CHEF Conference in Lyon 2017

Construction and beam-tests of silicon-tungsten prototype modules for the CMS High Granularity Calorimeter for HL-LHC

On behalf of the CMS Collaboration

Thorben Quast

III. Physikalisches Institut

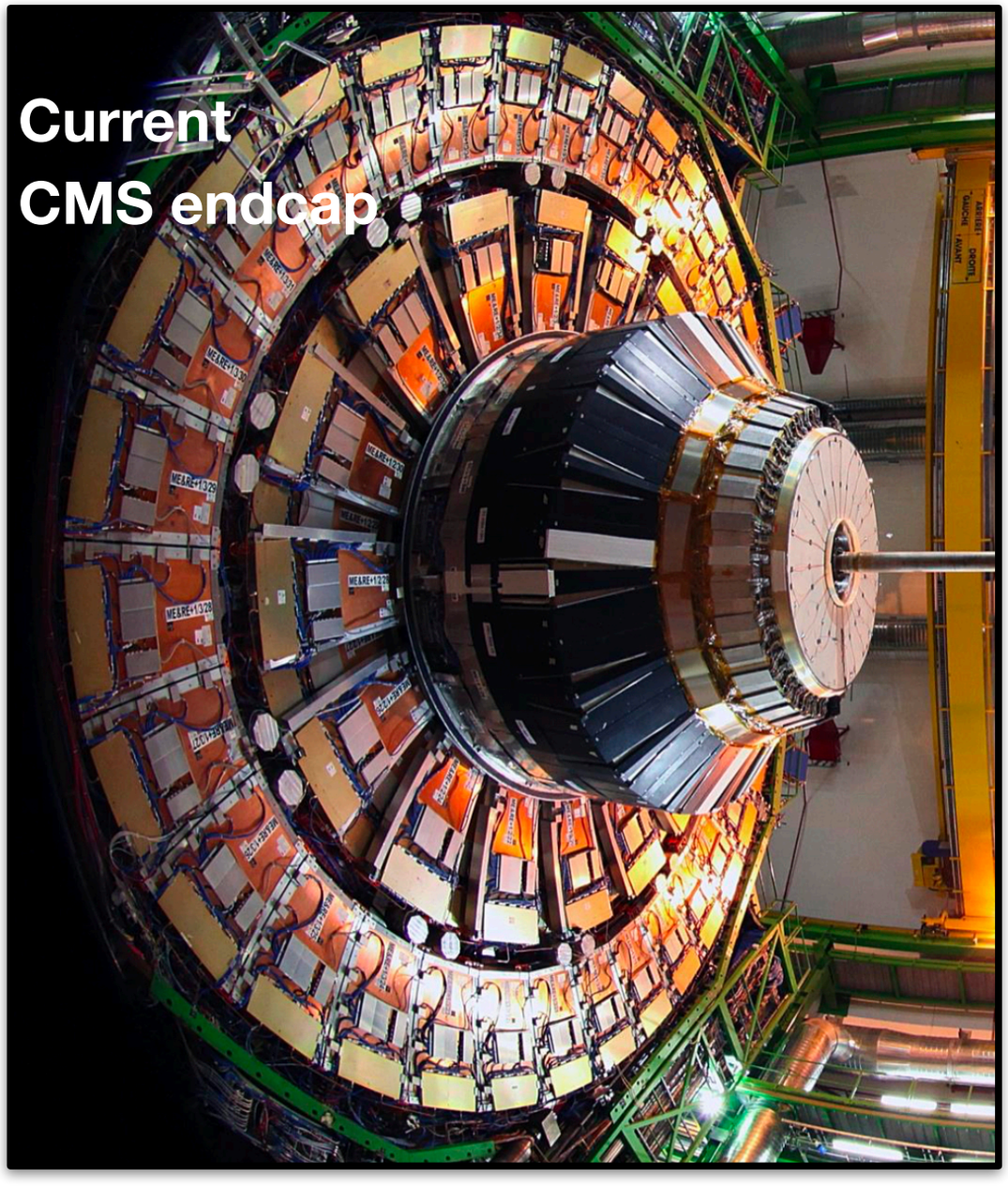
RWTH AACHEN UNIVERSITY

06 Oct 2017

Endcap calorimeters must be upgraded for HL-LHC

Calorimeters designed for radiation dose equivalent to 500fb^{-1}.

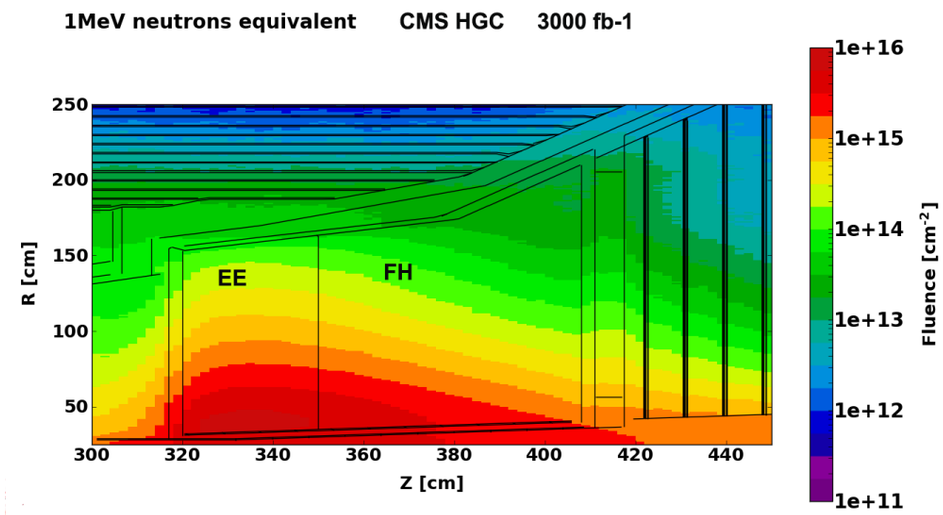
➡ Replacement of CMS' complete endcap calorimeter during HL-LHC upgrade.

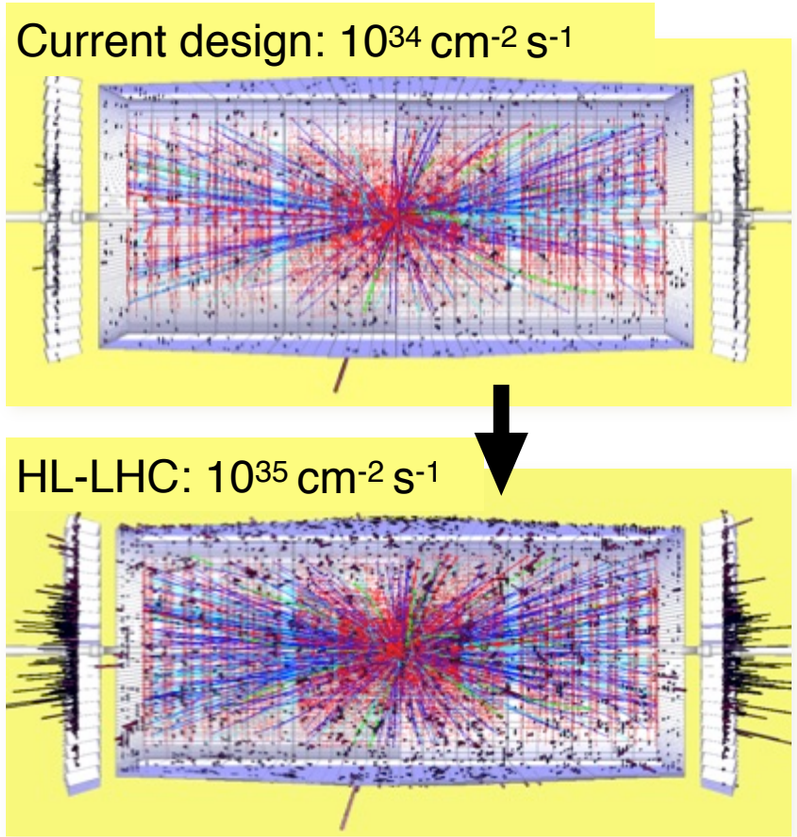


Radiation hardness

Increased pileup

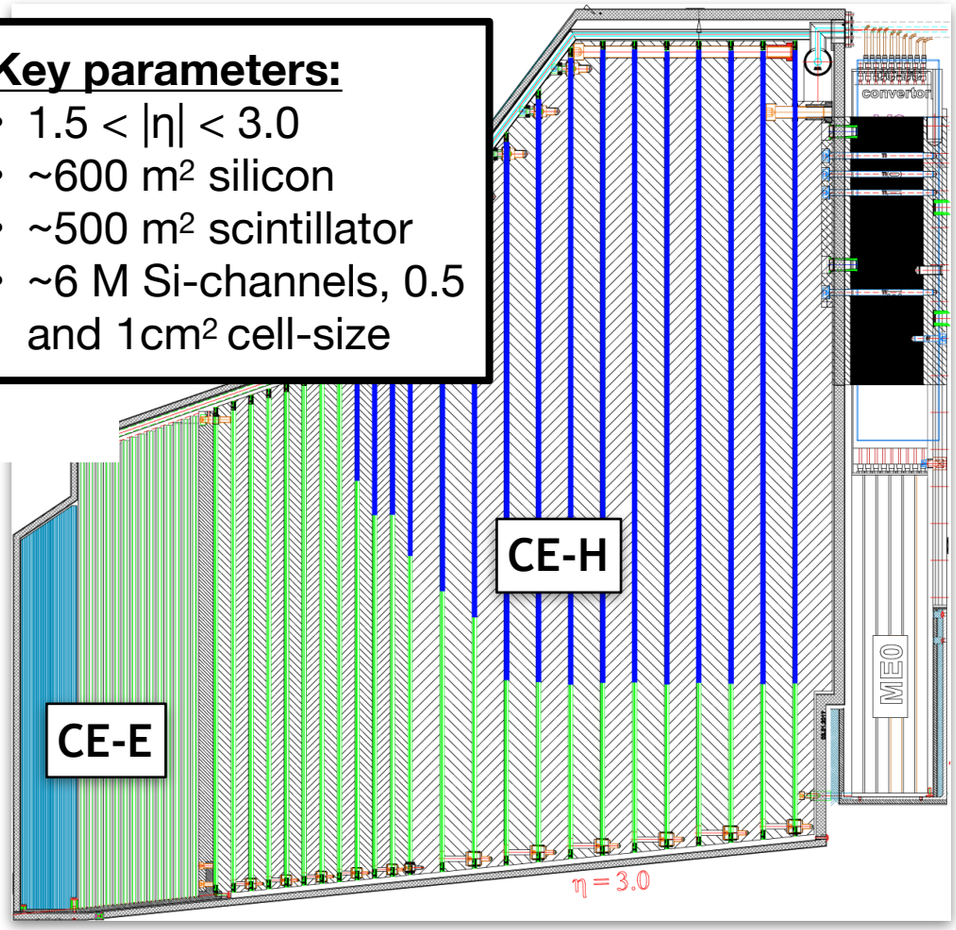
HL-LHC Conditions





CMS HGCAL related talks at this conference

Key parameters:
- $1.5 < |\eta| < 3.0$
- ~600 m^2 silicon
- ~500 m^2 scintillator
- ~6 M Si-channels, 0.5 and 1cm^2 cell-size



	Sensor	Absorbers	Sampling layers & depth
CE-E	silicon	Cu, CuW, Pb	28: 25 X_0, ~1.3 λ
CE-H	silicon & scintillator	stainless steel	24: ~8.5 λ

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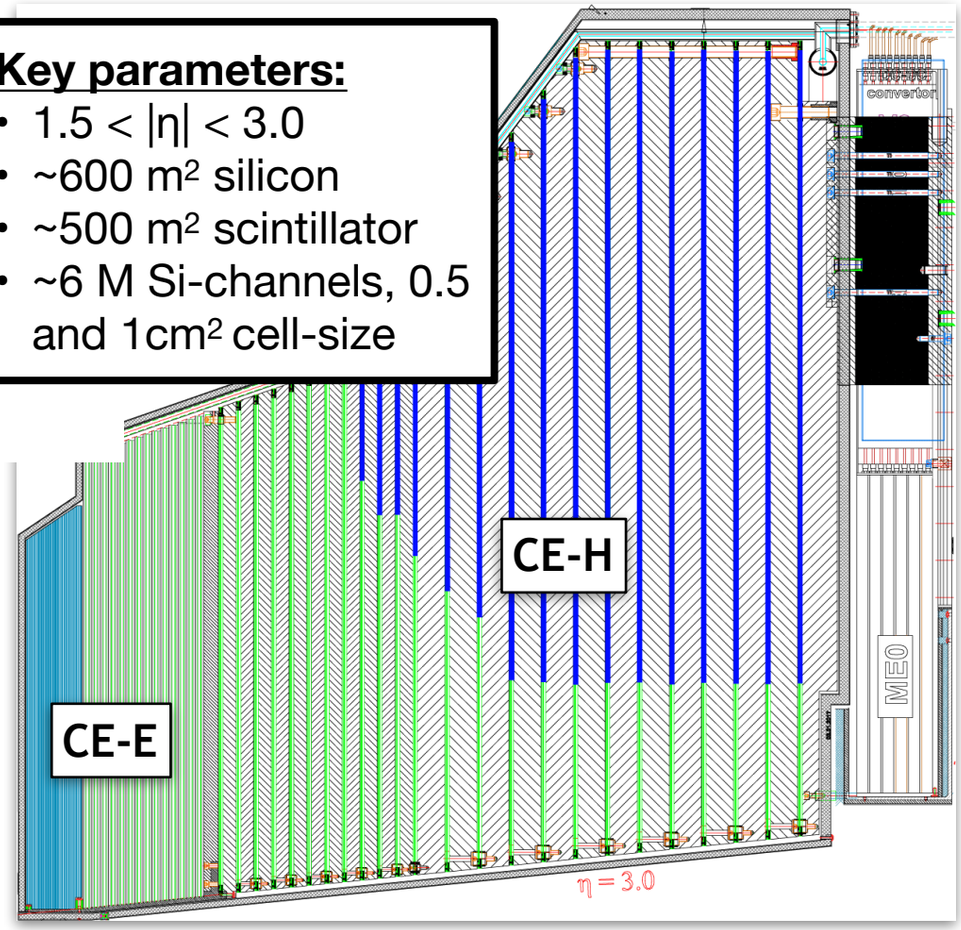

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The other four HGCal related talks at CHEF 2017

1. *"The CMS HGCAL detector for HL-LHC upgrade"*, Jean-Baptiste Sauvan, 03 Oct at 11:30.
2. *"Electronics and triggering challenges for the CMS High Granularity Calorimeter"*, Artur Lobanov (04 Oct at 10:10).
3. *"Large-Area Silicon Detectors for the CMS High Granularity Calorimeter"*, Elias Pree (06 Oct at 10:00).
4. *"Scintillator performance at low dose rates and low temperatures for the CMS High Granularity Calorimeter for HL-LHC"*, Francesca Ricci-Tam (06 Oct at 10:20).

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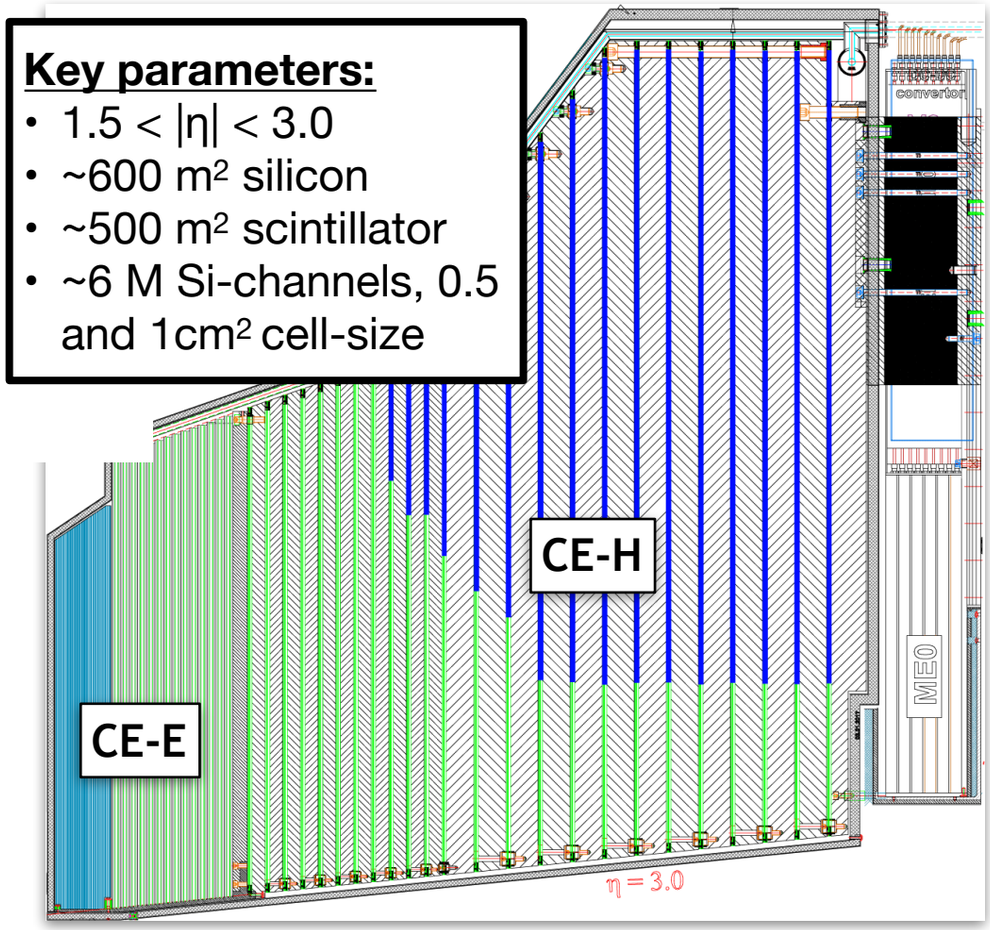

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➡**This talk: HGCal beam tests**

✓Successful series of beam test of CE-E part prototype at FNAL and CERN in 2016.

◉Extended setup including CE-H (Si) parts and CALICE AHCAL under test this year.

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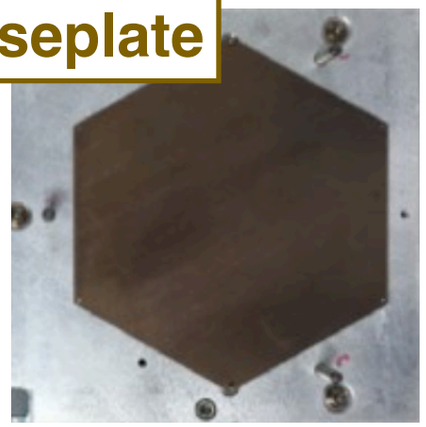
Module construction for the beam tests

- Module assembled as glued stack of **baseplate**, **Kapton**, **Si sensor** and **PCB**.

baseplate



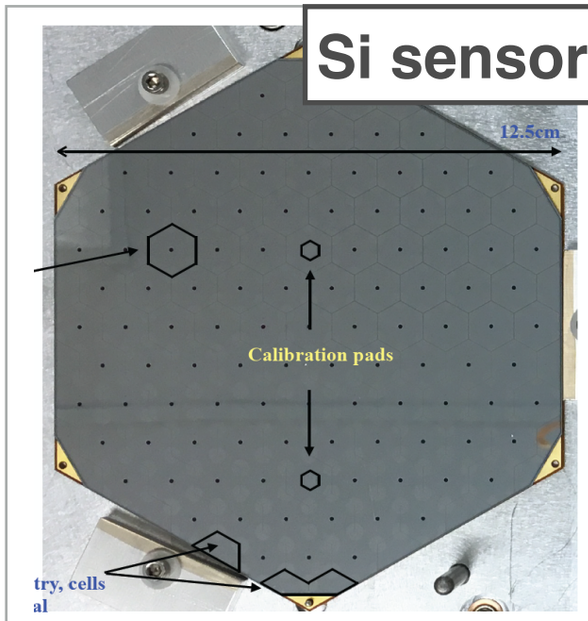
- EM: CuW
- Hadronic: Cu

Kapton

- Gold plated.

+

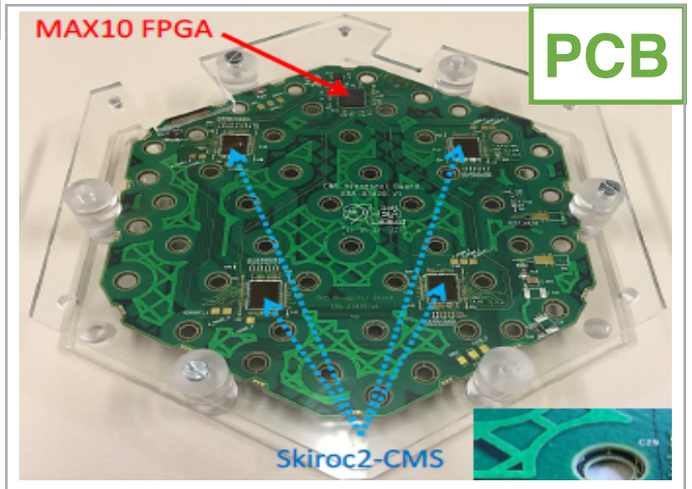
Si sensor



6” silicon sensors:

- n-type, 128 cells.
- 1 cm² cell-size.
- 300 µm depleted region.

PCB



- **Skiroc2-CMS** ASIC, 64 ch., 4 chips/module
- Developed for CALICE and adjusted for CMS requirements.
- Skiroc2 ASIC in 2016, 2 chips/module.

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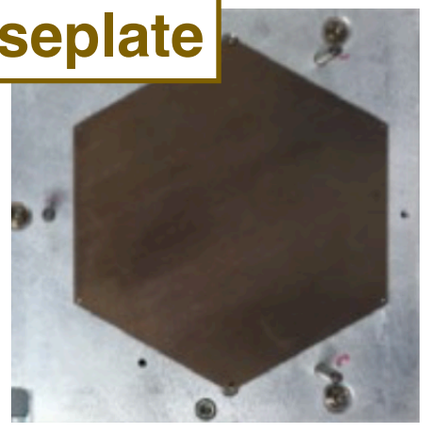

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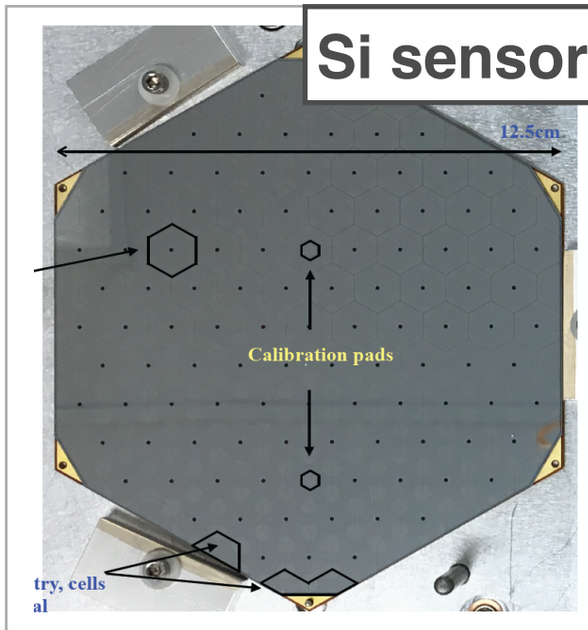

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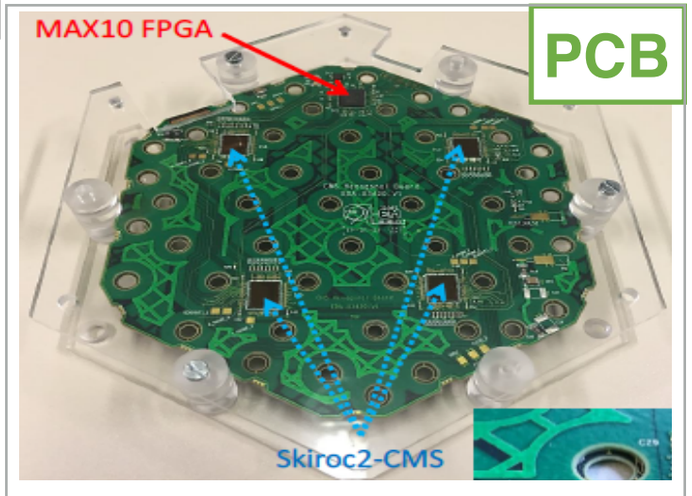

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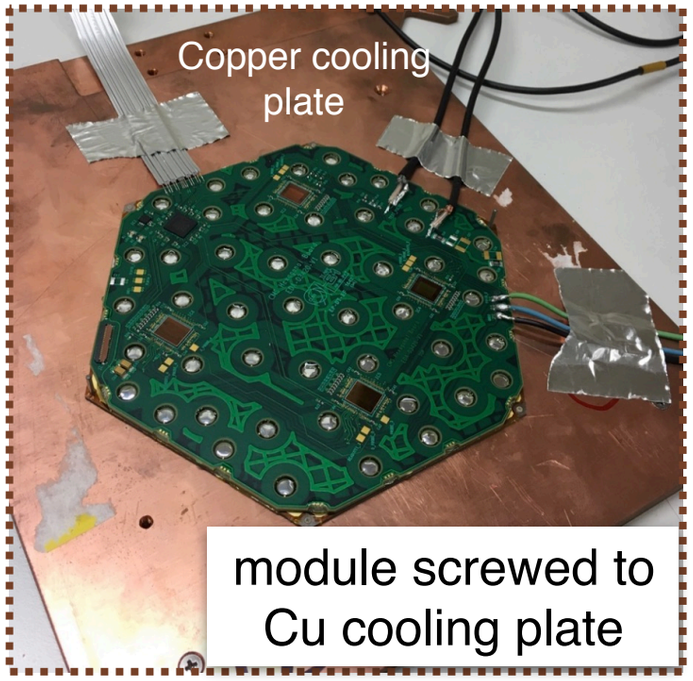
gluing

wire bonding



module screwed to Cu cooling plate

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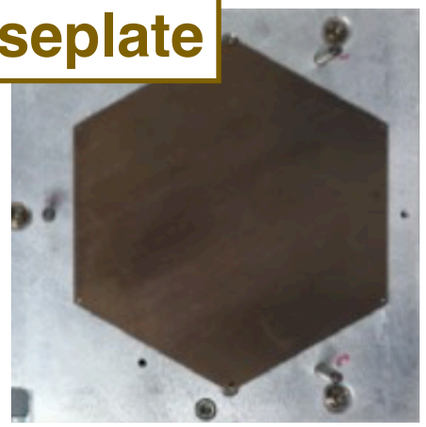

