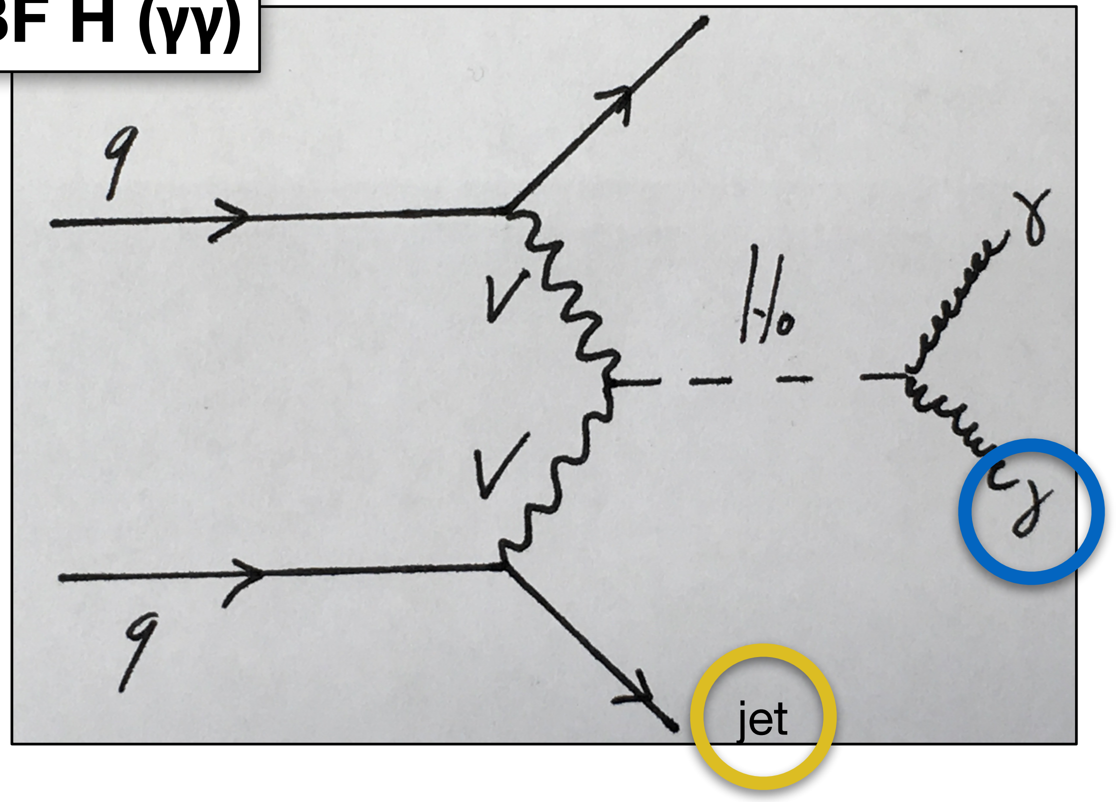
\+ 200 PU →



III. Physikalisches Institut
RWTH AACHEN UNIVERSITY
CERN

HGCal = 3D imaging calorimeter with timing capabilities

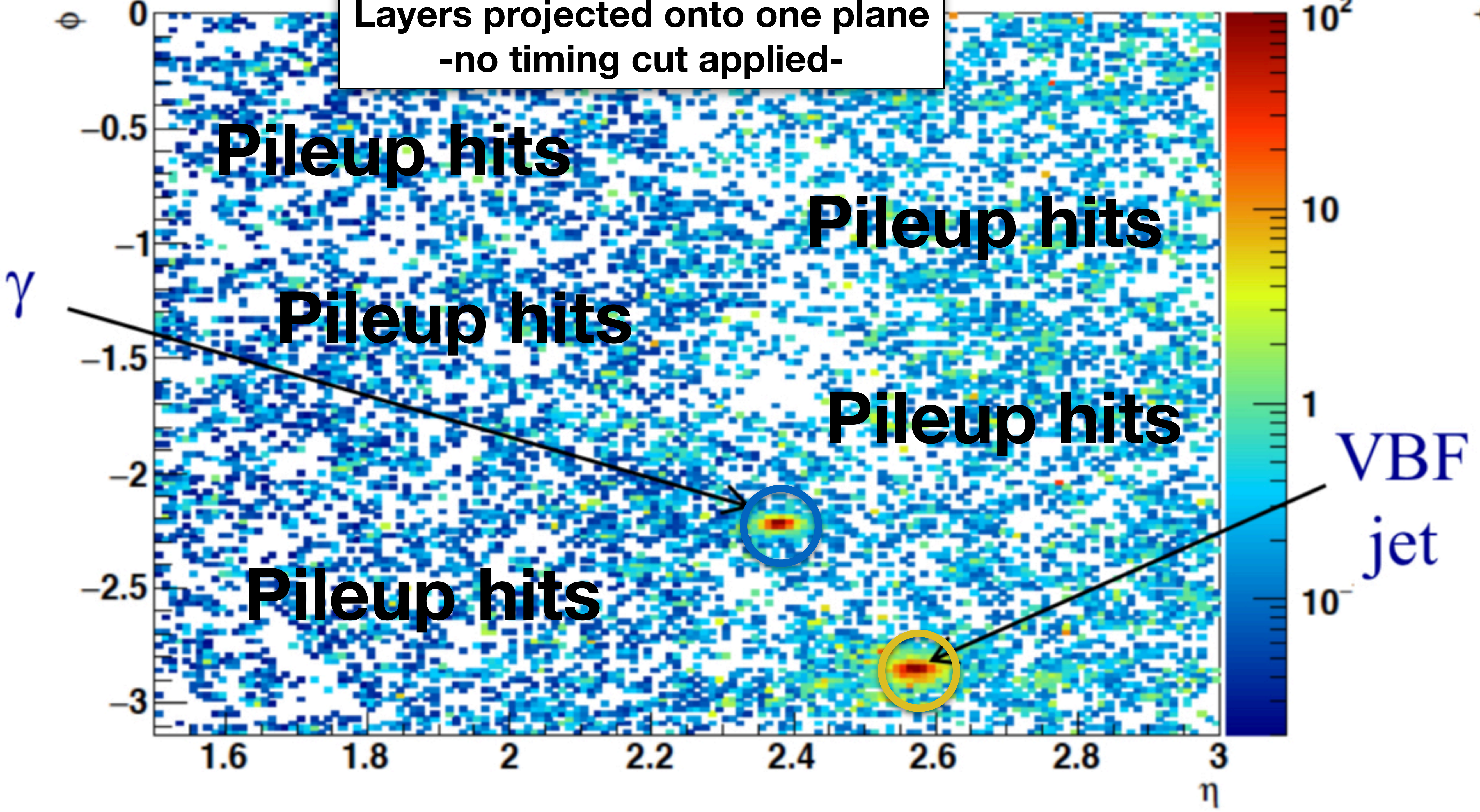
VBF H (γγ)



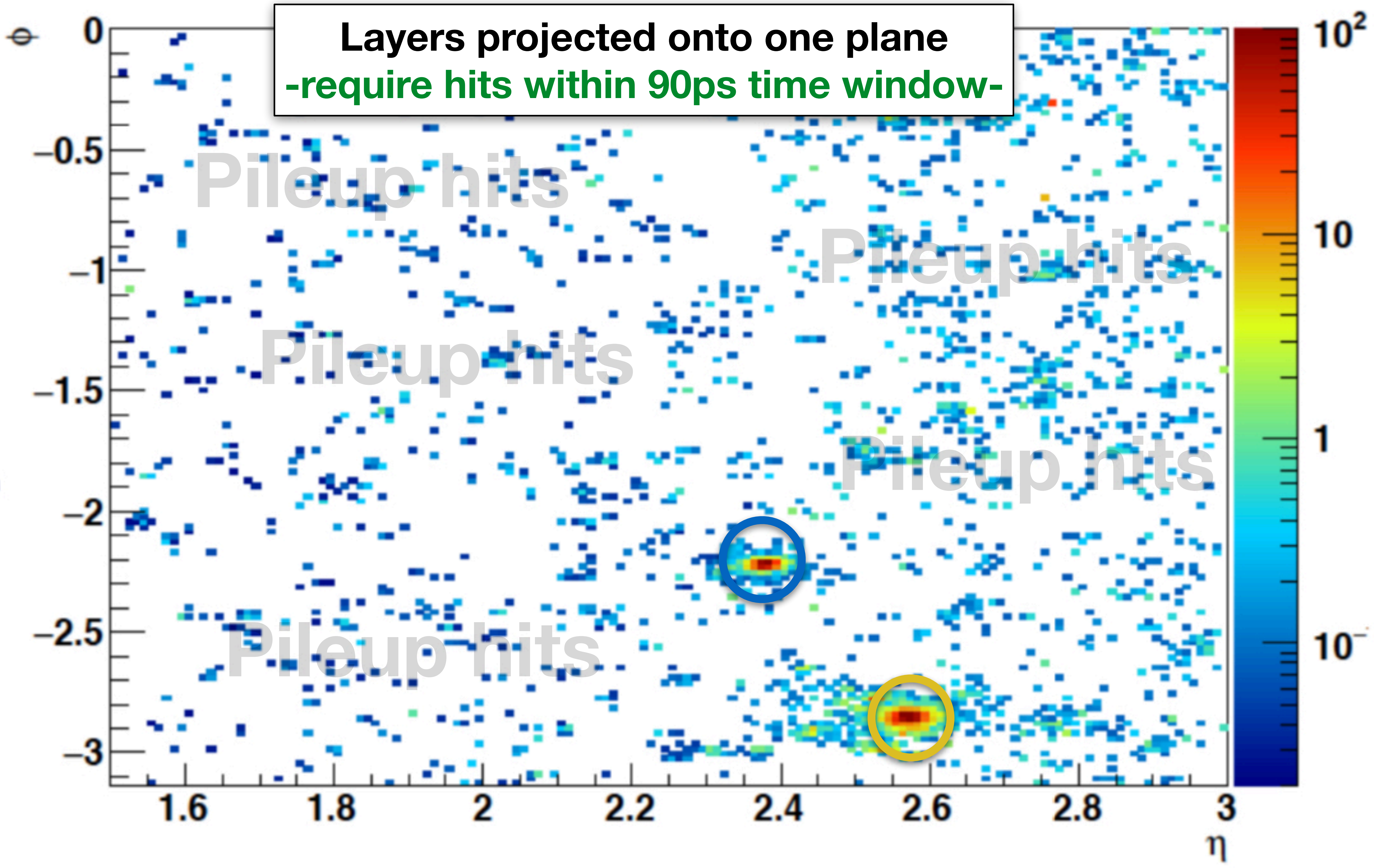
+ 200 PU

Similar concept as foreseen for CLIC

Layers projected onto one plane
-no timing cut applied-



Layers projected onto one plane
-require hits within 90ps time window-



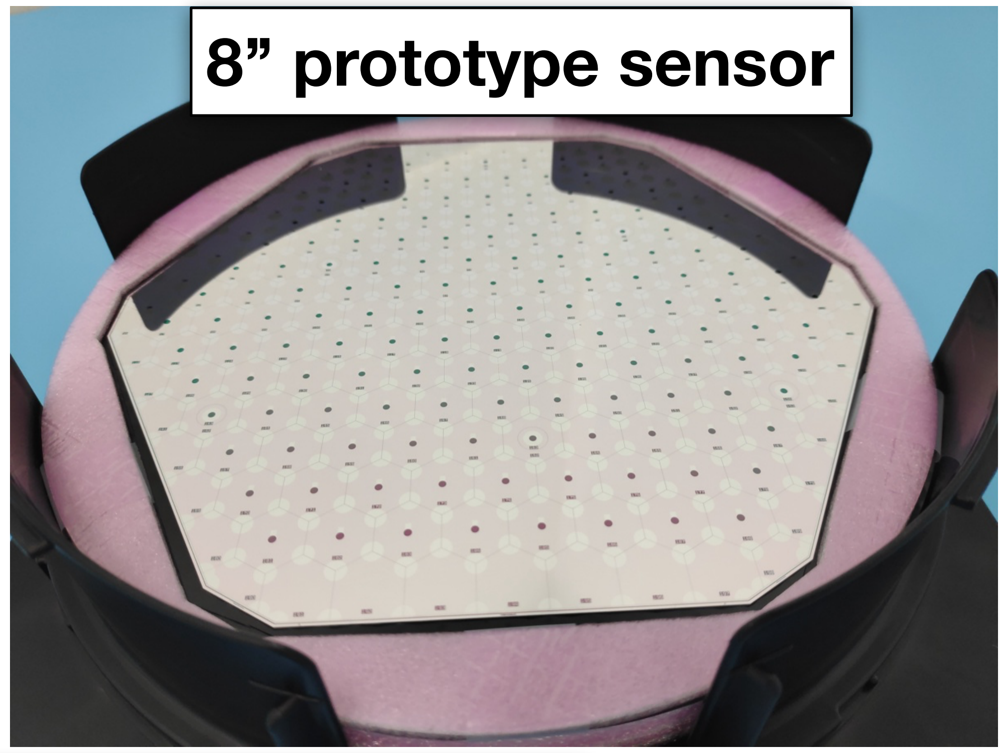
Design and prototyping

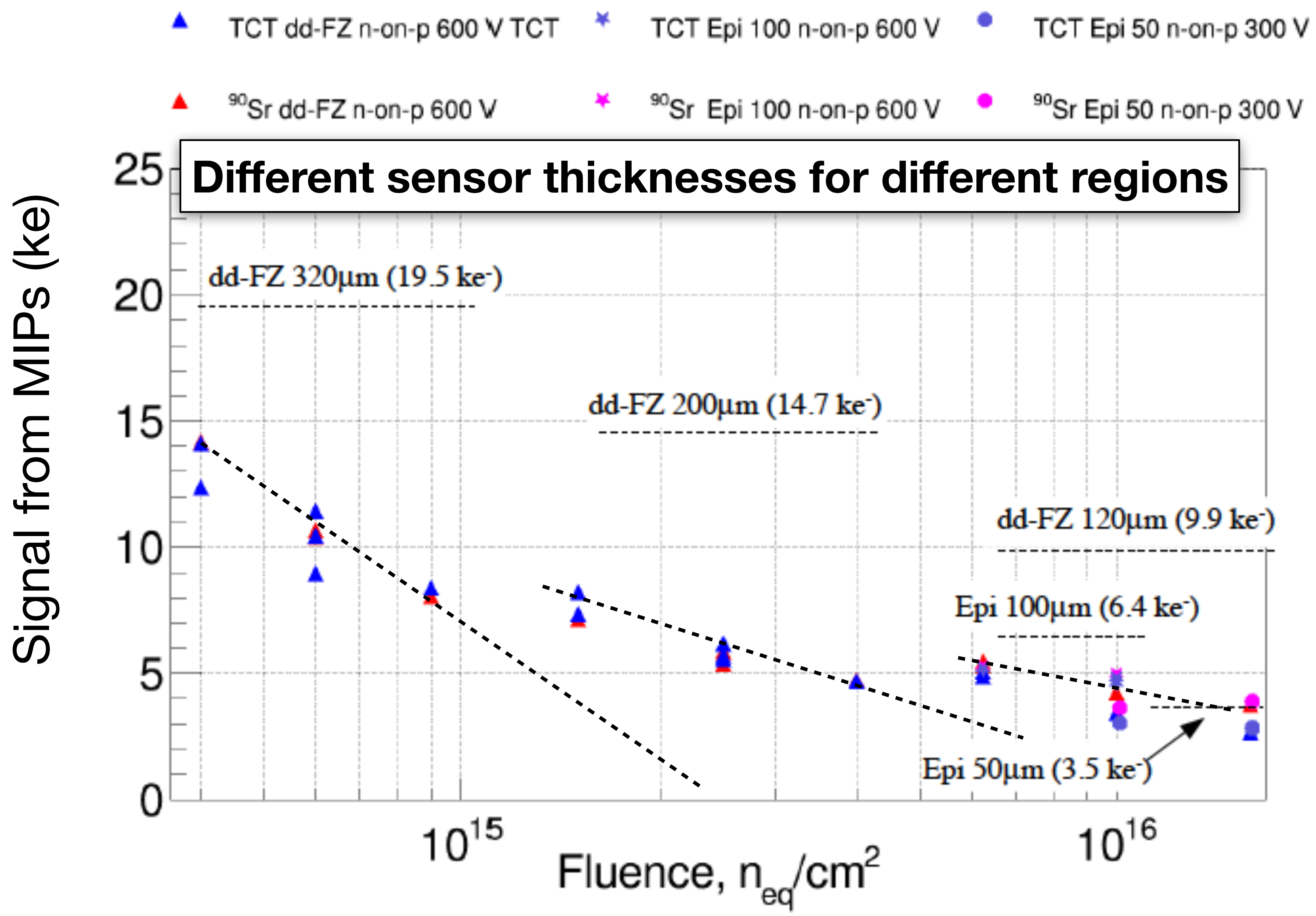
III. Physikalisches Institut
RWTH AACHEN UNIVERSITY
CERN

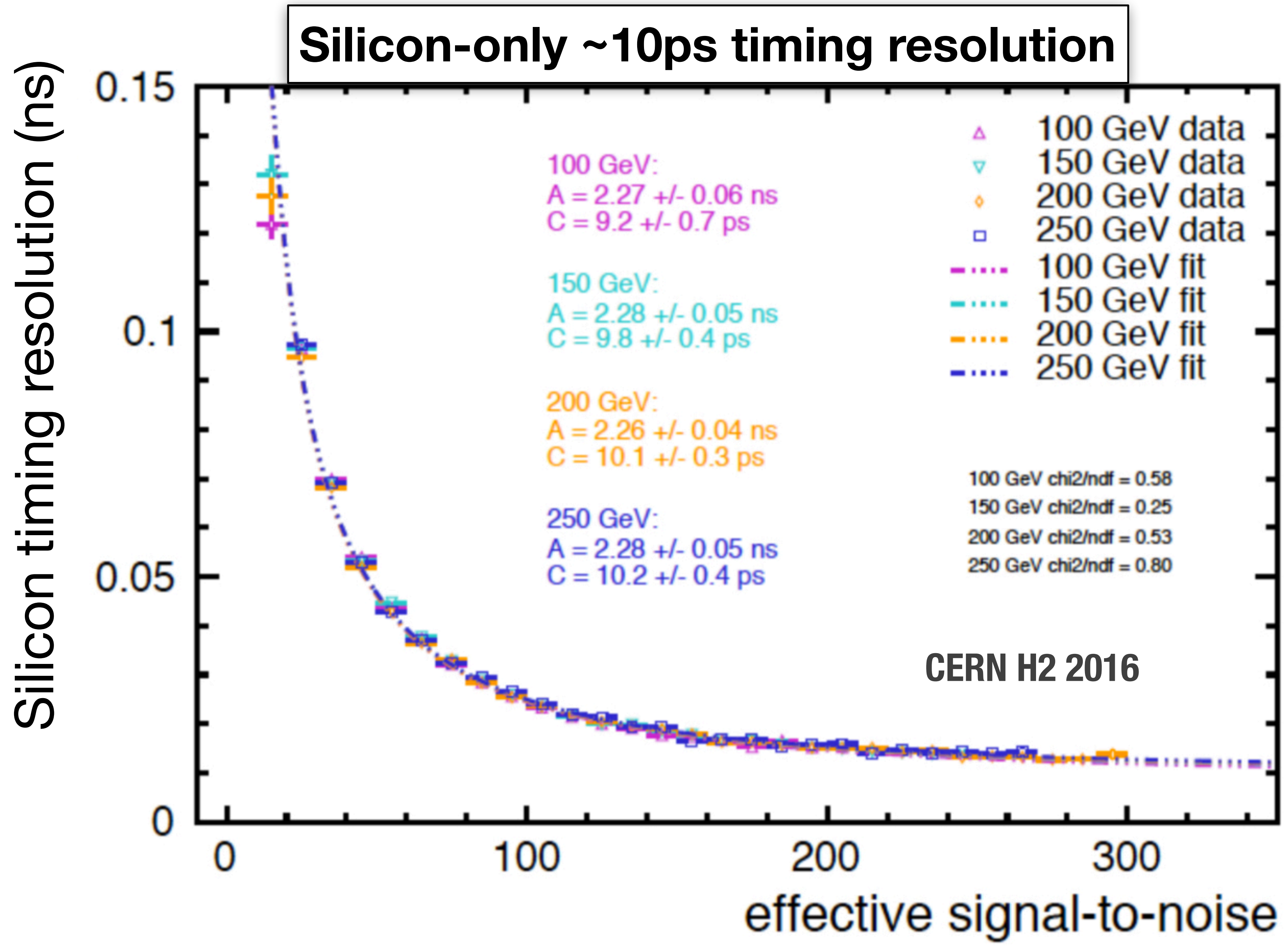
Silicon sensors: Radiation hard and fast signals

Silicon sensors

- For regions with high fluences, HGCAL uses 600m^2 of silicon
- Hexagonal wafers to maximise used area (—> minimise costs)
- Followed HEP standard initially 6” wafers. New baseline: 8”







Minimising degradation

- Operation at -30° C: Reduce increasing bulk leakage current
- Increasing the bias voltage up to -800V to reduce signal loss

Silicon sensor characterisation: IV and CV

<u>**Electrical behaviour of silicon sensors crucial for HGCAL powering budget.**</u>

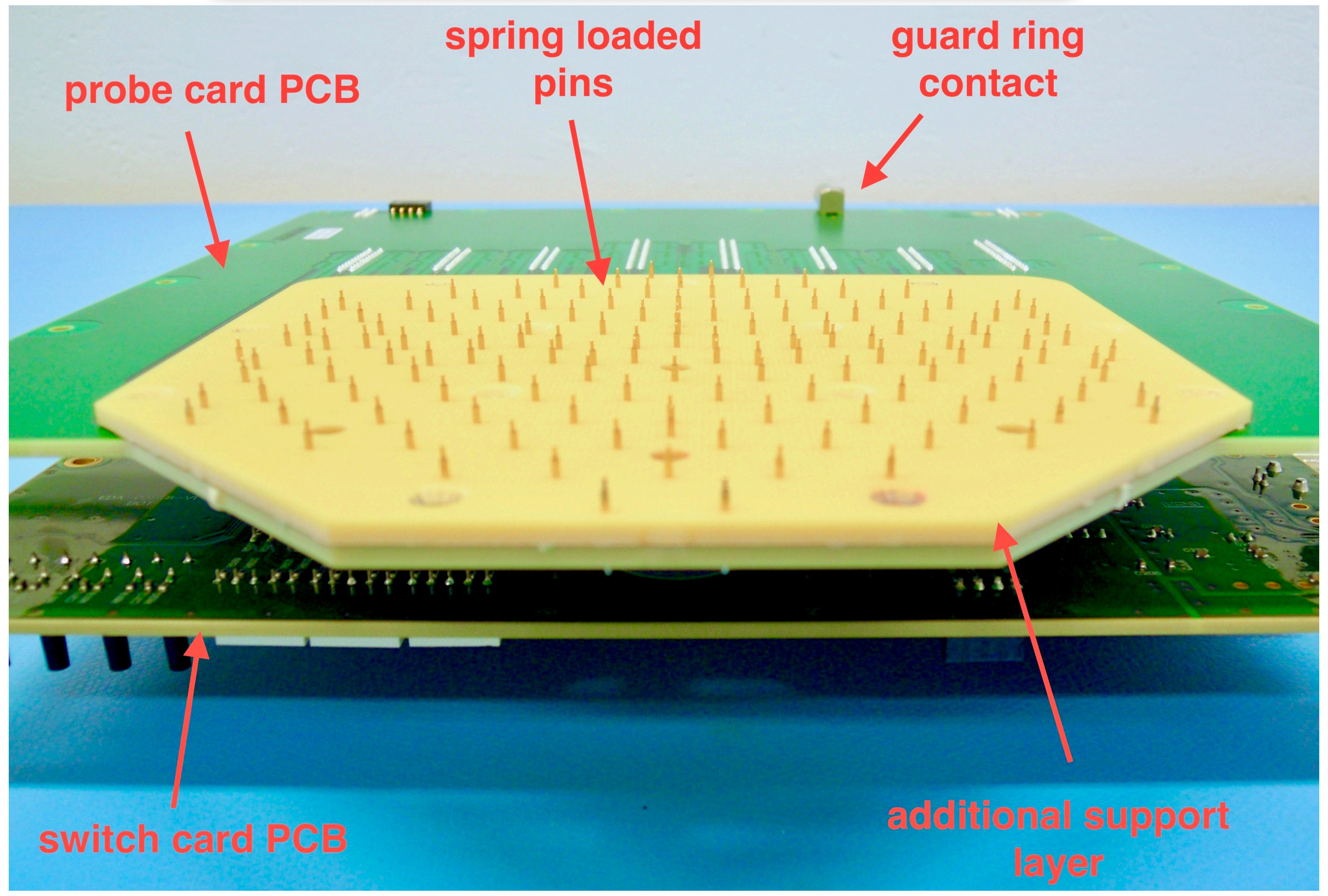
➡**Per-batch sensor tests before module assembly**

