Detector performance studies for the CMS High Granularity Calorimeter

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On behalf of the CMS Collaboration

CERN

Why beam tests? Can we not just simulate?

TARGETS of the HGCAL test beam team:

- Validate the overall conceptual design of the HGCAL - i.e. can it be built similar to the original Technical Proposal and does it work as planned?
- Compare the measured performance of the prototype systems with GEANT4-based simulation
- Start to build a team of people who will be able to follow the design, development and construction of the new calorimeter

Beam tests are critical to test the performance of devices and **tune/validate the simulations*** particularly for hadron calorimeters

*here "the simulations" means the geometry description and use of appropriate physics list etc. (Rong-Shyan Lu)

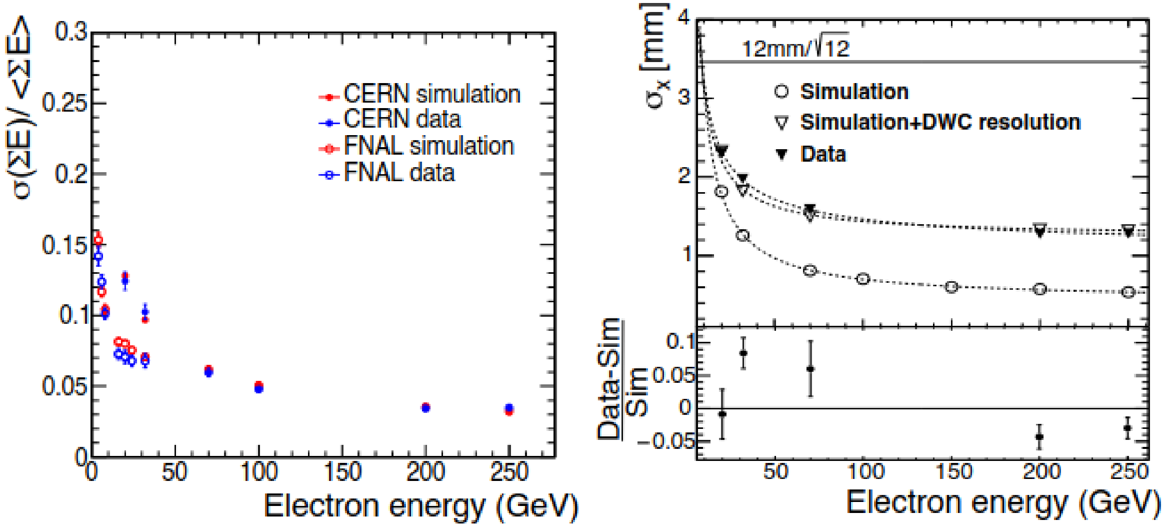
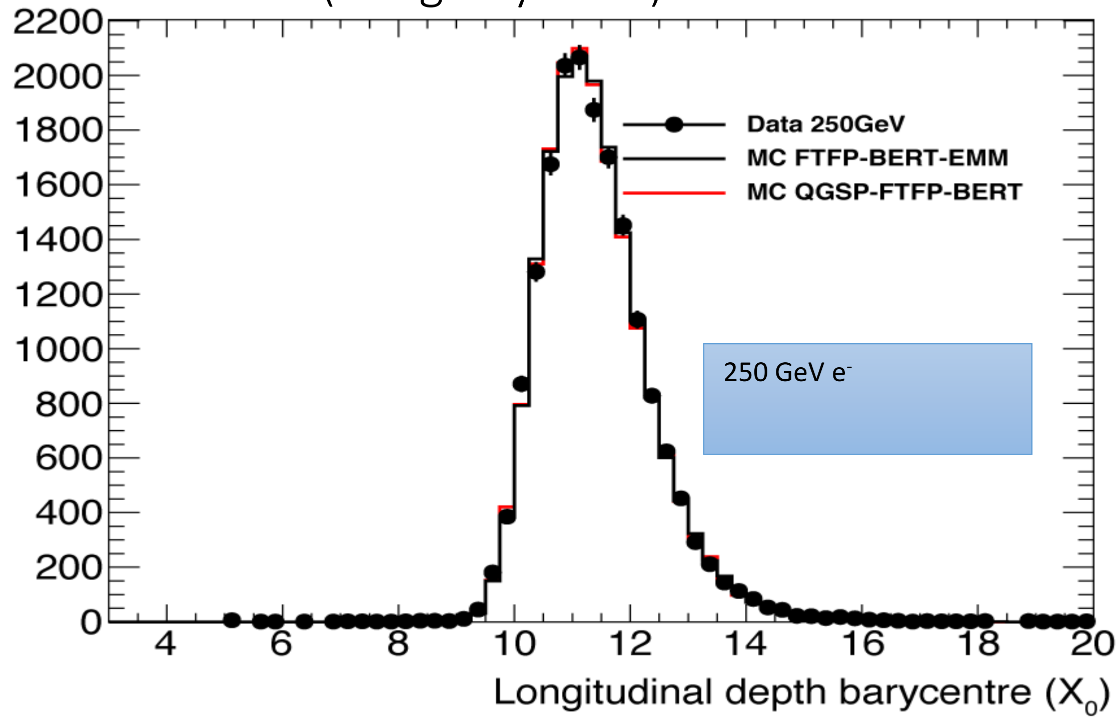
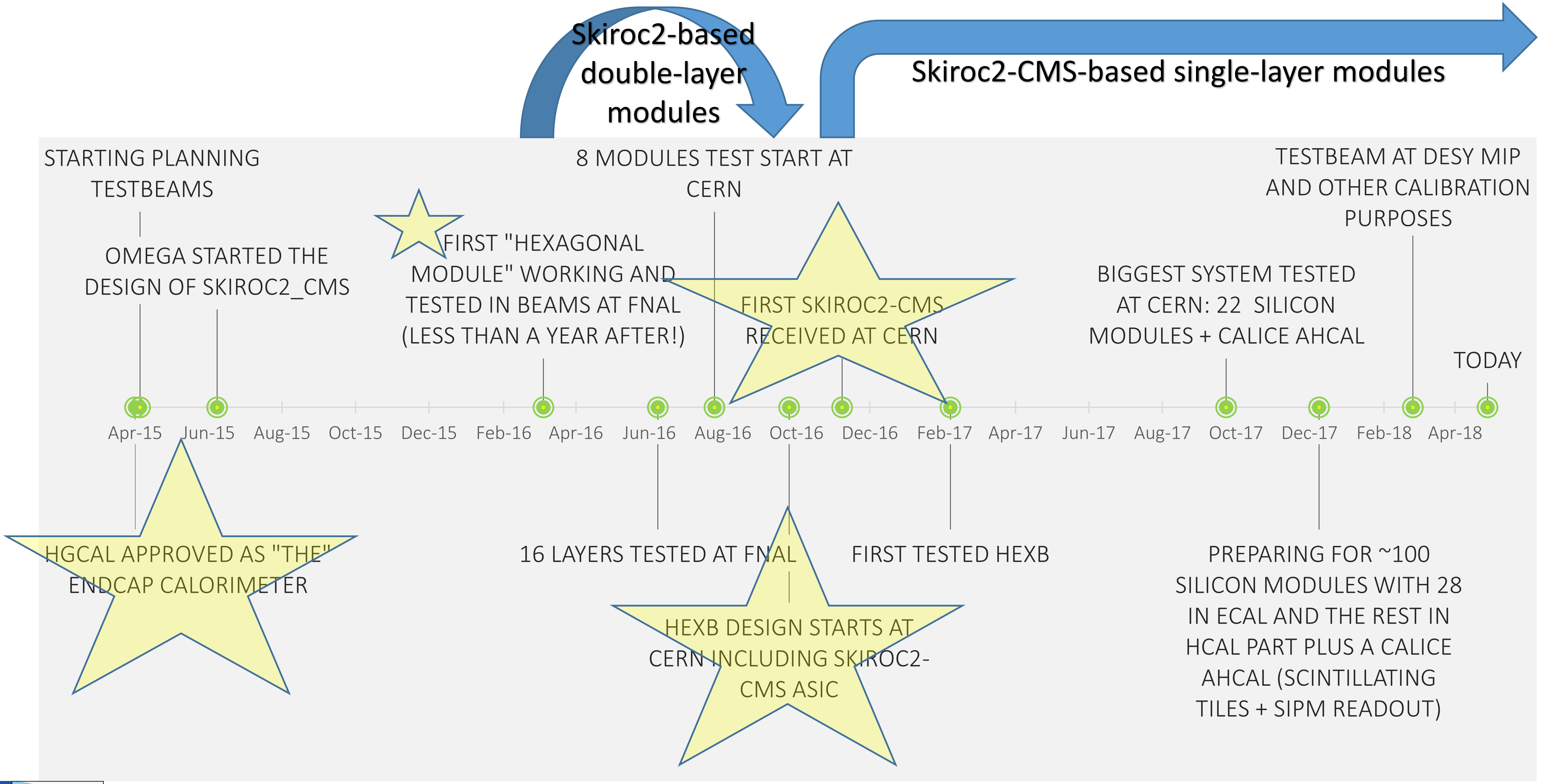


Figure 5.21: Energy and position resolution: (left) relative energy resolution as a function of the electron energy in data and simulated showers, for test beams at FNAL and CERN; and (right) residual width of the x-coordinate reconstruction at a depth of 6 X_0 as a function of incident electron energy.

CMS HGCAL Beam tests
Results from 2016 & 2017

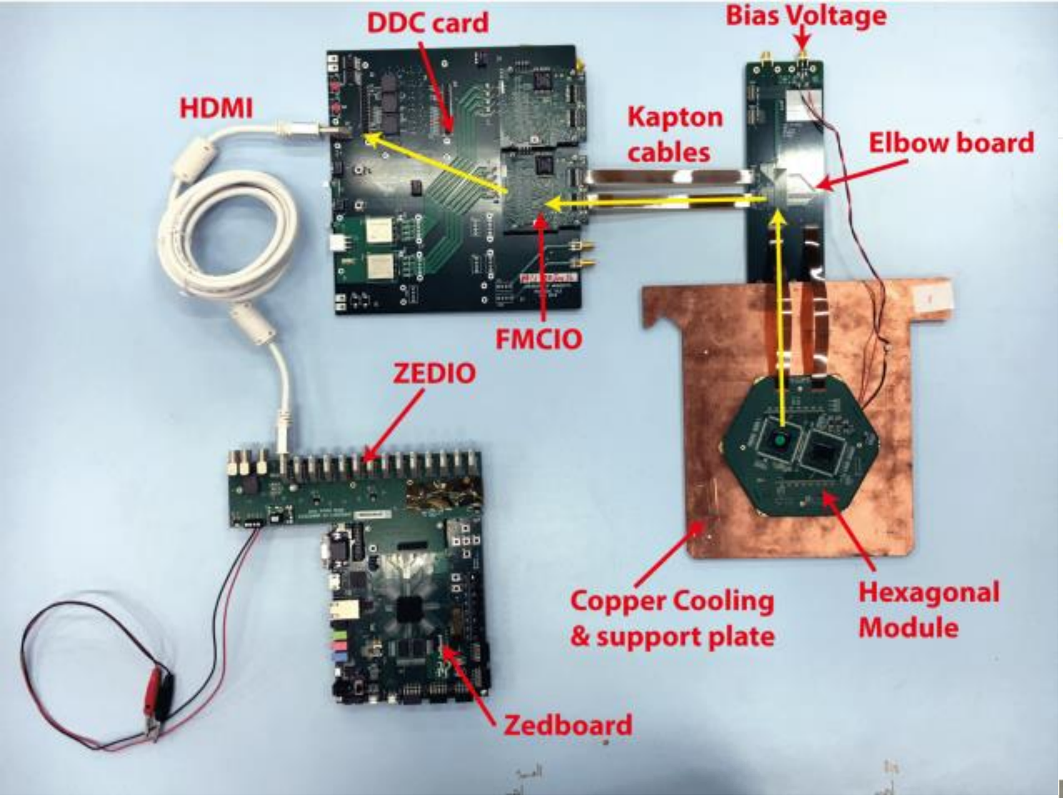


Major beam/system-test related milestones in the HGCAL project



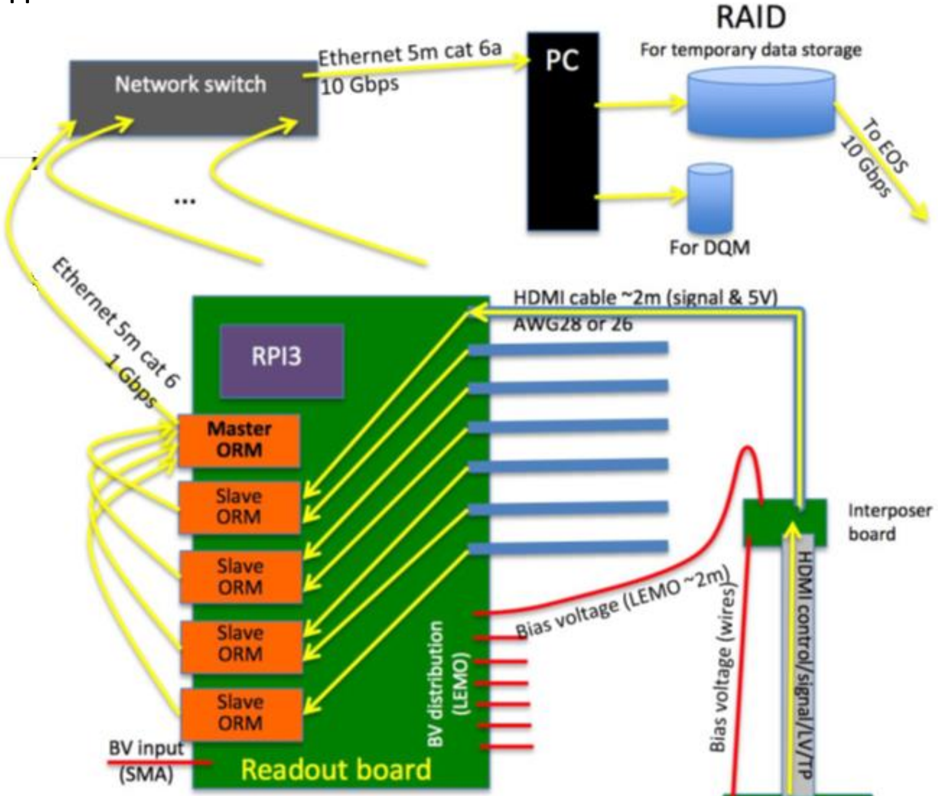
Two iterations of the electronics chain for beam tests

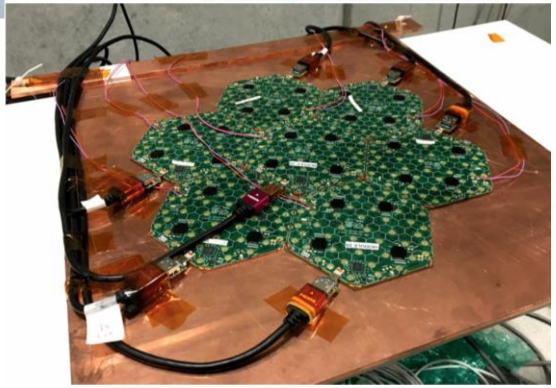
still on going, and not related with the final system



Readout system in 2016

Fast deploy system (mix of market electronics with ad-hoc design)
Know-how generation, training people and prepare the rest of the system (mechanics, electronics, SW, facilities…)

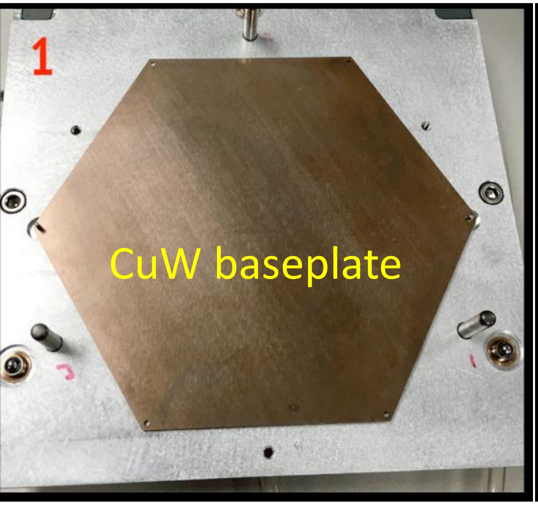


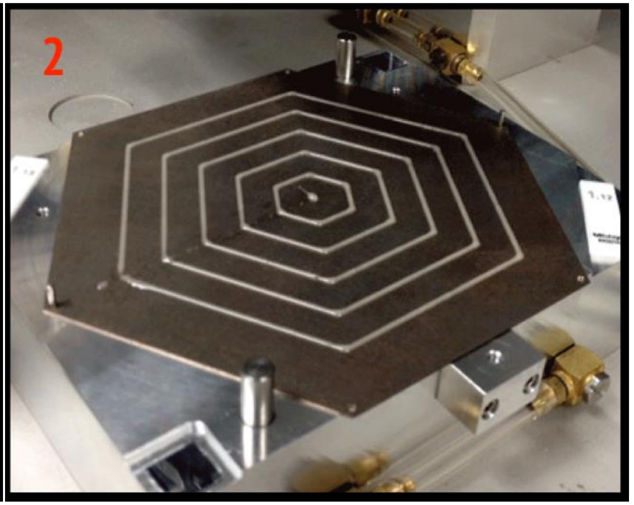


Readout system from 2017

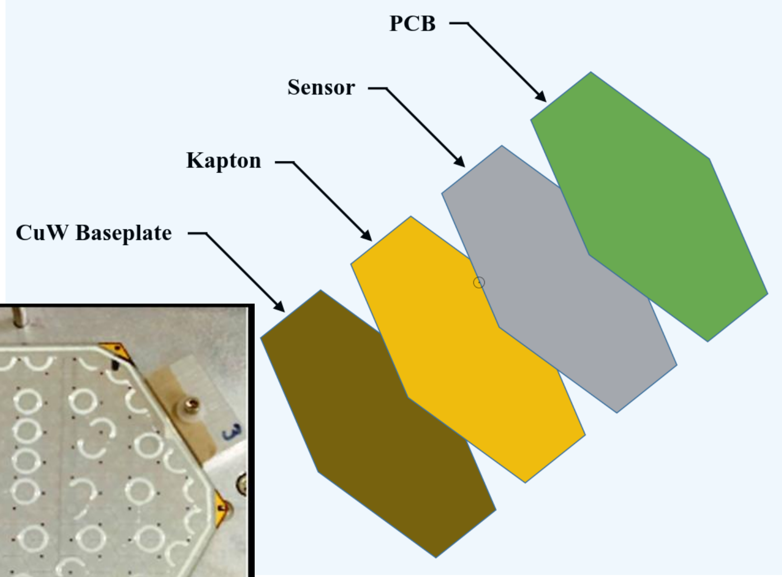
Skiroc2-cms added (ToT, ToA, data handling improvements…)
Very scalable,
Relatively inexpensive (ORM from CMS)
Quite high bandwidth up to ~14000 channels @ 50 Hz
Fully integrated on EUDAQ Software (reconstruction on real time during testbeam and data quality assurance)

