國立臺灣大學
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Beam-tests of prototype modules for the CMS High Granularity Calorimeter at CERN

PIXEL2018: International Workshop on Semiconductor Pixel Detectors for Particles and Imaging 2018

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On behalf of the CMS collaboration

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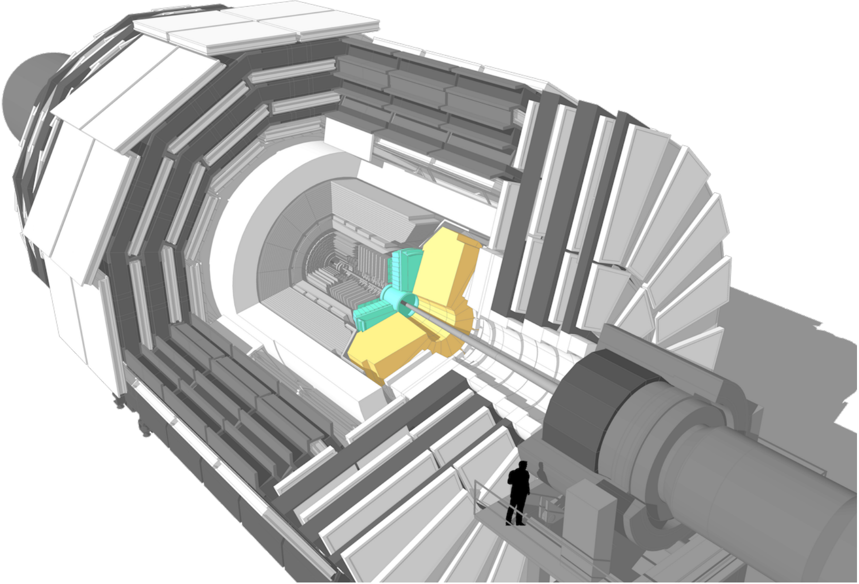
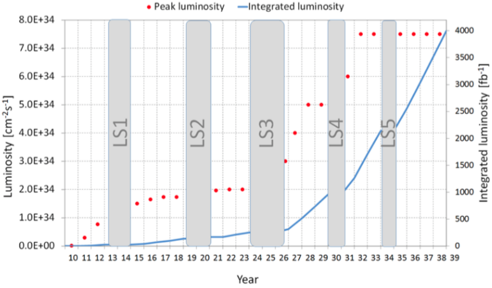
Outline

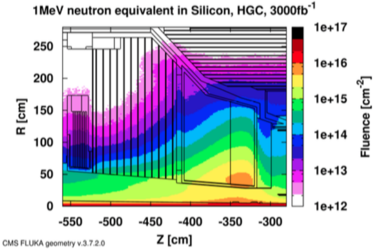
1. Motivation for upgrade
2. HGCAL prototype
3. Preliminary results

CMS will replace its endcap calorimeters in 2024-25



High luminosity LHC





High lumi LHC

- Luminosity : $5 \times 10^{34}\ cm^{-2}s^{-1}$
- Integrated luminosity : 3000 fb^{-1}
- Fluences : up to $10^{16} neq/cm^2$ in ECAL endcap
- Average pileup : 140 (maximum of 200)

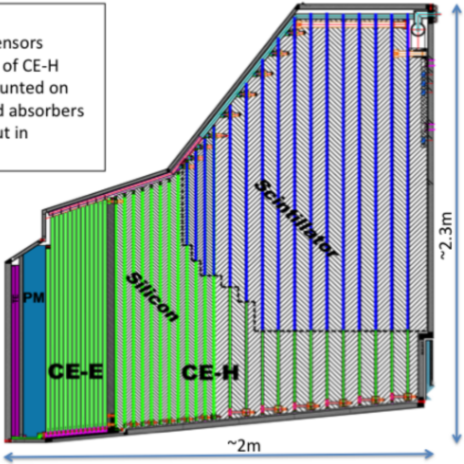
Need to replace endcap calorimeters

- Radiation tolerant
- Good timing resolution (pileup mitigation)
- Tracking capability (shower reconstruction, PFA)

