Geant4, geant-val & DRD6

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on behalf of the Geant4 Group at CERN

DRD6 Collaboration Meeting @CERN

9-11/4/2024

Geant4, in a nutshell

- Geant4 is the mainly used toolkit for calorimetry simulation in HEP
  - For instance: at CALOR2022 every simulation result relied on detailed Geant4-based simulations (with only one exception for a space science application)
  - Geant4 is currently supporting all the big LHC Experiments in their Run3 productions and FCC for its detectors design
  - The main LHC experiments currently use the Geant4-recommended Physics List **FTFP_BERT**, eventually with mild variants (e.g. ATLAS adopts **FTFP_BERT_ATL**)
- Generating particles showers in calorimeters is still the most challenging simulation task:
  - Several hadronic physics models are adopted within a single Physics List with often overlapping ranges of applicability
  - Still the most computationally heavy tasks in HEP
- DRD6 is the most natural DRD Collaboration for a tight collaboration with the Geant4 Team @CERN

Geant4, in a nutshell

- Geant4 development is divided in two macro areas: SW R&D and Physics Development/Validation

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*

Physics Development/Validation

1. *Improve existing physics models and provide alternative ones (Geant4 has multiple models for the same physics process)*
2. *Continuous physics validation on experimental benchmarks with geant-val (e.g. calorimetry test-beams)*
3. *Support users choices on physics modeling and speed up solutions*

- We believe DRD6 will play a crucial role for Geant4 physics validation by creating new benchmarks and setting new requirements

Geant4 validation over calorimeter beam tests

- Often Experiments publish test-beam results and comparison with old Geant4 releases
  - Their benchmarks are not systematically tested over the years/sw-releases
  - This makes their findings hardly useful for Geant4 physics modeling development

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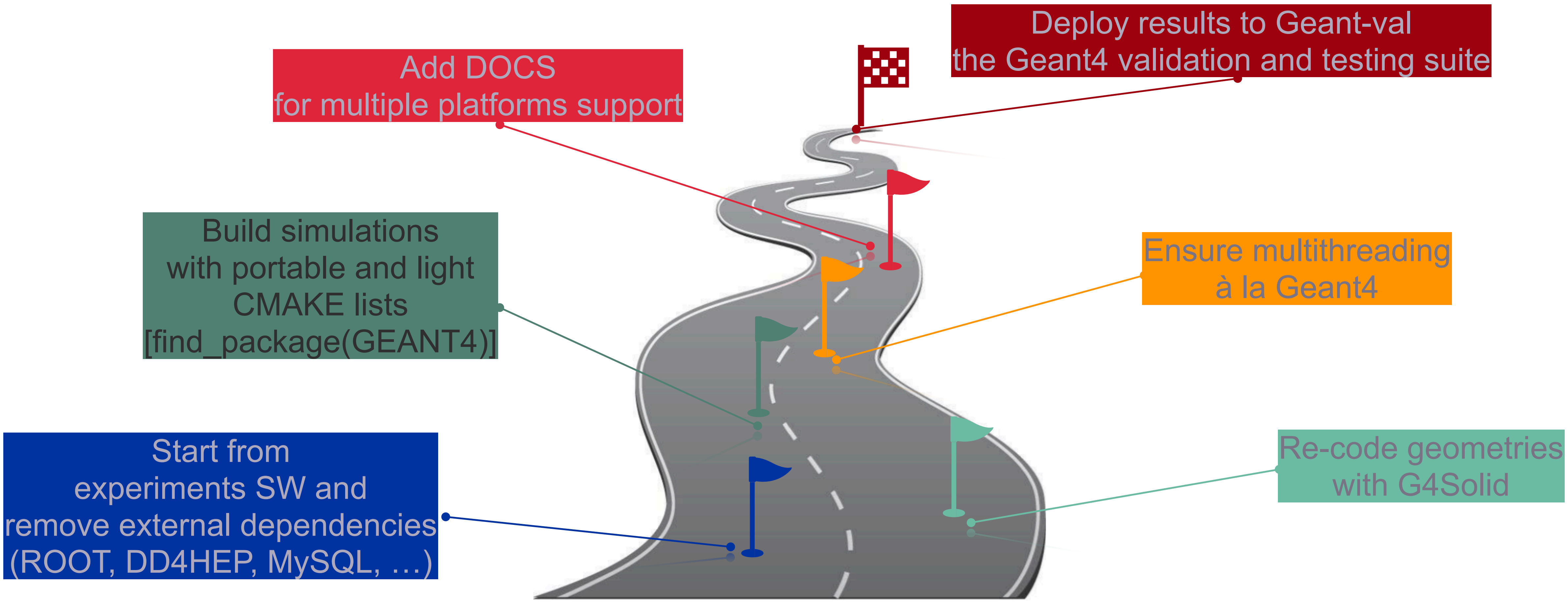
- Porting test-beam simulations from experiments framework to geant-val allows us to:
  - Study real calorimetric cases within a Geant4-only environment
  - Test new Geant4 releases over real experimental data before the release is exposed to the public
  - Ensure systematic regression testing and Physics Lists' comparison according to our needs
  - Validate internal changes in the Geant4 physics models as soon as needed
  - Ensure code and data preservation over long time scales

From experiments to geant-val, a winding road

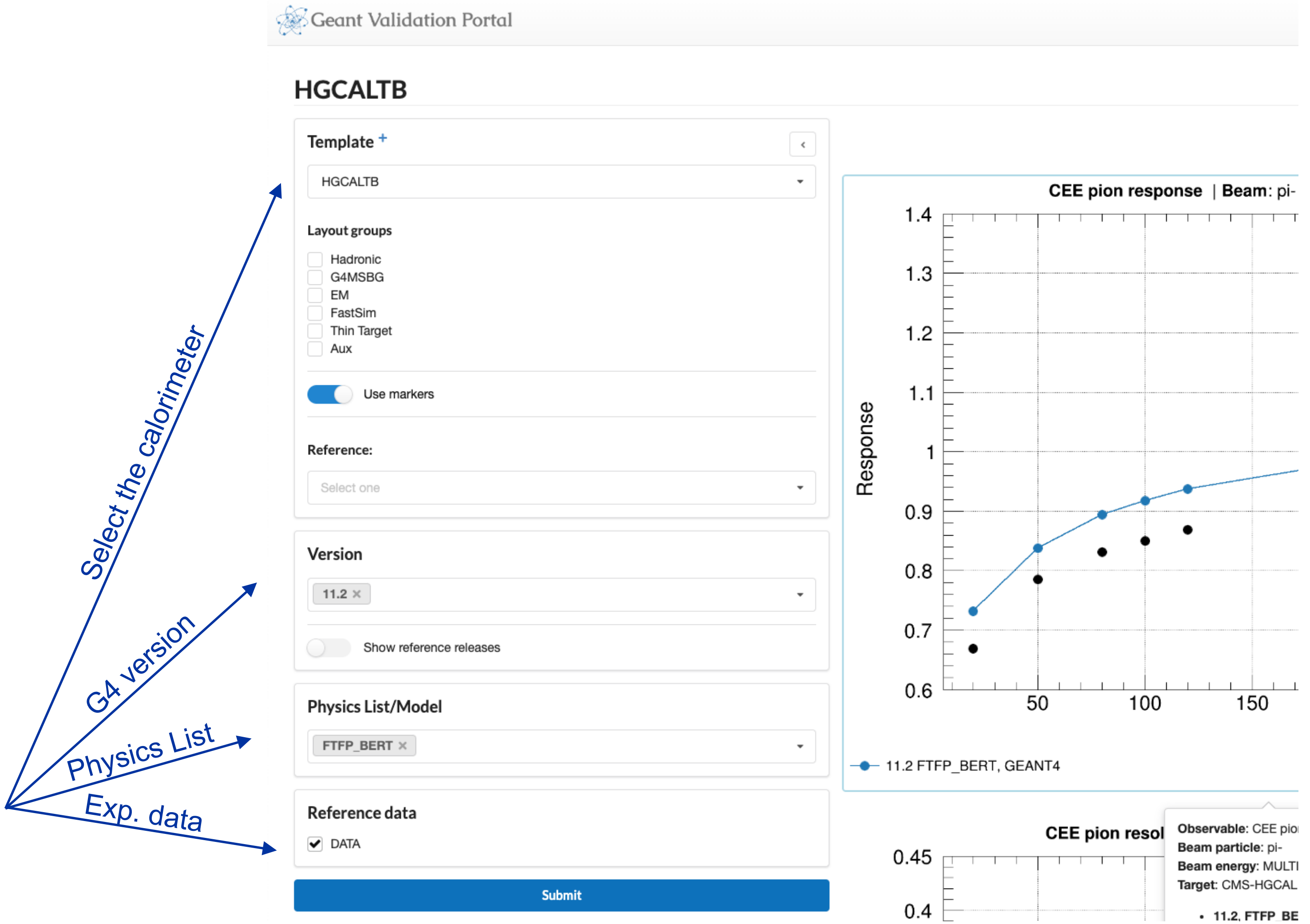


Geant-val - geant-val.cern.ch

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 data-base and fetch the information via a web interface