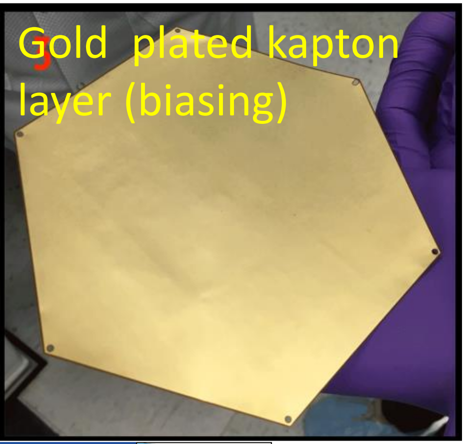
Module assembly for testbeam prototype (2016)

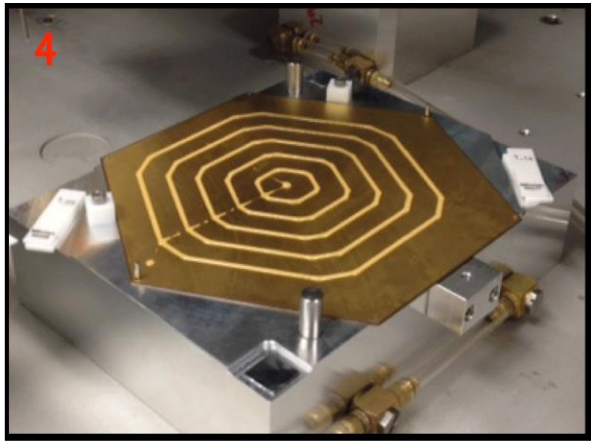


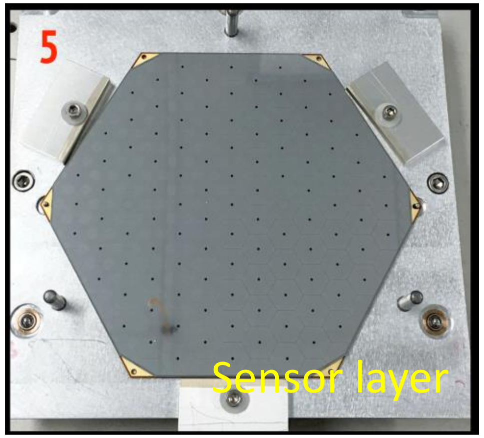


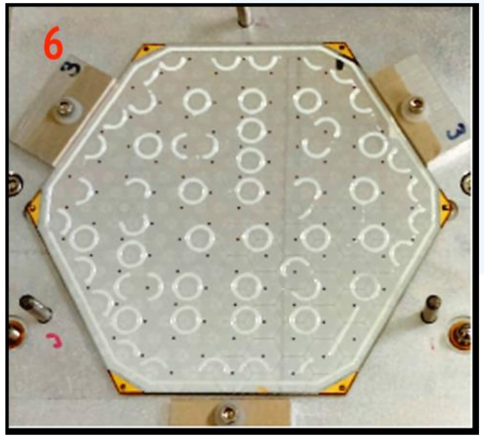
Four layers design for the sensor module
For 2016, PCB (top layer of the stack) was interconnection.
For 2017, PCB was already the front end electronic board
These modules for beam tests is enabling us to tune our module production process





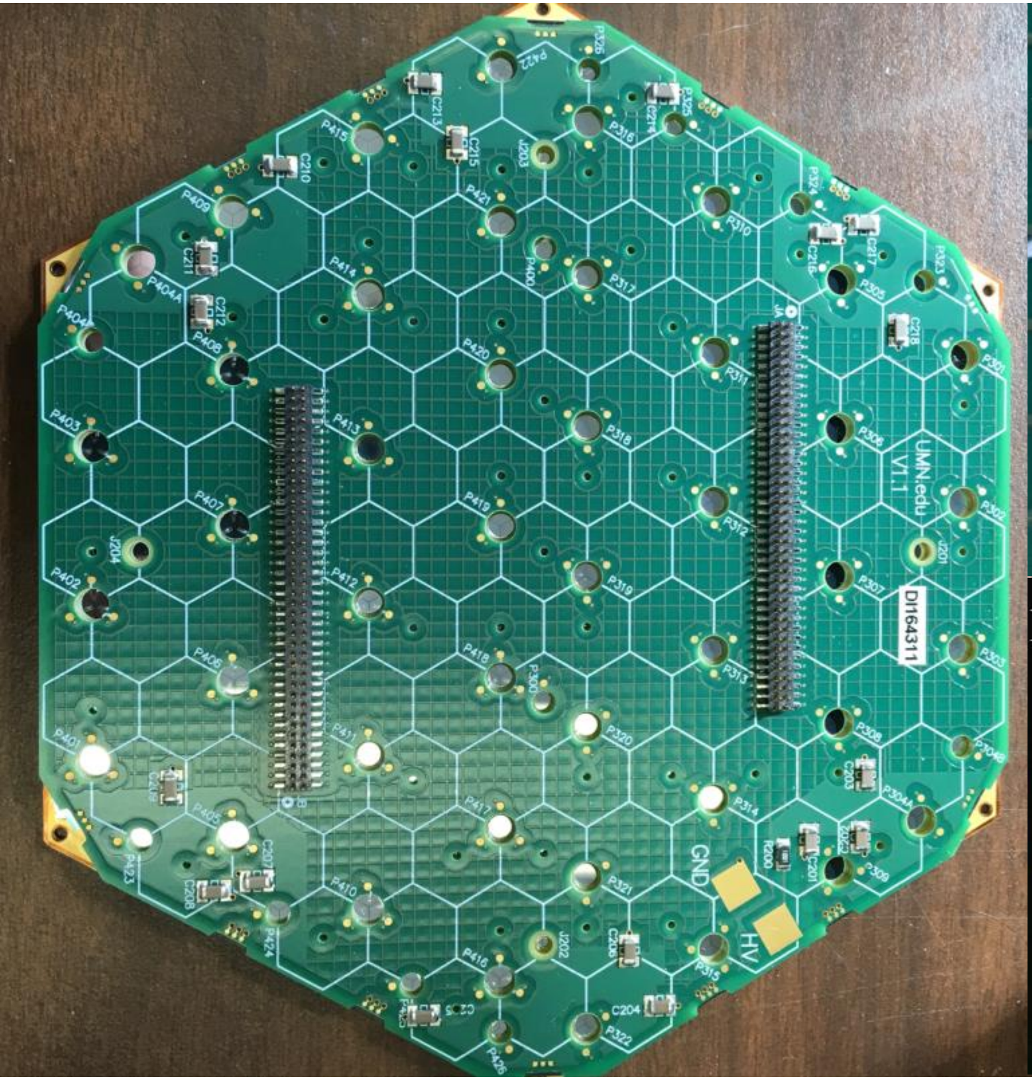


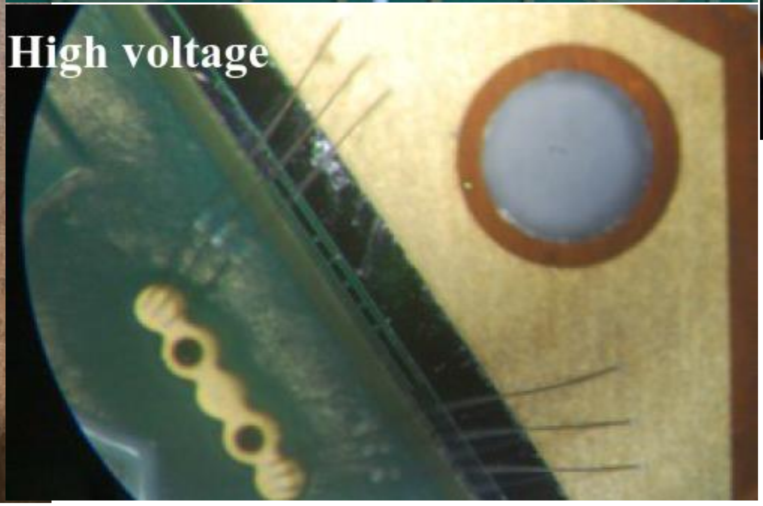




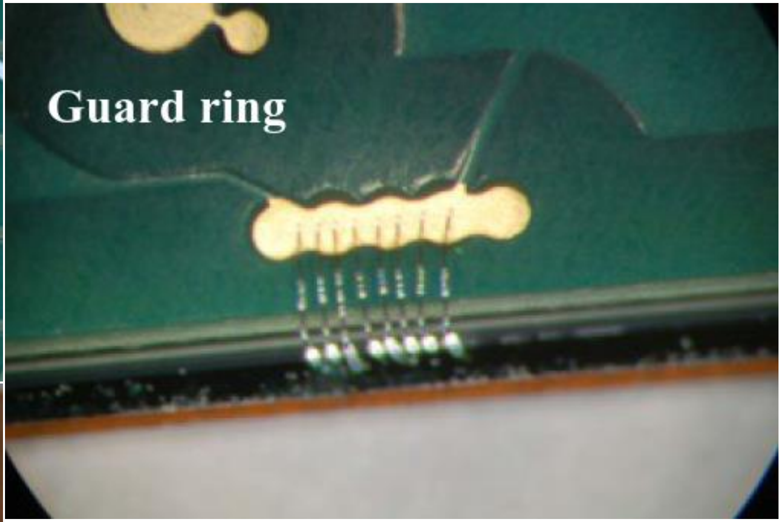
After the sensor glued and wire bonded to the PCB

2016 module example





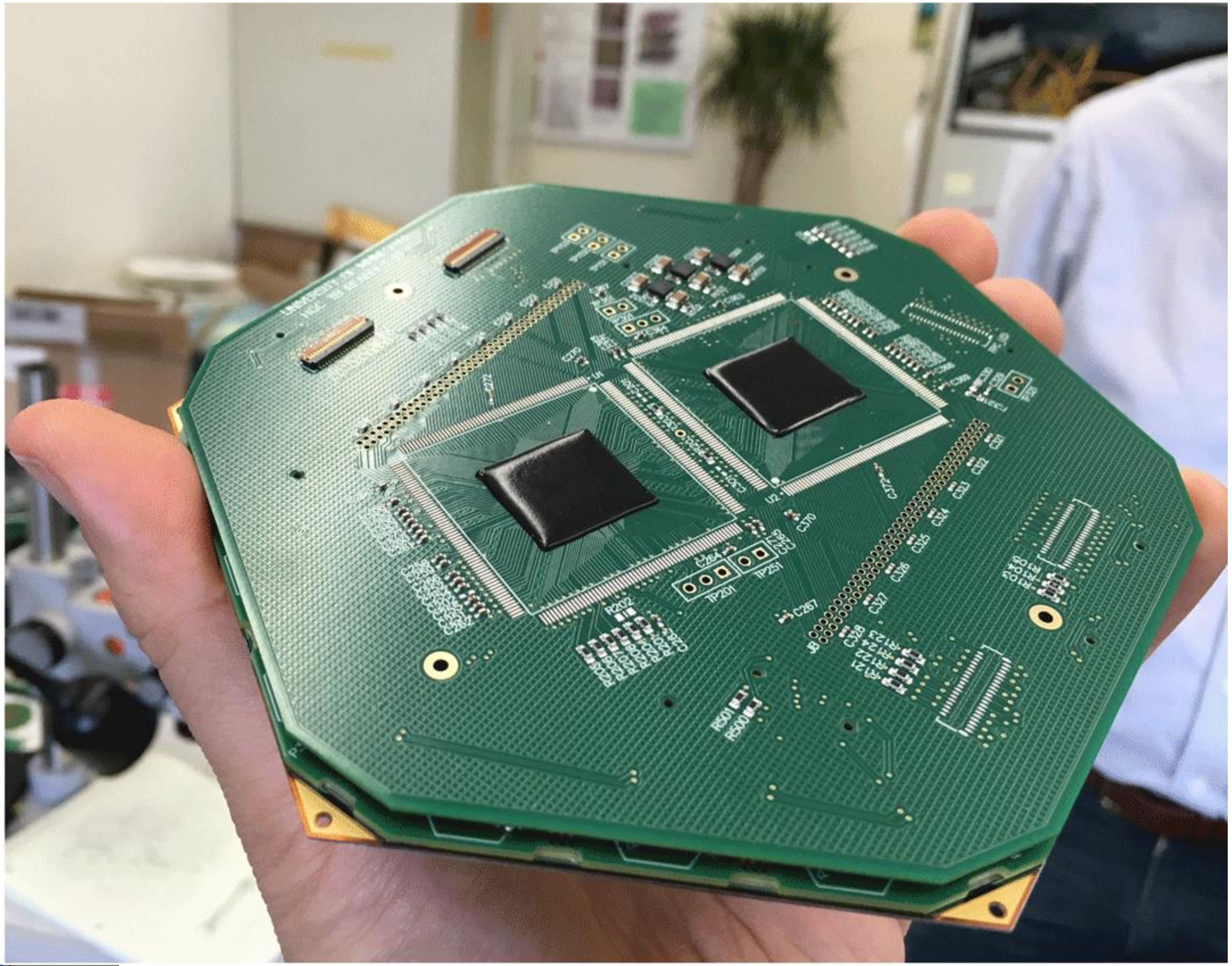
~700 wirebonds on each module



6 minutes each module

Finally mounted device. First Hexaboard

2016 module example



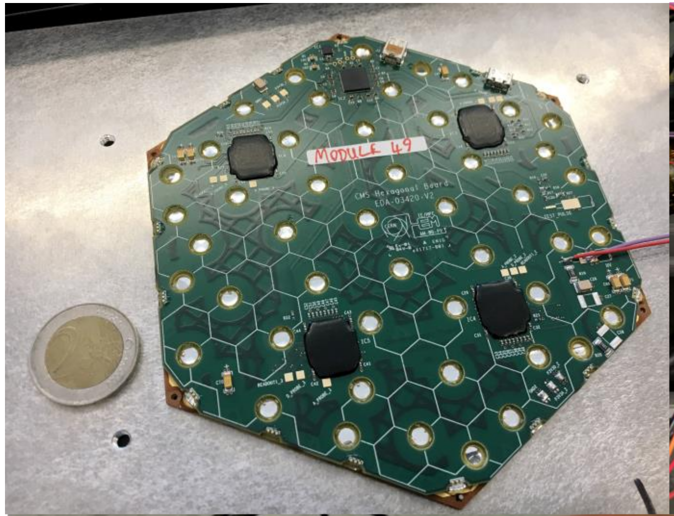
Skiroc2 ASIC is inherited from CALICE. Already working, Well known, and tools already developed.

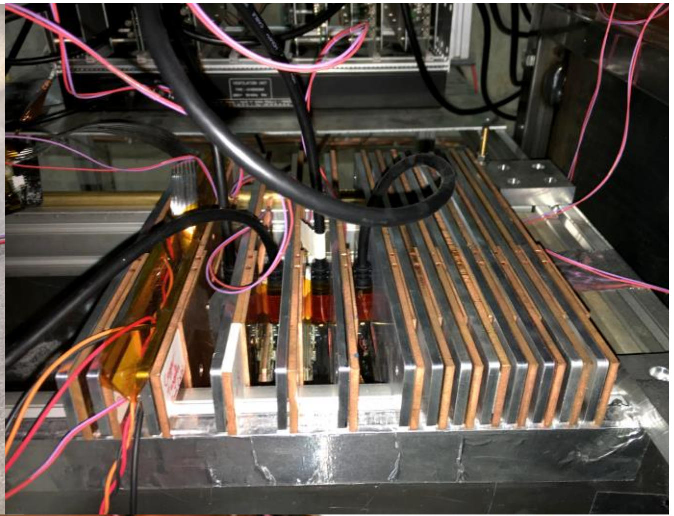
Starting point that allows the start of the other parts of the work, like mechanics, system debug, sensor studies, software development (control, data handling, reconstruction, data quality assurance…)

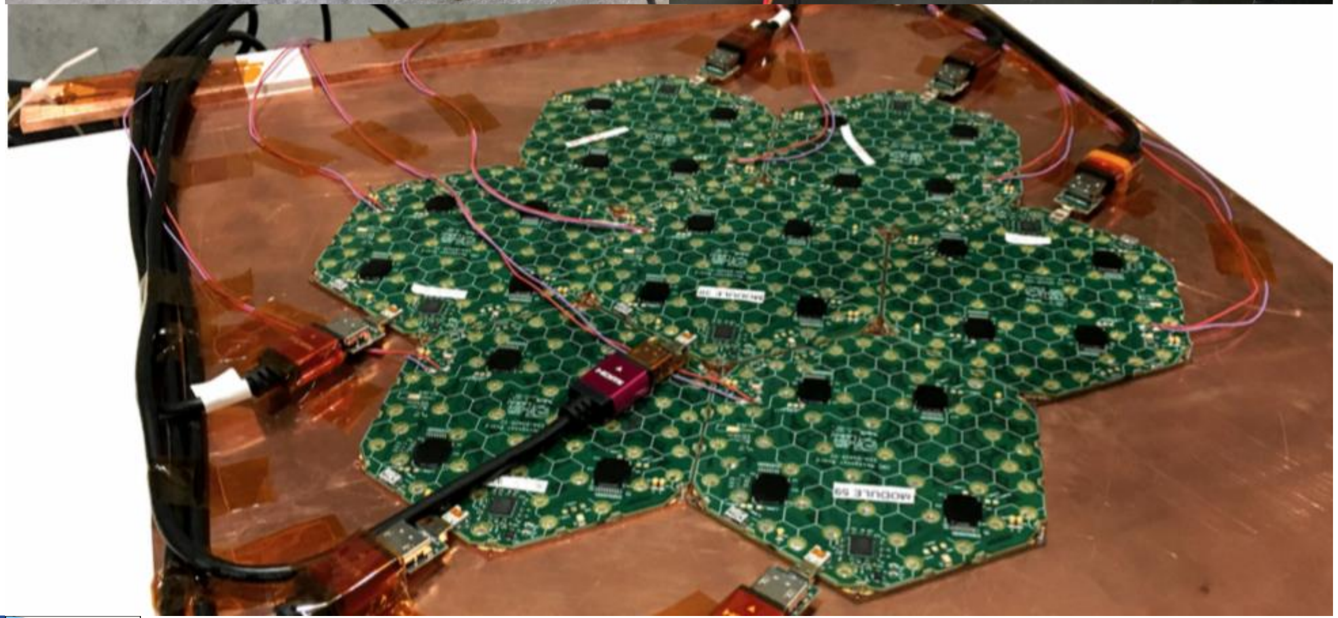
It is a two layers design, that gave us the flexibility need in this first beam tests, using well know electronics, to simplify calibration and debugging of the new parts

