The Phase-2 Upgrade of the CMS Experiment

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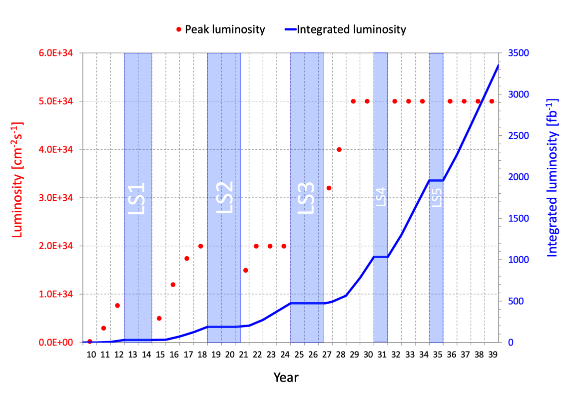
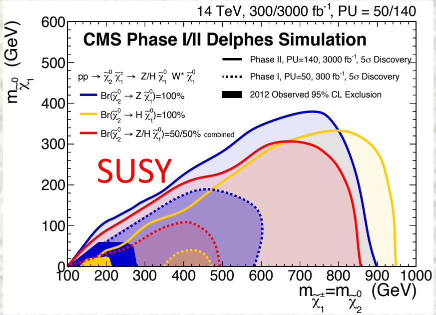
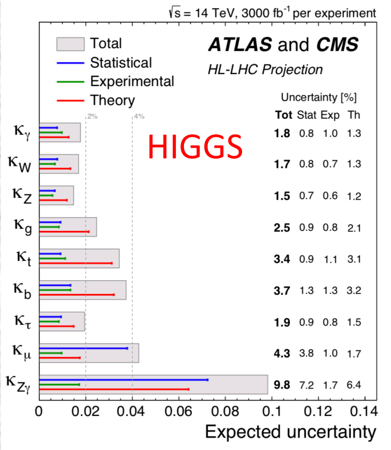
On behalf of the CMS collaboration

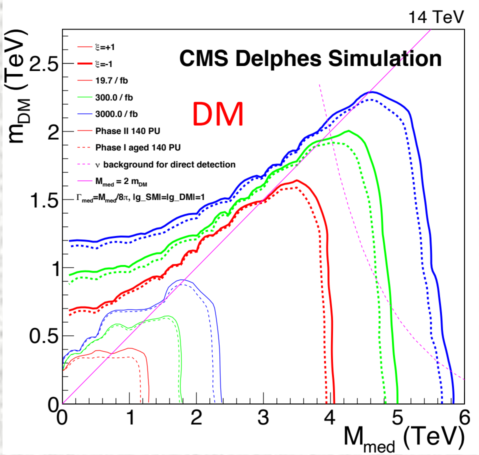
Motivation

- The High Luminosity Large Hadron Collider (HL-LHC) will offer an unprecedented amount of data for physics analysis (10 x LHC Run 3)
- Precision measurements of Standard Model processes will possible
- Reach of new physics searches will be extended to higher energies and unexplored signatures will be investigated
- In order to succeed in this rich physics program significant challenges for the detector performance must be overcome

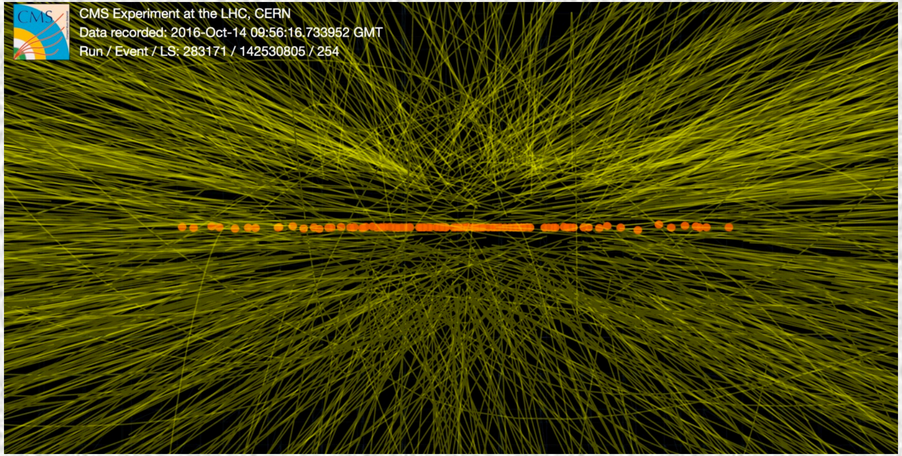


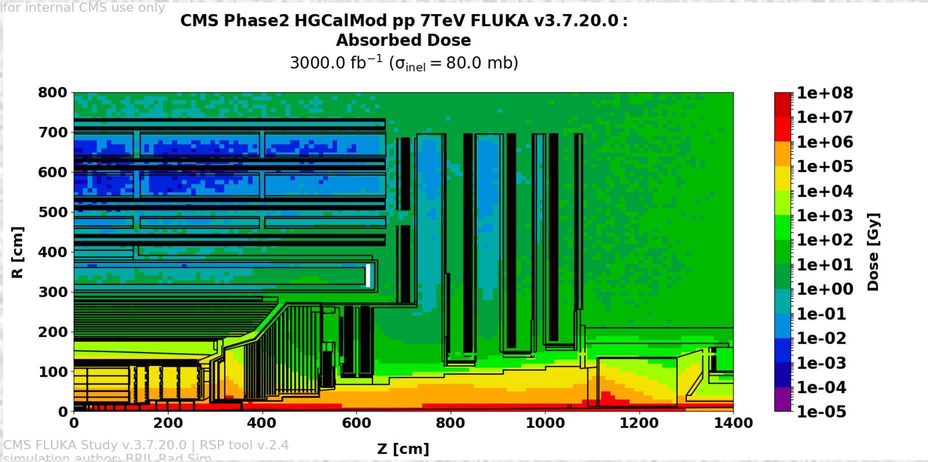






Challenges





The expected pileup (PU) at the nominal HL-LHC luminosity will be 140 (5 x LHC Run 2)

- Reduce sub-detectors granularity
- New sub-detector to include timing information in reconstruction (MTD)
- Novel trigger and DAQ system for better selectiveness, despite the high PU

Exposure of sub-detectors sensors and on-board electronics to radiation cause a progressive degradation of the performance

- Complete replacement of the Tracker and Endcap Calorimeter systems
- Major electronics overhaul and consolidation of the Barrel Calorimeters and Muon systems

Upgrade in a nutshell

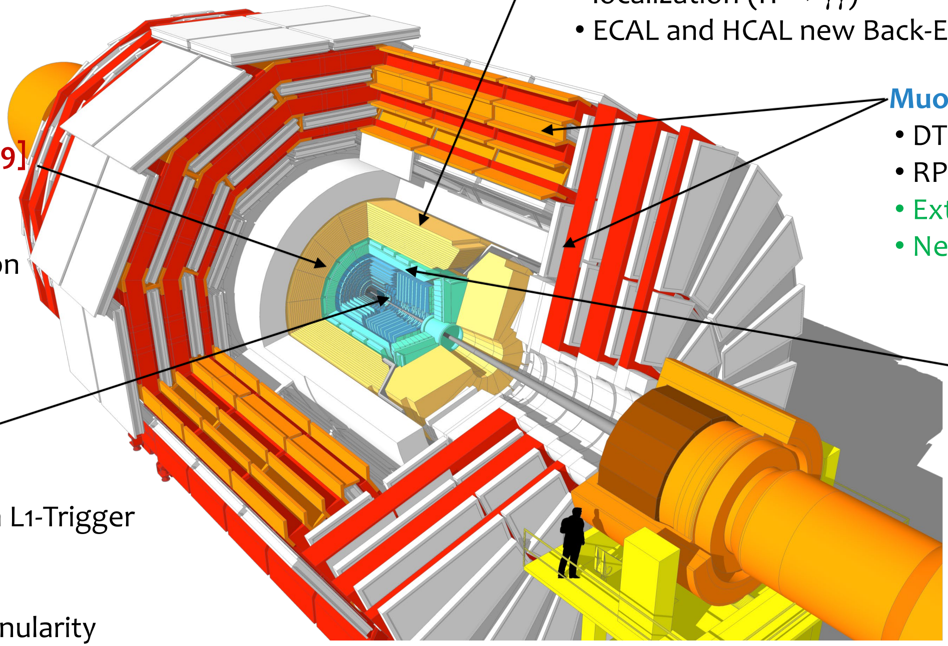
Replacements of existing system/detector
Electronics upgrade/replacement
New detector

L1-Trigger/HLT/DAQ [CMS-TDR-021 / 022]
- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

Barrel Calorimeters [CMS-TDR-015]
- ECAL crystal granularity readout at 40 MHz
- Precision timing for e/γ at 30 GeV, for vertex localization ($H \to \gamma\gamma$)
- ECAL and HCAL new Back-End boards

Calorimeter Endcap [CMS-TDR-019]
- 3D showers imaging for pattern recognition
- Precision timing for PU mitigation
- Si, Scint+SiPM in Pb/W-SS

Muon systems [CMS-TDR-016]
- DT & CSC new FE/BE readout
- RPC back-end electronics
- Extended GEM coverage to $\eta \simeq 3$
- New GEM/RPC $1.6 < \eta < 2.4$



