The CMS High Granularity Calorimeter for HL-LHC

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on behalf of the CMS Collaboration

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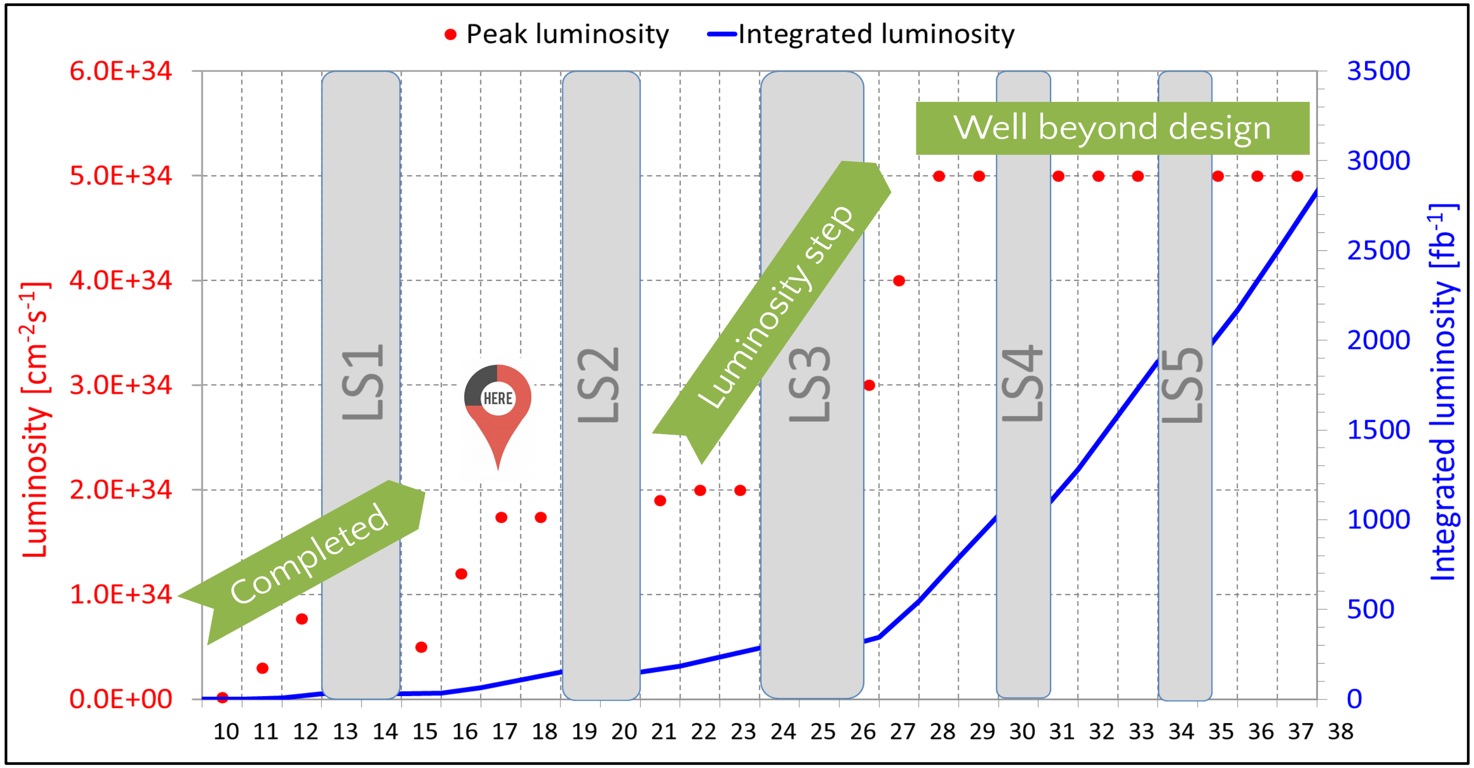
Outlook

In this talk:

- Brief Introduction
  - Toward the upgrade of CMS for the HL-LHC era
- The CMS Phase-II Endcap Calorimeter upgrade
  - Introduction to CMS Phase-II upgrade
- The HGCal detector
  - Layout, mechanics, read-out, electronics and performance
- The HGCal L1-Trigger
  - The HGCal L1-Trigger: hardware and software
- Plans and Conclusions

Introduction

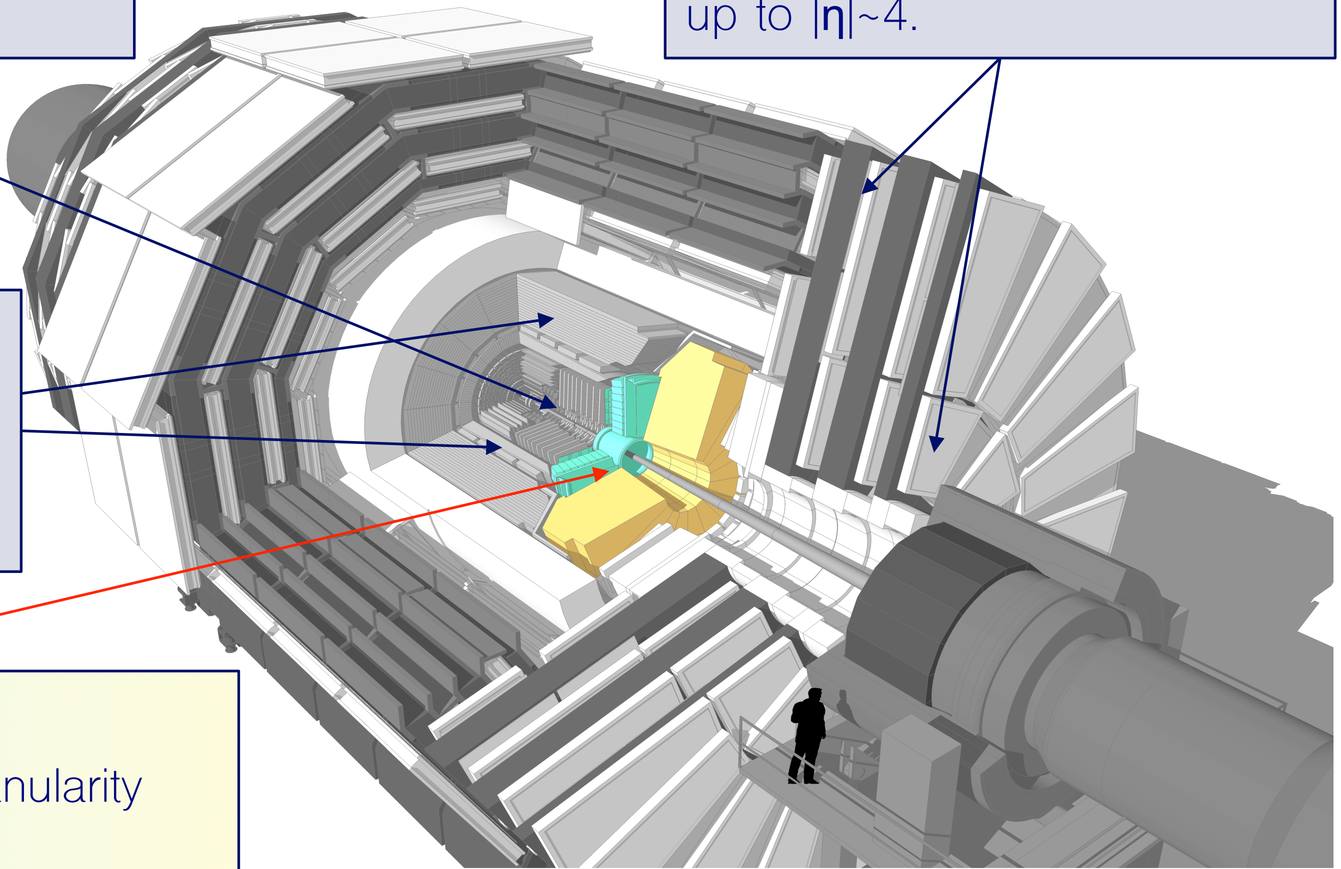
- **Machine upgrade**
  - ➔ Luminosity needed to deliver the demanding physics program for Phase-2
- **Detector upgrade**
  - ➔ To maintain excellent performance in the harsh HL-LHC environment
- **Key role of the forward calorimeter**
  - ➔ SM and BSM searches, complementary to the tracker upgrade



The CMS Phase-II Upgrade

New Tracker:
- More radiation tolerant, higher granularity and less material
- Coverage up to $|\eta|$~4.
- Tracks in hardware trigger

Muon Detector:
- Compete RPC coverage in forward region (GEM/RPC)
- Nominal coverage up to $|\eta|$ ~2.4. Investigating μ-tagging up to $|\eta|$~4.



Barrel Calorimeters:
- New electronics
- Higher granularity for L1 trigger
- Depth information in HCAL

New Endcap Calorimeter:
- More radiation tolerant, high granularity
- Coverage 1.47<$|\eta|$<3.0.
- Timing information to mitigate PU

HGCal General Layout

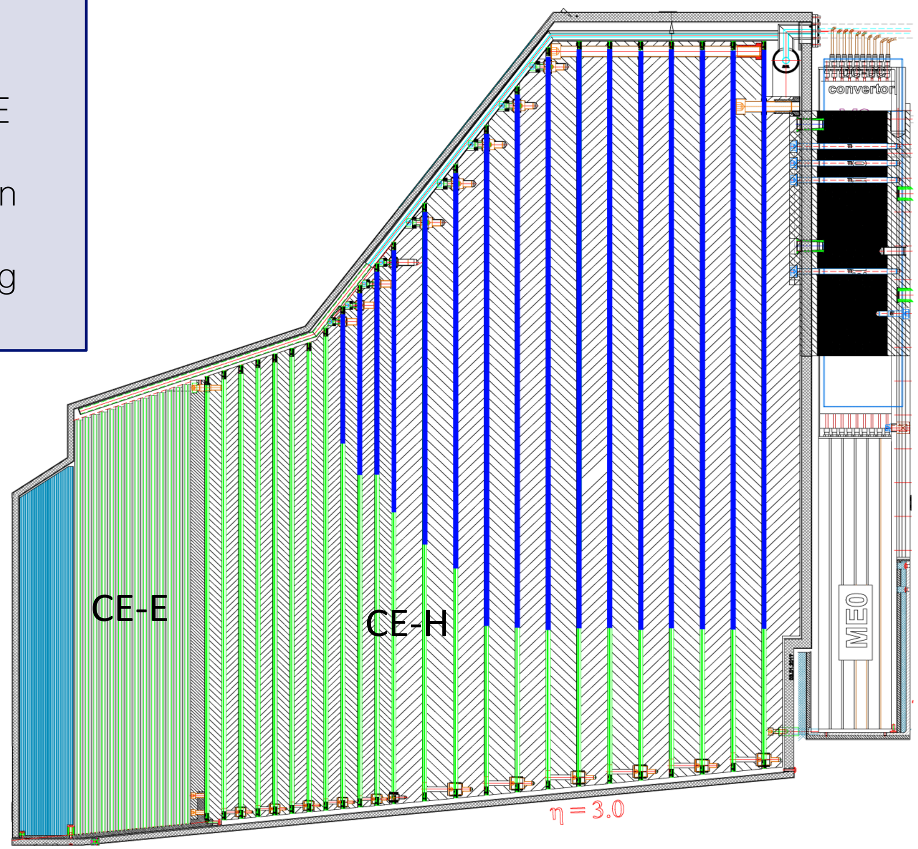
High Granularity sampling Calorimeter (HGCal)

Active Elements:

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

Key Parameters:

- EC covers 1.5<|η|<3.0
- Full System maintained at -30°C
- ~600m2 of silicon sensors
- ~500m2 of scintillators
- 6M Si channels, 0.5cm^2 or 1.0cm^2 cell size
- ~22000 Si modules
- Power at end of HL-LHC: ~60kW per endcap



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

Mitigating radiation damage:

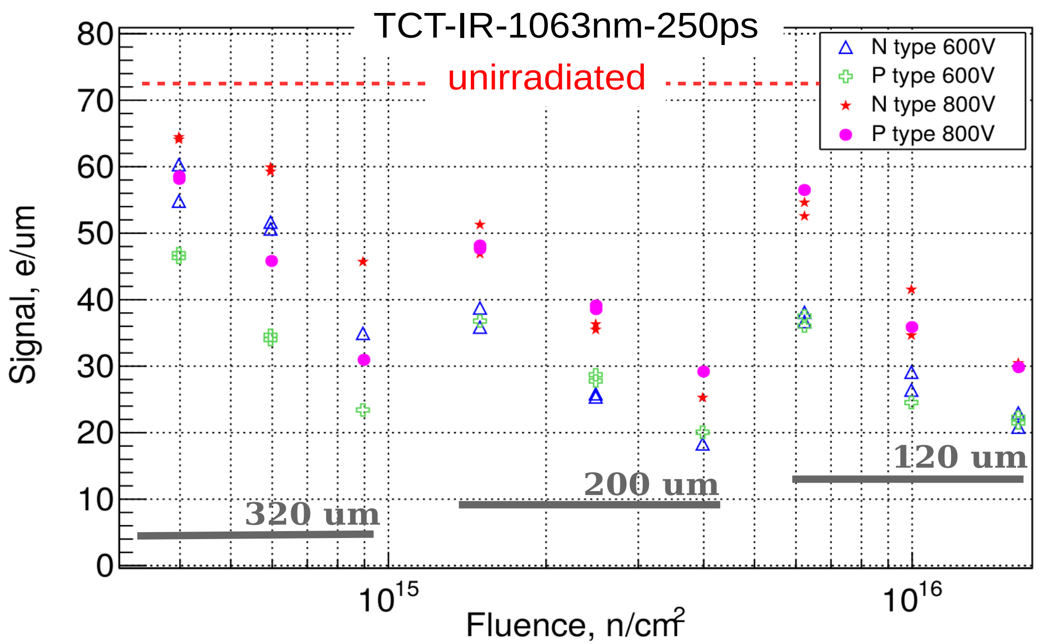
- Mitigate leakage current noise ➔ **cooled to -30˚C** (cooling fluid is CO_2)
- Mitigate signal loss ➔ **thinner sensors** and **higher** bias **voltage**

Potential to use timing information to reject the PU:

- Reach intrinsic **time resolution of O(25ps)**

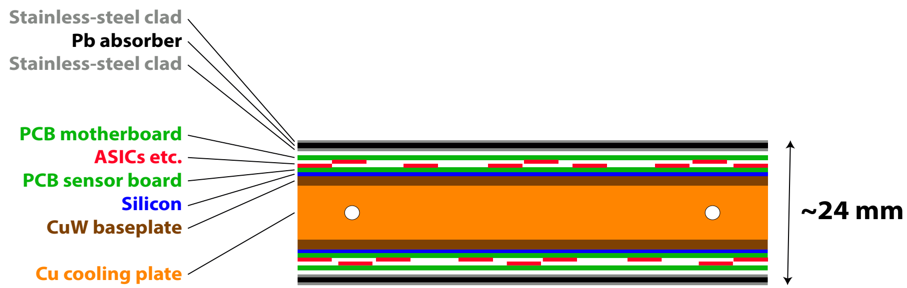
Si Sensors:

- 3 different active thicknesses: (100, 200, 300) μm
- Thinnest sensors in the innermost region with smaller cell size (~0.5cm²)
- Smaller cells ➔ less PU noise (less dose)



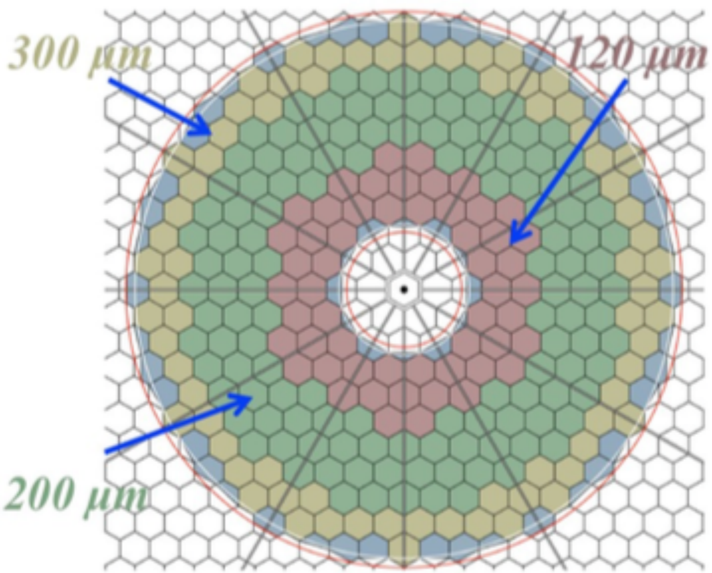
Mechanical Design:

