Including calorimeter test-beams into geant-val

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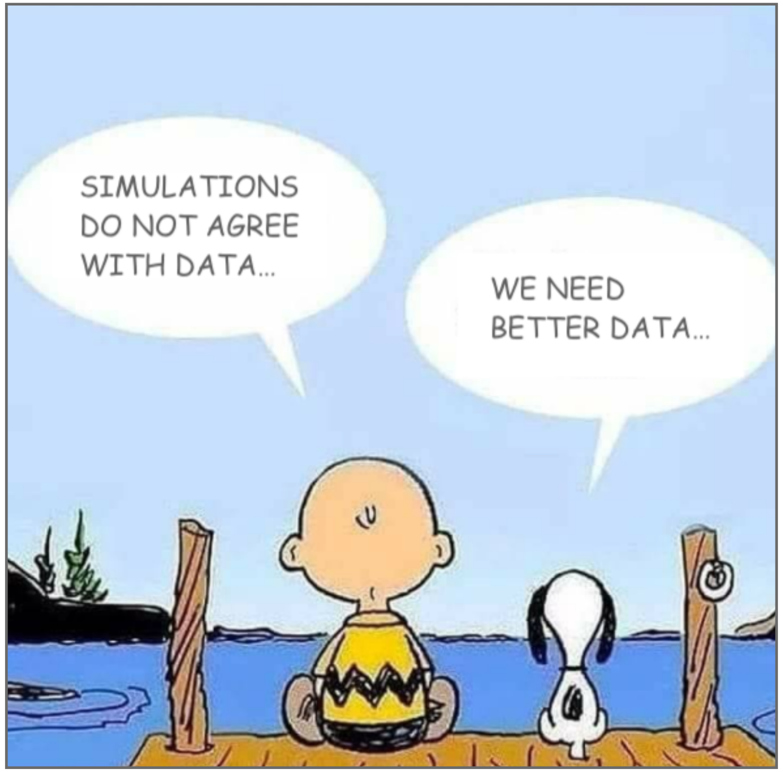
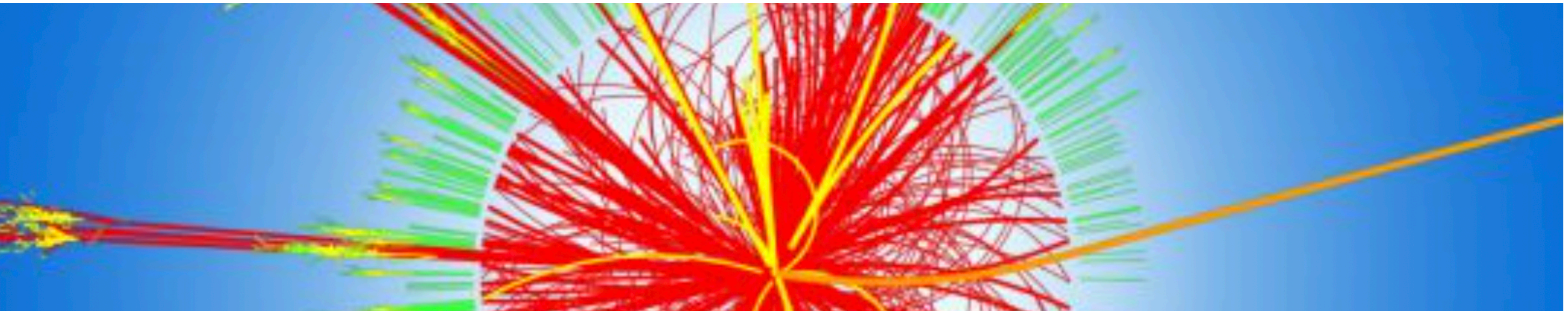
on behalf on the ***Geant4 Collaboration***

with inputs from ATLAS, CALICE and Dual-Readout Calorimetry Groups





CALOR 2022
19th International Conference on Calorimetry in Particle Physics

University of Sussex, Brighton
16-20 May 2022

Geant4, latest news

- Geant4 is going to support all the main LHC experiments re-starting with Run3. Some recent history:
  - Run2 (2015-2018) simulations used Geant4 releases from Geant4.9.6 (2012) to Geant4.10.4 (2017) producing $\mathcal{O}(10^{11})$ events.
  - To keep stable performance within the same Run, some developments in both hadronic and electromagnetic models were not included in official releases from Geant4.10.2 (2015) to Geant4.10.4 (2017).
  - The main LHC experiments currently use the Geant4-recommended Physics List **FTFP_BERT**, eventually with variants (e.g. ATLAS adopts **FTFP_BERT_ATL**).

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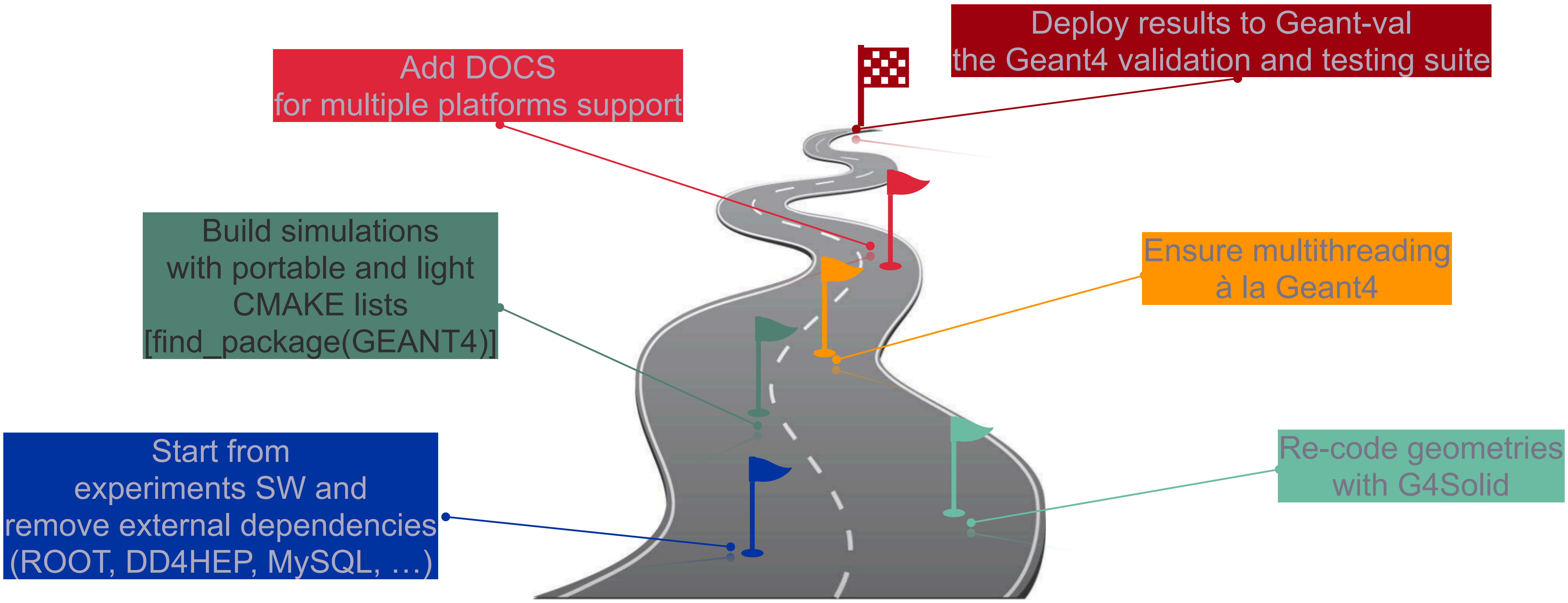
  - The main LHC experiments currently use the Geant4-recommended Physics List **FTFP_BERT**, eventually with variants (e.g. ATLAS adopts **FTFP_BERT_ATL**).
- Generating calorimeter showers is the most challenging simulation task:
  - Several hadronic physics models are adopted within a single Physics List with often overlapping ranges of applicability.
  - Still the most computationally heavy tasks in HEP. Geant4-R&D ongoing to parameterize/generate showers and to offload on GPUs the electromagnetic-shower component [*e.g.* Adept].