The hardware evolves step by step towards its final shape

2017 modules example







With new ASIC Skiroc2-CMS ready, and with some improvements from what we learnt with previous design

One layer only design. Readout PCB is now attached to the sensors

4 skirocs (instead of 2) for improving capacitance from the trace length

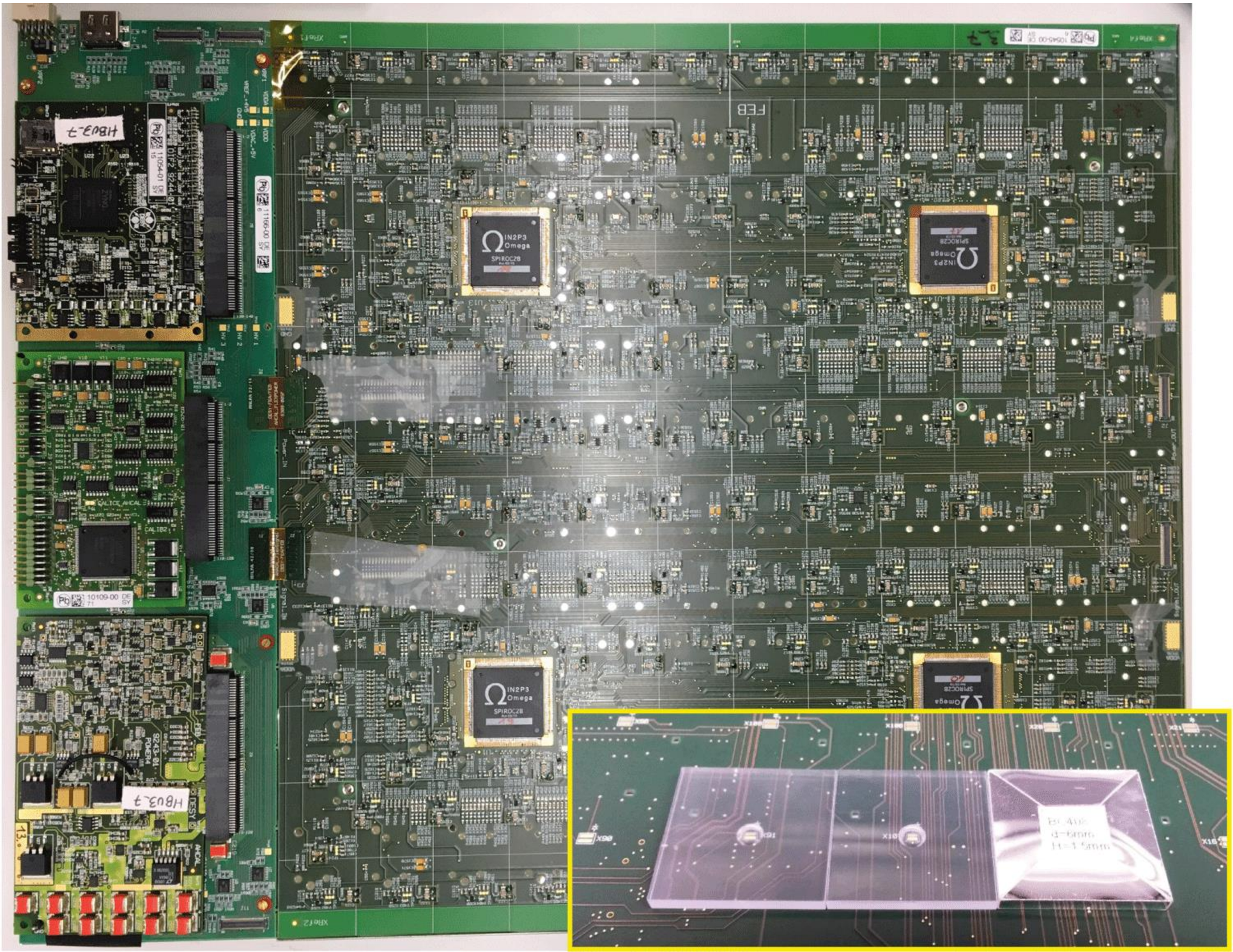
Only two connectors during working (HDMI and HV) plus one miniUSB for FPGA programming (offline)

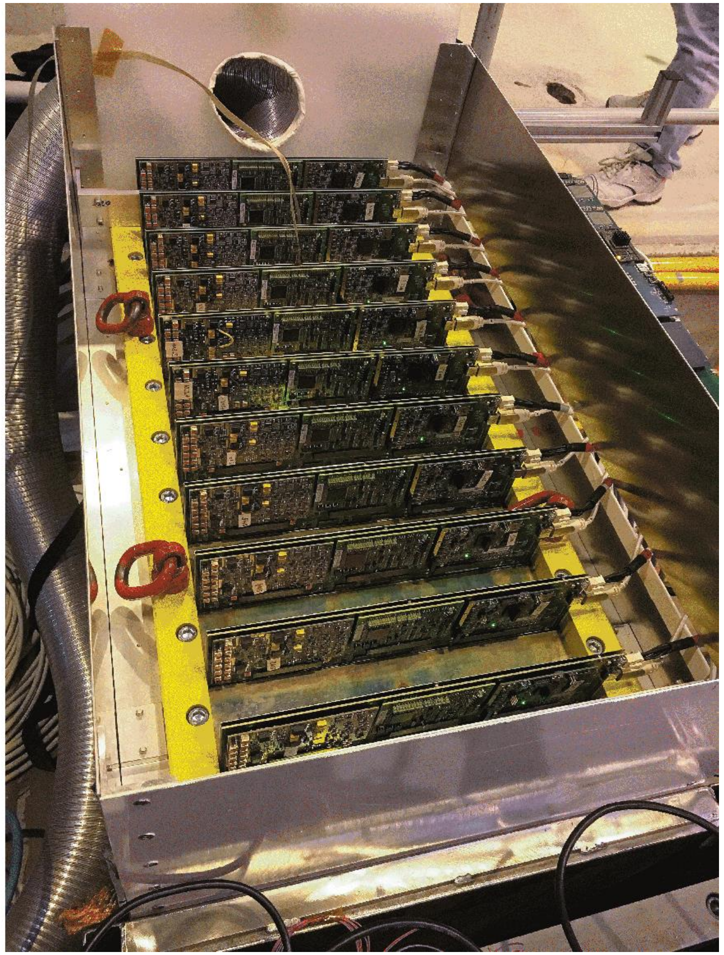
Better DAQ chain (smaller, faster and more reliable) avoiding proprietary parts.

Avoids data converters, kapton cables and other parts that reduce robustness while increase performance

The hardware evolves, approaching safely to final design

2017 modules example





Left: Scintillator+SiPM planes used in the AHCAL, including a closeup of one the tiles

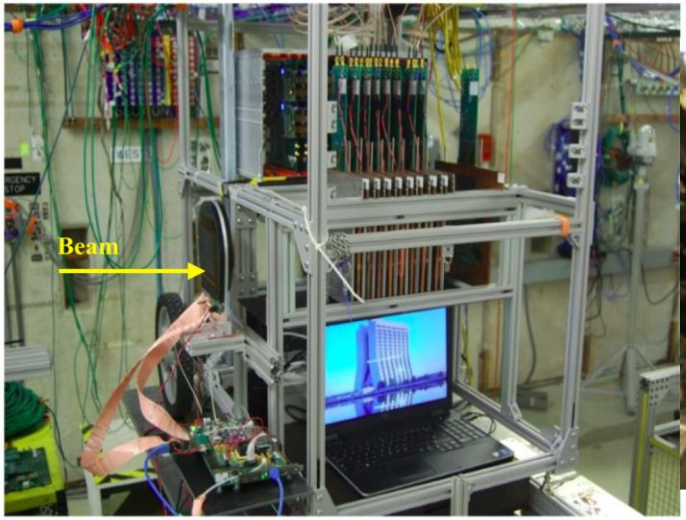
Right: layers of 74 mm-thick absorber interspersed with scintillator planes.

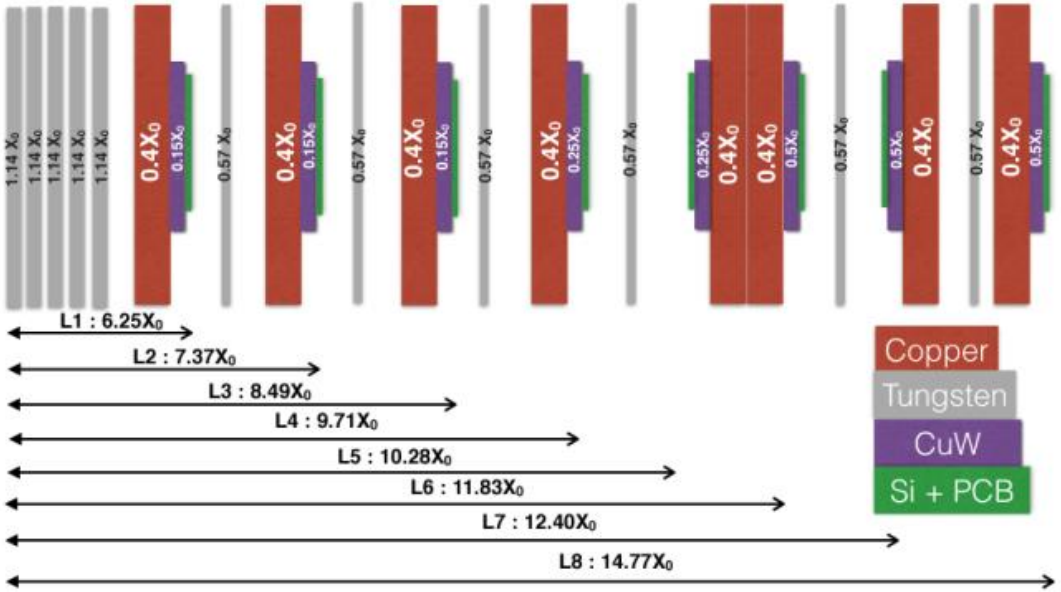
During the beam tests, we created a "looks like close to final" system and that includes the AHCAL (scintillator+SiPM)

SiPMs already used successfully in e.g. CMS HCAL Phase 1 upgrade

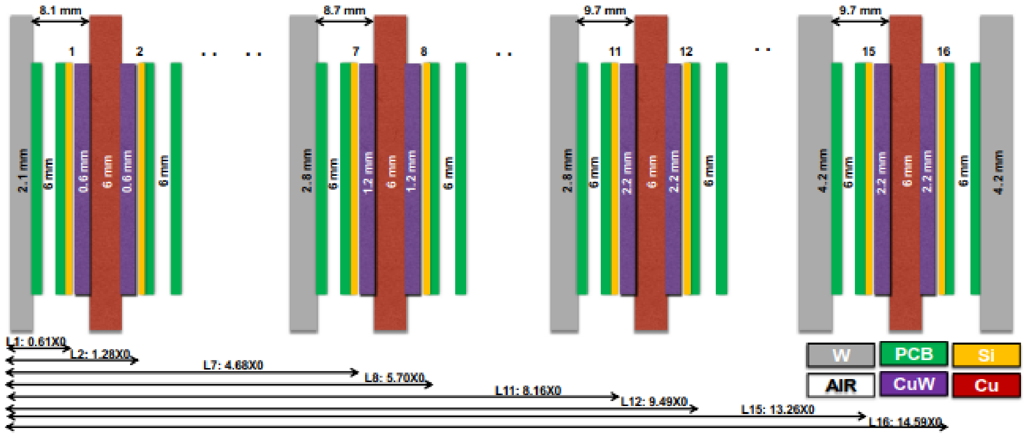
Tile boards or "megatiles" limited in size by CTE of different components. For first beam tests, modified CALICE AHCAL used for rear hadron calorimeter: 3x3cm² scintillator tiles + direct SiPM readout

Different facilities -> different beams -> different setups

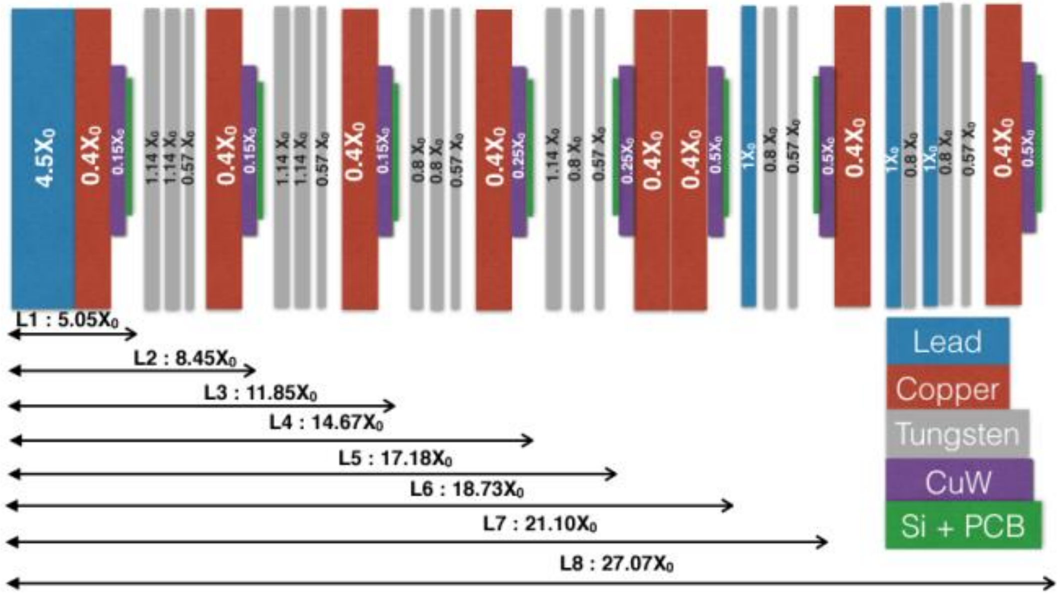




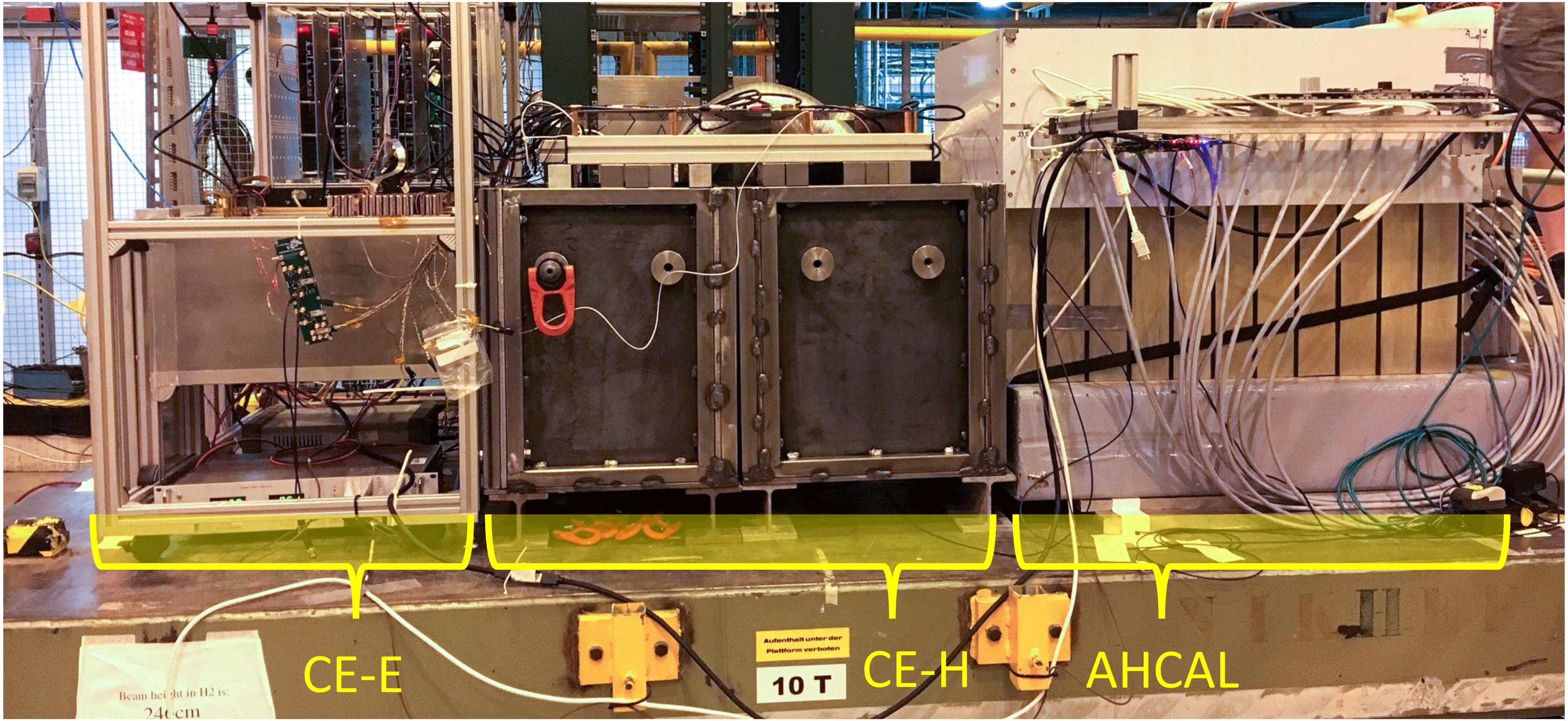
At FNAL, there was a ~15X_0 configuration with 16 layers where each module is double sided



