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# Test Beam Measurements of the CMS High Granularity Calorimeter


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(for the CMS collaboration)

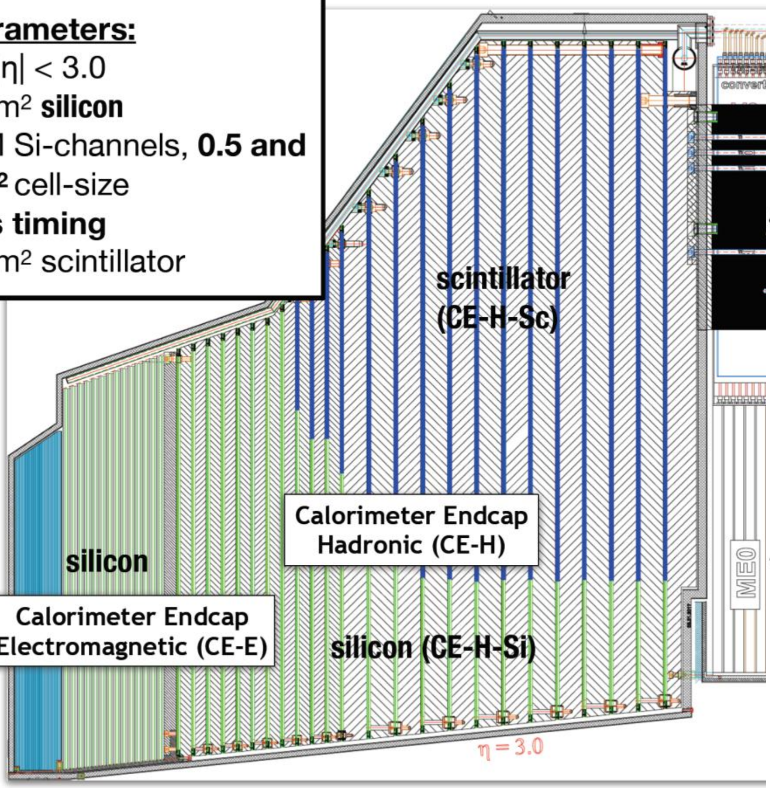

# Outline – HGCAL Test Beam Results

- Test Beam Setup
- Pedestal and Noise
- MIP calibration
- Electron Performance
- Pion Performance
- Timing Performance

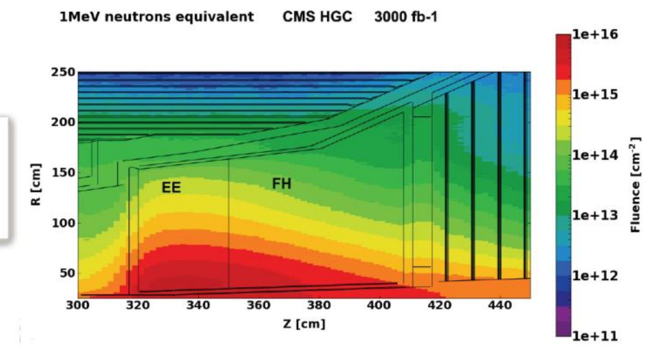
# Test Beam Setup

Replacement of entire **CMS endcap calorimeter** during **HL-LHC upgrade**

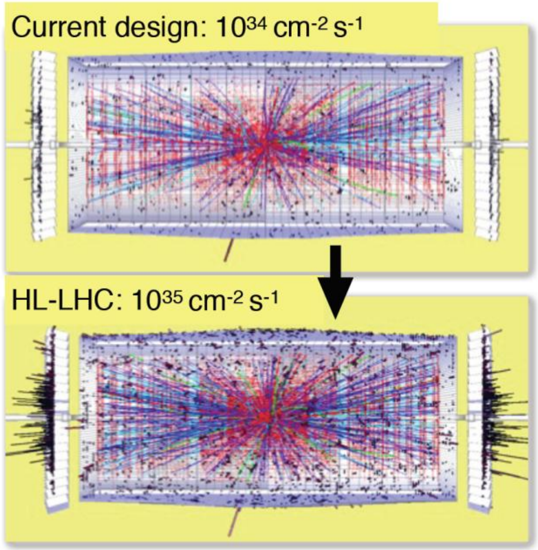
**Key parameters:**
- 1.5 < |η| < 3.0
- ~600 m² **silicon**
  - ~6 M Si-channels, **0.5 and 1cm²** cell-size
  - **50ps timing**
- ~500 m² scintillator




Radiation hardness




Increased pileup

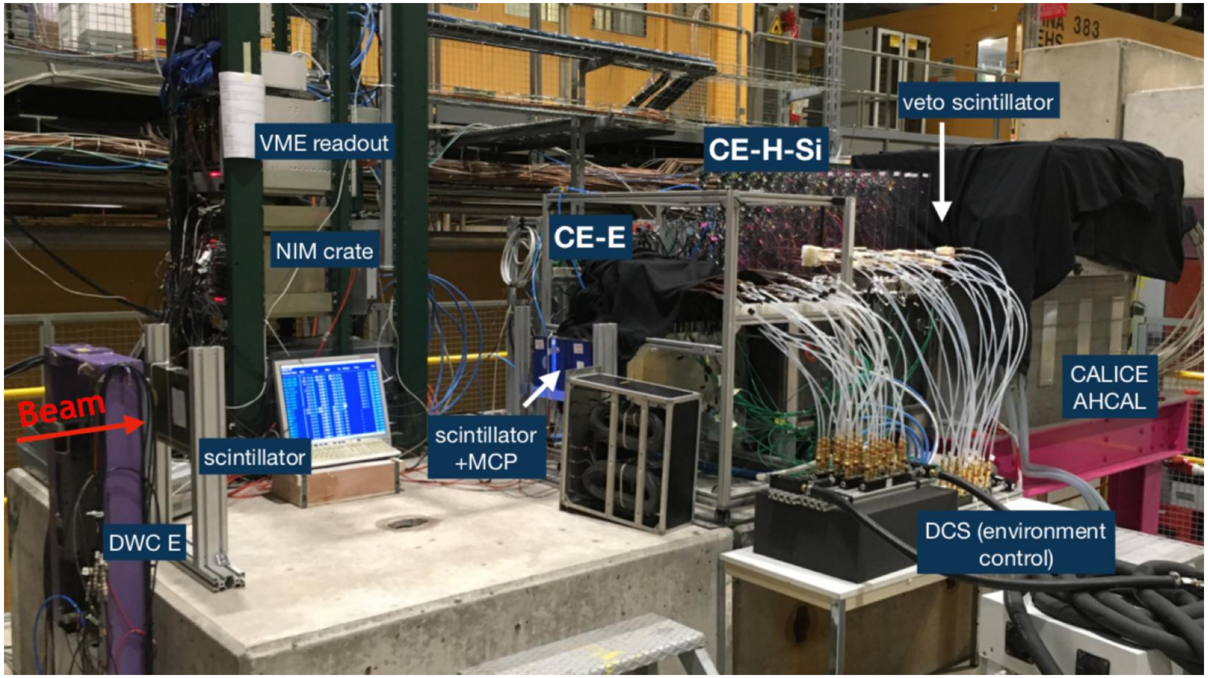


# Test Beam Setup

**Beam test setup at CERN SPS in October 2018**

First large-scale test of O(100) HGCal modules in the October 2018 data-taking at CERN

Large data set of electrons, pions and muons in wide energy range (20 GeV to 300 GeV)




28-layer CE-E setup from June +12-layer CE-H-Si setup (total: **94 modules**)
– 3 configurations (full CE-E vs full CE-H)

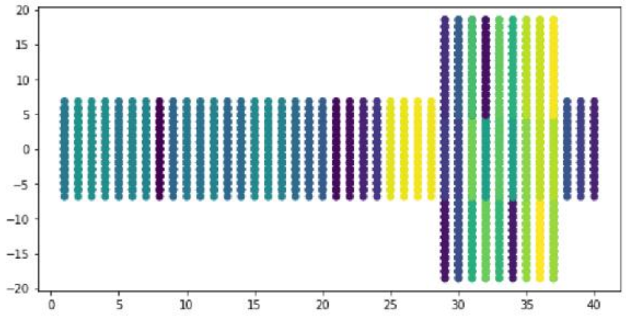
– Bias, current, environmental control, active water cooling (same as in June)

– Delay Wire Chambers, threshold Cherenkov counters, MCP-PMTs for timing reference

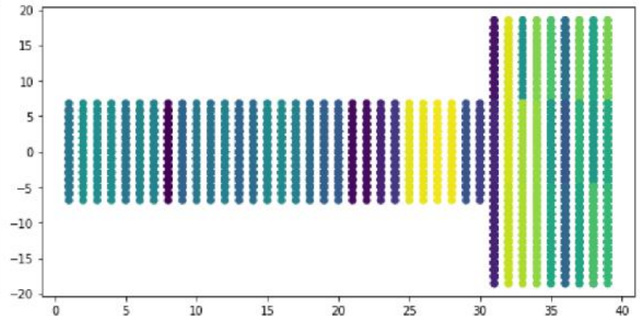
– CALICE AHCAL as scintillator CE-H

‣ **e, μ, hadrons up to 300 GeV**
– Trigger: 2x scintillators in front of CE-E + 1x additional (veto) behind CE-H-Si