Need new validation studies to foresee the Geant4 performance @Run3

From experiments to geant-val, a winding road

A new Geant4 validation program is testing recent releases on well-established test-beam results from the ATLAS, CALICE and Dual-Readout Calorimetry Collaborations.

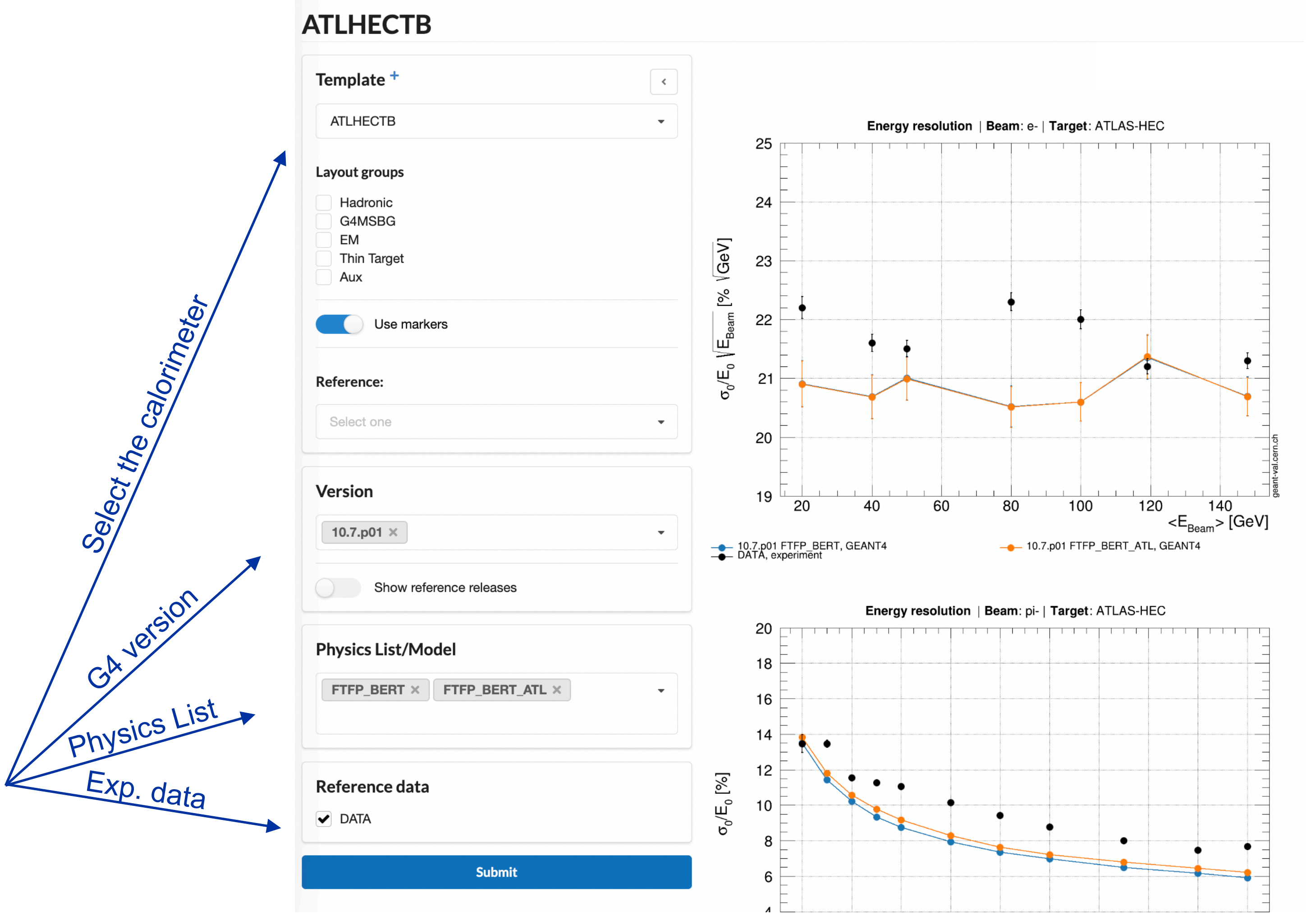


Geant-val - geant-val.cern.ch

Geant-val is the Geant4 validation and testing suite.

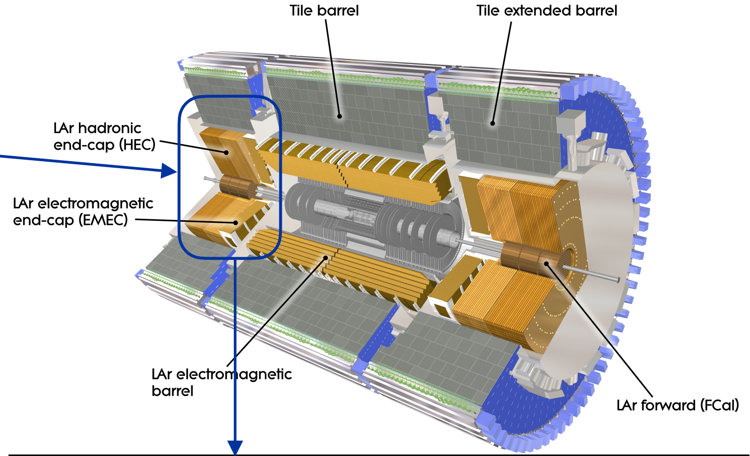
It contains ~40 Geant4 *tests* over several research fields (nuclear physics, HEP, biomedical, …).

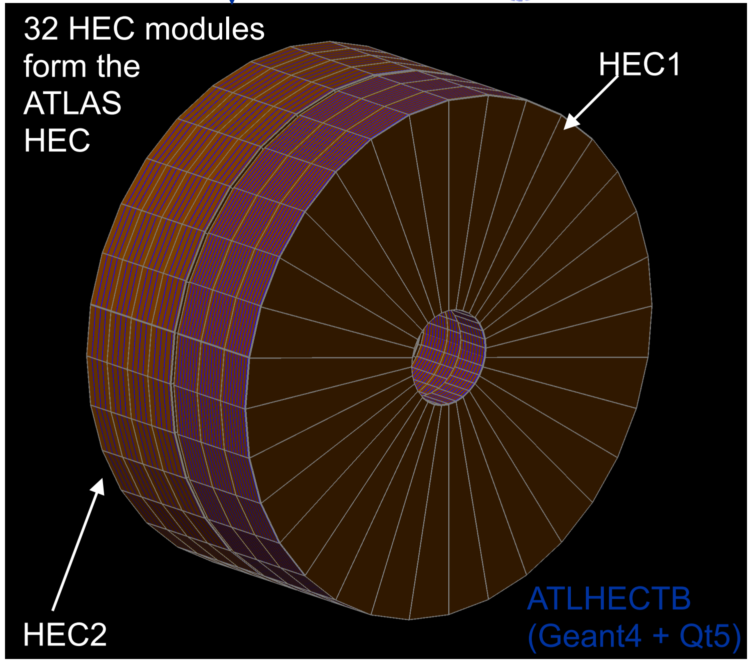
- **For the developers**, it allows to:
  - Create multiple jobs over beam energies, particle types, physics lists, …, and automatically submit them on HTCondor(lxplus).
  - Encapsulate variables in json files to later perform the analysis.
- **For the HEP Community**, it allows to:
  - Deploy results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



ATLAS hadronic end-cap calorimeter within 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 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 $\simeq 9.7\lambda_{int}$.