At CERN, only 8 modules available, but two configurations were explored. From 6X_0 to 15X_0 (CERN Setup 1) and from 5X_0 27X_0 (CERN Setup 2)



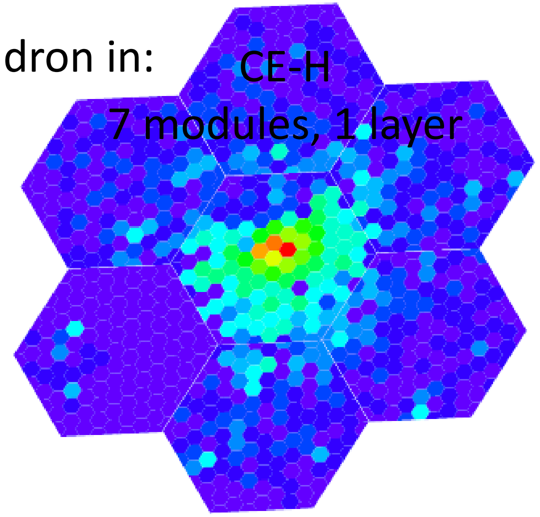
Different facilities -> different beams -> different setups

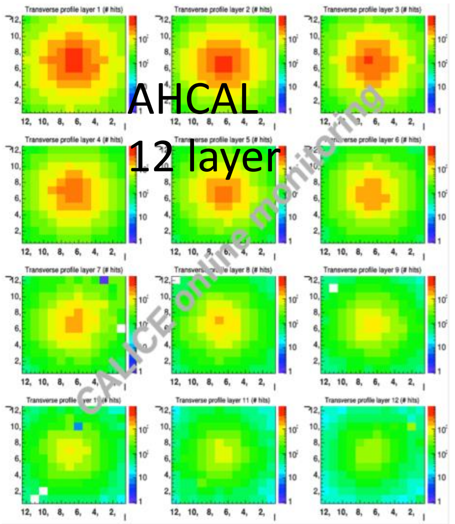


Full prototype (not all layers) from the last test beam on H2 beam line at CERN mounted on the scissor table in the H2

Signal reconstruction

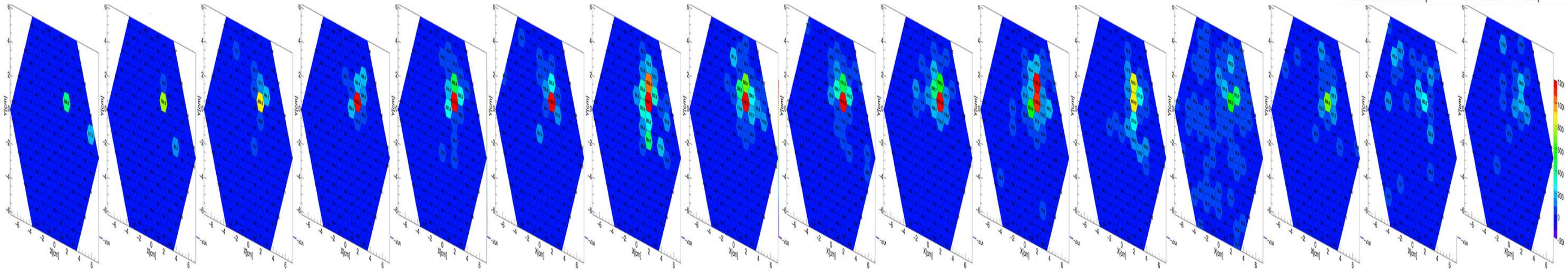
120GeV Hadron in:





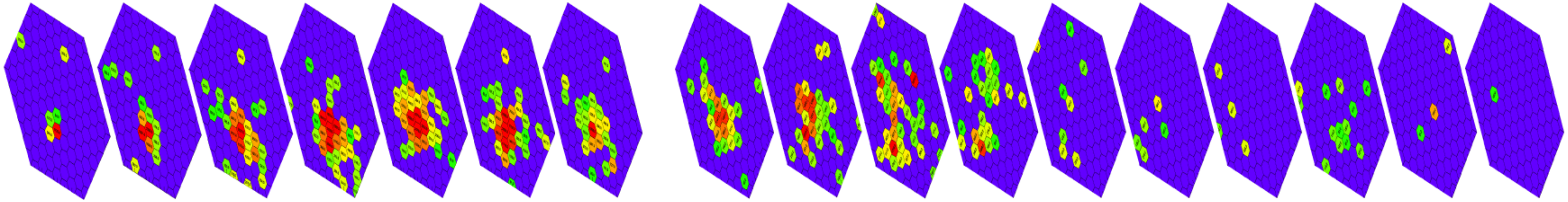
The geometries of all setups were reproduced in CMSSW. Data were taken with a wide range of electron energies: 4–32 GeV at FNAL and 20–250 GeV at CERN; as well as 120 GeV protons, muons and charged pions with energies between 20–350 GeV

32 GeV electron



$1\ X_0$ **$5\ X_0$** **$10\ X_0$** **$15\ X_0$**

300 GeV hadron



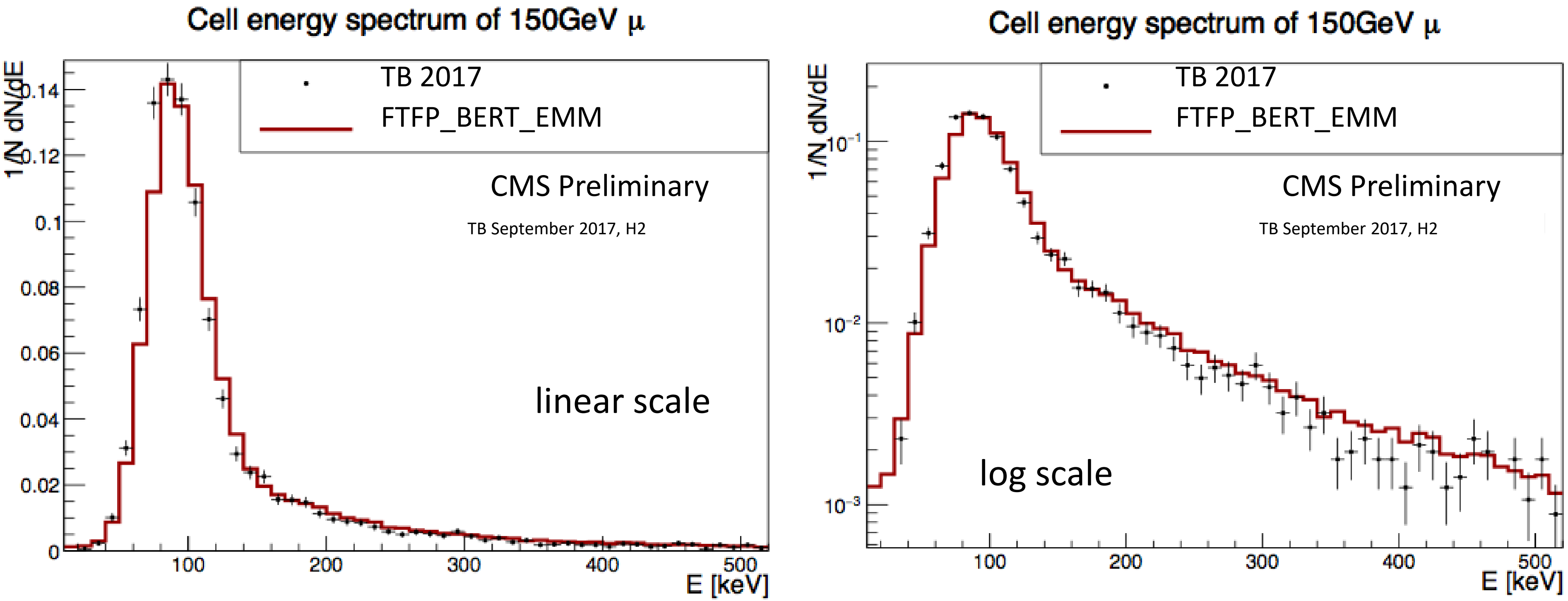
$3.0\ X_0$ $0.16\ \lambda$ | $4.6\ X_0$ $0.24\ \lambda$ | $6.3\ X_0$ $0.32\ \lambda$ | $7.8\ X_0$ $0.4\ \lambda$ | $9.5\ X_0$ $0.48\ \lambda$ | $13.0\ X_0$ $0.65\ \lambda$ | $16.5\ X_0$ $0.85\ \lambda$ | $24\ X_0$ $1.3\ \lambda$ | $27\ X_0$ $1.7\ \lambda$ | $29\ X_0$ $2.0\ \lambda$ | $32\ X_0$ $2.3\ \lambda$ | $35\ X_0$ $2.6\ \lambda$ | $38\ X_0$ $2.9\ \lambda$ | $42\ X_0$ $3.3\ \lambda$ | $45\ X_0$ $3.5\ \lambda$ | $48\ X_0$ $3.8\ \lambda$ | $51\ X_0$ $4.1\ \lambda$

Single MIP spectra for 2017 muon runs

Shown at DPG 2018

Energy spectrum of exposed cells well defined through additional readout of four upstream delay wire chambers: Reference tracks.

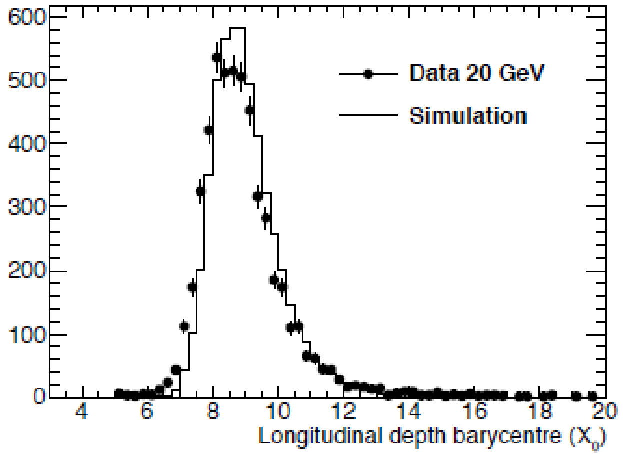
From Geant4 simulation: 1MIP = 84.9 keV (300um PinN silicon sensor).

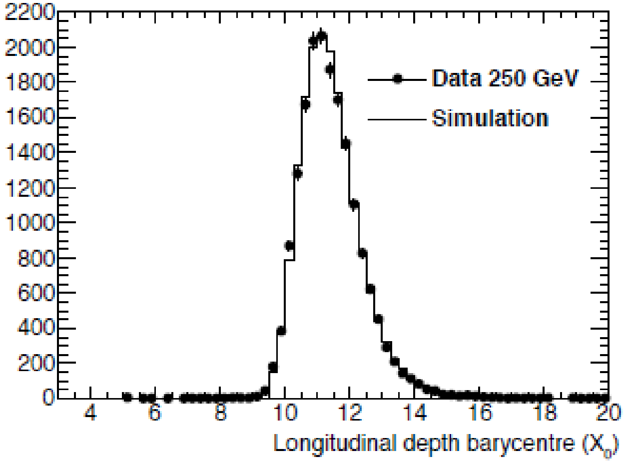


- Simulated energies are smeared assuming S/N ~ 6.

➡ No bad surprises. Good agreement even in the Landau tails.

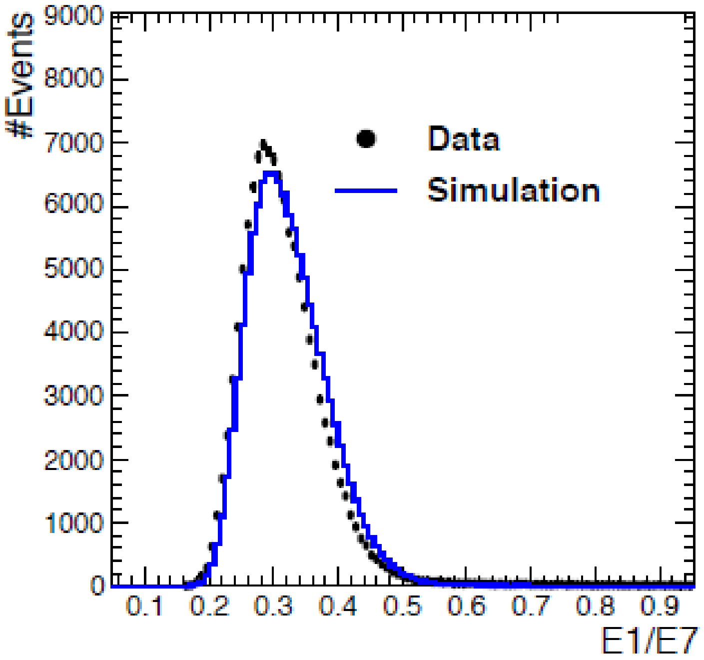
Shower shape studies

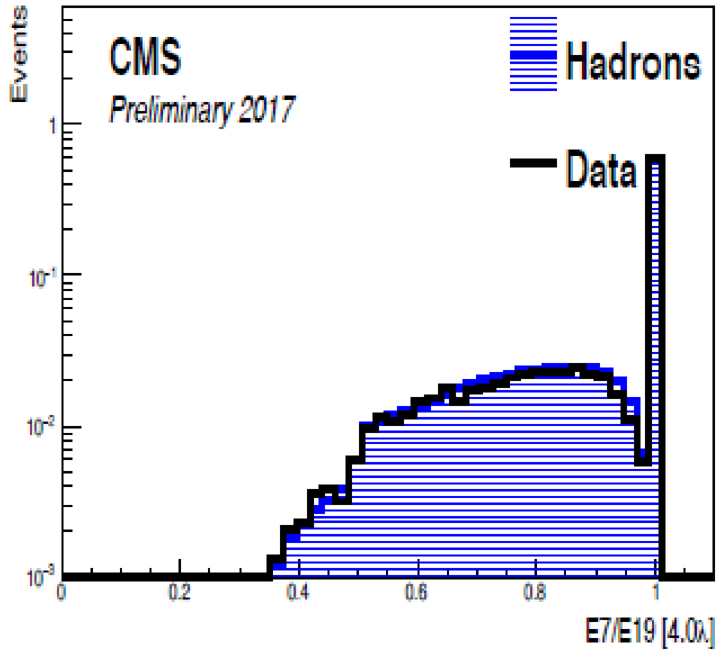




Longitudinal depth barycentre distribution comparision between data and simulation for electron energies of 20 and 250 GeV at CERN in 2016 (From TDR 10.18)

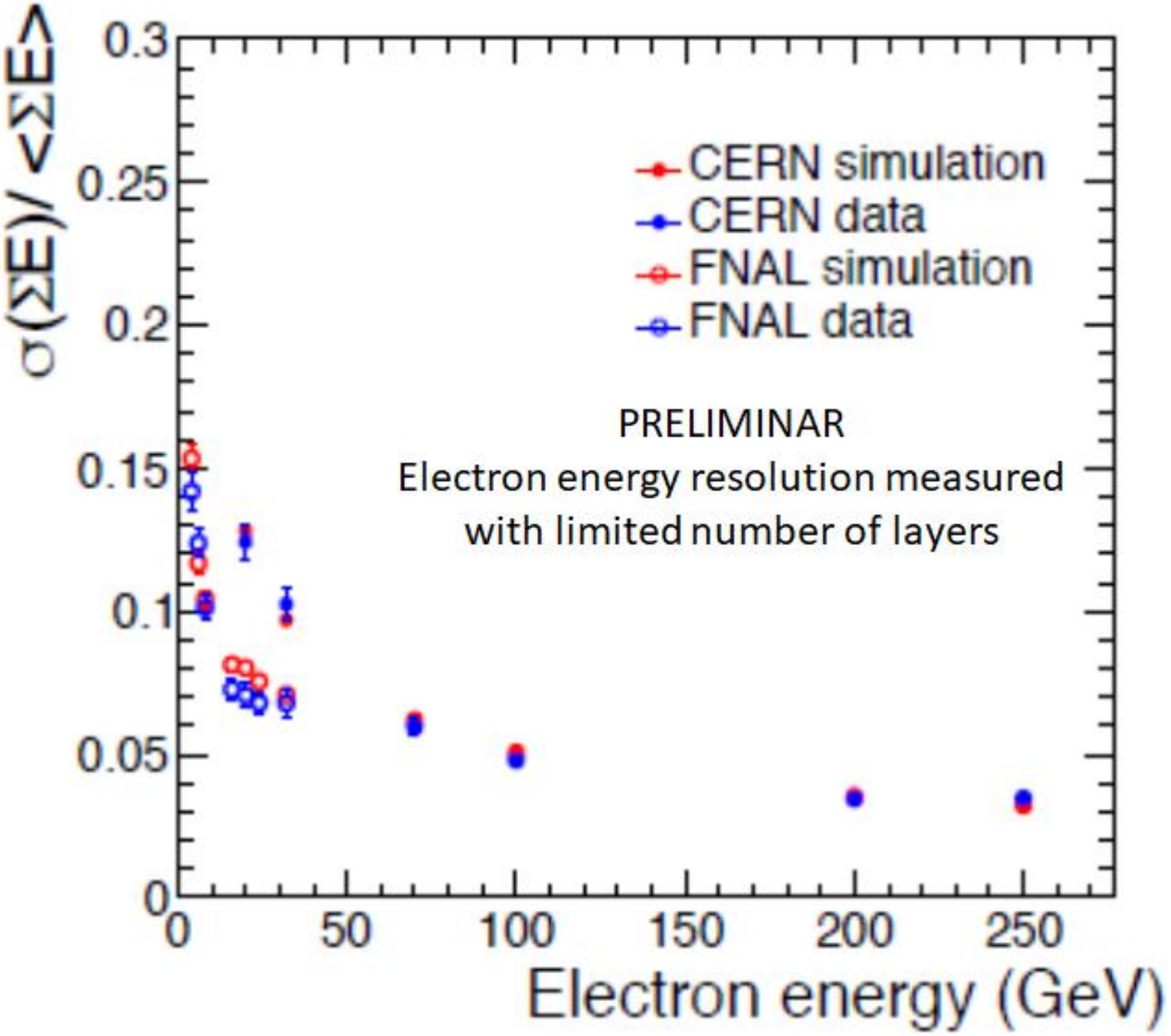
Distribution (left) of the ratio E1/E7 for 100 GeV electrons at a depth of around 1 X_0 for data (points) and simulated showers (histogram); and (right) transverse shower profile (E7/E19) measured at a depth of 4λ from incident 200 GeV charged hadrons (20% pions; 80% protons). From TDR Figure 5.20





