Performance of CMS High-Granularity Calorimeter (HGCAL) Prototype in Beam Test Experiment at CERN

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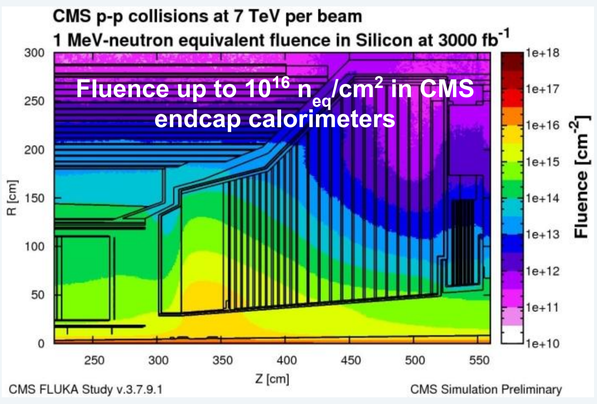
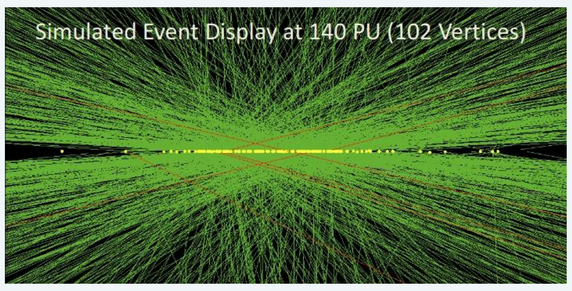
On behalf of the CMS Collaboration

Motivation for HGCAL upgrade

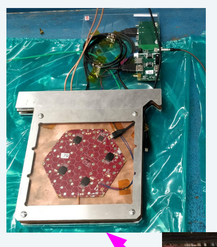
High luminosity Large Hadron Collider (HL-LHC) run is expected to start around 2027. HL-LHC will integrate 10 times more luminosity than the LHC over 10 years of operation.

- The HL-LHC run will allow to collect more statistics for Higgs and other Standard Model (SM) precision measurements and Beyond Standard Model (BSM) physics searches.
- It will pose various challenges for the CMS detector:
  - Very high radiation dose in the forward region of the detector
  - High Pile up condition : <PU> ~ 140 - 200

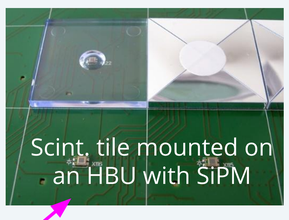




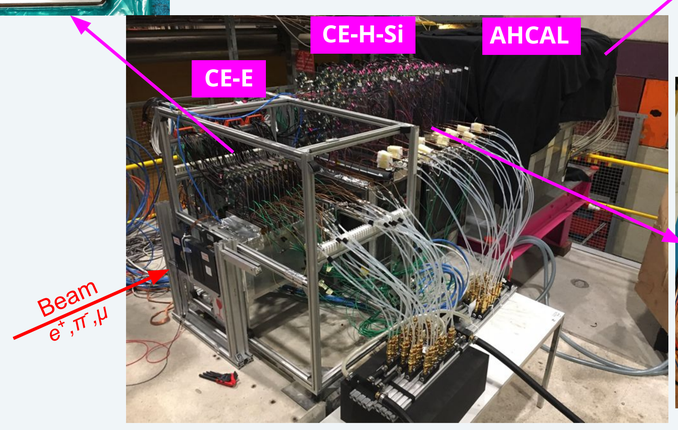
Beam Test at H2 SPS beamline

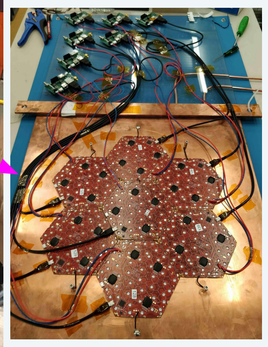


CE-E :
- **Silicon sensors**
- **28** sampling layers, **1 module per layer**
- Pb/Cu/CuW absorber
- **~ 26 X_0 , ~ 1.4 λ_{int}**
- ~3.5k channels



CALICE AHCAL[3] :
- **Scintillator+SiPM**
- **39** sampling layers
- Stainless steel absorber
- **~ 4.3 λ_{int}**
- ~22k channels

