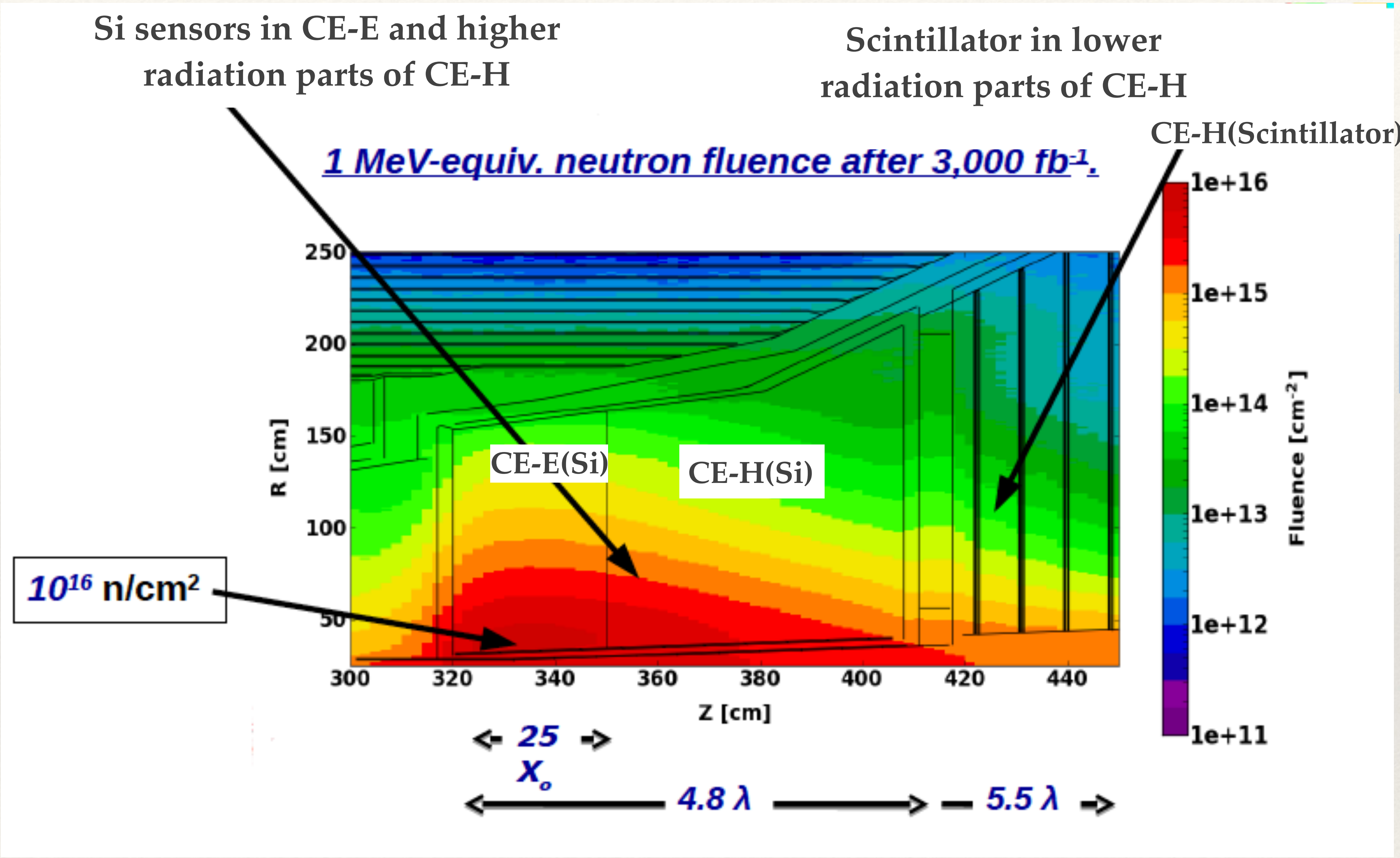
Large scale beam-tests of silicon and scintillator-SiPM modules for the CMS High Granularity Calorimeter for HL-LHC

Shilpi Jain on behalf of the CMS collaboration

PANIC conference, 1st September - 5th September, 2017

Why High Granularity Calorimeter (HGCAL) in HL-LHC



Detailed review of HGCAL in Luca's talk

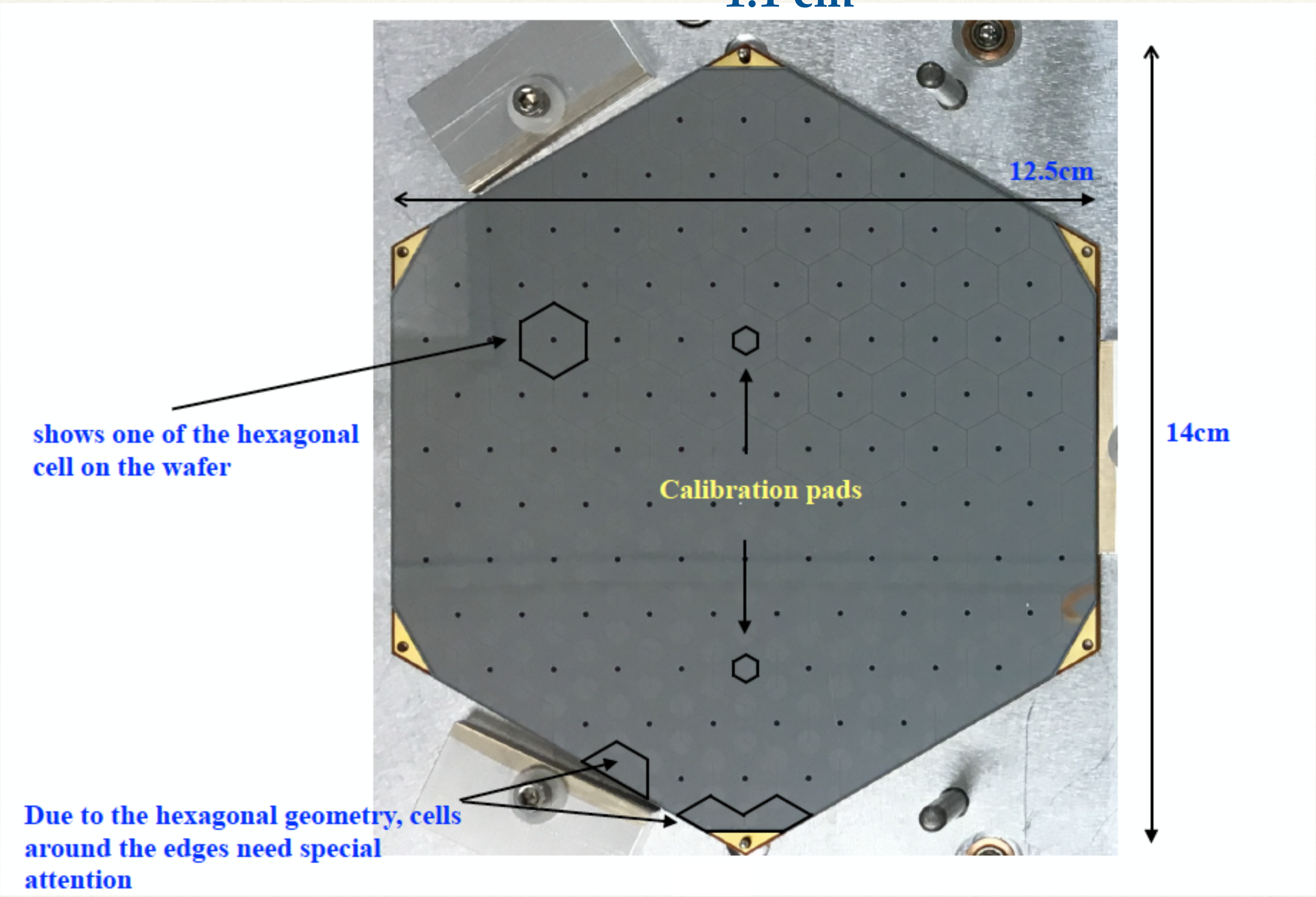
- Important role of the forward calorimeter for physics at the HL-HLC
- Current CMS calorimeters will suffer radiation damage by the end of LHC running
- Detector upgrade important to maintain excellent performance in the harsh HL-LHC

Why beam tests?

- Proof of concept of the baseline design
- Study the calorimetric performance:
  - Pedestal and noise stability
  - Calibration with MIPs
  - Response to electrons and hadrons
  - Comparison of test beam results with the simulation
- We had successful series of beam tests both at CERN and Fermilab in 2016 and 2017
  - Tested several configurations
    - good agreement between data and simulation

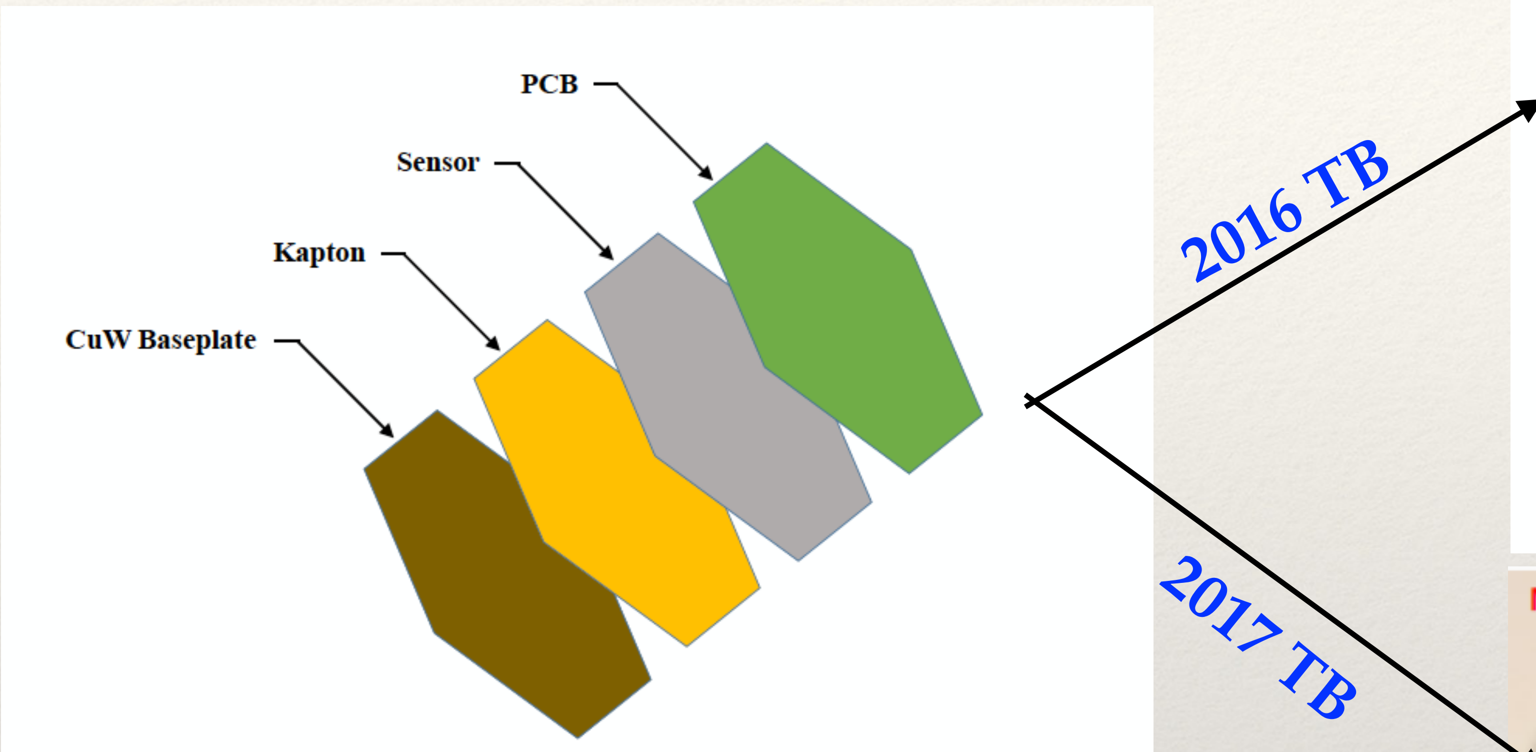
What has been tested - Hexagonal Si sensor

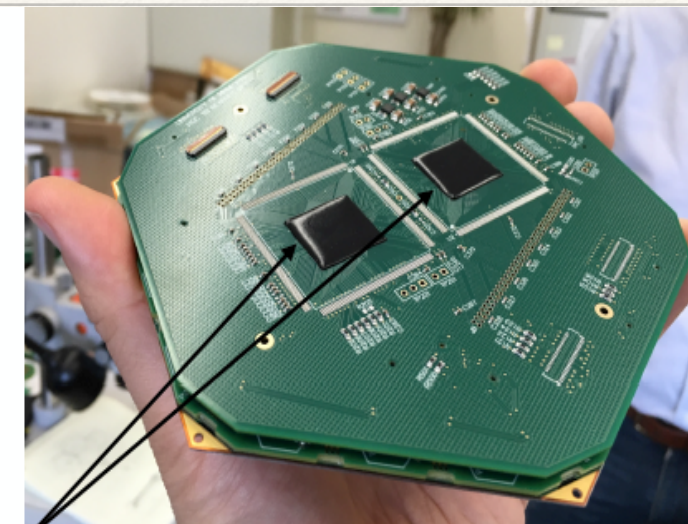
"p on n" with 200 μm (300 μm) in 2016 (2017) active thickness, made from 6" wafer, cell size 1.1 cm^2



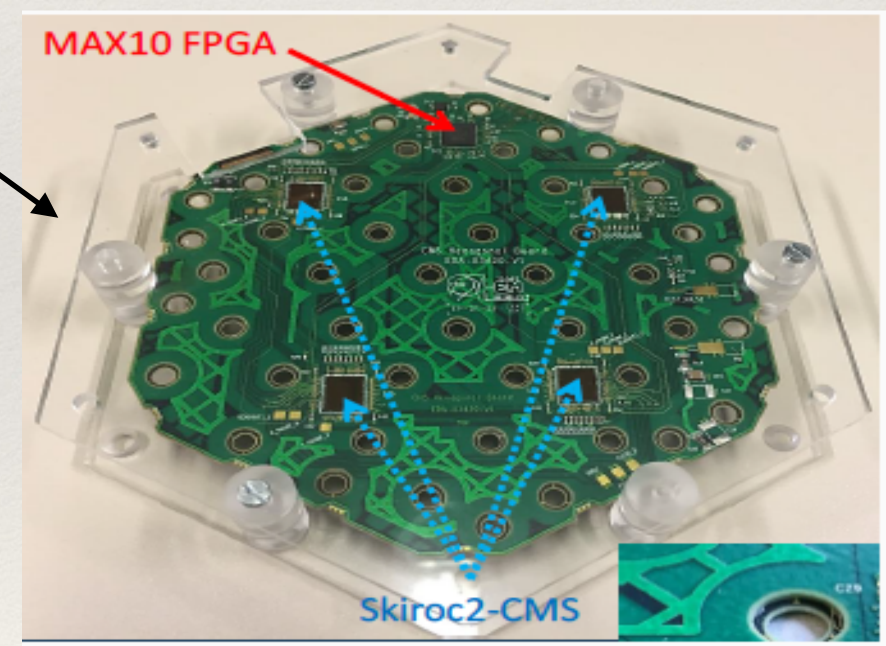
- 128 hexagonal cells
- 2 calibration pads

Module Assembly





SKIROC 2 ASIC developed by OMEGA group designed for ILC. Not the final front-end chip for CMS.

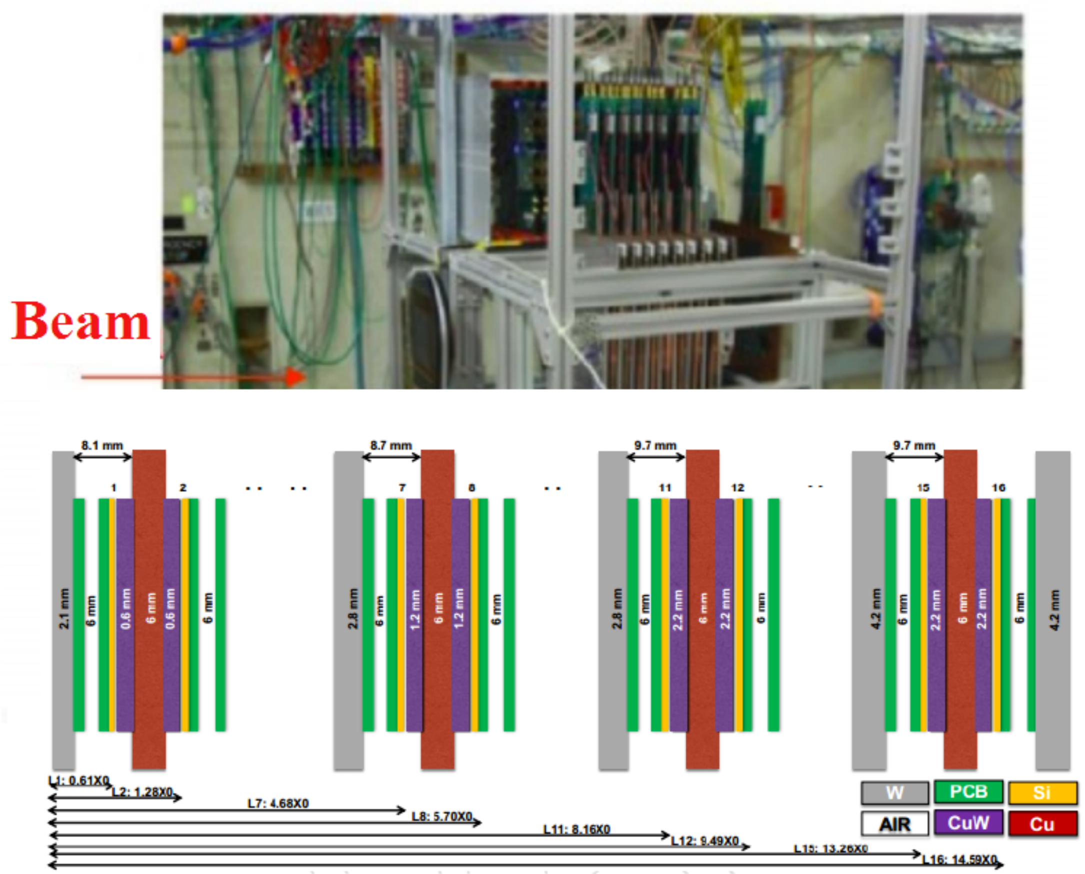


- Glued stack of baseplate, Kapton, sensor and PCB

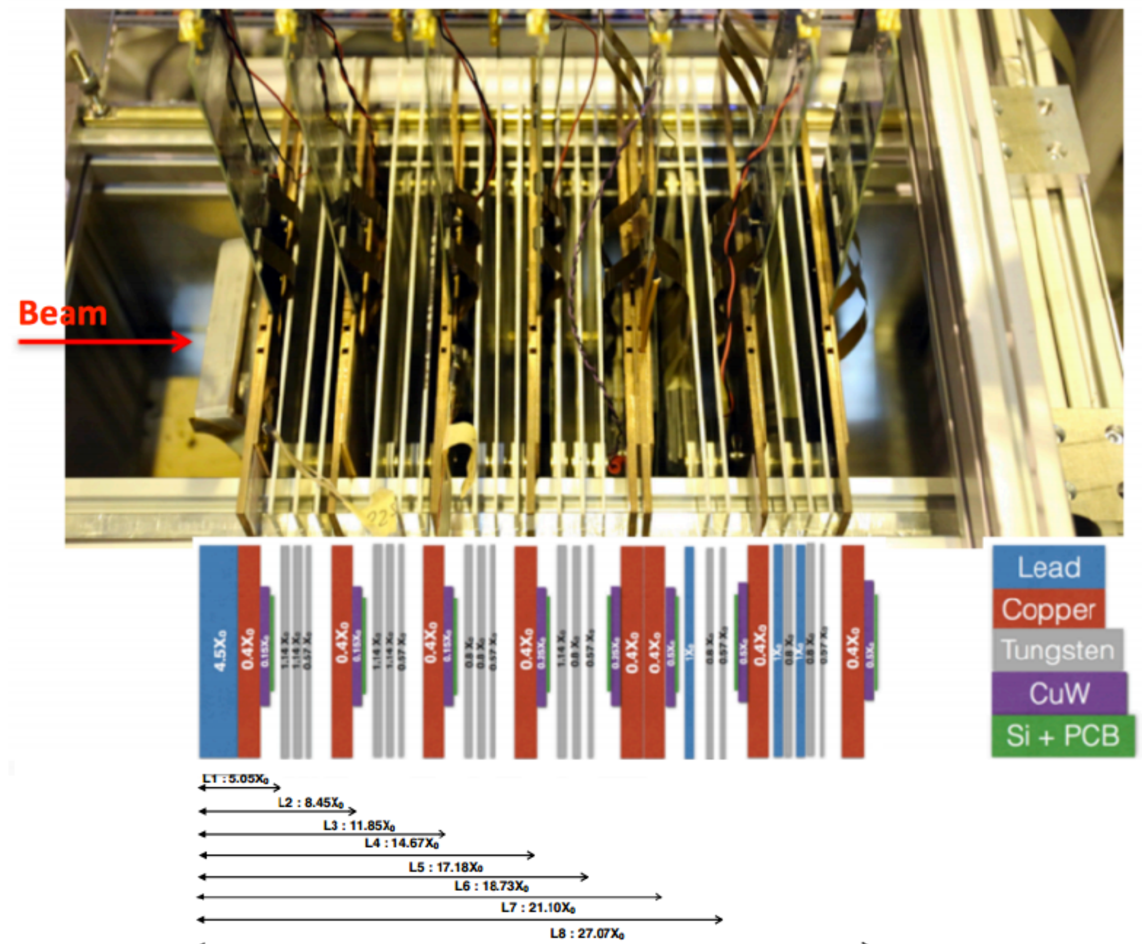
- "Single" layer PCB with sensor and readout
- 2 SKIROC2 in 2016 TB (4 SKIROC2CMS in 2017 TB)
- 1 FPGA for reading and controlling the ASICs (in 2017)

