IMPERIAL

Towards calorimetry at 100 TeV: lessons from CMS High Granularity Calorimeter

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(on behalf of the CMS collaboration)

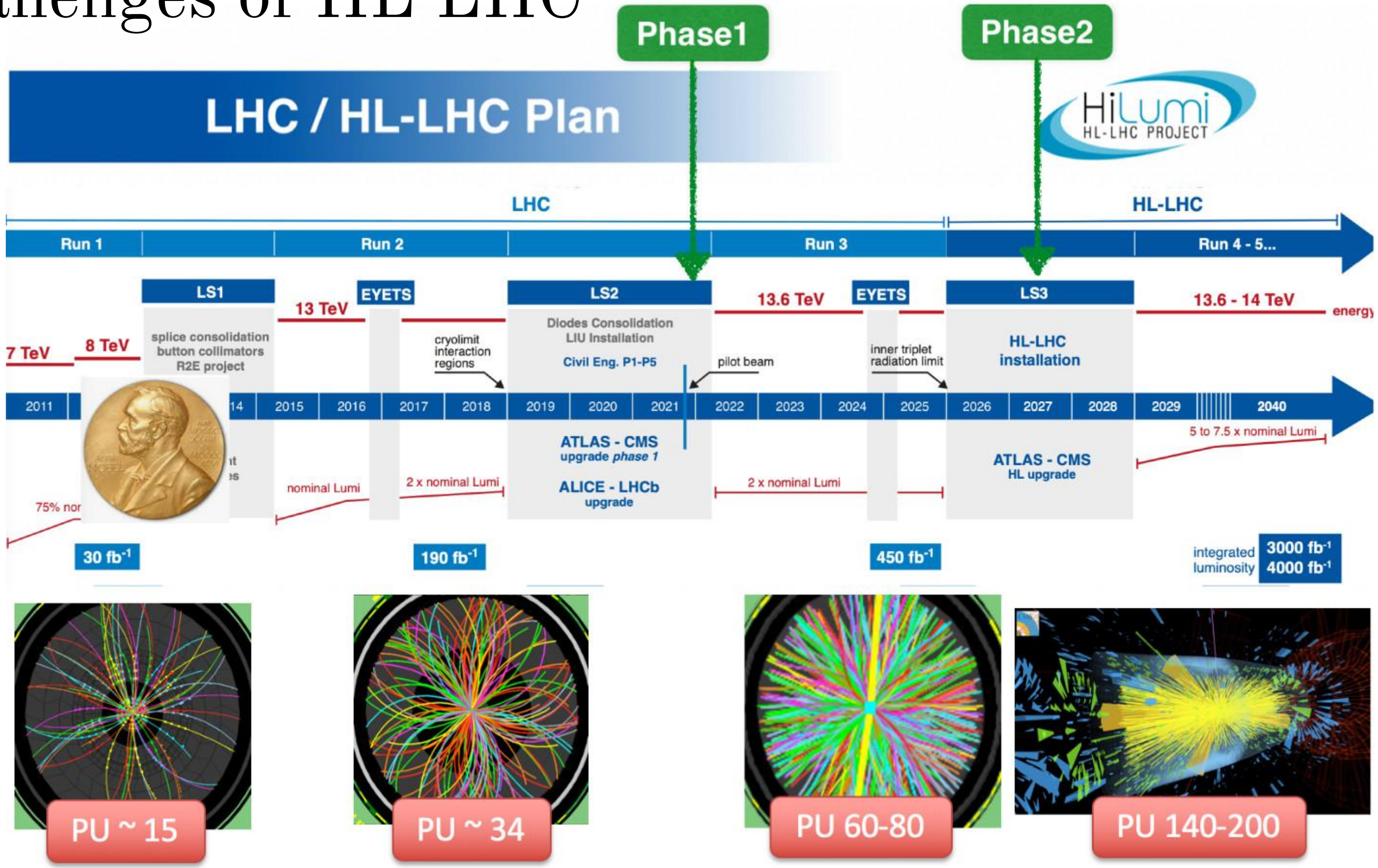
FCC-UK Meeting, 12 November 2025

The Institute for Particle Physics Phenomenology, Durham, UK

Physics motivation: Collecting a larger statistics

- Precision study of known SM processes
  - top quark property measurements
  - second generation Higgs couplings
- Study of reactions initiated by VBF processes
- Narrow boosted jets from τ
- Merged jets from hadronic decays of W,Z

Challenges of HL LHC



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CMS during HL-LHC

Technical proposal CERN-LHCC-2015-010 https://cds.cern.ch/record/2020886
Scope Document CERN-LHCC-2015-019 https://cds.cern.ch/record/2055167/files/LHCC-G-165.pdf

