The CMS High Granularity Calorimeter for HL-LHC

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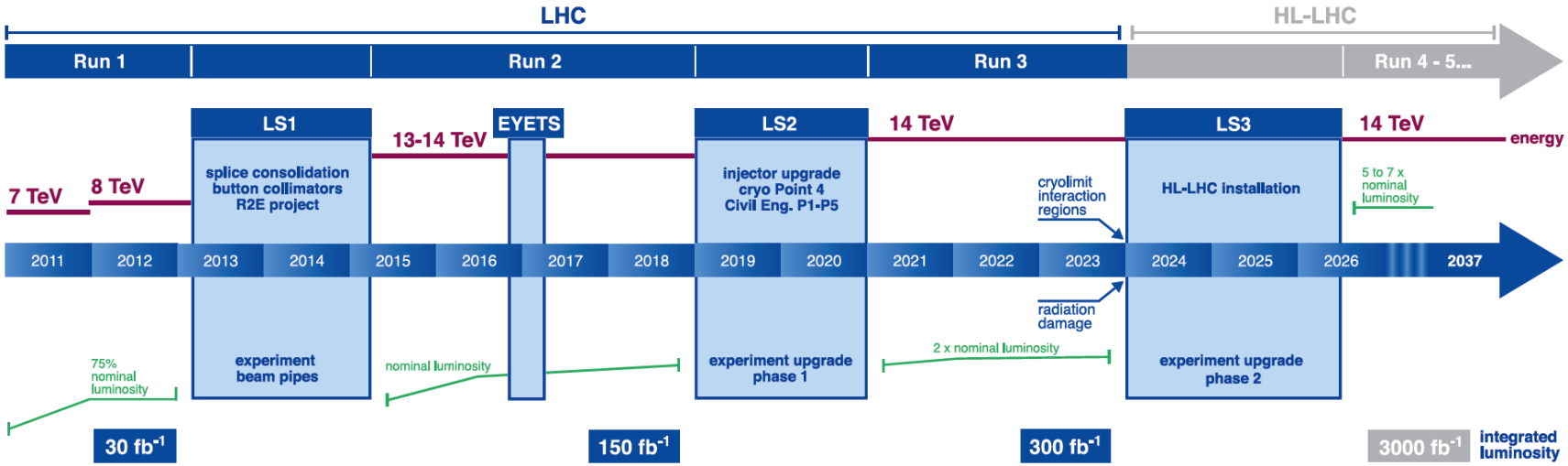
Outline

- LHC after 2026
- Physics goals
- What it implies for detectors
- Needed detector performance
  - Endcap Calorimeter ($1.5<|\eta|<3.0$)
- High Granularity Calorimeter
  - Detector design
  - FE/Backend electronics
  - Test-Beam performance
  - Performance of CMS@2026 in endcap region (Simulation)
  - Schedule

LHC in 2026 and Physics Goals

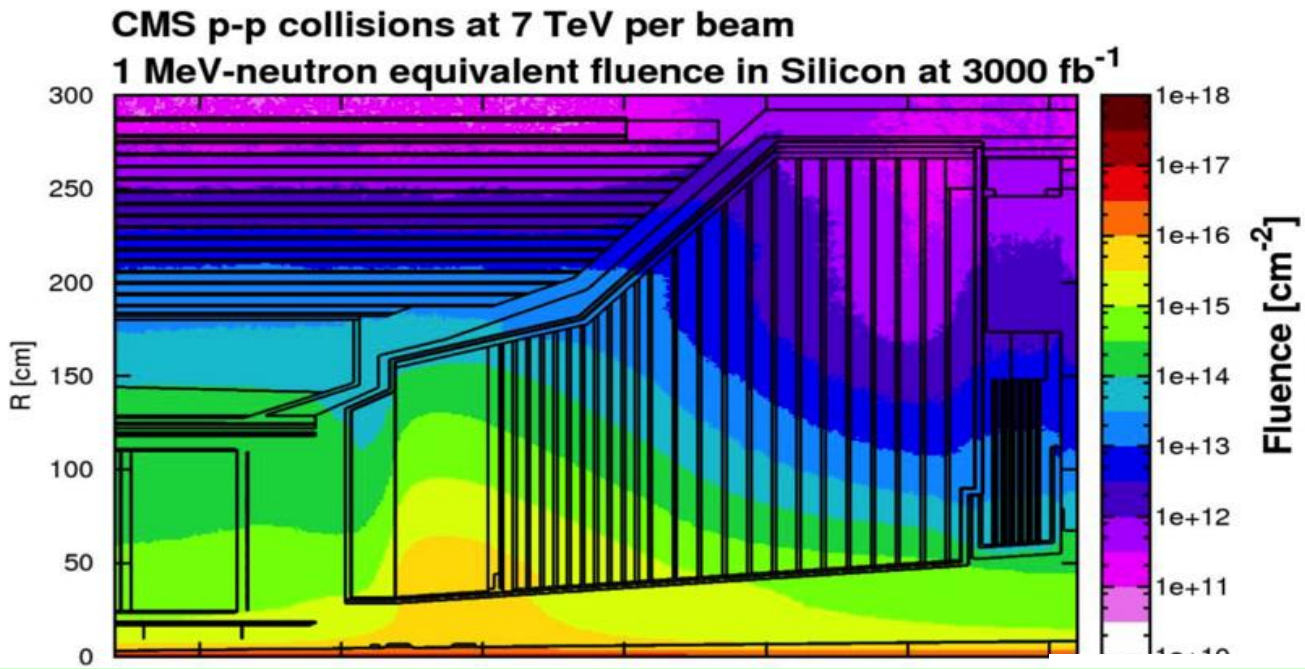
LHC: Past Performance and Future Time Line



- **Physics reach: SM, Higgs, Searches for BSM particularly processes initiated by Vector Boson Fusion (VBF), Search for highly-boosted objects**
- **Significant Increase in Instantaneous (x5) and Integrated Luminosity (x10)**
  - **Radiation hardness, Pile-up mitigation, Object Reconstruction → Big challenge**
  - **Upgrade of many sub systems of CMS Experiment**
    - **EndCap Calorimeter in $1.5<|\eta|<3.0$ region needs complete upgrade**
  - **Detection and triggering capability on narrow VBF and merged jets**

Implications on Detector

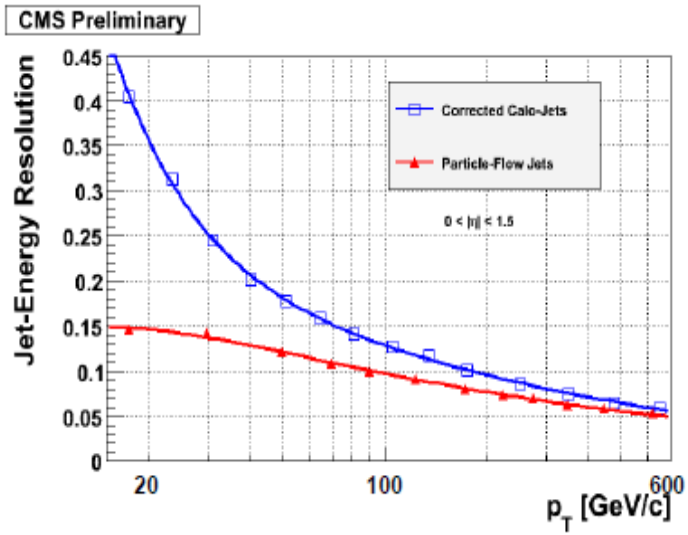
HL-LHC Radiation Levels

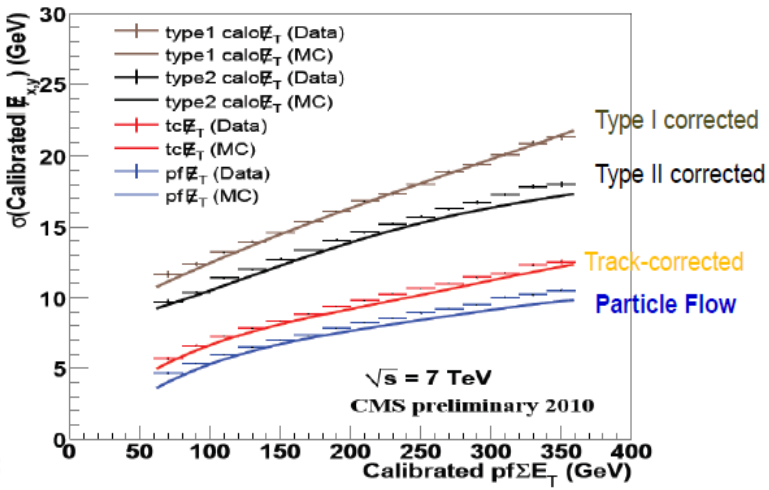


- **Increase in Integrated luminosity (~3000 fb^{-1})**
  - **10^{16} n_{eq}/cm^2 and up to 2 MGy absorbed dose in HGCAL**
  - **Requires substantially enhancement in radiation tolerance of the detector**
- **Increase in instantaneous luminosity (x 5)**
  - **Huge pile up (140-200 collisions/bunch crossing), High Occupancy**
- **Reconstruction of *Calorimetric* objects (Gamma, $e^{\pm}$ and Jets)**
  - **Precision timing: Timing spread of 0.8 ns to be measured accurately to mitigate the pileup**
  - **High granularity in Longitudinal and Transverse Direction**

Particle Flow Objects

PF: Inputs from Tracker + ECAL +HCAL





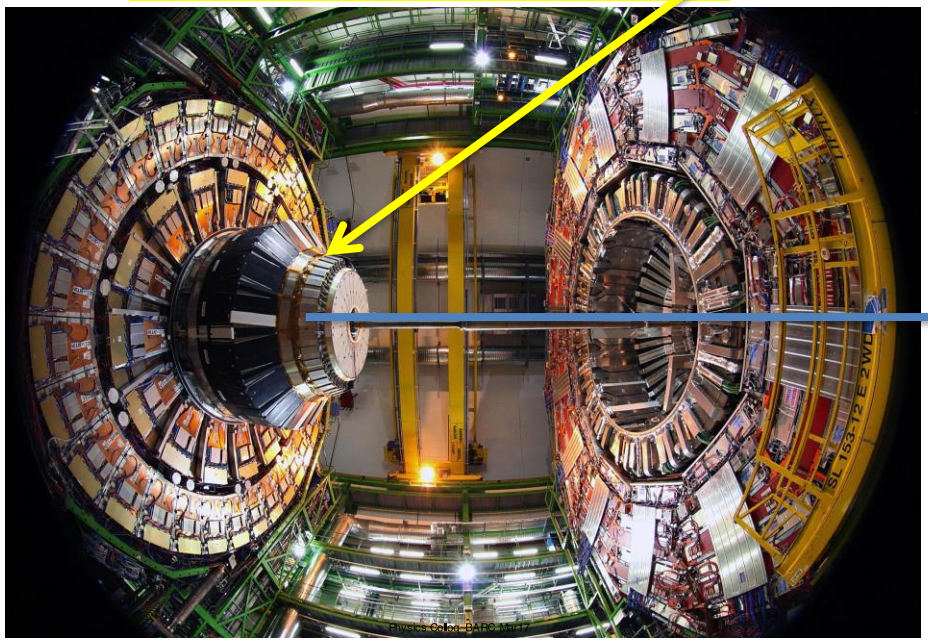
- **Granularity is more important than energy resolution**
- **Granularity should be better than Moliere radius in ECAL**
  - **to provide separation between closely spaced showers (particularly in high pileup environment)**

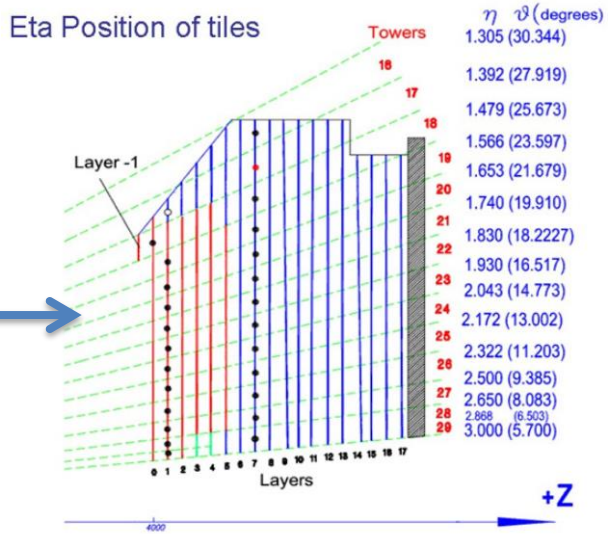
Candidate: Silicon/Scintillators

- **Compact detector with thin sensors**
- **Bonding between silicon and FE**
- **Calibration: Silicon and scintillator tiles should have good sensitivity to MIPs**
  - **Low-capacitance Si cells, small area, Scintillator with good light yield**
- **Coarse objects to be reconstructed in real time**
  - **Sophisticated embedded systems and triggering algorithms needed!**

High Granularity Calorimeter

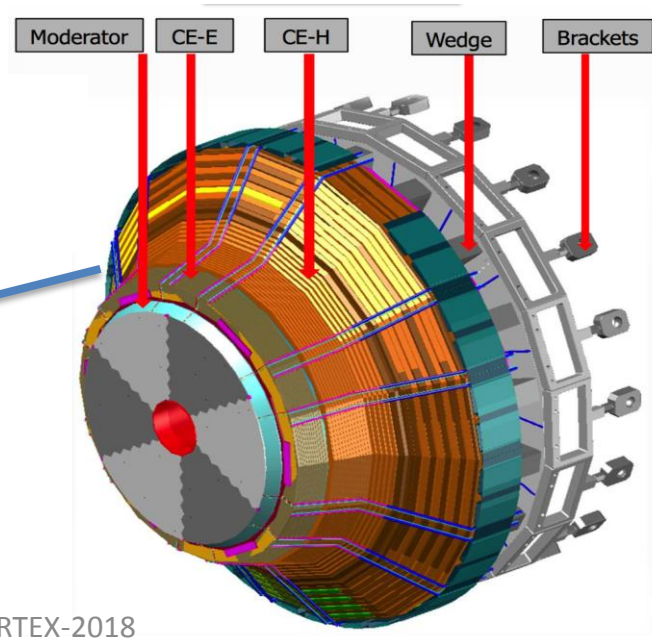
Existing Endcap Calorimeter



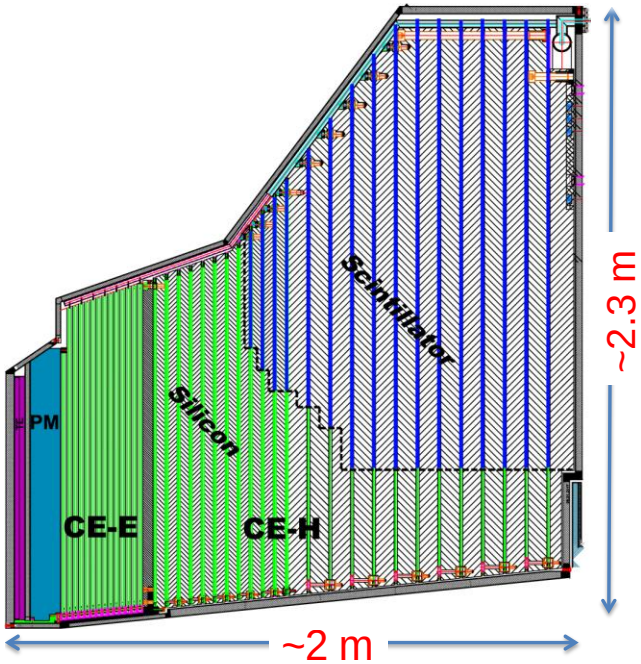


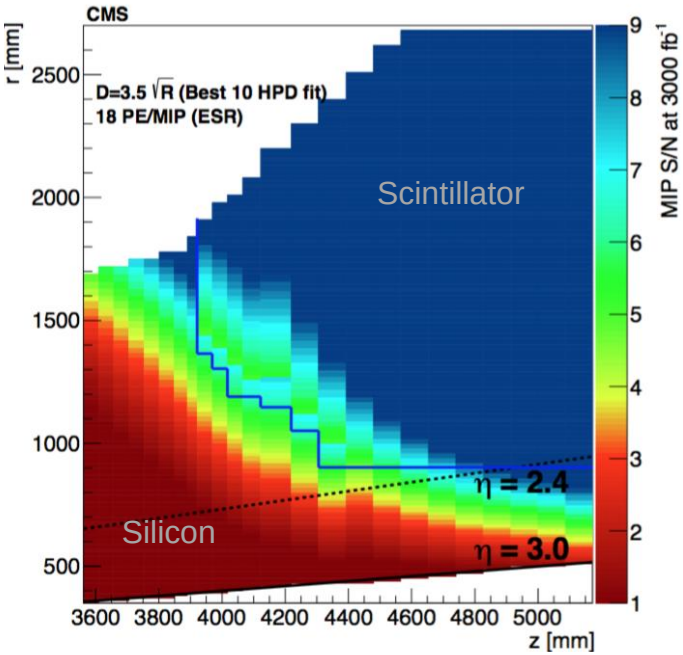
Upgraded Endcap Calorimeter: HGCAL

- **Electromagnetic Calorimeter (23 Tons)**
  - **26 Radiation Length (~ 1.7λ)**
  - **CE-E: 28 Silicon Layers**
  - **28 × 0.9 X_0**
- **Hadron Calorimeter (205 Tons)**
  - **~ 9 Interaction Length**
  - **CE-H: 24 Layers of Si + Scint**
    - **8 Si + 16 Mixed (Si+Scint)**
  - **12 × 0.3λ + 12 x 0.45λ**