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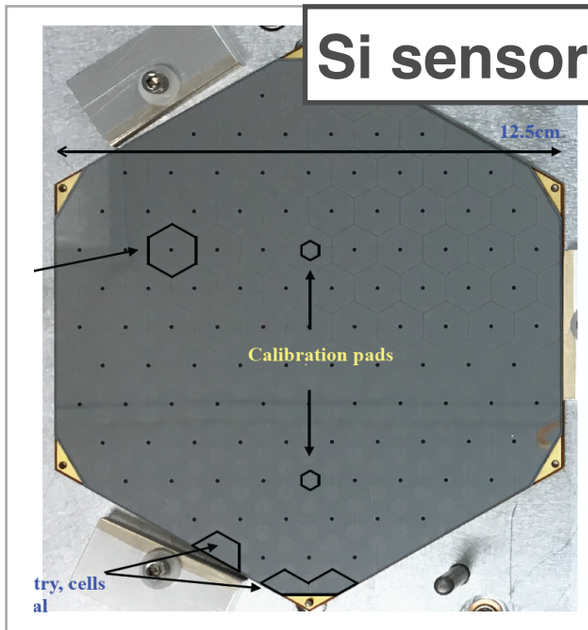

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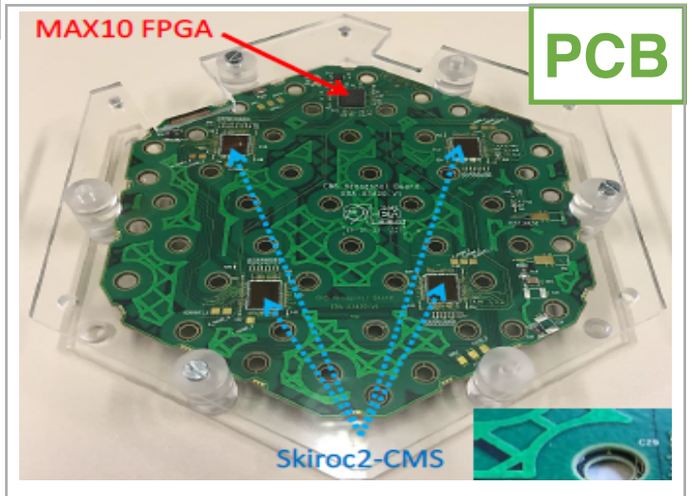

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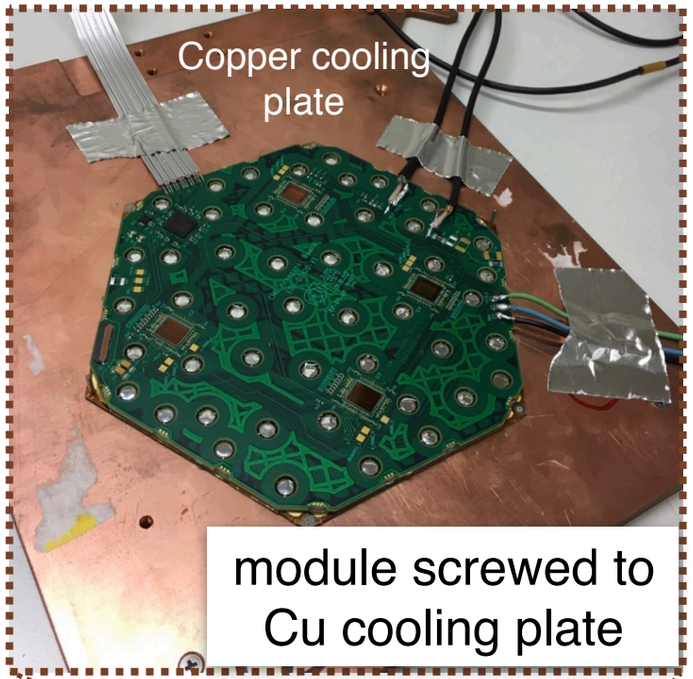
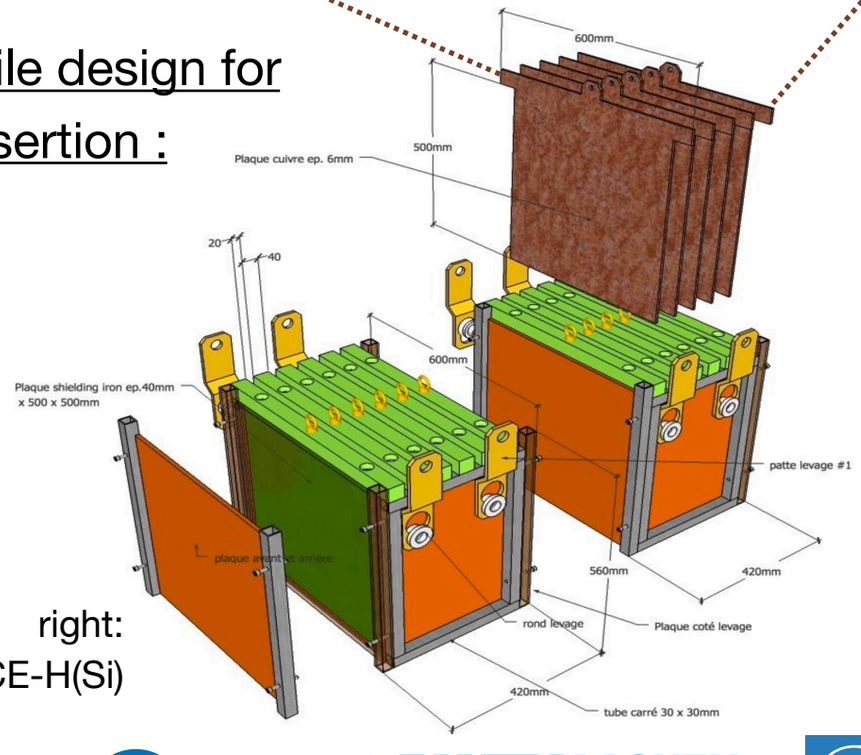


module screwed to Cu cooling plate

Hanging file design for flexible insertion :



right: structure for CE-H(Si)

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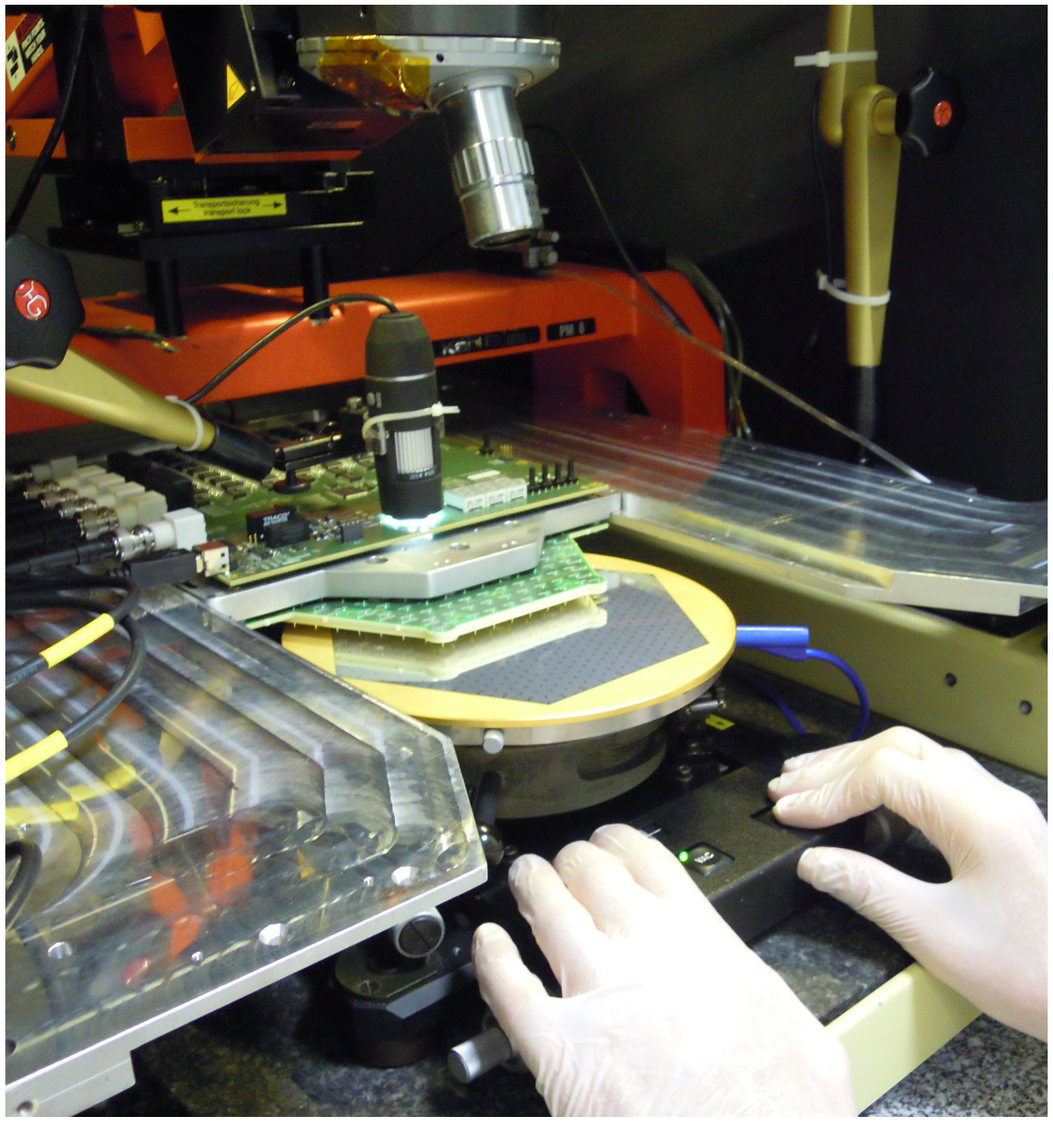
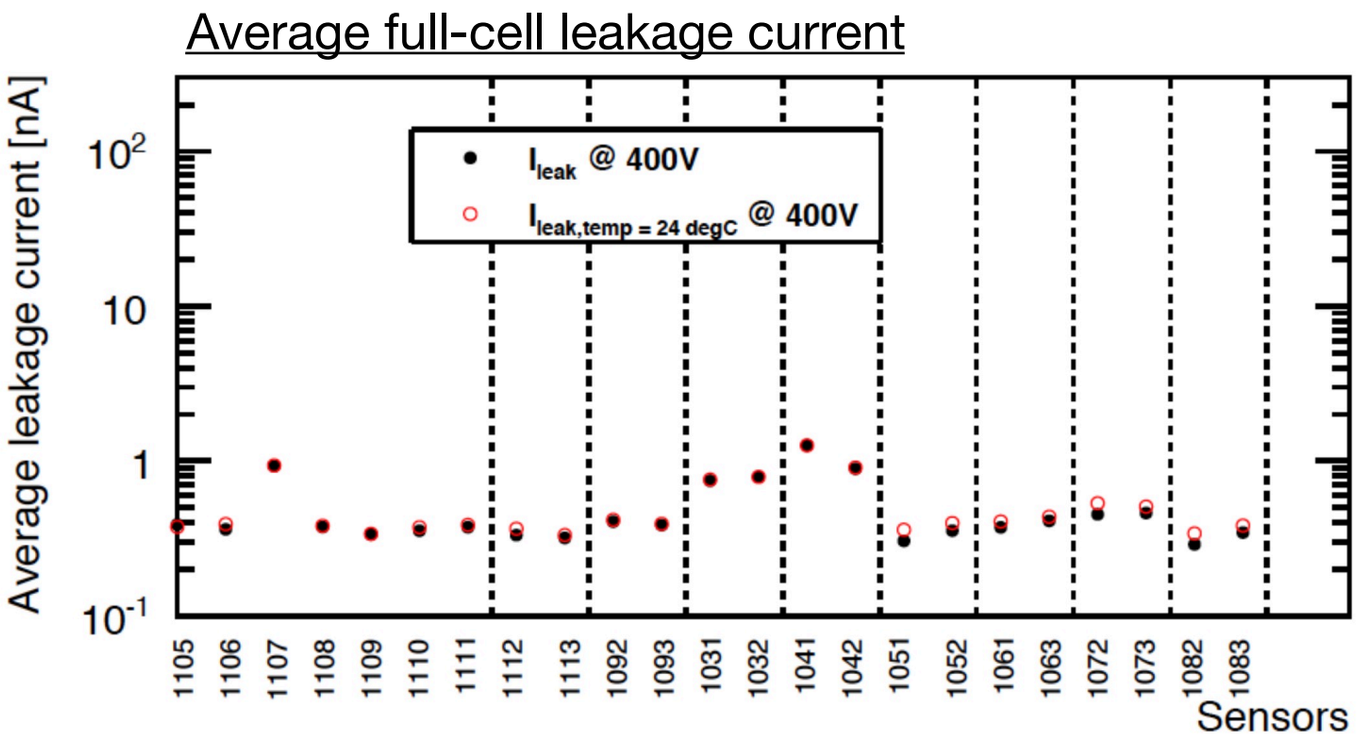
Tests of silicon sensors at CERN

➡ Perform IV and CV measurements on probe station at FNAL and CERN to characterise sensors used in test beam.

Probe-card measurement in probe station @CERN



+ Contact all cells with spring-loaded pins.
+ All neighbour cells biased.
+ Automatic switching between cells through custom designed switching unit.



! More on the HGCAL sensors by Elias Pree in his talk "*Large-Area Silicon Detectors for the CMS High Granularity Calorimeter*" today at 10:00.

Setup and results with the CE-E prototype in 2016

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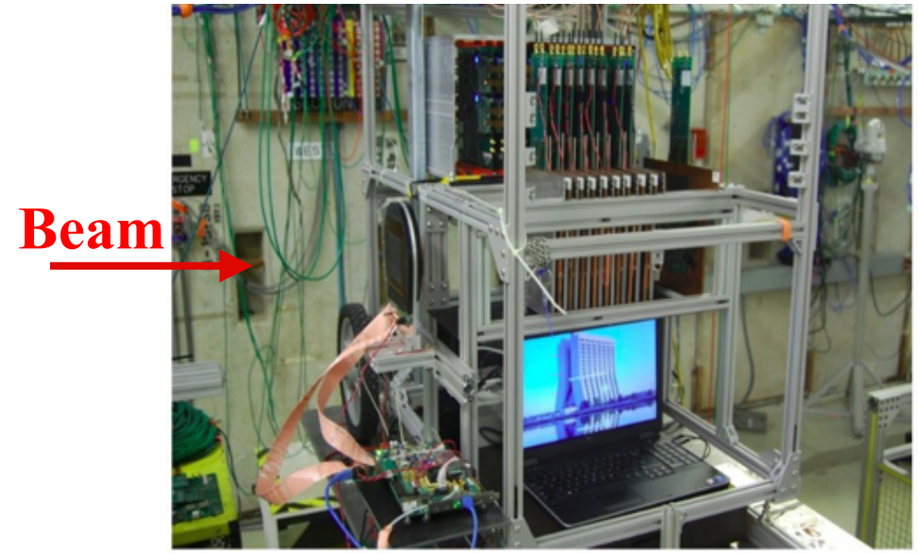
Tests of CE-E with beam setups at FNAL and CERN

- Common effort between CERN and FNAL in test beams 2016 to test a CE-E prototype.

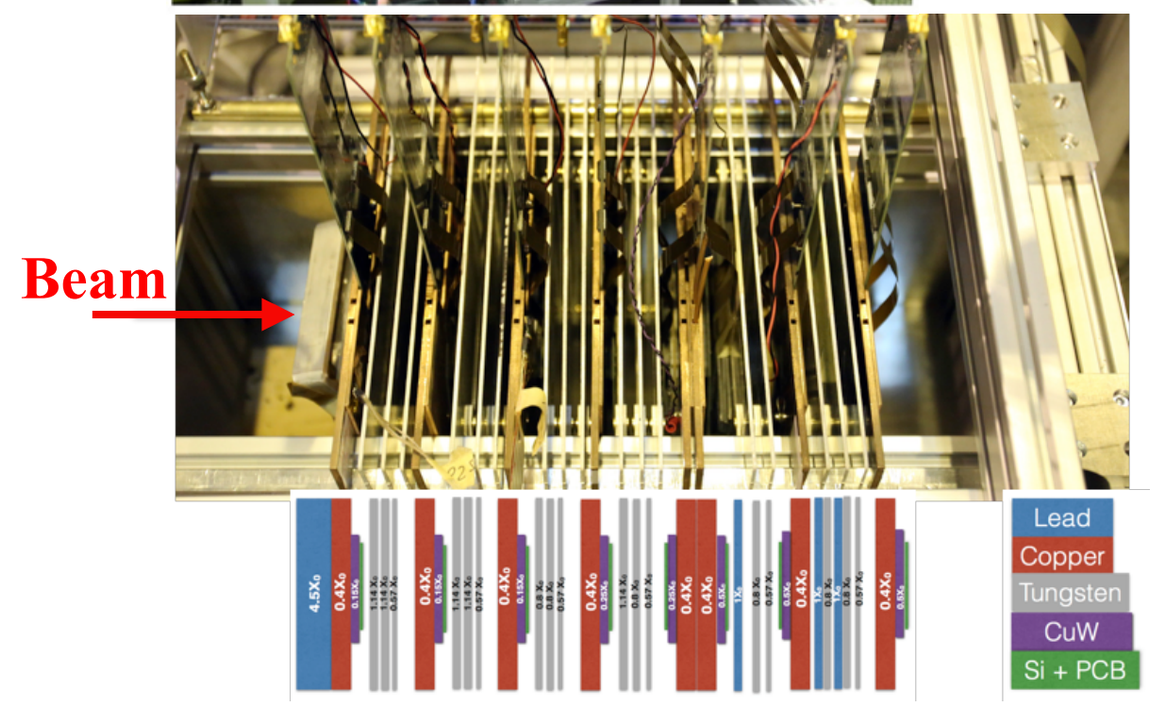
Fermilab

- Up to **16 HGC modules** tested.
- **Electron** beam with **4-32 GeV**.
- **0.6-15 X_0 tungsten** absorber configuration.
- 120 GeV protons.



CERN

- Up to **8 HGC modules** tested.
- **Electron** beam with **20-250 GeV**.
- **6-15 X_0 & 5-27 X_0 tungsten** absorber configurations.
- 125 GeV muons and pions.



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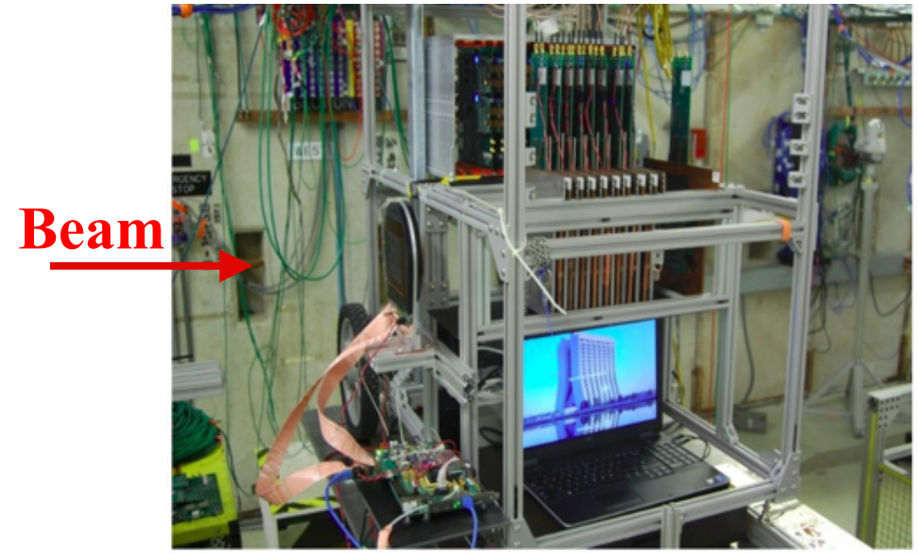

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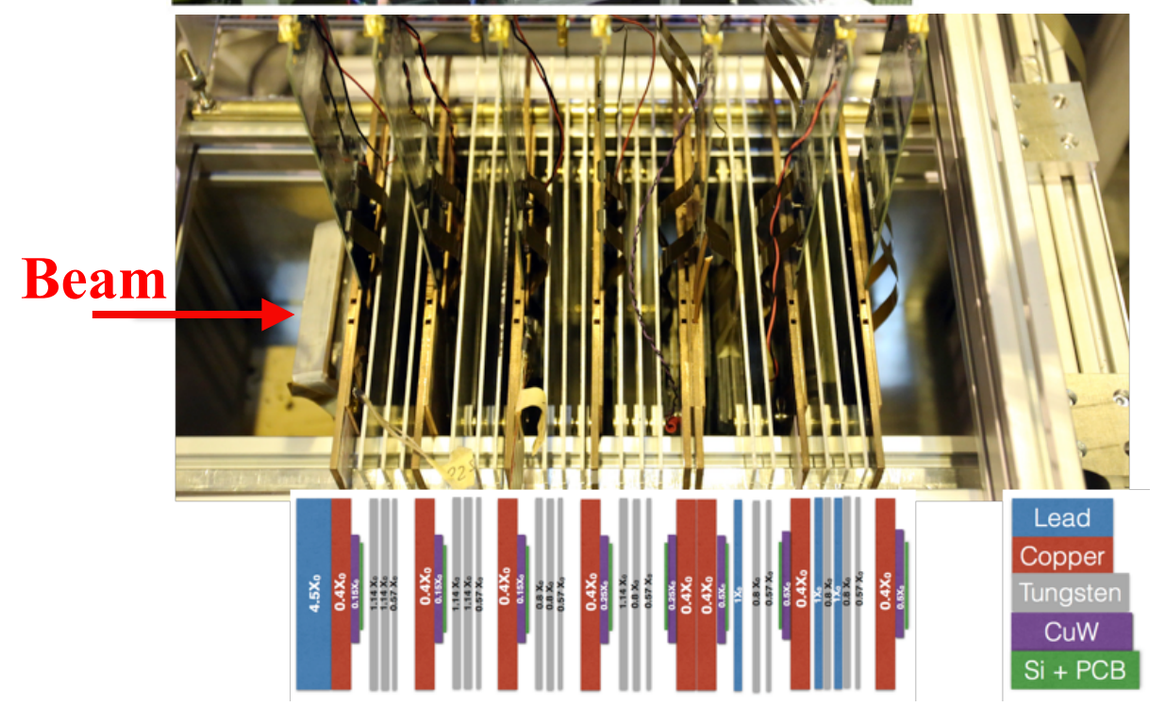


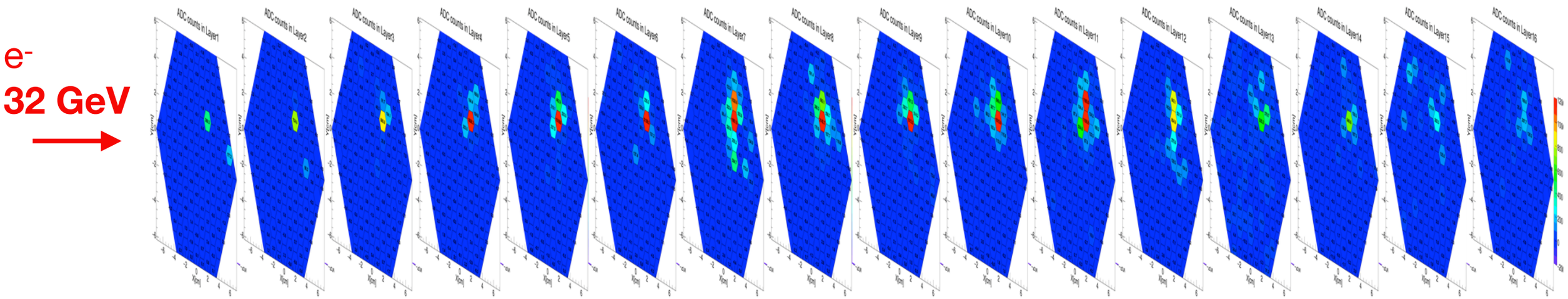
+ detailed GEANT IV based simulations for both setups

➡ Main goals for test beams 2016:

1. Proof of concept of the proposed design with a preliminary chip (*Skiroc2*).
2. Comparison of results to simulation.

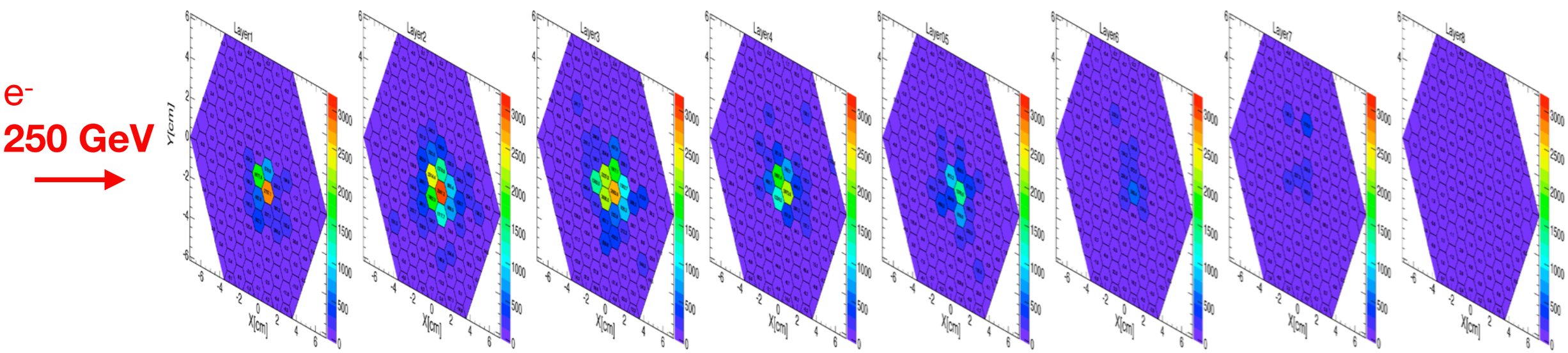
Electron induced showers visualised in 2016

Fermilab: **32 GeV electron** passing through **15 X_0**.



