End of Fellowship Report

Lorenzo Pezzotti
CERN EP-SFT, Geant4 Group

SFT Meeting - 22/4/2024

$ whoami

2018	2019	2020	2021	2022	2023	2024

Education

PhD Student
@University of Pavia and INFN
working on
Detector R&D and simulation

CERN Senior Fellow
@EP-SFT Geant4
working on validation
over CERN detector data

Collaborations

ATLAS EXPERIMENT

Dual-Readout
Calorimetry
Collaboration

G4

Elected Roles

Software Coordinator
for the Dual-Readout
Calorimetry Collaboration

Geant4 Validation TF
Coordinator
(with D. Konstantinov)

How the fellowship started

A

Alberto Ribon <Alberto.Ribon@cern.ch>

a me

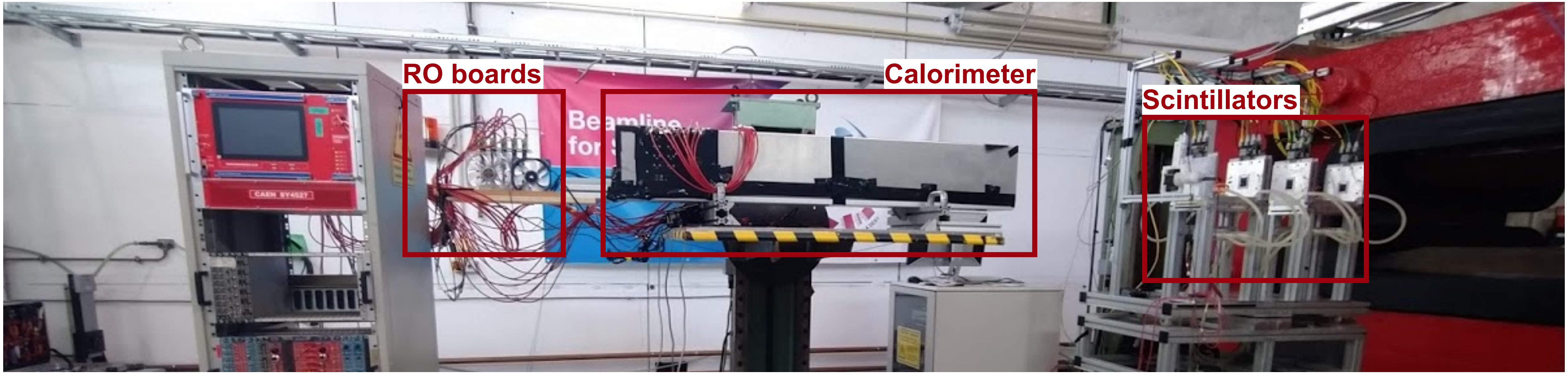
Ciao Lorenzo,

… regarding your contribution to Geant4 as a Fellow, I was thinking of
the validation of hadronic physics for you. The idea would be to create
stand-alone applications of Geant4 to compare Geant4 simulations with test-beam data.
It is important that the applications are “stand-alone”, i.e., they do not depend on the
experiment framework, so that we can use them regularly for Geant4 validation.
What do you think?

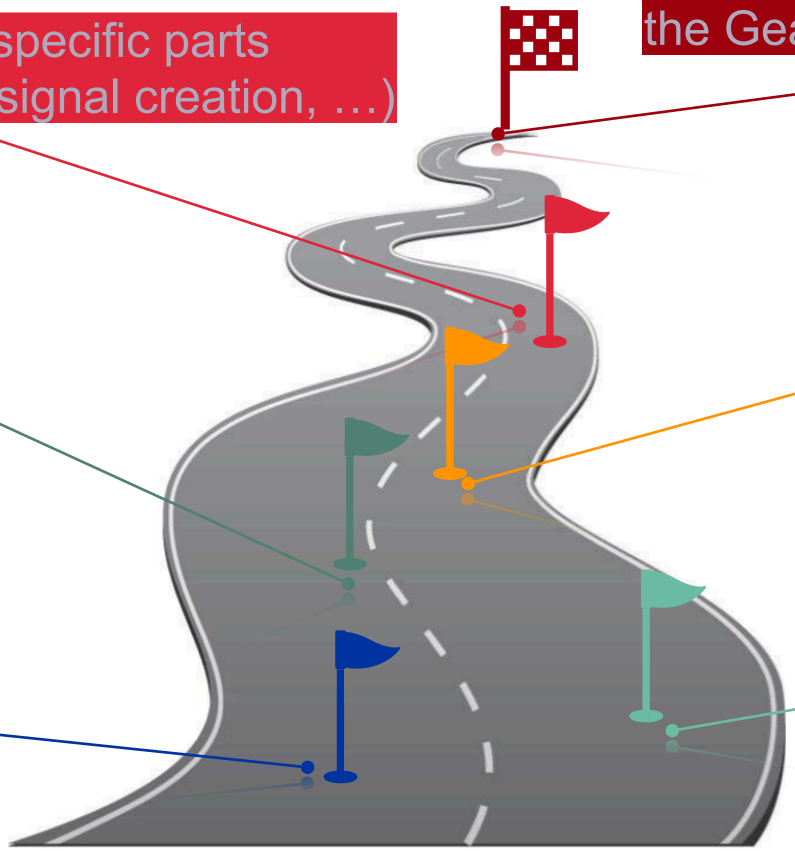
email exchange with Alberto (my translation), 20/4/2020

Why test beams?

- Calorimeters are tested at beam lines with isolated particles $(e^-, \pi^-, p, \ldots)$ for performance benchmarking
  - Possible to steer particles at any point on the calorimeter surface, without the need of disentangling contributions from different particles (no pile-up)
  - No need to de-convolute the calorimeter response with other detectors (trackers, pre-showers, …)
  - Possible to select the primary particle energy at will (almost never the case in real experiments!)



From experiments to geant-val, a winding road



Deploy results to Geant-val
the Geant4 validation and testing suite

Recode simulation-specific parts
(sensitive detectors, hits, signal creation, …)

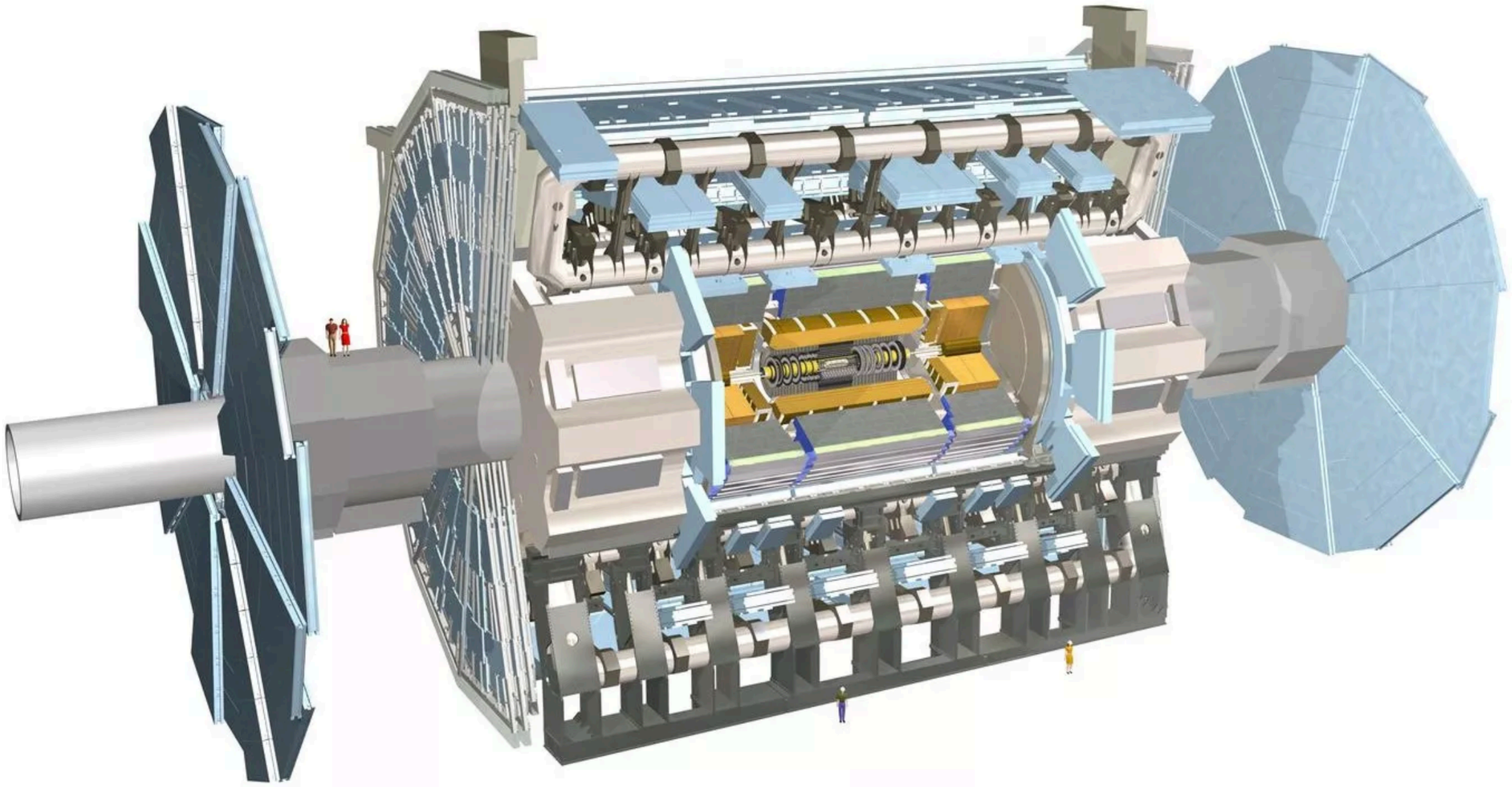
Build simulations
with portable and light
CMAKE lists
[find_package(GEANT4)]

Ensure multithreading
à la Geant4

Start from
experiments SW and
remove external dependencies
(GeoModel, DD4HEP, MySQL, …)

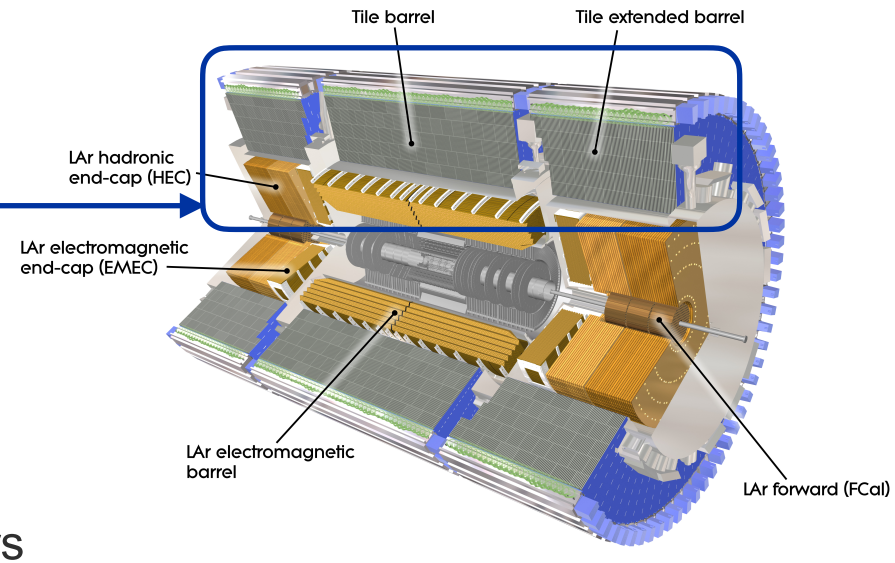
Re-code geometries
with G4Solid

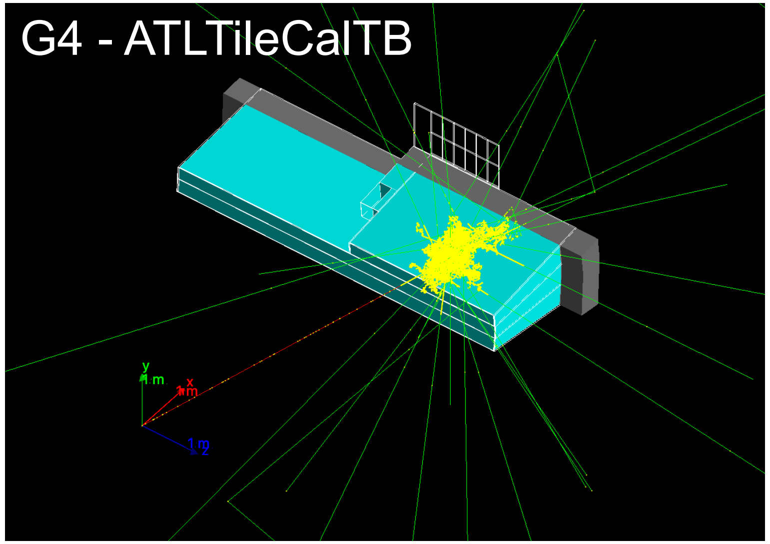
Geant4 studies with the ATLAS Experiment