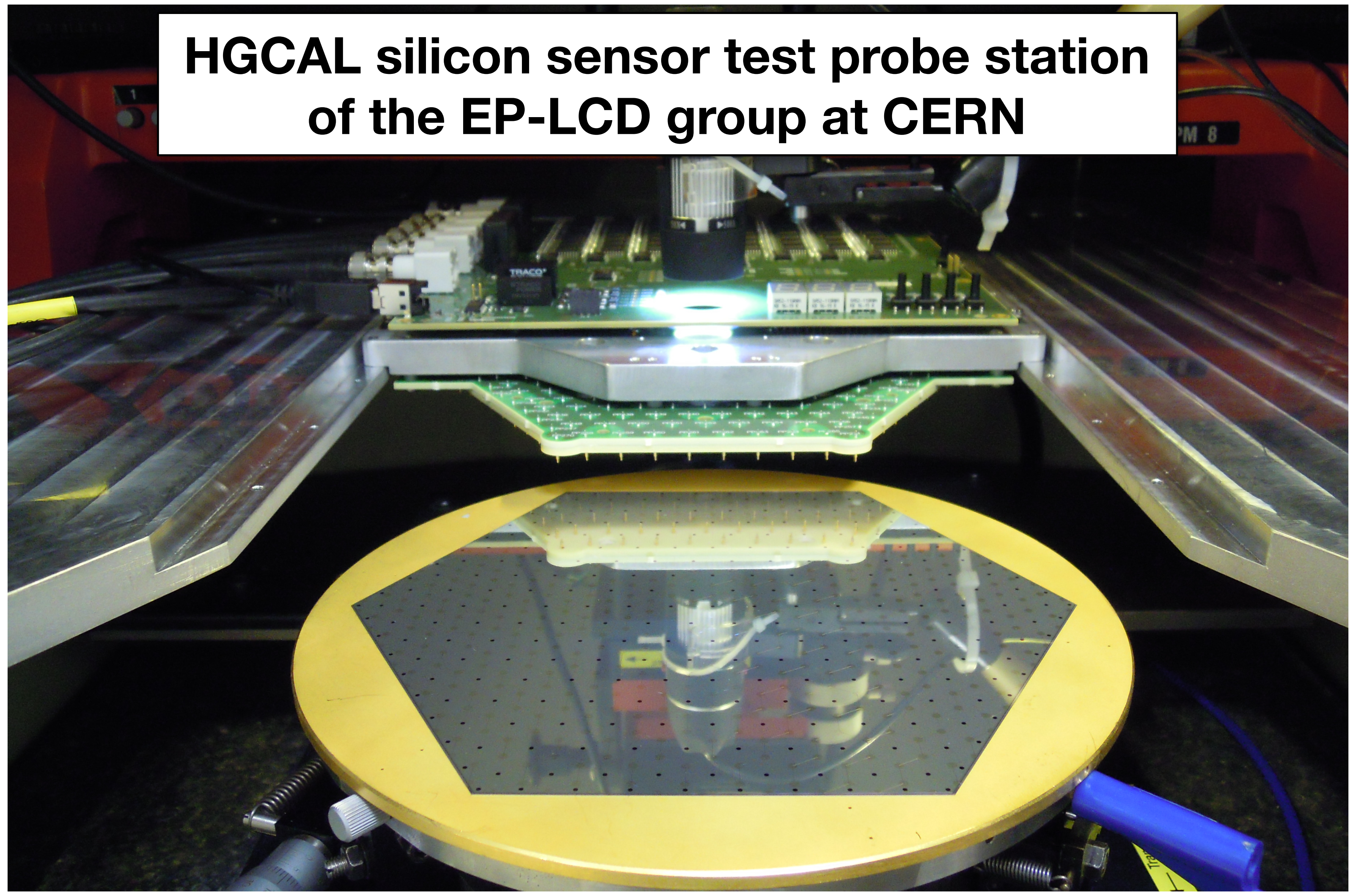
- **IV** and CV, interpad capacitance and resistance measurement

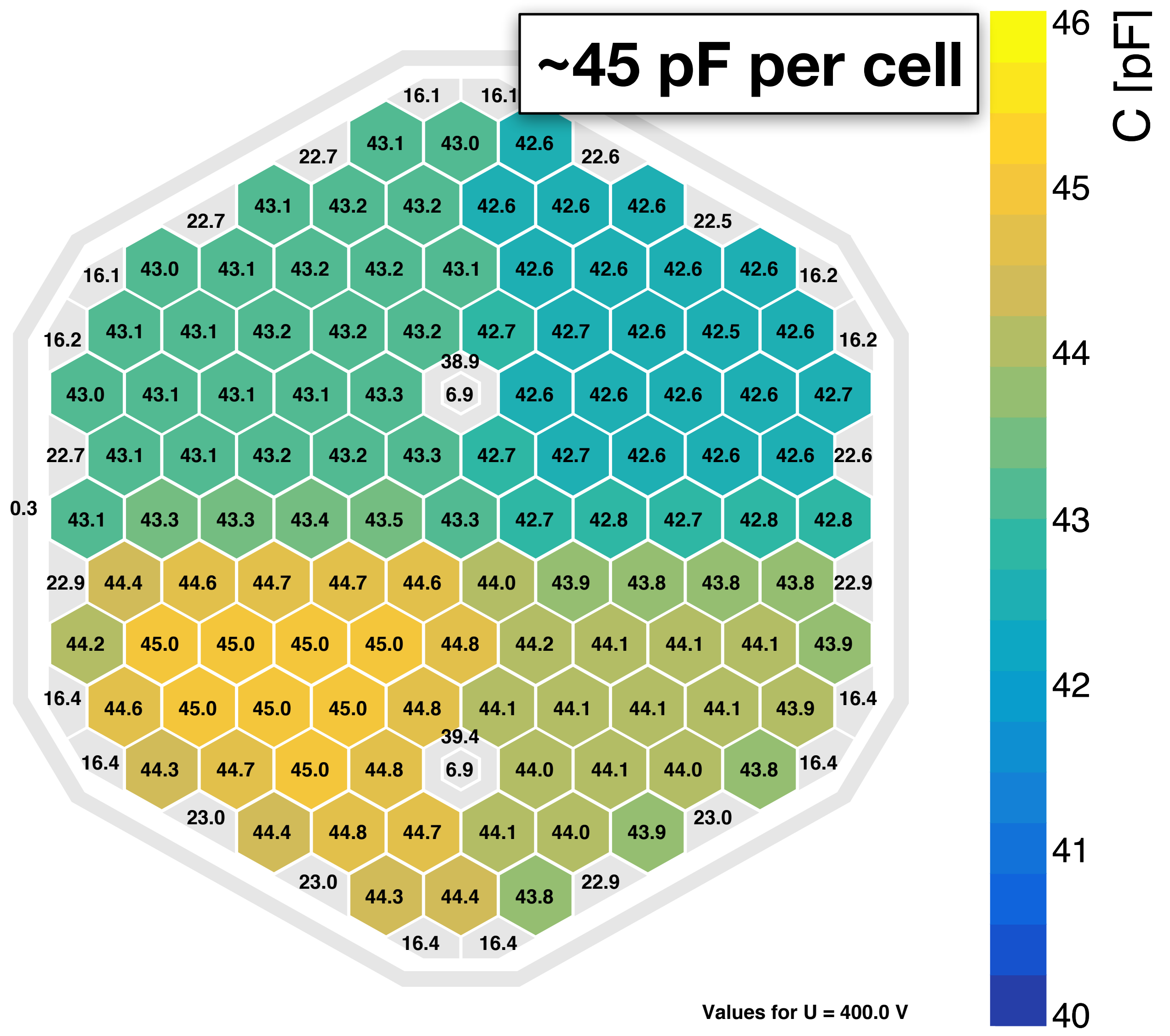
➡**Switching and probe-card setup**

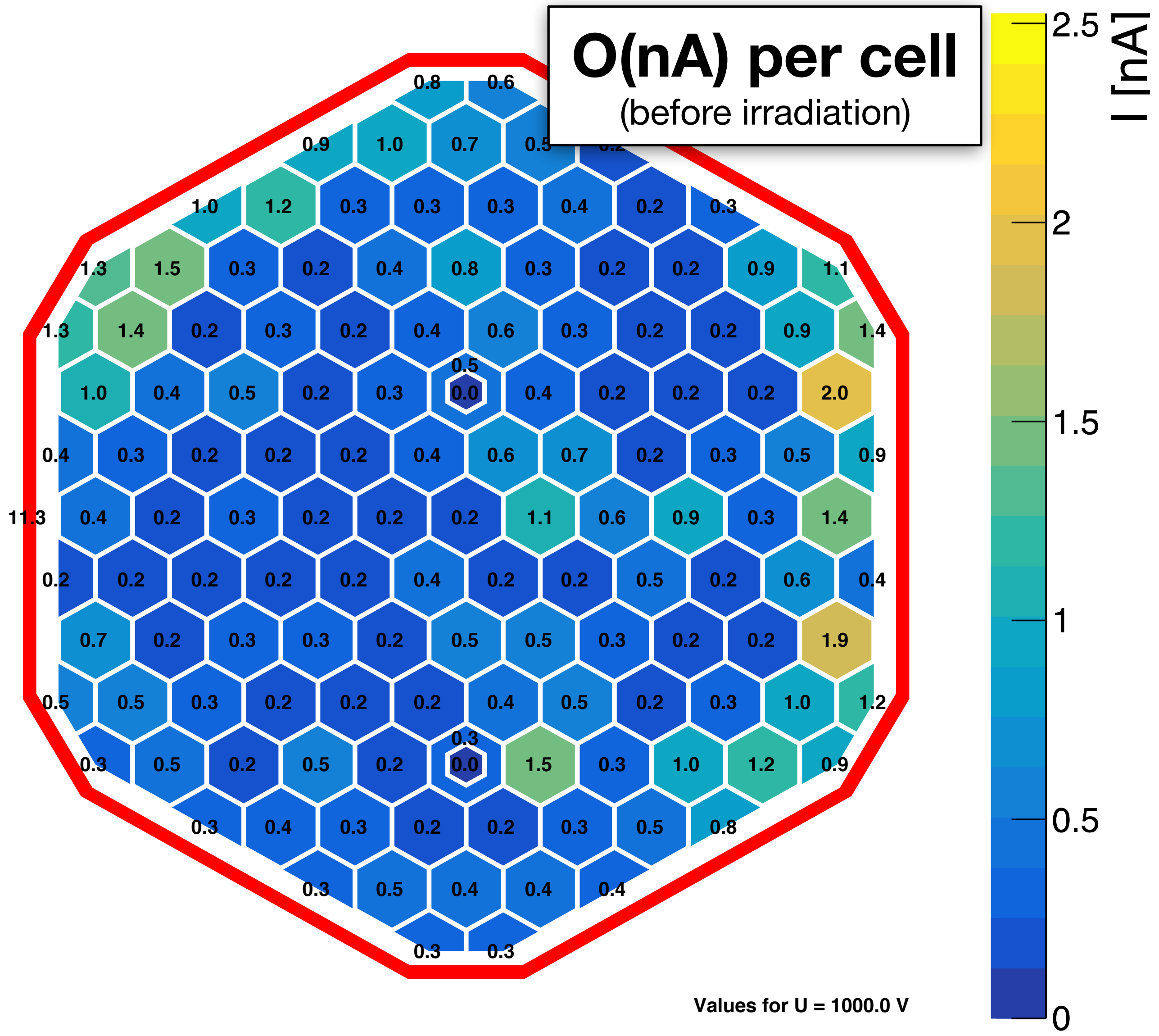
- Contact all cells via pogo-pin card
- Switch between channels using switching card
- All pads biased while one is tested
- **Pro: time efficient (typical IV: ~1hr per wafer)**

Probe- and switchcard design

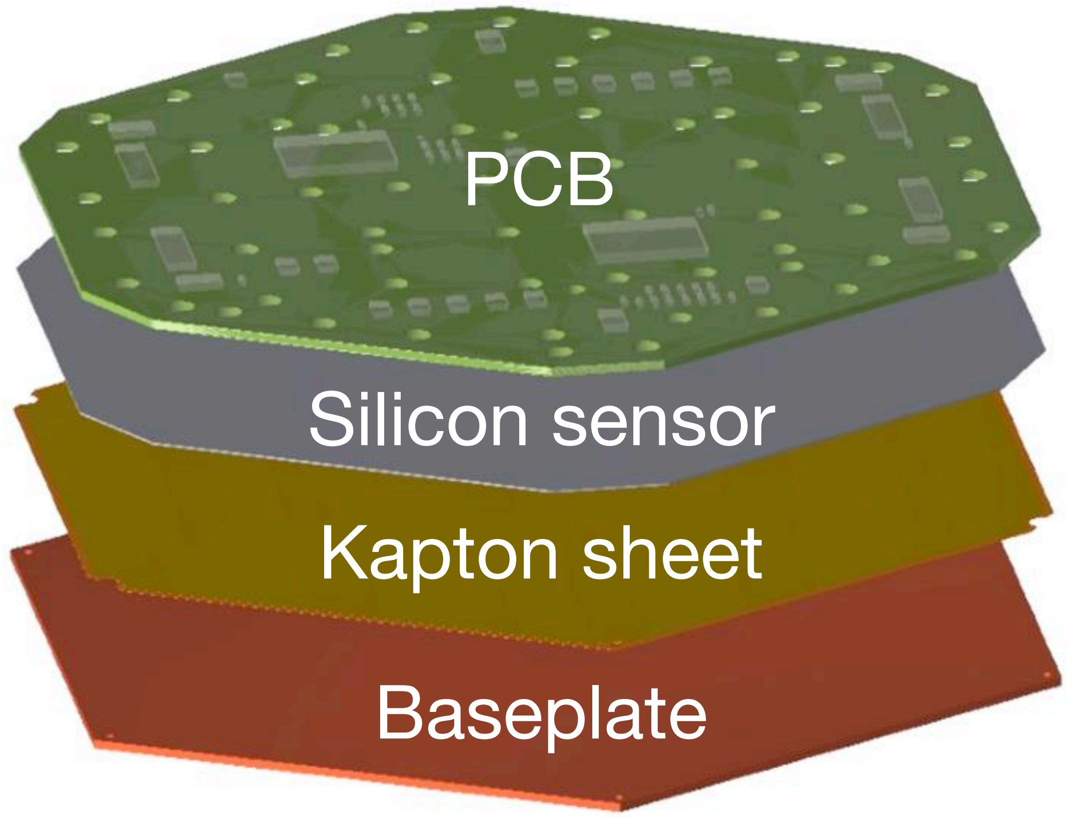








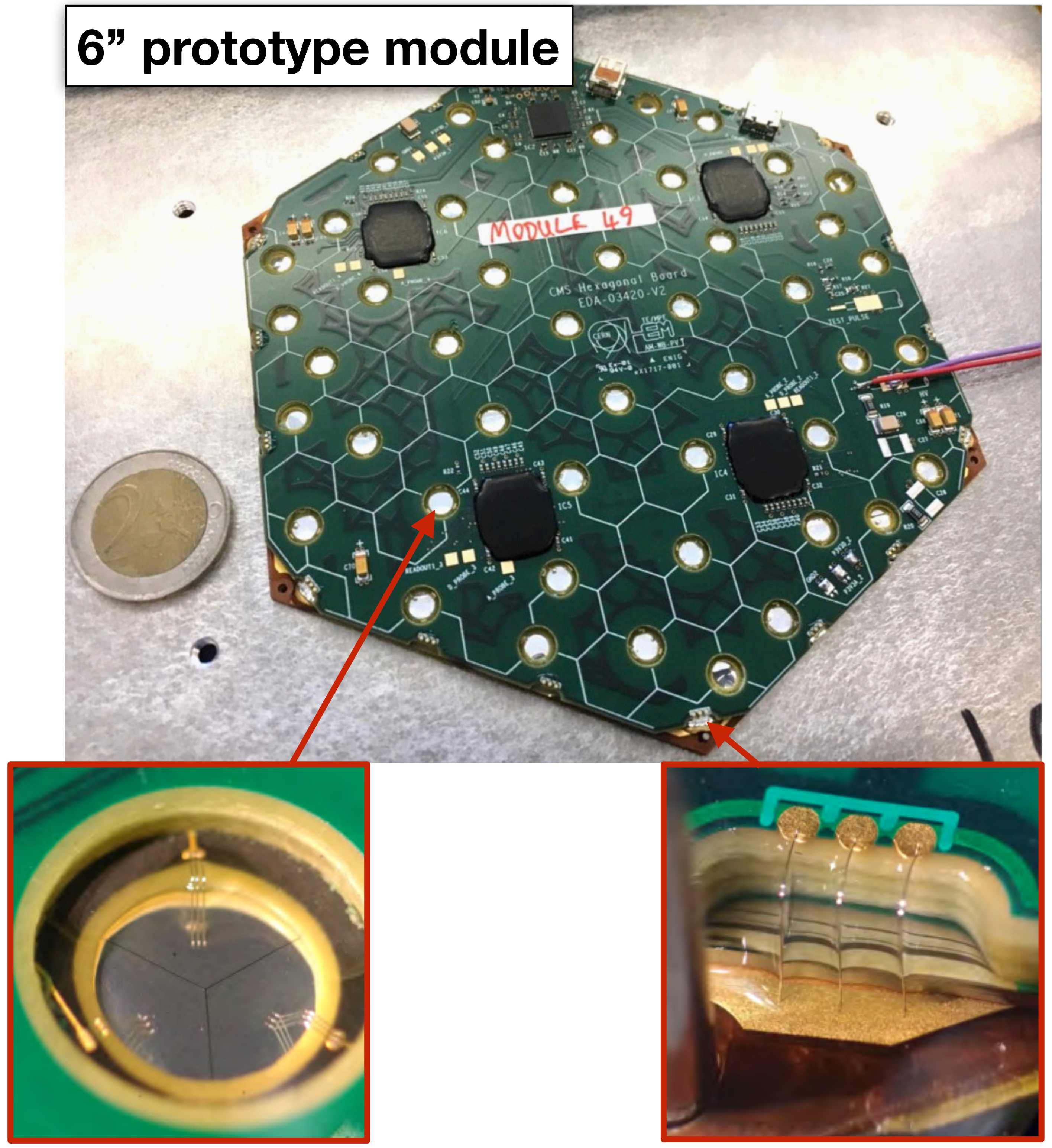
Silicon modules and cassettes



Silicon modules

Sandwich of **PCB**, **sensor**, **biasing layer** and **baseplate** for rigidity/cooling.

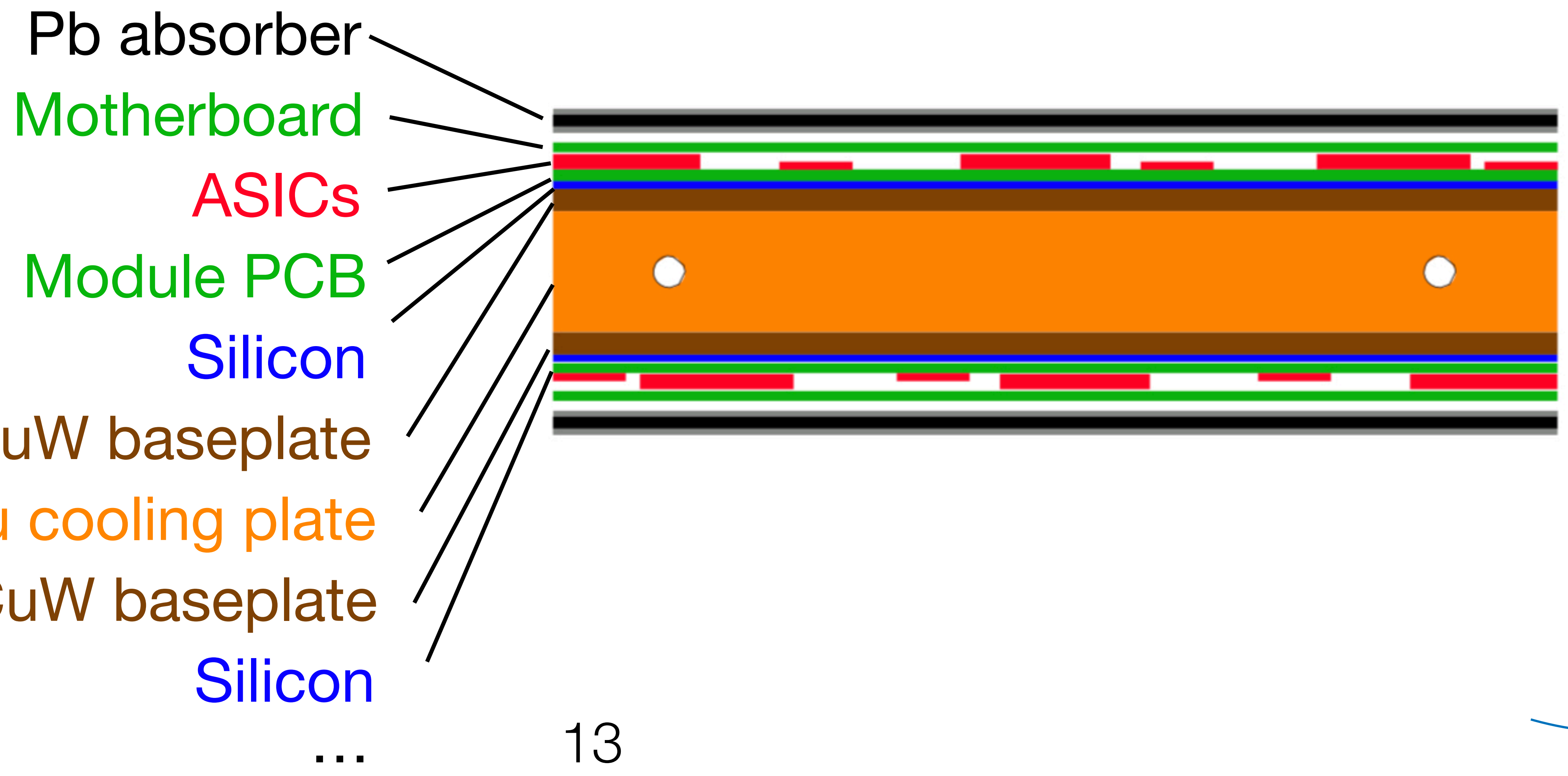
- Challenge: wire-bonding from PCB onto silicon
- CE-E baseplates act as absorbers (CuW)
- CE-H: PCB baseplates (good thermal properties and cheaper)

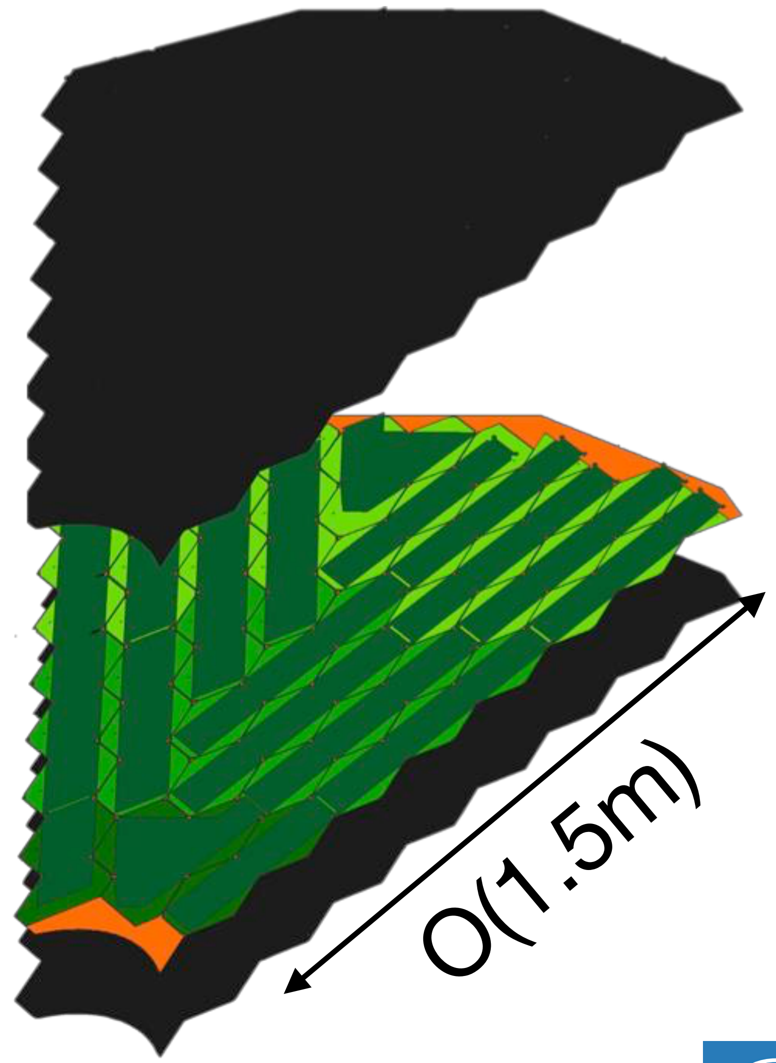


CE-E cassettes

Self-supporting sandwich structures (with absorbers)

- Modules placed on both sides of Cu cooling plate and closed with Pb plates





Scintillator+SiPM for lower radiation region

~500m² of scintillator for regions of lower radiation

- Rely on experience from CALICE and CMS HCAL upgrade

➡Radiation hardness of scintillators & Si-PMs well understood

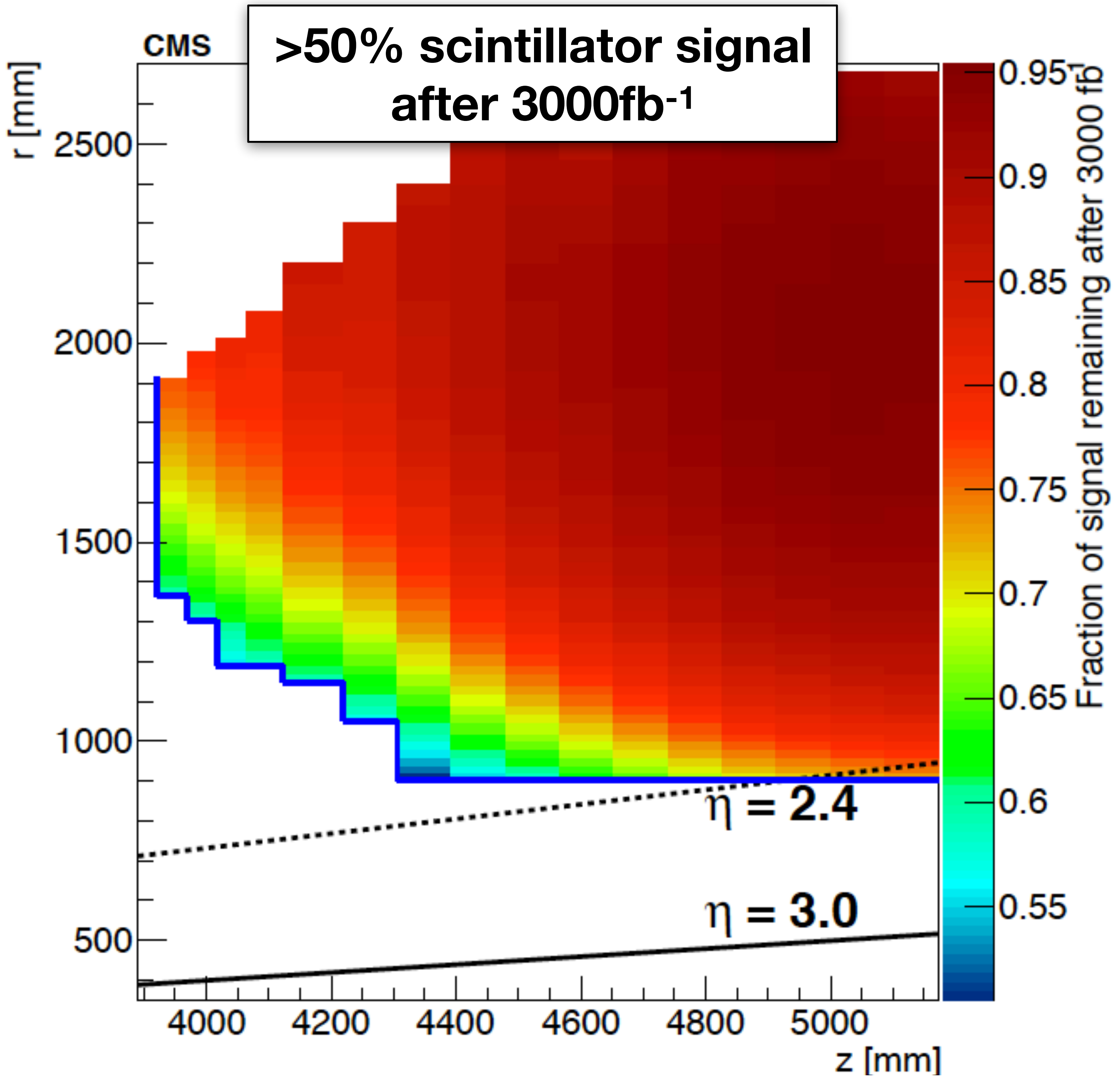
➡Overall S/N for MIP remains > 5 after 3000 fb^{-1}