0.6 X_0 **15 X_0**

CERN: **250 GeV electron** passing through **27 X_0**.



5 X_0 **8.5 X_0** **12 X_0** **15 X_0** **17 X_0** **19 X_0** **21 X_0** **27 X_0**

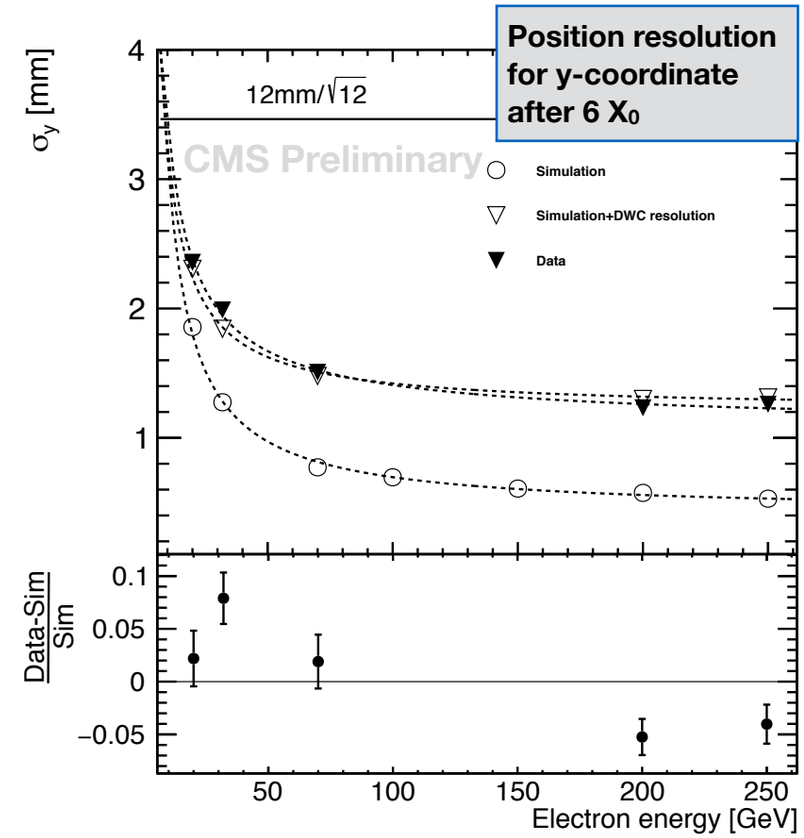
Results of 2016 are summarised

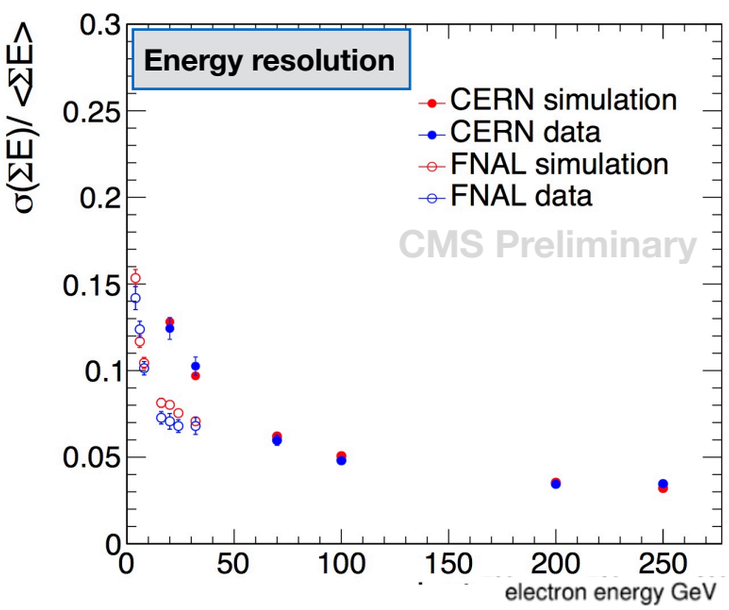
Main results from 2016 are documented for the technical design report and are targeted for publication in NIM/JINST:

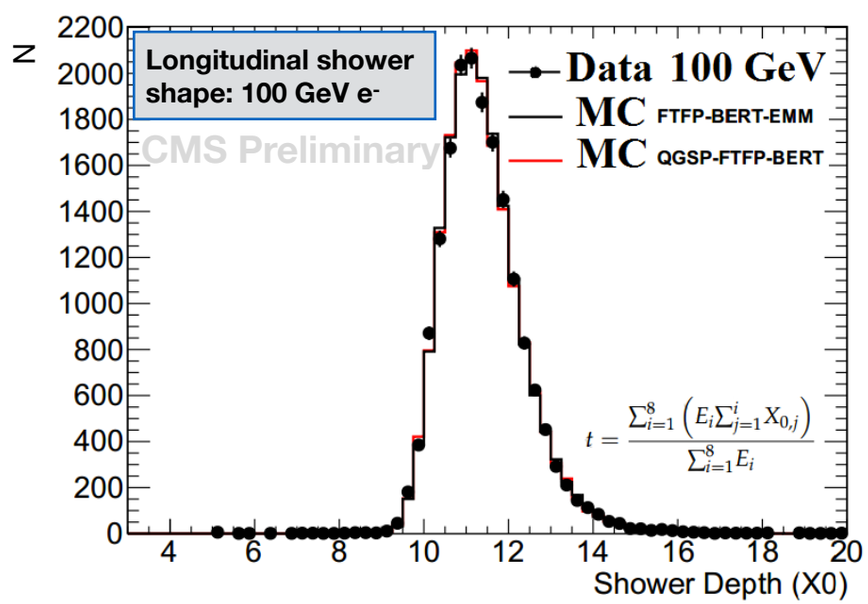
✓ Calibration, linearity, shower shapes and energy resolution of 8-16 modules.

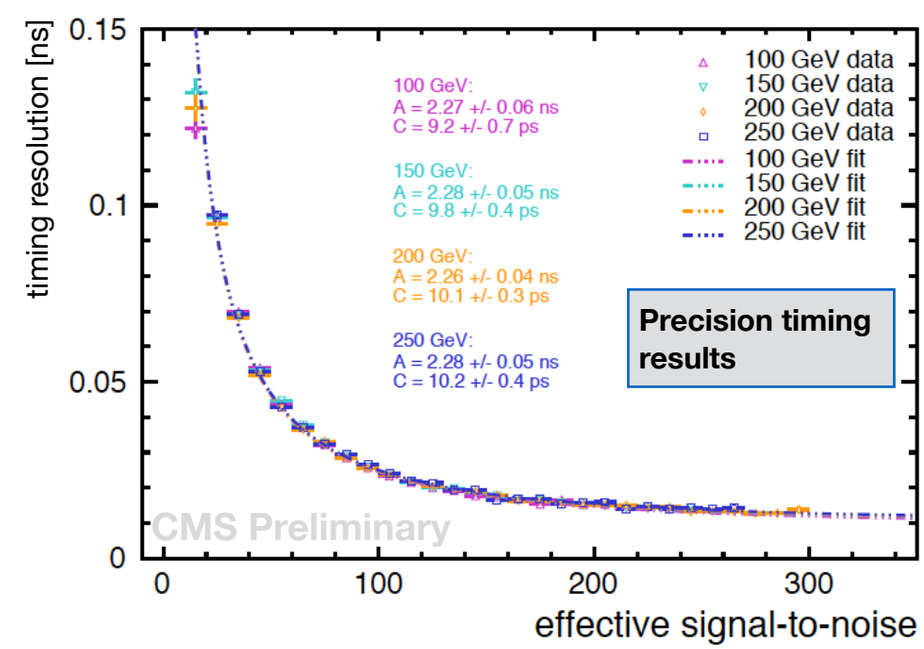
✓ Position resolution of incident electrons as a function of their energy.

✓ Precision timing results of the full module at CERN.









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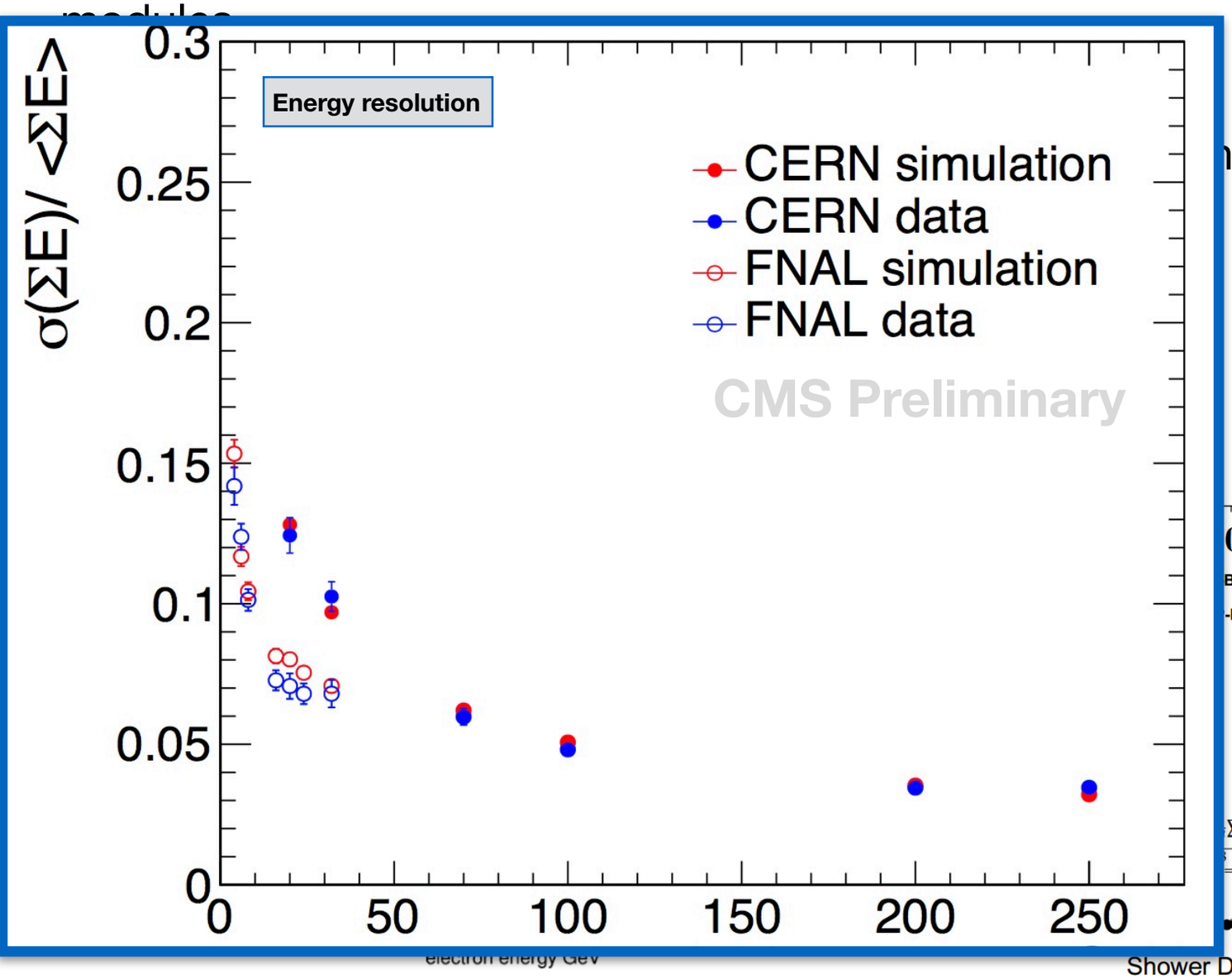

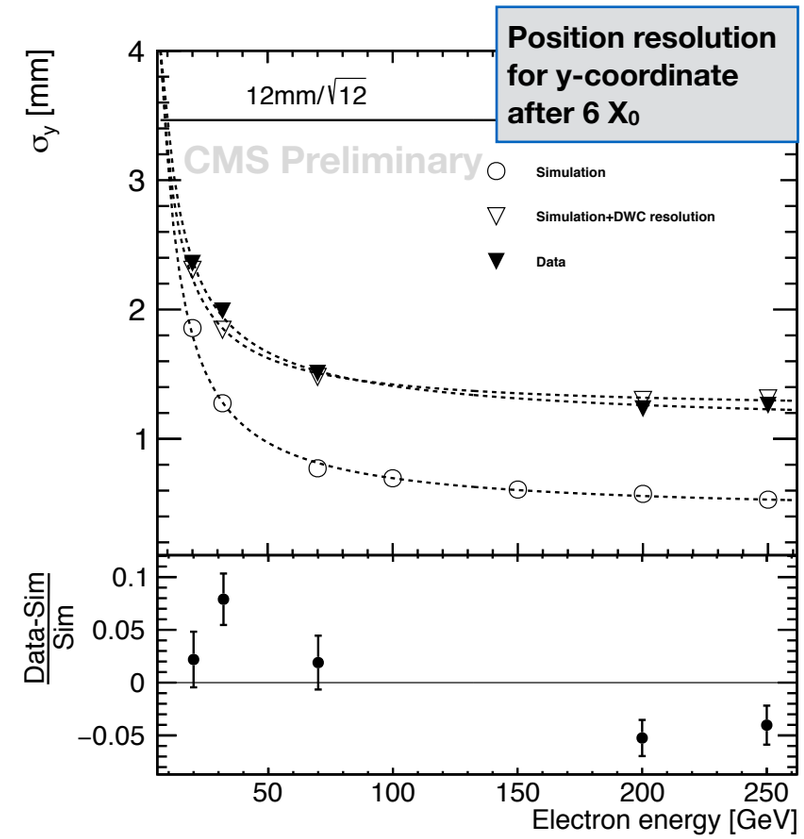

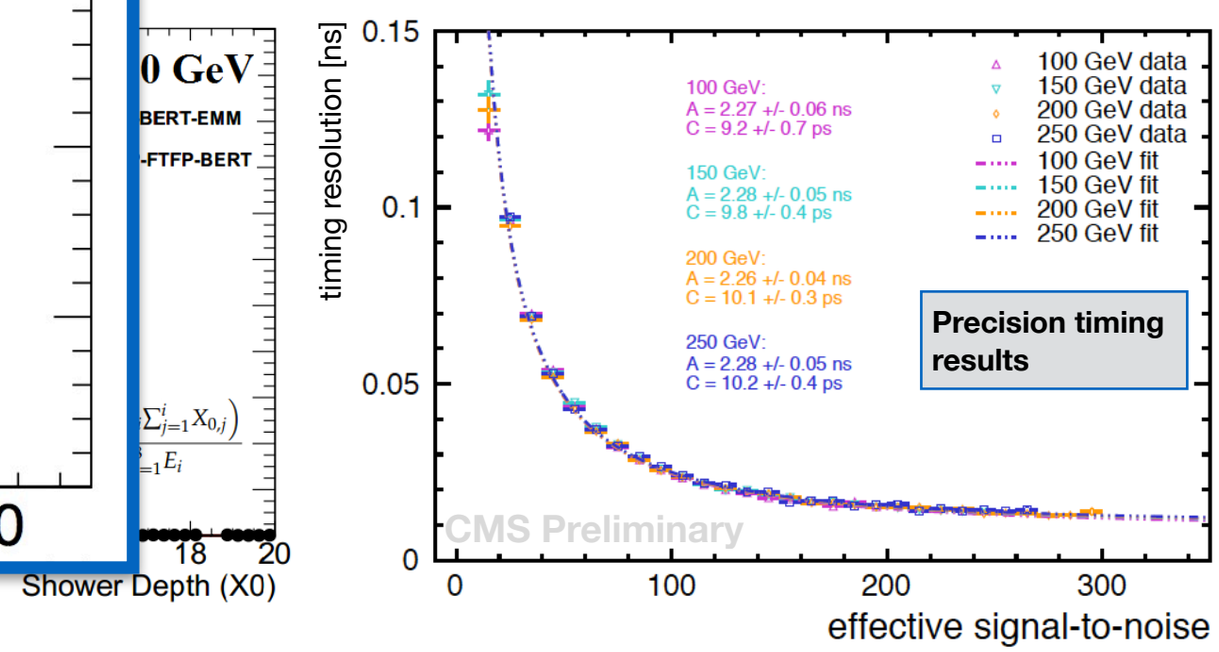

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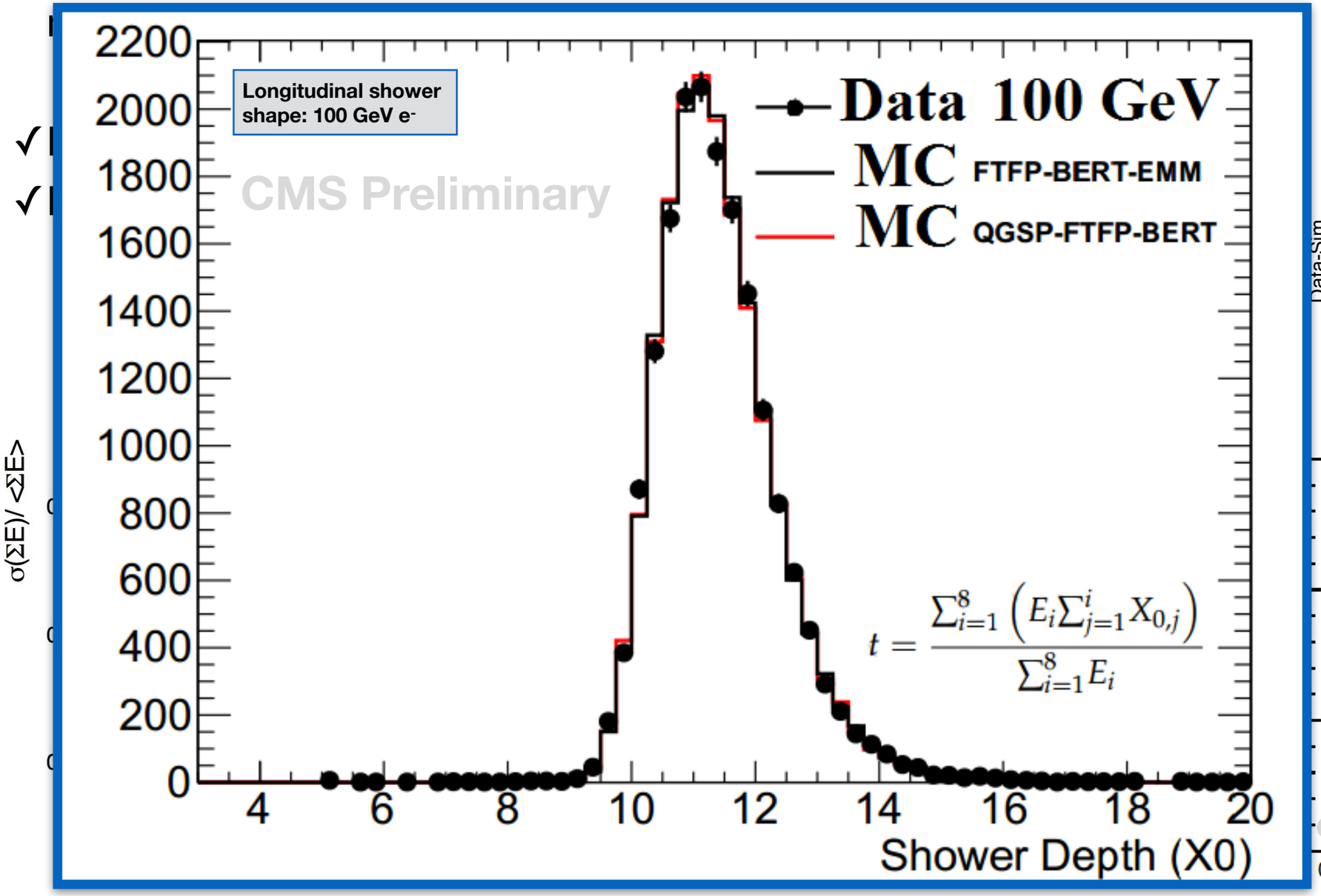