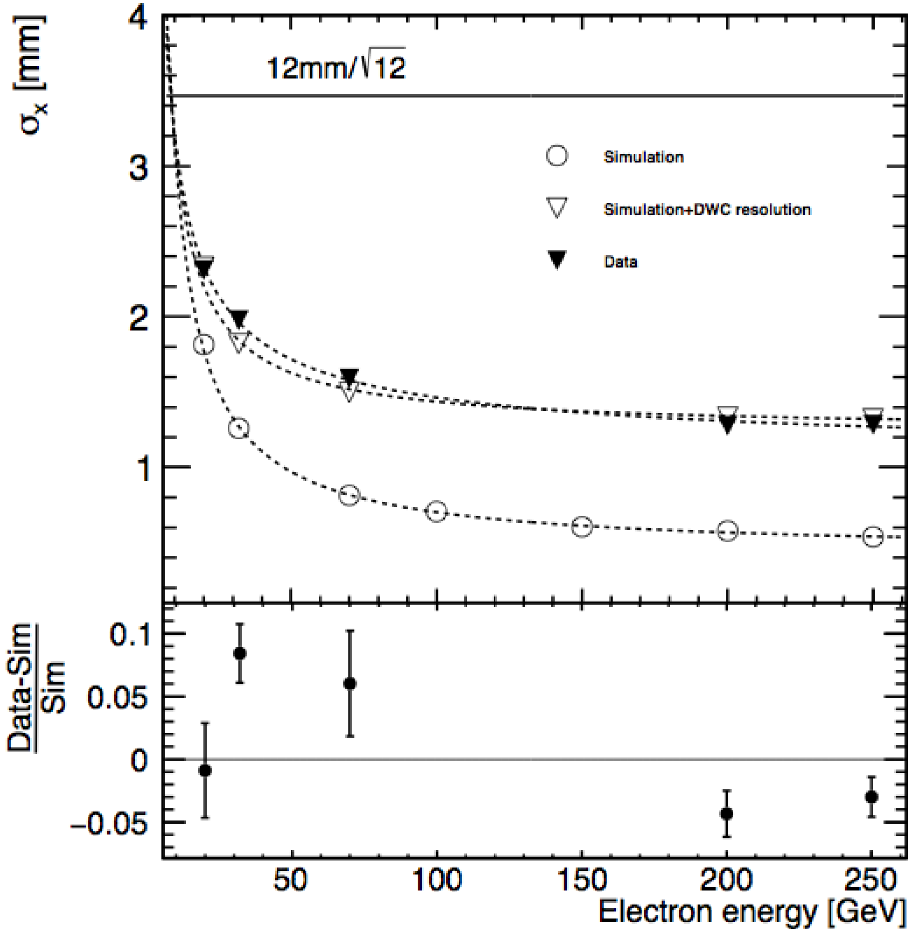
Energy resolution

Relative energy resolution as a function of the electron energy in data and simulated showers, for test beams at FNAL and CERN
This results are not the last one.
For having the full energy resolution, we still need the whole 28 layers system
As expected, FNAL setup (16 layers, 0–15 X_0) performed better than CERN one (8 layers, 5–27 X_0) for low energy electrons.



Spatial resolution

as documented in detector note on TB2016 analyses



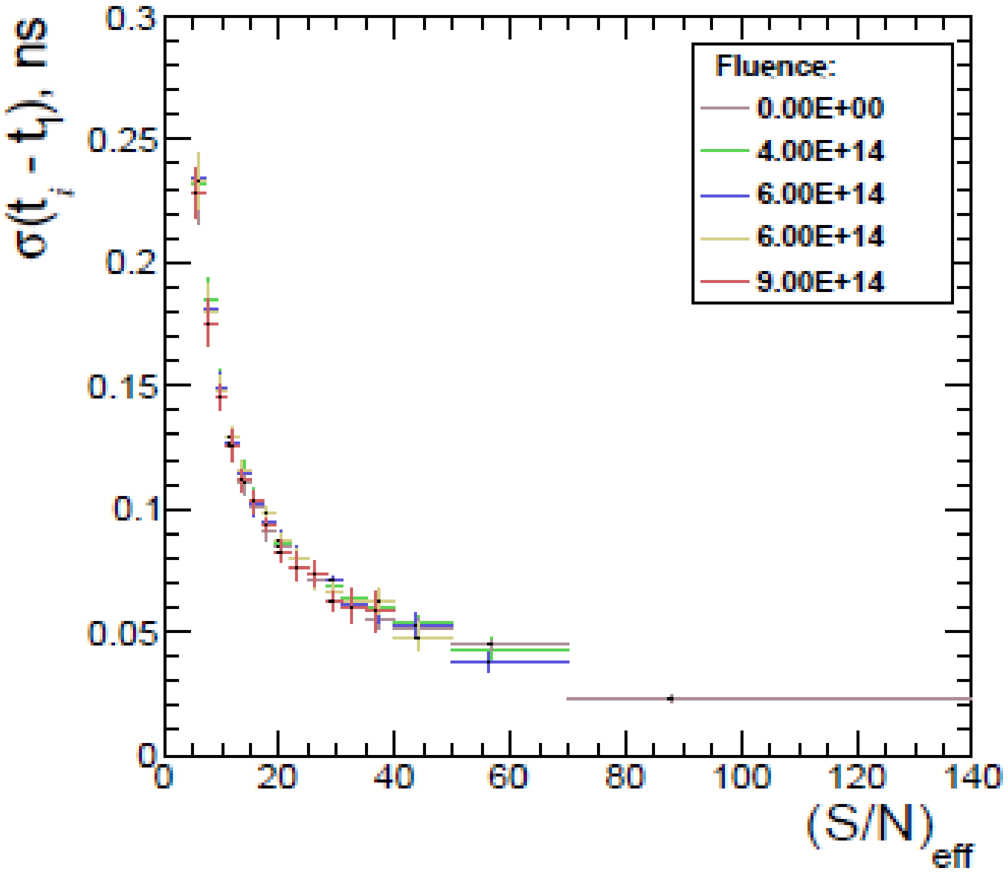
Residual width of the x-coordinate reconstruction at a depth of $6X_0$ as a function of incident electron energy

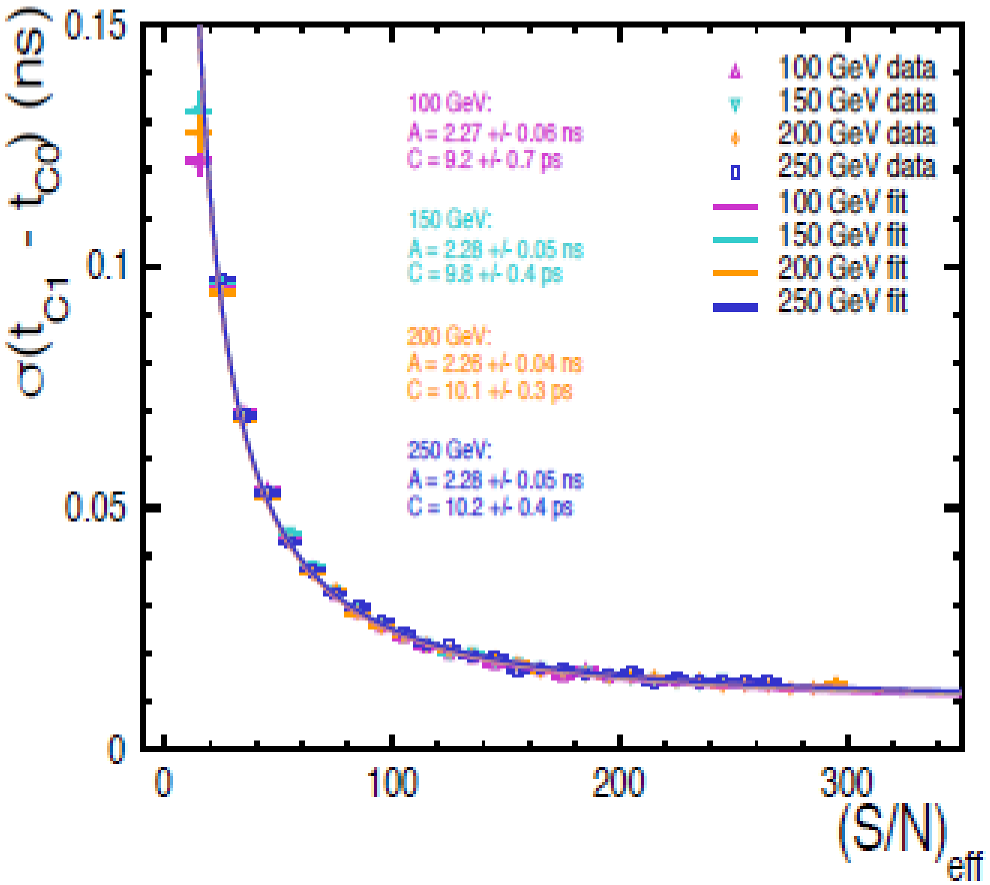
The small cell sizes gives us a position resolution better than 1mm, in each layer, for high pT electromagnetic showers, with little effort. This has been confirmed by the test beam (TDR Section 5.2).

We will be also able to measure the shower direction. The axis of electromagnetic showers is determined using a principal component analysis methodology as a starting point for the construction of shower shape variables.

2015 testbeams. Understanding the silicon

One single diode devices. Different fluences and sizes





Time resolution vs signal-to-noise is compatible between the unirradiated and irradiated diodes.

Single sensor time resolution at large S/N = 25/√2 ~15 ps, in agreement with the unirradiated results.

Same performance with the **Irradiated** diodes → ~15 ps resolution for one single diode

Description of beam test at DESY March 2018

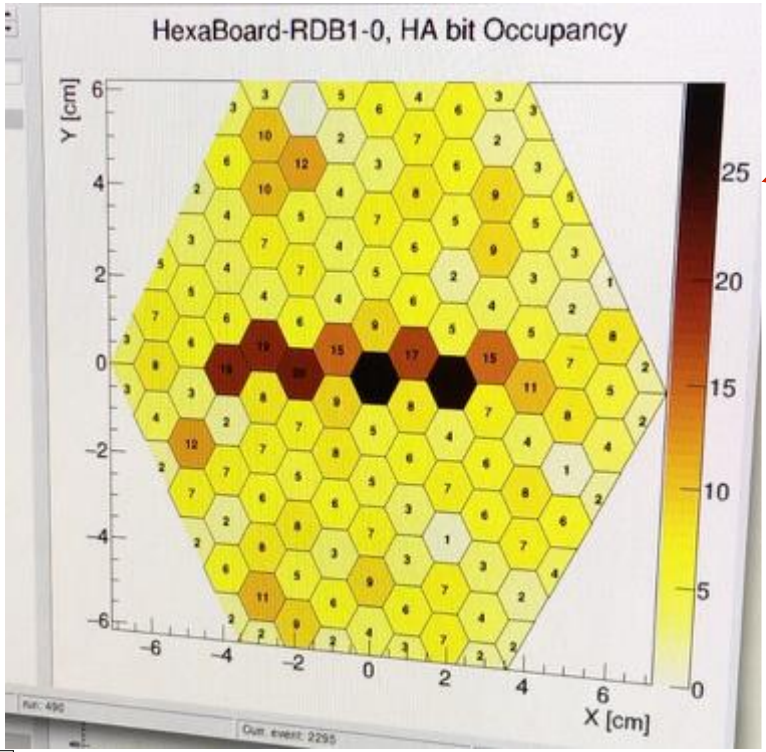
Shown at DPG 2018

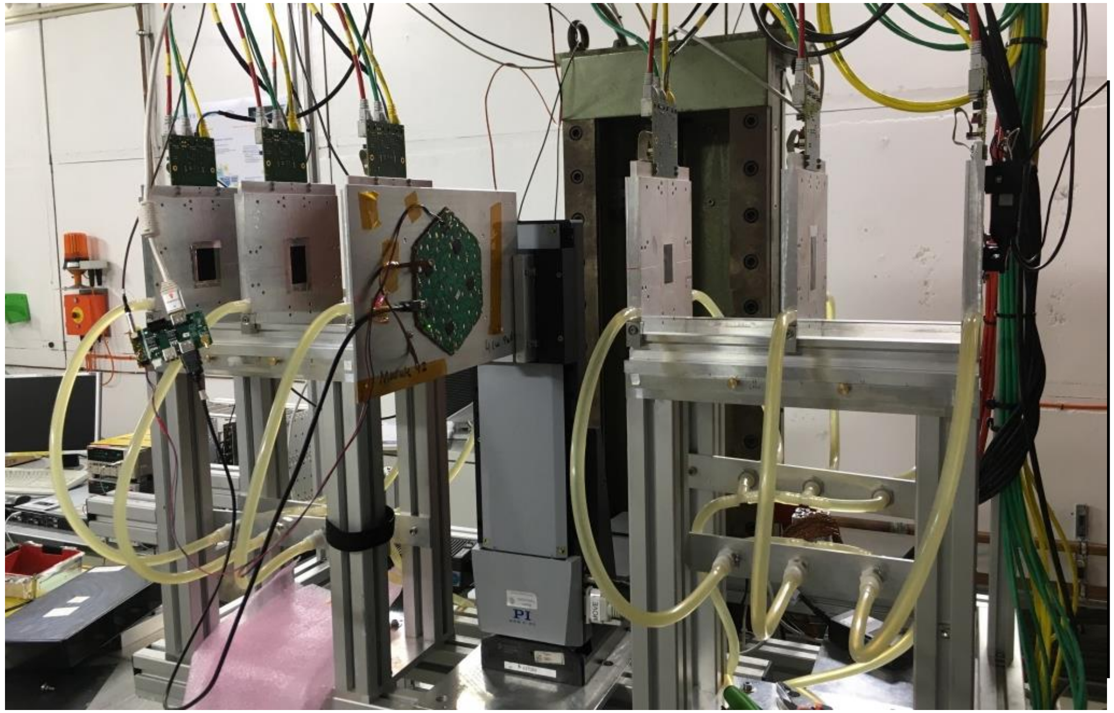
Beam test at DESY with DATURA high precision tracking telescope.

3-6 GeV electrons recorded at ~40Hz (limited by the DAQ system).

1+2 HGCal modules under test.

beam telescope for precise tracking with ~8 microns resolution.





Two experimental goals:

1. Detailed **MIP calibration** of each cell as a function of the impact position. Also varying the bias voltage.
2. Calorimetric measurements.

   Comparison of **response** of channels in consecutive modules.

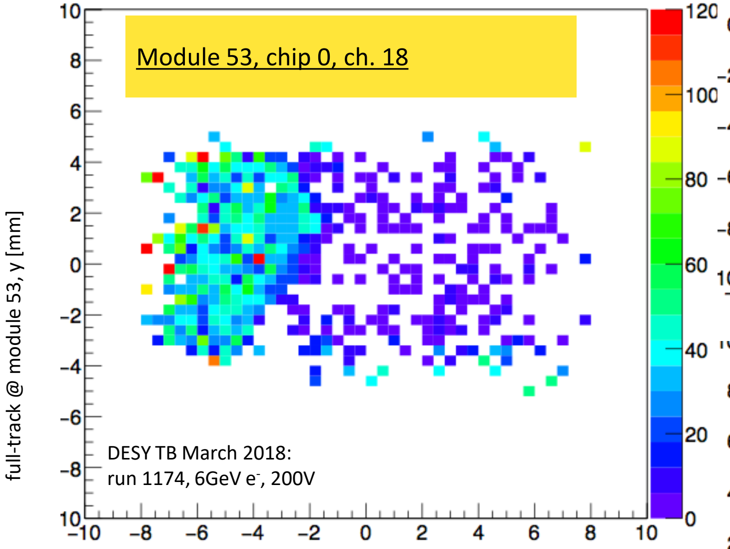
   Comparison to GEANT4 physics lists.