HGCAL Design and its Radiation Tolerance

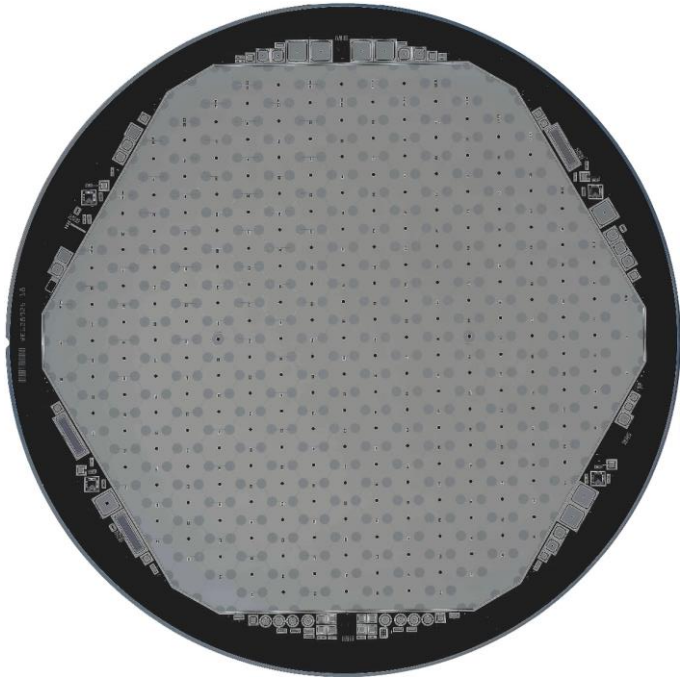


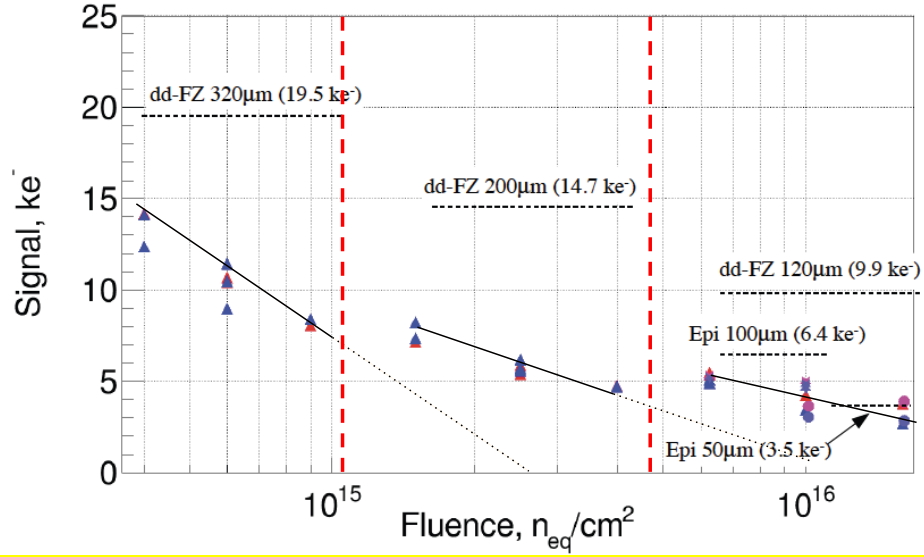


- **600 m² of hexagonal 8-inch silicon sensors**
  - **Sensor thickness: 120 µm, 200 µm, 300 µm**
  - **Hexagonal pad size of 0.5cm²/1.1cm², 6 Million channels**
- **27000 silicon sensor modules to be assembled with baseplates and FE electronics**
- **500 m² Scintillators (4-30 cm², 3960 Modules) coupled to SiPM (0.4M Channels)**
- **CE-E: Si and Cu/CuW/Pb and CE-H: Si + Scint and steel**
- **Data readout from all layers**
- **Trigger readout from alternate layers in CE-E and all layers of CE-H**

High Granularity Calorimeter: Silicon Sensors and Scintillators

Silicon Sensors

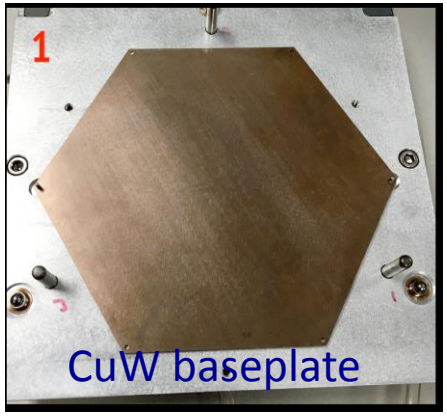


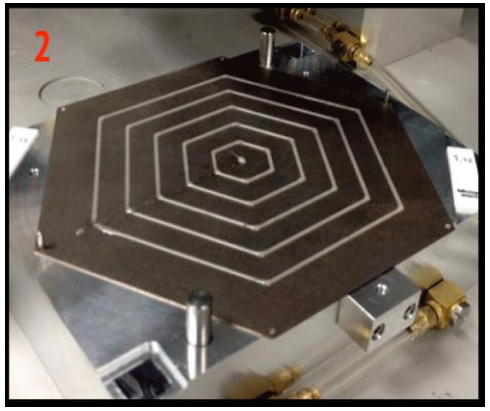


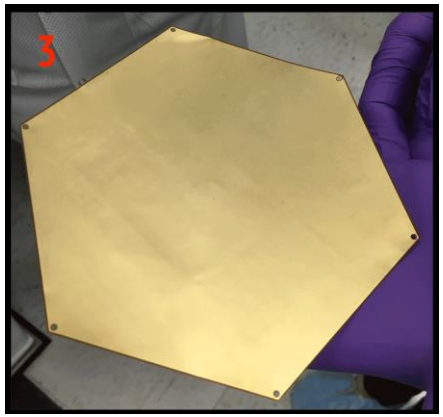
Thinner sensors have higher radiation tolerance

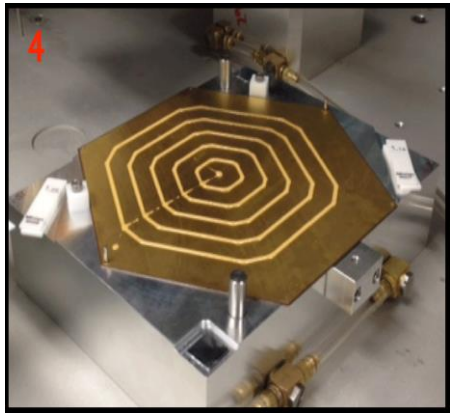
- **Planar n-on-p DC-coupled**
  - **Robust against non-Gaussian noise due to surface charge effects induced by radiation-**
- **Crystal orientation <100>**
- **432 cells per sensor for 120 µm and 192 cells per sensor for 200 µm and 300 µm**
- **Vbd > 800 V, Resistivity 3-8.5 kohm.cm,**
- **Vfd ~107-260 V (300 µm) and 47–115 V (200 µm)**

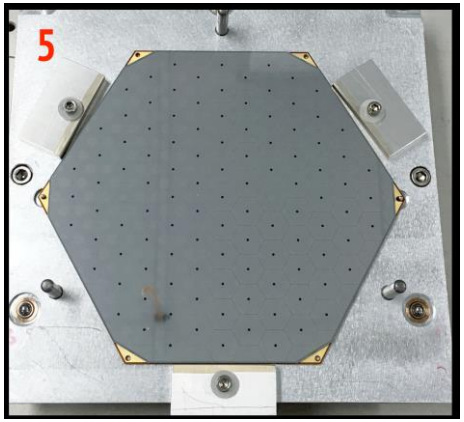
6-inch Silicon Sensor Module Assembly at UCSB for Test-Beam