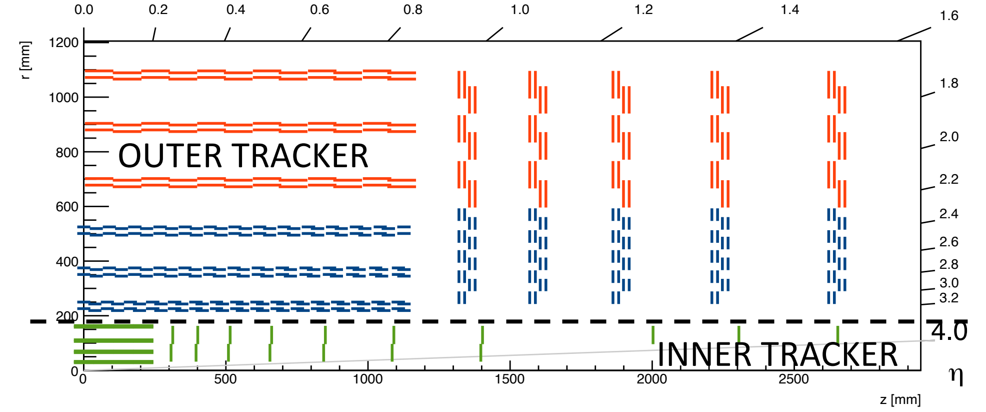
MIP Timing Detector [CMS-TDR-020]
- Precision timing for PU mitigation
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

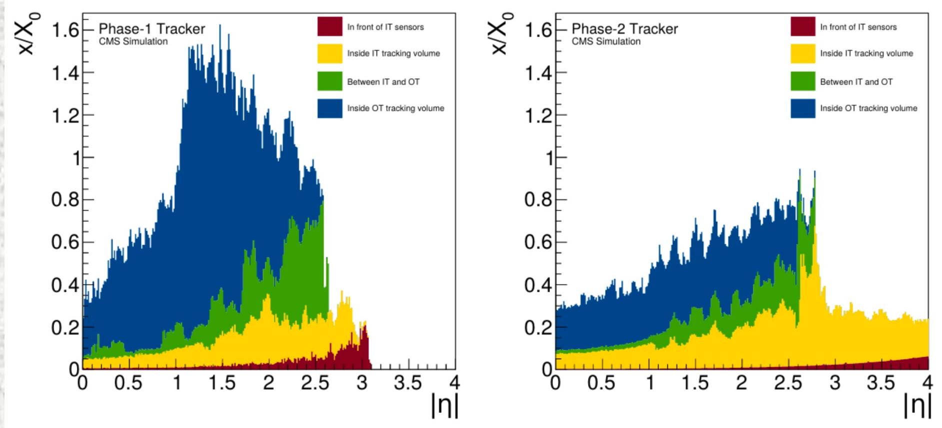
Tracker [CMS-TD-014]
- P_T module design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$
- Much reduced material budget
- Si-Strip and Pixels increased granularity

Tracker Upgrade - 1

Requirements

- Radiation tolerance (fluences up to 2.3 x 10^{16} n_{eq}/cm^2 in pixel layer 1)
- Increased granularity (occupancy <1% in all tracker regions in order to ensure efficient tracking at high PU)
- Reduced material budget in the tracking volume to improve primary vertex reconstruction
- Extended tracking acceptance up to $|\eta| = 4$
- Tracking information to be made available at trigger level





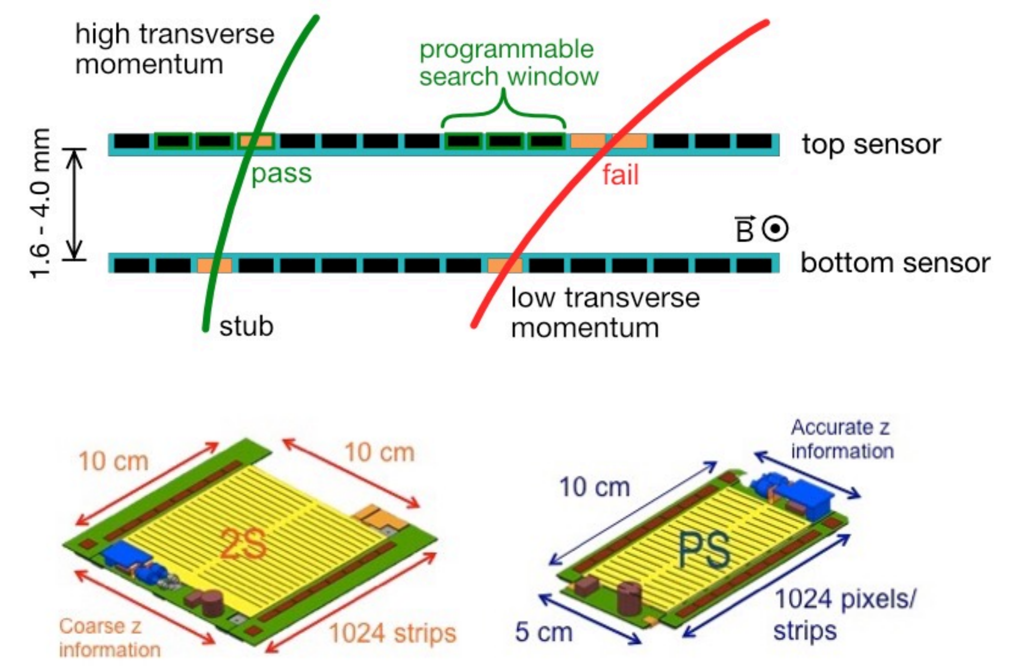
Tracker Upgrade - 2 - OT

p_T module concept

- Exploit bending of charged particle tracks in CMS'4T B-field
- Correlate hits from 2 closely spaced sensors to form "stubs" compatible with a track $p_T > 2$ GeV
- Tuneable offset and window for homogeneous p_T threshold throughout the Outer Tracker

Tracker input to the L1 trigger

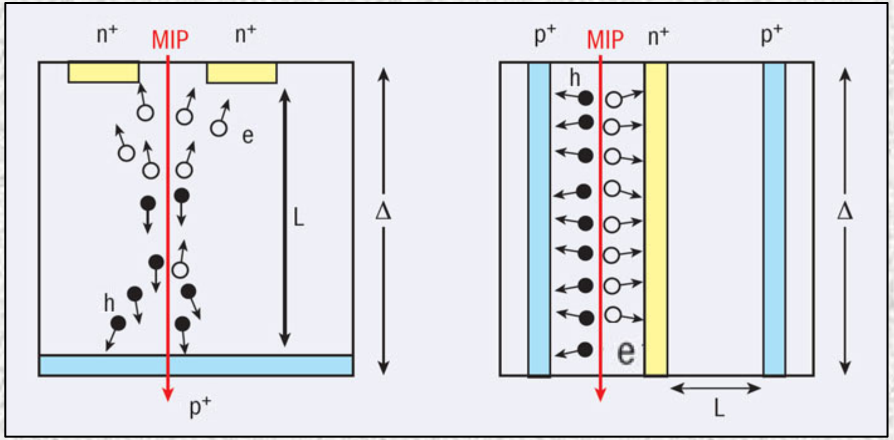
- Stub information is sent out at BX frequency of 40 MHz
- Full data read-out at ~750 kHz

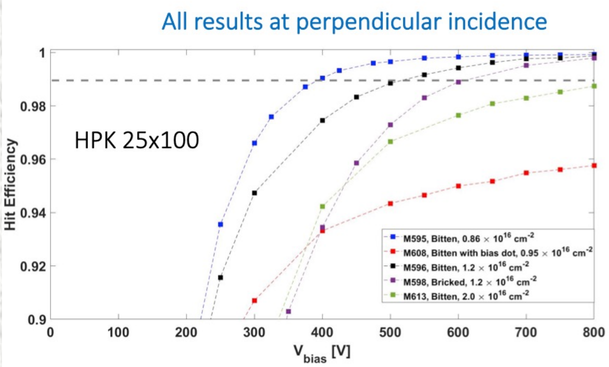


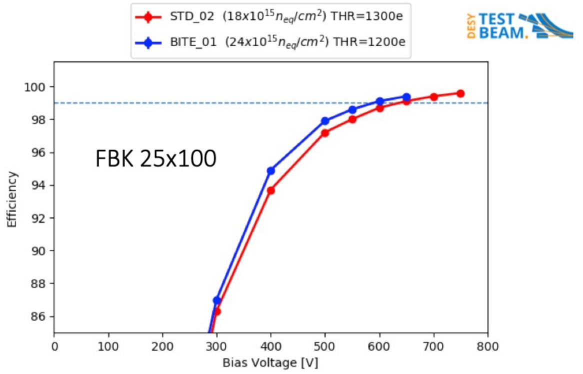
2 strip sensors with 2 x 1016 channels each (5 cm x 90 µm)	Sandwich of 1 strip (2 x 960) and 1 macro-pixel sensor (32 x 960 - 1.5 mm x 100 µm)