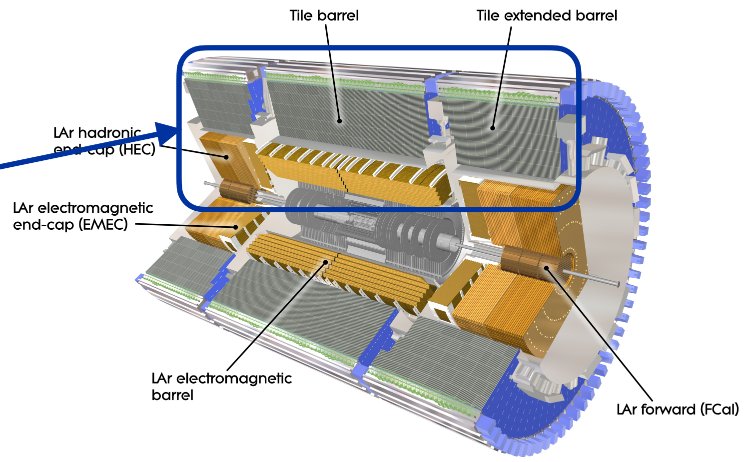


The past

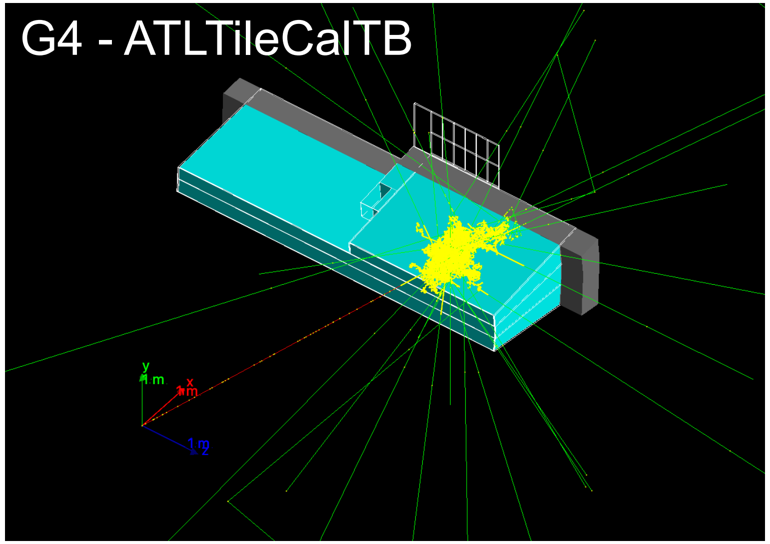
Examples from calorimeters taking data as we speak

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

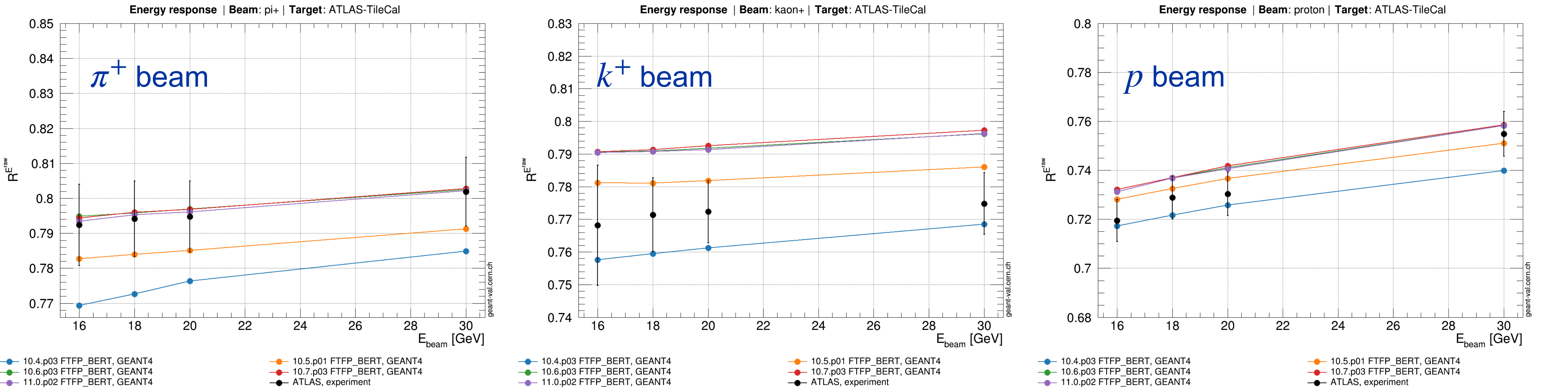


- TileCal beam test:
  - 2 Long Barrel Modules and 1 Extended Barrel module are regularly exposed to the SPS particle beams
  - The 2017 beam test studied the calorimeter response and resolution for π^+, p and k^+ in the energy range 16-30 GeV
  - Cherenkov auxiliaries used to tag π^+, p and k^+



Hadronic response - π^+, k^+, p

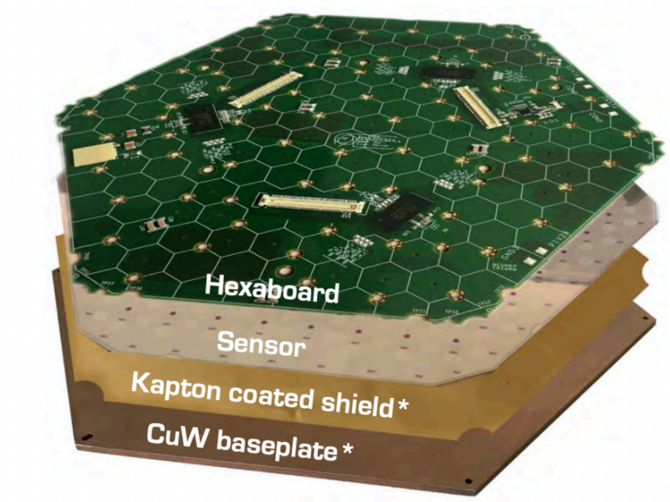
- It was possible to disentangle contributions from π^+, k^+ and p in the ATLAS TileCal:
  - Visible difference in the response to p and π^+: it is due to the baryon number conservation law for which high f_{em} processes (*e.g.* $\pi^+ + n \rightarrow \pi^0 + p$) are prohibited for p-induced events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



The present

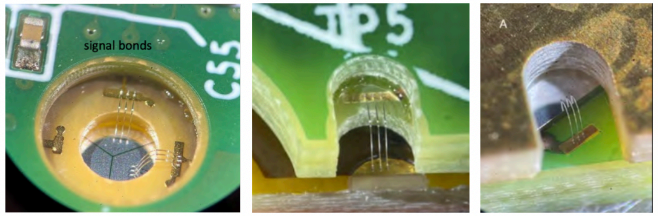
Examples from calorimeters to be installed at the LHC High-Luminosity Upgrade

The 2018 HGCAL test beam



* 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)