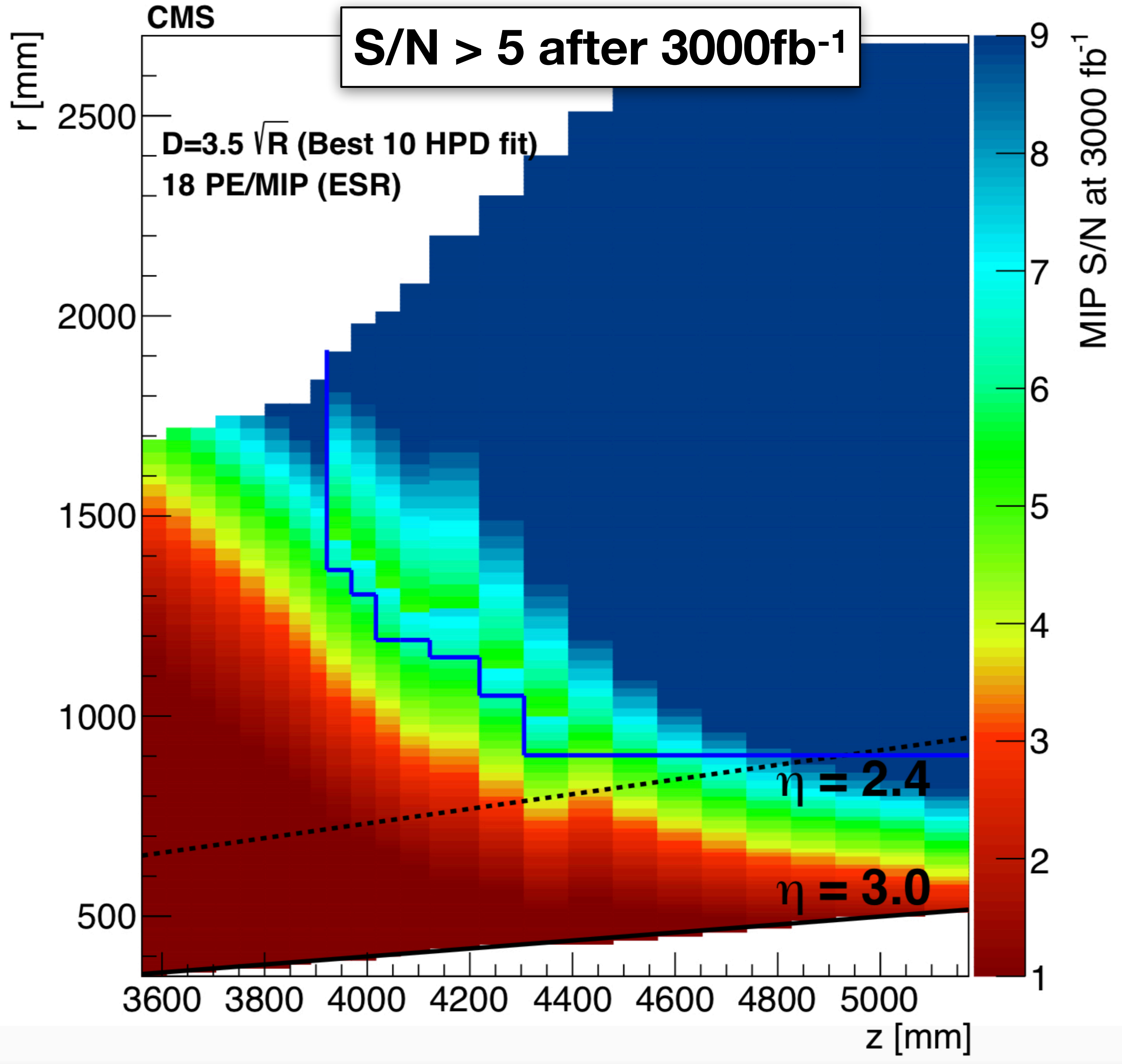
SiPM-on-tile design

- 400k SiPMs integrated into the PCB, need to be cooled
- readout directly on detector
- more compact and cost-effective

R&D commitment from DESY

- e.g. validate interplay SiPM - HGCROC
- e.g. assembly and quality control
- …





HGCAL tile-modules

R&D commitment from DESY ctd.

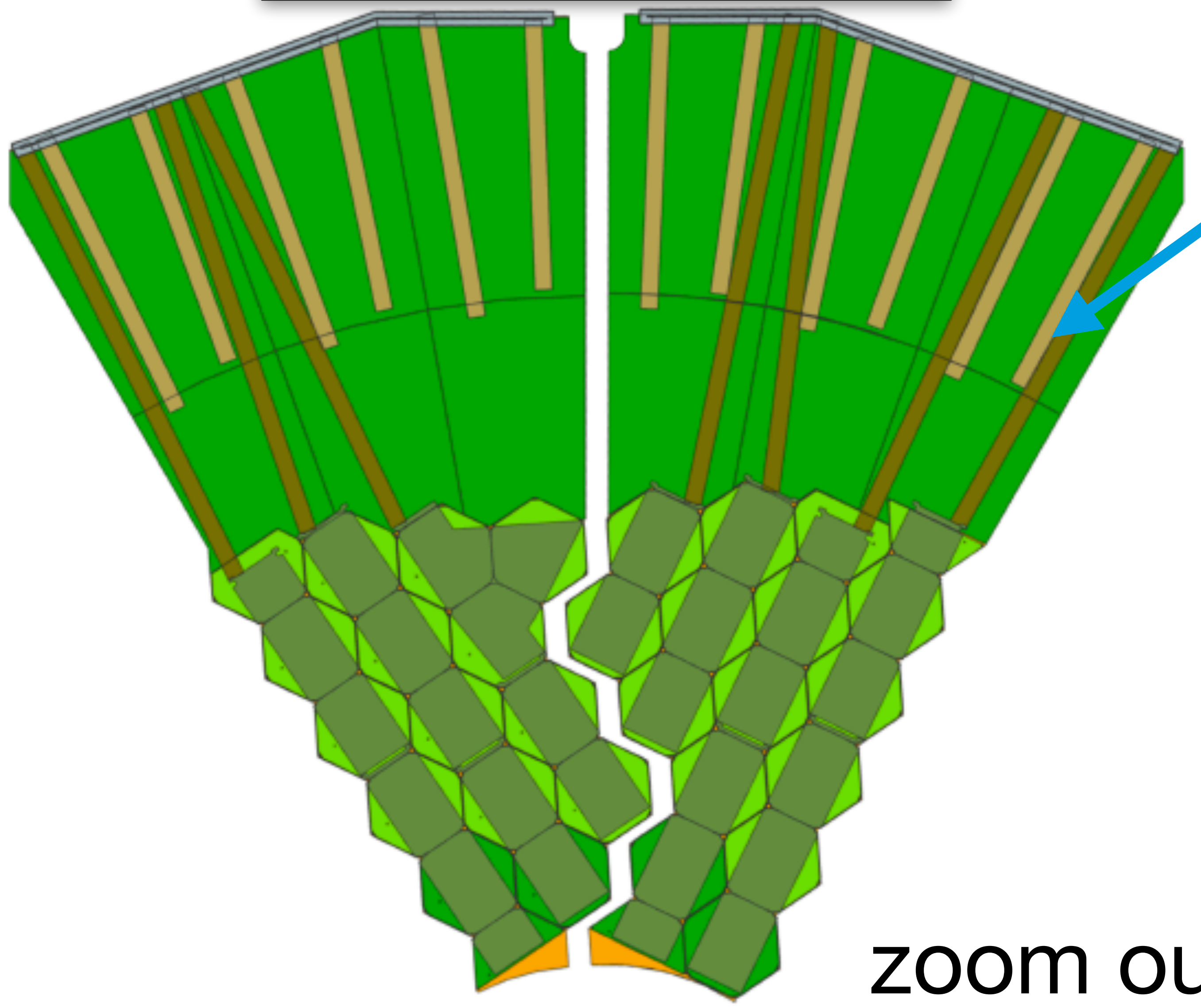
- e.g. tile-board development
- e.g. tile-board characterisation (electronically, thermo-mechanically)
- …

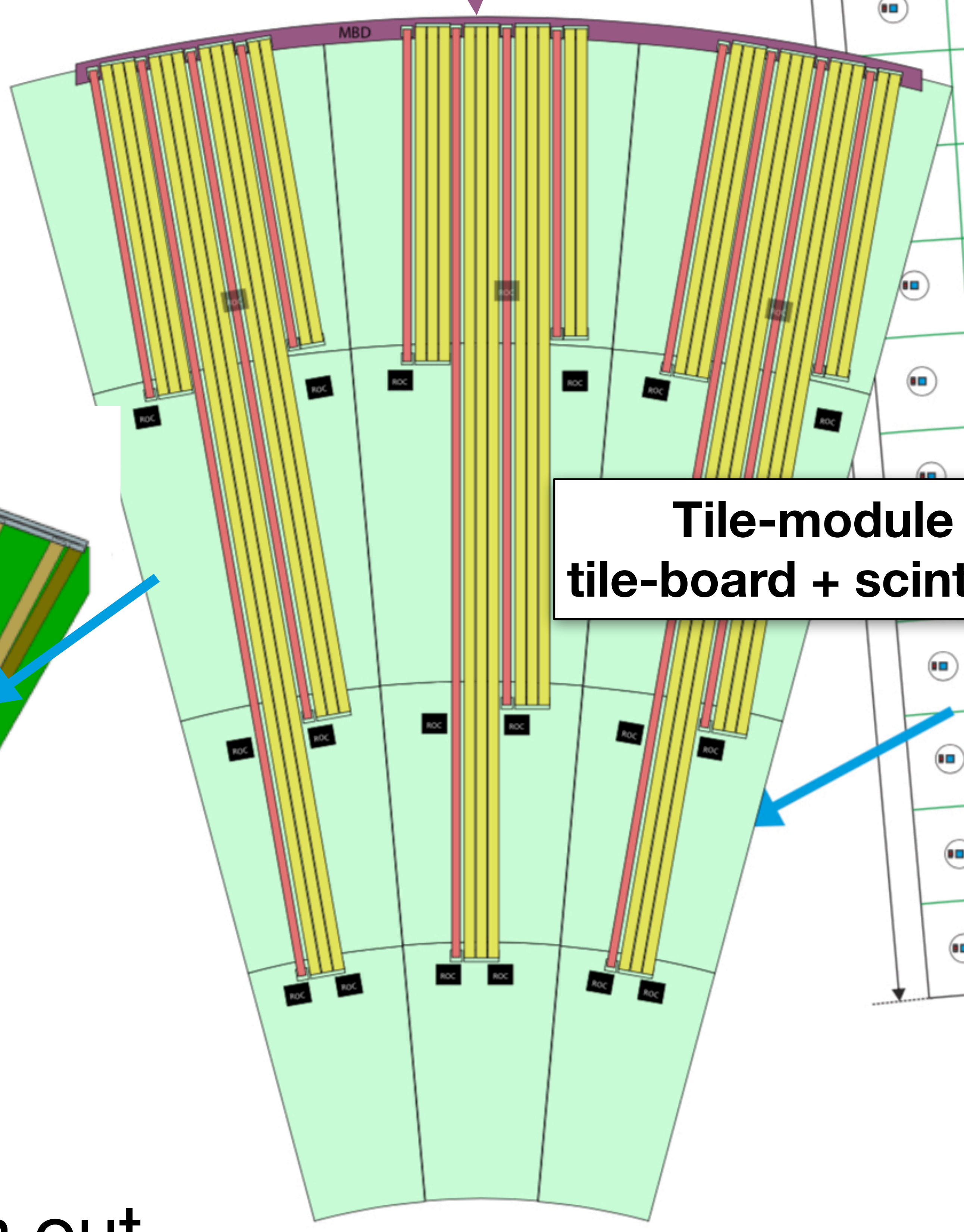
New technical challenges

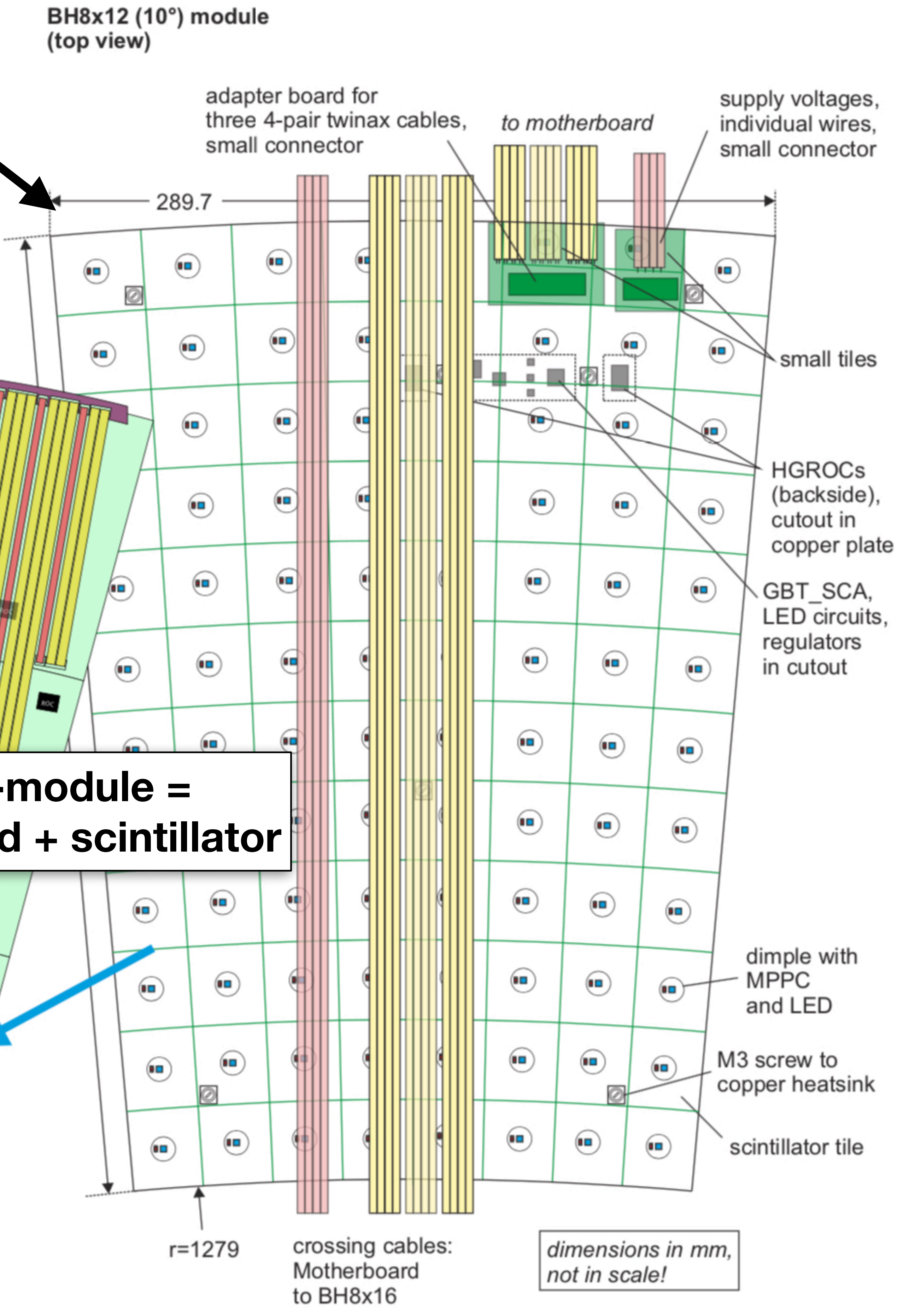
- High-speed data transfer
- Cooling of SiPMs through PCB
- Thermo-mechanical rigidity +/- 40 °C
- Radiation hardness

Arranging scintillator tiles in r-ϕ grid with constant azimuthal angle: 4 - 32 cm² area / tile

Mixed cassette in CE-H

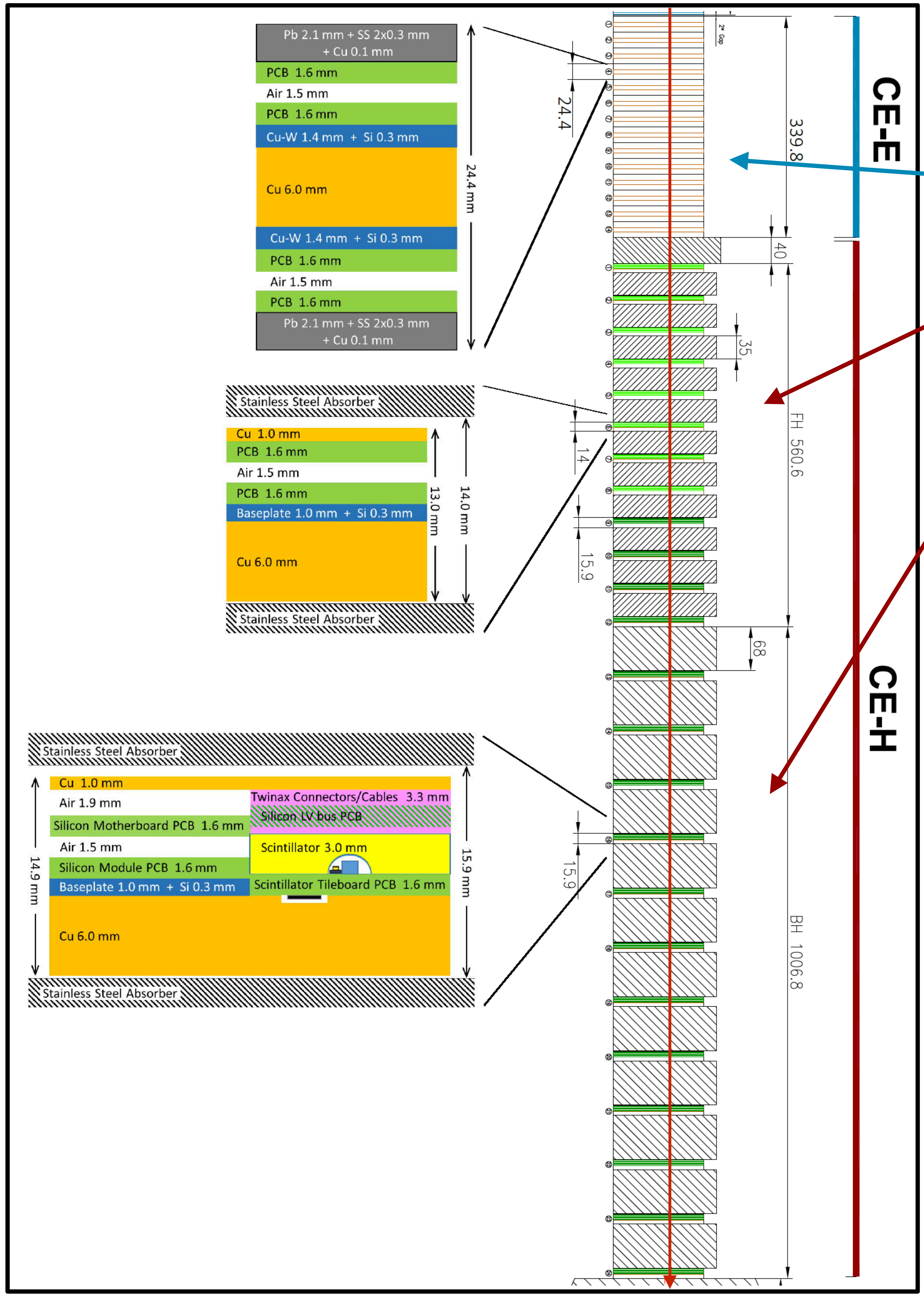






zoom out ⟷ zoom in

Longitudinal structure and lateral coverage



Longitudinal sampling

52 layers for total depth of 10 λ

- CE-E: 28 fine samplings for 26 X_0 / 1.5 λ
- CE-H (1): 12 samplings in the first 3.5 λ
- CE-H (2): 12 samplings in the last 5 λ

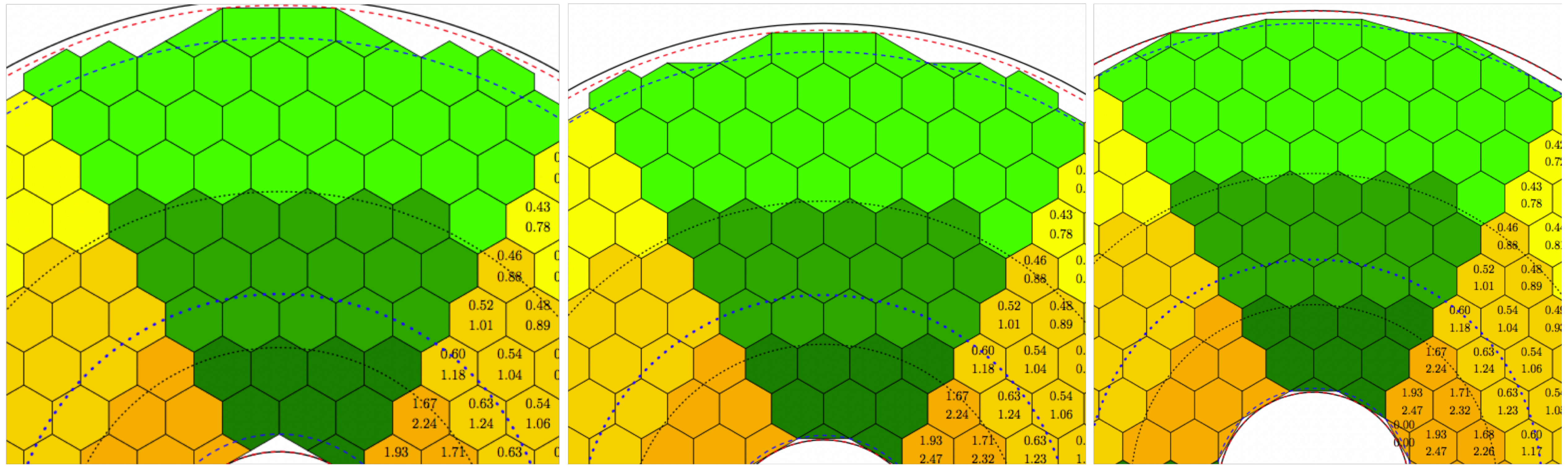
Main constraint: fit into existing detector endcap —> limited space

- e.g. air gap in CE-E: limited space, very difficult for electrical components and connectors

Inner/Outer coverage

Best coverage by (currently) **18** variants of hexagonal modules

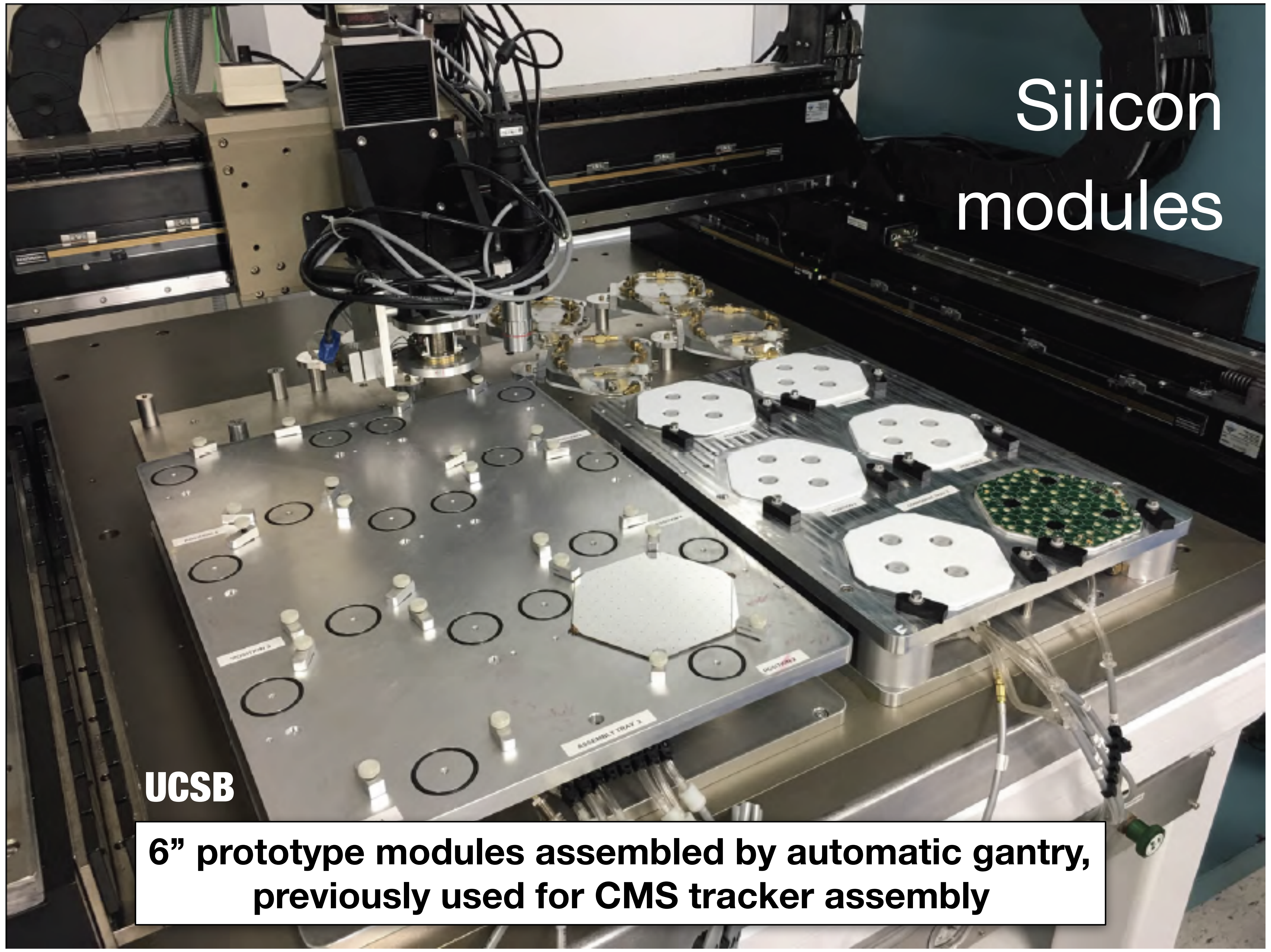
coverage & complexity



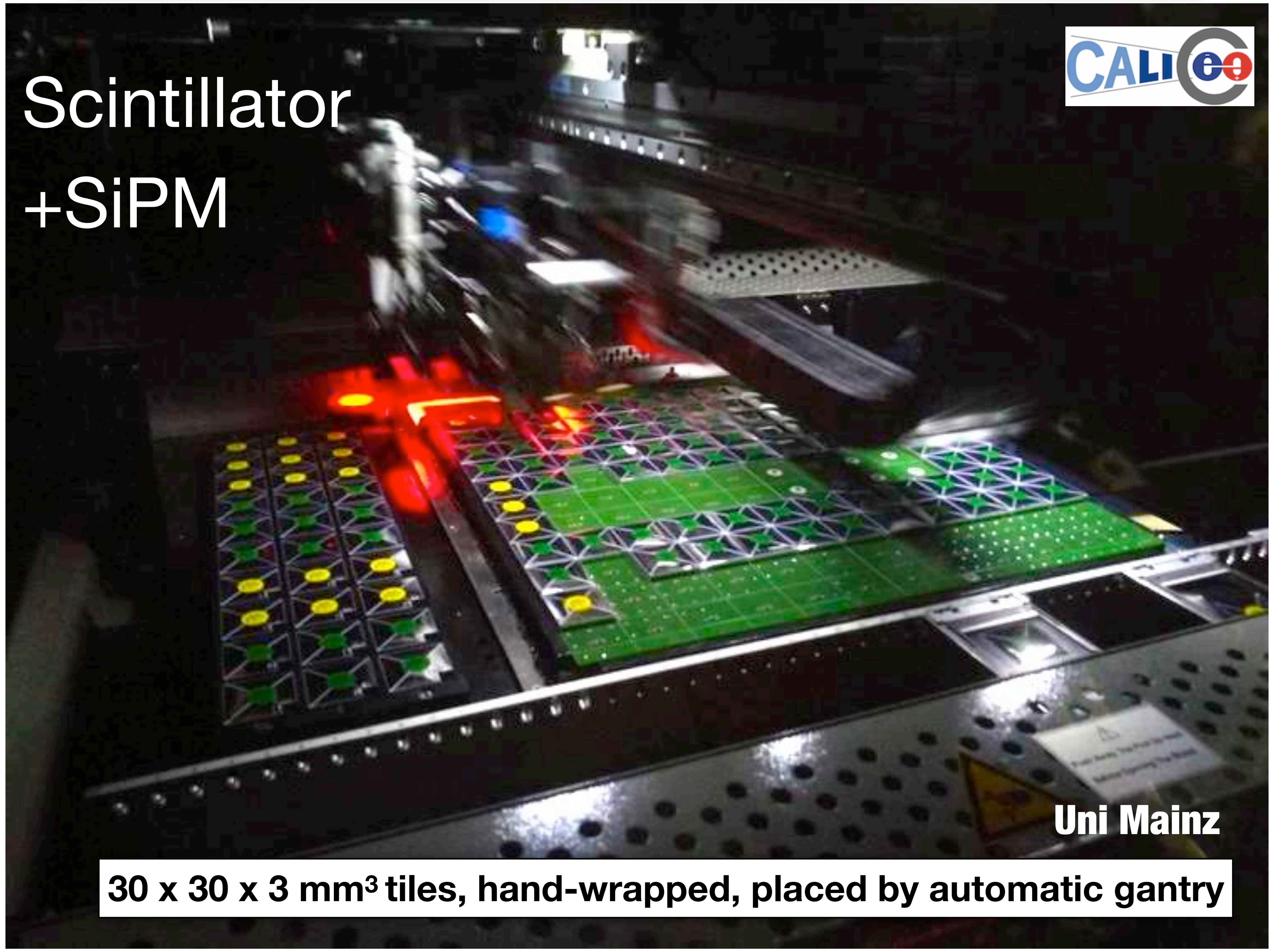
III. Physikalisches Institut RWTH AACHEN UNIVERSITY CERN