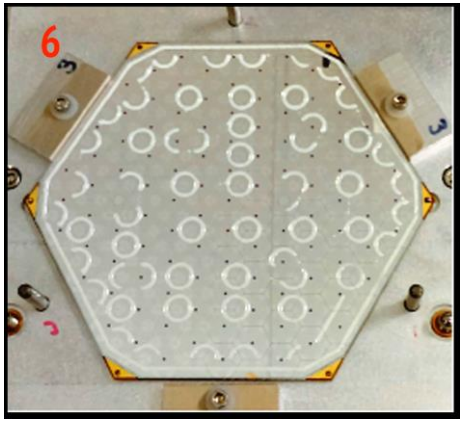


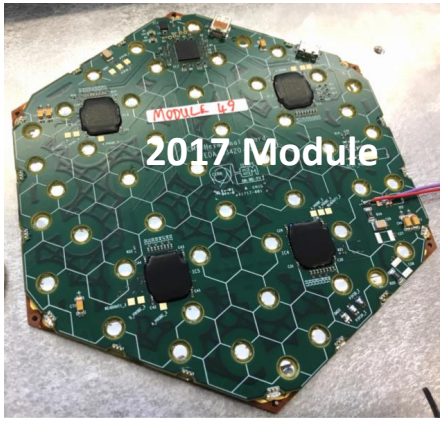


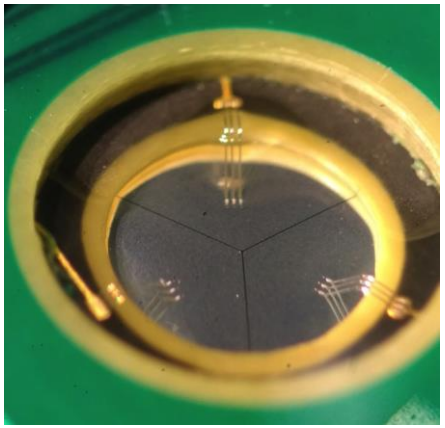




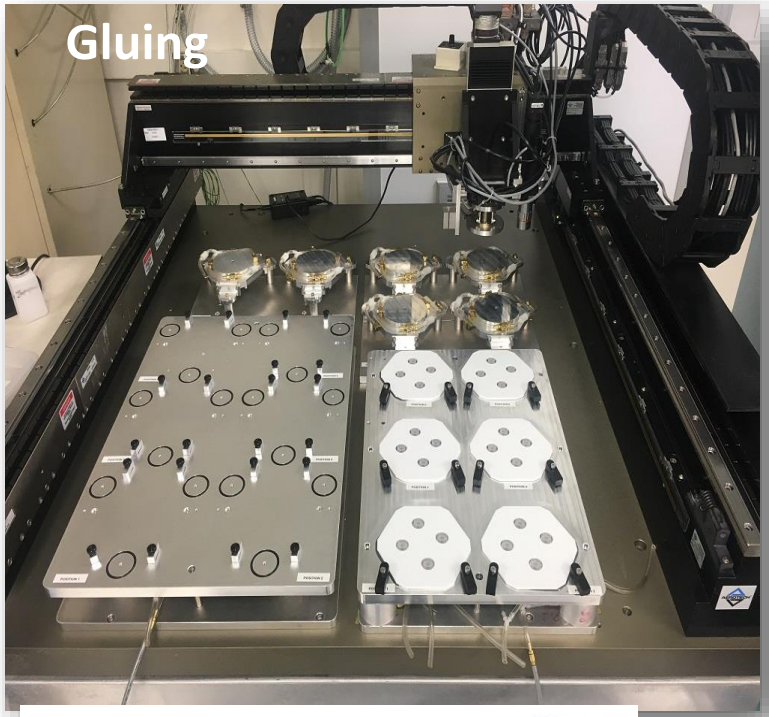


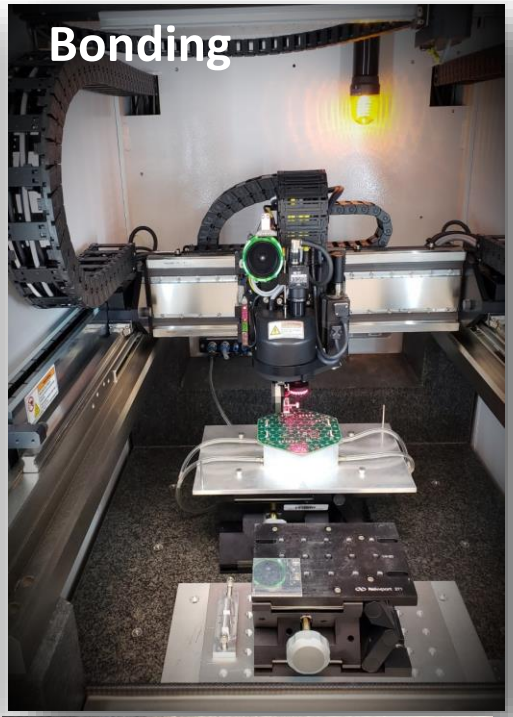


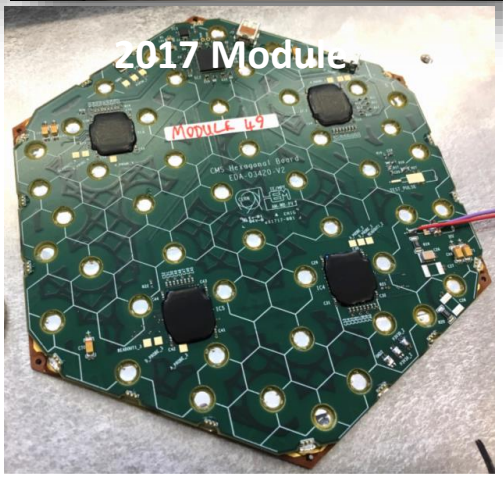




Module Assembly Line





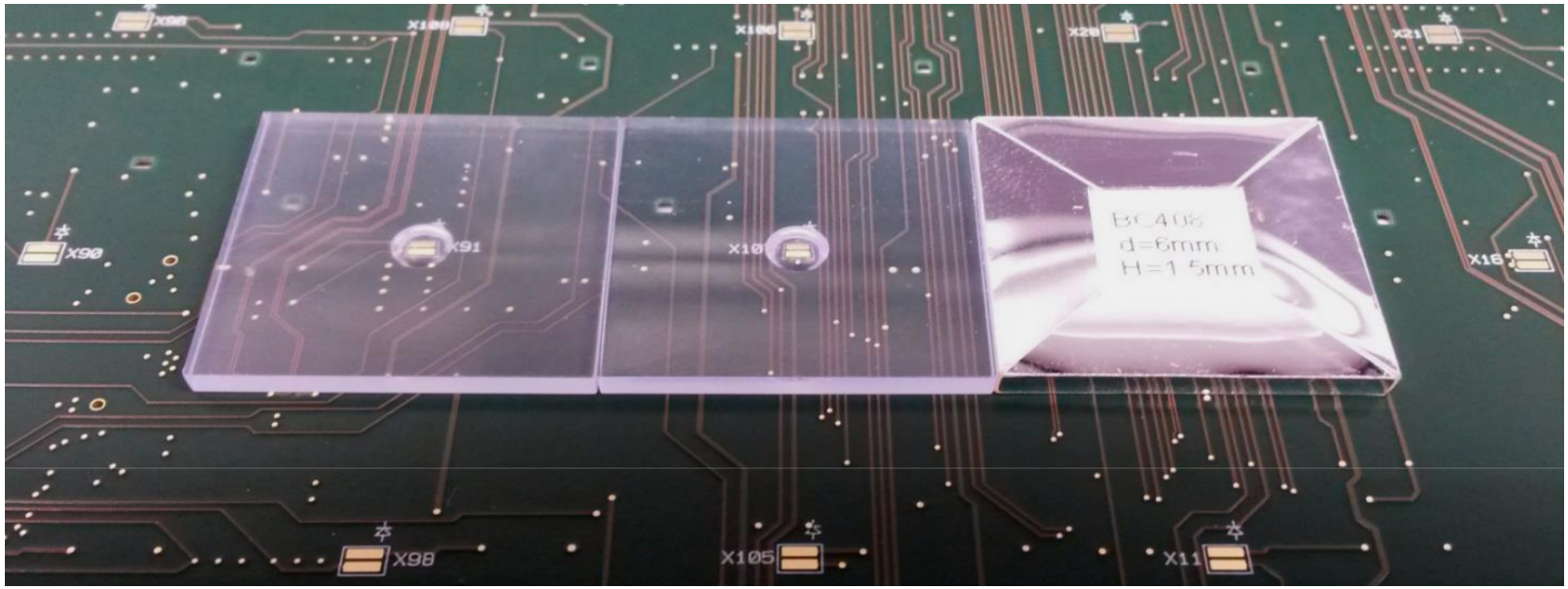


Several Module Assembly Centers to be setup

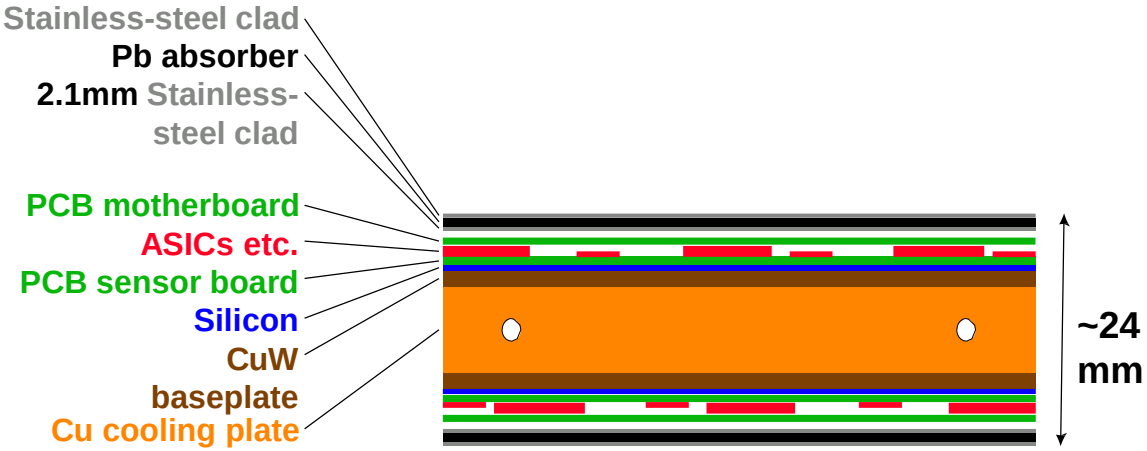
~20 Modules/day to be assembled during production phase

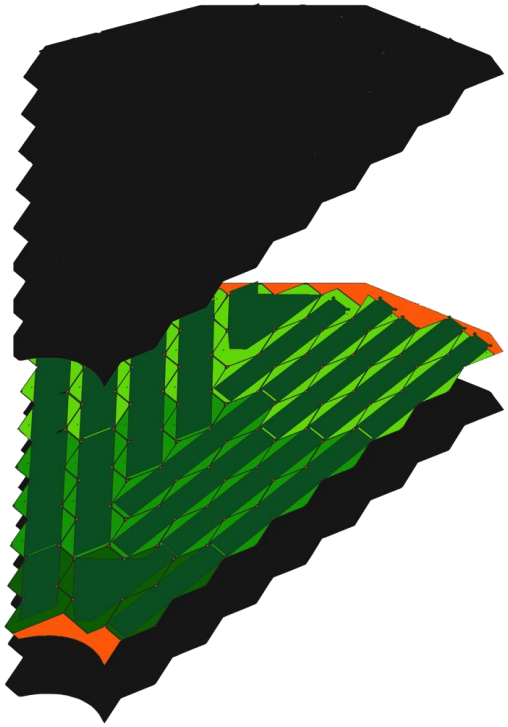
Scintillator Layers in CE-H

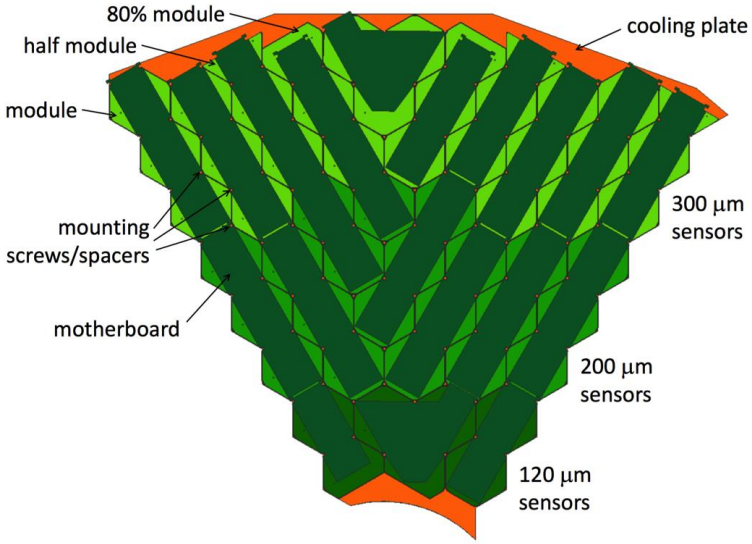
- Several layers of scintillating tiles (400,000) of size 4-30 cm^2 with on tile SiPM (500 m^2) to be installed in low radiation zone area of endcap calorimeter
- Concept developed by CALICE-AHCAL
  - Automated assembly facility developed by CALICE-AHCAL
- SiPM mounted under the dome of a tile to ensure efficient and uniform light collection: SiPM based detector system already operation in CMS Calorimeter
- Two materials considered: Poly-Vinyl-Toluene (PVT) or Polystyrene (PS)



CE-E and CE-H Cassettes





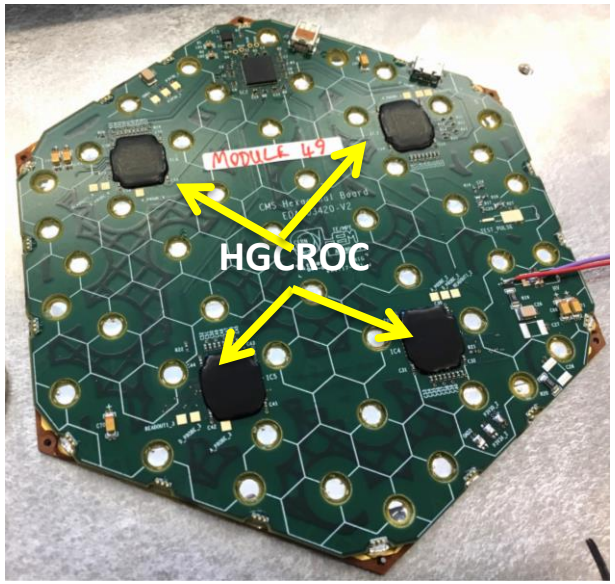


- **Detector with FE electronics to be maintained at -30°C**
- **Power budget: 110 kW/side**
  - **Designed for 300 kW for both sides**
- **Two phase CO_2 fluid**

High Granularity Calorimeter: FE/Backend Electronics

HGCAL FE-ASIC Requirements

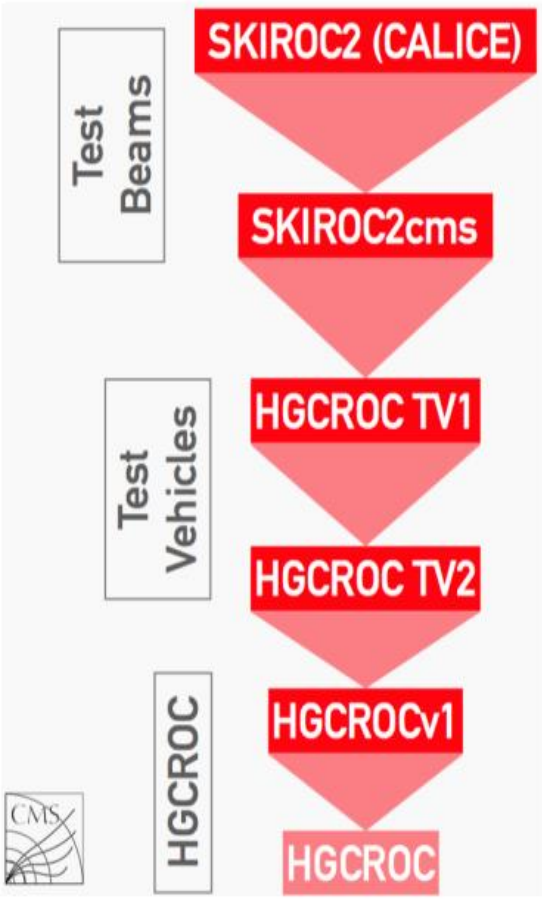
- Low noise (< 2000 e-, 0.32 fC) and high dynamic range: 0 – 10 pC
  - ADC, Time over Threshold (ToT), Time of Arrival (ToA), Zero suppression, linearization, summing of trigger data
  - MIP: 10k – 20k e- (1.5 – 3 fC)
  - Integral linearity better than 1% over the full range
- Ability to provide timing information with a precision better than 100 ps for pulses > 20 fC



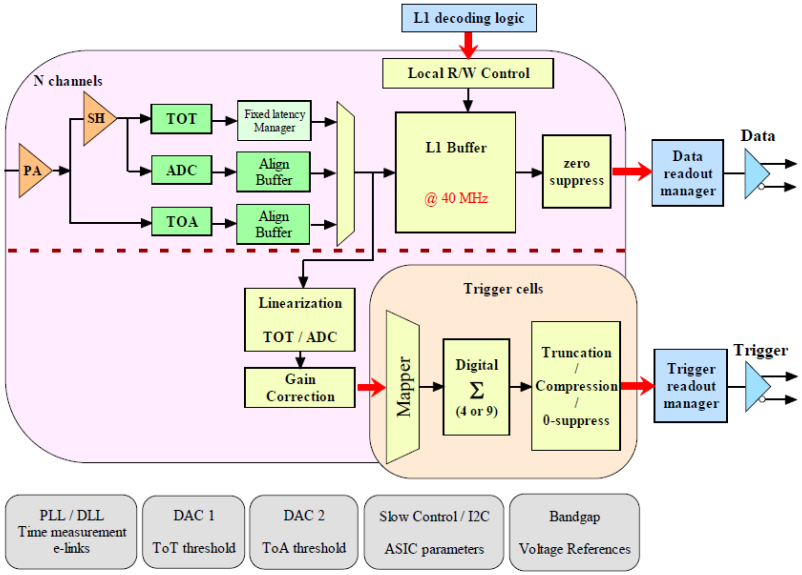
- Compatibility with negative and positive inputs
- Buffering of the data to accommodate the 12.5 μs latency of the L1 trigger
- Fast shaping time (<20ns) to minimize out-of-time pileup
- High-speed readout links to interface with 1.28 Gb/sec low power GBT serializer
- Use 130nm CMOS with 1.5V supply
- < 20 mW/Channel (FE Board + Motherboard)
- High radiation resistance (~2MGy and 10^{16} neq/cm^2)

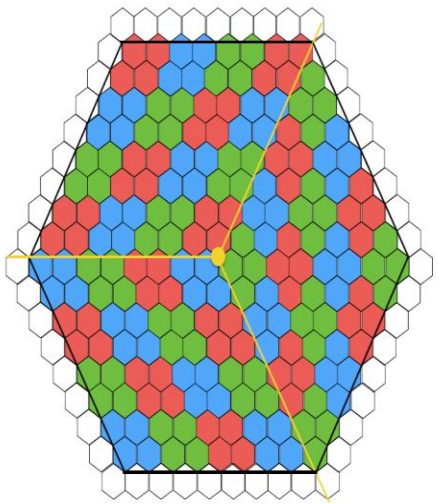
FE-ASIC Evolution

- SKIROC2 ASIC first used by CALICE for SiW ECAL
- SKIROC2CMS received in Q3-Q4/2016
  - Sampling at 40 MHz, Gain (Low/High), Time over Threshold (ToT), Time of Arrival (ToA)
- Test Vehicle 1 (TV1) received in August 2016
  - CMOS 130 nm architecture
  - Dedicated for pre-amplifier studies
- Test Vehicle 2 (TV2) received in May 2017
  - Dedicated for analog channel study
- HGVRCO v1 received recently
  - All analog and mixed blocks
- Final HGCROC submission for production in 2020
  - 78 channels i.e. 3/6 chips per sensor



