Validating Geant4 against calorimeters beam tests

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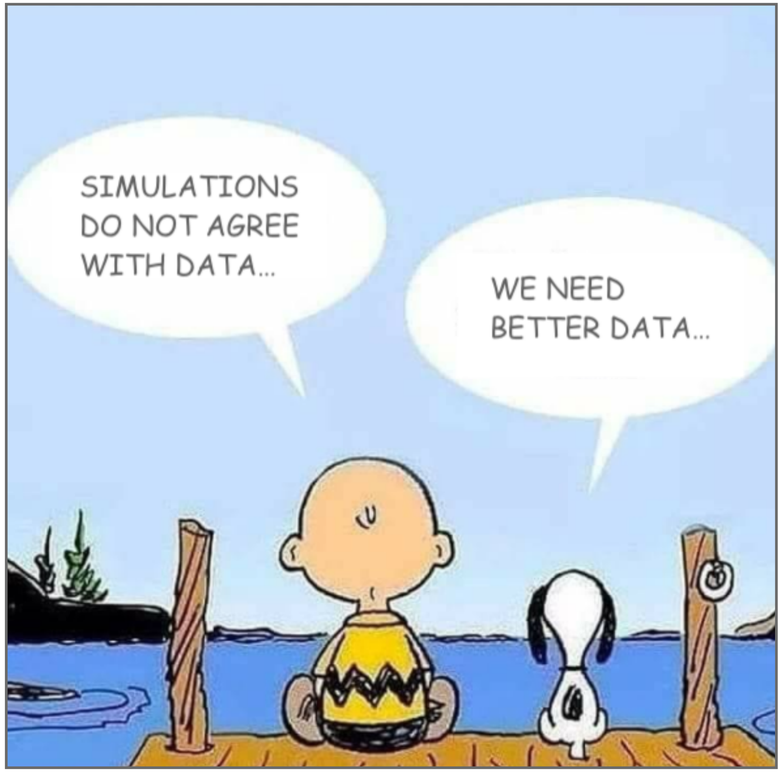
CERN

*on behalf on the **Geant4 Collaboration***
with inputs from ATLAS, CMS and
Dual-Readout Calorimetry Groups



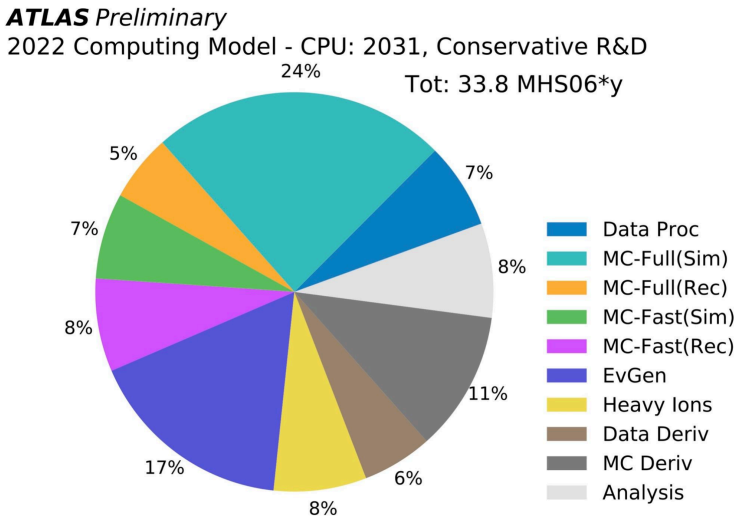
CALOR 2024 Tsukuba

20th International Conference on Calorimetry in Particle Physics

Tsukuba International Congress Center
19–24 May 2024

Geant4 support and development: LHC and Beyond

- Geant4 currently supports all the main LHC Experiments with their Run3 Monte Carlo productions
- Monte Carlo full-simulation is still the most CPU-intensive task in High-Energy Physics
- Geant4 will keep supporting LHC Experiments for the High-Luminosity operations
  - Therefore extensive software R&D is dedicated making Geant4 faster



ATLAS conservative Run4 projection of the computing breakdown

- At the same time, the predictive power of Geant4 is used more and more for detector design studies at Experiments targeting high precision physics like FCC-ee, ILC and EIC
  - A long-term effort to validate Geant4 physics models on calorimeter beam tests is ongoing, with the ultimate goal to improve our description of physics and comparing it with physics models from Monte Carlo codes like FLUKA.CERN

Geant4 development, in a nutshell

SW R&D

1. *Improve, optimize and modernize the existing Geant4 code to gain in performance for the detailed simulation*
2. *Trade precision for performance using fast simulation techniques both with parameterizations and with ML methods*
3. *Investigate the use of accelerators such as GPUs. See the Adept and Celeritas projects*

Physics Development/Validation

1. *Improve existing physics models and provide alternative ones*
2. *Continuous physics validation on experimental benchmarks with geant-val (e.g. calorimetry test-beams)*
3. *Create and test interfaces to use physics models from external Monte Carlo codes in any Geant4 simulation. E.g. the Geant4-to-FLUKA.CERN interface*

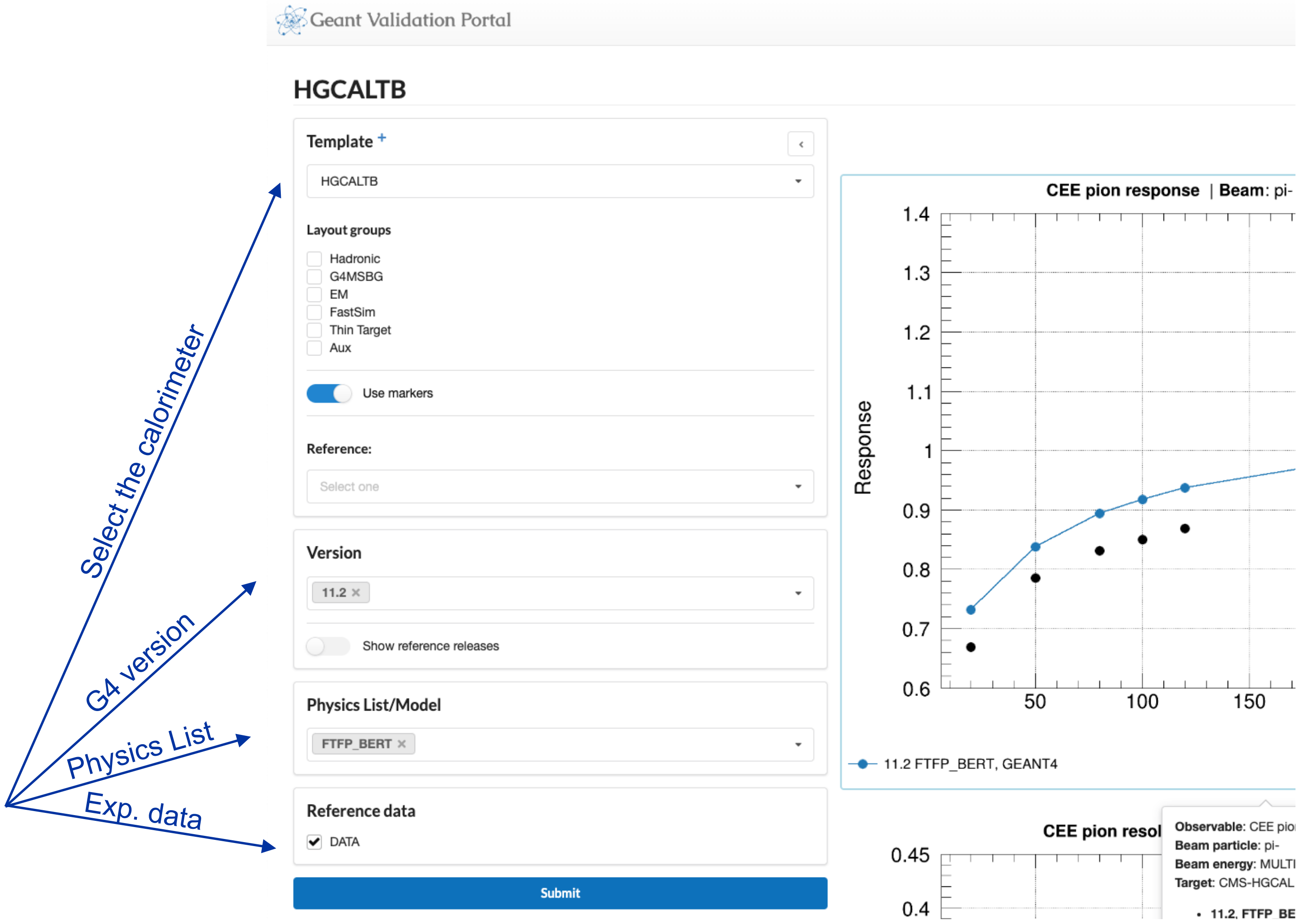
Discussed in this presentation

Geant-val - geant-val.cern.ch

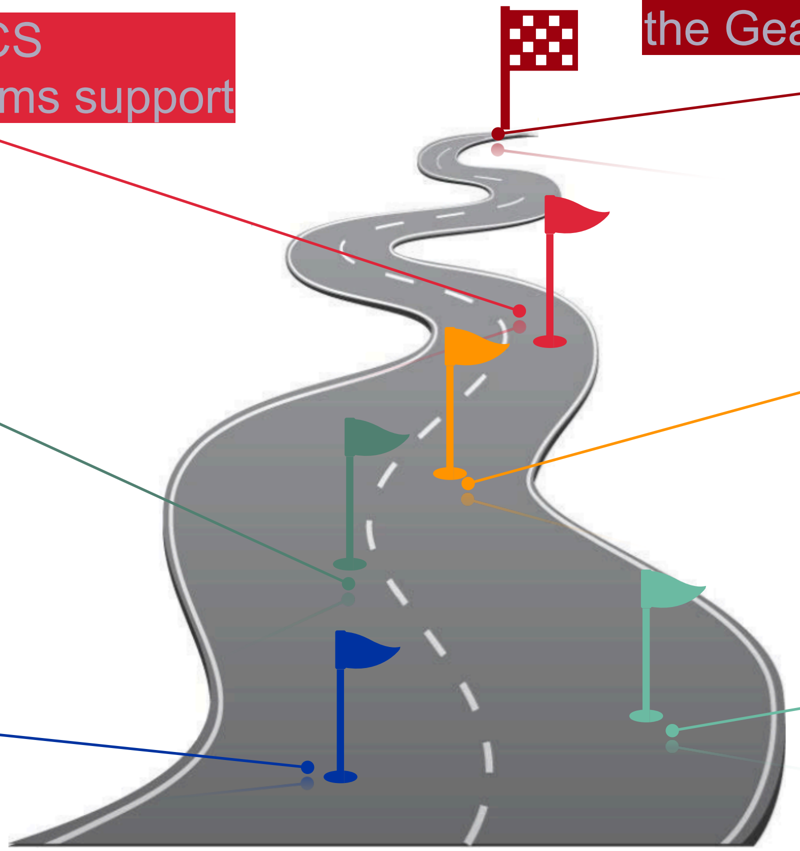
Geant-val is the Geant4 validation and testing suite