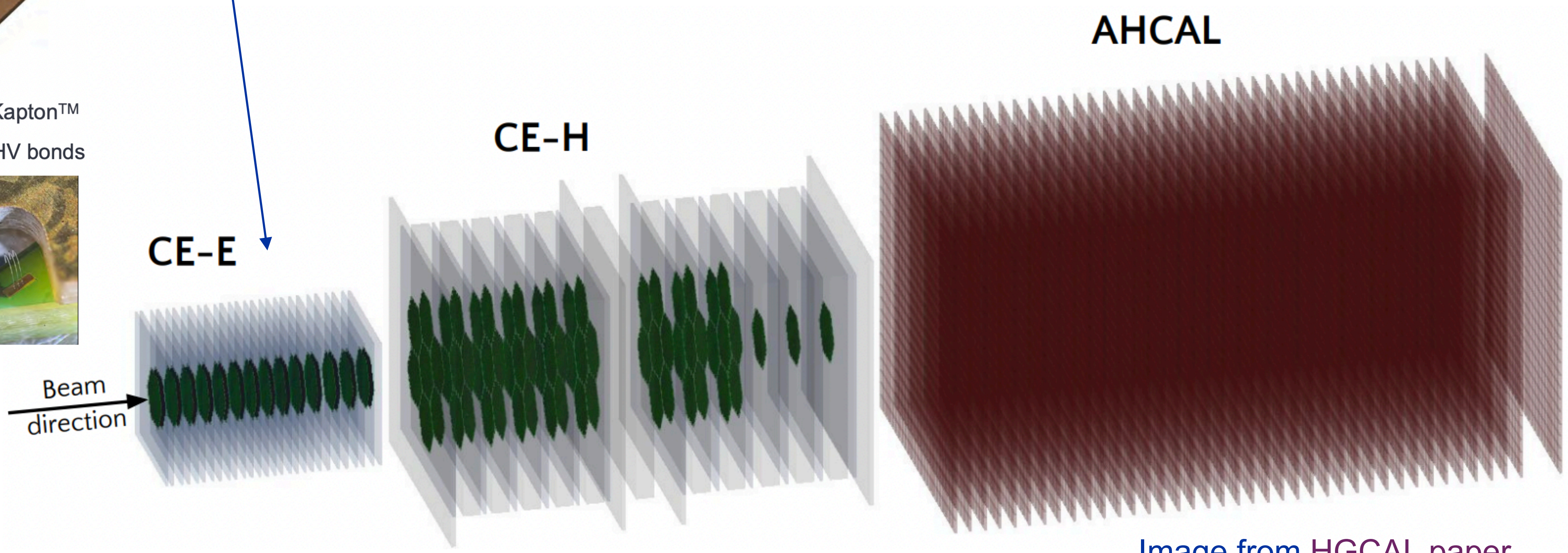


Image from HGCAL paper

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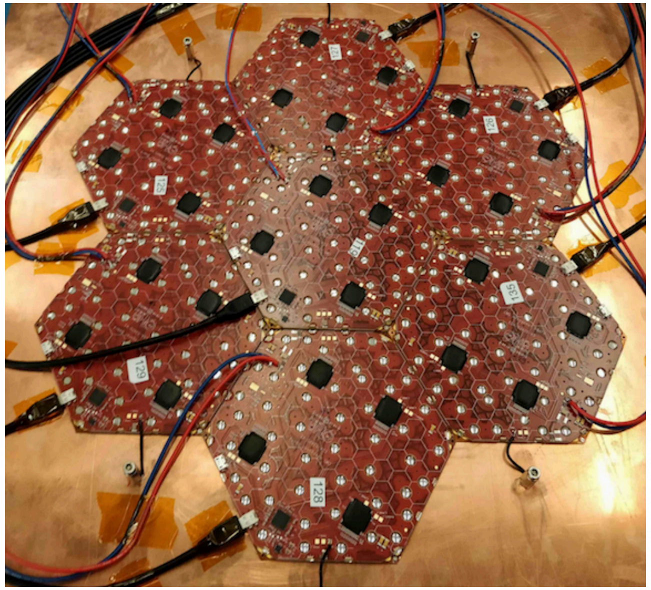
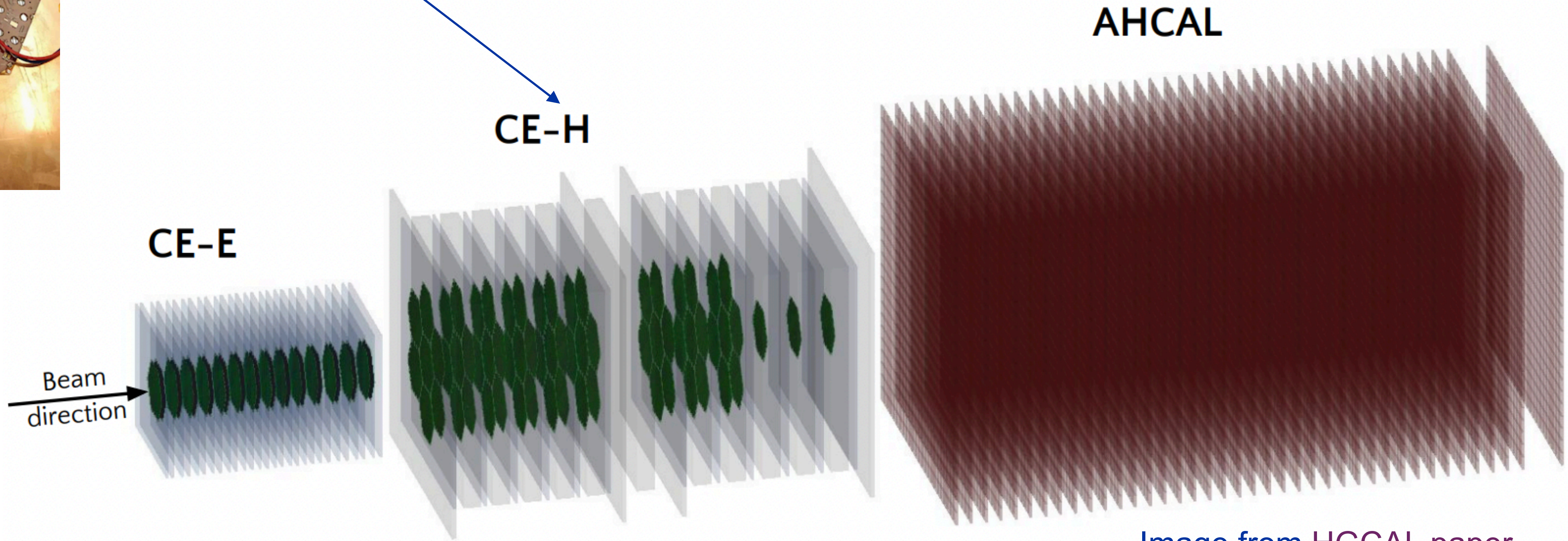


Three calorimeters involved:

- CEE: 28 layers of HGCAL Si pads with 128 ($\simeq$ 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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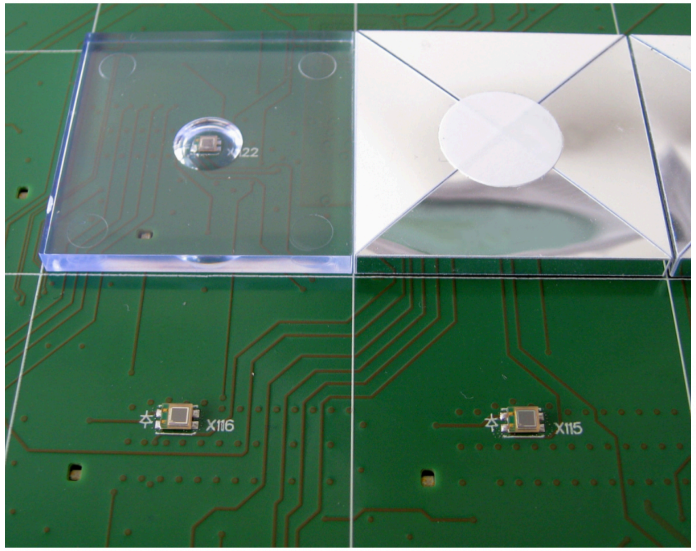