Complete replacement**

L1-Trigger/HLT/DAQ**
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193

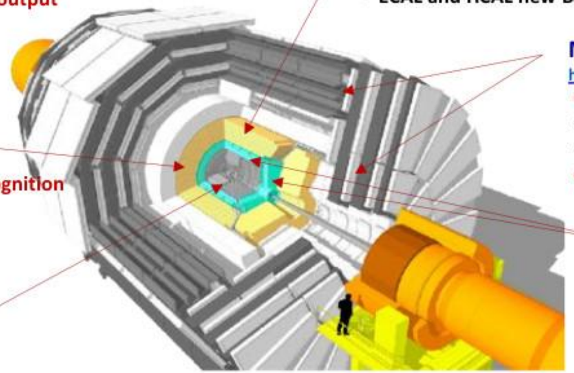
- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

Calorimeter Endcap**
https://cds.cern.ch/record/2293646

- 3D showers imaging for pattern recognition
- Precision timing for PU mitigation
- Si, Scint+SiPM in Pb/W-SS

Tracker**
https://cds.cern.ch/record/2272264

- 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



Major Electronics Upgrade/ Consolidation *

Barrel Calorimeters*
https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz
- Precision timing for e/γ at 30 GeV, for vertex localization ($H \rightarrow \gamma\gamma$)
- ECAL and HCAL new Back-End boards

Muon systems* ***
https://cds.cern.ch/record/2283189

- Extended GEM coverage to $\eta \simeq 3$
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$

New Detector System***

MIP Timing Detector***
https://cds.cern.ch/record/2296612

- Precision timing for PU mitigation
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

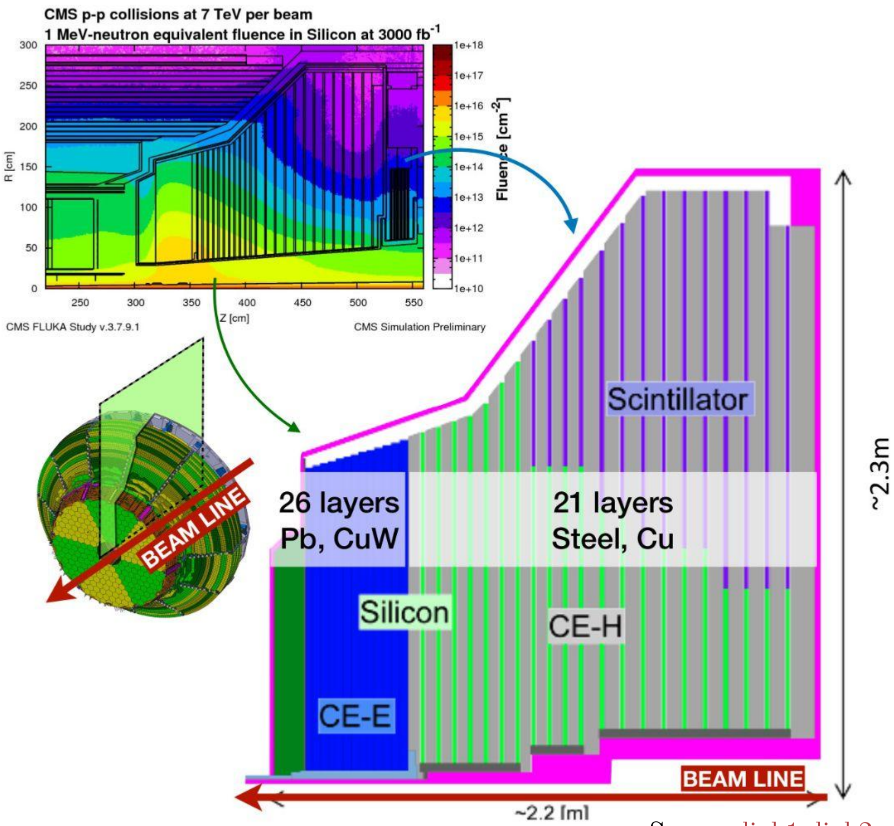
Beam Radiation Instr. and Luminosity
Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

New paradigms for a HEP experiment to meet the unprecedented challenges and fully exploit the HL-LHC luminosity and physics potential

Source: link

CMS High Granularity Calorimeter (HGCAL)

- A sampling calorimeter
- Replace ECal and HCal at $1.5<|\eta|<3$
- High pileup (~200) and rad. dose (~2 MGy)
- High granularity
  - (Si: 0.6-1.2 cm^2; Sci: 4-30 cm^2)
- High radiation tolerant (100, 200, 300 μm)
- CE-E:
  - 26 layers ($27.7X_0/1.6\lambda$)
- CE-H:
  - 21 layers (9.4λ)
- Channels- Si: 6M, Sci: 250K
- Precise timing ~30 ps
- Operation at -30°C
- 5D : x,y,z,t,E