ATLAS Tile Calorimeter beam test

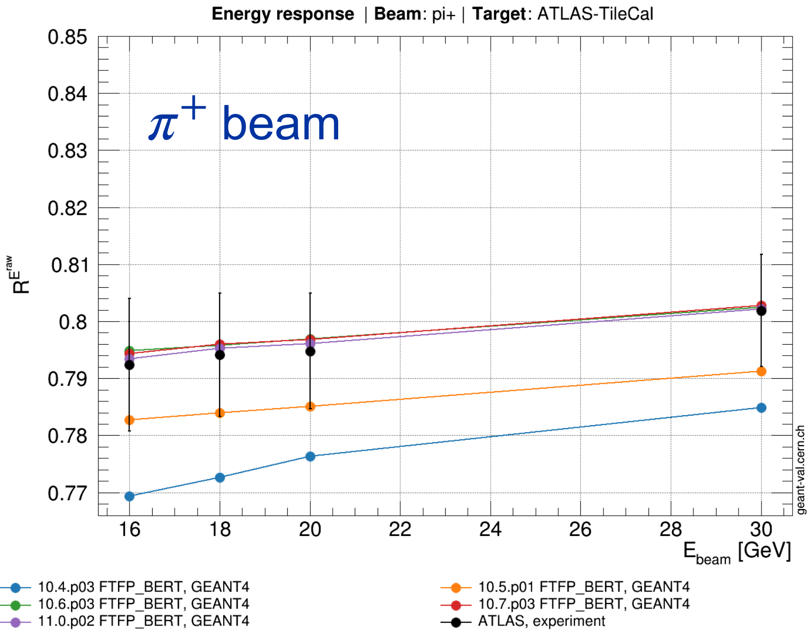
- ATLAS TileCal:
  - Mostly used to reconstruct hadronic jets in the range $|\eta| < 1.7$ thanks to 3 cylinders containing 64 modules each
  - Measure light in scintillating tiles immersed in iron
    Readout is grouped in pseudo projective cells with each layer readout by two PMTs
  - Each barrel consists of 11 tile rows grouped in 3 longitudinal layers
- TileCal beam test:
  - 2 Long Barrel Modules and 1 Extended Barrel module are regularly exposed to the SPS particle beams
  - The 2017 beam test studied the calorimeter response and resolution for π^+, p and k^+ in the energy range 16-30 GeV
  - Cherenkov auxiliaries used to tag π^+, p and k^+

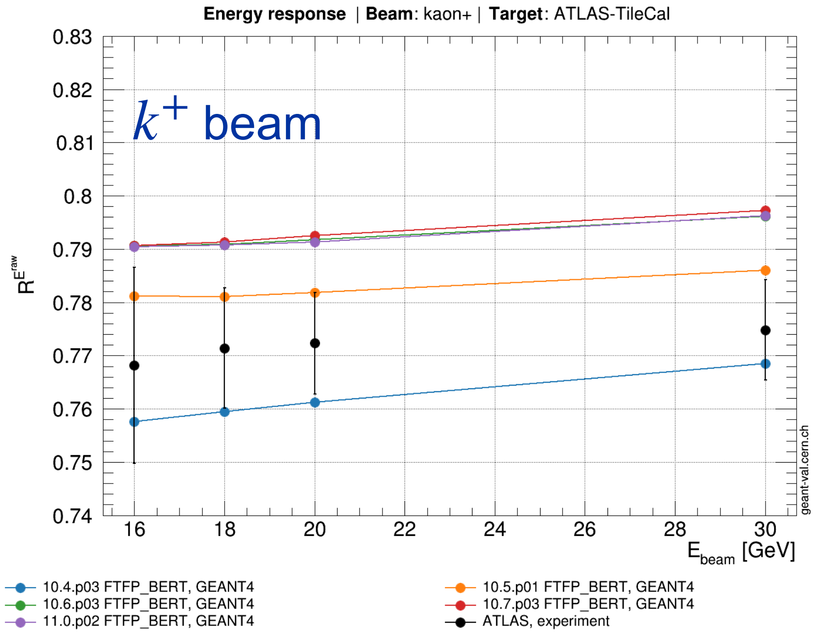


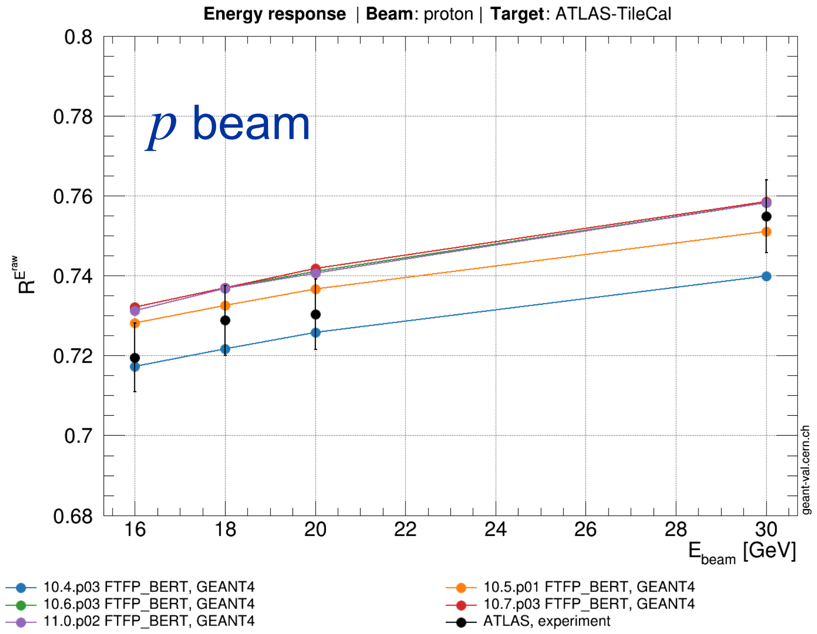


Hadronic response - π^+, k^+, p

- It was possible to disentangle contributions from π^+, k^+ and p:
  - Visible difference in the response to p and π^+: it is due to the baryon number conservation law for which high f_{em} processes (*e.g.* $\pi^+ + n \rightarrow \pi^0 + p$) are prohibited for p-induced events
  - Overall good description from FTFP_BERT of these effects

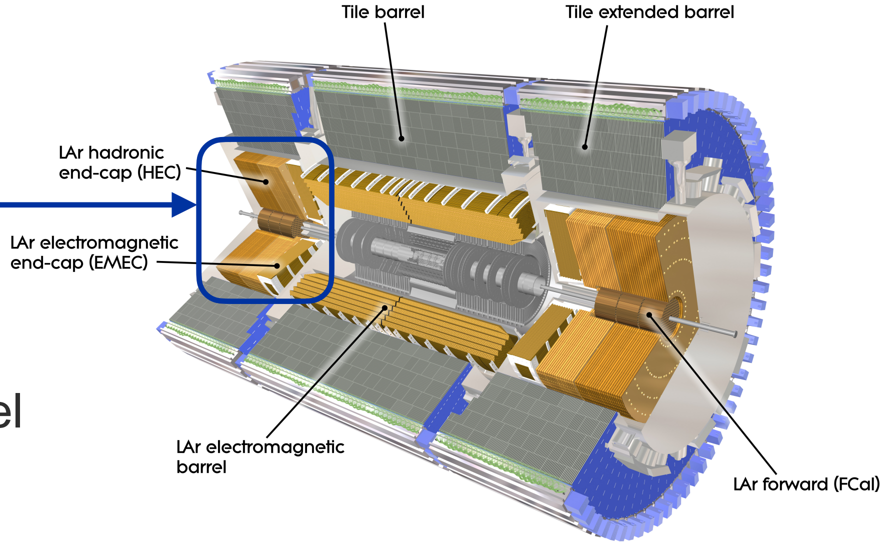




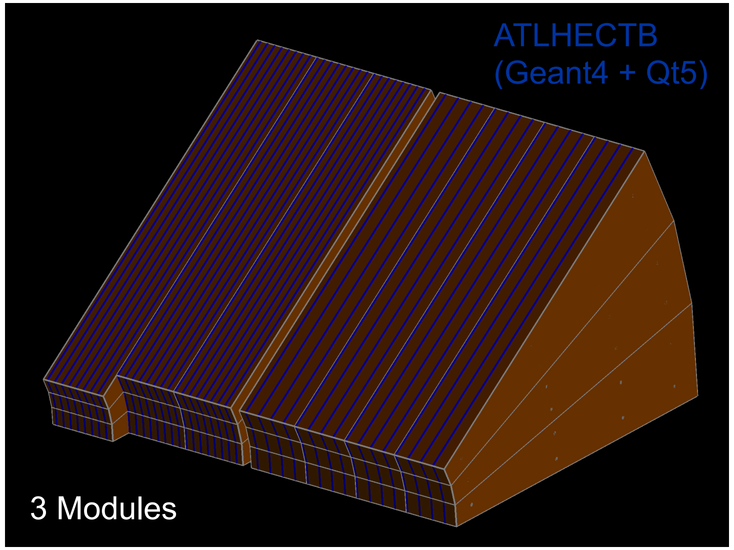


ATLAS Hadronic End-Cap Calo beam test

- The ATLAS HEC:
  - Covers the range $1.5 < |\eta| < 3.2$. Divided into two wheels (HEC1-2) each consisting of 32 azimuthal modules
  - It uses 8.5-mm-gap LAr sampling regions inserted between parallel copper plates, with 2.5 cm (HEC1) and 5.0 cm (HEC2) thickness
  - It has four longitudinal layers with a thickness of $\simeq 103X_0$ or $\simeq 9.7\lambda_{int}$



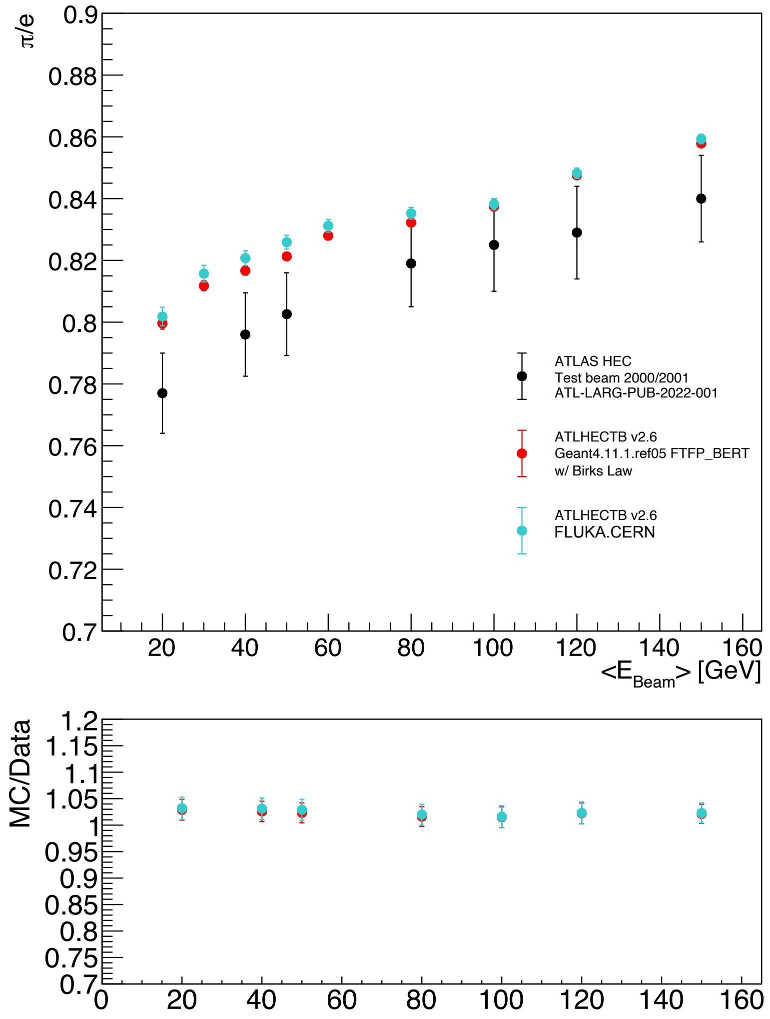
- HEC beam test:
  - Tested in 2000-2001 at CERN-SPS-H6 beam line
  - Tests performed with 3 ϕ−wedges
  - Involving e^-, μ^- and hadrons with $6 \leq E_{Beam} \leq 200$ GeV