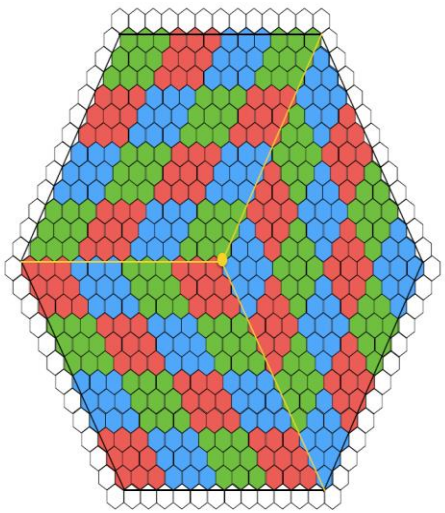
1.28 Gb/s electrical links





200/300 µm

Channel Sum: 2x2



120 µm

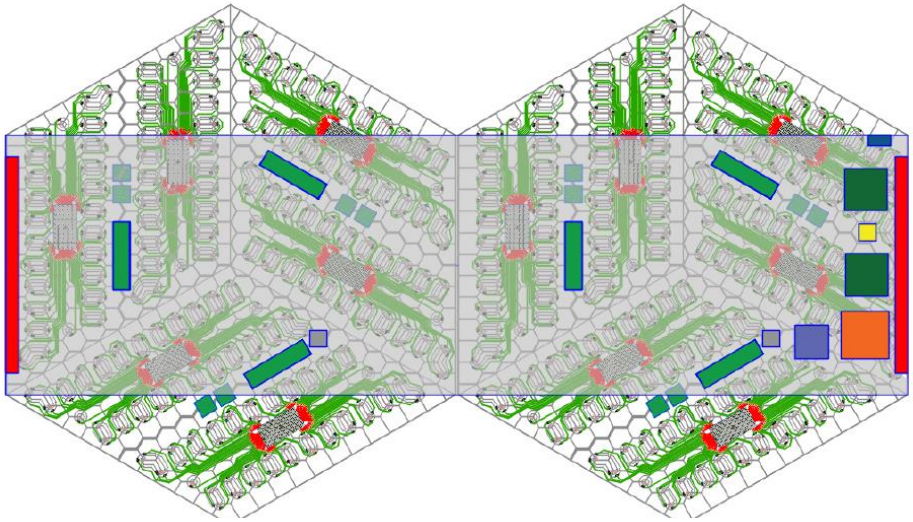
Channel Sum: 3x3

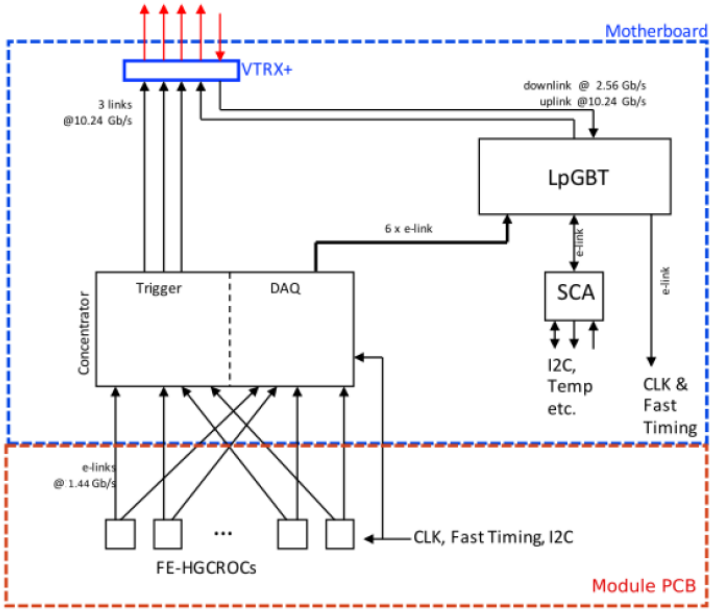
- **Measures charge and time @40MHz**
  - **72 reading out standard cells**
  - **2 reading out calibration cells**
  - **4 channels not connected to any sensor cells for common-mode noise estimation**
  - **Total Sum, 2x2 sum (200 µm and 300 µm) and 3x3 sum (120 µm), Similar Area**
- **Charge measurement: ADC + Time Over Threshold (ToT)**
- **10 bit TDC for Time of Arrival (ToA)**
- **On-board computation of trigger sums**

Motherboard

Data concentrator (for DAQ and Trigger) and LpGBT links

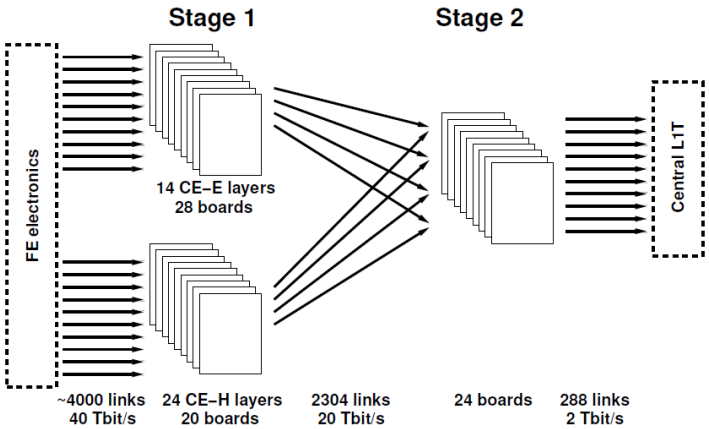
- **Motherboard (Data Concentrator Card)**
  - Concentrator chip: correlates signals from multiple modules
  - 2 Modules/Motherboard
  - Aggregates, formats and serializes data
  - Receives and distributes fast control signals
  - 1.28 Gb/sec Input Electrical link
  - 10.24 Gb/link, Output optical link





Trigger Primitive Generator (TPG) board

- Raw data coming from selective sensors on LpGBT links
  - Alternate layers from the CE-E, i.e. 14 of the first 28 layers.
  - All 24 of the CE-H layers.
- Different types of raw data
  - 2x2 sum (200 µm and 300 µm) and 3x3 sum (120 µm), Similar Area
  - Sum all channels read by HGCROC as per corresponding map
  - Zero suppressed at FE, thus different latency (size) at each BX
- Maximum latency (set by FE concentrator) to 36 BX
- Two stage system with identical hardware
- Trigger primitives passed to central L1 correlator for L1 decision (within 5 us)
- VU9P FPGA daughter card on common hardware board

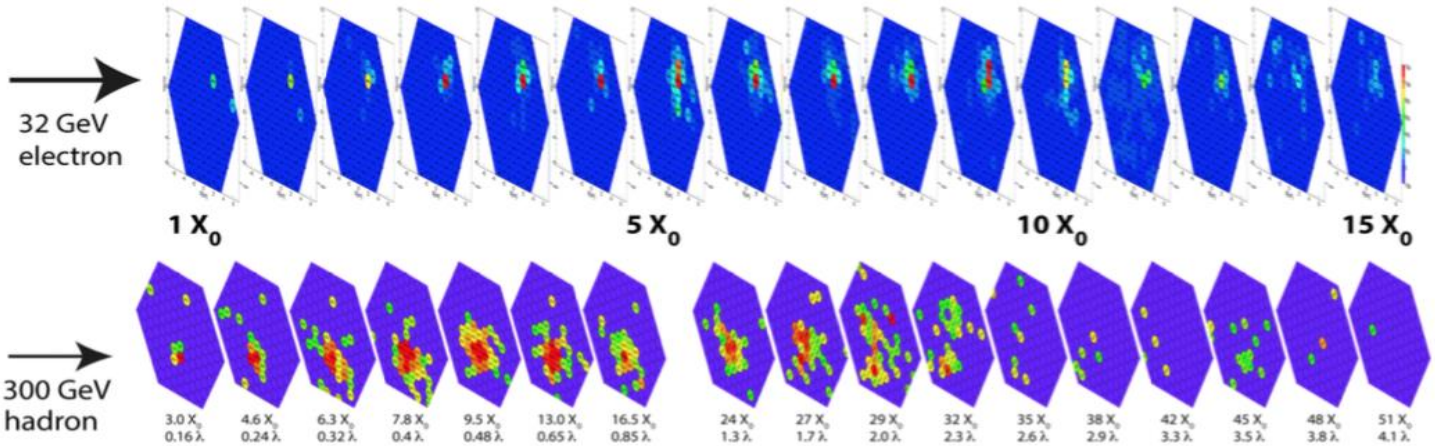


- Stage 1
- The trigger cells are clustered within each layer separately, to form 2-D clusters for each layer.
- Stage 2
- The 2D clusters are clustered together across layers to form 3D clusters.
- The energy maps for each layer are combined to give a total energy map
- CMS-HL-LHC- L1-trigger rate 750-1000 kHz

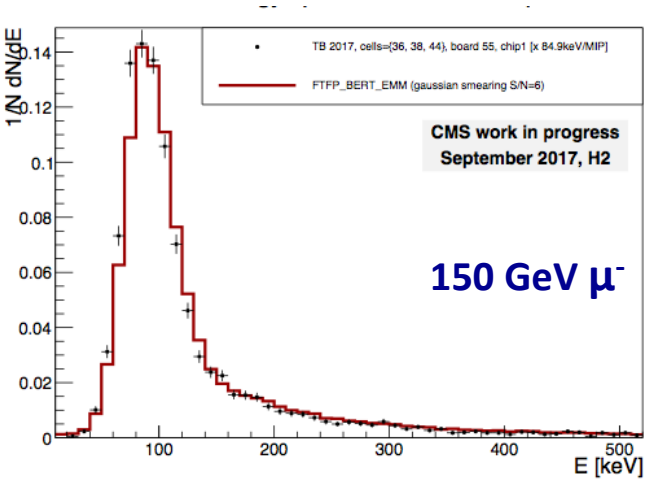
High Granularity Calorimeter: 2016-2018 Test Beam Results

http://iopscience.iop.org/article/10.1088/1748-0221/13/10/P10023/meta

HGCAL Performance at CERN/FNAL Test Beam: 2016-2018



- **Studies in 2016-2017 validated basic design with stable performance**
- **Modules assembled at UCSB, MIP seen in all layers (S/N ~8)**
- **Limited Number of layers: FNAL-16 Layers and CERN-8 Layers**



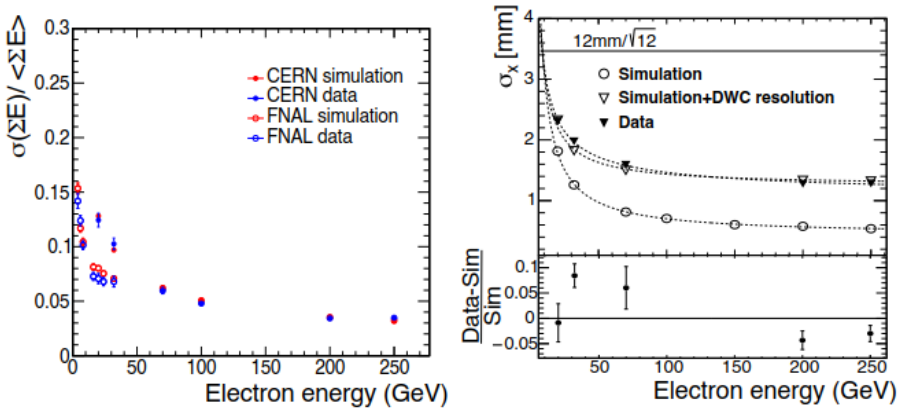
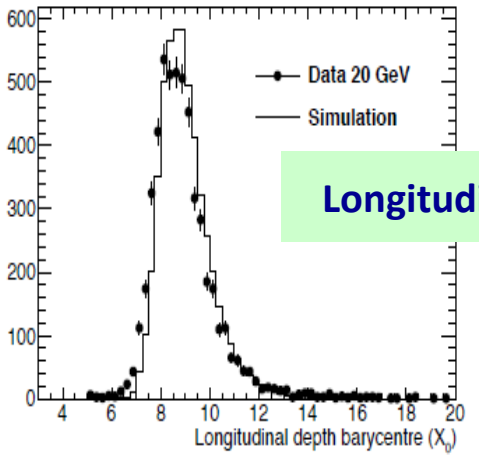
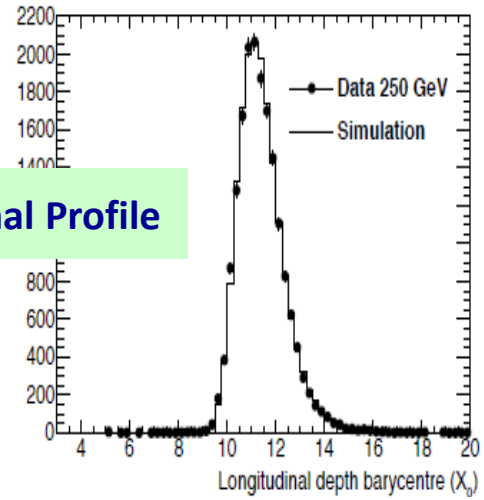


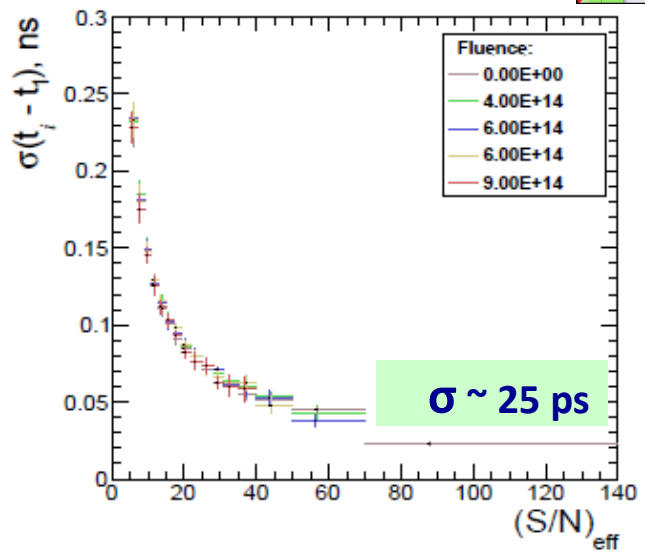
Figure 5.21: Energy and position resolution: (left) relative energy resolution as a function of the electron energy in data and simulated showers, for test beams at FNAL and CERN; and (right) residual width of the x-coordinate reconstruction at a depth of 6 X_0 as a function of incident electron energy.