Towards mass production of detector elements

Automated assembly of silicon prototypes:
O(100) modules for beam tests



Automated assembly for CALICE prototypes:
28000 tiles on 158 boards



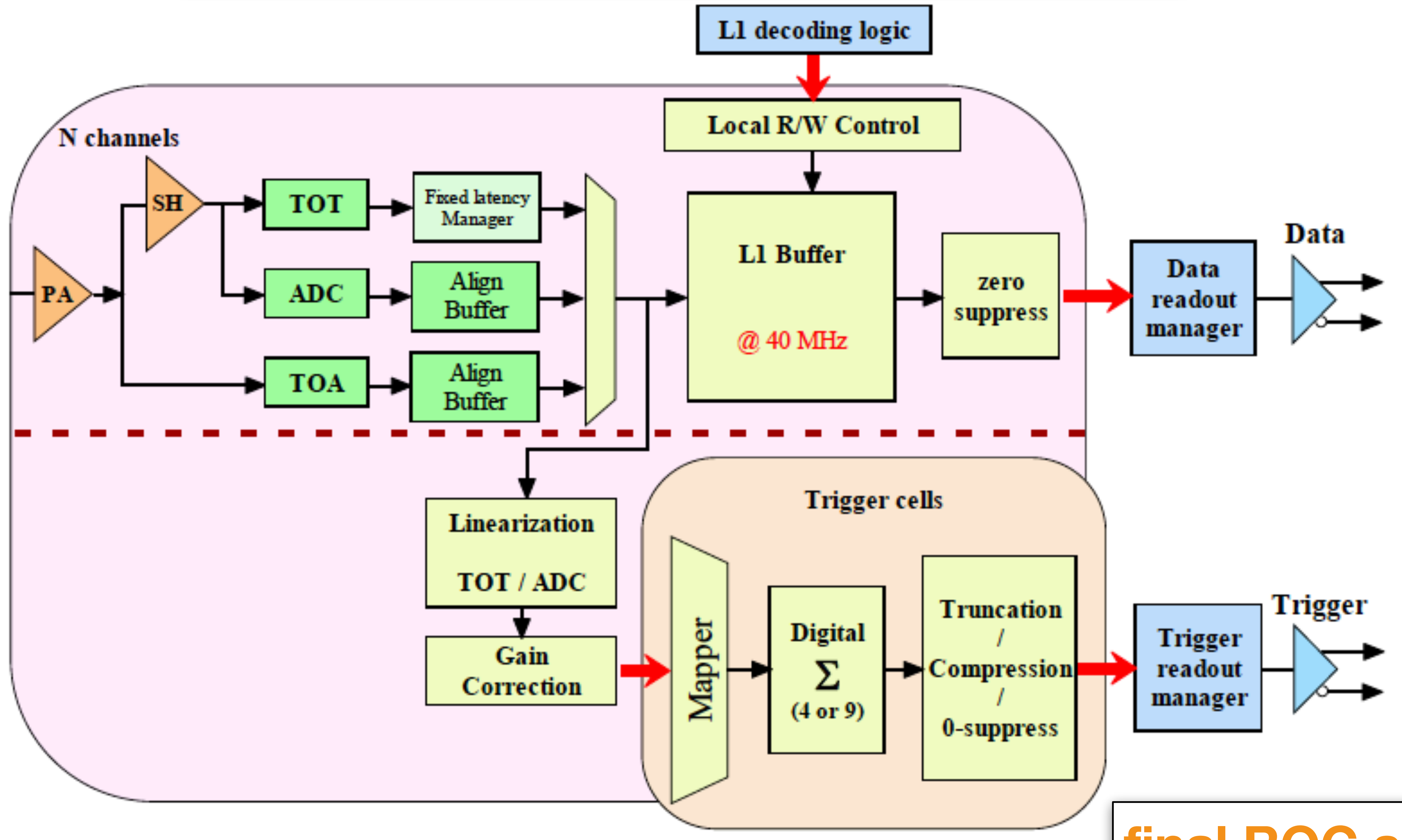
Assembly centre development at five locations around the world.
Leading institutes: UCSB (Si) and **DESY (Scint.+SiPM)**

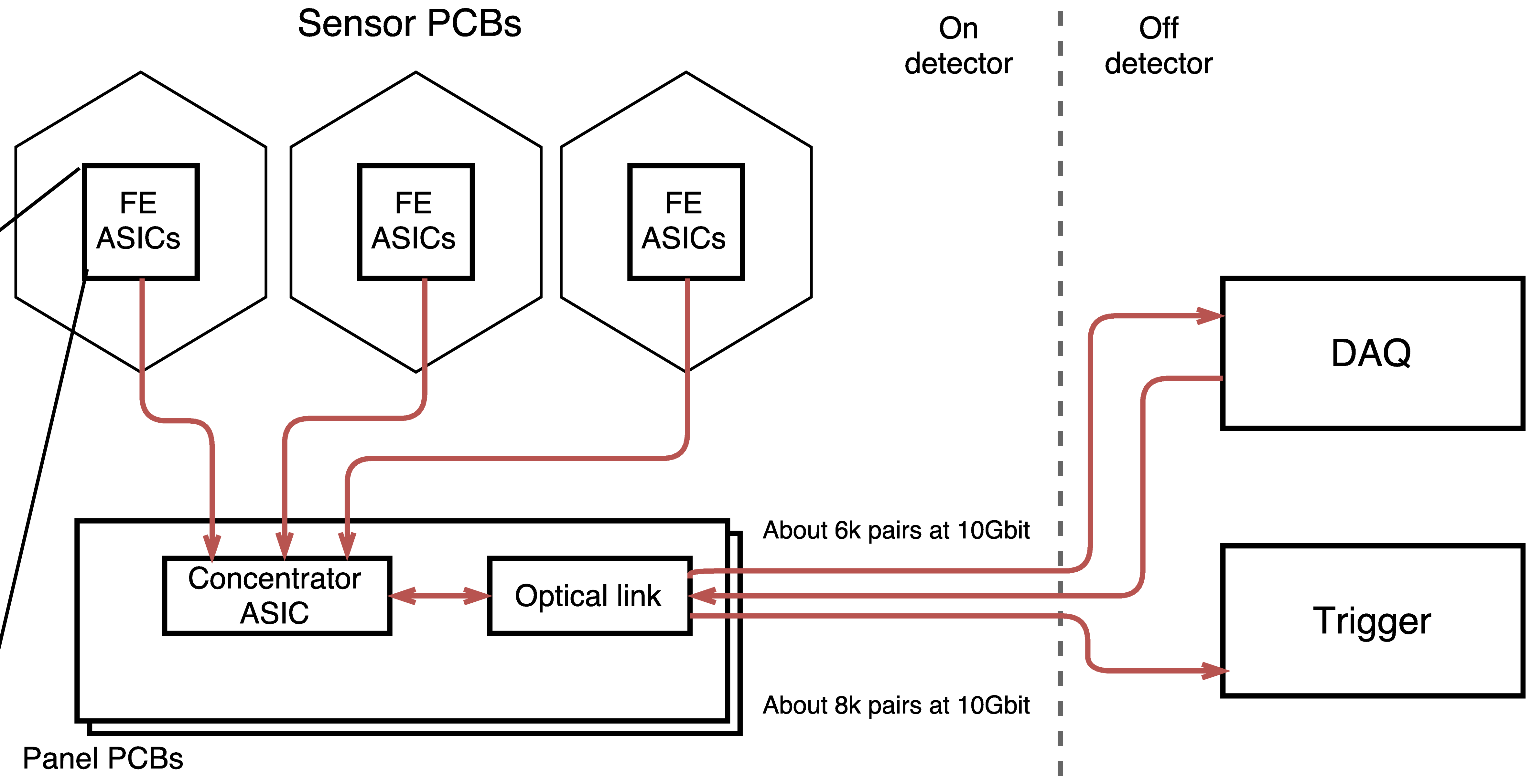
Front-end electronics are challenging

Front-end electronic requirements:

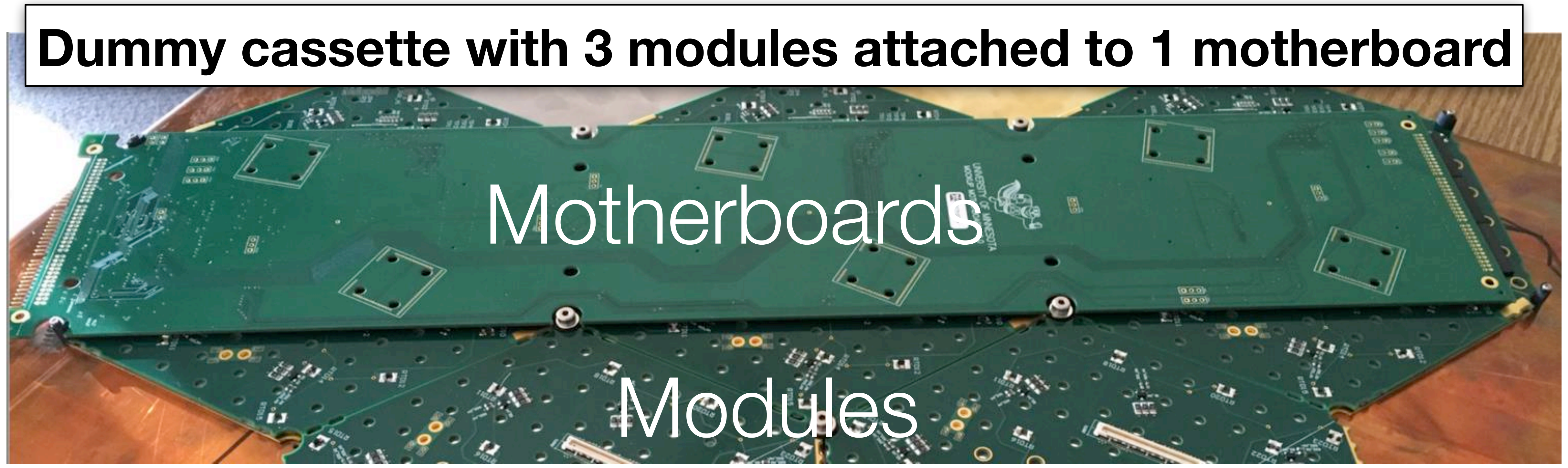
- **Low noise** (<2500e) and **high dynamic range** (0.2fC -10pC)
- Timing information to **tens of picoseconds**
- Computation of **trigger sums**
- Buffering to **12.5µs** L1 latency
- **<20mW** per channel (cooling limitation)
- …

HGCROC ASIC both for silicon and SiPMs





Dummy cassette with 3 modules attached to 1 motherboard

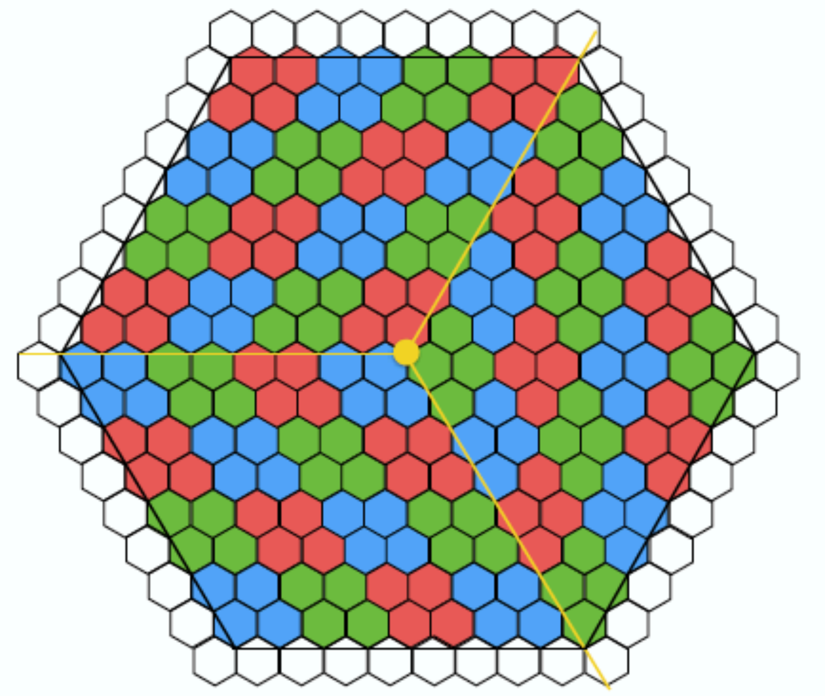


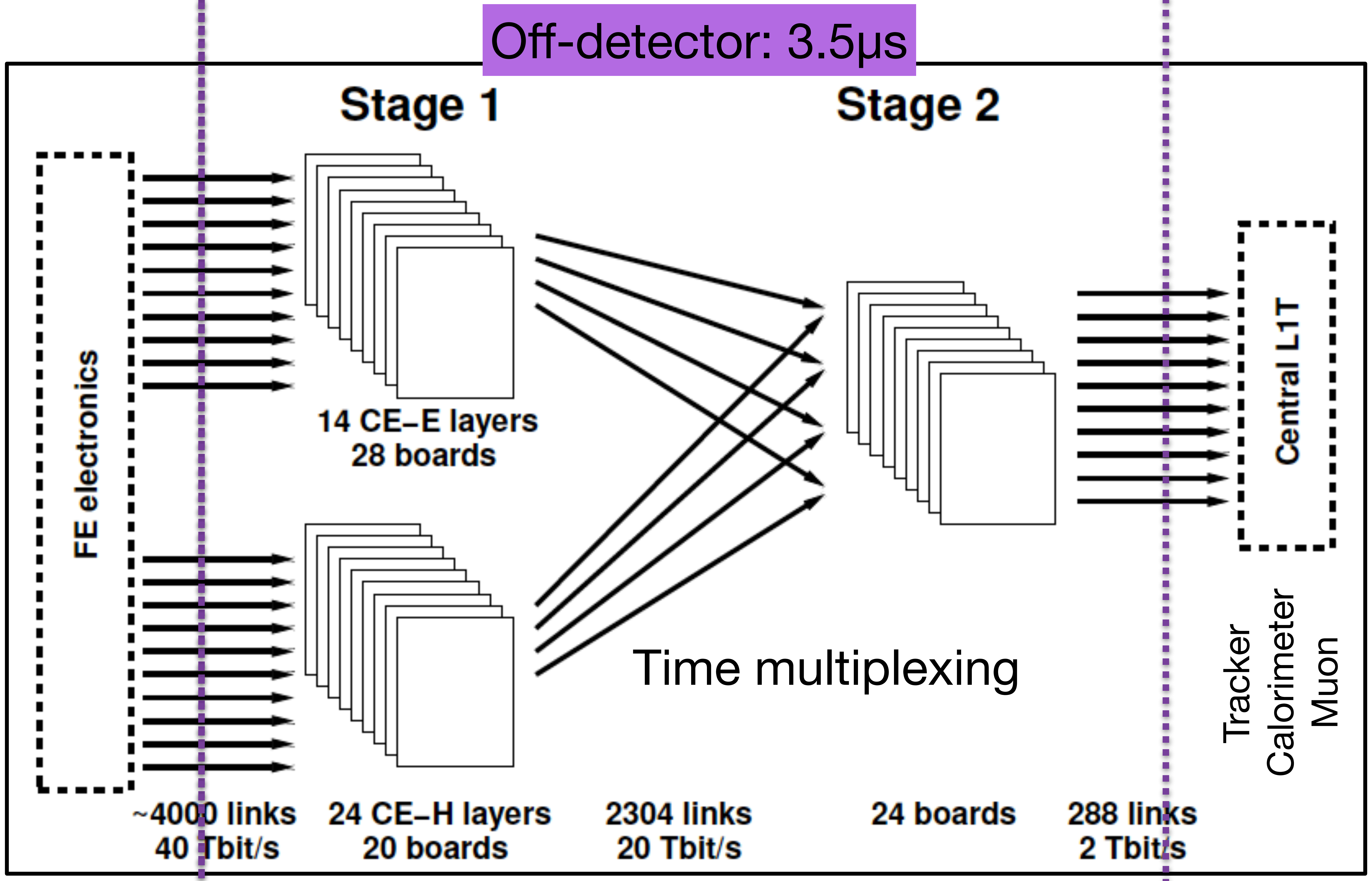
final ROC submission by 2021!

Trigger objects from HGCAL

300TB/s → Trigger cell sums $\xrightarrow{\text{40TB/s}}$ 2D clusters per layer (NN) $\xrightarrow{\text{20TB/s}}$ 3D clusters $\xrightarrow{\text{2TB/s}}$

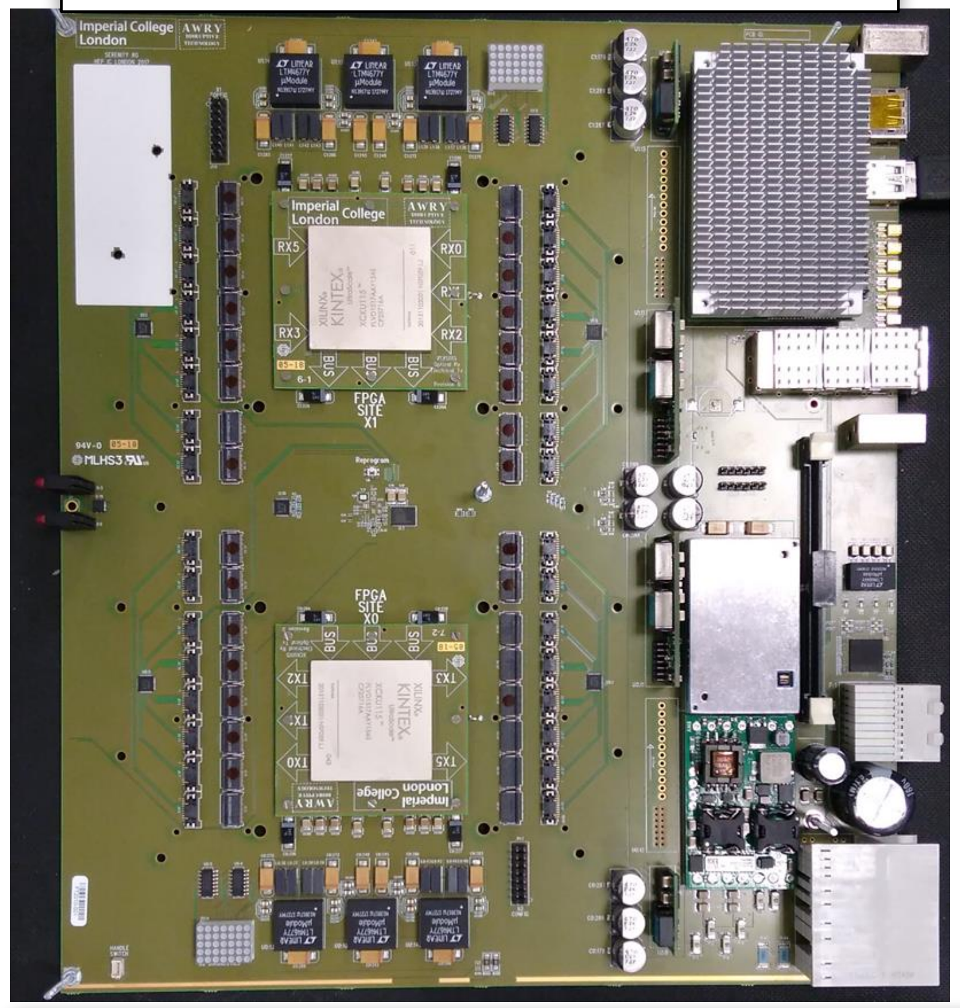
On-detector: 1.5µs





➡Profit from generic boards for whole CMS trigger and DAQ systems

“Serenity” BE board in development



up to 96 links in and out, each 16 Gb/s

Requirements become features

✓ Radiation tolerance

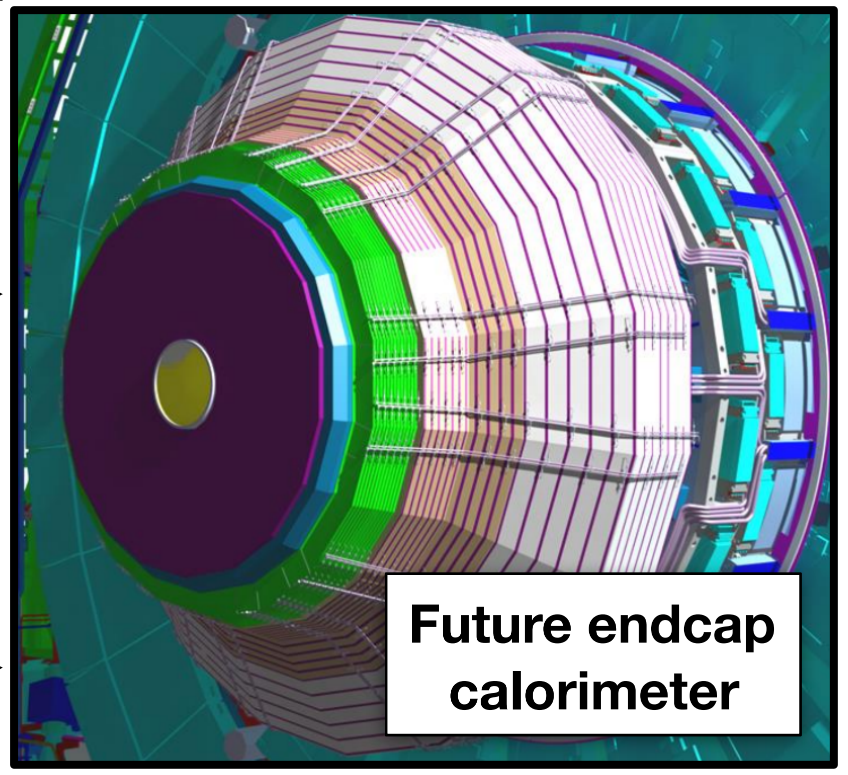
fully preserving the energy resolution after 3000 fb^{-1}

✓ Dense calorimeter

preserve lateral compactness of showers

✓ Fine lateral granularity

two shower separation + observation of narrow jets, minimise pileup contributions in energy & timing measurements



✓ Fine longitudinal granularity

fine sampling of the shower: good energy resolution, pattern recognition, pile-up discrimination, …

✓ Precision time measurement

high energy showers for pile-up rejection, primary vertex identification

✓ Contribute to L1 (Hardware) trigger

<u>Many engineering challenges not mentioned:</u>

- 2x 250 t detector to assemble and install
- Operation at -30°C will require two-phase CO_2 cooling system
- …

Does the design meet the expectation?