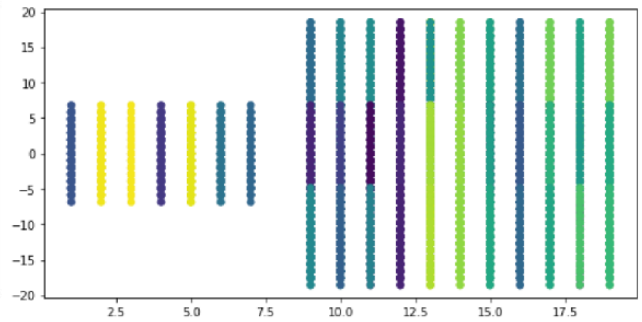
**Configuration 1:**
- EE: 28 layers X 1 module
- FH: 9 X 7 + 3 X 1
- FH absorbers between all layers



**Configuration 2:**
- EE: 28 layers X 1 module
- FH: 2 X 1 + 9 X 7
- No FH absorbers between 2 X 1 layers



**Configuration 3:**
- EE: 8 layers X 1 module
- FH: 12 X 7
- FH absorbers between all layers

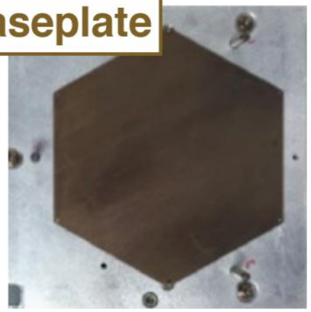


Focus on EM showers | Focus on hadronic showers

- ➢ Setup complemented with **CALICE AHCAL** prototype, **39-layer scintillator+SiPM sampling calorimeter**, mimicking somewhat the proposed design of HGCAL back part
- ➢ **Delay wire chambers** for particle tracking,
- ➢ **MCP** for time reference measurement
- ➢ **Threshold Cherenkov Counters** for hadron identification integrated in the data taking

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

**baseplate**



- CuW
- Cu

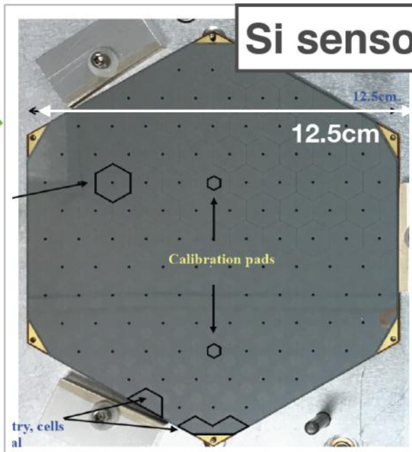
**Kapton®**

- Gold plated

+

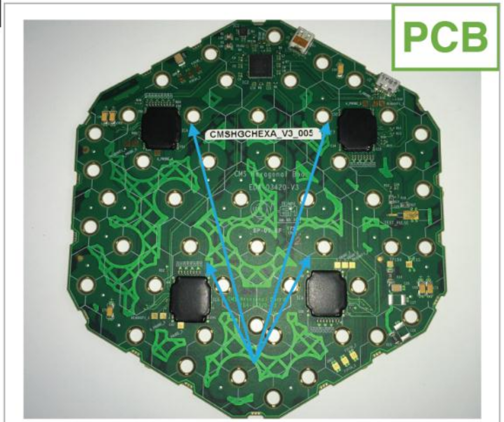
Active material

**Si sensor**



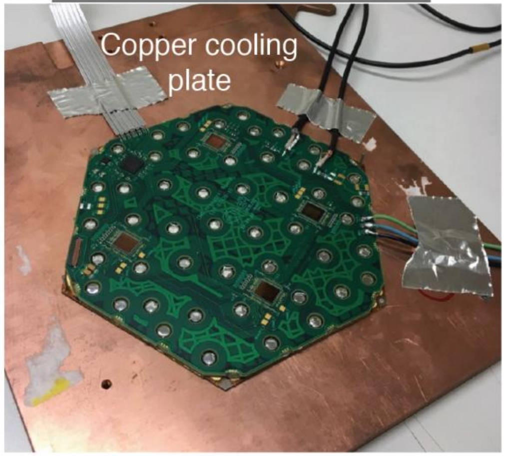

6" silicon sensors:
- n-type, 128 cells
- 1 $cm^2$ cell-size
- depletion: 200 & 300μm