Tracking upgrade - 3 - IT

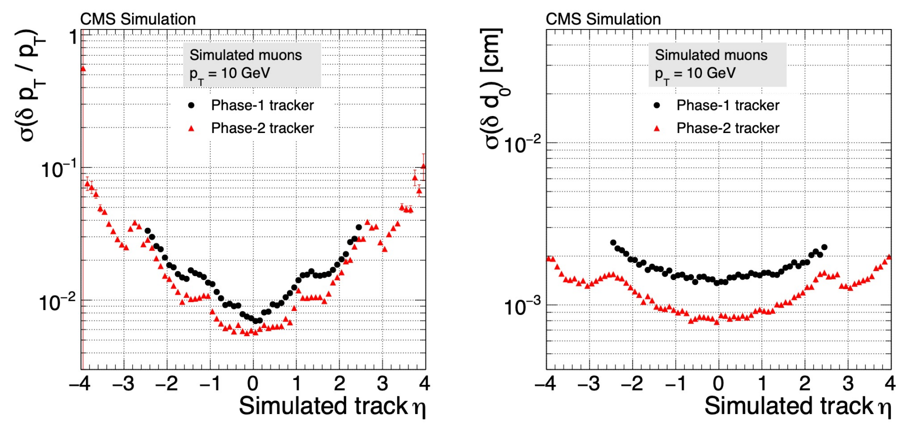
- Reduce sensor thickness in order to improve radiation tolerance (or use 3D sensors)
- Reduce pixel sensors dimensions from 100 x 150 µm² to 25 x 100 µm² or 50 x 50 µm² (choice between squared and rectangular pixels will be made next fall based on outcomes of test beam measurements and CMS full reconstruction simulations)
- Optimize modules powering

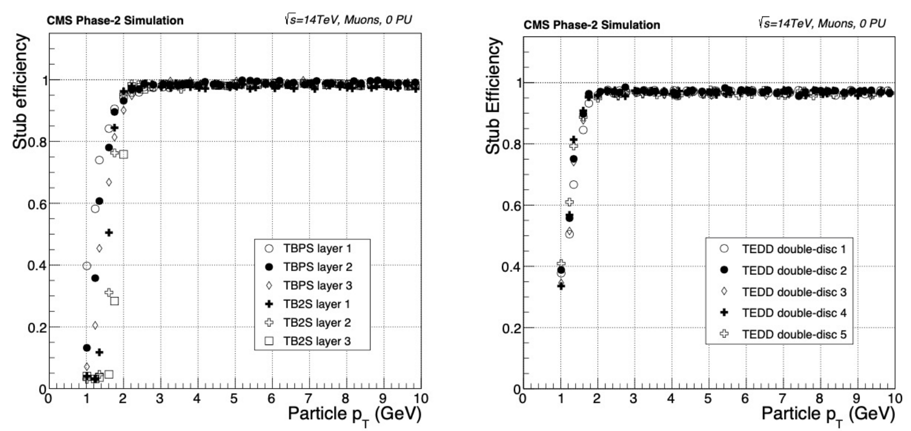


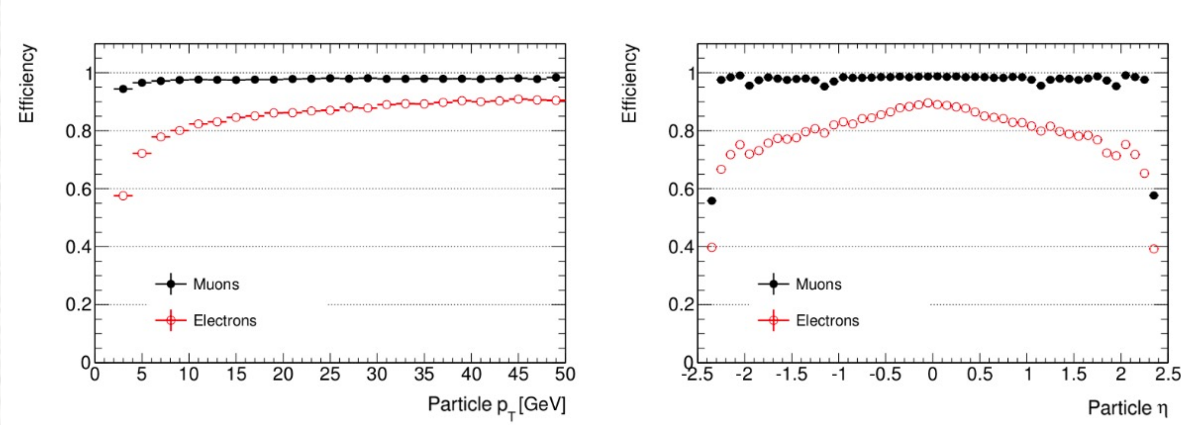




Tracker upgrade - 4 - performance



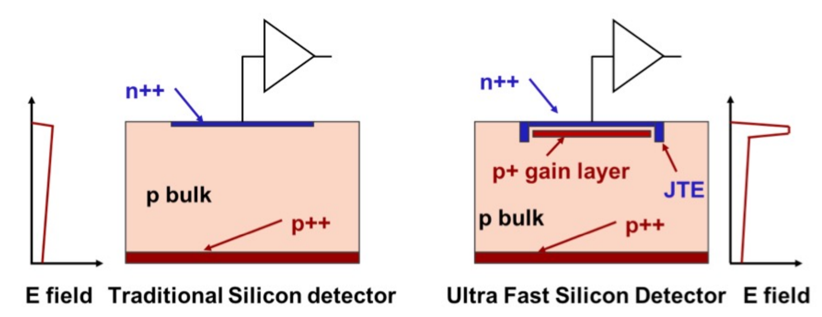


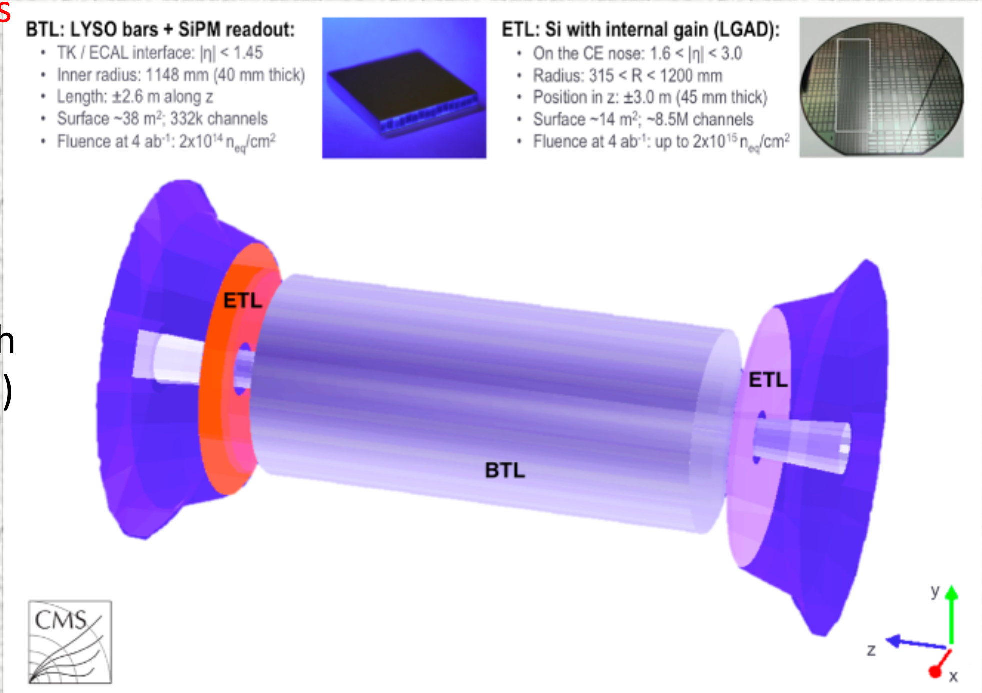


L1 tracking efficiency for prompt muons and electrons for tt events in a scenario with 200 pileup events on average

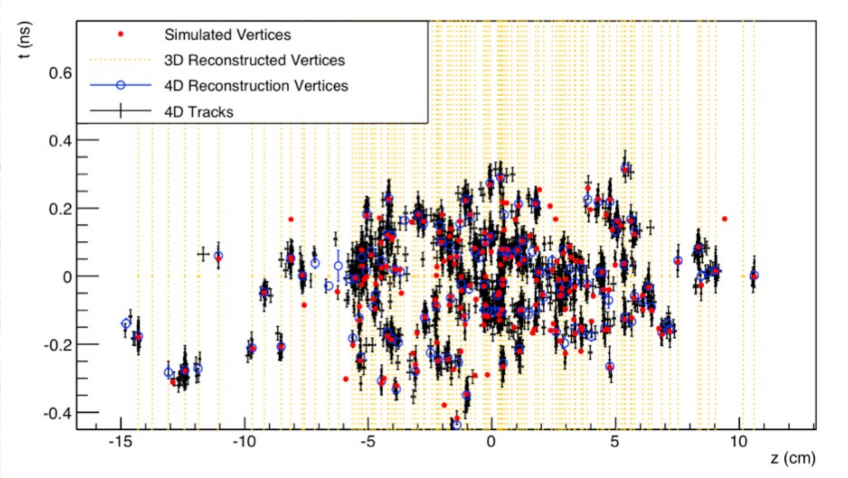
MIP Timing Detector (MTD) - 1

- Measure the production time of minimum ionizing particles (MIP) with a precision of 30 ps (before irradiation) and 50 ps (after irradiation)
- Use this measurement to disentangle PU interactions via 4D vertex reconstruction
- Barrel section (BTL): LYSO crystals coupled to SiPM
- Endcap section (ETL): Planar silicon devices with internal gain, Ultra Fast Silicon Detectors (UFSD) → higher radiation tolerance