Shower Studies with Test Beam Data

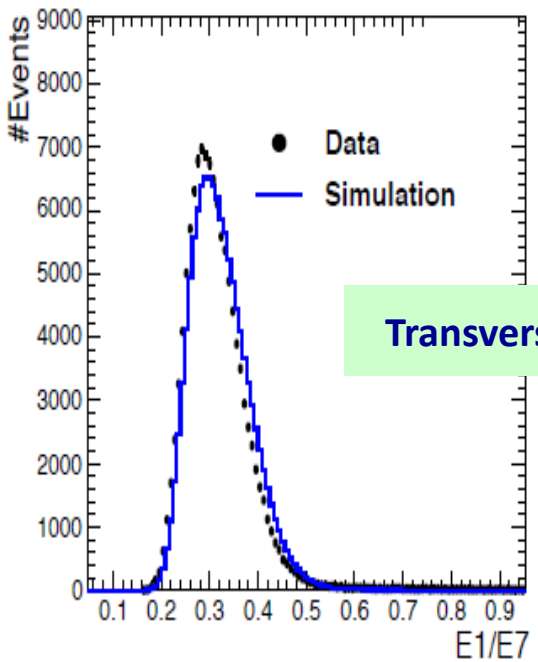


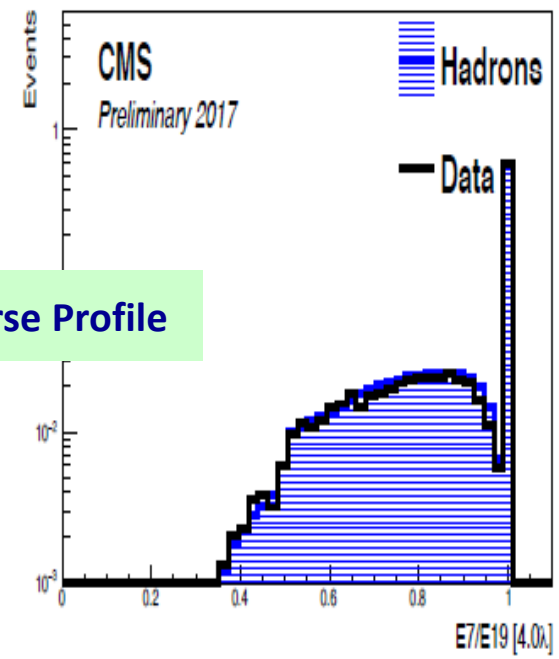


Longitudinal Profile



σ ~ 25 ps





Transverse Profile

Time resolution remains similar for un-irradiated and irradiated sensors

Simulation of longitudinal and transverse profile of showers matches with data

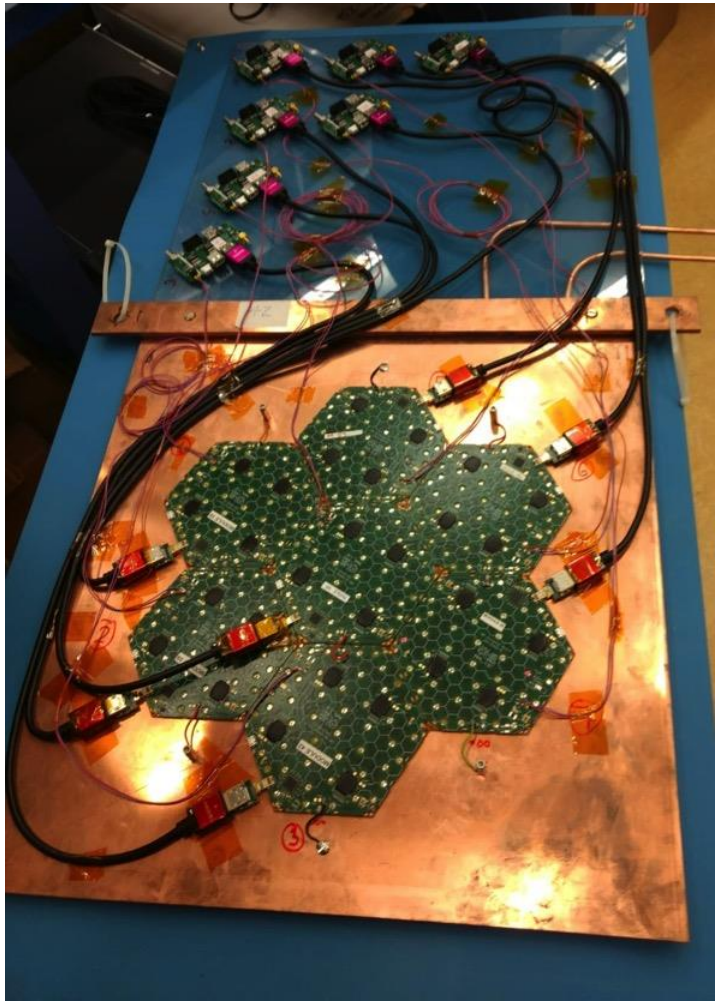
E7, E19 represents energy sum of 7 or 19 pixels around a pixel of highest energy deposit

http://iopscience.iop.org/article/10.1088/1748-0221/13/10/P10023/meta

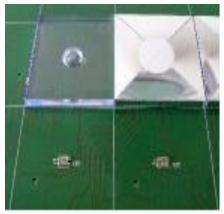
HGCAL TB: Oct.-2018

- To build and operate ~100 prototype hexagonal silicon modules in a beam (official LHCC milestone for HGCAL)
  - Have 93 working modules
- Measure performance of combined ECAL+HCAL & compare with simulation
  - Silicon-based 28 Layers of ECAL
    - 1 Module/Layer (26 X_0, 1λ)
  - Front HCAL from CMS HGCAL
    - 9 Layer: 7 Modules/Layer, 3 Layers with 1 Module/Layer (4l)
  - Scintillator + SiPM rear HCAL from CALICE
    - 39 Layer, 576 Tiles/Layer (4λ)
- Final large-scale beam tests before LS2 i.e. before the Engineering Design Review of HGCAL!
- Electrons and pions of 20, 30, 50, 80, 100, 120, 150, 200, 250 and 300 GeV

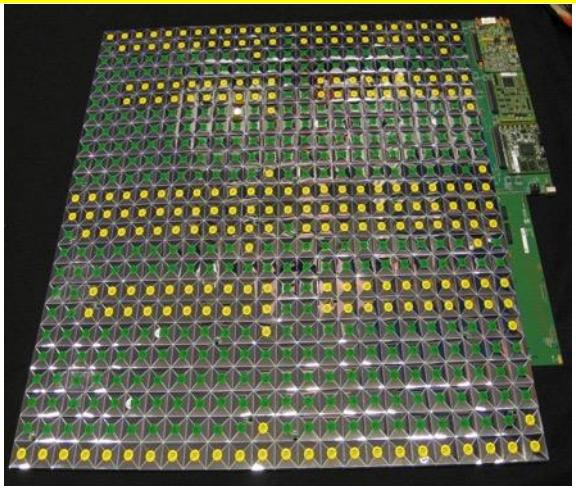
CE-H Layer with 7 Silicon Modules



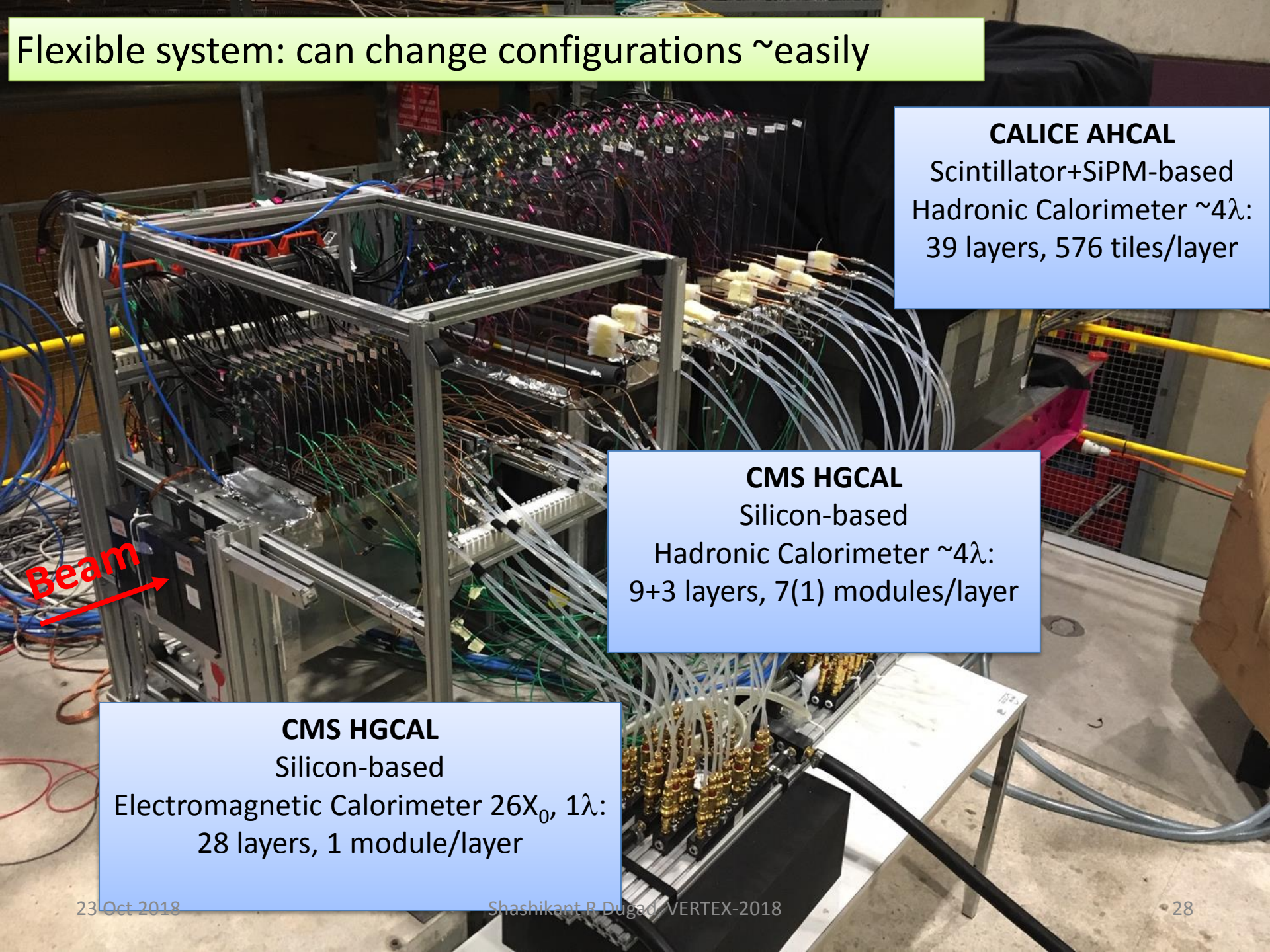
CE-H Layer with AHCAL Scintillators



SiPM



Flexible system: can change configurations ~easily

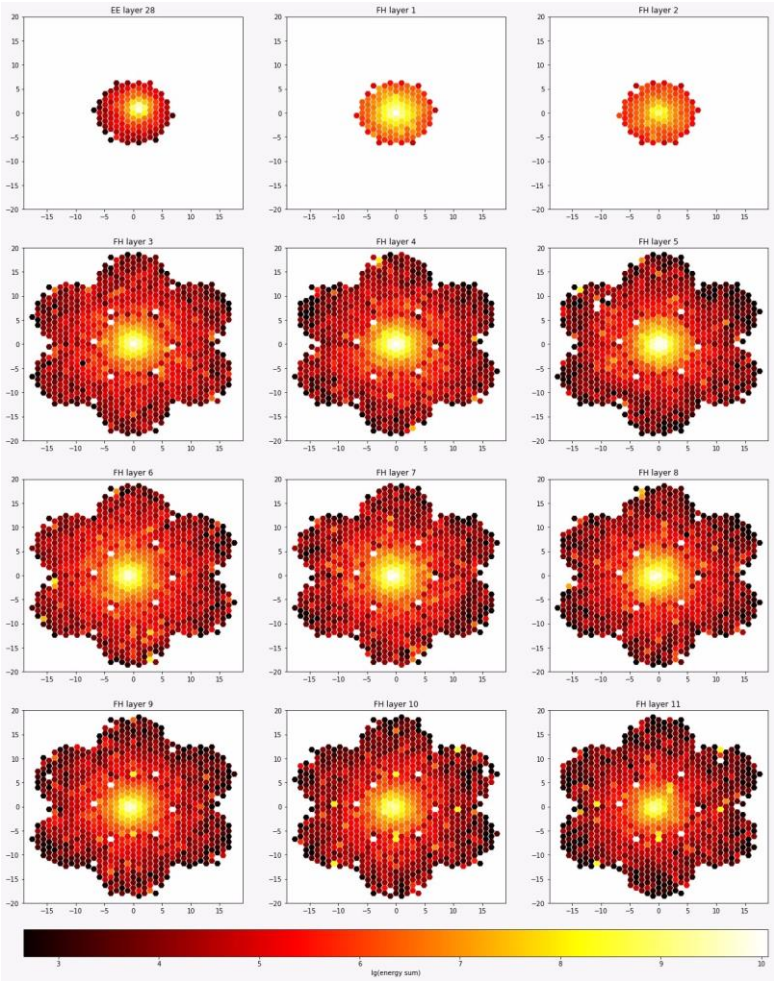


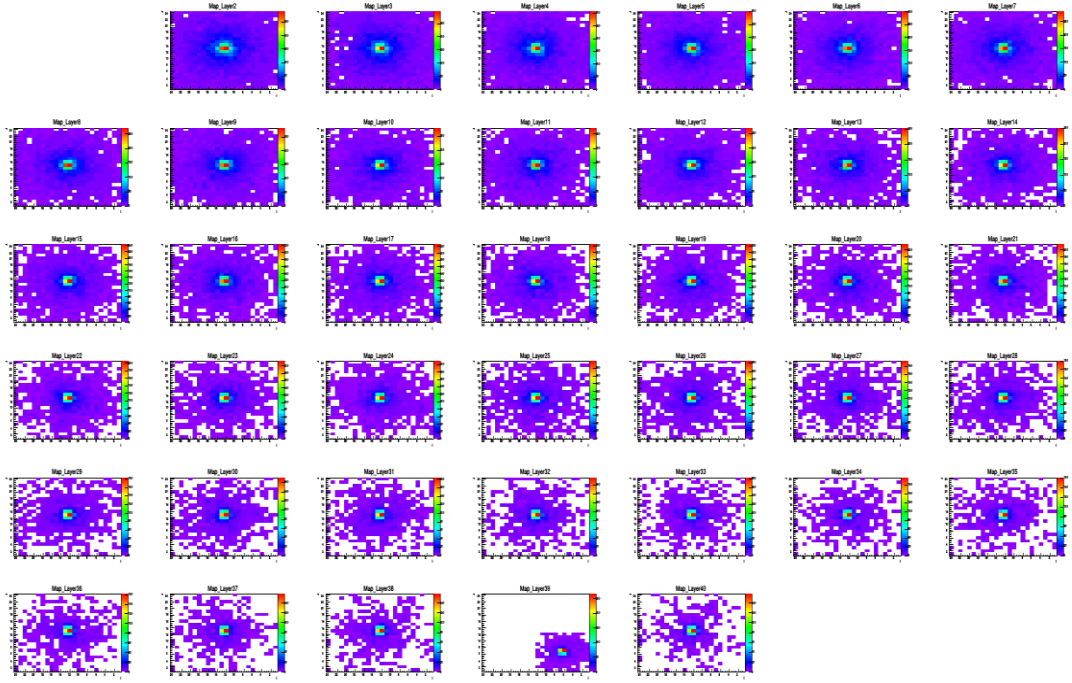
CALICE AHCAL
Scintillator+SiPM-based
Hadronic Calorimeter ~4λ:
39 layers, 576 tiles/layer

CMS HGCAL
Silicon-based
Hadronic Calorimeter ~4λ:
9+3 layers, 7(1) modules/layer

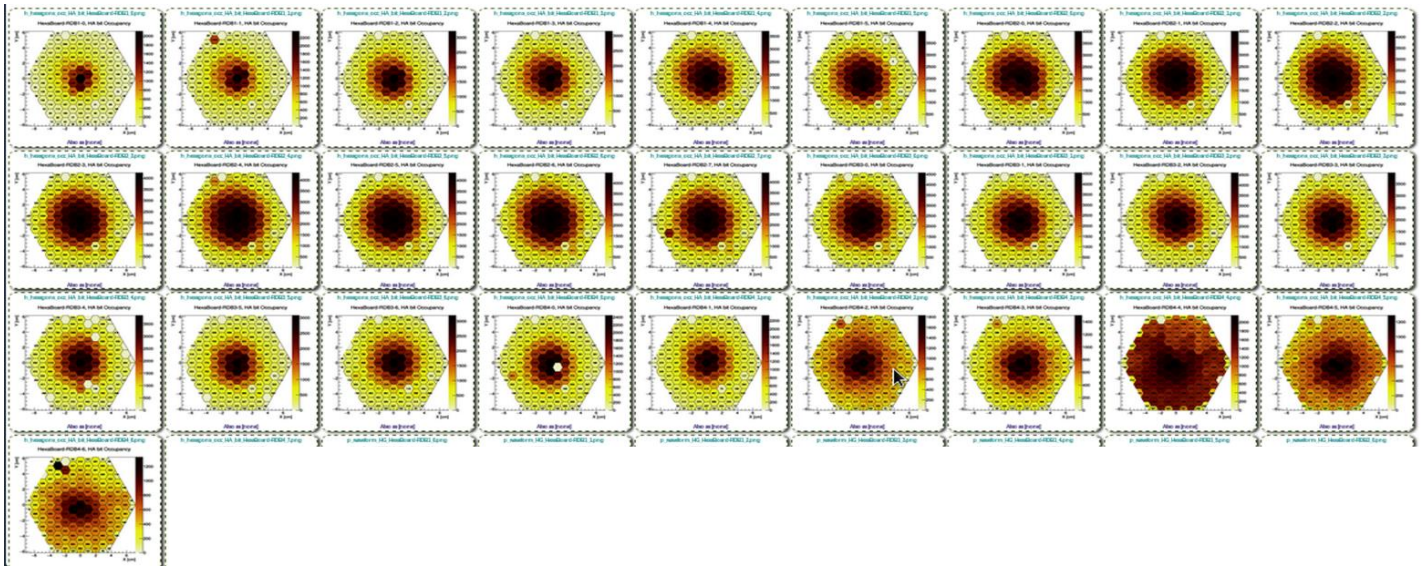
CMS HGCAL
Silicon-based
Electromagnetic Calorimeter $26X_0$, 1λ:
28 layers, 1 module/layer