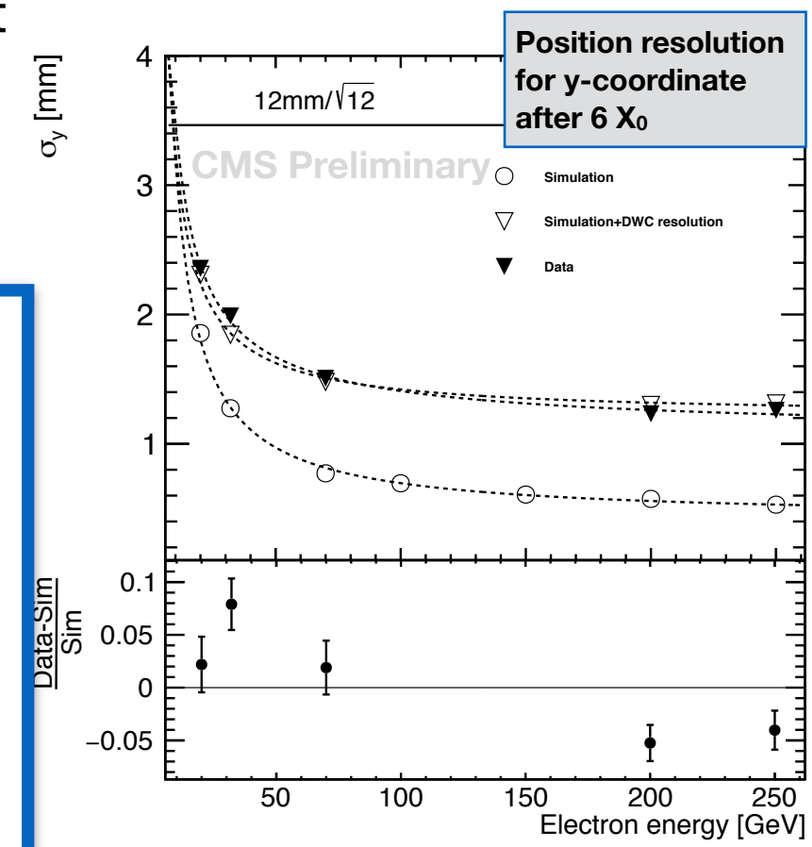

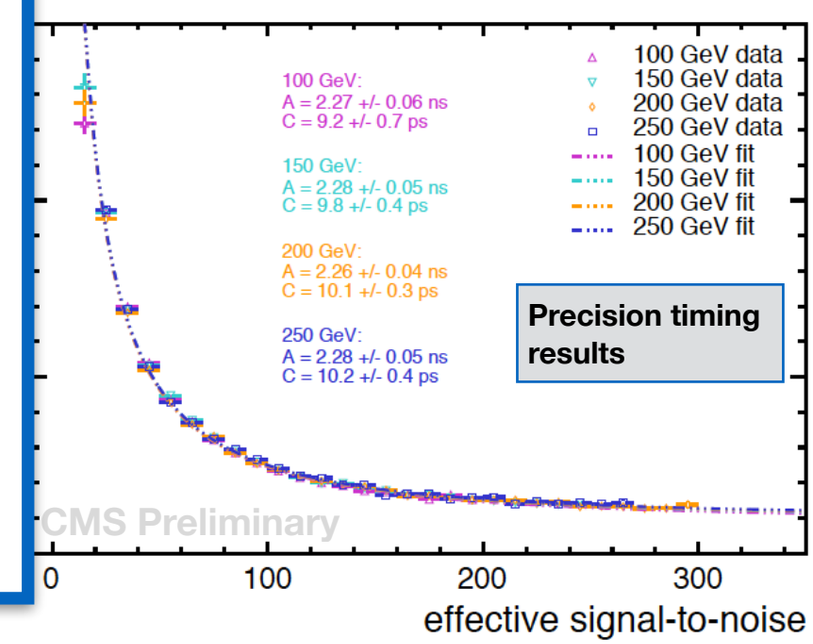

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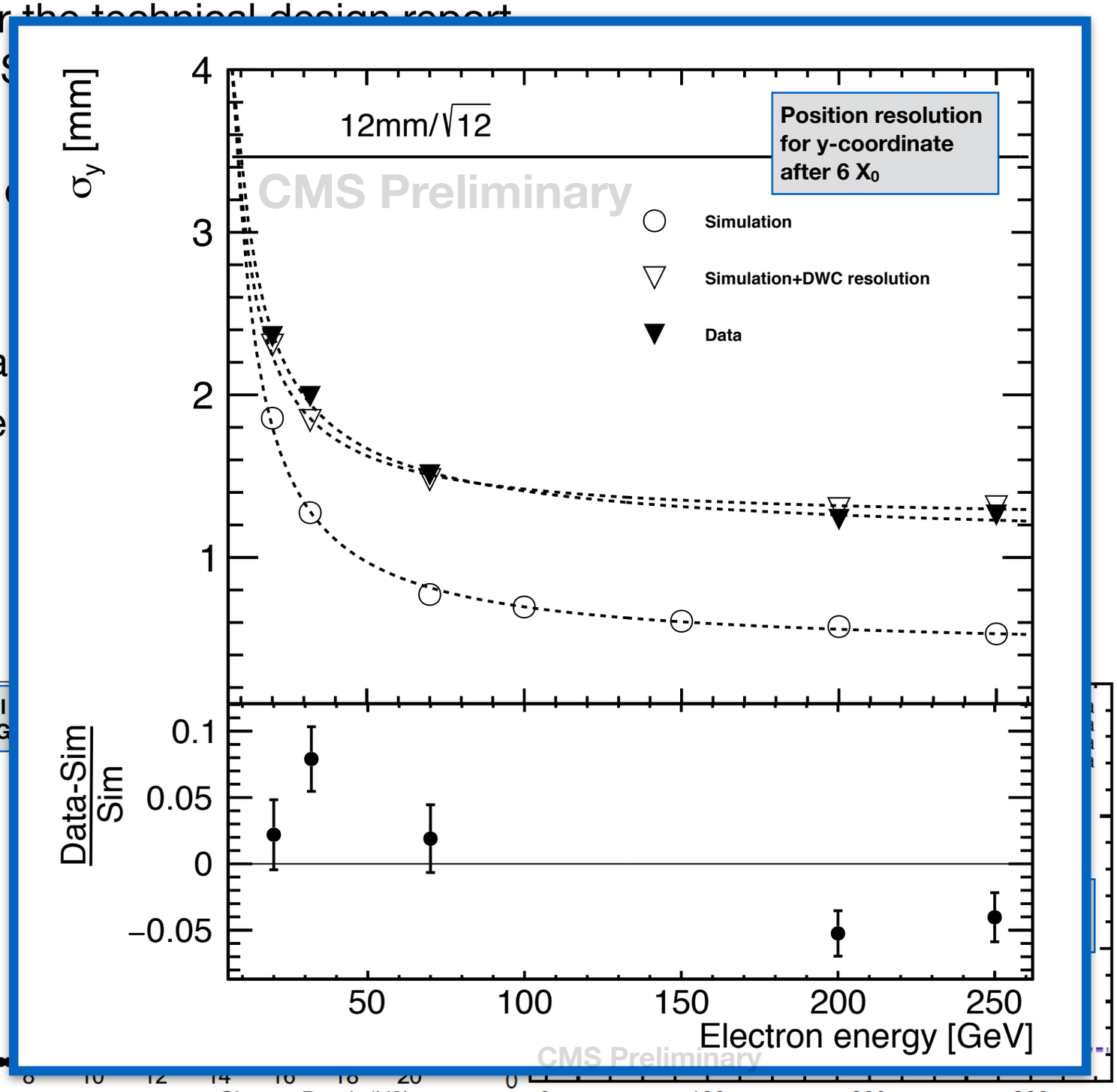
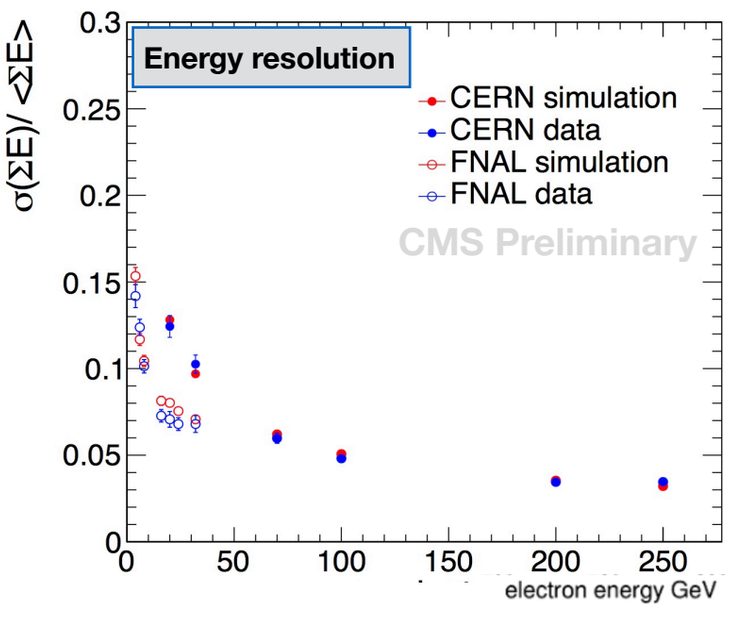
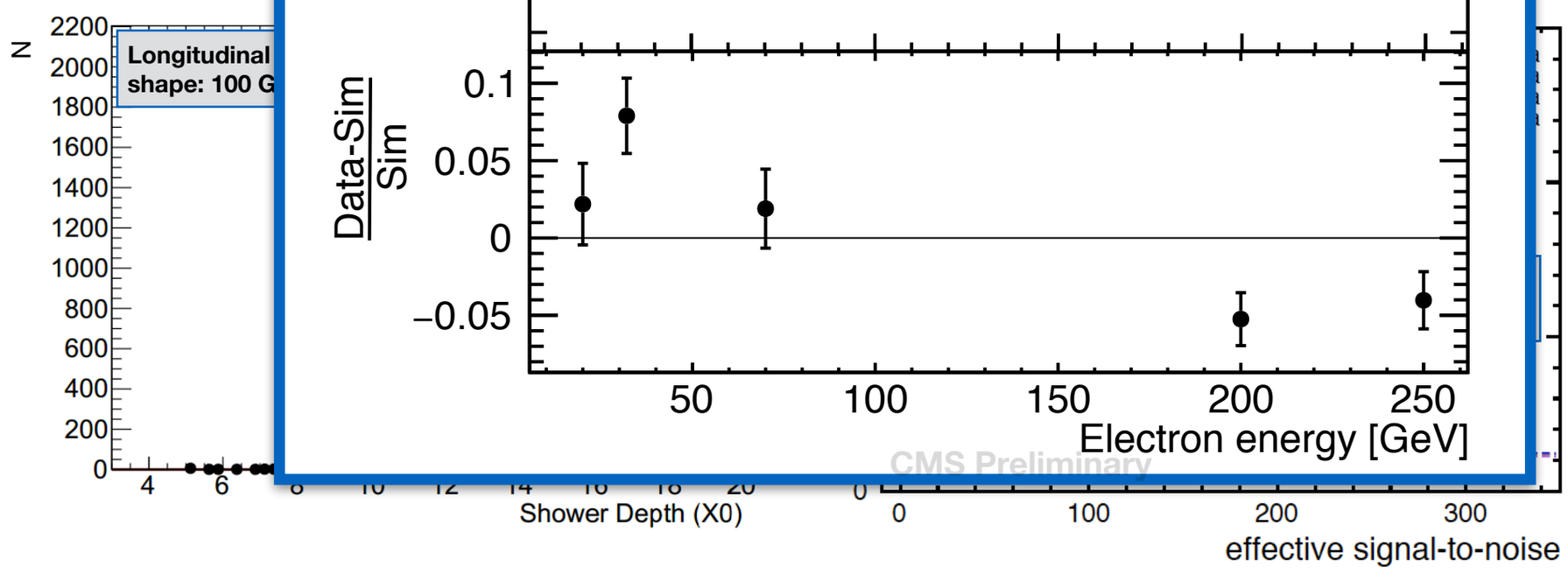
✓ Position resolution of incident electrons a

✓ Precision timing results of the full module







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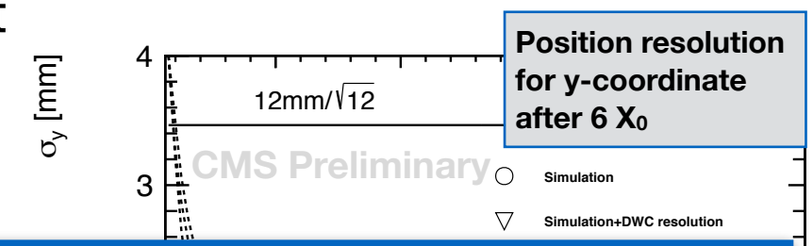

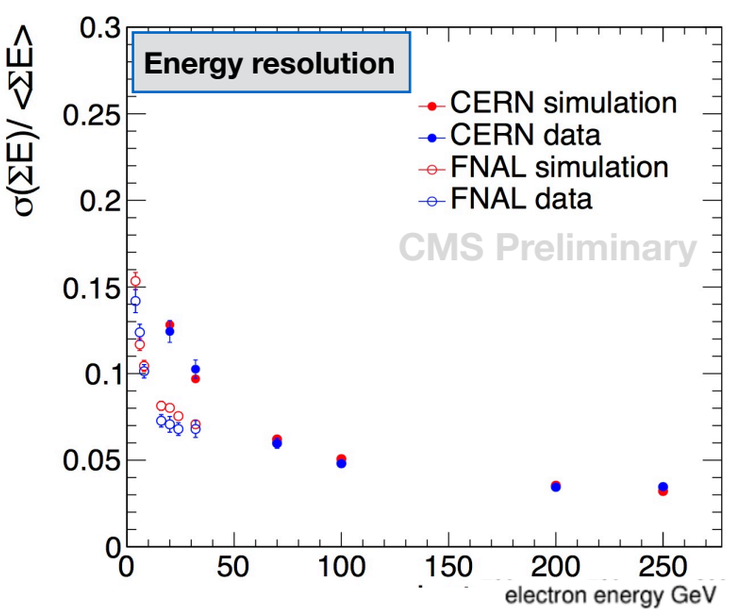

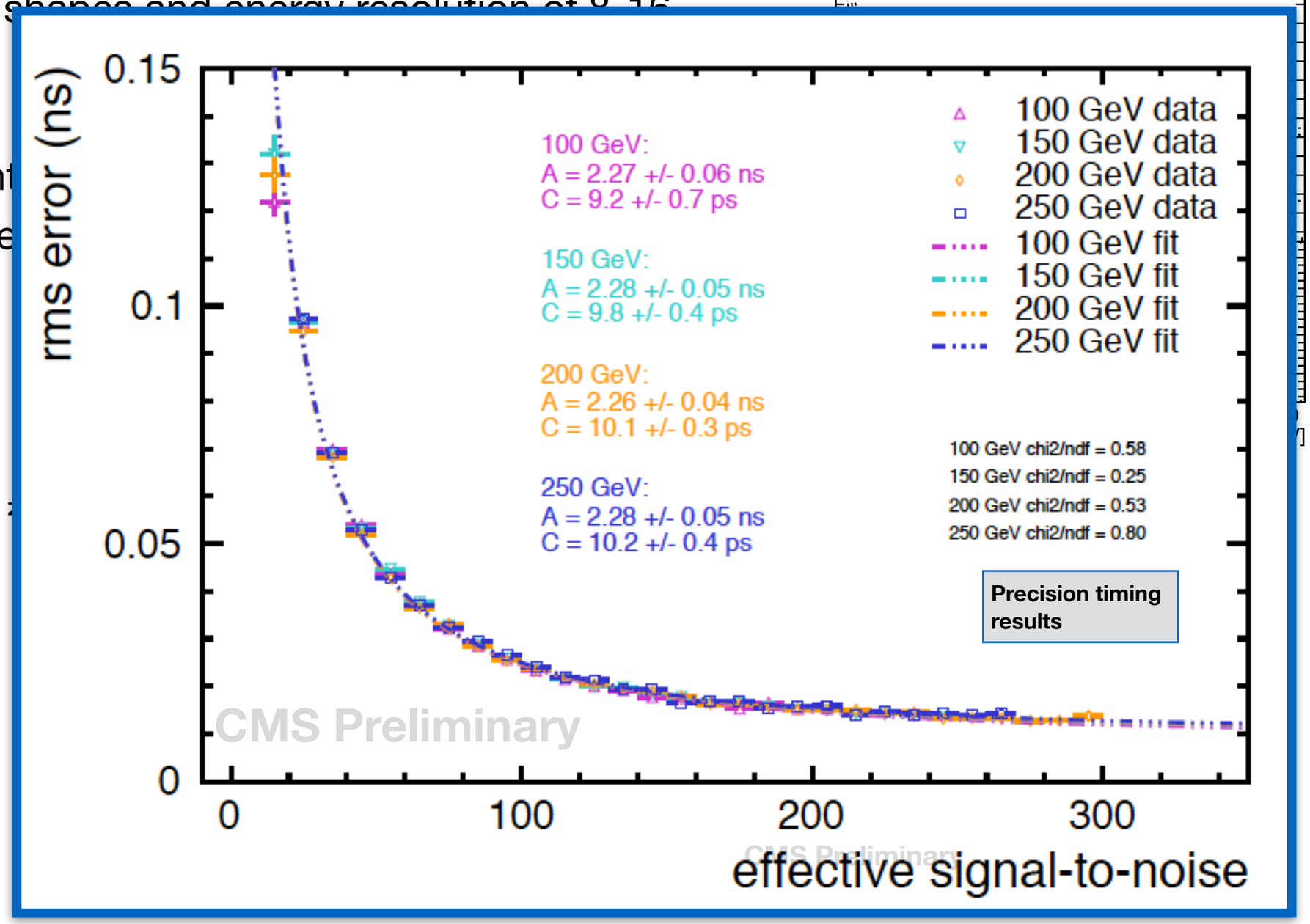

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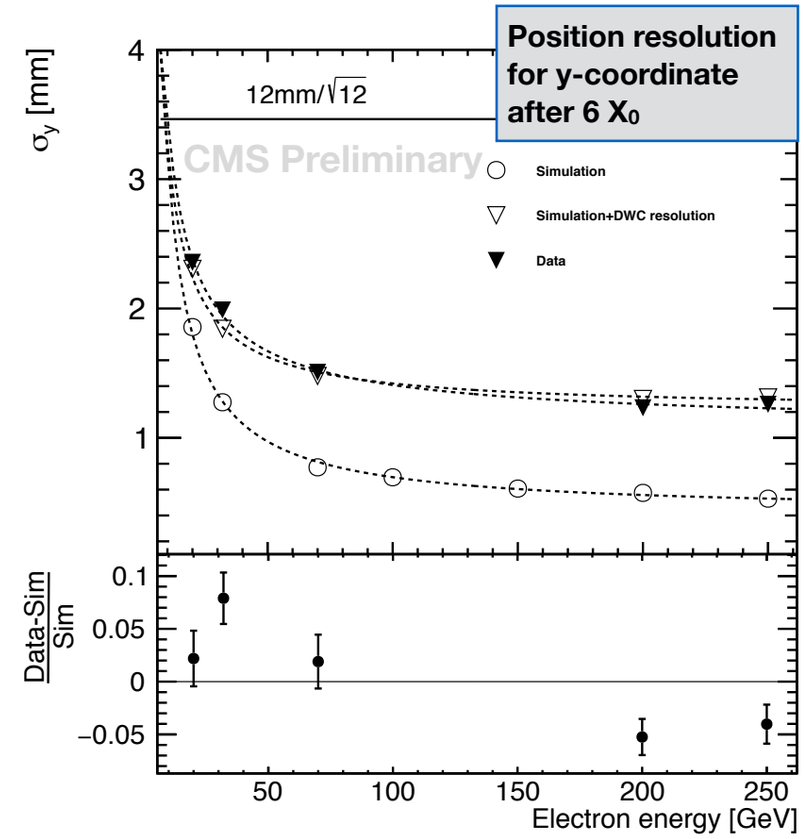
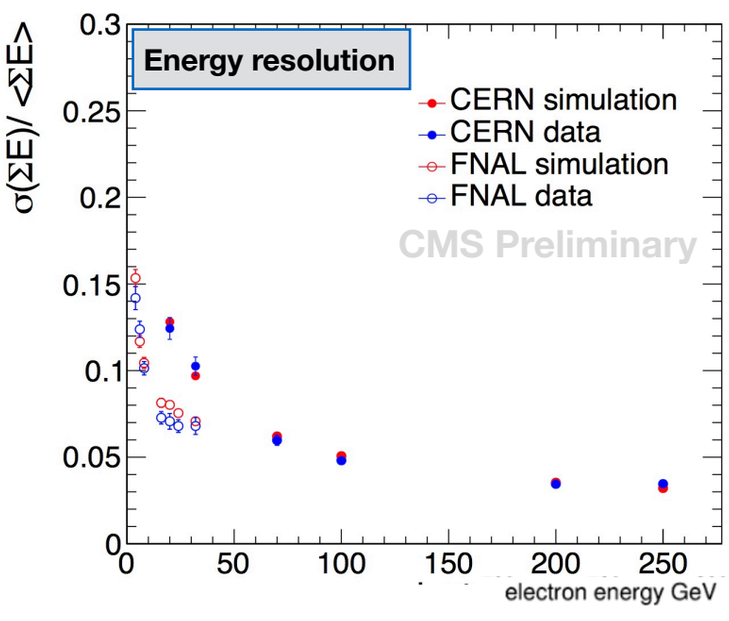
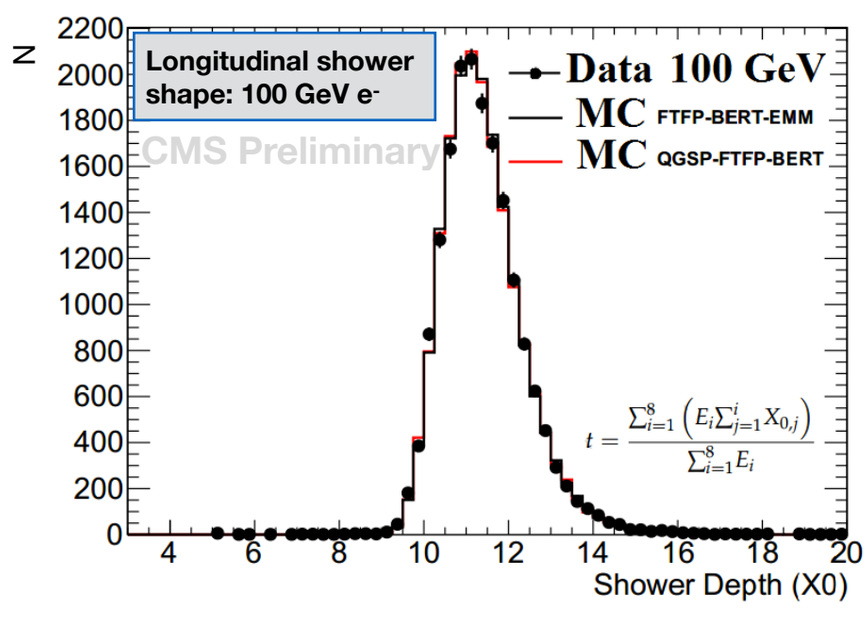
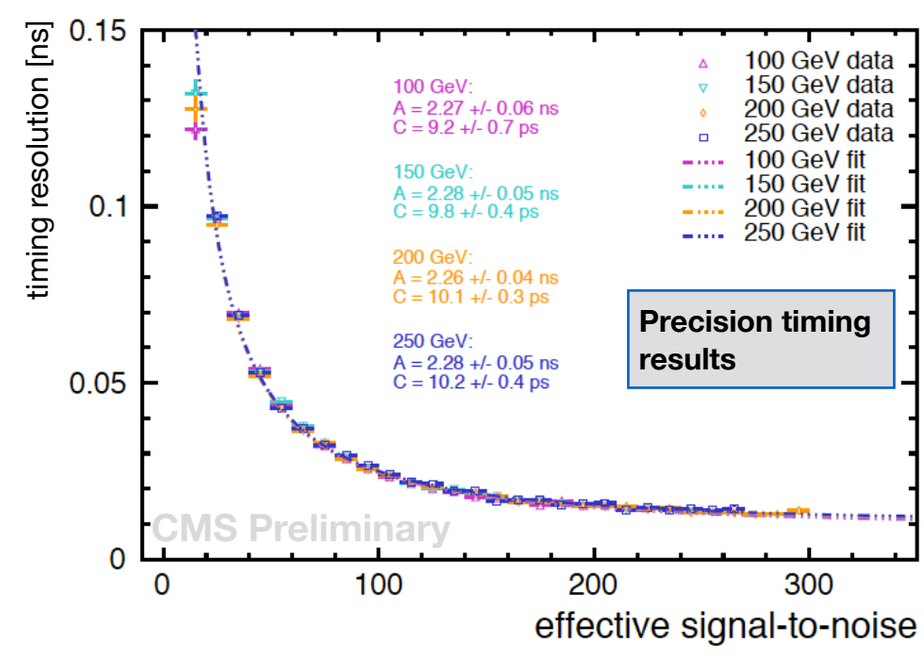
Overall agreement between data and simulation within ~percents.

➡ **Basic validation of the simulation of the CE-E part.**









Towards the extended setup in 2017

High ambitions for beam tests in 2017

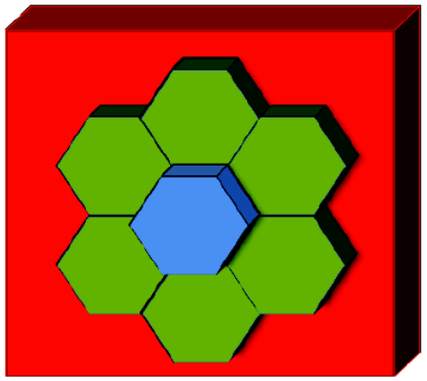
Goal as defined at beginning of 2017: Prototype with 112 6”-modules

- 28 layers with one module in CE-E, 12 layers with 7 modules in CE-H (Si).
- Gradual upscaling of the system towards a full **CE- E+H (Si)+H (scint.)** prototype.

➡ Extend and consolidate measurements from 2016.

➡ Measurements on hadron-induced showers with HGC modules.

Original ambition:



CE-E, CE-H (Si), CE-H (scint. +SiPM) (CALICE AHCAL prototype)

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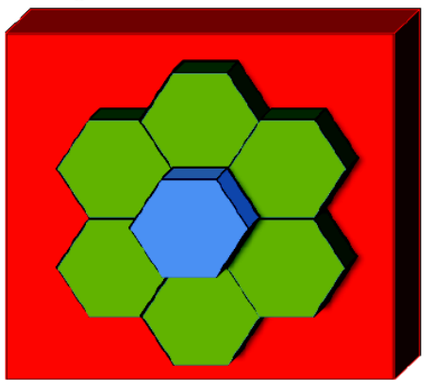

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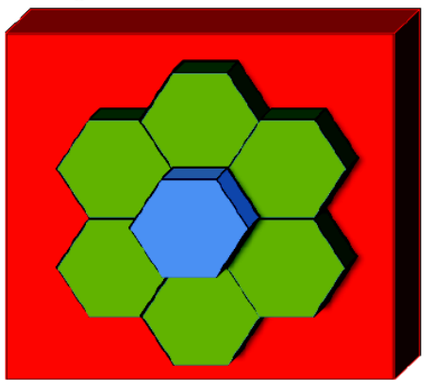
Revised strategy:

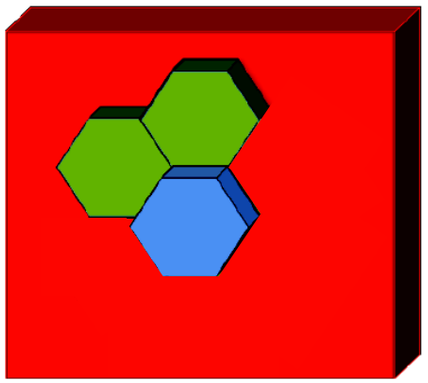
- Period 1: **8-15 May**
  - One CE-E Module.
- ~~Period 2: **31 May-7 June**~~
  - ~~As many modules as possible.~~
- Period 3: **12 July-19 July**
  - CE-E + CE-H (Si) + AHCAL

- Less layers.
- Less modules per layer.

Original ambition:



Realised prototype:



CE-E, CE-H (Si), CE-H (scint. +SiPM) (CALICE AHCAL prototype)

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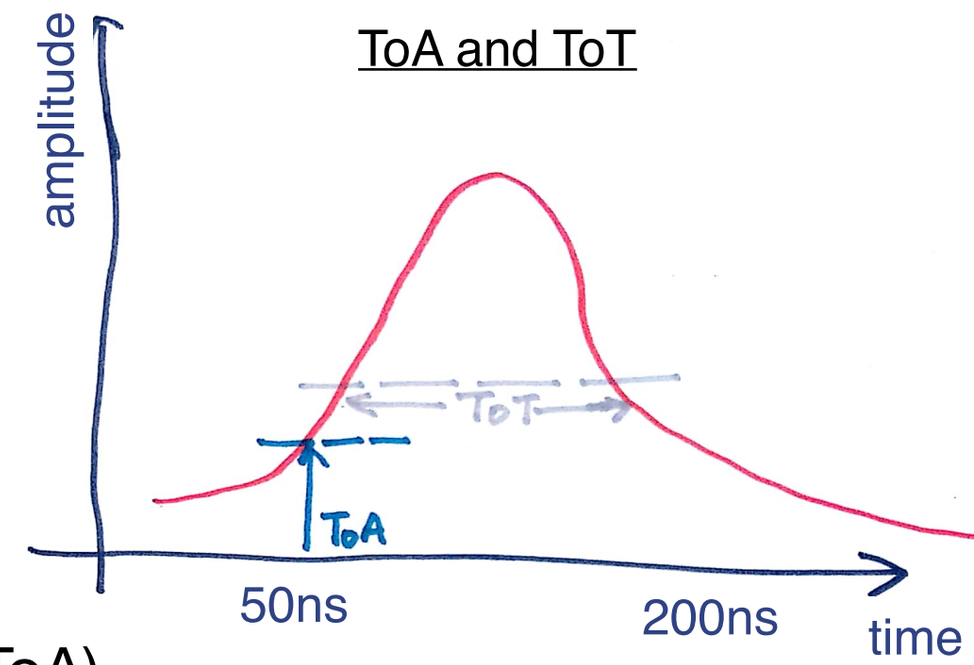
Skiroc2-CMS is the new readout chip in 2017

- Skiroc2-CMS is based on the CALICE Skiroc2.
- Shapes, amplifies and digitises signals from the silicon sensors.