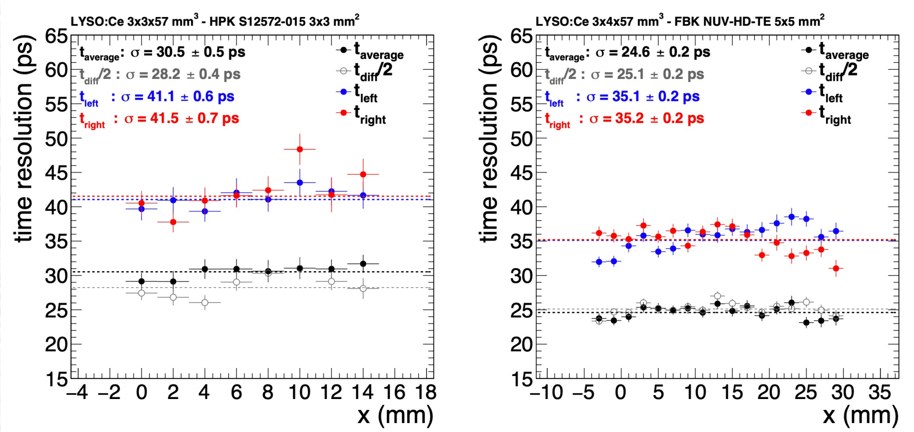




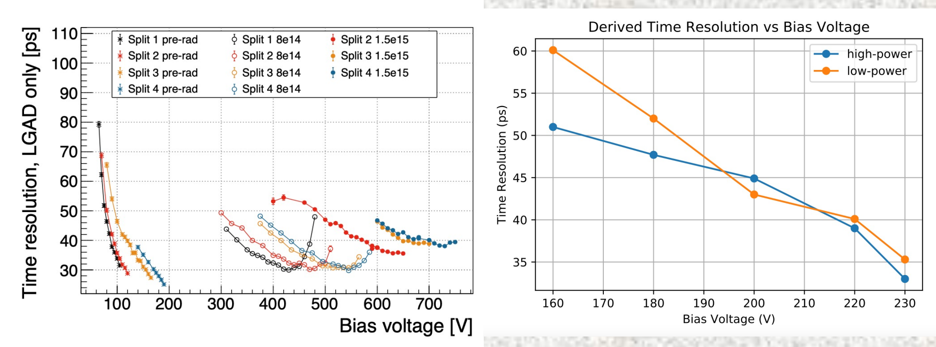
MIP Timing Detector (MTD) - 2



Simulated and reconstructed vertices in a bunch crossing with 200 pileup interactions assuming a MIP timing detector with ~30 ps time resolution covering the barrel and endcaps. Many of the vertices that appear to be merged in the spatial dimension are clearly separated when time information is available.



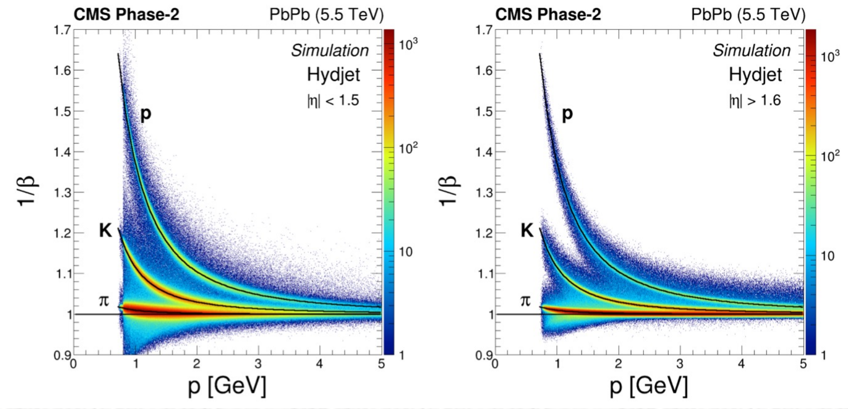
Test beam measurements of LYSO-SiPM assemblies



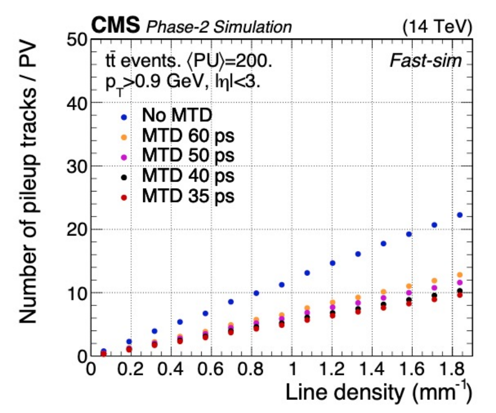
Test beam measurements of LGAD sensors and electronics

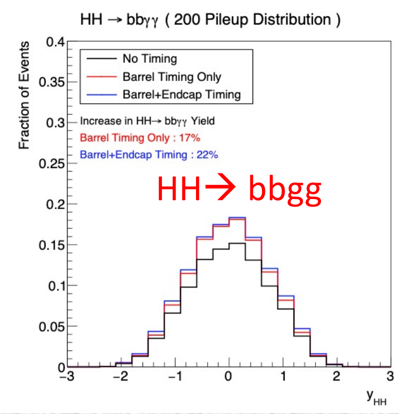
MIP Timing Detector (MTD) - 3

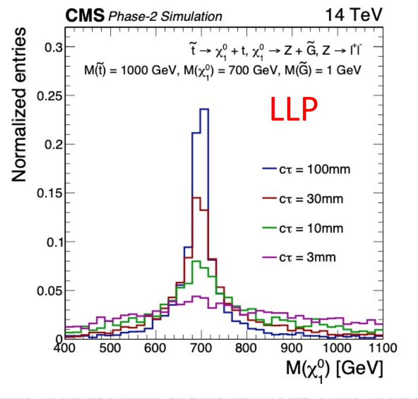
- The addition of track-time information from MTD improves the reconstruction of tracks and primary vertices and also the identification efficiency of leptons, photons and b-jets
- As a consequence many physics analysis will benefit of this improved reconstruction (Higgs, Long Lived Particle Searches, SUSY searches)

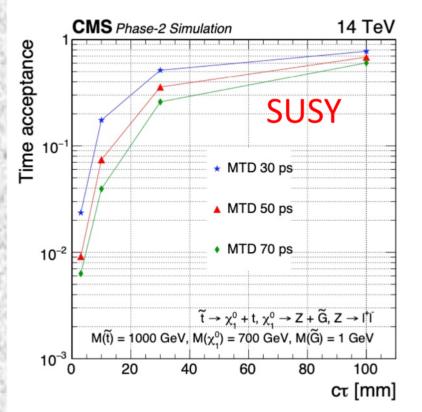


MTD Time of flight discriminating power



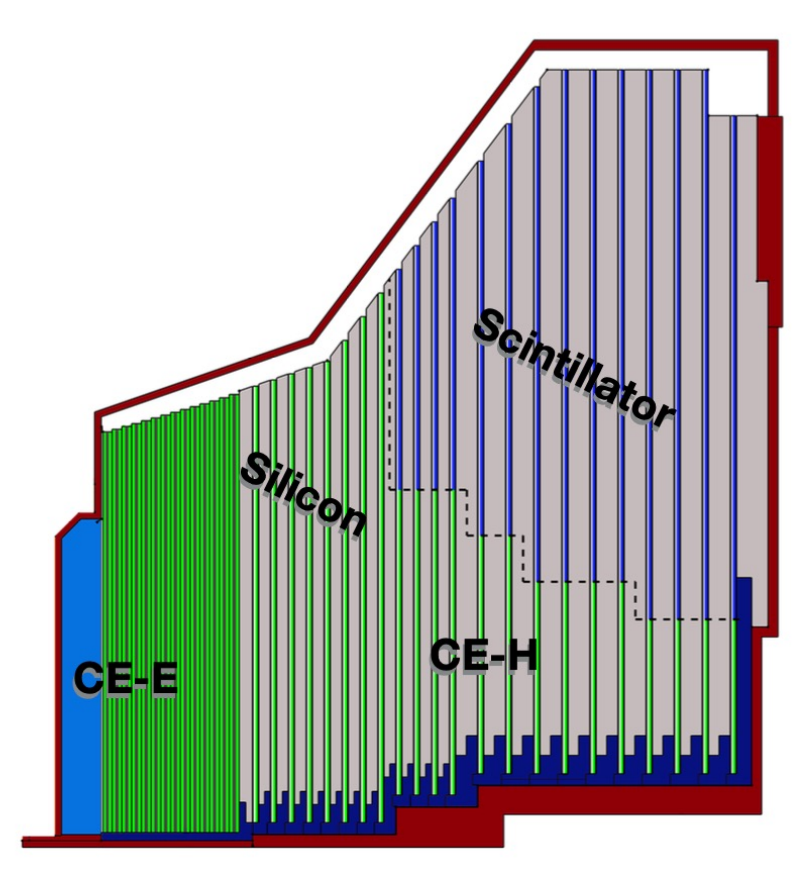






High Granularity Calorimeter (HGCal) - 1

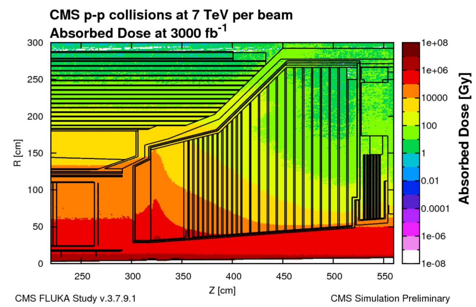
- New endcap calorimeter of CMS:
  - Need to replace ECAL crystals and HCAL scintillators as they were designed for 500 fb^{-1}
  - Need to improve jet energy resolution
- Maximize granularity to fully exploit CMS Particle Flow reconstruction
  - **fine lateral granularity**
    - two-shower separation + narrow jets observation
    - minimize pileup contribution to energy measurements
  - **fine longitudinal granularity**
    - electromagnetic energy resolution (e.g. for $H \to \gamma\gamma$)
    - pattern recognition
    - discrimination against pileup
  - Fully utilise **timing** (real novelty in calorimetry!)
  - Use information at **trigger level**