CMS High Granular Calorimeter (HGCAL)

Active Elements:
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- "Cassettes": multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H

Key Parameters:
- Coverage: 1.5 < |η| < 3.0
- ~215 tonnes per endcap
- Full system maintained at -30ºC
- ~600m² of silicon sensors
- ~500m² of scintillators
- 6M Si channels, 0.5 or 1 cm² cell size
- ~27000 Si modules
- Power at end of HL-LHC: ~110 kW per endcap



Electromagnetic calorimeter (**CE-E**): Si, Cu & CuW & Pb absorbers, 28 layers, 25 X_0 & ~1.3λ
Hadronic calorimeter (**CE-H**): Si & scintillator, steel absorbers, 24 layers, ~8.5λ

- More details about HGCAL project in Chia-Hung Chien's poster : The CMS High Granularity Calorimeter for HL-LHC

Overview and goals of the beam tests

Main goals

- Validation of basic design of the HGCAL
- Comparisons with GEANT4 simulation
- Test calorimetric performance of silicon based calorimeter

2016 beam tests

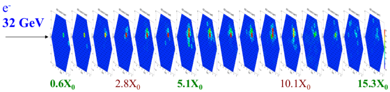
- Timing study with irradiated silicon diodes at CERN
- Electromagnetic calorimeter prototype using 6" modules and SKIROC2 ASIC (designed for CALICE SiWECal) at FNAL and CERN

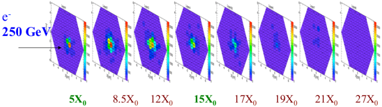
2017/2018 beam tests

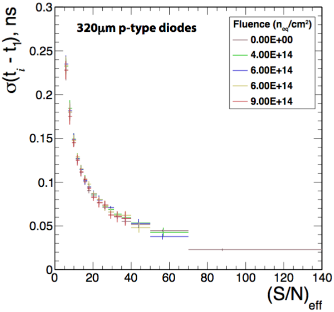
- New 6" modules using SKIROC2_CMS ASIC (with time over threshold and time of arrival measurements)
- Various configurations tested at CERN with up to 20 modules in 2017
- Beam test at DESY (March/April 2018) with few modules
- Larger scale beam tests :
  - CE-E prototype with 28 modules at CERN (June 2018)
  - Prototype with 94 silicon modules + the CALICE Analog Hadronic CALorimeter prototype (sampling calorimeter using scintillator tiles as active medium) at CERN (October 2018)

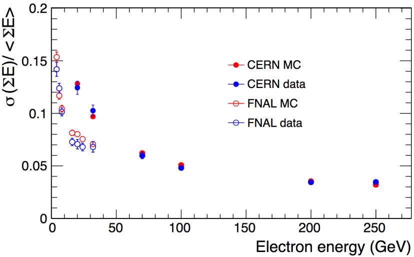
Results from 2016 beam tests

- Precision timing study with irradiated silicon diodes
- Electromagnetic calorimeter prototype using 6" modules and SKIROC2 chip (designed for CALICE SIWECal)
  - FNAL beam test : 16 modules with total thickness $\approx 15X_0$
  - CERN beam test : 8 modules, with total thickness $\approx 27X_0$
- Beam tests results in this paper : N. Akchurin et al. *First beam tests of prototype silicon modules for the CMS High Granularity Endcap Calorimeter* (link)









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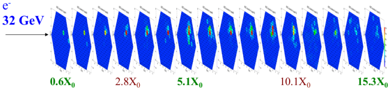
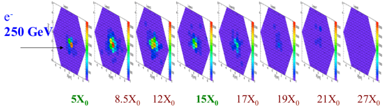
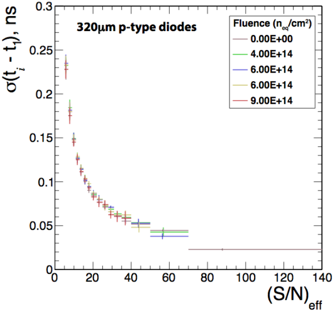
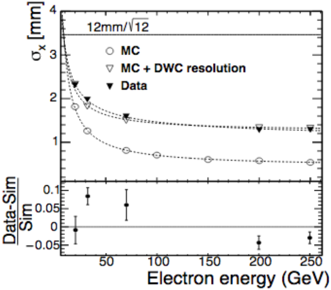
FNAL: 32 GeV electron passing through 16 layers (15 X_0)