Beam tests of HGCal prototypes since 2016

Main objectives for beam tests:

- Technological **prototyping** of the detector modules
- **First experience** with a **FE ASIC** with components of the ultimate (HGC)ROC **in beam conditions**: ADC, ToT, ToA
- **Physics performance** of the CE-E and CE-H silicon / scintillator parts
- Check **agreement** with **simulation**

Time

2016 ➡ *N. Akchurin et al 2018 JINST 13 P10023*

2017 First beam tests with **Skiroc2-CMS** ASIC

March 2018 @ **DESY** **3 modules**

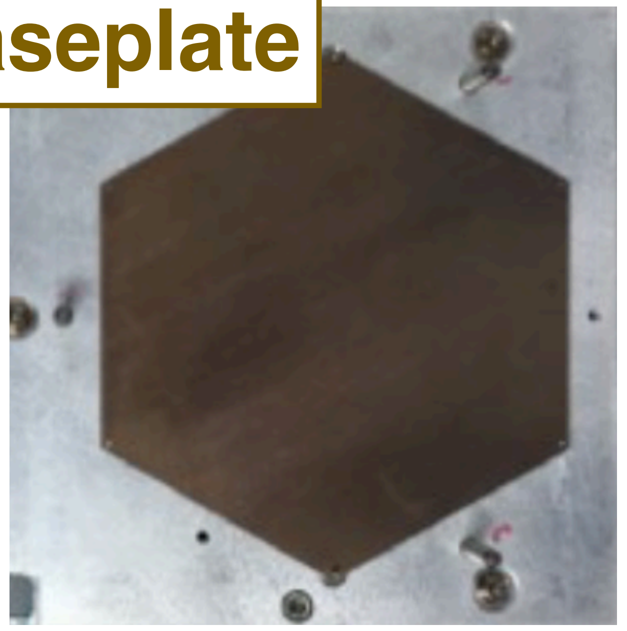
June 2018 @ CERN's **SPS** **full CE-E: 28 modules**

October 2018 @ CERN's **SPS** **full prototype: 94 modules**

HGCal prototype modules

Modules assembled as glued stack of **baseplate**, **Kapton®**, **Si sensor** and **PCB**:

baseplate



- CuW
- Cu

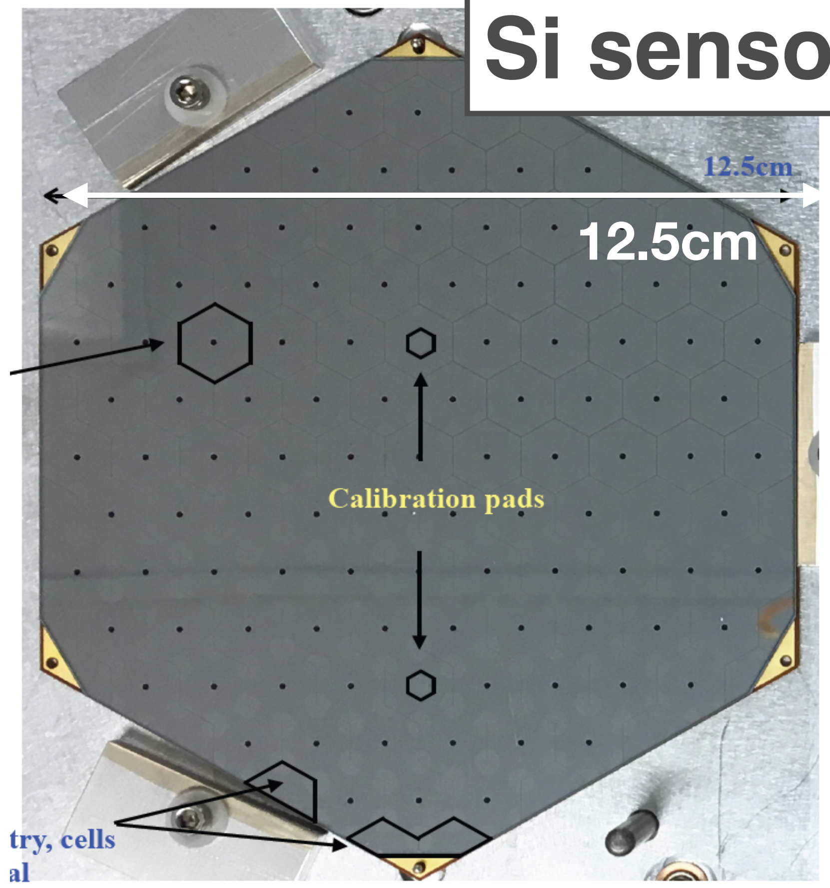
Kapton®

- Gold plated

+

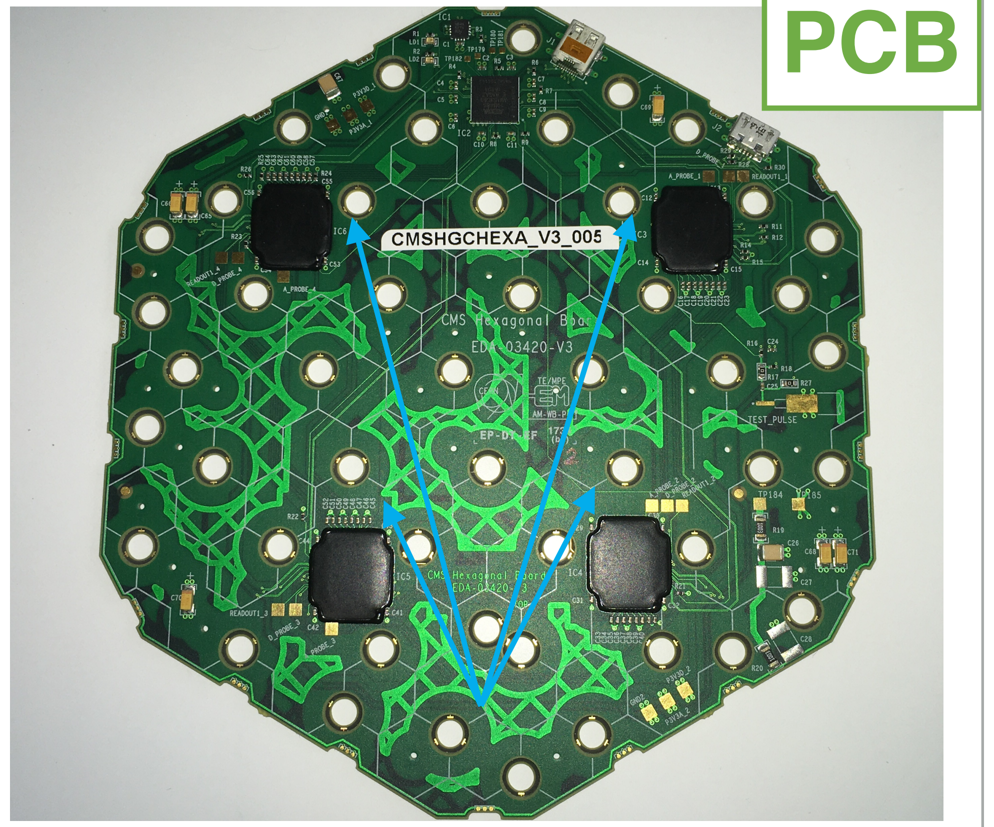
Active material

Si sensor



6" silicon sensors:
- n-type, 128 cells
- 1 cm^2 cell-size
- depletion: 200 & 300µm

PCB

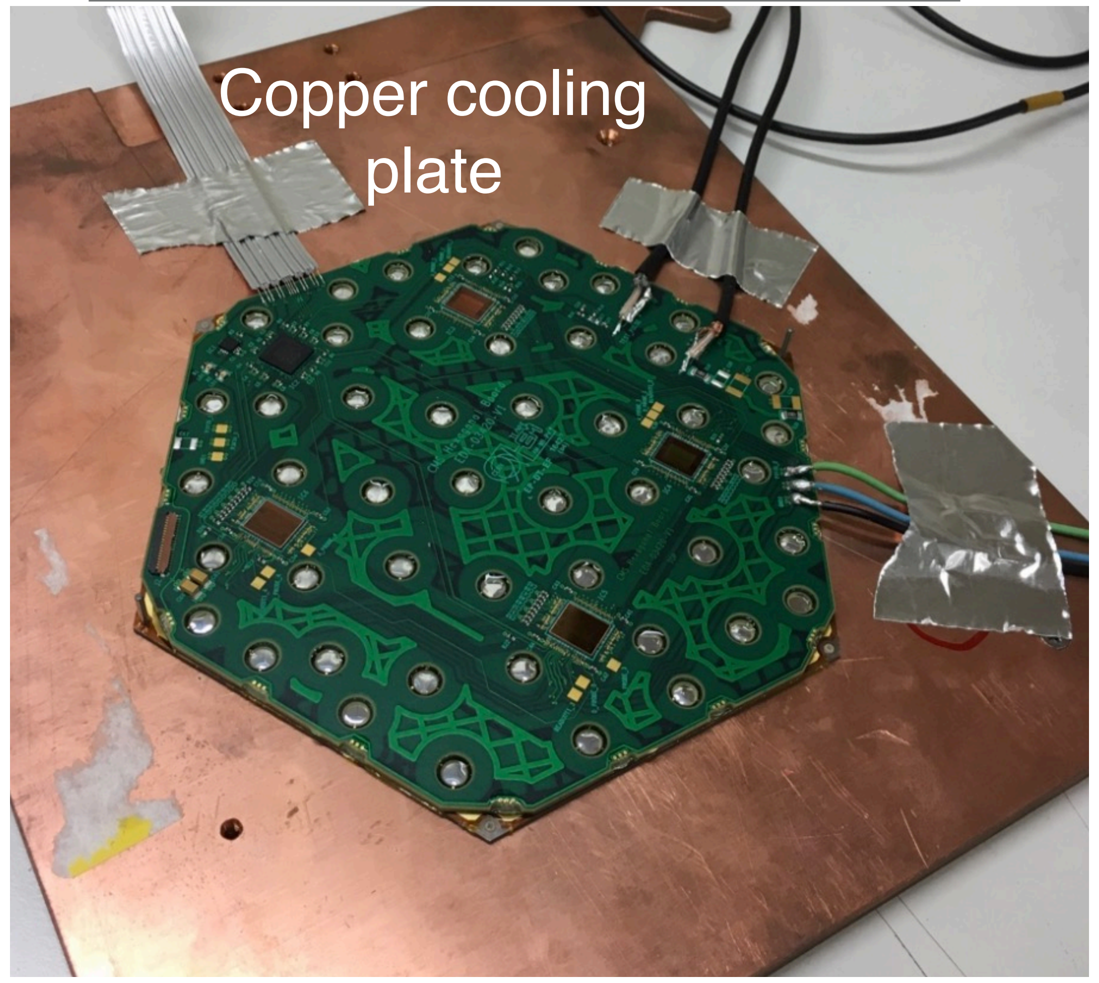


- Skiroc2-CMS ASIC, 64 ch., 4 chips/module
- Developed for CALICE (Skiroc2) & adjusted for HGCal requirements

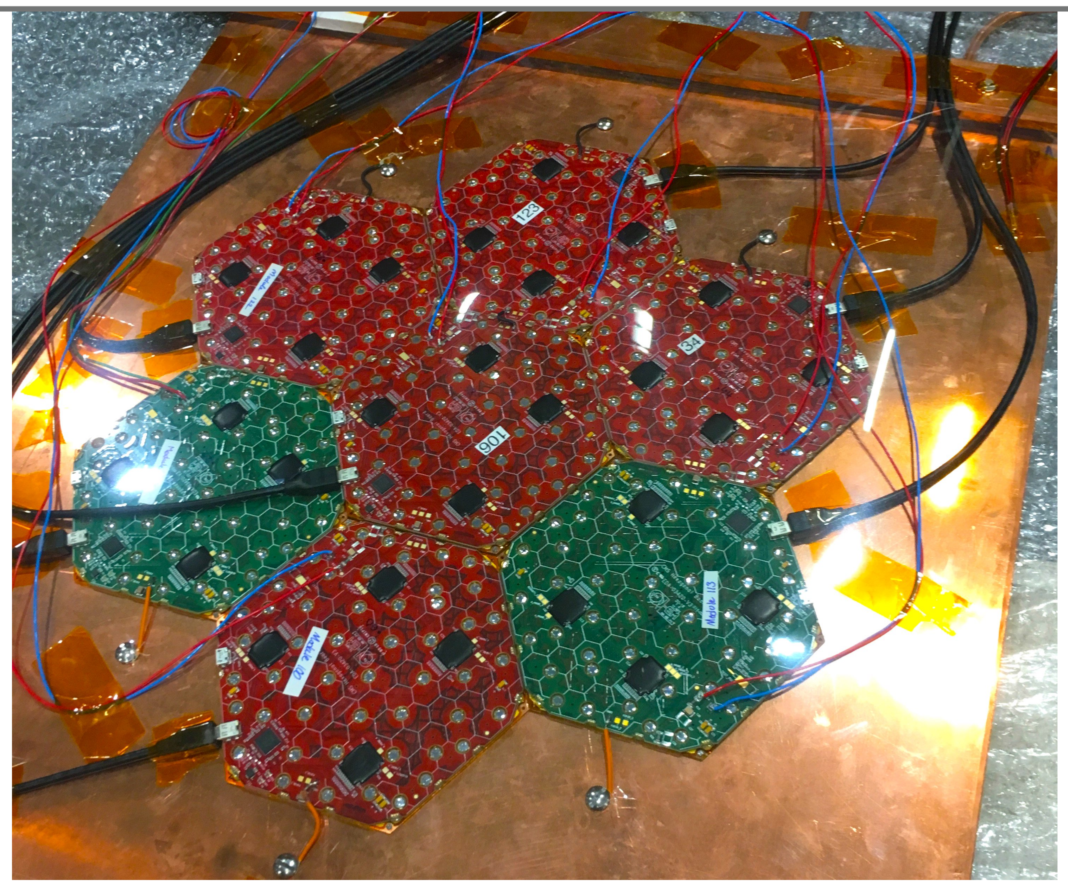
gluing

wire bonding

1-module layer in CE-E



7-module "daisy" layer in CE-H-Si



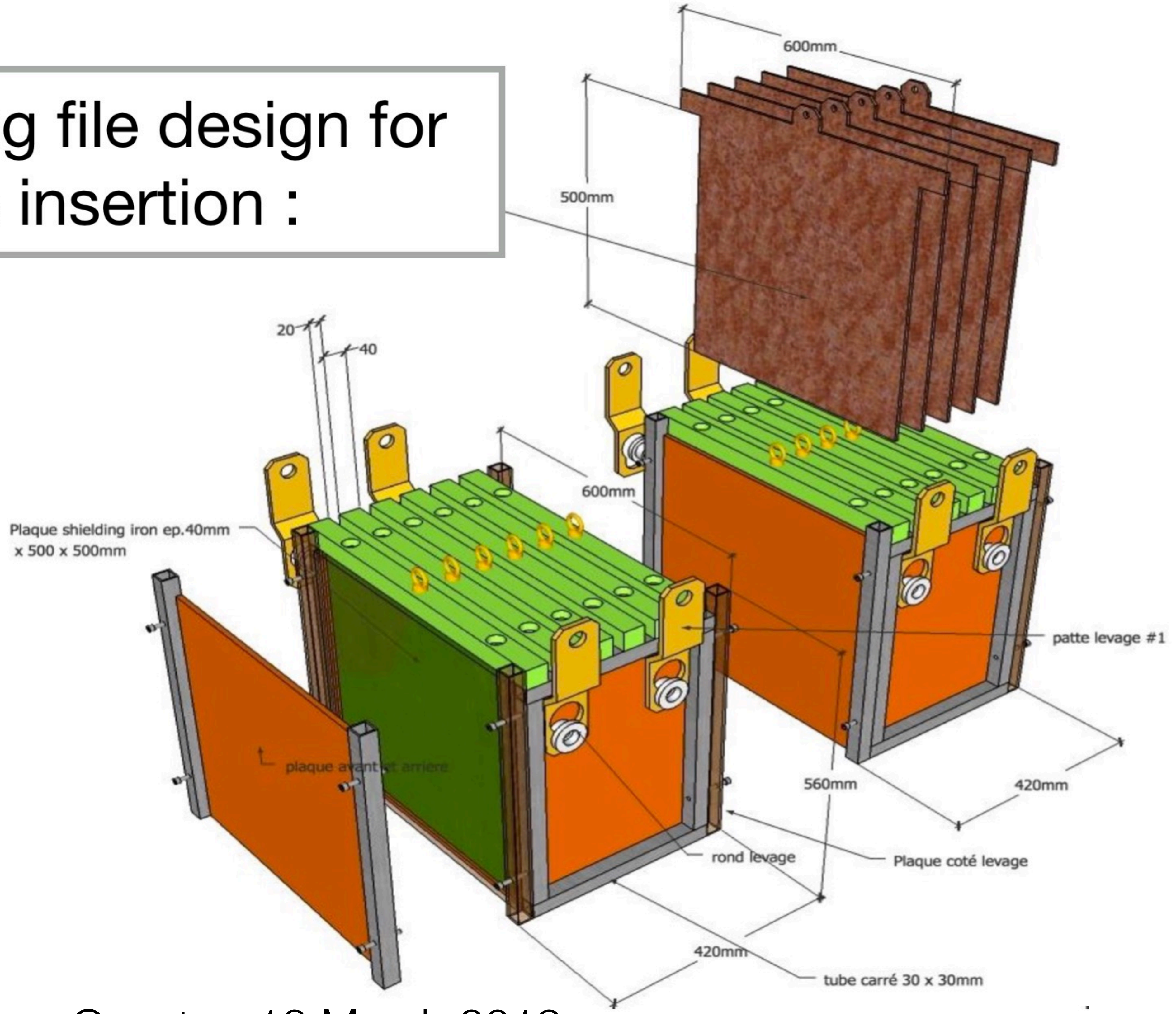
III. Physikalisches Institut RWTH AACHEN UNIVERSITY CERN

HGCal prototype absorbers & mechanics

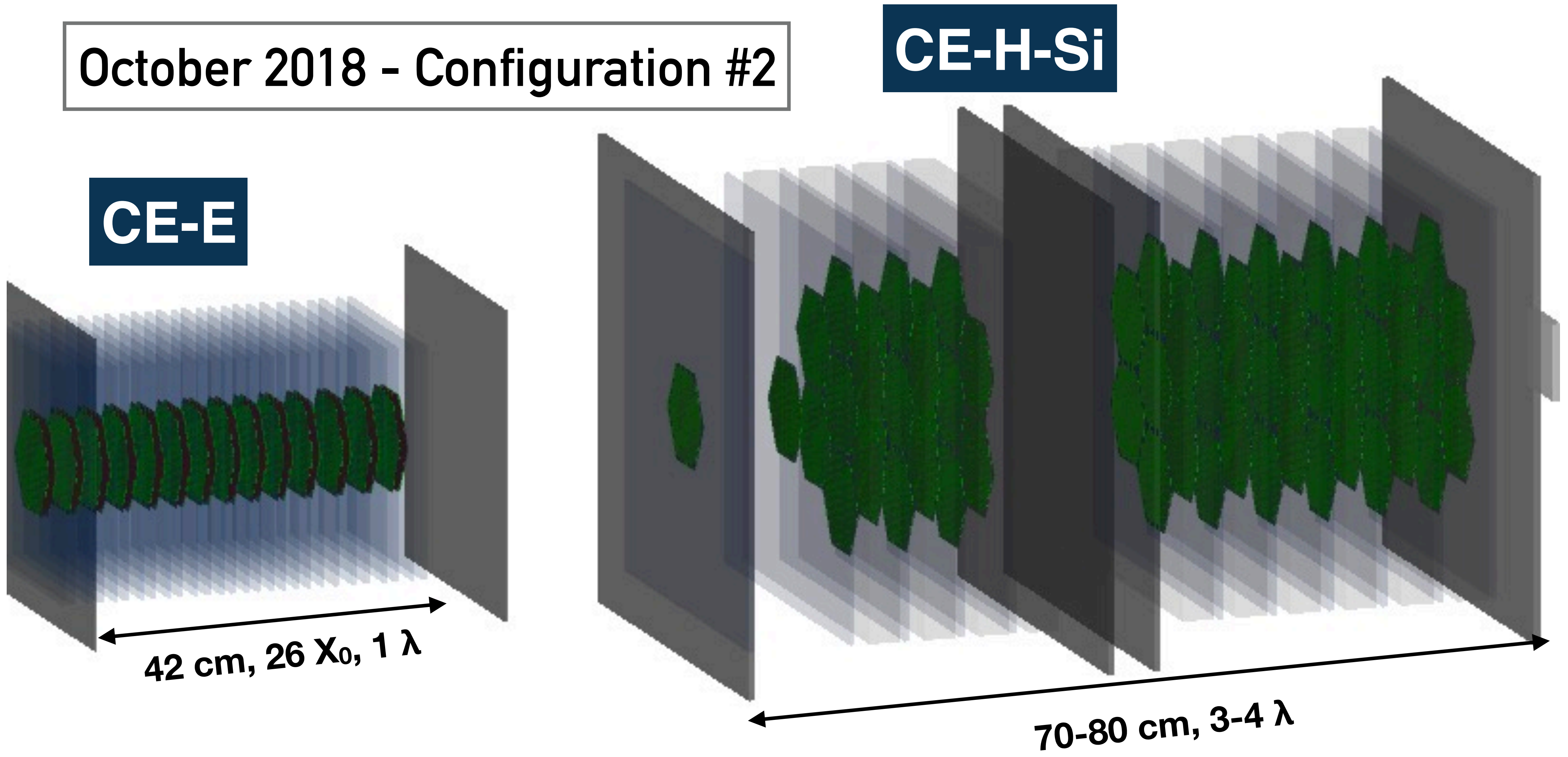
Passive material

- **CE-E:**
  - **material: Pb, W, Cu**
  - **thickness: 5-6 mm**
- **CE-H-Si:**
  - **material: Fe**
  - **thickness: 4 cm**
  - **weight: O(1000kg)**

Hanging file design for flexible insertion :

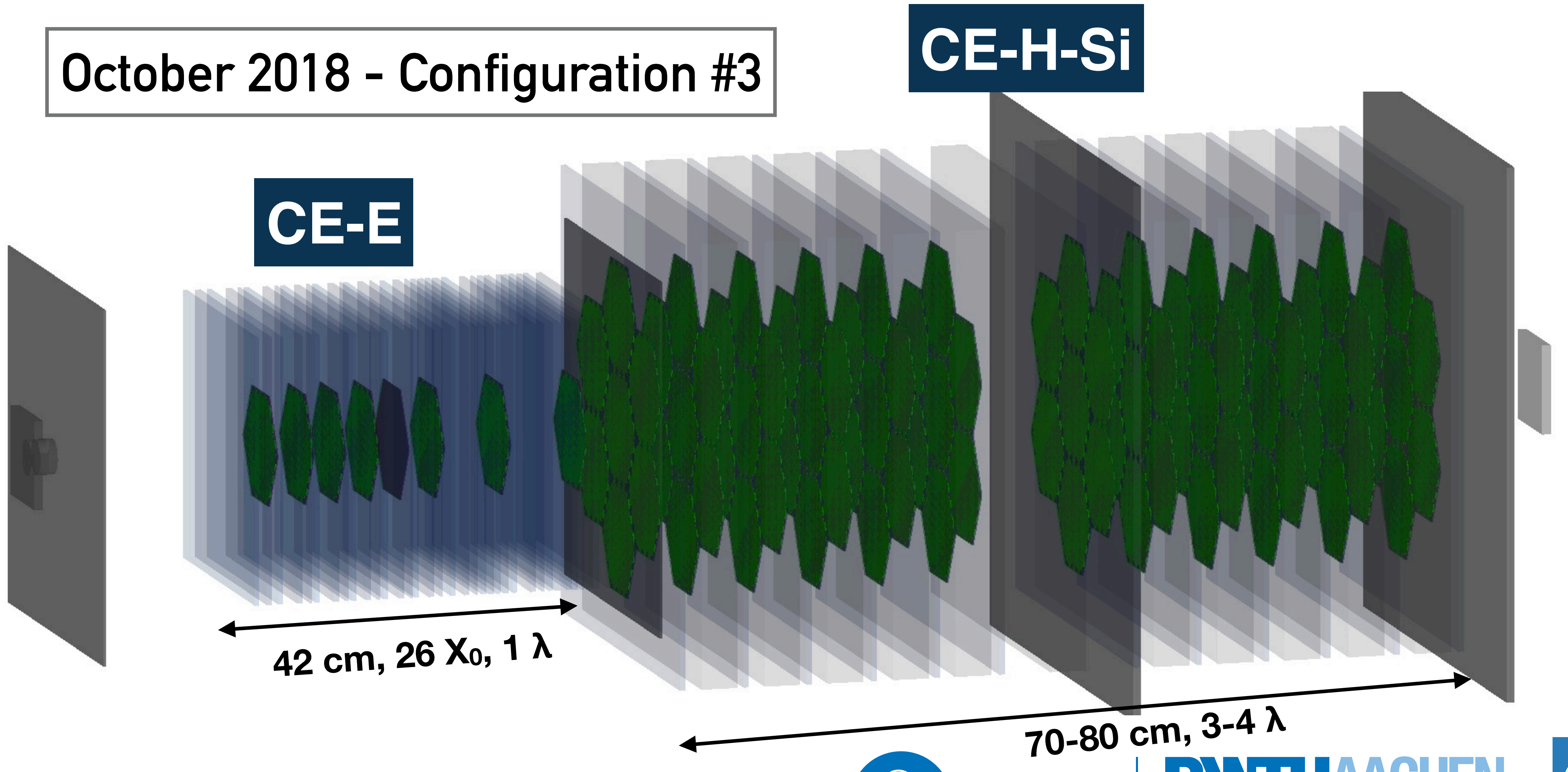


October 2018 - Configuration #2



few hours!

