Testing Geant4 on the CMS HGCAL test beam

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CERN, EP-SFT

Simulation bi-weekly meeting
9/4/2024

The HGCAL test beam

~400 authors

- A section of the CMS HGCAL was exposed to muons, electrons and charged pions in beam test at the CERN SPS in October 2018
- The paper summarizing the hadronic results was published on May 2023

PREPARED FOR SUBMISSION TO JINST

Performance of the CMS High Granularity Calorimeter prototype to charged pion beams of 20–300 GeV/c

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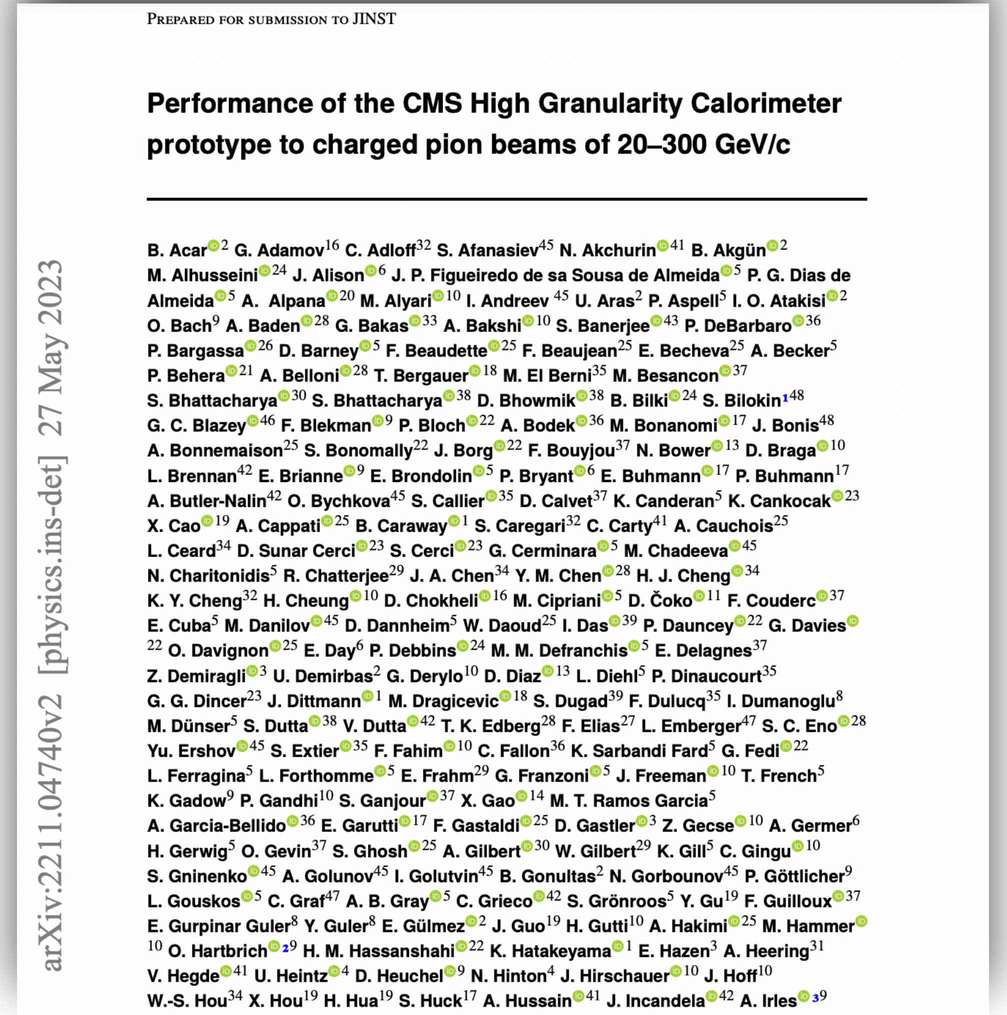
The HGCAL test beam

~400 authors

- A section of the CMS HGCAL was exposed to muons, electrons and charged pions in beam test at the CERN SPS in October 2018
- The paper summarizing the hadronic results was published on May 2023
- What makes this paper a very good candidate for geant-val:
  - From the paper "*This is the first report summarizing results of hadronic showers measured by the HGCAL prototype using beam test data*"
    → The only data for hadronic comparison with G4
  - From the paper "*The calorimeter sections are simulated using GEANT4 version 10.4.3*"
    → An old G4 version was used
  - The test-beam combines the silicon-based section with the Analog Hadronic Calorimeter of CALICE (AHCAL)
    → Another important detector for geant-val


PREPARED FOR SUBMISSION TO JINST

arXiv:2211.04740v2 [physics.ins-det] 27 May 2023

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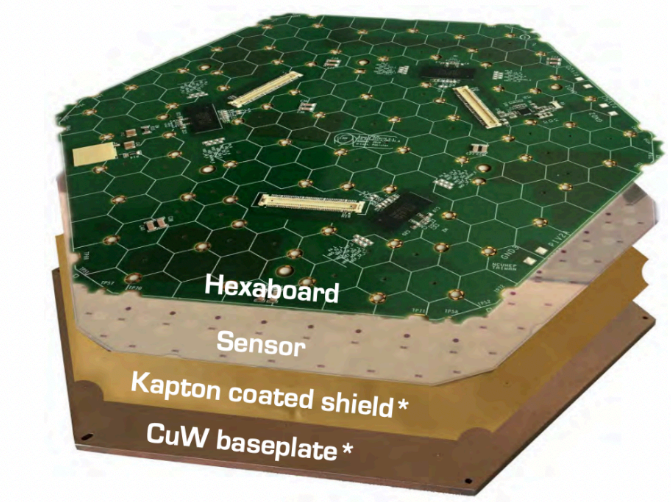
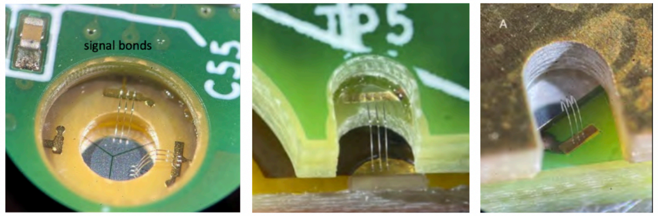
The HGCAL test beam geometry



* In CE-H, PCB baseplate with laminated Kapton™

signal bonds shield bonds backside HV bonds



Three calorimeters involved:

- CEE: 28 layers of HGCAL Si pads with 128 ($\simeq$ 1.1 cm^2) hexagonal cells (26 X_0)

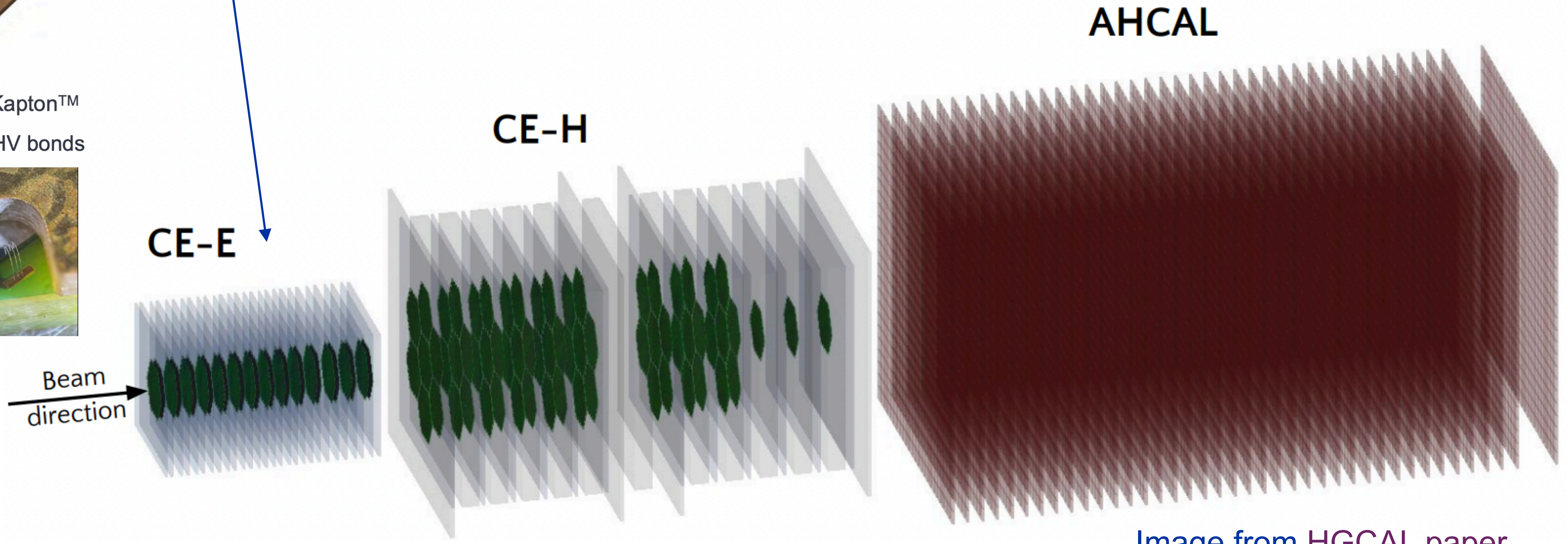
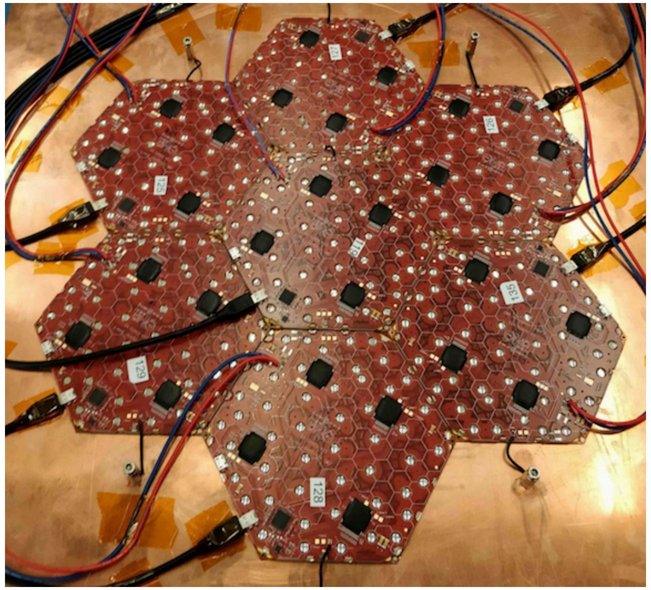