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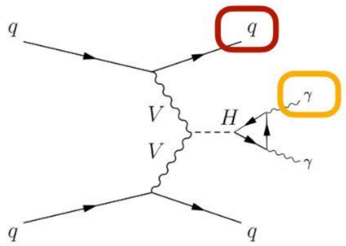
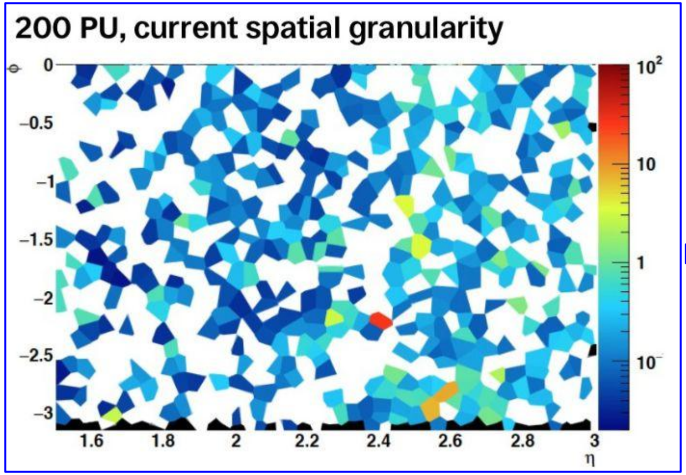
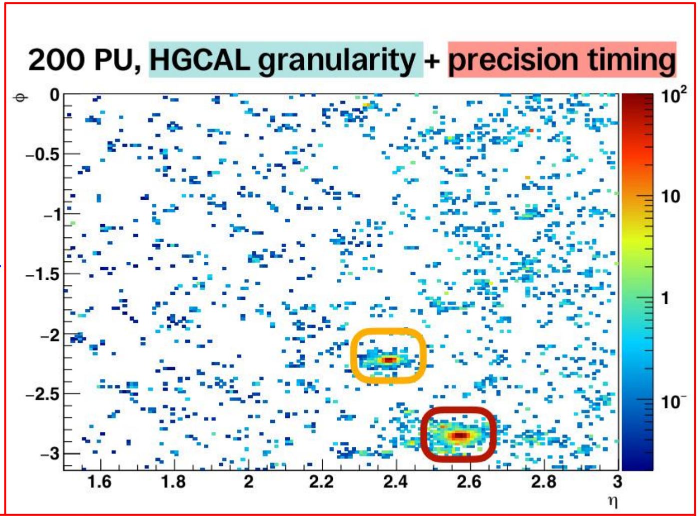
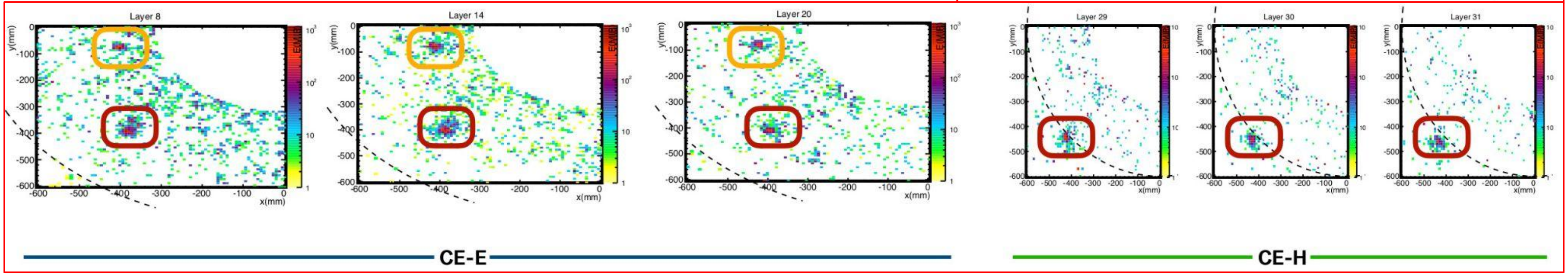
Vector Boson Fusion with HGCAL



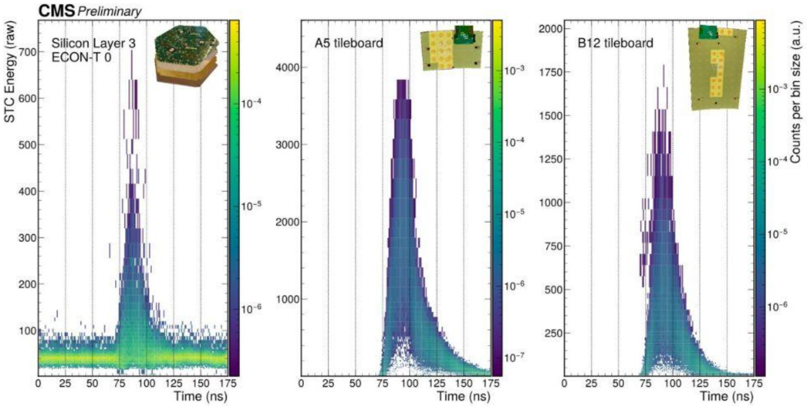


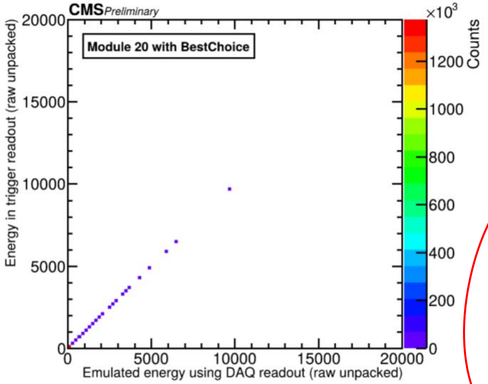


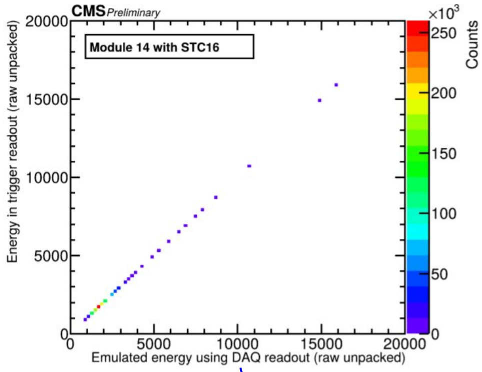


Source: [link]

