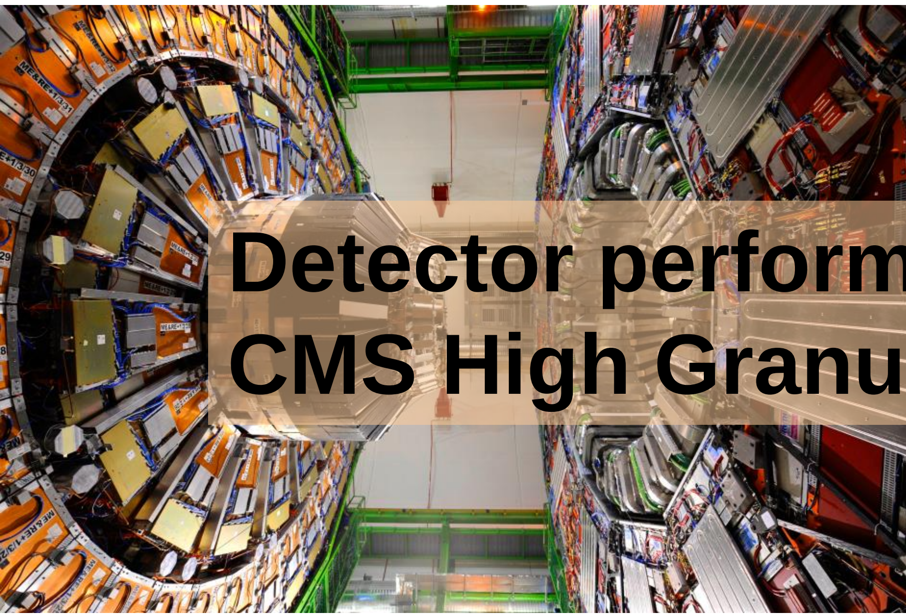
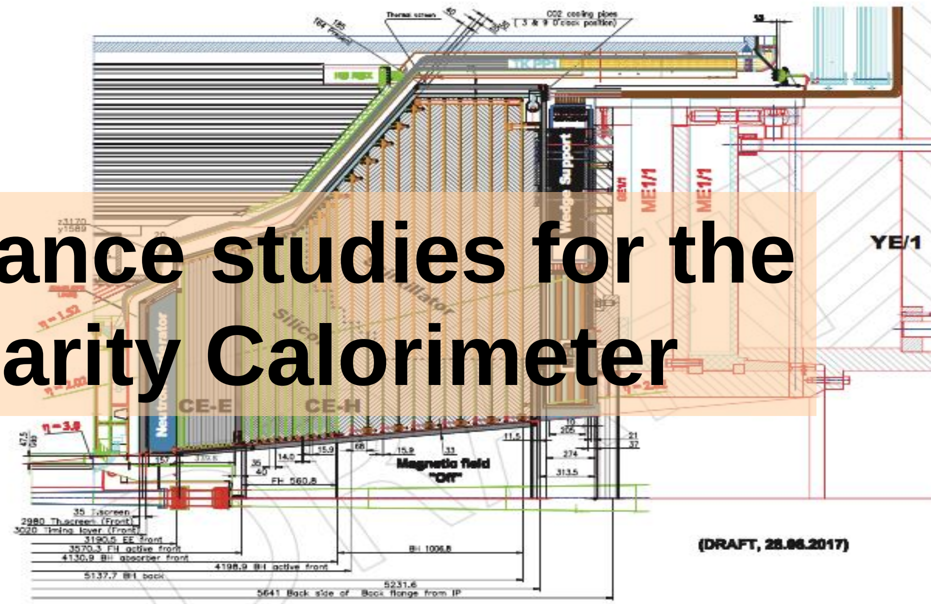
中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences
Beijing





Detector performance studies for the CMS High Granularity Calorimeter

Feng Wang

On behalf of the CMS collaboration

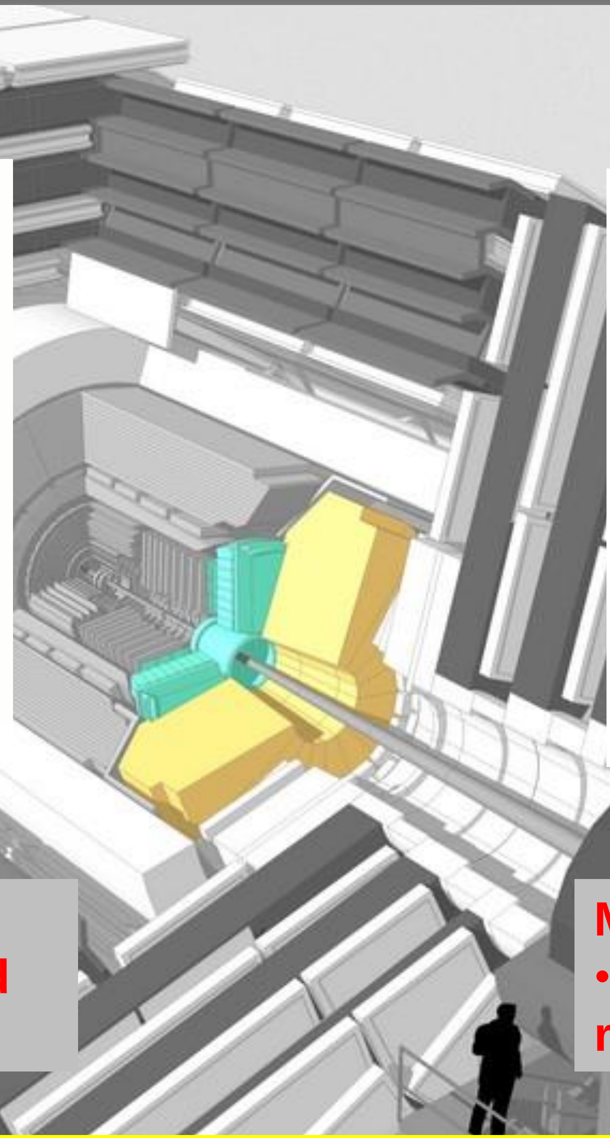
31/05/2018

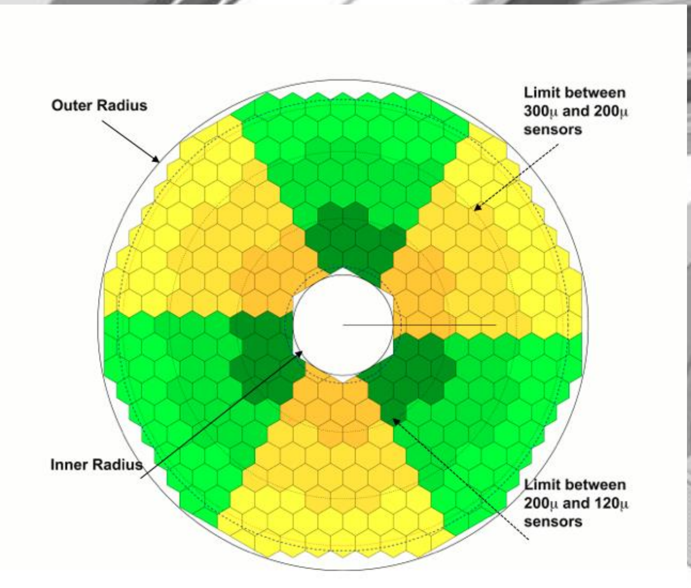
Outline

- Introduction of CMS HGCAL
- Beam test and detector performance
- Next to do

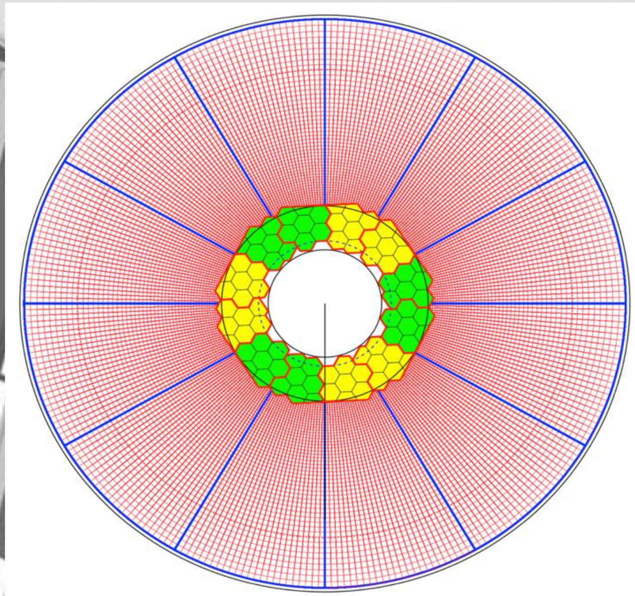
The CMS HGCAL

Detail refer to Stathes' talk





CE-E 9th layer



CE-H 22nd layer

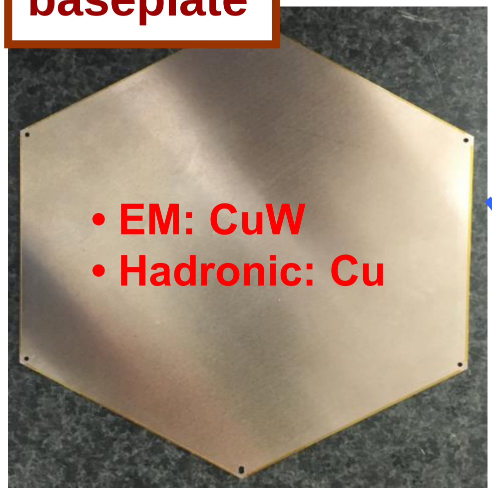
Si-only layer
- **Sensor thickness optimized vs radiation hardness**

Mixed Si-scintillator layer
- **Boundary optimized vs radiation hardness**

Whole calorimeter will be operated at -30°C

HGCAL module

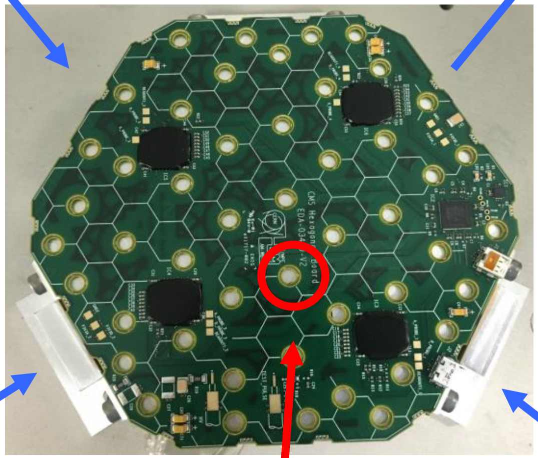
baseplate



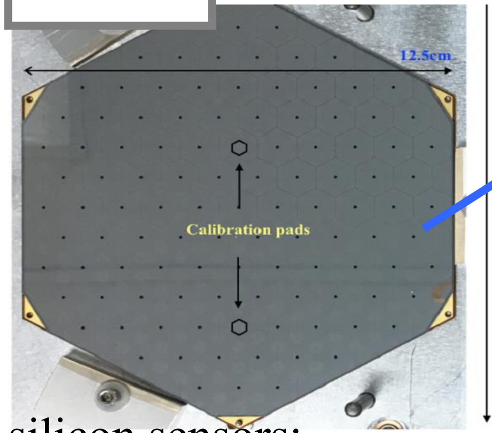
Kapton®

Glue

Glue



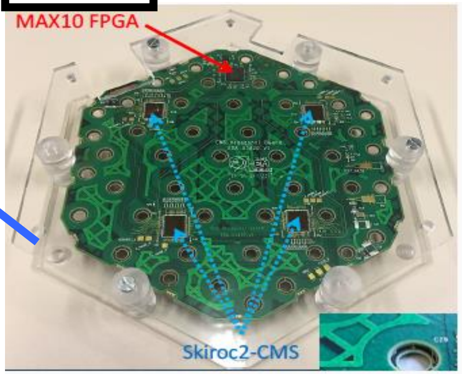
sensor



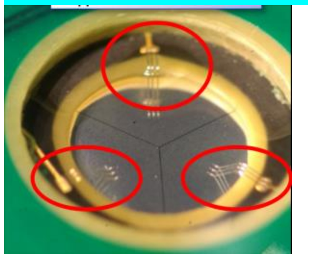
Glue

Glue

PCB



wire bonding



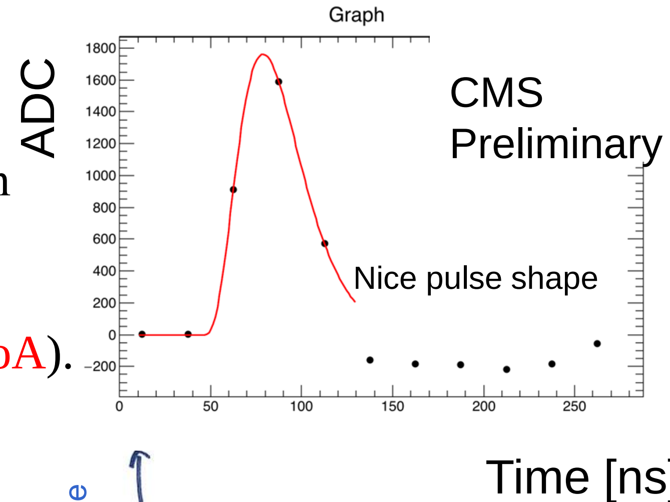
6" silicon sensors:
- n-type, 128 cells.
- 1 cm^2 cell-size.
- 200 &300 μm depleted region.