October 2018 - Configuration #3



Joint beam test efforts with CALICE - AHCAL

- **28-layer CE-E setup**

+12-layer CE-H-Si setup (94 modules)

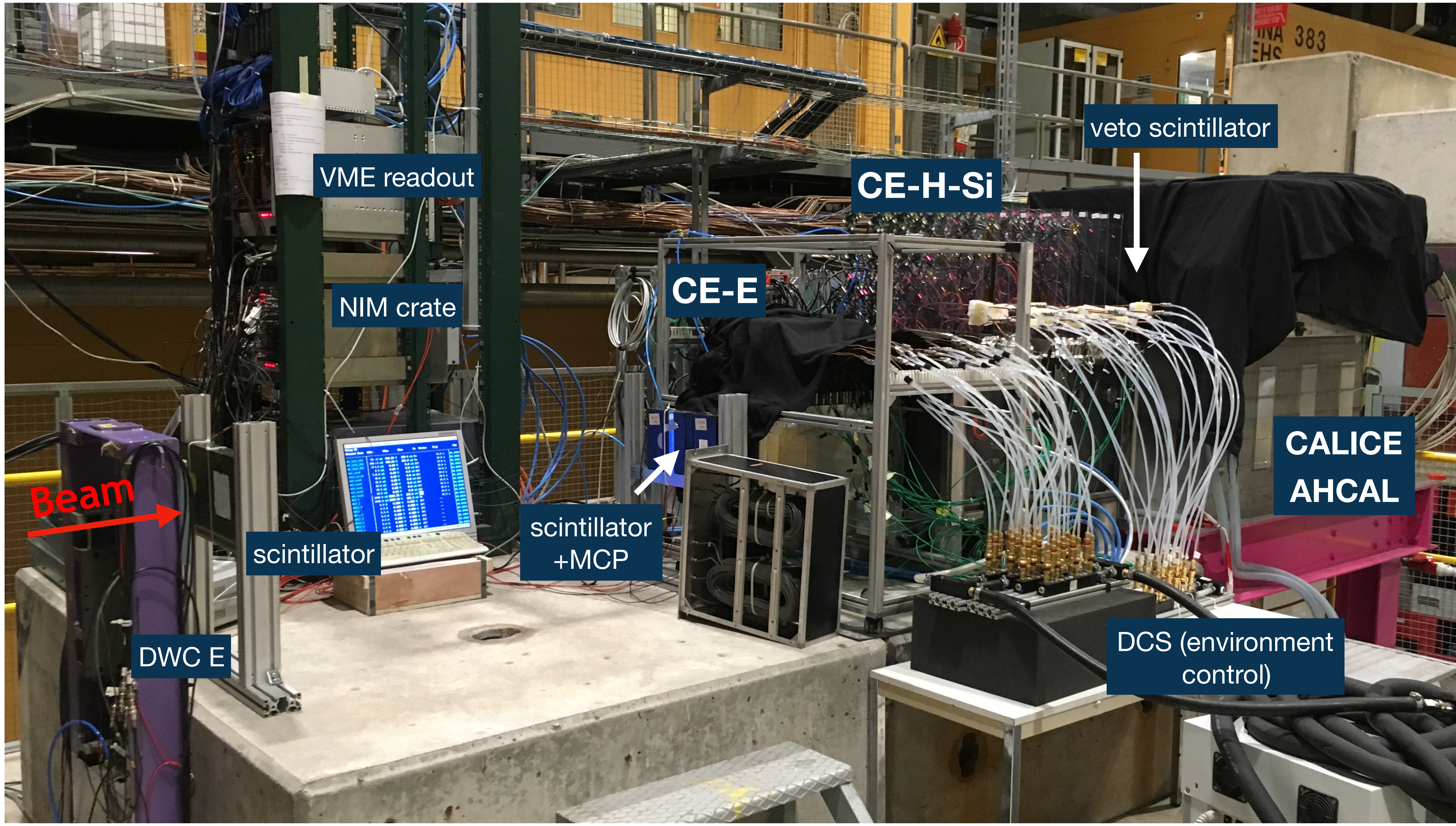
- 3 configurations tested

- Environmental control
- Delay Wire chambers
- Threshold Cherenkov counters
- MCPs for timing
- CALICE - AHCAL

- **e, μ, hadrons up to 300 GeV**
- Trigger: 2x scintillators in front of CE-E

  + 1x additional (veto) behind CE-H-Si

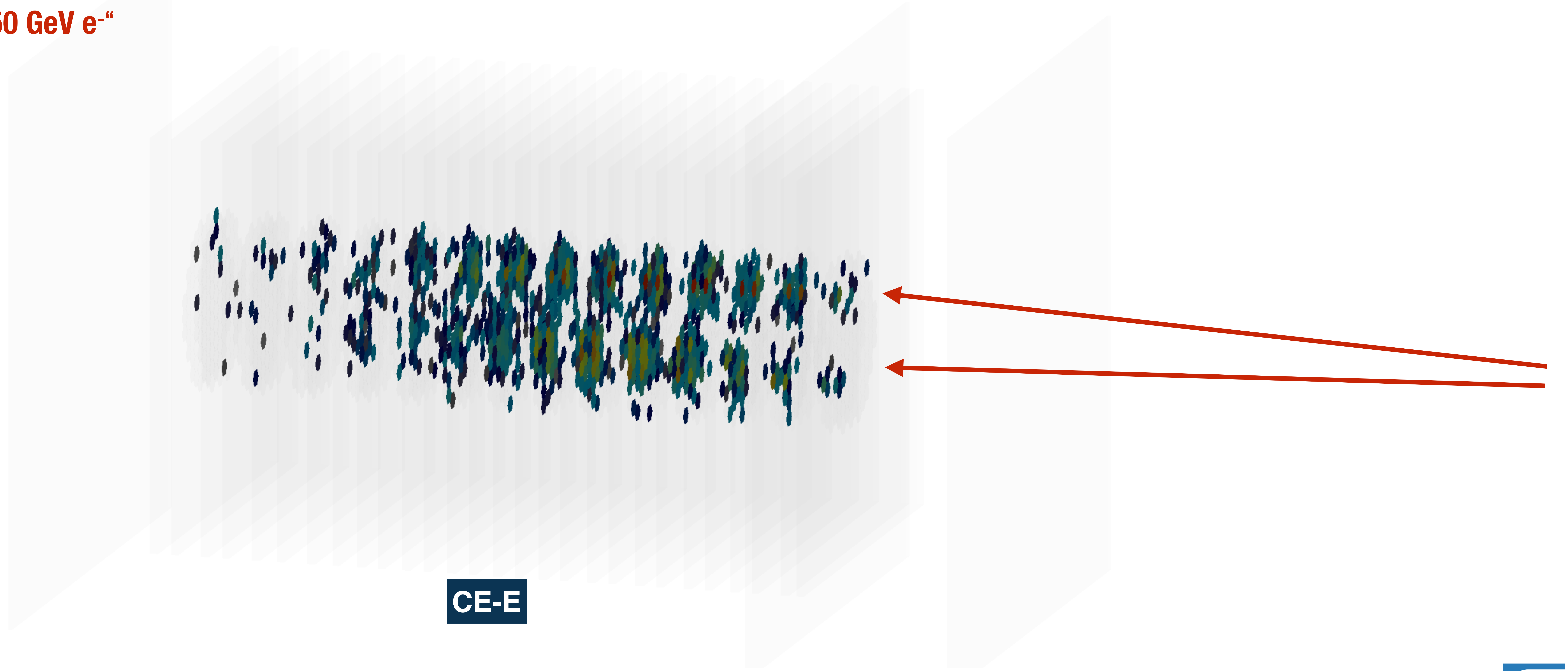
➡ **First large-scale test of O(100) HGCal modules**



HGCAL = Imaging calorimeter

June 2018 run 407 - event 1:

"150 GeV e-"



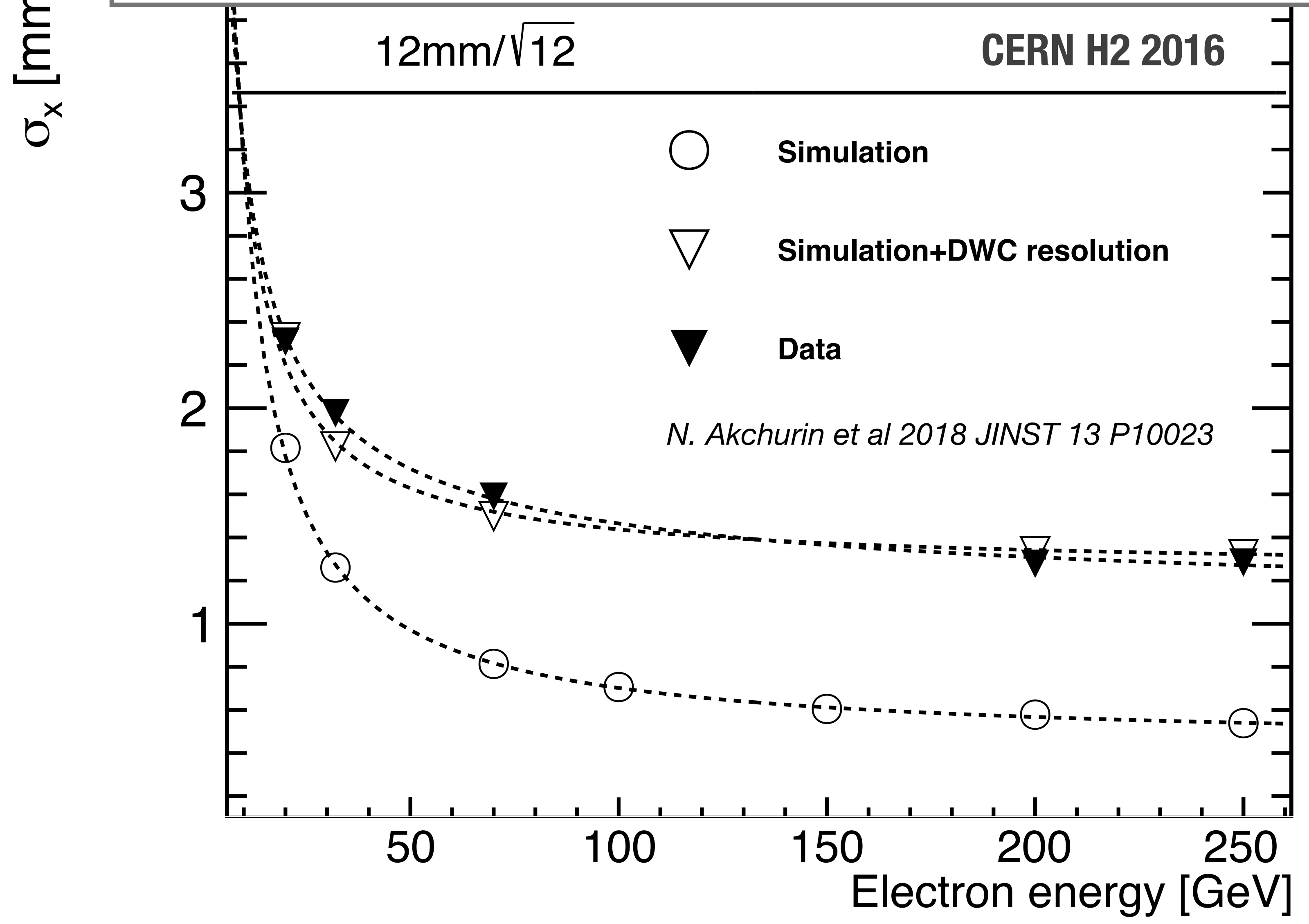
HGCAL = Imaging calorimeter

October 2018 run 517 - event 30:

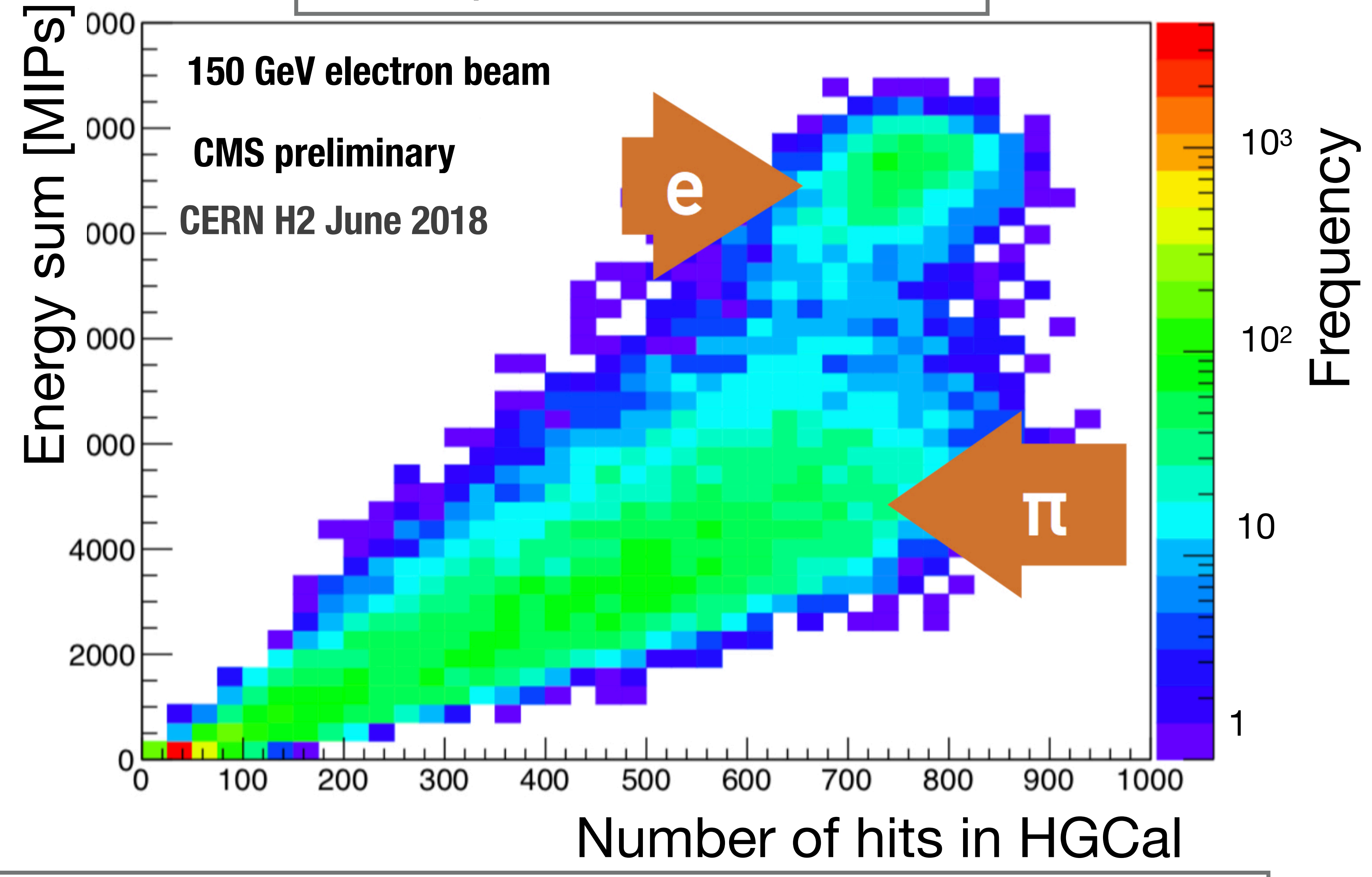
250 GeV π^-

Preliminary beam test results validate the design

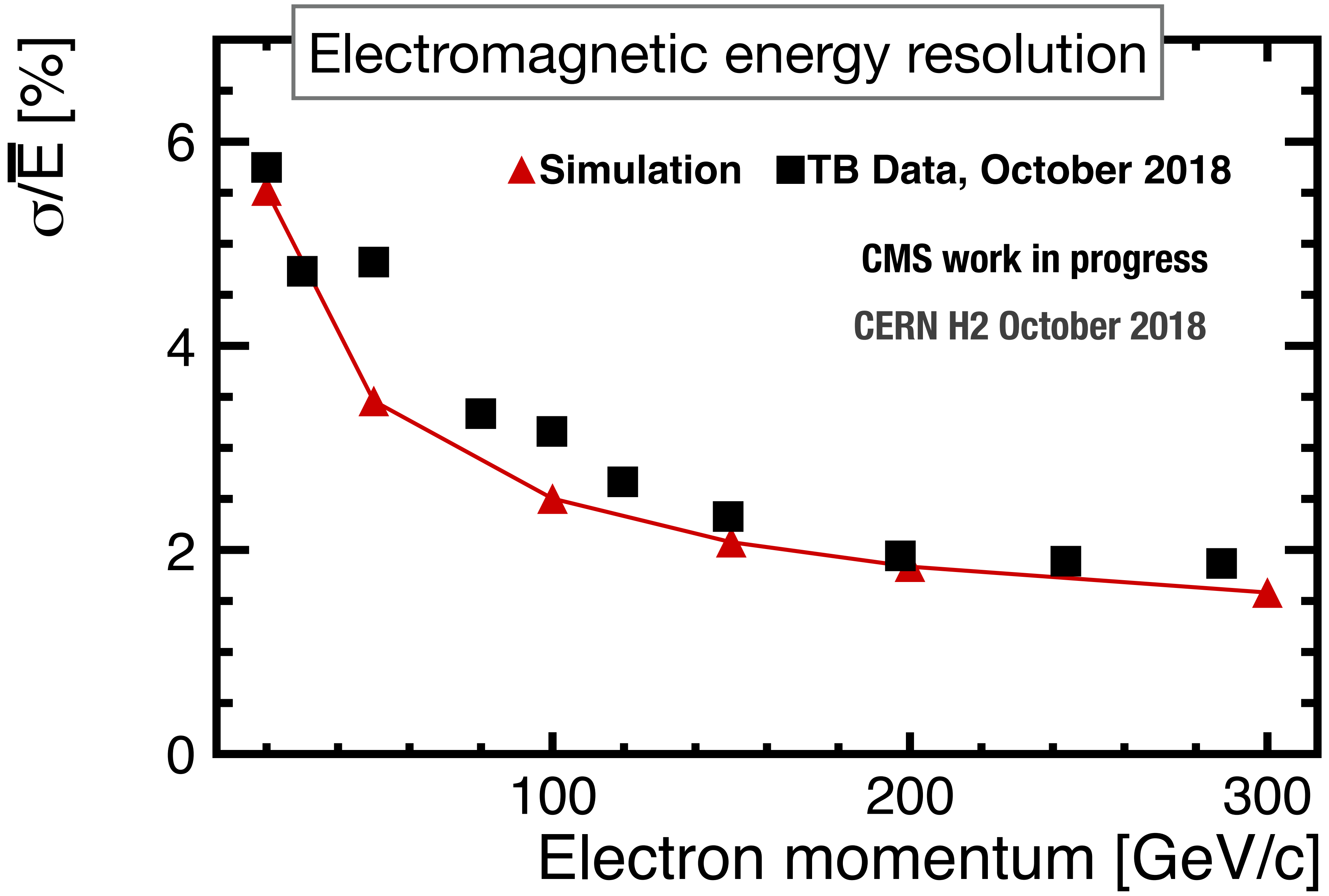
Position resolution for EM showers below 1mm



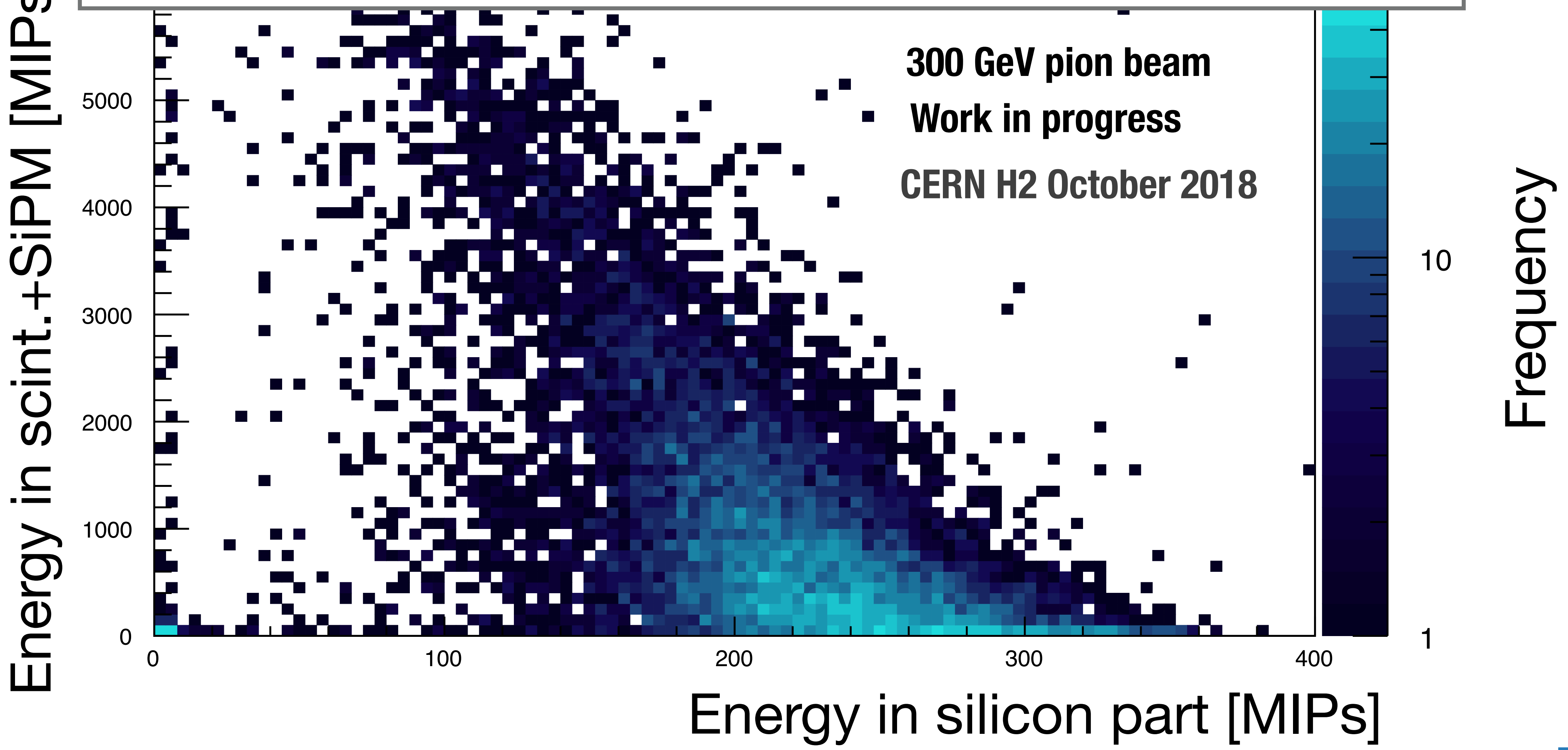
e-π separation with HGCal



Electromagnetic energy resolution



Si & Scint.+SiPM measurements for hadronic showers

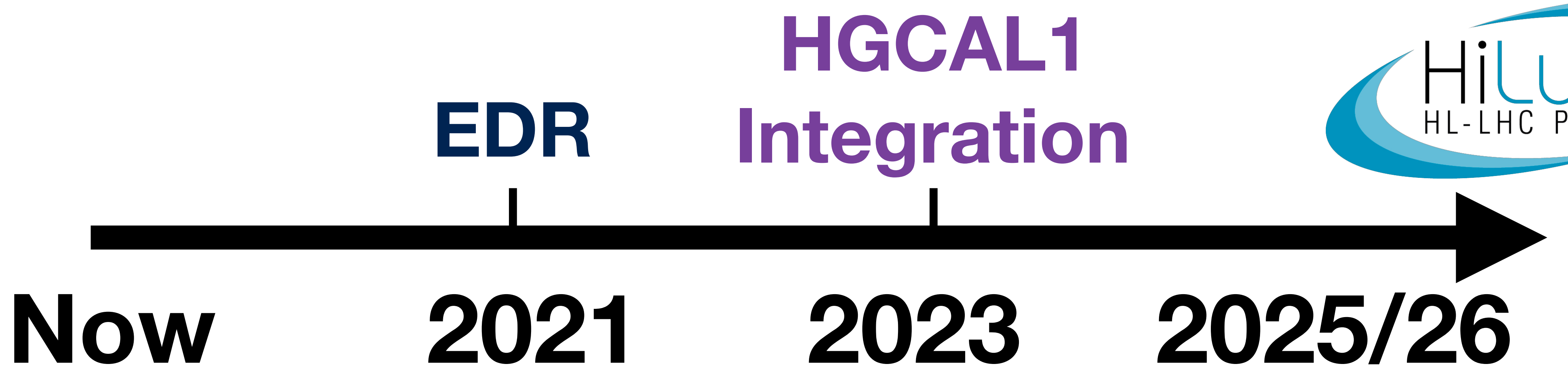


Does the design meet the expectation?

- Yes, it does.