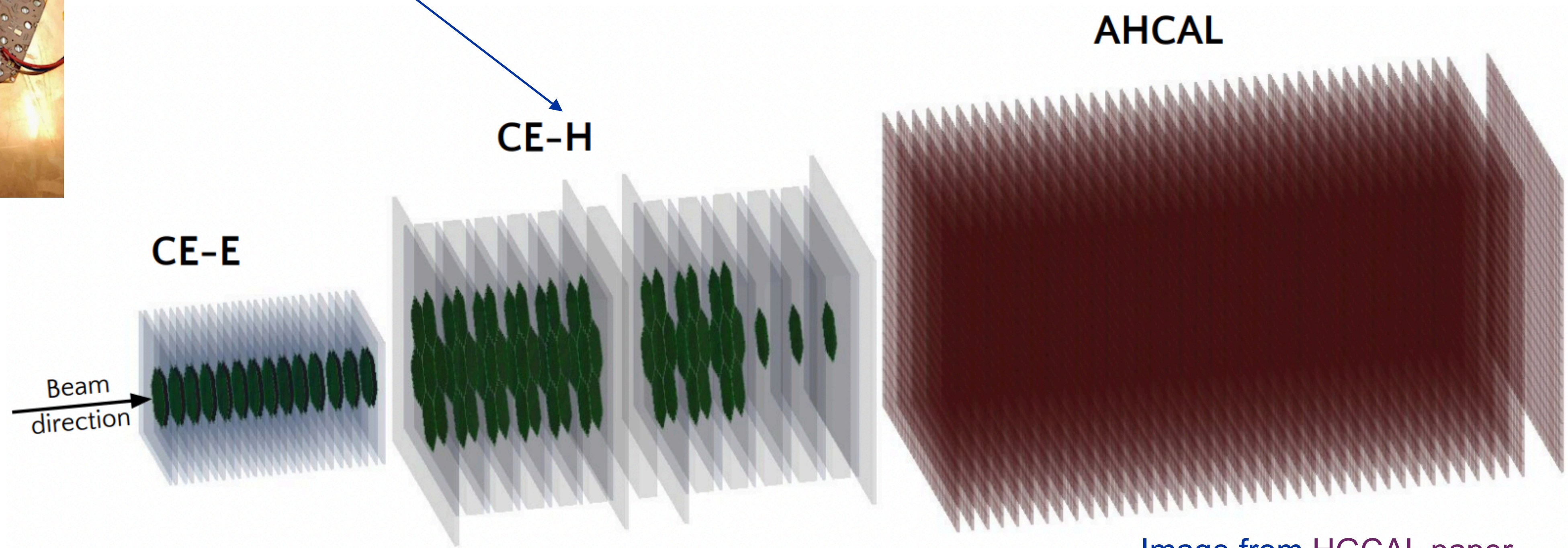
Image from HGCAL paper

The HGCAL test beam geometry



Three calorimeters involved:

- CEE: 28 layers of HGCAL Si pads with 132 ($\simeq$ 1.1 cm^2) hexagonal cells (26 X_0)
- CHE: 12 layers of HGCAL Si pads, first 9 use 7 sensors in a daisy-like structure (3.4 λ_{int})



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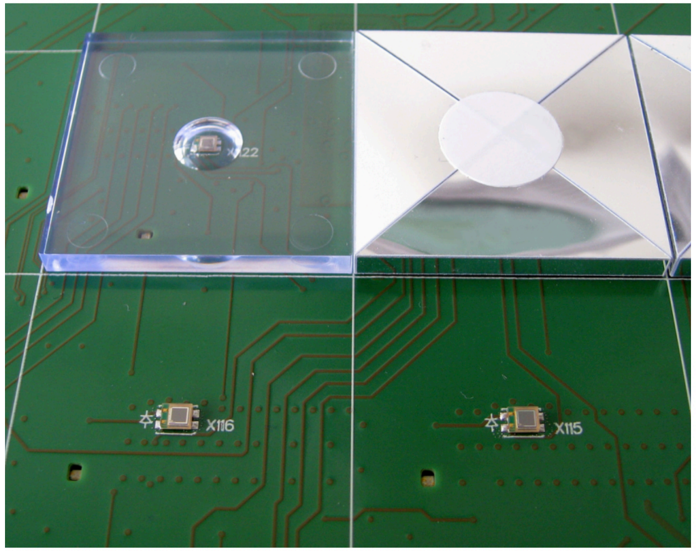

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- AHCAL: 39 layers of 24×24 ($3 \times 3 \times 0.3$ cm^3) plastic tiles (4.4 λ_{int})

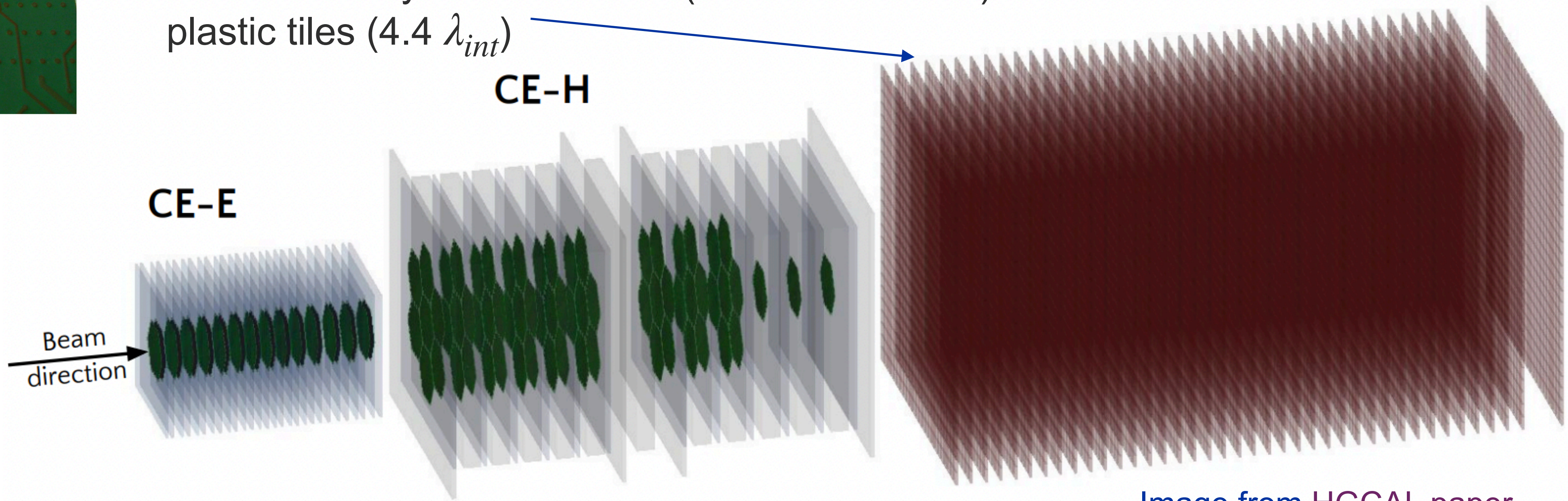
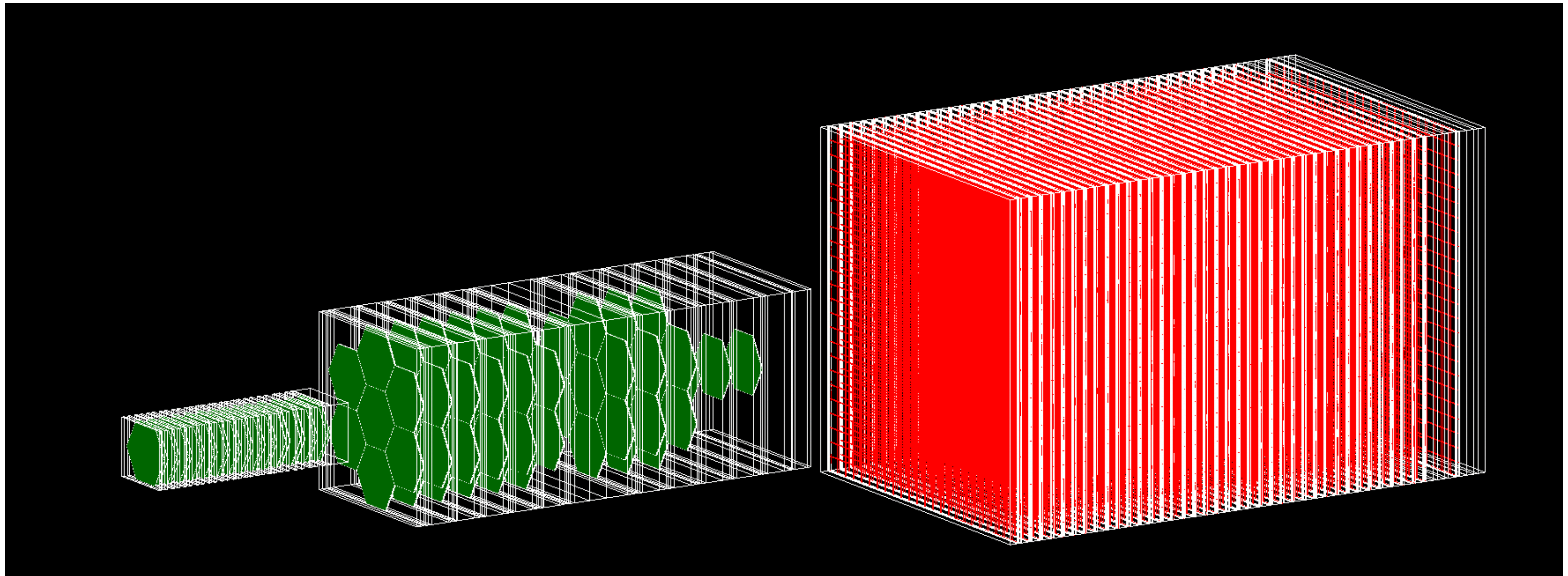


Image from HGCAL paper

The geant-val simulation

- The HGCAL test-beam simulation is fully integrated into CMSSW → I adopted the usual approach to port it to geant-val:
  - Created a new repo under the geant-val GitHub organization [HGCALTB]
  - Geometry ported with a gdml file. All other parts including G4Actions, sensitive detectors, hit, hit collections, noise, signal cuts, calibration, analysis, …, coded by us in a Geant4 fashion
  - HGCALTB-1.0 released in April 2024, the first feature complete release