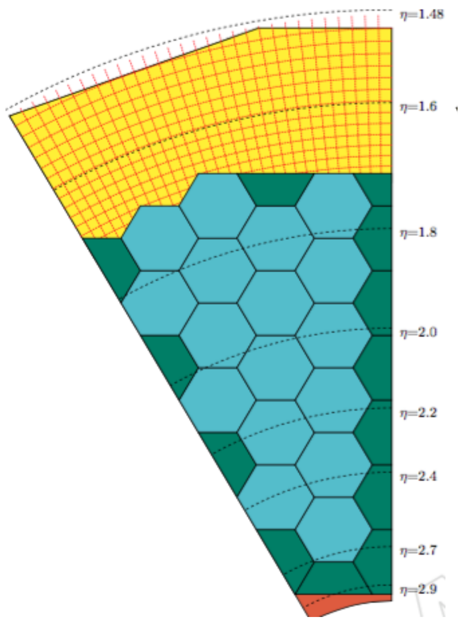
- CE-E: Pb+Cu absorber integrated into cassettes
- CE-H: steel absorber, full disk + cassettes inserted between absorber

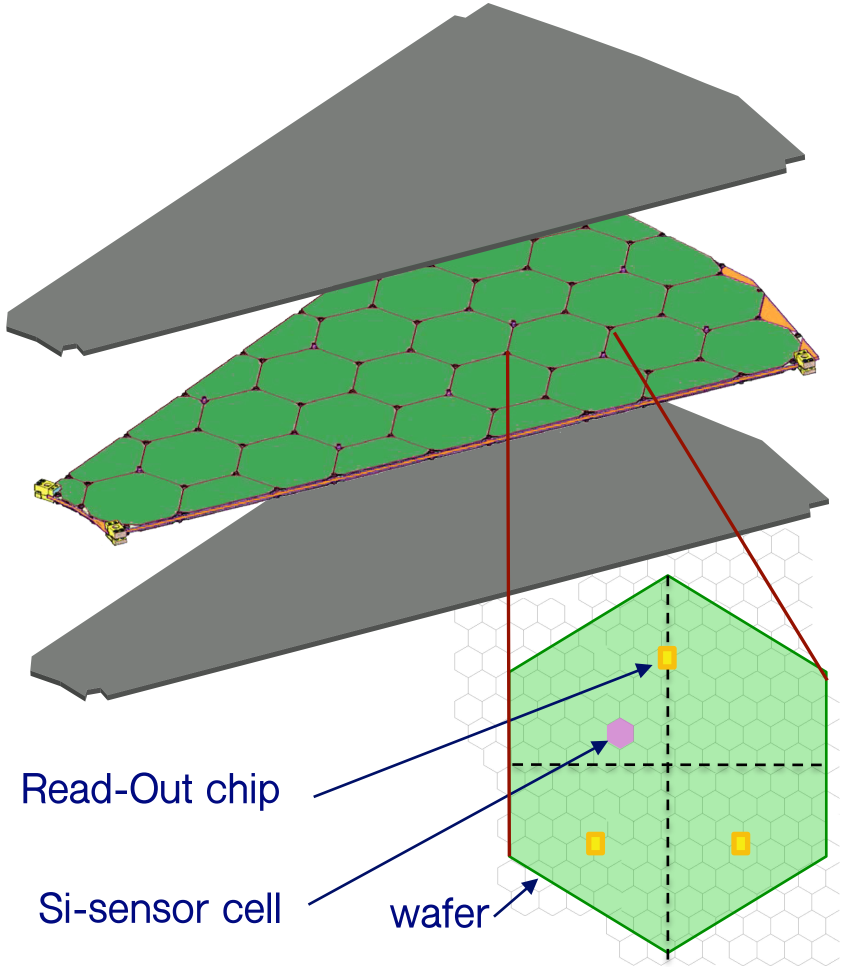


Layers structure:

- Only Si in CE-E+front CE-H, mixed layers with Si/plastic scintillators for rest of CE-H
- Plastic scintillators with on-tile SiPM in CE-H low|η| region, (radiation is tolerable)



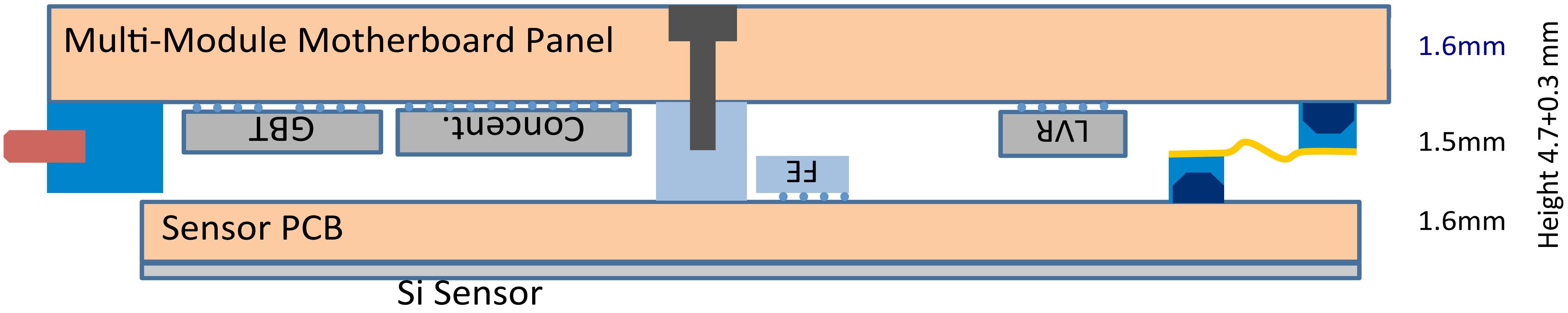




HGCal Silicon Sensor Readout

- Each wafer (hexagons cut from 8" circular wafers) is made up of 432 (192) hexagonal 0.5 (1.0) cm^2 cells with 6 (3) readout chips
- 2 PCBs/layer: 1st PCB wire-bonded to Si sensor, Motherboard (2nd PCB)
- Data are transmitted by lpGBT links: ~8k links dedicated to trigger data and ~8k links dedicated to full resolution data. Try to reuse common developments as much as possible

From EPS-2017



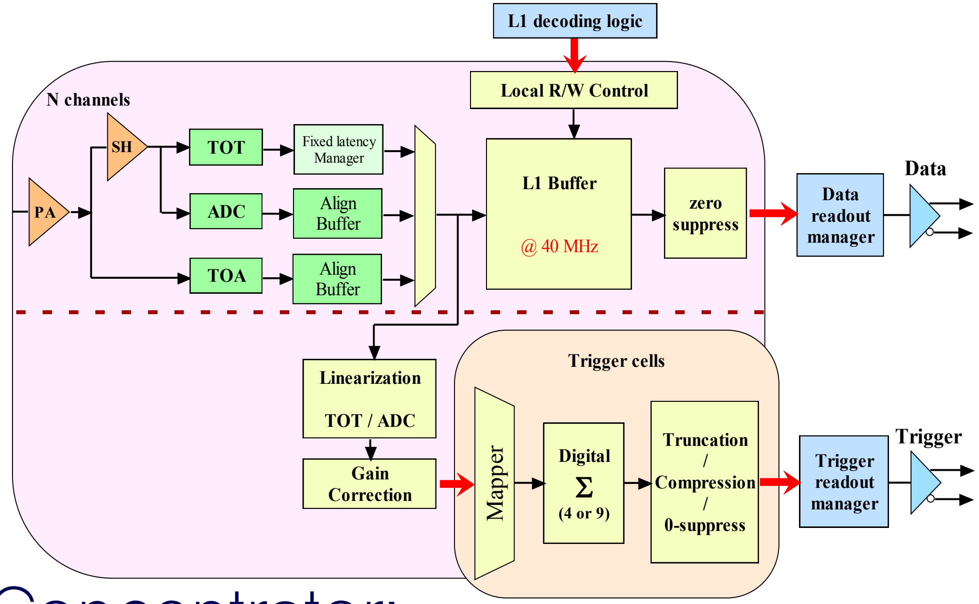
- ~16000 LpGBT links for 25000 modules

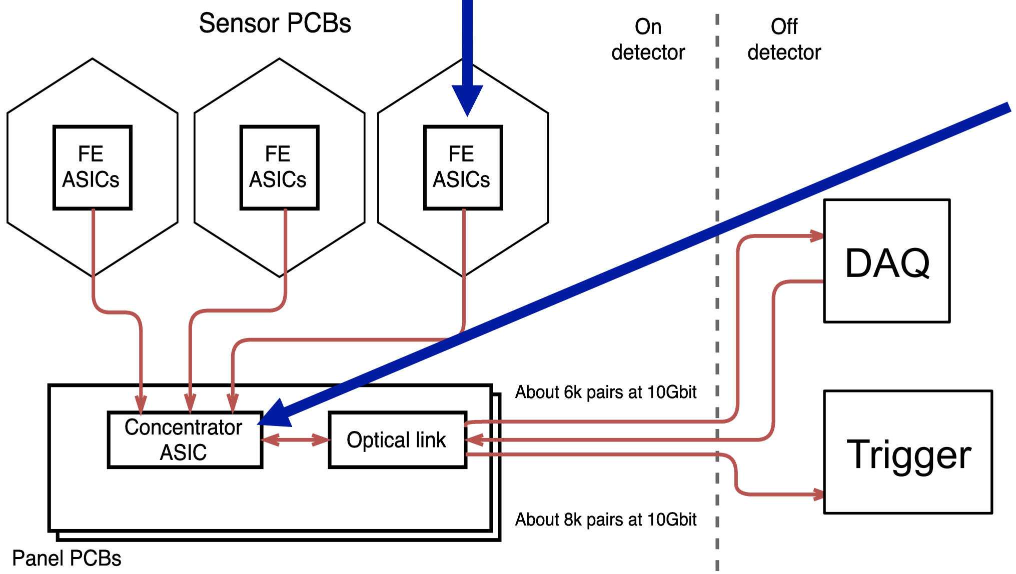
HGCal Electronics

Need high dynamic range: from single MIPs (for calibration) up to TeV showers achieved using traditional ADC for the small signals and TOT for high signals

<u>FE ASIC (HGCROC):</u>

- **V1 submitted** in July17, final DV2 2019
- 32 channels, dual polarity
- 72 channels in final version of HGCROC
- 11-bits ADC/TOT + TOA
- Digital sum of cell energy in Trigger Cell
- TC Energy truncation and compression



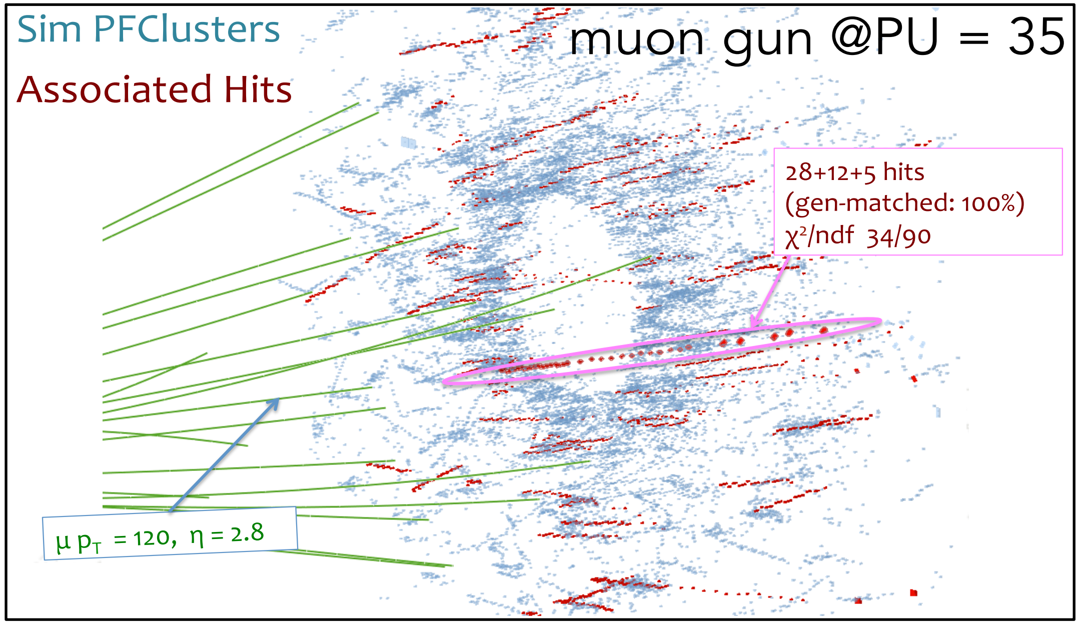


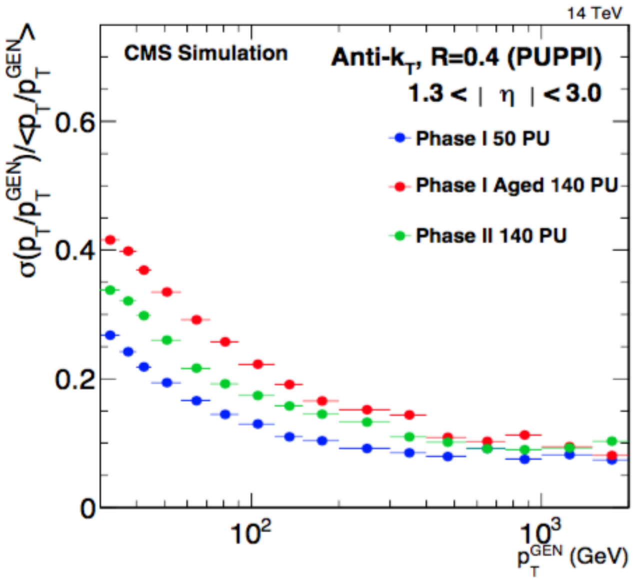
<u>Concentrator:</u>

- Receives, selects and transmits trigger and data
- HGCROC trigger output:
  - 4 e-links @ 1.28 Gb/s
- HGCROC data output:
  - 1 e-links @ 1.28 Gb/s
- First online data reduction:
  - Threshold or fixed number of highest TC selection, transmit TCs + Global Sum

Particle Flow with HGCal

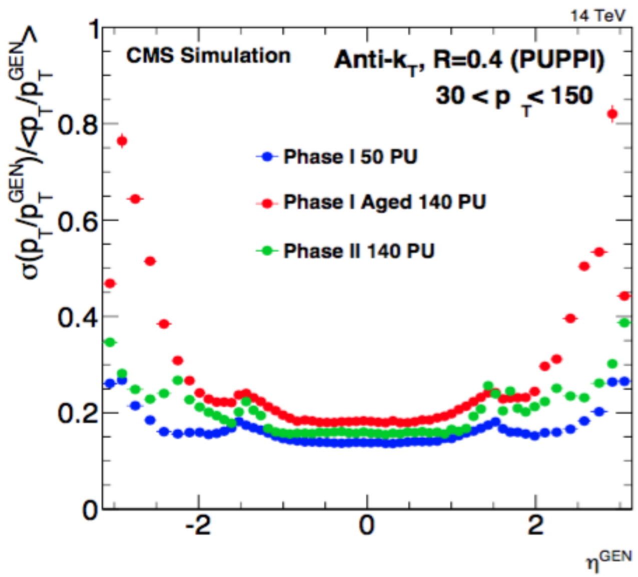
- Combining all the information from the different CMS sub-systems to identify all the stable particles in the event
  ➔ build complex objects like MET, Jet, Taus
- Big challenge in PU200 environment
- Matching between tracks and HGCal clusters, promising performance