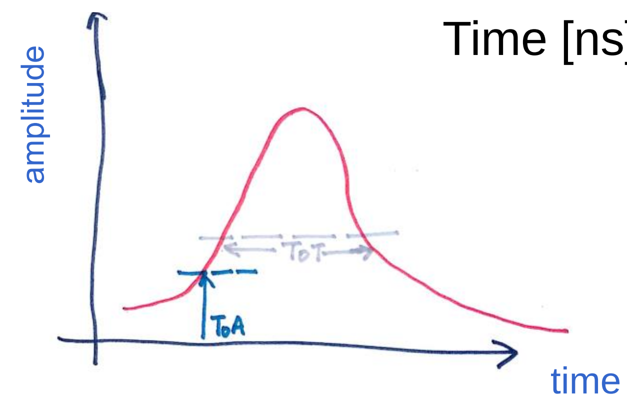
Skiroc2-CMS ASIC,
- Developed for CALICE and adjusted for CMS requirements.

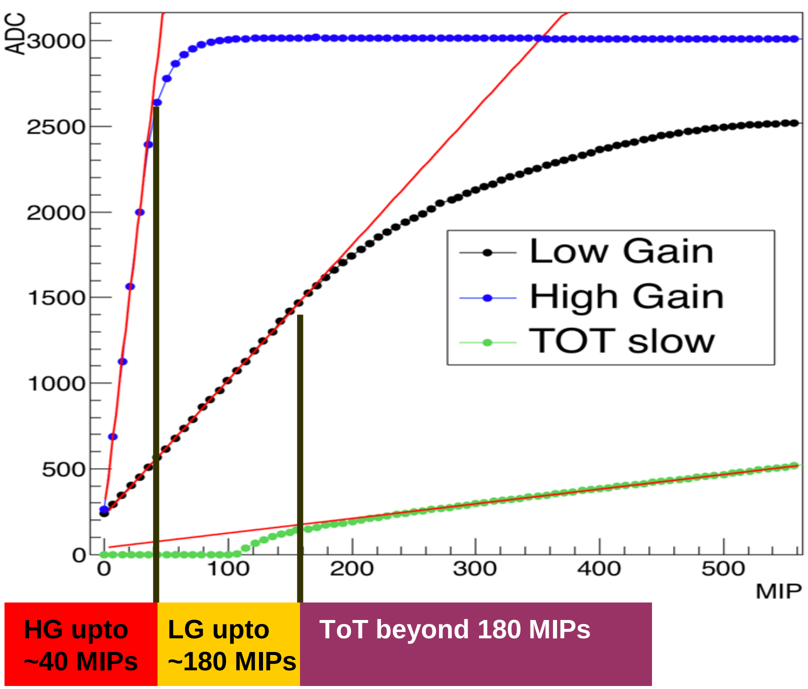
SKIROC2-CMS used in TB of 2017

Skiroc2-CMS is based on the CALICE Skiroc2.

- 64 channels of large dynamic range
- Shapes, amplifies and digitises signals from the silicon sensors.
- Four quantities read out: Low- and High gain, "Time over Threshold" (ToT) and "Time of Arrival" (ToA).
- 13 rolling analog memory cells with 40MHz clock.
  - -- 11 contain useful data
  - -- Low Gain, High Gain







- Larger pulses stay longer over some threshold.
  - ToT is a measure of the signal pulse amplitude.
  - ToT cover the high dynamic range.
- ToA: Time when the signal crosses a certain threshold
  - PU mitigation could be improvement by time information

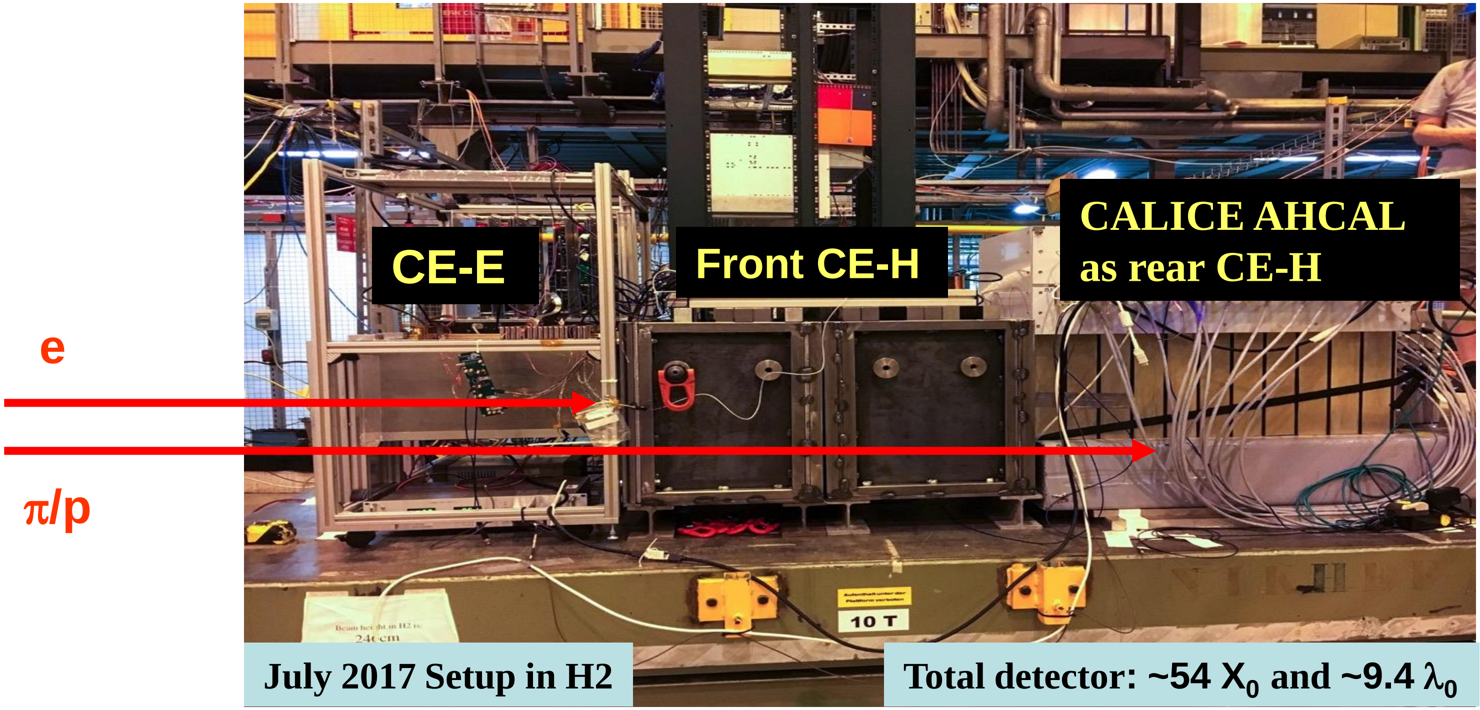
Test beam from 2016 to 2017

Date	Location	No. of module	PCB type	ASIC type	Database
2016	FNAL	16 Si modules	"2 layers" PCB	SKIROC 2 ASIC	e beam (4-32 GeV)
2016	CERN	8 Si modules	Single layer PCB (V1)	SKIROC 2 ASIC	e beam (20-250 GeV) π beam (125 GeV)
8-15May 2017	CERN	1 Si module	Single layer PCB (V1)	SKIROC 2CMS ASIC	e beam (20-250 GeV)
12-19 July 2017	CERN	10 Si modules	Single layer PCB (1 V1 & 9 V2)	SKIROC 2CMS ASIC	e beam (80 GeV) π beam (300 GeV)
29 Sep-2 Oct 2017	CERN	17 Si modules	Single layer PCB (1 V1 & 16 V2)	SKIROC 2CMS ASIC	e beam (20-90 GeV) hadrons beam (100-350 GeV)
19-23 October 2017	CERN	20 Si modules	Single layer PCB (1 V1,16 V2 & 3 V3)	SKIROC 2CMS ASIC	e beam (20-80 GeV) hadrons beam (50-120 GeV)

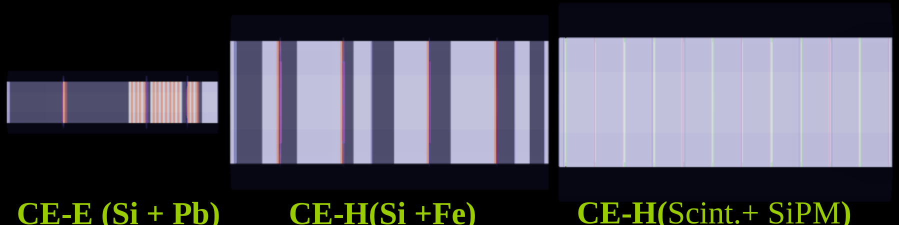
2017 From July to October	AHCAL is also tested together with HGCAL 12 active layers 144 scintillator tiles (each 3 mm thick) of 3×3 cm^2 Readout by SiPM

Test beam setup in July 2017

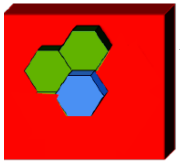
- CE-E part: Hanging file structure with **lead** absorber.
- CE-H (Si) part: Hanging file structure with **iron** absorber.
- Data taking together with CALICE AHCAL prototype as CE-H (scint.+SiPM) part.



