Performance of CMS High Granularity Calorimeter prototypes in testbeam experiments

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CHEF2019 conference, Kyushu University, Fukuoka, Japan
26 November 2019

Outline

- Introduction
- HGCAL Beam Test Setup in October 2018
- Signal reconstruction and calibration
- Physics performance
  - Electromagnetic Showers
  - Hadronic showers
- Summary

CMS **H**igh **G**ranularity **CAL**orimeter

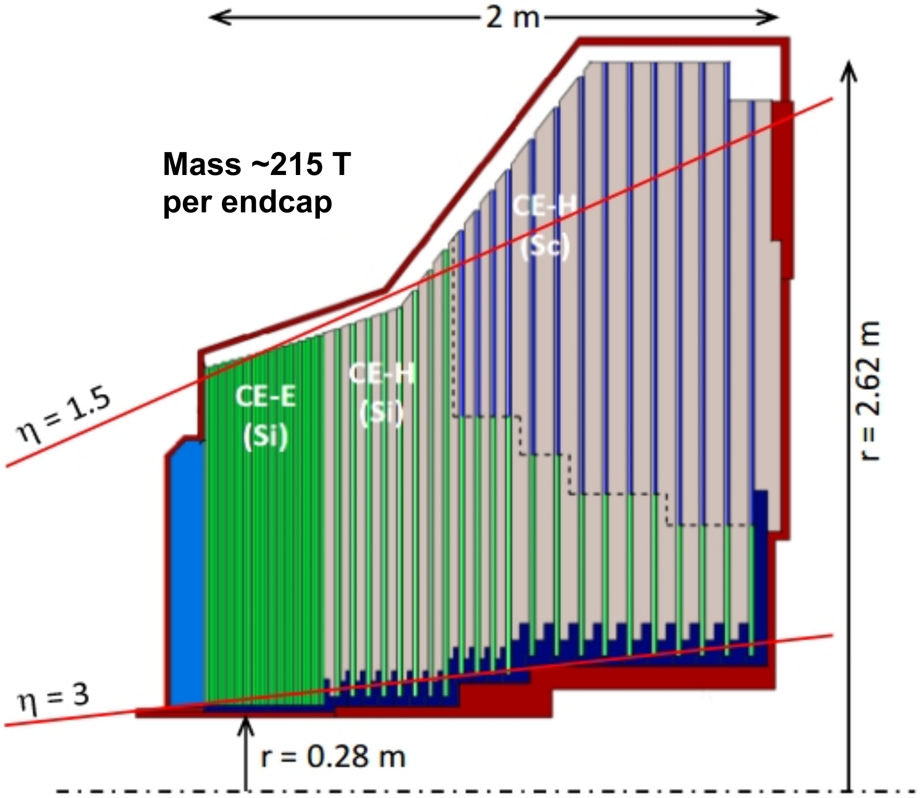
To sustain the harsh environment of HL-LHC run, forward region of CMS will be replaced by High Granularity Calorimeter (HGCAL).

Active Elements:

- Electromagnetic part of HGCAL:
  - **CE-E** : **Si** sensors as active layers, Cu/CuW/Pb absorber
  - **28 layers, 25 X_0 & ~1.3 λ**
- Hadronic part of HGCAL:
  - **CE-H** : **Si** & **SiPM-on-scintillator** as active layers, steel absorbers
  - **22 layers, ~7.2 λ**

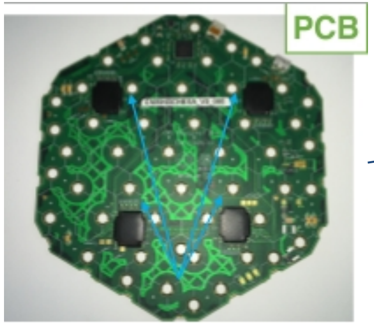
Key-parameters:

- HGCAL covers 1.5 < |η| < 3.0
- Full system maintained at -30°C
- **~640 m²** of Si sensors & **~370 m²** of scintillators
- **6.1M Si channels**



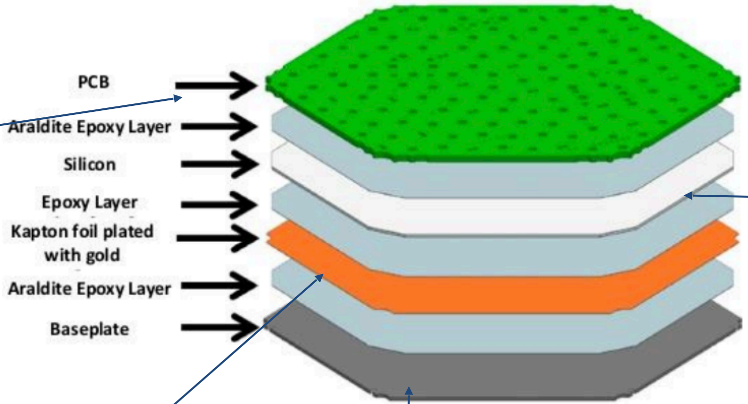
For more details, see the talk Status and plans for the CMS HGCAL upgrade project by Felix Sefkow

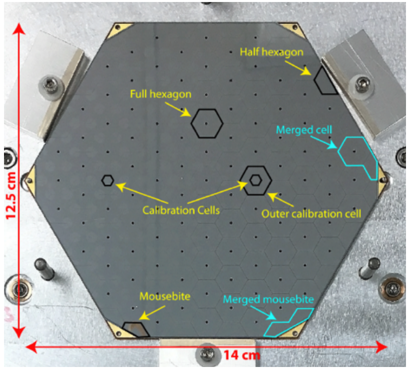
HGCAL prototype 6” Silicon sensor module



Skiroc2-CMS ASIC

- 64 channels, 4 chips/module
- Based on CALICE chip adjusted for CMS requirements.