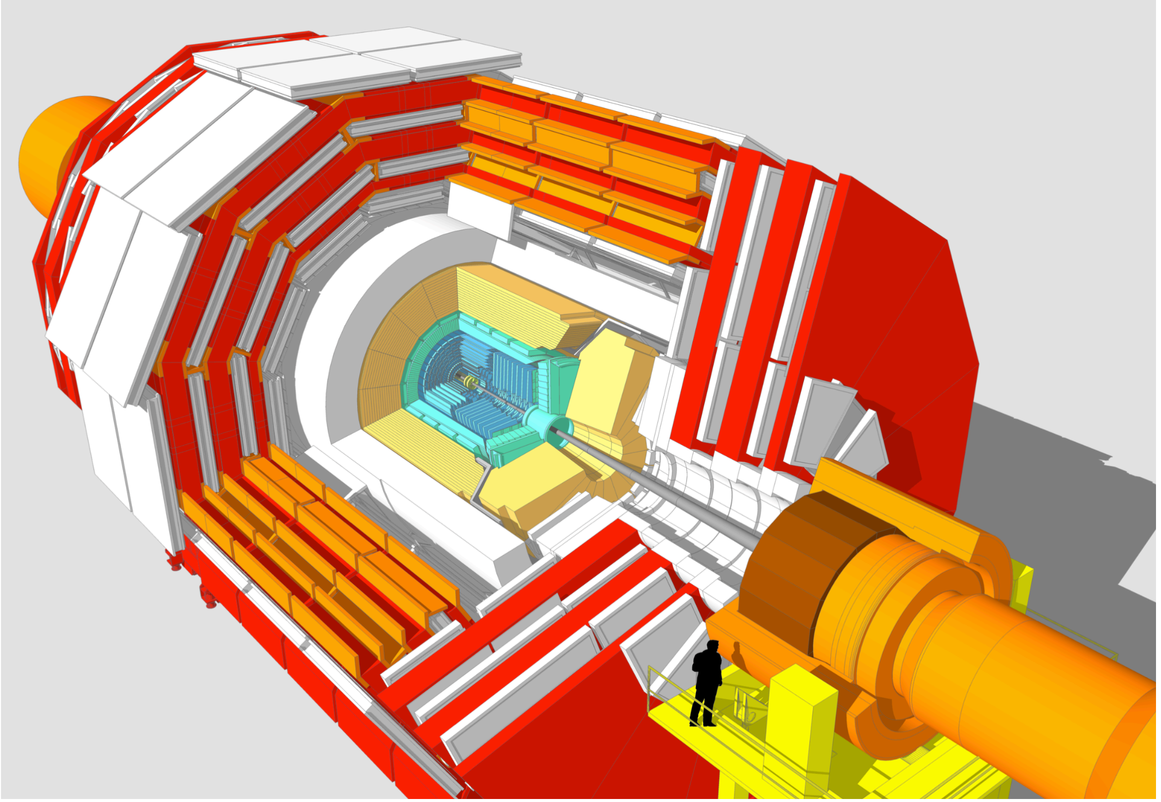
ATLAS HEC response (G4 vs FLUKA.CERN)

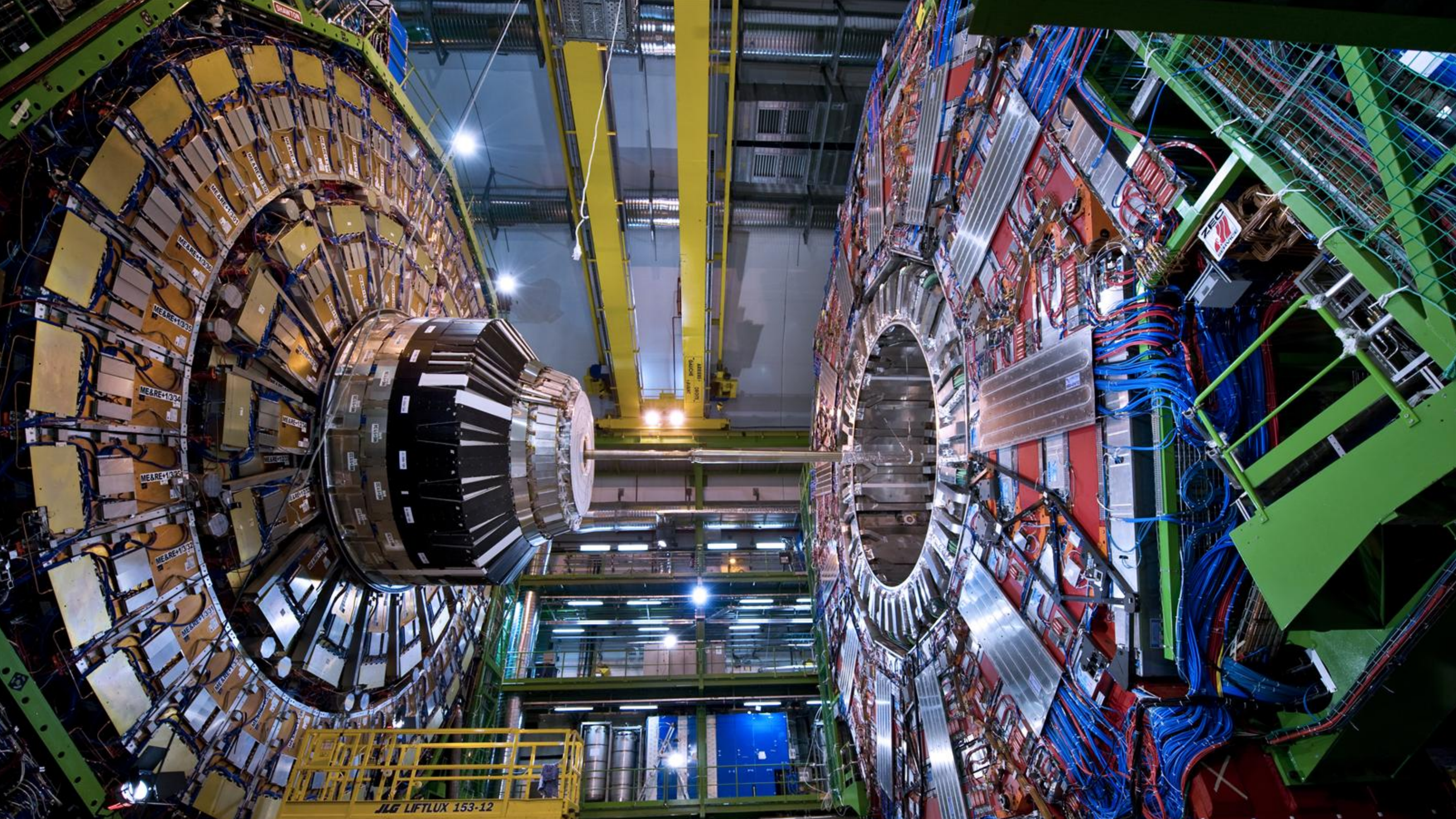
- π/e extracted as the average π^- reconstructed energy, using the calibration at the electromagnetic scale, divided by the average value for same energy e^- beams
  - Recent Geant4 releases slightly overestimate the hadronic response
  - Thanks to the recent Geant4-to-FLUKA.CERN interface it is now possible to test hadronic models by FLUKA.CERN inside a Geant4 simulation
  - Overall very good agreement between Geant4 (11.1) and Fluka.CERN (4-3.3) in describing ATLAS calorimeters