**PCB**




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

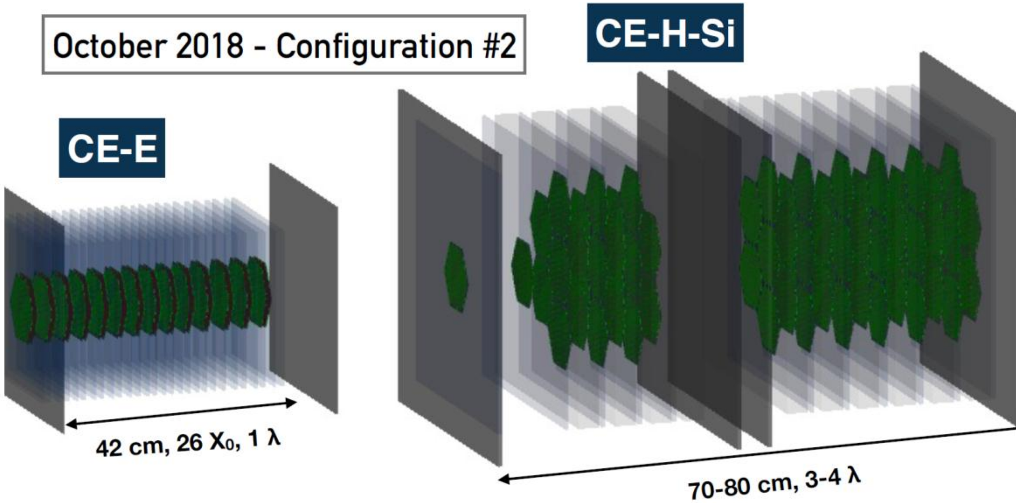
1-module layer in CE-E



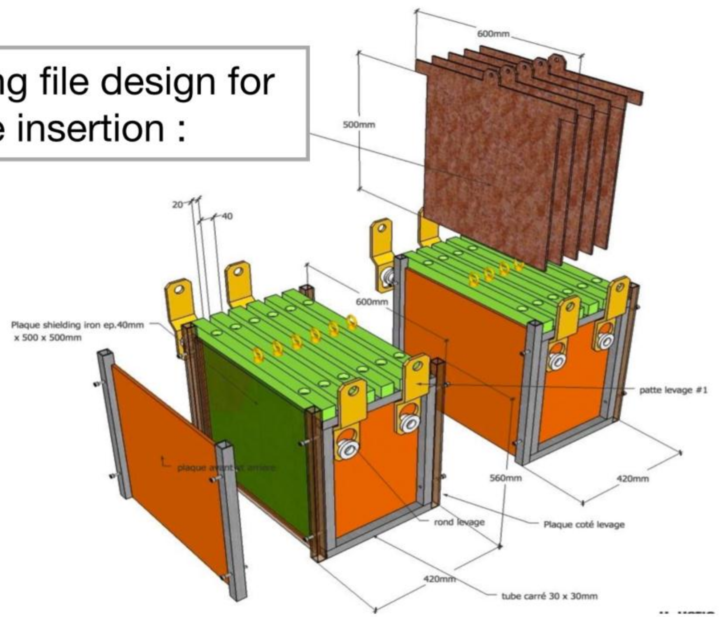

7-module "daisy" layer in CE-H-Si

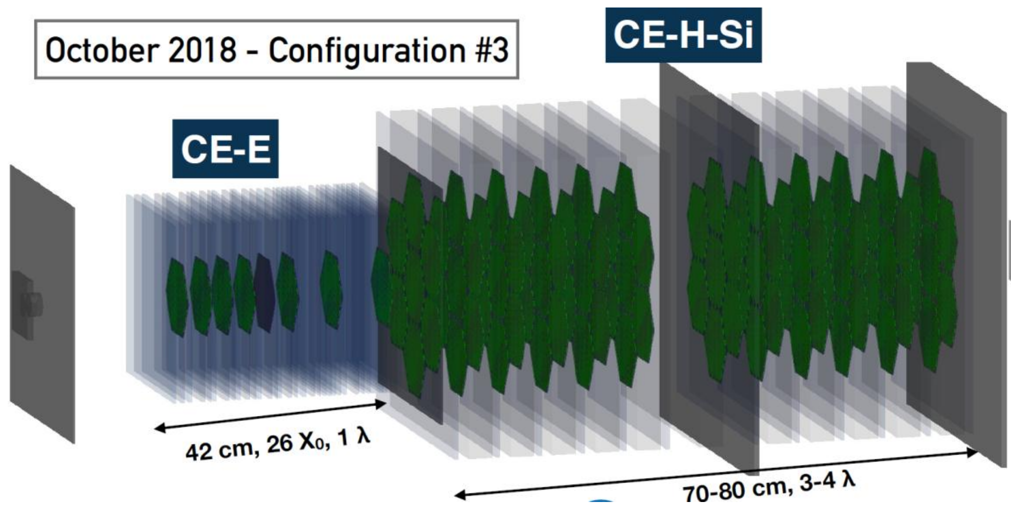
Passive material

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

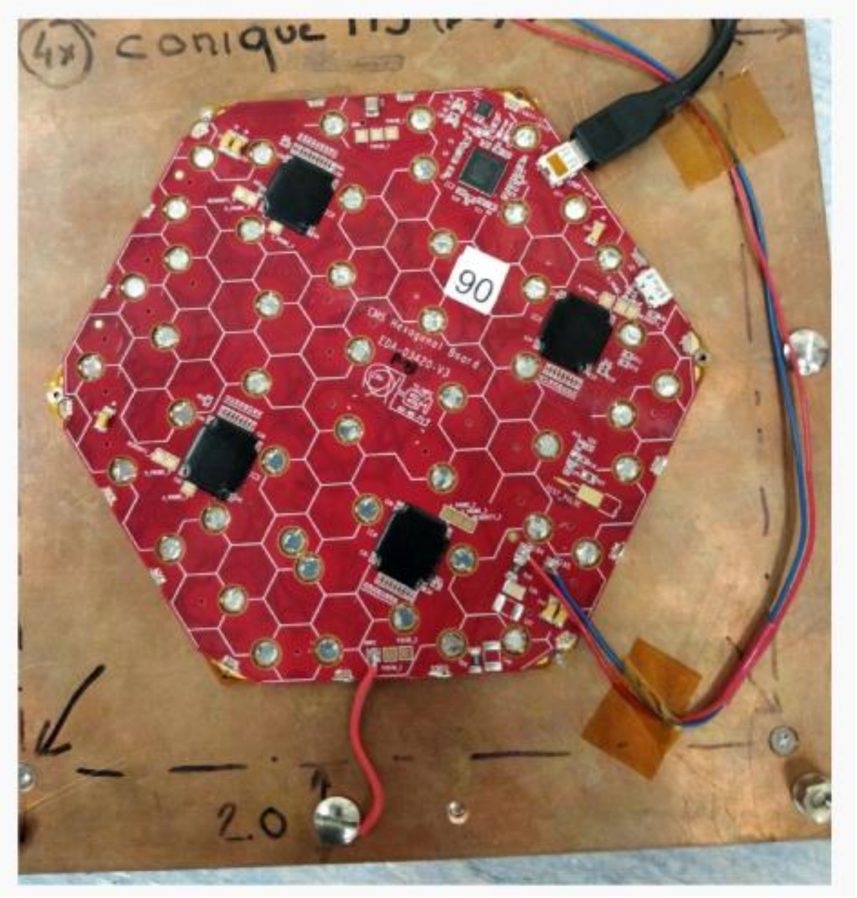



Hanging file design for flexible insertion :



## 6 inch Si prototype module




- **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, Time over Threshold (ToT), Time of Arrival (ToA)

  - **Physics performance** of the CE-E and CE-H silicon / scintillator parts

  - Check **agreement** with **simulation**

# Pedestal and Noise

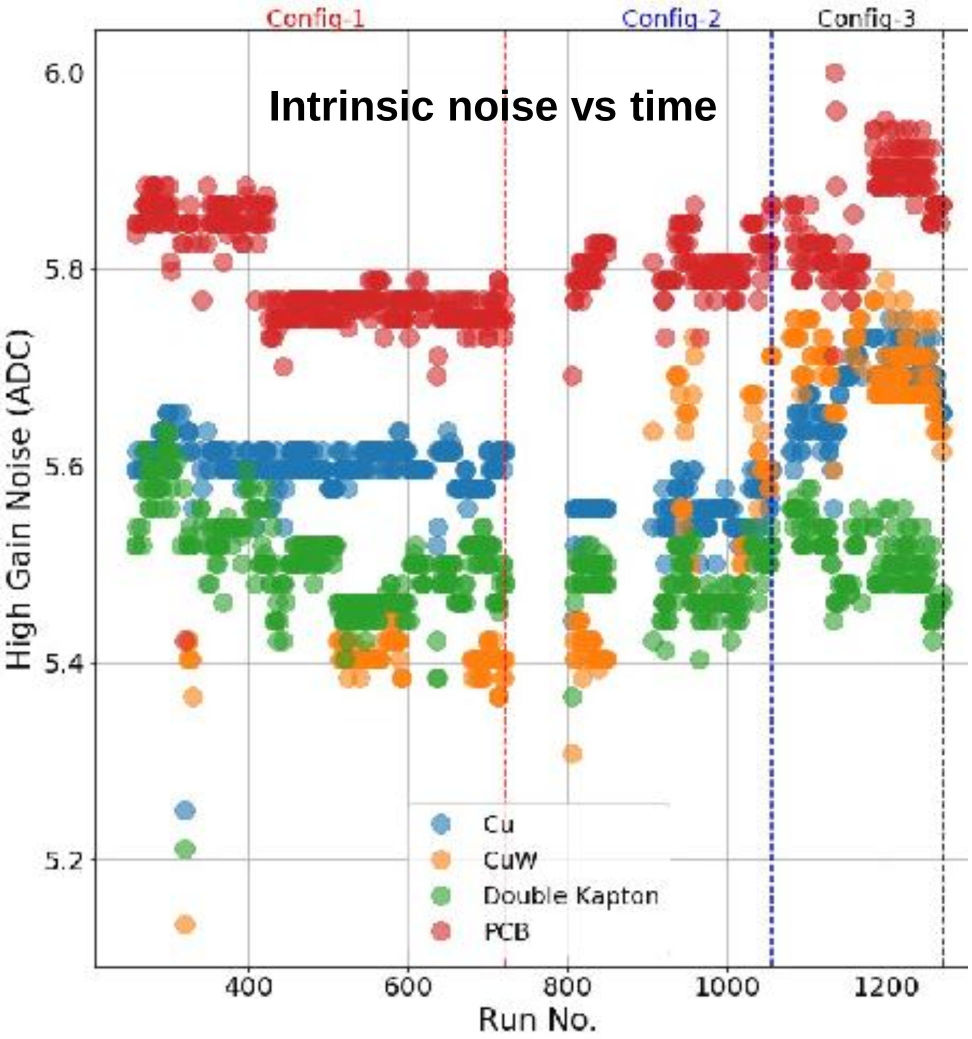
Major problem in beam tests of 2017 was the **large common-mode noise (several MIP)**

‣ Understood noise coupling to sensor through Cu/CuW baseplate

➤ **Grounding** module electronics to the baseplate **reduced the noise dramatically**

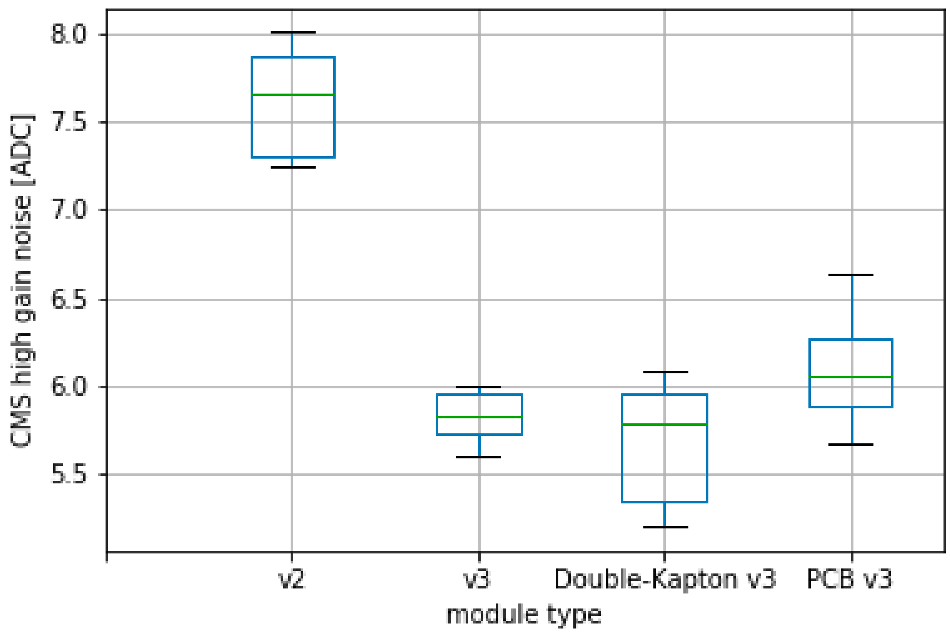
◉ **Implication on silicon module design**, studying different design solutions in 2018:

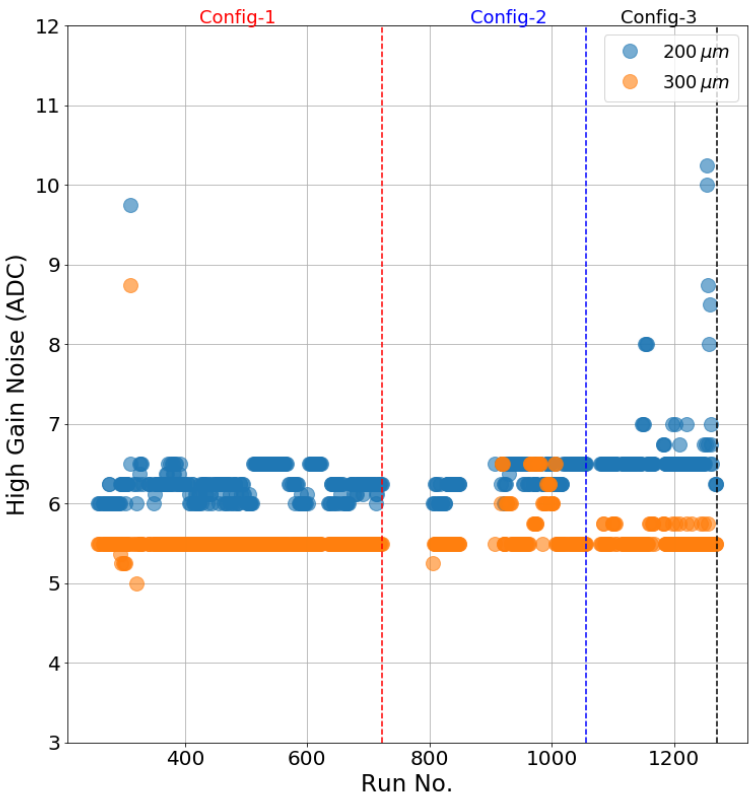
‣ E.g.: second Cu-kapton layer as shielding (“double Cu-kapton”). PCB baseplate for CE-H-Si