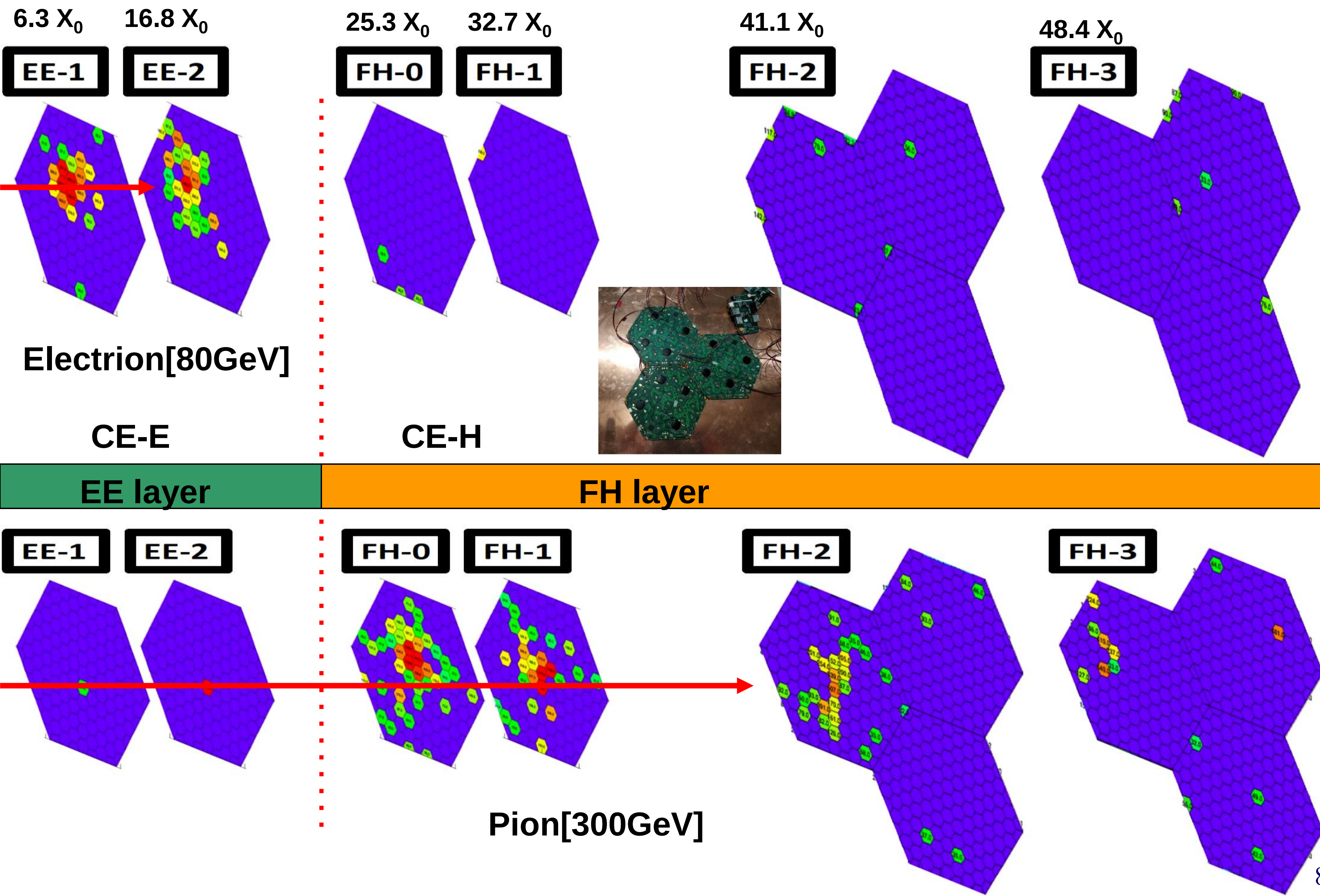
Geometry in Simulation for 2017 Beam test



Test 10 modules in July 2017
-- 2 in CE-E
-- 8 in CE-H (1 module in 2 layers + 3 modules in 2 layers)



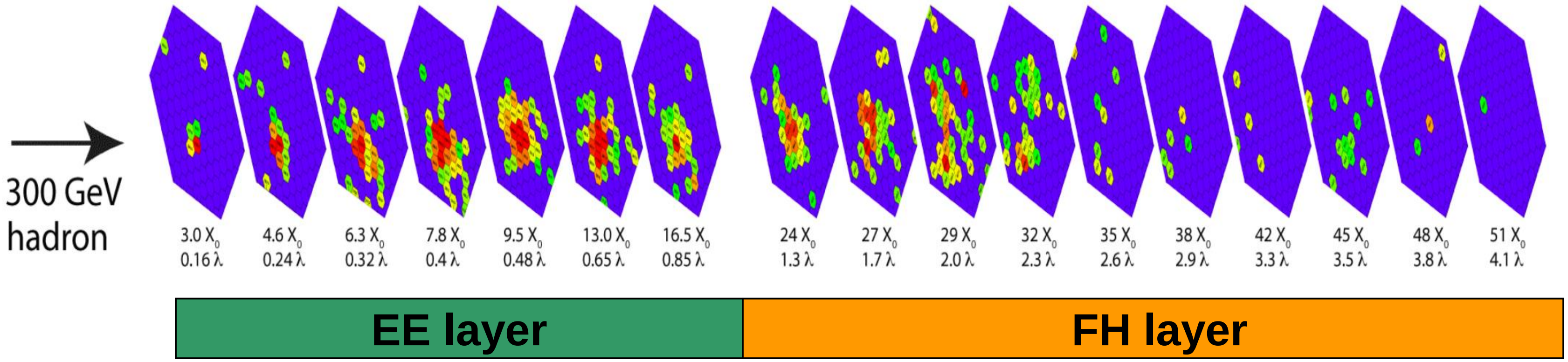
Showers for electrons and pions



More data taking in Fall 2017

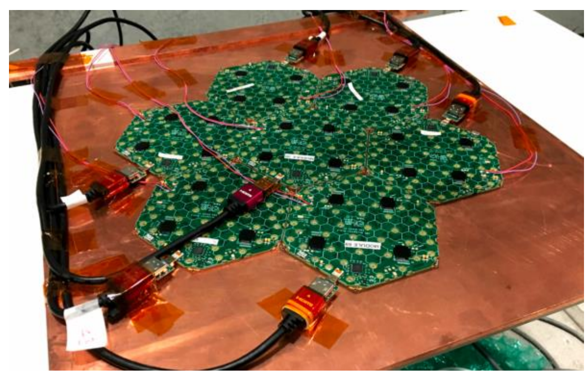
Several configurations were explored with more module completed （up to 20 modules finally）

- **29/09 - 02/10 in H2：** 17 modules **7 layers in EE**, **10 layers in FH.**

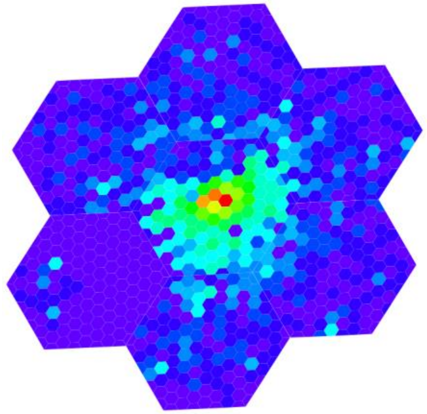


- **19/10 - 23/10 in H6a：** 20 modules : **5 layers in EE**, **7 layers in FH.**

- Increase the statistics with respect to the July period.
- Test the data integrity taken by the daisy structure shown right.

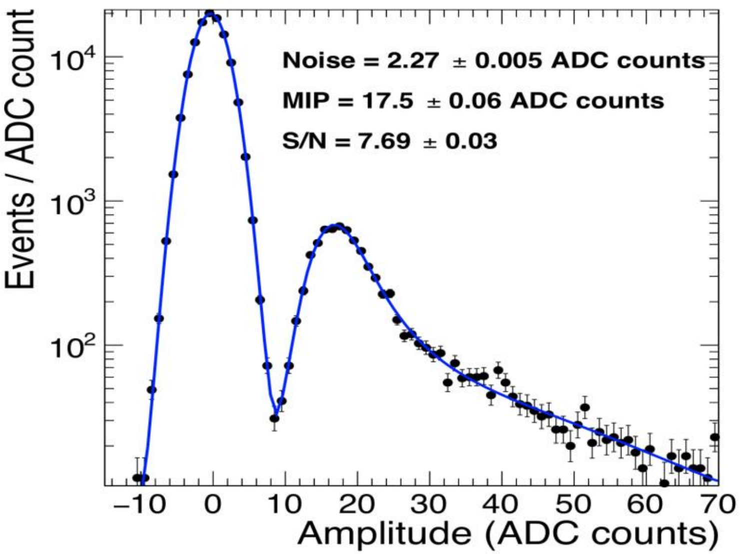


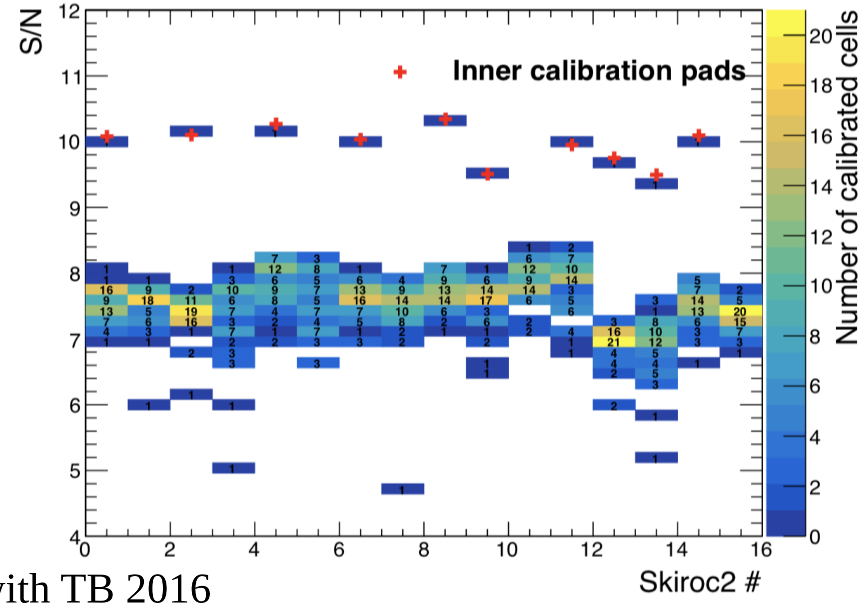
FH: - 1x 7 module layer
- 1x 3 module layer
- 5x 1 module layers