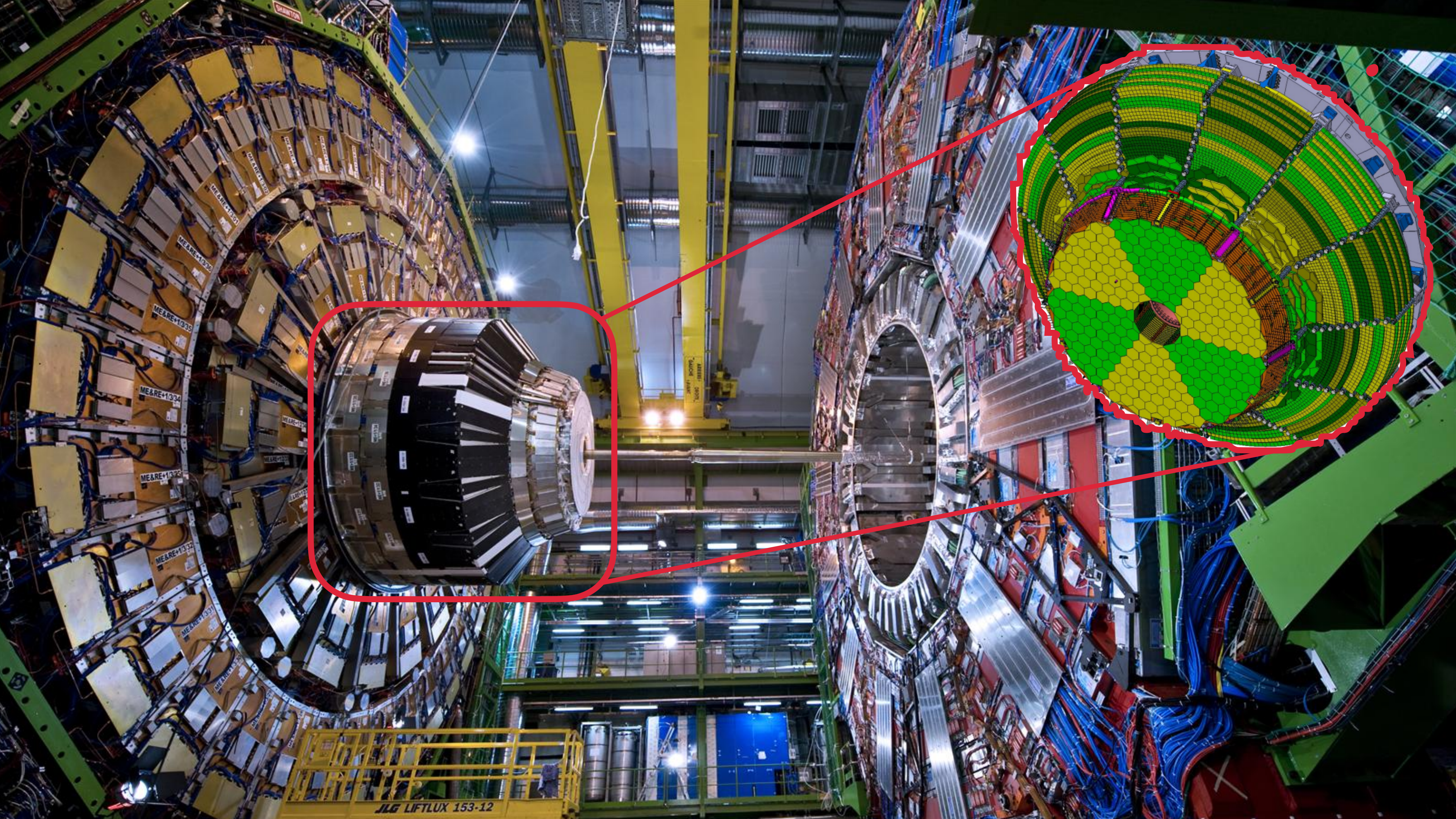
π^- beam



Geant4 studies with the CMS Experiment




JLG LIFTLUX 153-12

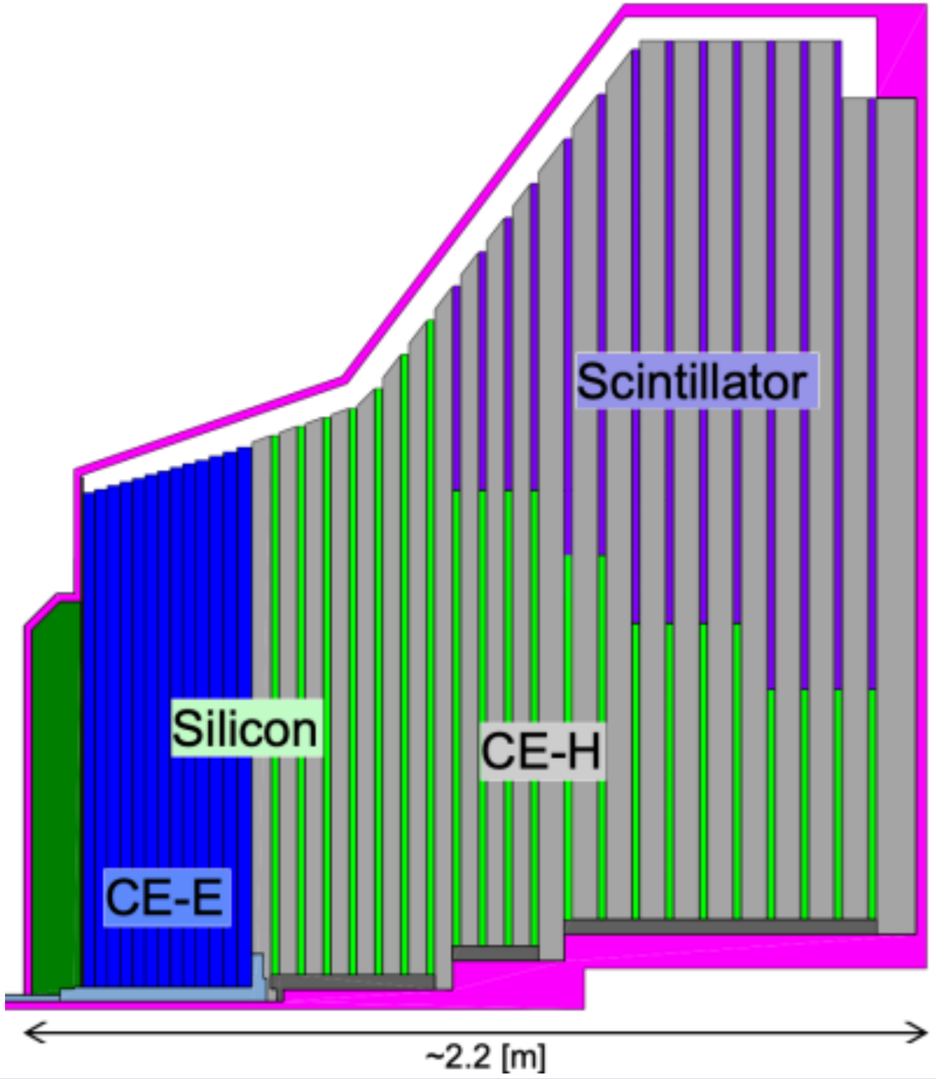


JLG LIFTLUX 153-12

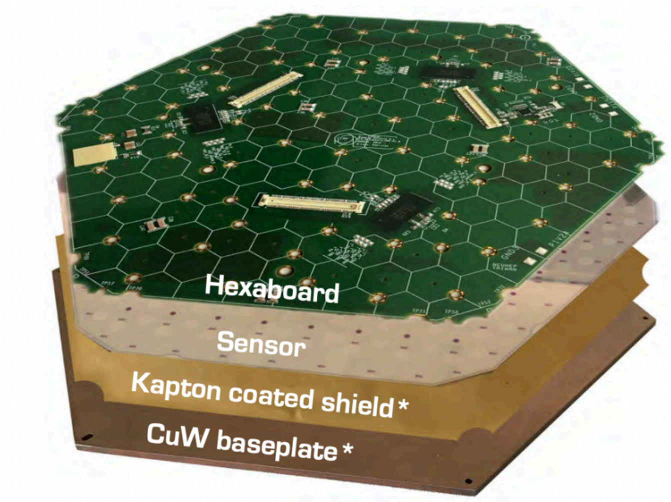
HGCAL detector concept

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

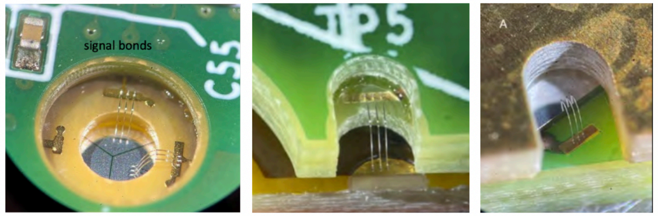
Per Endcap	CE-E	CE-H Si	CE-H Si+Scint
Absorber	Pb, CuW, Cu	Stainless steel, Cu	
Depth	27.7 X_0	10 λ	
Layers	26	7	14
Weight	23 t	205 t	



The HGCAL test beam geometry



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



Three calorimeters involved:

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

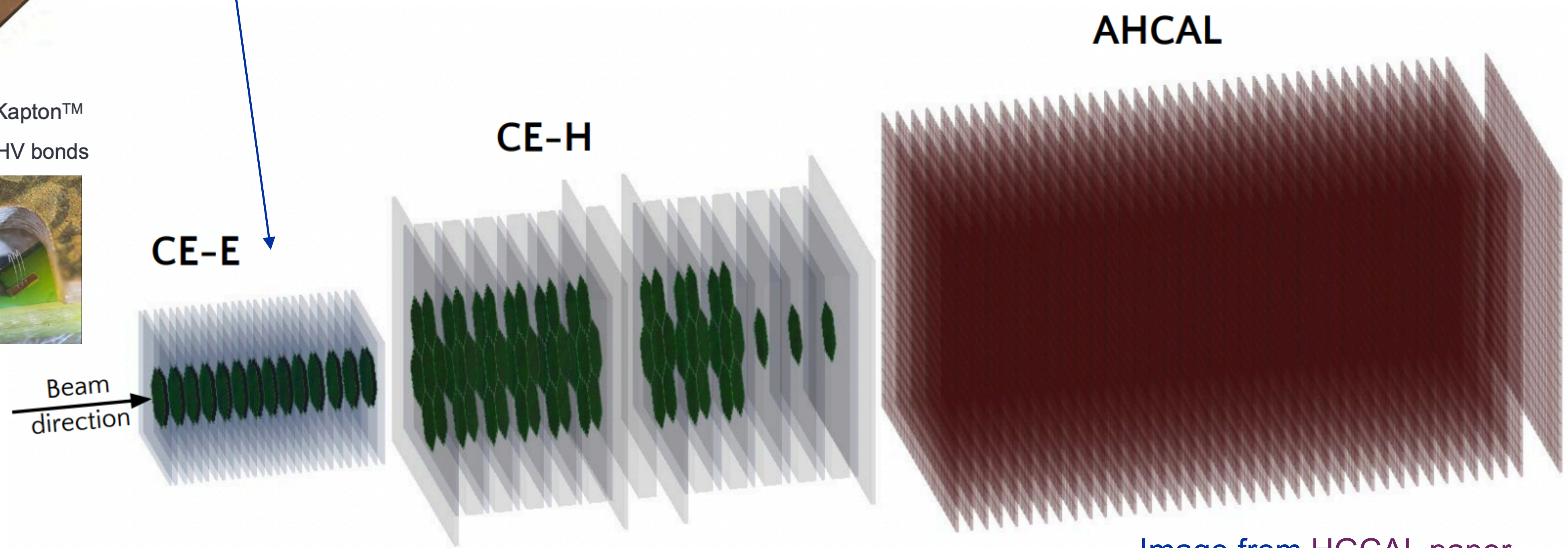
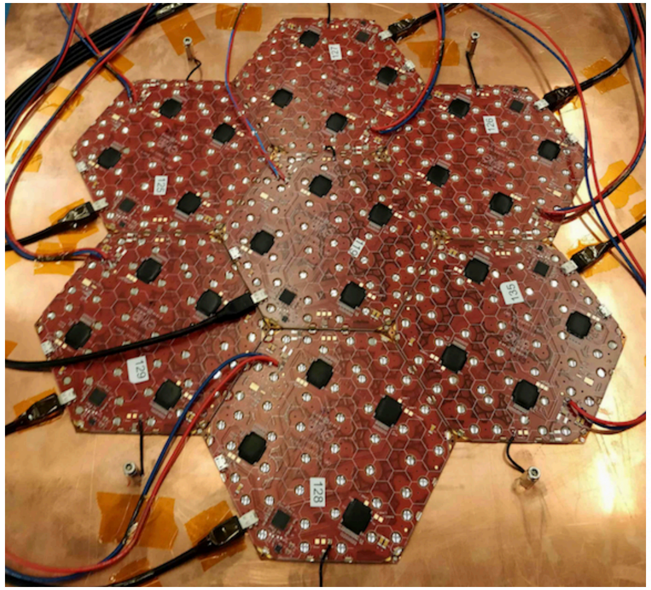


Image from HGCAL paper

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})

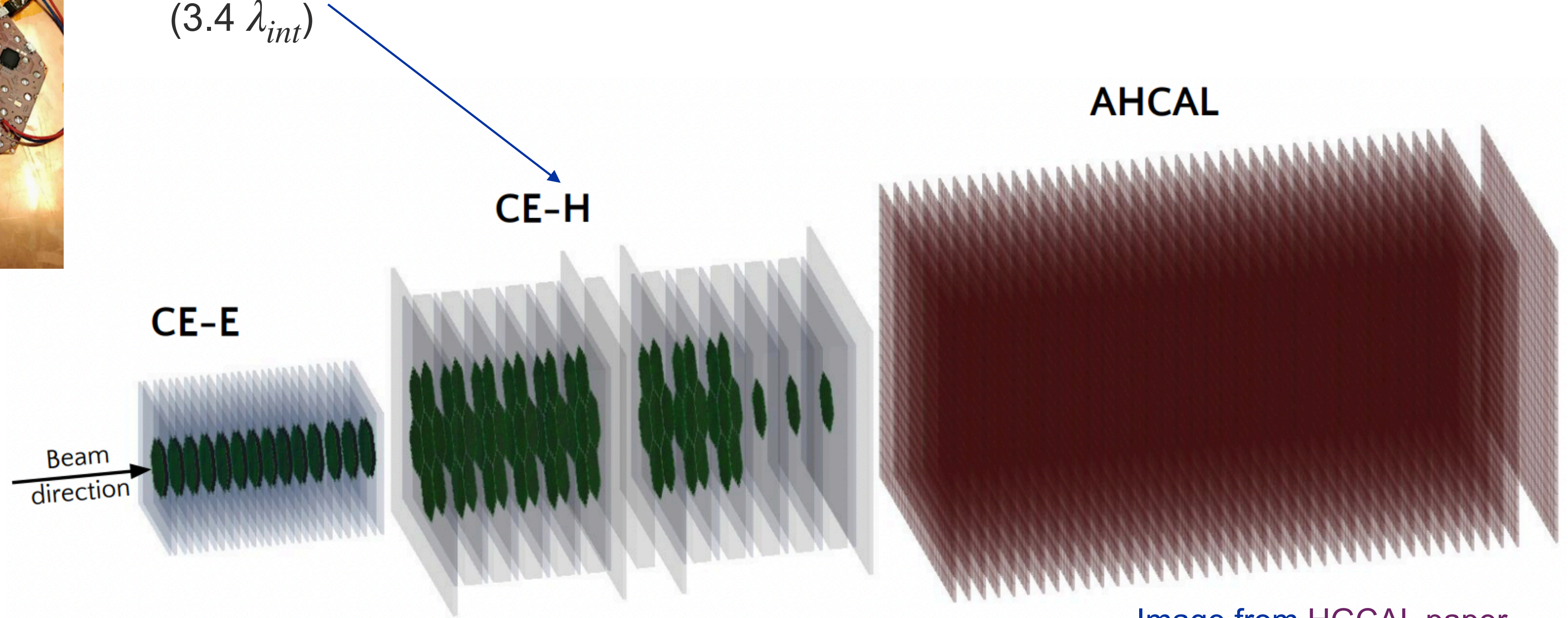
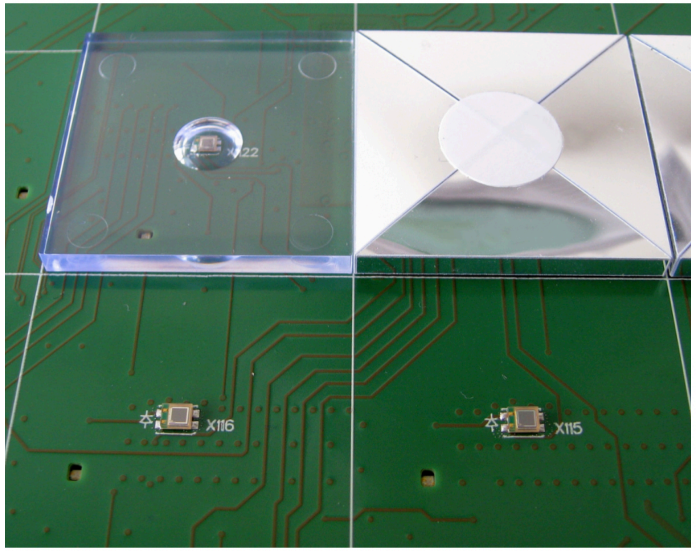


Image from HGCAL paper

The HGCAL test beam geometry



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- CHE: 12 layers of HGCAL Si pads, first 9 use 7 sensors in a daisy-like structure (3.4 λ_{int})
- AHCAL: 39 layers of 24×24 ($3 \times 3 \times 0.3$ cm^3) plastic tiles (4.4 λ_{int})