- 64 channels.
- **13 SCA rolling analog memory** with 40MHz clock.
  - Overwrites every 13x25ns.
- Four quantities read out: Low- and High gain, **"Time over Threshold" (ToT)** and "Time of Arrival" (ToA).

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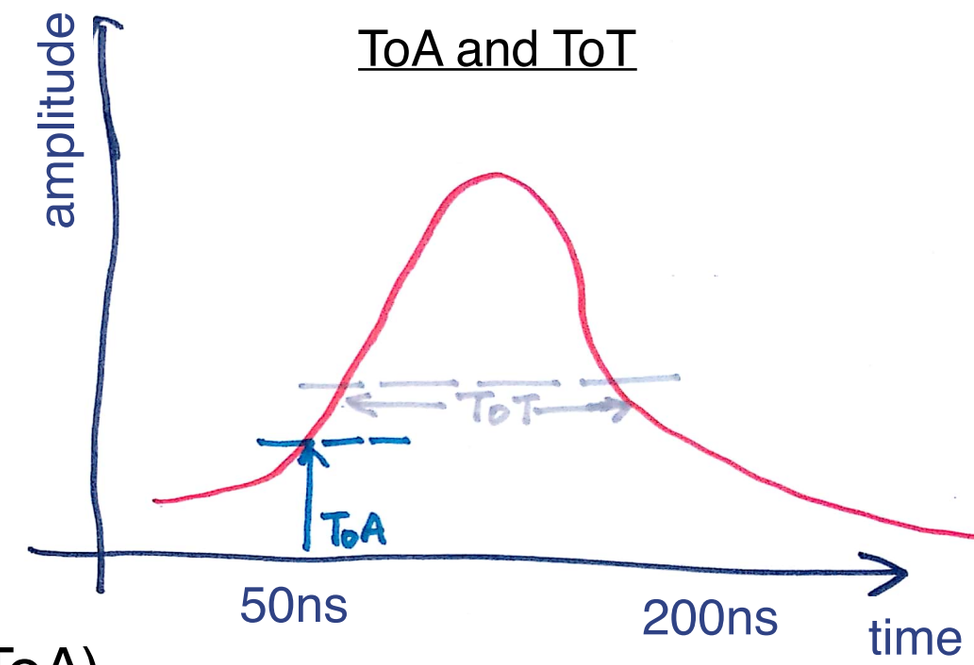

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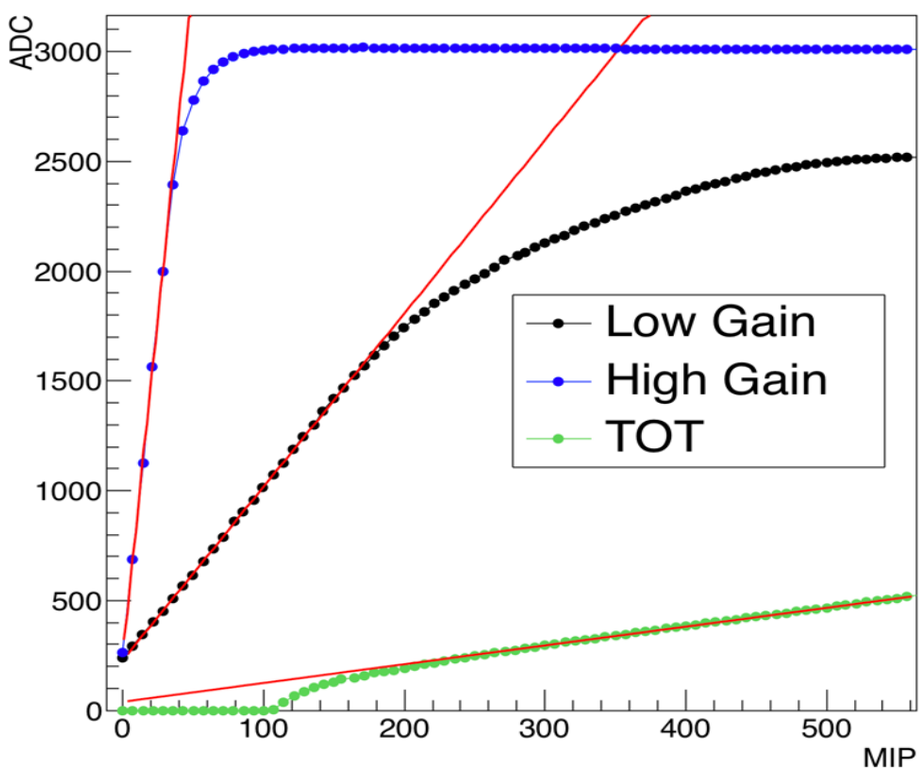
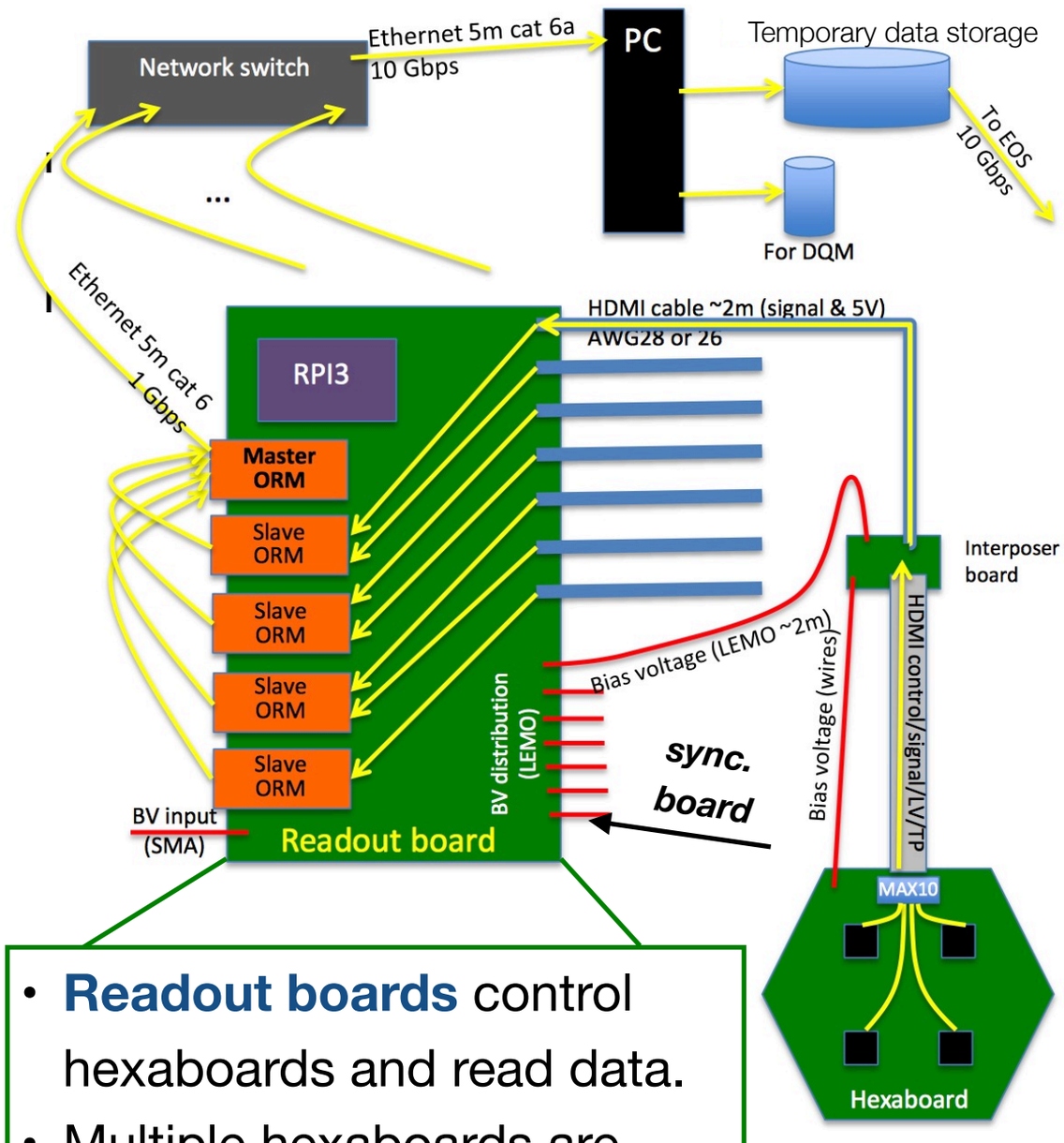


- Larger pulses stay longer over some threshold.
  - ToT is a measure of the signal pulse amplitude.
  - ToT can be used for energy reconstruction when low gain is saturated (left plot).

left: Relation of HG-LG and LG-TOT with test pulses in the lab.

New DAQ hard- and software in 2017

HGCAL Data Flow



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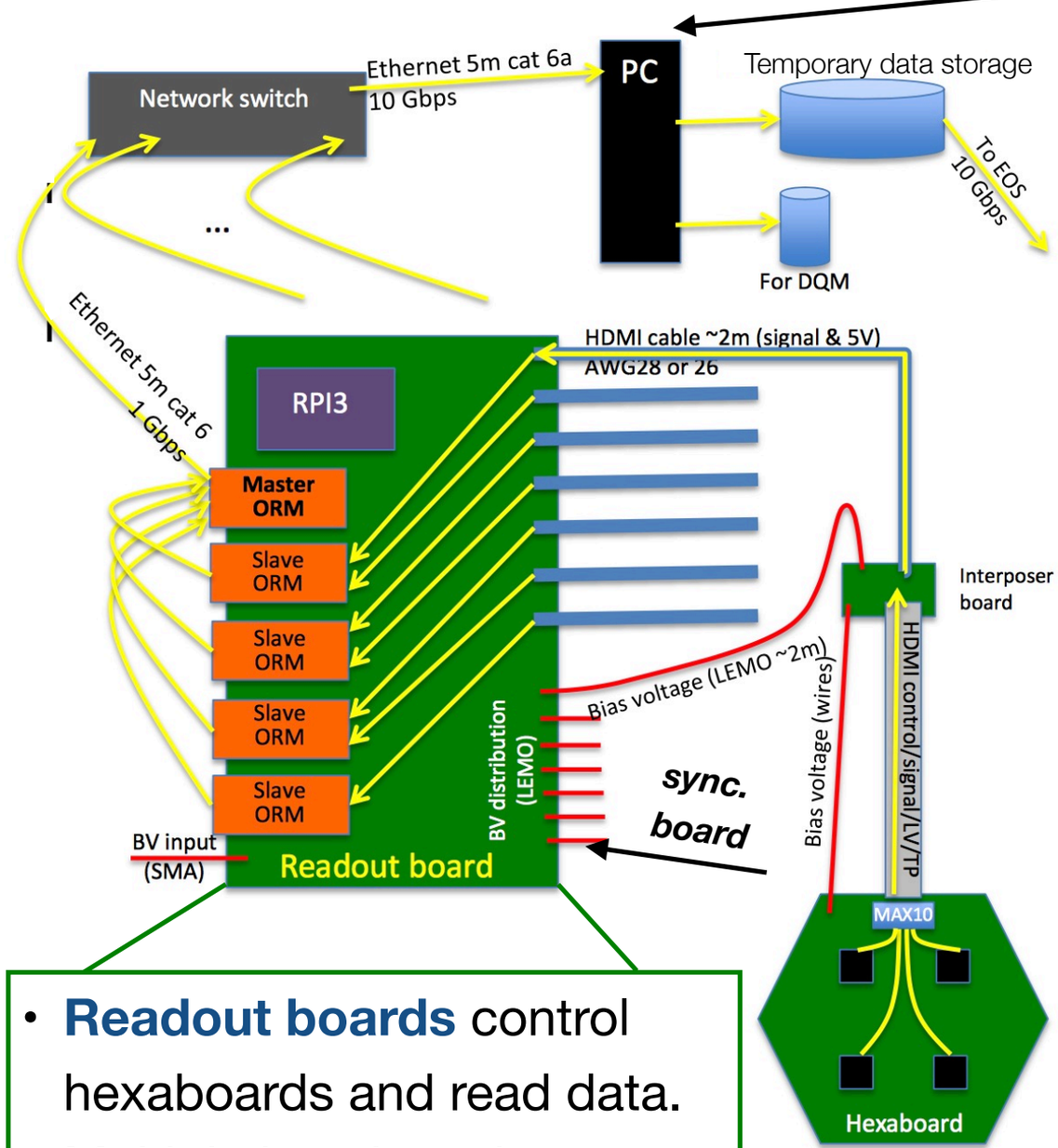
- Multiple hexaboards are connected to one readout board.

New DAQ hard- and software in 2017

HGCAL Data Flow



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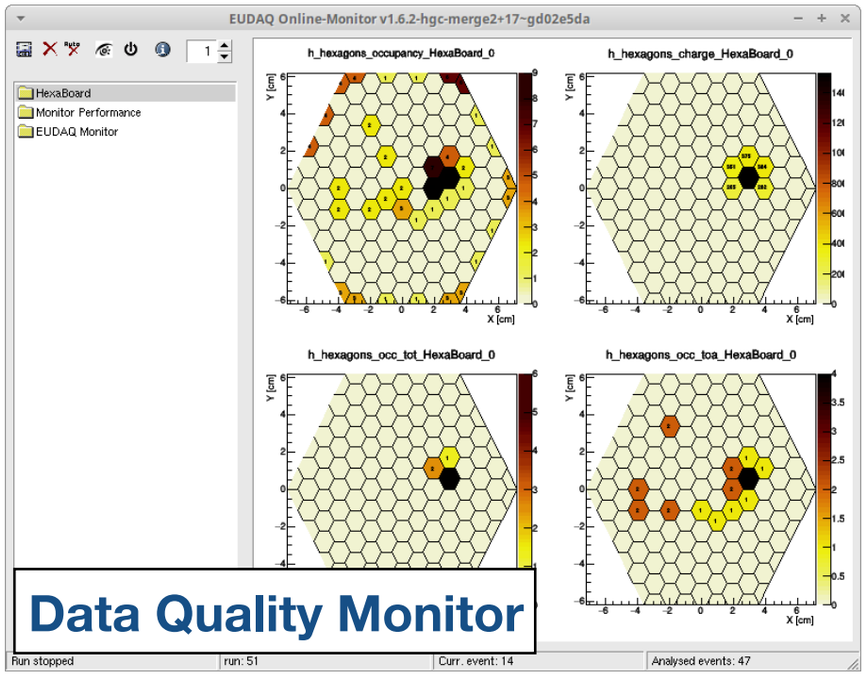
DAQ software based on EUDAQ1 and IPBUS.

- Producers for
  - ✓HGCAL
  - ✓AHCAL
  - ✓Wire Chambers
- Built-in **DQM**.



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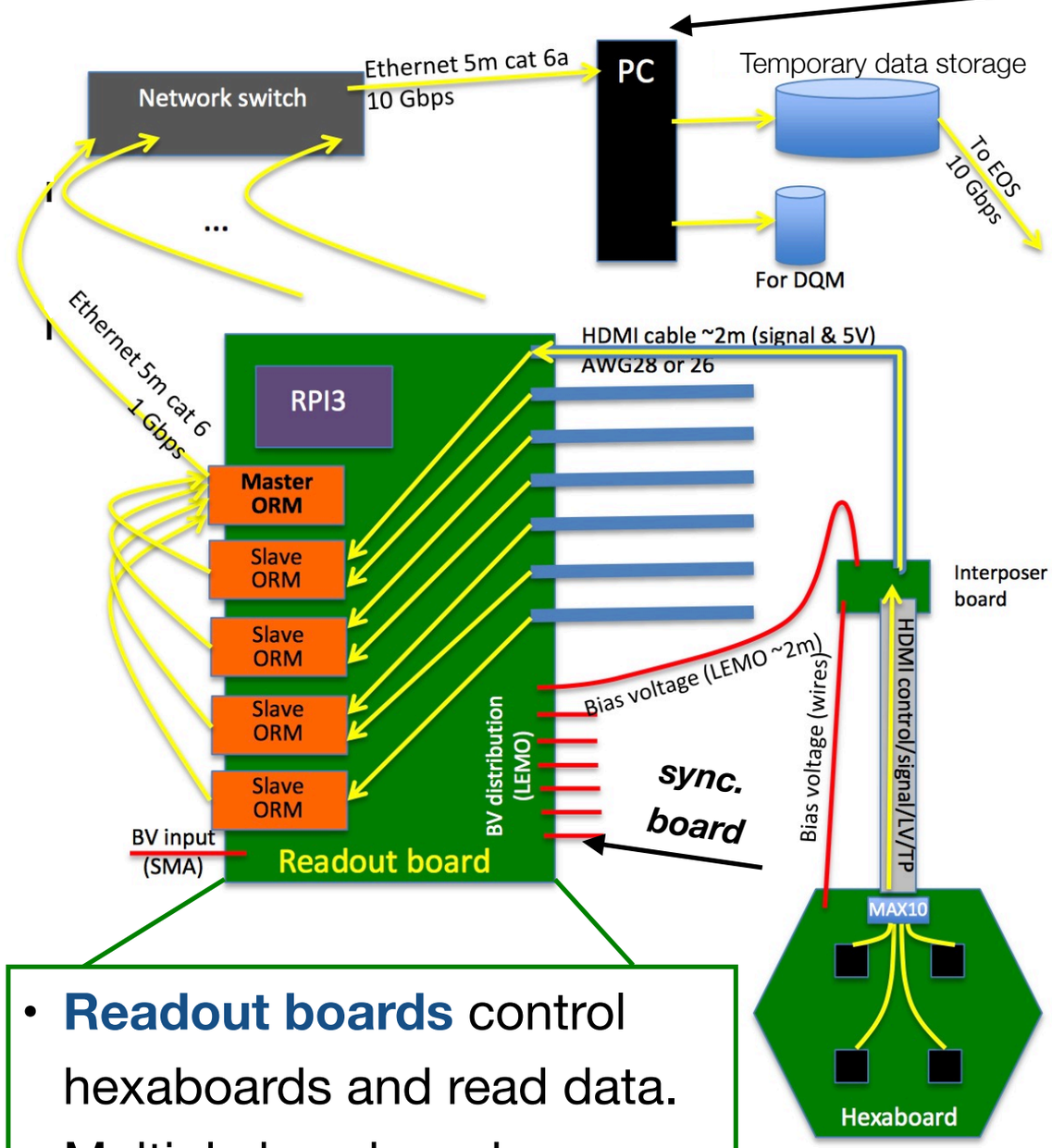
New DAQ hard- and software in 2017

HGCAL Data Flow



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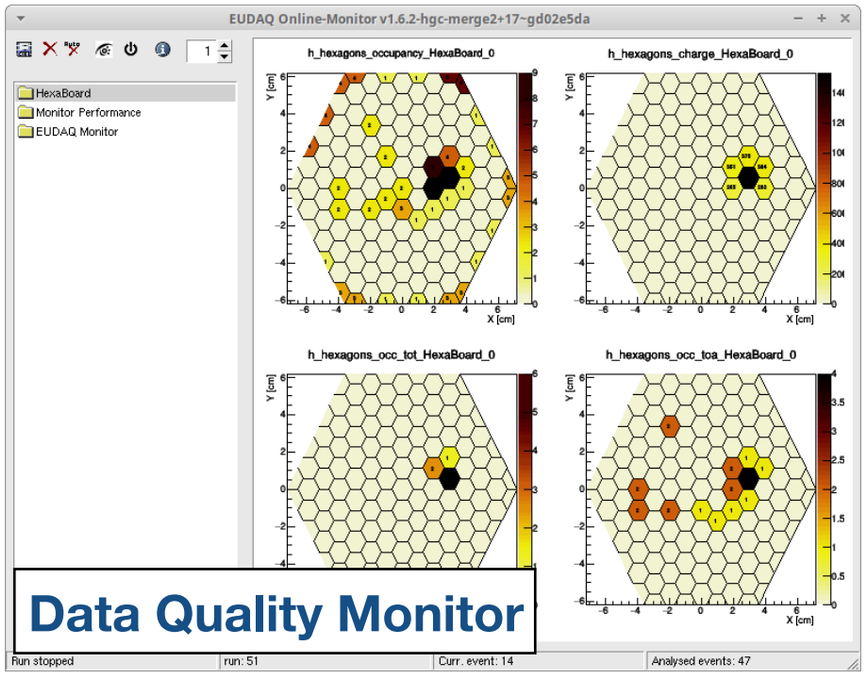
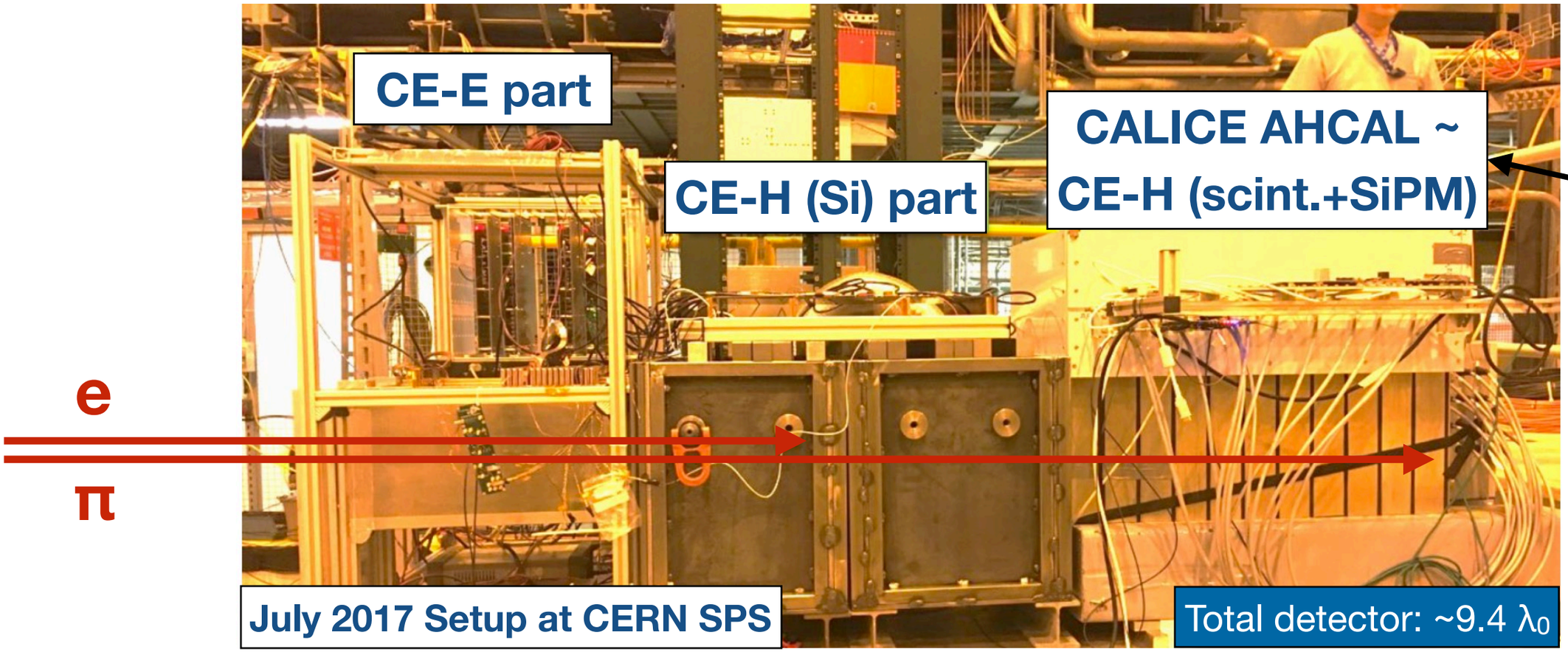


Positive aspects:

- The DAQ is cheap and scalable.
- Reuses existing components from CMS: The Optical Readout Modules (ORMs).
- Simple Raspberry PIs as interface to computers.
- Readout using IPBUS protocol works well and reliably.

Multi-module setup with CALICE AHCAL in July

- CE-E part: Hanging file structure with **lead** absorber.
- CE-H (Si) part: Hanging file structure with **iron** absorber.
- Data taking together with CALICE AHCAL prototype as CE-H (scint.+SiPM) part.



"Prototype tests for a highly granular scintillator-based hadron calorimeter" by Felix Sefkow.