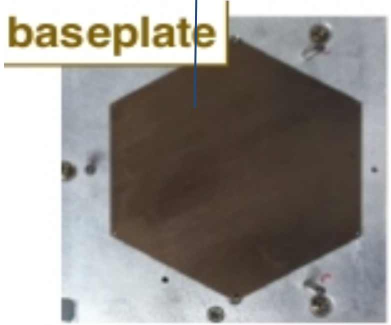




6” silicon sensors

- n-type, 128 cells
- 1 cm² cell size
- depletion: 200 & 300 μm

Gold plated



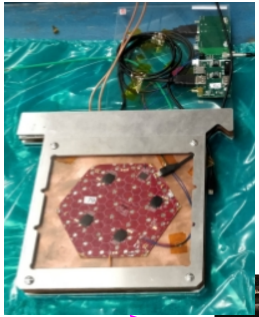
Cu/CuW or PCB

For more details, see talks on :

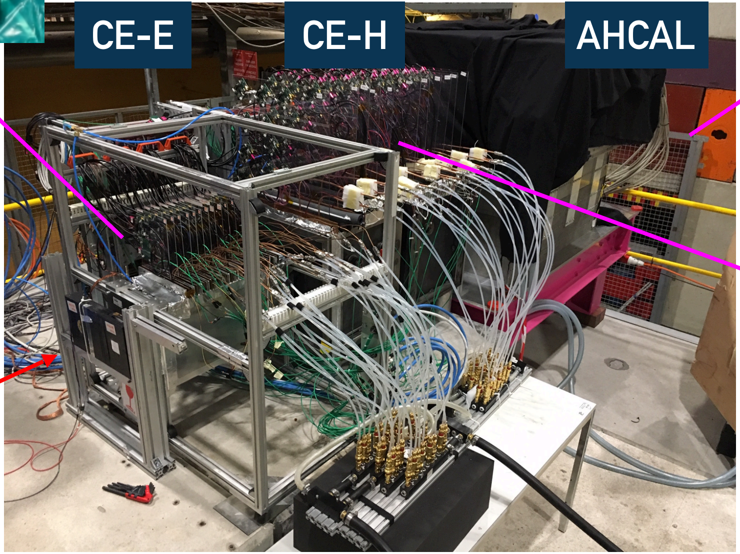
Si sensors for the HGCAL upgrade: challenges, sensor design & electrical characterization by **Erica Brondolin**

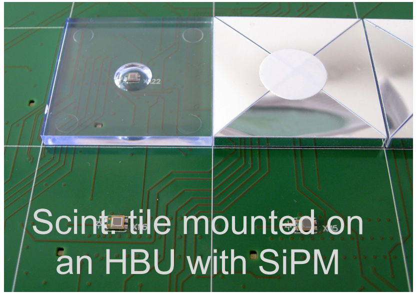
Versatile systems for characterization of large-area Si pad sensors for HGCAL by **Pedro Dias De Almeida**

Beam test setup in October 2018

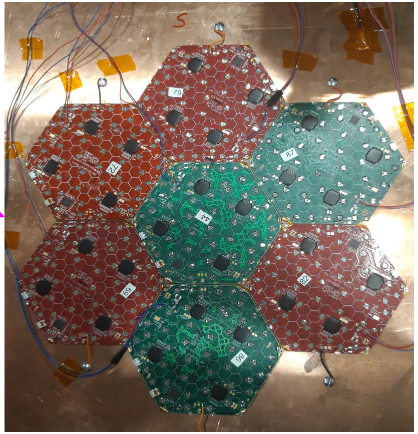


CE-E: Hanging file structure
- Double sided cassettes
- **Lead/Copper absorber**
- **~ 26 X_0, 1.4 λ_{int}**





CALICE AHCAL:
- Scintillator/SiPM
- **Steel absorber**
- 39 layers, 14k channels
- **~ 4.4 λ_{int}**



CE-H: Hanging file structure
- Single sided cassettes
- **Steel absorber**
- **~ 3.4 λ_{int}**

First large-scale test of more than 90 HGCAL modules in October 2018 data-taking at CERN.
The setup was exposed to e^+ & π beam of energies ranging from 20 to 300 GeV and 200 GeV μ beams.

Reconstruction and calibration

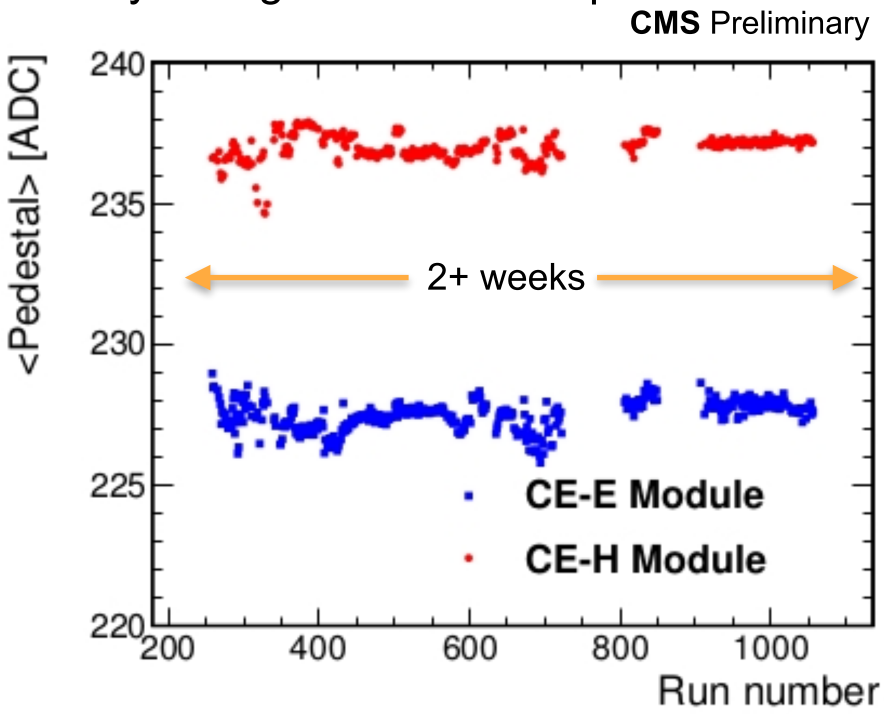
The results are presented based on only CE-E and CE-H sections of the beam test setup.