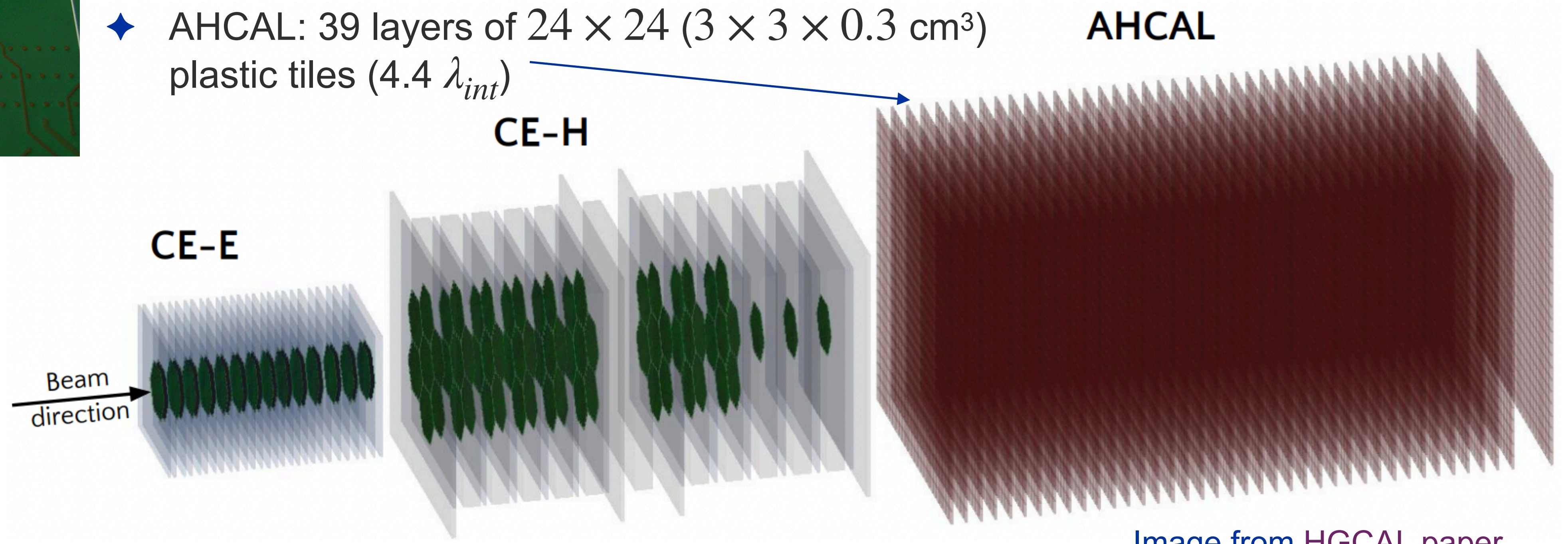
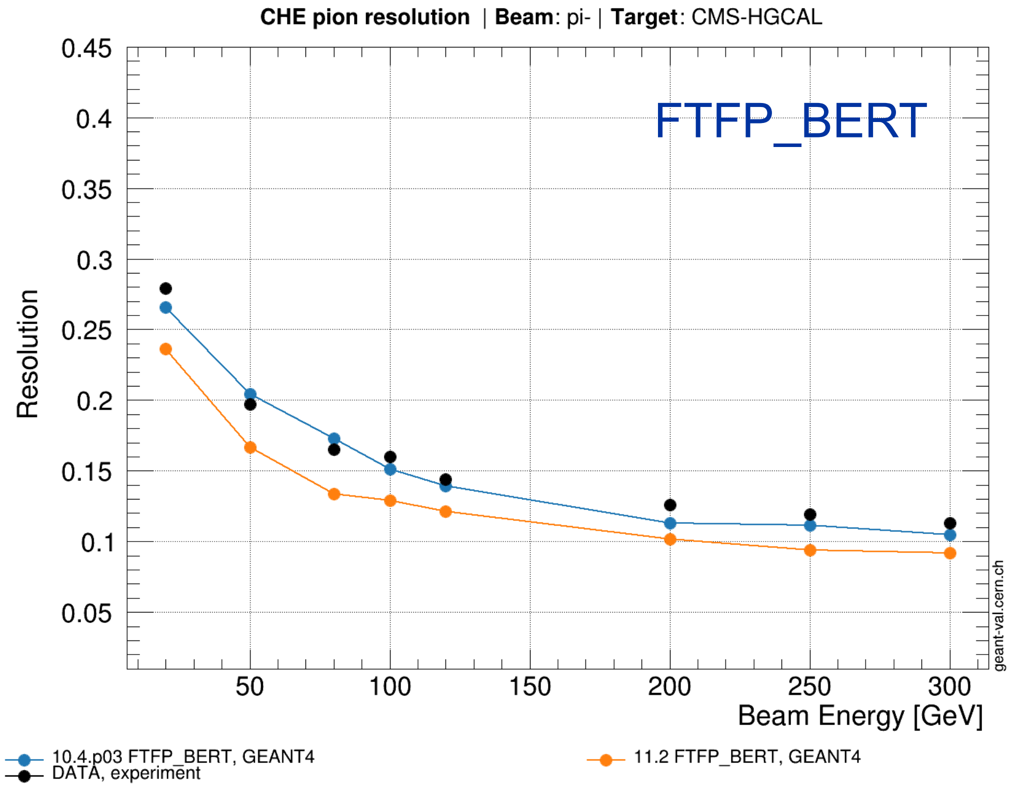
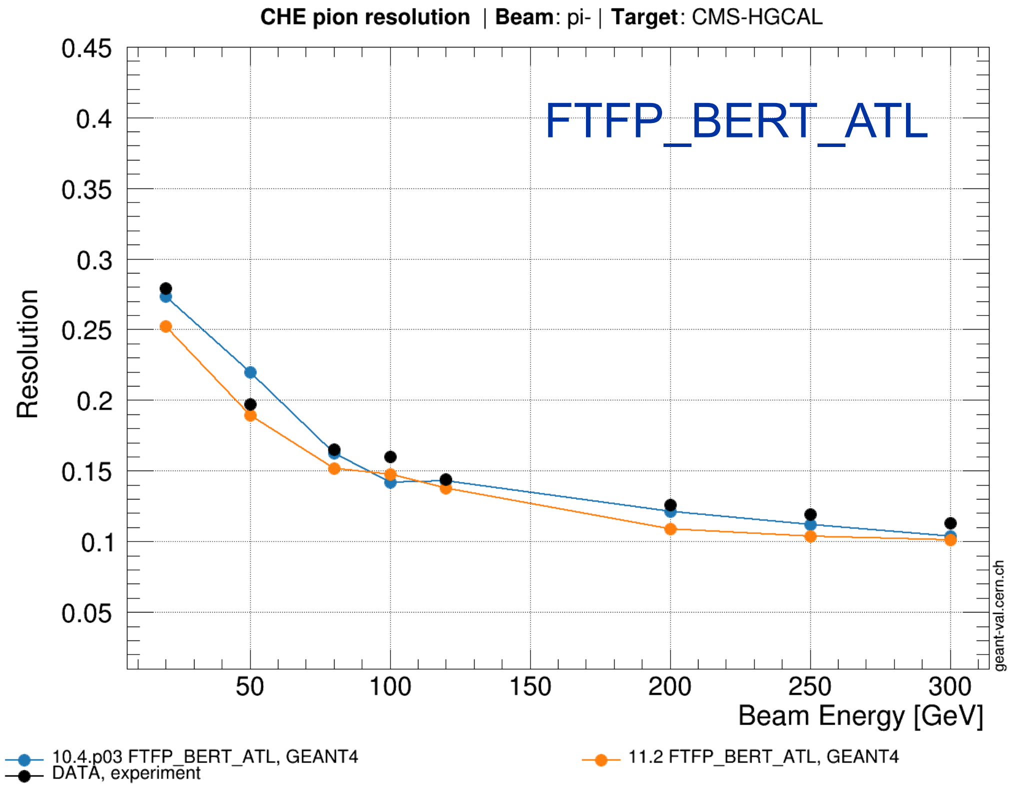


Image from HGCAL paper

π^- energy resolution

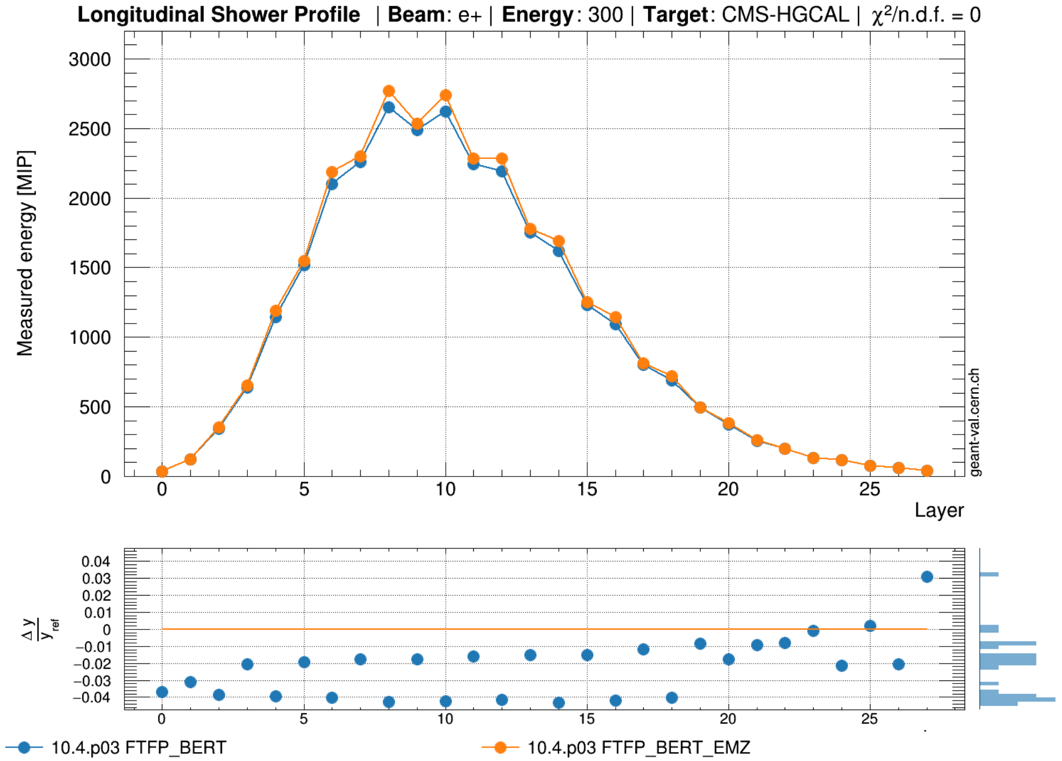
- The decrease in hadronic signal fluctuations was already observed in ATLAS Calorimeters; a special hadronic model tune introduced in FTFP_BERT_ATL was proposed by us to mitigate this problem
- The same changes seem to improve the agreement with data for the CMS HGCAL as well