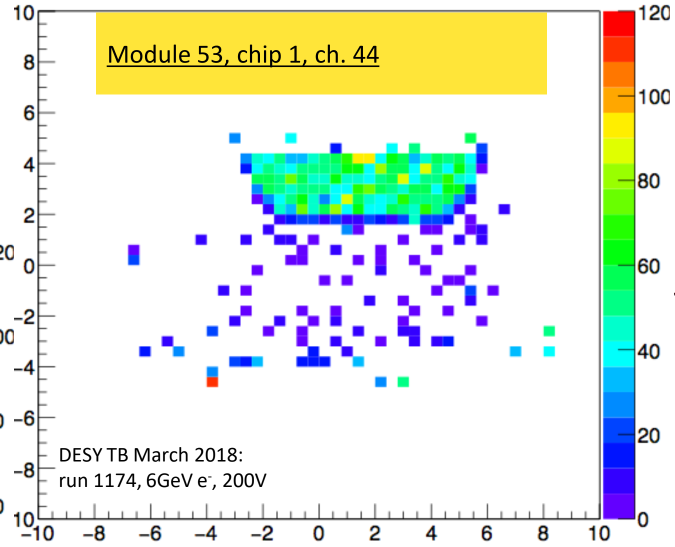
HGCal and DESY Telescope data correlated

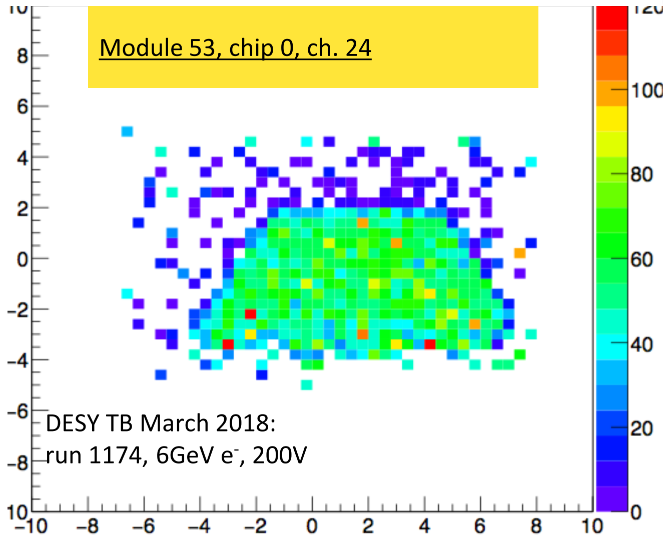
Shown at internal system test meeting in April 2018

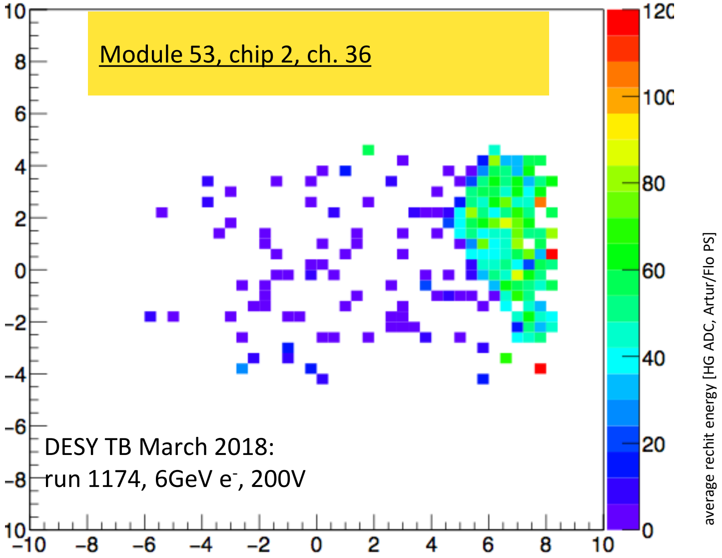
High precision tracking system

Reading of the channels for each point (with MIP)







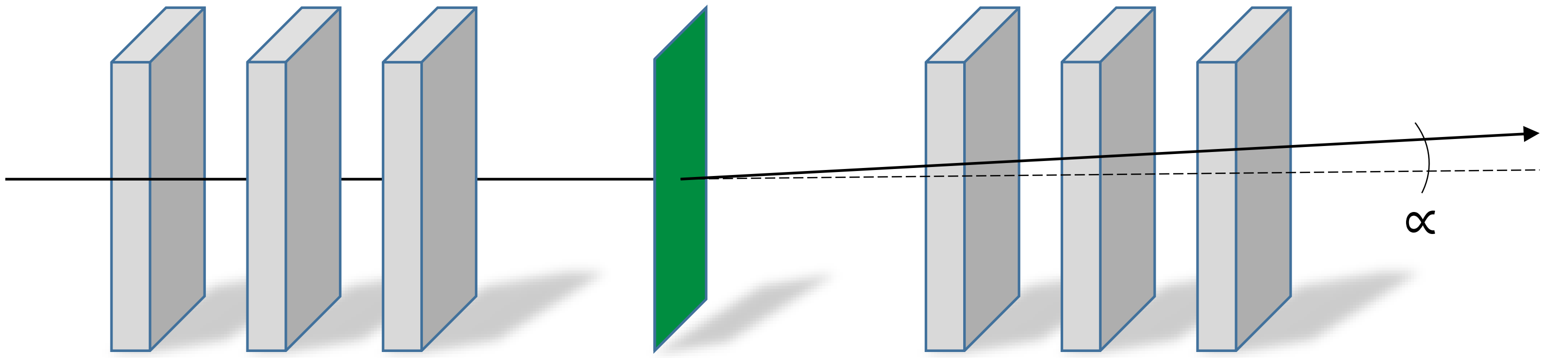


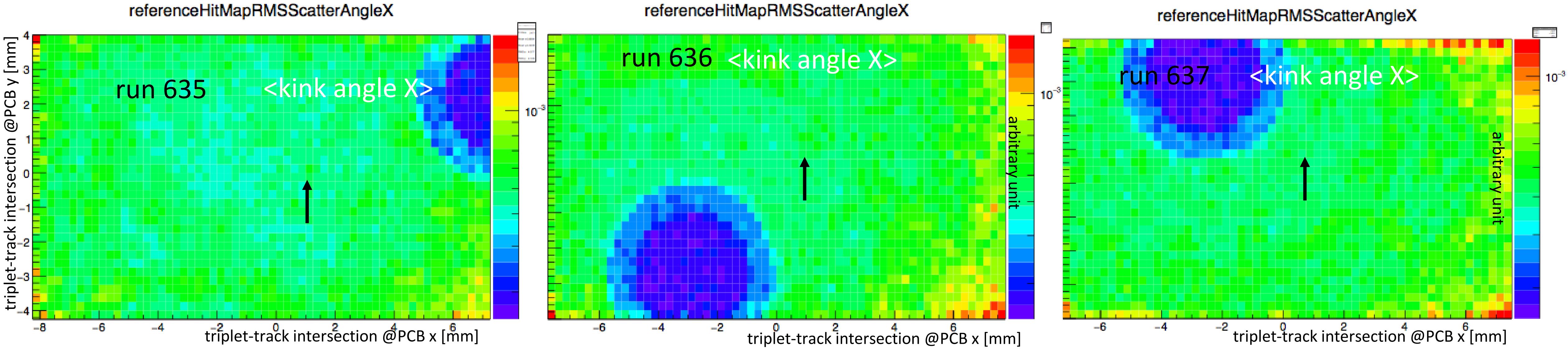
Exact shape of the hexagonal cells was drawn

Material-budget measurements at DESY

Shown at internal system test meeting in April 2018

measurement of kink angle vs incidence position
+
Surface scan
=
2D image of material budget





Extensive laboratory tests ongoing/planned in 2018 at CERN, FNAL, DESY… For example, for silicon part of HGCAL

- Component level (functionality, performance before/after irradiation)
  - Silicon sensor (6”, 8”, p-on-n, n-on-p etc.) — CERN, FNAL, HEPHY
  - ASICs (SKIROC2-CMS, HGCROC, Concentrator…) — Omega (LLR), CERN, Saclay, Imperial
  - Powering (on-detector FEAST etc.; off-detector) — CERN
  - Optics (lpGBT + VL) — CERN
  - Hexaboard — CERN, LLR
- Module level (functionality, performance, mechanics)
  - Module structure vs IV characteristics — UCSB, CERN
  - Thermal/power cycling — UCSB, CERN
  - External signal sources
    - IR laser — CERN, Minnesota, Pune…
    - Cosmics — CERN, UCSB, Pune, IHEP…
- System level (functionality, performance, integration)
  - Module + motherboard + powering (on-detector & off-detector) + trigger + readout + services — CERN…
    - **Use “final” components as they become available**
  - Beam tests — CERN, DESY, FNAL, IHEP

But there are much more!!

Similar tests for Scintillators+SiPM

Mechanical designs improving engineering on modules and cassettes, etc

Reconstruction software and data analysis…

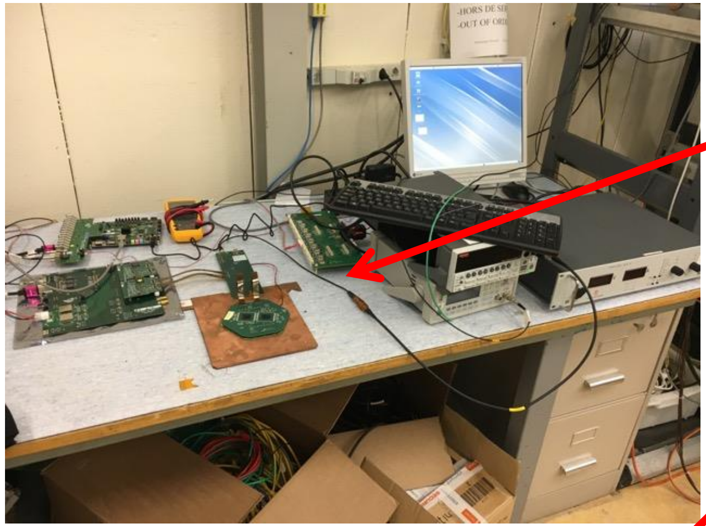
Some examples of ongoing laboratory system tests

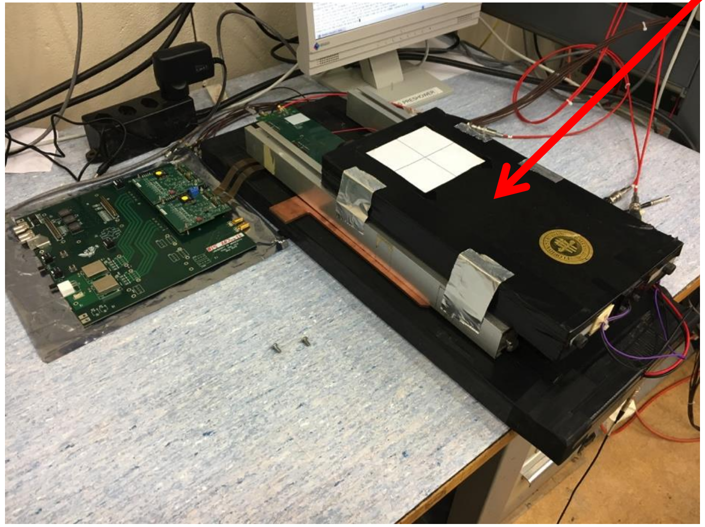
(@CERN, building 27)

3D-printed rails for studying possible inductive effects from FEAST board to silicon module below

Modules inside "Vienna box" for calibration of ToT vs temperature; also making a cosmic-ray setup

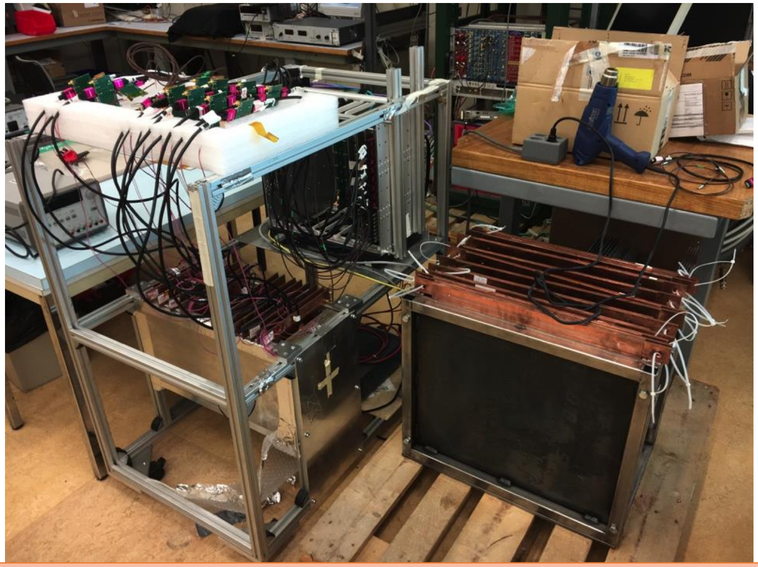
Small- and large-scale test stands being used to understand and tune systems





@CERN: 1-module standalone systems for studying long-term stability. Also providing small systems for developing institutes' expertise

Can also use in cosmic-ray setups



@CERN: In lab 27, testbeam setup used to study noise, grounding schemes etc.

Further beam tests planned at CERN in 2018: Performance of large system

O(100) 6” silicon modules (2017 version)

All mechanics and most DAQ components (hardware & software) exist

June test (10 days): 28-layer CE-E with Pb absorbers

- Energy/position resolution & comparison to MC (up to ~100 GeV)

October test (14 days): CE-E + 12-layer CE-H (silicon) + AHCAL with steel absorbers

- ~14k channels (same as existing ECAL endcaps)
- Energy/position resolution & comparison to MC (up to ~250 GeV)
- Possibly explore timing performance
- N.b. @50 Hz trigger rate, approx 500 Mbytes/sec data-taking rate

During LS2: no beams at CERN, but plenty of other facilities

e.g. DESY, FNAL, IHEP Beijing

Joaquín B González

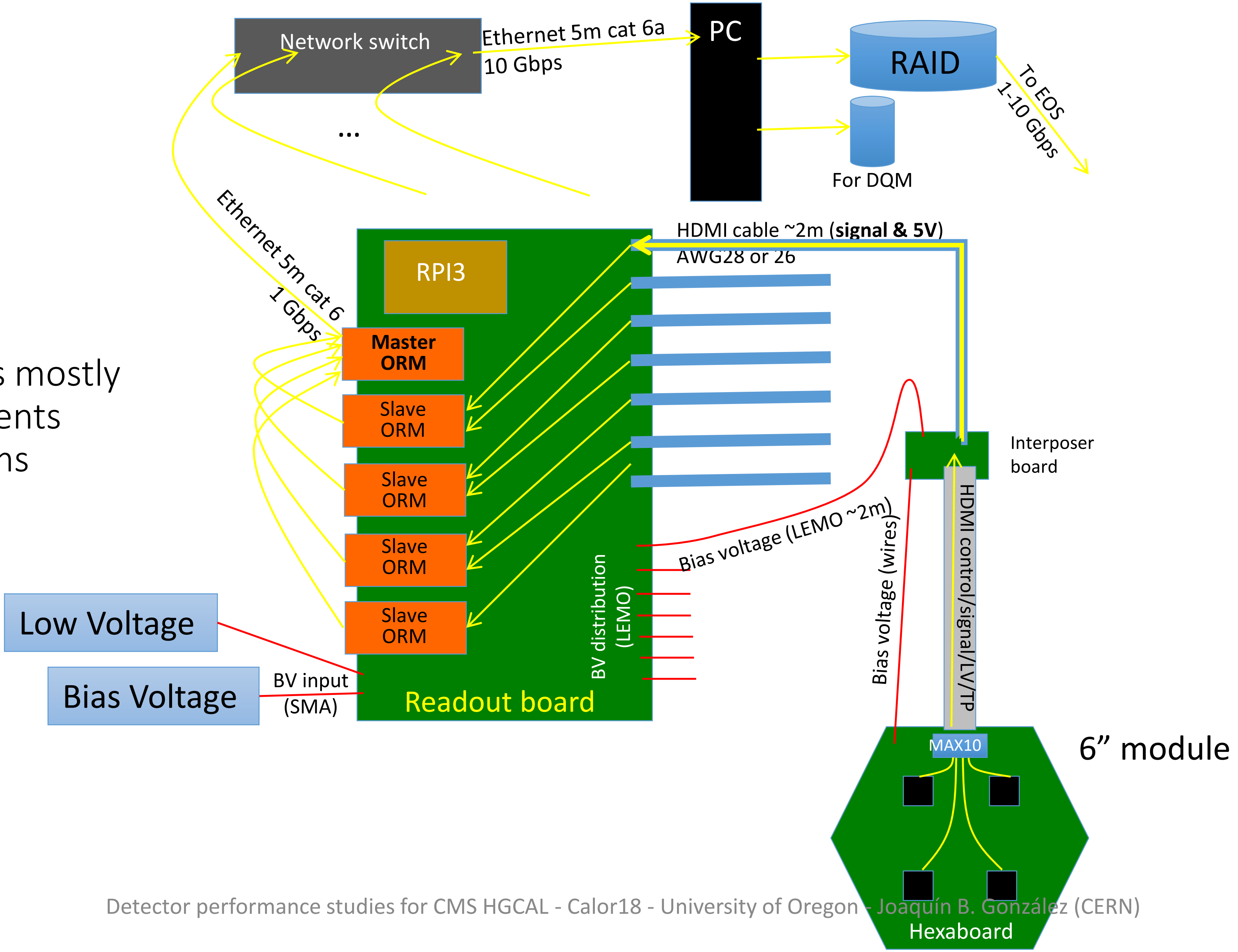
On behalf of CMS Collaboration

CERN

The DAQ is evolving following the schedule

But there are still a few steps more

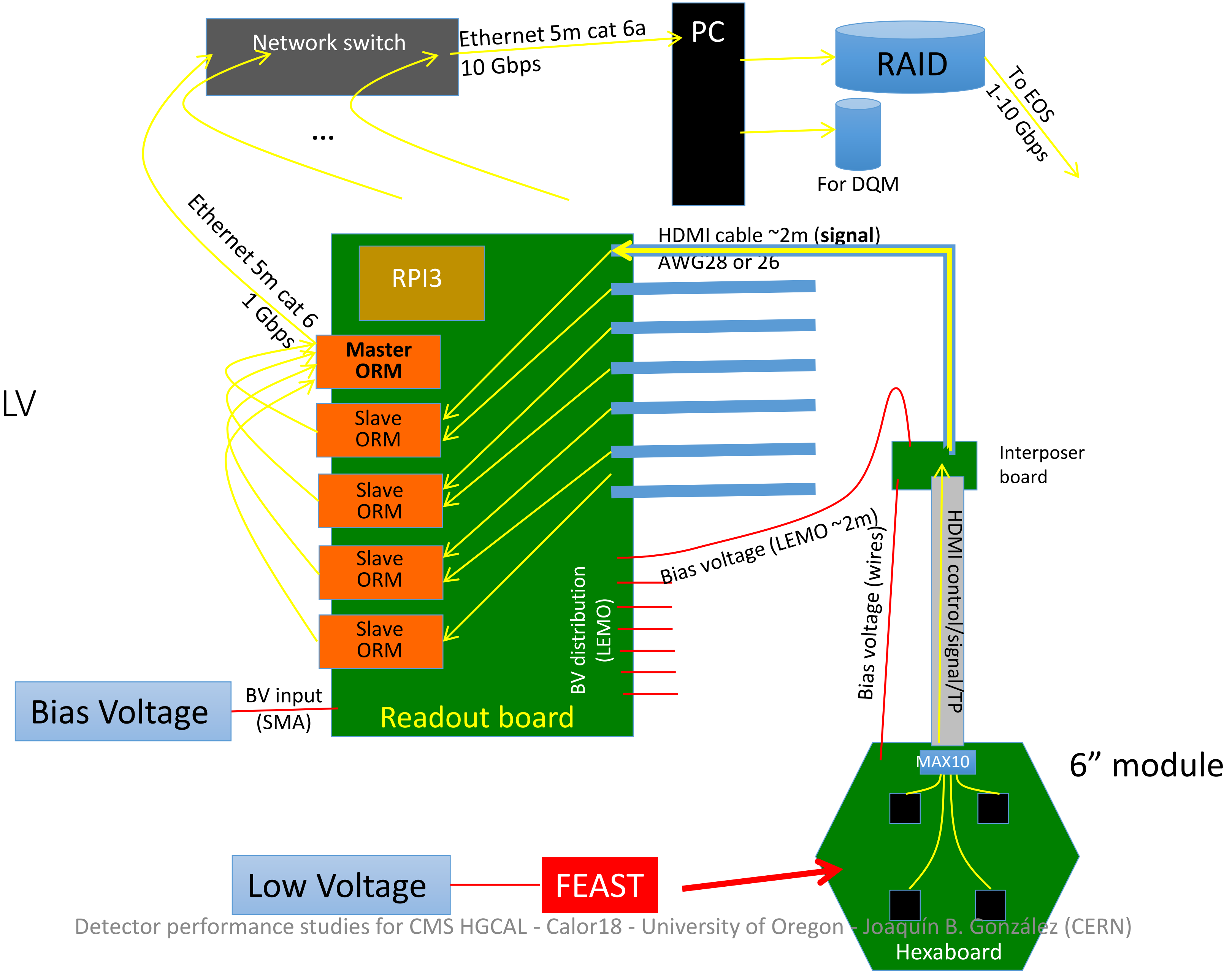
Present system uses mostly temporary components including Skiroc2-cms