Overview of tests done in 2016

FNAL



CERN



FNAL

- 16 Si modules, 15 X_0
- e beam (4-32 GeV)
- p beam (120 GeV) for calibration

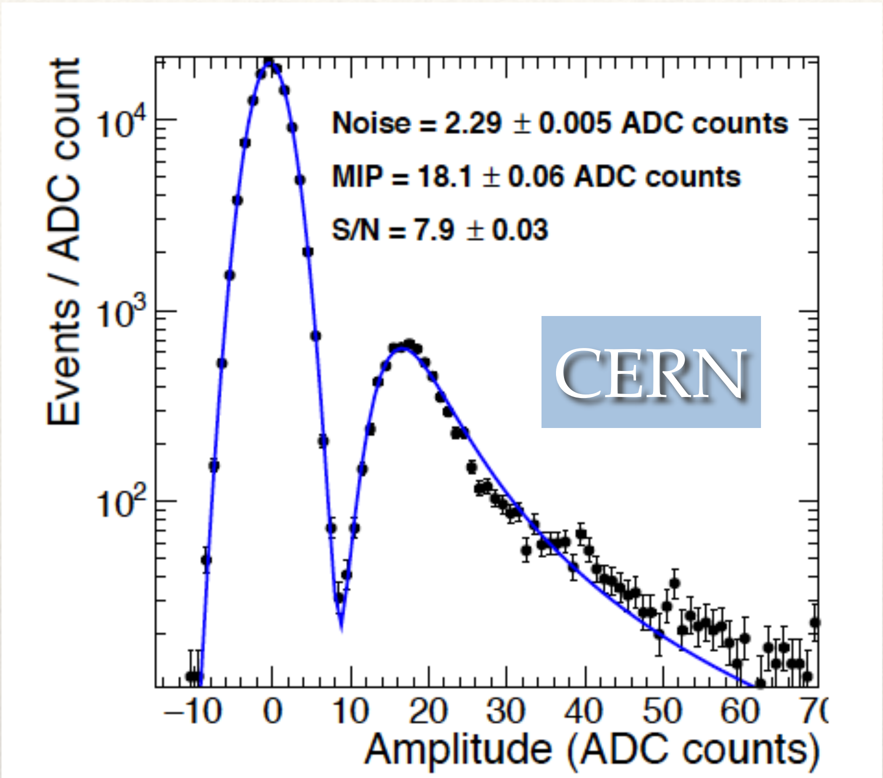
CERN

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

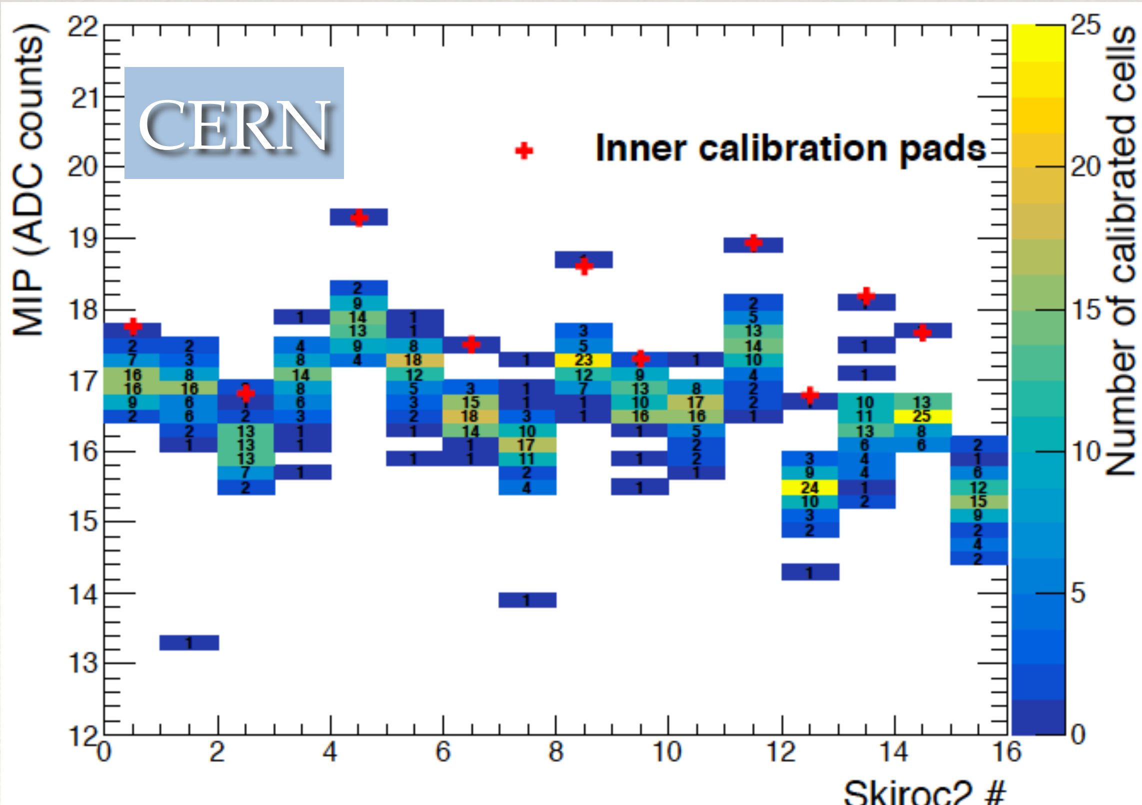
ASIC: SKIROC2

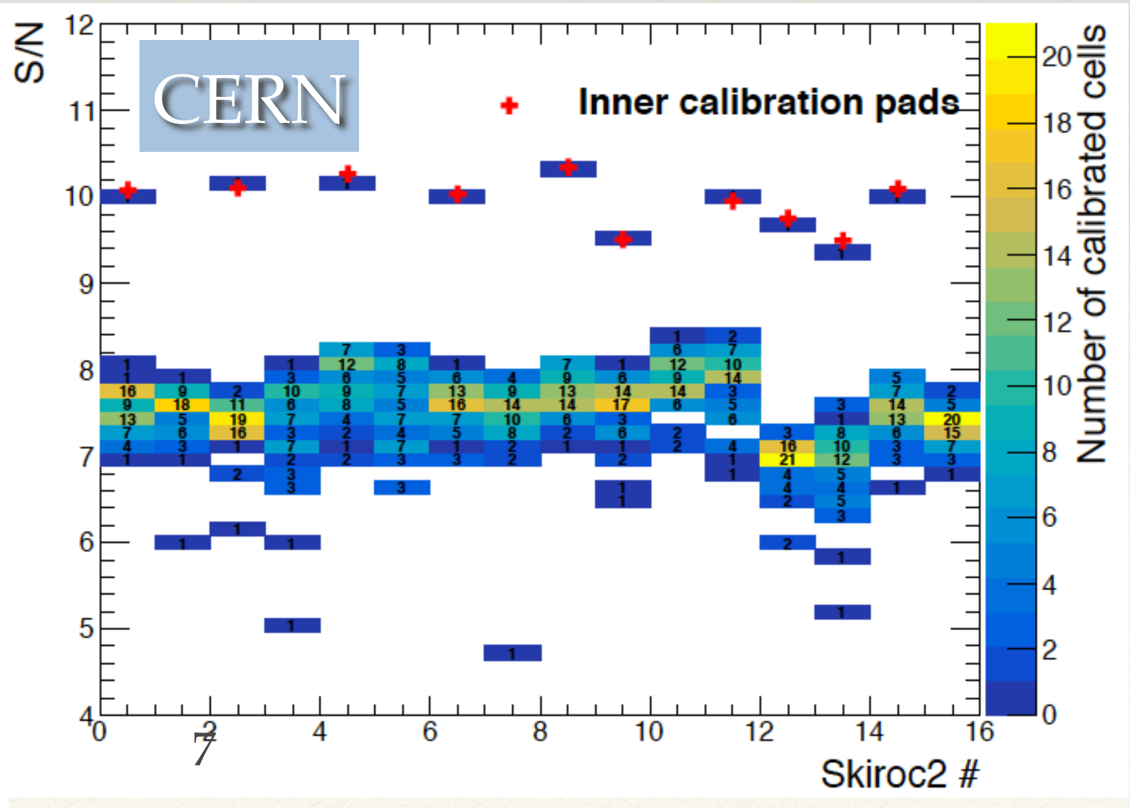
Tested configuration: prototype for CE-E

MIP Calibration in 2016 TB

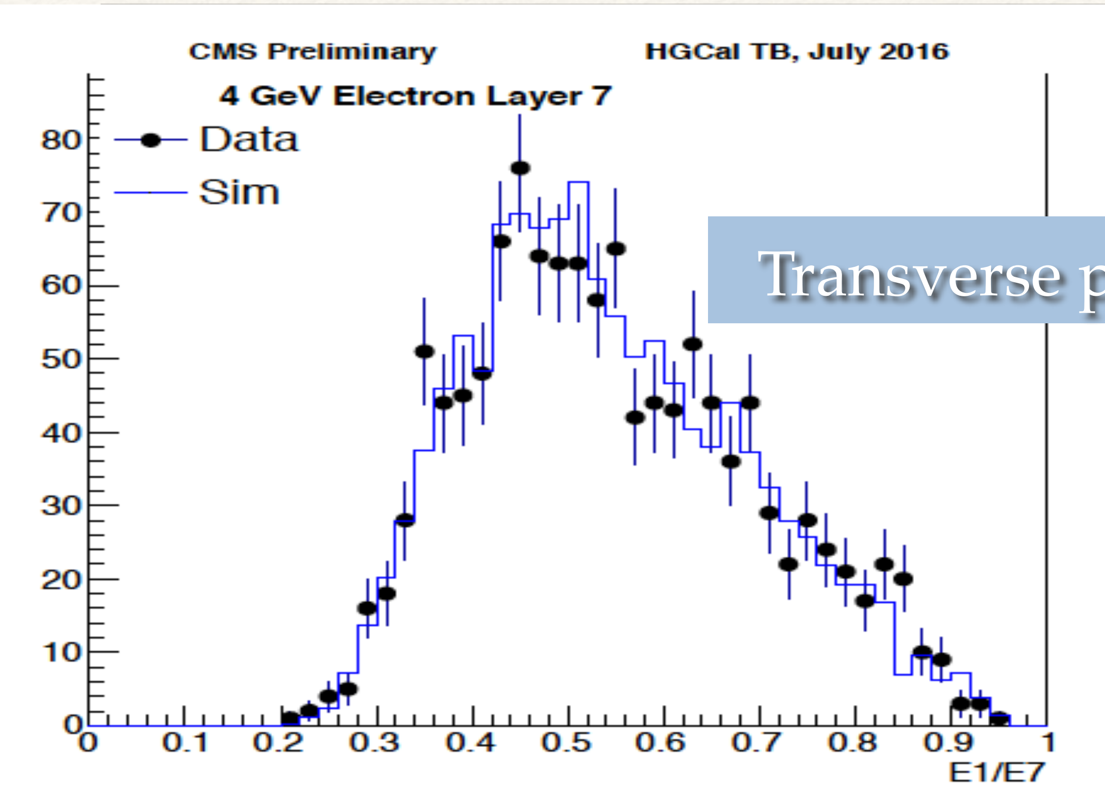


- FNAL: p beam (120 GeV)
- CERN: π beam of 125 GeV
- Calibrate only central cells of sensors within trigger area
- Variations due to electronics and cell size