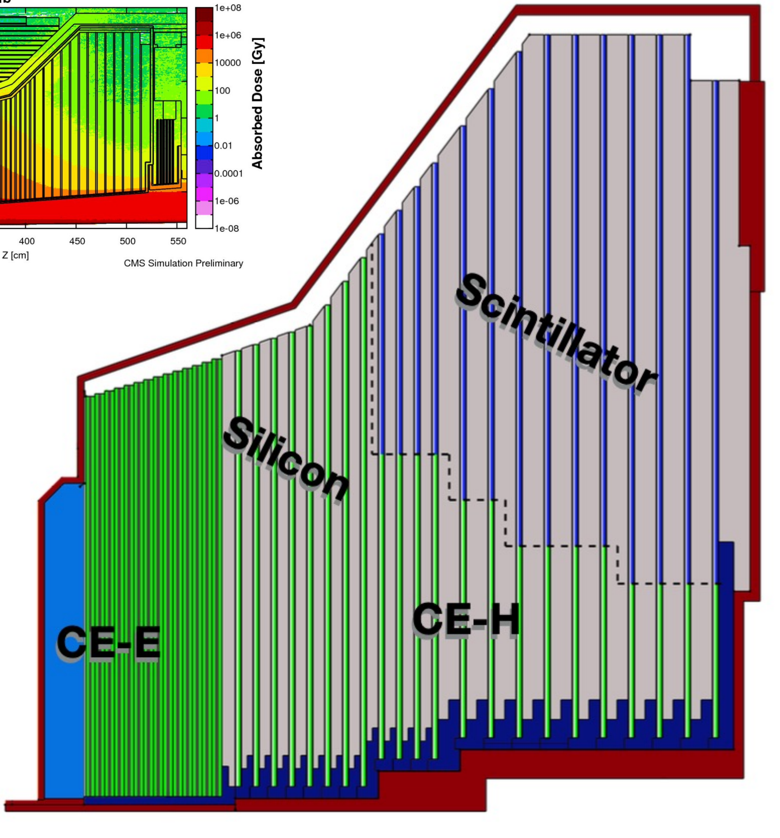


High Granularity Calorimeter (HGCal) - 2

5D sampling calorimeter (Energy, time, x, y, z)

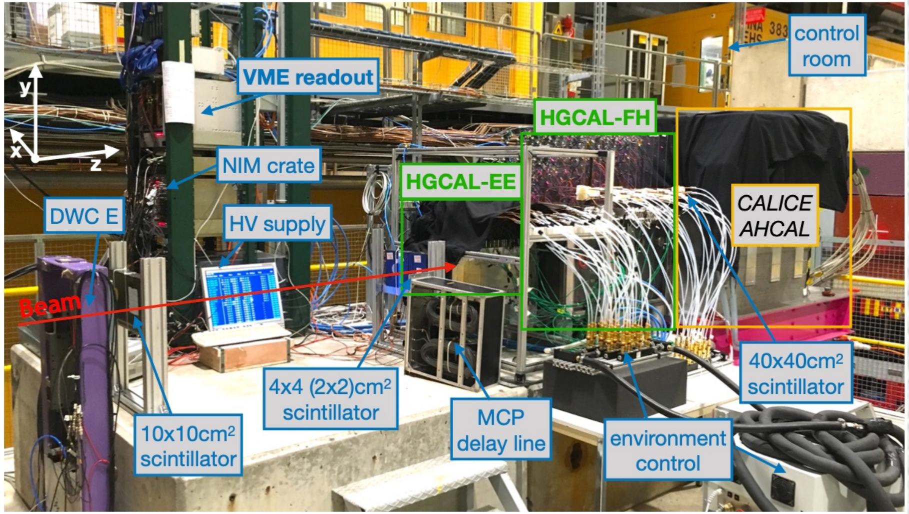
- 28 layers **Si-based** EM compartment (CE-E), ~25X_0 and ~1.3λ
- 22 layers hadronic compartment (CE-H), **Si-based** + Scintillator tiles, ~8.5λ
- Coverage:1.5<$|\eta|$<3.0

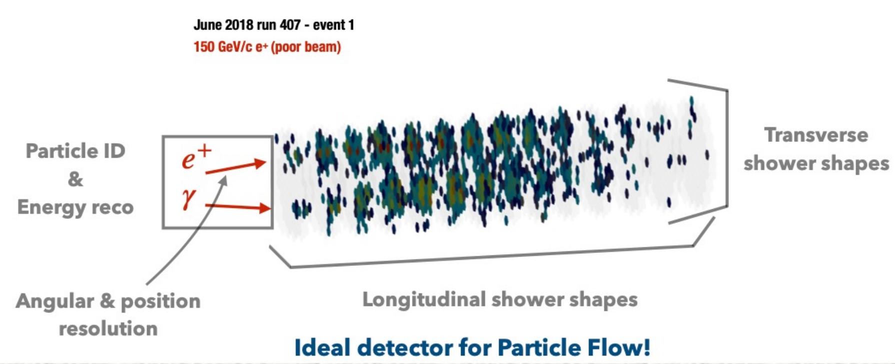


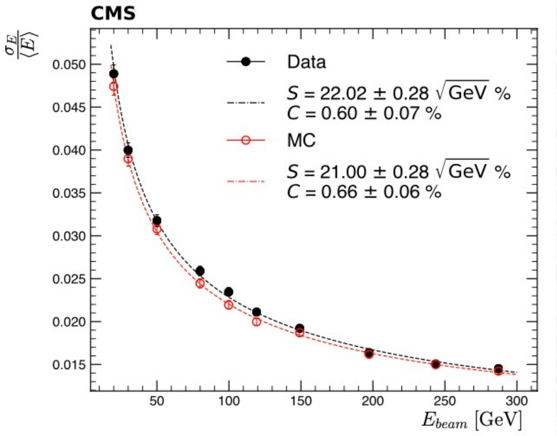


Both endcaps	Silicon	Scintillators
Area	~ 620 m^2	~ 400 m^2
Channel size	0.5 - 1 cm^2	4 - 30 cm^2
# modules	~ 30'000	~ 4'000
# channels	~ 6 M	240 K
Op. temperature	-30 °C	-30 °C

High Granularity Calorimeter (HGCal) - 3





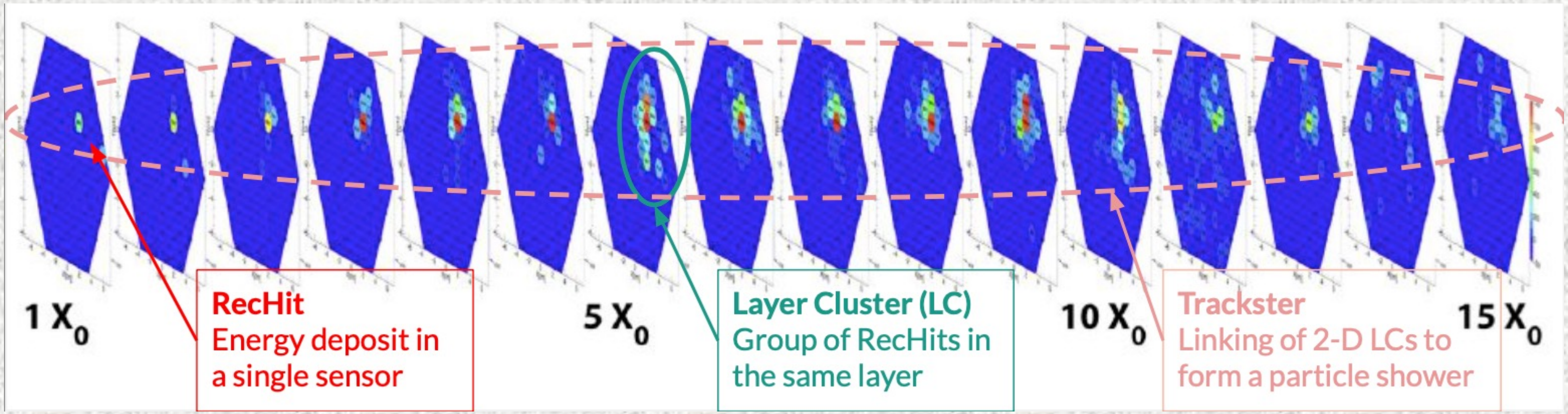


Excellent electromagnetic performance of the first HGCAL large scale prototype at CERN SPS test beam facility.