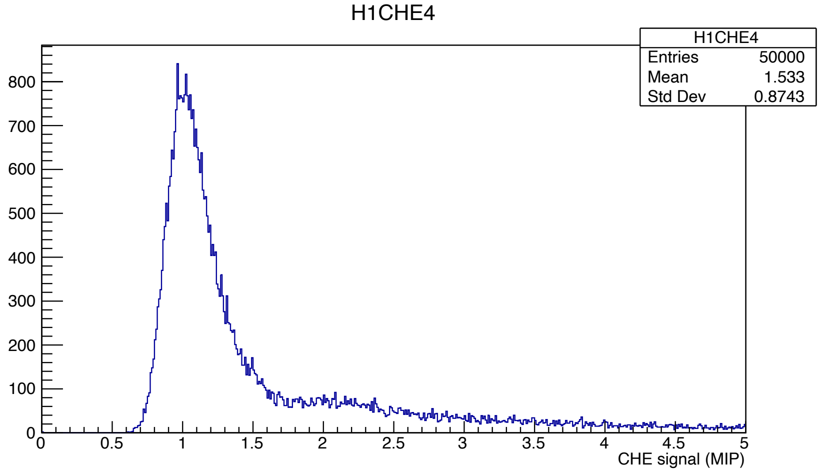
From geant-val HGCALTB

MIP calibration and signal simulation

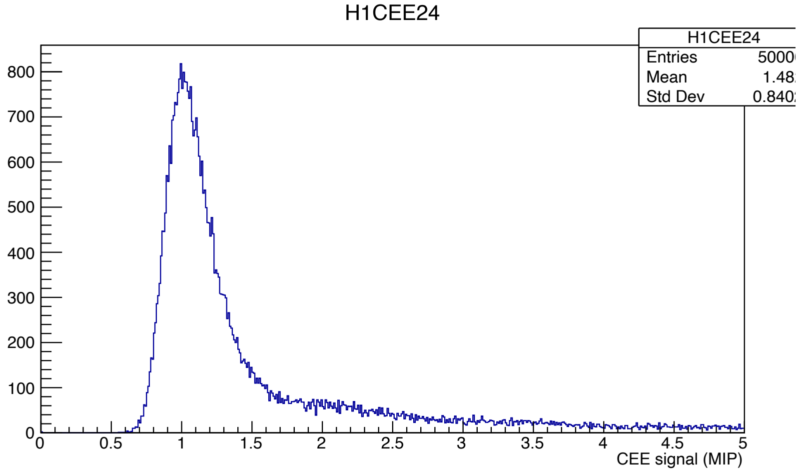
- As described in the paper, each active element is calibrated at the minimum-ionizing-particle (MIP) scale
  - From HGCAL paper "*The actual energy deposited by muons of 200 GeV is higher than minimum ionizing particles. However, these serve as a robust tool for the detector calibration, and are referred to as MIPs in this context*"

Results from geant-val HGCALTB: 200 GeV μ^-

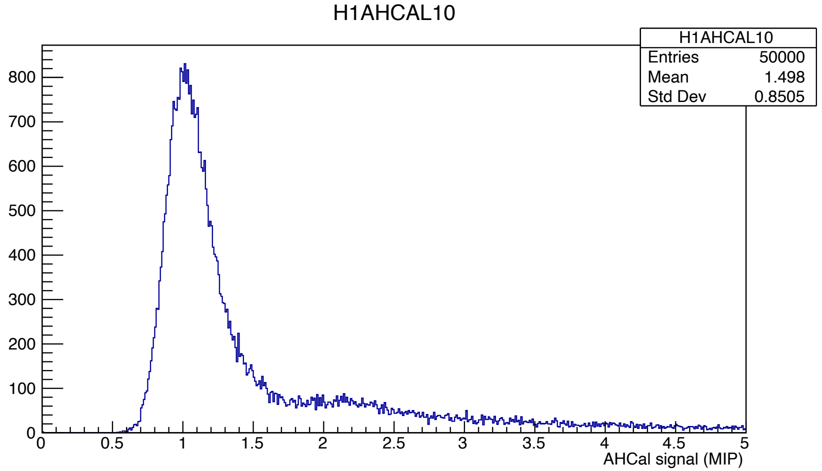
Cumulated signal at CHE layer 4 after MIP calibration



Cumulated signal at CEE layer 24 after MIP calibration



Cumulated signal at AHCAL layer 10 after MIP calibration



MIP calibration and signal simulation

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  - From HGCAL paper "*The actual energy deposited by muons of 200 GeV is higher than minimum ionizing particles. However, these serve as a robust tool for the detector calibration, and are referred to as MIPs in this context*"
- Birks Law for signal creation in the AHCAL plastic tiles is included
  - Signal creation in plastic tiles is smeared according to the CMSSW Birks equation
- After the MIP calibration, a Gaussian noise is applied to each individual cell to mimic the electronic noise (~0.12 MIP for silicon cells, as reported in arXiv:2012.06336v1)
- A hit time cut of 500 ns is included
- Only cells with a signal > 0.5 MIP are kept for analysis

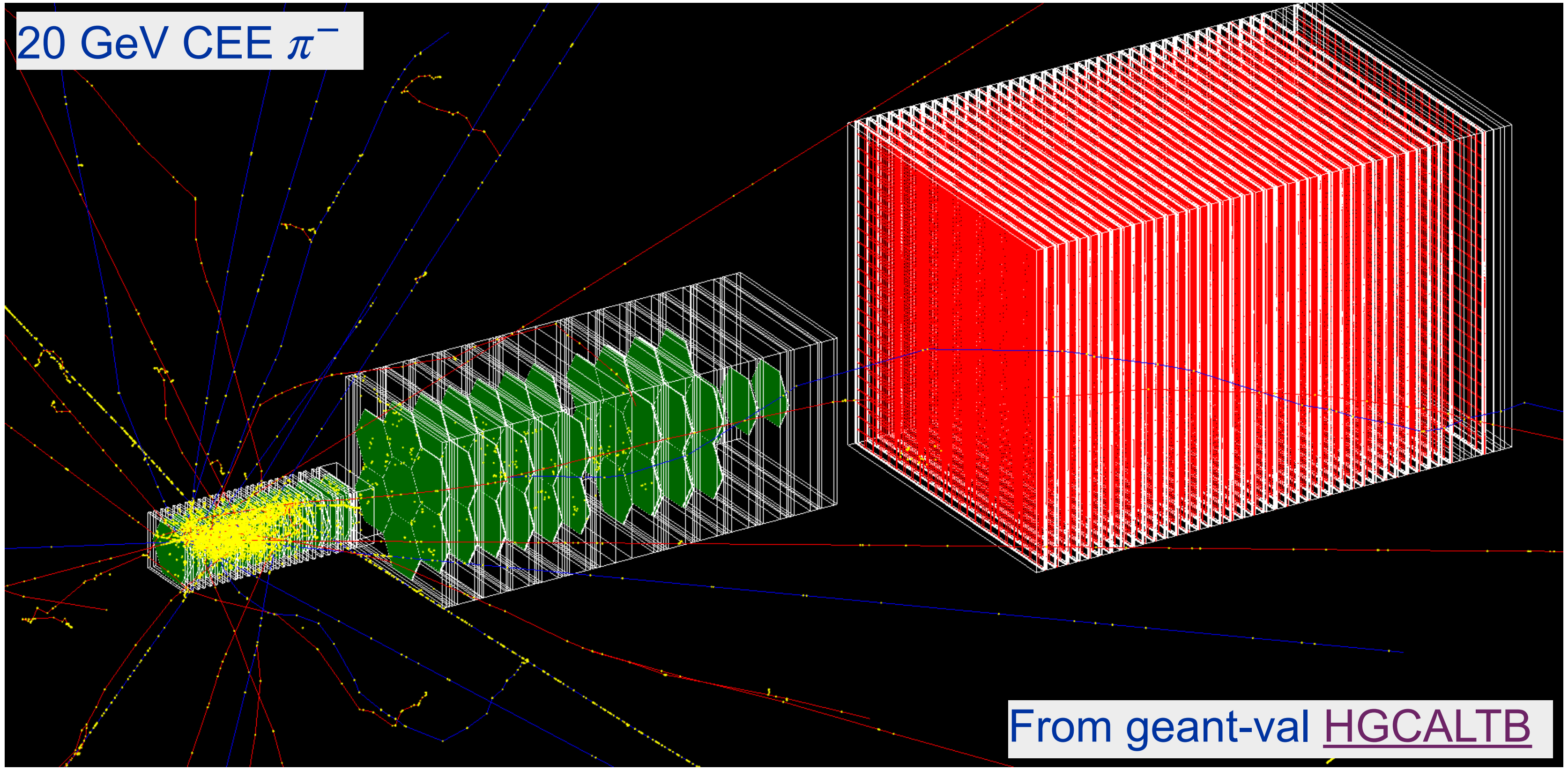
The calibration problem

- To reconstructed π^- energies, three additional calibration constants (from MIP to MeV) for the sections (CEE, CEH, AHCAL) are needed
- The CMS solution: $E(GeV) = \alpha \times E_{MIP}^{CEE} + \beta \times (E_{MIP}^{CHE} + \delta \times E_{MIP}^{AHCAL})$
  - with $\alpha = 10.5$ MeV/MIP estimate with 50 GeV e^+
  - $\beta = 80$ MeV/MIP estimated with 50 GeV π^- and
  - $\delta = 0.4$ as the factor that minimizes the hadronic energy resolution

NOTE: Calibration constants estimated with experimental data are used also to reconstruct π^- energies in simulation $\rightarrow$ any discrepancy in the mean value is a direct consequence of the hadronic shower mismodelling in Geant4

The calibration problem

- Hadronic variables (namely response and resolution) needed to evaluate the Geant4 agreement with the data highly depends wether the original π^- interacts in the electromagnetic (CEE) or in the hadronic section (CEH)