It contains ~40 Geant4 *tests* over several research fields (nuclear physics, HEP, biomedical, …).

- For the developers, it allows to:
  - Create multiple jobs over beam energies, particle types, physics lists, …, and automatically submit them on HTCondor(lxplus)
  - Encapsulate variables in json files to later perform the analysis
- For the HEP Community, it allows to:
  - Deploy results on a common database and fetch the information via a web interface

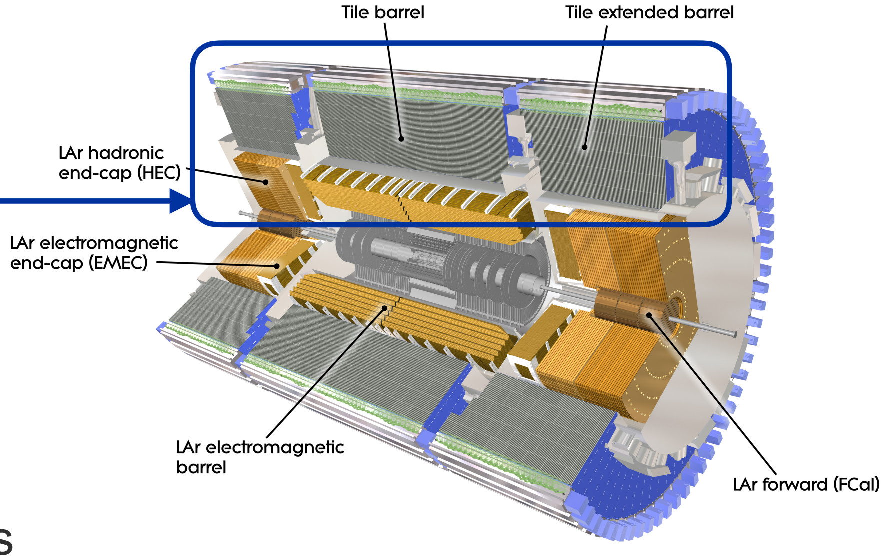


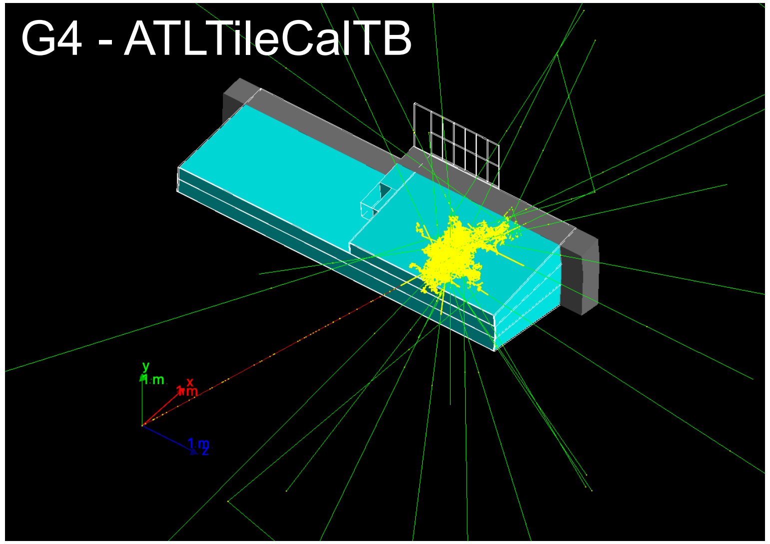
From experiments to geant-val, a winding road



ATLAS Tile Calorimeter beam test in Geant4

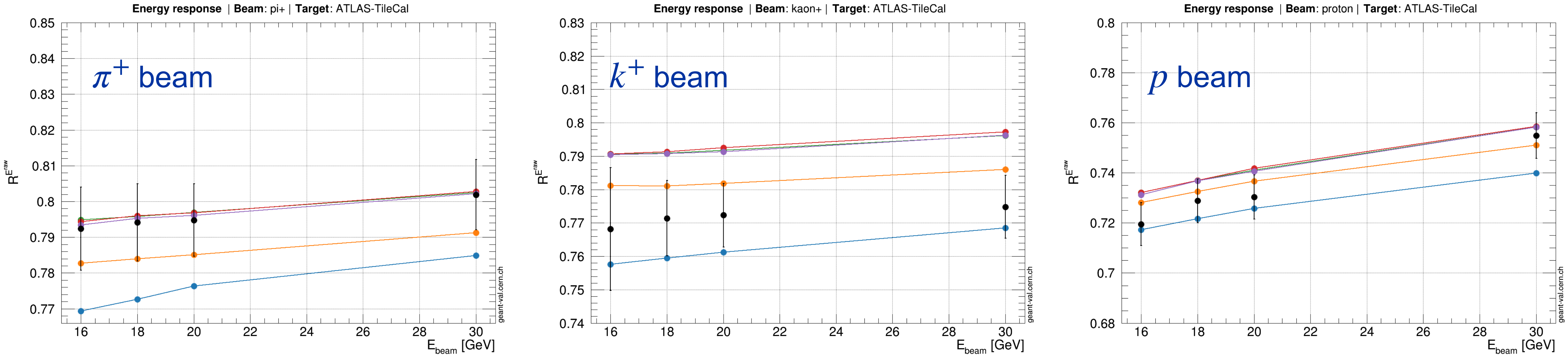
- ATLAS TileCal:
  - Mostly used to reconstruct hadronic jets in the range $|\eta| < 1.7$ thanks to 3 cylinders containing 64 modules each
  - Measure light in scintillating tiles immersed in iron
    Readout is grouped in pseudo-projective cells with each layer readout by two PMTs
  - Each barrel consists 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 Physics List of these effects



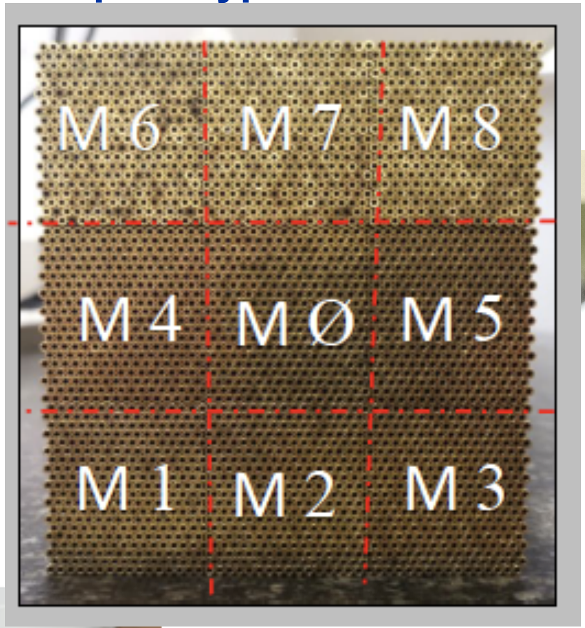
FTFP_BERT PL, regression testing 2017-2021

- 10.4.p03 FTFP_BERT, GEANT4
- 10.6.p03 FTFP_BERT, GEANT4
- 11.0.p02 FTFP_BERT, GEANT4
- 10.5.p01 FTFP_BERT, GEANT4
- 10.7.p03 FTFP_BERT, GEANT4
- ATLAS, experiment

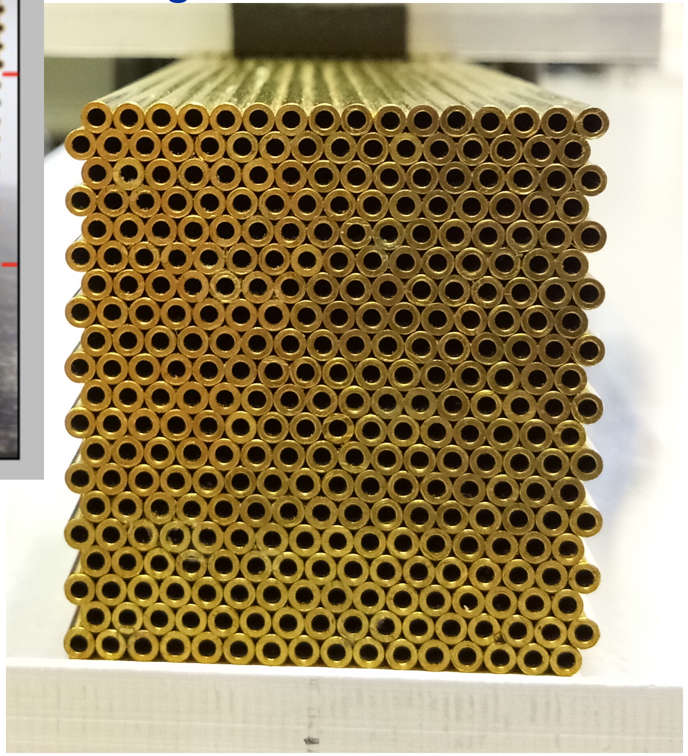
The Bucatini Dual-Readout Calorimeter in G4

- The latest capillary-tube-based dual-readout prototype features:
  - EM dimensions of $10 \times 10 \times 100$ cm^3, $\simeq 90\,\%$ 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.