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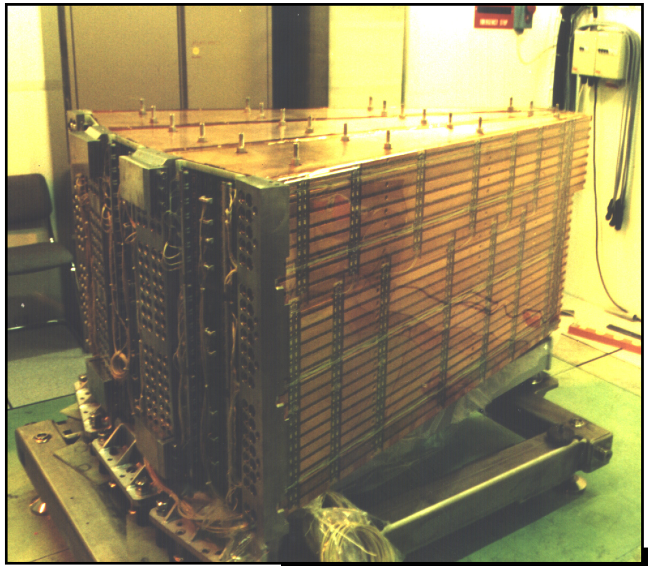
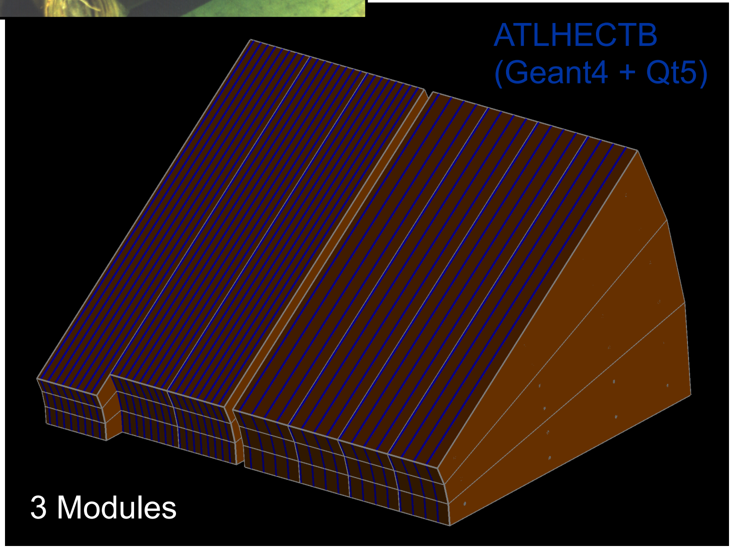
- Beam-tests:
  - Tested in 2000-2001 at CERN-SPS-H6 beam line.
  - Tests performed with 3 $\phi-$wedges.
  - Involving e^-, μ^- and hadrons with $6 \leq E_{Beam} \leq 200$ GeV.

ATL-PHO-LARG-2001-013

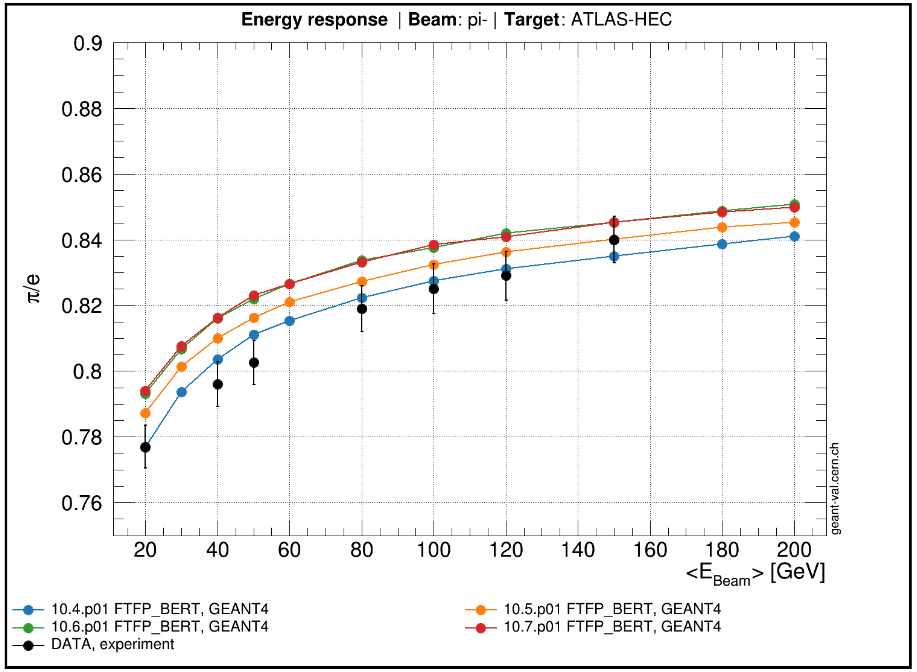




ATLAS HEC: energy response

- π/e extracted as the average π^- reconstructed energy, using the calibration at the electromagnetic scale, divided by the beam energy.
  - **FTFP_BERT** regression testing: →
    - Increase in π observed from Geant4.10.4 (2017) to Geant4.10.6 (2019), driven by inputs from thin target results.
    - FTFP_BERT currently overestimates π of $\simeq 2\,\%$.

FTFP_BERT evolution from 2017 to 2020



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    - FTFP_BERT currently overestimates π of $\simeq 2\,\%$.
  - Geant4.10.7 physics list comparison: →
    - Best MC-to-data agreement by **FTFP_BERT_ATL** (transition region between **FTF** and **BERT** is [9,12] GeV, instead of [3,6] GeV).
    - **QGSP_BERT** is $\simeq 3\,\%$ higher than **FTFP_BERT**.

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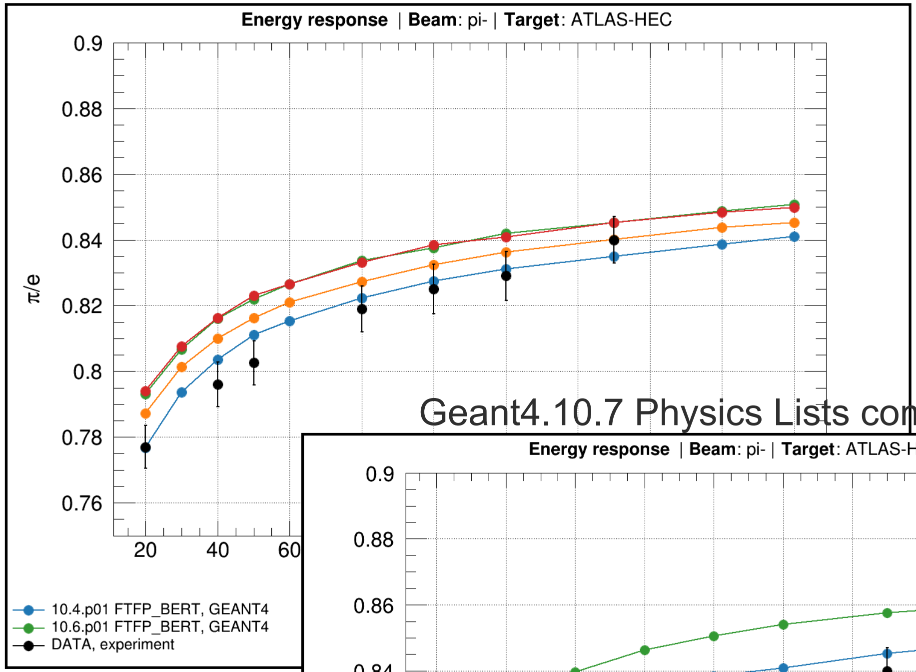
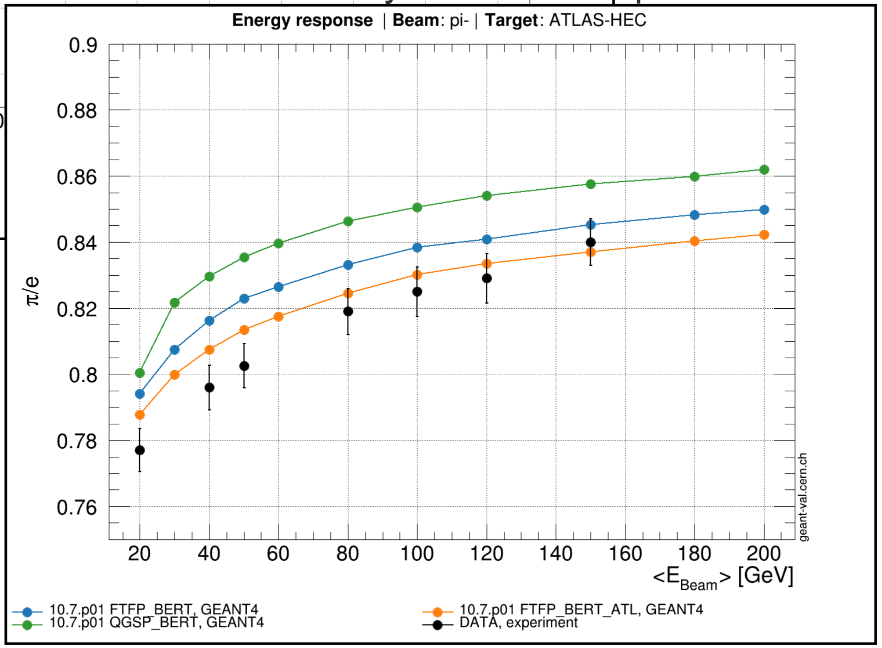