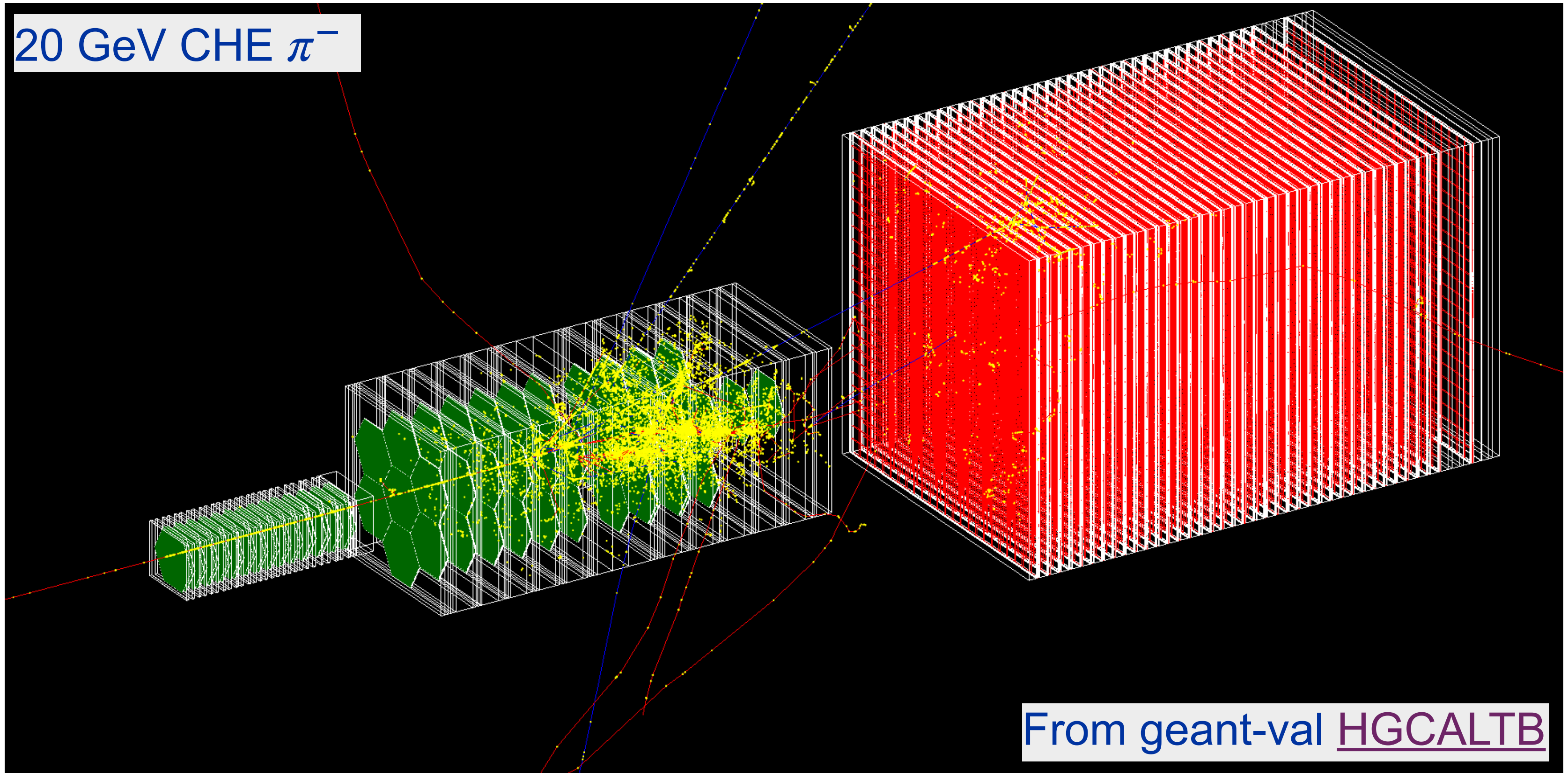
π^- undergoing a nuclear reaction in the electromagnetic section are defined as CEE-π^-

CEE-π^- energies are calibrated at the electromagnetic scale (CEE section is calibrated with e^+), therefore we expect reconstructed energies smaller than the nominal one

Remember that non compensating calorimeters have $h/e < 1$

The calibration problem

- Hadronic variables (namely response and resolution) needed to evaluate the Geant4 agreement with the data highly depends wether the original π^- interacts in the electromagnetic (CEE) or in the hadronic section (CEH)



π^- undergoing the first nuclear reaction in the hadronic section are defined as CHE-π^-

CHE-π^- energies are calibrated at the hadronic scale (CHE section is calibrated with π^-), therefore we expect reconstructed energies on average at the nominal one

Tagging π^- nuclear breakups

- To tag the layer i where the nuclear breakup happened we require that
  - the layer i has at least 3 cells above the 0.5 MIP threshold,
  - the total energy deposited in a radius of 10 cm around the center-of-gravity in layer i is greater than 12 MIPs (40 MIPs) for pions of beam energy 20 GeV (200 GeV), and
  - the transverse energy spread, defined by the ratio of the energy deposited in a radius of 2 cm around the layer center-of-gravity to that in a radius of 10 cm

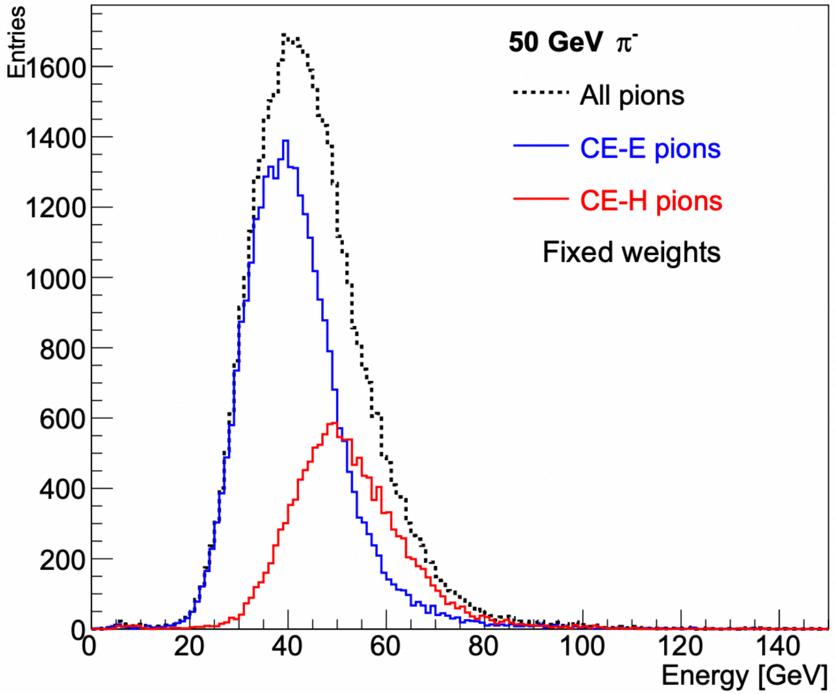
$$R_i = \frac{\sum_{layer=i}^{i+2} E_{2cm}^{layer}}{\sum_{layer=i}^{i+2} E_{10cm}^{layer}} < 0.96$$

- The first layer (in CEE or CHE) fulfilling these conditions is considered the closest one to the nuclear breakup

Reconstructing π^- energies

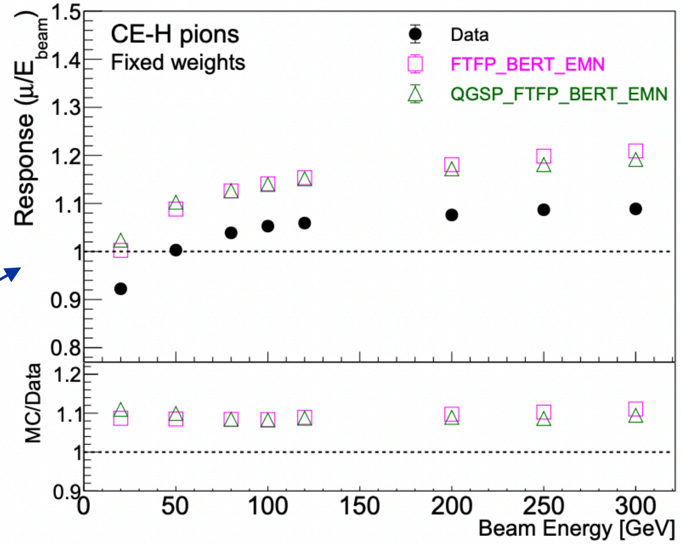
- The reconstructed energy distribution is a superposition of two distributions
- One for CEE-π^- interacting in the electromagnetic section and one for CEH-π^- interacting in the hadronic section
- Better to report energy response (mean) and resolution (σ/E) for the two distributions separately

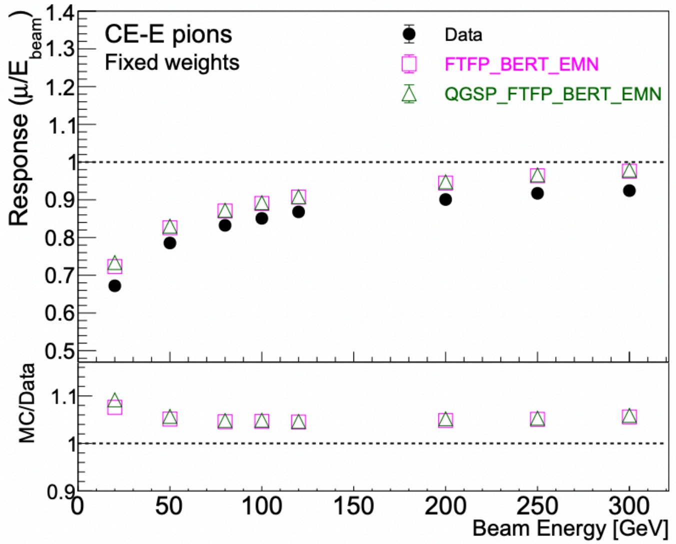
Experimental data from HGCAL TB paper



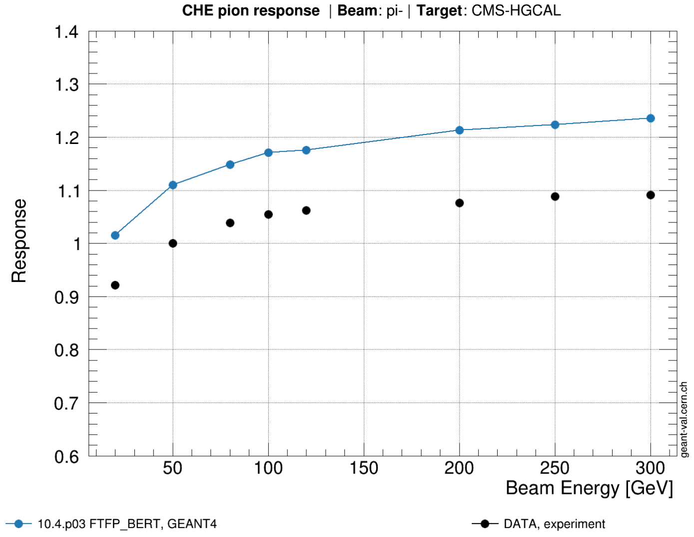
π^- response - geant-val vs CMSSW

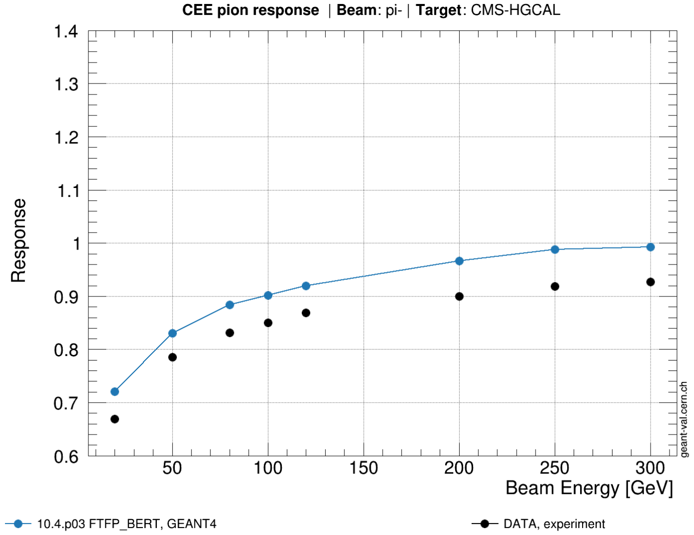
- Results from HGCAL TB paper
  - Geant4-10.4 FTFP_BERT _EMN overestimates the hadronic response (up to $\simeq 10\%$) especially for π^- showering in the hadronic section