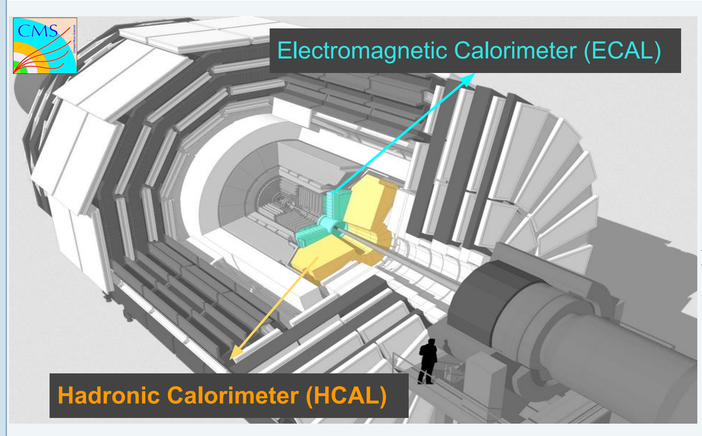




CE-H-Si :
- **Silicon sensors**
- **12** sampling layers
- Upto 7 modules per layer in daisy formation
- Stainless steel absorber
- **~ 3.4 λ_{int}**
- ~8.4k channels

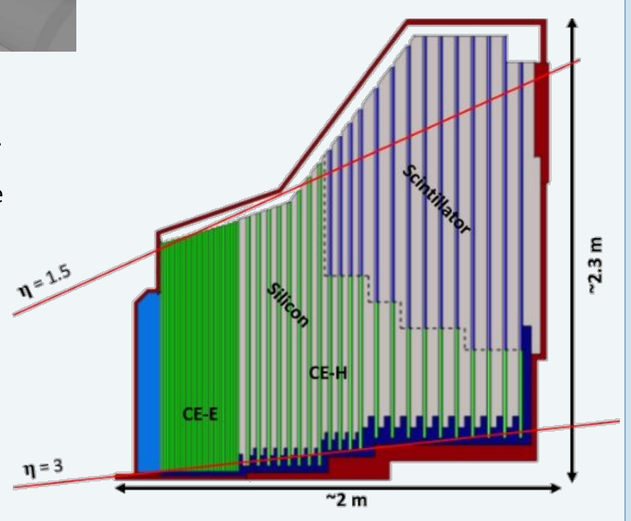
e^+, π^- with energy ranging from 20 GeV to 300 GeV and 200 GeV μ^- beam was used.
First large-scale beam test with 94 modules over the course of around two weeks during October 2018.

High Granularity Calorimeter



- To cope with the harsh environment without losing physics performance in the HL-LHC run, **endcap calorimeters** of CMS will be replaced by High Granularity Calorimeter (HGCAL) [1].
- **Requirement:**
  - Radiation Tolerant
  - Dense enough for shower containment
  - Fine longitudinal and lateral granularity

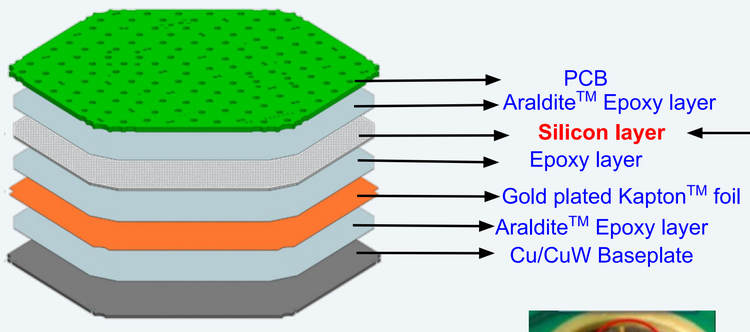
- **Features:**
  - Sampling Calorimeter with **50 sampling layers**.
  - **1.5 < |η| < 3.0** coverage
  - **6M Si channels** with 0.5 cm^2 or 1.1 cm^2 cell size
  - **240k scintillator channels** , 4-30 cm^2 cell size
  - System maintained at **-30 ^{0}C**
- **Active elements:**
  - Hexagonal modules based on Si sensors in electromagnetic compartment (CE-E) and high radiation regions of hadronic compartment (CE-H) of endcap calorimeter (CE).
  - Scintillator on tiles with SiPM readout in low-radiation region of CE-H.