Occupancy of Si-HCAL (9+3 Layers) and CALICE-Scint-HCAL (39 Layers) for 300 GeV Pions

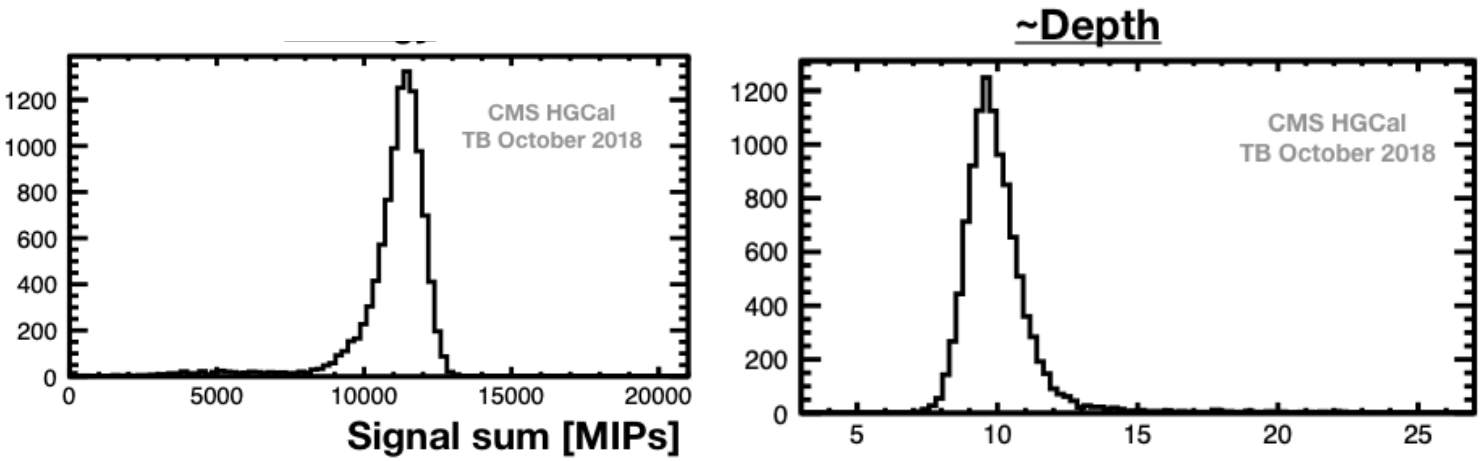




Electrons in 2018 Setup



100 GeV Electrons (Last 3 layers had instability)

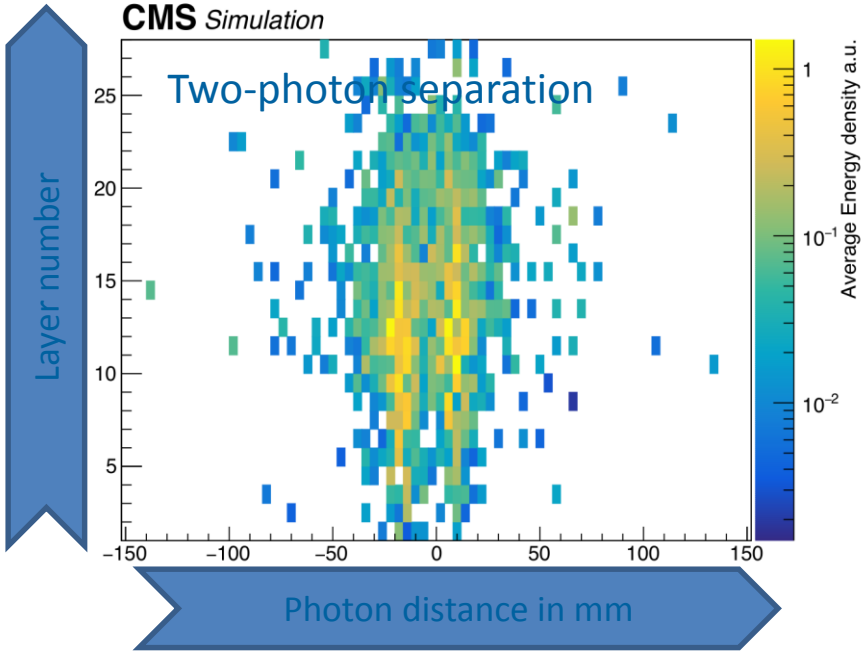


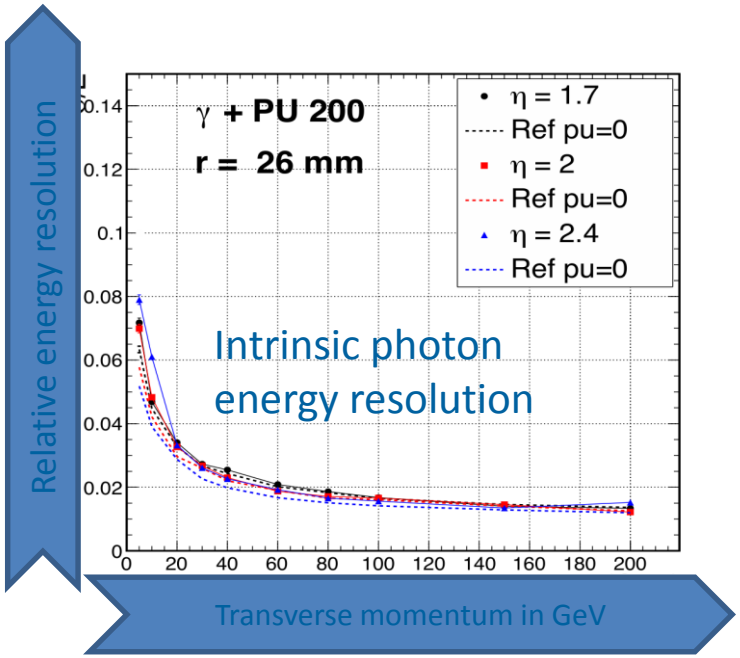
150 GeV Electrons

High Granularity Calorimeter: Performance in CMS Detector (Simulation)

Merged Object Reconstruction During HL-LHC: Simulation Results

- **EM shower direction resolution: < 7 mRad for p_t > 25 GeV**
- **EM shower position resolution: 0.6 mm (from beam test)**
- **3000 fb^{-1}: SNR decreases, resulting noise hardly visible in energy resolution, as long as channel-to-channel inter-calibration uncertainty < 3% -> MIP calibration**





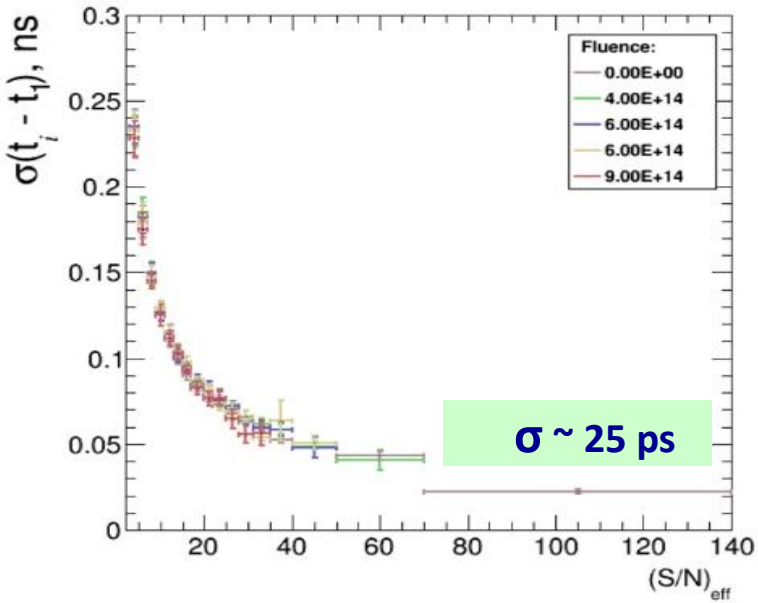
Background during HL-LHC: Simulation Results

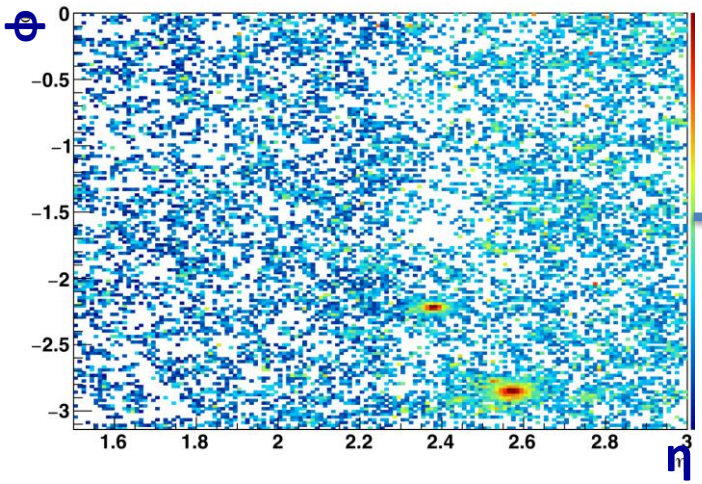
Precision Timing of HGCAL:

- EM > 2 GeV OR Ch. Hadrons > 5 GeV
  - Timing Resolution ~ 25 ps at high S/N

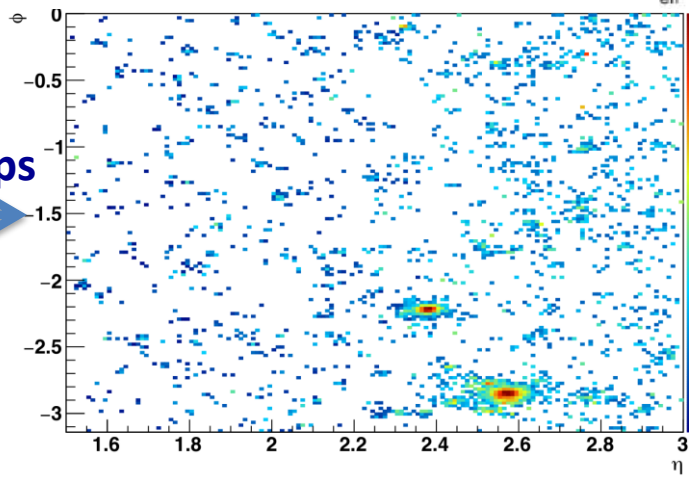
Background Rejection:

1. Apply Timing Cut
2. PF with precision timing

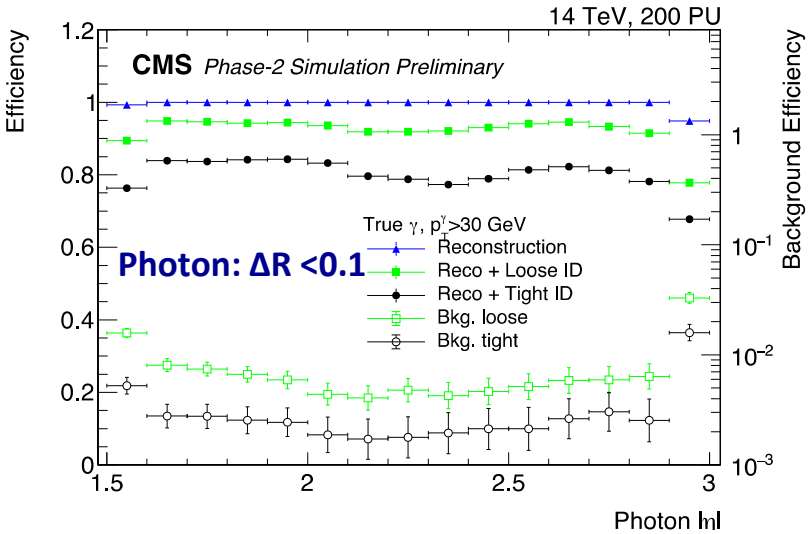


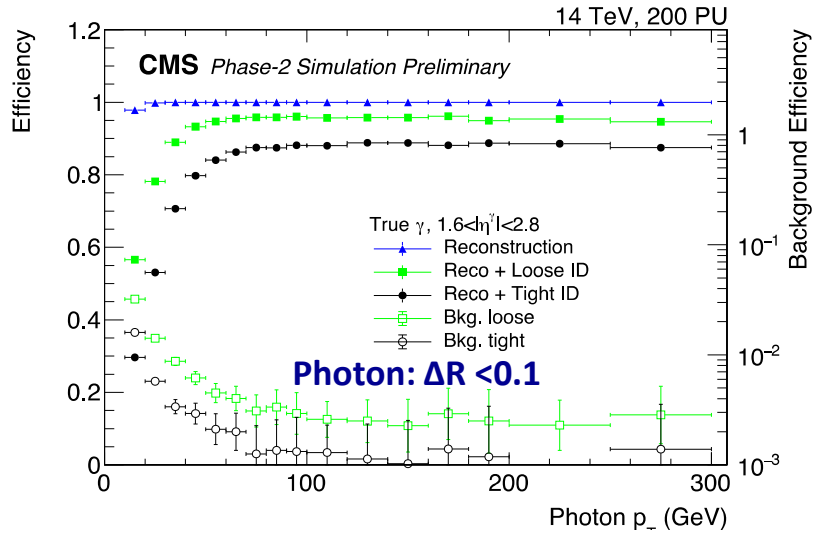


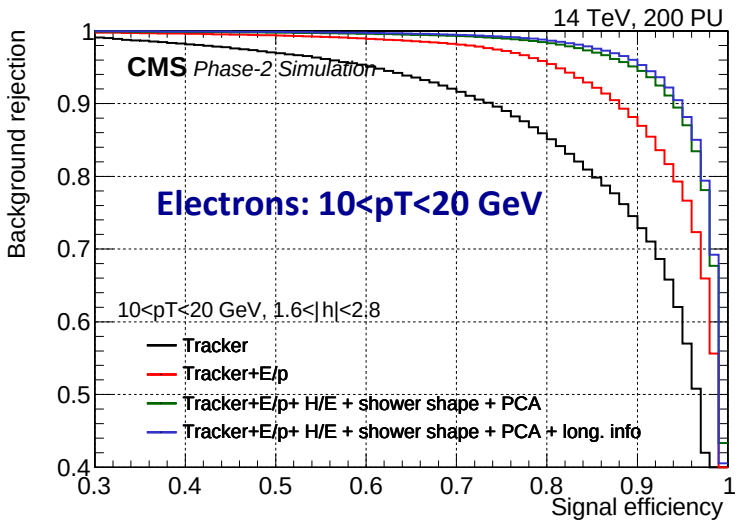
1. |Δt| < 90 ps

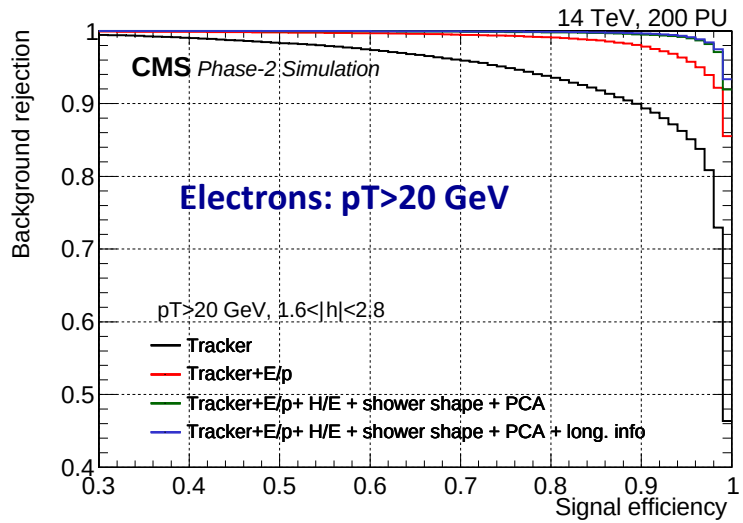


Object Reconstruction during HL-LHC: Simulation Results



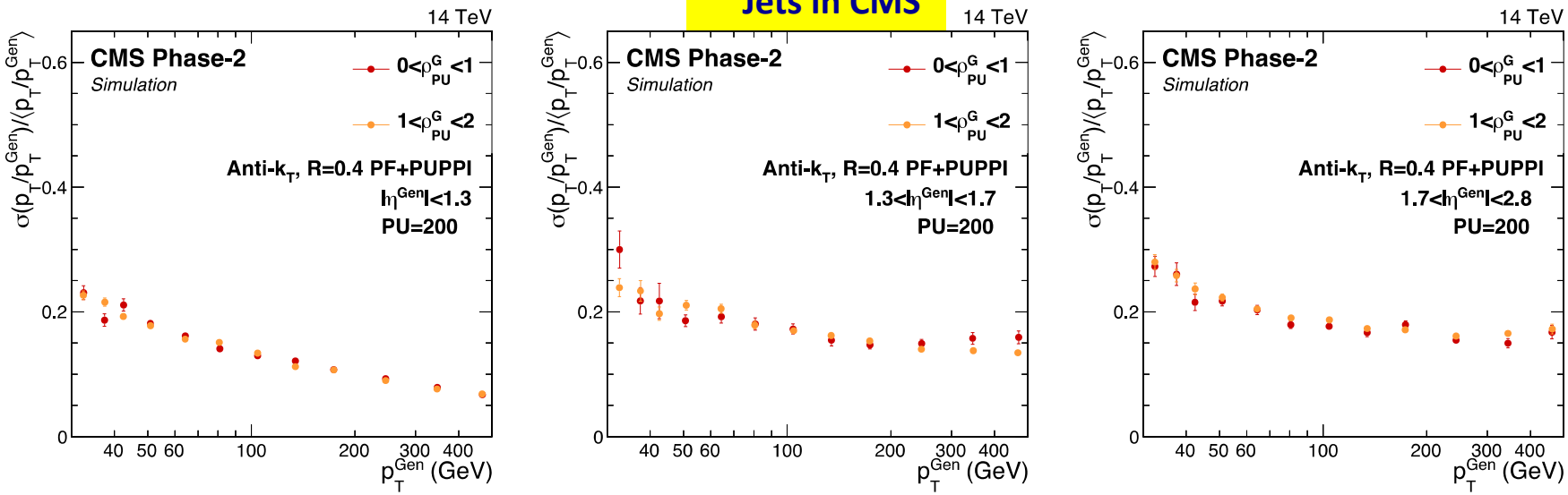




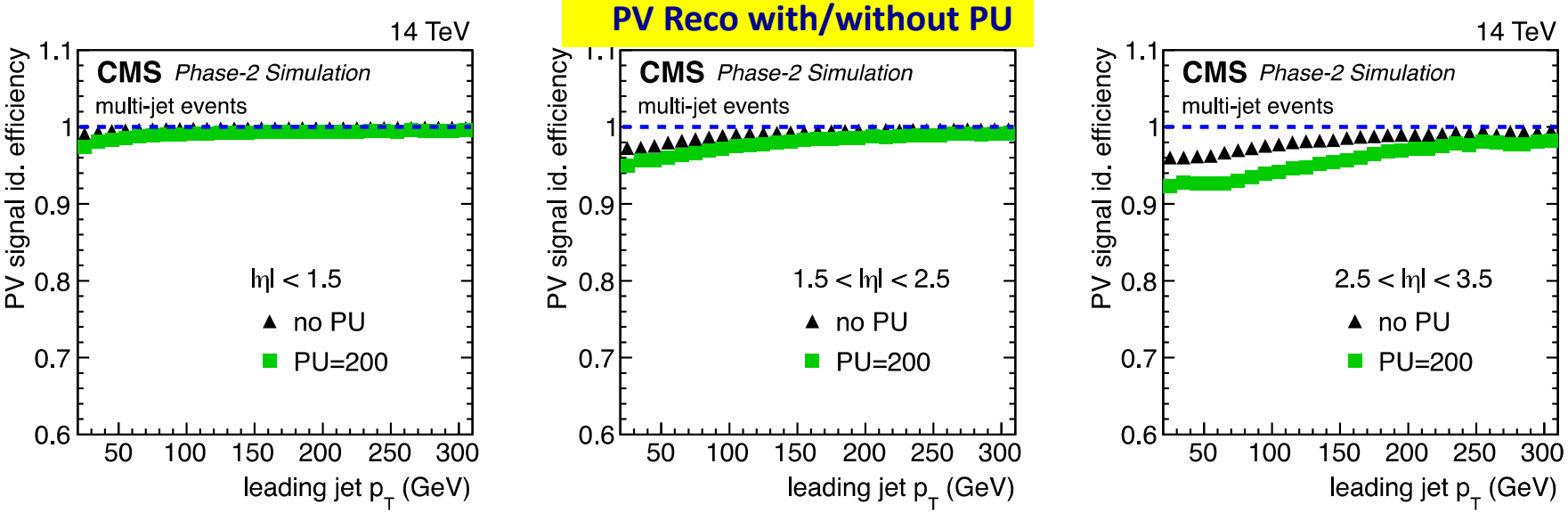


Object Reconstruction during HL-LHC: Simulation Results

Jets in CMS

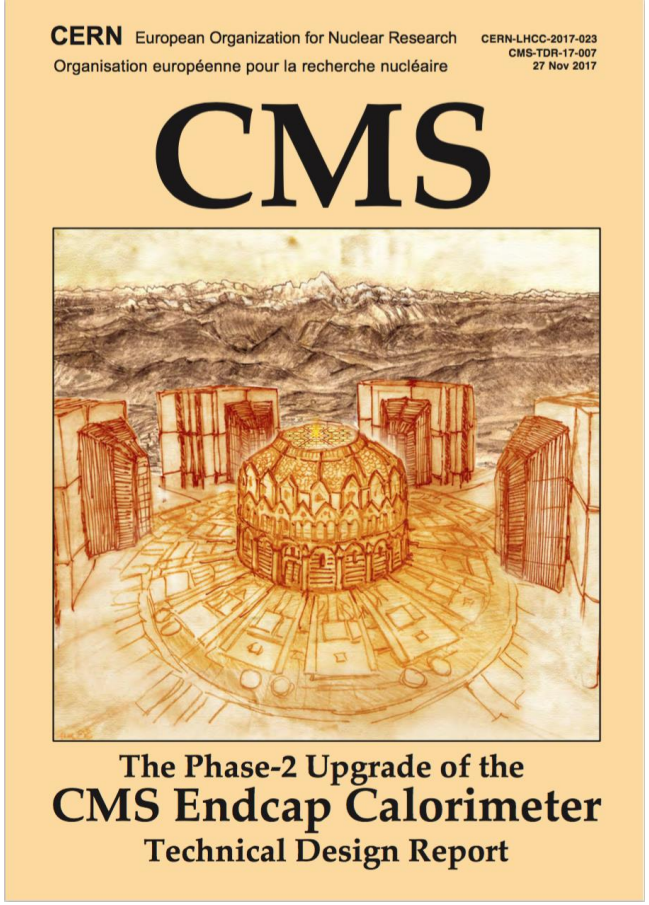


PV Reco with/without PU



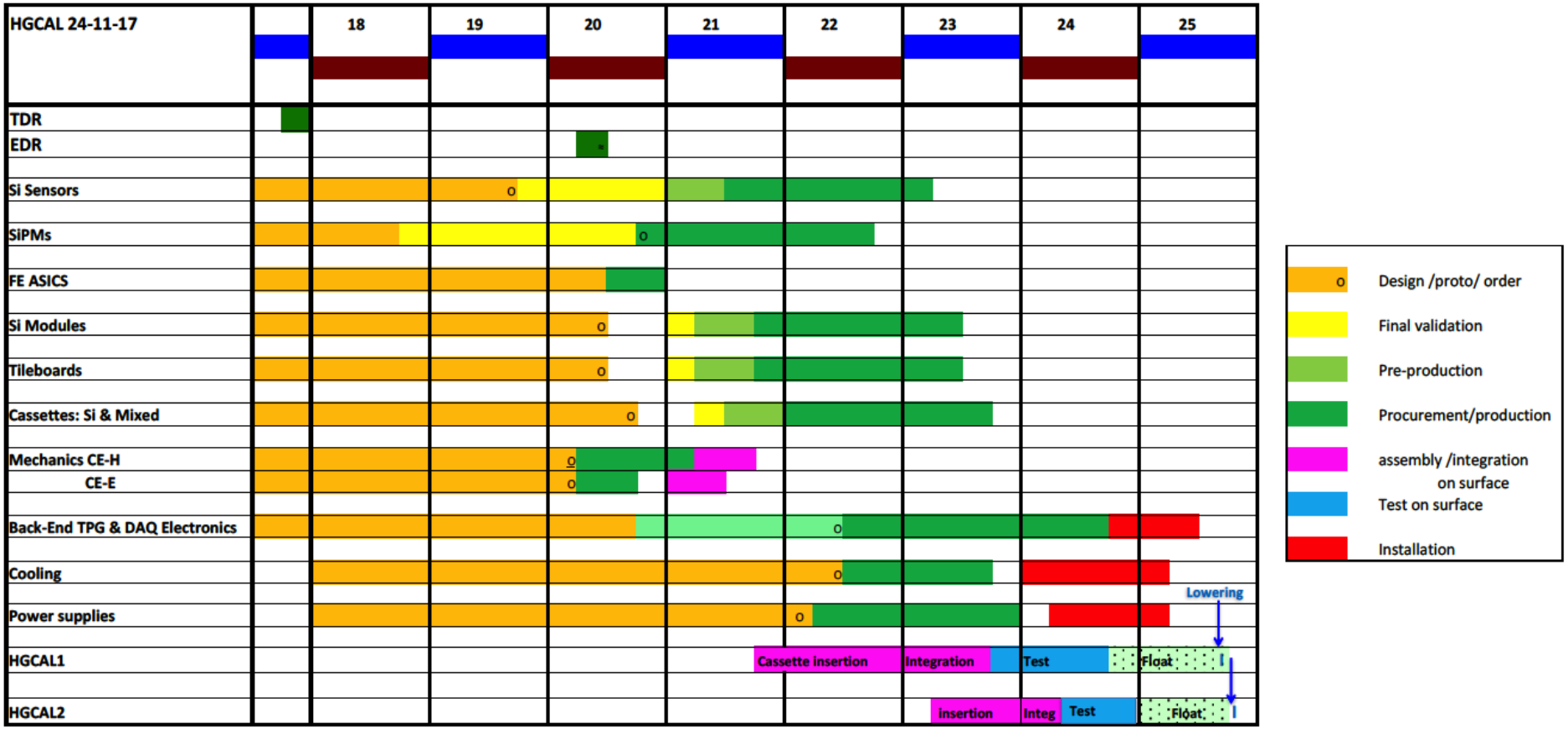
High Granularity Calorimeter: Timeline

HGCAL TDR Submitted in Nov-2017 and accepted on 18th April 2018



- CMS-TDR-17-007
- Further R&D Continues
- Engineering Design Review by 2020
- Production to start in 2021

HGCAL Execution Schedule



Summary

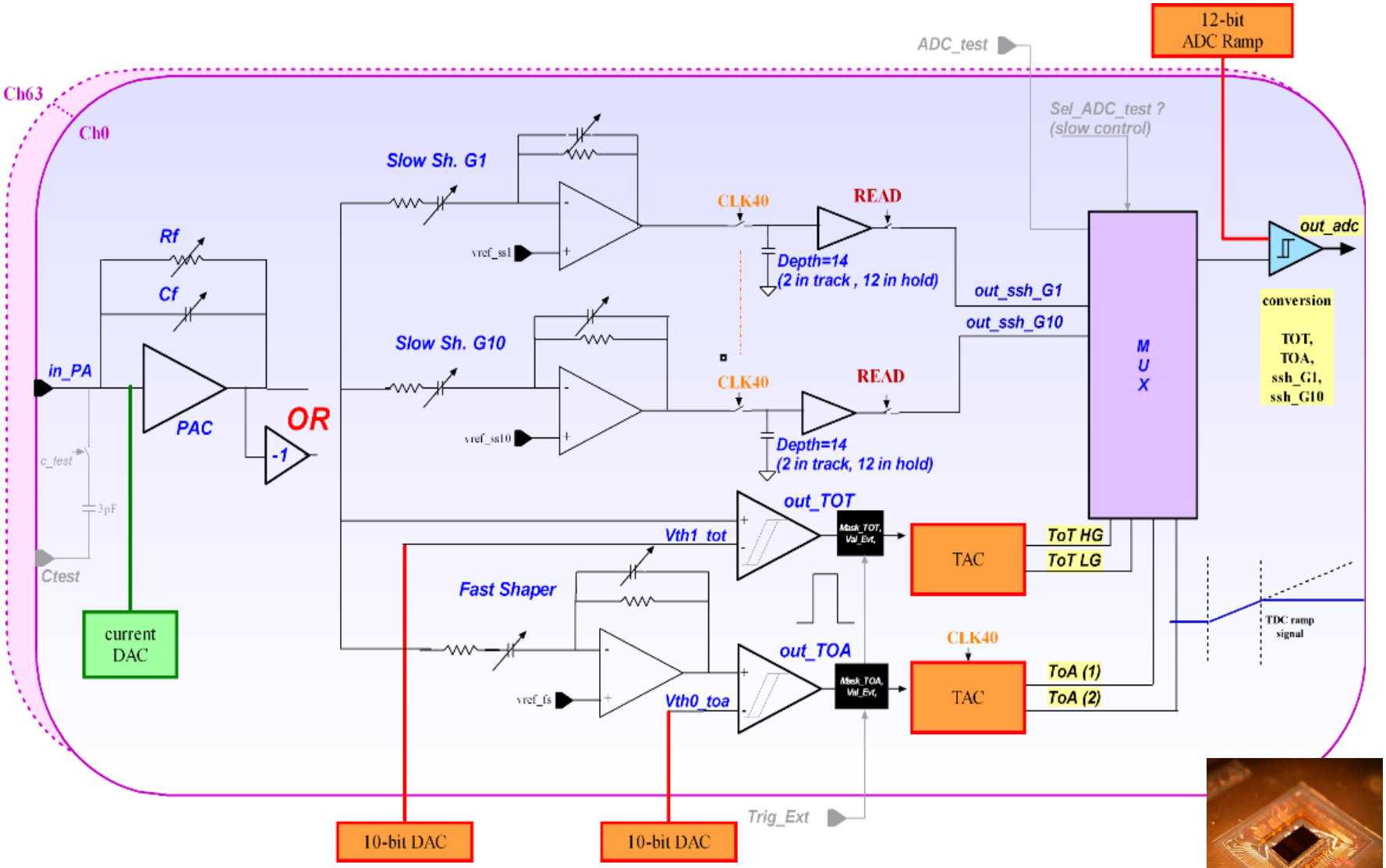
- **High Granularity Calorimeter is a next generation calorimeter**
  - **5-dimensional Calorimeter (X, Y, Z, t, ΔE)**
  - **Radiation Tolerant**
  - **Ideal for reconstruction of VBF processes, merged jets, etc.**
- **Granularity of detector is in sync with particle flow approach**
- **TDR Submitted in Nov-2017 and approved on 18 April 2018**
  - **Engineering Design Review by 2020**
  - **2 years for finalization of design, prototyping etc.**
- **Procurement and production must be completed during 2020-2023**
  - **Installation will start in 2025!**
- **Building this detector is a technological challenge, as is exploiting its features for richer physics**