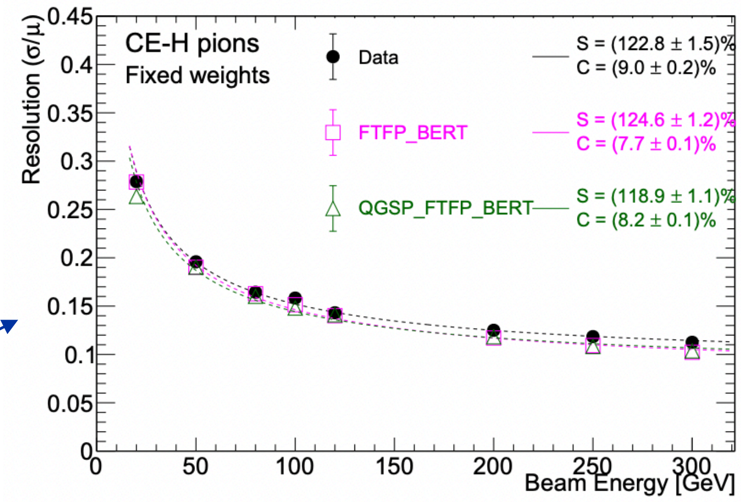
- Geant-val HGCALTB-1.0
  - Geant4-10.4.p03 FTFP_BERT shows excellent agreement with the CMSSW simulated results

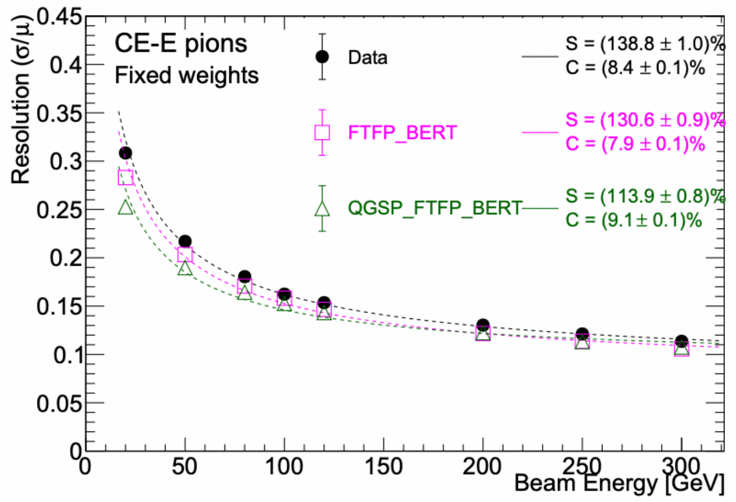




π^- resolution - geant-val vs CMSSW

- Results from HGCAL TB paper
  - Geant4-10.4 FTFP_BERT reproduces well signal fluctuations for CEH π^-, but underestimates them for CEE π^- especially in the low-energy part





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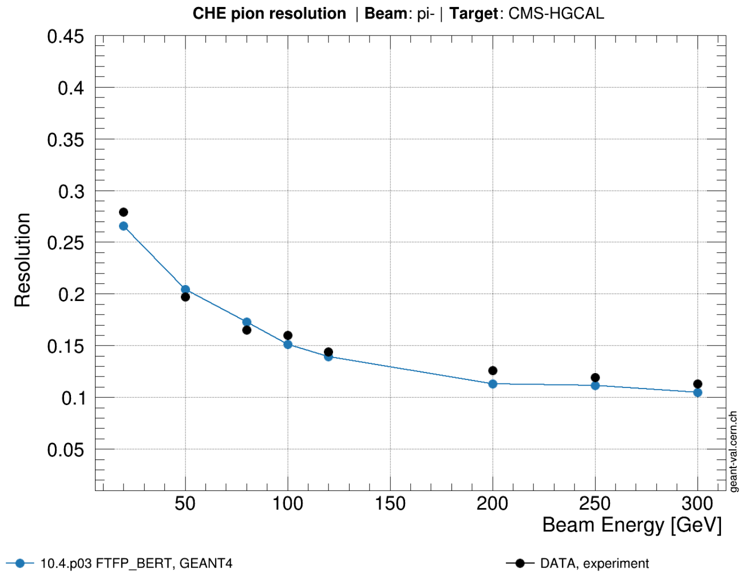
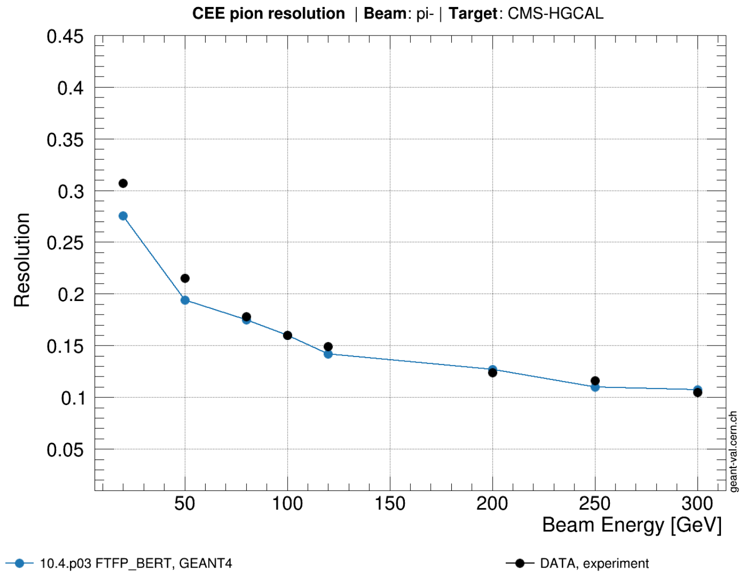
  - Geant4-10.4.p03 FTFP_BERT shows excellent agreement with CMSSW simulated results