CERN: 250 GeV electron passing through 8 layers (27 X_0)







1 Motivation for upgrade

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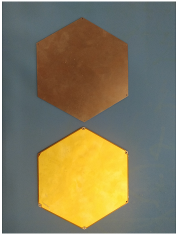
Module assembly

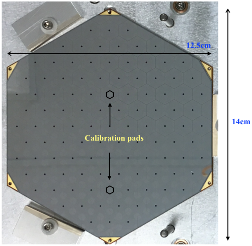
Glued stack

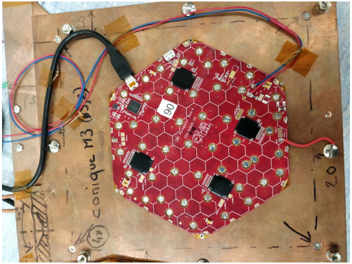
- Baseplate (CuW for CE-E, Cu for CE-H), thickness : 1.2 mm
- Kapton foil with gold layer
- 6" silicon sensor from HPK
- PCB holding 4 SKIROC2_CMS readout chips (32 channels per chip are connected to a silicon pads)
- Silicon pads wire bonded through holes in the PCB

Silicon sensors

- 6" hexagonal sensor
- Physical thickness : 320 μm
- Depleted thickness : 300 μm (4 modules with 200 μm)
- 134 individual silicon cells with an area of $\approx 1.1 cm^2$ for the full cells
- 2 inner calibration pads with 1/9th of the area of the full cell (for MIP sensitivity after irradiation)

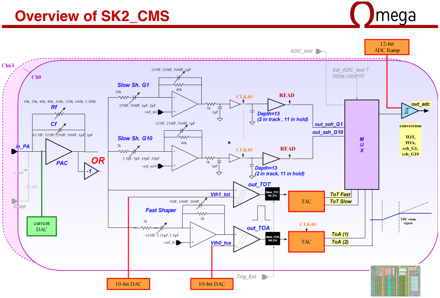


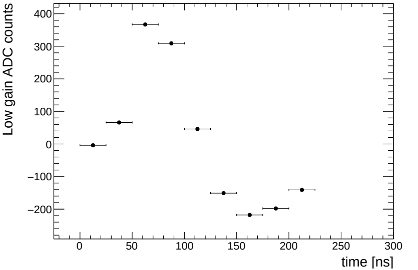




Readout CHIP : SKIROC2_CMS

- Derived from CALICE SKIROC2 chip
- 64 channels (though 32 are connected to a silicon pad)
- 2 slow shapers (shaping time between 10 and 70 ns) per channel with
  - a 13-deep 40 MHz analog memory used as waveform sampler
  - 12-bit ADC
- Fast shaper (shaping time between 2 and 5 ns) and discriminators for
  - Time over threshold to measure large signal (preamplifier saturation region)
  - Time of arrival (50 ps timing resolution foreseen)
- More details in this paper : J. Borg et al. *SKIROC2_CMS an ASIC for testing CMS HGCAL*





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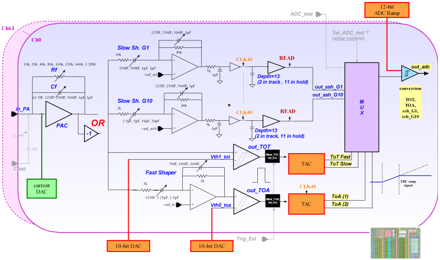
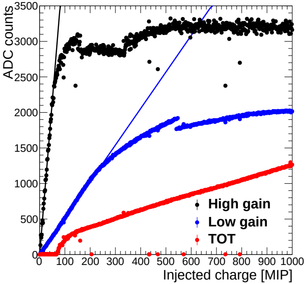
Overview of SK2_CMS