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- CHE: 12 layers of HGCAL Si pads, first 9 use 7 sensors in a daisy-like structure (3.4 λ_{int})
- AHCAL: 39 layers of 24×24 (3×3 cm²) plastic tiles (4.4 λ_{int})

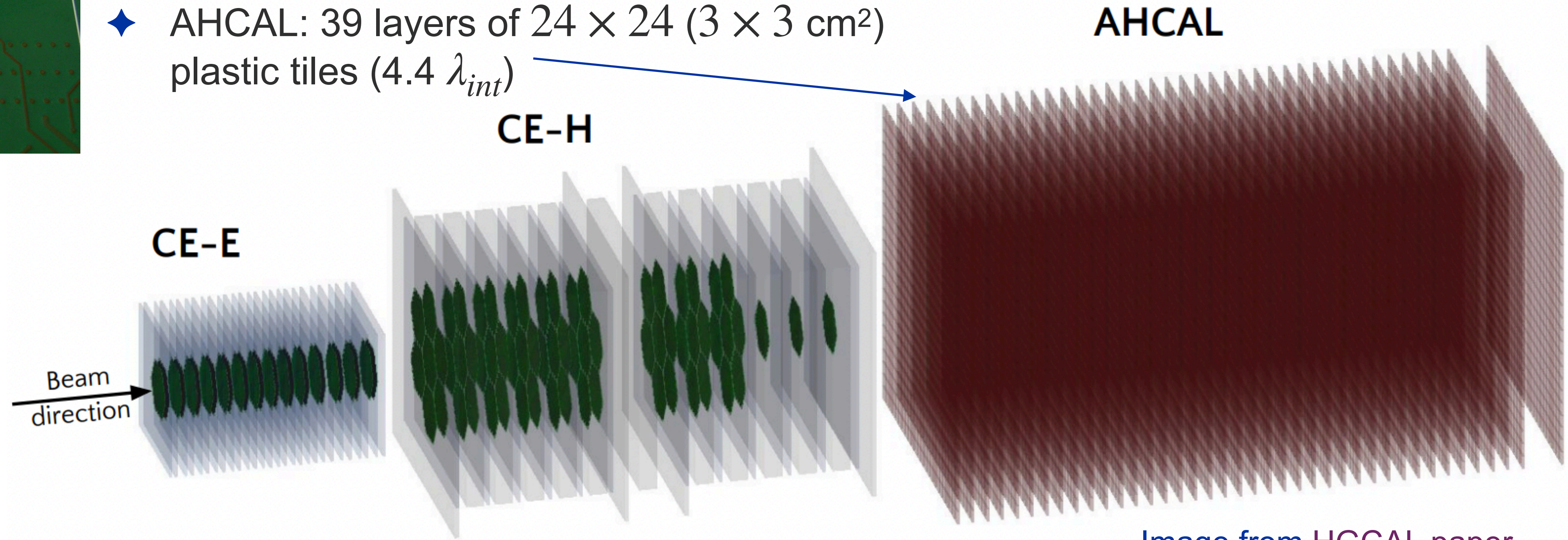
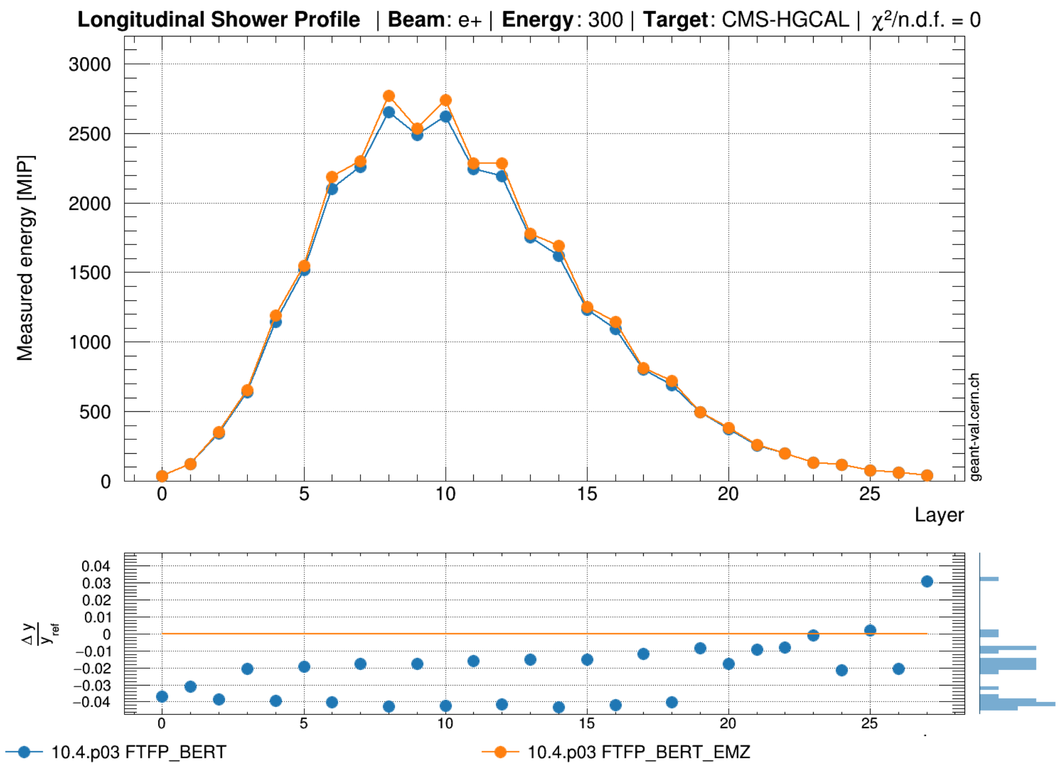
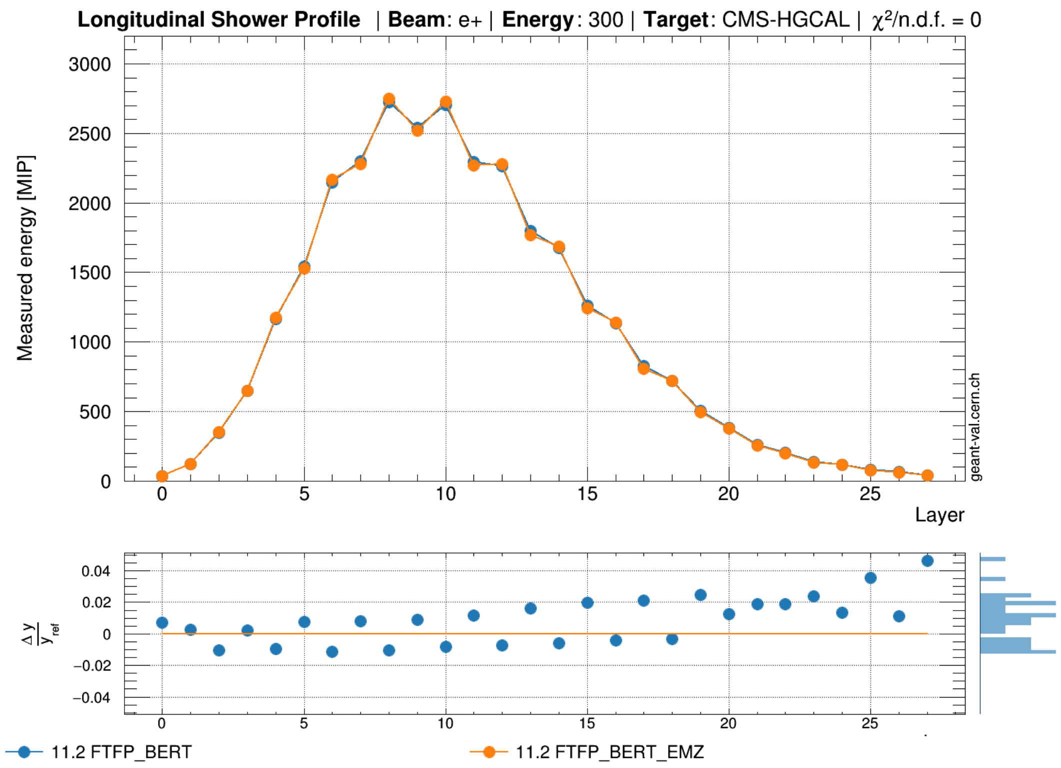