Busy times ahead

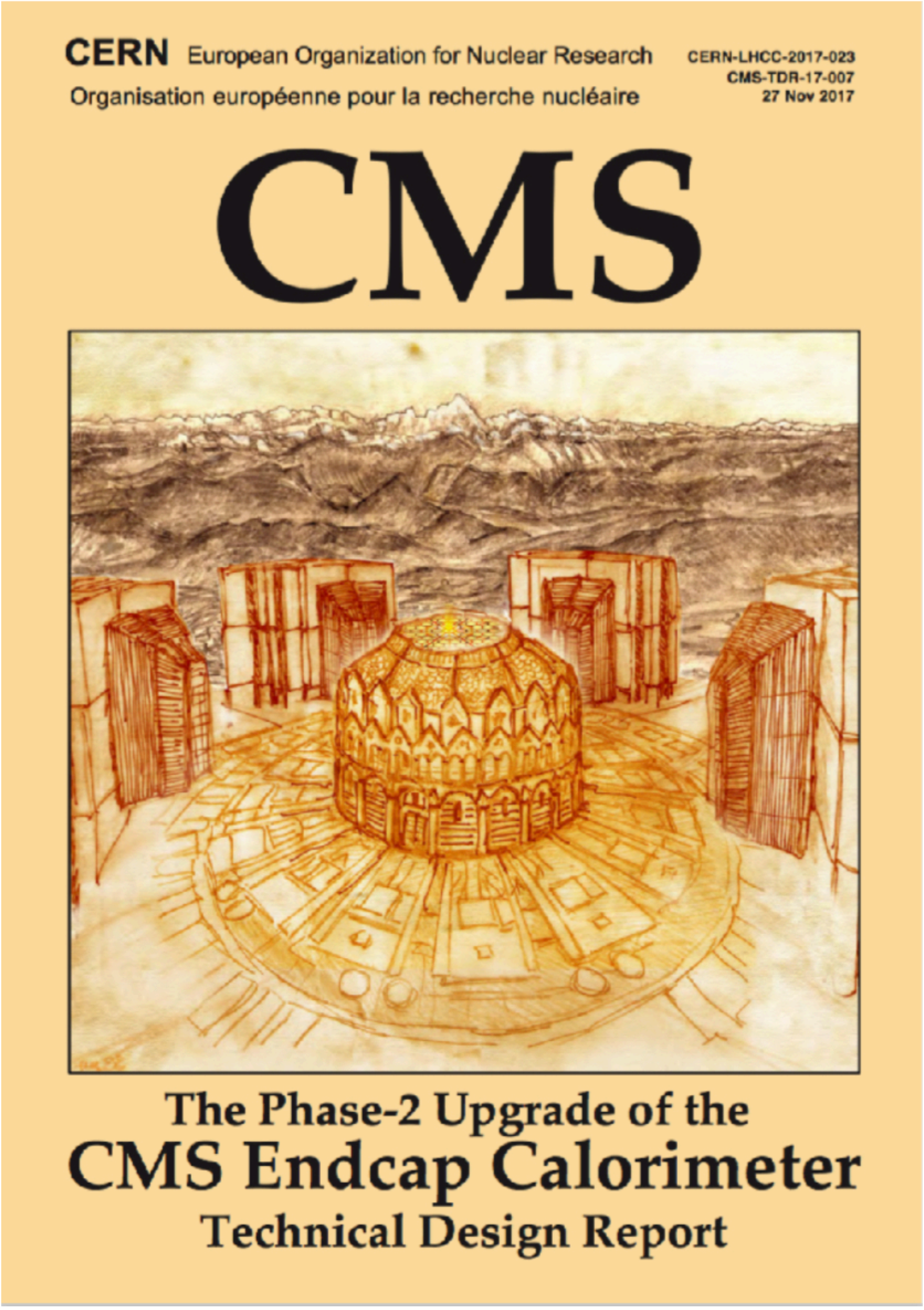
- Important progress since the Technical Proposal and ongoing developments since the Technical Design report
- Next major step: **Engineering Design Review due early-2021**
    - Validation of silicon sensors and SiPMs
    - Final version of very front-end ASIC
    - Si modules and scintillator tileboards designed
    - Cassettes and mechanics design ready
- Production starting in 2021
- Challenges ahead **towards the construction of the first large-scale high granularity calorimeter at colliders**



Summary

High Granularity Calorimeter is an imaging calorimeter inspired by CALICE

- Harsh radiation environment, high pileup & occupancy during HL-LHC
- 3D energy & time measurement of particle showers
- Proof-of-concept through extensive prototyping and beam tests
- Challenging project in terms of mechanical and electrical engineering



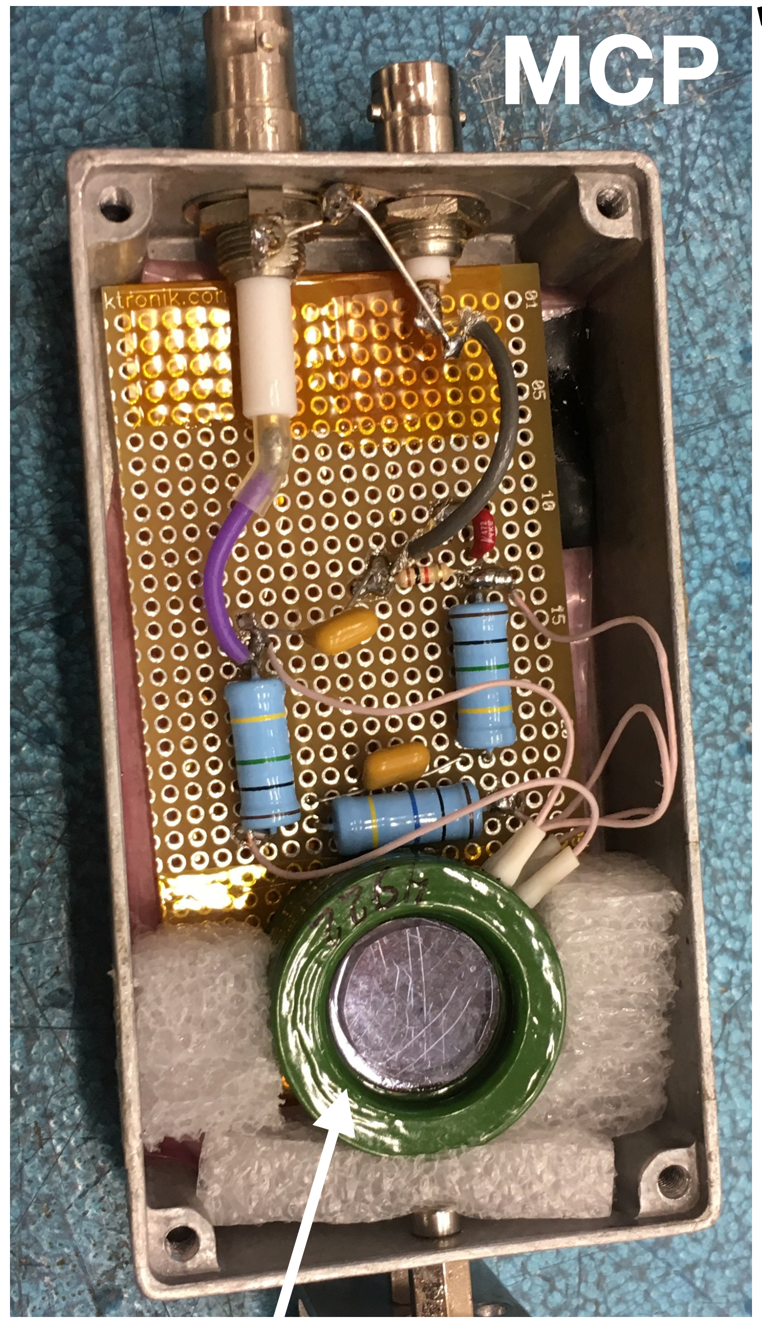
Backup

III. Physikalisches Institut
RWTH AACHEN UNIVERSITY
CERN

Backup

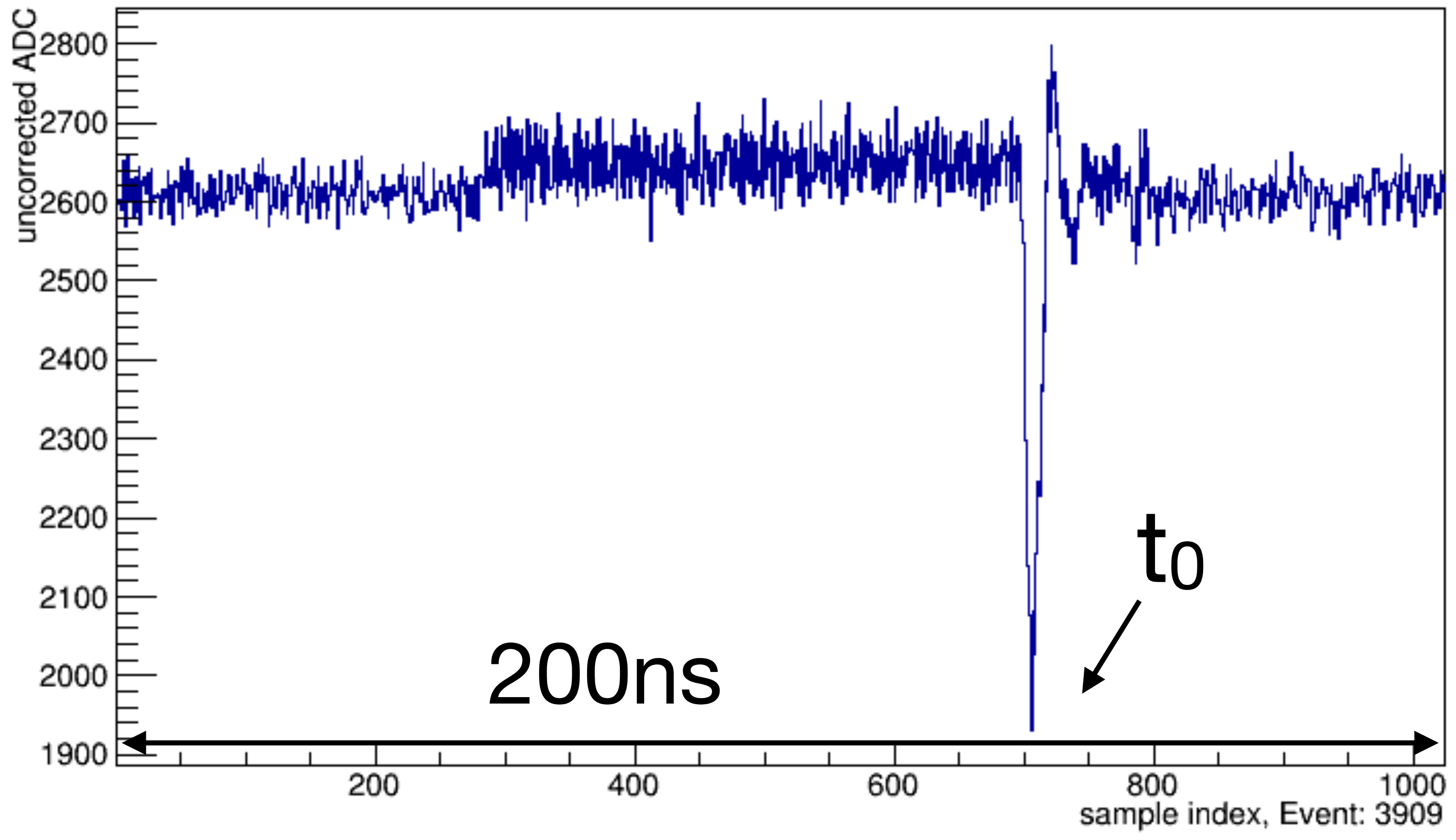
Skiroc2-CMS designed to provide timing resolution of 50ps

- 2 MCPs for O(10ps) t_0 measurement installed in front of CE-E



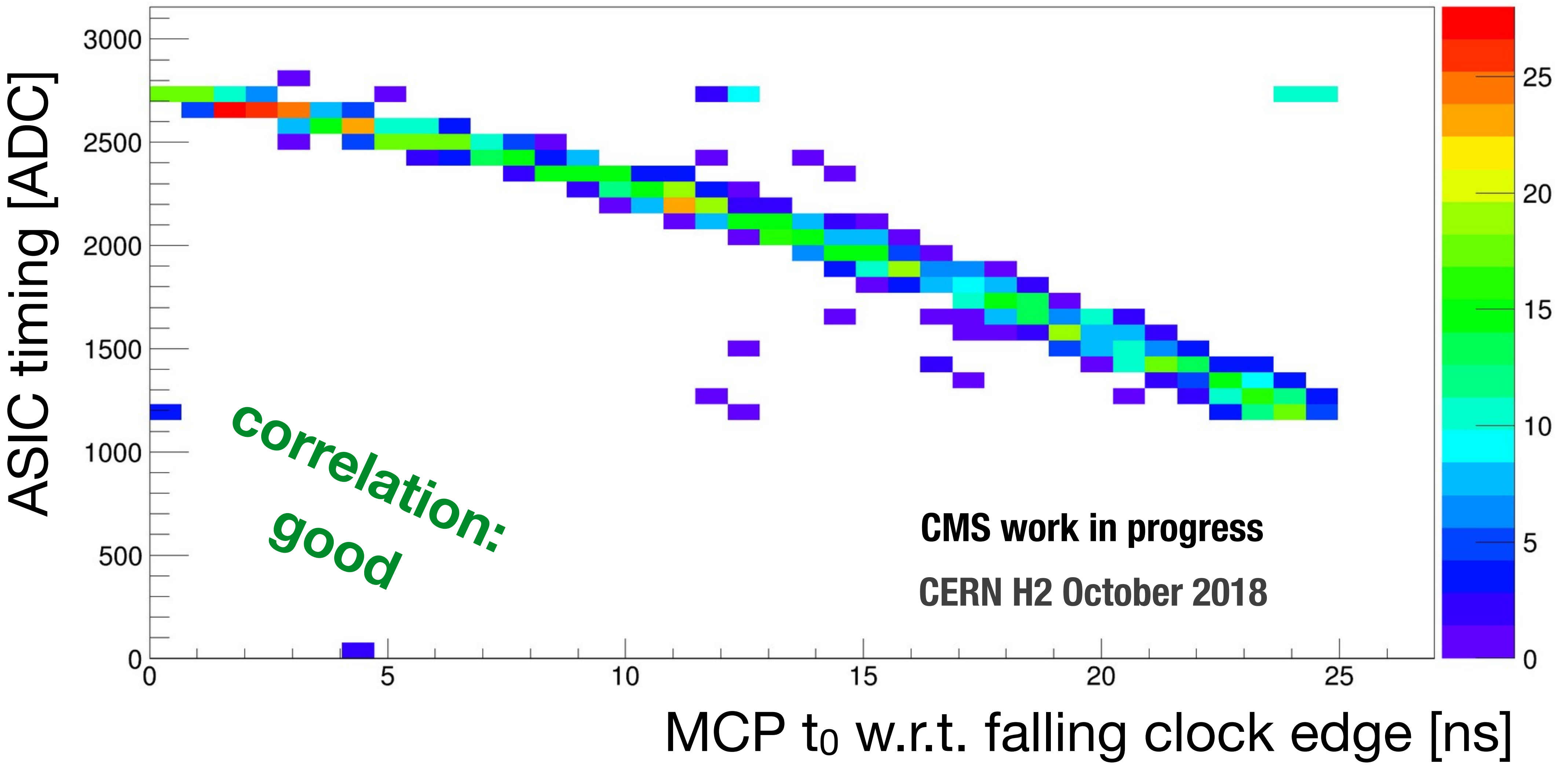
sensitive area (~1cm²)

Digitised MCP Waveform



waveform analysis for many events

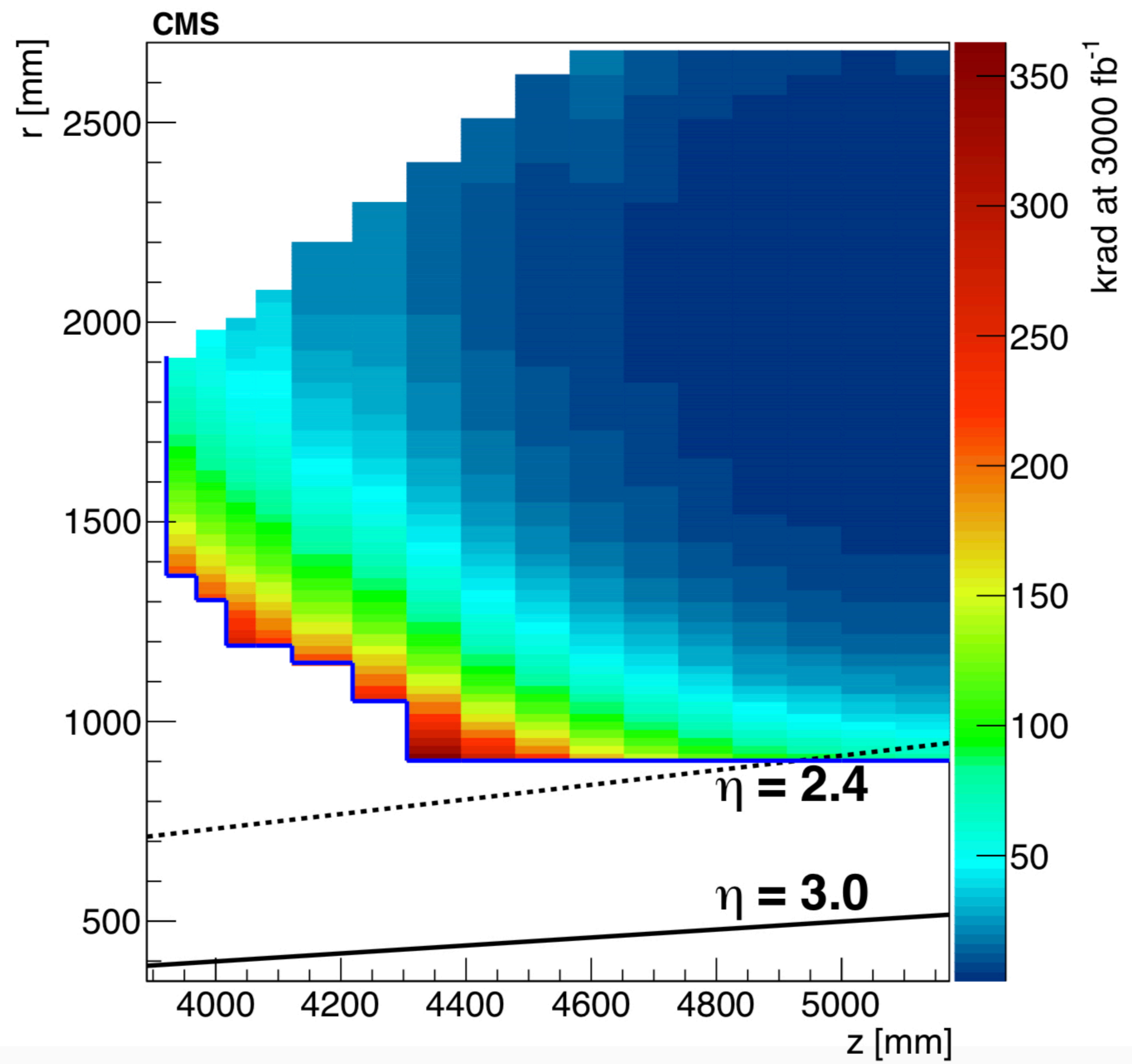
MCP-t_0 correlation to HGCal ASIC timing

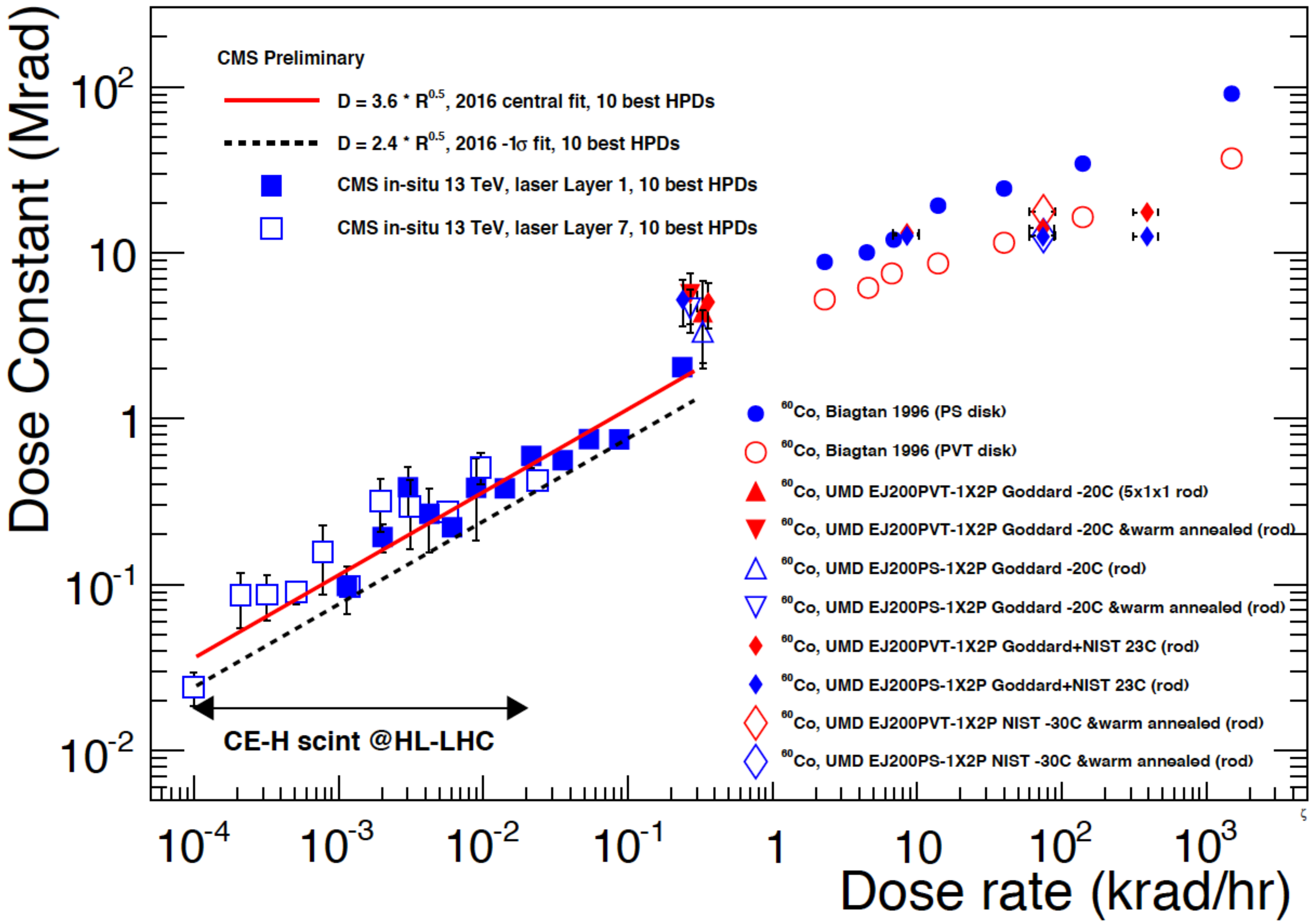


➡Facilitated: Timing calibration

➡**Possible: Unbiased measurement of timing resolution**

Backup





III. Physikalisches Institut RWTH AACHEN UNIVERSITY

Scintillator Studies

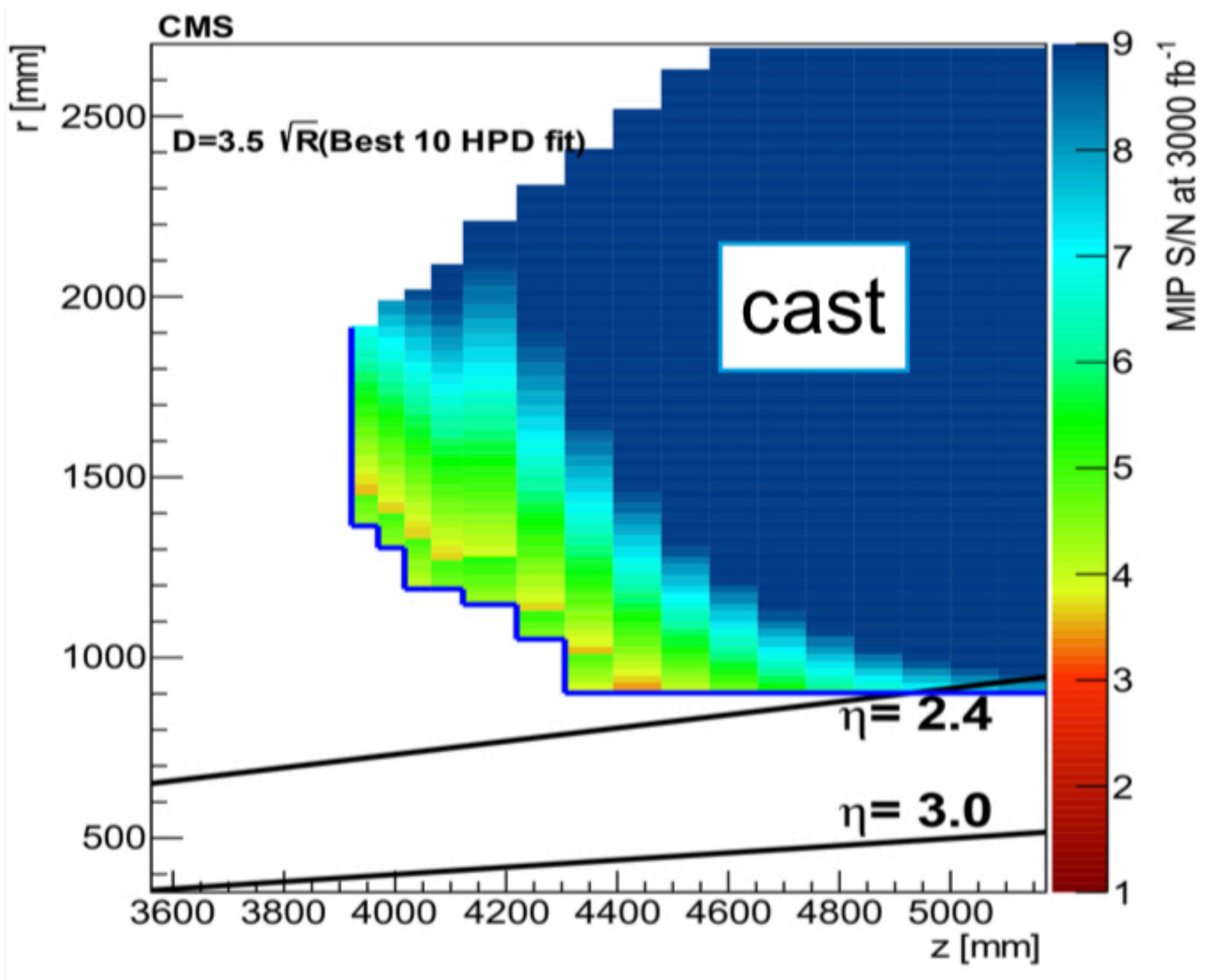
Material selection and wrapping

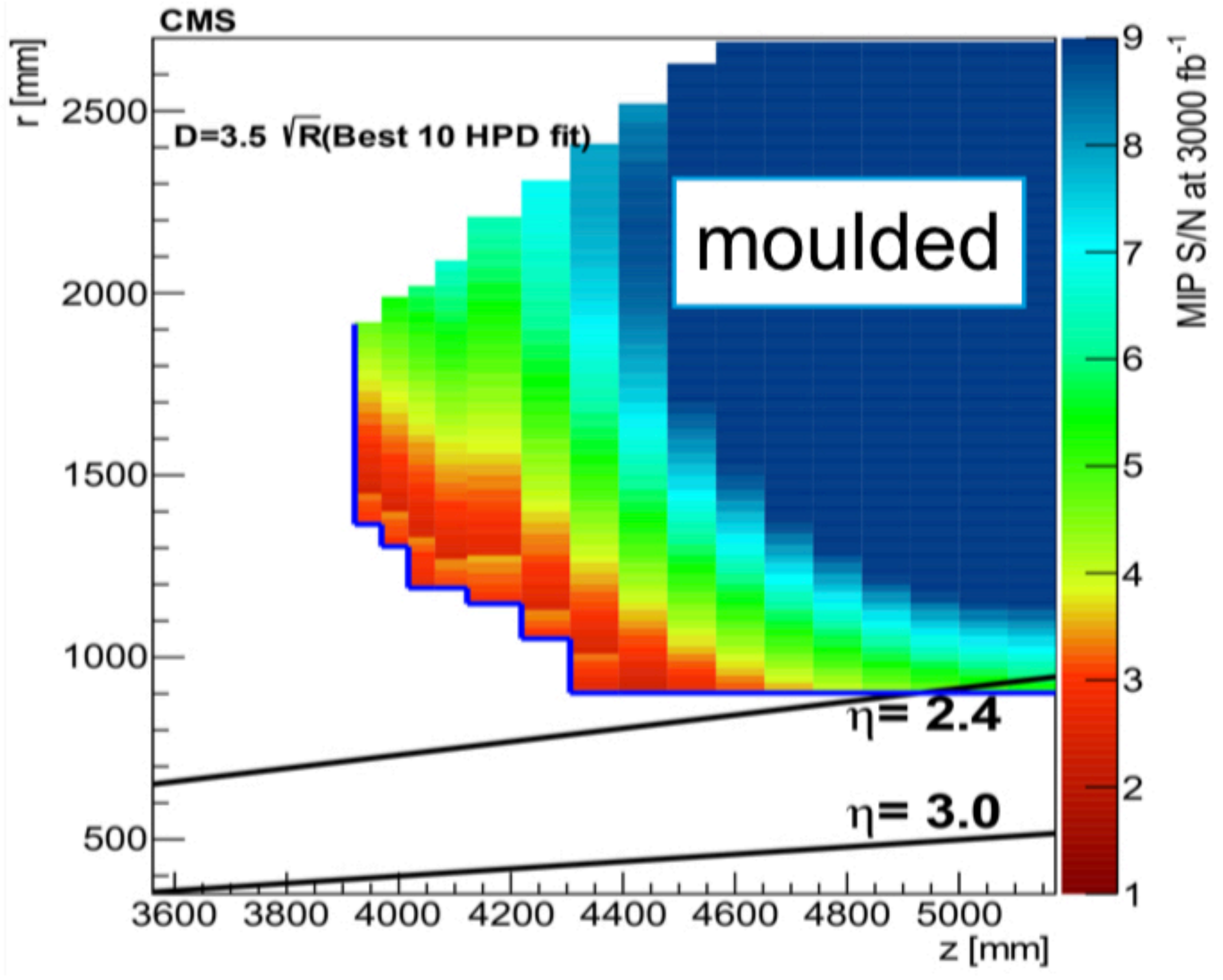
Active R&D area, many experienced groups