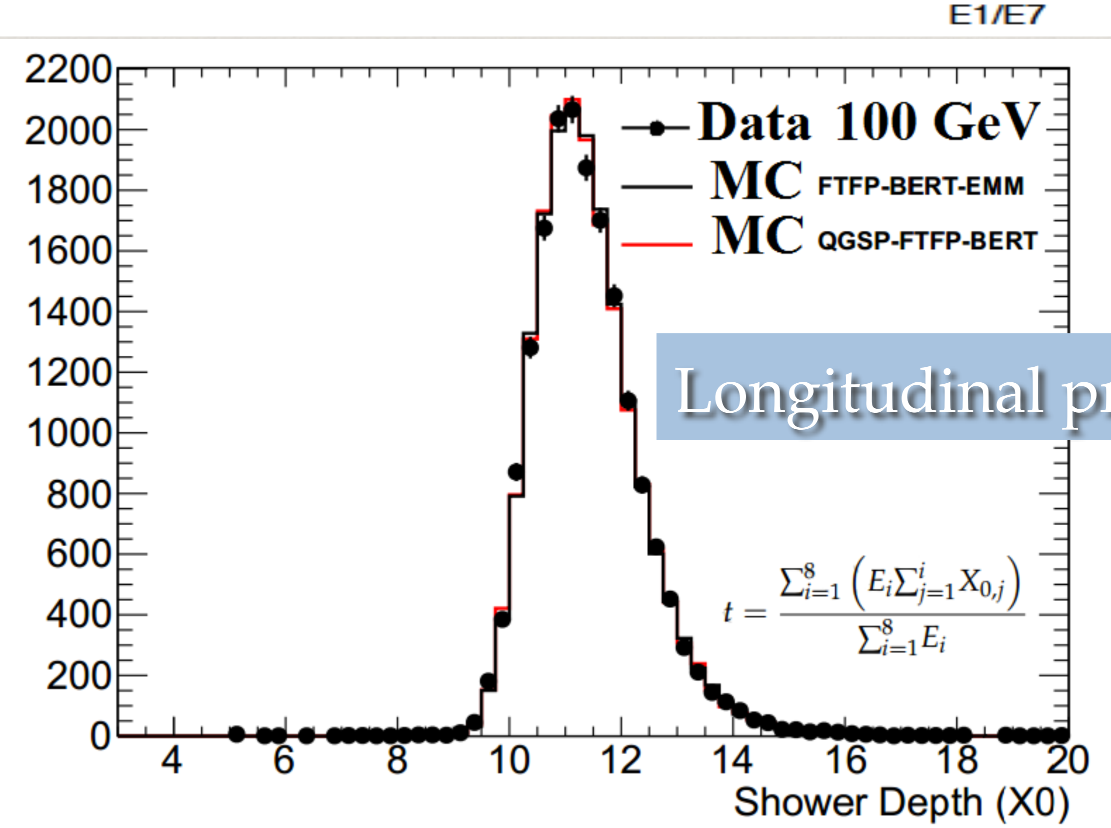


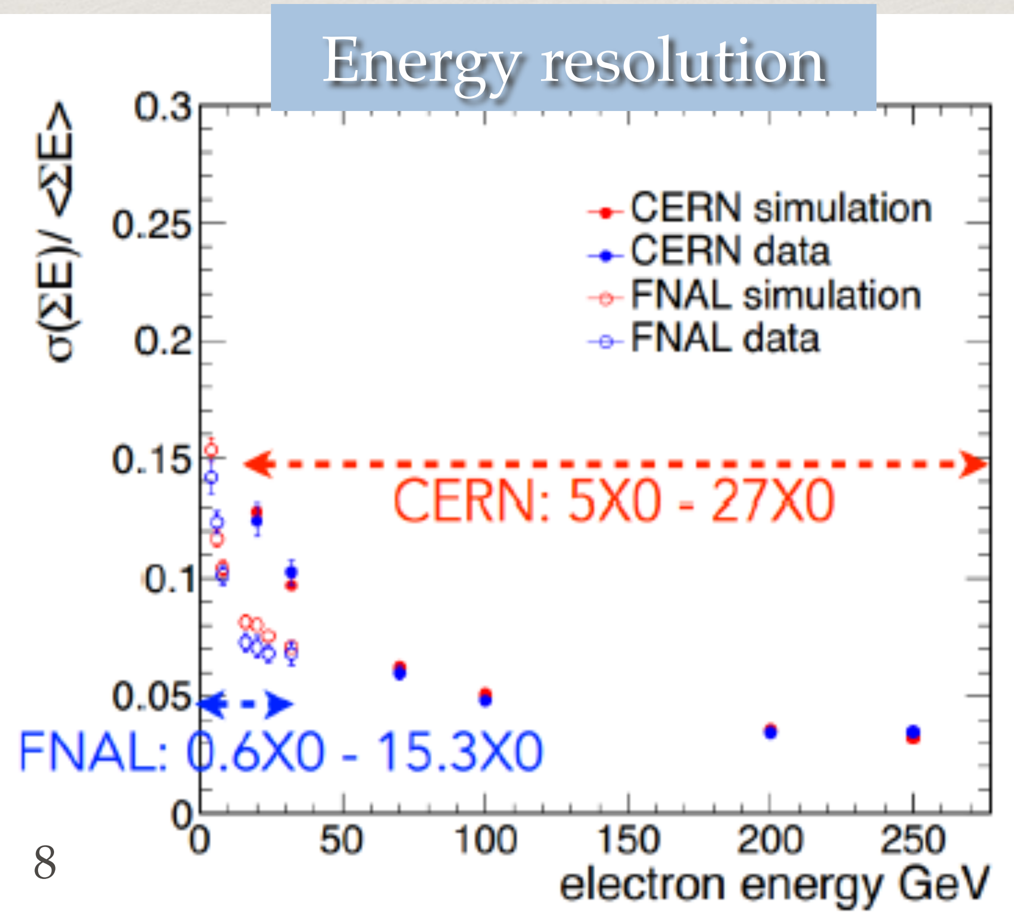


Shower profile and energy resolution in 2016 TB

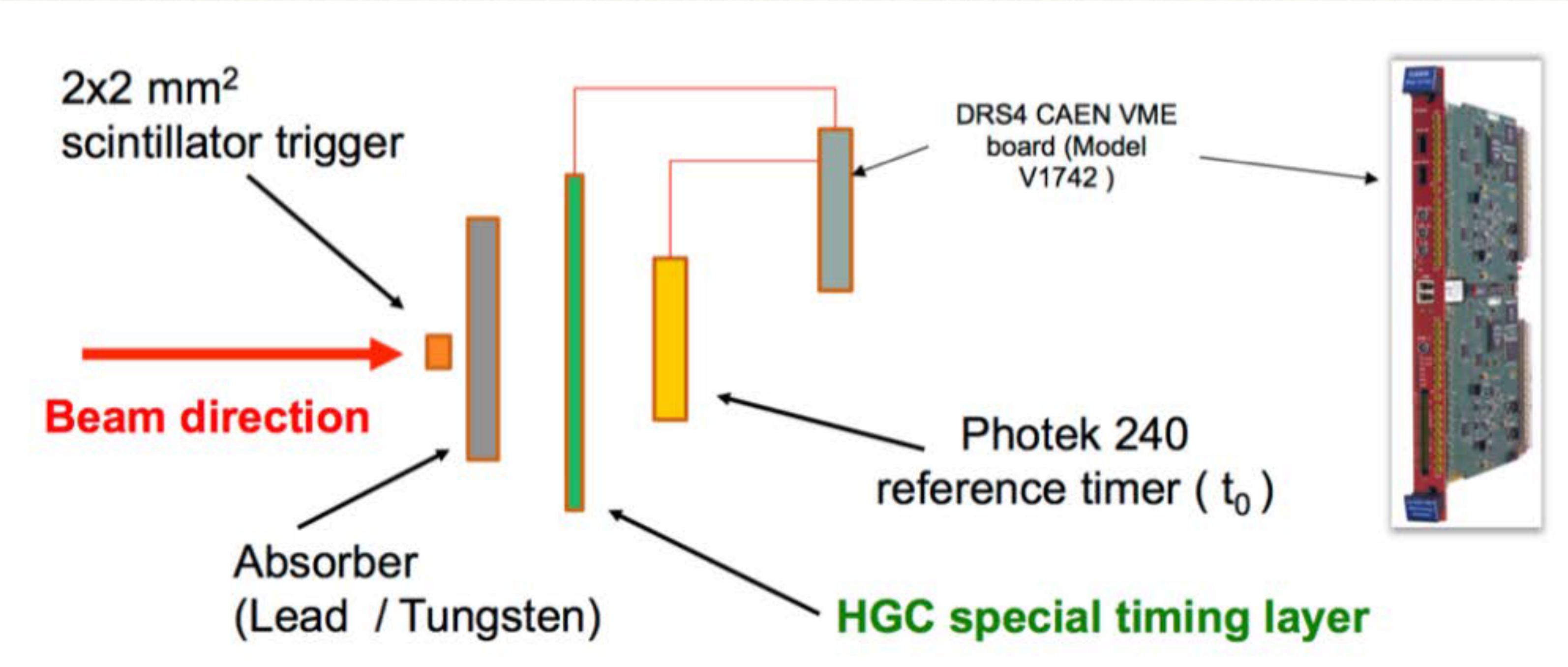


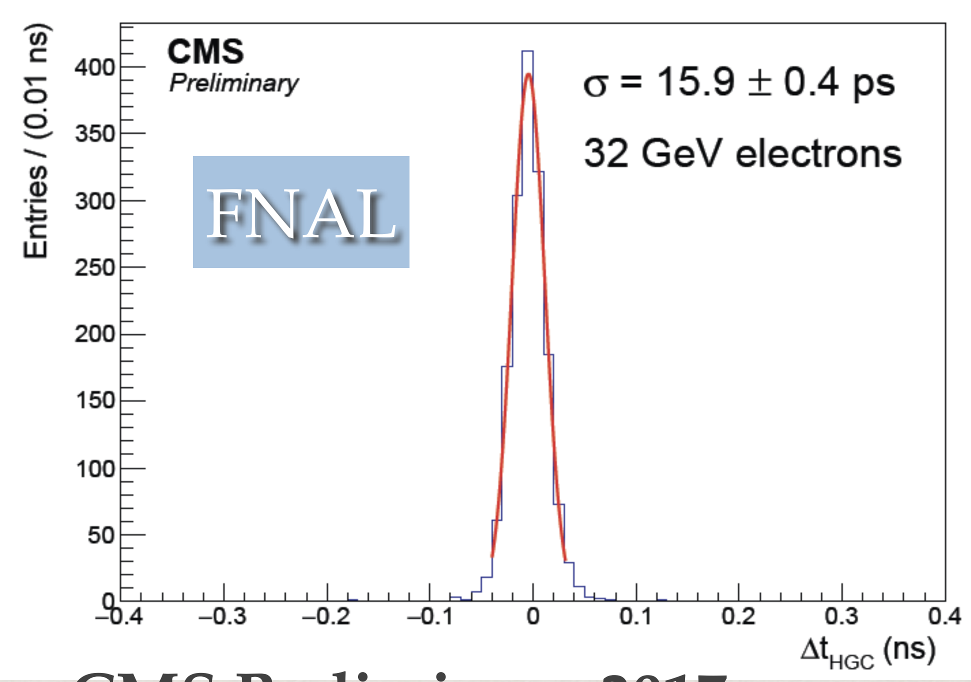
- Looked at various transverse and longitudinal shower profile and energy resolution
  - good agreement between data and Simulation
- Note in preparation, summarizing all 2016 results





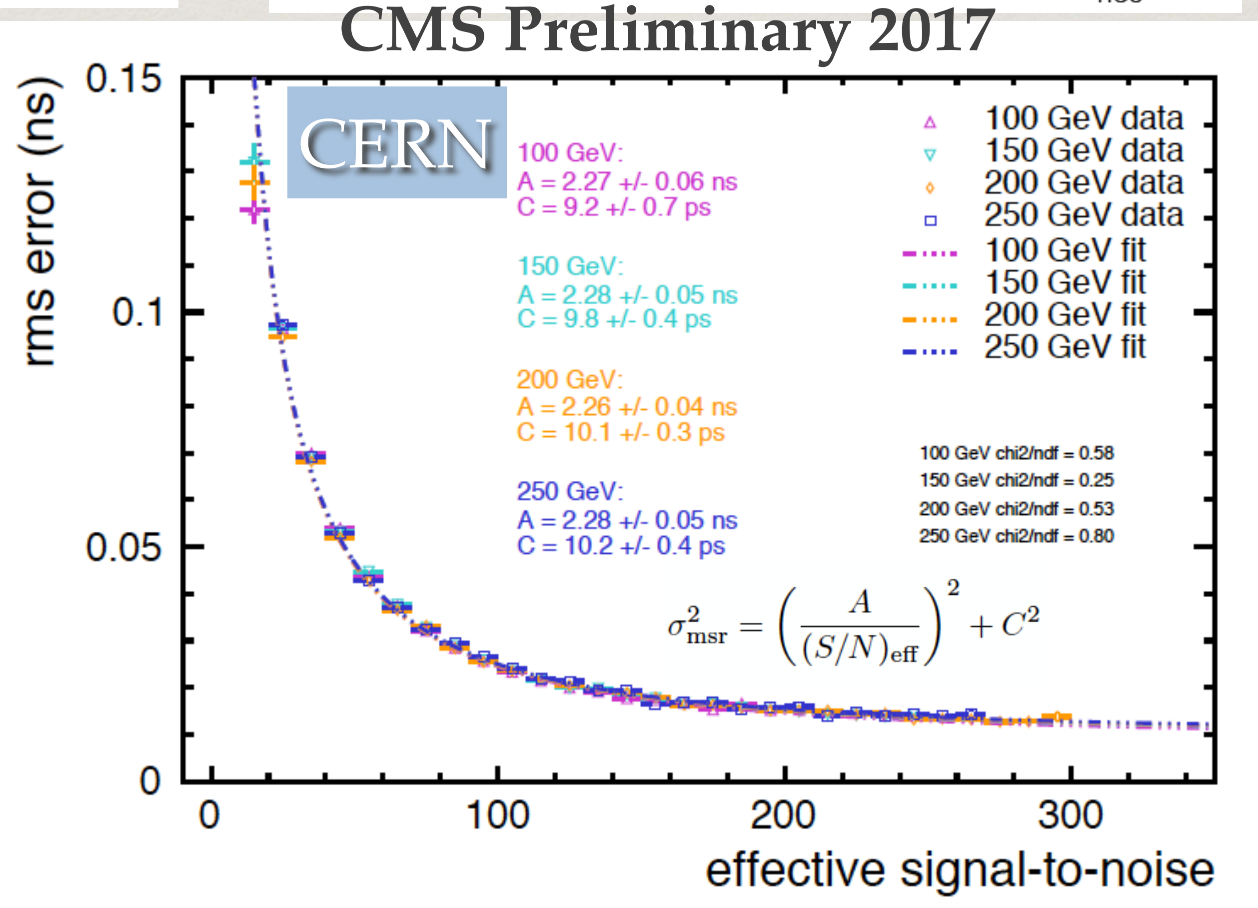
Timing resolution in 2016 TB





- Timing test with a single 300 μm HGC layer with fast readout
  - FNAL: Timing resolution measured using Photek MCP-PMT as reference
  - CERN: Measured as difference in time between two cells.
- **Time resolution of ~16 ps** obtained with 32 GeV electrons (FNAL)
- Tests with larger energy range at CERN (100-250 GeV)
  - **Timing precision better than 10 ps** at high energy with good S/N

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

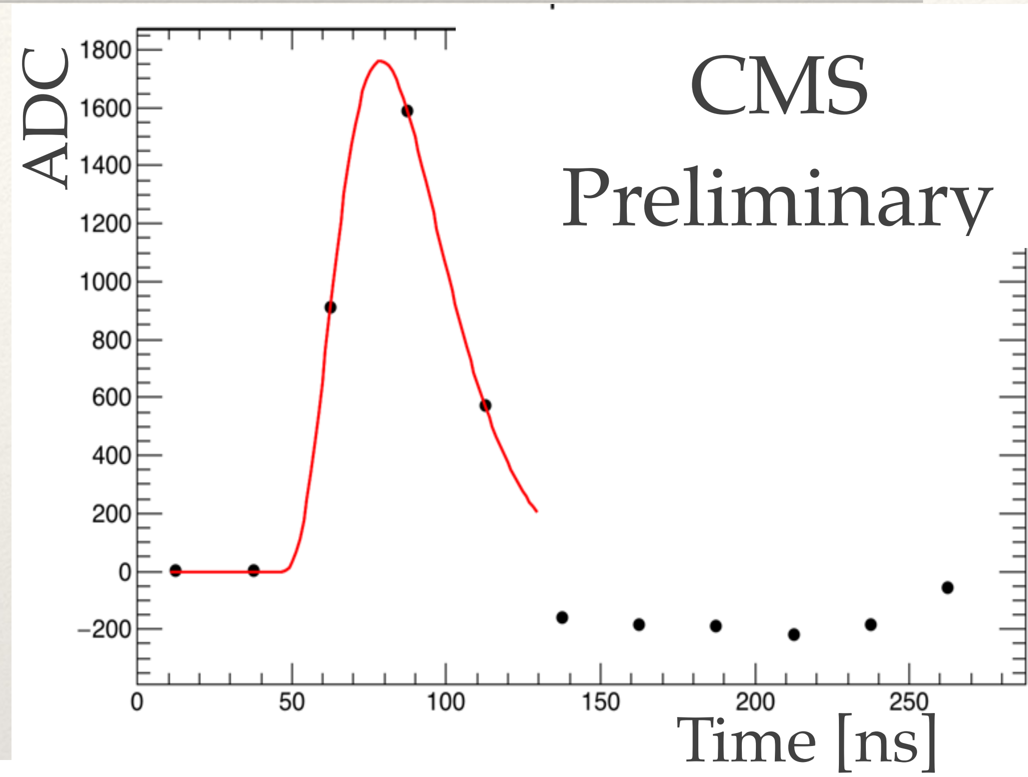


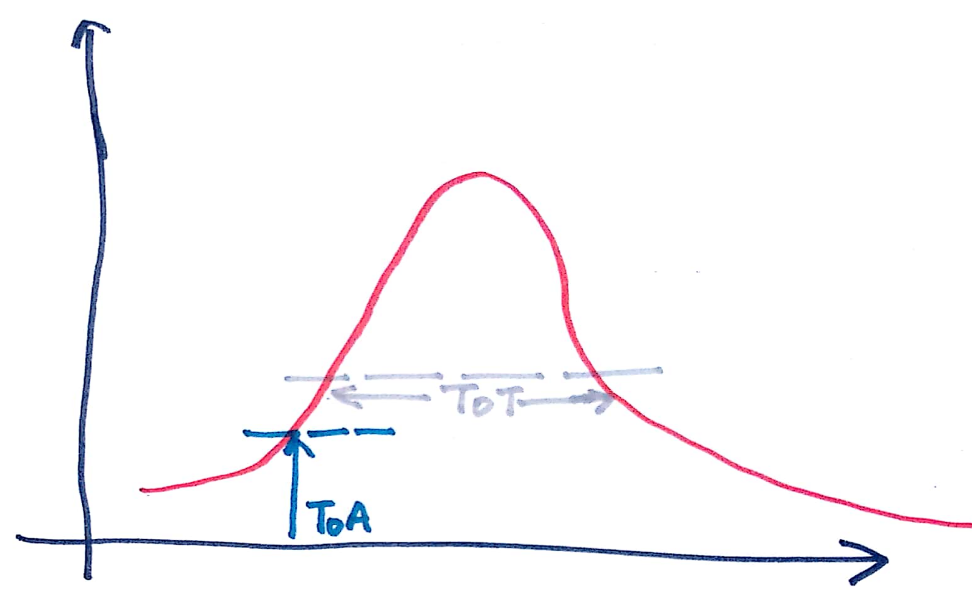
2017 Test Beam

SKIROC2CMS - used in TB of 2017

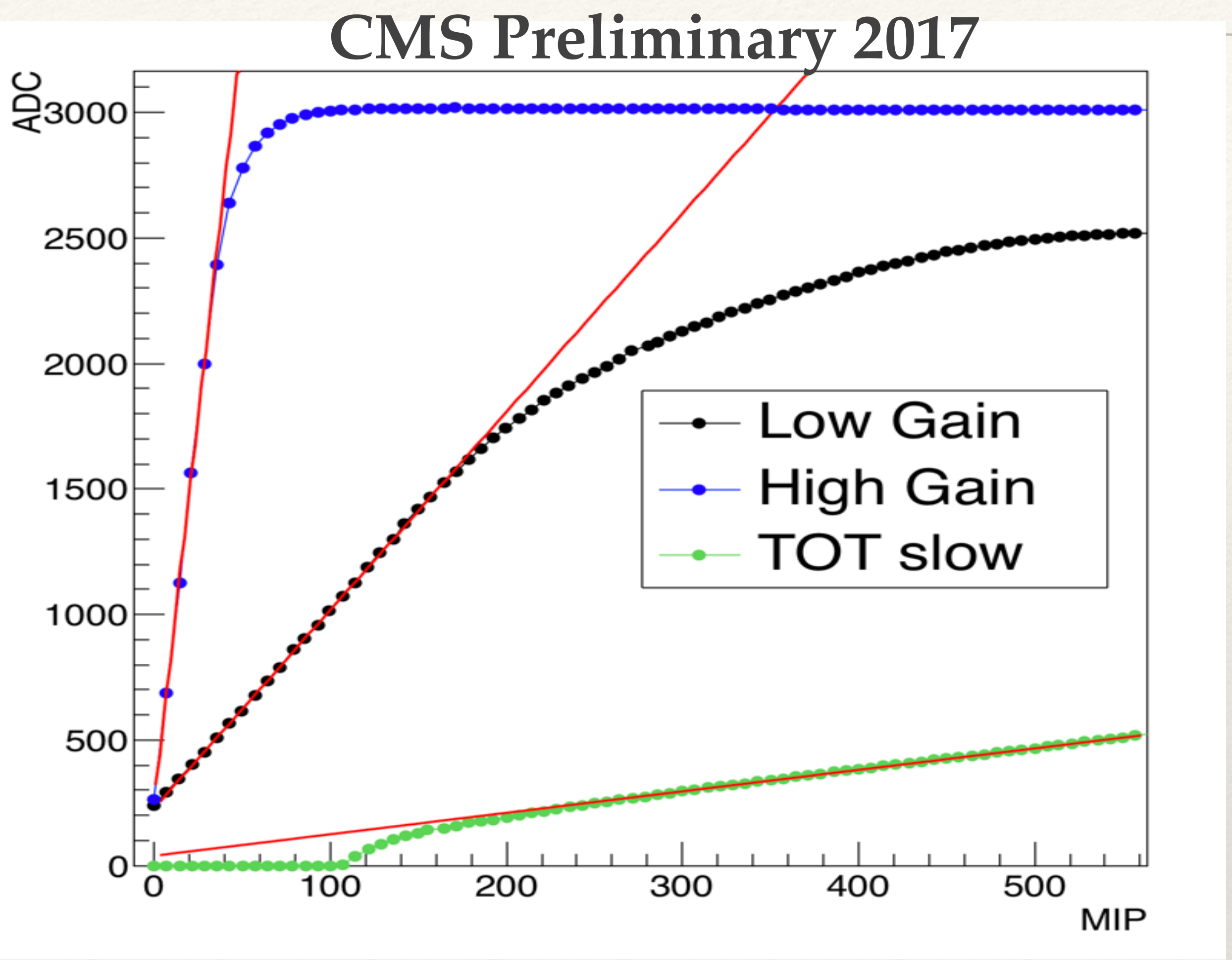
- Shapes, amplifies and digitizes signals from Si sensor
- 64 channels
- 13 Switched Capacitor Array (SCA)analog memory —> time samples after every 25 ns
  - 11 contain useful data
  - Low Gain, High Gain
- Nice feature: Time over Threshold (ToT) and Time of Arrival (ToA)
- ToT: the time a pulse is over a certain threshold is proportional to its amplitude
  - The time can therefore give a measure of the amplitude, even if the signal saturates
- ToA: Time when the signal crosses a certain threshold
  - Important for PU mitigation

Nice pulse shape can be seen — constructed using the ADC from 11 useful SCAs.
We currently use a function which is already being used in CMS ECAL