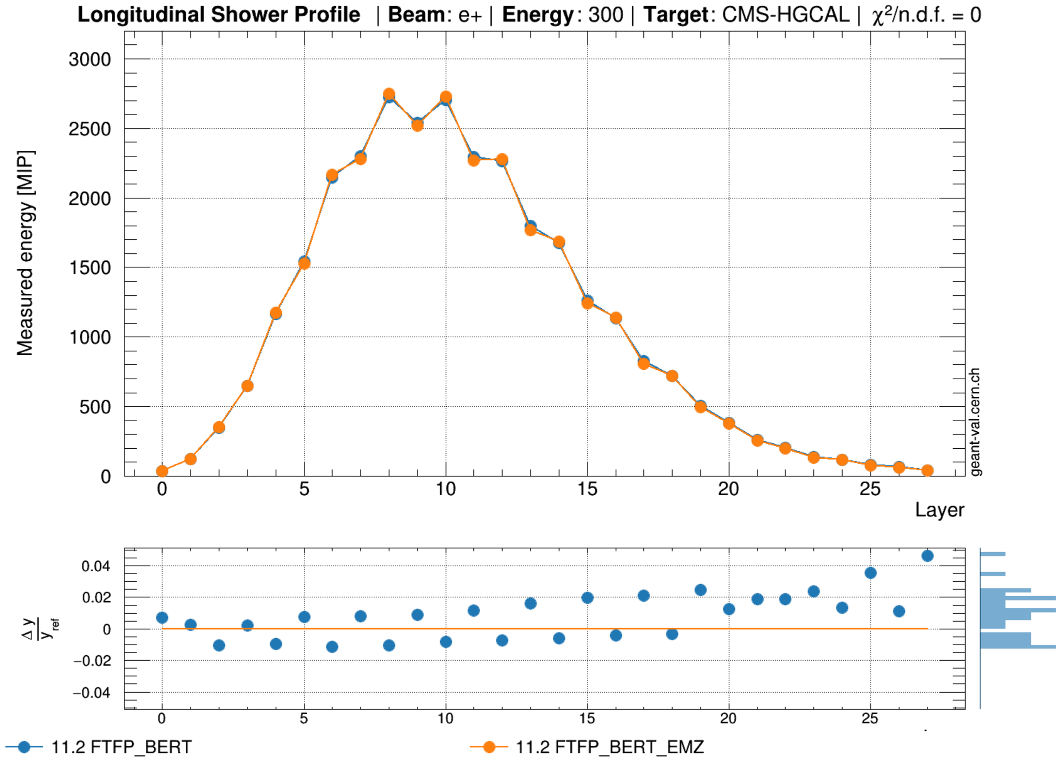




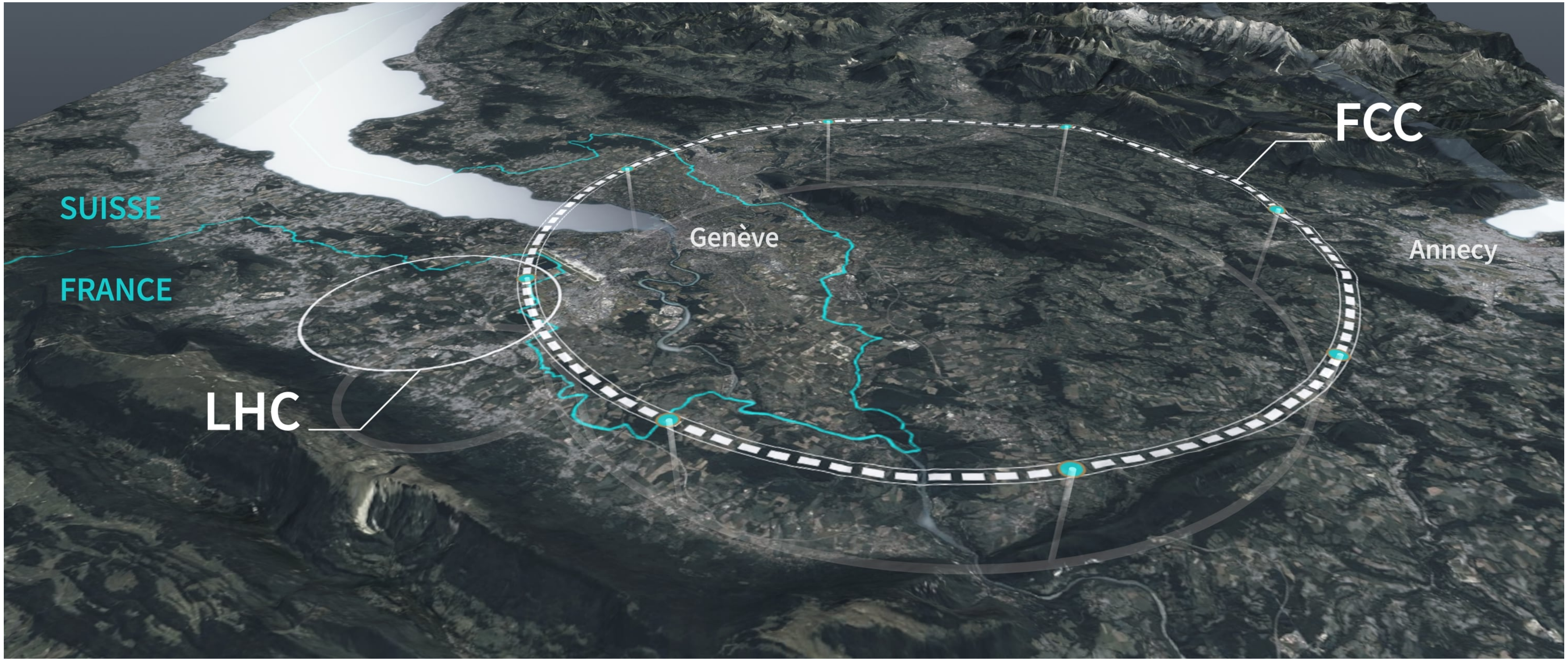
Extension to EM physics

- 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





Geant4 studies
with the
FCC detectors prototypes



CALICE SiW Calorimeter

- New highly-granular calorimeters for future Higgs factories by CALICE provide unprecedented shower sampling capabilities, thus enabling superior Geant4 validation
- The CALICE SiW calorimeter features:
  - 30 longitudinal layers (silicon + tungsten) with a total thickness of $24X_0$ ($\simeq 1\lambda$),
  - each silicon layer readout by 36×9 Si-cells,
  - with an active area of 18×18 cm²

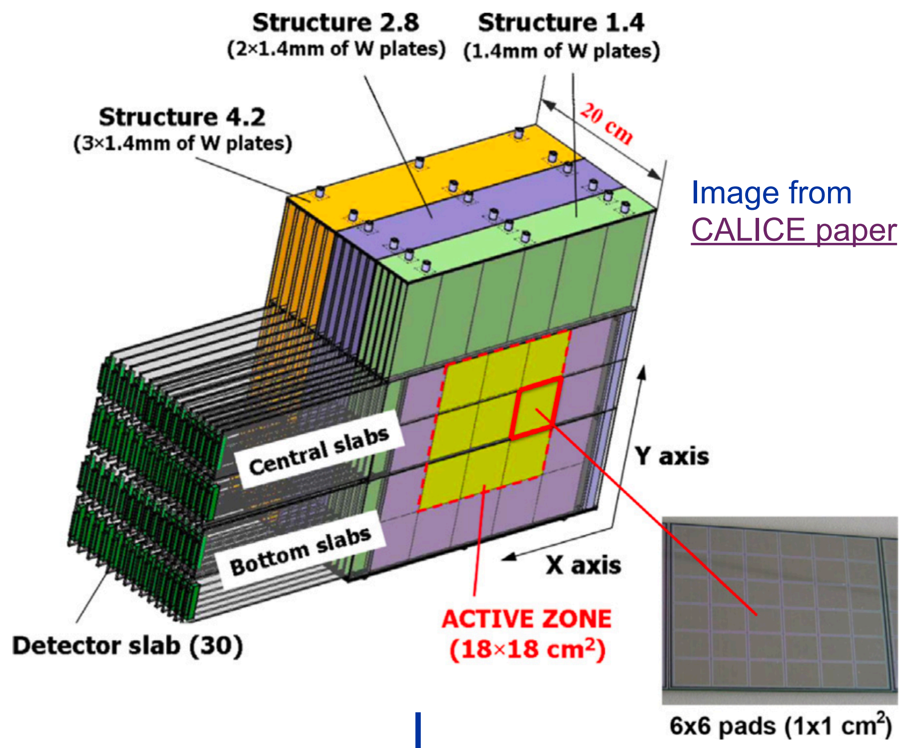
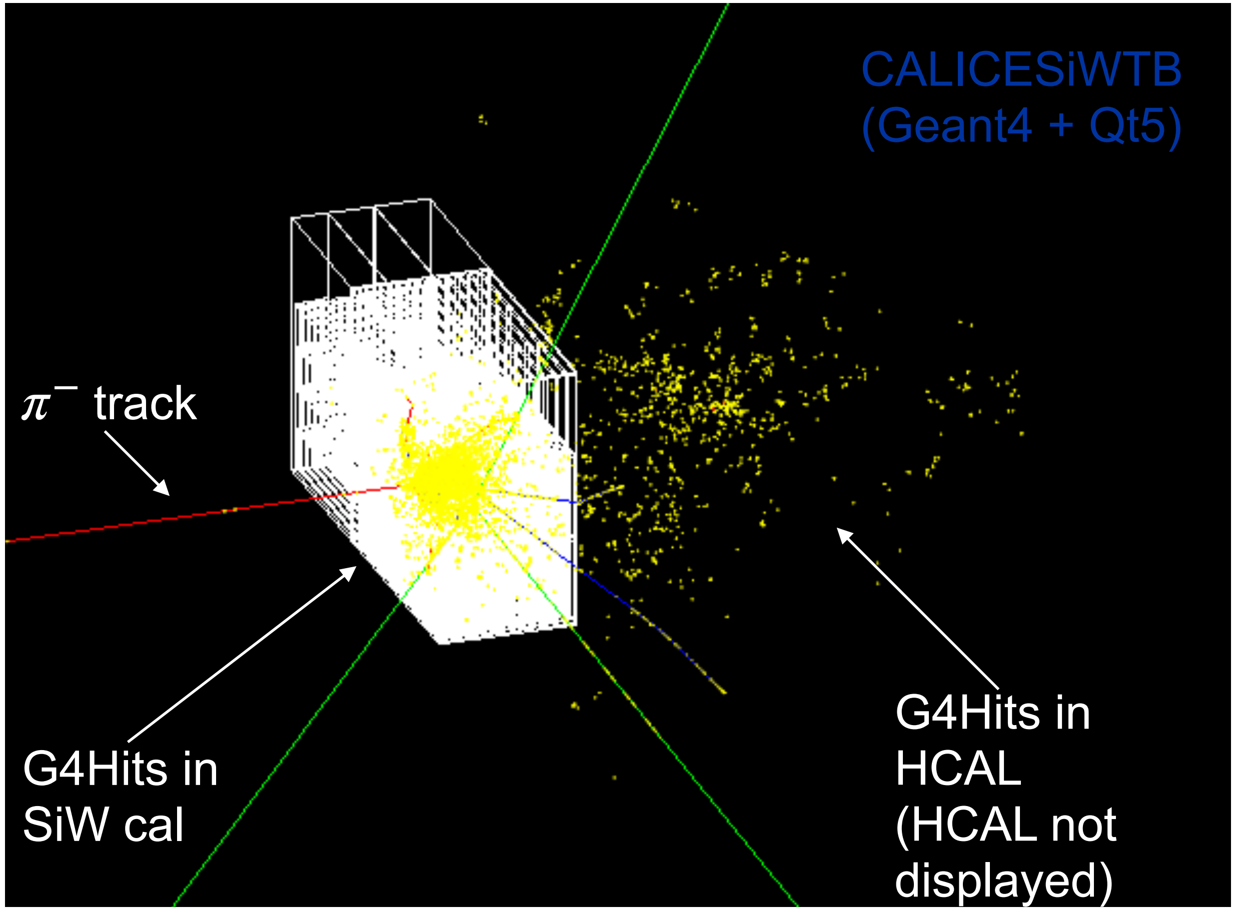


Image from CALICE paper

9720 sensitive volumes

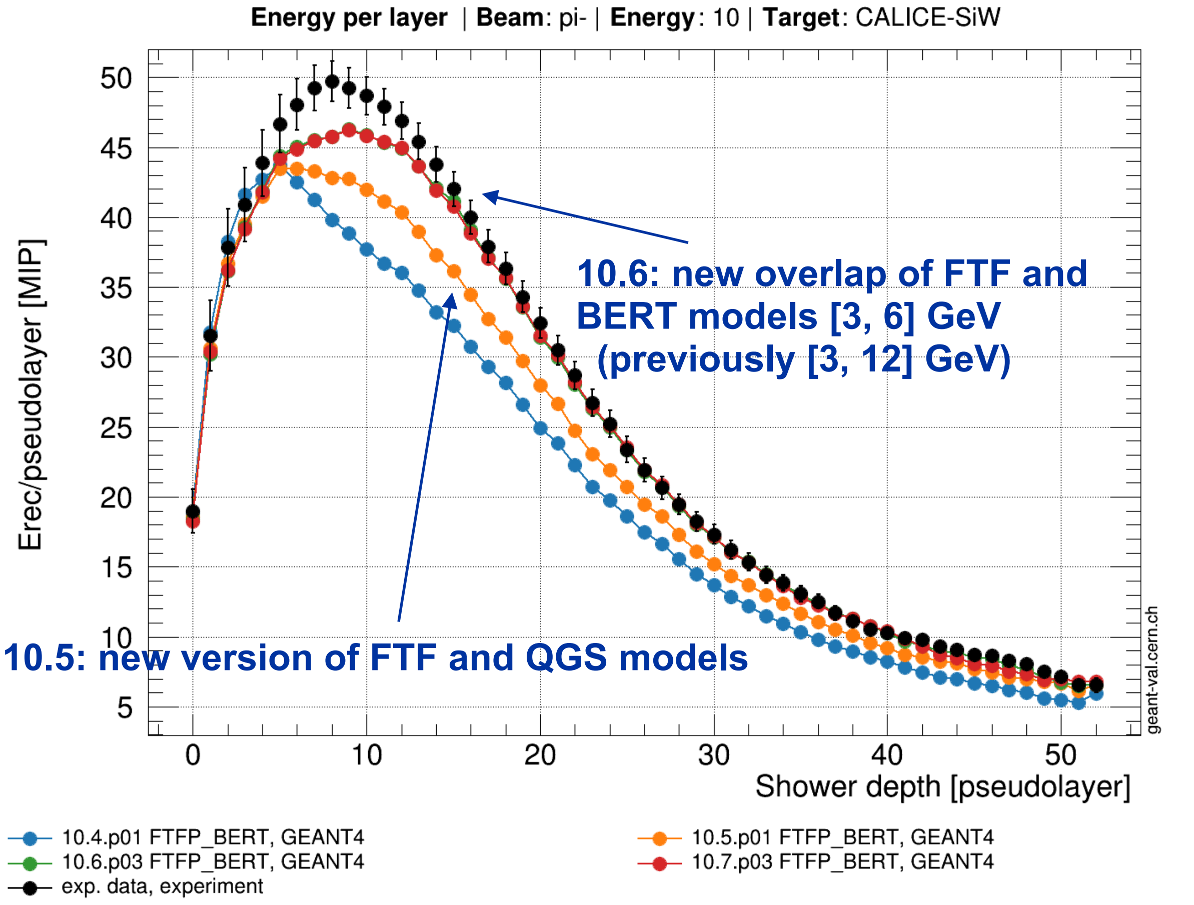
Tagging nuclear breakup events

- Beam tests performed at FNAL in 2008 involving 2, 4, 6, 8 and 10 GeV π^- studying the first development stages of hadronic showers
- Energy depositions in each cell calibrated in MIP units (extracted with μ^- runs)
- Events with a single nuclear breakup are tagged as those with:
  - three consecutive layers measuring > 8 MIP, or
  - $\dfrac{E_i + E_{i+1}}{E_{i-1} + E_{i-2}} > 6$ and $\dfrac{E_{i+1} + E_{i+2}}{E_{i-1} + E_{i-2}} > 6$
- Starting from the first-interaction layer, it is possible to measure the longitudinal energy (or hit) distributions, as a function of the beam energy, *regardless of the depth of the first interaction*