- USA : Fermilab, FSU, NIU, Rochester, TTU, UMD
- Russia and Dubna Member States

Material selection

- **Cast:**
  - PVT-based: more expensive, more machine time
  - EJ-208 proposed as baseline
- **Injection-moulded:**
  - PS-based, less machine time & labour, cost is in the mould
  - lower light yield in past experience
  - can be used in most of the detector
- Extruded is ruled out





Felix Sefkow, 31 Jan 2019

Irradiation Studies

On the way

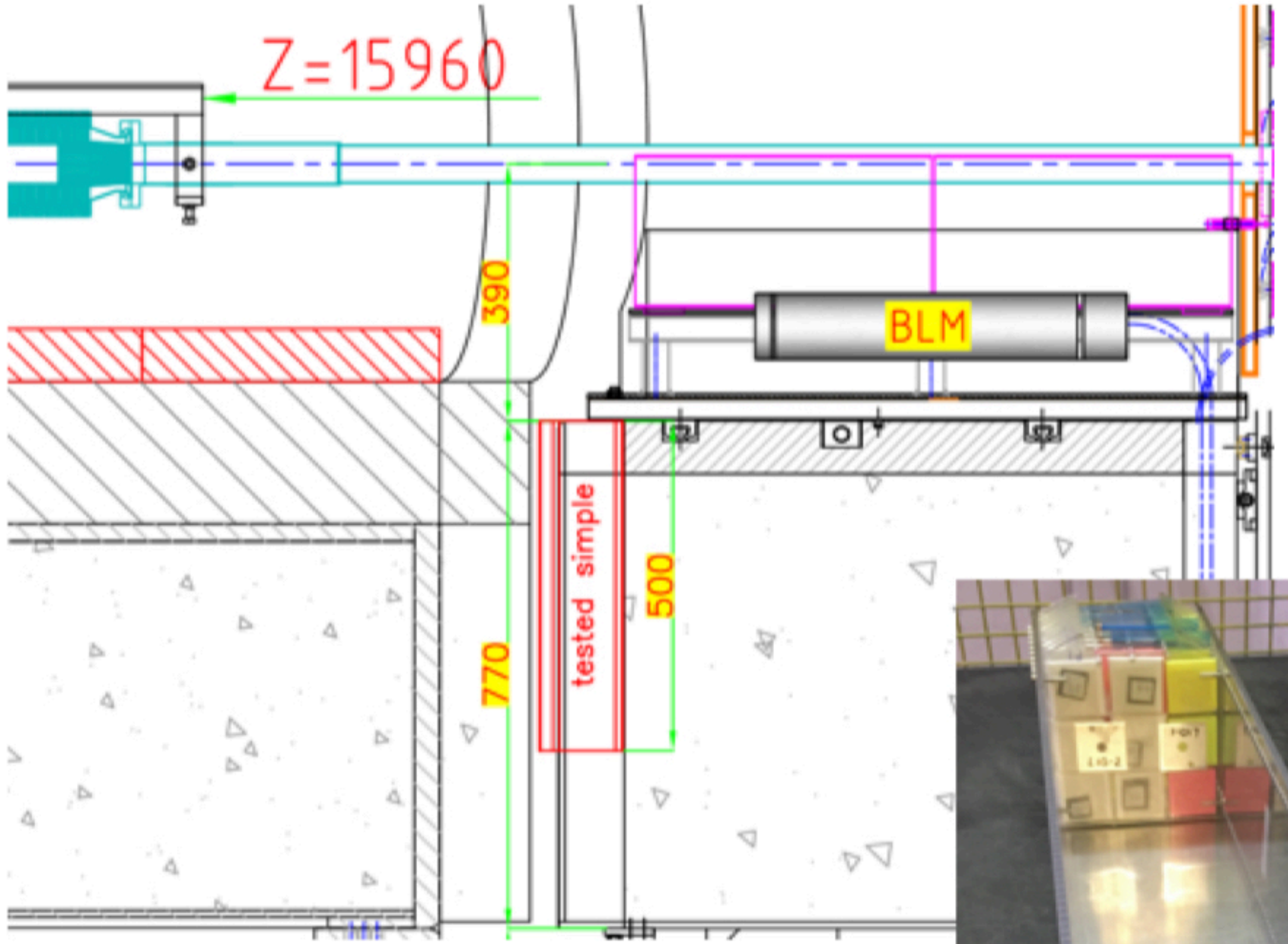
Felix Sefkow, 31 Jan 2019

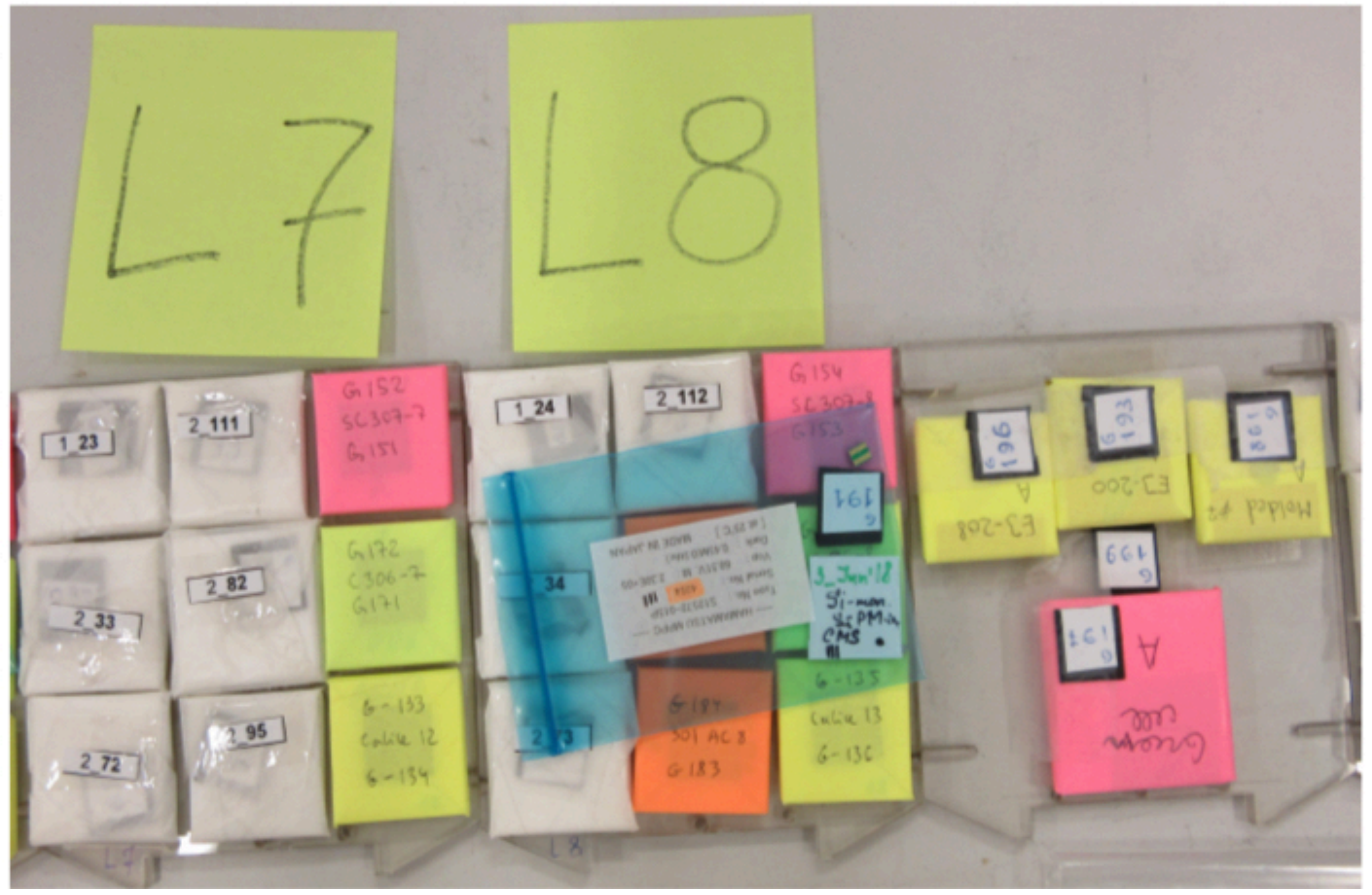
CASTOR Radiation Facility

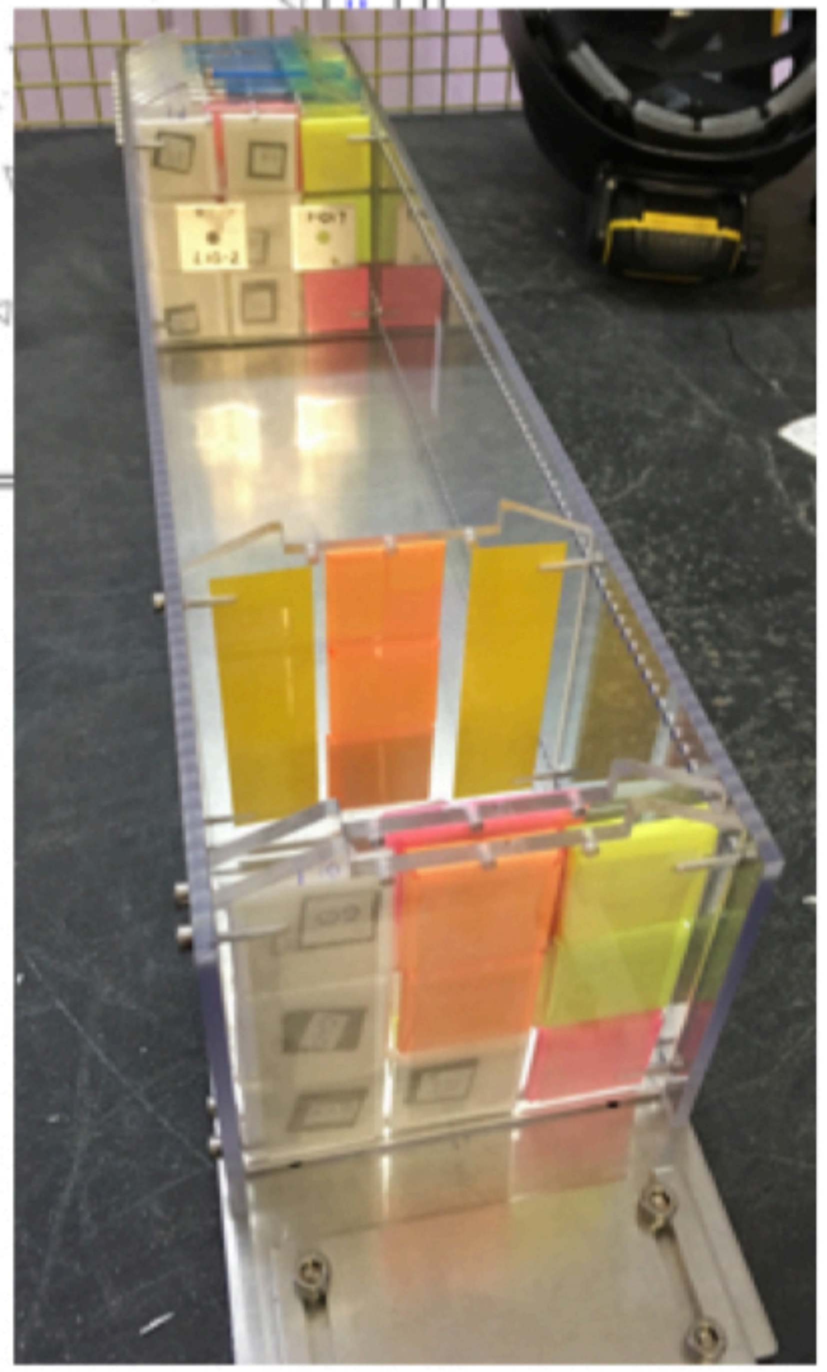
- 46 fb^{-1}, 6 months
- P. De Barbaro, with Dubna, Protvino
- large variety of materials and doses in 2018
- analysis ongoing, results in spring

Reactor-based

- T.Edberg, with UMD, NIU
- **Goddard: cold irradiation (- 20 ^{o}C)**
  - 1.5 Mrad at 0,3 krad/h
  - variety of sizes and materials
- **NIST**
  - EV-200 doped with anti-oxidants
- recently, analysis ongoing







Backup

Tileboard Thermal Tests

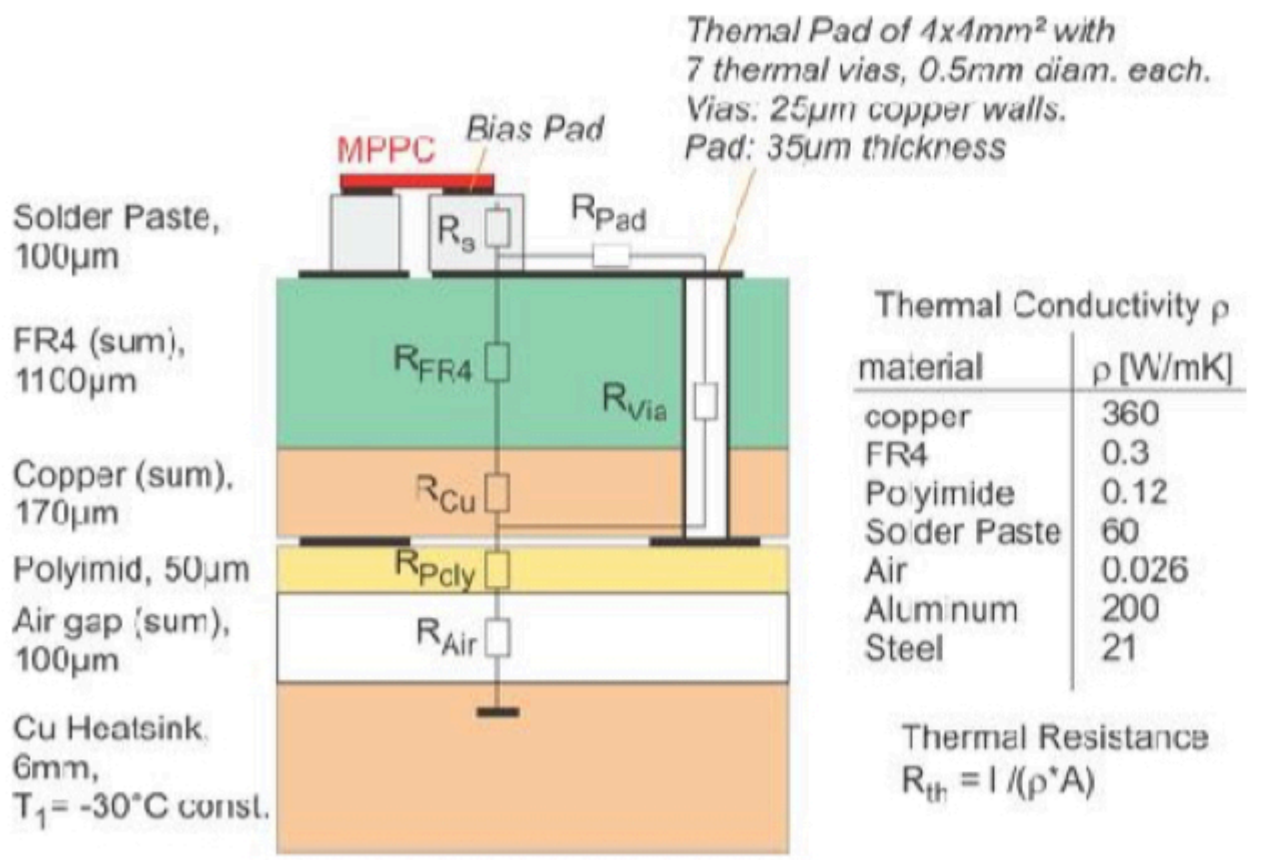
Mixed Cassette Mockup Effort at Fermilab

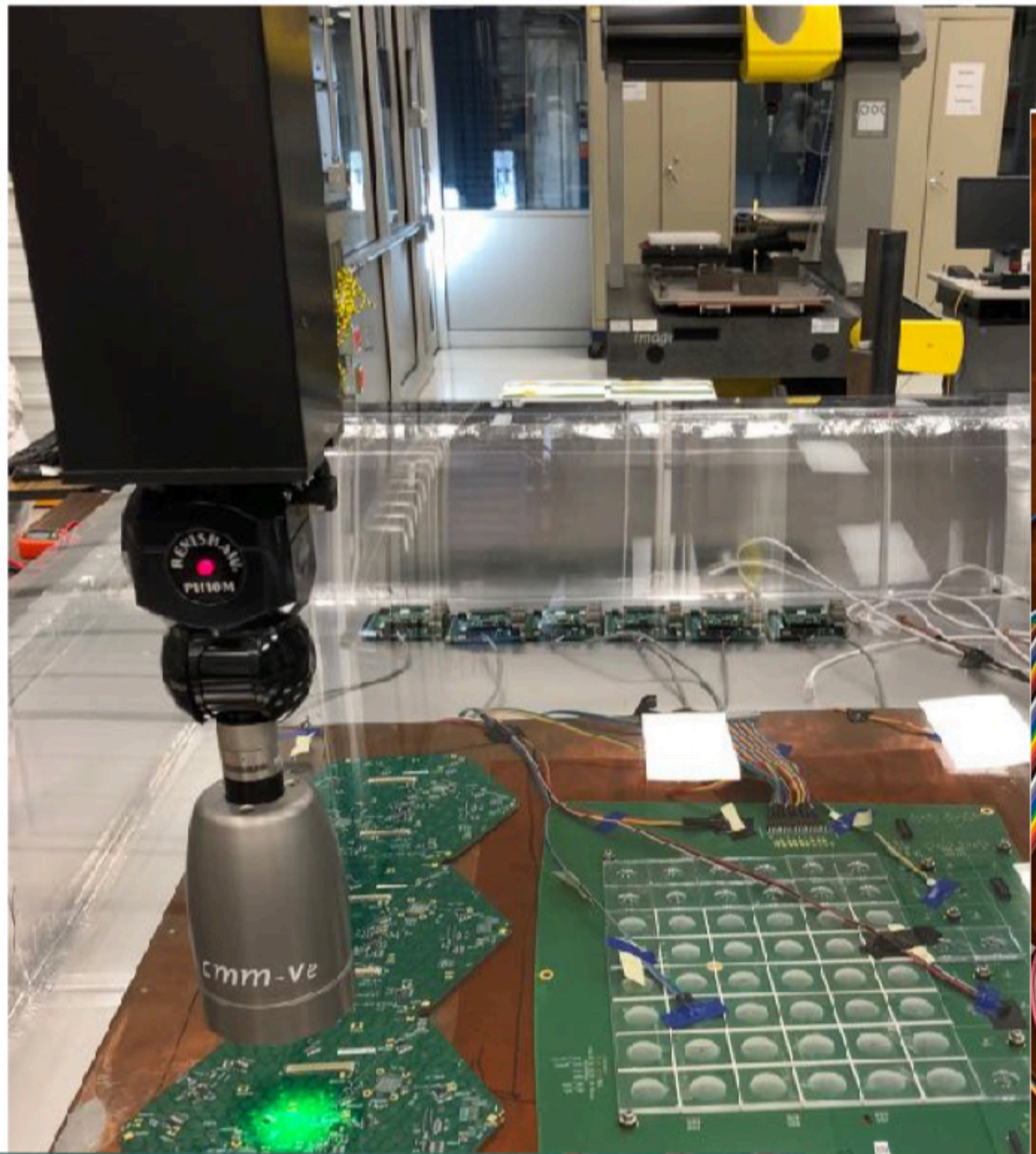
Felix Sefkow, 31 Jan 2019

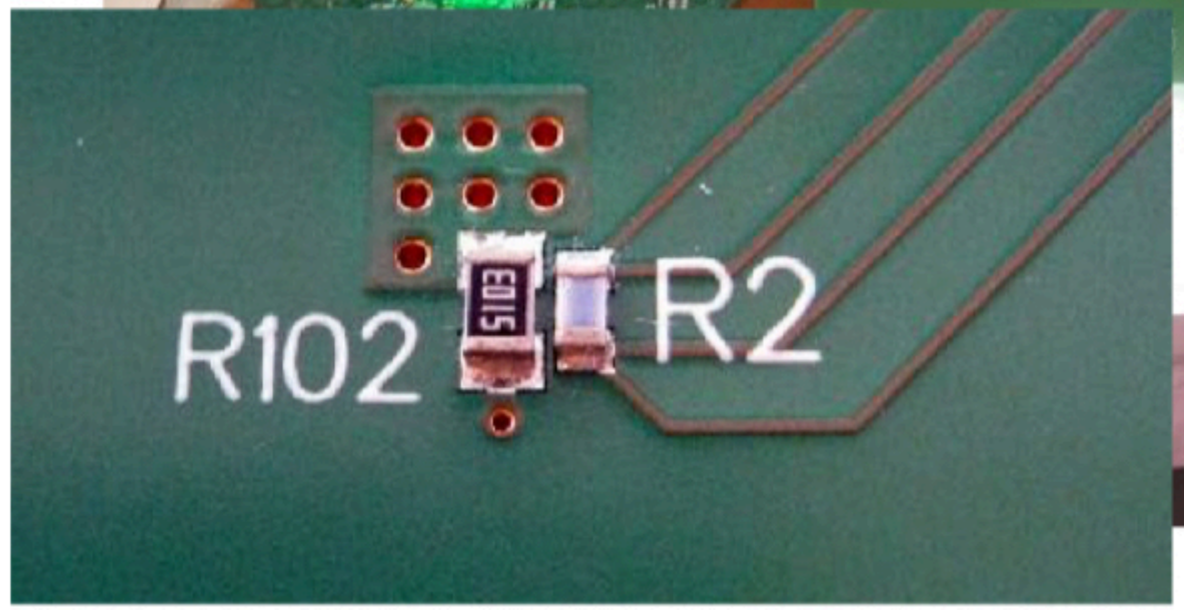
Thermal teststand at Fermilab

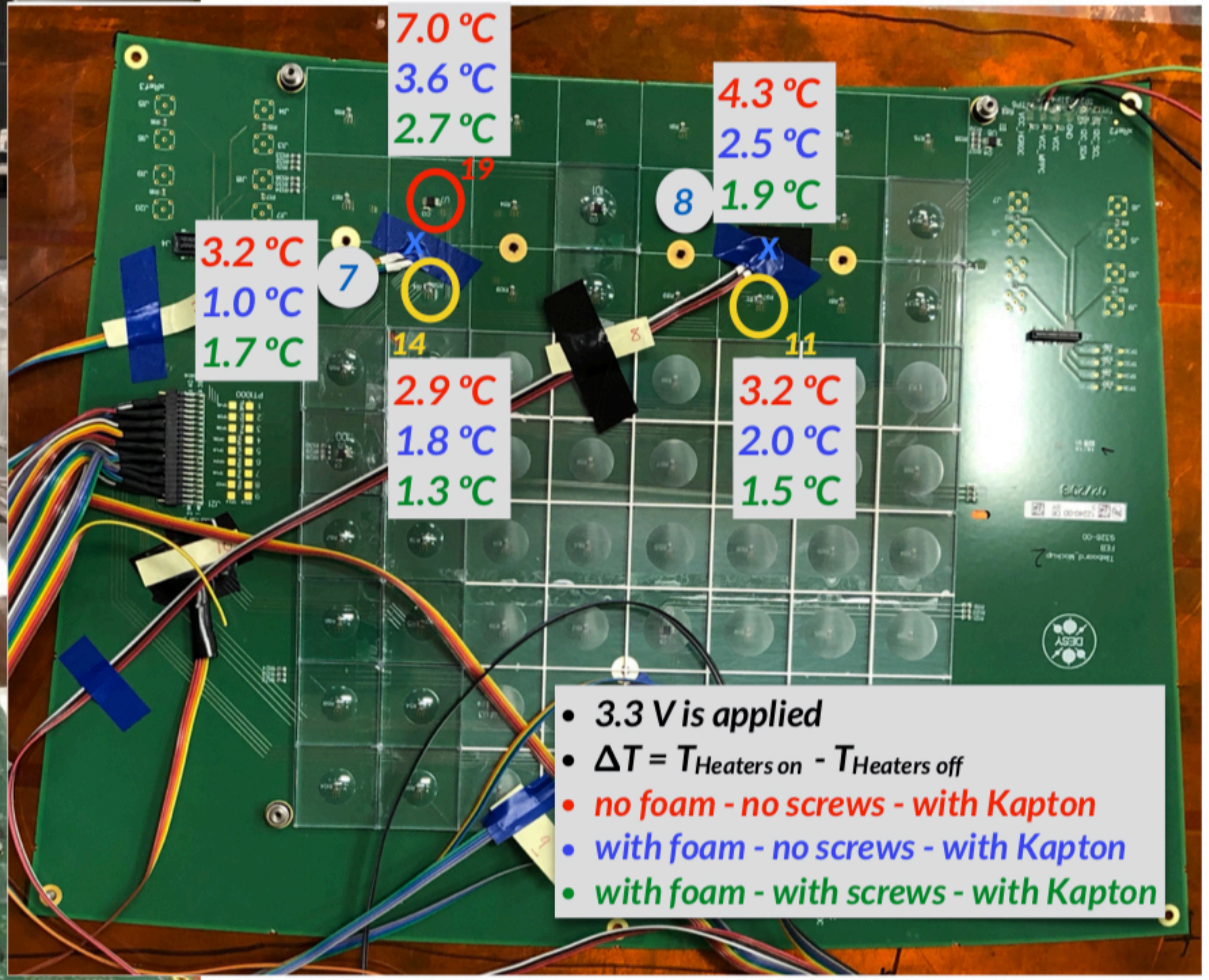
Mock-up tileboard (DESY):

- Full cycle to -30°C ✔
- validate SiPM cooling through PCB using thermal vias
- max increase with load: 2K
- no strong gradients
- heat conductance bottleneck: contact to cooling plate (100 K/W)









III. Physikalisches Institut
RWTH AACHEN UNIVERSITY