For more details on AHCAL, don't miss the talk :
The CALICE AHCAL - a highly granular SiPM-on-tile hadron calorimeter prototype
by Katja Kruger

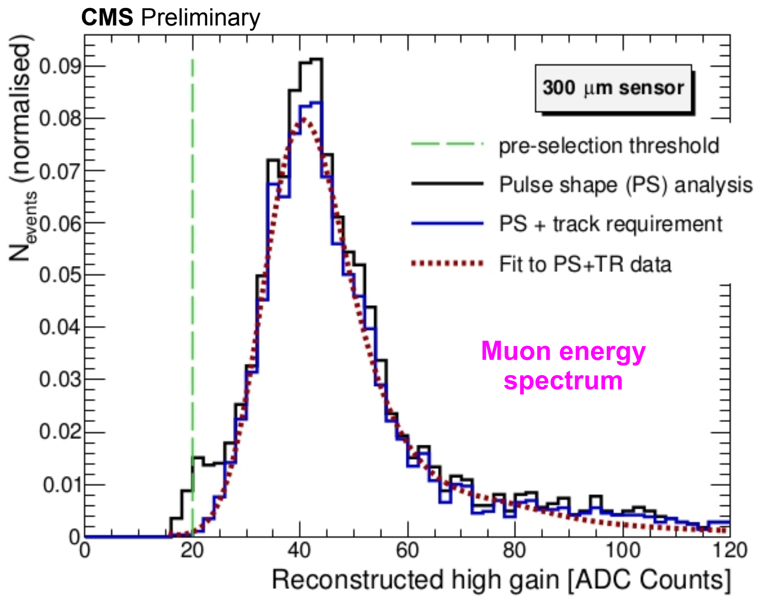
Pedestal stability across data taking period

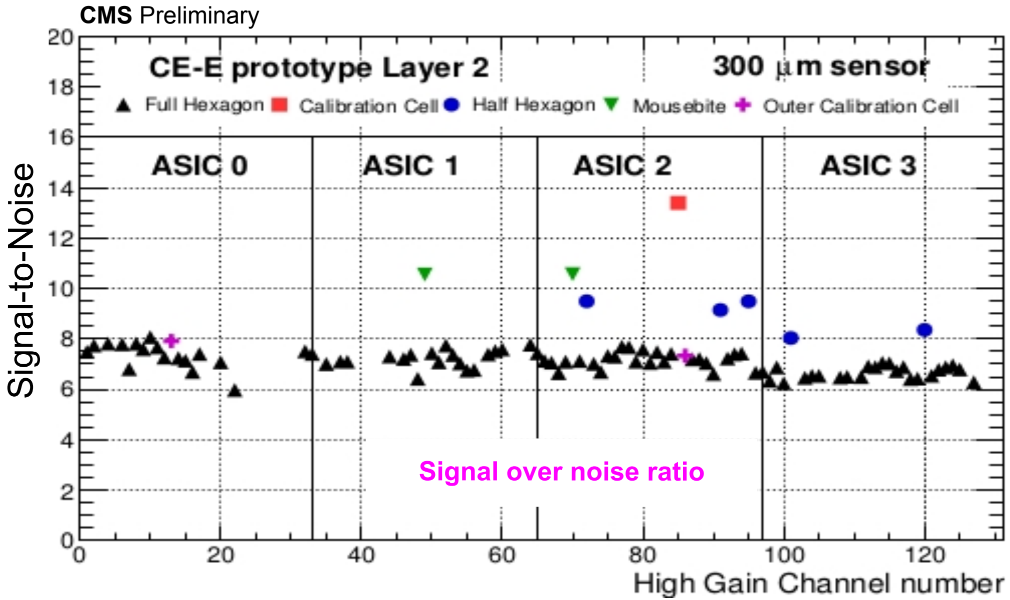
- Pedestal runs were recorded when there is no beam in the detector during the full duration of experiment. Complementary: using muon data for pedestals.

Average pedestal values over the period of 2 weeks of beam test experiment are within expected measurement uncertainties for the CE-E prototype and the CE-H prototype Si readout channels.



MIP calibration using muon beam



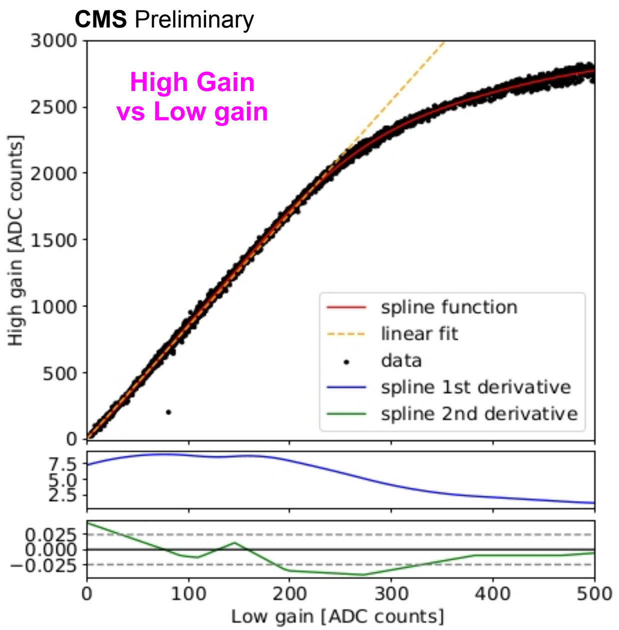


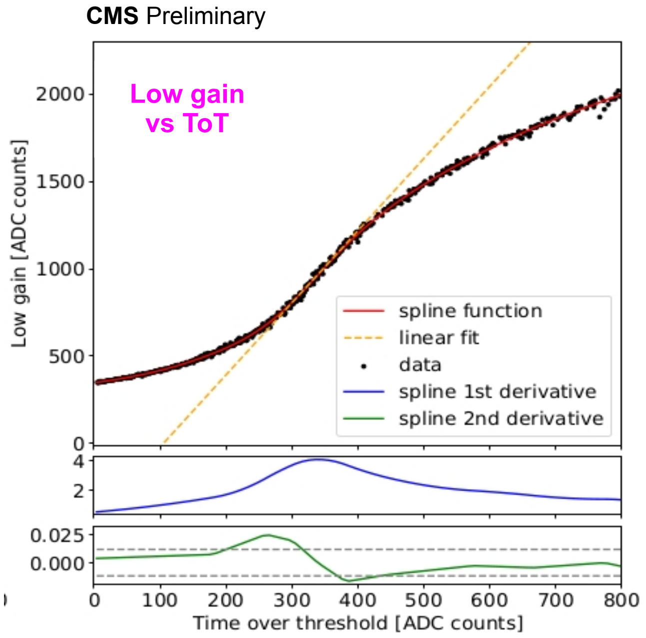
- Silicon sensor channels are calibrated **in terms of MIPs** using 200 GeV μ beam.
- MIP calibration constants are extracted by fitting a **Landau distribution with convoluted Gaussian distribution** over the energy spectrum.