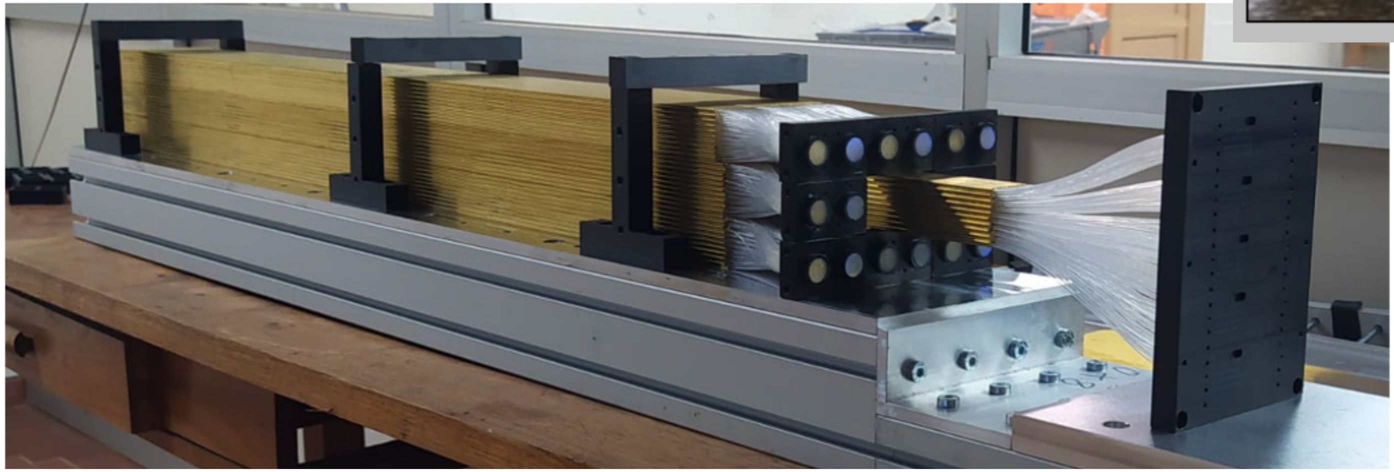
Full prototype - 9 towers



A single tower



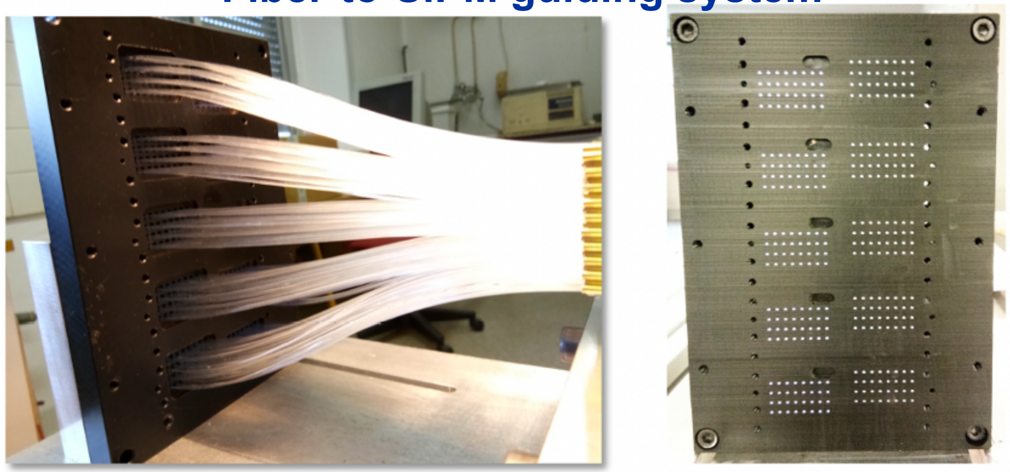
Prototype rear end

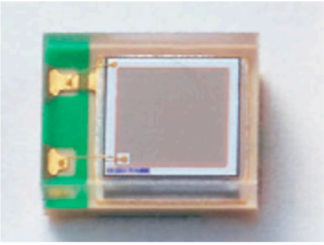


Towards superior Geant4 EM validation

- 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

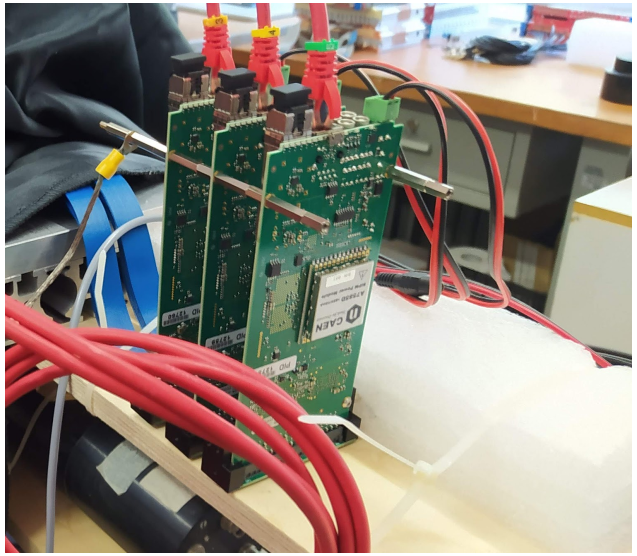
Fiber-to-SiPM guiding system





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

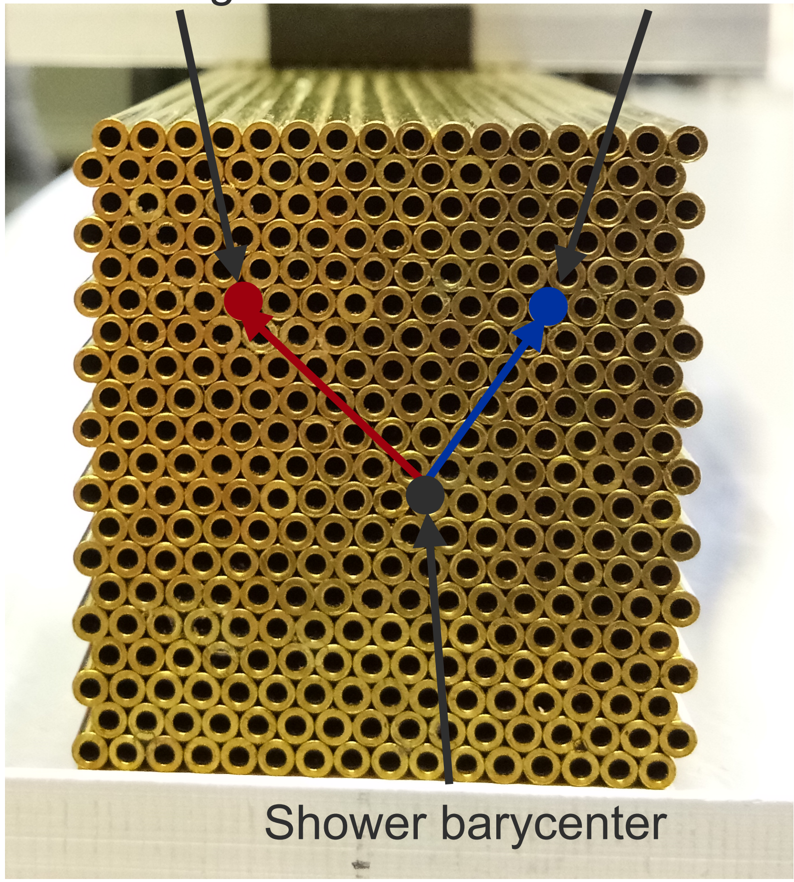
Front end board housing 64 SiPM



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

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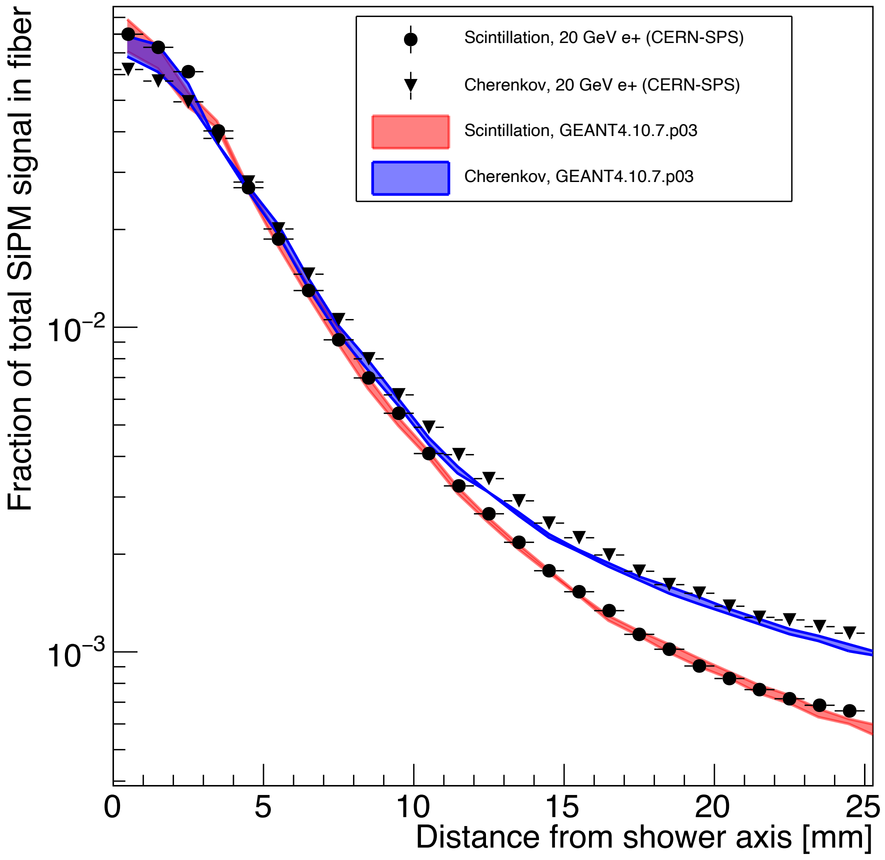
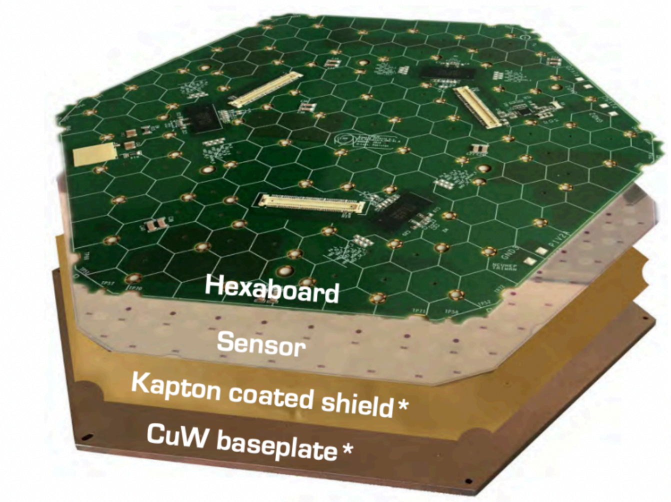
  - Summer 2021 and 2023
  - Using e^+ beams with energies 10-125 GeV
- Lateral profile measurement, *i.e.* measuring the average signal carried by a fiber located at a distance r from the shower barycenter
- Achieved millimetric sampling of EM showers:
  - The average signal drops by two orders of magnitude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

CERN SPS 20 GeV e^+ - GEANT4



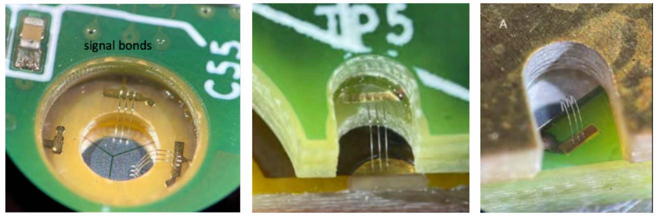
N. Ampilogov et al 2023 JINST 18 P09021

The CMS HGCAL beam test in Geant4



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

signal bonds shield bonds backside HV bonds



The 2018 SPS TB involved three calorimeters

- CEE: 28 layers of HGCAL Si pads with 132 ($\simeq$ 1.1 cm^2) hexagonal cells (26 X_0)

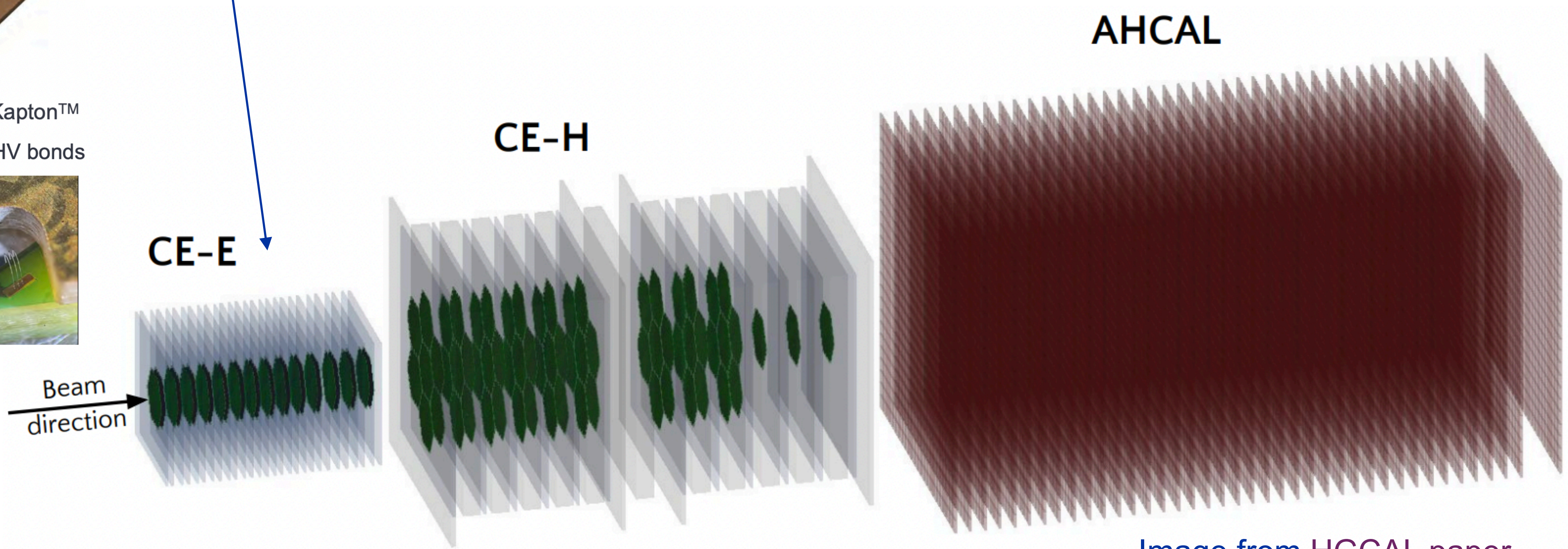
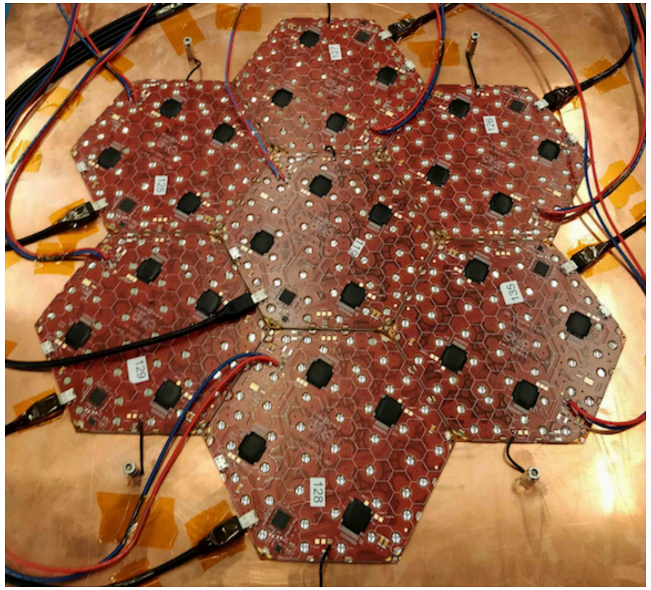


Image from HGCAL paper

The CMS HGCAL beam test in Geant4



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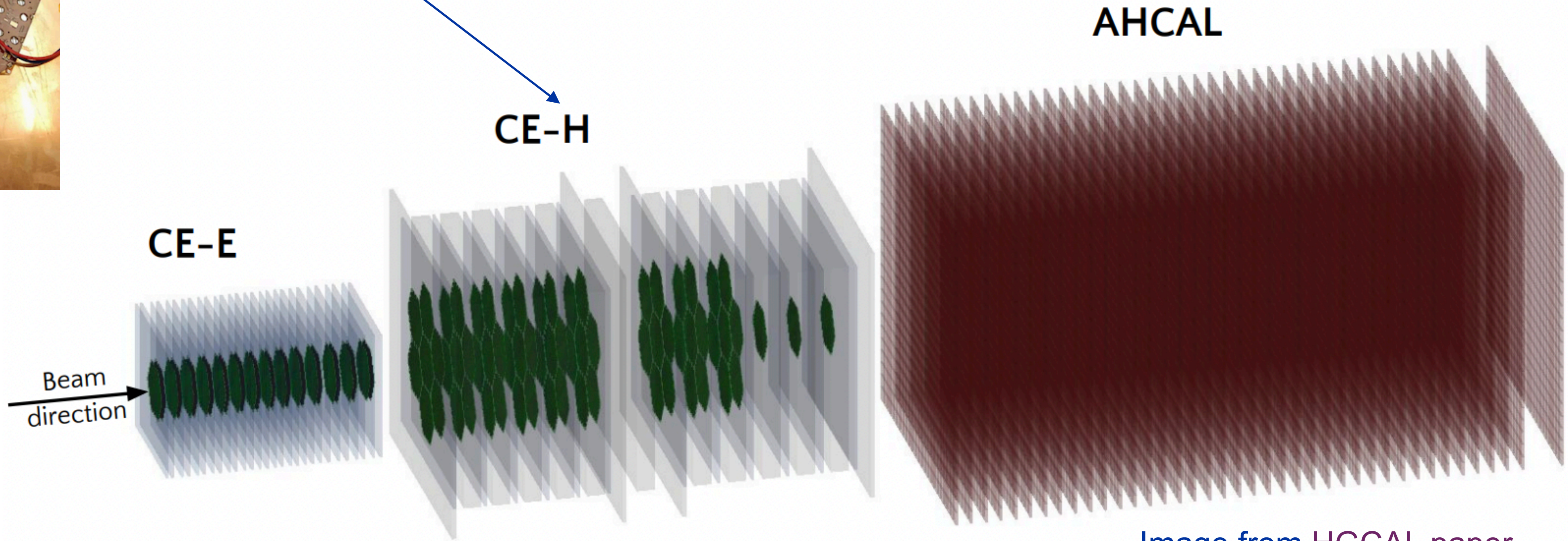
- CEE: 28 layers of HGCAL Si pads with 132 ($\simeq$ 1.1 cm²) hexagonal cells (26 X_0)
- CHE: 12 layers of HGCAL Si pads, first 9 use 7 sensors in a daisy-like structure (3.4 λ_{int})