Much more information in M. Bonanomi talk at BTTB9

High Granularity Calorimeter (HGCal) - 4

- The Iterative Clustering (TICL) is a modular framework integrated and under development in CMS software
- Main purpose: processing calo 5-D rechits (x, y, z, t, E) and returning particle properties and probabilities
- In a nutshell: grouping 2-D Layer Clusters into 3-D clusters (Tracksters) iteratively to reconstruct different particle species using different seeding inputs

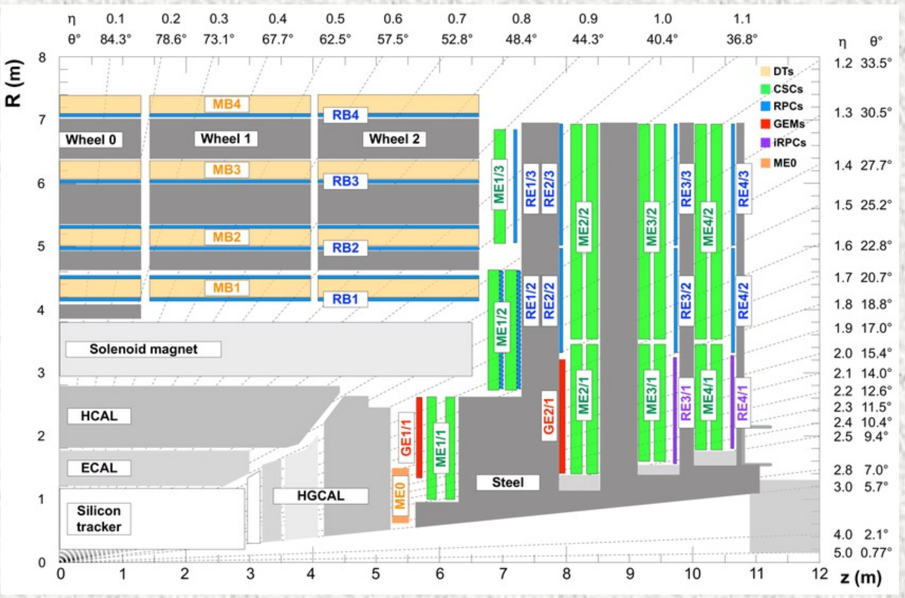


More information in L. Cristella talk at CHEP2021

Muon System - 1

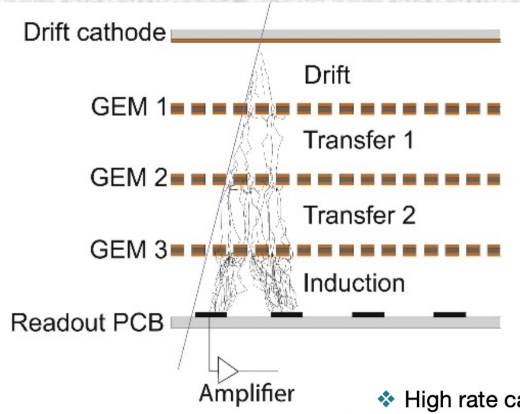
Current muon detectors are expected to withstand HL-LHC radiation levels.
Upgrading/replacing the electronics of the existing DTs, CSCs and RPCs to **ensure longevity and improve trigger performance**.

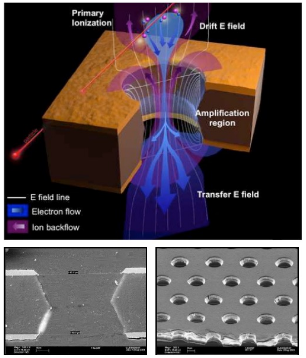
- DT Drift Tubes barrel chambers: 40 MHz readout with improved z/t-precision
- RPC Resistive Plate Chambers: readout with improved t- precision
- CSC Cathode Strip Chambers: readout with higher bandwidth and latency in ME234/1 using current ME1 and replace ME1 with higher radiation tolerance components
- New stations:
  - Gas Electron Multiplication (GEM): GE1/1, GE2/1, iRPC: RE3/1, RE4/1, $1.6 \le \eta \le 2.4$
  - GEM: ME0 extended coverage $1.15 \le \eta \le 3$



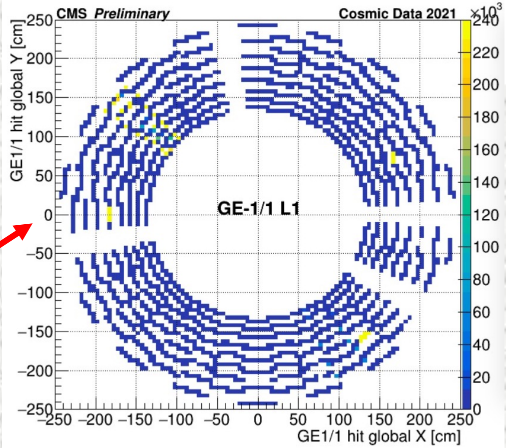
Muon System - 2

- These GEM detectors are built using GEM foils which consists of a thin layer of insulating polymer coated on both sides with copper and chemically perforated with a high density of microscopic holes
- The installation of GE1/1 station has been [recently completed](#) in view of the LHC Run 3
- **September 2020**: GEM DAQ included in global data-taking for the first time
- **2020-2021**:
  - DAQ software commissioning (under development)
  - Calibrations: latency scan
  - GEM-EMTF trigger link
  - connectivity tests
  - Cosmic muon data taking



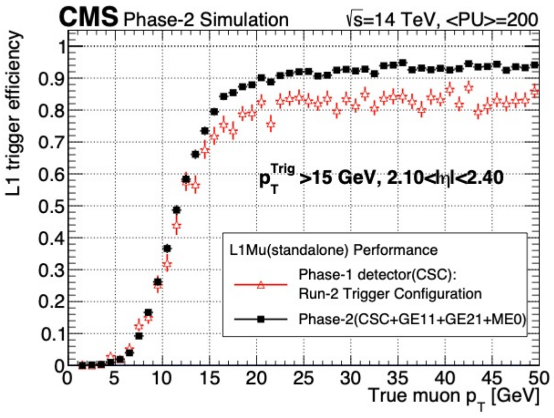


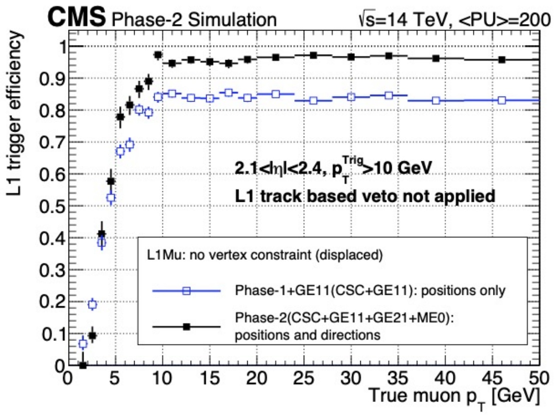
- High rate capability, up to O(MHz/cm²)
- Efficiency > 98%
- Space (time) resolution ≈ 300 μm (8 ns) [1]
- Gas mixture: Ar/CO_2 70/30



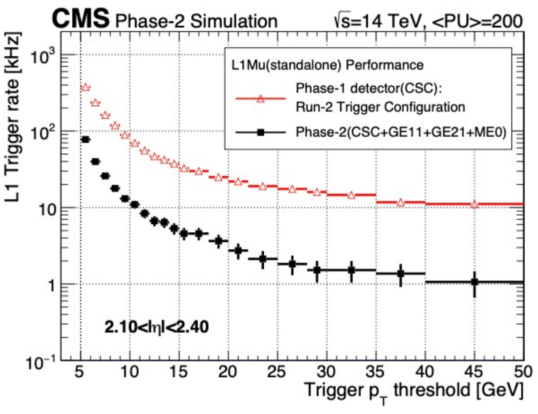
More information on the GE1/1 upgrade in F. Simone talk at iWORID2021

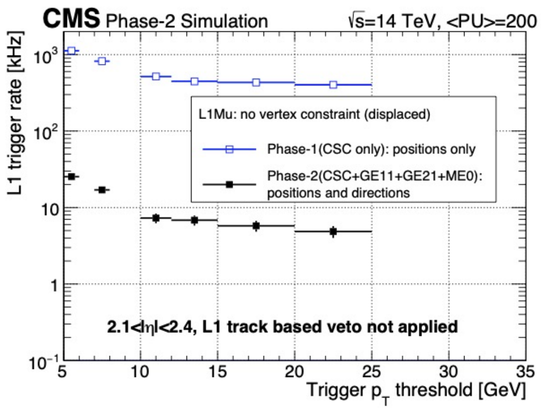
Muon system - 3





L1 Muon trigger efficiency for the *prompt* muon trigger (left) and *displaced* muon trigger algorithm (right), as a function of a true muon p_T in the region 2.1 < |η| < 2.4. The L1 trigger pT threshold is 15 GeV (left) and 10 GeV (right).

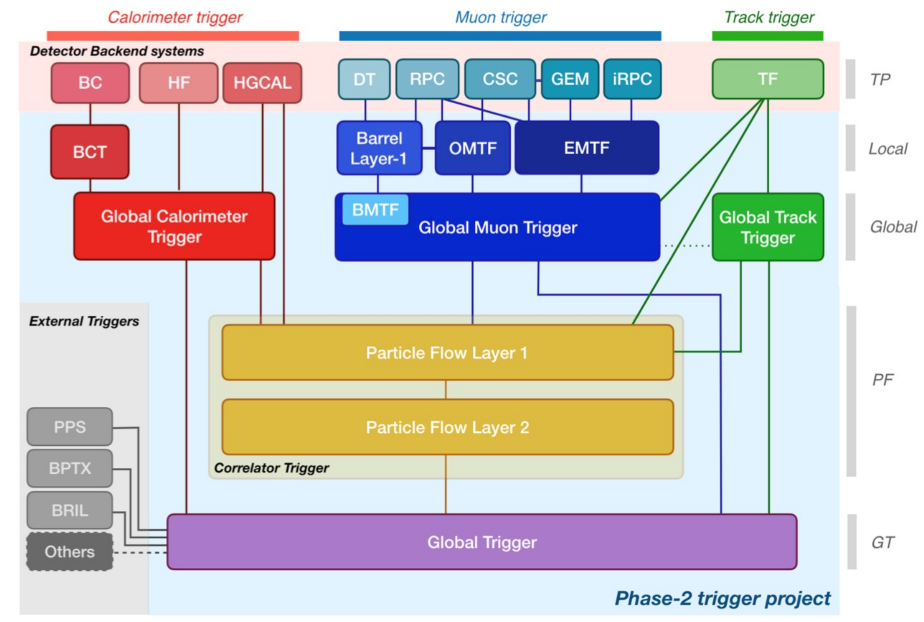




L1 *prompt* (left) and *displaced* (right) muon trigger rates, with and without GEM chambers, as a function of muon trigger p_T threshold in the region 2.1 < |η| < 2.4. The L1 track based veto is expected to further reduce the displaced muon trigger rate by a factor of 3–8.