- Signal over noise ratio is found to be **~ 7** for most calibrated **300 μm Silicon** cells.
- Overall **~ 85% channels** from CE-E & CE-H prototype were calibrated (using muons and parasitic runs).

Gain Intercalibration

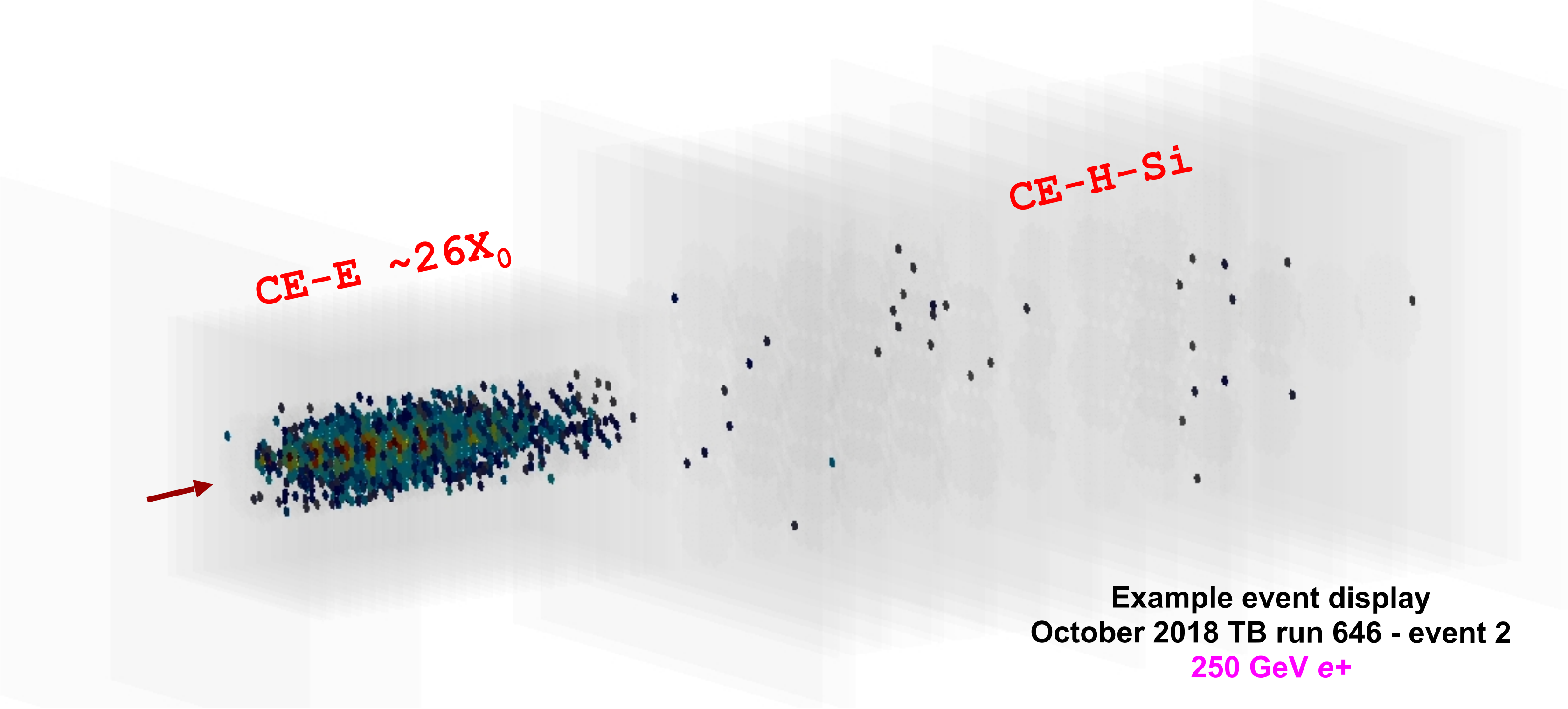
- SKIROC2-CMS ASIC provides different gain stages (High Gain/Low Gain) and Time over Threshold (ToT) to allow a wide dynamic range for energy measurements.
- To ensure a linear response over a large dynamic range, gain intercalibration is performed.





Sufficient overlap in ranges to allow a reliable gain inter-calibration coefficients obtained through the fits of these correlation measurements.

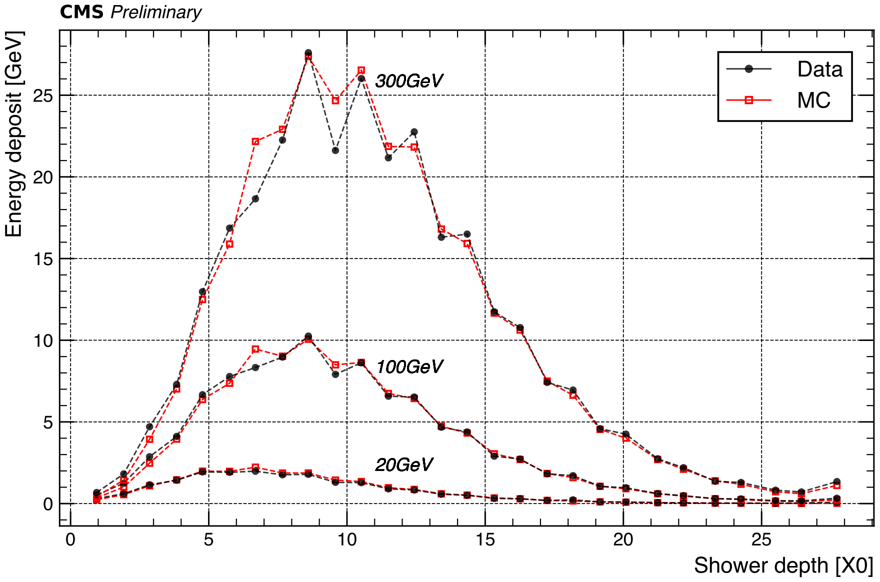
Physics Performance
(using 20-300 GeV e^+)