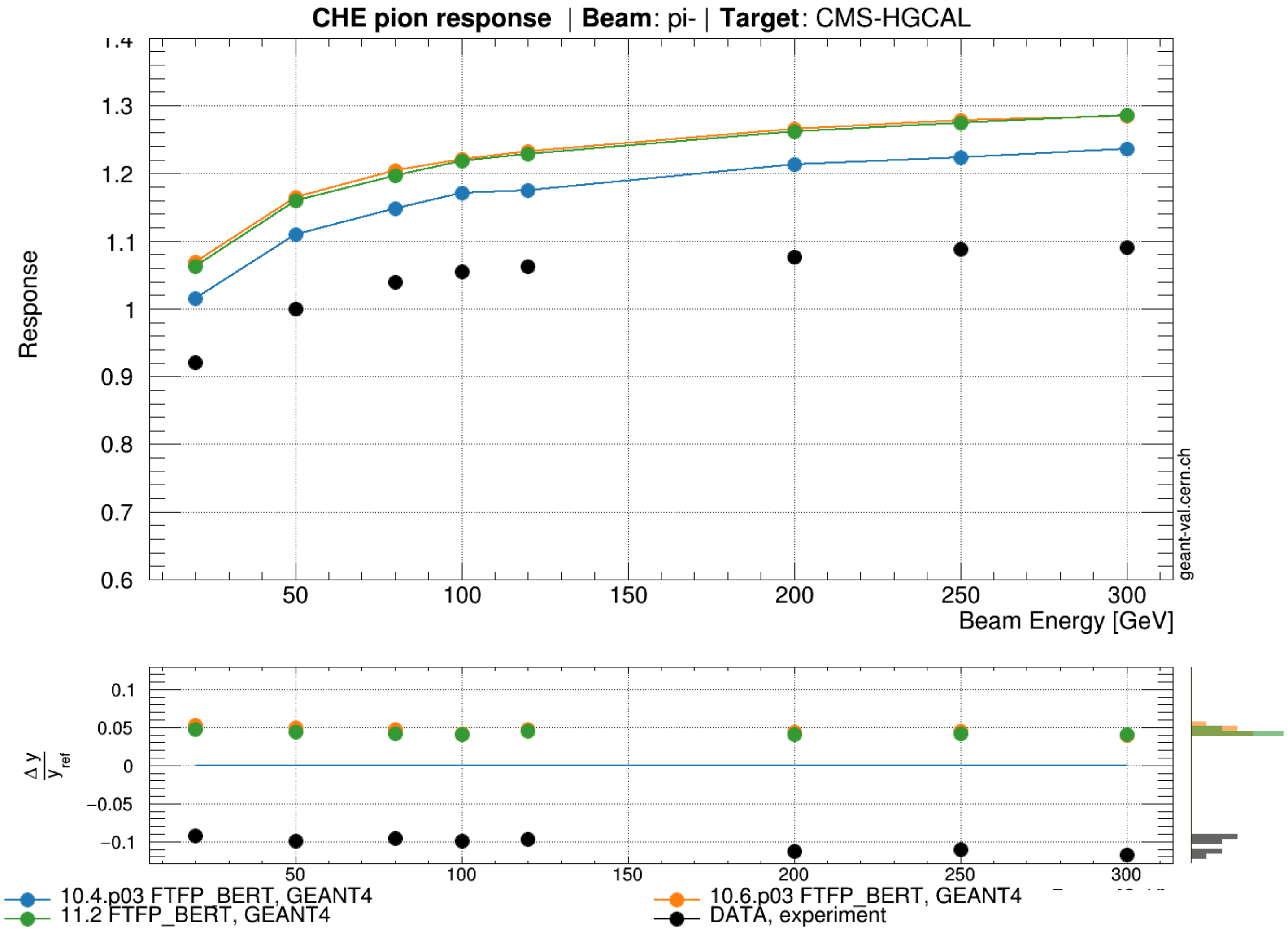




π^- response - regression testing

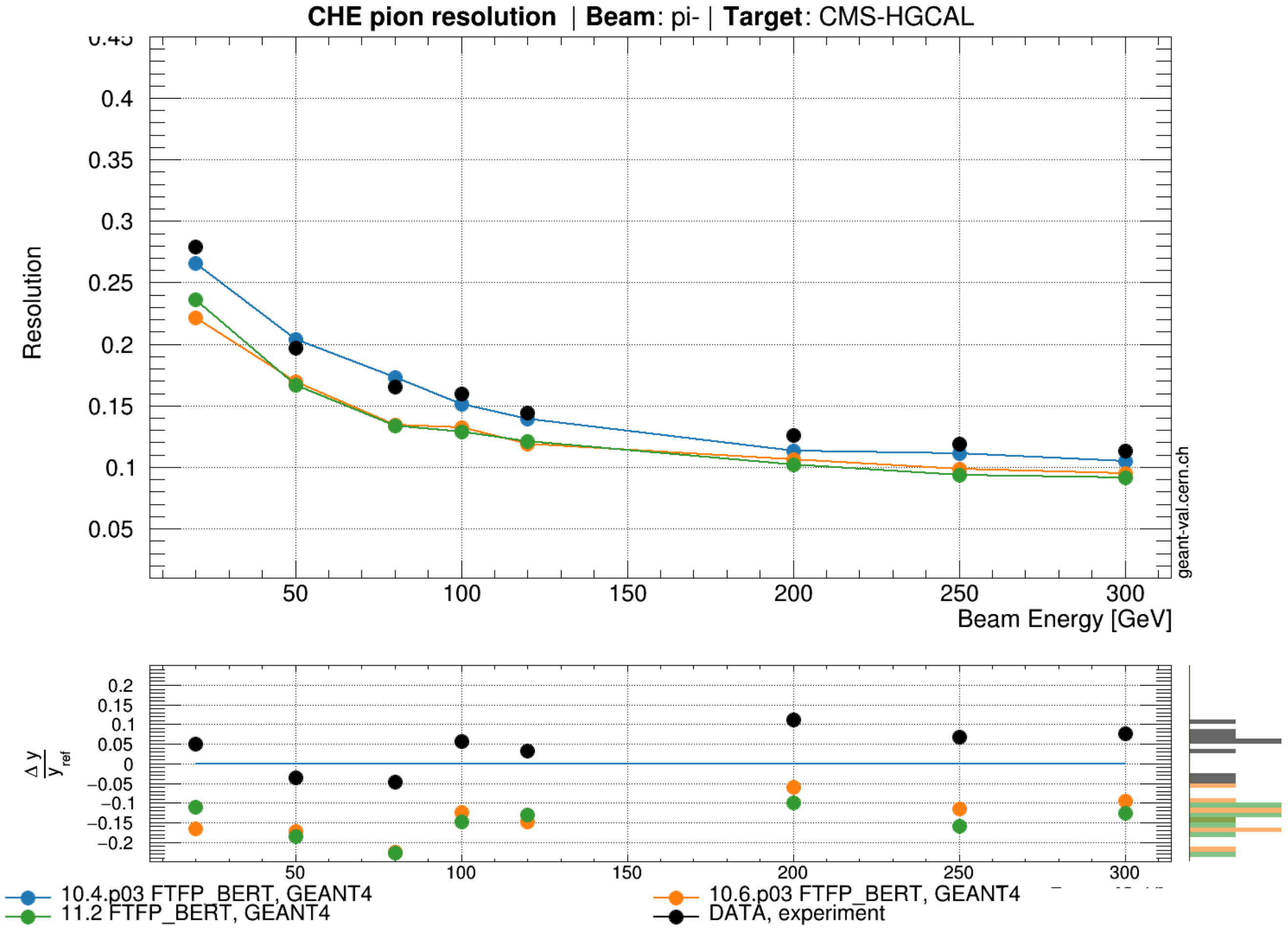
- Regression testing of FTFP_BERT from 10.4 (2017) to 10.6 (2019) to 11.2 (2023) shows a response increase till 10.6 and stable results afterwards
  - Consistent with other results from ATLAS calorimeters
  - Currently, Geant4 overestimates the hadronic response in the HGCAL up to ~15 % for CHE pions (~8% for CEE pions)

- Regression testing results for QGSP_BERT and FTFP_BERT_ATL are available on geant-val website



π^- energy resolution - regression testing

- Regression testing of FTFP_BERT from 10.4 (2017) to 10.6 (2019) to 11.2 (2023) shows good agreement with data and G4-10.4,
  then a ~15% drop in signal fluctuations and stable results since G4-10.6
  - Consistent with other results from ATLAS calorimeters
  - Currently Geant4 underestimates signal fluctuations in the CMS HGCAL



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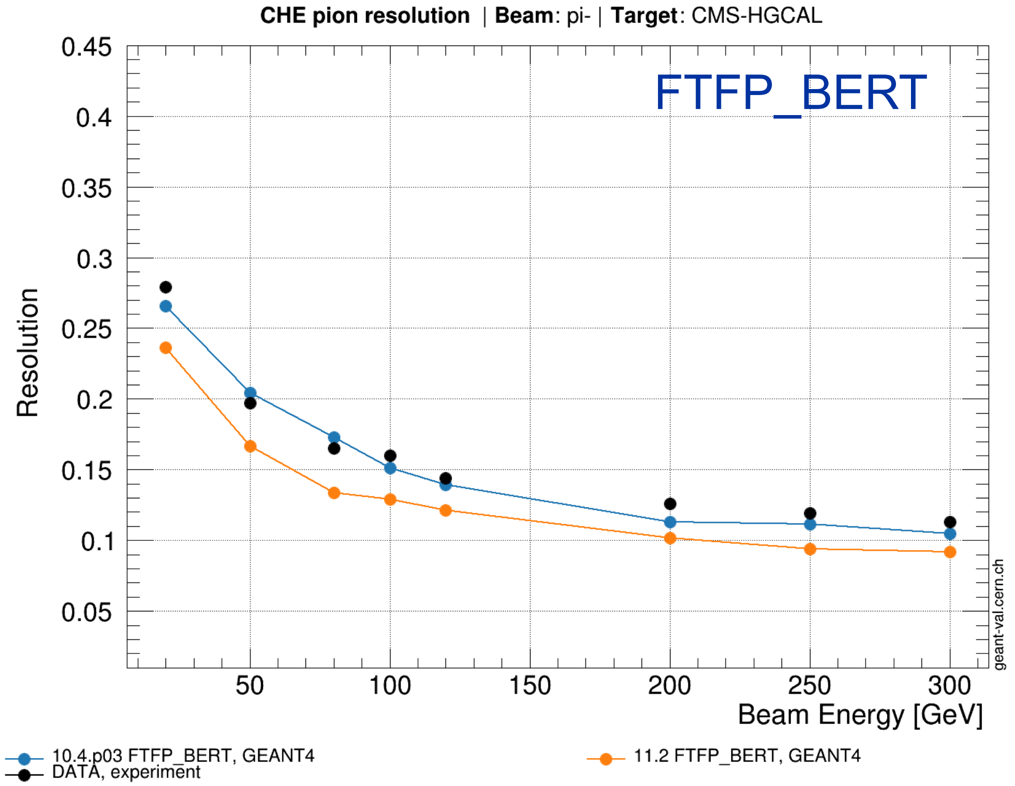
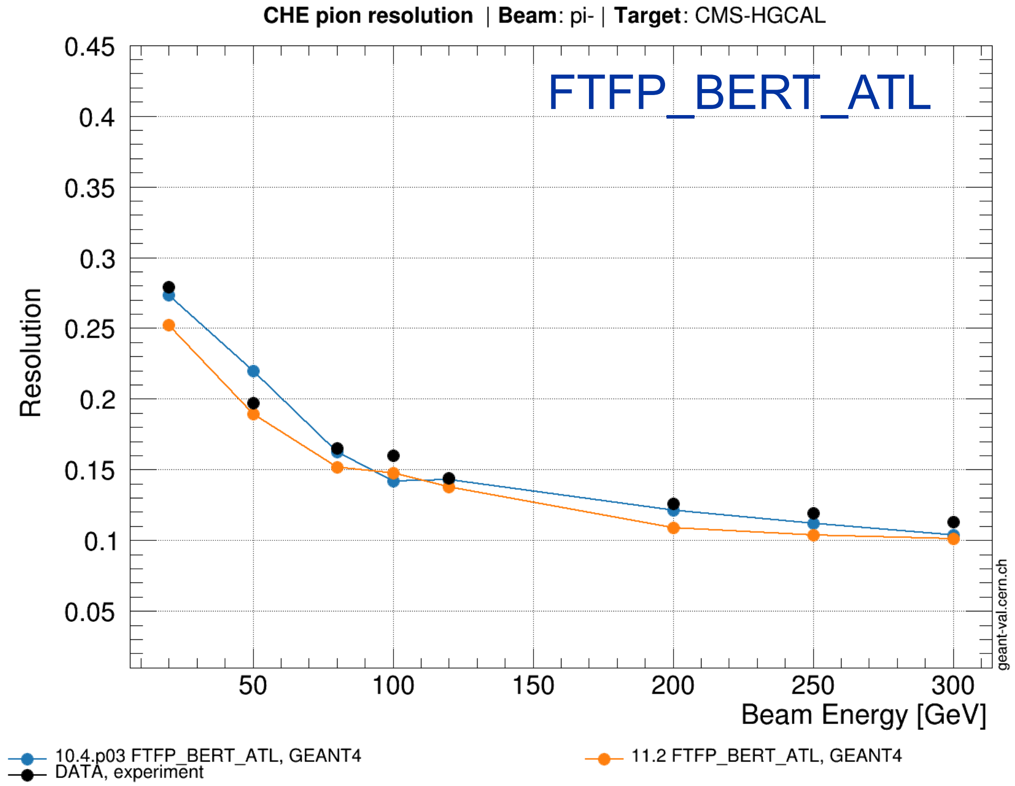
π^- energy resolution

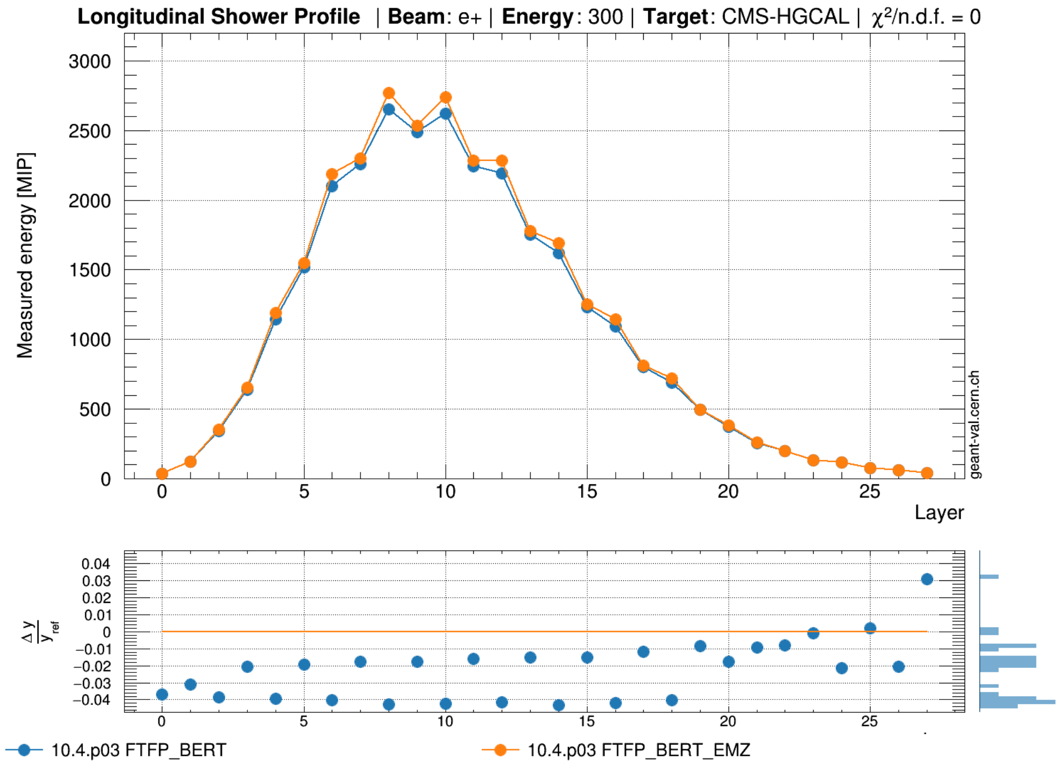
- The decrease in hadronic signal fluctuations (from G4-10.4 to 10.6) was already observed in ATLAS Calorimeters, a special tune introduced in FTFP_BERT_ATL and G4-11.2 was propose to mitigate this problem
- The same changes seem to improve the agreement with data also for the CMS HGCAL