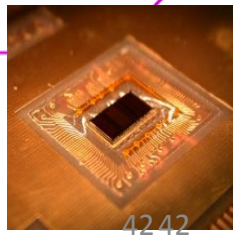
Backup Slides

SKIROC2 Features

- 64 channels, AMS SiGe 0.35 µm, 70 mm^2
- Very large dynamic range:
  - HG for 0.5-150 MIP, LG for 150-2500 MIP
  - Auto-trigger, Analog storage, Digitization & Token-ring Readout
- Very low noise (0.4fC = 2500 e-) and very large dynamic range (2fC up to 10 pC) charge preamplifier
- 180ns shaping time Slow Shapers for charge measurement
- 2-bit shaping time adjustable Fast Shaper (50 to 100ns)
- 10-bit DAC for discriminator threshold, With 4-bit adjustment on each channel
- Analogue Memory depth : up to 15 events can be stored
- Trigger Discriminator for auto-trigger on ½ MIP
- 8-bit adjustable delay to position the Hold signal
- Digitization of either time and charge or of both charges
- Rail Supply: 3.3V
- Ultra low power consumption : 1.5uw / channel, (1.7mW / device)

SKIROC2-CMS (HGCROC) Architecture





- Hexagonal on 200 mm p-type silicon wafer
  - to maximize wafer area usage
  - to minimize number of modules
  - p-type more radiation-tolerant than n-type
- Planar DC-coupled diodes as active cells
  - 192 cells (1 cm²) on 200 and 300 µm sensors
  - 432 cells (0.5 cm²) on 120 µm sensors
- Three thicknesses based on radiation and occupancy considerations

Table 5.1: Longitudinal structure of the HGCAL, comparing the thicknesses of what is simulated in CMSSW with what is described in the engineering sections of this document. The thickness is measured in centimeters (cm), radiation lengths (X_0), and nuclear interaction lengths (λ).

	CMSSW			TDR design		
	cm	X_0	λ	cm	X_0	λ
Neutron moderator	18.0	0.4	0.2	15.7	0.3	0.2
Electromagnetic section	32.1	26.7	1.6	33.9	25.4	1.6
1st hadronic section	59.7	33.8	3.1	60.2	35.2	3.7
2nd hadronic section	110.6	62.8	5.8	100.6	49.9	5.2
Total	220.4	123.6	10.7	210.4	110.9	10.7

Thickness [µm]	# cells	Cell size [cm²]	Cell C [pF]	Bulk polarity	Expected Fluence [E15 n cm⁻²]	# wafers (8 inch)	# partial 8 inch wafers
300	192	1.18	45	p (n)	0.1-0.5	13164	1284
200	192	1.18	65	p	0.5-2.5	8712	144
120	432	0.52	50	p	2-7	3000	324
					Total:	24876	1752

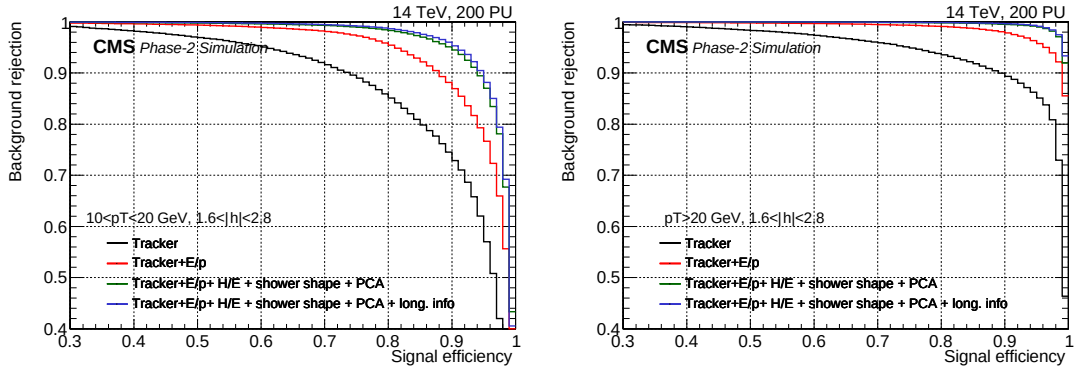


Figure 11.3: Purity as a function of the efficiency for electrons (left) with $10 < p_T < 20$ GeV, and (right) with $p_T > 20$ GeV for different sets of input variables in the BDT multivariate estimator.

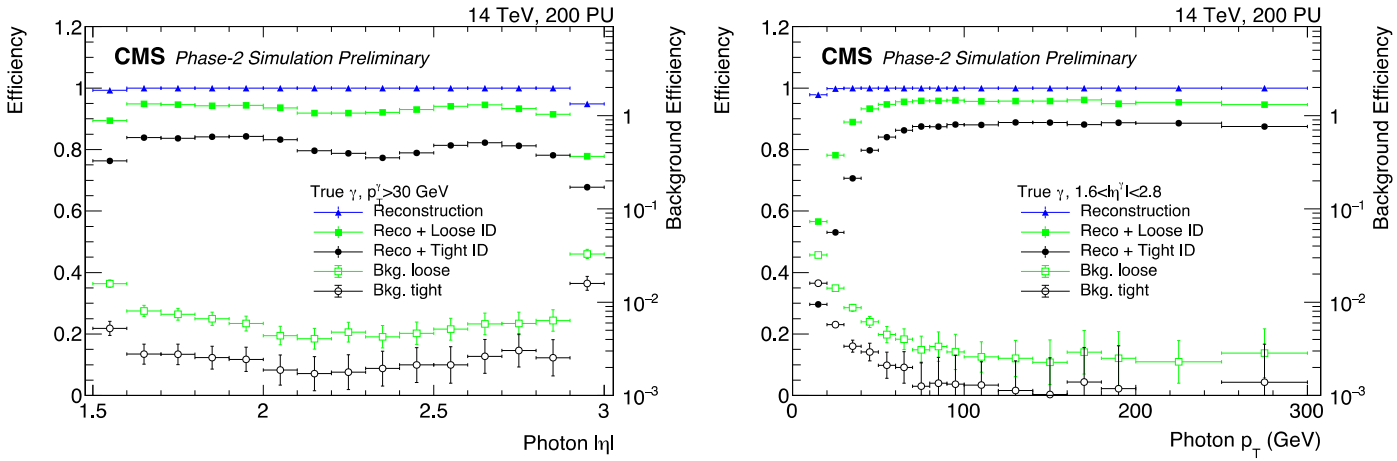


Figure 11.7: Photon reconstruction efficiency, identification efficiency, and photon misidentification probability, for two ID working points, (left) as a function of generated photon $|\eta|$ and (right) p_T. The photon reconstruction efficiency is defined as the efficiency for which a reconstructed photon is found within $\Delta R(\eta, \phi) < 0.1$ of a generated prompt photon. Identification efficiencies for signal photons are relative to the generated prompt photon. Misidentified photons are defined as reconstructed photons not matched to an isolated generated photon.

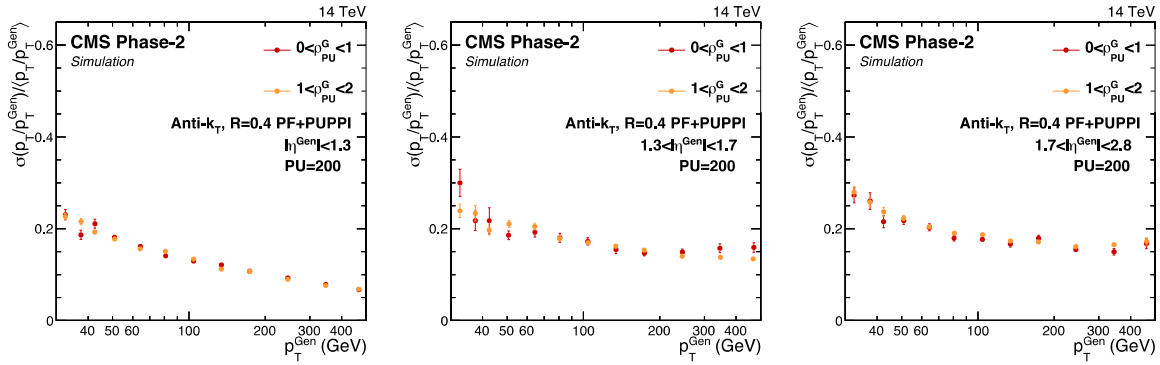


Figure 11.8: Corrected jet response resolution in (left) $|\eta| < 1.3$, (middle) $1.3 < |\eta| < 1.7$, and (right) $1.7 < |\eta| < 2.8$ as a function of $p_{\mathrm{T}}^{\mathrm{Gen}}$ for PF+PUPPI jets in the PU=200 sample.

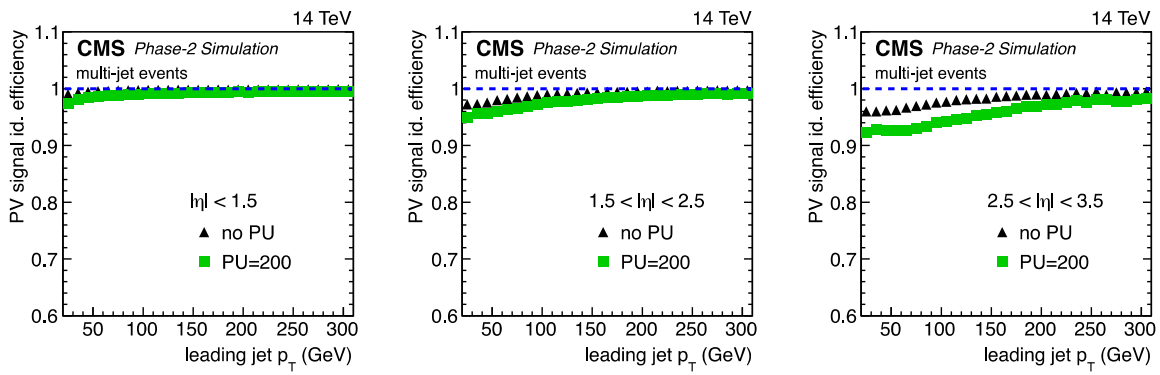
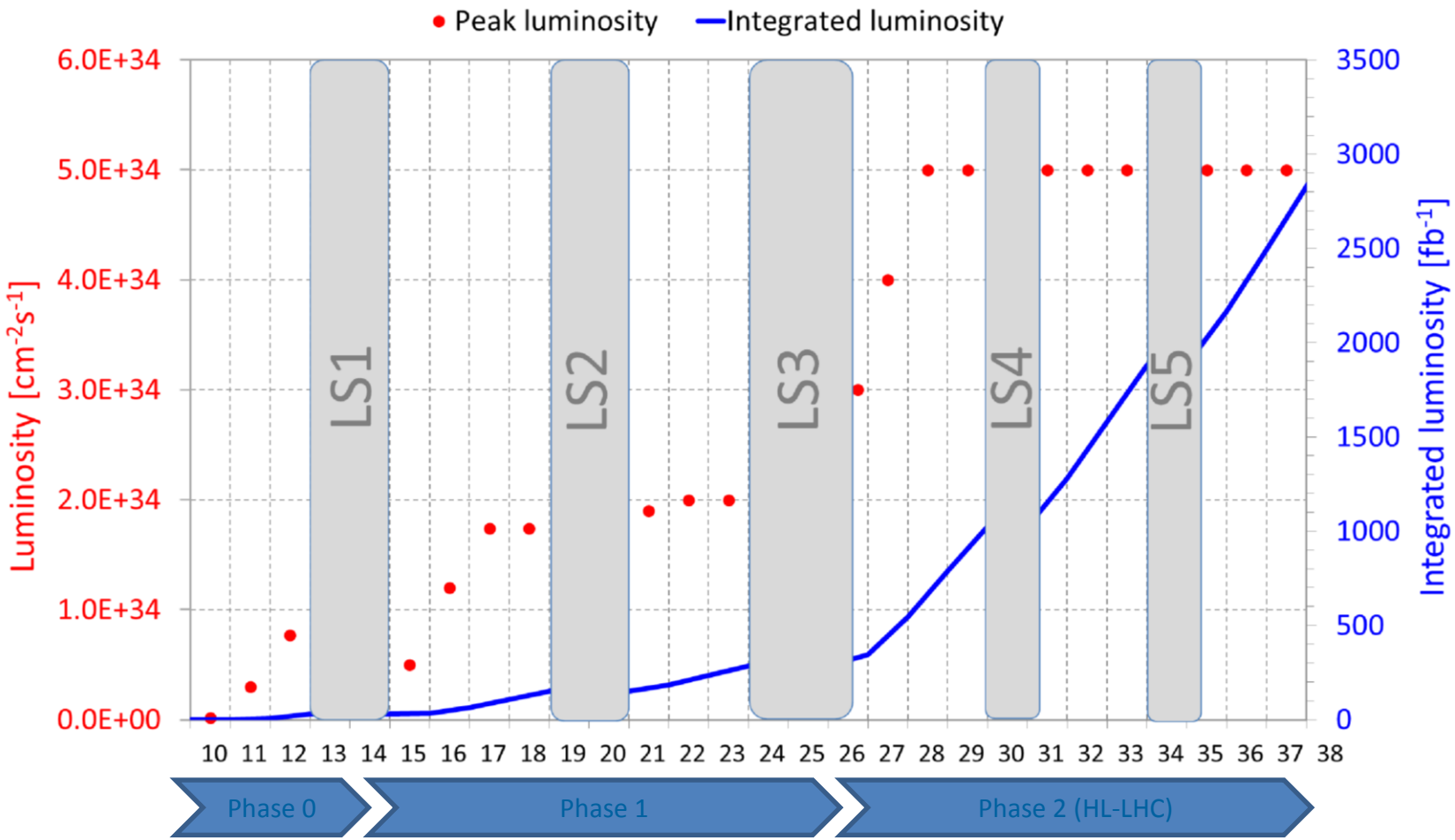


Figure 11.11: Efficiency to reconstruct the hard interaction vertex and to identify it correctly as the primary vertex (PV), as a function of the leading jet p_{T} in simulated multi-jet events with ≥ 2 jets. The leading jet, i.e. the jet with highest p_{T}, is contained in the $|\eta|$ range (left) 0–1.5, (middle0 1.5–2.5 or (right) 2.5–3.5. The identification efficiency for PV signal jets increases with the leading jet p_{T}. Compared to events without pileup (black triangles), it is slightly lower at PU = 200 (green squares).


Peak luminosity
Integrated luminosity
Luminosity [cm-2s-1]
Integrated luminosity [fb-1]
6.0E+34
5.0E+34
4.0E+34
3.0E+34
2.0E+34
1.0E+34
0.0E+00
3500
3000
2500
2000
1500
1000
500
0
LS1
LS2
LS3
LS4
LS5
10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38
Phase 0
Phase 1
Phase 2 (HL-LHC)