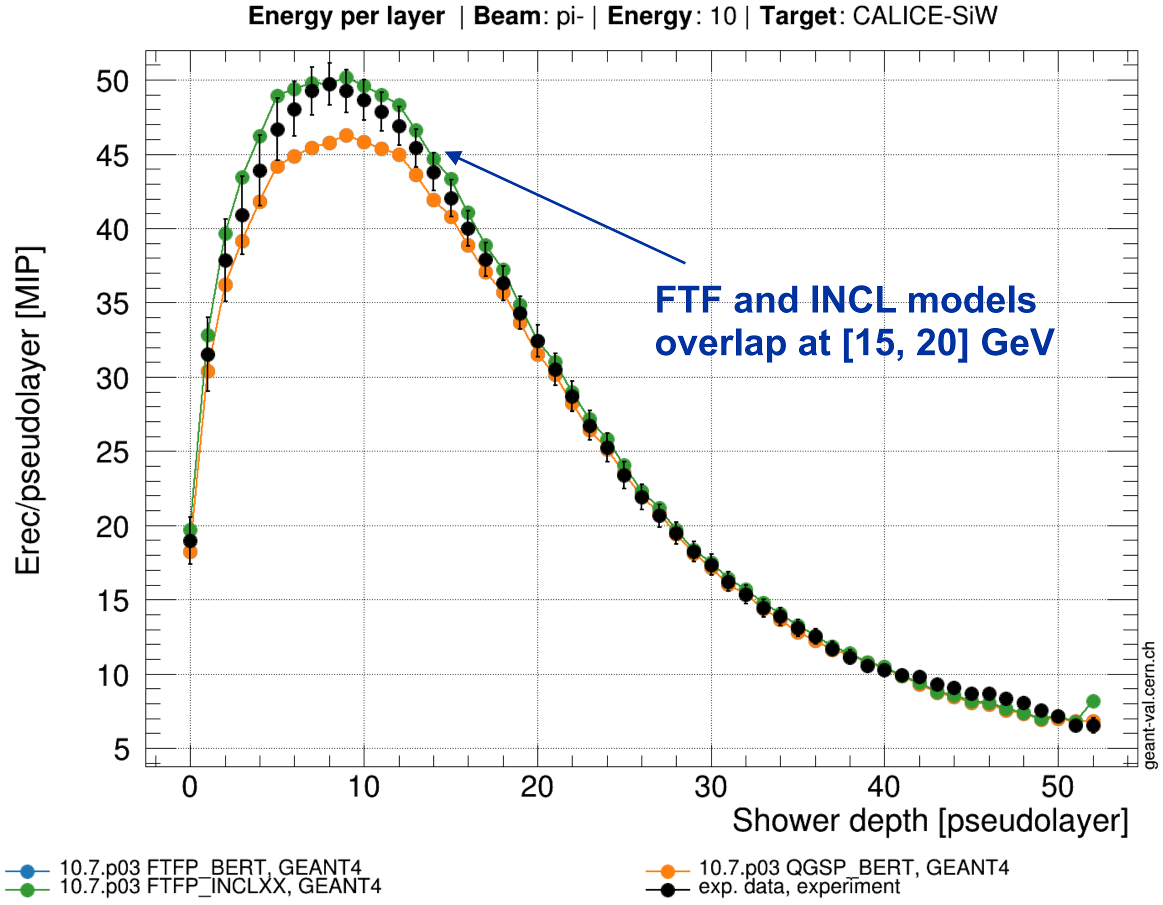


CALICE SiW: longitudinal energy distributions

10 GeV π^-, exp. data from NIM A794



***FTFP_BERT** Physics List regression testing*

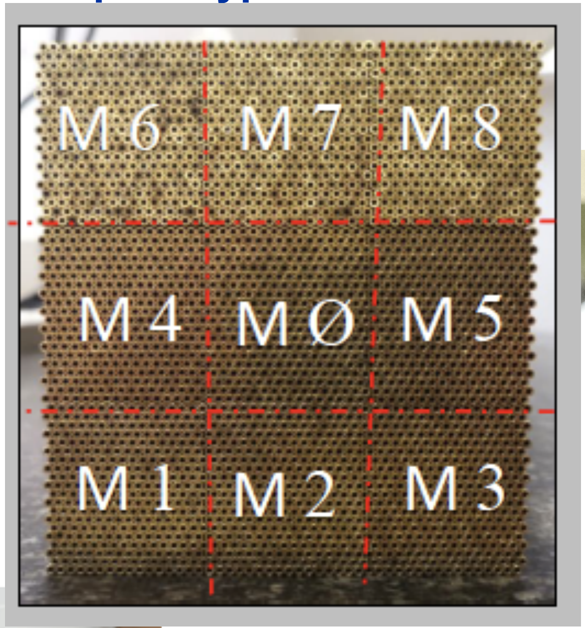


Physics Lists comparison

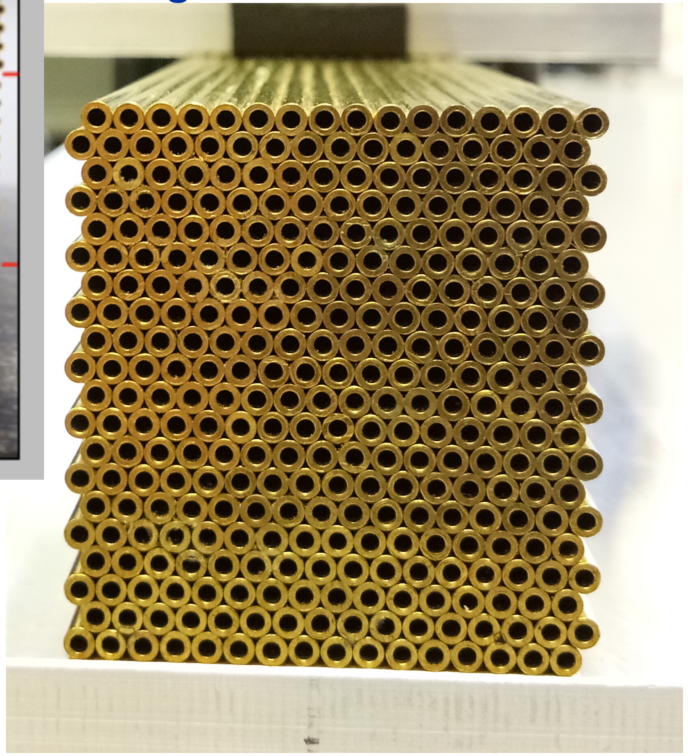
The Bucatini Dual-Readout Calorimeter

- The latest capillary-tube-based dual-readout prototype features:
  - EM dimensions of $10 \times 10 \times 100$ cm³, $\simeq 90\,\%$ EM containment
  - 9 towers, each containing 16×20 capillaries (160 Cherenkov and 160 Scintillating)
  - Brass capillary tube outer diameter of 2 mm and inner diameter of 1.1 mm. 1-mm-thick fibers.

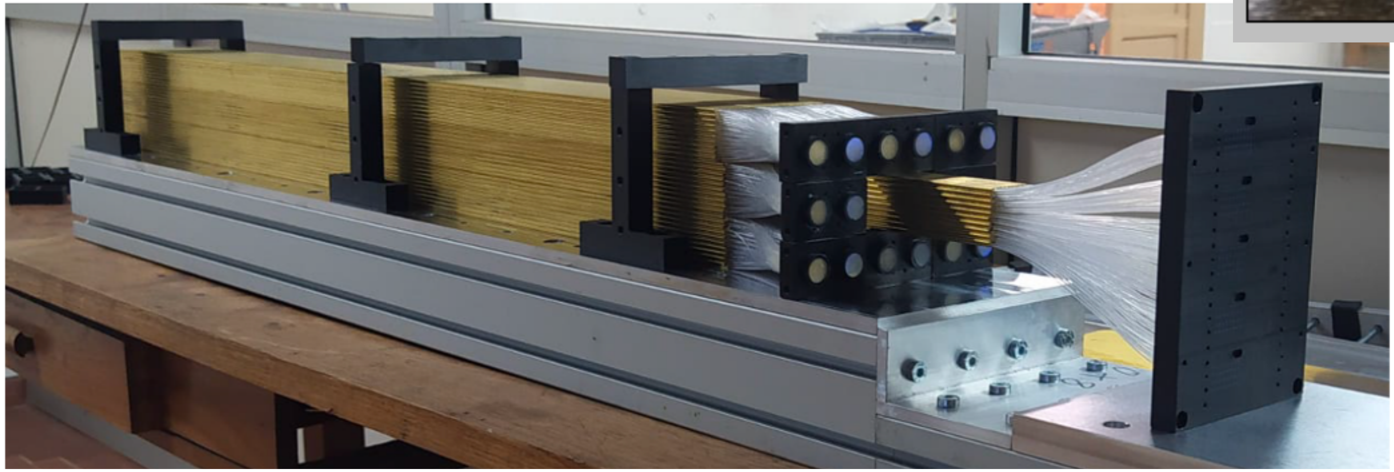
Full prototype - 9 towers



A single tower



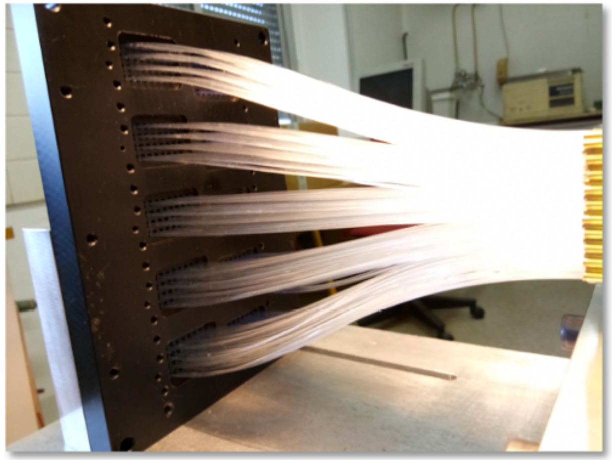
Prototype rear end

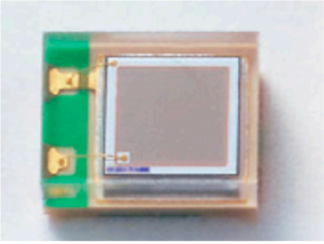


Towards superior Geant4 EM validation

- ✦ Superior granularity achieved using a hybrid readout system:
  - 320 SiPMs in the central tower independently read-out using
    - 5 FEE readout boards, operated in self-trigger mode
  - Surrounding 8 towers read-out by two PMTs per tower providing an independent Cherenkov and Scintillation light readout