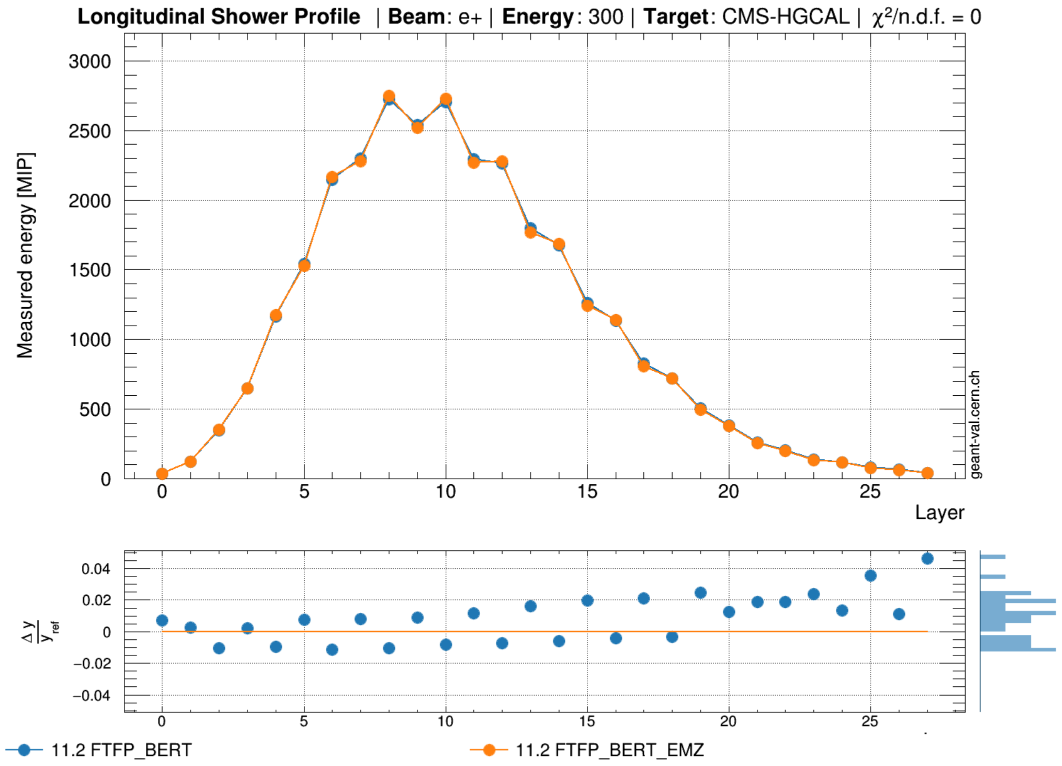




Extension to em physics

- 300 GeV e^+ longitudinal shower profile:
  - The differences observed between default em-physics option and the most precise one (EMZ) are largely suppressed in recent Geant4 releases
  - If confirmed it would speed up the HGCAL simulation for em showers by a factor ~2





Conclusions

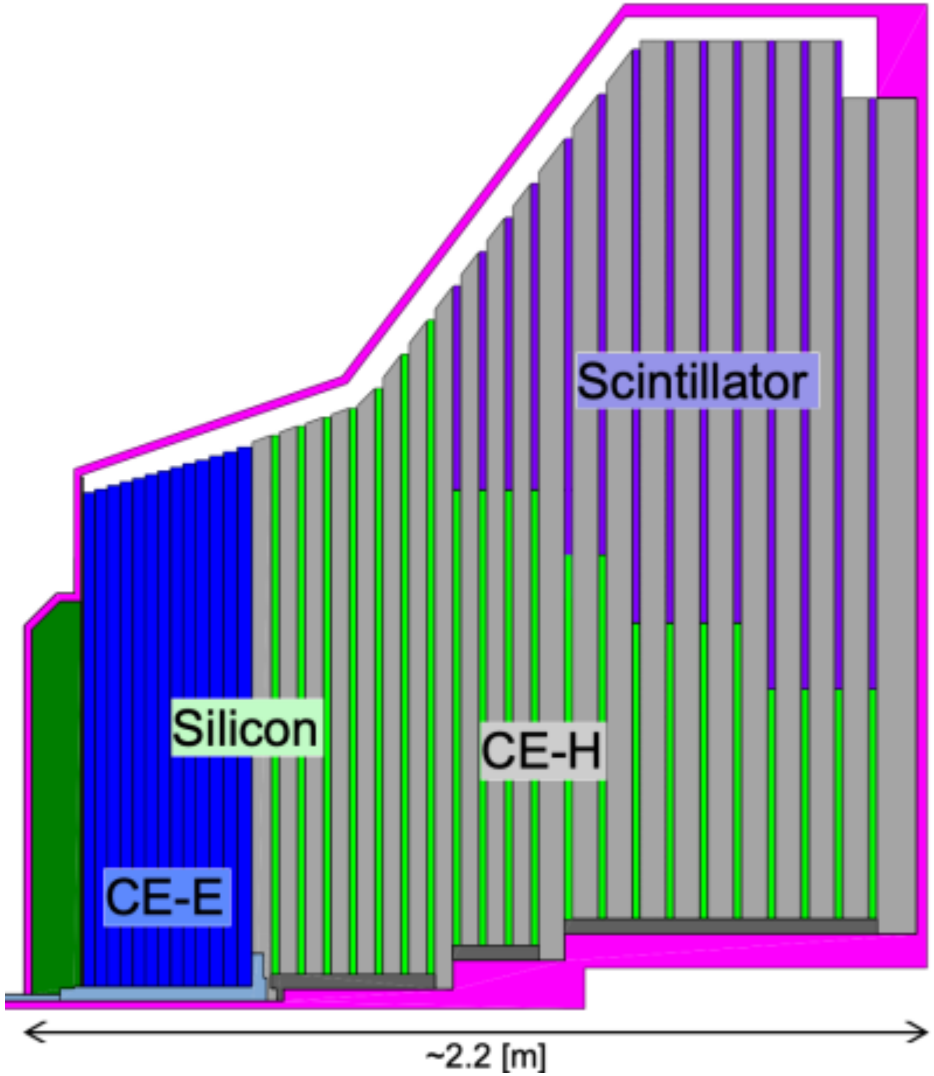
- A new Geant4 test targeting the most recent CMS HGCAL test-beam was developed and included in geant-val
  - The first feature complete version (HGCALTB-1.0) was released in April 2024
- Comparison with CMS results, using Geant4-10.4, shows good agreement for π^- hadronic showers starting either in the electromagnetic or hadronic section
- FTFP_BERT regression testing indicates
  - an increase in the simulated hadronic response coming from G4-10.5 and 10.6, stable since then. Latest G4 releases are up to 15% off w.r.t. CMS data
  - a decrease in hadronic signal fluctuations (similar to what observed with ATLAS) leading to too optimistic energy resolutions. The FTF parameter changes introduced for ATLAS help also the CMS case.
- e^+ shower profile show systematic differences up to 5% between em_opt0 and _EMZ. Newer releases largely fix this discrepancy and could relax the need for EMZ in CMS production
- Two draft PRs show how to use HGCALTB with Celeritas and Adept

Backup material

HGCAL detector concept

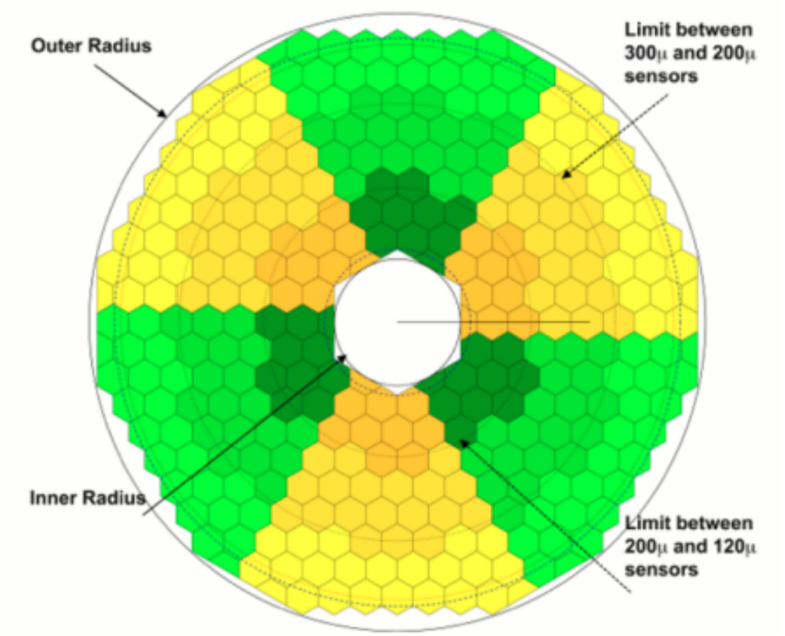
Both Endcaps	Silicon	Scintillator
Area	~620 m^2	~370 m^2
Channel Size	0.5 - 1.2 cm^2	4 - 30 cm^2
# Channels	~6 M	~240 k
# Modules	~27000	~4000
Op. Temp.	-30 C	-30 C