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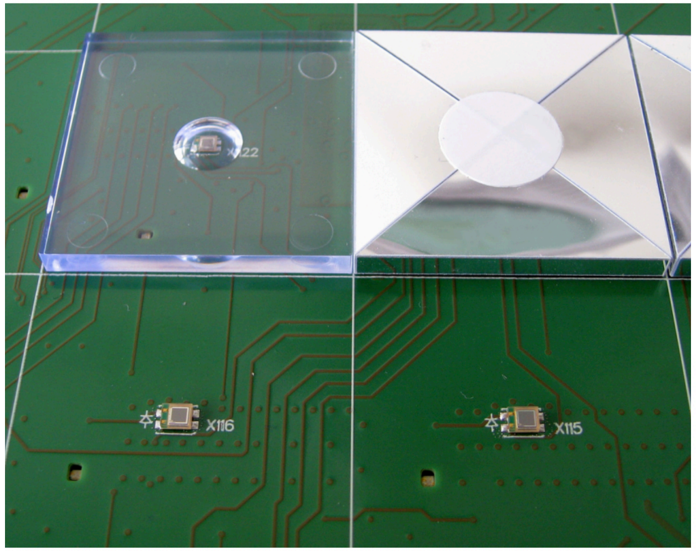

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- CHE: 12 layers of HGCAL Si pads, first 9 use 7 sensors in a daisy-like structure (3.4 λ_{int})
- AHCAL: 39 layers of 24×24 ($3 \times 3 \times 0.3$ cm^3) plastic tiles (4.4 λ_{int})

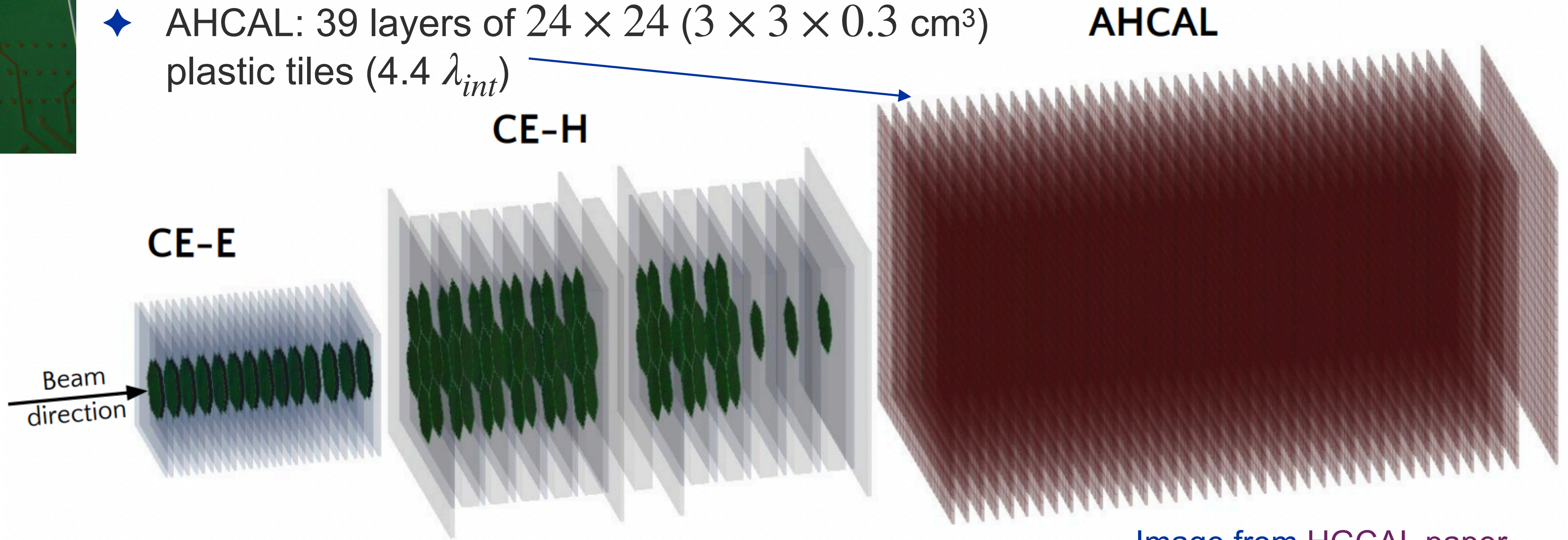
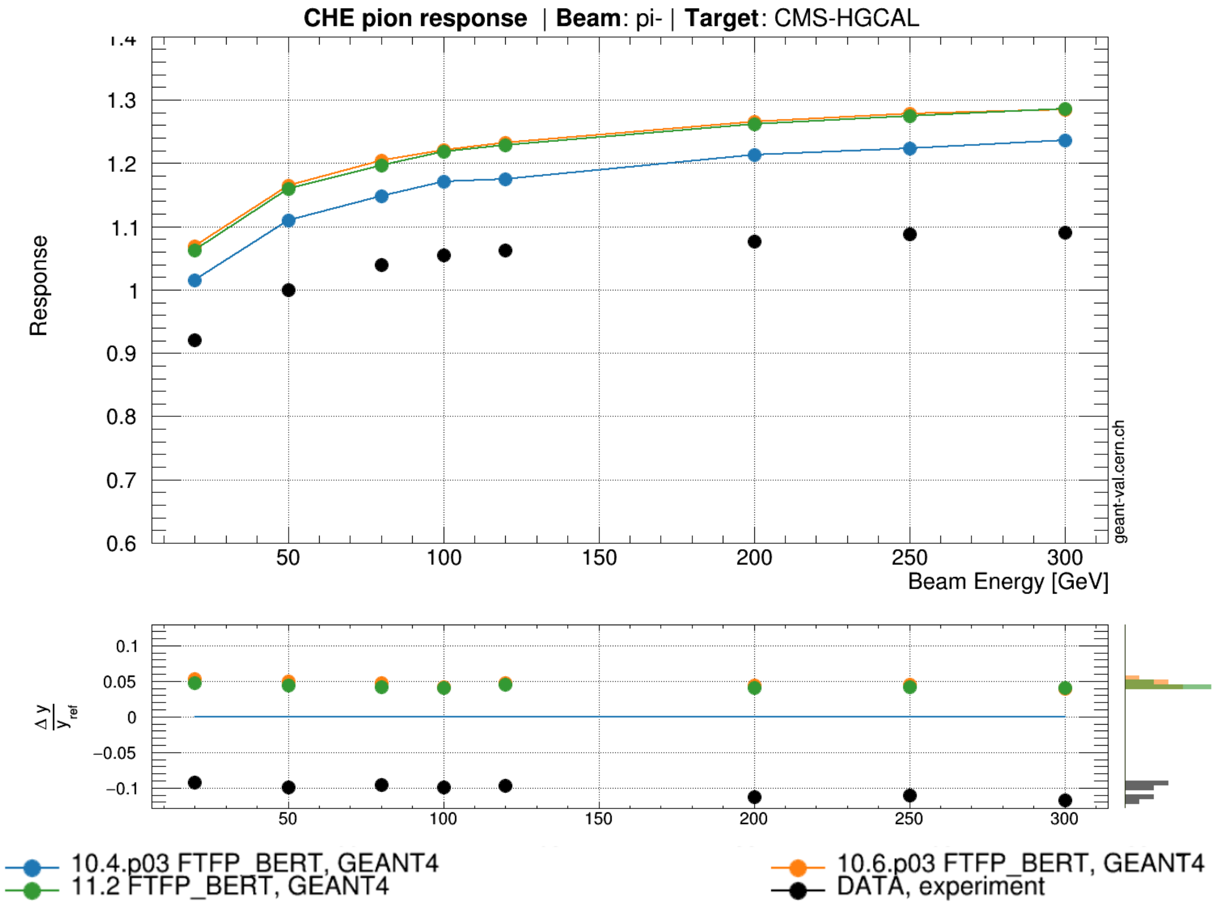