Trigger - 1

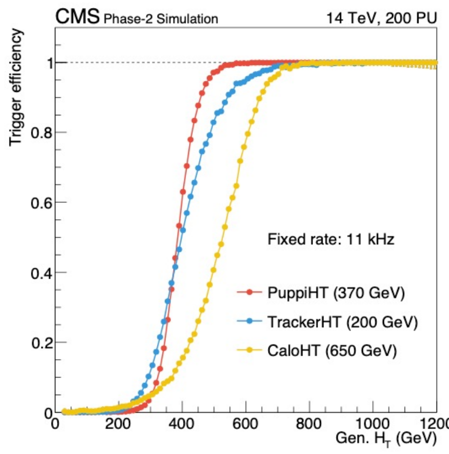
- CMS will keep a 2-level triggering approach: L1 & HLT
- Key features of Phase2 Upgrade of Level-1 Trigger:
  - Increase bandwidth 100 kHz → 750kHz
  - Increase latency 3.8 μs → 12.5 μs
- Include information from tracker and HGCAL
- Sophisticated FPGA-based algorithms: using particle-flow (PF) reconstruction techniques or Machine-Learning based approaches.
- Increase trigger acceptance and physics sensitivity while maintaining Run-2 thresholds.
- Scouting into HL-LHC data @ 40 MHz: storing only high-level information.

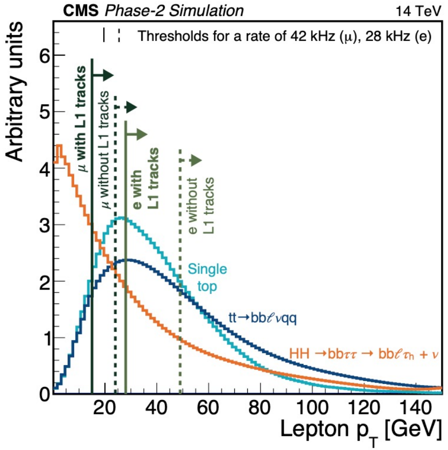


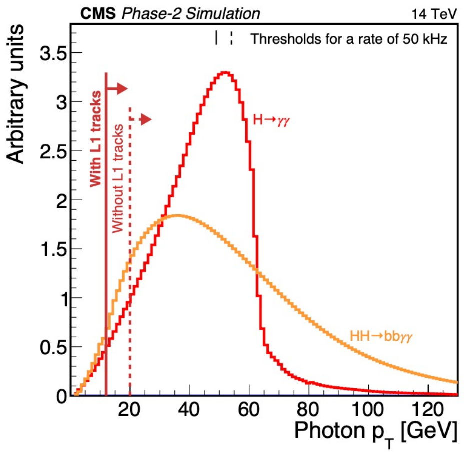
Four distinct and independent trigger processing paths: a calorimeter trigger, a muon trigger, a track trigger and a particle-flow (correlator) trigger

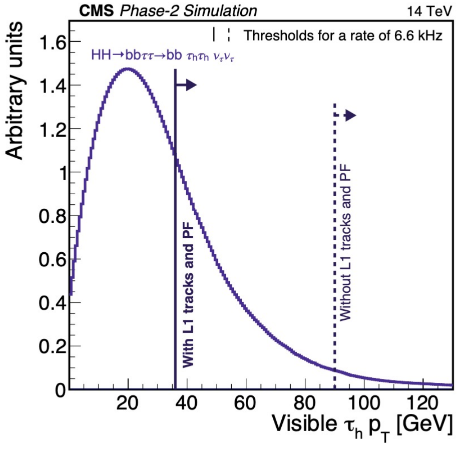
Trigger - 2

- Extensive use of tracking to reach near offline performance (sharper efficiency turn-on curves) + reconstruction of Primary Vertex.
- Exploit complementarity of different object flavour:
  - **Standalone objects**: robust triggers based on independent sub-detectors
  - **Track-matched objects**: tracking used to confirm standalone objects, significant improvement with simple design
  - **Particle-flow (PF) objects**: ultimate performance improvement, combine all information to match offline algorithms, require most processing time and resources for calculation