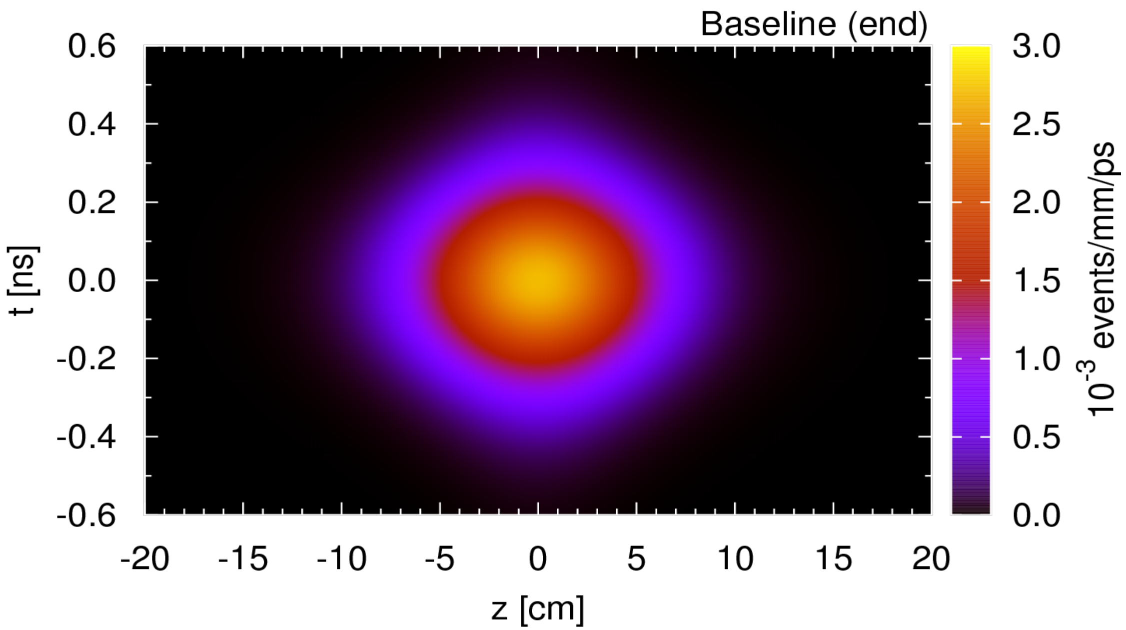
Expected **jet p_T resolution <20%** for jet with **p_T> 20 GeV** (PU140)

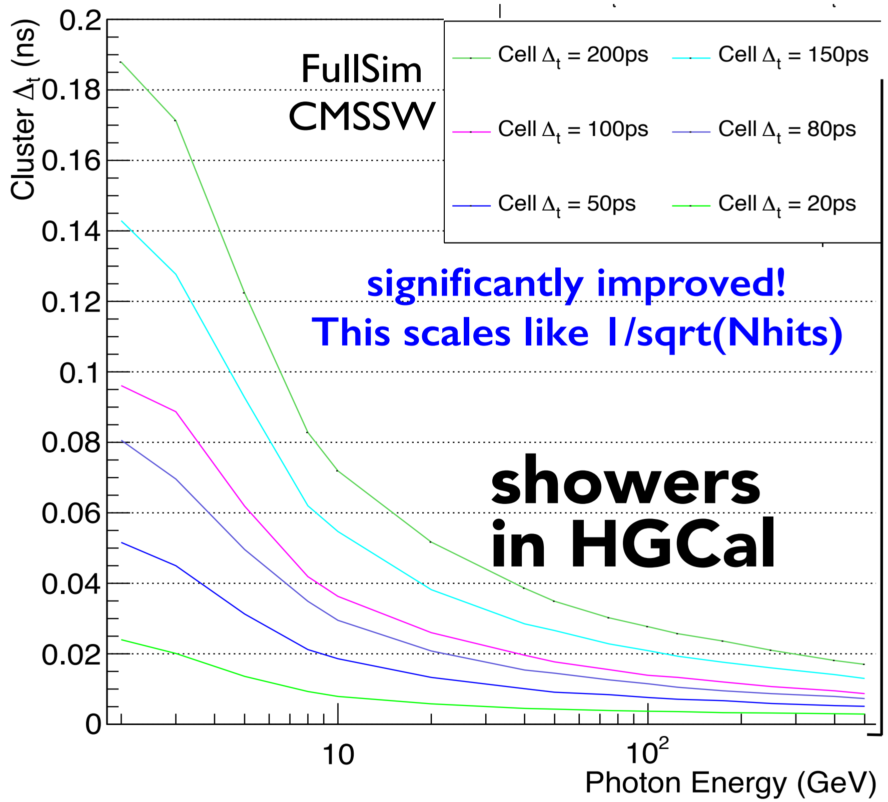
Jet **p_T resolution uniform in eta** if compared to the current Phase-I endcap calorimeter projection (aged+PU140)



Timing information to mitigate the PU

- Possible to resolve the vertex position for neutral particles with ~1cm uncertainties ➔ better particle ID, PU reduction and global event reco.
- PU reduction by a factor x5-x6 if time resolution is O(20ps)

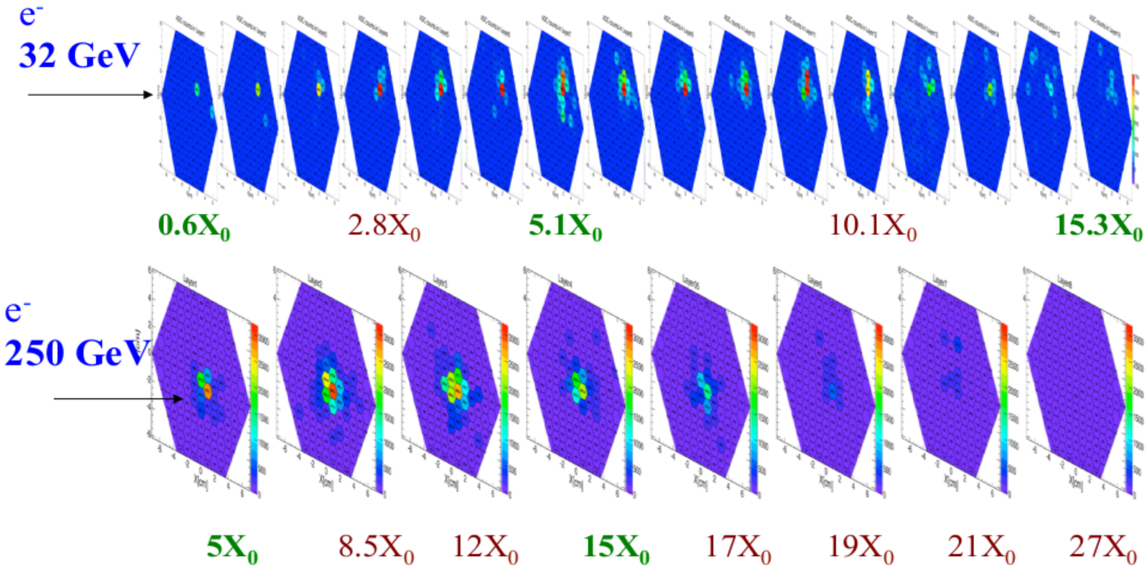


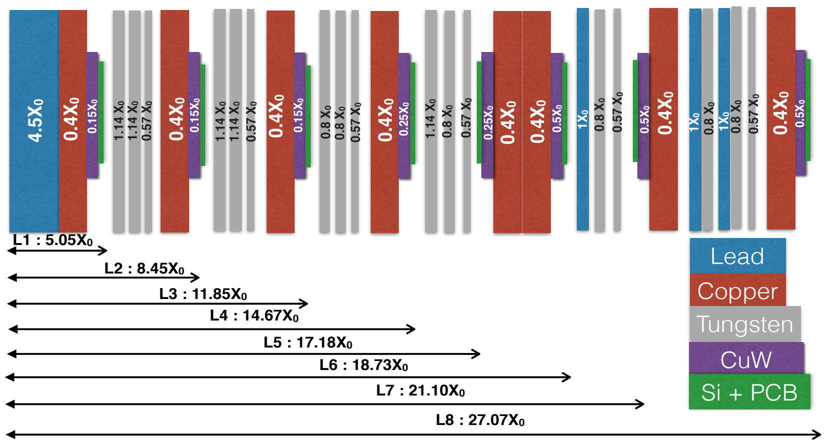


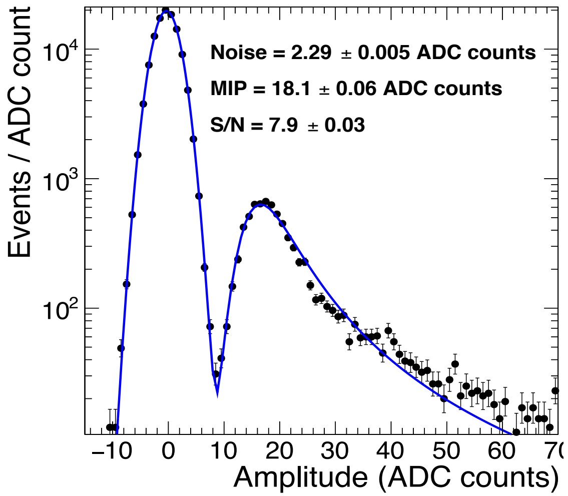
Δ_t is 68% effective RMS
20ps * c = 6mm

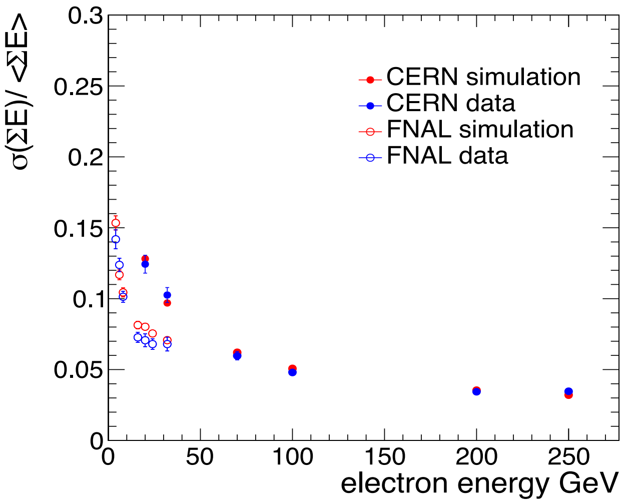
HGCal Test-beams

- Validate concept of hexagonal Si sensors and Geant4 simulation
- Used SKIROC2, developed for CALICE: 64 channels per chips, 2 chips/module







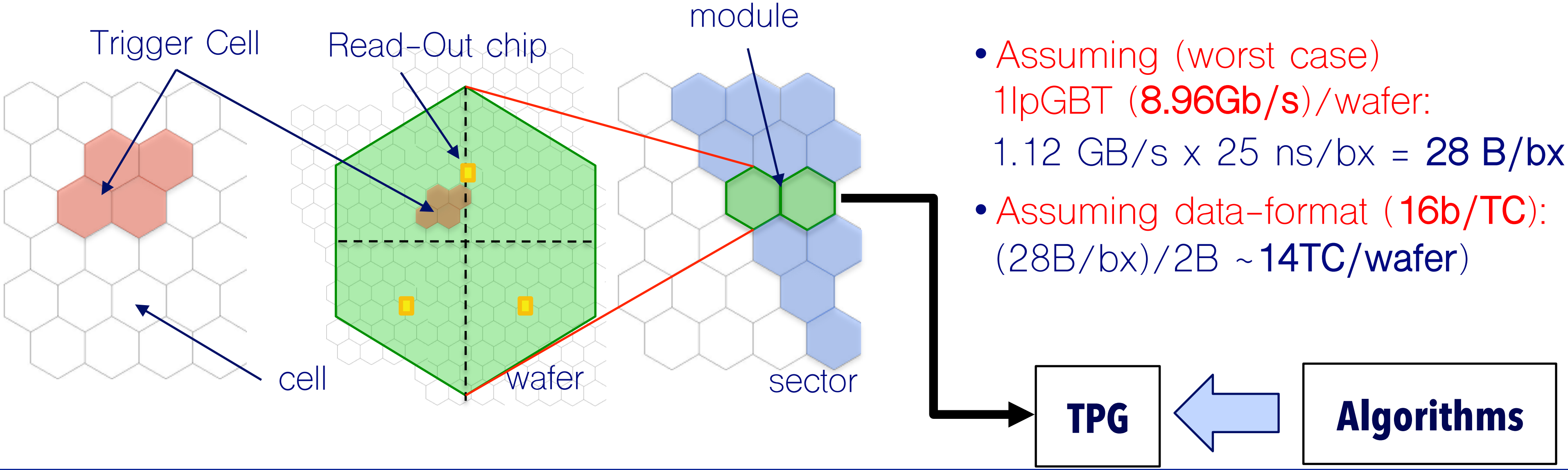


Much more information in Shilpi's talk

CMS L1-Trigger Phase-II Upgrade

- The new L1-Trigger:
  - The CMS L1-Trigger system is required to select/reject each bx ➔ First step of analysis
  - Time-multiplexed structure + tracker information + latest generation of FPGA + fast optical links ➔ For the first time a **particle flow reconstruction at L1 is possible**
  - Change in maximum rate: from O(100kHz)➔O(1MHz) + fixed latency from 4μs to 12.5μs
- HGCal L1-Trigger:
  - Trigger Cell (TC) = 4 or 9 hexagonal cells (48 per wafer)
  - Online data reduction at front-end → select average 10% TCs per module
  - The selected TC is used as input to back-end algorithms

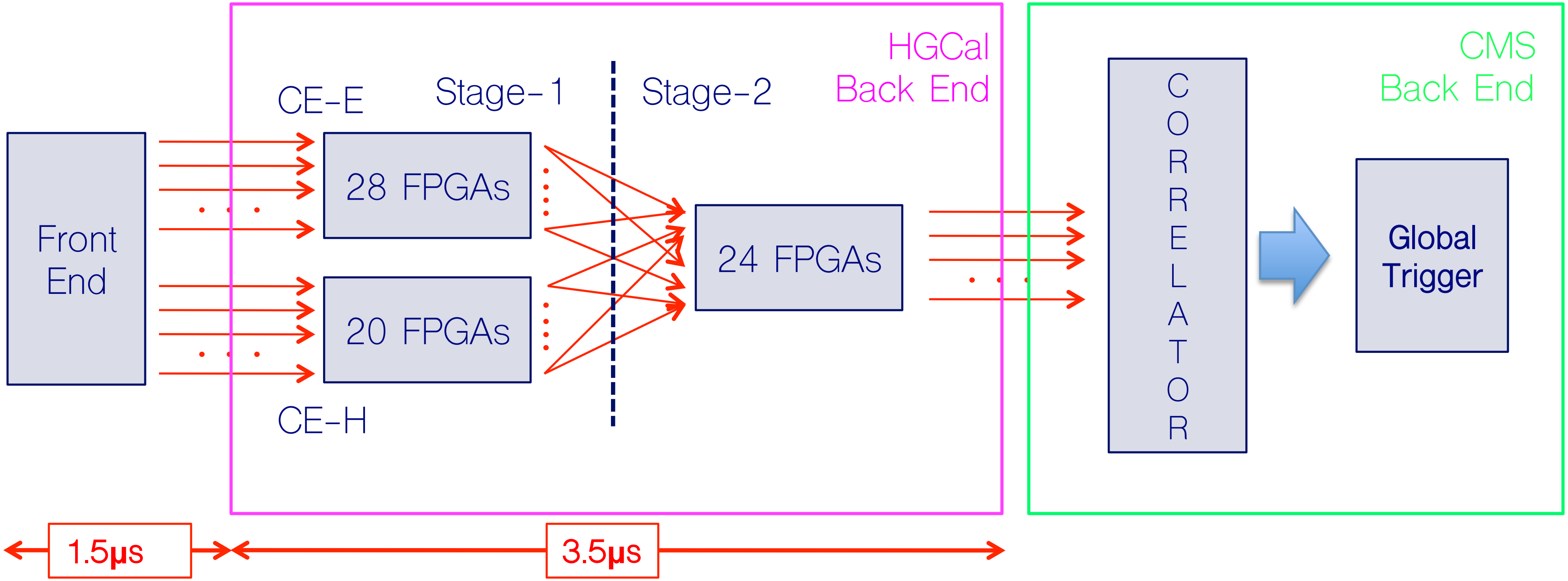
    → produce the trigger primitives to be sent to the correlator