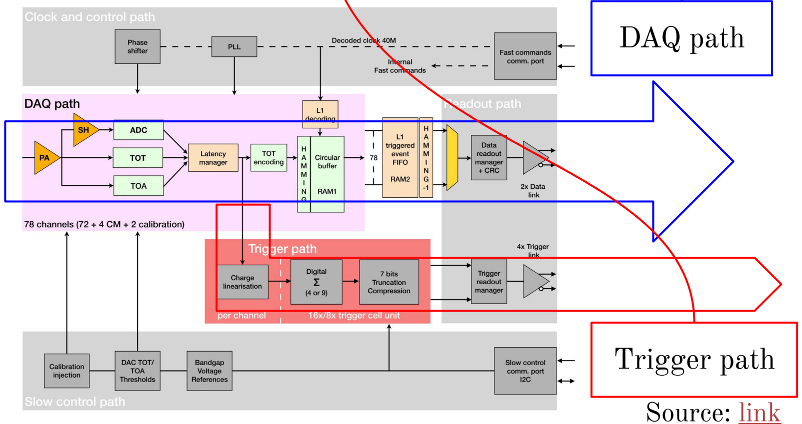
2024 test beam: trigger readout







- First end-to-end readout test
- Successful emulation of trigger signal using DAQ data



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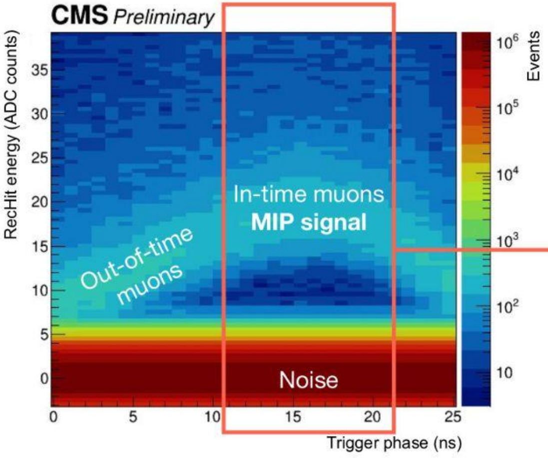
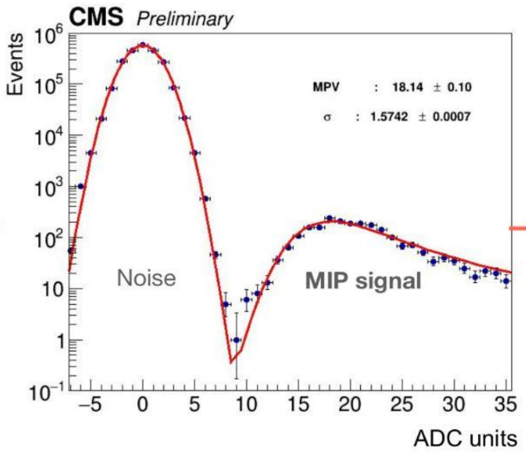
2024 test beam: MIP and S/N

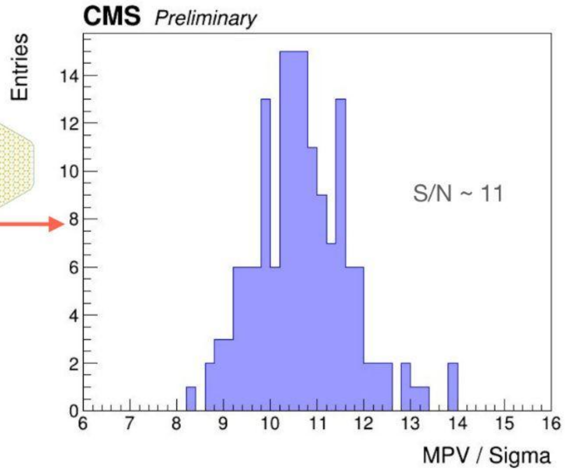
- Muon beam data



Clear MIP peak visible versus time (asynchronous beam)



Landau+Gauss fit to pedestal-subtracted distribution in the signal region to extract the scale per-cell