Example event display
October 2018 TB run 646 - event 2
250 GeV e+

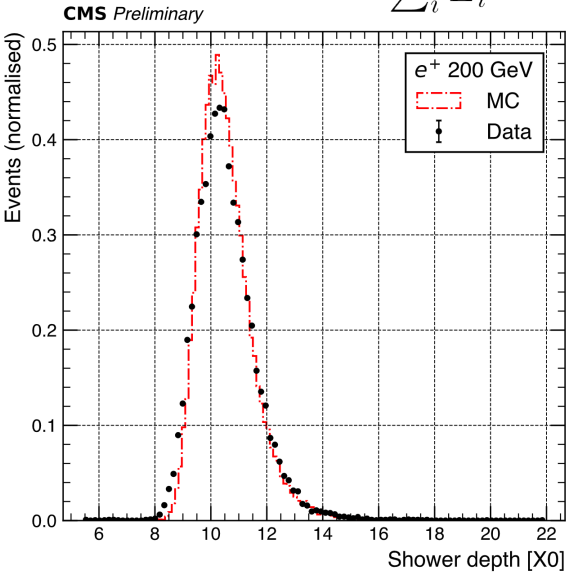
EM showers: Longitudinal Shower Shapes

Longitudinal shower profile: average energy deposited by *e*+ showers in each layer of CE-E



Shower depth: center of gravity of shower

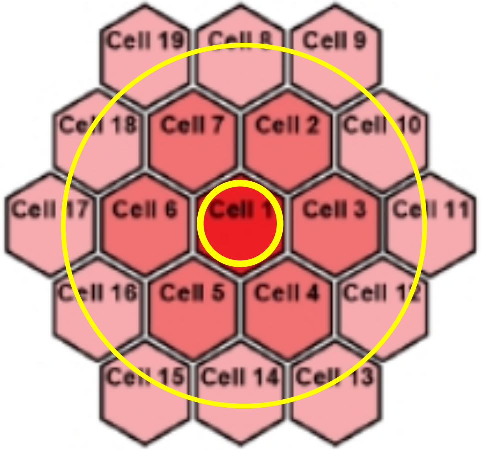
$$SD[X_0] = \frac{\sum_i E_i z_i[X_0]}{\sum_i E_i}$$



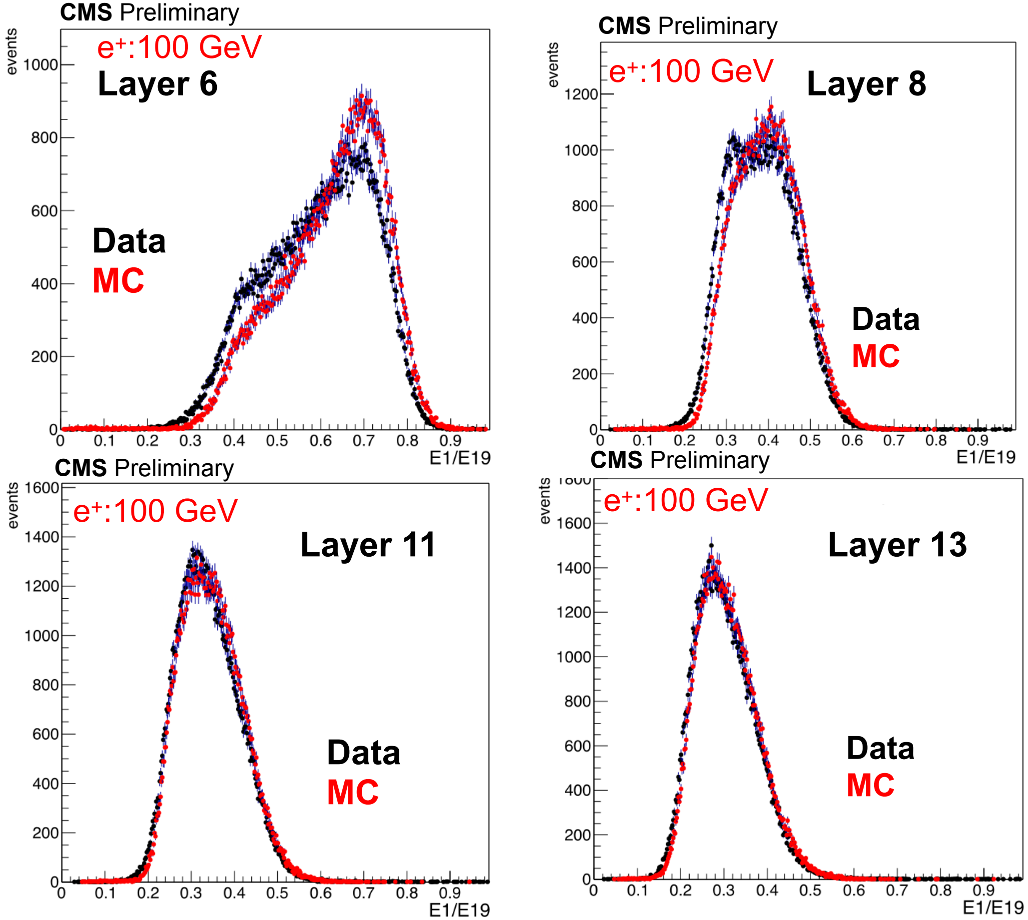
The GEANT4 FTFP_BERT_EMN physics list closely models the longitudinal shower shapes measured in the data using e+ momenta raging from 20-300 GeV.