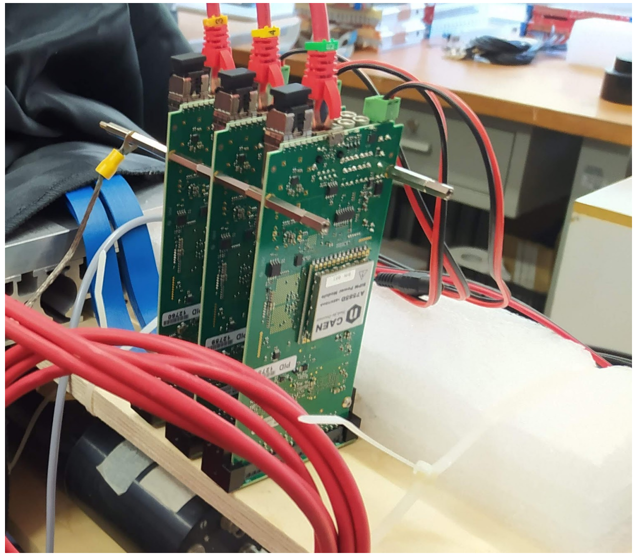
Fiber-to-SiPM guiding system





Hamamatsu SiPM: S14160-1315 PS
Cell size: $15\ \mu m$

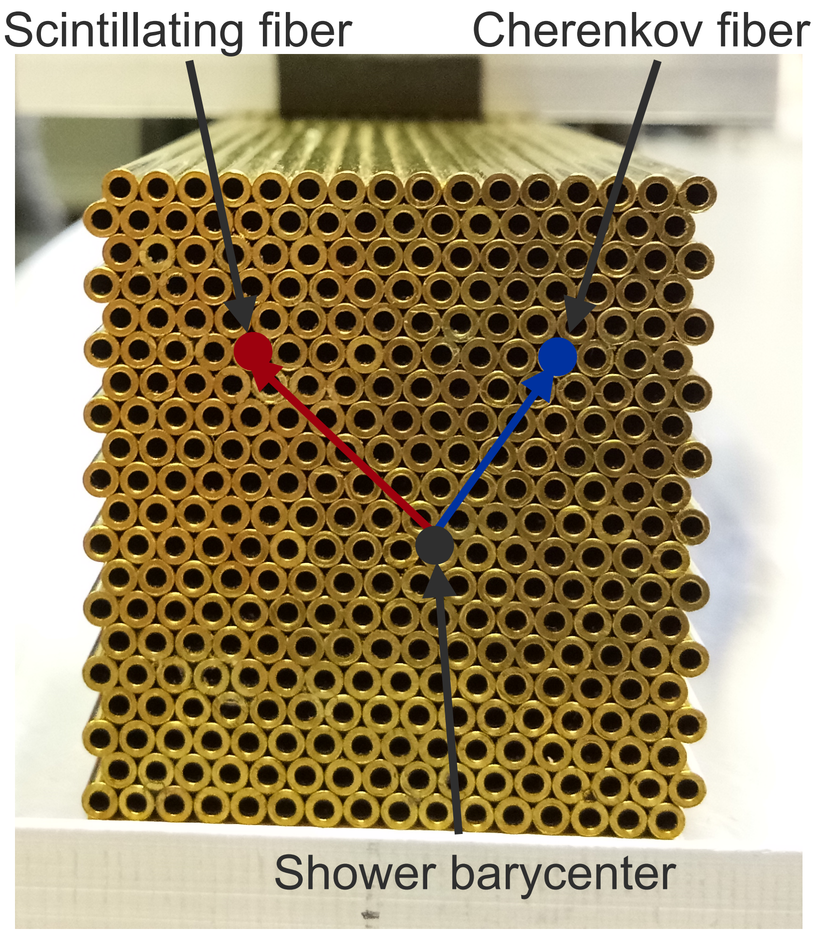
Front end board housing 64 SiPM



Readout Boards CAEN A5202

Dual-Readout Calorimeter: e^+ shower shape

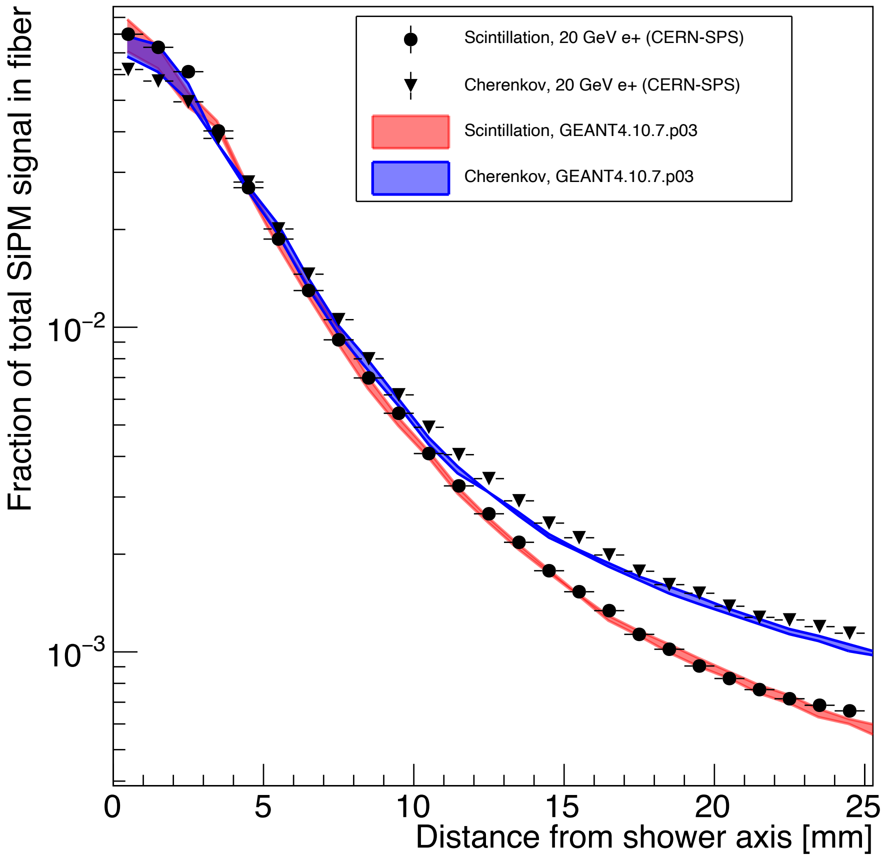
- Tested with e^+ beams at CERN-SPS-H8 beam line
  - Summer 2021 and 2023
  - Using e^+ beams with energies 10-125 GeV
- Lateral profile measurement, *i.e.* measuring the average signal carried by a fiber located at a distance r from the shower barycenter



Dual-Readout Calorimeter: e^+ shower shape

- Tested with e^+ beams at CERN-SPS-H8 beam line
  - Summer 2021 and 2023
  - Using e^+ beams with energies 10-125 GeV
- Lateral profile measurement, *i.e.* measuring the average signal carried by a fiber located at a distance r from the shower barycenter
- Achieved millimetric sampling of EM showers:
  - The average signal drops by two orders of magnitude over a distance on (only!) 2.5 cm

CERN SPS 20 GeV e^+ - GEANT4



N. Ampilogov et al 2023 JINST 18 P09021

What's next?

Expanding our testing suite to
ALICE
LHCb
and new variables
from ATLAS/CMS

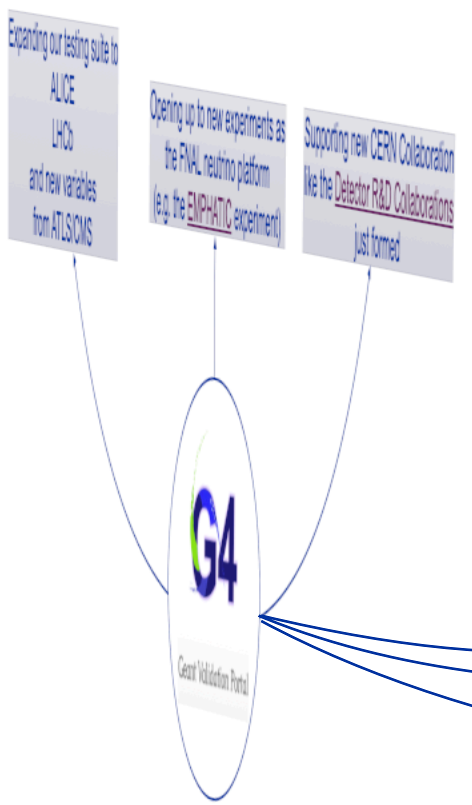
Opening up to new experiments as
the FNAL neutrino platform
(e.g. the EMPHATIC experiment)

Supporting new CERN Collaboration
like the Detector R&D Collaborations
just formed

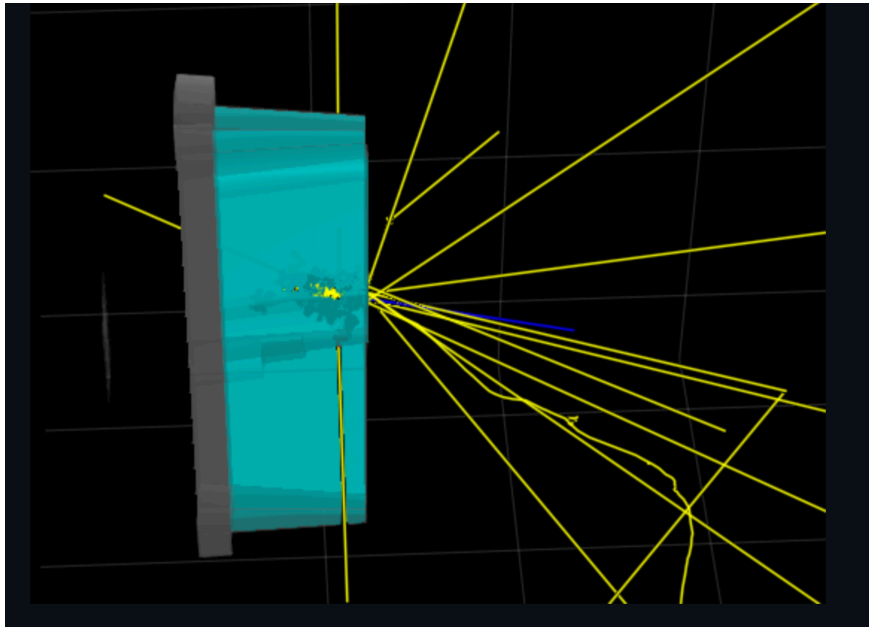
Geant Validation Portal

Horizontal development: not changing the activity but expanding it

What's next?



ATLTileCalTB.jl by Pere



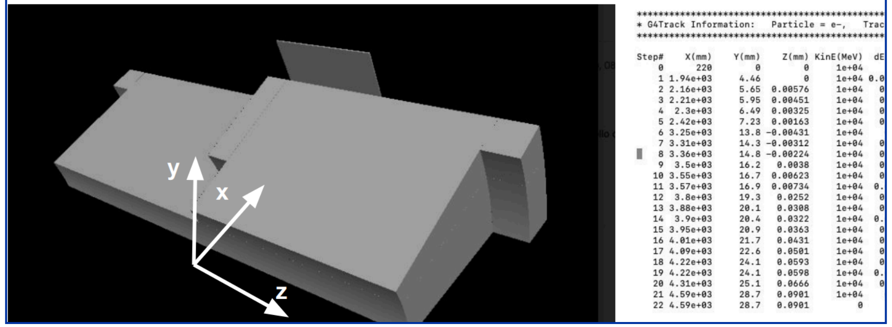
From ATLAS-Adept Team slides

Using TileCal test beam geometry (ATLTileCalTB)

- Use the gdml from the testbeam: TileTB_2B1EB.gdml
  - More complex geometry
  - Added a **caloregion** definition in the gdml (for TBEnv)

```
<userinfo>
  <auxiliary auxtype="Region" auxvalue="caloregion">
    <auxiliary auxtype="volume" auxvalue="Tile::TileTBEnv0x491dcfa0"/>
    <auxiliary auxtype="gamcut" auxunit="mm" auxvalue="0.7"/>
    <auxiliary auxtype="ecut" auxunit="mm" auxvalue="0.7"/>
    <auxiliary auxtype="poscut" auxunit="mm" auxvalue="0.7"/>
    <auxiliary auxtype="pcut" auxunit="mm" auxvalue="0.7"/>
  </auxiliary>
</userinfo>
```

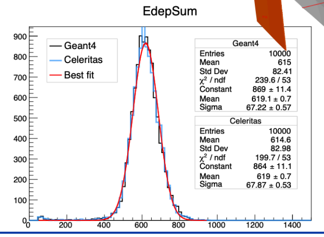
Electron hits the barrel a

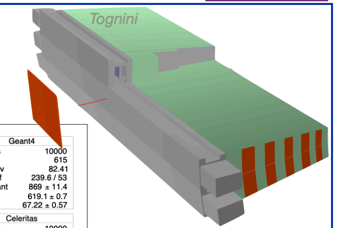


From Celeritas Team slides

EM offloading with FullSimLight

- ATLAS FullSimLight: hadronic tile calorimeter module segment
  - 64 segments in full ATLAS, 2 in this test beam
  - 18 GeV π^+ beam, no field
  - FTFP_BERT (default) physics list





Vertical development: attaching new activities to the existing ones

Other activities during my fellowship

Work

- Created a G4 test for conservation laws in hadronic interactions [1]
- Created a G4 implementation of the ATLAS Liquid Argon Barrel calorimeter [1,2]
- Collaborated with FNAL Colleagues on a G4 test for the lepto-nuclear process

Other activities during my fellowship

Learning

- Developed a good understanding of the LHC Experiments' most challenging features to be reproduced in Geant4
- Consequently, delved into Geant4 physics processes, especially the hadronic ones
- Acquired a deep understanding of the Geant4 physics kernel and the details of the hadronic framework, thanks also to several discussions with model developers
(many thanks to V. Uzhinsky, V. Grichine and A. Ribon)

Other activities during my fellowship

Publications

- Published two articles in international journals
  - *Particle flow with a hybrid segmented crystal and fiber dual-readout calorimeter*, JINST 17 P06008
  - *Exposing a fibre-based dual-readout calorimeter to a positron beam*, JINST 18 P09021
- one conference proceeding
  - CALOR2022: *Including Calorimeter Test Beams in Geant-val*, Instruments 2022, 6, 41
- and new results will be shown at the upcoming CALOR2024 Conference

Other activities during my fellowship

Teaching

- 2022 Summer School supervisor: *Simulating ATLAS TileCal for Geant4 validation*
- 2023 Summer School supervisor: *Testing hadronic models on ATLAS hadronic calorimeters*
  - co-supervisor of the Master Thesis at the University of Rome I: *Simulation and Reconstruction for Boosted Boson Tagging at the ATLAS Experiment*
- 2022 and 2023 Geant4 Course in South Korea lecturer

10th Geant4 Tutorial, Nov. 2023 - Jeju Island, South Korea

Acknowledgments

Heartfelt thanks to EP-SFT,

in particular to the Geant4 Group,

with a special mention to Jonas and Mihaly,

even more to Dmitri,

and above all to Alberto