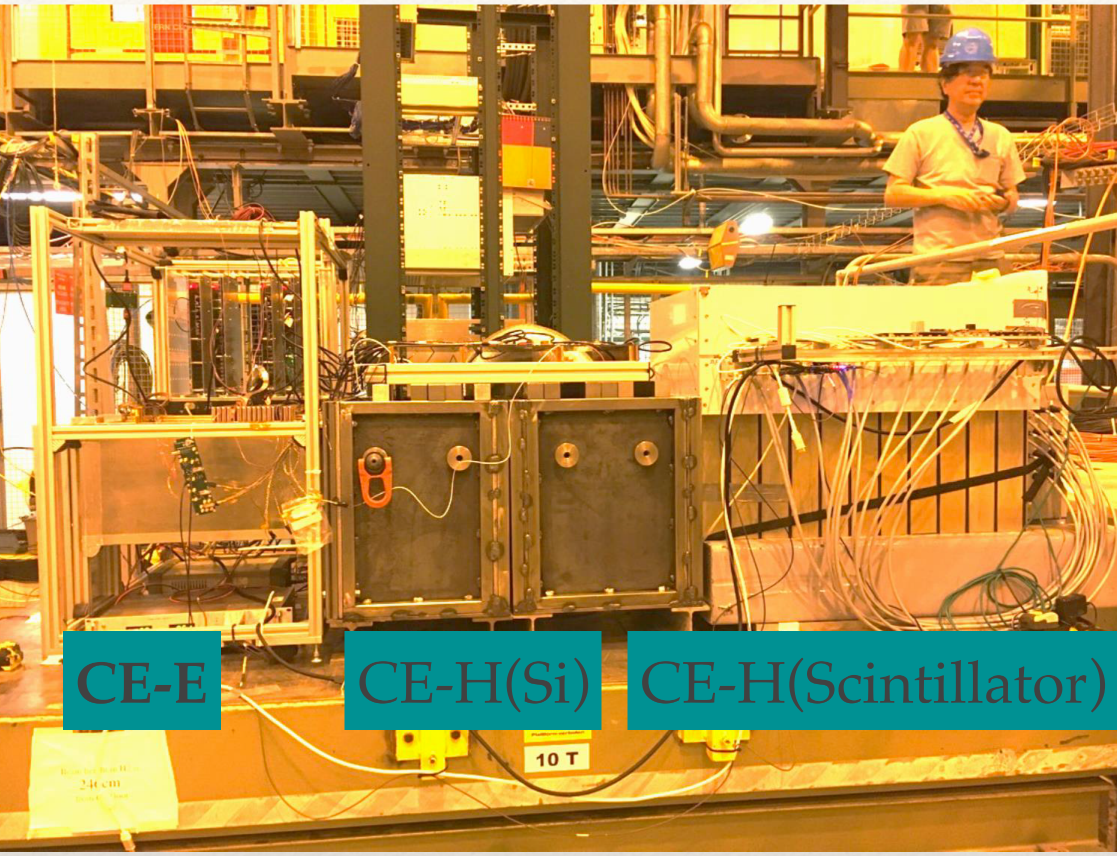


LG/HG and ToT calibration in a test bench



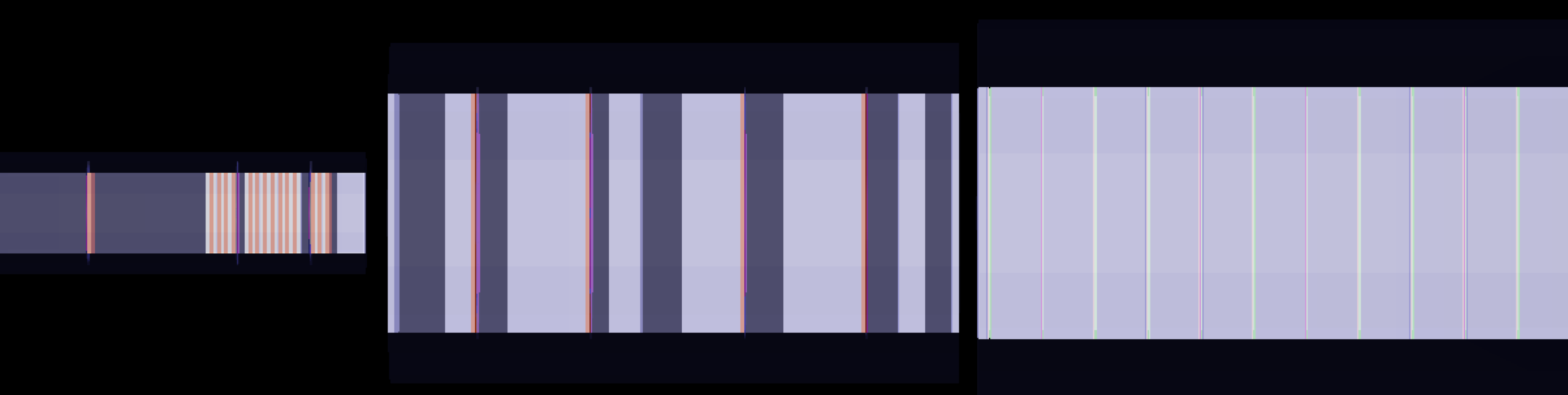
- Cover a large dynamic range using 3 “Gains”
  - HG upto ~40 MIPs - used essentially for MIP calibration
  - LG upto ~180 MIPs
  - ToT beyond 180 MIPs

Test beam setup in July 2017

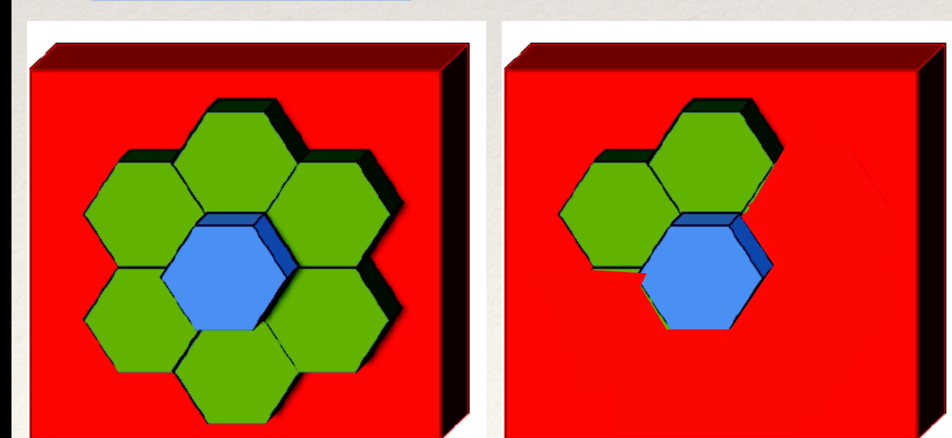


- In 2016, we tested only CE-E
- In 2017, tested a prototype with CE-E, CE-H(Si) and CE-H(Scintillator)
- If all the layers are equipped we would have 112 (28 CE-E + **12 layers with 7 modules in CE-H (Si)** + **CE-H(Scintillator)**) silicon modules and ~ 14000 channels.
- This July, we managed to test 10 modules (**2 in CE-E** and **8 in CE-H - 1 module in 2 layers + 3 modules in 2 layers** + **CE-H(Scintillator)**)
  - Main bottleneck was the hexaboard production, setup had to be reduced compared to the initial goal

Geometry in Simulation for 2017 Beam test

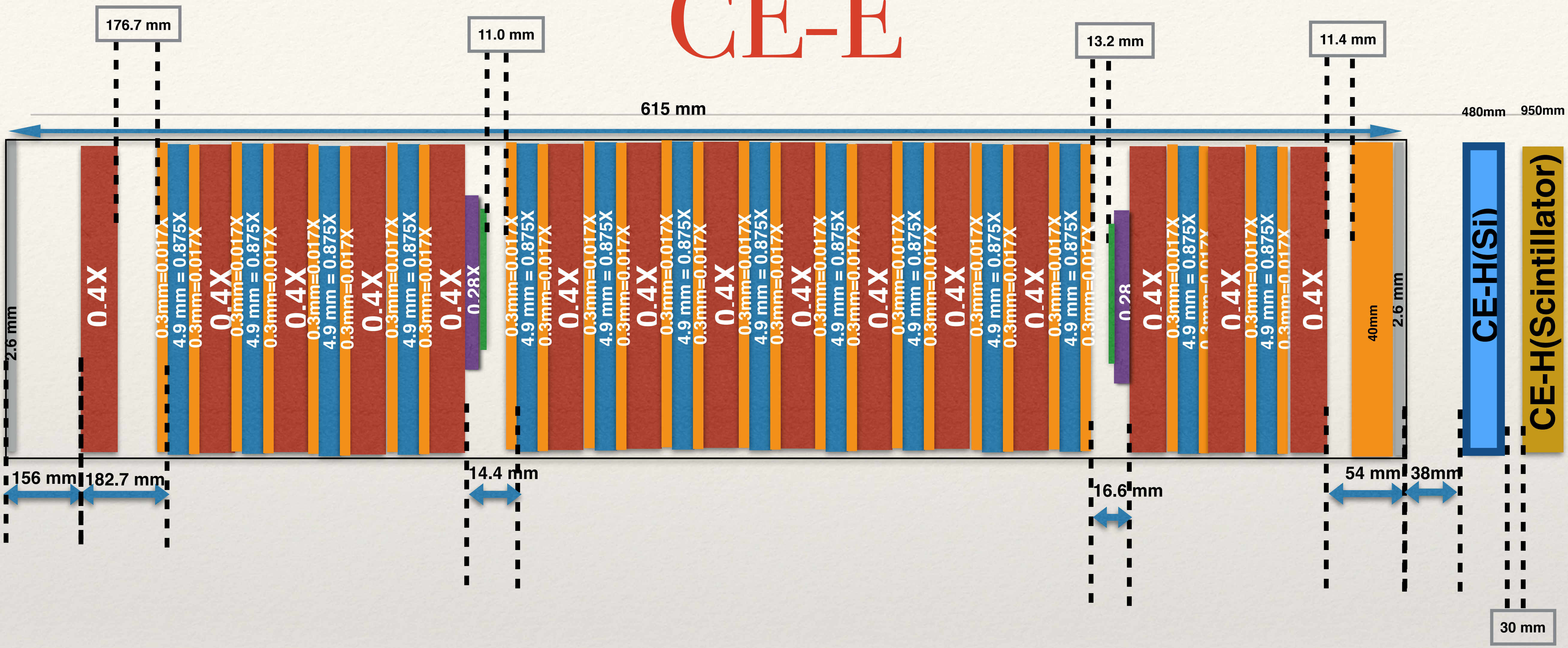


Original goal | Realised prototype



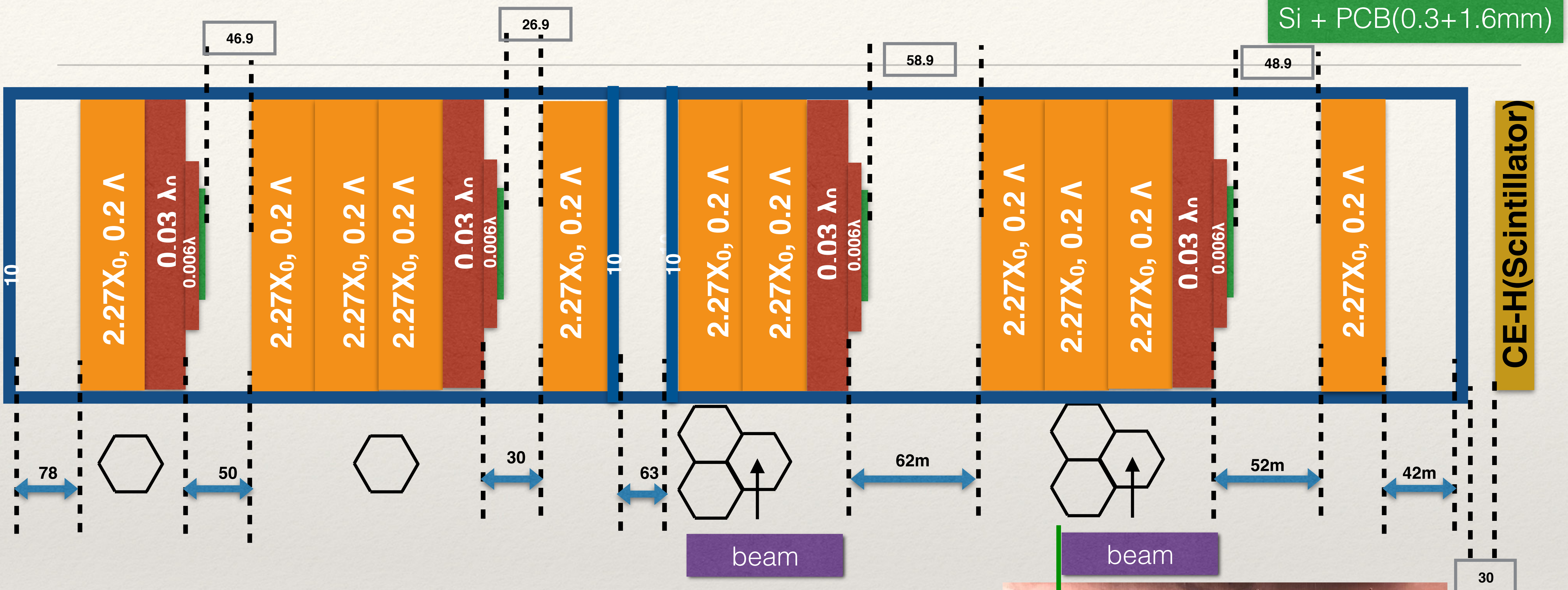
CE-E, **CE-H(Si)**, **CE-H(scintillator)** (CALICE AHCAL prototype)

CE-E

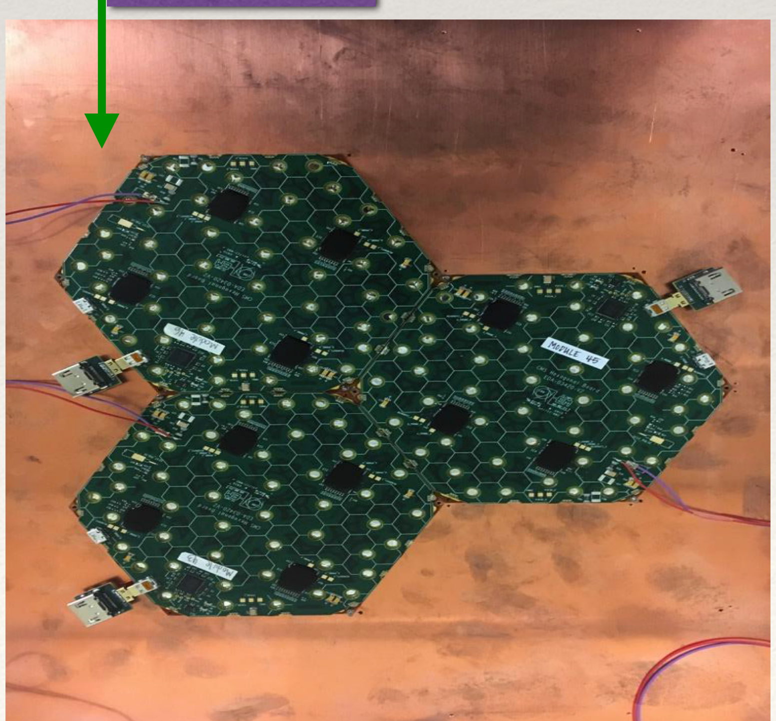


- 14 layers of Fe-Pb-Fe absorber
- 2 layers of Si
  - First layer after ~6.3 X_0; second layer ~16.8 X_0
- Total X_0: 22
- Total λ_0: 1.3

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

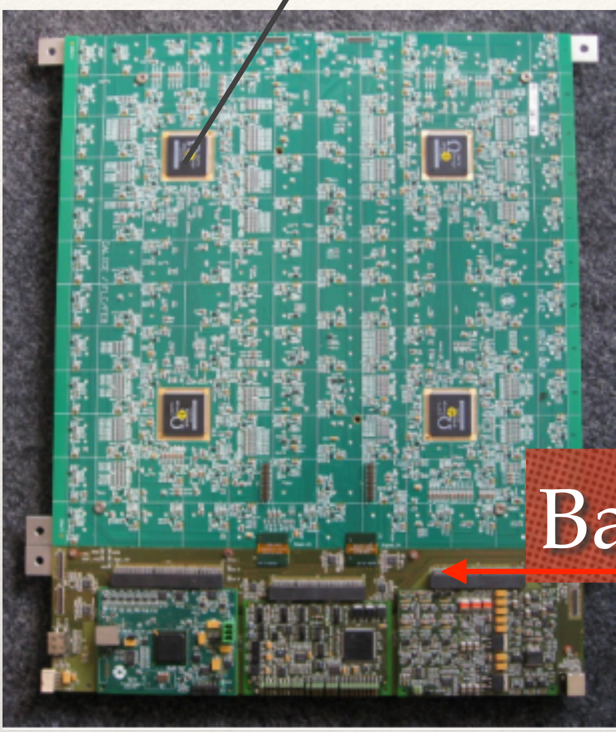


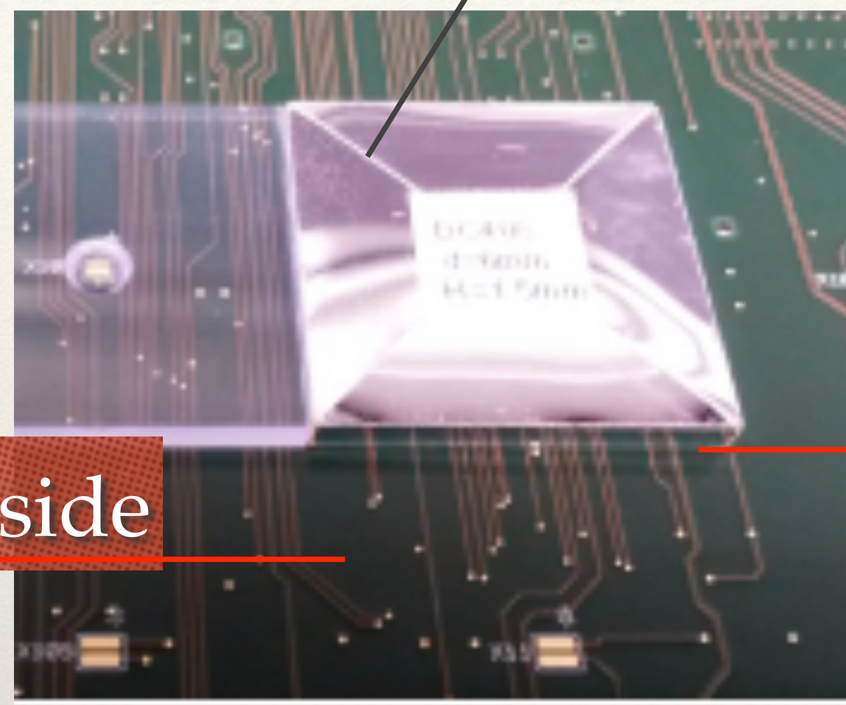
CE-H (Scintillator)