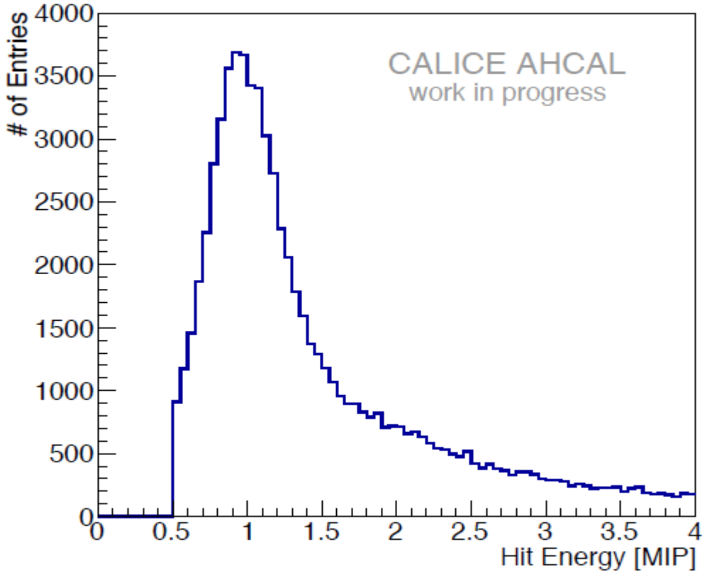
TB October 2017, H6
120 GeV hadron

MIP signal





MIP signal in a typical silicon cell in CE-E section with TB 2016

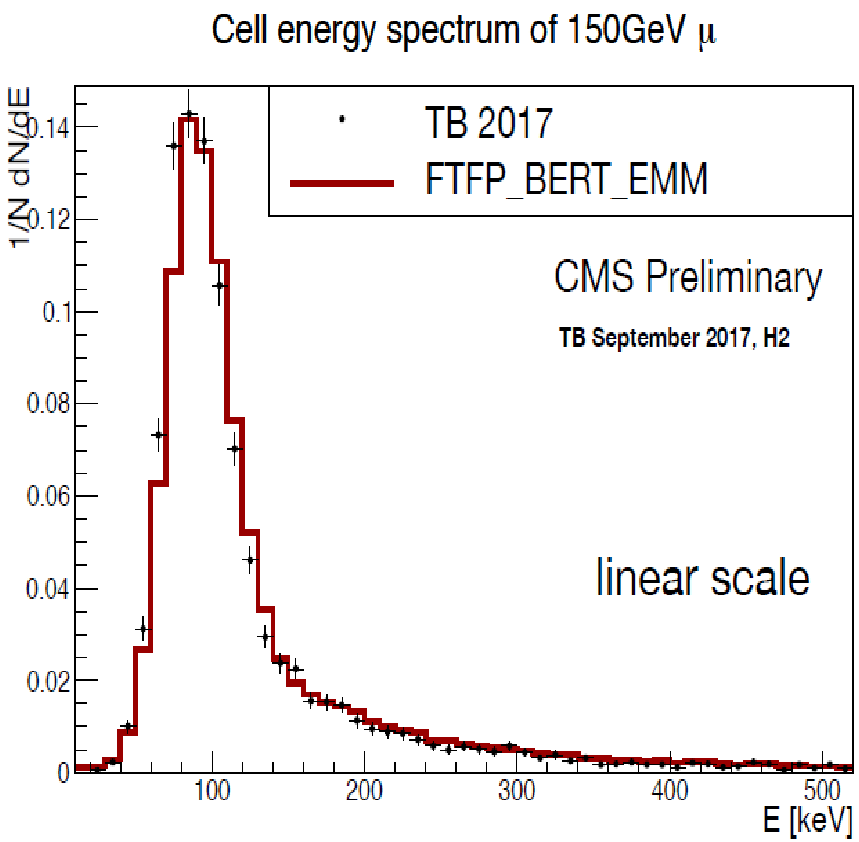


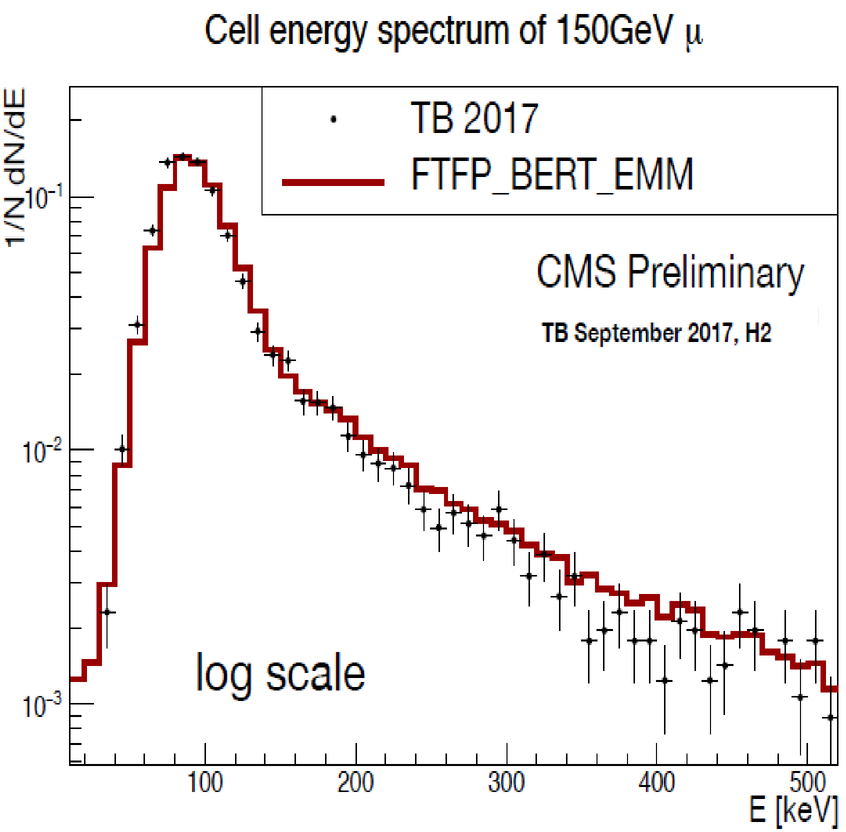
MIP signal in AHCAL of CE-H section with TB 2017

Amplitude spectrum of signals with TB 2016 & 2017.

- S/N is almost between 7 and 8 for all measured silicon cells in (10 for calibration pads)
- spectrum of signals seen in the 864 cells of the AHCAL in 2017 following a simple tracking and preliminary calibration.

Recorded MIP spectra match the simulation



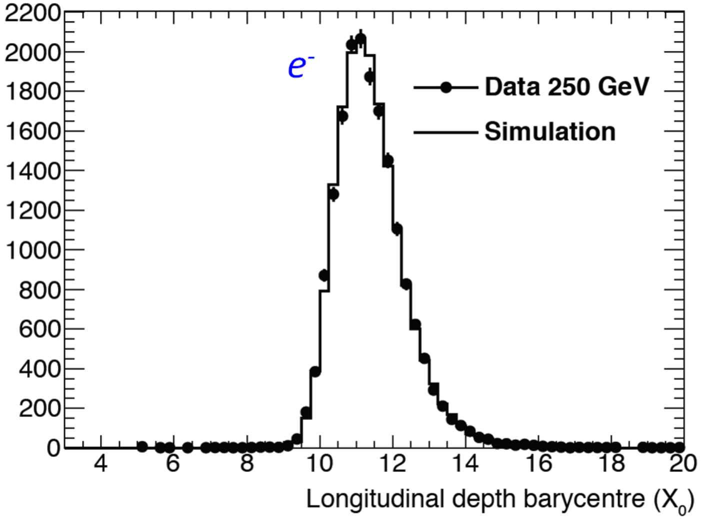


Good agreement between data and simulation even in the Landau tails.

MIP calibration:

- Muon is used for calibration
- Select events with the Delay Wire Chamber information to clean up noise. (for which cell is hit by MIP)
- Fit by a Landau convoluted with Gaussian to obtain MIP-to-ADC value.

Shower shape



Definitions of Longitudinal shower depth :

$$\sum_{i=1}^{8} \lambda_{0i} \cdot Elayer_i / \sum_{i=1}^{8} Elayer_i$$

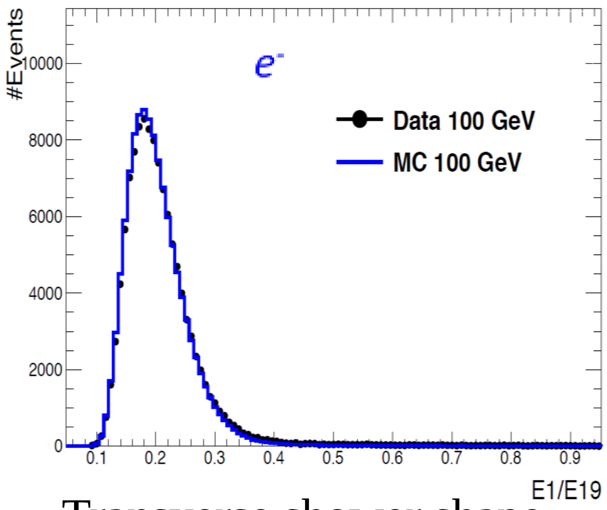
Definitions of transverse shower shape:

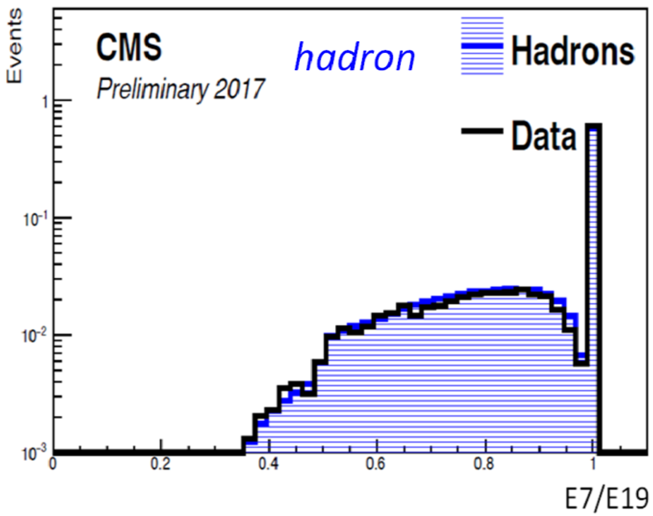
$$E1/E7 = E_{\max} / \left(E_{\max} + \sum_{i=2}^{7} E_i \right)$$

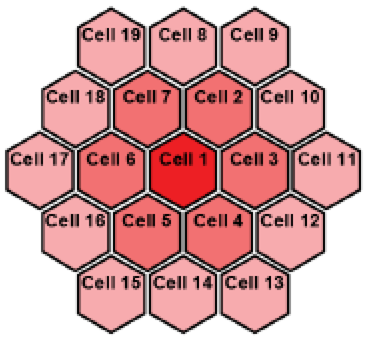
$$E1/E19 = E_{\max} / \left(E_{\max} + \sum_{i=2}^{7} E_i + \sum_{i=8}^{19} E_i \right)$$

$$E7/E19 = (E1/E19)/(E1/E7)$$

Longitudinal shower depth for 250 GeV electron beams at CERN 2016







Transverse shower shape

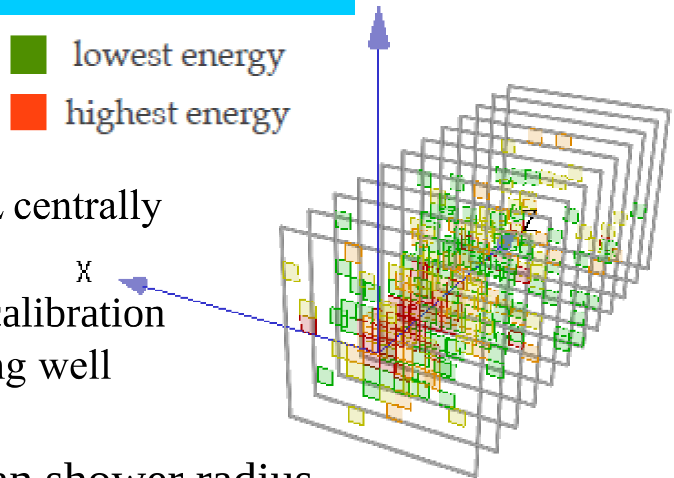
100 GeV electrons at a depth of around 12 X_0 , TB 2016.

200 GeV hadrons at a depth of $4\lambda_0$ **(20% pions and 80% protons), TB 2017.**

Shower shape

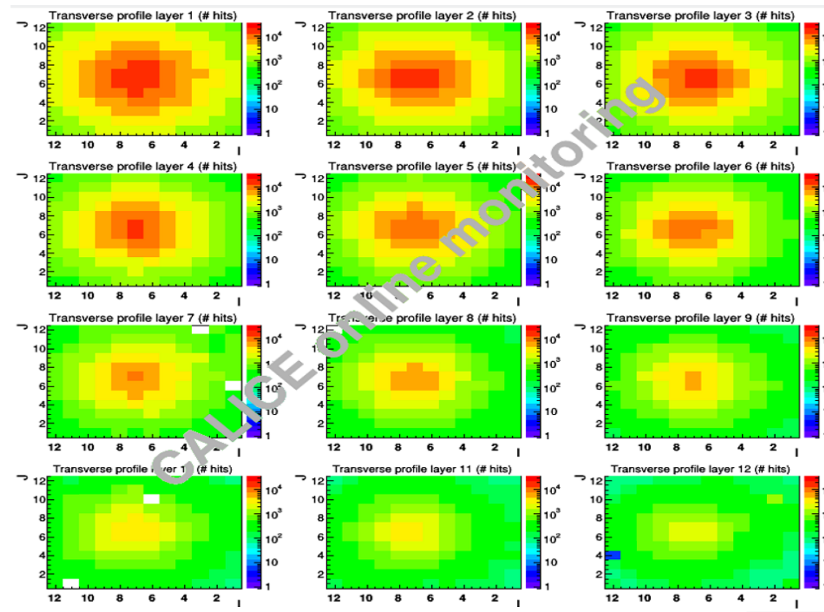
AHCAL shower profiles, 300 GeV pions, TB at CERN 2017

Refer to Felix Christian & Naoki 's talk

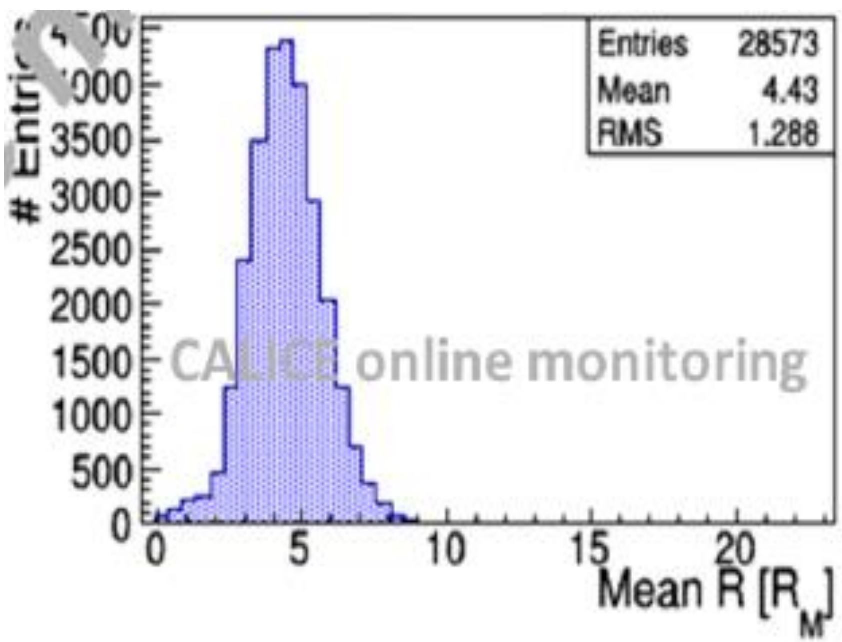


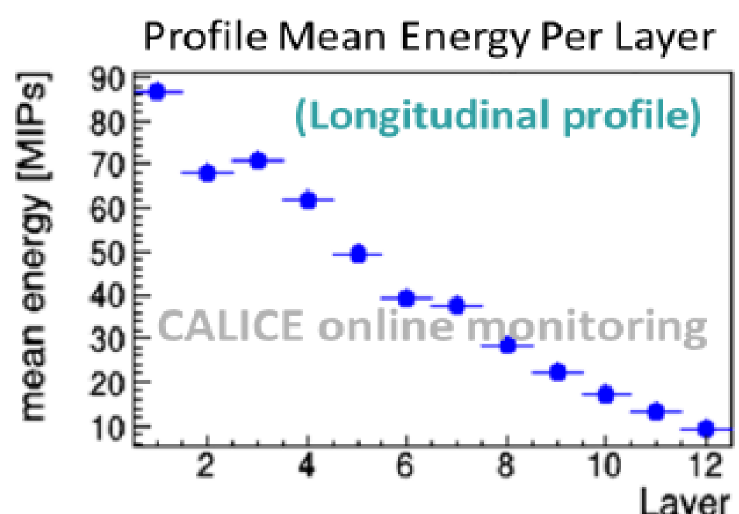
- Beam hits AHCAL centrally (Event display).
- Very preliminary calibration
- Detector performing well with HGCAL.