Geant4.10.7 Physics Lists comparison

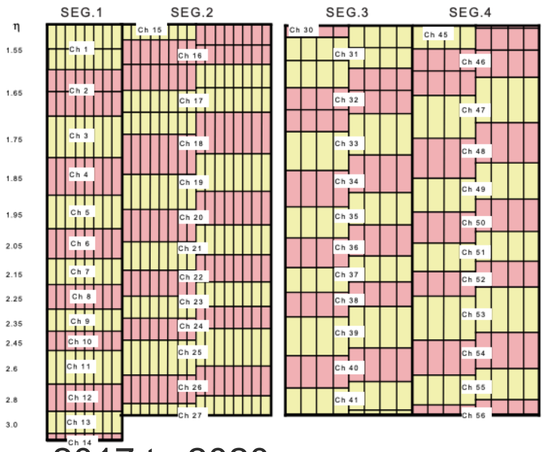


ATLAS HEC: hadronic shower shape

- 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}.
- Average shower depth:
  - Extracted as the mean (L_0) of the energy profile, as a function of E_{Beam}.
  - Excellent description ($\simeq 0.1~\%$) from Geant4.10.7.

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



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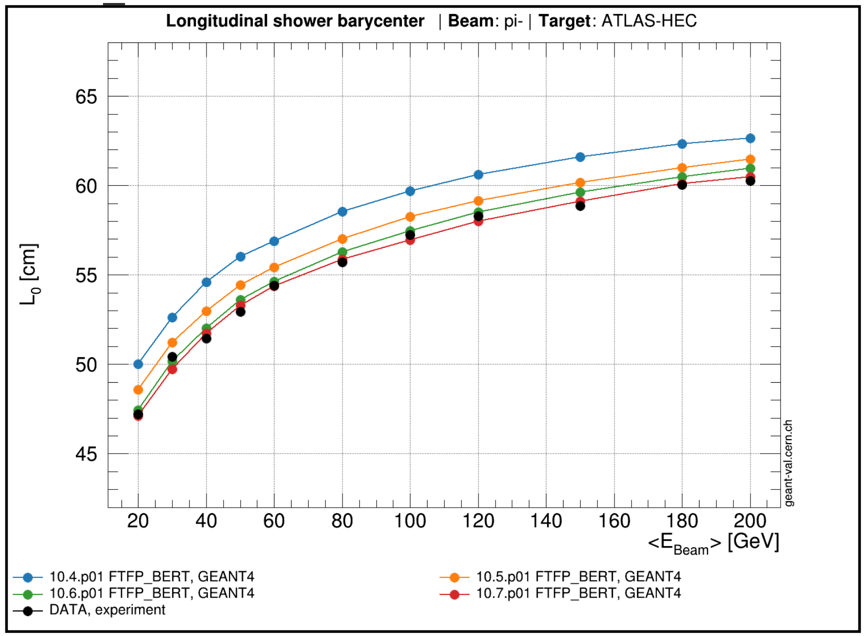

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- Average shower length:
  - Extracted as the RMS (σ_L) of the energy profile.
  - Currently within $\pm 2\ \%$ agreement w.r.t. test-beam data.

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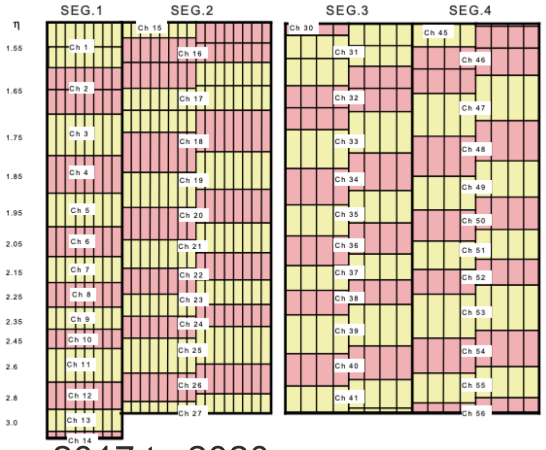

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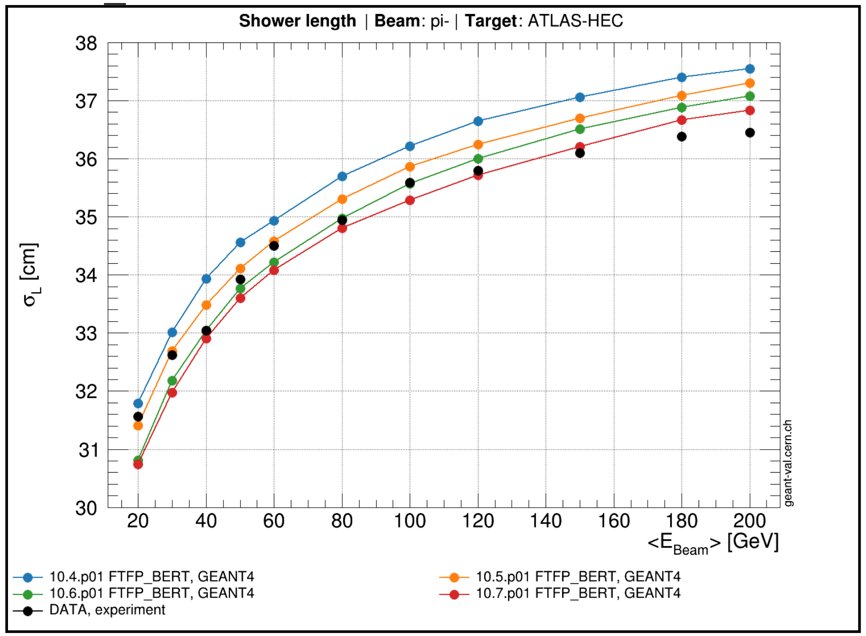
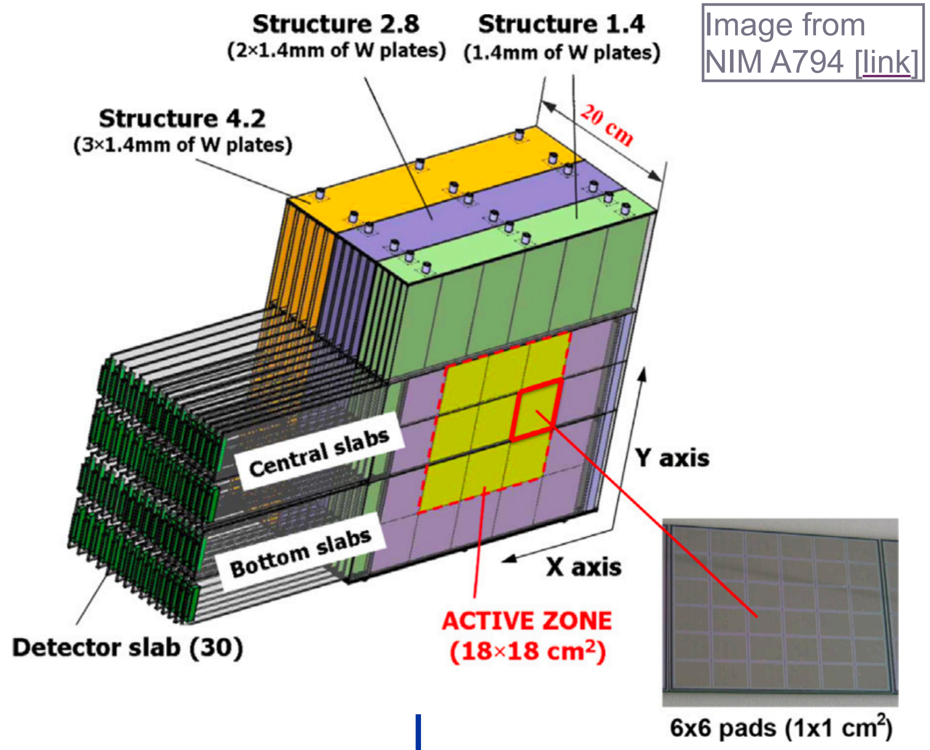