# Pedestal and Noise

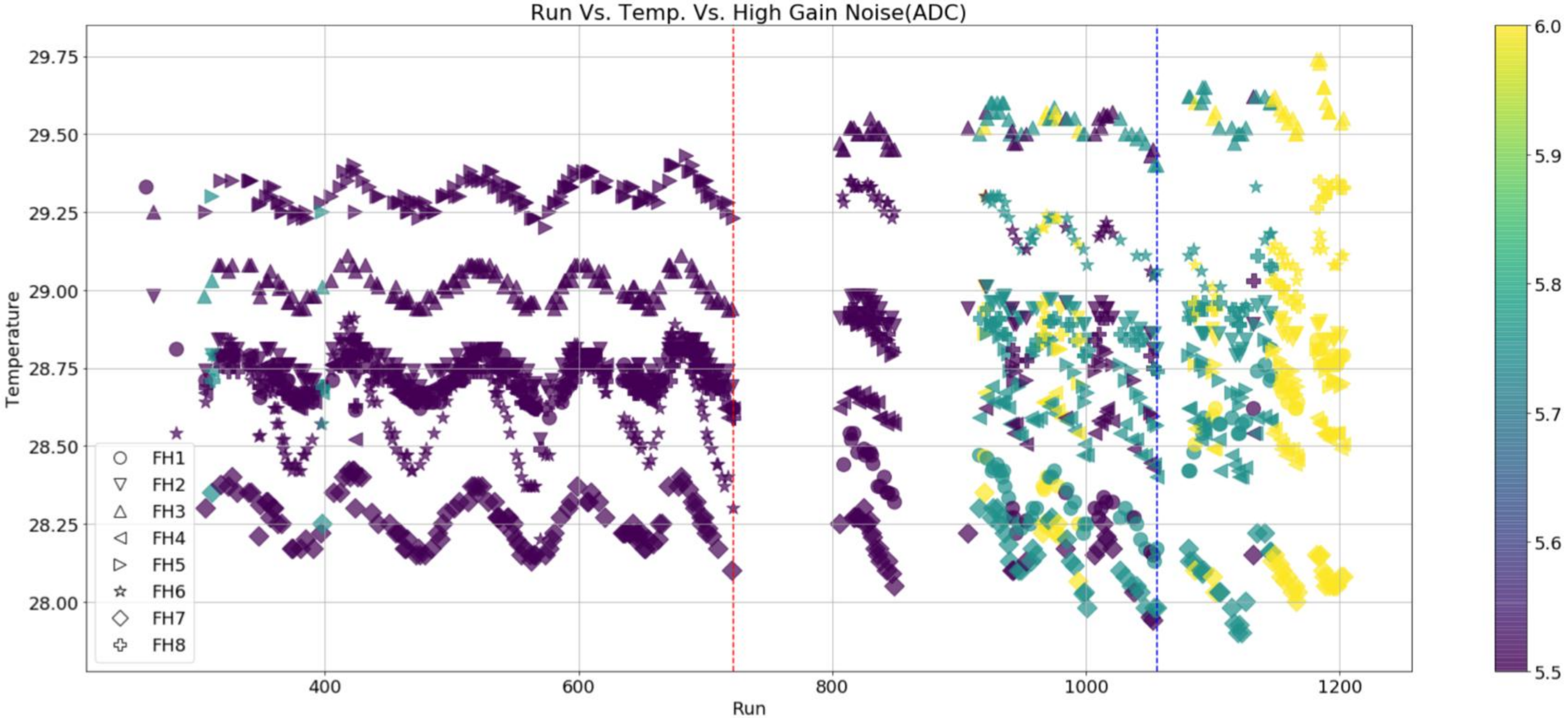
- Intrinsic (common-mode subtracted) noise levels very similar for different v3 PCB design modules
  v2 PCB raw noise higher than v3



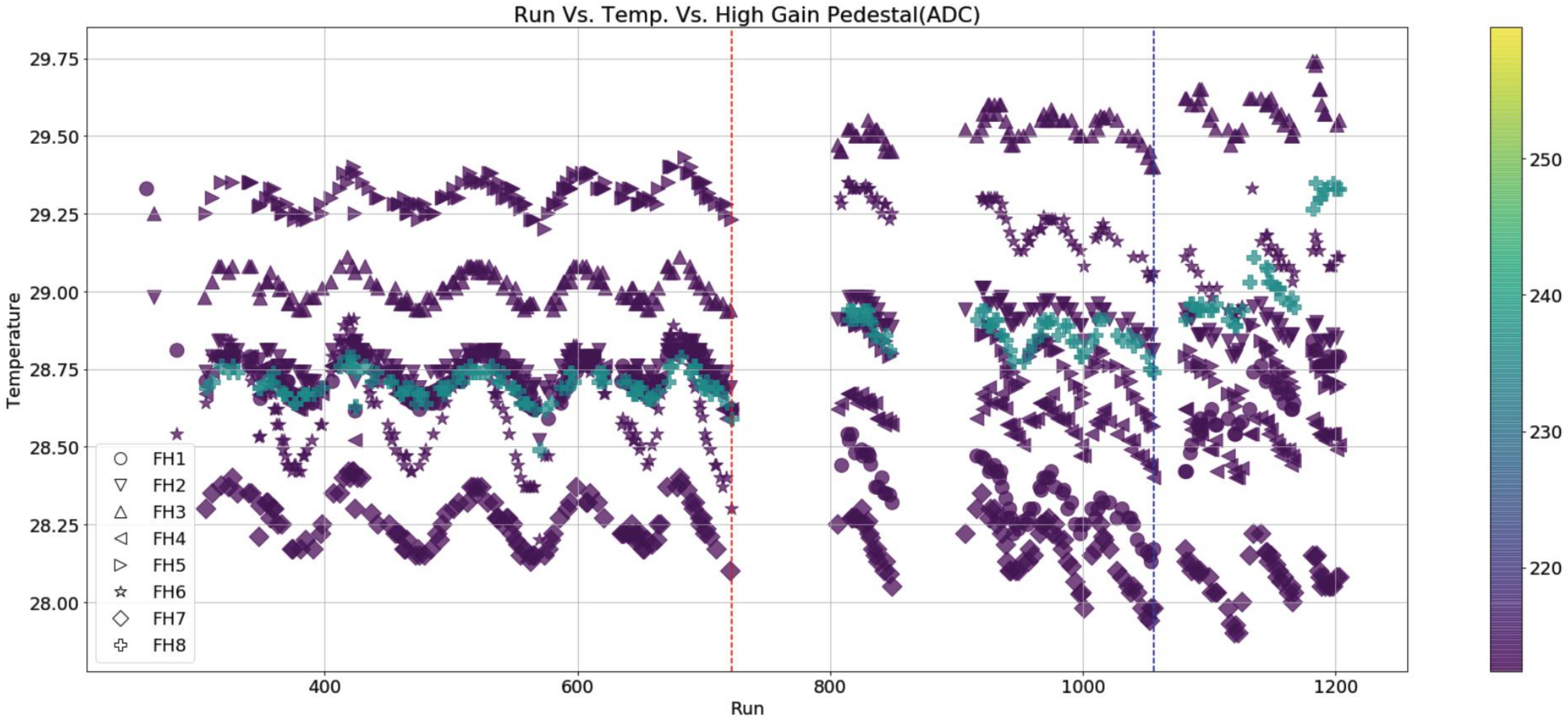




- Intrinsic noise higher for 200 μm sensors than for 300 μm sensors

No temperature dependence of the noise
– Temperature also quite stable



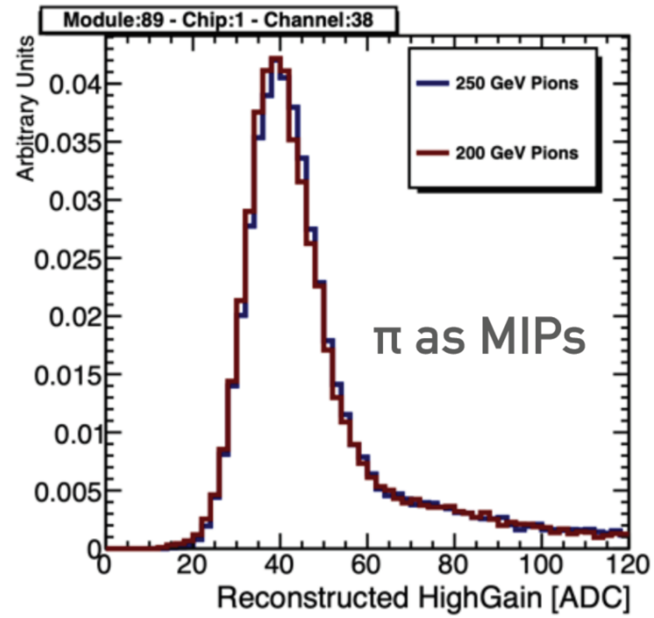
Pedestal values quite stable over the stable temperature range