From CALICE

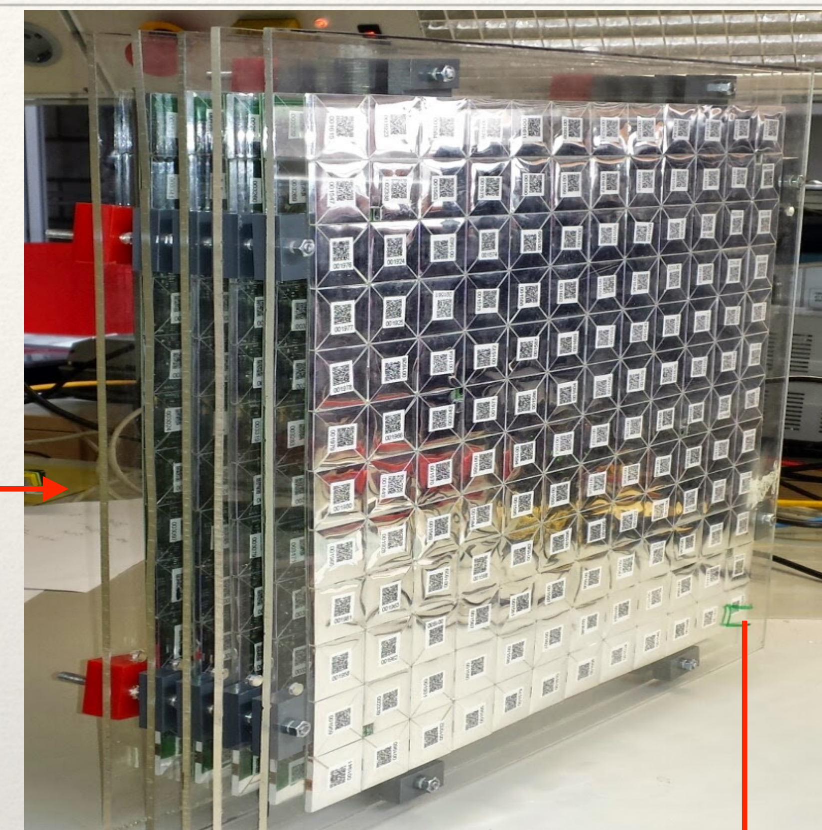
SPIROC2B

Plastic scintillator



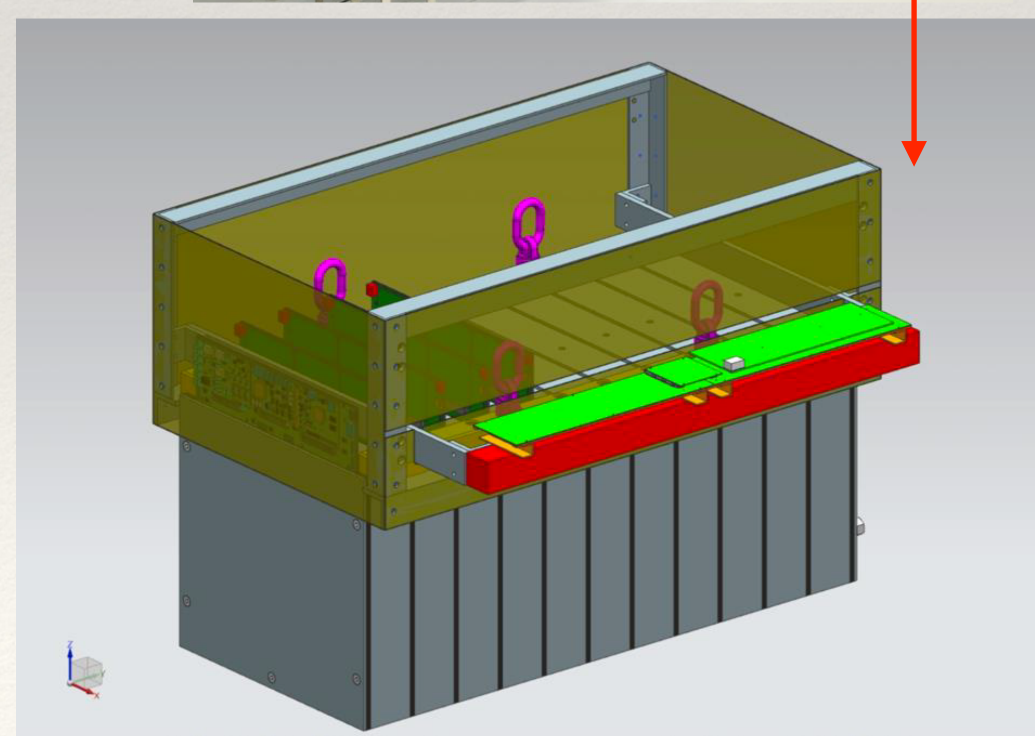


Back side



Central Interface board

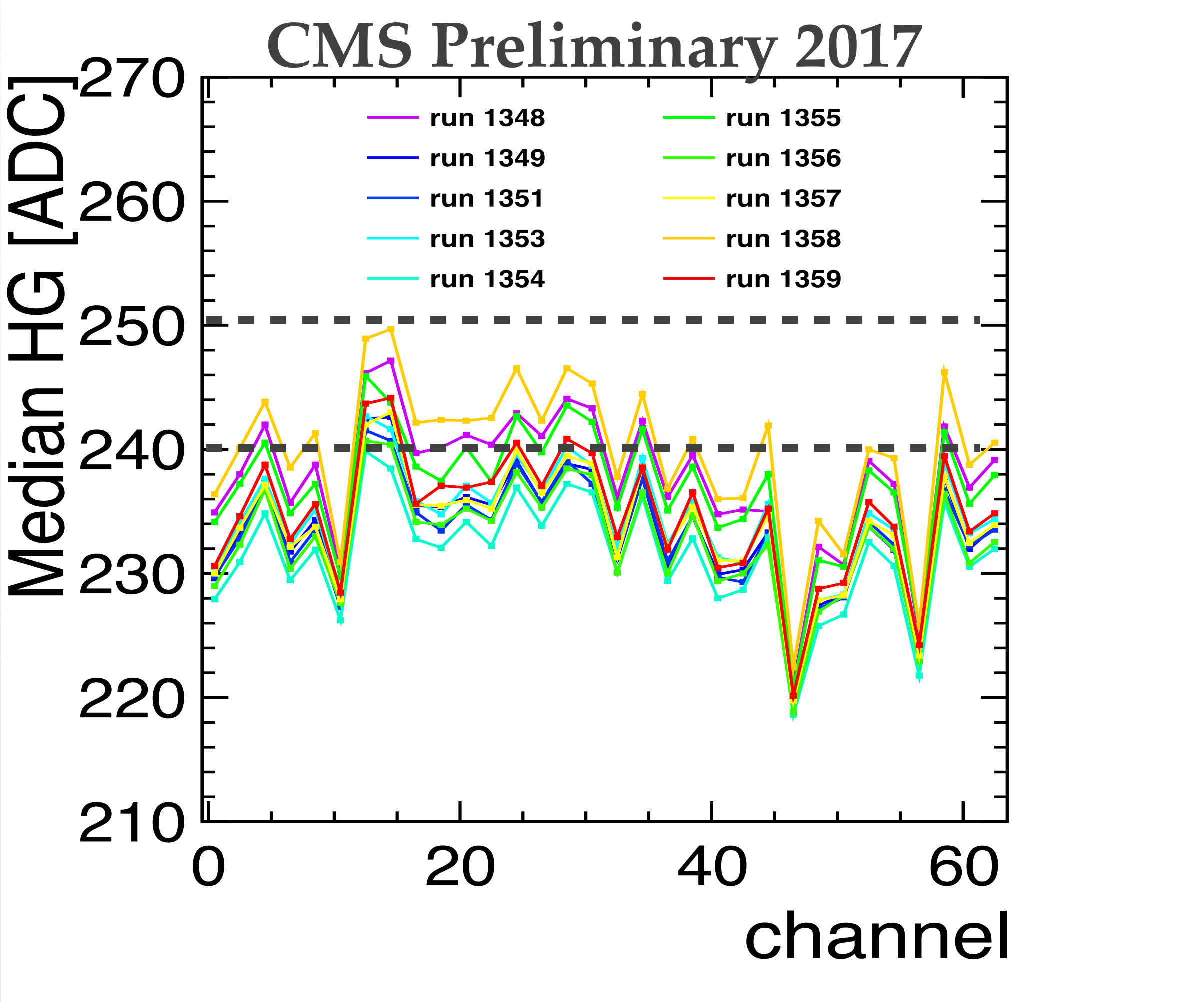
- 12 active layers of 36 x 36 cm^2
  - 144 scintillator tiles (each 3 mm thick) of 3 x 3 cm^2
- Absorber stack with 74 mm steel plates
- Total of ~5 λ_0



Total detector: ~54 X_0 and ~9.4 λ_0

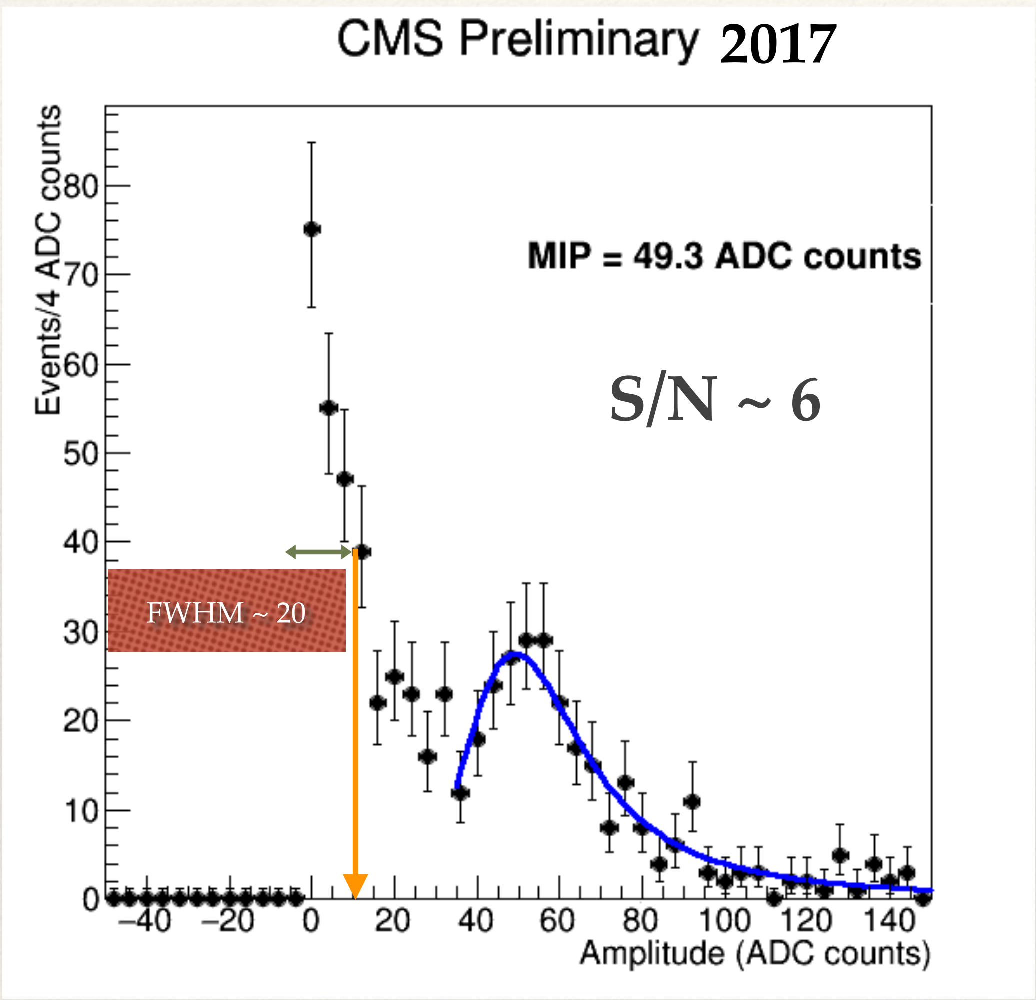
First look at the July 2017 Test beam data

Pedestal stability



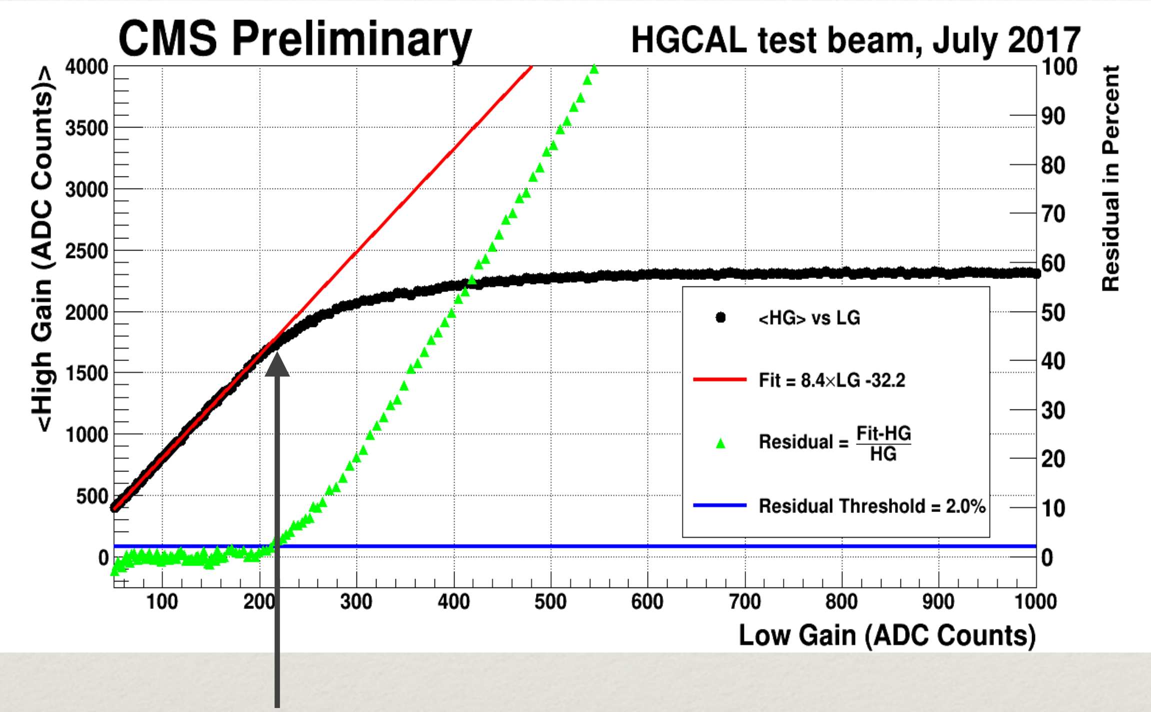
- Pedestal measured using first two time samples
- Measured as median of the distribution per SCA, per channel
- Stable within 10 ADC (~0.2 MIP) counts over a week

MIP calibration

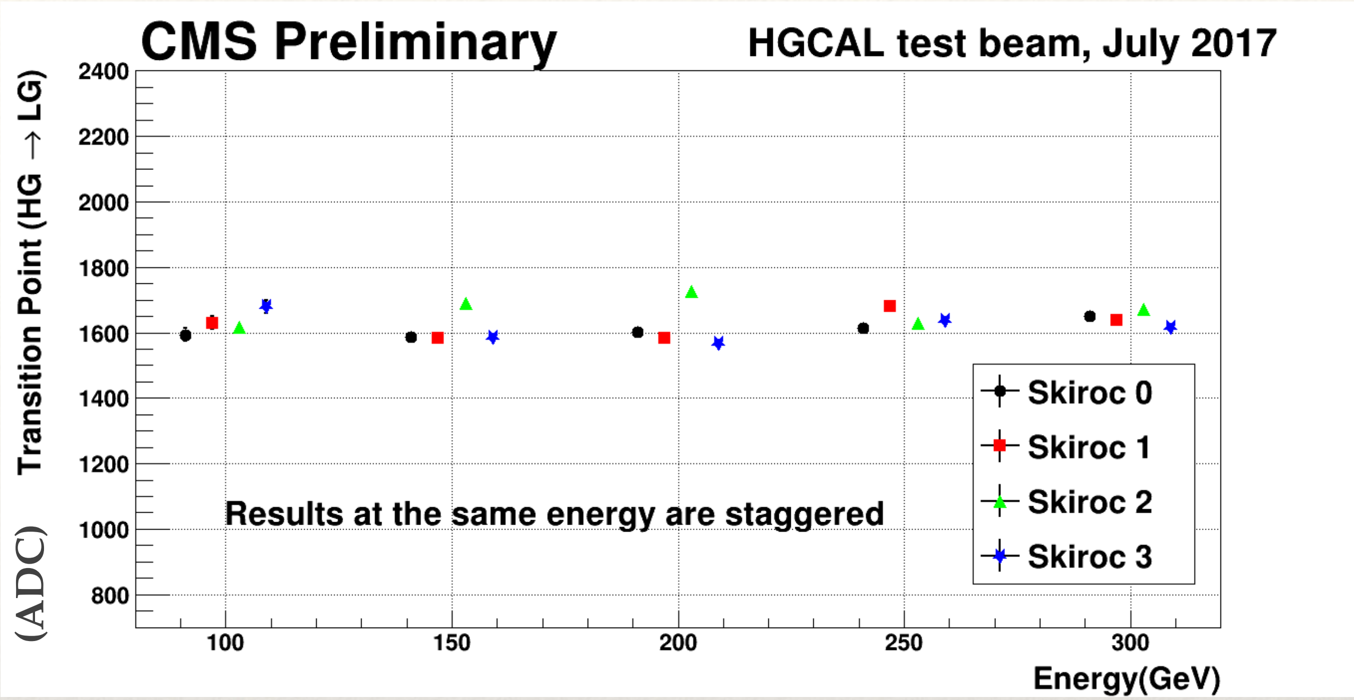


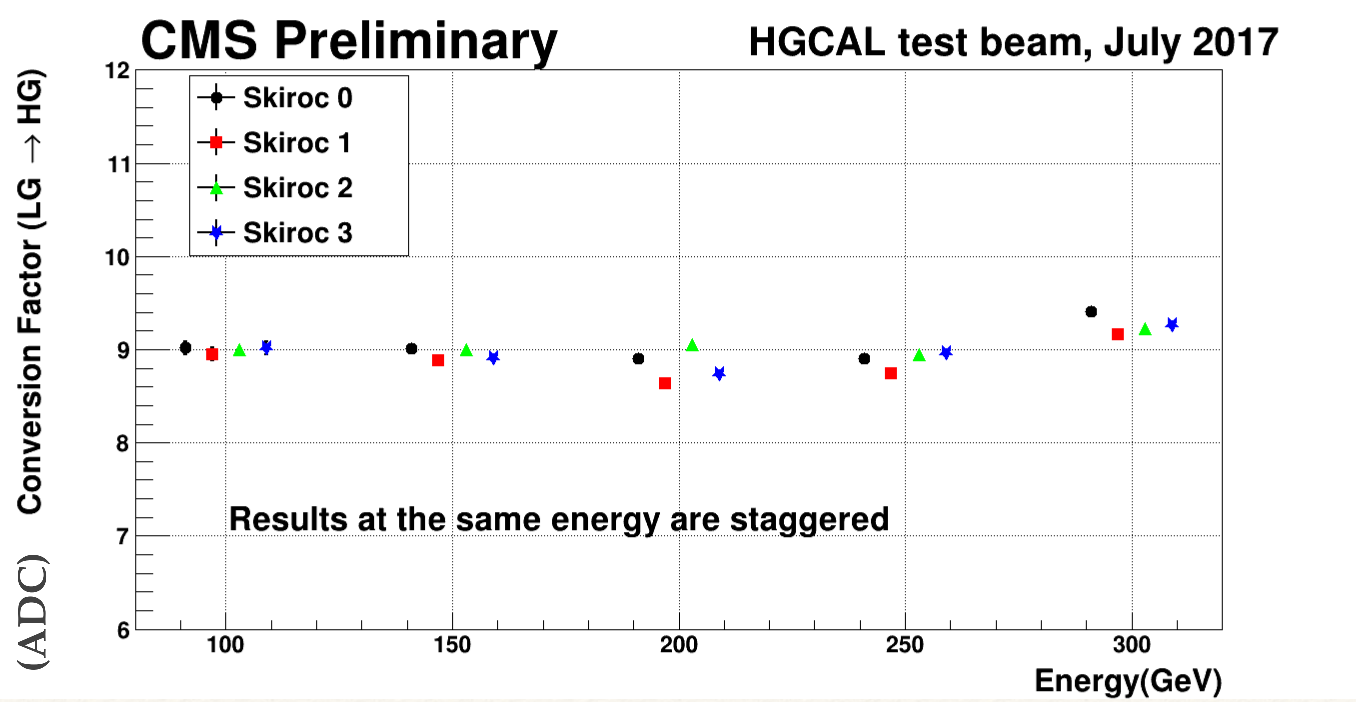
- We can see MIP using single muons traversing the silicon
- Reconstruct amplitude using pulse shape fit
- Perform a fit to the Signal with Landau convoluted with Gaussian
- Preliminary MIP ~ 49 ADC
- FWHM ~ 20 ADC
  - σ_{Gaus} (noise part) ~ 8.5 ADC
  - S/N ~ 6