CALICE SiW Calorimeter within G4

- 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 cm^2.
- Simulation recently ported by CERN EP-SFT to a standalone Geant4 application for internal validation.

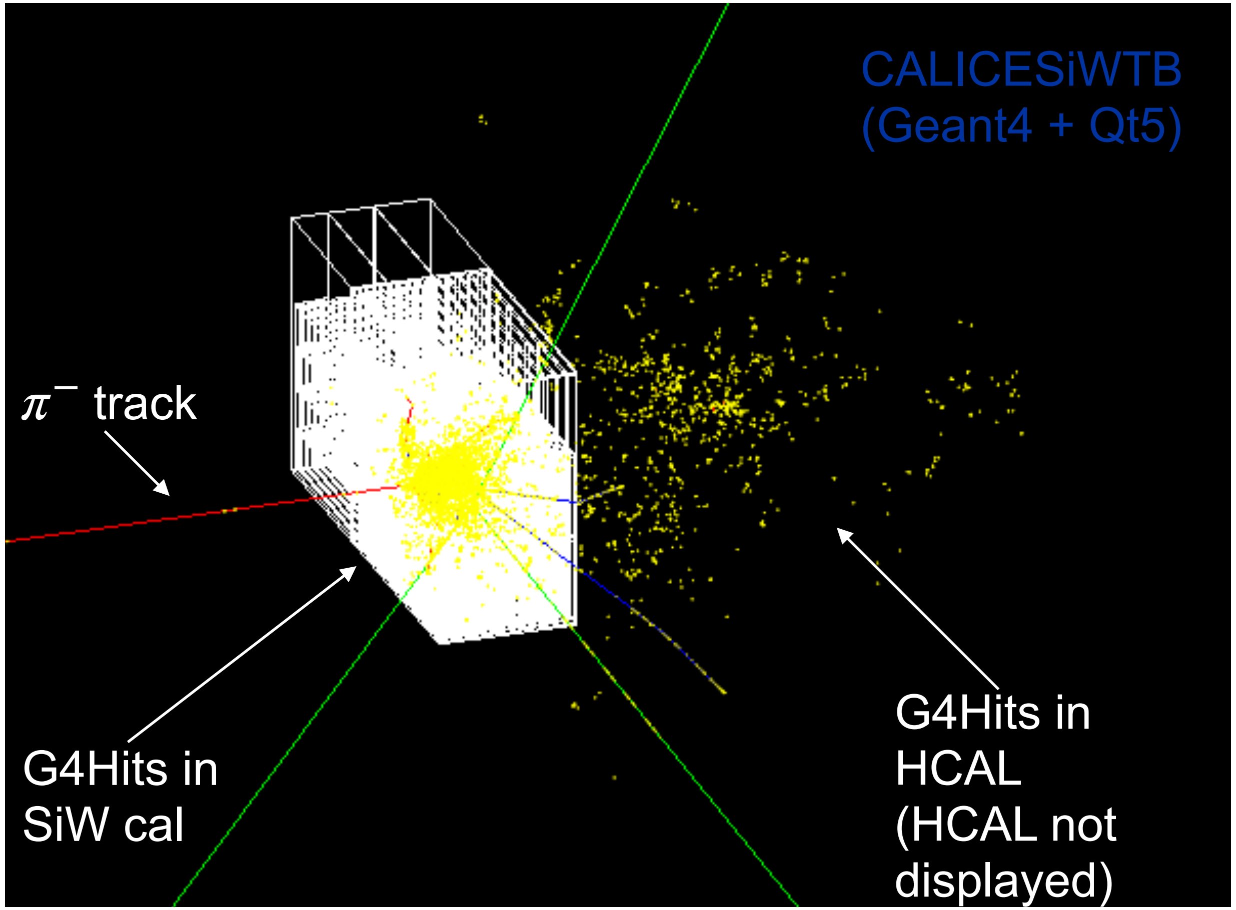
Image from NIM A794 [link]



9720 sensitive volumes

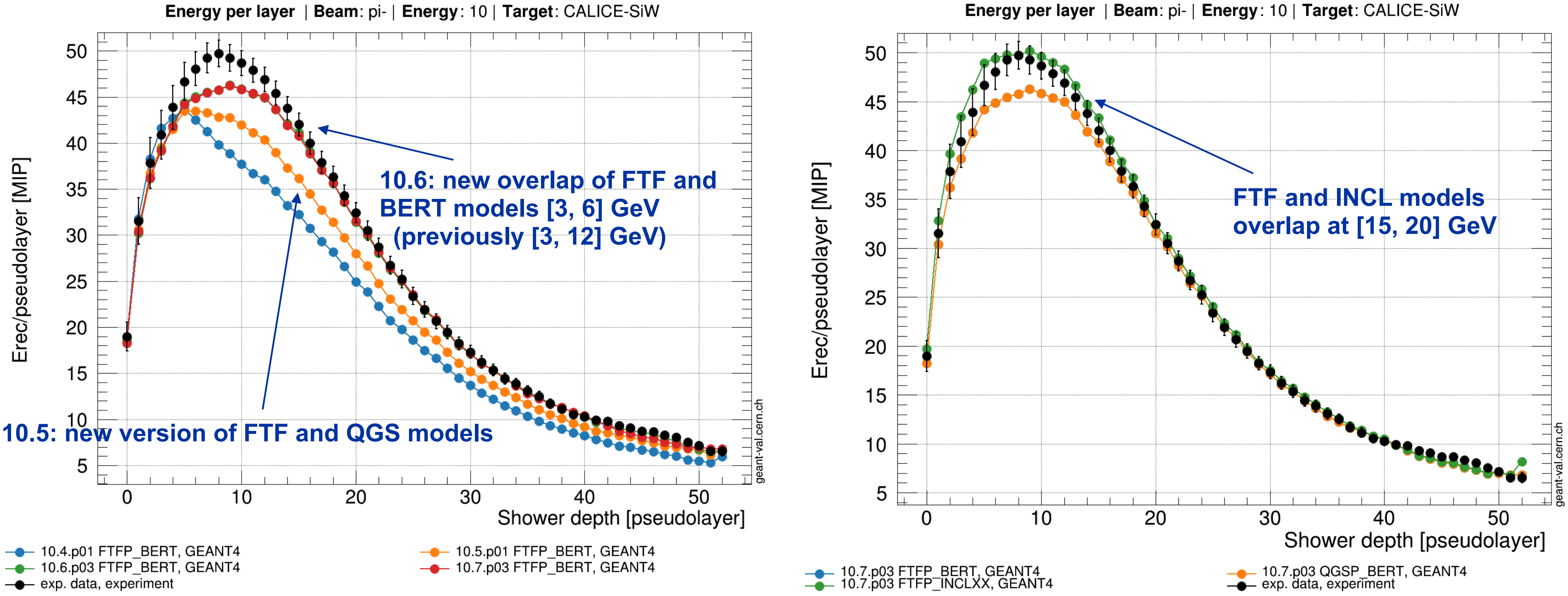
Tagging nuclear breakup events

- 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
  - $\frac{E_i + E_{i+1}}{E_{i-1} + E_{i-2}} > 6$ MIP and $\frac{E_{i+1} + E_{i+2}}{E_{i-1} + E_{i-2}} > 6$ MIP
- 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 A796