EM showers: transverse shower shape

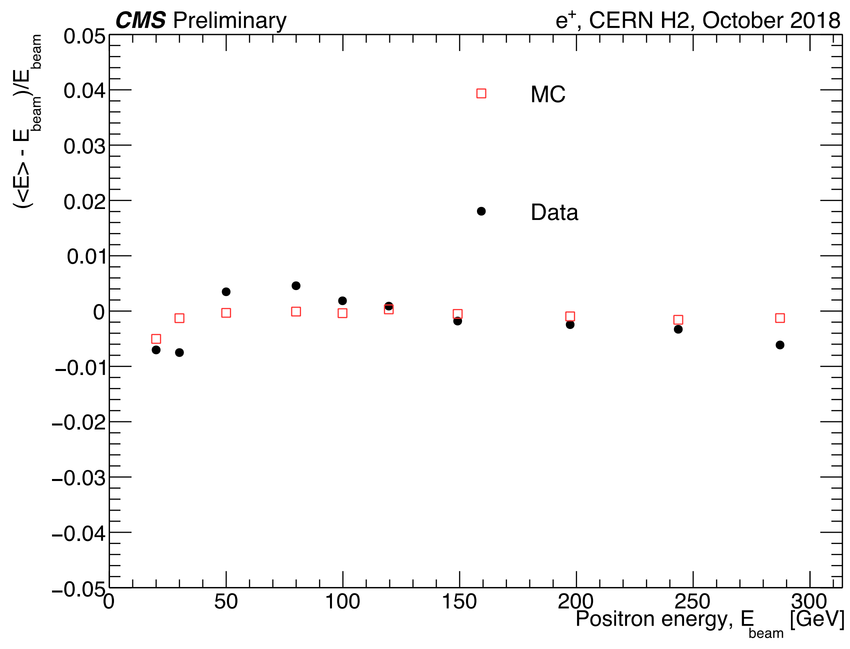
$$E1/E19 = E_{max} / \left(E_{max} + \sum_{i=2}^{7} E_i + \sum_{i=8}^{19} E_i \right)$$

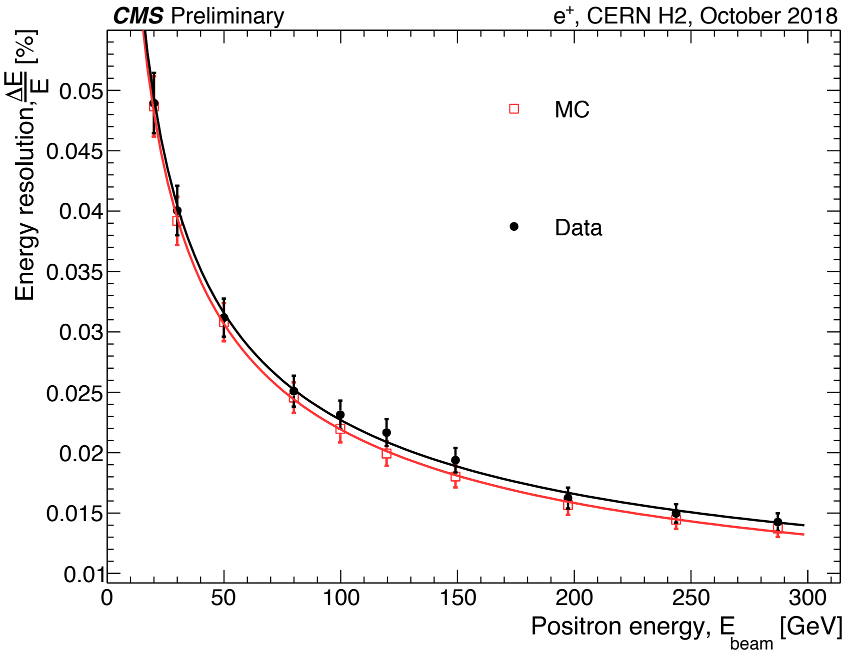


- Transverse shower shapes predicted by the FTFP_BERT_EMN physics list in layers closer to shower maximum agrees well with those measured in the data.



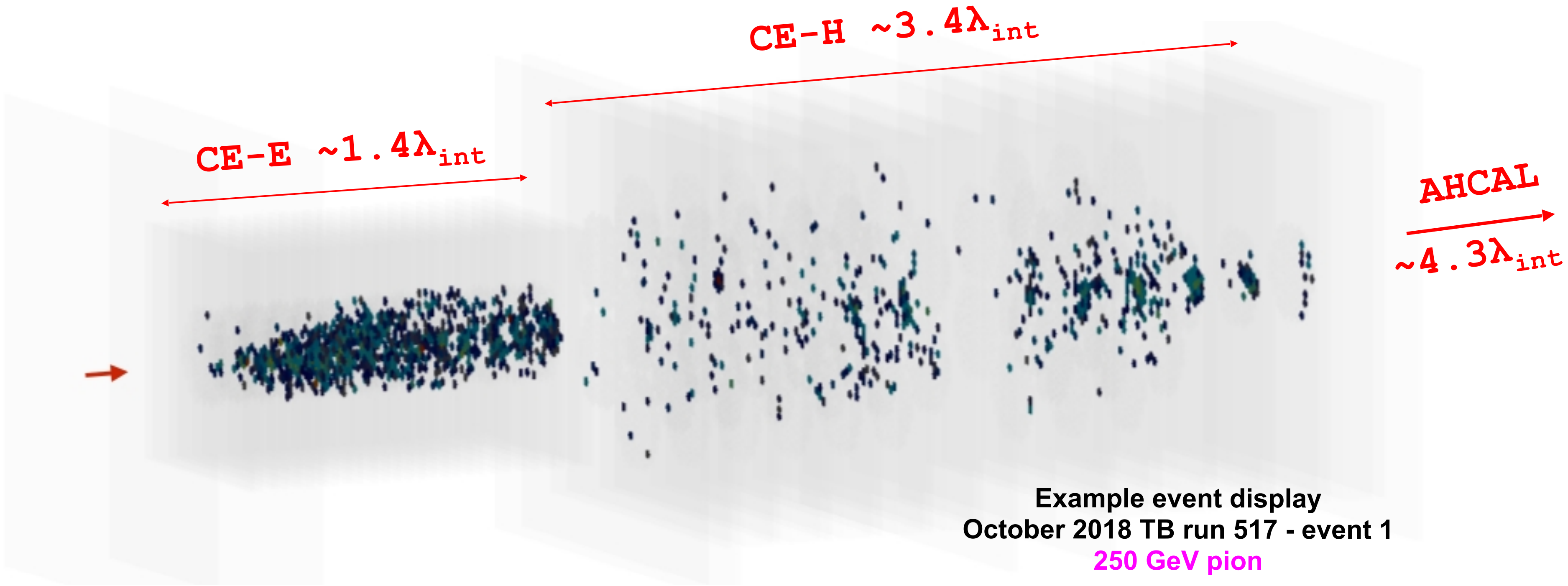
EM showers: linearity & energy resolution





- Energy response of e^+ as a function of beam energy is linear within ± 0.5%.
- Both the resolution and linearity of response measured in data are well described by the simulation.