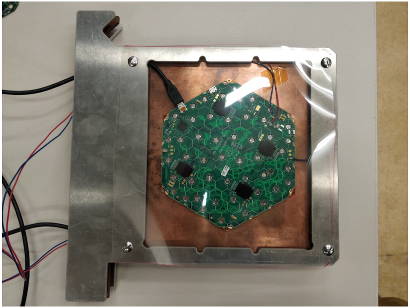




CE-E prototype

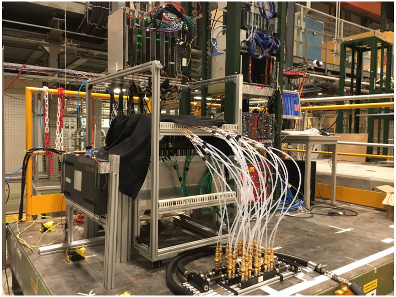
Mini cassette

- 4 mm thick lead absorber plate
- 6 mm thick copper cooling plate holding 2 modules on its 2 faces
- Copper cooling pipe inside the copper plate
- Aluminium frame and mylar foil



ECAL prototype

- 14 mini cassetes (i.e. 28 silicon modules)
- Total depth : $\approx 24\ X_0,\ 1\lambda_I$
- Water cooling to keep constant temperature : $28^\circ C$



CE-H prototype

CE-H layer

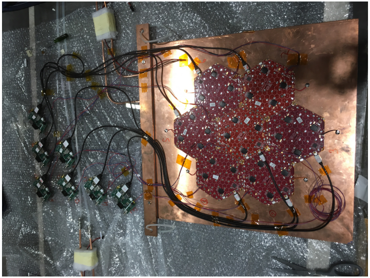
- 6 mm thick copper cooling plate holding 7 modules (only on front face)
- Copper cooling pipe glued to the backside of the copper plate

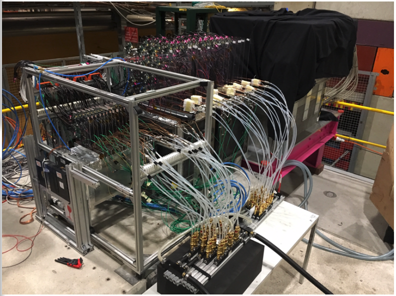
CE-H (silicon part) prototype

- 12 layers (9 with 7 modules + 3 with 1 module), 12k electronic channels in total
- Separated by 4 cm thick steel absorber plates
- Total depth : $\approx 3.5\lambda_I$
- Water cooling to keep constant temperature : $28^\circ C$

CALICE AHCAL prototype

- 38 layers using scintillator tiles (tile size : $3\times 3cm^2$)
- $\approx$ 22k channels
- Separated by 1.75 cm thick steel absorber plates
- Total depth : $\approx 4\lambda_I$





DAQ systems

Extra detectors in the beam line :

- 2 scintillators in coincidence for the trigger + 1 veto scintillator between HGCAL and AHCAL prototypes to reject pion in electron run
- 4 delay wire chambers readout with TDC
- 2 MCP detectors for timing reference readout with 5 GHz digitizer