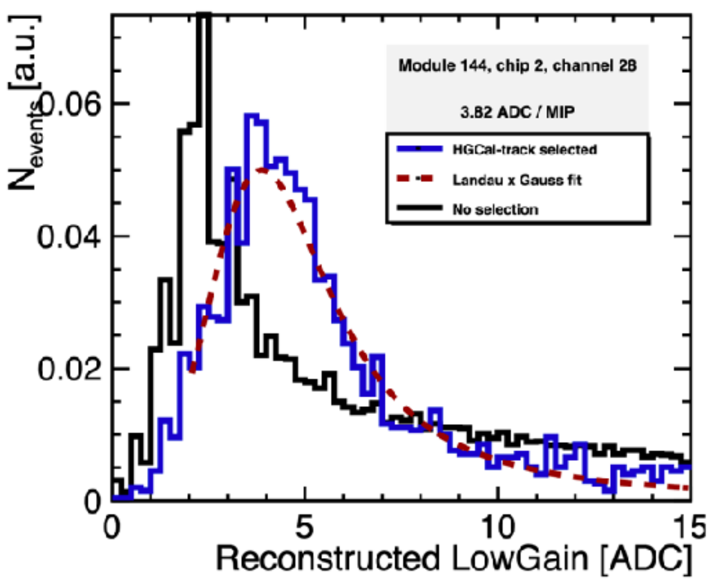


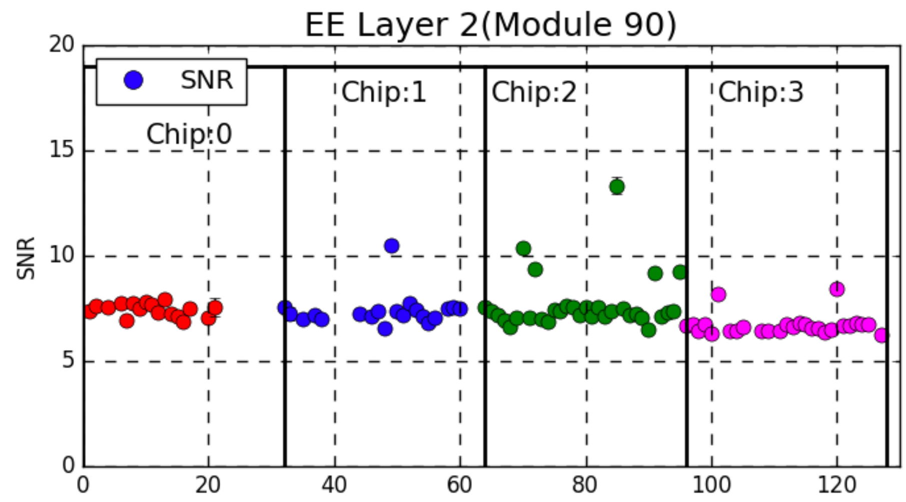
# MIP Calibration

- MIP calibration possible with HGC-only tracking
  - ➢ good agreement with DWC-selection
- Reliable MIP reconstruction even in Low Gain (S/N ~ 4, cf. S/N ~ 7 in High Gain)
- All types of cells and sensors calibrated:

Overall **7531 channels (63%), 363 chips (97%)**

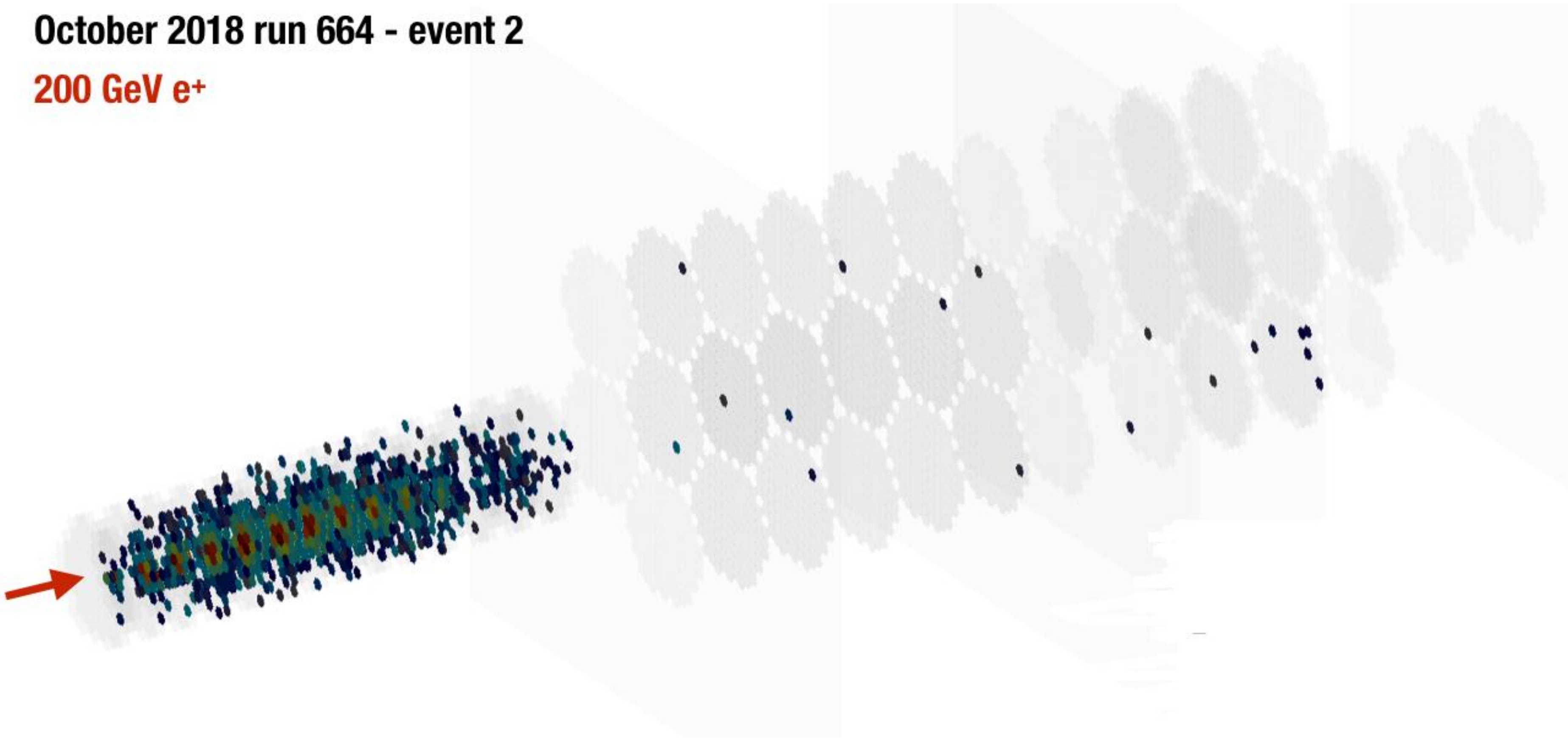


# HGCAL Imaging

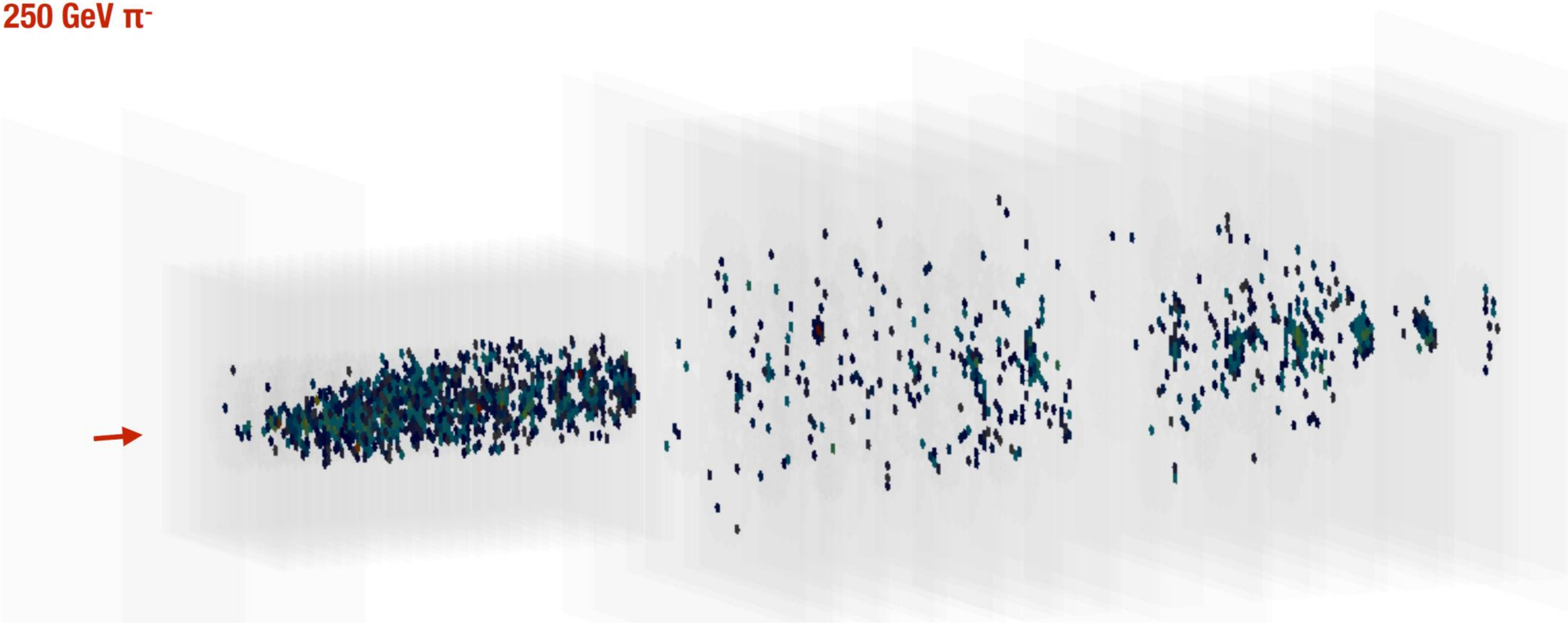
# Electron Event Display



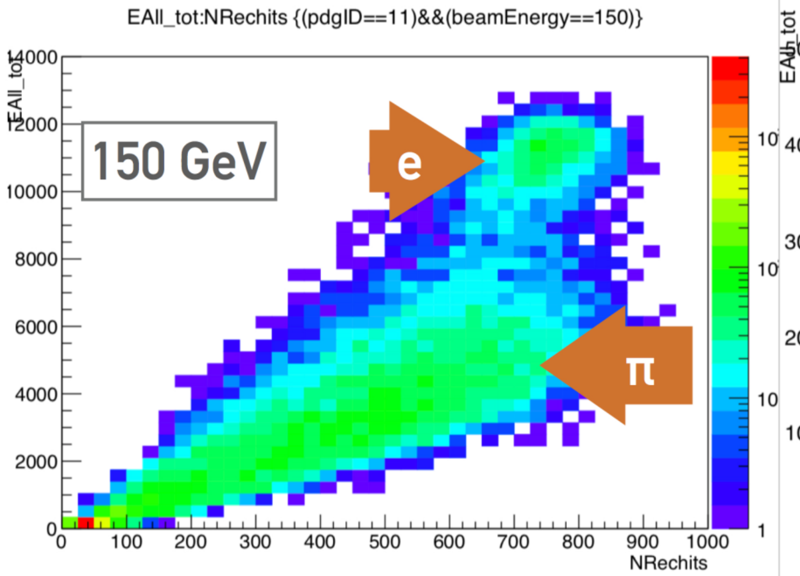
# Pion Event Display

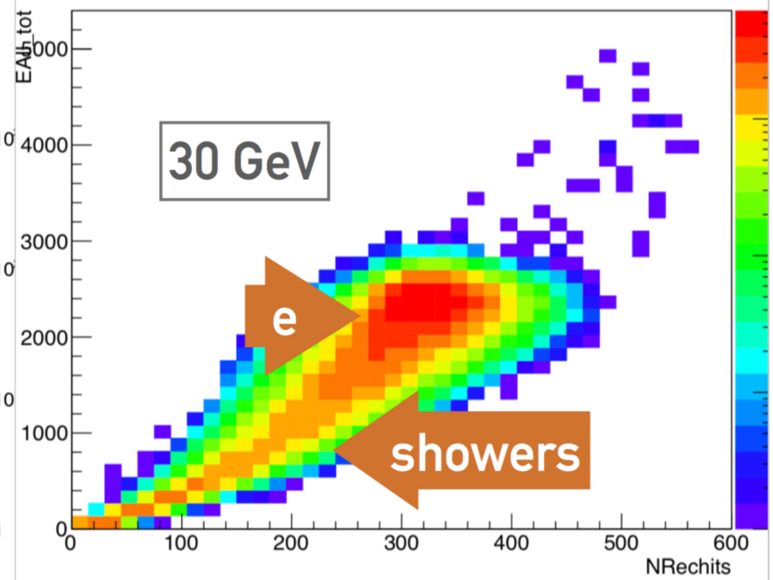
October 2018 run 517 - event 1:

250 GeV $\pi^-$



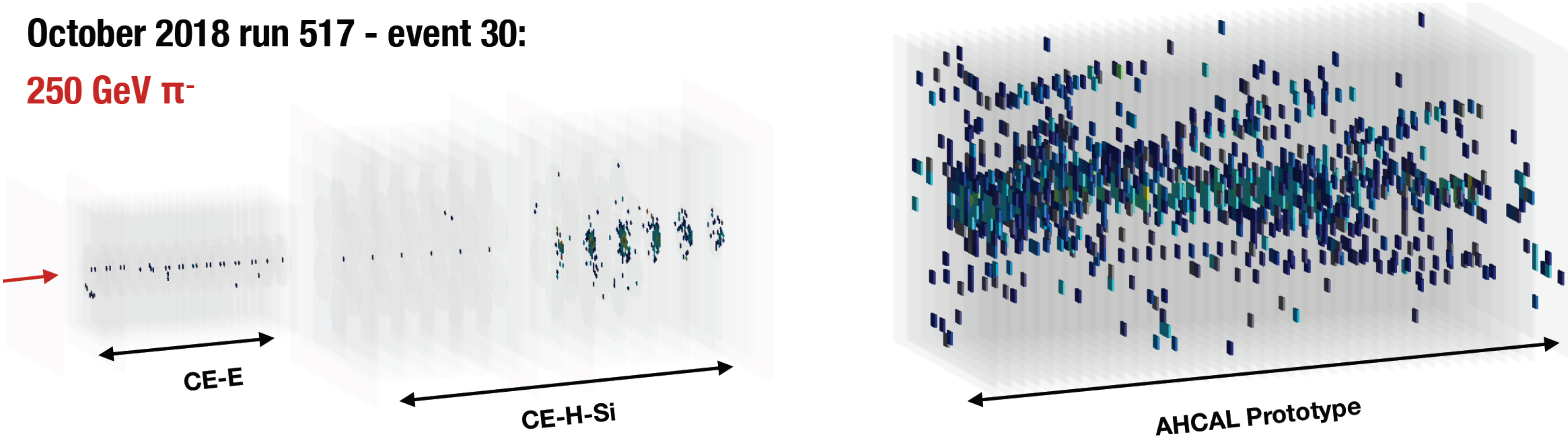
e-π separation with HGCal



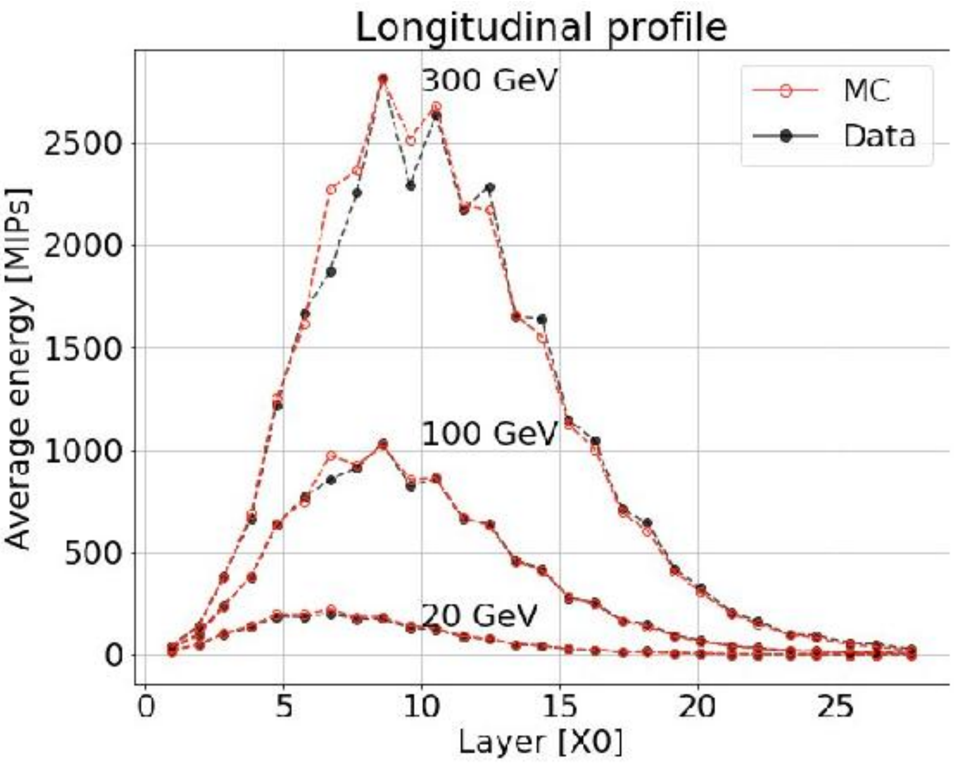

**October 2018 run 517 - event 30:**

**250 GeV π⁻**



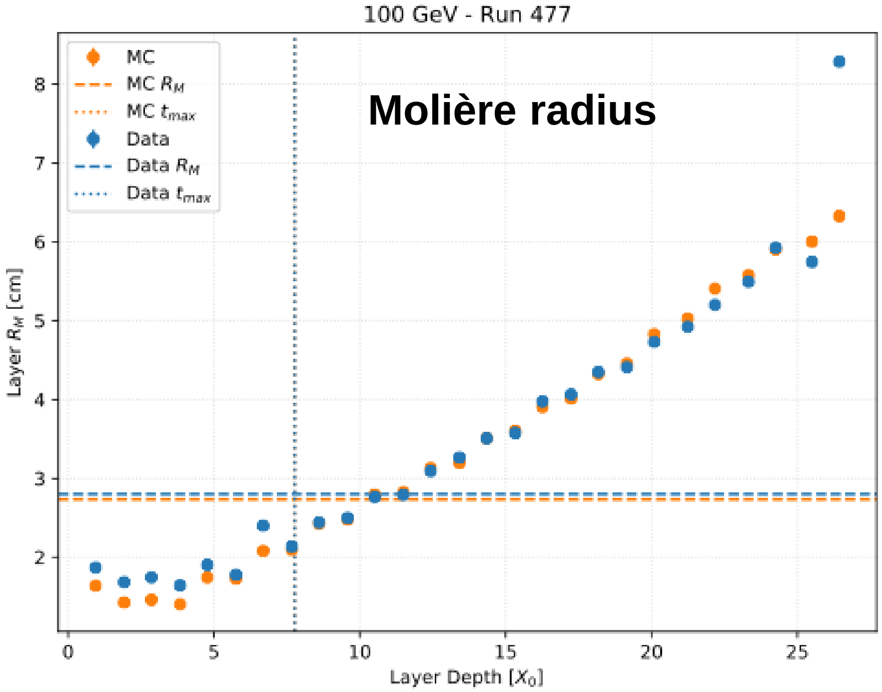
# Electron and Pion Performance

Description of the Monte Carlo simulation for HGCAL beam tests
- Tuning detector / beamline / beam spot for realistic simulation