The DAQ is evolving following the schedule

But there are still a few steps more

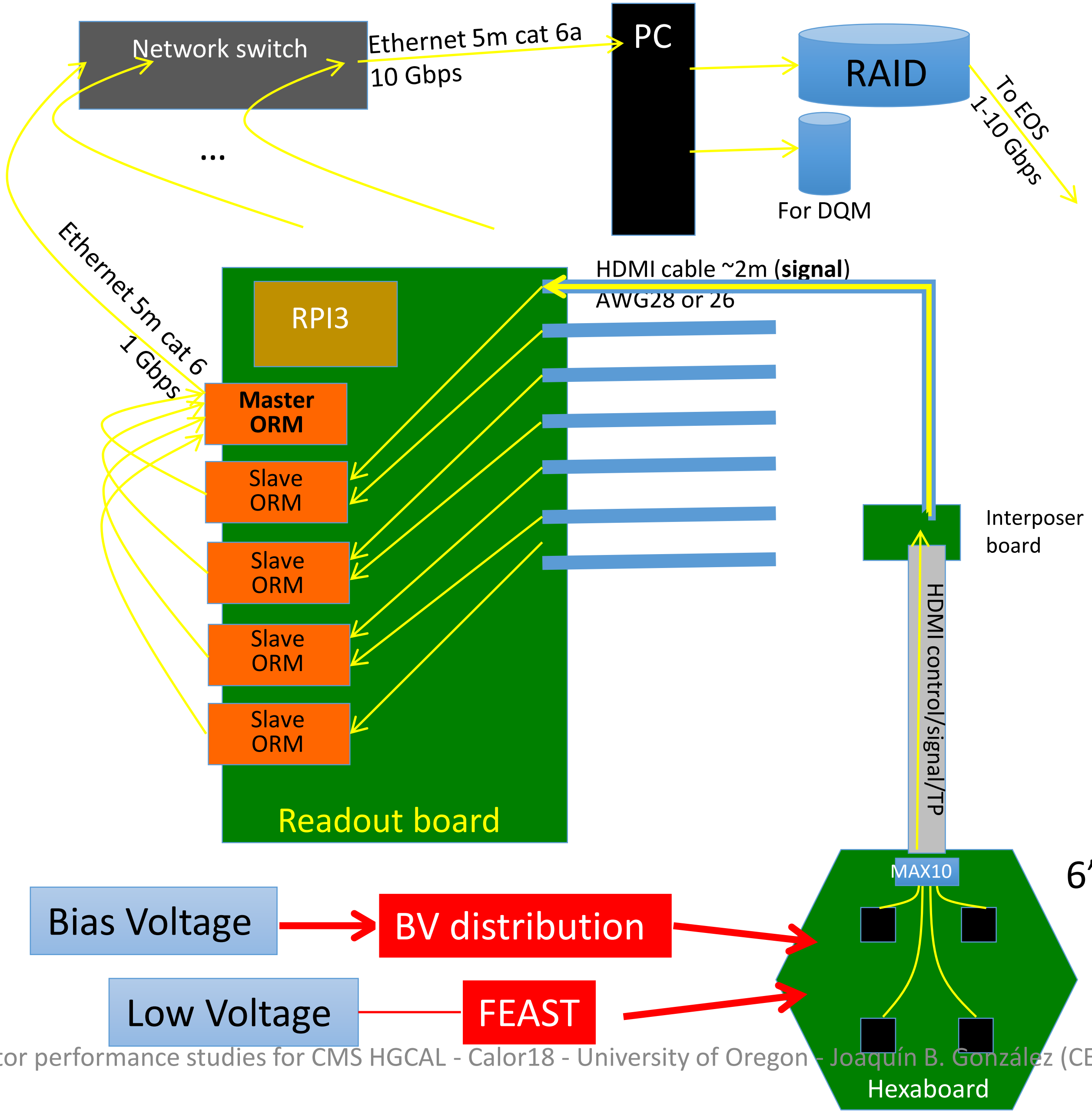
Step 1: Use FEAST for LV power



The DAQ is evolving following the schedule

But there are still a few steps more

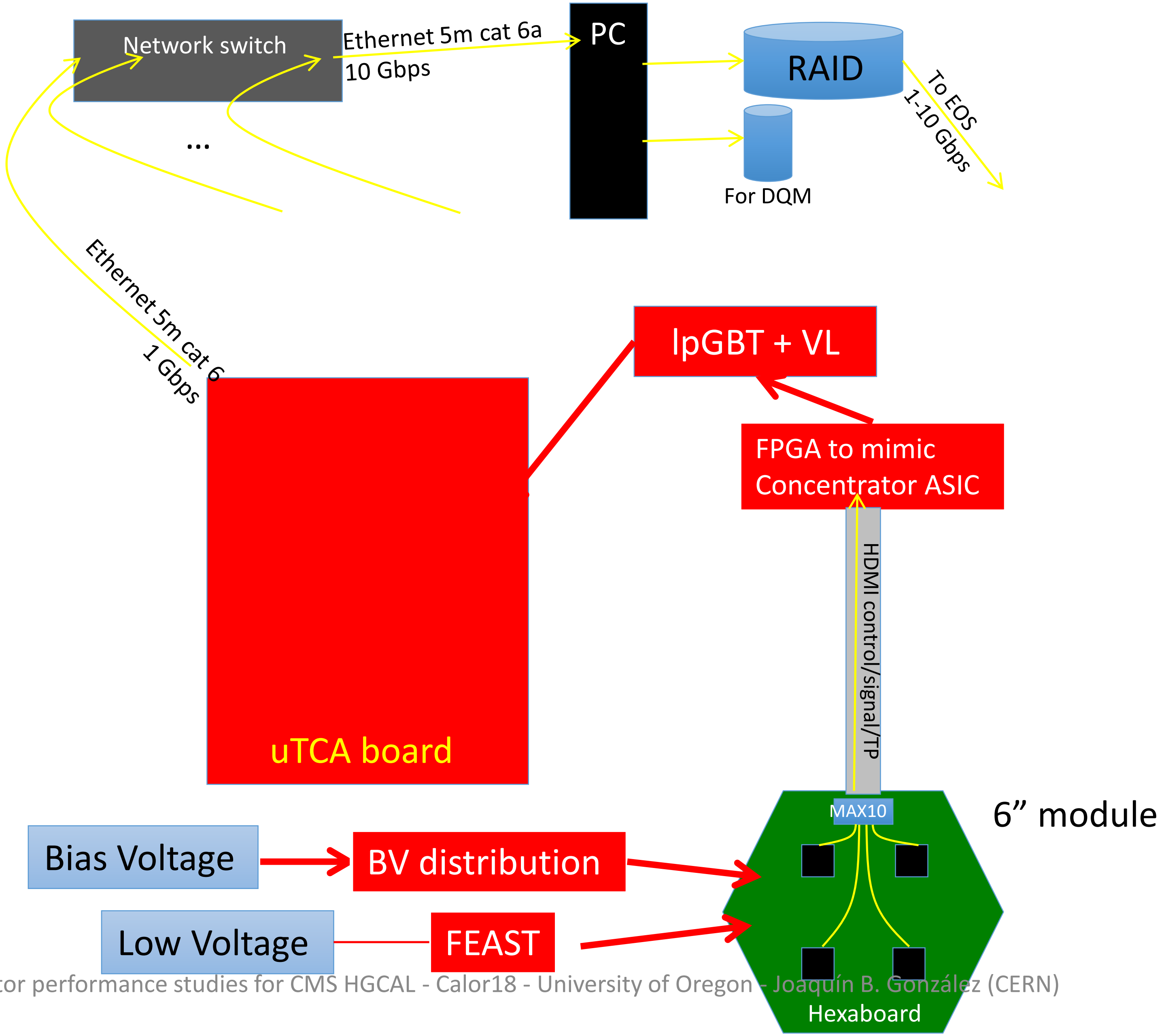
Step 2: move BV distribution away from proprietary board



The DAQ is evolving following the schedule

But there are still a few steps more

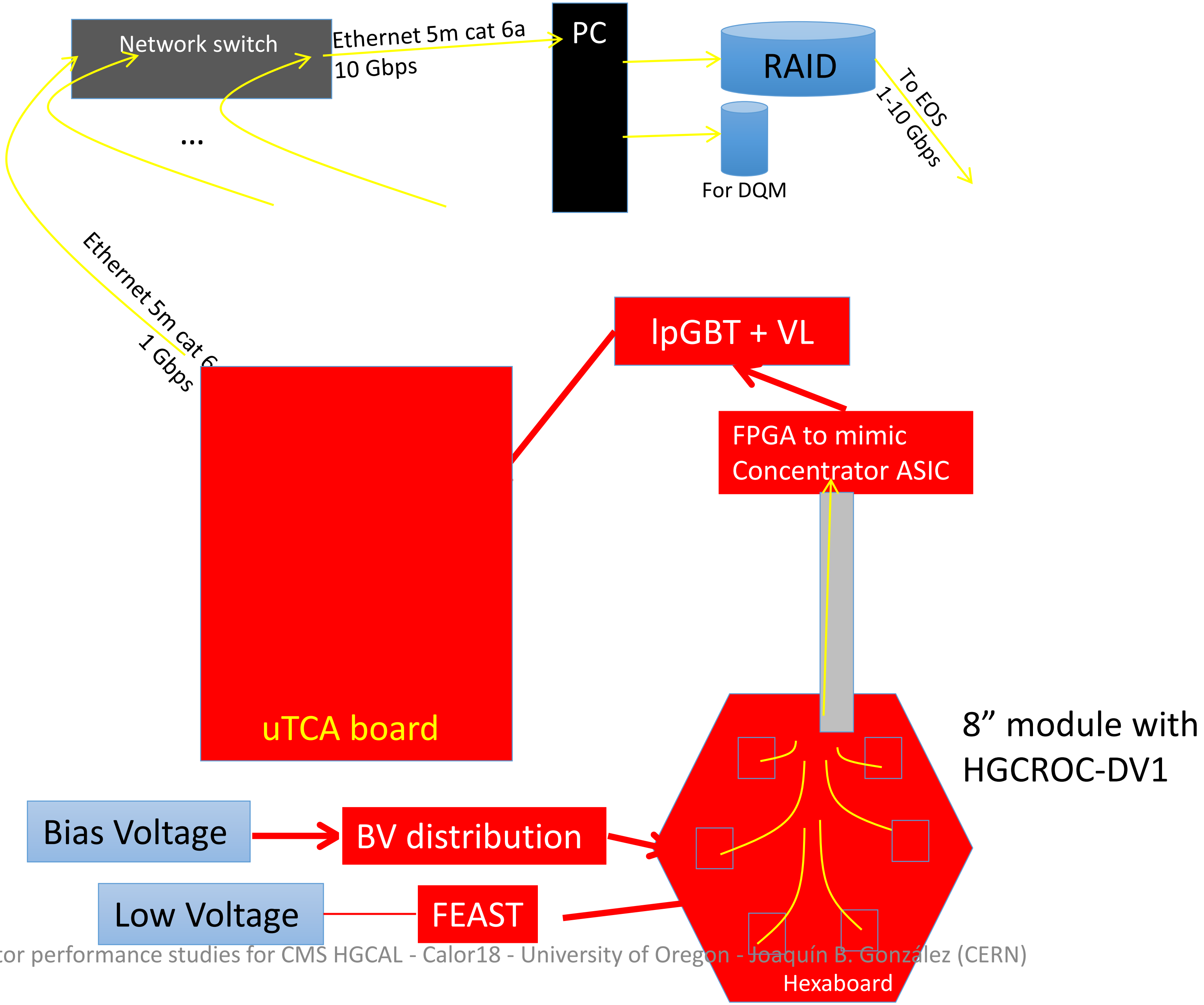
Step 3: lpGBT+VL with FPGA mimicking concentrator ASIC



The DAQ is evolving following the schedule

But there are still a few steps more

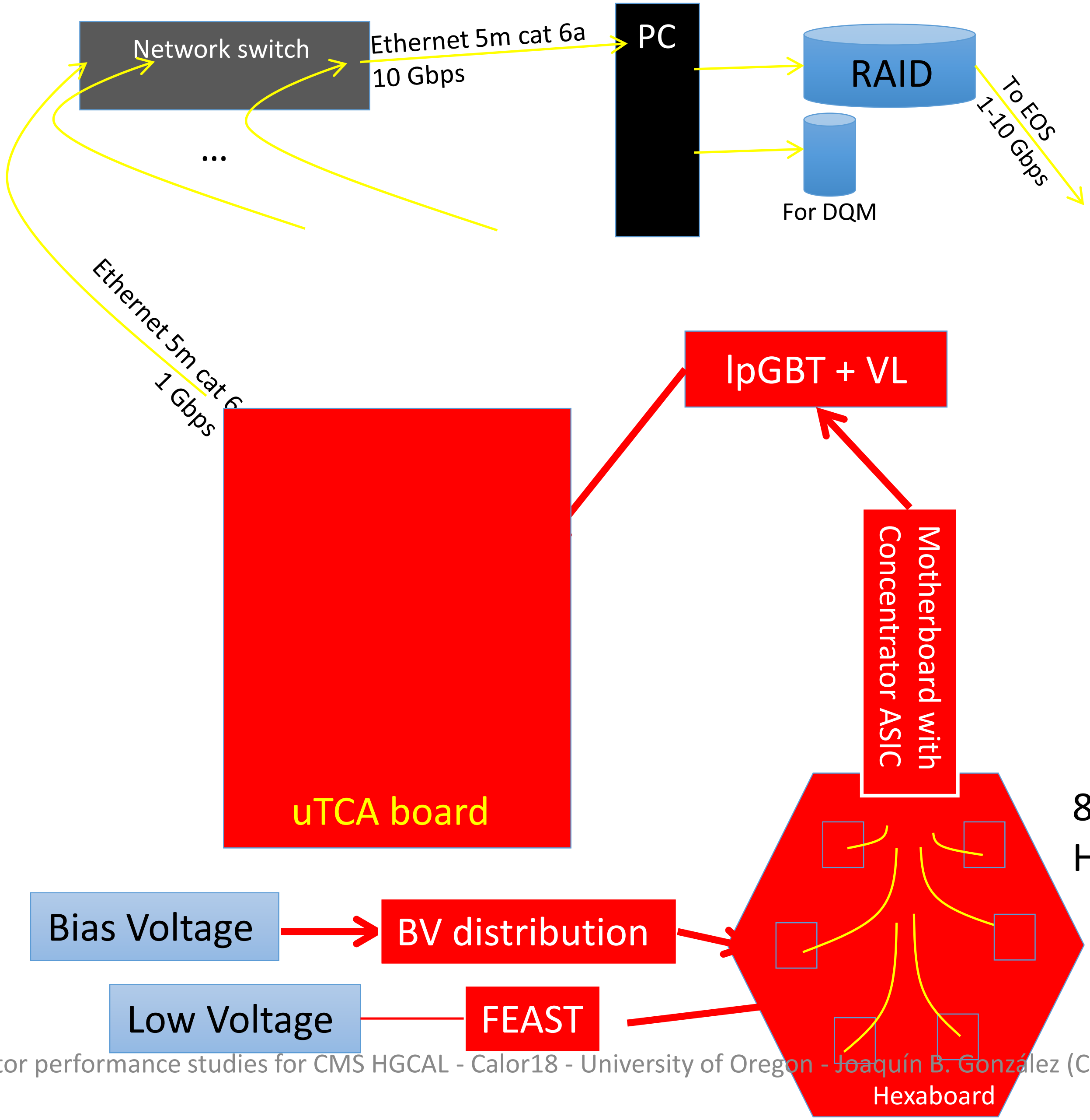
Step 4: use 8” module with HGCROC-DV1



The DAQ is evolving following the schedule

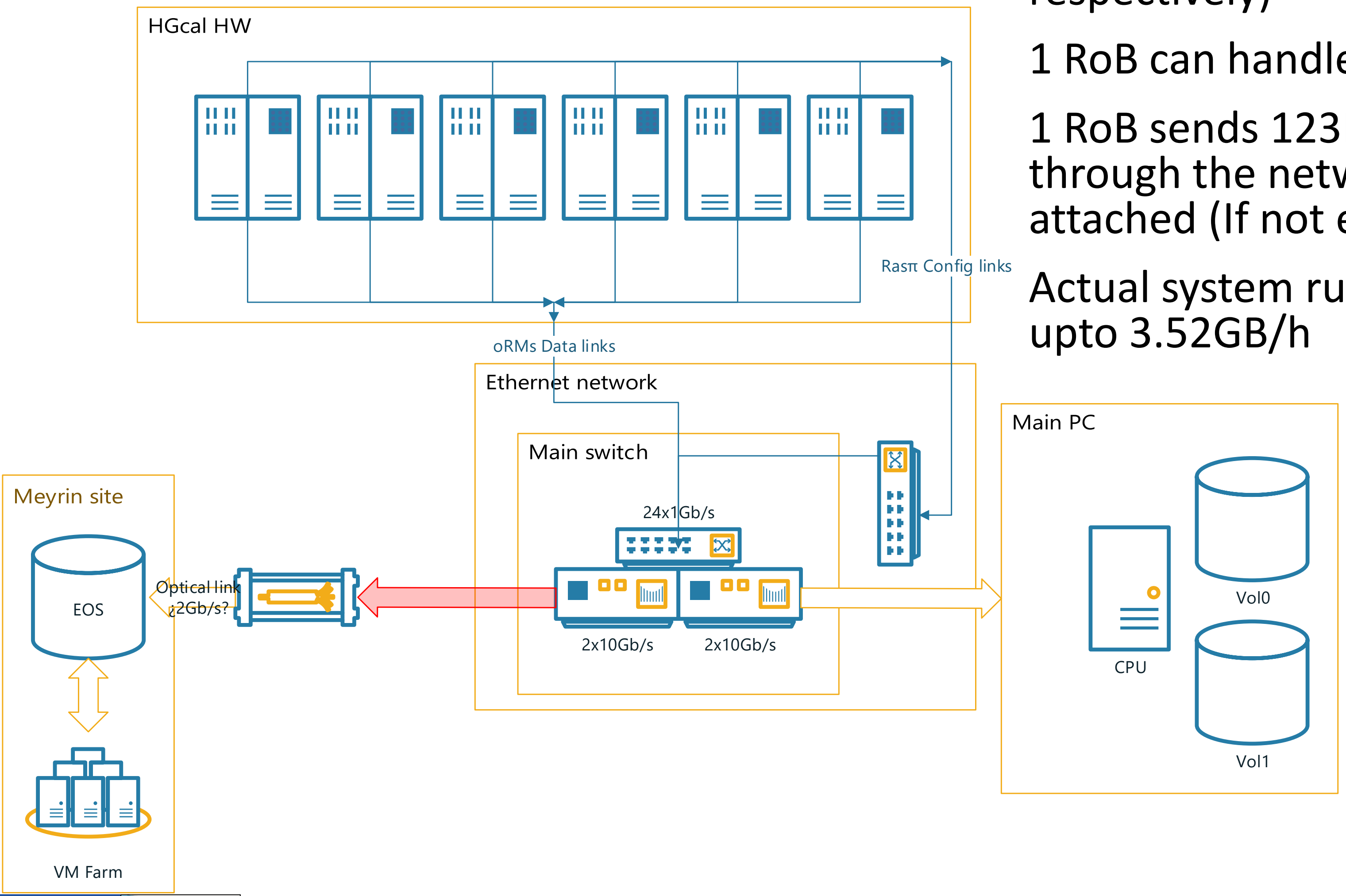
But there are still a few steps more

Step 5: use motherboard & concentrator ASIC



Highlights from the Backend of testbeam DAQ

As it is on 2018



Biggest test beam we had 20 HexB with 3 RoB (8, 5 and 7 respectively)

1 RoB can handle up to 8 HexB

1 RoB sends 123KB of raw data (plus headers <150KB in total through the network) no matters how many HexB there are attached (If not existing, it fills up with zeros, timestamps, etc.)