Good performance for channels exposed to beam

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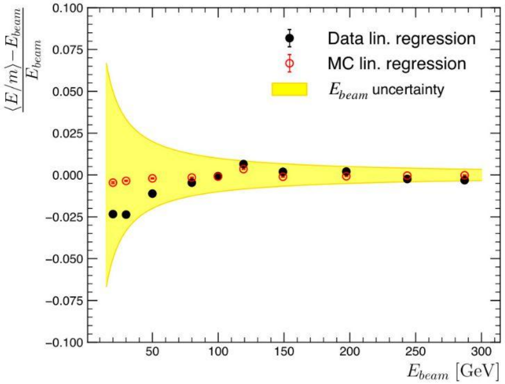
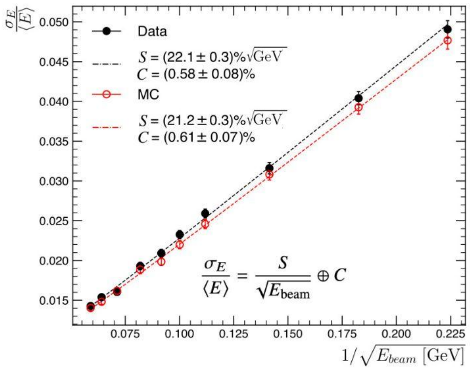
2018: Test beam energy and timing resolution (electron)

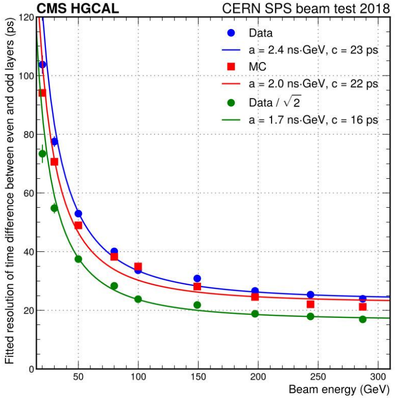
- e⁺ beam data, reconstructed in CE-E

Linearity



Energy resolution





Resolution using half-showers in even/odd layers scaled by √2 as estimate of the performance with all layers

- Energy response **linear within ±1.5%** above 50 GeV

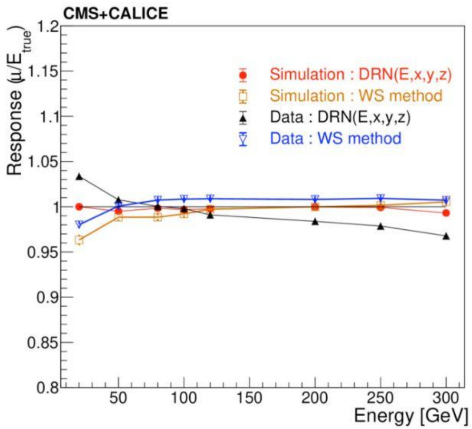
- Energy resolution within the physics performance target: **0.6 % constant term**
  - Compatible with performance of the current CMS electromagnetic calorimeter (< 1%)

Source: link

2018: Test beam energy resolution (pion)

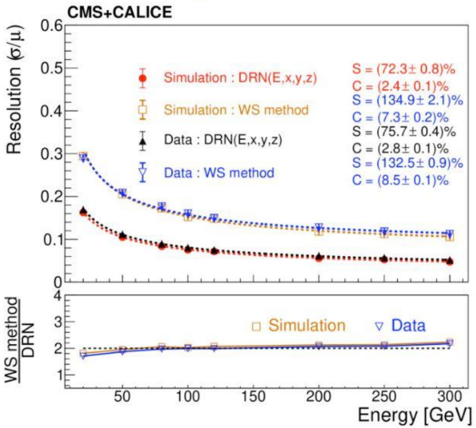
- π beam data, reconstructed in CE-E, CE-H and CALICE AHCAL
- **GNN-based reconstruction (DRN)** to fully exploit the high-granularity and account for hadronic showers fluctuations

Linearity



- Energy response **linear within few %**

Energy resolution



- Excellent data/simulation agreement
- DRN method brings a **x2 improvement** of the resolution w.r.t. energy-dependent weighted reconstruction (WS)