Physics Performance
Pions

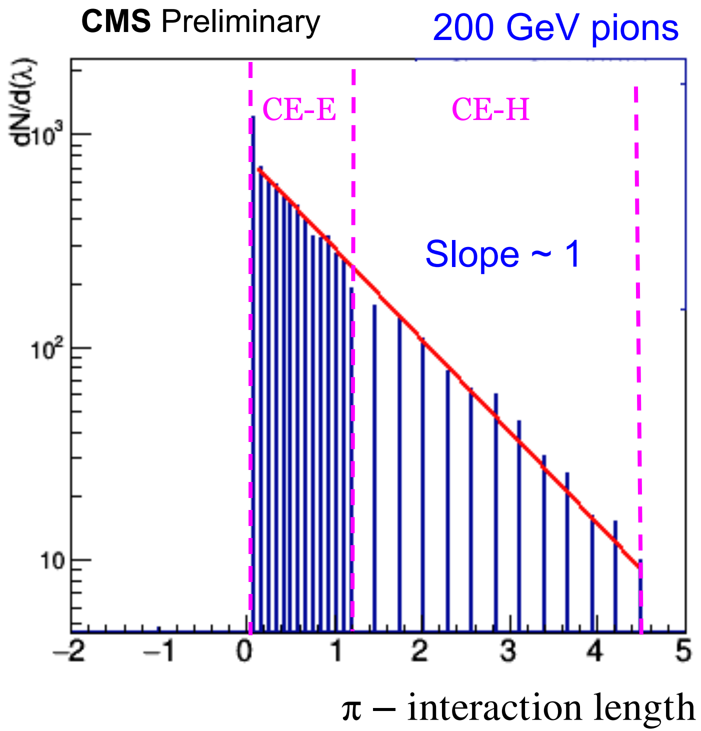


Example event display
October 2018 TB run 517 - event 1
250 GeV pion

Hadron shower start point

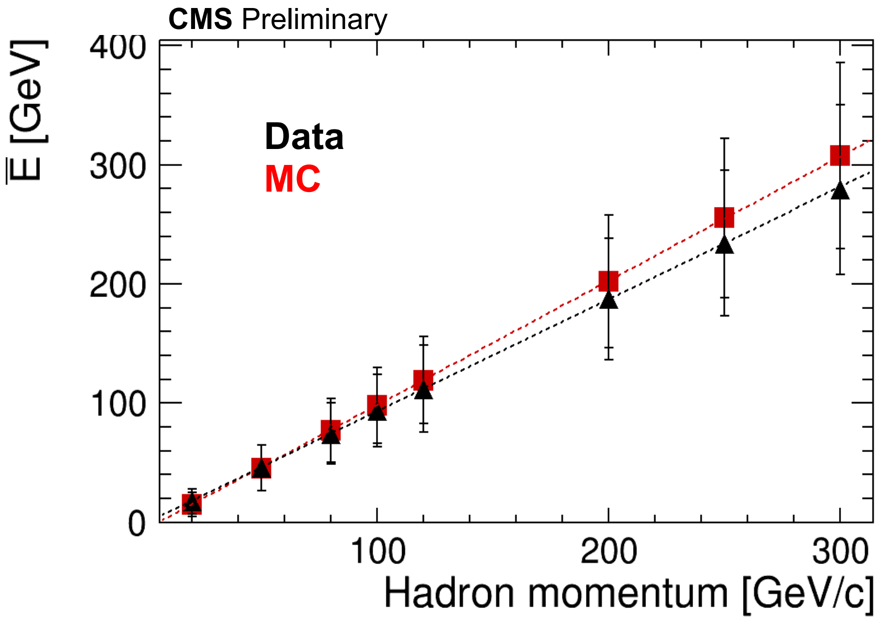
- TB setup was exposed to pion beam of energy ranging between 20 GeV to 300 GeV.

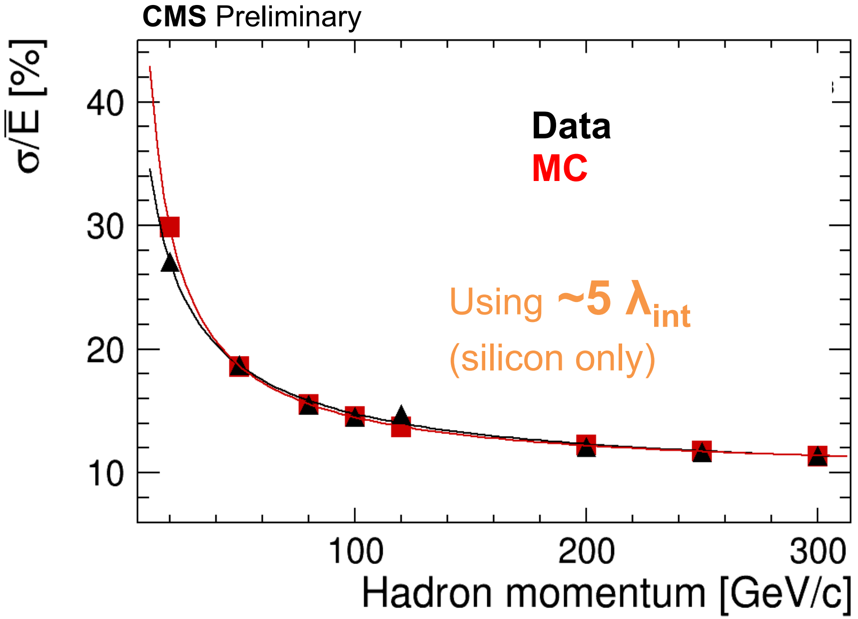
  - The shower start point is the depth of the first hadronic interaction point.
  - Important input to combine energies deposited in calorimeter compartments of different absorbers.
  - A preliminary shower start finder algorithm based on hit multiplicity in consecutive layers is implemented.
  - As expected, the number of showers surviving without a hadron interaction falls exponentially as a function of pion interaction length.