Image from HGCAL paper

HGCAL: electromagnetic shower profile

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





The future

Examples from calorimeters prototypes for future e^+e^- colliders

CALICE SiW Calorimeter within G4

- 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

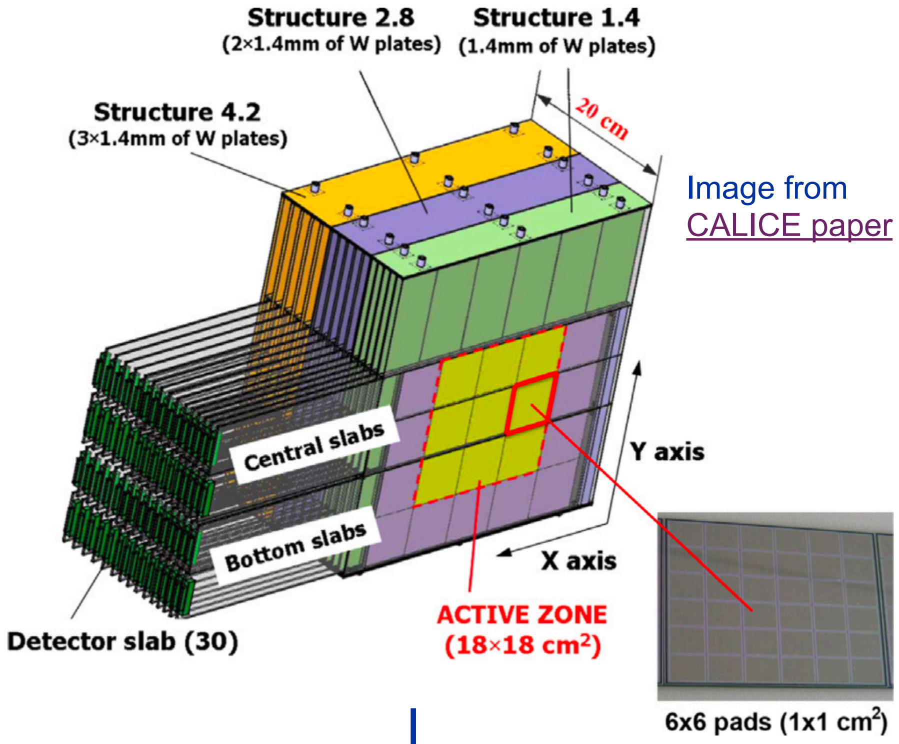
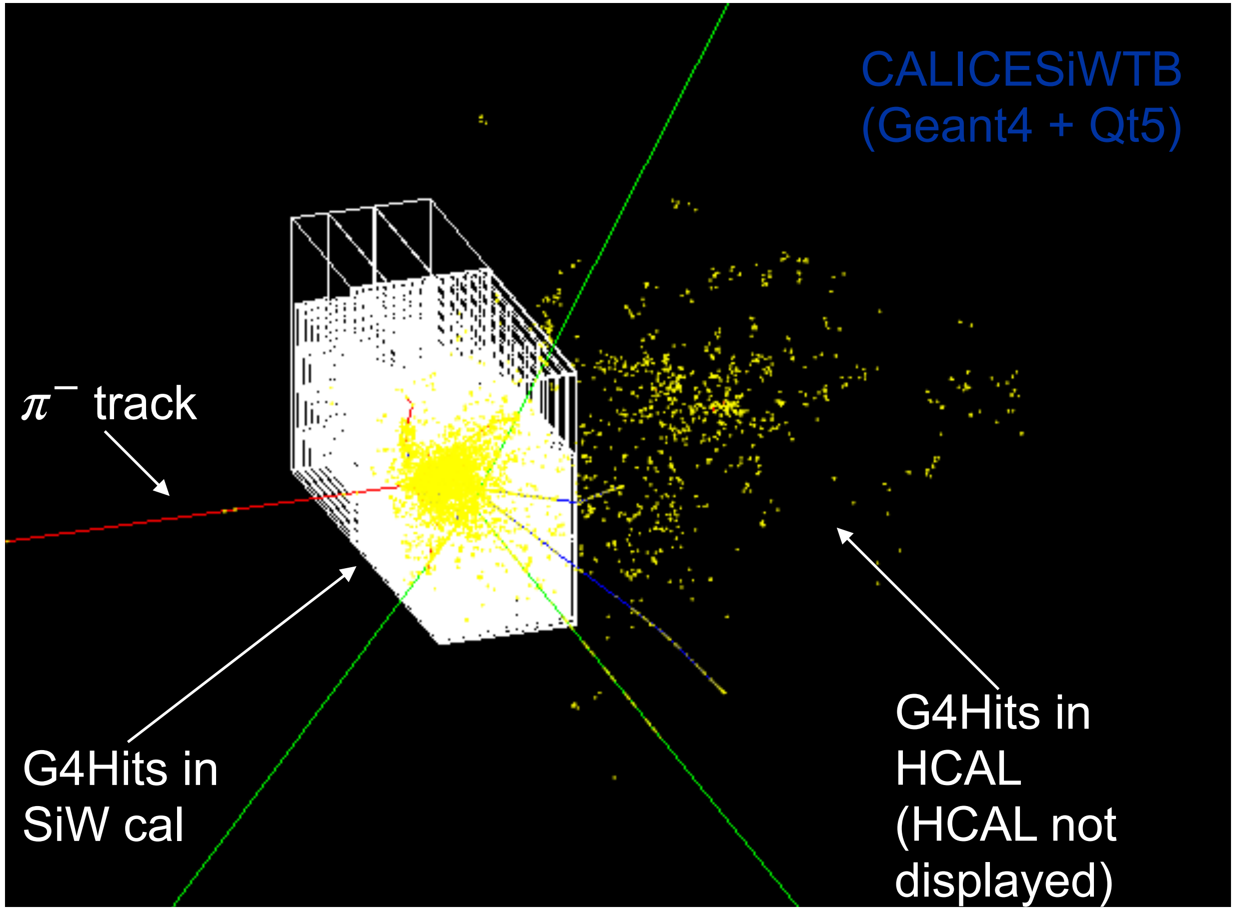