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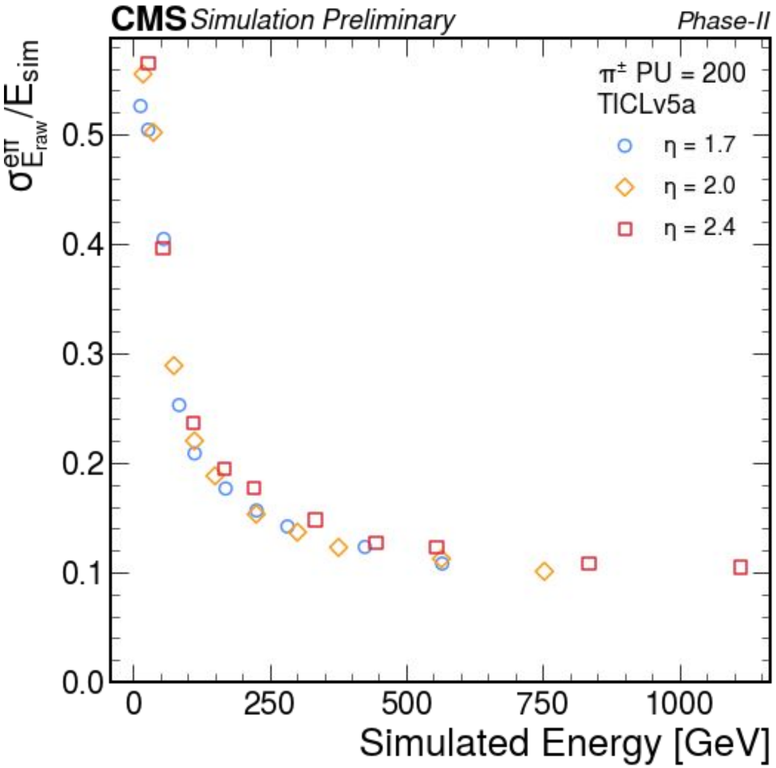
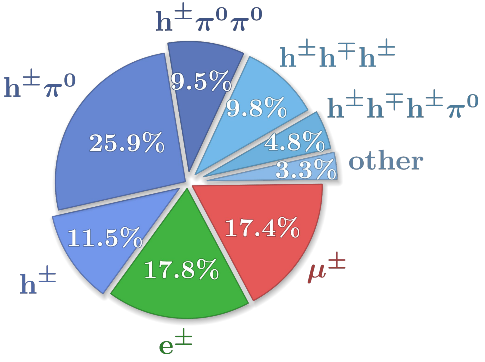
Energy resolution with full geometry

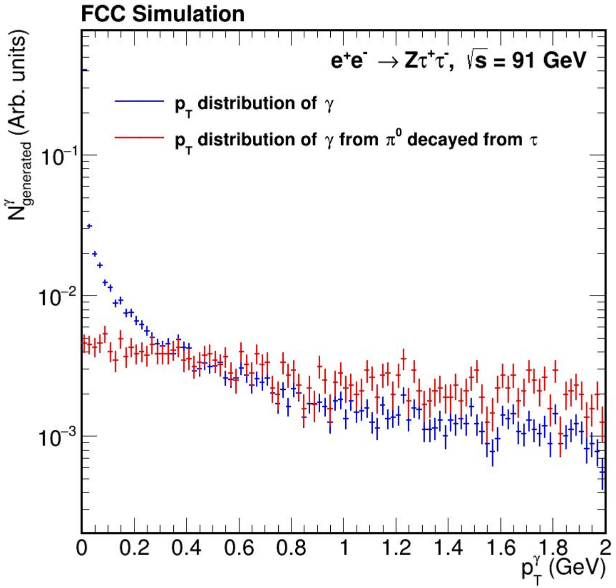


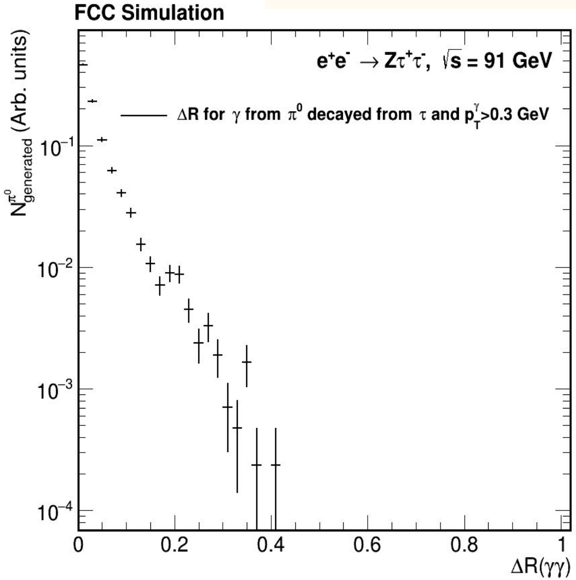
- The raw deposited energy resolution for the case of a single pion in PU 200 is shown as a function of simulated energy
- The cluster reconstruction follows TICLv5 algorithm that uses DNN [CMS-DP-2024-124] to keep or reject Tracksters within the seed window
- A better hadronic energy correction due to trackster-trackster linking
- A promising cluster separation in high density environment → FCC-hh
- Jet energy resolution → 10% at higher energy

Role of highly granular calorimeter in τ identification (private work)

[with Anne-Marie Magnan]







- There are 40% of events where τ decays to hadrons and π^0
- In case of τ identifications we generally apply cuts on p_T and hadron mass, however with high granular calorimeter (cell size < 0.5x0.5 cm^2) we can we can aim at reconstructing $\pi^0 \rightarrow 2\gamma$ to help τ ID