- Assuming (worst case) 1lpGBT (**8.96Gb/s**)/wafer: 1.12 GB/s x 25 ns/bx = **28 B/bx**
- Assuming data-format (**16b/TC**): (28B/bx)/2B ~**14TC/wafer**)

HGCal Trigger Primitive Generator

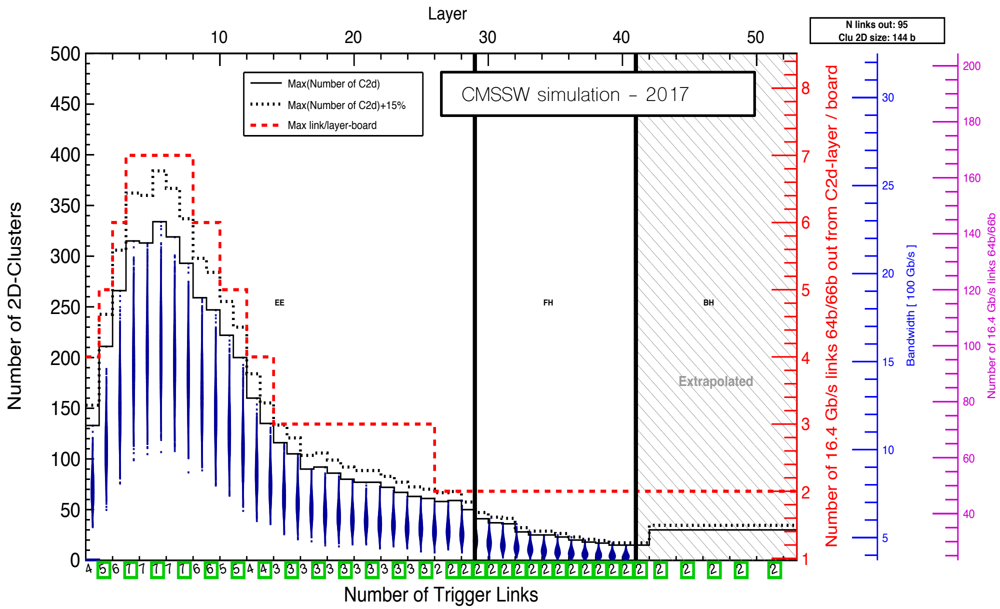
- Time-Multiplexed Two-stage architecture:
  - **Stage-1:** Dynamical clustering techniques based on the Nearest Neighbour TCs to generate 2D-clusters in each HGCal trigger layer.
  - **Stage-2:** Generation of 3D-clusters relying on the longitudinal development of the shower, exploiting the projected position of each 2D-cluster to identify its direction.
  - The Stage-1→Stage-2 data transmission is x24 time-multiplexed to allow all data from one endcap to be processed by one FPGA



- Performance – Stage-1/2 cluster and data-format

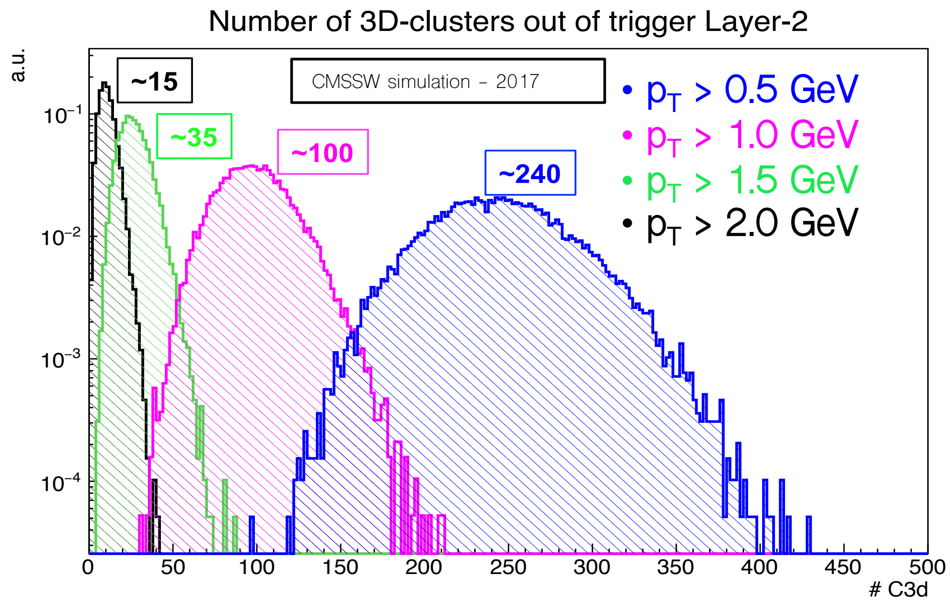
Number of 2D-cluster per each layer

- $t\bar{t}$+PU200 event → max ~300 2D-clusters
- Constraint: 4 links/board output from Stage-1 and max 96 total links input to the Stage-2
- 24x Time-Multiplexed allows for an average cluster size up to 144b



Number of 3D-cluster per each endcap

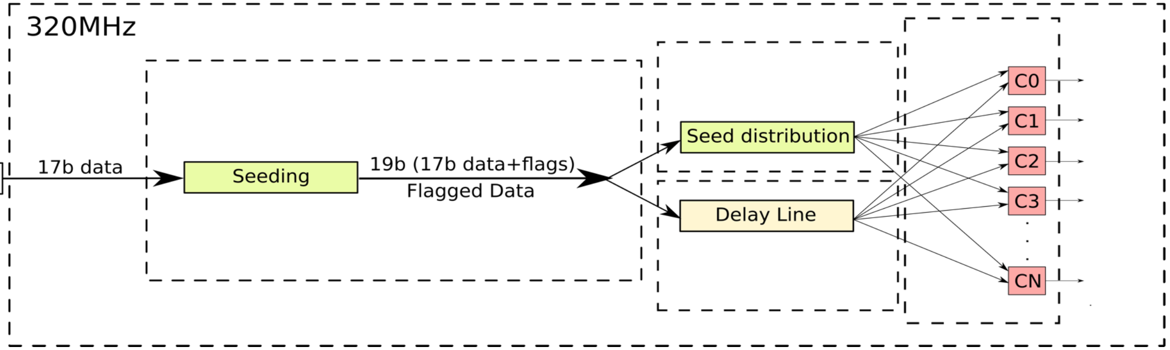
- $t\bar{t}$+PU200 event → max ~200 3D-clusters with p_T>1.0 GeV
- Define the bandwidth to the correlator: ~40 kbit/(endcap x bunch-crossing)



Firmware implementation

- L1-trigger Stage-1 algorithm, based on the nearest neighbours, has been succesfully implemented in VHDL
  - Sufficient FPGA resources on Virtex7 (LUT~70%)

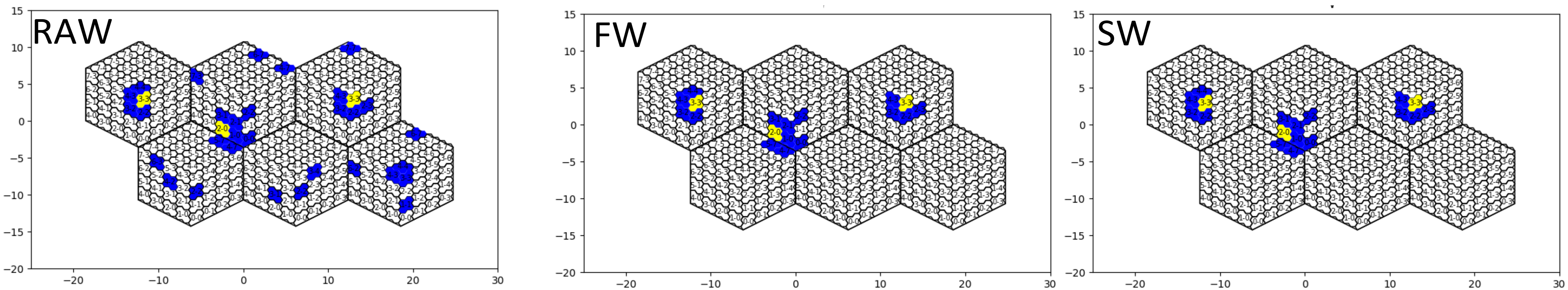
Resource	Utilization	Available	Utilization %
LUT	305519	433200	70.53
LUTRAM	24966	174200	14.33
FF	229316	866400	26.47
BRAM	365	1470	24.83
IO	139	600	23.17
GT	74	80	92.50
MMCM	3	20	15.00



- Generation of random RAW clusters to compare the hardware (HW) vs software (SW) reconstruction

- A first simulation test shows a perfect agreement between the clustering outputs in SW and in FW.

Seeding Threshold (e.g. 5 MIP_t)
Clustering Threshold (e.g. 2 MIP_t)



Conclusion

- The **endcap calorimeters** will be **replaced** with the **HGCal** to face the harsh radiation environment and the high PU scenario at HL-LHC era.

- **Innovative solutions** have been adopted to guarantee **radiation hardness** and **high granularity** (0.56-1.06 cm^2) of the detector using **Si sensors** as well as large dynamic range (**ADC+TOT**), low power consumption and timing accuracy **O(50)ps** of the read-out chips

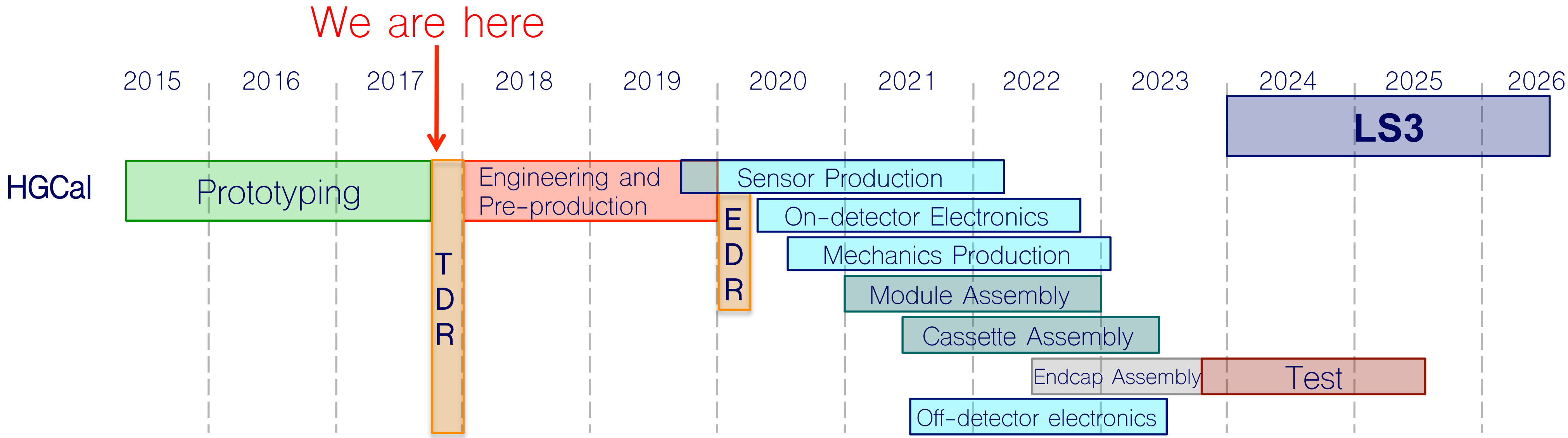
- The high granularity and longitudinal segmentation allow full **exploitation of particle shower properties** for offline object identification, that can also benefit from **timing information to mitigate the PU** contamination

- The **HGCal L1-trigger** represents a real challenge:
  - **output** at **~40MHz** performing an impressive data reduction **from 300Tb/s** (HGCROC output) **to ~2Tb/s** (correlator input) in **less than 5µs** while preserving **good object reconstruction** performance

- Use of **track info + high granularity + latest FPGA** and **fast optical links**
  - **PF-based approaches exploitable at L1-trigger** level for the first time.

Status and Plans

- For HGCal trigger, a 2-staged time-multiplexed architecture is proposed as baseline and first results in hardware confirm its feasibility
- The **testbeam in 2017** at CERN and FNAL with modified SKIROC2_CMS, HGROC ASIC are almost over but **more** testbeam are scheduled **in 2018**
- TDR expected for the end of the year + refining of the clustering and reconstruction algorithms (both for L1 and offline) will continue



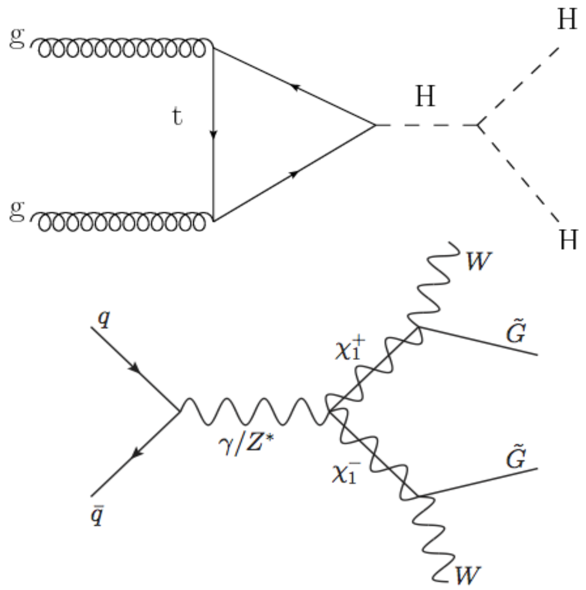
Many challenges ahead and **short time** for producing such a **complex device**:

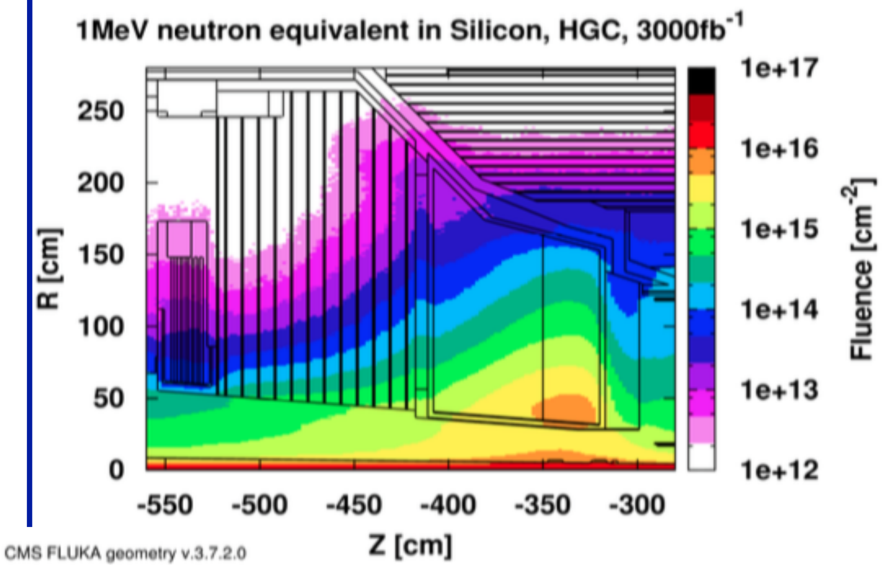
➔ **we are progressing well and according to schedule**

Back-Up

Physics goal for HL-LHC

- HL-LHC (2026-203X) specification:
  - $L_{inst.}=5x10^{34}cm^{-2}s^{-1}$@13TeV
  - <Pile-Up (PU)>≤200
- Exploit the LHC at very high luminosity:
  - Precision measurements of H-sector
  - W,Z trilinear and quadrilinear couplings
  - Rare H-decays + SUSY + Dark Matter
- HL-LHC challenges:
  - High luminosity → high PU
  - High n-fluence → degradation of $PbWO_4$
  - Dose in forward region ~$3x10^5$ Gy
  - High data rate to L1-trigger O(100 Tb/s)
- The scientific goals require:
  - High efficiency on lepton/photon reconstruction
  - Low trigger threshold
    - →not to compromise EWK physics
  - Jet energy resolution maintained at very high PU