Image from CALICE paper

9720 sensitive volumes

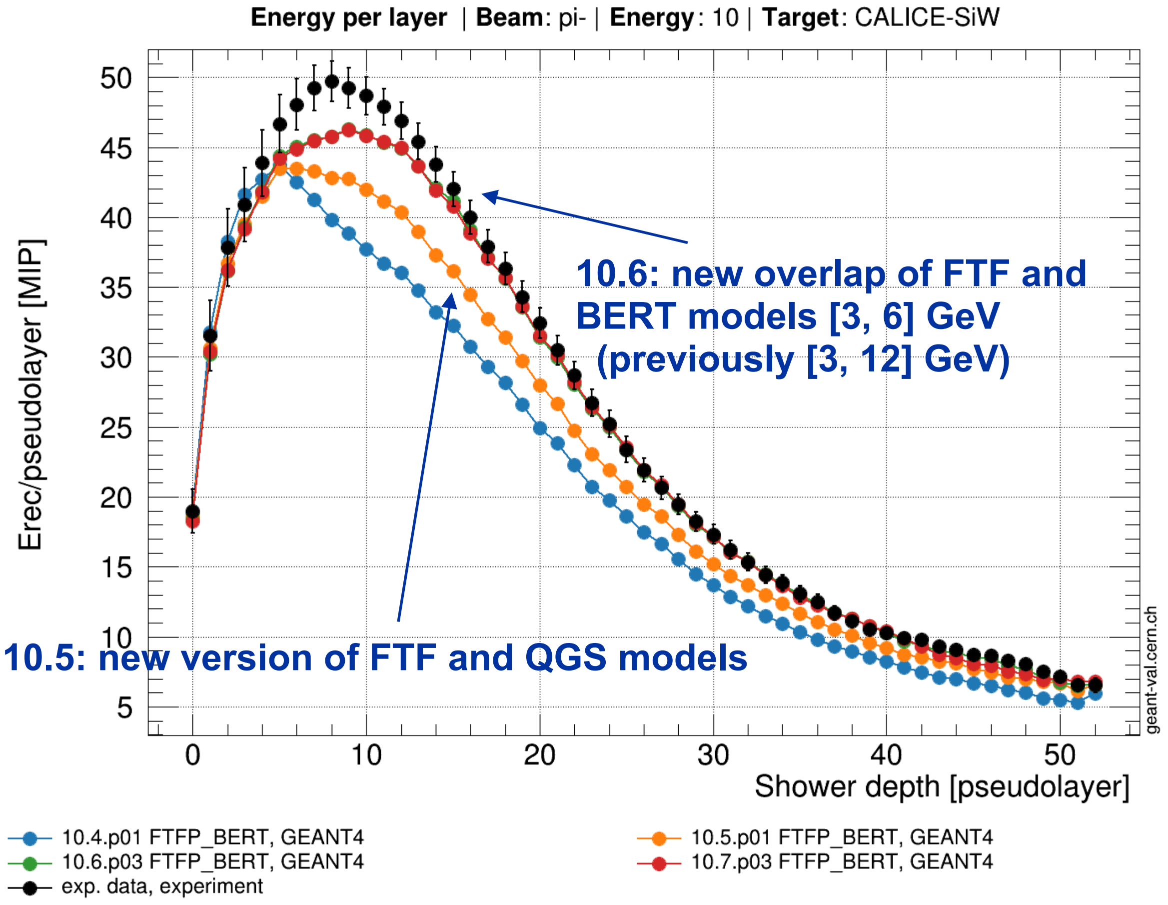
Tagging nuclear breakup events

- 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
  - $\frac{E_i + E_{i+1}}{E_{i-1} + E_{i-2}} > 6$ and $\frac{E_{i+1} + E_{i+2}}{E_{i-1} + E_{i-2}} > 6$
- 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*

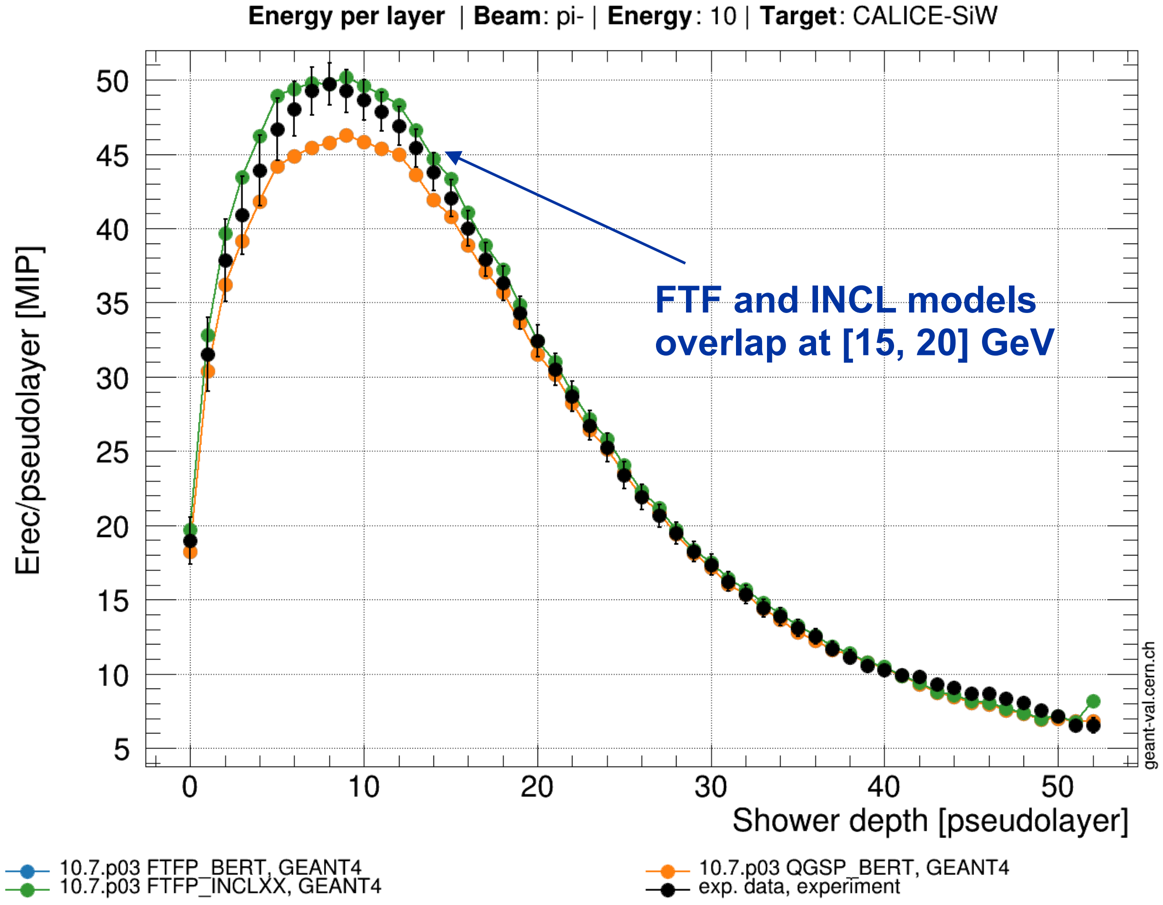


CALICE SiW: longitudinal energy distributions

10 GeV π^-, exp. data from NIM A794



***FTFP_BERT** Physics List regression testing 2017-2020*

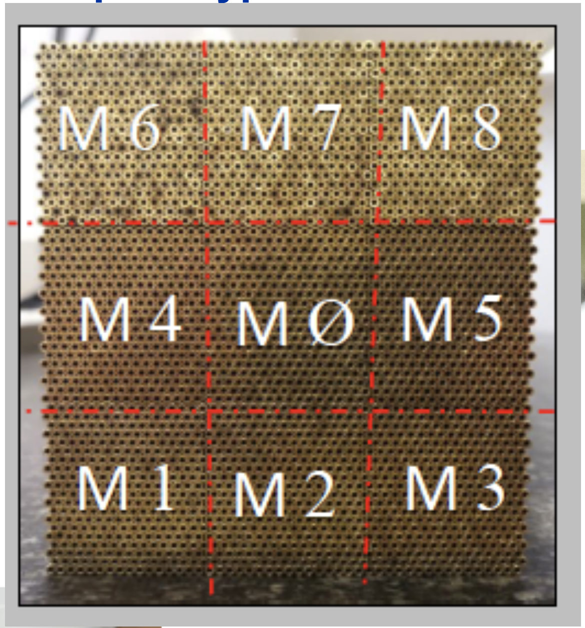


Physics Lists comparison - Geant4.10.7.p03

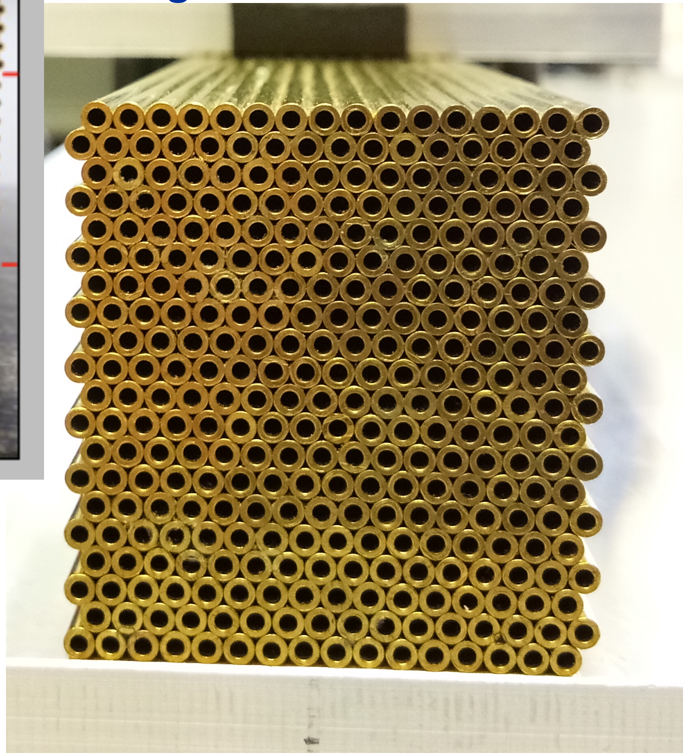
The Bucatini Dual-Readout Calorimeter within Geant4

- 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.