High gain to Low gain calibration



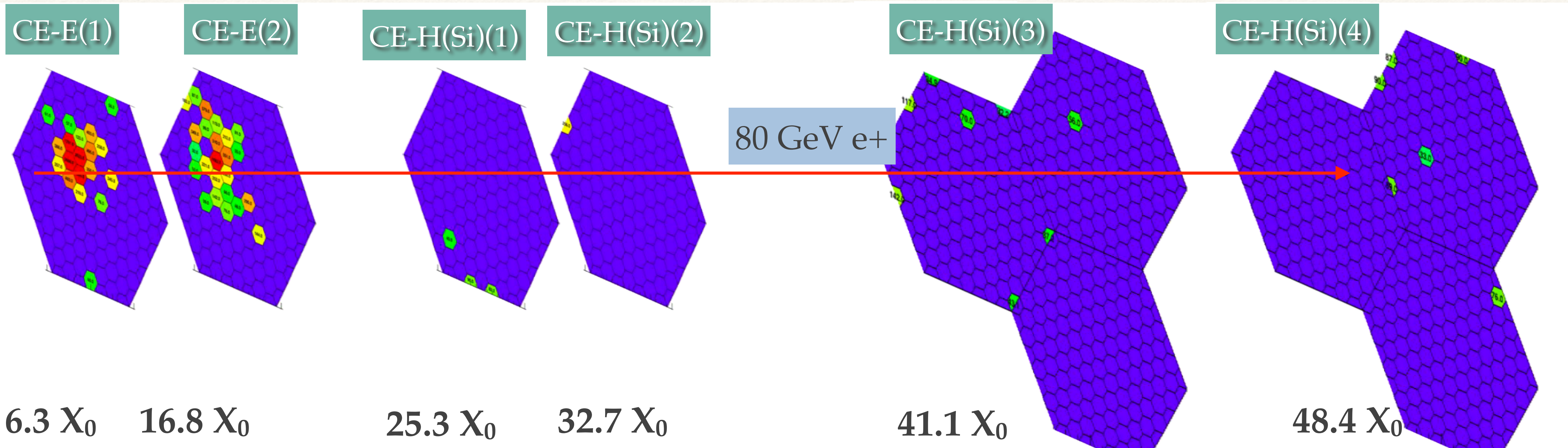
Turning point

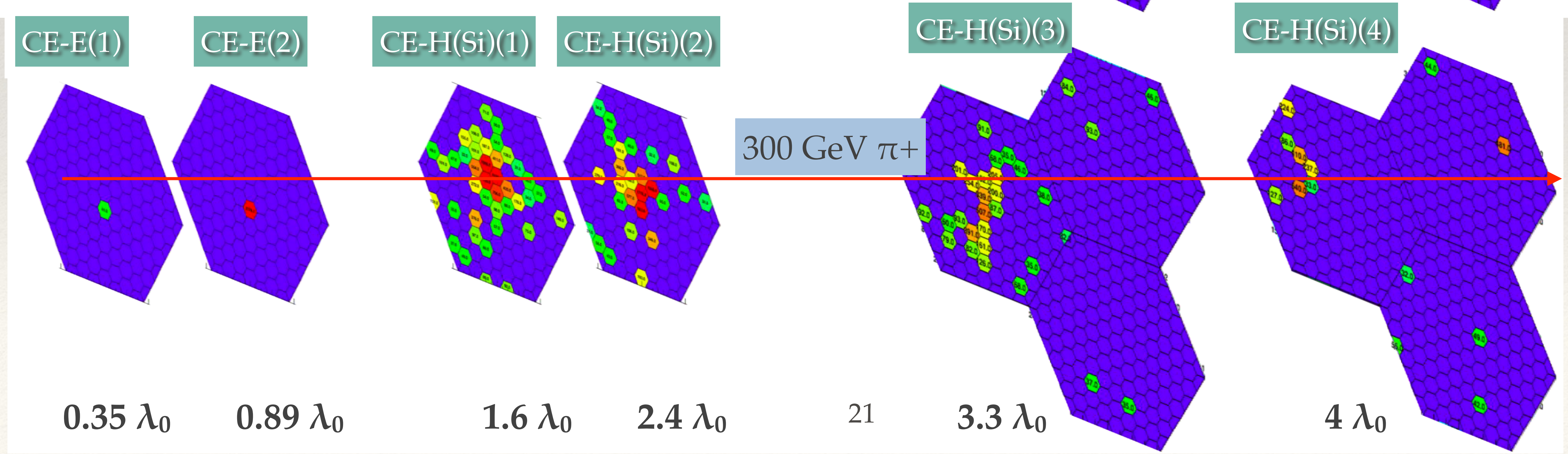




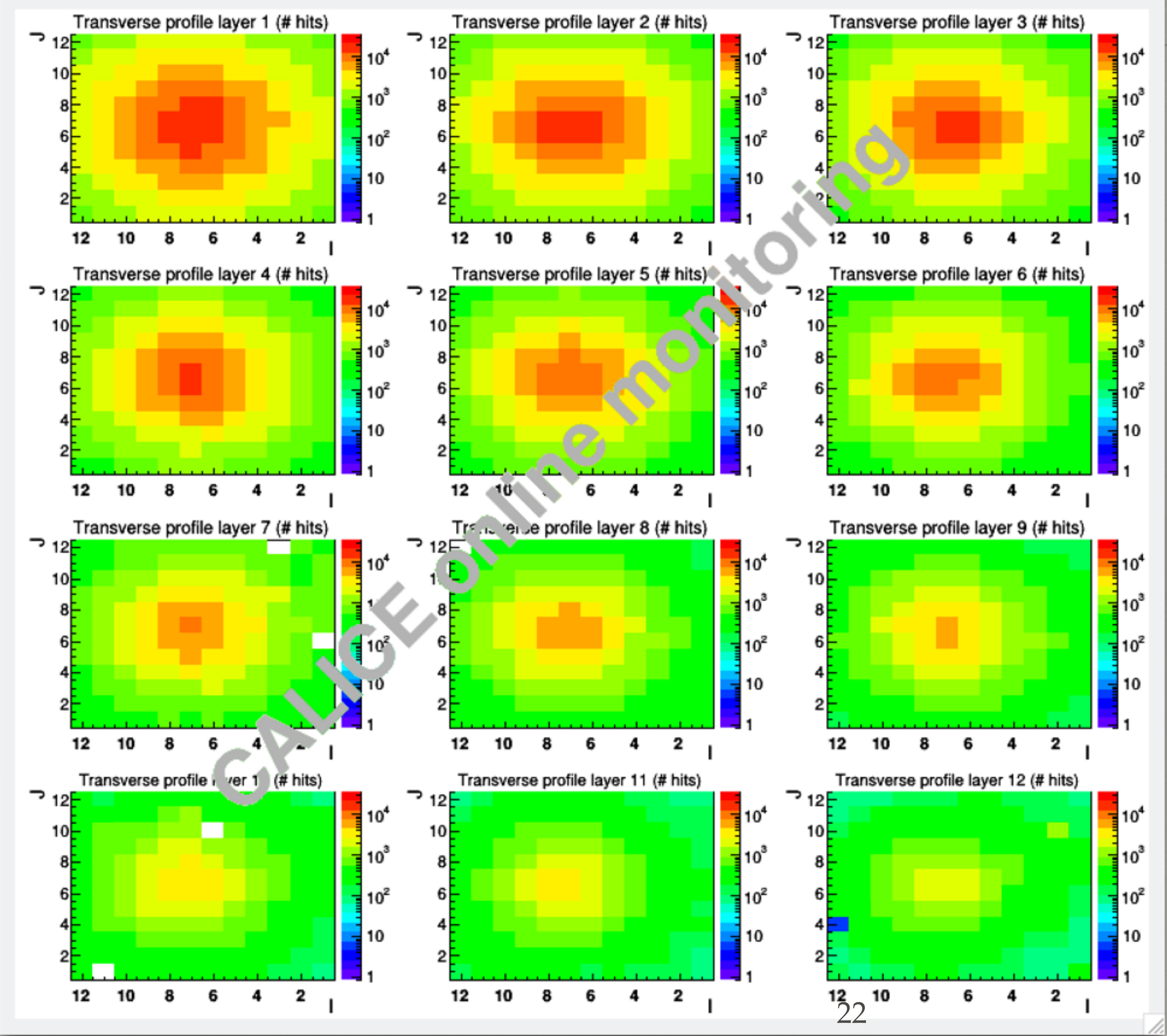
- Turning point and the conversion factor from HG to LG (slope of the straight line fit) are stable with energy for all the SKIROC2-CMS chips

Showers for electrons and pions





Hit map in CE-H (Scintillator): Online Monitoring

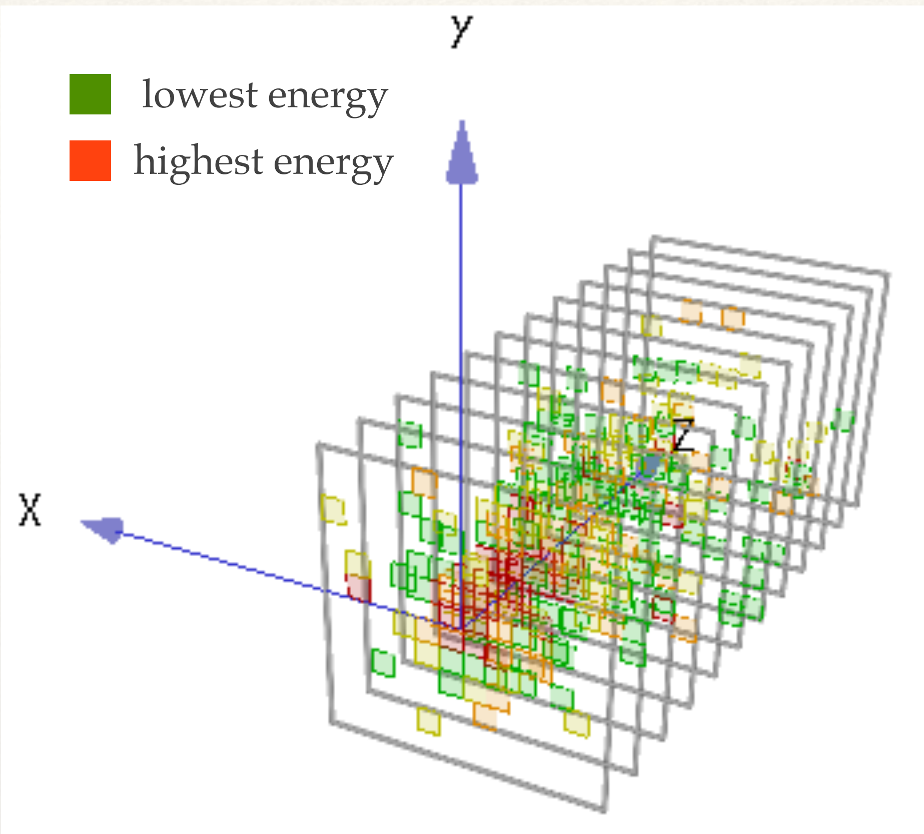


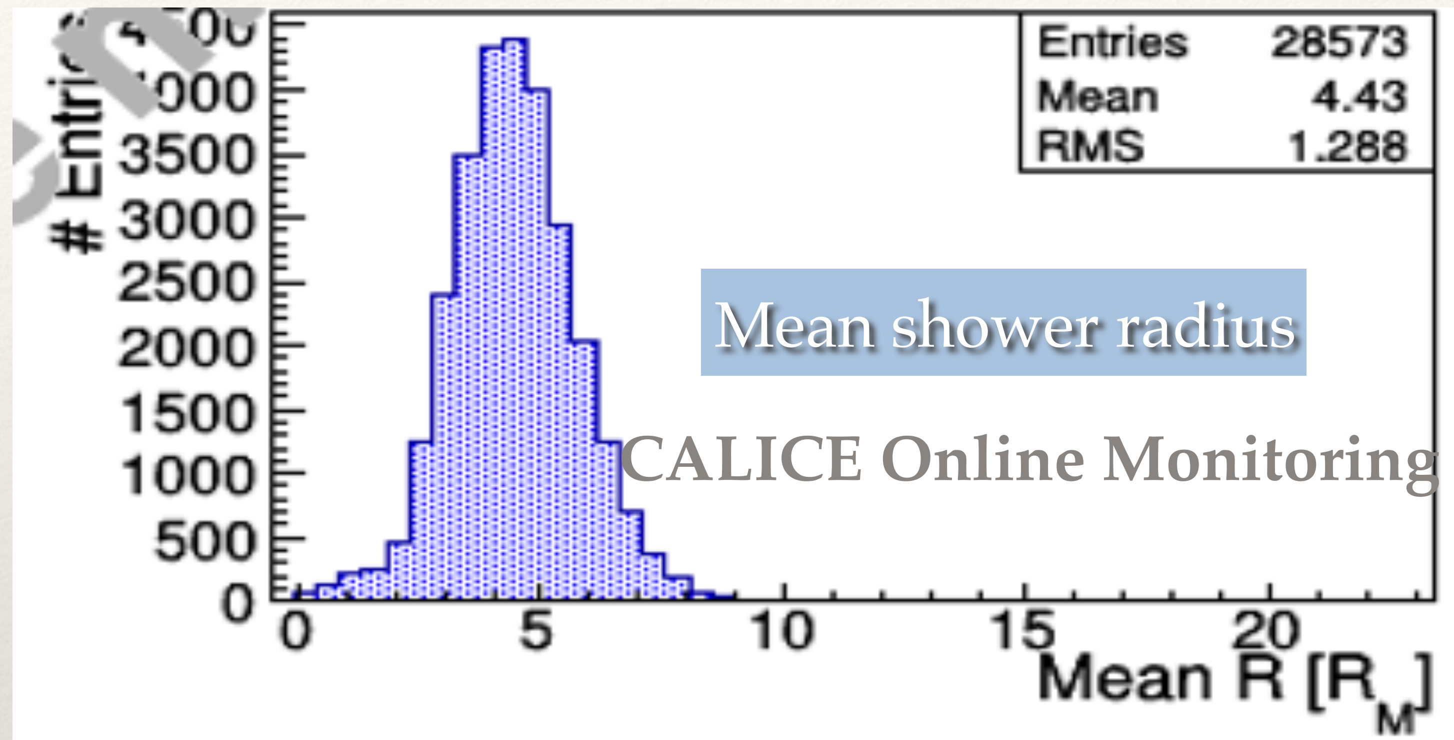
300 GeV π+

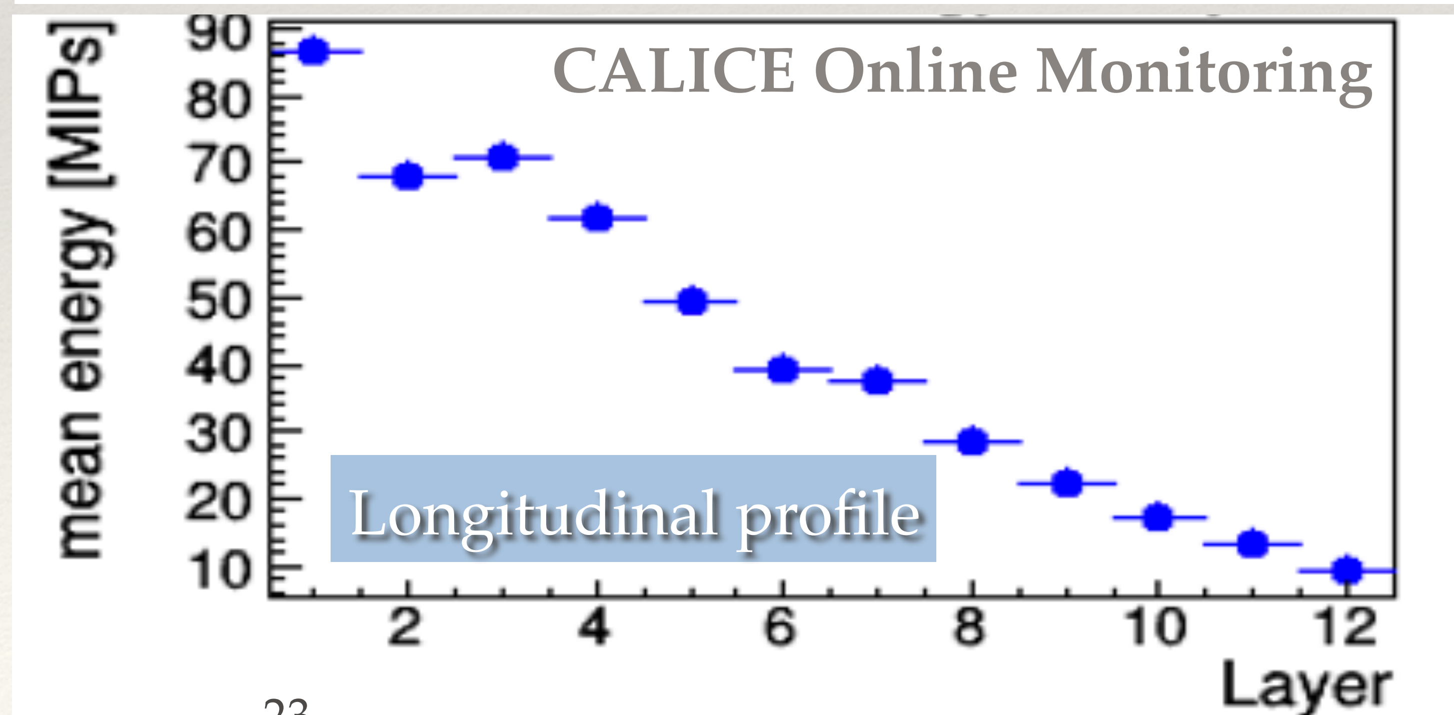
- Online reconstructed data (very preliminary calibration)
- Number of hits in each cell
- Shower well centered

Showers in CE-H(Scintillator): Online monitoring

300 GeV π^+







- Very preliminary calibration
- Detector performing well

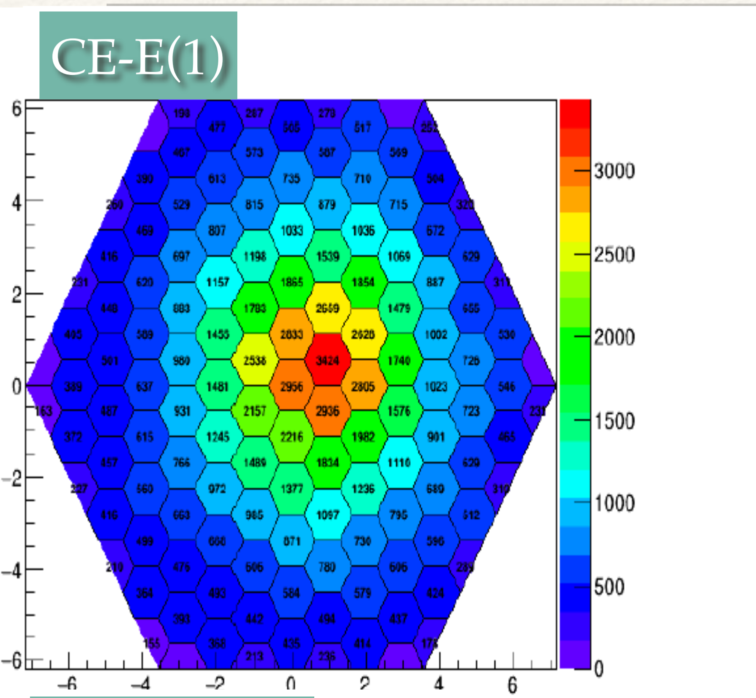
Outlook

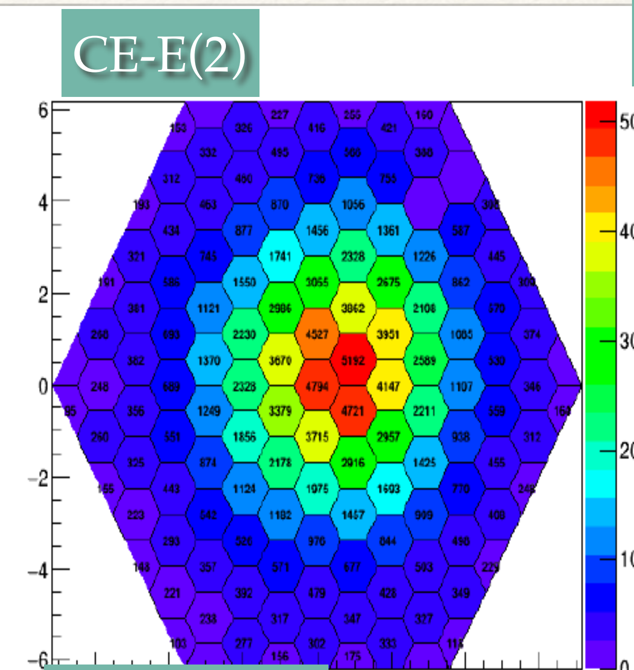
- Successfully constructed and operated (using pions and electrons) an HGCAL prototype with CE-E, CE-H(Si) and CE-H(Scintillator) this year
- SKIROC2CMS being used for the first time in a test beam:
  - nice pulse shape seen using 11 time samples
- Preliminary analysis reflects:
  - Pedestal is stable
  - MIP can be seen
  - Detectors worked fine
- Test beam happened just last month
  - analyses are ongoing
  - We will have more results soon
- We will have more beam time this year (September/October) with more modules.
- Aim to complete the whole planned system in 2018