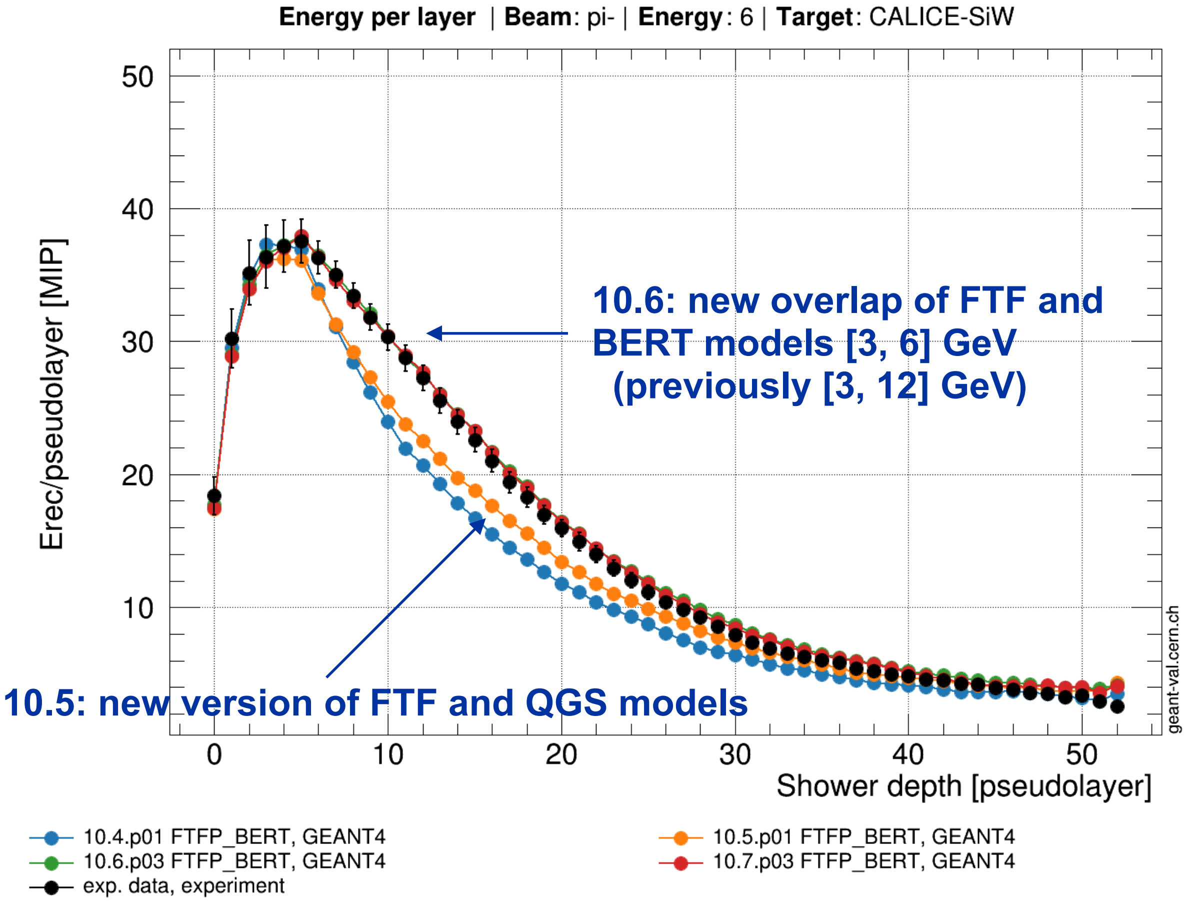


***FTFP_BERT** Physics List regression testing 2017-2020*

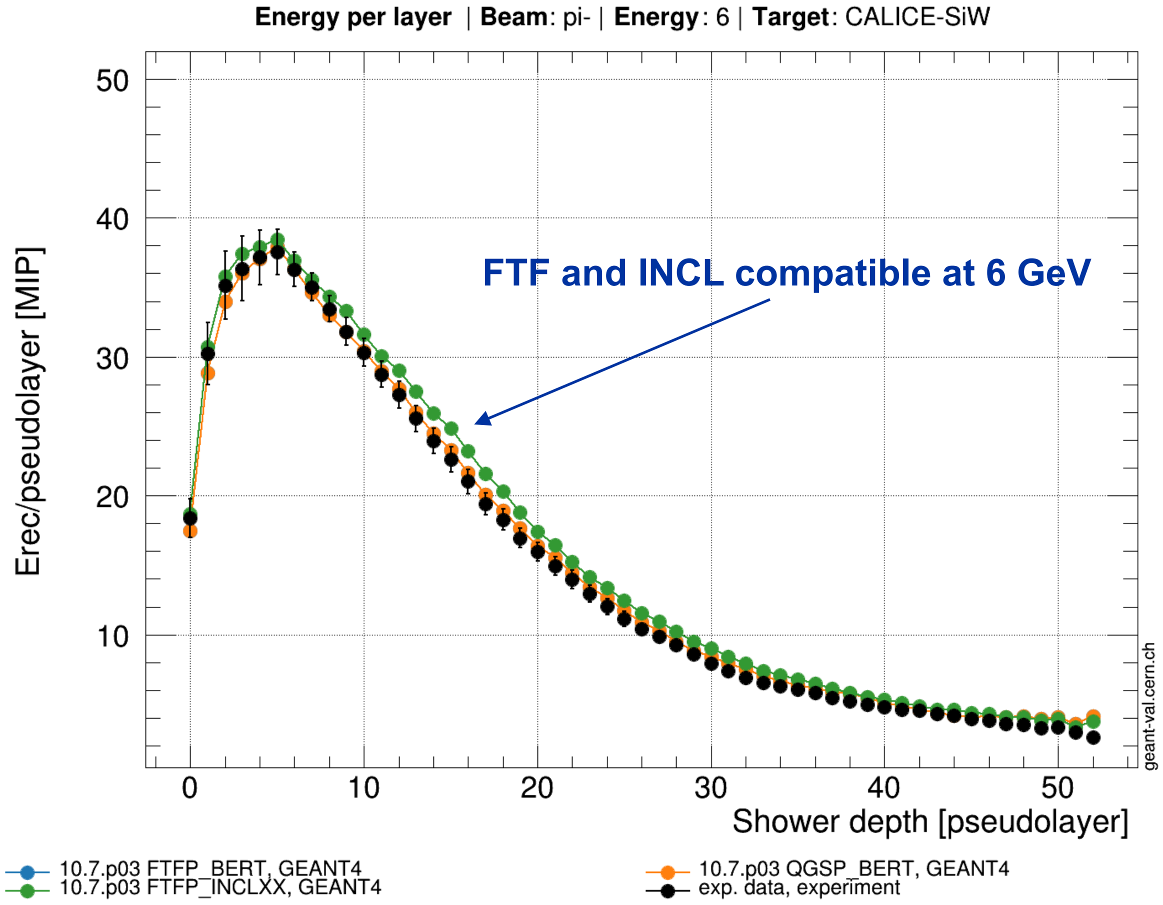
Physics Lists comparison - Geant4.10.7.p03