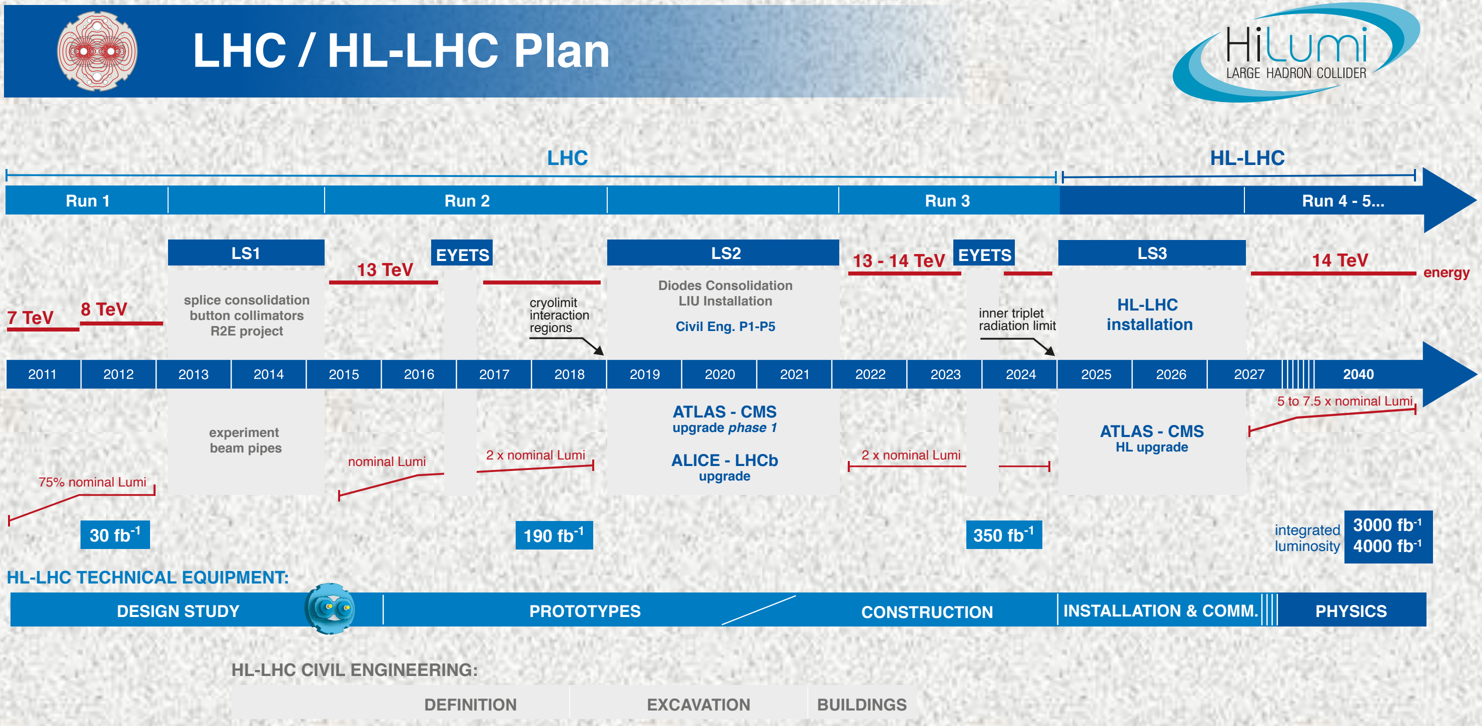


Conclusions

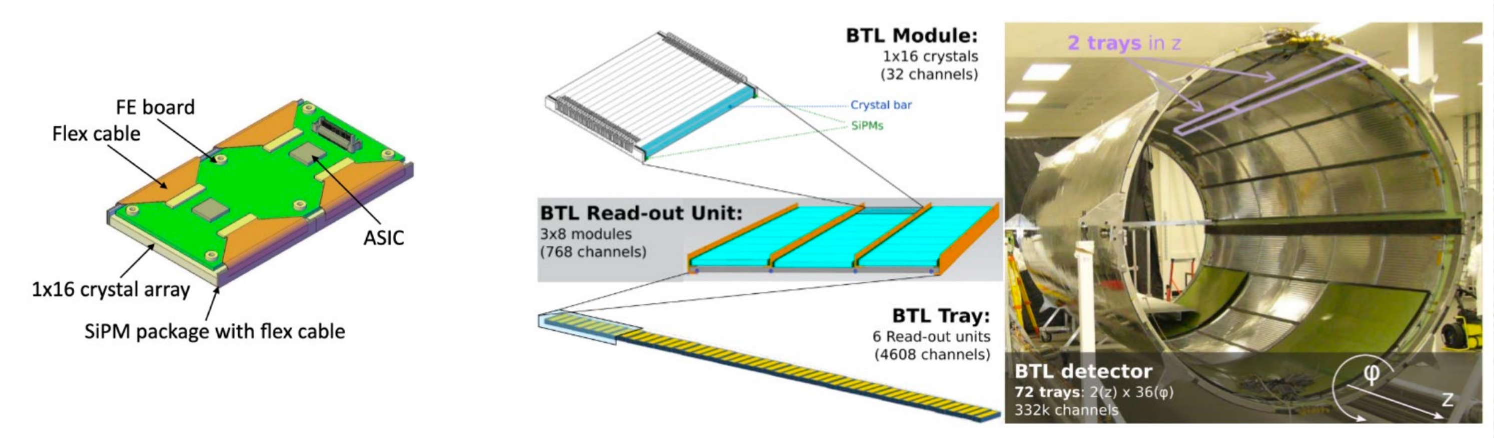
- In response to the unprecedented challenges of the HL-LHC environment the CMS Phase-2 upgrade introduces new paradigms
  - p_T modules for L1 Trigger Tracking
  - High Granularity Calorimetry and Precision Timing for PileUp mitigation
- The installation of the first Phase 2 subdetector, the GEM GE1/1 station, has been recently completed
- Many R&D programs are currently at fully swing and many challenges still lie ahead.
- This, together with the commitment and support of CERN and of all the Funding Agencies and Institutes, provide a solid footing for successful completion of the HL-LHC Upgrade program.

Backup

LHC Timeline



The Barrel Timing Layer: Overview



Key features:

- LYSO crystals with dual end SiPM readout
- Basic unit : 1x16 array of crystals (~3x3x57 mm^3)
- Arranged in trays and segmented in readout units
- Coverage of $|\eta| < 1.45$, surface ~38 m^2, 332 k channels
- Nominal fluence : 2 x 10^{14} n_{eq}/cm^2

Recent Progress:

- LYSO qualification and testing
- SiPM characterization and procurement
- ASIC and FE prototyping and testing
- System tests with FE/BE integration
- Mechanics design.

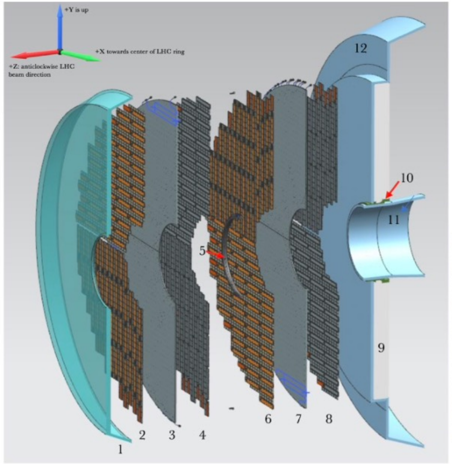
The Endcap Timing Layer: Overview

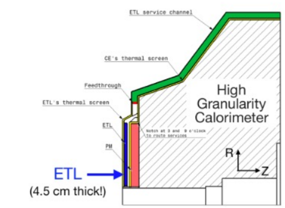
Key features:

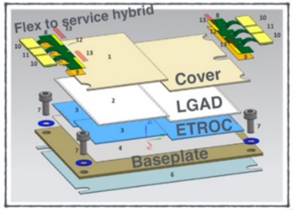
- LGAD detectors
- Basic unit : Module (~4x6 cm^2)
  - The LGADs are bump bonded to ETROC ASICs mounted on two sides of cooling plates.
- Two disks per endcap mounted on the HGCAL nose.
- Coverage of $1.6 < |\eta| < 3.0$, surface ~14 m^2, 8.5 M channels
- Nominal fluence : 2 x 10^{15} n_{eq}/cm^2

Recent Progress:

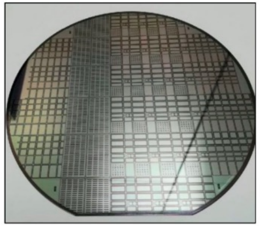
- LGAD characterization
- ASIC prototyping
- System and Mechanics design prototyping



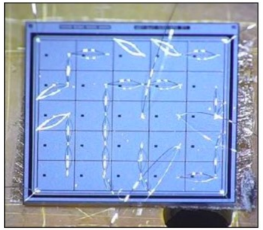




FBK UFSD3



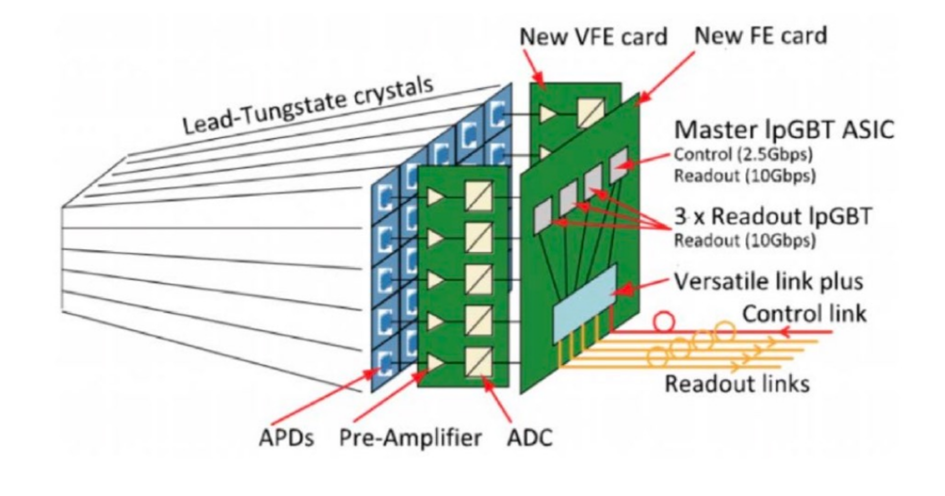
LGAD prototype sensors

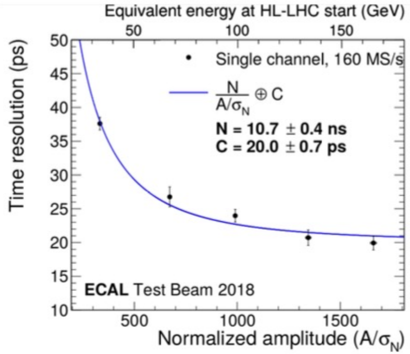


5x5 array from HPK

Barrel Calorimeters

- **Replace all active on-detector electronics components (ECAL)**
  - Digitization at 160 MHz
  - On the fly pulse-shape discrimination to help discriminate against spikes
  - Oversampling - noise reduction, pile-up mitigation
  - Time resolution: 30 ps for E > 50 GeV
- **Streaming of all digitized data off-detector (using lossless compression)**
  - Lifts Phase-1 trigger latency bottleneck of 3.8 μs
  - trigger primitive generation off-detector
  - Cell information - 5 x 5 crystals → single crystal
- **Replace all off-detector electronics components (HCAL+ECAL – ATCA)**
- Reduce the operating temperature from 18 C to 9 C to mitigate APD ageing effects.





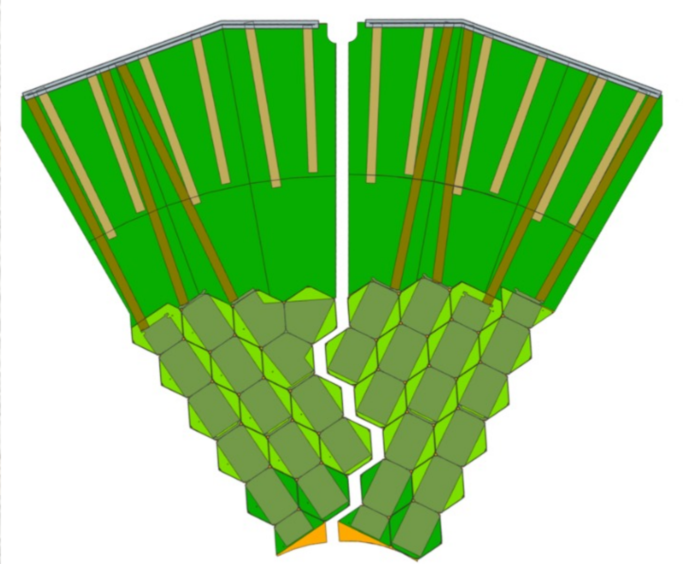
High Granularity Calorimeter (HGCal) - materials

SILICON

- 8'' hexagonal geometry: most efficient use of Si area.
- p-type bulk → more radiation-tolerant than n-type.
- Sensor thickness and cell size vary with radiation levels
- Operation at -30° C: Reduce increasing bulk leakage current.
- Increasing the bias voltage up to -800V to reduce signal loss.

SCINTILLATOR

- Cheaper than silicon.
- Rely on experience from CALICE and past CMS HCAL upgrade.
  - Radiation hardness of scintillators and SiPMs well understood.
  - Overall ***S/N for MIP*** remains ***> 5*** after 3000 fb^{-1}.
- **SiPM-on-tile design**
  - 40k SiPMs integrated into the PCB, need to be cooled.
  - Light ***readout*** directly on ***detector***.
  - More compact and cost-effective.



Mixed cassette in CE-H