Hadron showers: linearity & energy resolution

- Pion energy is reconstructed using energies deposited in **CE-E** & **CE-H** **(excluding AHCAL).**
- Energies measured in CE-E & CE-H are combined using a software compensation technique minimizing the resolution for different pion energies.

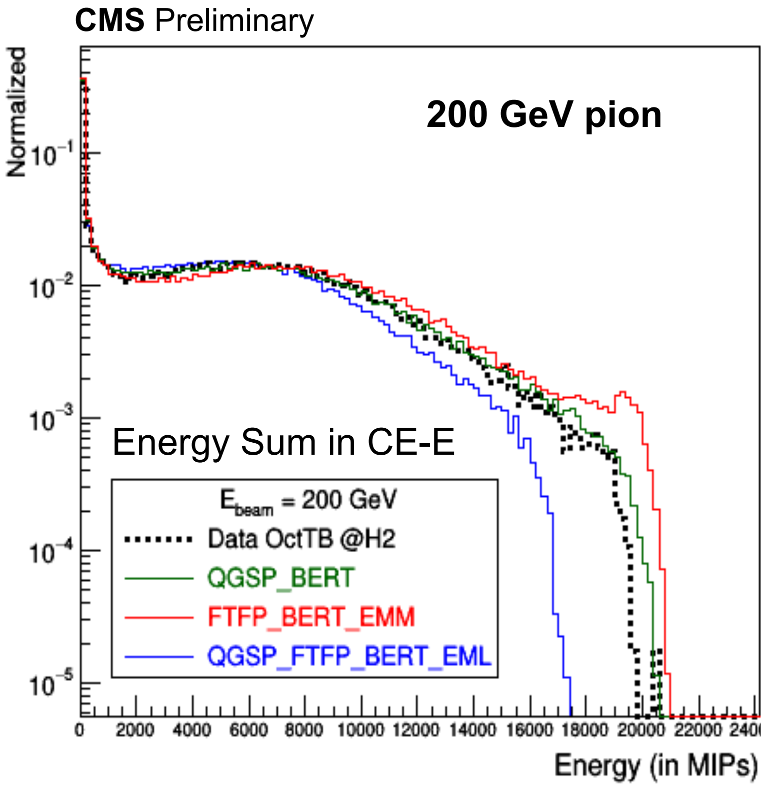




Average response & response measured in data are well described by simulation based on FTFP-BERT_EMM list.

Hadron showers in CE-E

- Understand energy sharing among compartments with different absorbers to get the best resolution, and for measuring longitudinal shower profiles.
- An out-of-box of energies measured in terms of number of MIPs suggests QGSP-BERT modelling the data better than FTFP based lists for high energy pions.



Summary

- First large scale beam test was performed in October 2018 at the H2 beamline at CERN.
  - More than 90 modules were incorporated in HGCAL TB setup.

- Pedestal and noise values remained stable over a period of two weeks of data taking.

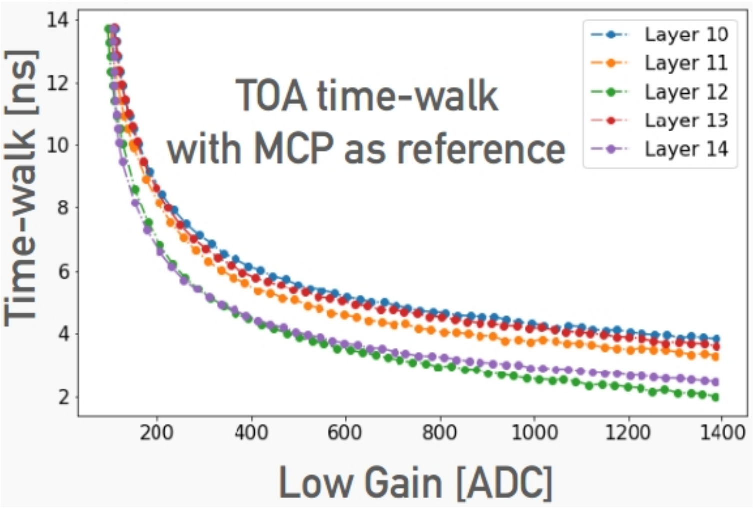
- More than 6 Million events were recorded using ***e+***, ***π*** and ***μ*** beam.
  - Performance of electrons and pions has been studied in terms of response and resolution and is found to be in good agreement with simulation.
  - Analysis of EM showers is almost complete, and is expected to be submitted for publication in coming months.
  - Performance measurement of hadron showers will follow a few months after.

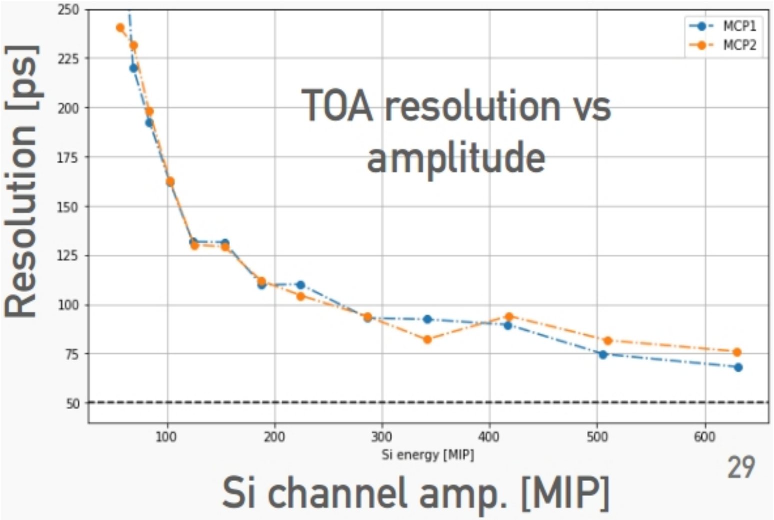
- For the timing studies using test beam data, see the talk "Precision timing calorimetry with the CMS High Granularity Calorimeter" by Artur Lobanov.

Backup

Timing resolution

- Timing is measured with **Time Of Arrival (ToA)**
- **MCPs** from MTD were used as reference which was placed just in front of HGCAL TB setup
  - Single MCP resolution reaching 20 ps floor
- TOA calibration using data from asynchronous beam
  - Time-walk derived with time reference (e.g. MCP)





TOA resolution close to SKIROC2cms spec. of 50 ps