Image from HGCAL paper

CMS HGCAL: π^- response, regression testing

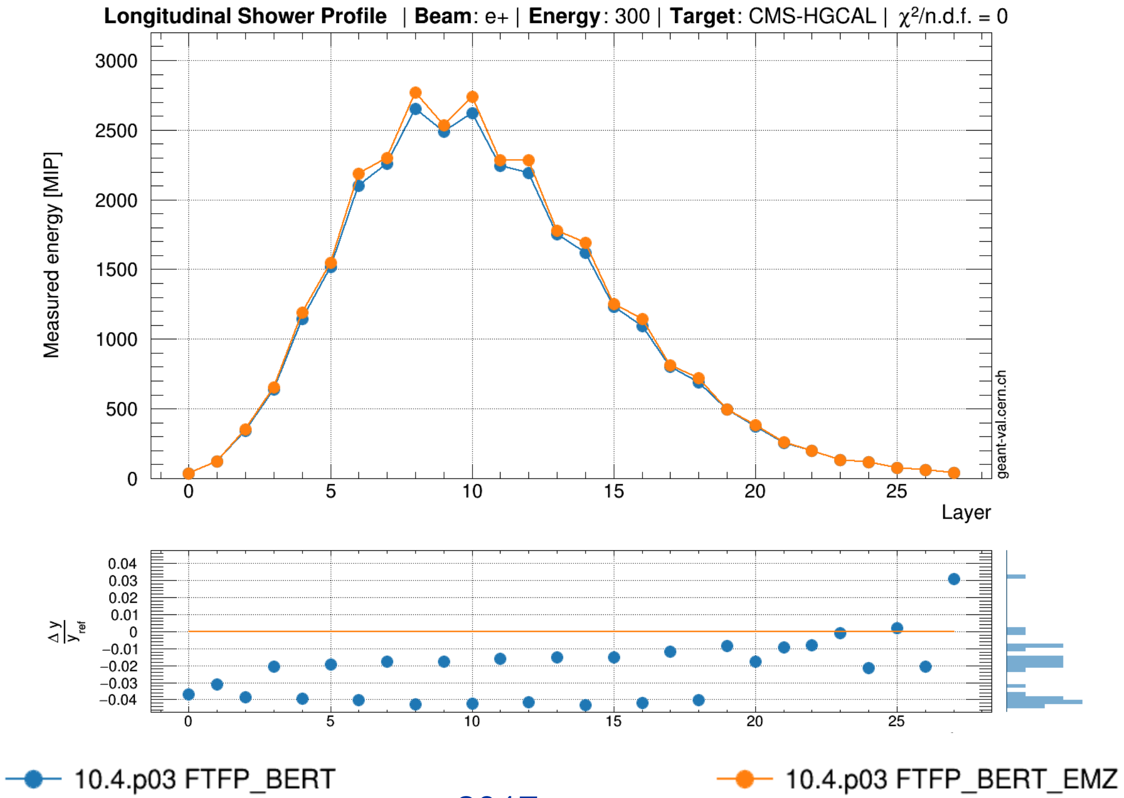
- Regression testing of the FTFP_BERT Physics List from 10.4 (2017) to 10.6 (2019) to 11.2 (2023) shows a response increase till 10.6 and stable results afterwards
  - Currently, Geant4 overestimates the hadronic response in the HGCAL up to ~15 % for π showering inside the hadronic section
  - Investigations with CMS are ongoing in order to tackle this problem



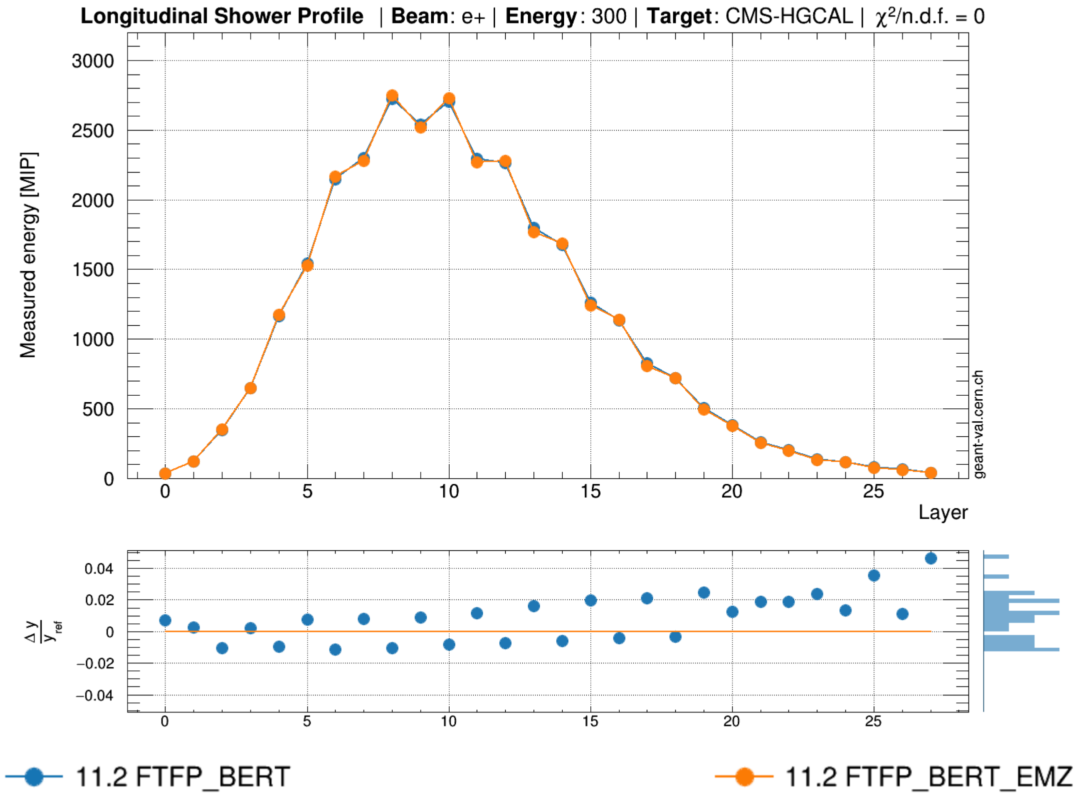
FTFP_BERT PL, regression testing 2017-2023

CMS HGCAL: electromagnetic shower profile

- 300 GeV e^+ longitudinal shower profile as studied in geant-val
  - Recent improvements in the FTFP_BERT electromagnetic components helped aligning its performance with the high-precision FTFP_BERT_EMZ option, resulting in a narrowing of differences between the two
  - If confirmed it would speed up the HGCAL simulation for em showers by a factor ~2!



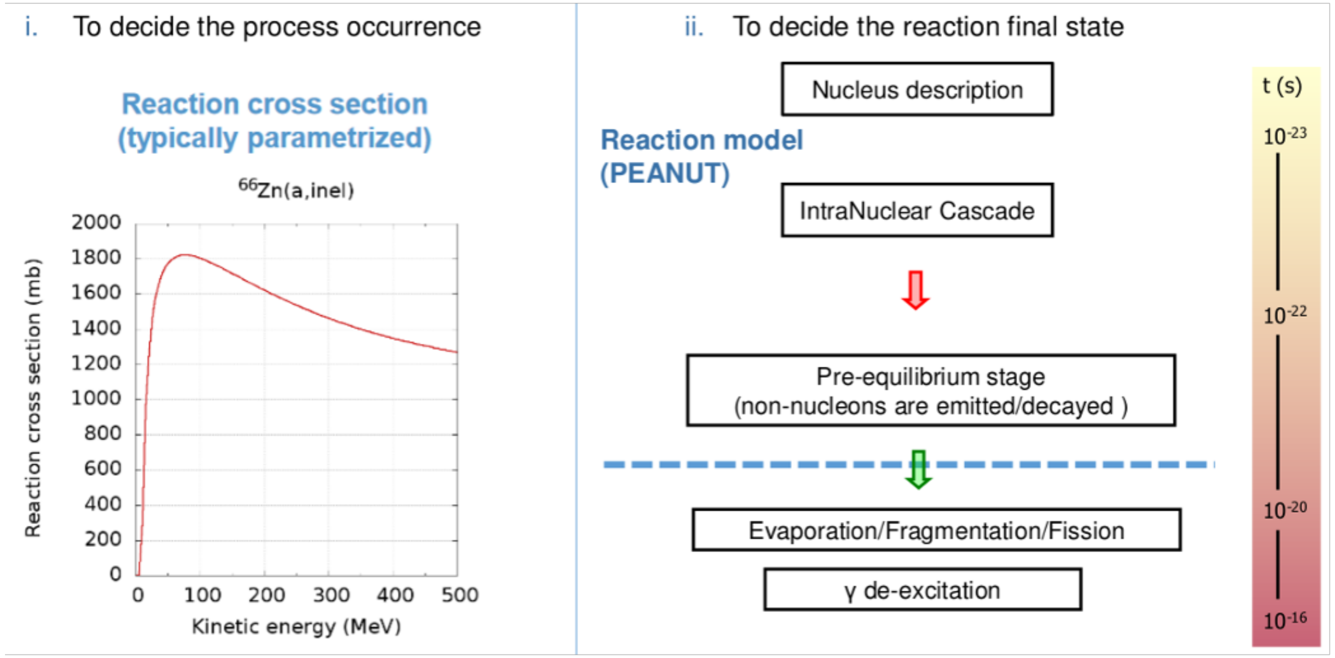
2017



2023

Geant4 interface to FLUKA.CERN

- Geant4 11.2 (December 2023) introduces a new Geant4 to FLUKA.CERN interface to exploit FLUKA.CERN hadron-nucleus interactions modeling in any Geant4 simulation
- It works for hadrons up to 20 TeV kinetic energy
(20-100 TeV: more accurate models with DPMJET are used and are not included at the moment)
- Support for photonuclear reactions is also included (leveraging the nuclear environment description)