Hit map of each layer

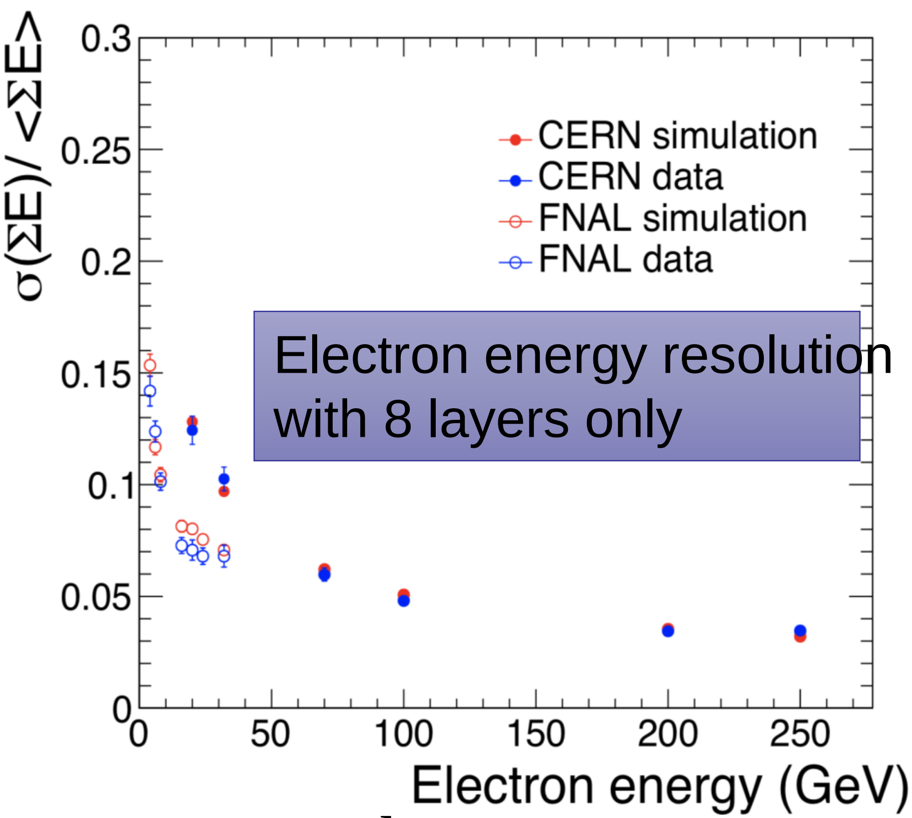


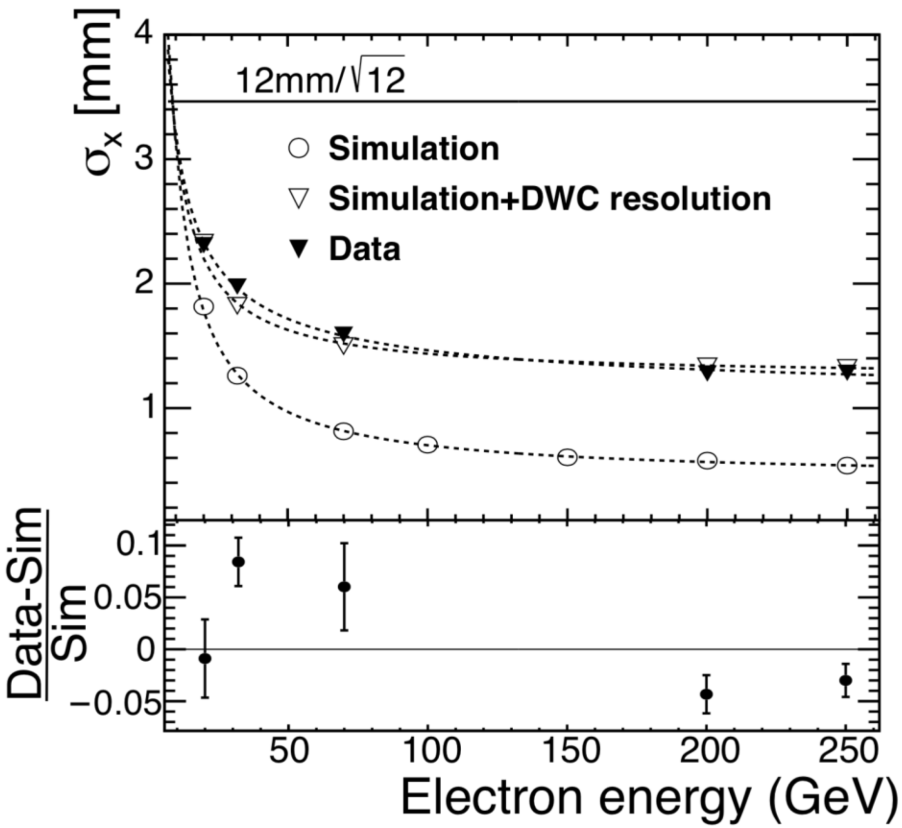
Mean shower radius





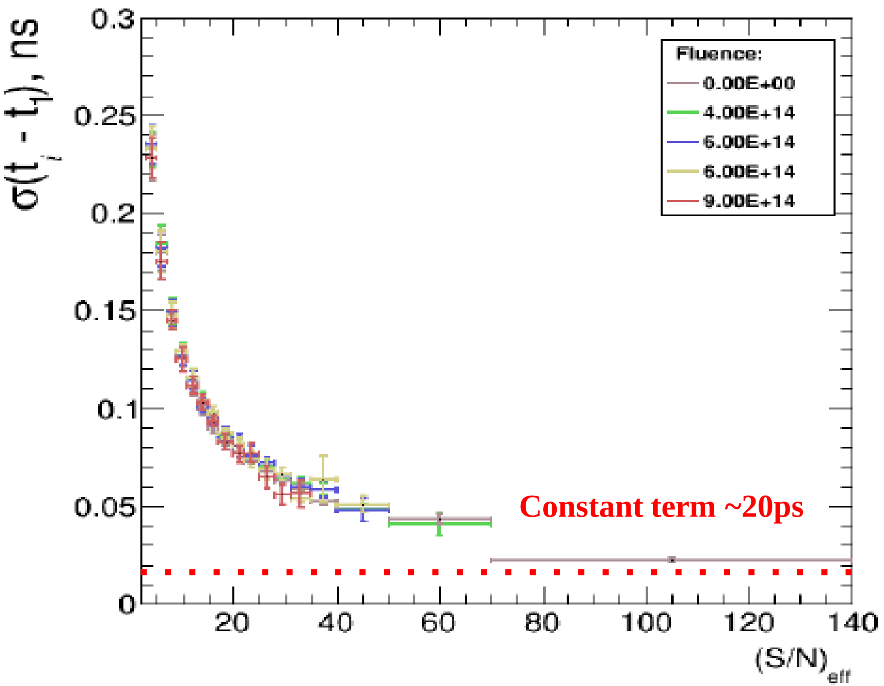
Electron energy & position resolution

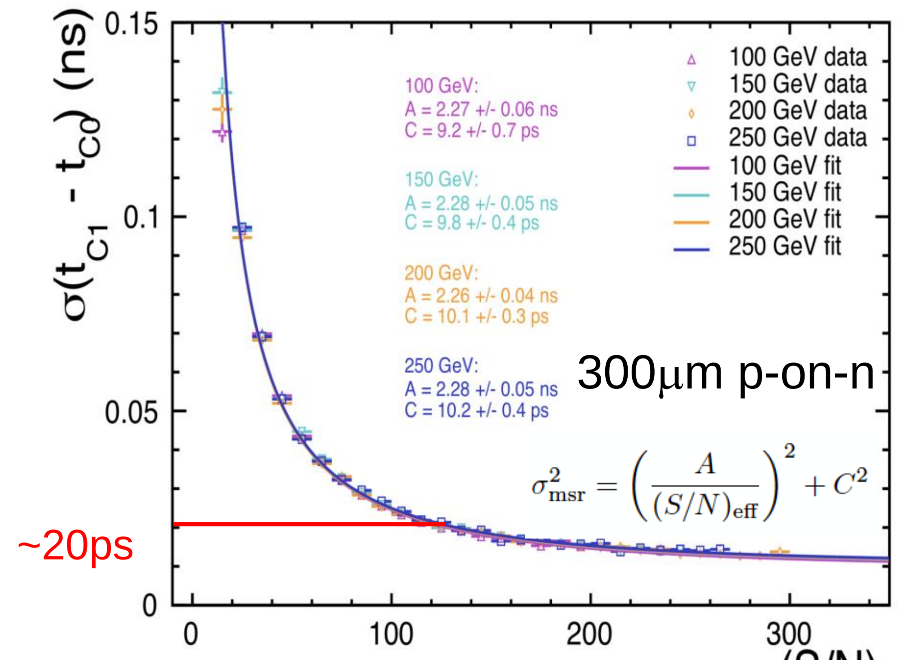




- Energy resolution:
  - -- Distributions from electrons match those predicted by simulation (to within 5%)
  - -- Beam tests in 2016 & 2017 with few layers validated basic design
- Position resolution:
  - -- The DWC contribution to the uncertainty is quite large
  - -- The agreement between data and simulated showers is very good with DWC uncertainty
  - -- The intrinsic spatial precision at this depth is around 0.6mm for high-energy electrons

Time resolution

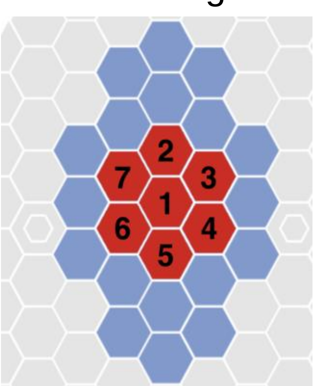




$$(S/N)_{eff} = \frac{(S/N)_{\mathrm{ref}}(S/N)_{\mathrm{dut}}}{\sqrt{(S/N)^2_{\mathrm{ref}} + (S/N)^2_{\mathrm{dut}}}}$$

- Time resolution:
  - -- The intrinsic timing resolution does not significantly depend on the fluence at a given S/N ratio
  - -- Tests with larger energy range at CERN (100-250 GeV)
  - -- It is better than 20 ps for S/N > 100
  - -- The n-on-p diodes showed very similar performance

25 fast timing cells



Next step

- **More test beam in 2018:**

  -10 days @ DESY in March: low-energy showers & studies of performance vs position

  - Two tests with extended prototypes foreseen at CERN:

    10 days @ CERN in June: 28-layer electromagnetic section

    14 days @ CERN in October: 28-layer EM + 12-layer hadronic section + CALICE AHCAL

  - Possibly some time in intense beam @ IHEP Beijing

References

- The CMS collaboration, *CMS Endcap Calorimeter Technical Design Report*, Technical Design Report **CERN-LHCC-2017-023 (Nov. 2017).**
- CMS collaboration, *Technical Proposal for the Phase-II Upgrade of the CMS Detector*,CERN-LHCC-2015-010, **LHCC-P-008 (June 2015).**
- J. Borg, S. Callier, D. Coko, F. Dulucq, C. deLa Taille, L. Raux, T. Sculac and D. Thienpont, *SKIROC2 CMS an ASIC for testing CMS HGCAL*, **Journal of Instrumentation, Vol 12. (February 2017)**
- CMS collaboration, S. Jain, *2017 Construction and first beam-tests of silicon-tungsten prototype modules for the CMS High-Granularity Calorimeter for HL-LHC* ***JINST*** **12 C03011**
- F. Pitters, "*The CMS High-Granularity Calorimeter for Operation at the High-Luminosity LHC*", **TIPP 2017**
- Wurzburg "*Beam-tests of prototype modules for the CMS High Granularity Calorimeter with electrons and hadrons at CERN* ", **DPG2018**
- Huaqiao Zhang ,"*CMS High Granularity Calorimeter Upgrade*", **HEP2018HK**
- Yung-Wei Chang, "*Construction and beam-tests of silicon-tungsten and scintillator-SiPM modules for the CMS High Granularity Calorimeter for HL-LHC*", **HSTD11-2017**
- S. Jain, "*Large scale beam-tests of silicon and scintillator-SiPM modules for the CMS High GranularityCalorimeter for HL-LHC*", **PANIC2017**

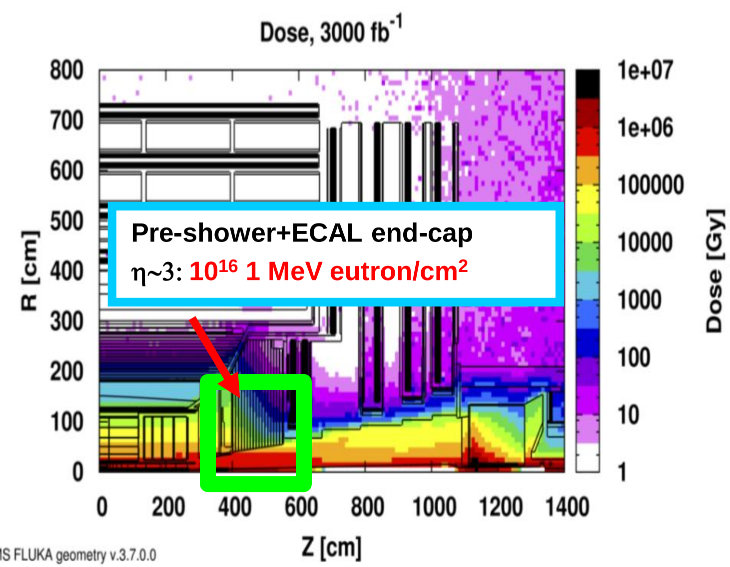

Thank you

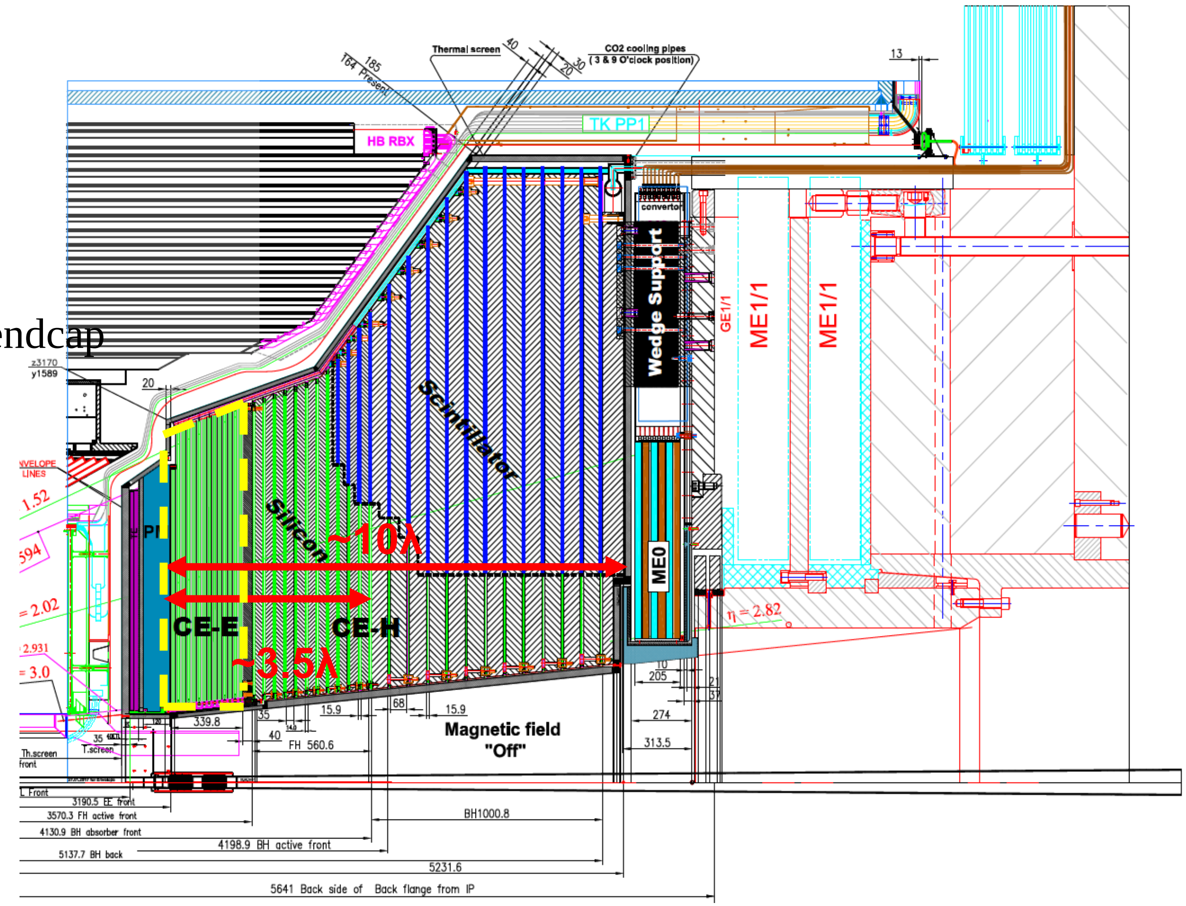
Back up

The CMS HGCAL

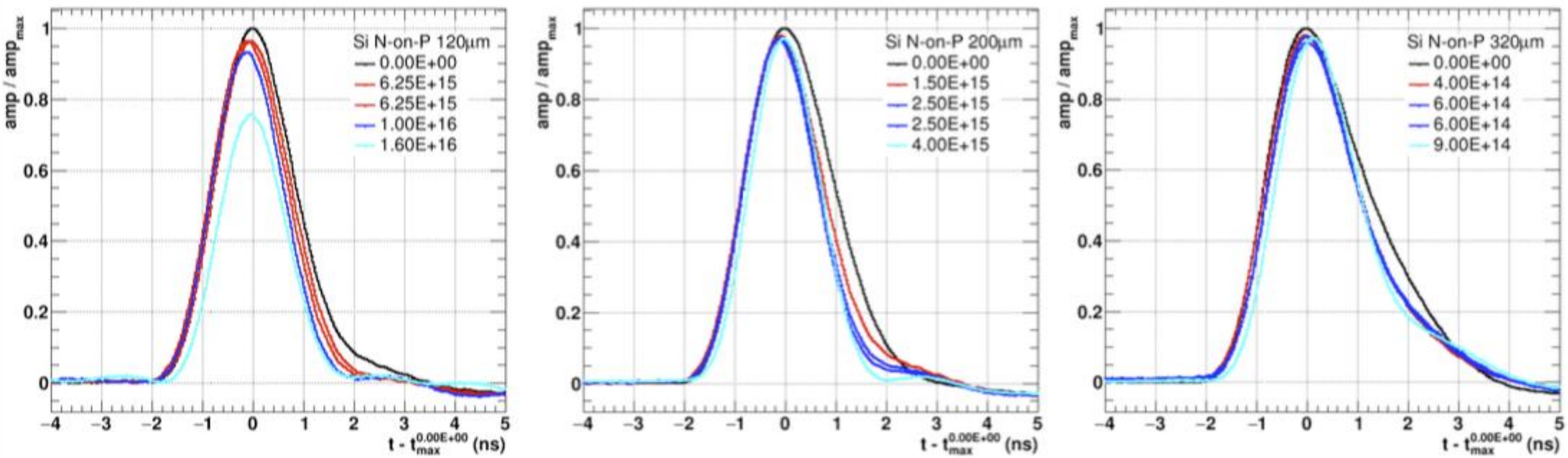
Key Parameters:

- HGCAL covers $1.5 < \eta < 3.0$
- Full system maintained at -30°C
- ~600m^2 of silicon sensors
- ~500m^2 of scintillators
- 6M Si channels, 0.5 or 1 cm^2 cell size
- ~27000 Si modules (CE-E:16008)
- Power at end of HL-LHC: ~60 kW per endcap

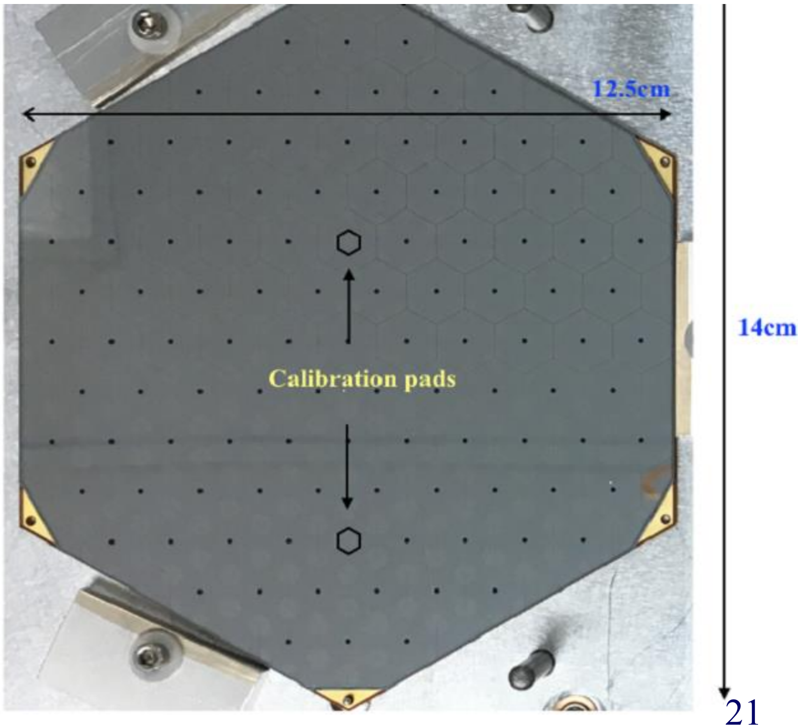




Endcap Electromagnetic calorimeter (EE): Si, Cu & CuW & Pb absorbers, 28 layers, 25 X_0 & ~1.3 λ_0
Front Hadronic calorimeter (FH): Si & scintillator, steel absorbers, 12 layers, ~3.5 λ_0
Backing Hadronic calorimeter (BH): Si & scintillator, steel absorbers, 12 layers, ~5 λ_0



Thickness	300 μm	200 μm	100 μm
Maximum dose (Mrad)	3	20	100
Maximum n fluence (cm^{-2})	6×10^{14}	2.5×10^{15}	1×10^{16}
EE region	$R > 120$ cm	$120 > R > 75$ cm	$R < 75$ cm
FH region	$R > 100$ cm	$100 > R > 60$ cm	$R < 60$ cm
Si wafer area (m^2)	290	203	96
Cell size (cm^2)	1.05	1.05	0.53
Cell capacitance (pF)	40	60	60
Initial S/N for MIP	13.7	7.0	3.5
S/N after 3000 fb^{-1}	6.5	2.7	1.7