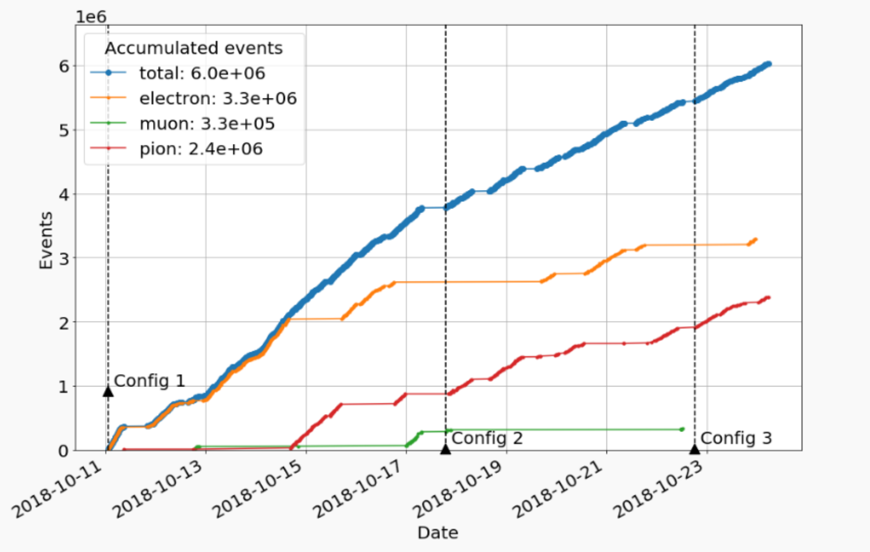
Custom DAQ boards

- SYNCH board (1 synch board in total)
  - board creates 40 MHz clock
  - receives and distributes triggers to RDOUT boards, AHCAL, TDC and digitizer
- RDOUT boards connected to up to 8 modules
  - distribute low and bias voltage to the modules
  - send commands to the MAX10 FPGA on the modules (trigger, slow control)
  - read out the data using IPbus protocol

DAQ software

- eudaq framework https://eudaq.github.io/
- Collects data from each detector types
- Provides DQM framework

Beam test summary



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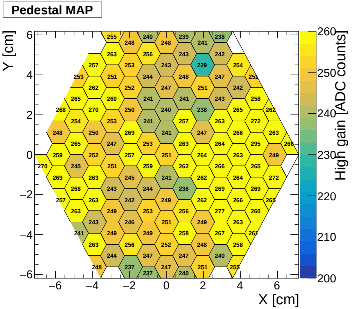
Analysis procedure

- Pedestal estimation and subtraction for each channel and each memory slot (13-deep 40 MHz analog memory)
- Common mode noise estimation for each module and each time sample
- Pulse shape fit to extract high and low gain amplitudes, after hit pre-selection
- Gain choice between high gain, low gain and ToT and hit energy calibration
  - High gain calibrated using muon runs
  - 1 MIP $\approx$ 40-50 ADC counts (high gain), S/N$\approx$6-7 for MIP
  - Low gain calibrated using high gain
  - ToT calibrated using low gain



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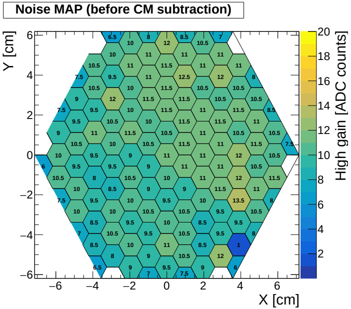

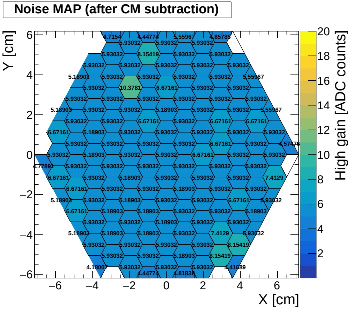

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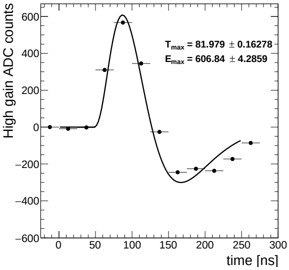

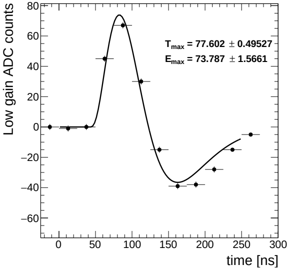

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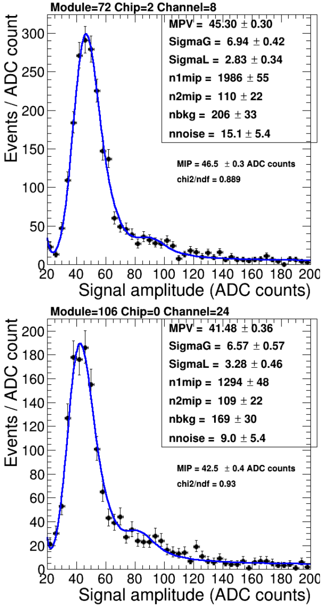