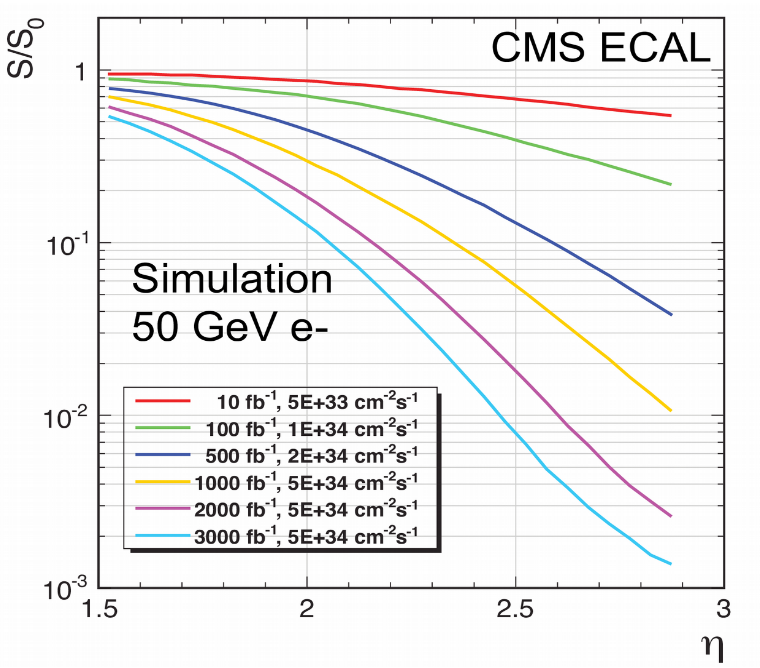




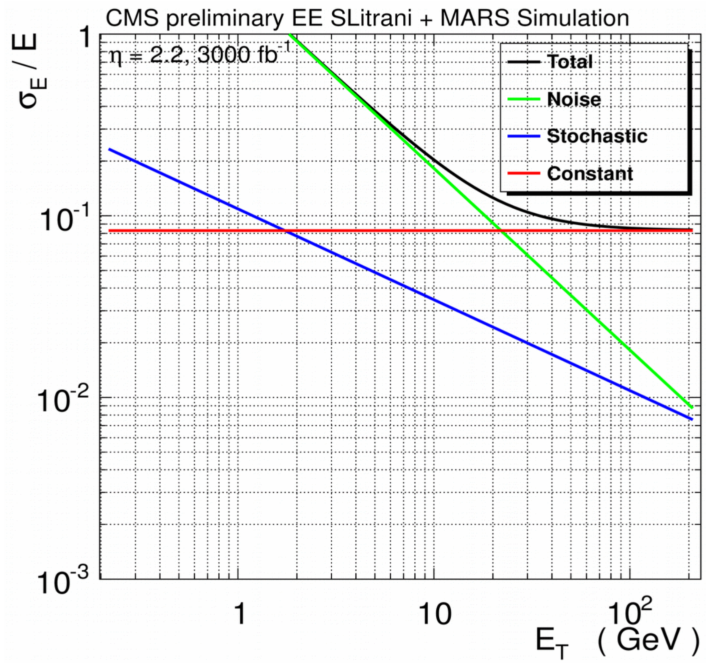
Current Detector degradation

From TIPP-2017

- Current endcap is made of $PbWO_4$ crystals
- Radiation damage results in **deteriorated signal yield**
  - Formation of colour centres that cause light absorption
  - Laser monitoring mitigates this but only to a certain point
  - **Energy resolution constant** term after 3000 fb^{-1} expected to be ~**9%**



signal loss with eta

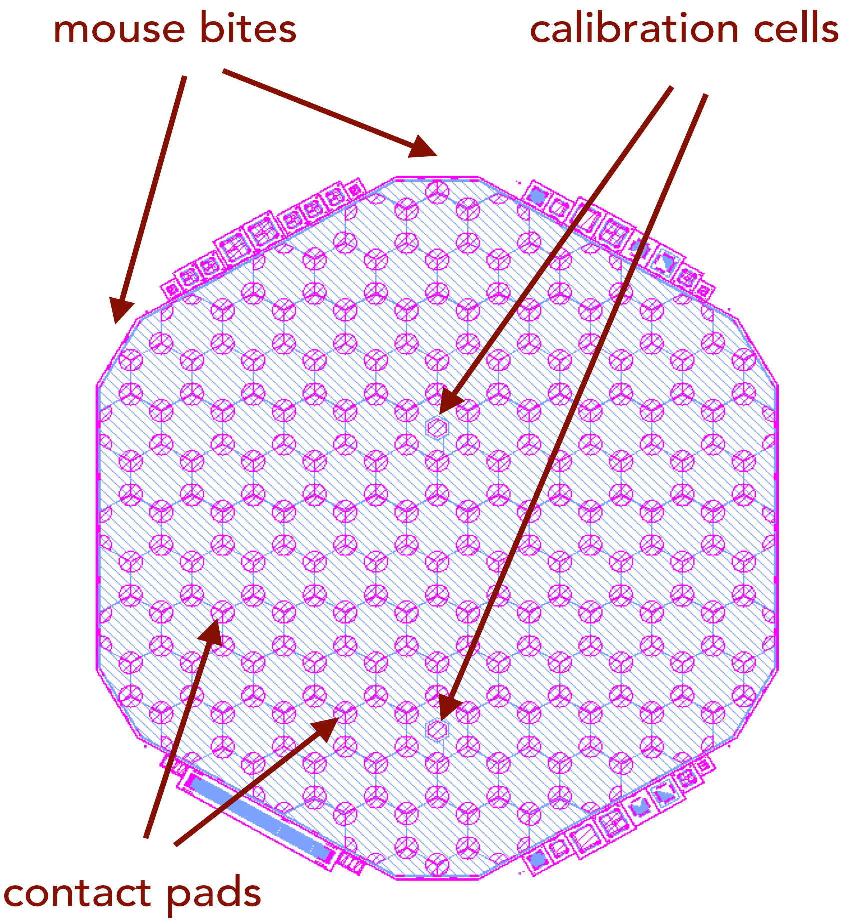


energy resolution after 3000fb^{-1} for current EC

HGCal Si-Sensor and Wafers

From TIPP-2017

- **Hexagonal geometry** as largest tile-able polygon
  - **6” and 8”** sensors considered
  - Cell sizes of **~0.5 cm² and ~1 cm²**
  - Cell capacitance of **~50 pF**
  - Will most likely need n-on-p for inner layers
- Some design goals
  - **1kV sustainability** to mitigate radiation damage
  - **Four quadrants** to study inter-cell gap distance and its influence on V_{bd}, C_{int} and CCE
- A few more details about those sensors
  - Active thickness by **deep diffusion or thinning**
  - Inner **guard ring is grounded**, outer guard ring is floating
  - Truncated tips, so called **mouse bites,** for module mounting
  - **Calibration cells** of smaller size for single MIP sensitivity at end of life



Hamamatsu 6” 128ch design

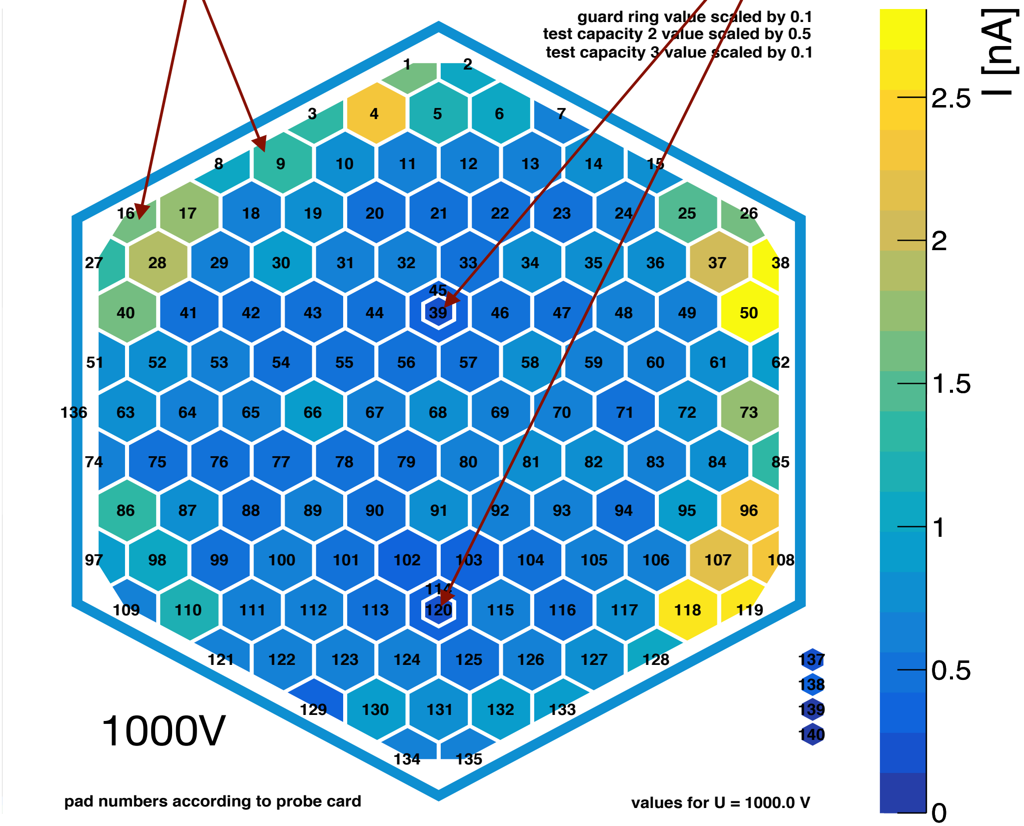
HGCal Si-Sensor and Wafers

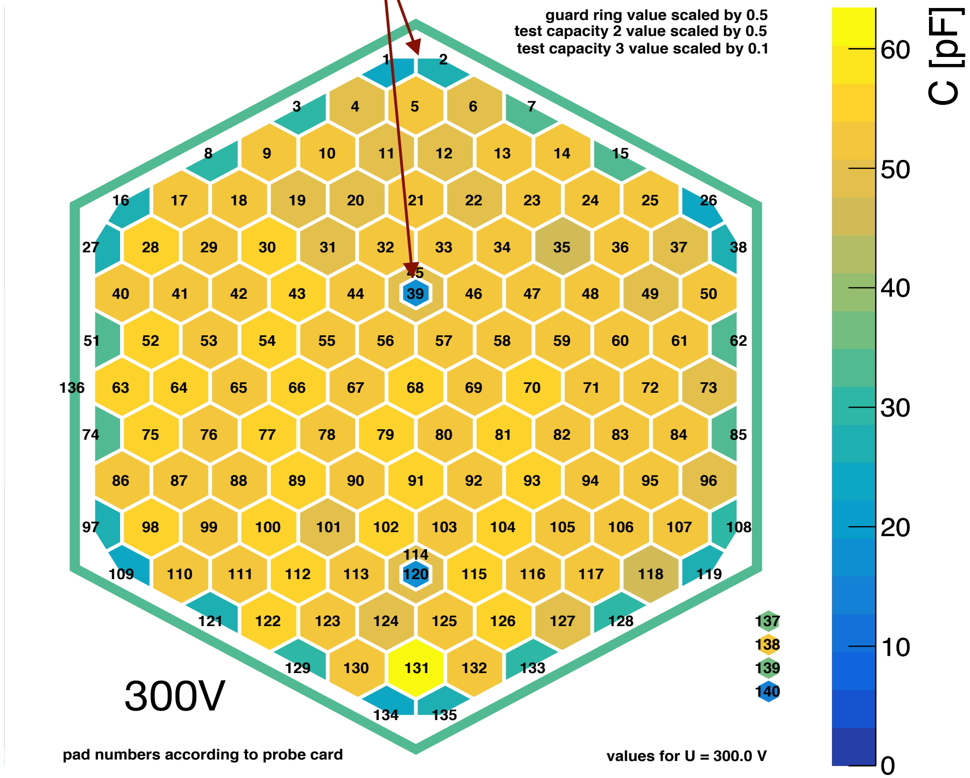
From TIPP-2017

higher leakage currents at the edge region

lower leakage currents in the calibration cells

mouse bites & calibration cells show lower capacitances than full cells (smaller size)

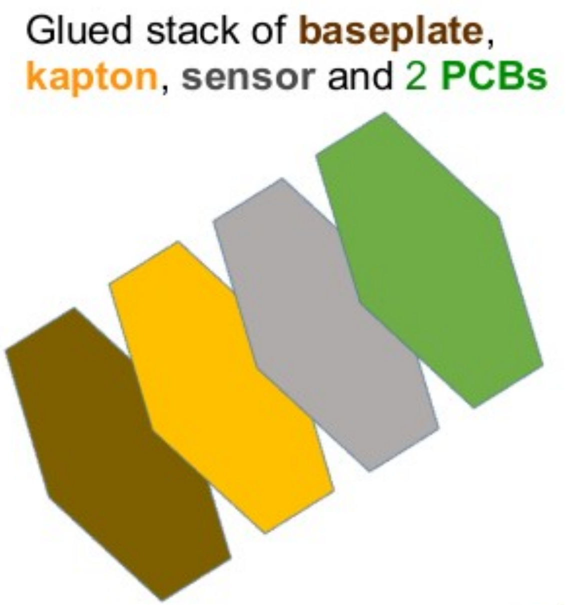




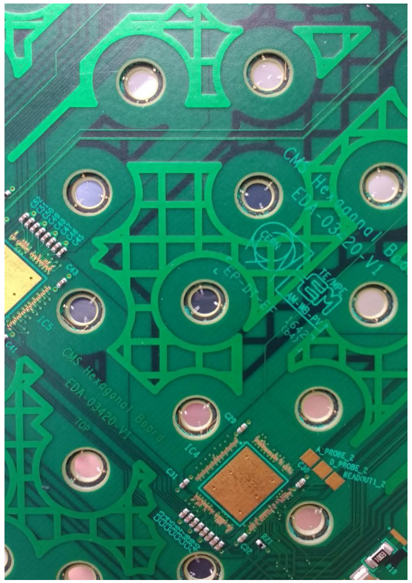
IV and CV example measurements done with probe card plus external switching unit

From TIPP-2017

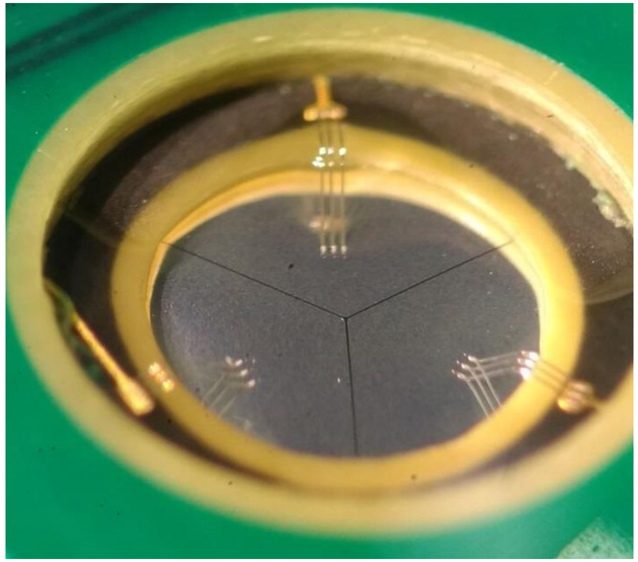
- Preliminary module design is as following
  - First, the **sensor** is glued unto **W/Cu baseplate covered with Au/Kapton foil**
  - Then, the **readout PCB** is glued unto the sensor
  - **Wire bonds through holes in the PCB** connect readout board to sensor cells
- Per hole in the PCB, we can connect to 3 cells compared to 4 with squares
  - Makes routing more difficult. Investigating sensor design features that could help.