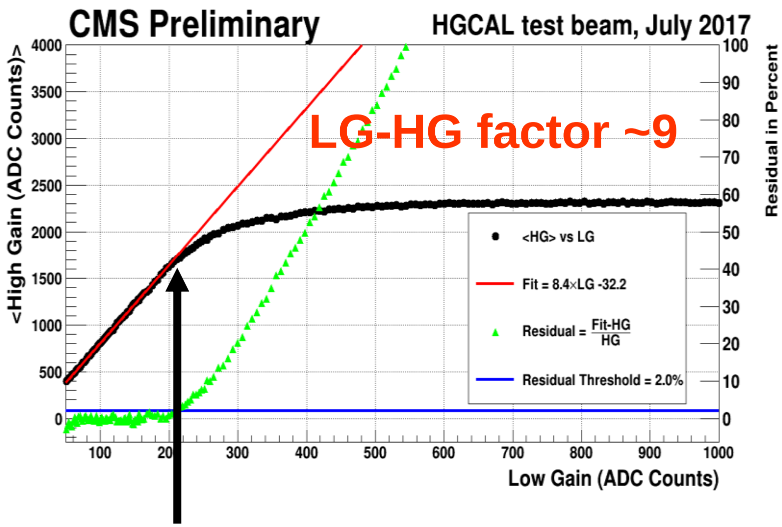
Design requirement

Energy resolution: **25%/ sqrt(E)⊕1%**

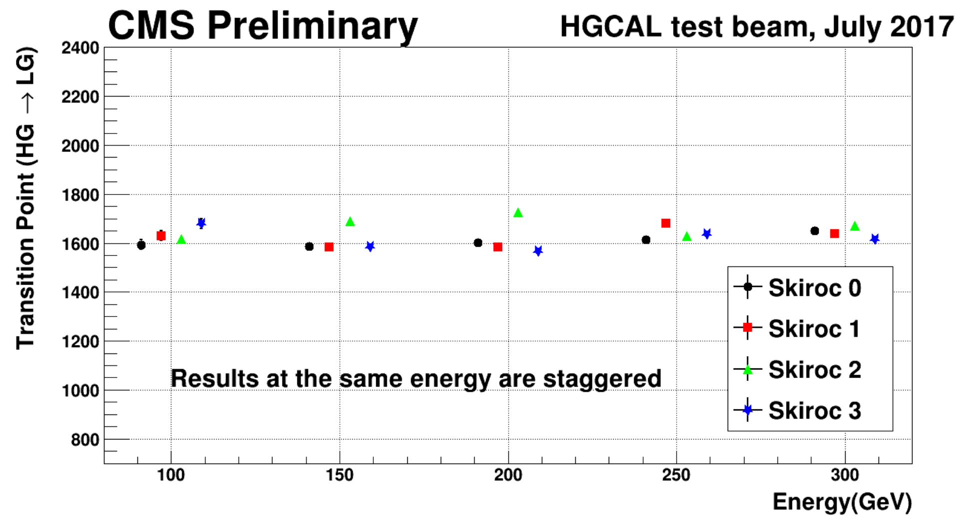
Time resolution : **50 ps**

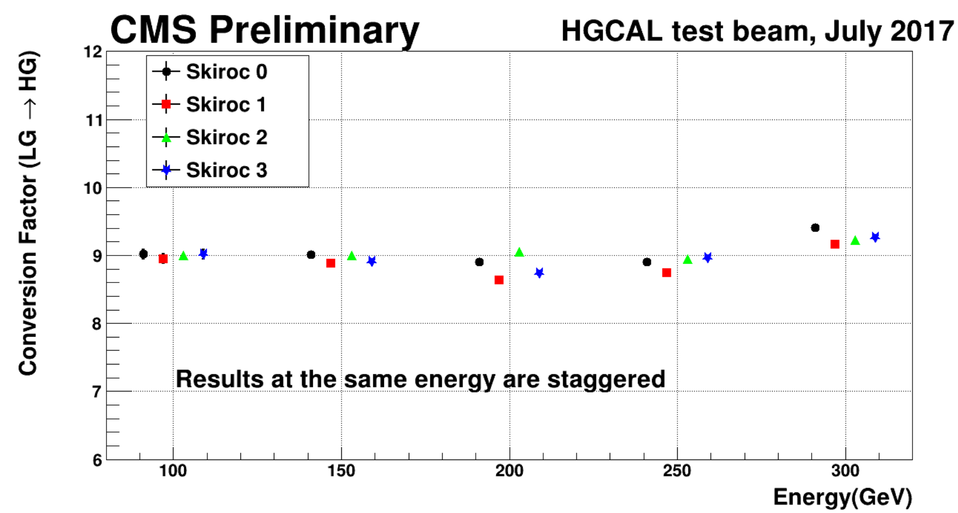
Radiation tolarence : **1×10^{16} 1MeV neq/cm^2**

High gain to Low gain calibration



Turning point



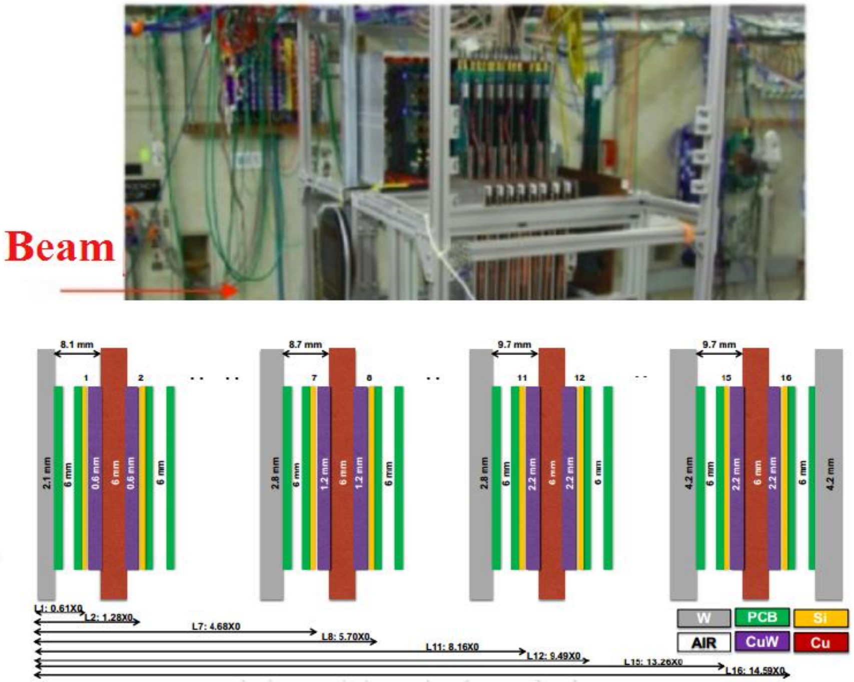


Gain calibration:

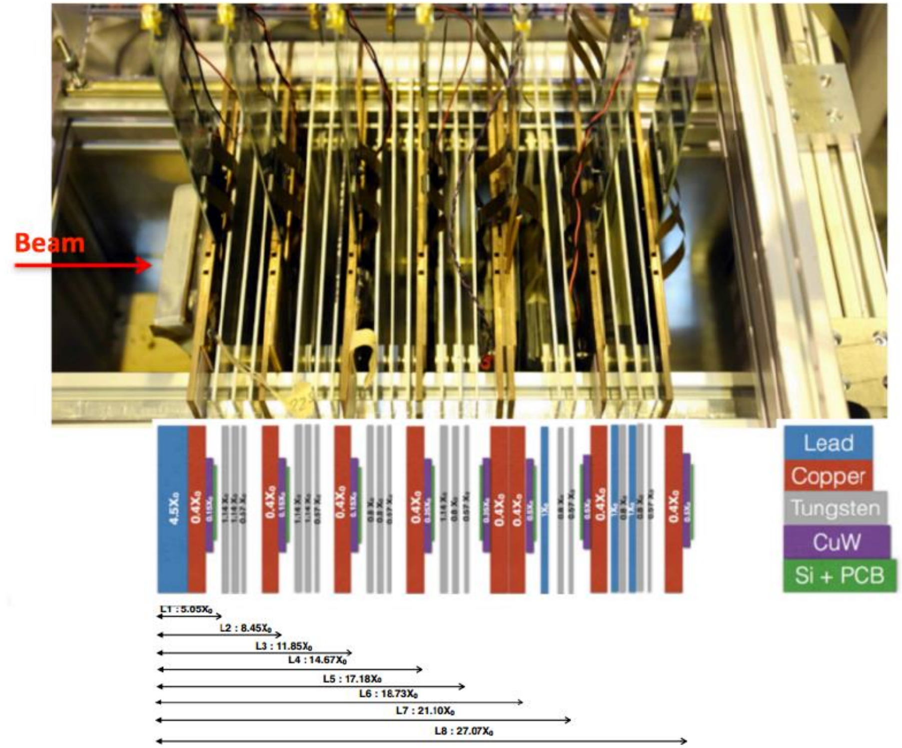
- Linear fit in linear region (red curve).
- Transition point (1600 HG ADC counts) and fit slope are stable with energy of all the readout chips.
- Calibration factor for LG-to-HG value is obtained.

Overview of tests done in 2016

FNAL



CERN



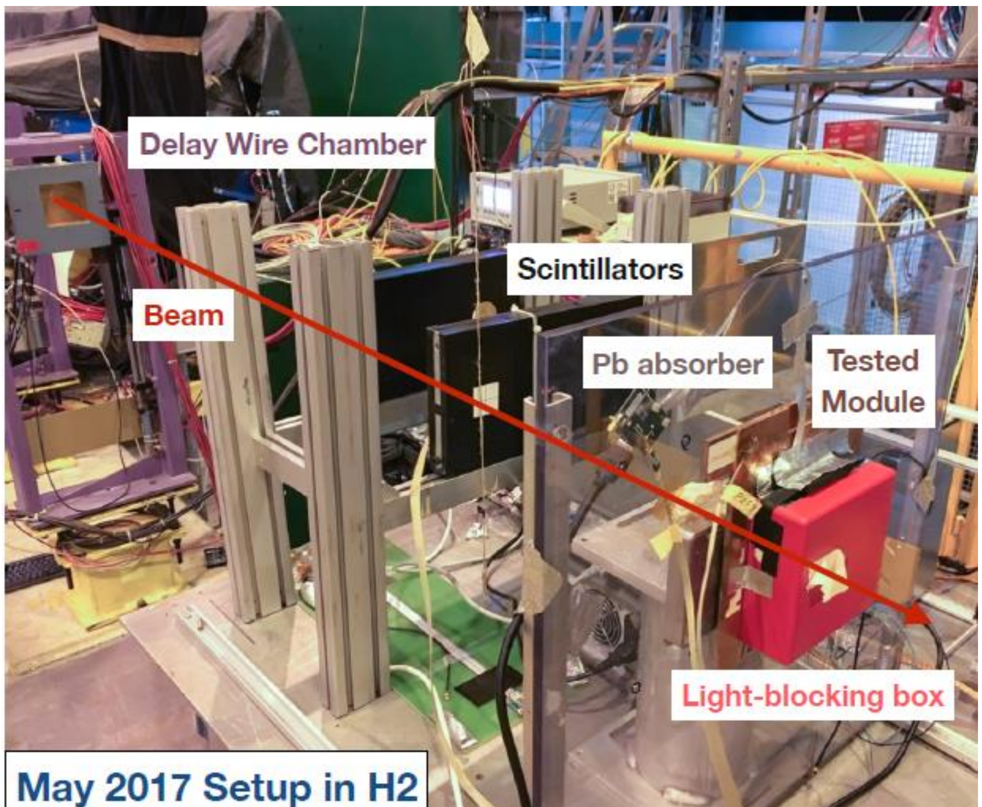
FNAL:
16 Si modules, 15 X_0
e beam (4-32 GeV)

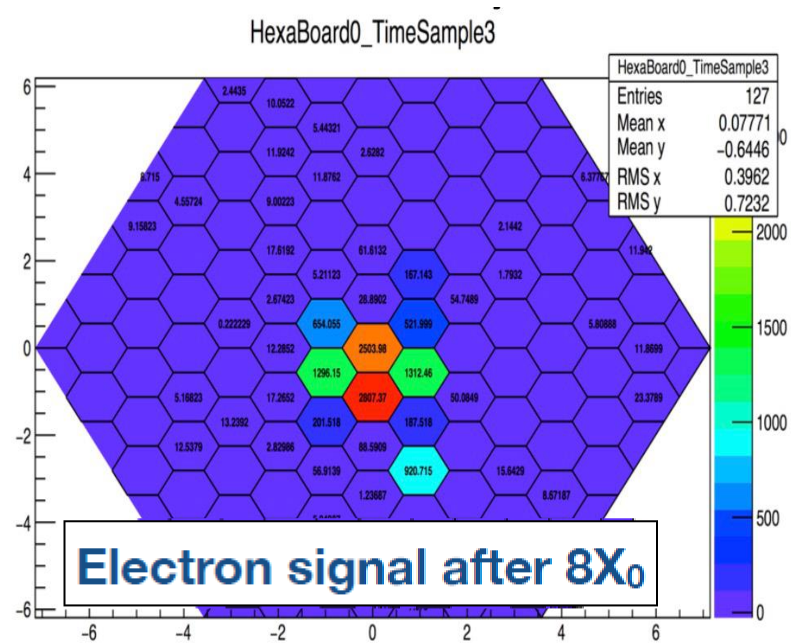
CERN
8 Si modules, Two setup: 5-27 X_0 and 6-15 X_0
e beam (20-250 GeV)
π beam (125 GeV), " (120 GeV) for calibration

One module tested at CERN's SPS in May 2017

One Si module mounted on Cu cooling plate and mounted on plexiglass support.