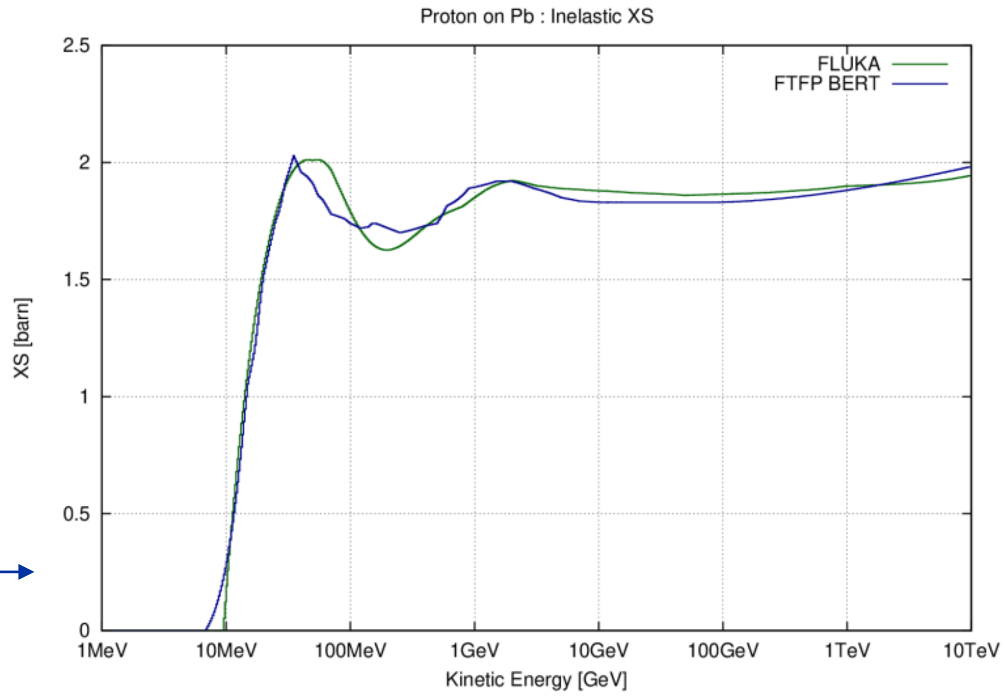
Both cross-section and
final states modeling
for the hadron-nucleus interactions
are handled
by the Geant4-to-FLUKA.CERN interface

Geant4 to FLUKA.CERN interface

- The interface contains
  - Standalone code isolating inelastic scattering cross-sections and hadron-nucleus interactions final states as computed by FLUKA.CERN
  - FLUKA.CERN wrappers and helper tools, together with utilities to interface FLUKA.CERN to the Geant4 environment (particle IDs, random numbers, …)

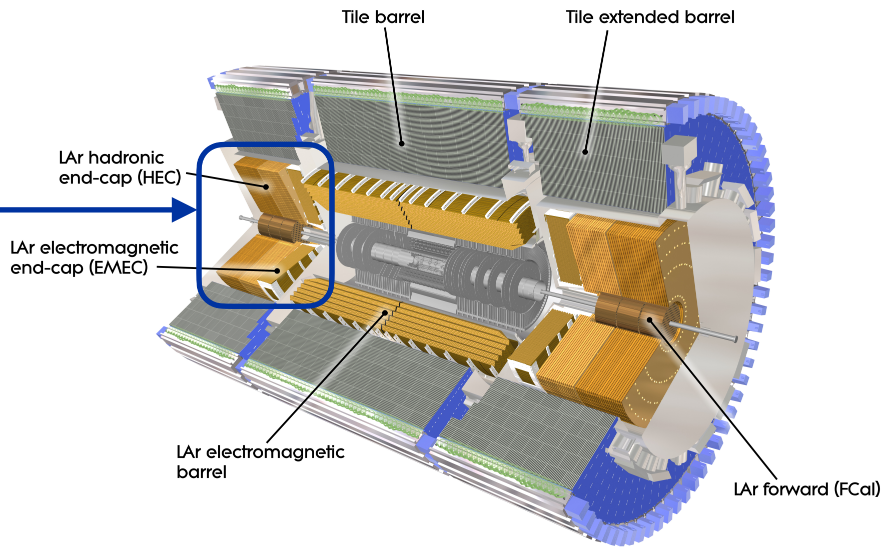
- All of it is available at `geant4-11.2/examples/extended/hadronic/FlukaCern/`
  - Two examples show how to access FLUKA.CERN hadronic processes
    - at single interaction level →
    - at a physics list level

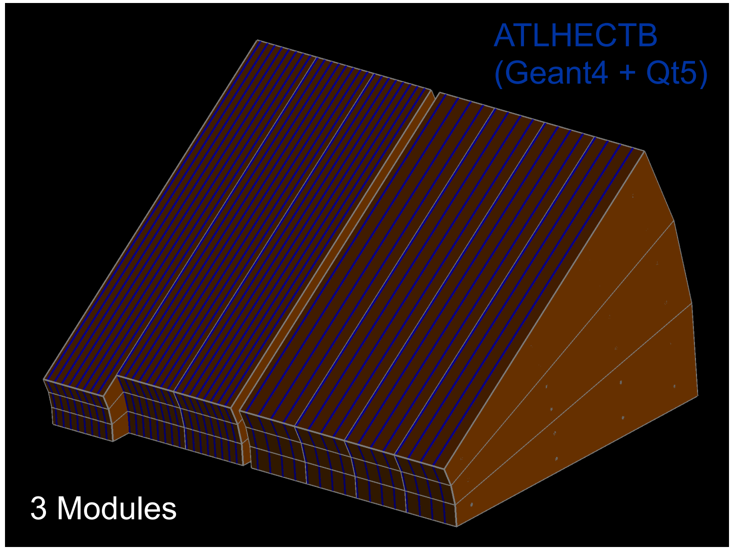
p on lead inelastic scattering cross-section comparison for Geant4 and FLUKA.CERN



ATLAS Hadronic End-Cap Calo beam test in G4

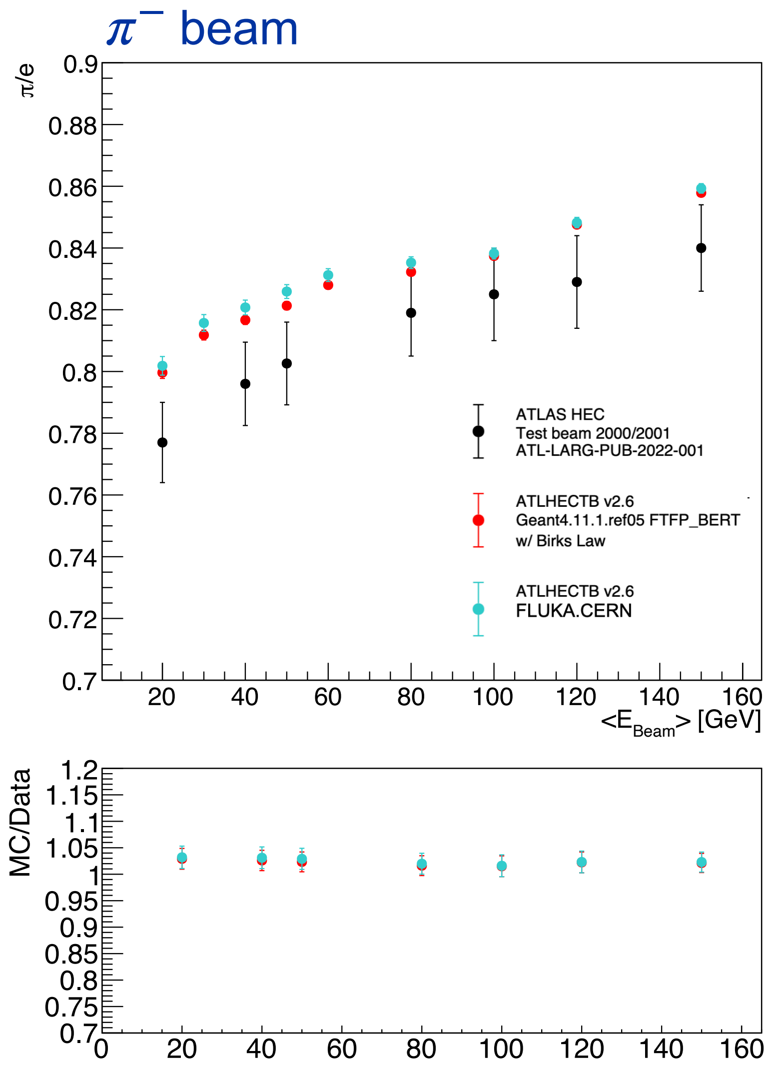
- The ATLAS HEC:
  - Covers the range $1.5 < |\eta| < 3.2$. Divided into two wheels (HEC1-2) each consisting of 32 azimuthal modules
  - It uses 8.5-mm-gap LAr sampling regions inserted between paralle copper plates, with 2.5 cm (HEC1) and 5.0 cm (HEC2) thickness
  - It has four longitudinal layers with a thickness of $\simeq 103X_0$ or $\simeq 9.7\lambda_{int}$
- HEC beam test [CDS Pubnote]:
  - Tested in 2000-2001 at CERN-SPS-H6 beam line
  - Tests performed with 3 $\phi-$wedges
  - Involving e^-, μ^- and hadrons with $6 \leq E_{Beam} \leq 200$ GeV





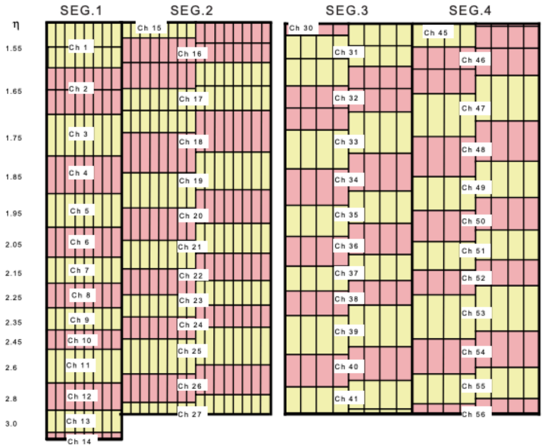
ATLAS HEC response (G4 vs FLUKA.CERN)

- 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
  - Overall very good agreement between Geant4 (11.1) and FLUKA.CERN (4-3.3) in describing ATLAS calorimeters response



ATLAS HEC hadronic shower shape (G4 vs FLUKA.CERN)