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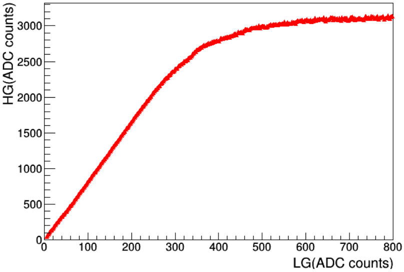
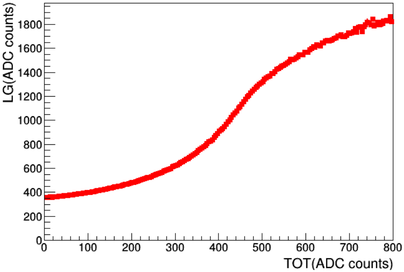
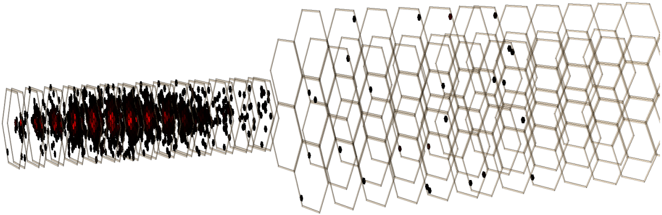
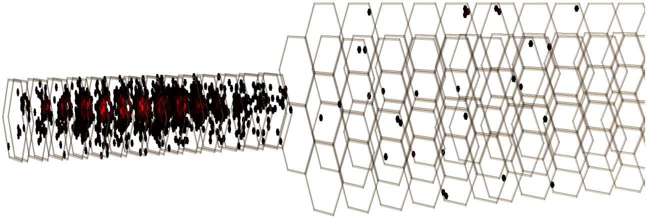


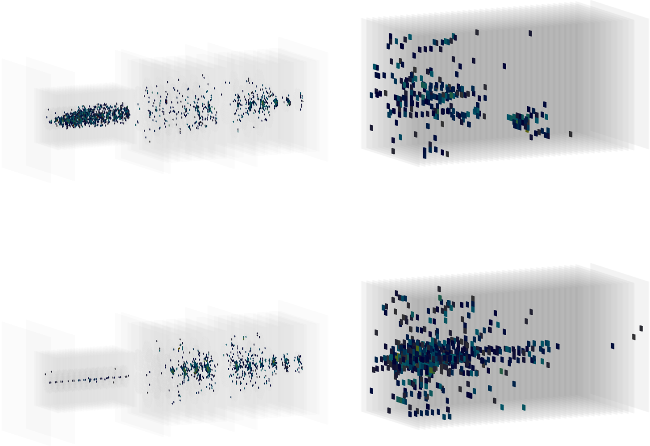


Event displays : 300 GeV EM showers



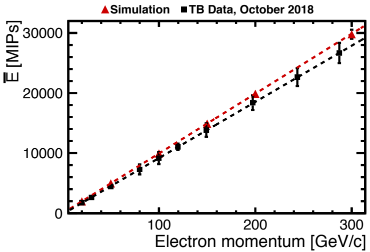


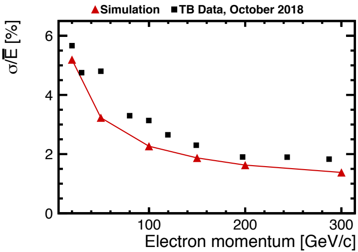
Event displays : 300 GeV hadronic showers



Electromagnetic shower results

- Energy sum from all layers (only CE-E prototype i.e. 28 modules)
- Beam energy corrected to take into account synchrotron radiation
- Simulation being tuned with momentum spread from SPS