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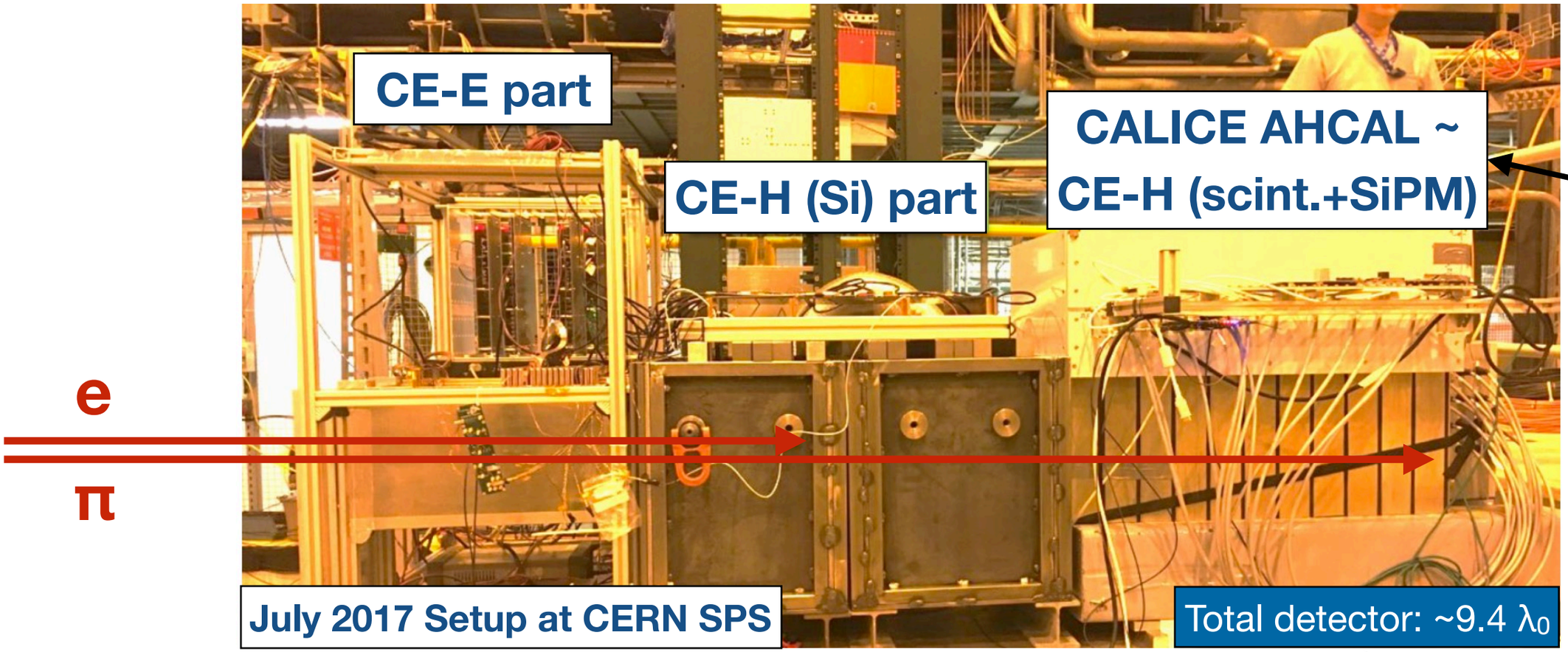
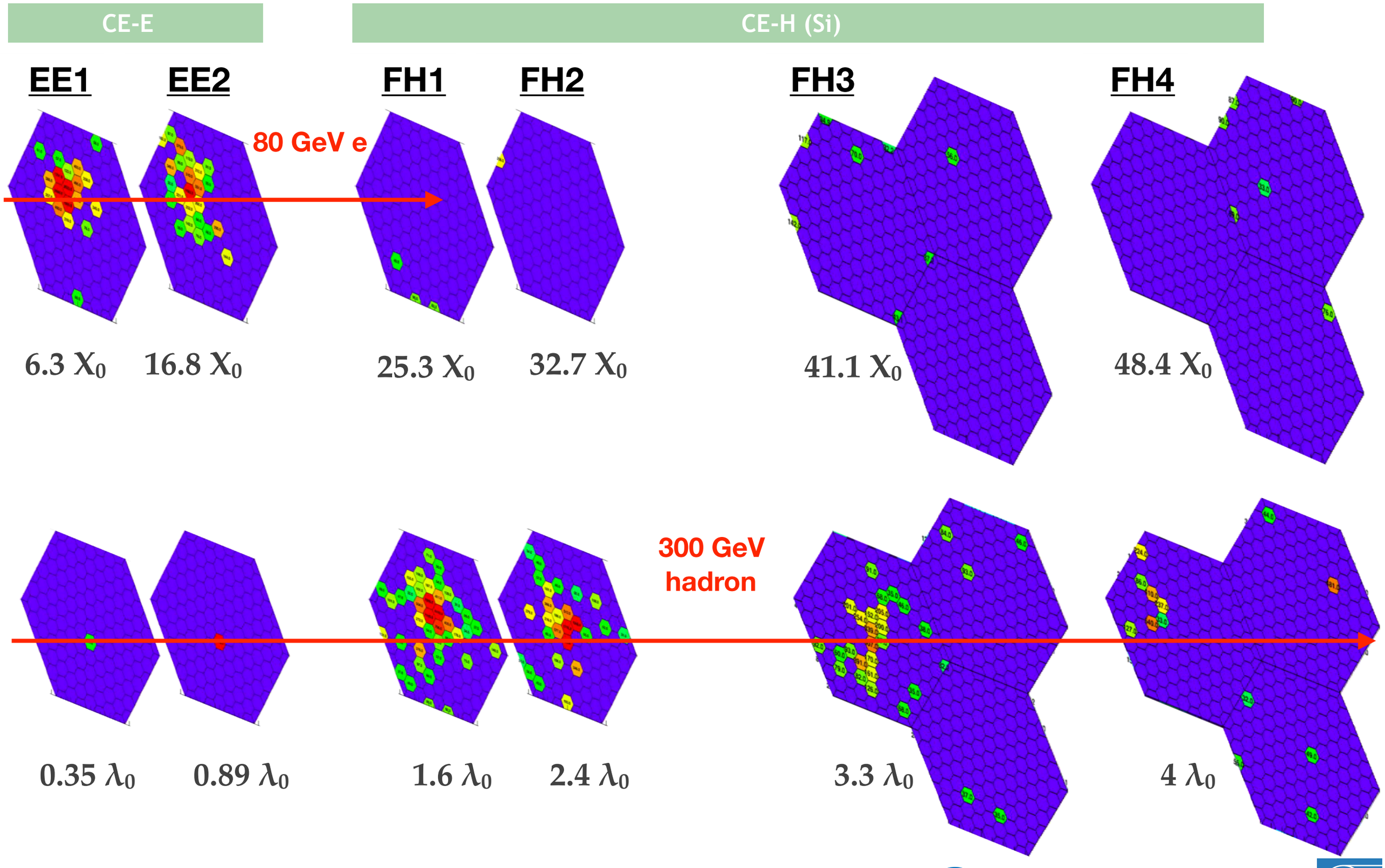


"Prototype tests for a highly granular scintillator-based hadron calorimeter" by Felix Sefkow.

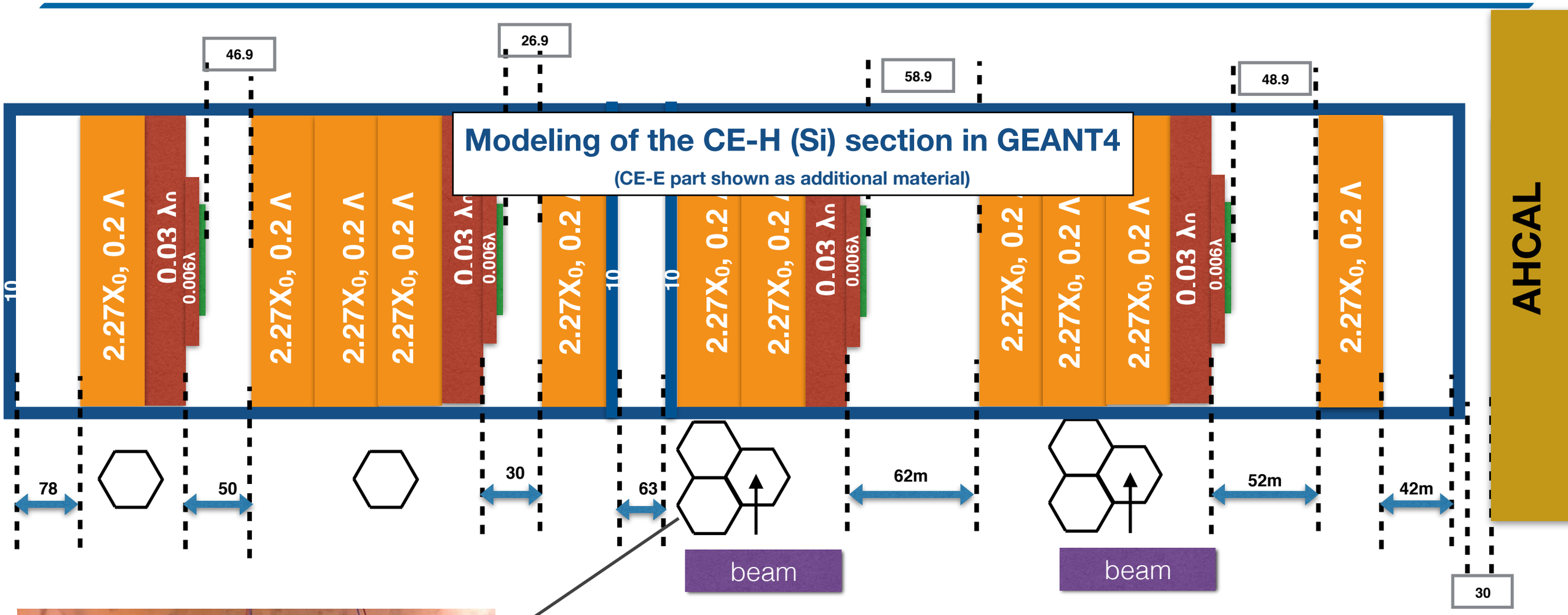
Limited number of modules =(

- 2 or 3 modules in the **CE-E** part.
- Limited number of layers: 4 instead of 12 in **CE-H (Si)**.
- Only 1 or 3 modules per layer instead of 7.

Hadron and electron showers are seen



O(10^6) events are simulated



- GEANT4 based simulation of the prototype using *CMSSW*.
  - "*FTFP_BERT_EMM*" physics list.
- CE-E section: 14 layers of Pb absorber and 2 sensitive silicon layers.
- CE-H (Si) section: 12 layers of Fe absorber and 4 sensitive silicon layers.

+ Simulation of AHCAL.

Analysis of the HGCal July Data

Shown here:
Work in progress

<u>First results are shown for:</u>

- MIP signals
- Energy sums
- Shower shapes

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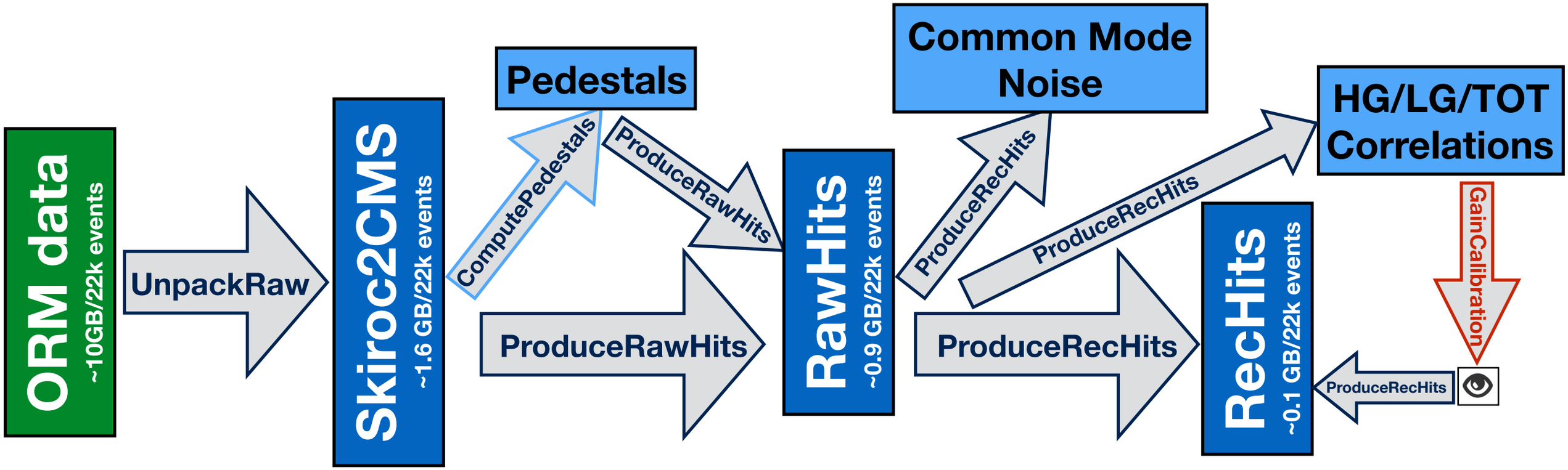
Full HGCal reconstruction workflow



RecHits data format (~100MB/22k events):

- Pedestals and common mode noise is subtracted.
- CMS Preshower Pulse fit is performed to the time samples.
- Switches between HG/LG/TOT **—> one energy per hit.**
- Location of each hit in the detector.

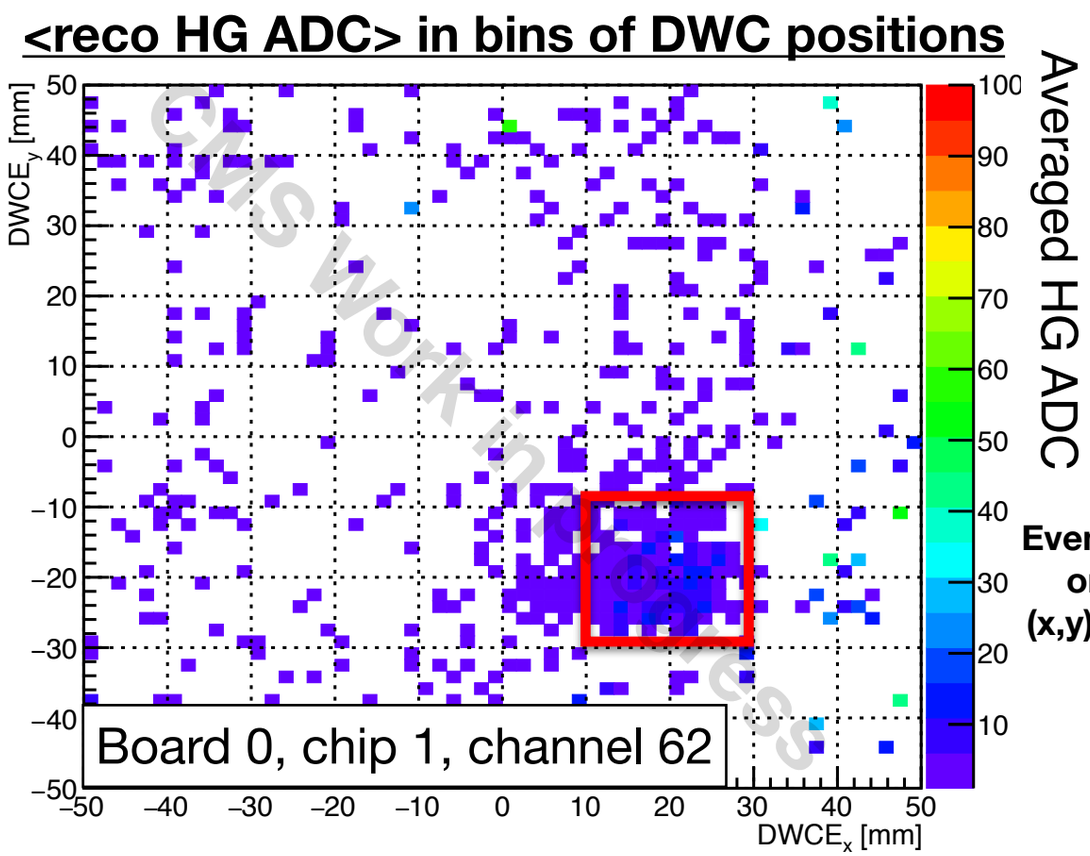
Input files
Reconstructed files
Meta files
Reconstruction tasks
Meta tasks
Visualisation/Analysis tasks
Inspection of output by analyst

MIP signals are seen despite high noise

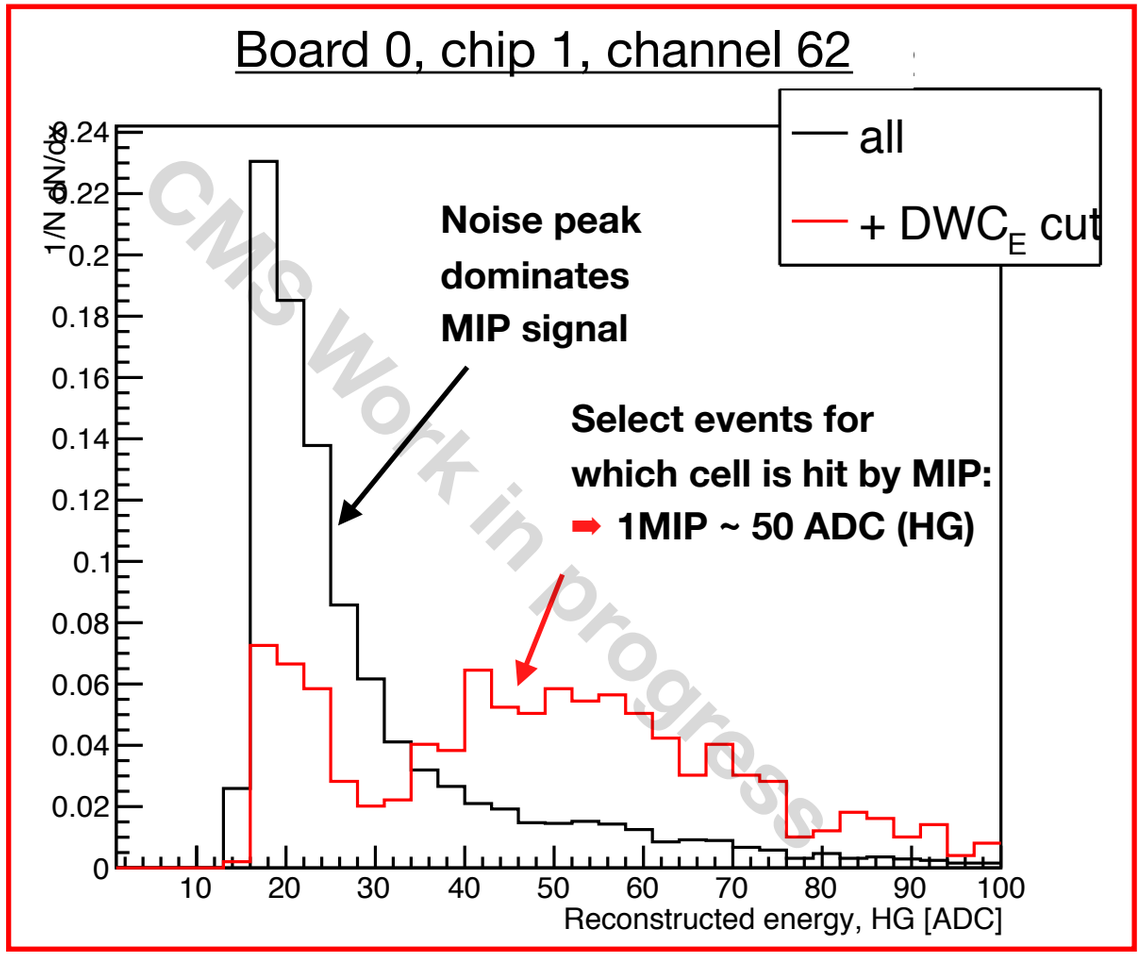
Work in progress

- MIPs from parasitic muons from experiments further upstream in the area.
- Large spread —> Large amplitude of noise peak.
  + Width smears into the expected MIP signal for most channels!

➡ Event selection with wire chamber information.



Event selection based on reconstructed (x,y) position on DWC



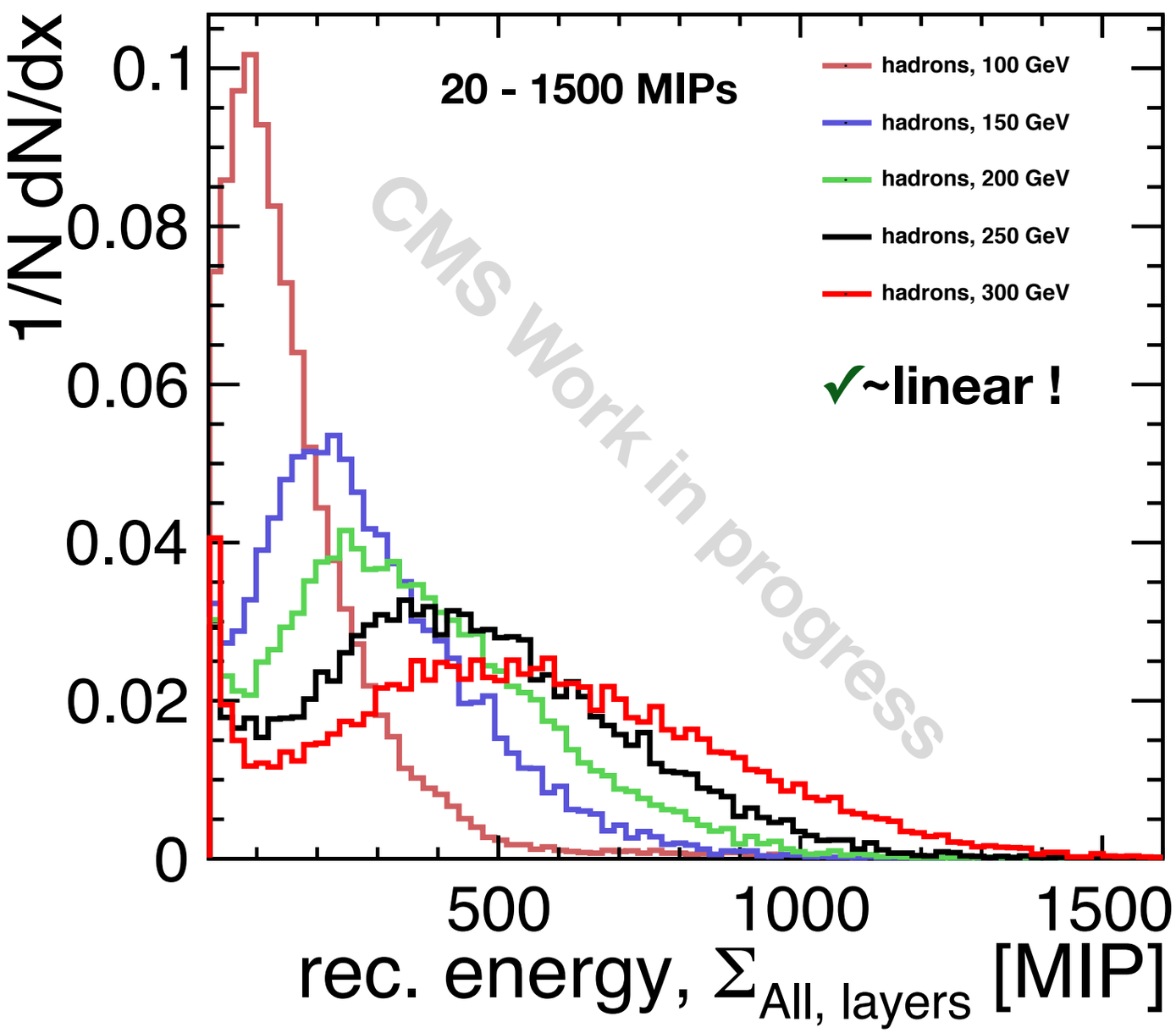
- Procedure similarly successful for other channels.

➡Different data streams can be synchronised & MIP signal ~50 ADC counts.

Energy sums - We do have a calorimeter

Work in progress

- Pedestal and common mode noise are subtracted.
- Sum of fitted pulse amplitudes over all cells in all layers. No weighting.
- Preliminary LG-TOT is included.



<u>Simple cuts:</u>

- Electron suppression:
  $E_{CE\text{-}E} / E_{CE\text{-}H(Si)} < 0.03$
- Inhibit noise contribution:
  4 MIP cut on cells prior to summing.

<u>Much room for improvement:</u>

- smarter selection of cells (clustering)
- dE/dX weights per layer

Transverse shower size - Data vs. sim.

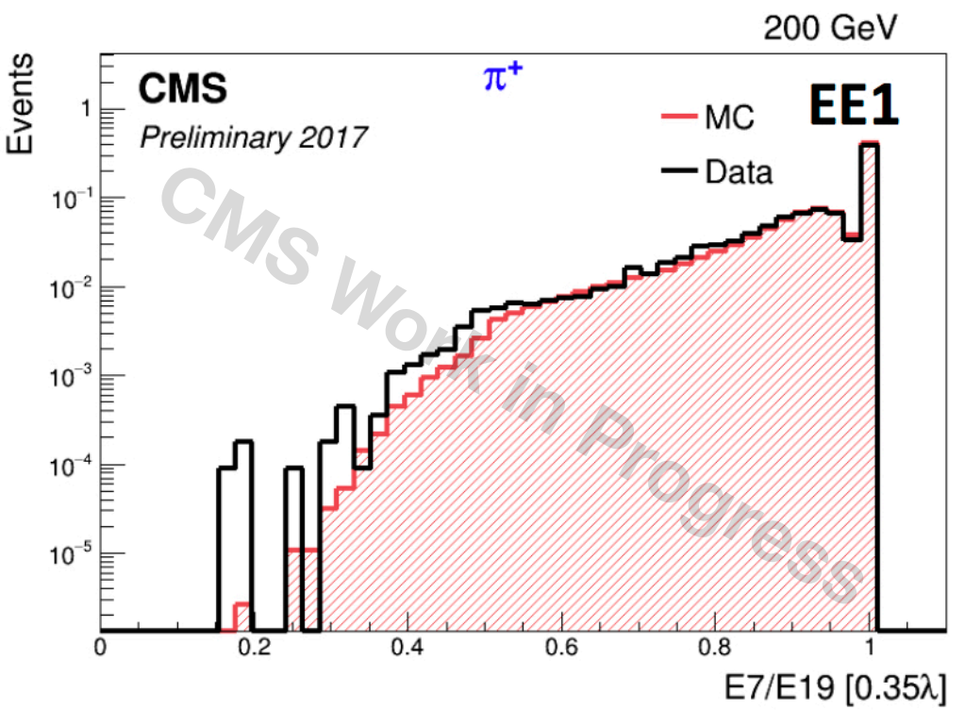
Work in progress

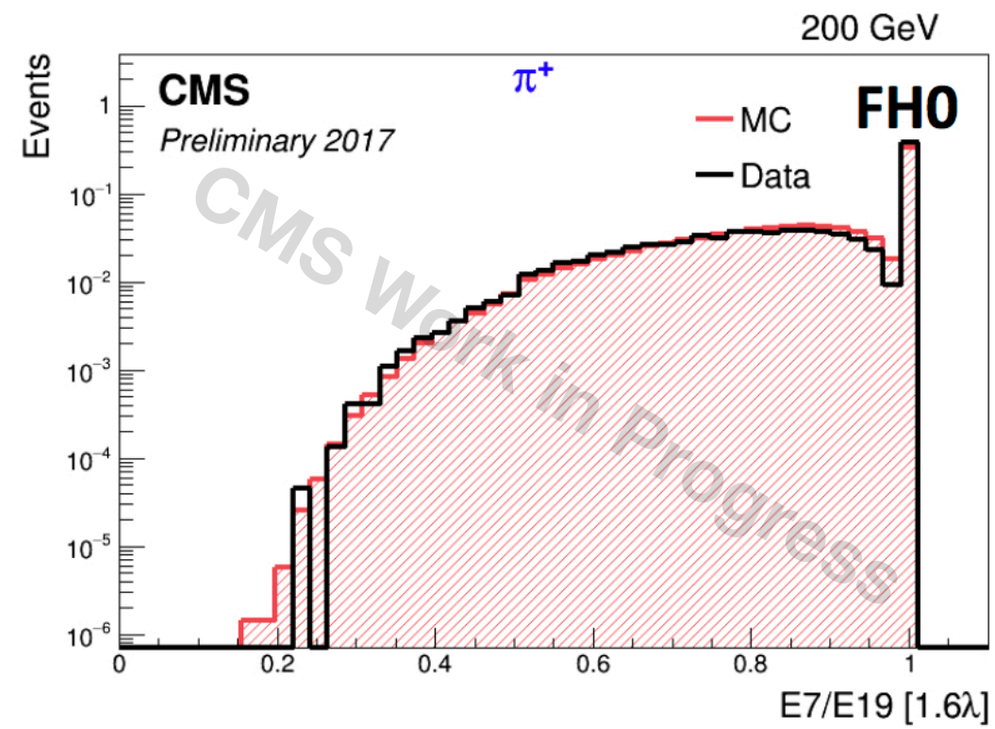
Definitions:

- E7: Sum of reconstructed energies of cell with most energy plus of one ring around it.
- E19: Sum of reconstructed energies of cell with most energy plus of two rings around it.