CALICE SiW: longitudinal energy distributions

6 GeV π^-, exp. data from NIM A796



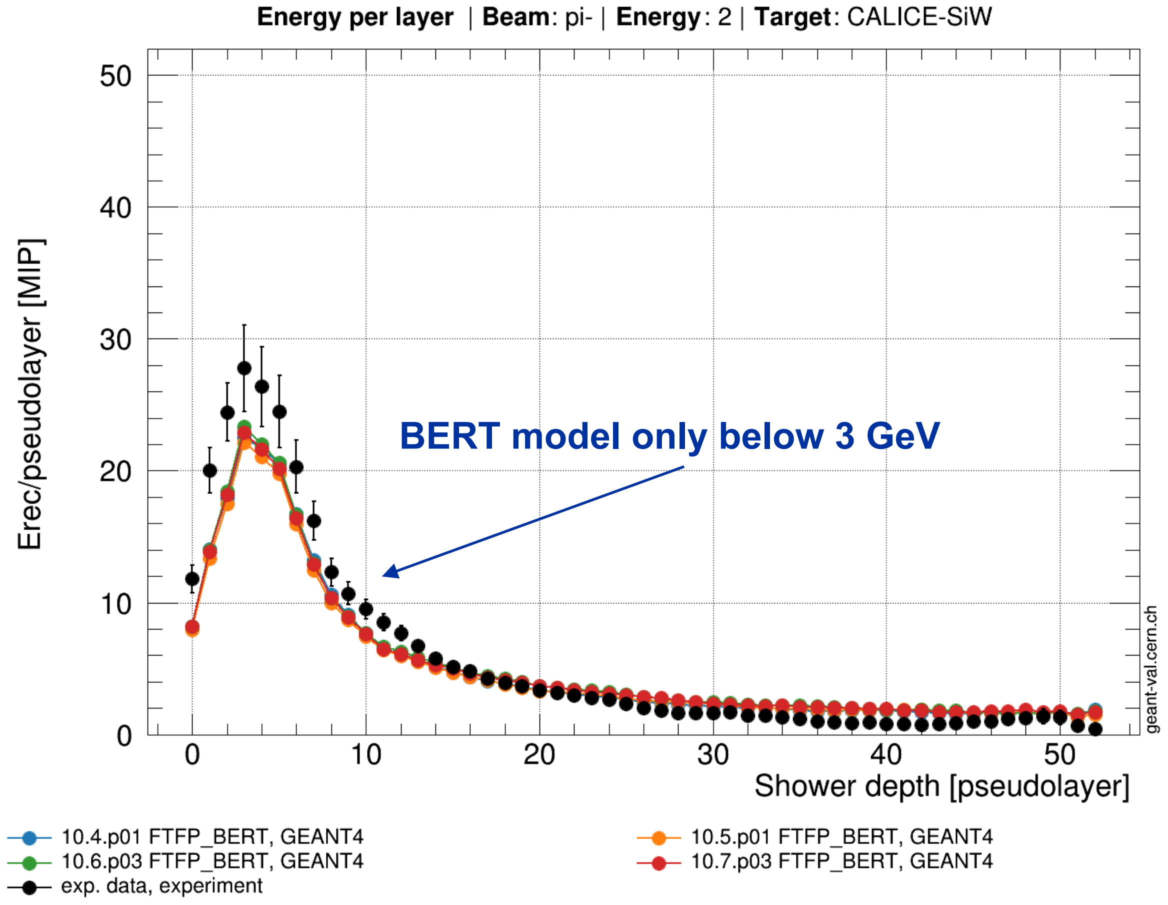
***FTFP_BERT** Physics List regression testing 2017-2020*



Physics Lists comparison - Geant4.10.7.p03

CALICE SiW: longitudinal energy distributions

2 GeV π^-, exp. data from NIM A796



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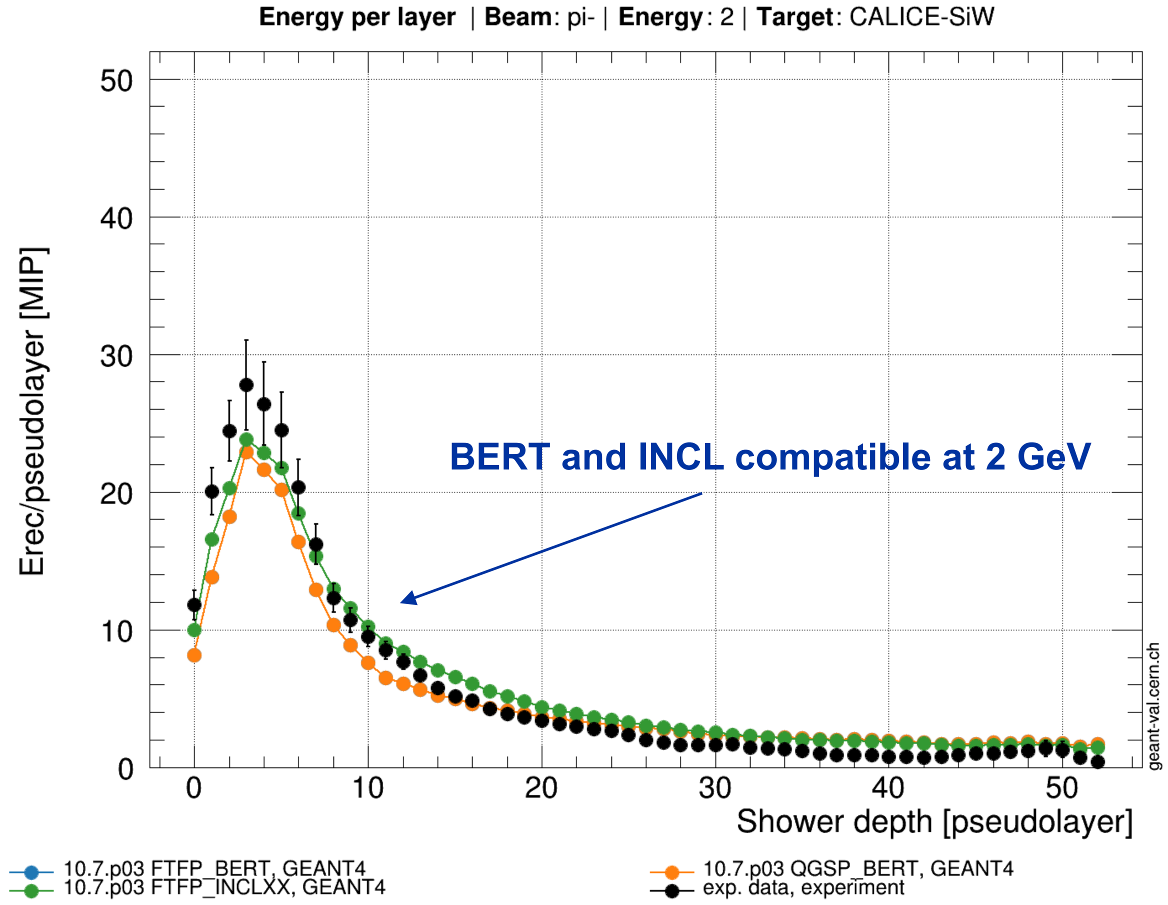
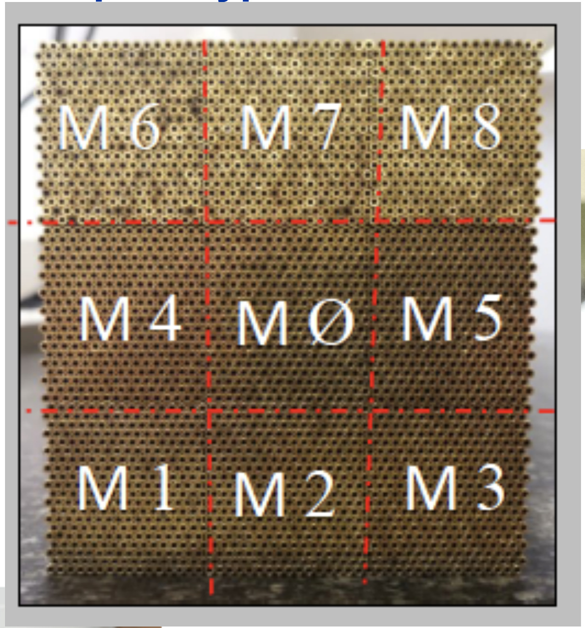