module design



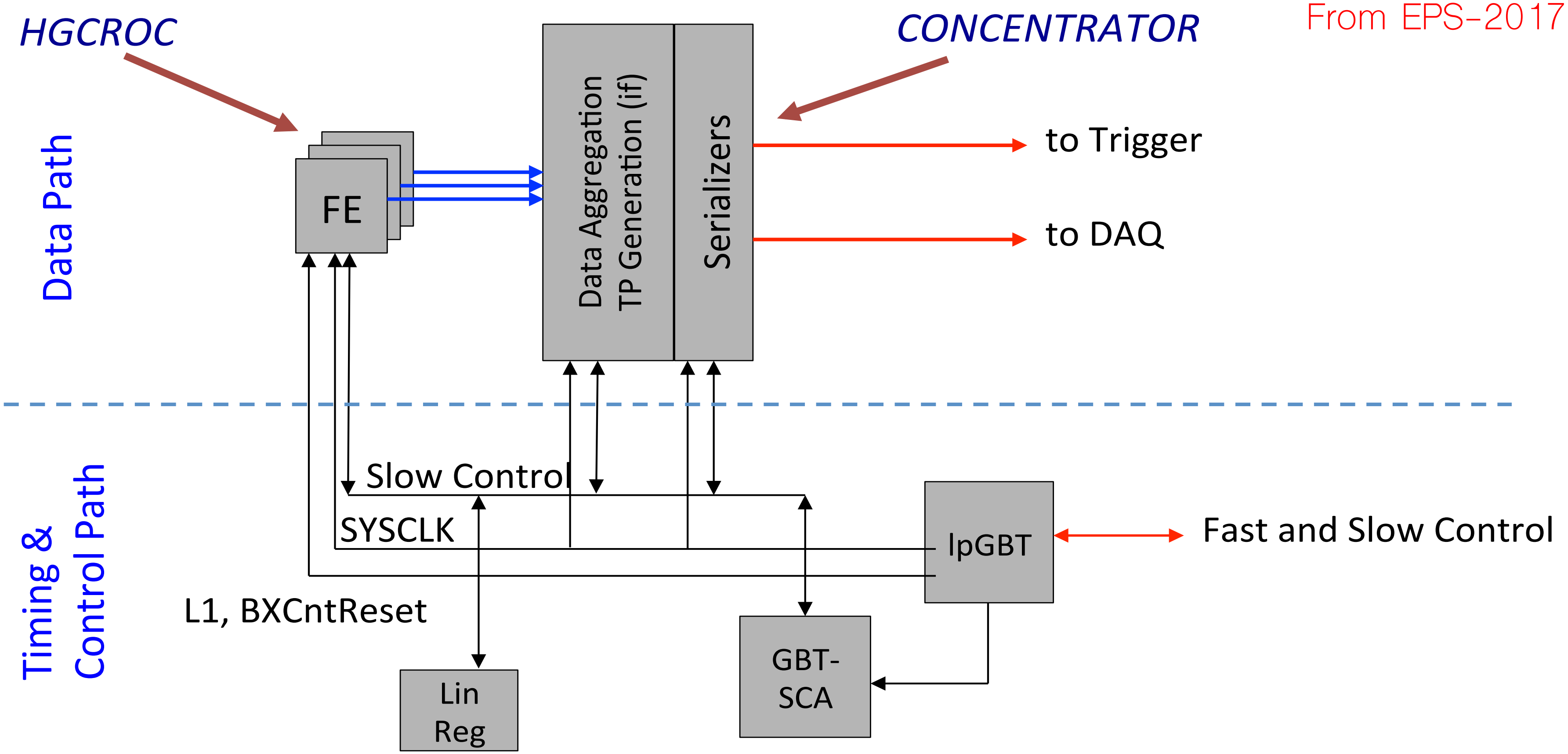
readout PCB



wire bonds

HGCal FE architecture

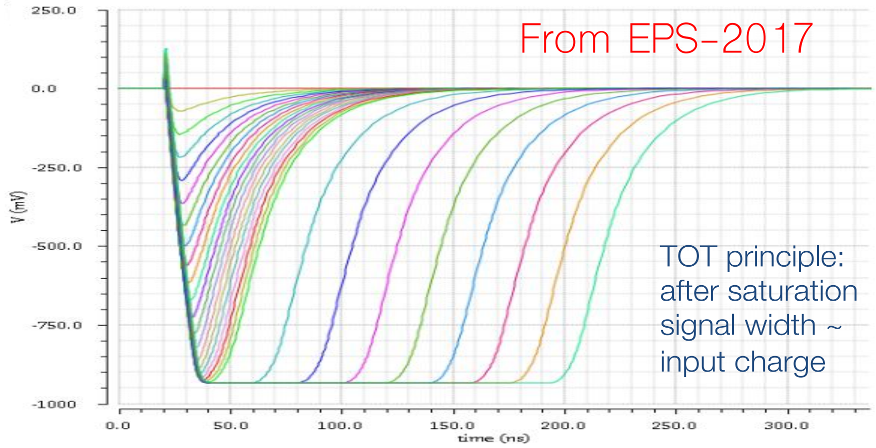
From EPS-2017

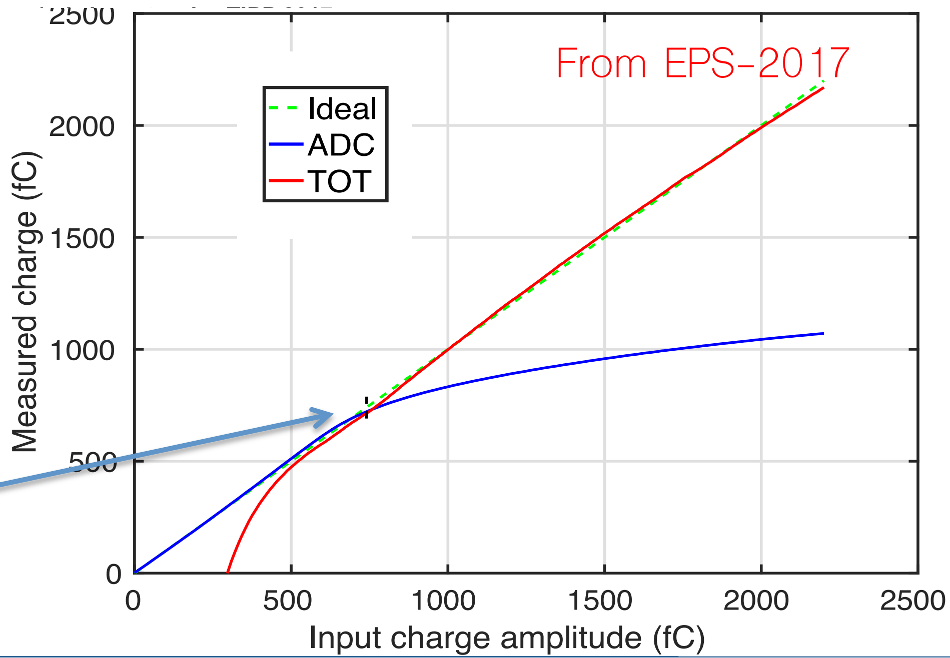


- Stringent requirements for Front-End Electronics
  - Low power (< 10 mW/ch for analog part)
  - Low noise (< 2000 e-, 0.35 fC)
  - High radiation (200 Mrad, 10^{16} N)
  - High dynamic range: 0 – 10 pC
  - MIP: 10k – 20k e- (1,5 – 3 fC)
  - System on chip (digitization, processing...)
  - High speed readout (5-10 Gb/s)
  - ~ 6.5 million channels
- Reusing standard HL-LHC electronics development (e.g. lpGBT)

HGCROC ADC/TOT

- **Key issues to be studied**
  - Noise
  - Resolution
  - Linearity
  - Stability
  - Calibration
  - Accuracy
  - Crosstalk
  - Radiation
  - Timing
  - Systematic effects



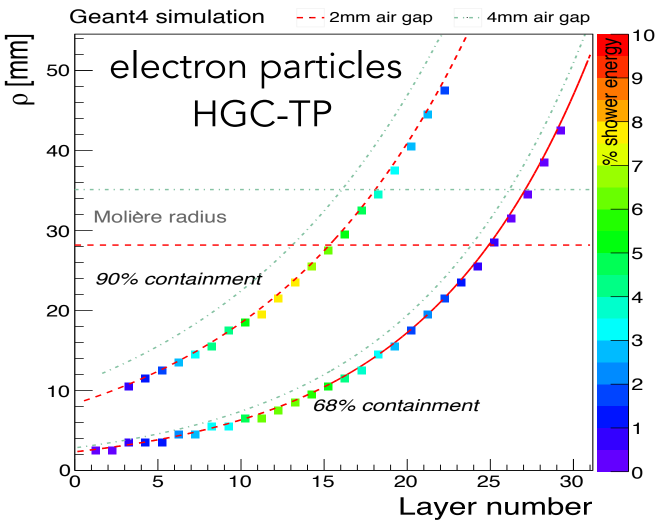


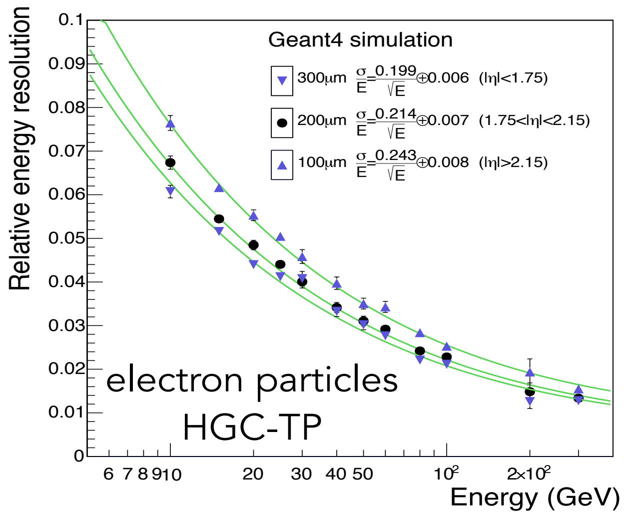
- **Important feature**
  - ADC / TOT switching

HGCal EM clusters properties

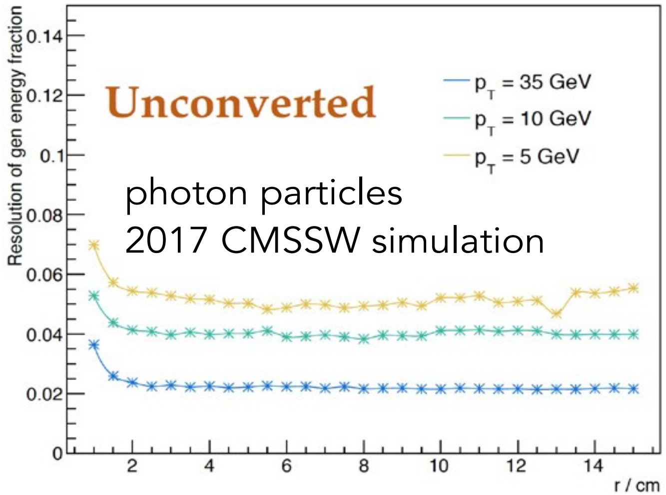
- From the CMS Phase II Upgrade Technical Proposal: https://cds.cern.ch/record/2020886?ln=en
  - Good energy resolution for EM showers
  - Molière Radius: 90% contained in ~2cm

From LHCP-2017





- From recent reconstruction developments*
  - measured energy resolution when considering energy deposited within a cylinder (radius r) around the shower axis
    => Indication of competitive energy resolution

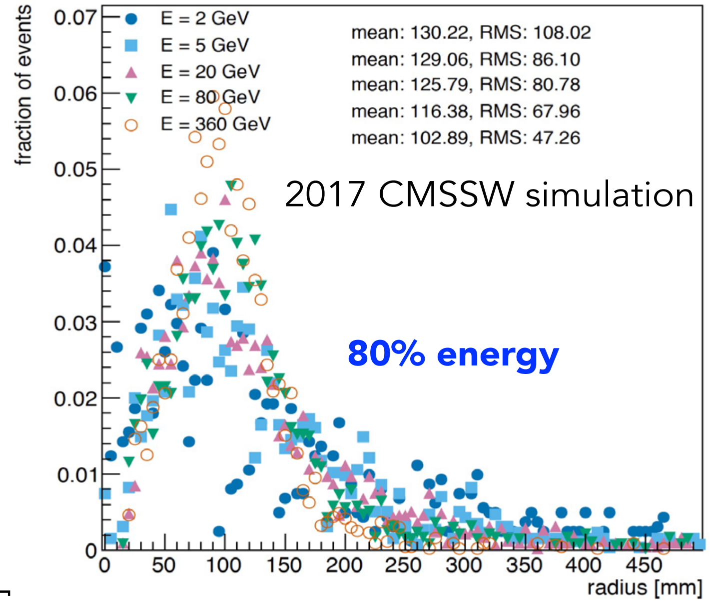


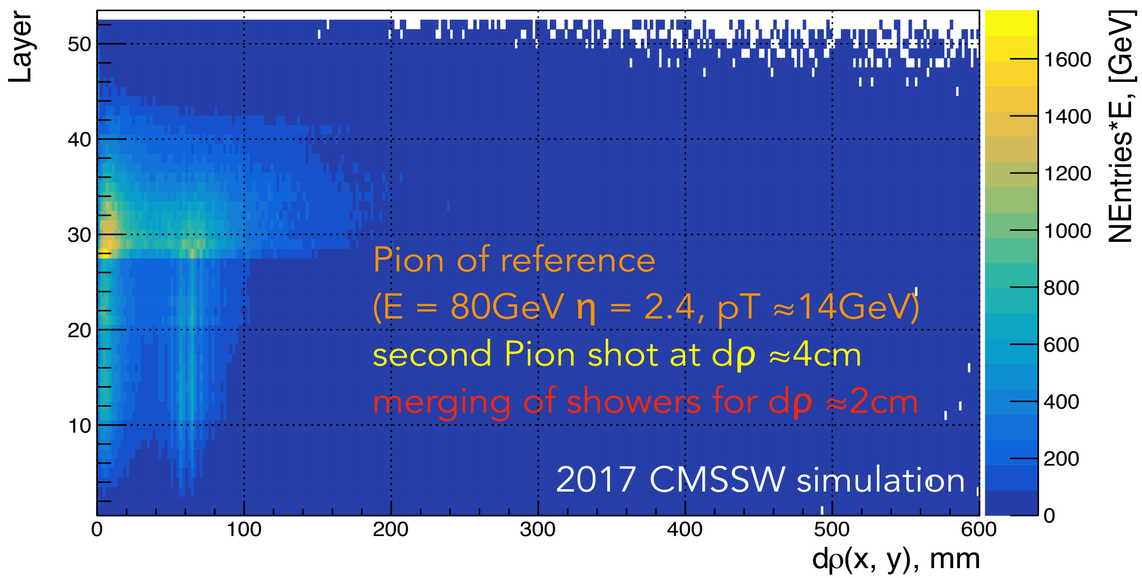
*Density-based imaging-clustering (see next)

HGCal Had. clusters properties

From LHCP-2017

- Charged pion showers:
  - ~80%-90% of the shower energy is contained in a ~10cm radius
  - the minimum separation distance needed to resolve and split two different clusters is almost an order of magnitude smaller than the full containment radius



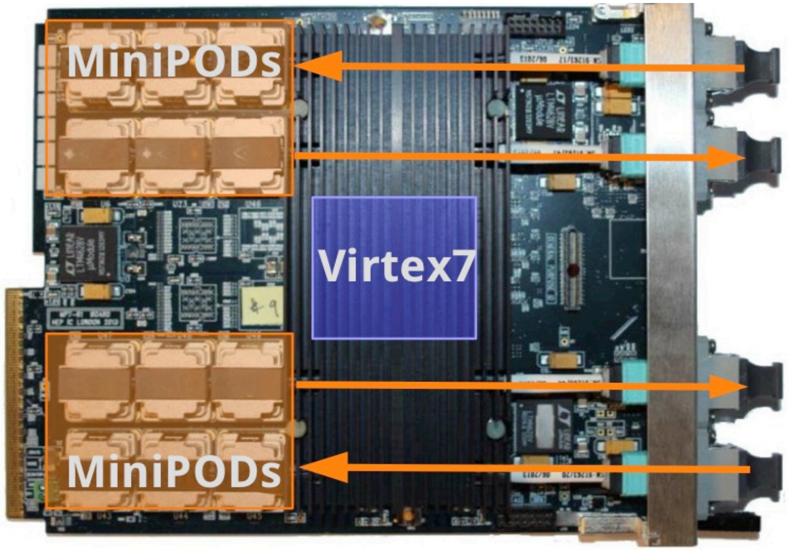


HGCal DAQ & TPG boards

- Both DAQ and TPG require boards with high I/O and significant processing power
  - Currently assume same hardware usable by both
  - Working assumption:
    - ATCA format
    - ~100 F/O links up to 16 or 25 Gbit/s in and out
    - Ultrascale(+) FPGA(s) for processing

From EPS-2017

Per Endcap	#
LpGBT links	~ 5k
Boards Stage 1 (2D Clustering)	48
Boards Stage 2 (3D Clustering, assuming 24x TMUX)	24



2012
MP7 - 72 links in and out, each ~ 9 Gb/s

2016
MPUltra - up to 96 links in and out, each ~16 Gb/s

NNC2d-Bandwidth evaluation $t\bar{t}$+PU200

- Estimation of the maximum number of 2D-clusters per layer:
  - Ttbar events from RelVal sample;
  - s(pp) cross-section evaluated @sqrt(s)=14TeV PU=200;
  - /RelValTTbar_14TeV/CMSSW_9_0_0_pre4-PU25ns_90X_upgrade2023_realistic_v3_D4TPU200c2-v1/GEN-SIM-RECO
  - **Nearest-Neighbors** (NN) clustering with SE>5mip$_T$, TE>2mip$_T$ (CMSSW)

Full Stat. !