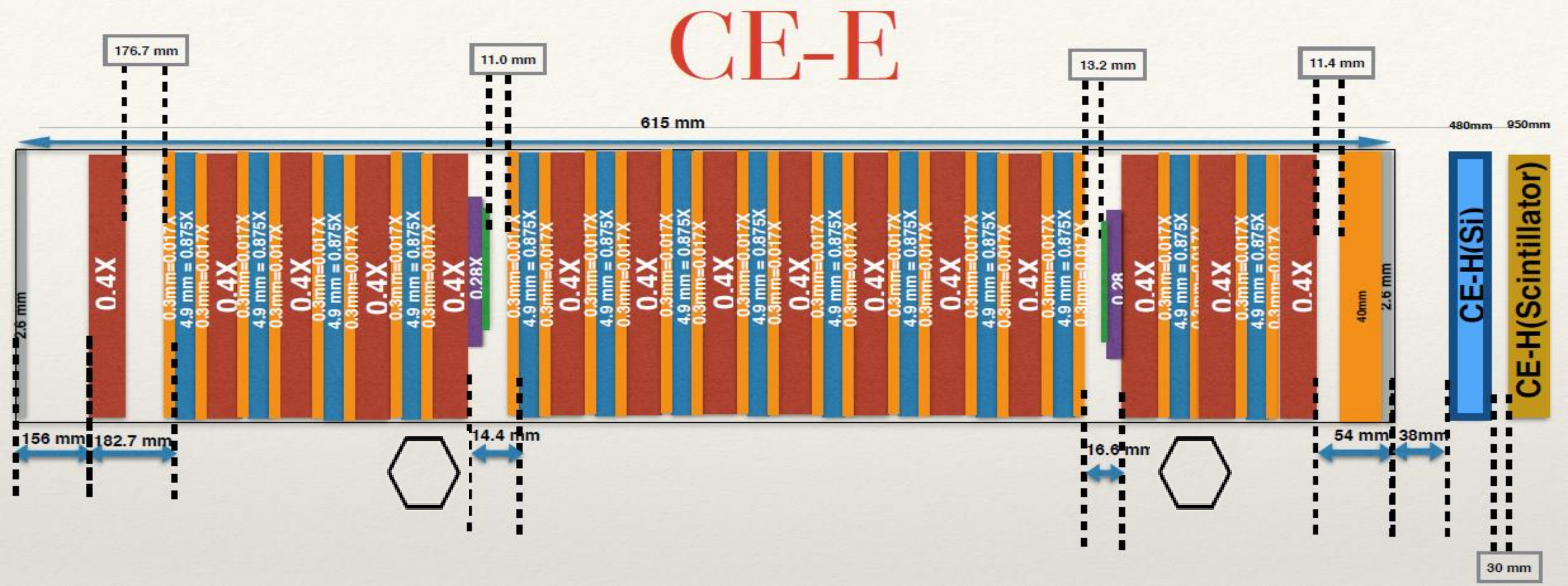
- Two scintillators as triggers.
- 8 X_0 upstream Pb absorber.

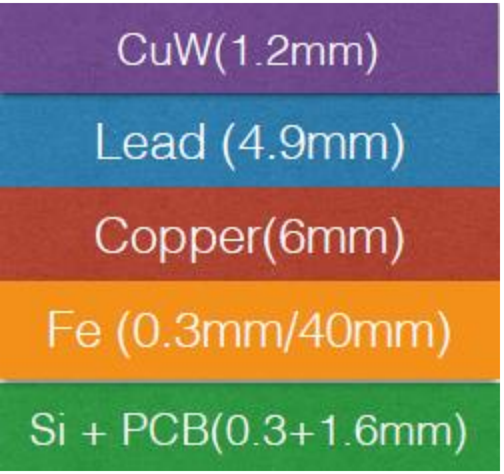




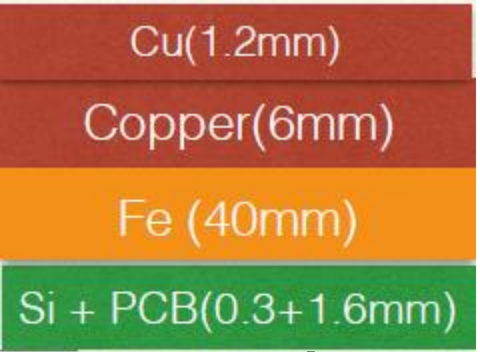
Electron signals seen in the module on the 1st day.

- ~10k events per energy with 20-250 GeV electron beams recorded.

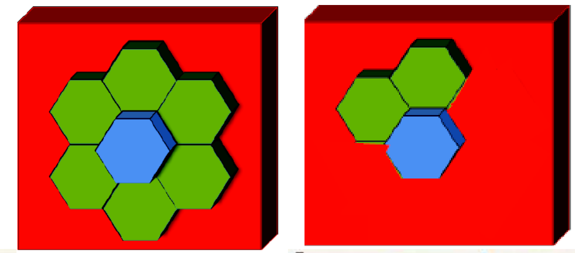


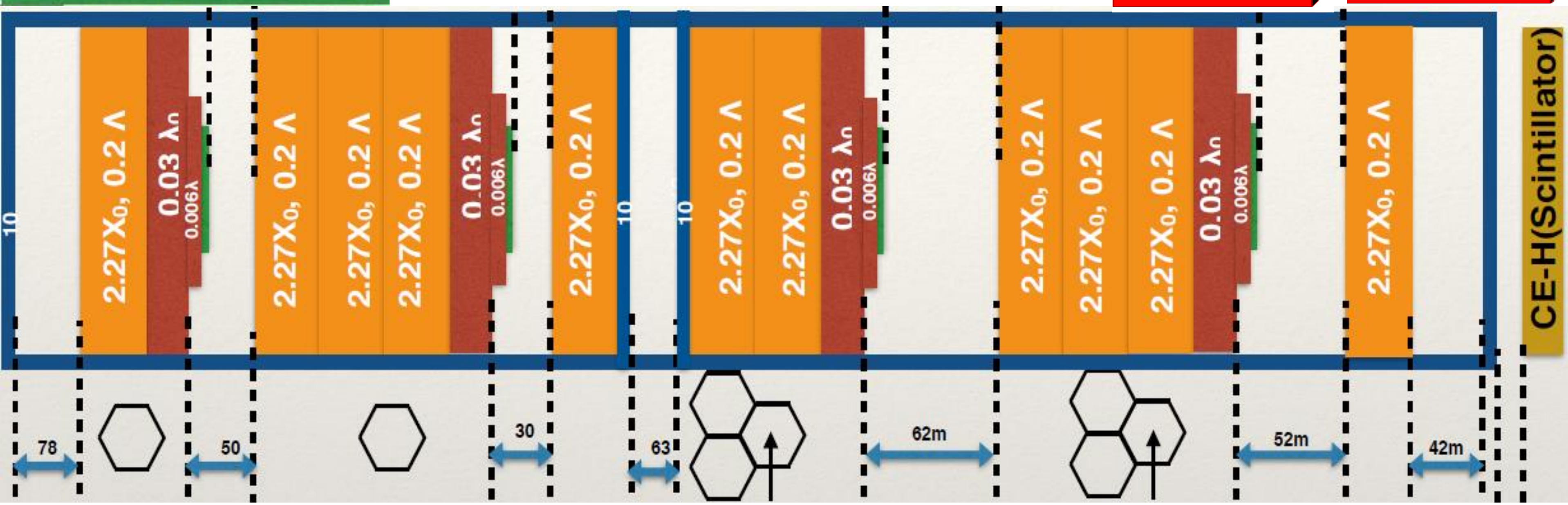


- 14 layers of Fe-Pb-Fe absorber
- 2 layers of Si
- First layer after ~6.3 X_0; second layer ~16.8 X_0
- Total X_0: 22
- Total λ_0: 1.3



CE-H (Si)

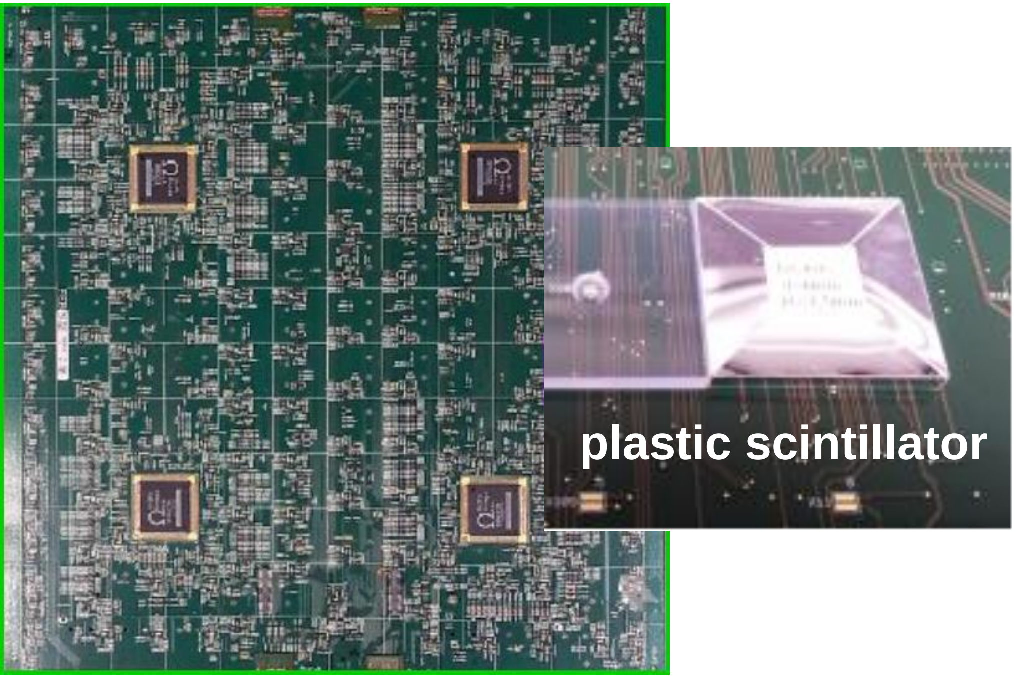




- ❖ 11 layers of Fe absorber
- ❖ Layers are at 1.6 λ_0, 2.4 λ_0, 3.3 λ_0 and 4 λ_0 (including EE)
- ❖ Total of ~ 4.4 λ_0 (including EE)
- ❖ Used 3 modules in two of the layers

CE-H (Scintillator)

From CALICE



Central Interface board

Active elements:

- 12 active layers of 36 x 36 cm^2
- 144 scintillator tiles (each 3 mm thick) of 3 $\times$ 3 cm^2
- Readout by SiPMs
- Absorber stack with 74 mm steel plates
- Total of interaction length ~5λ_0