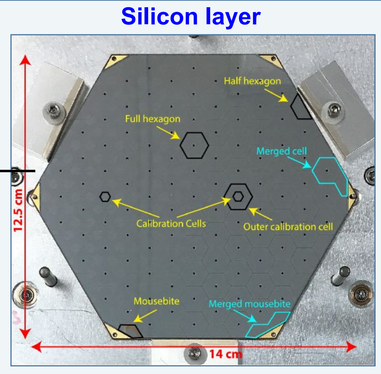
Electromagnetic calorimeter **(CE-E) : Si**, Cu & CuW & Pb absorbers, 28 layers, 25 X_0 & ~ 1.3 λ_0
Hadronic calorimeter **(CE-H) : Si** & **Scintillator**, steel absorbers, 22 layers, ~ 8.5 λ_0

Silicon sensor module

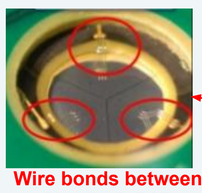
Layout of a generic silicon sensor module



Silicon layer



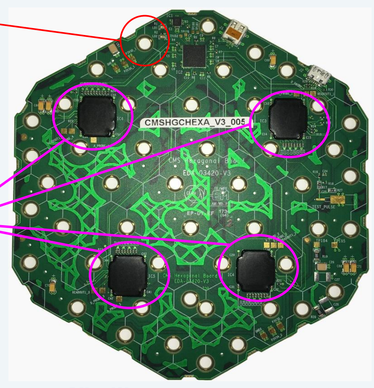
6" silicon sensor prototype module
- 128 silicon cells
  - p-on-n type Si
  - 200 or 300 μm active thickness
  - cell area ~ 1.1 cm^2



Wire bonds between Si cells & PCB

- **SKIROC2-CMS [2] readout chips**
  - Each chip can connect upto 64 channels
  - 4 chips per module
  - Different gain stages to provide large dynamic range: High Gain (HG), Low Gain (LG) and Time-over-Threshold (ToT)

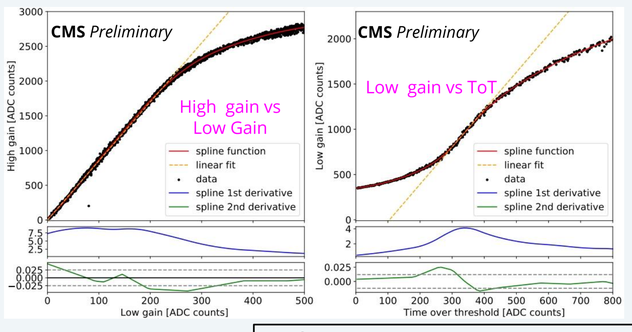
SKIROC2-CMS ASICs



6" silicon sensor prototype

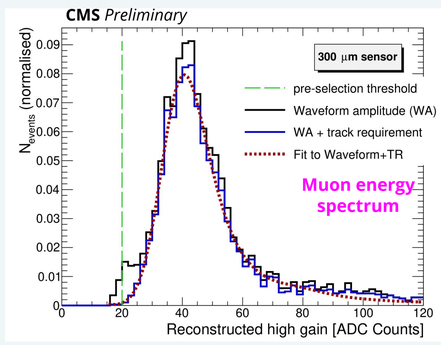
Calibration

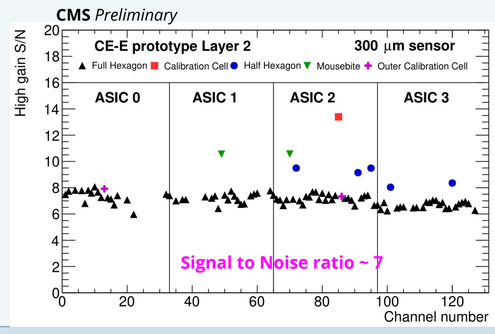
- Pedestal/Noise estimated and subtracted from each cell on event-by-event basis.
- Equalize response for different cells with minimum-ionizing-particles ⇒ 200 GeV muon beam
- Intergain calibration (HG-LG & LG-ToT) to ensure linear response over a large dynamic range.
- Signal to noise ratio is ~ 7 for 300 μm Si cells.