E7/E19 ~ transverse spread of the shower at a given sampling depth.
E7/E19 is computed for each layer in an event.

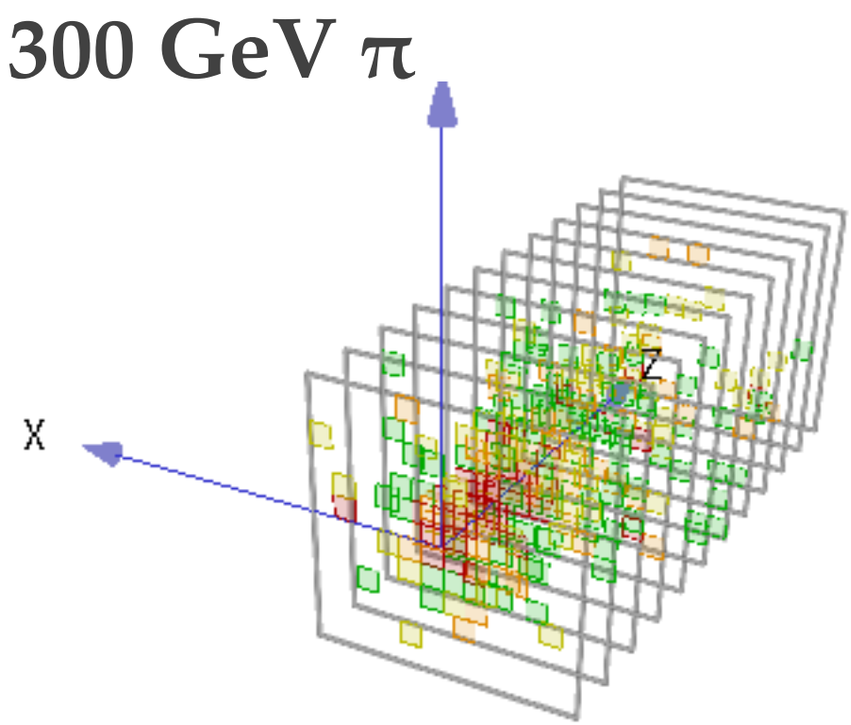
E7/E19 in data and compared to simulation ($E_{CE\text{-}E} / E_{CE\text{-}H(Si)} < 0.03$)





➡No obvious disagreement for most layers “out-of-the-box”.
➡Discrepancies to simulations are under investigation.

Outlook: Combination with the AHCAL data



- Beam hits AHCAL centrally.

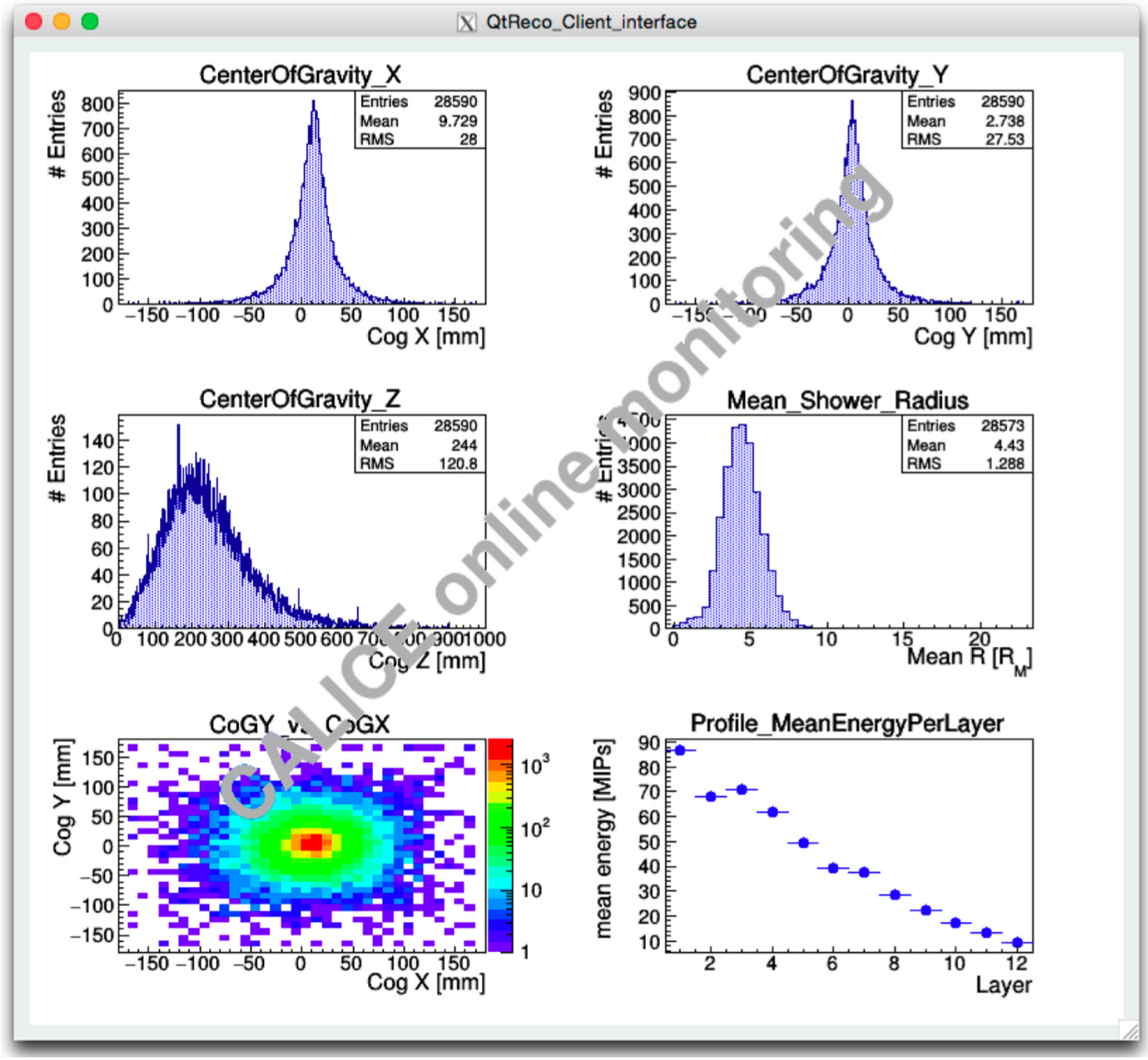
- **AHCAL has operated well.**

➡ Good data quality.

Offline analysis combined with HGCal data soon.

AHCAL Online Analysis:

- minimal selection: >=3 hits
- very preliminary calibration

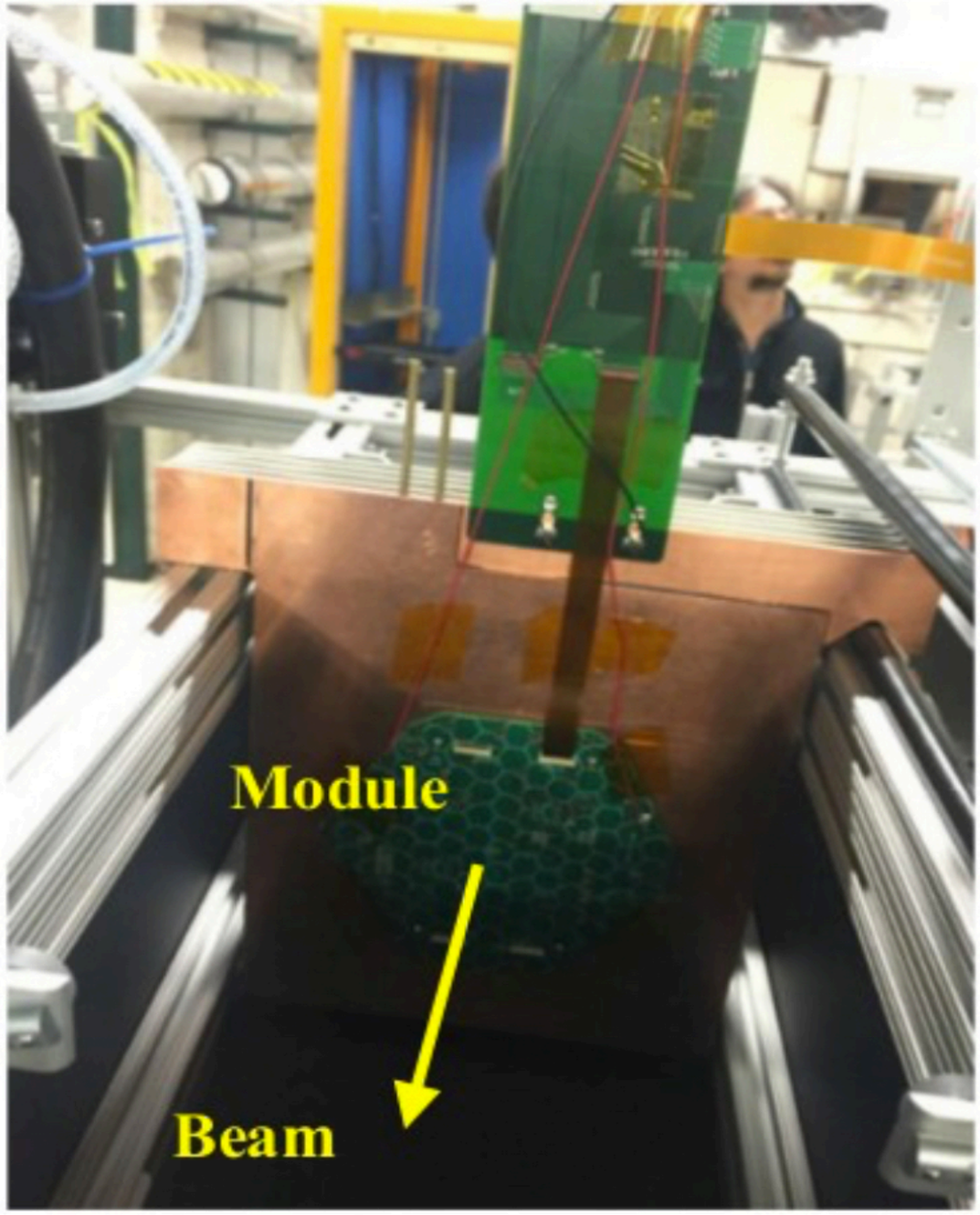


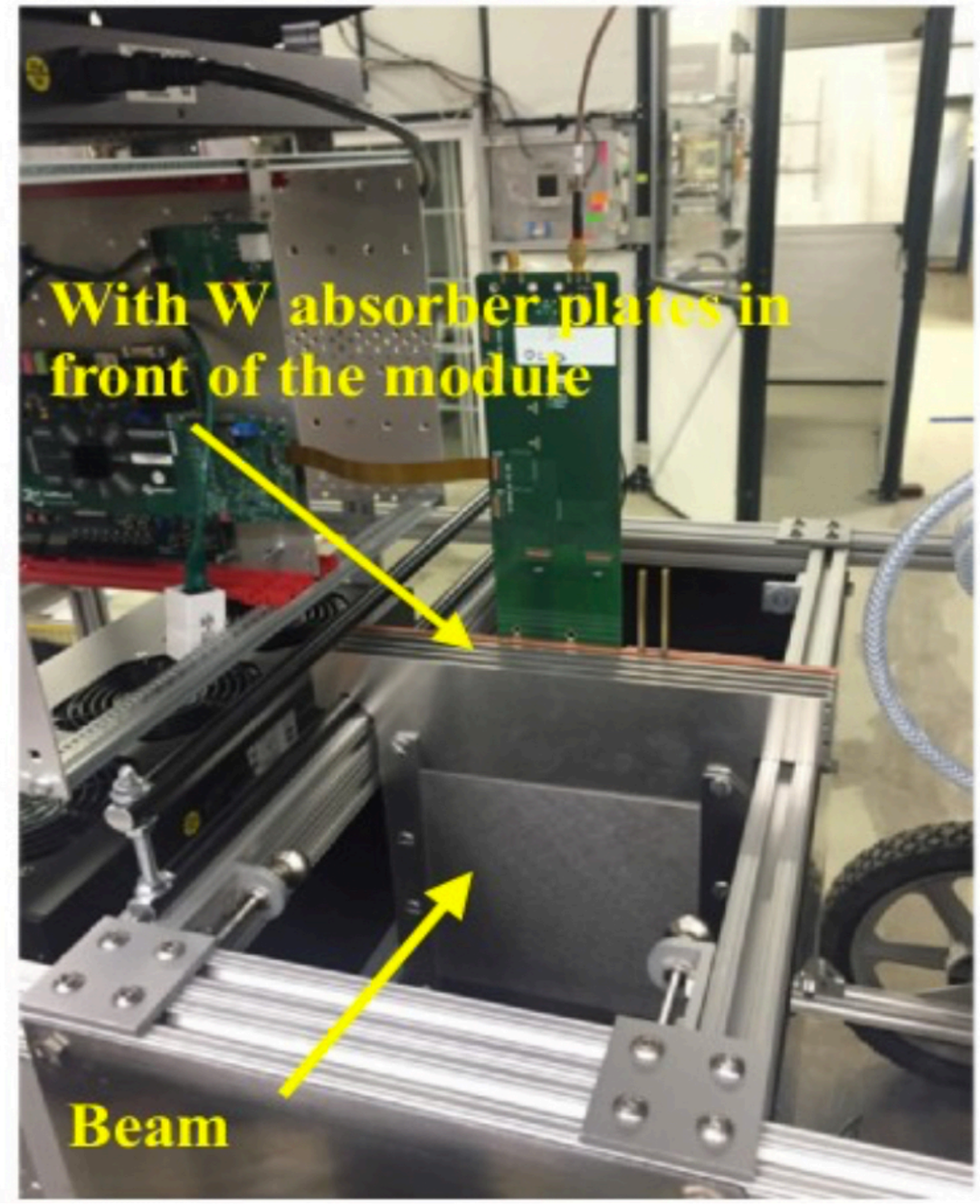
Summary

- CMS-HGCal TB related results with the CE-E prototype with data recorded in 2016 are summarised for publication.
- The upgraded CMS-HGCal prototype including FH-part and CALICE AHCAL has been tested with electrons and pions at CERN this year.
- Setup had to be reduced compared to the initial plan for the 2017 tests.
- Data taking in 2017 has been successful. Calibration is ongoing. Good quality of data. Comparison to simulation has started.
- Now, prototype is continuously extended and more tests are coming!

Additional material

Test beam mechanics in 2016





Hanging file design for flexibile insertion of absorbers and modules on cooling plates.

Timing Resolution (2016)

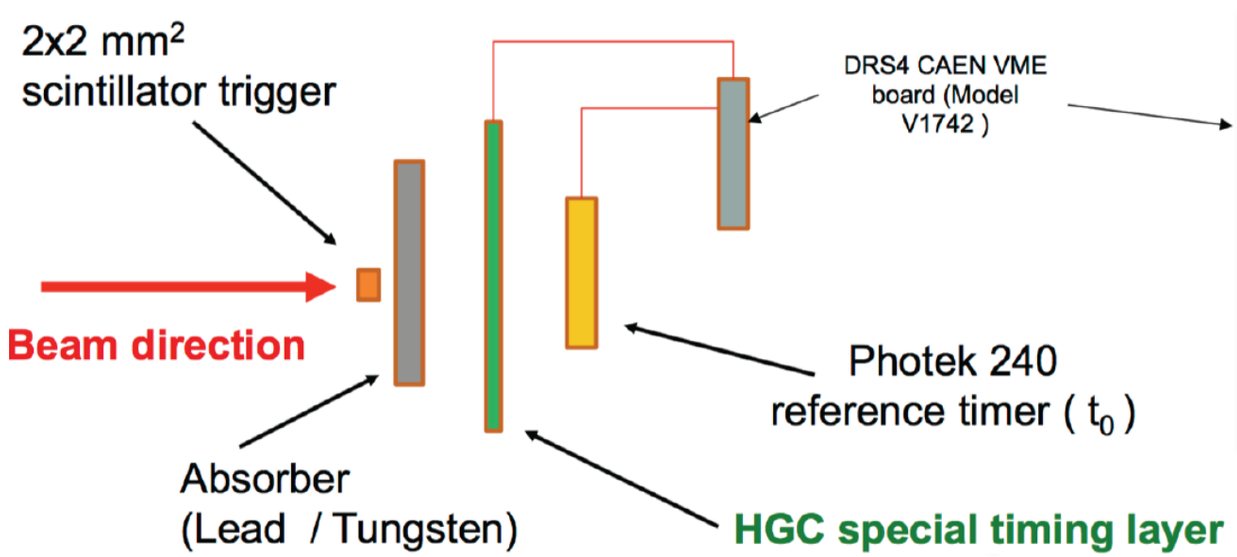
Initial study at FNAL.

Purpose of a good timing resolution:

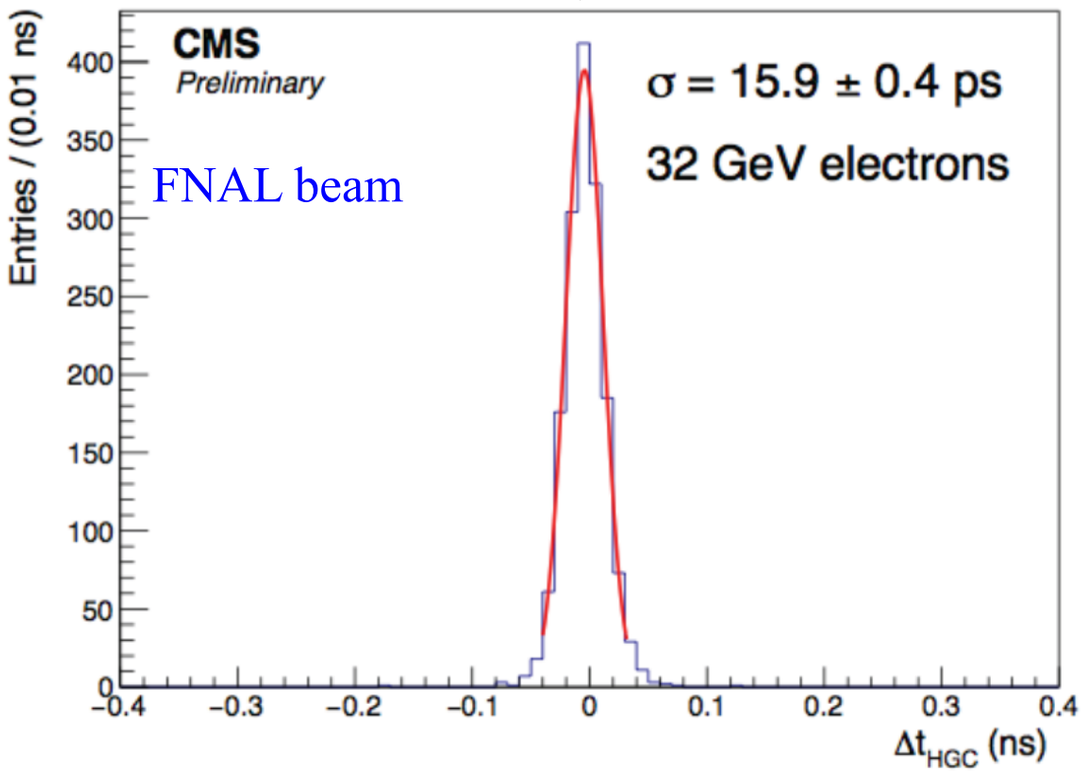
Use precision timing of EM shower for pileup energy removal.

➡ Reduction of impact of pileup.

Timing test with 300 µm HGC layer with fast readout:



Comparison of time stamps in HGC timing layer vs. Photek MCP-PMT



Results with 32 GeV e⁻ test beam:

➡ Precision around 16ps.

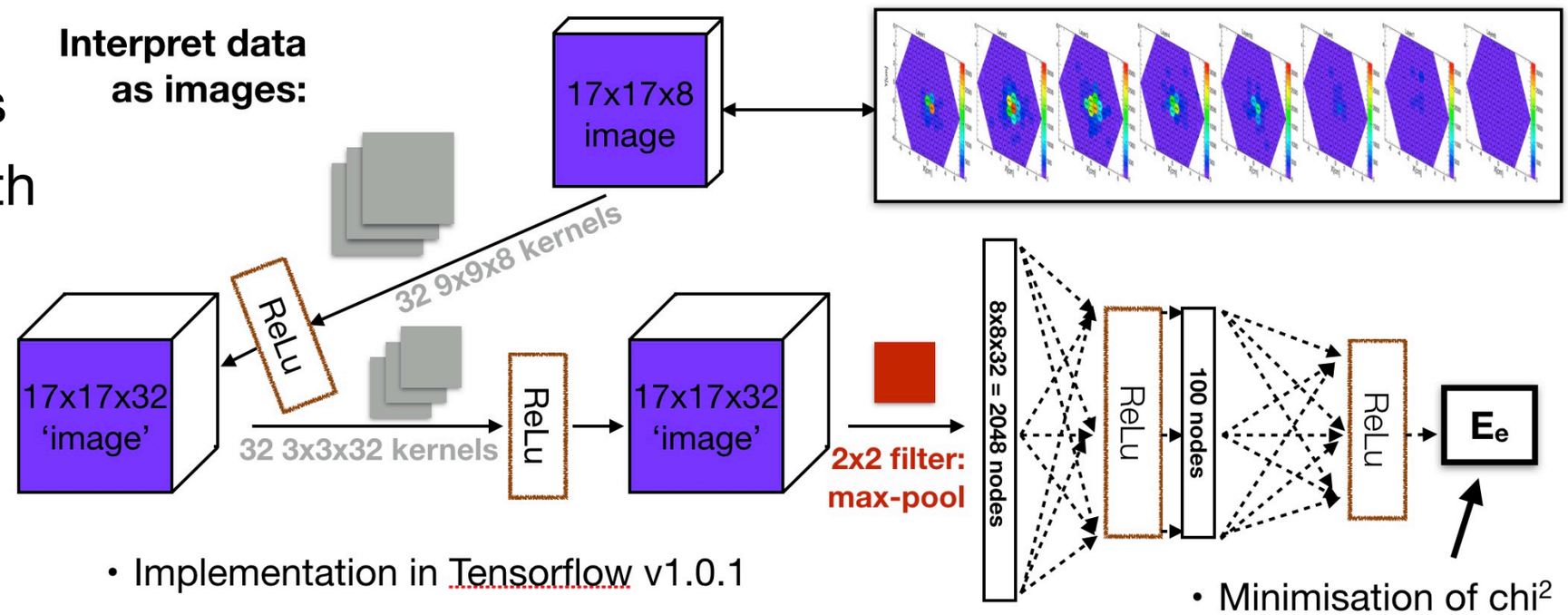
➡ Scaling with S/N.

Energies up to 250 GeV at CERN last November:

- Analysis ongoing.
- Expect better resolution with higher S/N, usage of multiple cells.