- The following has been assumed:
  - Raw link speed = 16.4Gb/s;
  - Link encoding = 64b/66b;
  - NtwMaps = 1008 (x8b)

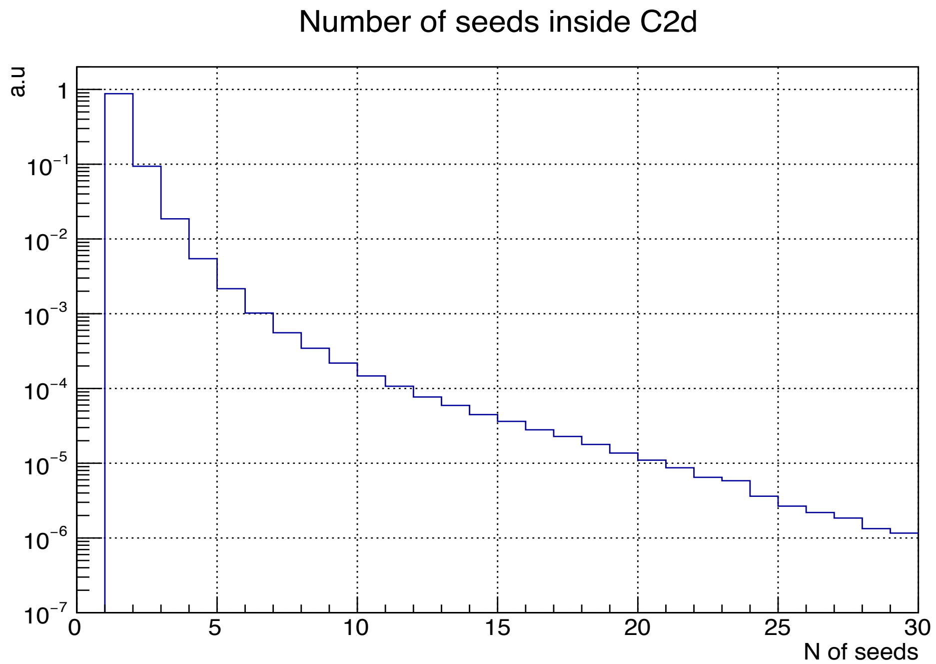
- So far:
  - Tmux=24 works,
  - Tmux=18 is probably OK,
  - Tmux=12 is probably not OK;

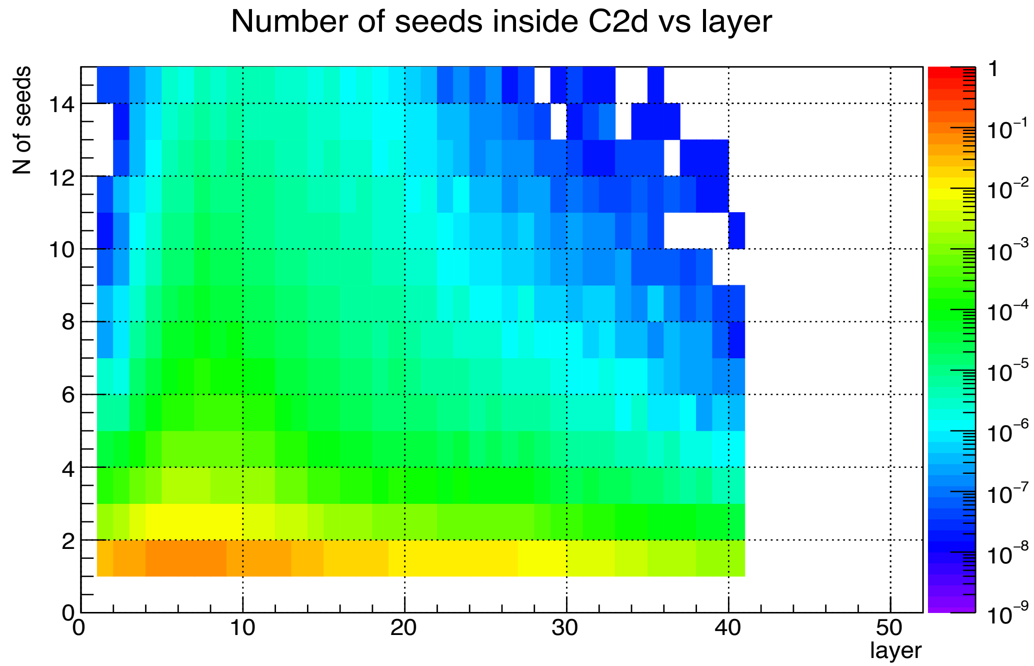
Tmux	Raw 2D-Cluster size [b]									
	64	*80*	*96*	*112*	*128*	*144*	*160*	*176*	*192*	*208*
12	122	134	143	152	161	170	186	195	206	213
18	84	93	99	104	111	117	128	135	144	148
24	73	78	81	87	91	95	103	105	111	113

Dynamic Range

Average 2D-Cluster size

NNC2d - TTbar+PU200 – High Stat.



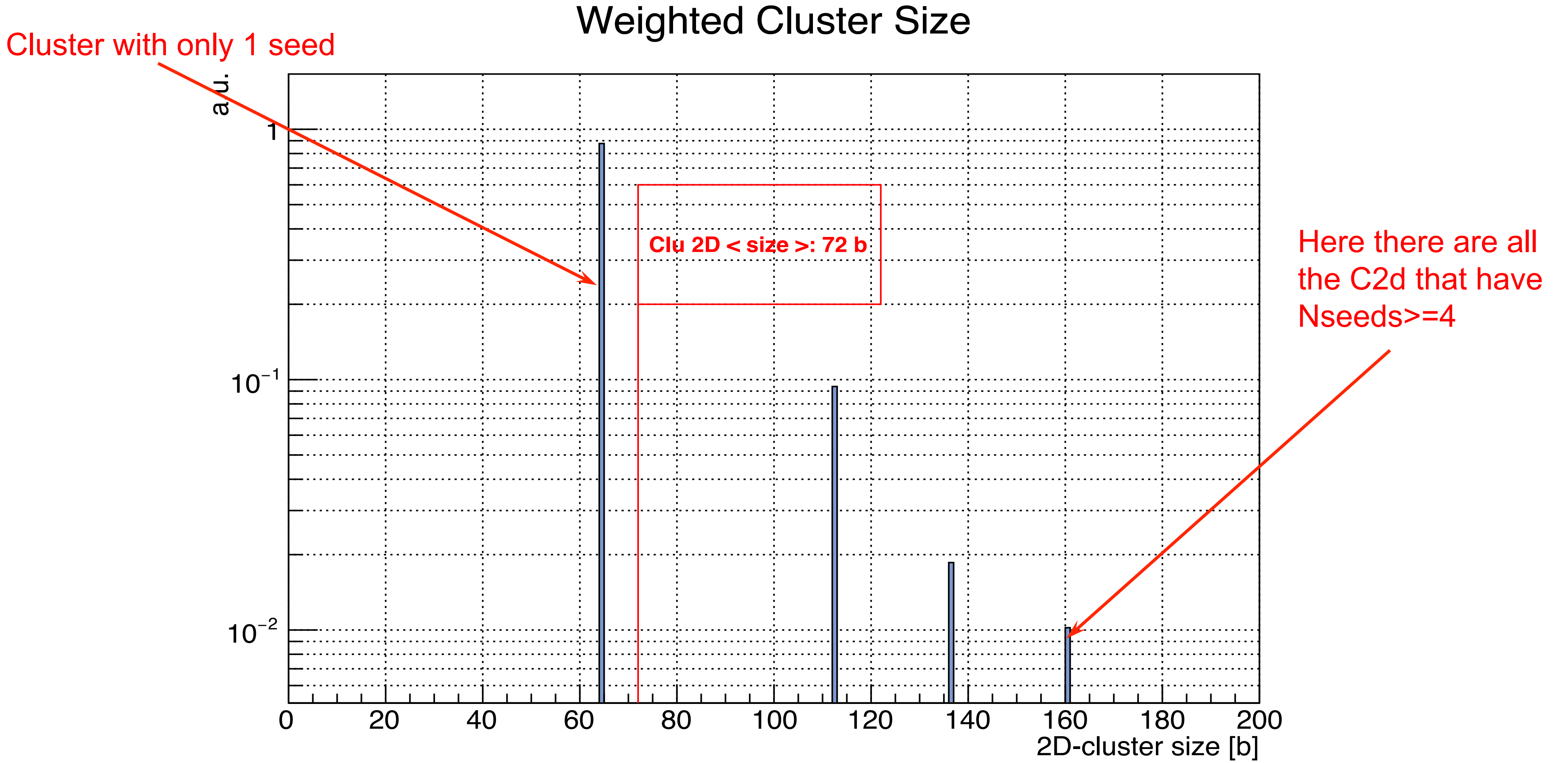


	Number of seeds inside 2D-clusters				
	1	***2***	***3***	***4***	***>=4***
[%]	87.72	9.39	1.86	0.54	1.03

Average 2D-Cluster size

NNC2d - TTbar+PU200 – High Stat.

IMax==0 ? 64b : 64b+24b*(IMax+1)



Matrix Inversion Calibration

- Calibration using single photon gun:
  - Cluster dedicated calibration starting from C2d energy

$$E_\pi = \sum_{i=0}^{layer} a_i d_{ie}$$

- Where d_{ie} are the energy deposits (in transverse mip – mipT) in the active layers, while the a_i are the coefficients to estimate. The RMS can be evaluated:

$$RMS^2 = \frac{1}{N} \sum_{e=1}^{sample} \left(\sum_{i=0}^{layer} a_i d_{ie} - E_{Te}^{true} \right)$$

- Where T_e is the pion truth energy. If we minimize the RMS^2, the problem to find the a_i reduces to a linear algebra problem of a matrix inversion:

$$M \cdot a = v \Rightarrow a = M^{-1} \cdot v$$

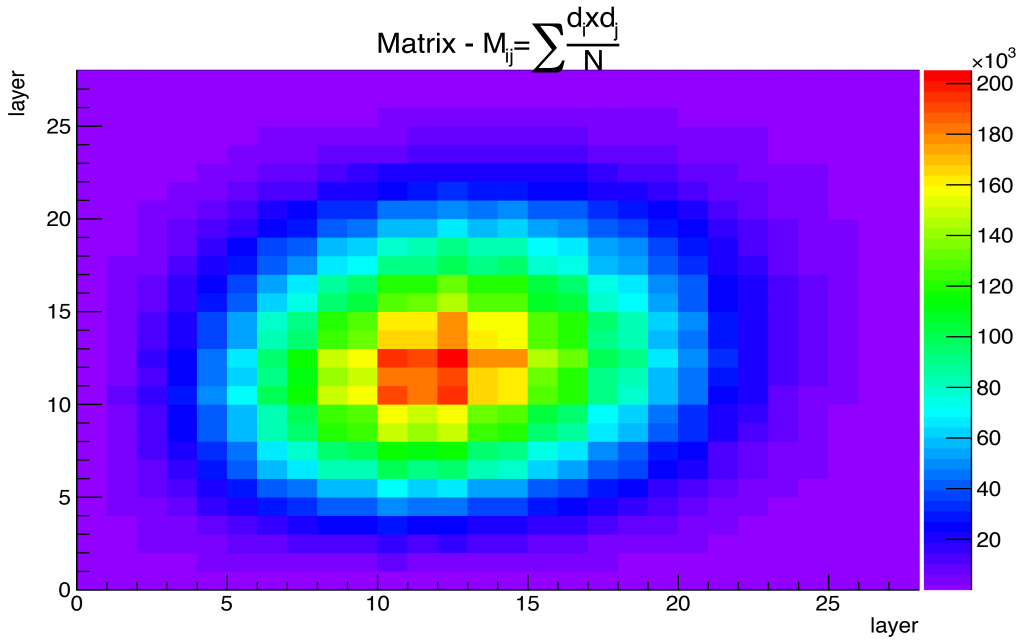
- Where M and v are thus defined as:

$$M_{ij} = \frac{\sum_{e=1}^{sample} d_{ie} d_{je}}{N} \qquad v_i = \frac{\sum_{e=0}^{sample} d_{ie} E_e^{true}}{N}$$

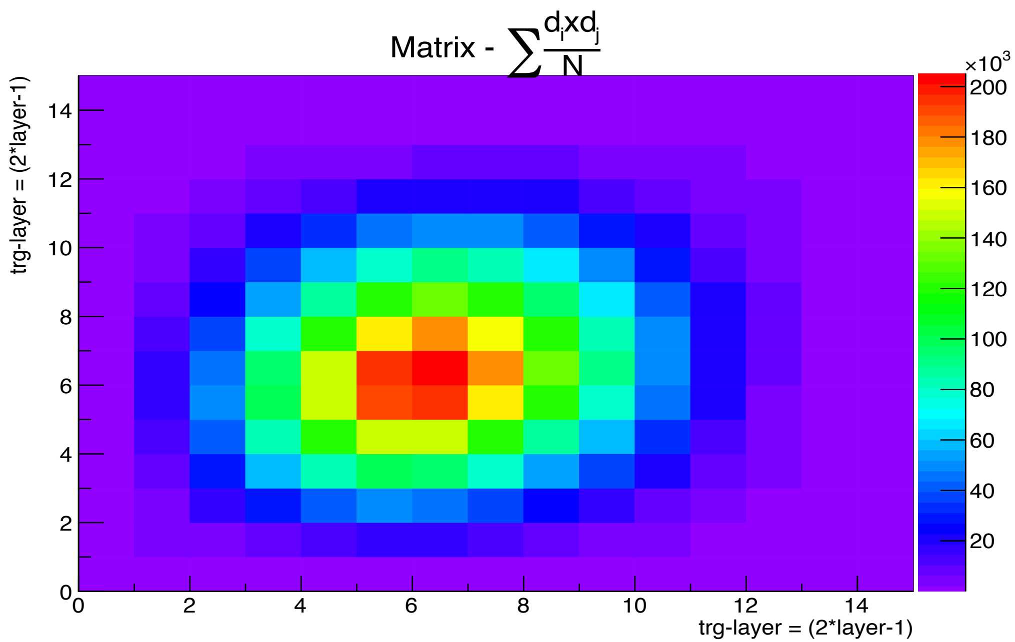
Matrix Inversion Calibration

- Estimation of the matrix element for photon clusters
  - Single-photon pT=50GeV no-PU
  - C3d+NNC2d-2D clustering with SE>5mip$_T$, TE>2mip$_T$ (CMSSW_9_2_0_patch2)
  - Energy encoding: 16b + Trunc: 0b
  - Most energetic C3d in a cone of **Δ**R=0.5 around the true photon