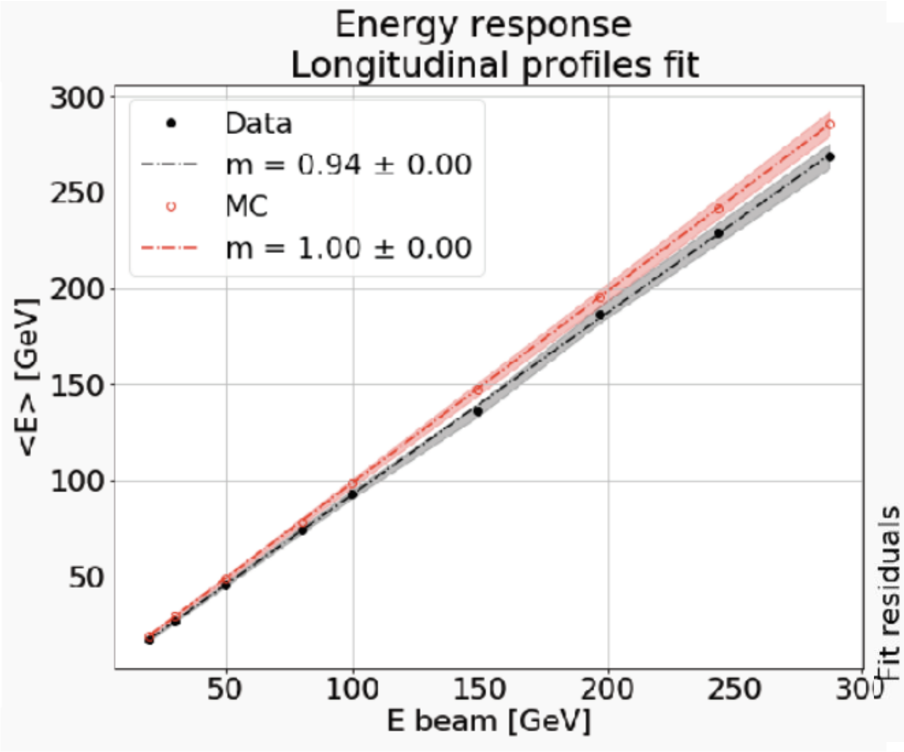

Longitudinal shower shapes and comparison to theory

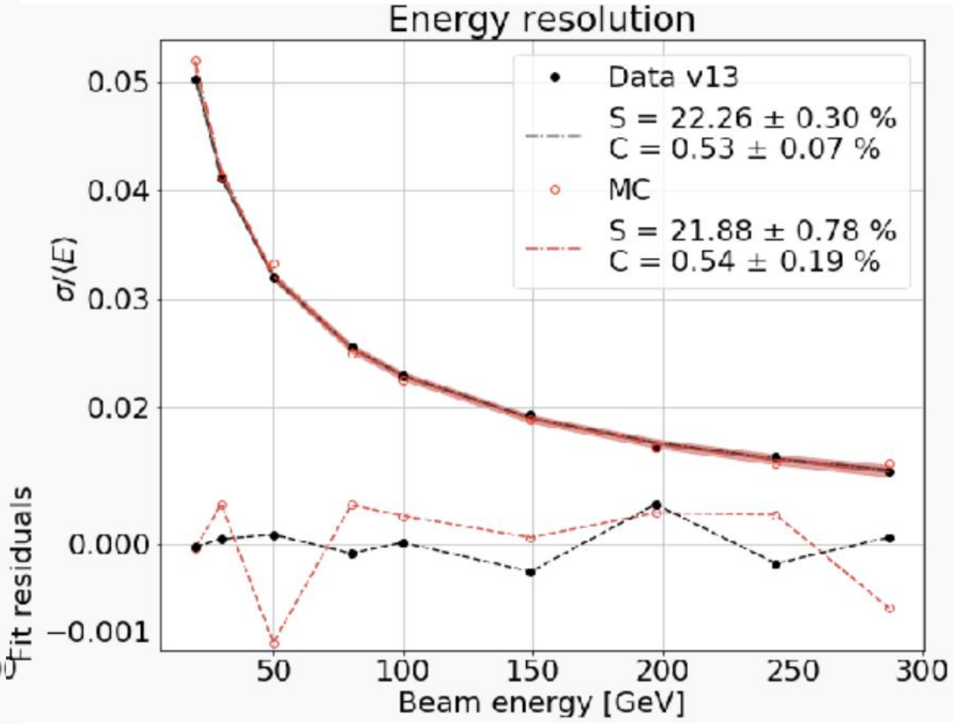
**Focusing on 28 layer CE-E**




Transverse dimension of the fully contained electromagnetic showers

## Energy reconstruction and resolution



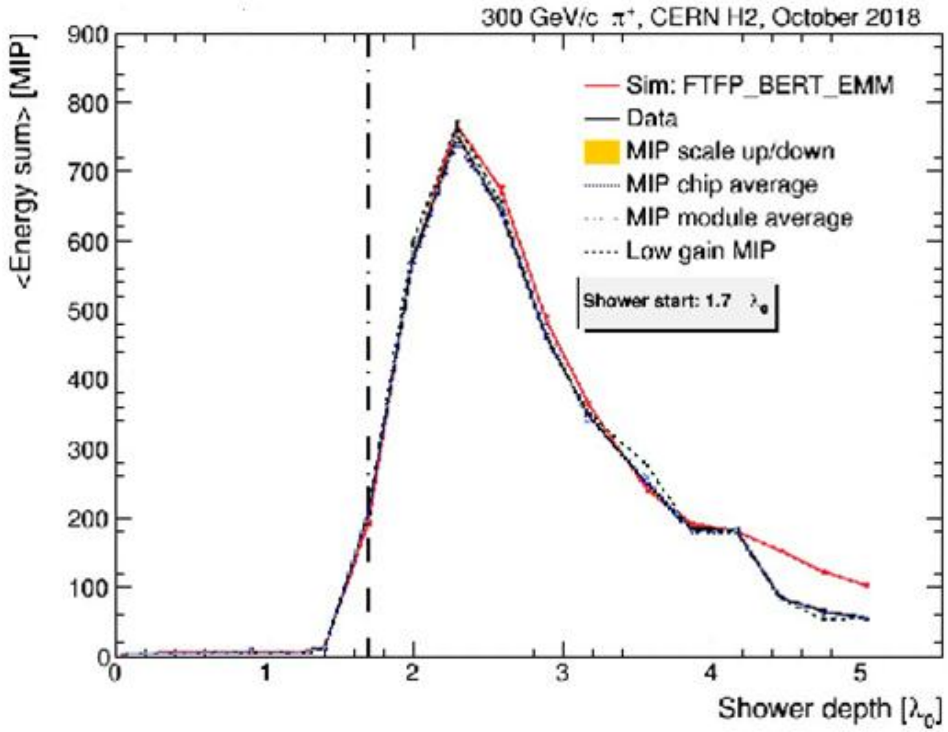



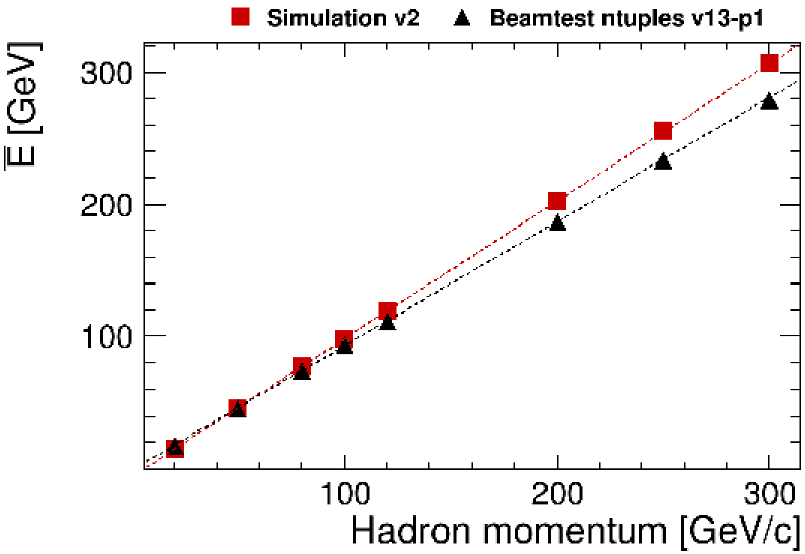

– Stochastic and constant terms in agreement with expectations

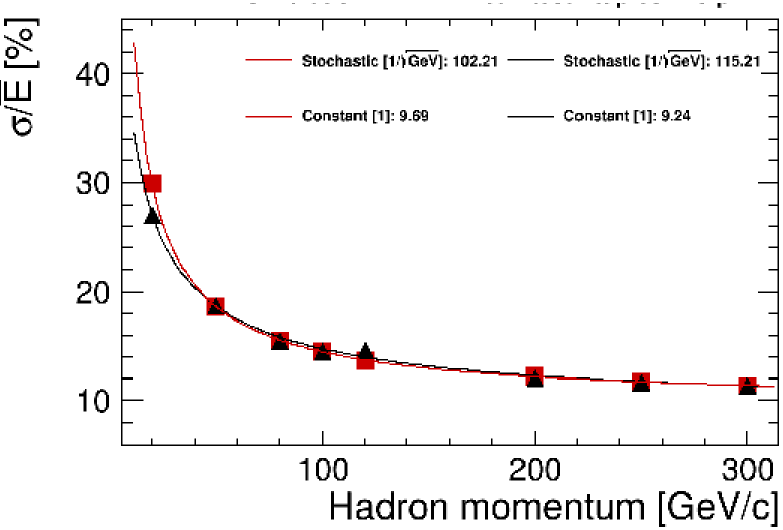
# Pion Performance

- Energy reconstruction: response and resolution
  - Inter-calibration of CE-E-Si/Sci and AHCAL
  - Software/ global compensation techniques