A machine learning based energy reconstruction

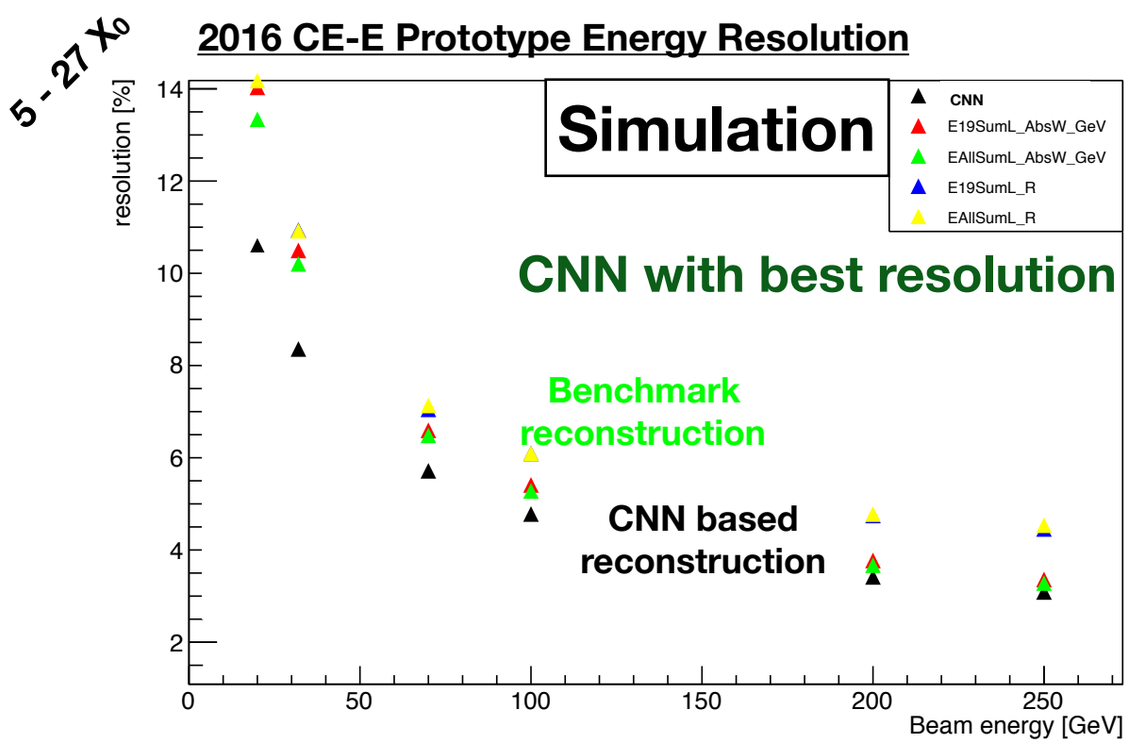
- Explore full content of features in the data in terms of energy reconstruction with a convolutional neural network (CNN).

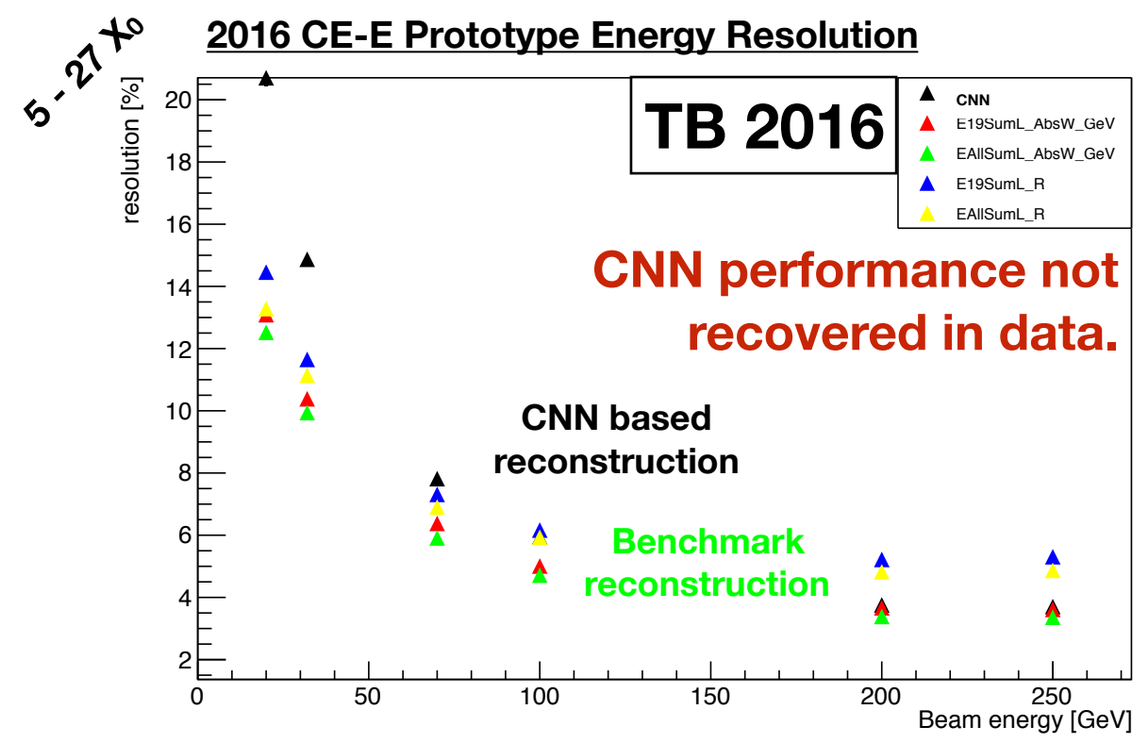


- Implementation in Tensorflow v1.0.1
- Minimisation of chi² cost function

Training on simulated data with 1-300 GeV electrons.

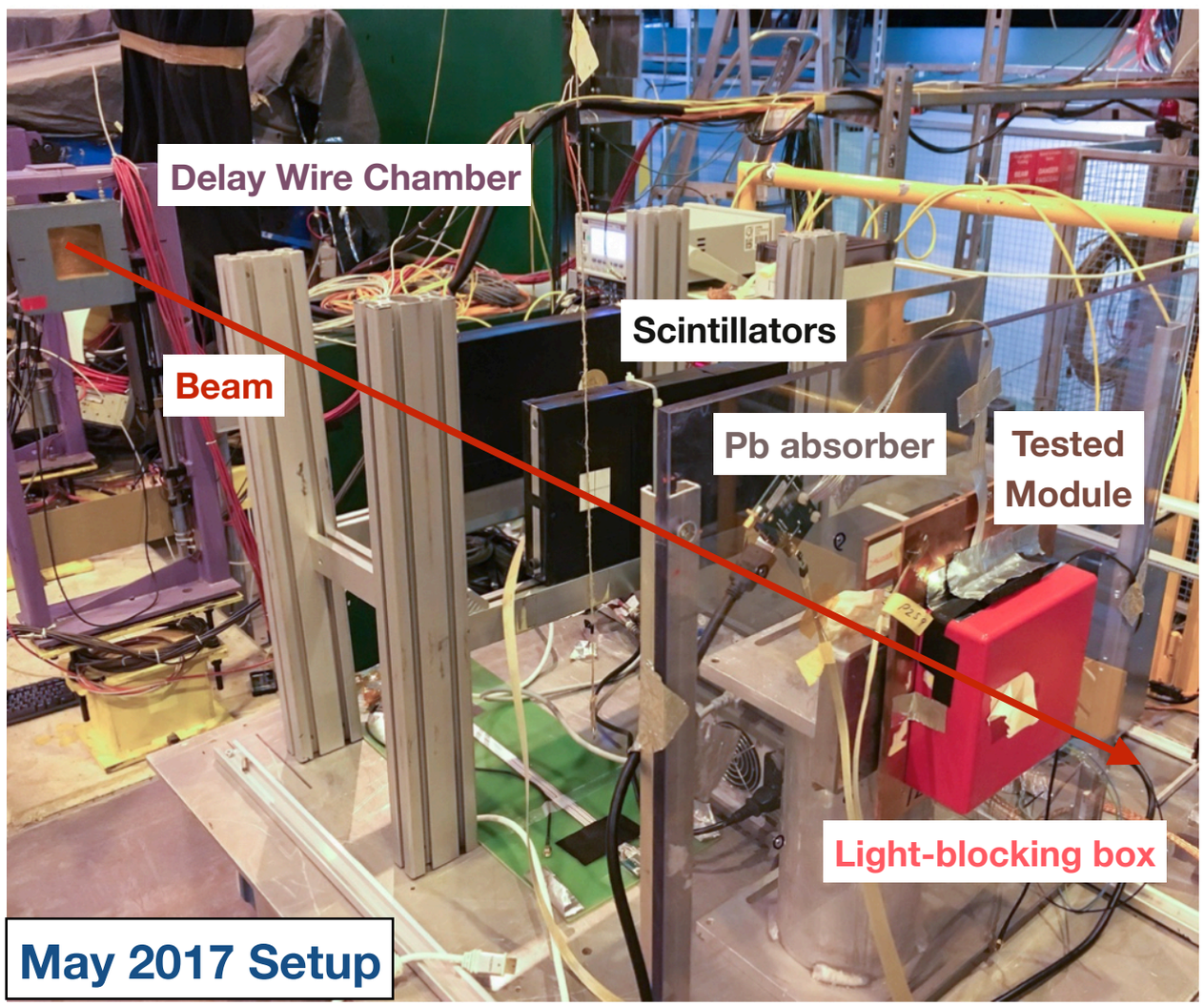
Evaluation on simulated and real test beam **energy binned electron** samples.



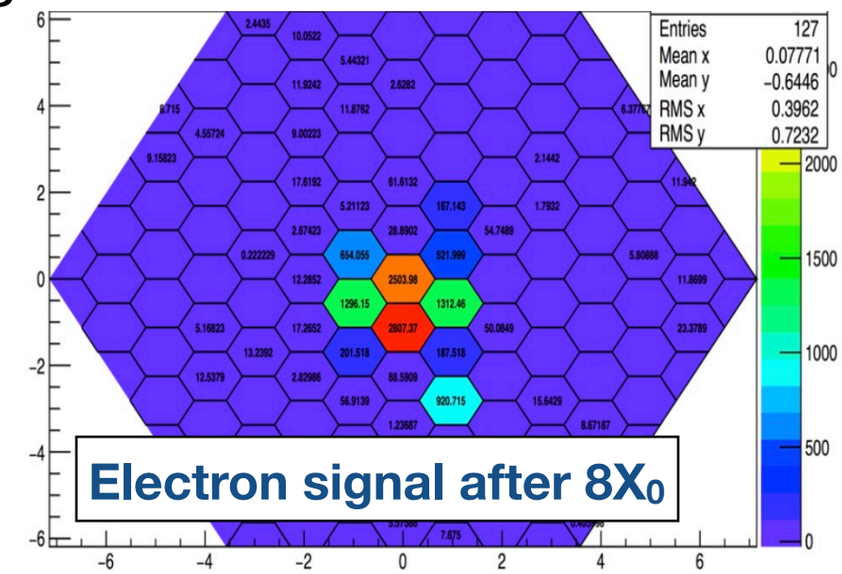


One module test in May 2017

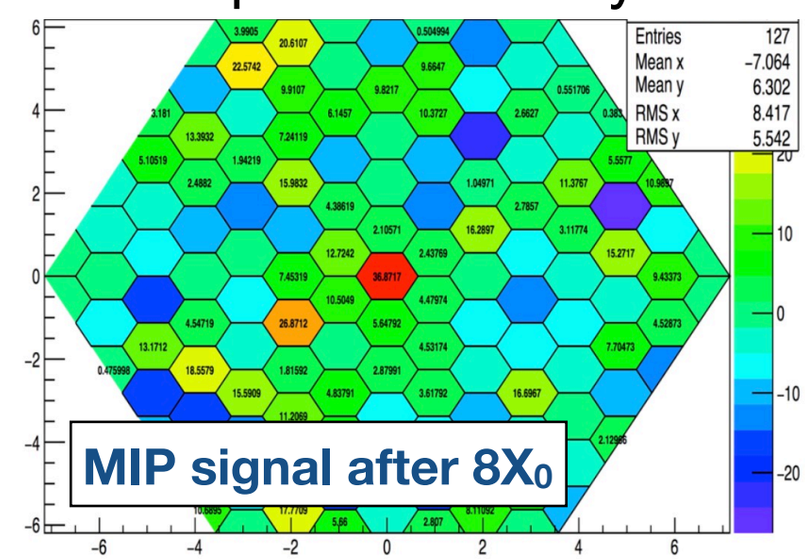
- One module mounted on Cu cooling plate and mounted on plexiglas support.
  - Two scintillators as triggers.
  - 8 X_0 upstream Pb absorber.



➡Electron signals seen in the module on the 1st day.



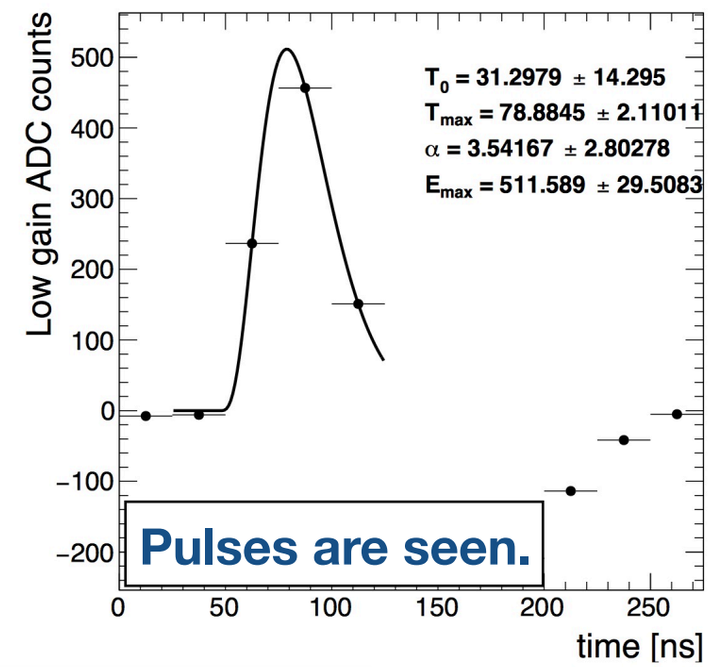
➡Contamination with pions this May.

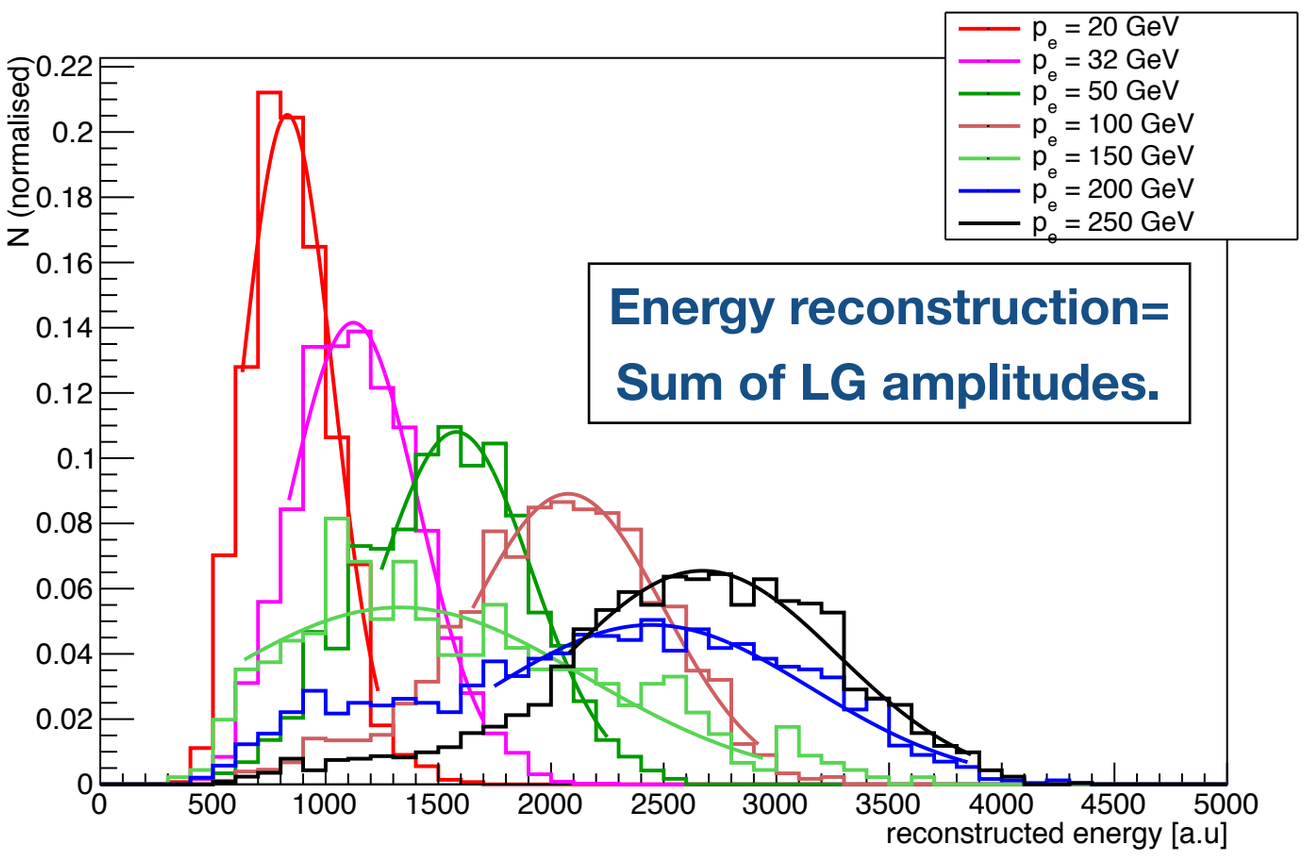


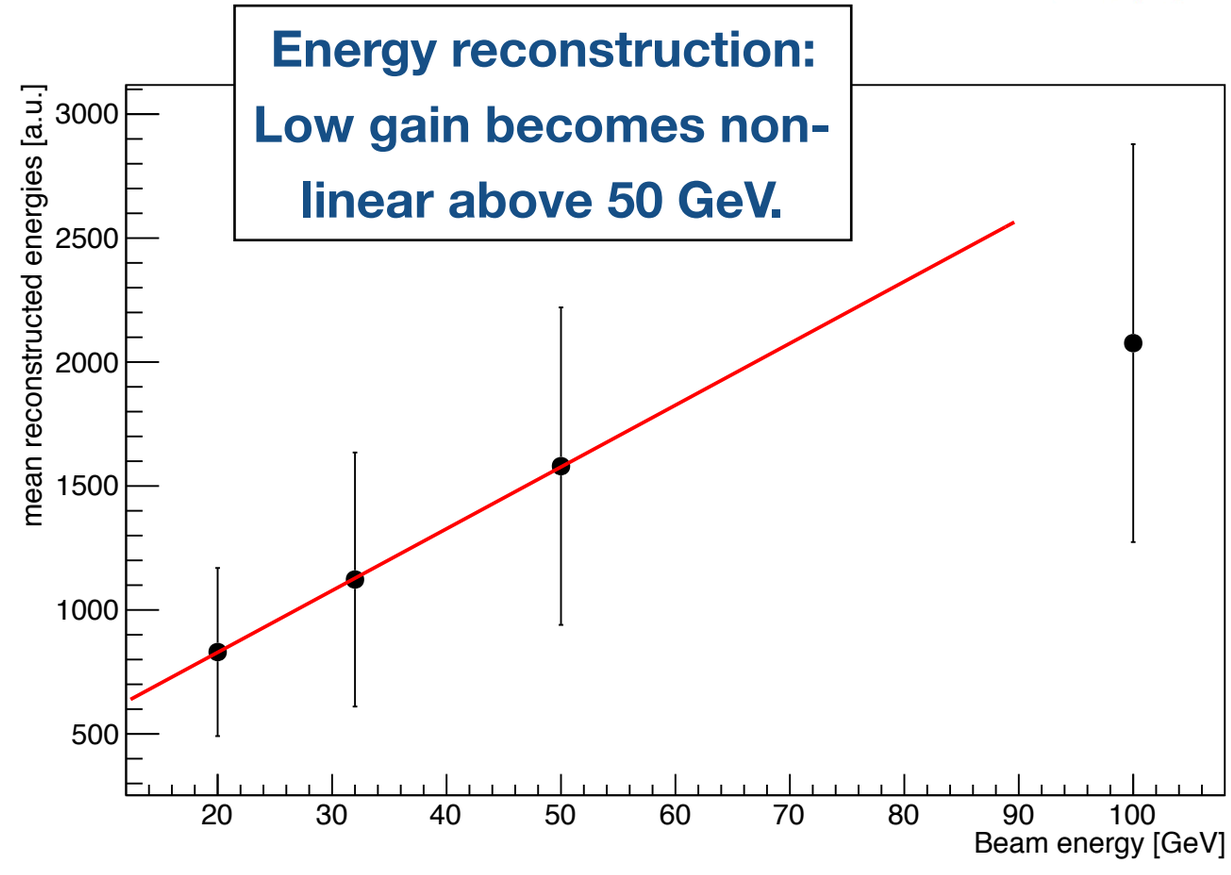
✓Comprehensive C++ based analysis framework was implemented.

Analysis of one module May 2017 data

- Comprehensive C++ based analysis framework is developed.
- Allows for a variety of studies with the data.







Longitudinal shower size - Data vs. sim.

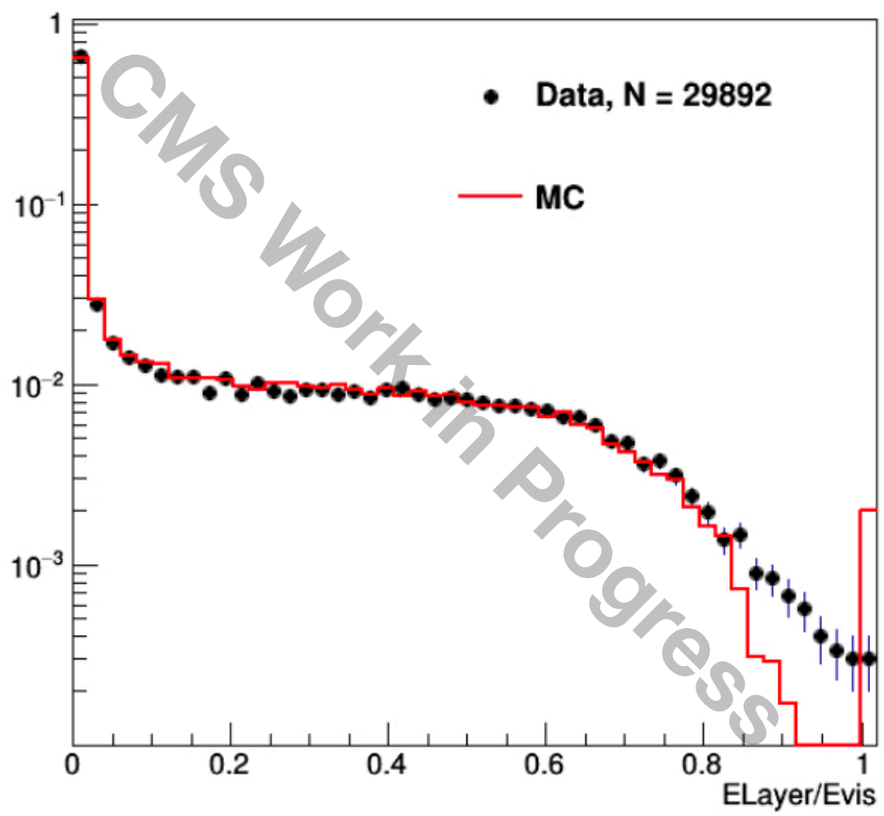
Work in progress

Definitions:

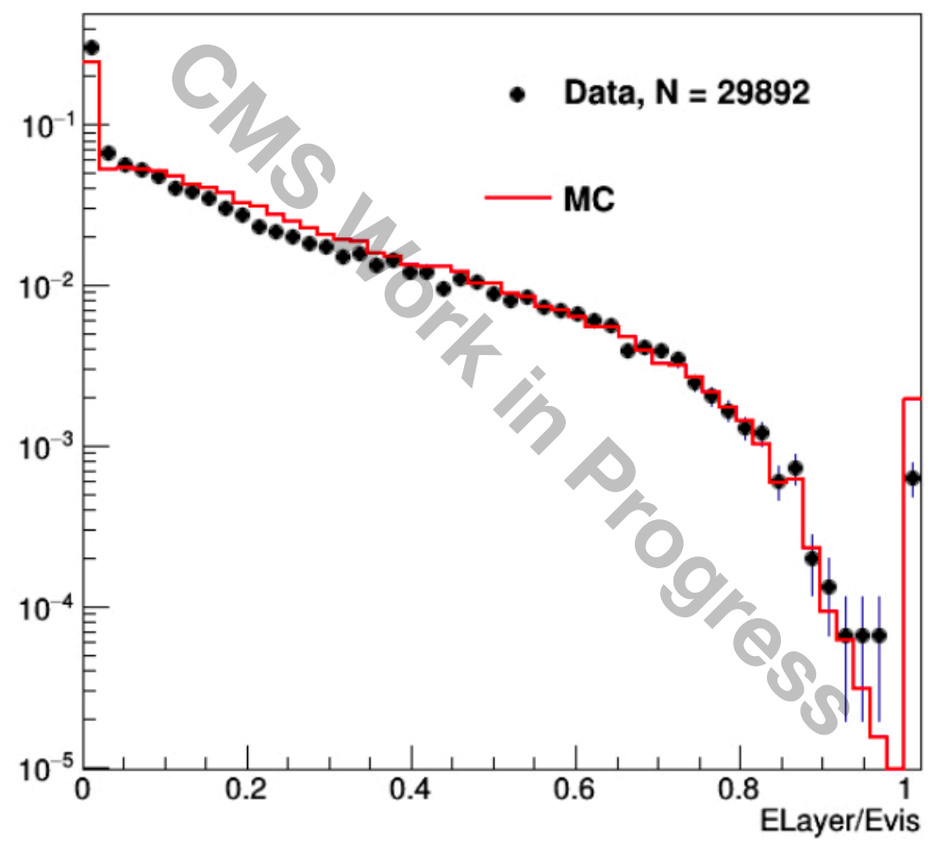
- ELayer: Sum of reconstructed energies in a given layer.
- Evis: Total sum of reconstructed energies over all cells in the calorimeter.

ELayer/Evis for many layers—> Longitudinal shower profile.

EE1: 200 GeV π



FH0: 200 GeV π



➡No obvious disagreement for most layers “out-of-the-box”.

➡Discrepancies to simulation, especially for EE-2, are under investigation.