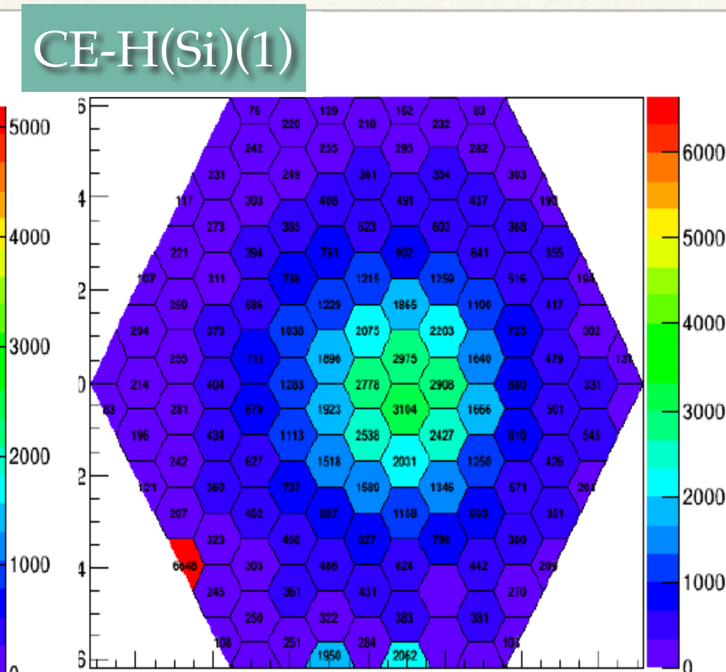
Thank you

Backup

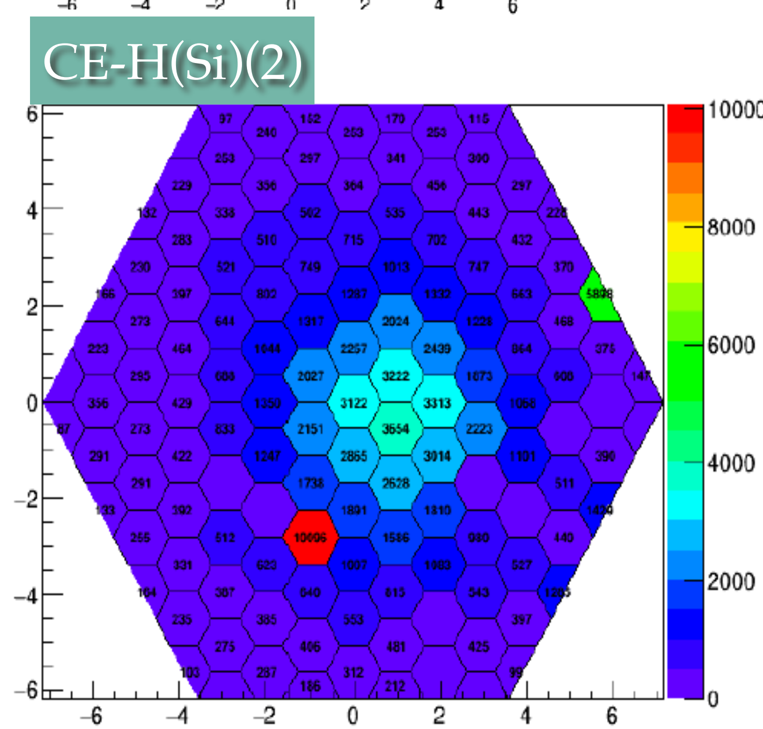
Hit map in CE-E and CE-H (Si)

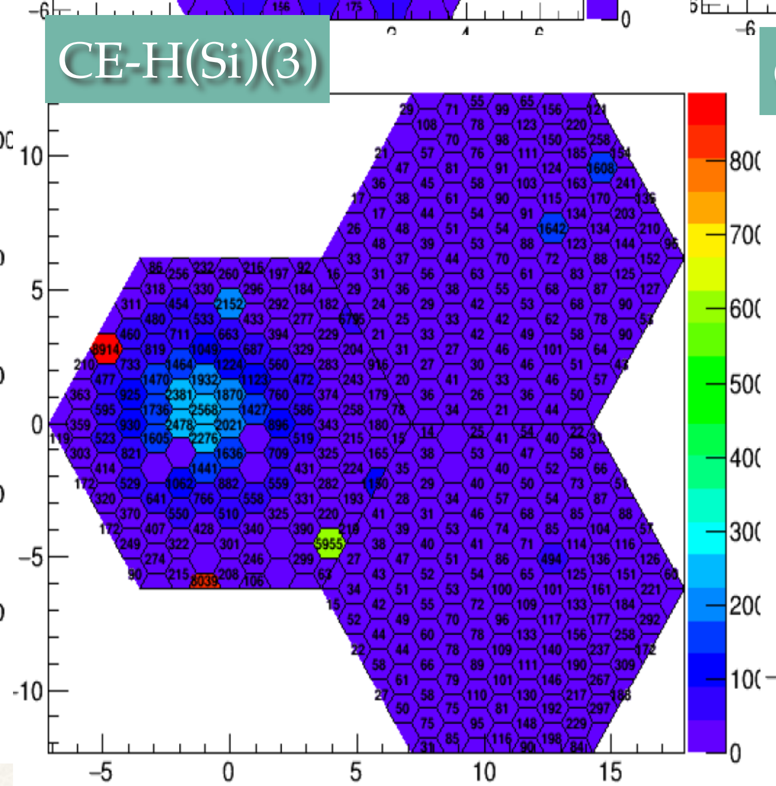


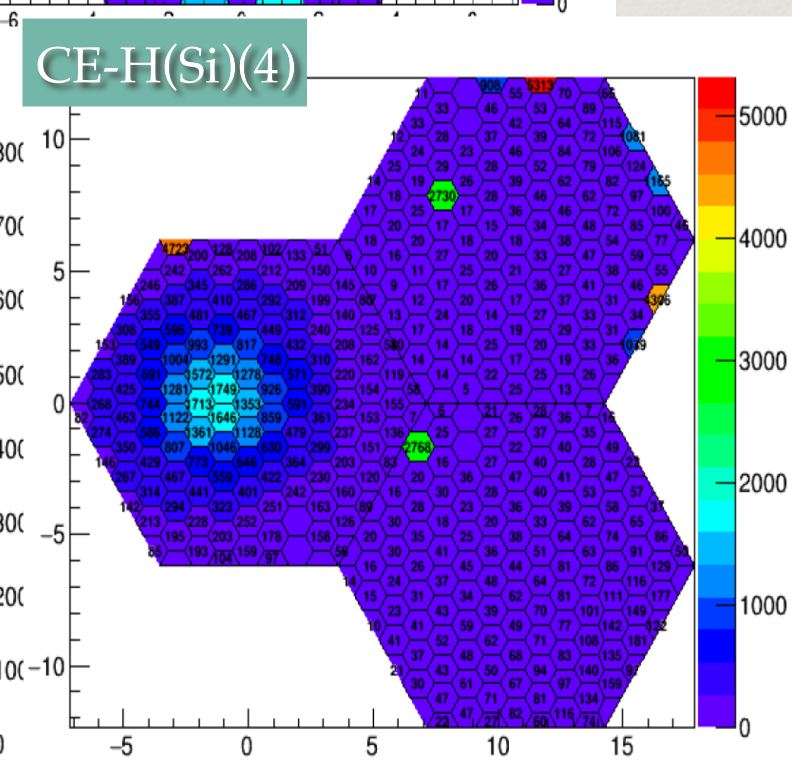




- Shown for 300 GeV pions
- Number of hits in each layer

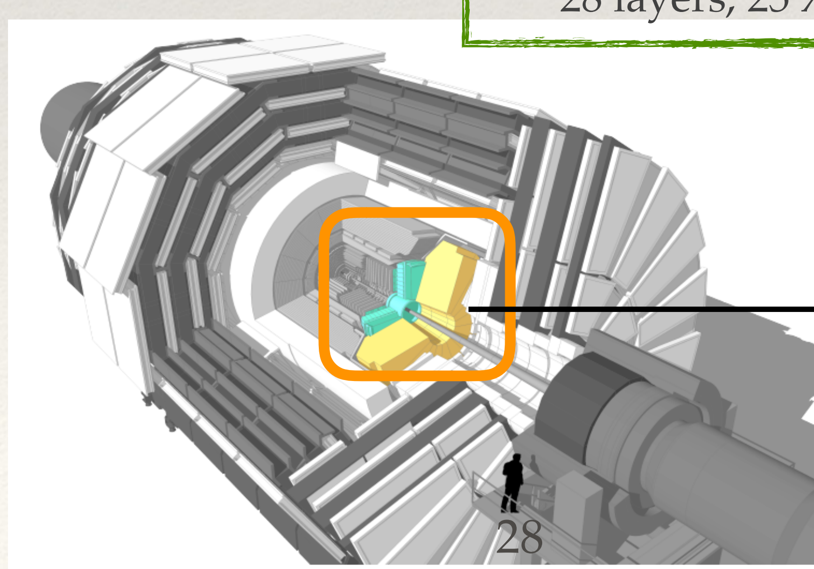


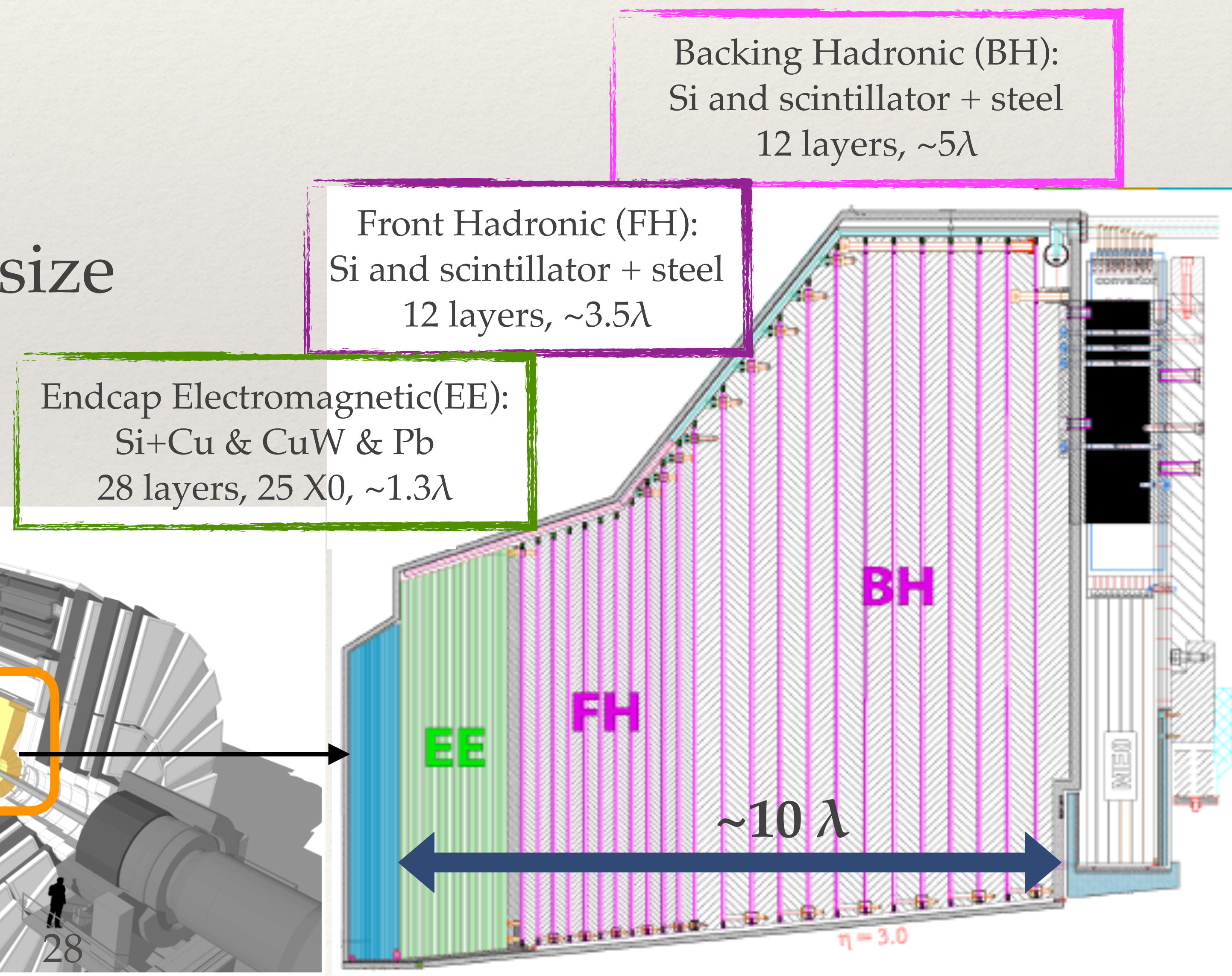




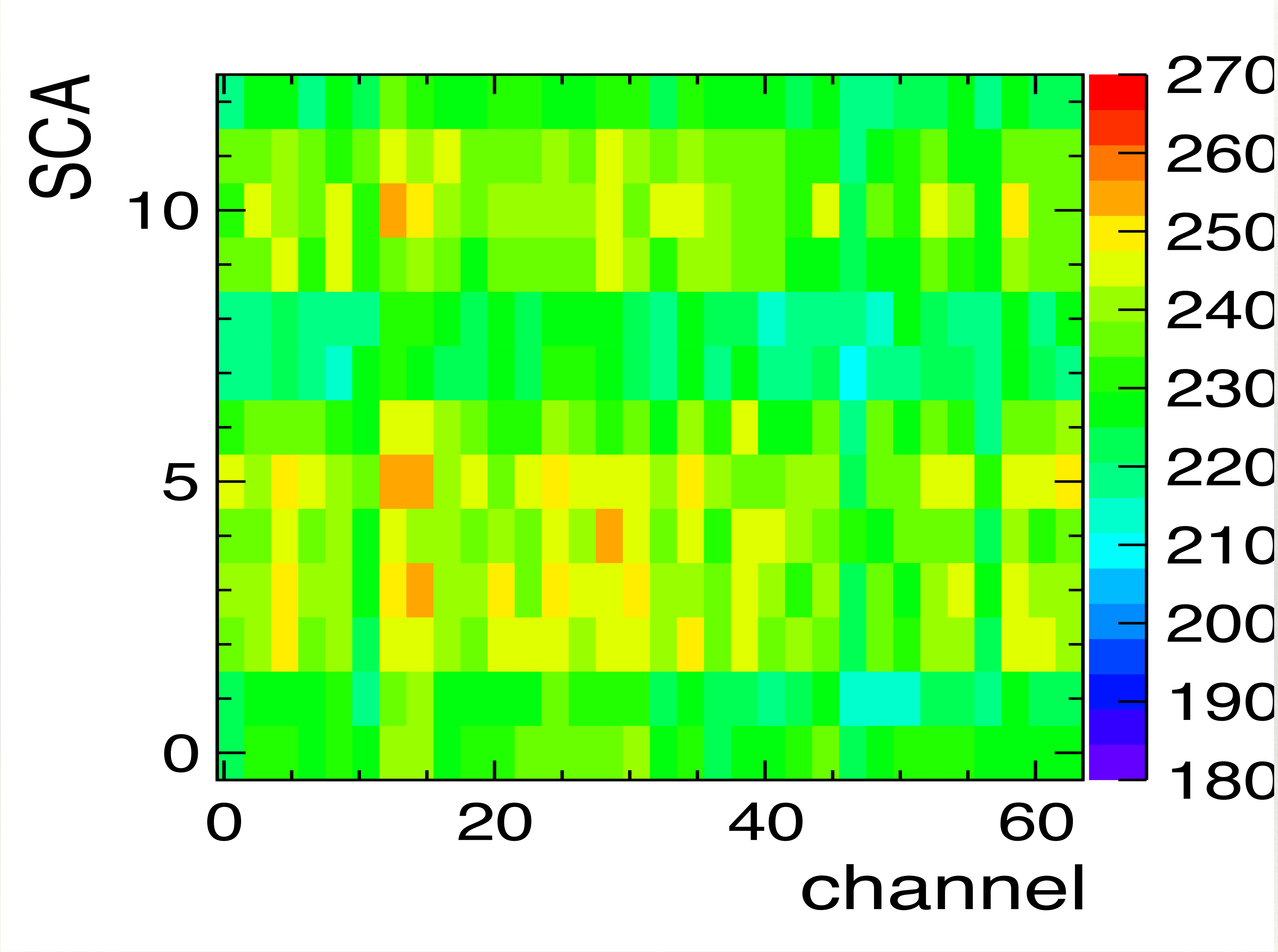
HGCAL Design overview

- High Granularity Calorimeter has a potential to address these challenges
  - Si/Tungsten electromagnetic section followed by two hadronic sections
- HGCAL covers $1.5 < \eta < 3.0$
- 6M Si channels, 0.5 or 1 cm2 cell size
- ~22k Si modules
- Present EE will be replaced by HGCAL