Summary

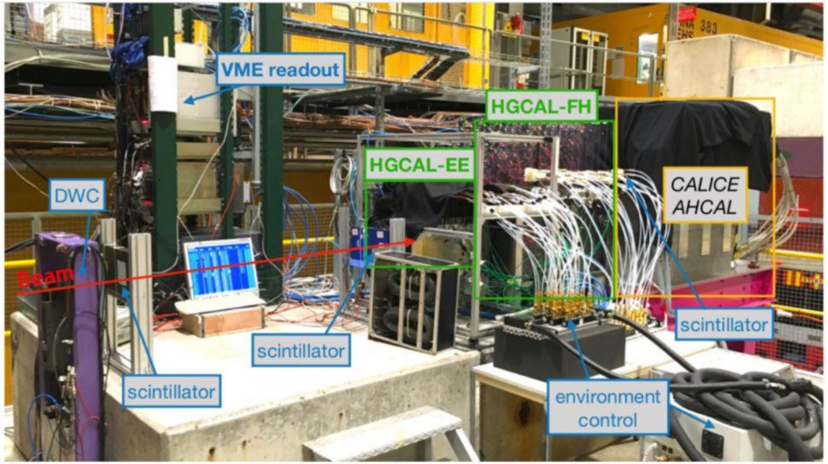
- CMS is approaching to Phase 2 upgrade
- A new high resolution detector HGCAL will replace Ecal+HCal ($1.5<|\eta|<3$)
  - Radiation tolerant, 6M+250K channels, 5D measurement
- A detail validation
  - Reported for 2018 and 2024 test beam
  - Shower studies will continue with 2025 test beam
- Private work:
  - An highly granular detector can be employed to better reconstruct the $\pi^0 \rightarrow 2\gamma$ to help τ ID

Thank you

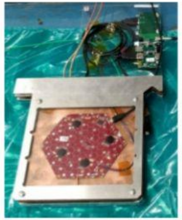
2018 test beam setup

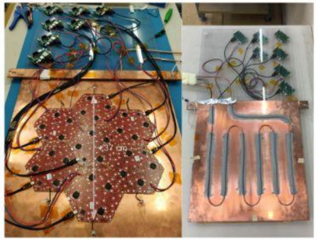
Carried out at the H2 beamline branching from SPS (*Super Proton Synchrotron*, CERN)

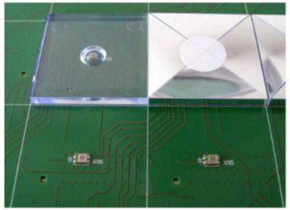
- $e^{\pm}$, π, μ beam of 20 to 300 GeV energy
- Results used in GEANT4 physics validation [docs]



- Electromagnetic section (**CE-E**)
  - Stack of 28 silicon modules
  - Pb/Cu absorber (+ CuW baseplates)
  - Double sided cassettes
- Hadronic section (**CE-H**)
  - 12 layers of up to 7 silicon modules assemblies
  - Steel absorber (+ Cu cooling/support plates)
  - Single sided cassettes
- Complemented by **CALICE AHCAL**
  - 39 layers of scintillator/SiPM-on-tile prototype
  - Steel absorber





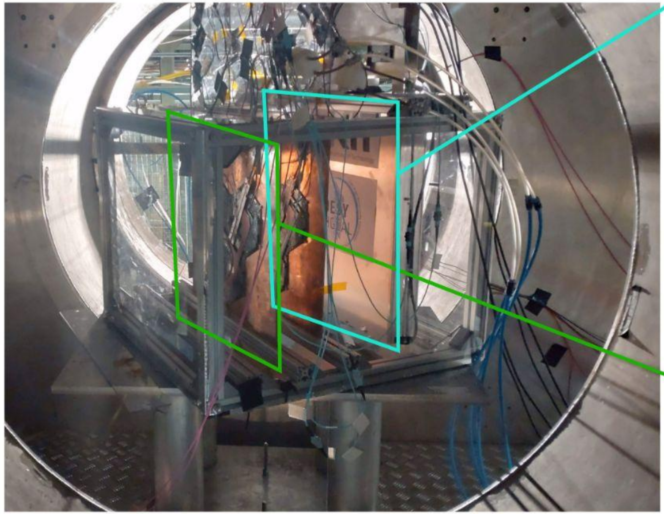


Source: link

2024 test beam setup

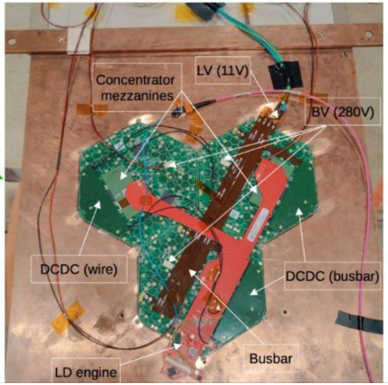
Carried out at the H2 beamline branching from SPS

- e±, π, μ beam of 20 to 300 GeV energy
- First run test with the detector within a 3T field
- Run control based on HERD/XDAQ