Reconstructed energy ⇒ (in MIPs)

$$E = \begin{cases} E_{HG}, & \text{if } A_{0,HG} < HG_{sat} \\ E_{LG}, & \text{if } A_{0,HG} > HG_{sat} \text{ and } A_{0,LG} < LG_{sat} \\ E_{ToT}, & \text{otherwise} \end{cases}$$

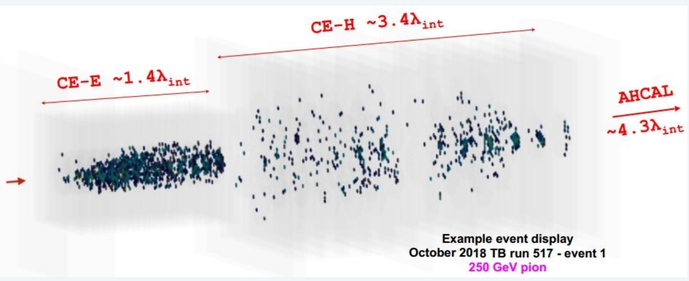


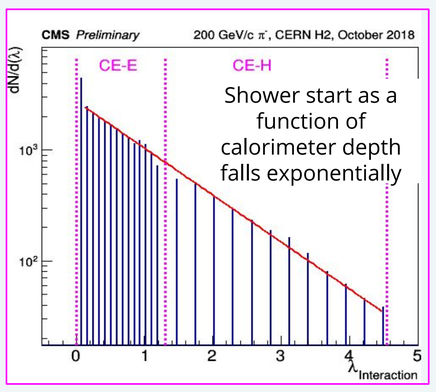


Physics Performance

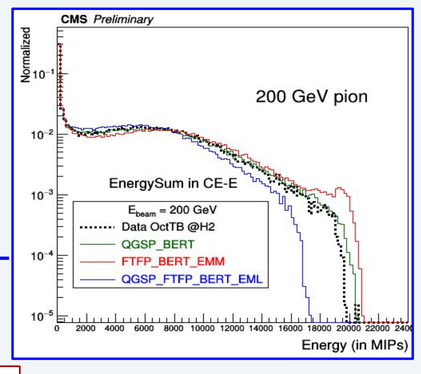
Electromagnetic shower: See Matteo's **"Electromagnetic performance analyses of HGCAL prototypes"** poster for detailed results of EM shower in HGCAL TB setup.

Hadronic Showers:
- Setup was exposed to 20 to 300 GeV charged pions.
- Results presented here are **without AHCAL.**

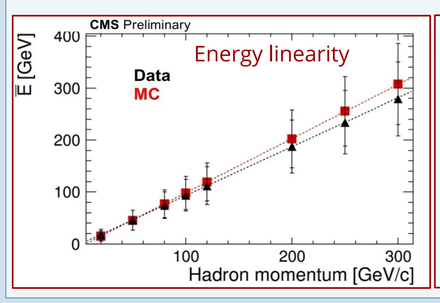


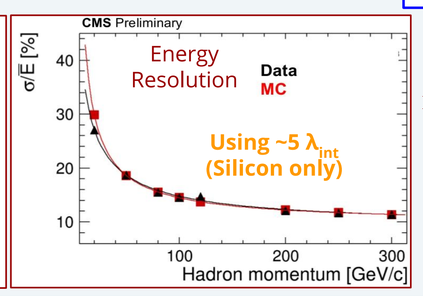


- A **shower start finder algorithm** is employed to find the first hadronic interaction in the calorimeter.



- GEANT4[4] based simulation for data/MC comparison with different physics lists
  - To choose best model for hadronic interactions.





- Preliminary results show good agreement between data and MC.

Summary

- First large scale beam test with ~100 modules.
- Overall 85% channels of CE-E and CE-H-Si were calibrated using muon beam data.
- Physics performance results show good agreement between data and simulation.
- Multiple publications are expected for submissions in the upcoming months based on beam test data.

Acknowledgement
- I would like to thank CMS HGCAL beam test analysis group and my PhD advisor Dr. Seema Sharma for valuable discussions and inputs.

References

1. CMS Collaboration, *The Phase-2 Upgrade of the CMS Endcap Calorimeter, CERN-LHCC-2017-023; CMS-TDR-019*
2. J. Borg et al, *Skiroc : Skiroc2-CMS an ASIC for testing CMS HGCAL, 2017 JINST 12 C02019*
3. Felix Sefkow et al, *A highly granular SiPM-on-tile calorimeter prototype, 2019 J. Phys.: Conf. Ser. 1162 012012*
4. S. Agostinelli et al, *GEANT4 - a simulation toolkit, 2003 NIMA Volume 506, Issue 3, Pages 250-303,* https://doi.org/10.1016/S0168-9002(03)01368-8