- The ATLAS HEC is made of 4 longitudinal layers
- It is possible to measure the energy profile as the energy fraction deposited in each layer:
  $F_i = < E_i > / E_{sum}, E_{sum} = \Sigma < E_i >$
- and the F_i dependence over E_{Beam}

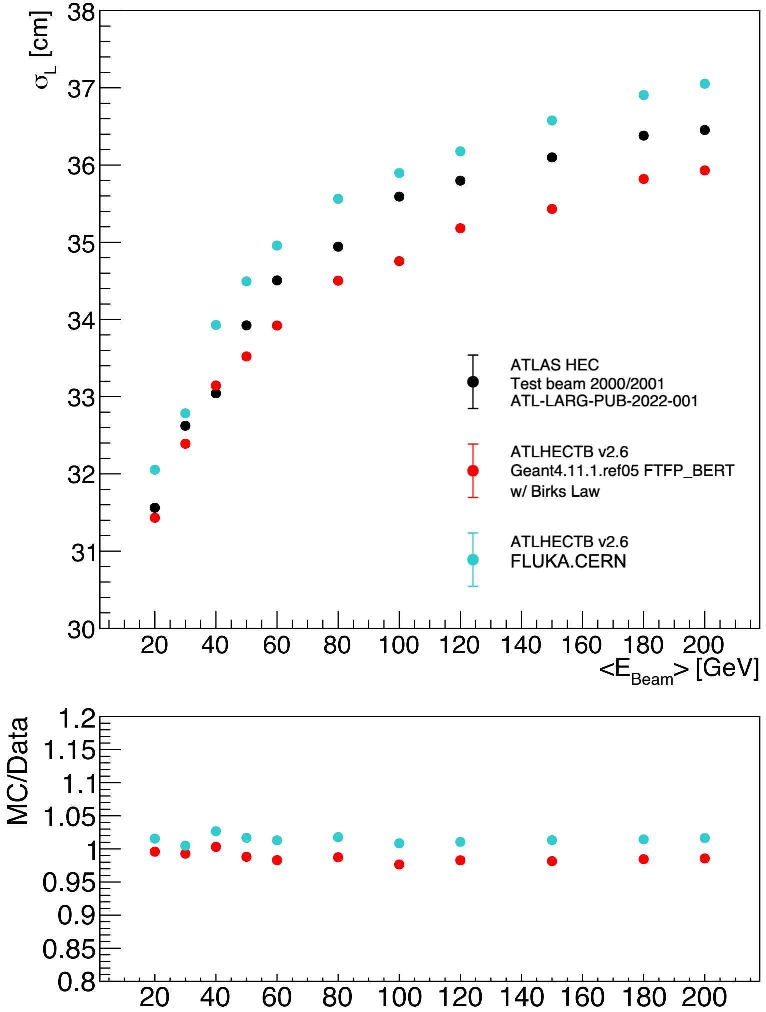


HEC
longitudinal structure

HEC layer	Number of LAr gaps	HEC length [cm]	HEC length $[\lambda_{int}]$
1	8	28.05	1.45
2	16	53.60	2.75
3	8	53.35	2.87
4	8	46.80	2.66

- Average shower length:
  - Extracted as the RMS (σ_L) of the energy profile
- FLUKA overestimates the shower length up to $2\,\%$ while Geant4 underestimates it up to $2\,\%$

π^- - shower length



Take home message

- GEANT4 needs experiments and experiments need Geant4
- The Geant4 Collaboration is carrying on a long term validation effort to bring beam tests simulations into geant-val
  - It will progress in parallel with and drive the Geant4 development till the next big collider
- Geant-val is an open project → *anyone is invited to contribute*
- We are more and more opening up to external physics engines, e.g. the new collaboration with the FLUKA.CERN Team
  - We need to understand the difference of physics engines with realistic simulations

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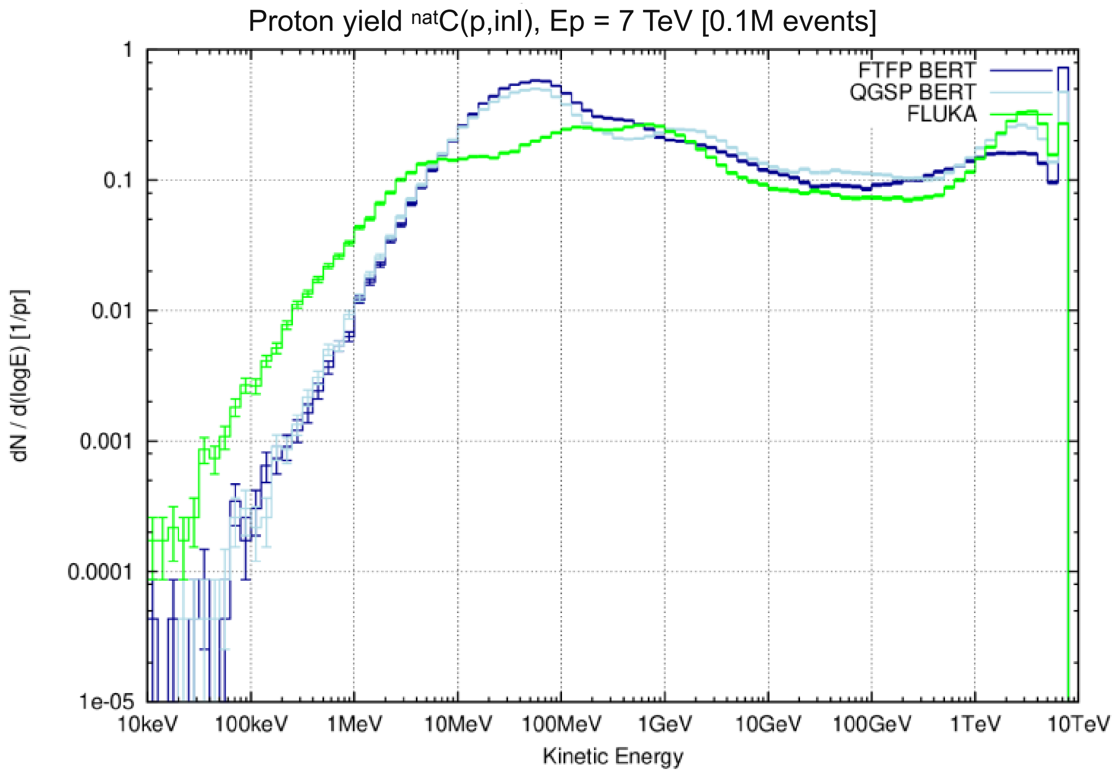
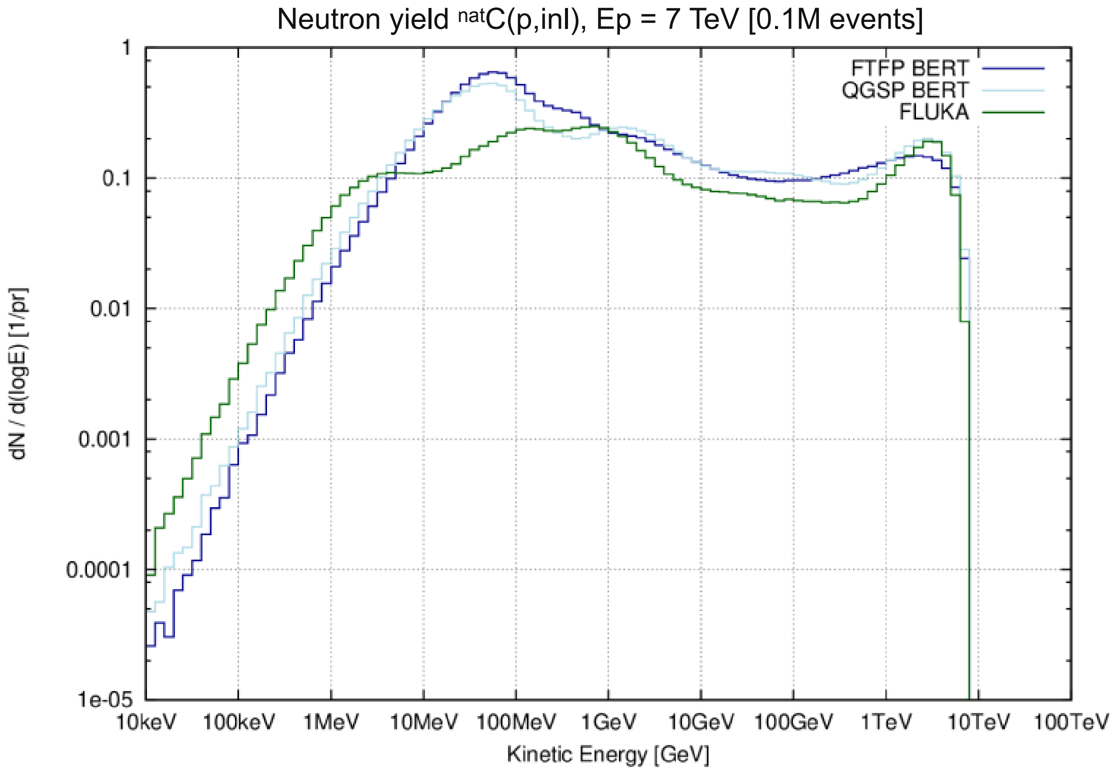
geant-val: Dmitri.Konstantinov@cern.ch
FLUKA.CERN interface: gabrielle.hugo@cern.ch

Backup material

Final state modeling: Geant4 vs. FLUKA.CERN

7 TeV p on carbon inelastic scattering:
proton and neutron yields





Final state modeling: Geant4 vs. FLUKA.CERN

7 TeV p on carbon inelastic scattering:
Deuteron/Tritons and He3/Alpha yields