All layers in EE



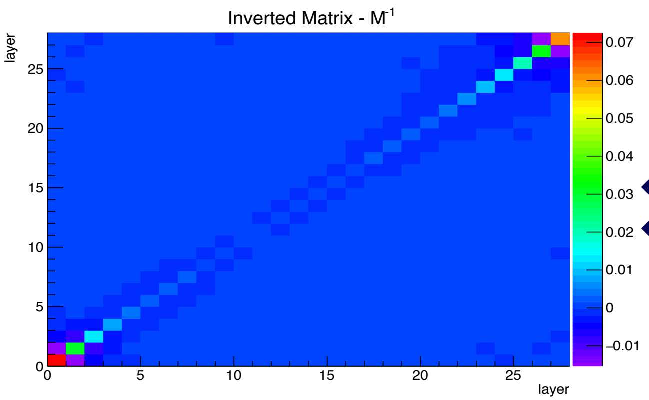
Only trg-layers in EE

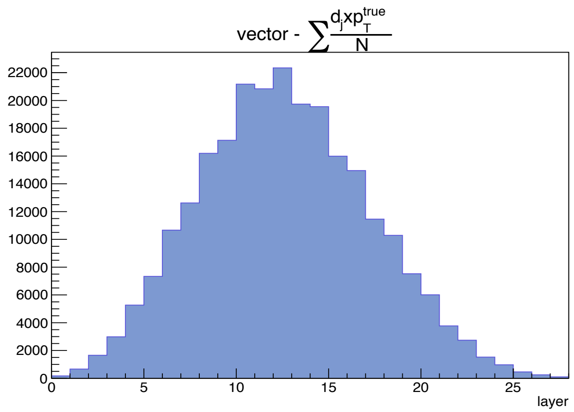


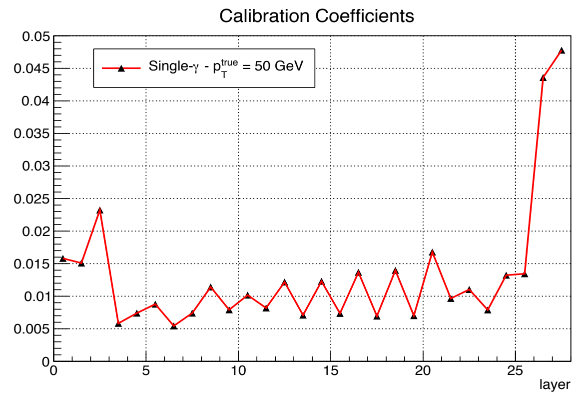
Matrix Inversion Calibration

- <u>Extraction of the calibration coefficients</u>
  - All coefficients are positive →Next step: errors

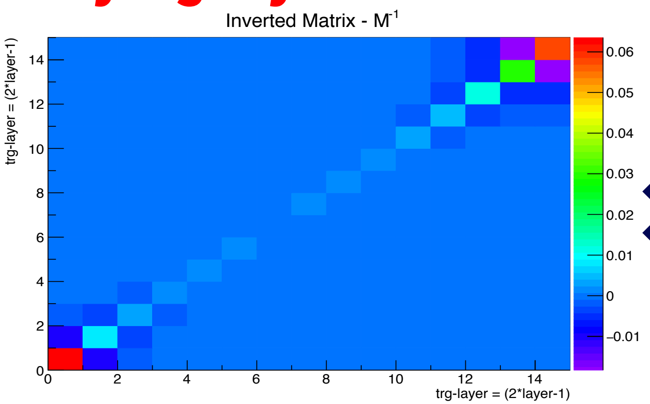
All layers in EE

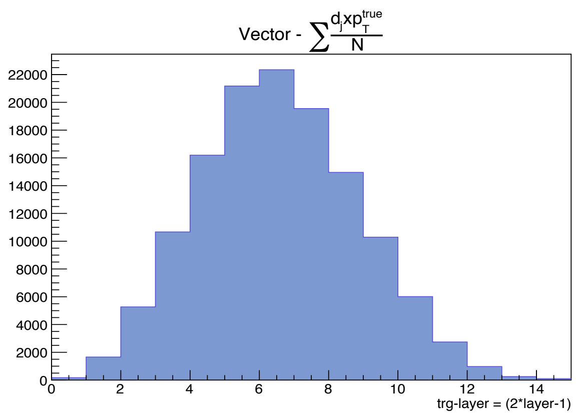


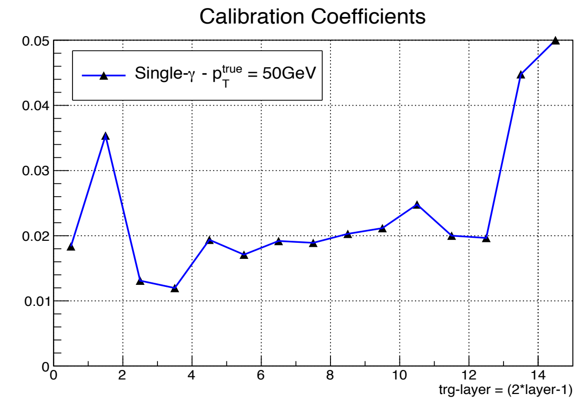




Only trg-layers in EE

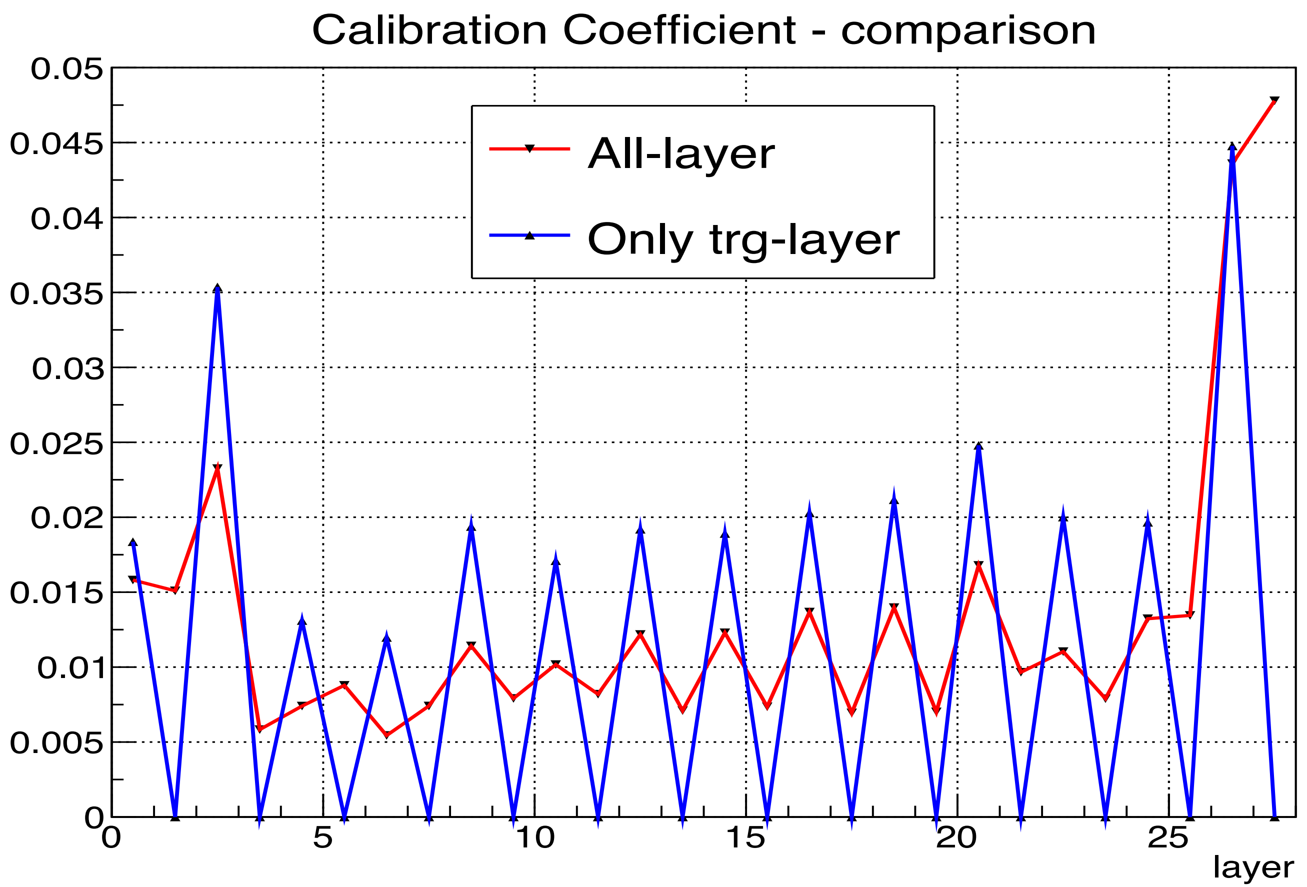






Matrix Inversion Calibration

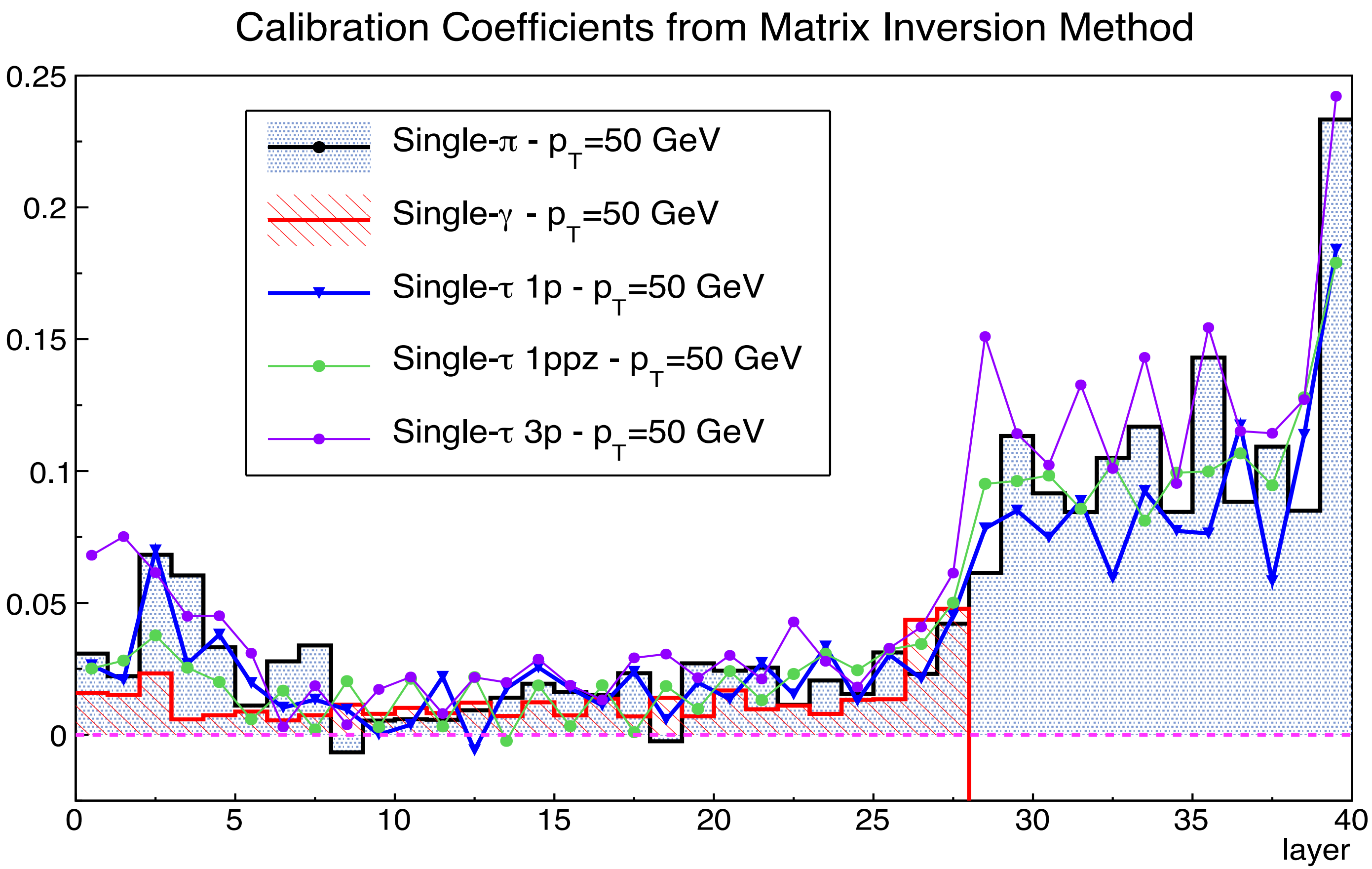
- Deeper look to the coefficients:
  - Comparison between coefficients values obtained using all the layers and only the trigger-layers
  - The coefficients estimated using trg-layers assume larger values (~double), to take care for the deeper absorber between the two active layer considered.



Matrix Inversion Calibration – Tau

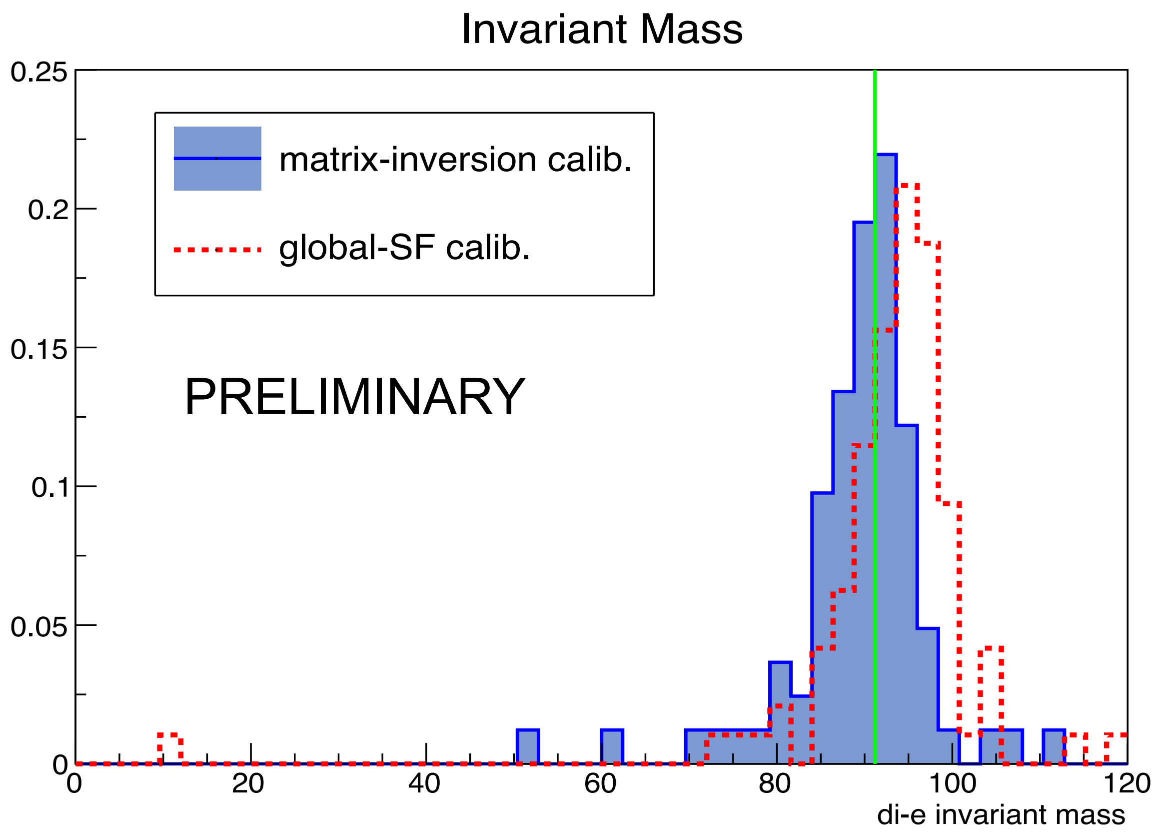
▪ Calibration Coefficients Shapes

- Comparison with respect those obtained from photons and pion
- Same clustering threshold for all physics objects (SE=2 mip_T and TE=2 mip_T)



Matrix Inversion Calibration

- <u>Application of the matrix inversion calibration coefficients</u>
  - Sample of Z→ee without PU
  - Compared with response obtained with the global scale factor cluster calibration



Mean=93.08
RMS=10.7
Res.=11.5%

Mean=89.33
RMS=8.18
Res.=9.15%

Tau clusters in HGCal

- Once again… look to taus!
  - Study of hadronic decay modes
  - Low multeplicity colimated jets, involving more HGCal 3D-clusters
  - Study the energy desity for tau-id @L1
  - Dedicated calibration