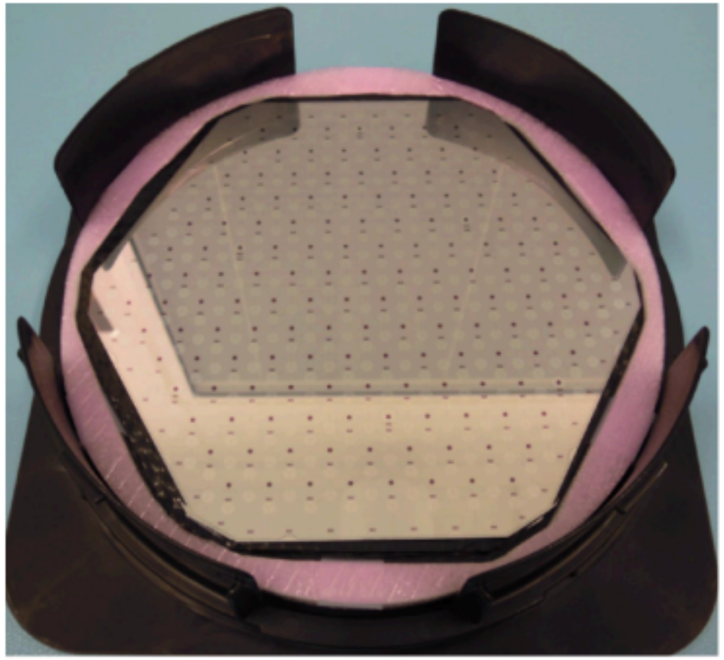
Per Endcap	CE-E	CE-H Si	CE-H Si+Scint
Absorber	Pb, CuW, Cu	Stainless steel, Cu	
Depth	27.7 X_0	10 λ	
Layers	26	7	14
Weight	23 t	205 t	

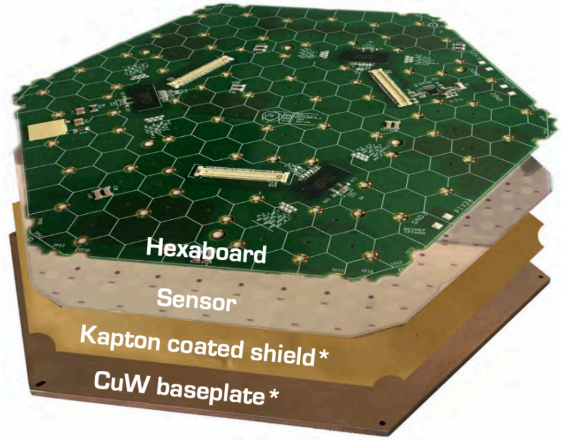


Silicon sensors

- Silicon sensors are hexagonal with three thicknesses of 120, 200, 300 μm to accomodate range in fluency
- Two pad sizes: one with ~1 cm^2 cells (outer region) and another with ~0.5 cm^2 cells (inner regions)
- Each Silicon module is a sandwich of Cu/W base plate, kapton, silicon, and the hexaboard.
  Sensors are wirebonded via holes in the PCB and the hexaboards contains the readout ASIC

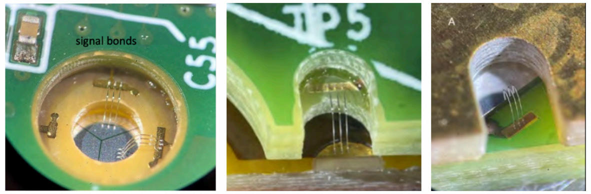






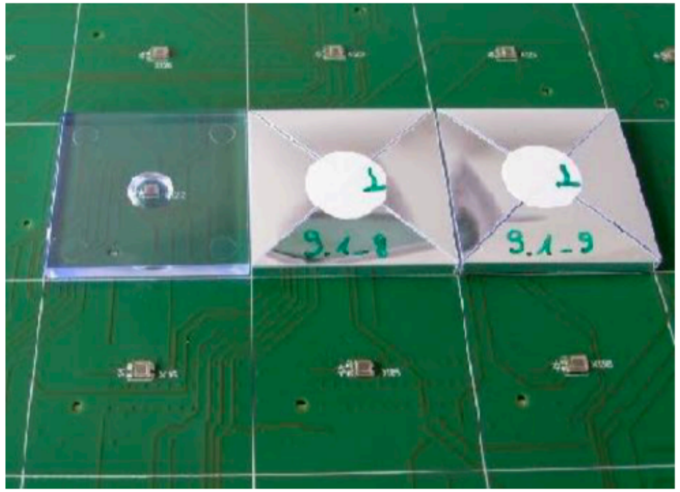
* In CE-H, PCB baseplate with laminated Kapton™

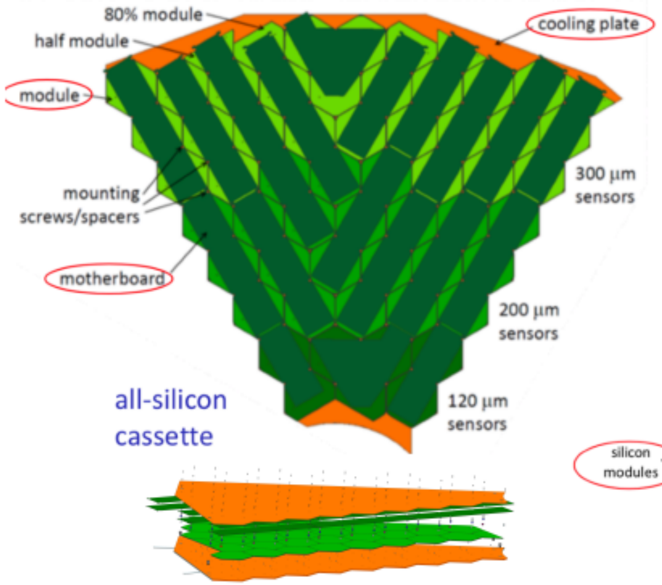
signal bonds shield bonds backside HV bonds

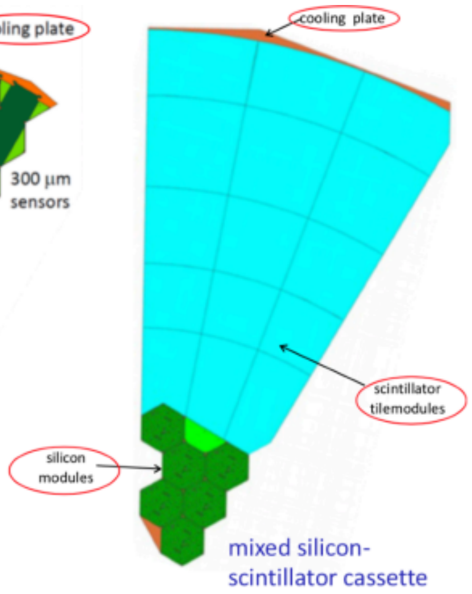


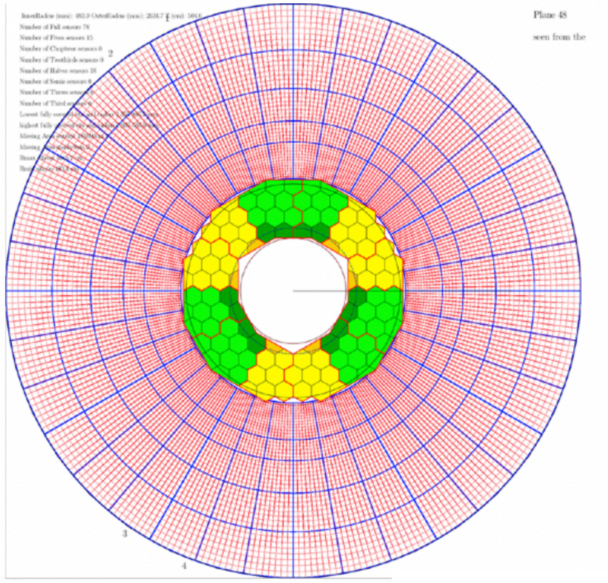
Scintillator tiles and cassettes

- The CEH scintillator system uses plastic tiles of 4-30 cm^2 with the light from illuminating the SiPMs underneath
- Tile sizes chosen to maintain a good signal-to-noise-ratio for MIP calibration (will be explained in the following)
- The whole detector is organized into *cassettes* comprised of a Cu cooling plate with multiple silicon modules and/or scintillating-tile-modules mounted on it







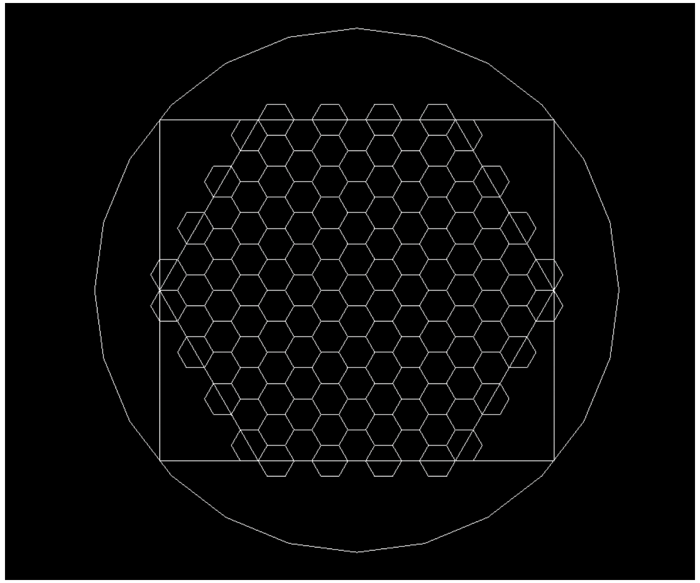


The geant-val simulation

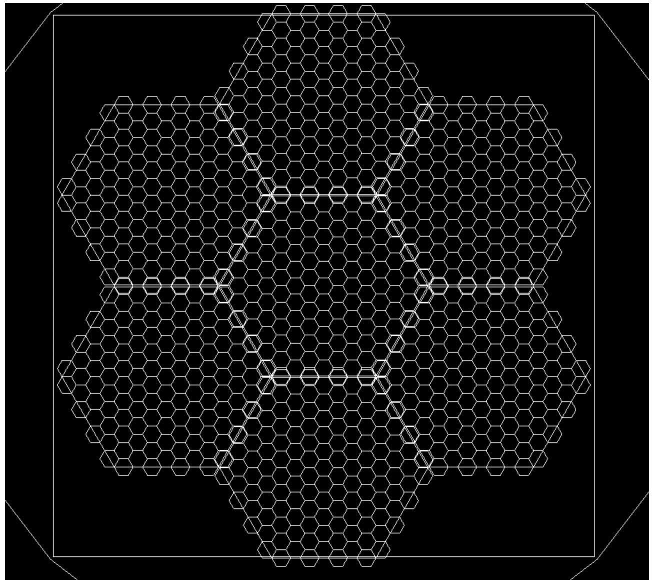
- The HGCAL test-beam simulation is fully integrated into CMSSW → I adopted the usual approach to port it to geant-val:
  - Created a new repo under the geant-val GitHub organization [HGCALTB]
  - Test-beam geometry ported from CMSSW with a gdml file provided by Sunanda (thanks!)
  - All other parts including G4Actions, sensitive detectors, hit, hit collections, noise, signal cuts, calibration, analysis, …, coded by us in a Geant4 fashion

Sensitive elements

CEE: Si wafer



CEH: 7 Si wafer



AHCal: 24x24 tiles