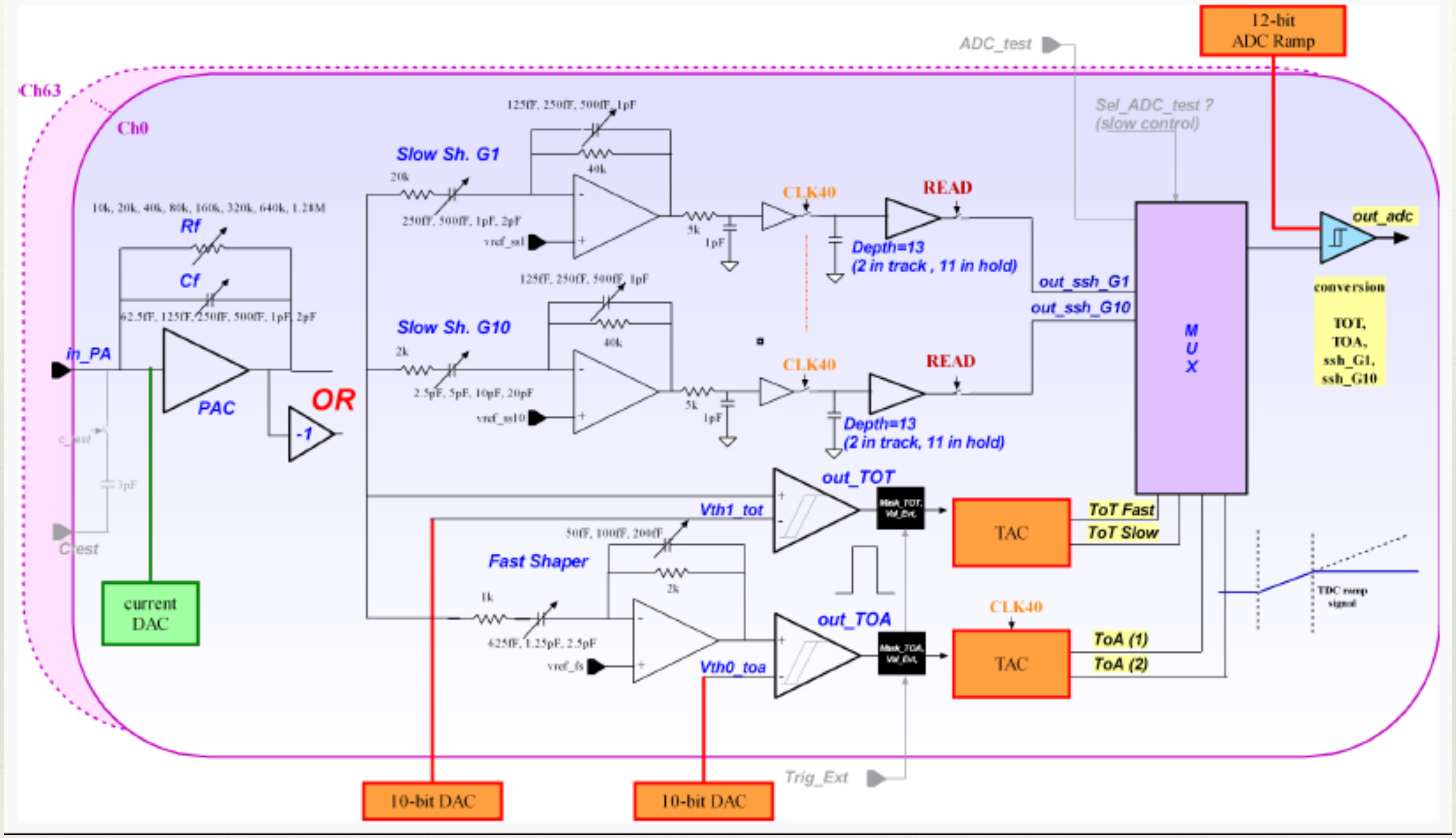




Pedestal

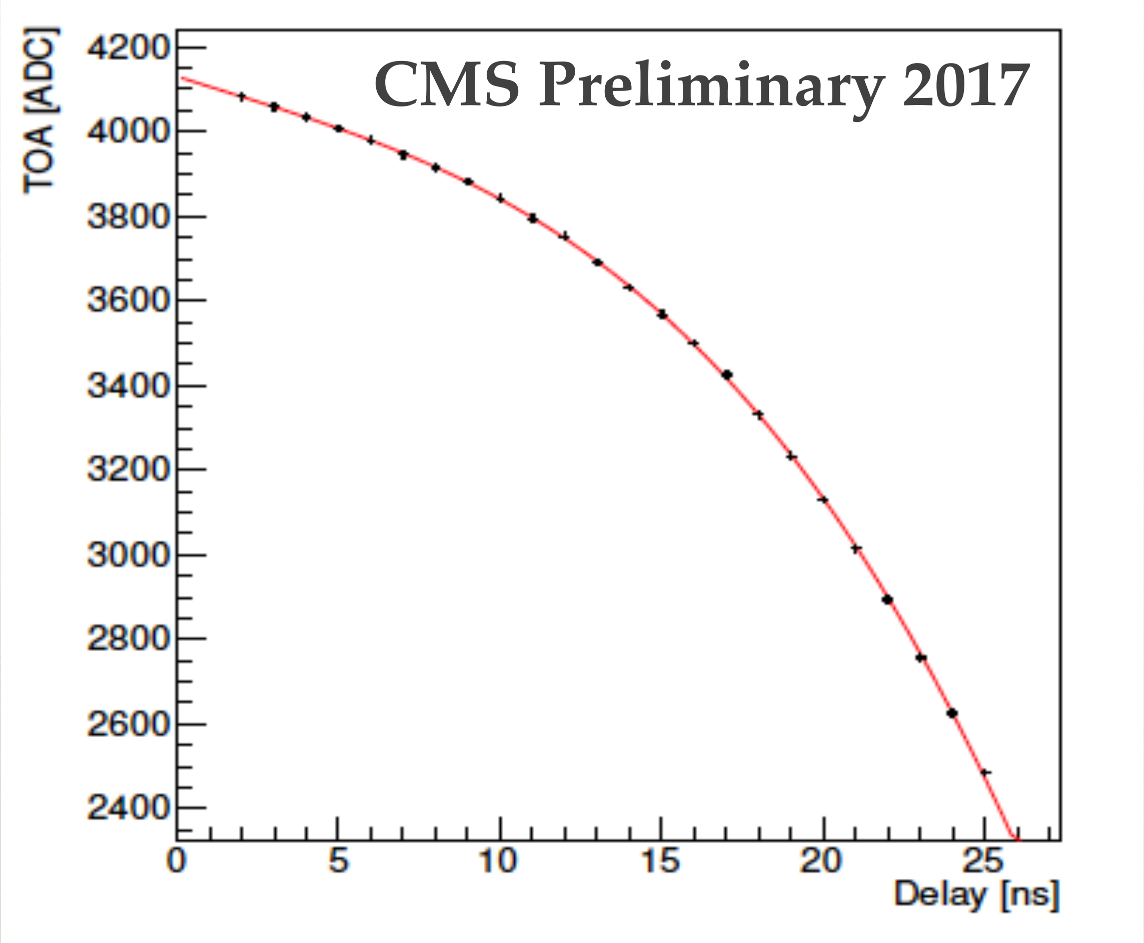


SCA
10
5
0
0
20
40
60
channel
270
260
250
240
230
220
210
200
190
180



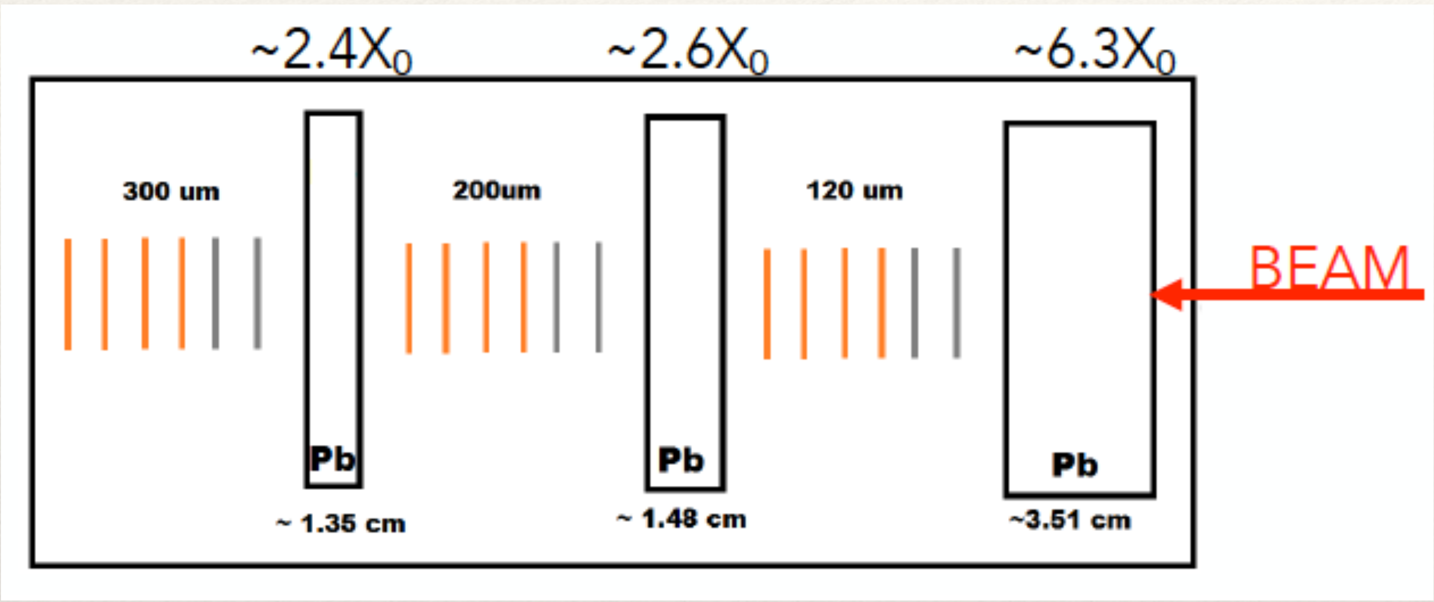
$$f(t) = \begin{cases} \left(\frac{(t-(T_{\max}-T_{\text{rise}}))}{T_{\text{rise}}}\right)^{\alpha} \; e^{-\alpha\left(\frac{(t-T_{\max})}{T_{\text{rise}}}\right)} & \text{if } t > (T_{\max}\text{-}T_{\text{rise}}) \\ 0. & \text{otherwise} \end{cases}$$

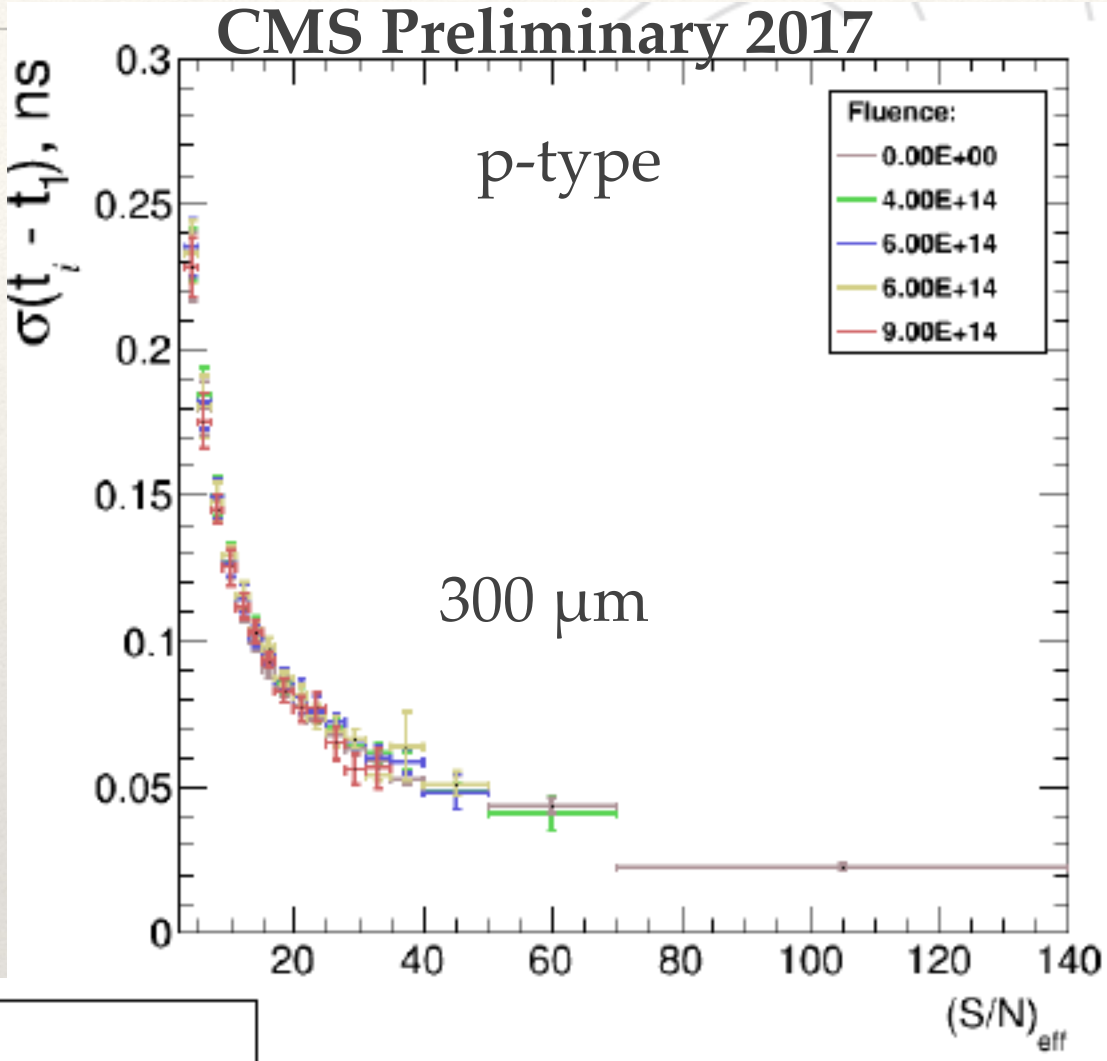
ToA



- ToA important for PU mitigation
- ToA is not linear for fixed input charge
- Every channel needs to be calibrated separately

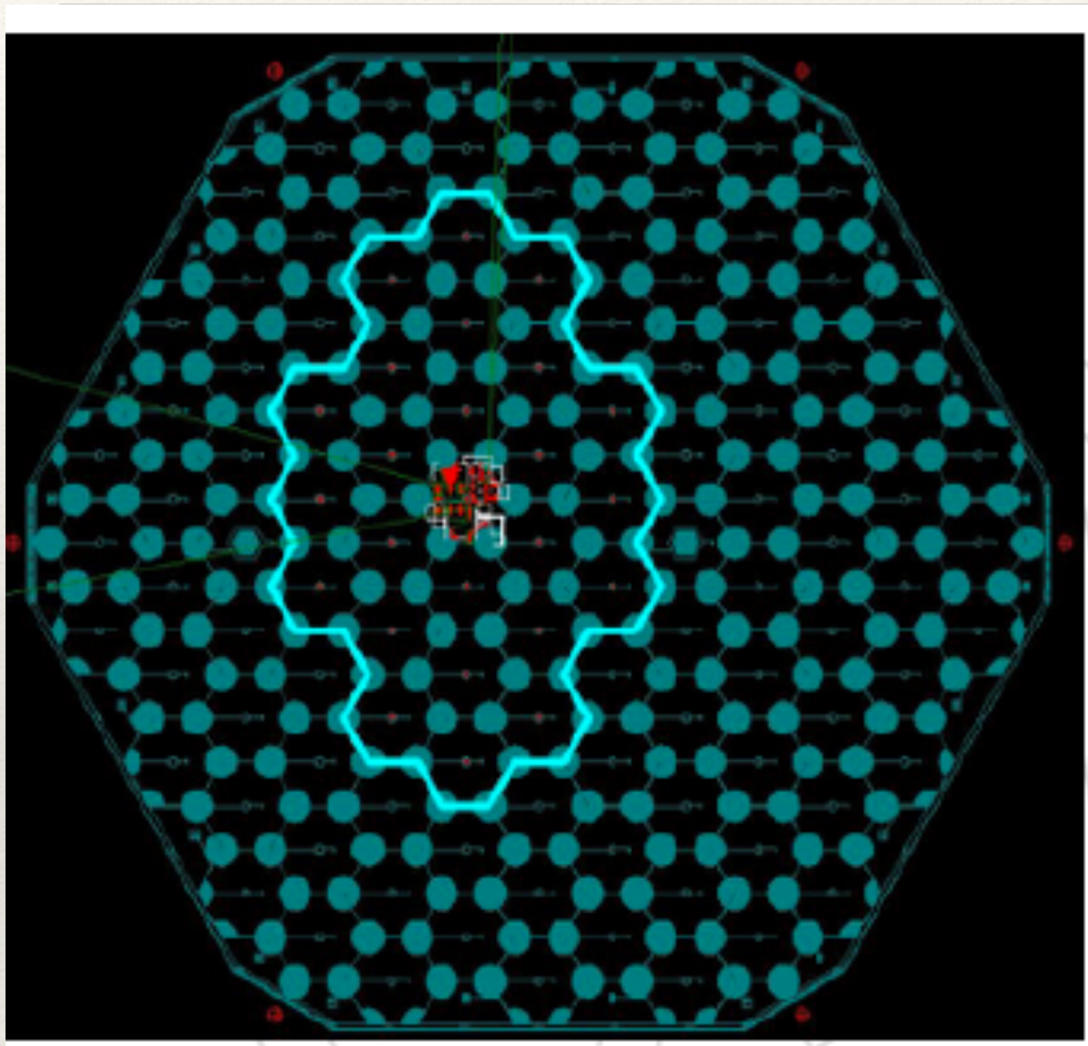
Precision timing with single diodes

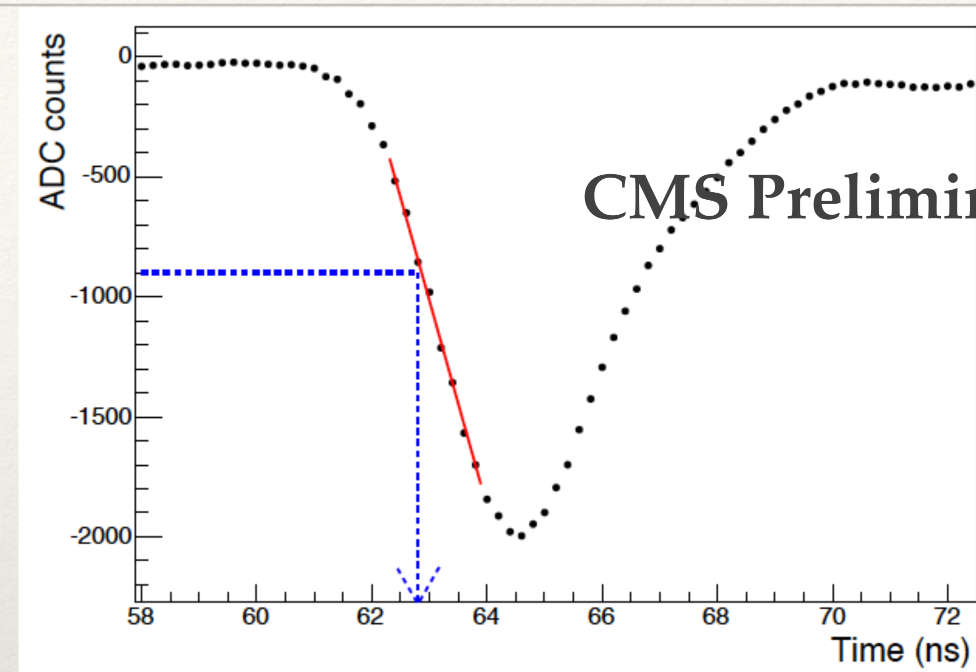


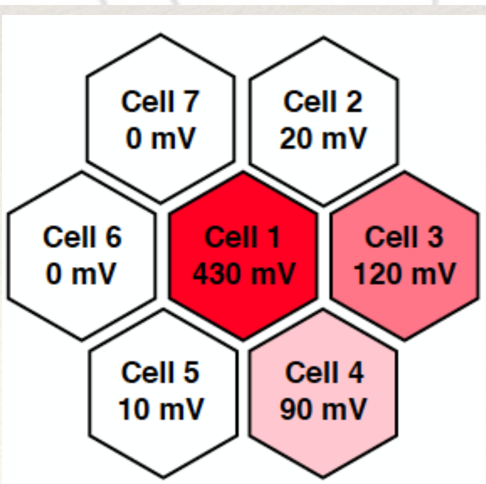


	N-type			P-type		
	$120\mu m$	$200\mu m$	$300\mu m$	$120\mu m$	$200\mu m$	$300\mu m$
0	11.7 ± 0.5	14.0 ± 3.0	16.5 ± 0.2	33.3 ± 1.9	18.2 ± 0.2	21.8 ± 0.5
1	15.1 ± 2.5	17.4 ± 2.5	18.1 ± 0.5	25.1 ± 6.9	19.1 ± 1.9	26.7 ± 2.6
2	16.7 ± 0.9	20.4 ± 2.3	19.1 ± 0.5	15.9 ± 5.9	15.8 ± 2.6	23.6 ± 1.4
3	20.6 ± 1.5	18.4 ± 2.3	22.3 ± 0.9	n/a	n/a	23.5 ± 1.1
4	n/a	19.4 ± 2.2	19.4 ± 3.9	n/a	n/a	22.0 ± 1.3

Precision timing measurement with modules







$$\sigma^2_{\rm msr} = \left(\frac{A}{(S/N)_{\rm eff}}\right)^2 + C^2$$