Scintillator tile modules

Silicon modules

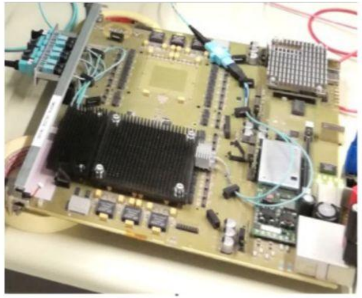


On detector | Off detector

10.24 Gb/s (up)
2.56 Gb/s (down)
optical links

Back-End
- ATCA boards
- DTH
- DAQ servers

DTH-P1



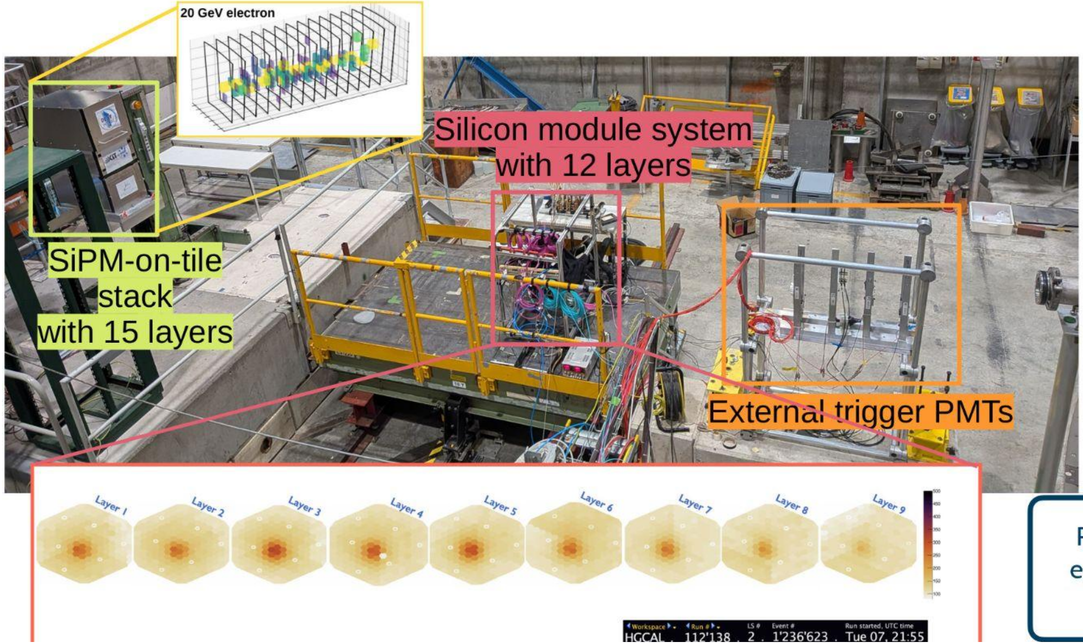
Serenity Z ATCA-based board

Source: link

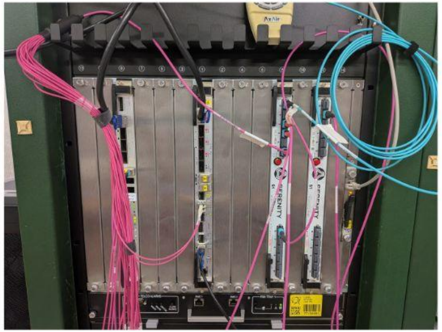
October 2025 test beam setup

Carried out at the H2 beamline branching from SPS

- e±, π, μ beam of 20 to 300 GeV energy
- Focus on data-taking for performance characterisation, using a full vertical slice



On detector | Off detector



Serenity S ATCA-based board

10.24 Gb/s (up)
2.56 Gb/s (down)
optical links

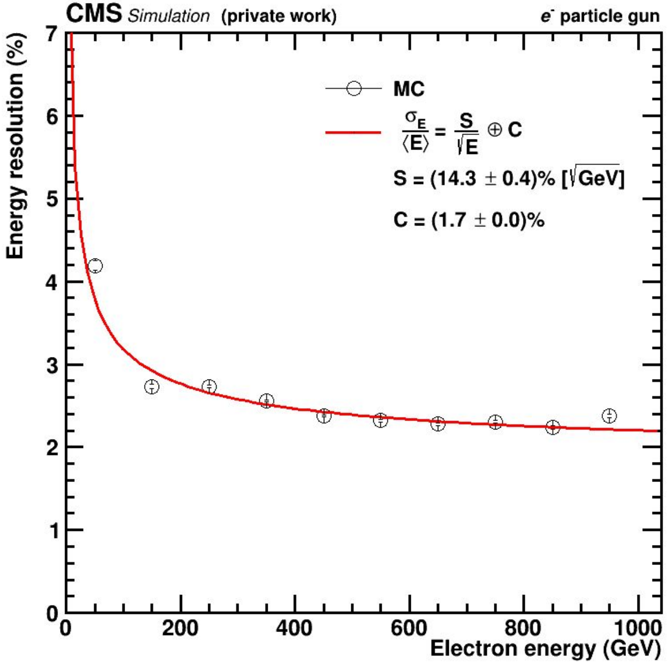
Back-End
- ATCA boards
- DTH
- DAQ servers

Rich set of data for refinements of calibrations, energy and timing performance measurements, study of electromagnetic showers

Source: link

Energy resolution with full geometry – (private work)

[with Paul Dauncey]



- HGCAL simulation
  - Electron particle gun at zero pileup
    - One particle per endcap
  - A complete HGCAL geometry (v16)
  - Methodology
    - Add clusters fragments for full cluster
    - Calculate detector response
    - Apply Cluster energy corrections
  - Constant noise ~ 2% (higher than TB-2018)
  - Stochastic noise ~ 14%
    - Lower compared to TB-2018
    - Little better compared to CALICE style sandwich (note 16% in sl25 of link)