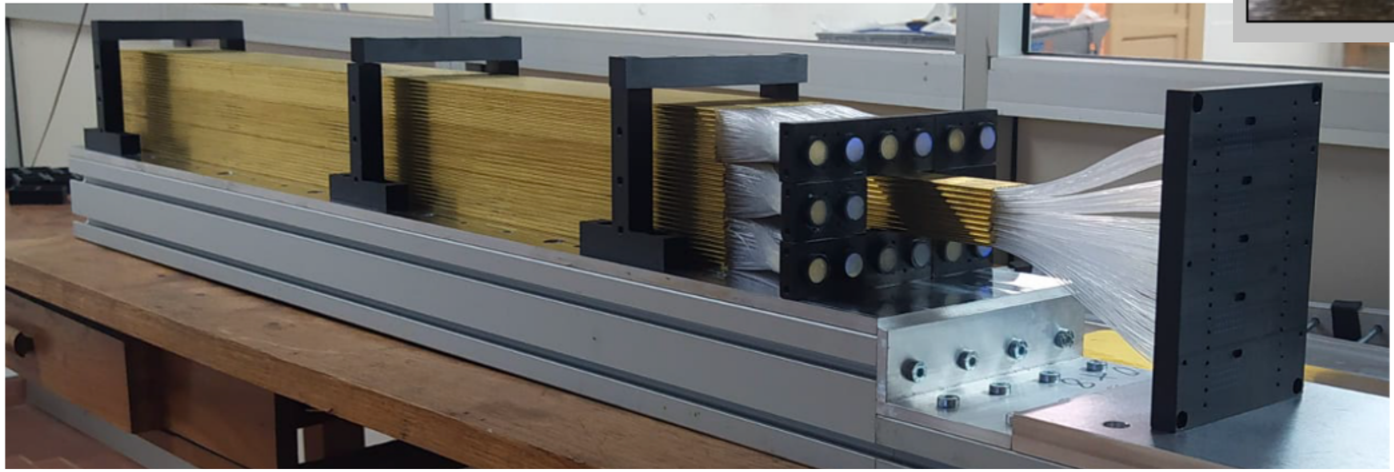
Full prototype - 9 towers



A single tower



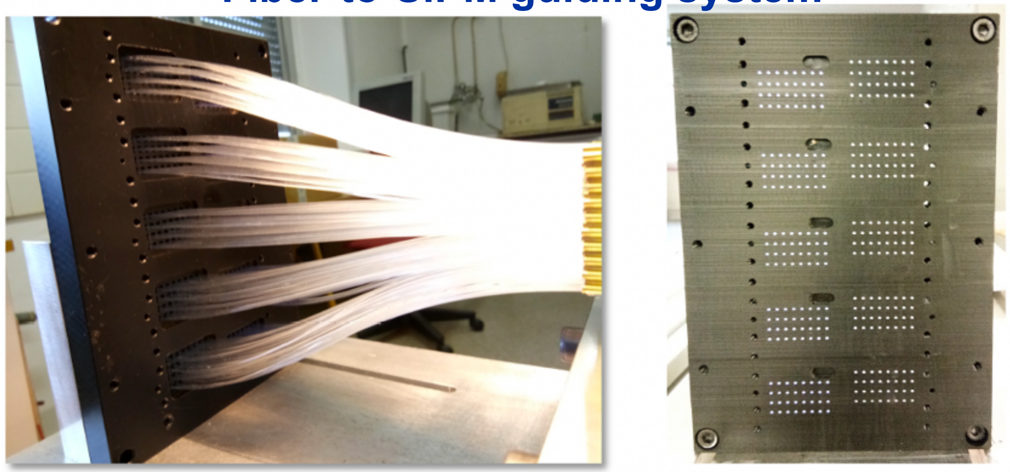
Prototype rear end

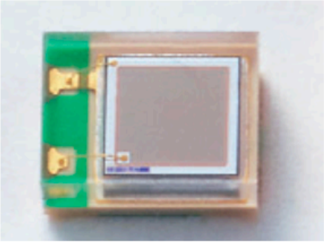


Towards superior Geant4 EM validation

- 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

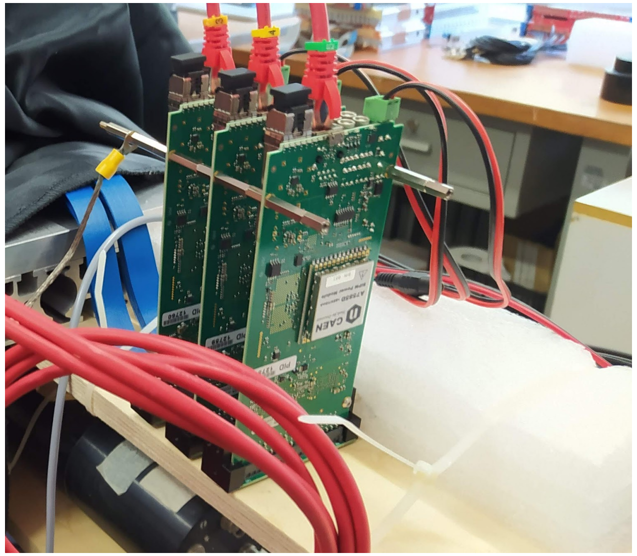
Fiber-to-SiPM guiding system





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

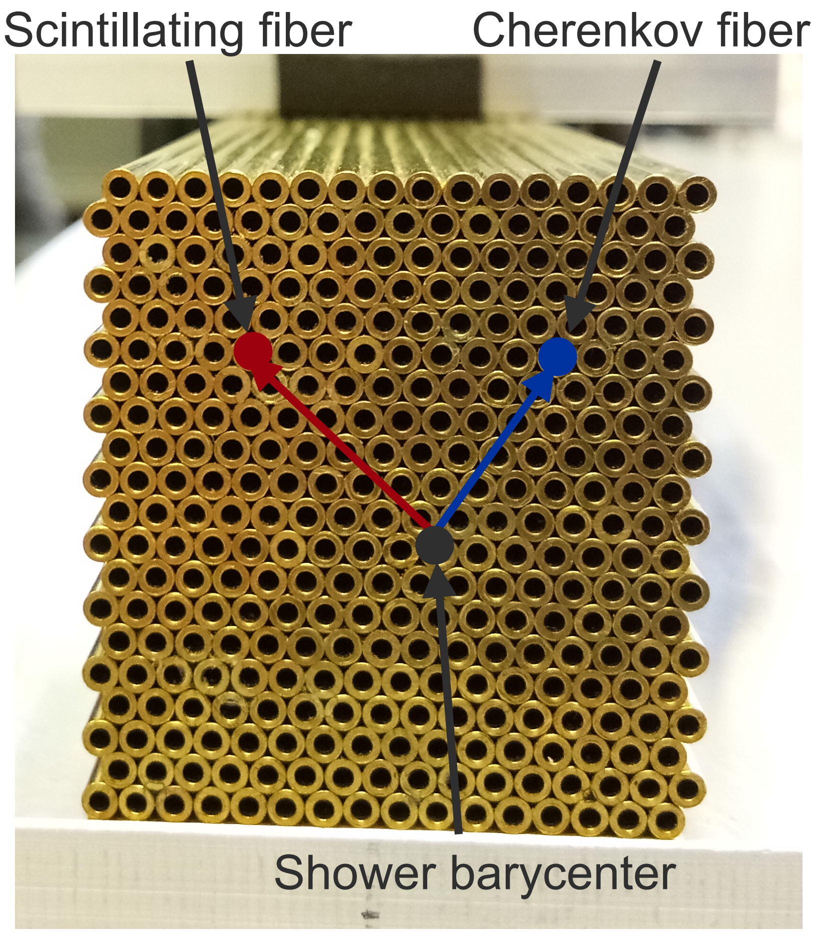
Front end board housing 64 SiPM



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



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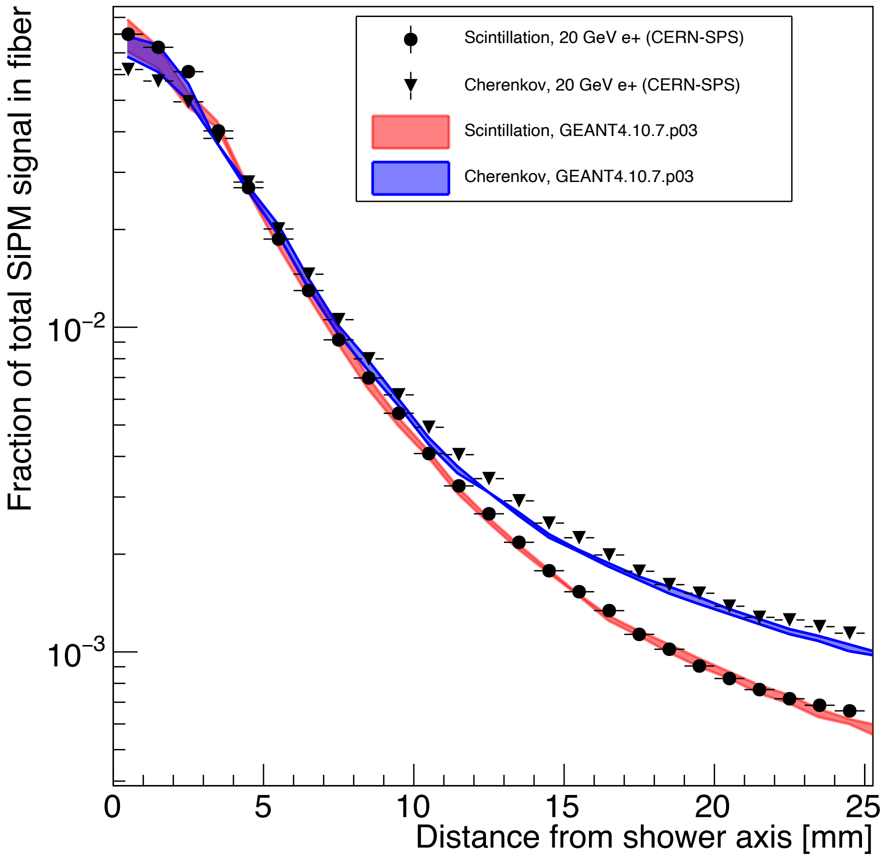
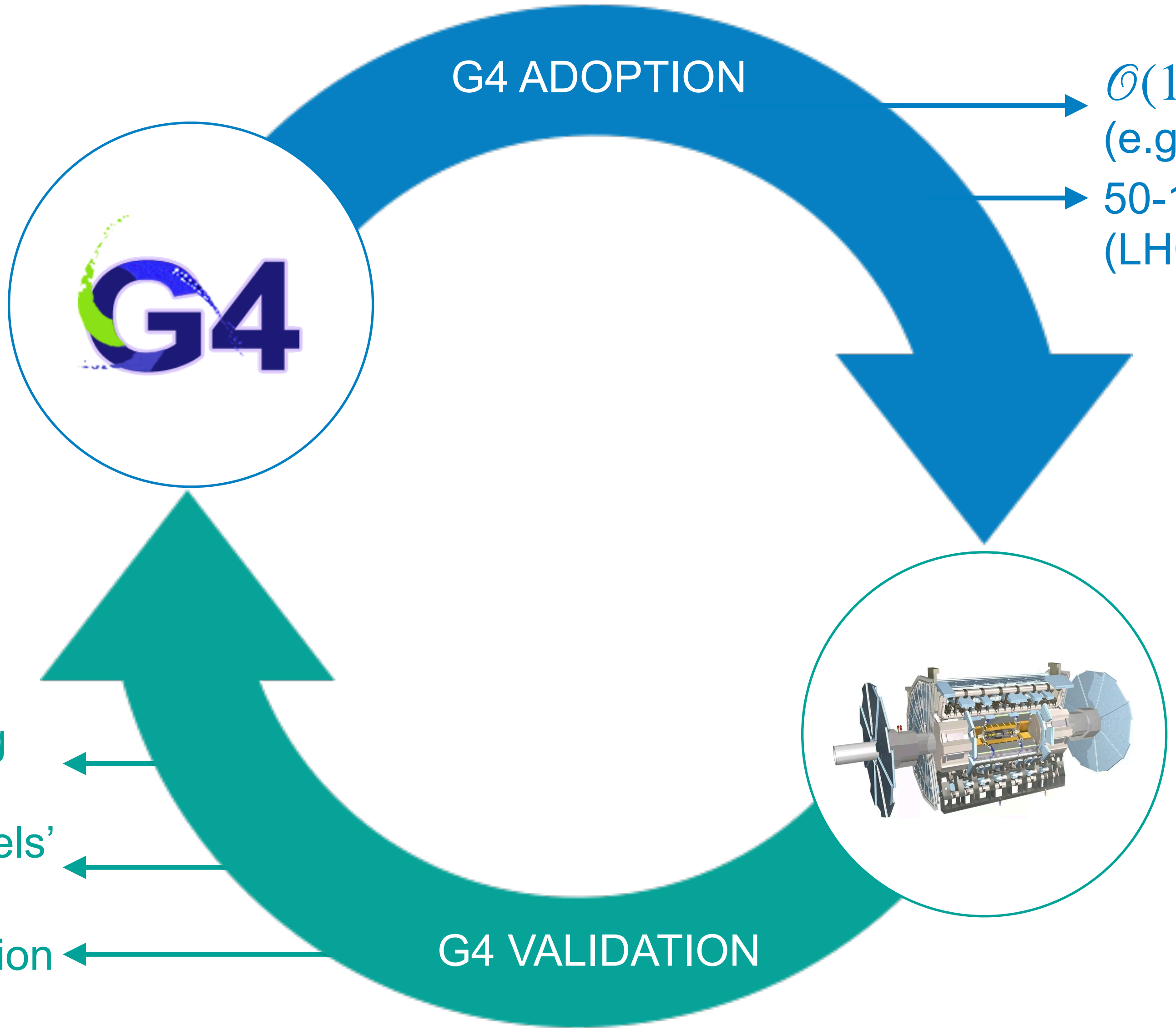
  - Summer 2021 and 2023
  - Using e^+ beams with energies 10-125 GeV
- Lateral profile measurement, *i.e.* measuring the average signal carried by a fiber located at a distance r from the shower barycenter
- Achieved millimetric sampling of em showers:
  - The average signal drops by two orders of magnitude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

CERN SPS 20 GeV e^+ - GEANT4



N. Ampilogov et al 2023 JINST 18 P09021



$\mathcal{O}(10^{11})$ event productions (e.g. CMS, ATLAS @Run2)

50-100 publications/year (LHC experiments)

Systematic testing over decades

Feedback to models' developers

Geant-val integration

Conclusion

- The Geant4 Group at CERN welcomes the creation of the DRD6 Collaboration and is willing to support new R&D studies on calorimetry
- DRD6 has the potential to facilitate the inclusion of new calorimetry benchmarks in geant-val, and to collect new requirements for Geant4 physics development towards future colliders
- Usually, one member of the Geant4 Group at CERN acts as representative for each of the most important Collaborations (ATLAS, CMS, LHCb, ALICE, …)
  - We believe it would be mutually beneficial to have a Geant4 representative at the DRD6 Software Working Group as well
- Our involvement in DRD6 might go beyond this as we could actively participate in the creation and organization of the DRD6 SW WG