Actual system runs around 50Hz ~> 6MB/s => 30.01MB/spill => upto 3.52GB/h

It can easily cope with 5 RoB. Capable up to 10 (not recommended). Farther than that, some modifications are needed (with actual ratio and dataflow). All future (solutions) modifications are already designed and prepared waiting for when we need them (Raid, HDD swapping, 10Gb/s electrical and optical links)

Safety system for laboratory & beam tests

PLC & WinCC-based monitoring, alarming and control (interlock) systems

Trialing new radiation-hard compact environmental sensors for humidity/temperature

Monitoring power supplies and cooling system, with automated actions including alarming, interlock, and other safety features.

Also feeds up web based user interface for shifters info and On call responsibles

New laboratory space in building 186 @CERN close to DSF, climatic chambers, TIF…

Two (joined) lab spaces equipped with anti-static flooring, climate control, air purification

Ready by ~June 2018

Different facilities -> different beams

The particle beams available at FNAL and CERN were rather different and complementary, particularly for electrons

Electron purity (verified with simulation) greater than 97% with 95% pion rejection. Energy spread for e- less than 5%

Electron purity at CERN was always higher than 98% and increased with energy. Spreads on the energies below 1%

In addition to electrons, data were taken with 125 GeV protons at FNAL, whilst at CERN we had incident 125 GeV negative pions as well as muons. These latter were produced from 125 GeV π− decays and thus had a range of energies.

The rate capability of the DAQ chain was around 30-40 Hz. In addition to “physics” runs, data were taken when the beam was not present, in order to estimate pedestals, noise and stability

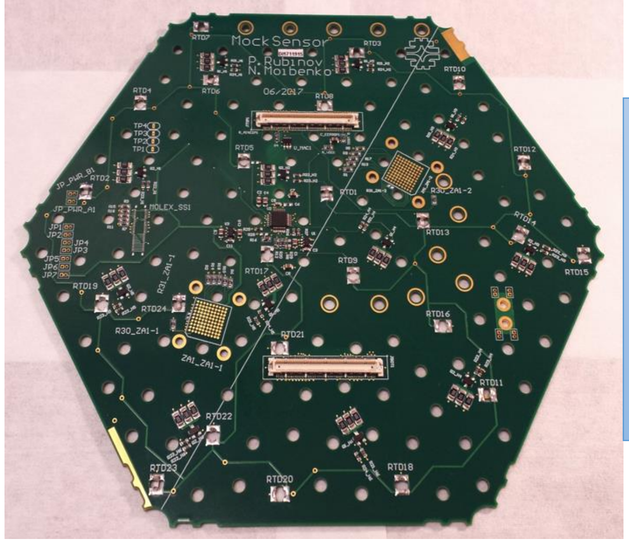
At both FNAL and CERN the main trigger source was plastic scintillators. At FNAL a single 2 × 2 cm2 scintillator was used, with two SiPMs as readout devices in coincidence. At CERN two consecutive scintillators with PMT readout

readout were used in coincidence, with the one closest to the detector defining the trigger size, at 4 × 4 cm2.

	e^-												π^-	p^+	μ^-
Energy (GeV)	4	6	8	16	20	24	32	70	100	150	200	250	125	120	30-120
FNAL	X	X	X	X	X	X	X							X	
CERN					X		X	X	X	X	X	X	X		X

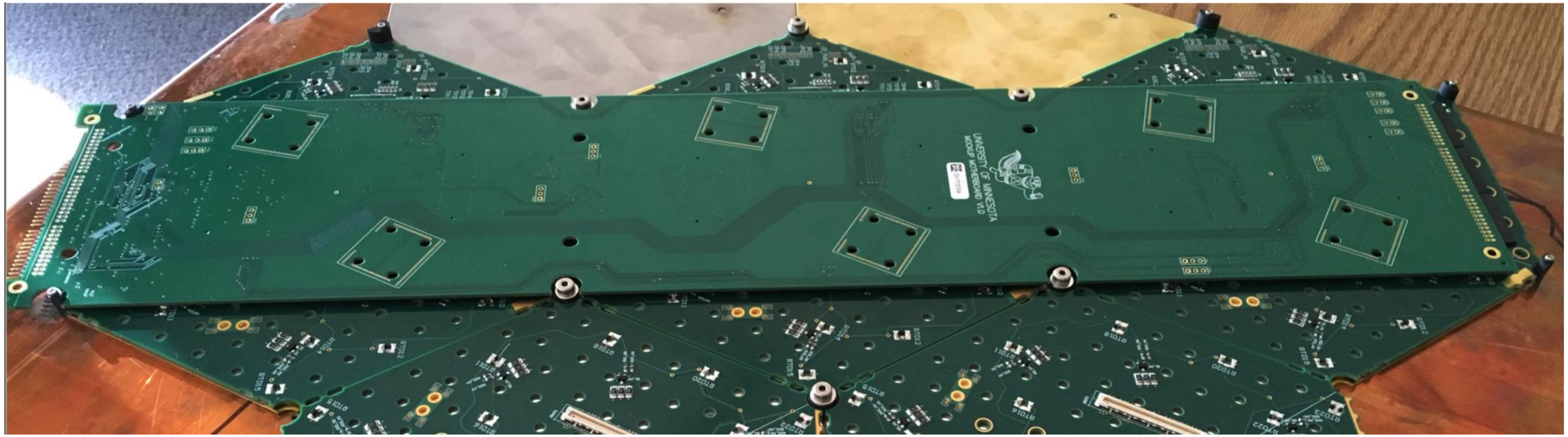
Table 1: Data taken at FNAL and CERN in 2016

@FNAL “dummy” cassette being assembled with PCBs containing only connectors and heat loads

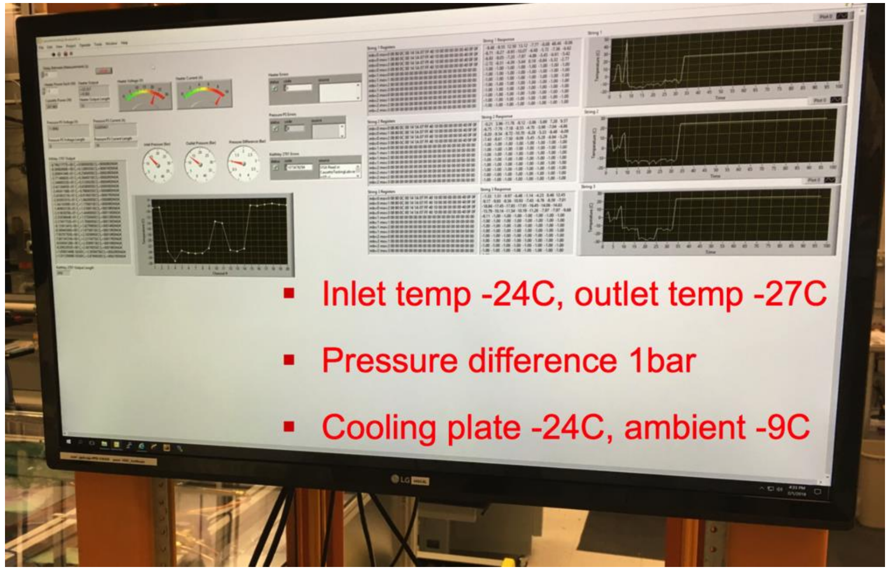


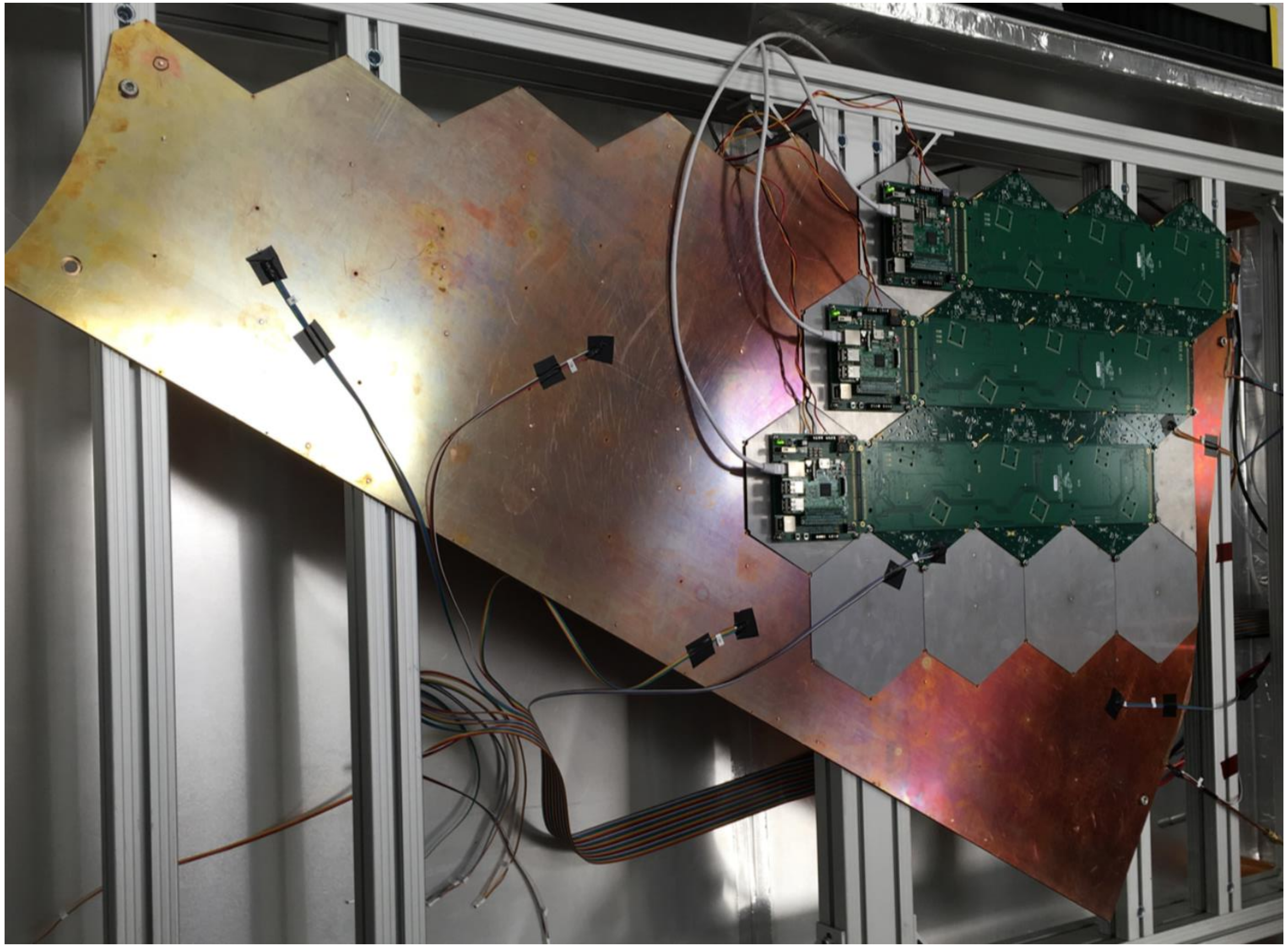
8” hexagonal PCBs glued to silicon and baseplates → **modules**
3 modules connected to a single “**motherboard**” providing power, data concentrator and optical links

Studying **connectivity, services layout, assembly procedures** etc.



Dummy cassette is installed in a cold box to study heat-transfer characteristics – works well!





MIP calibration constants per HexB for 2017 muon runs

Shown at DPG 2018

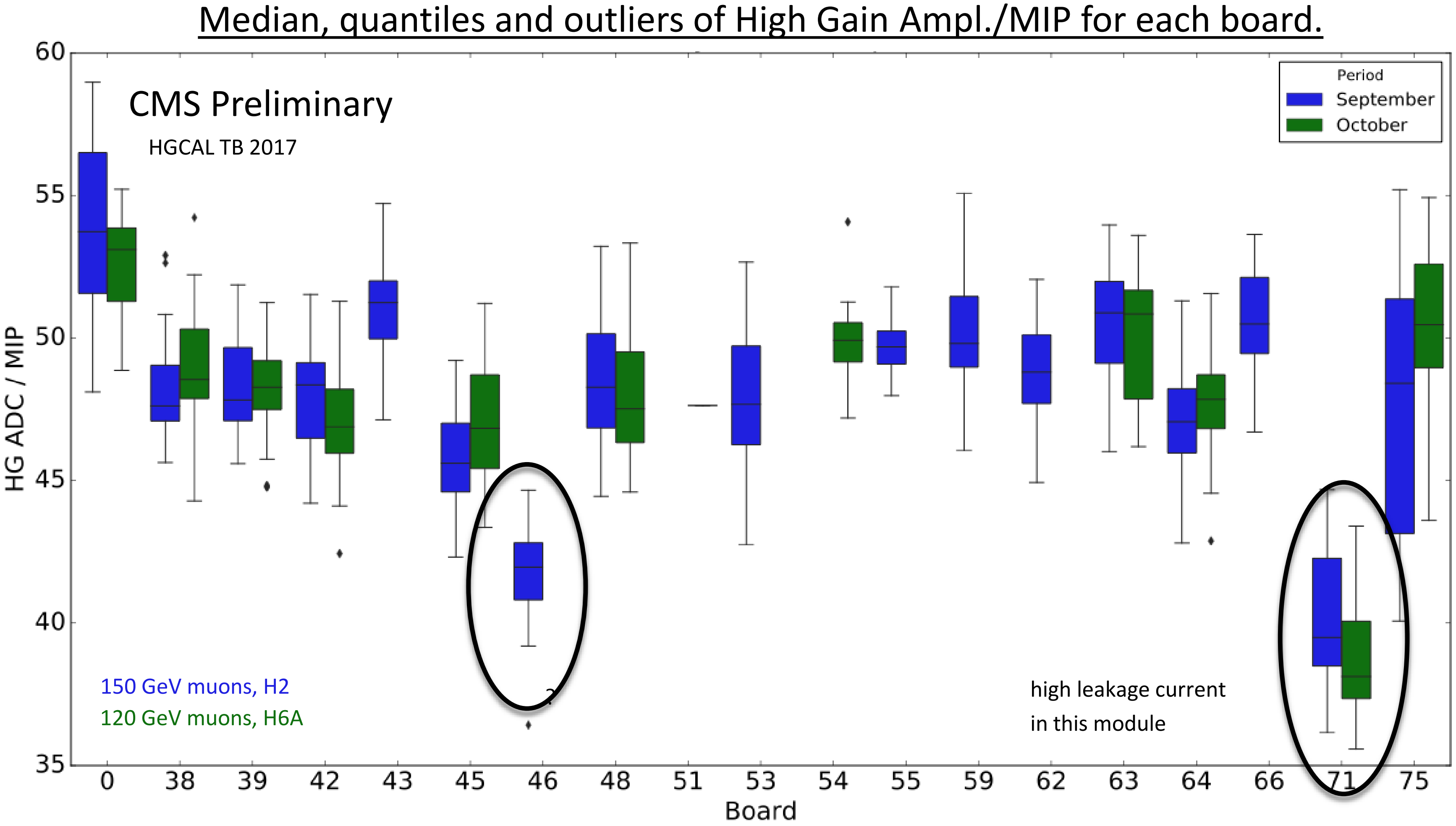
ONGOING WORK!!!

Several modules behaves much worse than the rest due to production (mainly) and other bugs

But apart from them, no relevant board-to-board variations were found after two month stored

Deep studies on modules 46 and 71 gave answers for changes in the design and the production processes

All of the modules responds mostly the same in different periods for the same tests (even the bad ones)



Where are we going next? Building the big guy

CMS Internal note published about 2016 and 2017 test beams [DN2017_011_v6]

TDR already released: TDR-17-007-Dec22

System mostly debugged, in PCB design, ASIC performance, calibration, data handling, data transmission and storing, mechanics, building process… Everything almost ready for production

During second half of 2018, we aim to equip a prototype mimicking th full CE-E (28 layers) and 12 CE-H silicon layers with at least 4 hexagonal modules equipped with the Skiroc2-CMS ASIC (76 modules in total). The CALICE AHCAL will again complement the silicon for the required hadronic depth (hadronic shower in 100ps precision)

Also plans for upgrading with the final ASIC when available, as for the rest of pieces of the final powering and readout chain.

Since CERN testbeam area won't be available in 2019/2020, facilities at FNAL and DESY will be increasingly valuable for further tests.