- Next steps :
  - Improve hit calibration
  - Apply weights for each layers

Conclusion

- New HGCAL prototype has been built with 94 silicon modules ($\approx$ 12k channels) between 2017 and 2018
- Combined data taking with AHCAL prototype, delay wire chambers and MCP has been a success
- Good preliminary results
  - Low noise
  - Good S/N for MIP
  - Reasonable data-simulation agreement
  - Energy and time resolution close to expectations
- Next plan for the data analysis :
  - Improve the calibration
  - Compare data and simulation
  - Apply clustering technique
  - Combine HGCAL data with AHCAL for hadronic shower study
  - Time precision study using MCP detectors

Back-Up

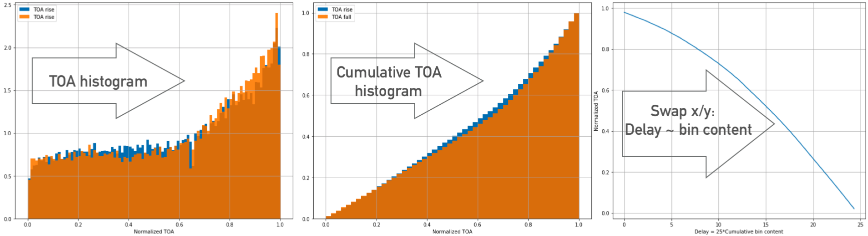
Calibration of ToA

ToA signal

- Using electron runs from June data
- ToA threshold : ≈10 MIPs
- ToA measure time between ToA trigger and next falling/rising edge (but skiping first edge) of the 40 MHz clock

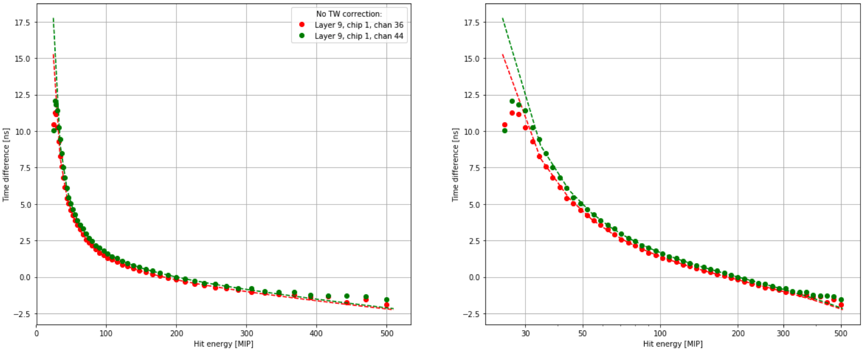
ToA calibration

- Beam is asynchronous → Time distribution expected to be uniform
- ToA range = 25 ns (with 12.5 ns offset)



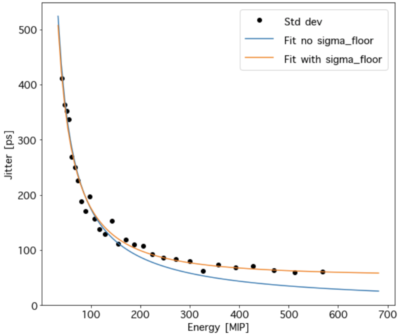
Time walk correction

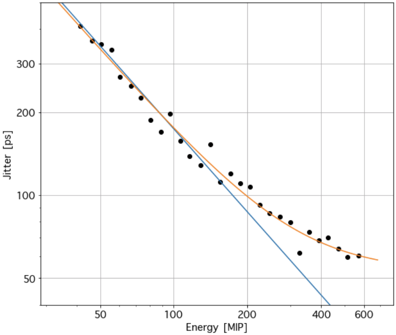
- Time walk can be large for low signal amplitude
- Time walk correction :
  - Select a reference channel (and small amplitude window to minimize TW effect)
  - Look at time diffence with neighbouring cells to extract the time-walk



Time resolution

- Time differences between 2 silicon pads
  - Assume same time resolution in each cell $\rightarrow$ $\sigma_t = \sigma_{\Delta_t}/\sqrt{2}$
  - Time resolution constant term $\approx$ 50 ps





- Next step : use MCP data for the time reference