- Shower shapes, comparison to MC
- Shower depth for CE-H-Si

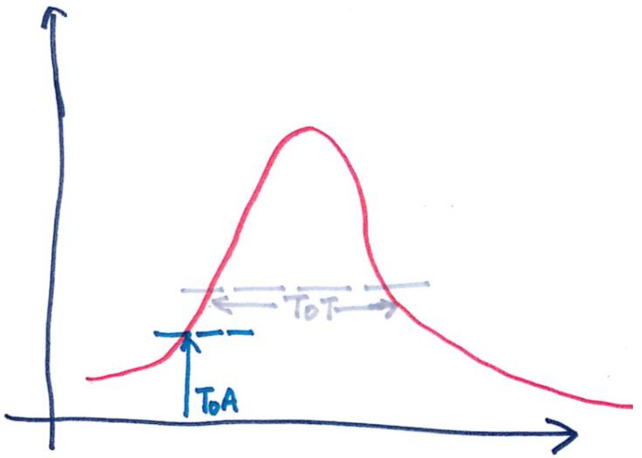


# Timing Performance

**Skiroc2-CMS is based on the CALICE Skiroc2.**



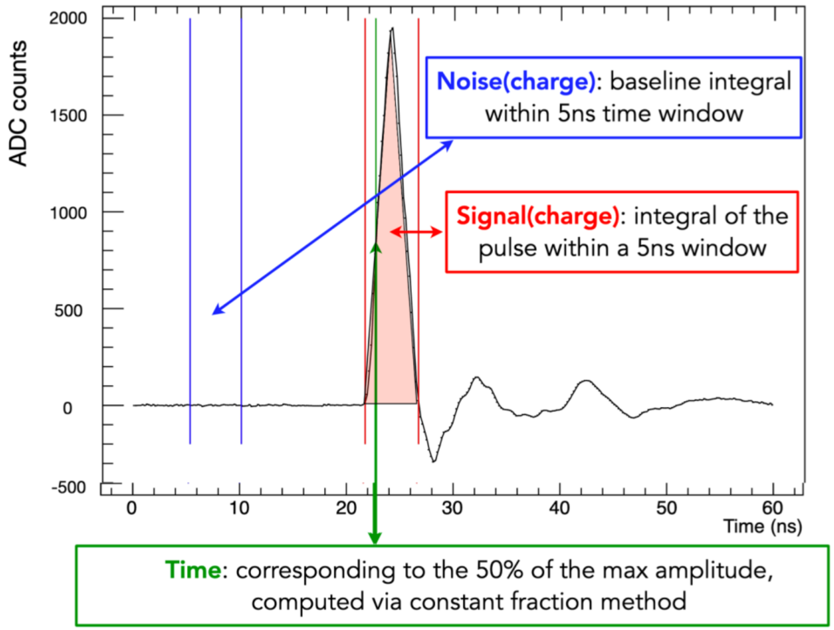

- Shapes, amplifies and digitises signals from the silicon sensors.
- 64 channels.
- **13 SCA rolling analog memory** with **40MHz clock**.

- **Overwrites every 13 x 25ns.**

- Four quantities read out:

Low- and High gain, "Time over Threshold" (ToT) and **"Time of Arrival" (ToA)**

- Two MCPs used to provide time reference
- Time of MCP signal is extracted from an interpolation of rising edge, at 50% of the max

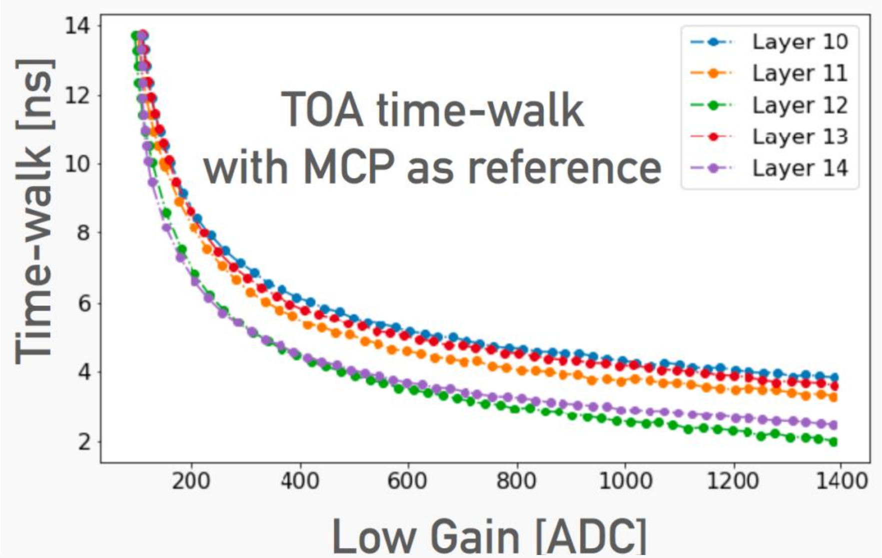


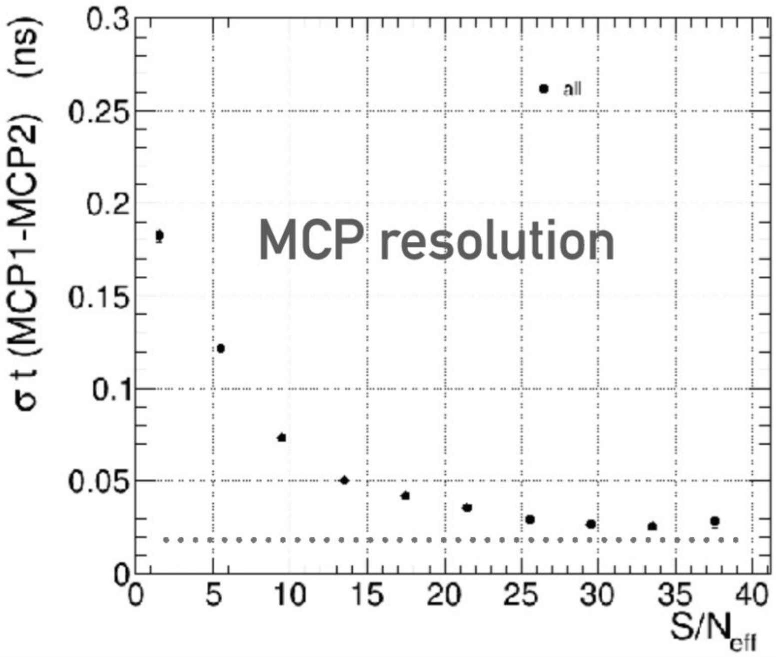
**Timing performance** measured with TOA

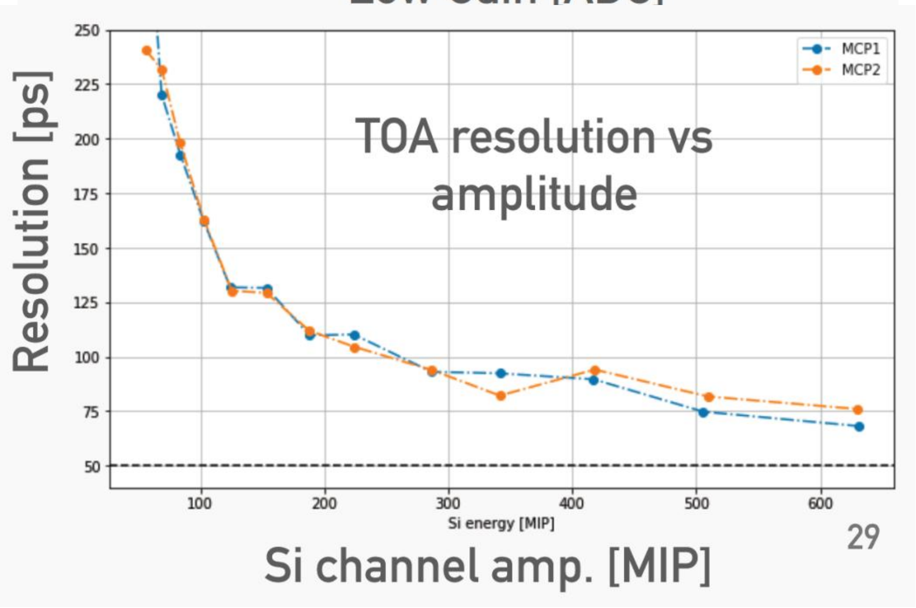
- Single **MCP resolution reaching 20 ps**

TOA calibration using data from asynchronous beam

- Time-walk derived with time reference (e.g. MCP)
  - TOA resolution close to SKIROC2cms specification of 50ps



# Summary & Outlook

- CMS High Granularity Calorimeter is a very challenging detector
  - Harsh radiation environment, high pileup & occupancy
  - 5D (3D position + energy + time) measurement of showers provides unique
  - opportunities in particle reconstruction for identification and pileup mitigation

- HGCal beam tests in 2018 October, CERN: First large-scale tests O(100) modules

- Beam characterising detectors incorporated
  - ✓ Delay wire chambers: tracking
  - ✓ Cherenkov detectors: hadron ID
  - ✓ MCP: O(10ps) timing reference

- Noise and Pedestal values stable over the 2-week data-taking period in the October 2018 CERN test beam

- Electron and Pion performance has been studied in terms of energy resolution and linearity and found consistent with expectations; Timing performance studied and excellent time resolution

- Future- move to measurement with modules of 8 inch sensors, irradiation effects, beam tests at DESY and FNAL