Physics Lists comparison - Geant4.10.7.p03

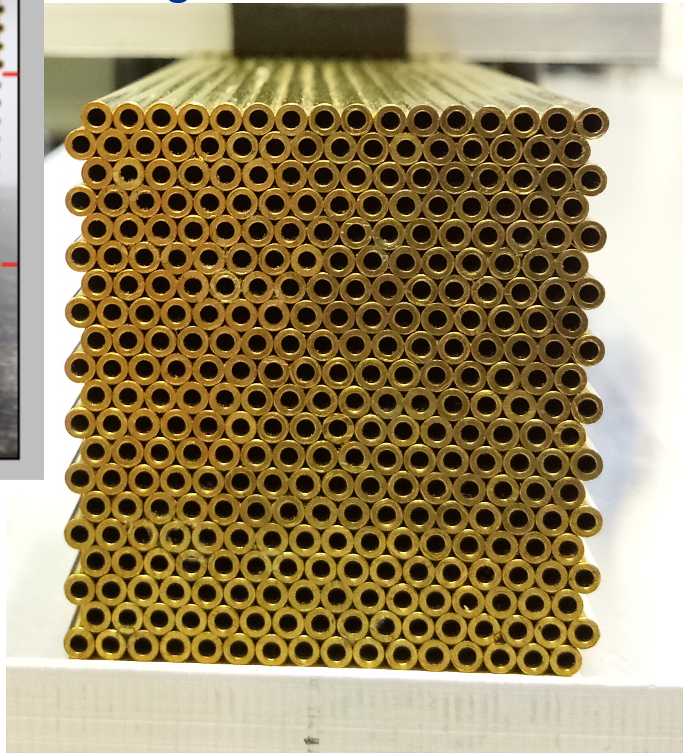
The Bucatini Dual-Readout Calorimeter within Geant4

- The new 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.

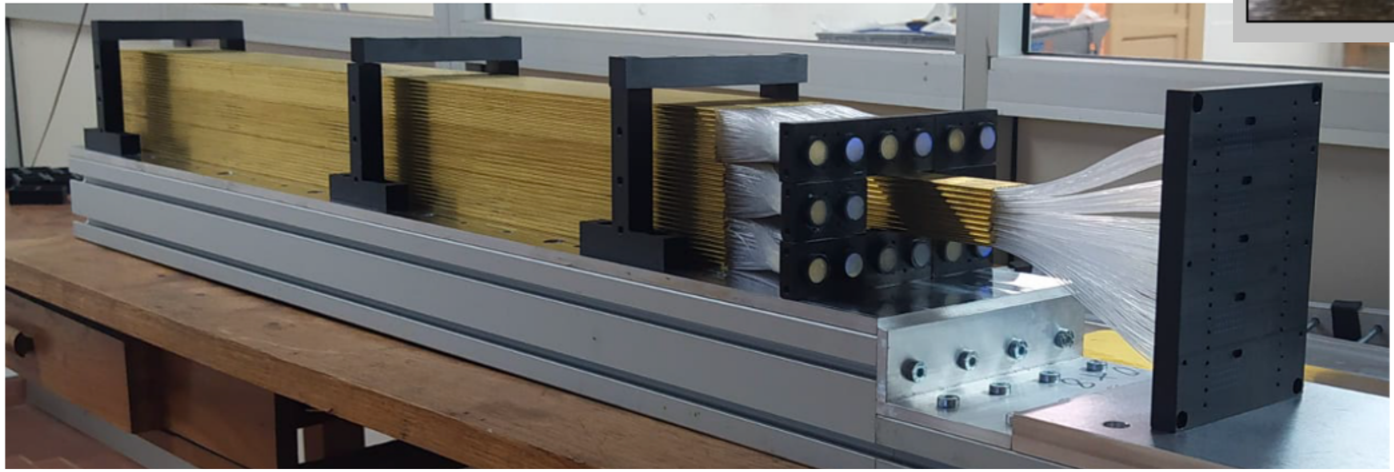
Full prototype - 9 towers



A single tower



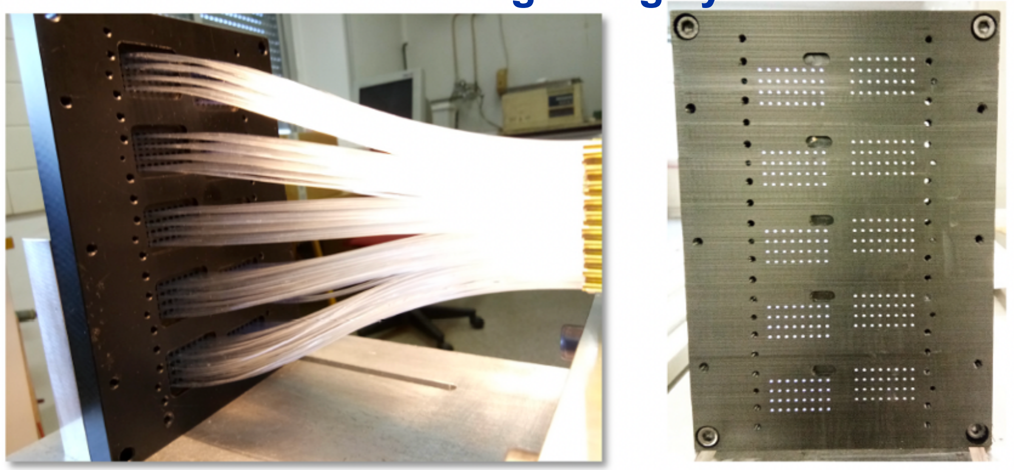
Prototype rear end



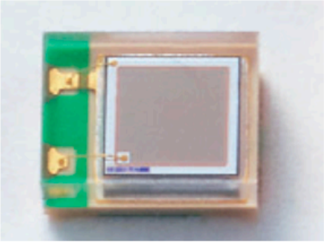
More details in R. Santoro [talk] at this Conference.

Towards superior Geant4 EM validation

Fiber-to-SiPM guiding system

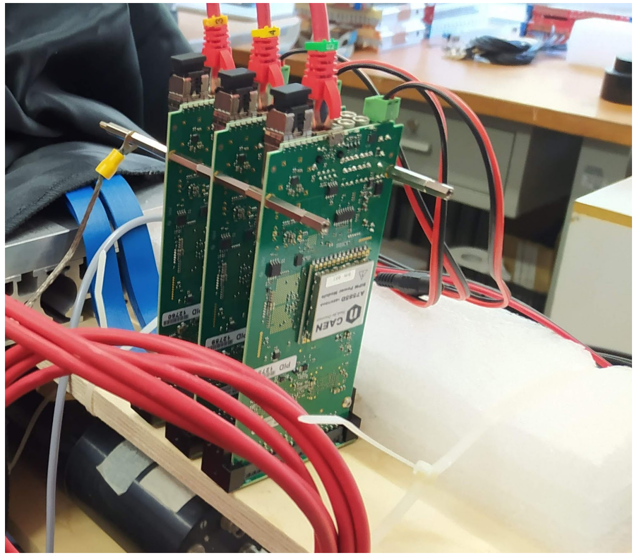


- Superior granularity achieved using a hybrid readout system:
  - 320 SiPMs in the central tower independently read-out using
    - 5 FEE readout boards, operated in self-trigger mode.
  - Surrounding 8 towers read-out by two PMTs per tower providing an independent Cherenkov and Scintillation light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



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

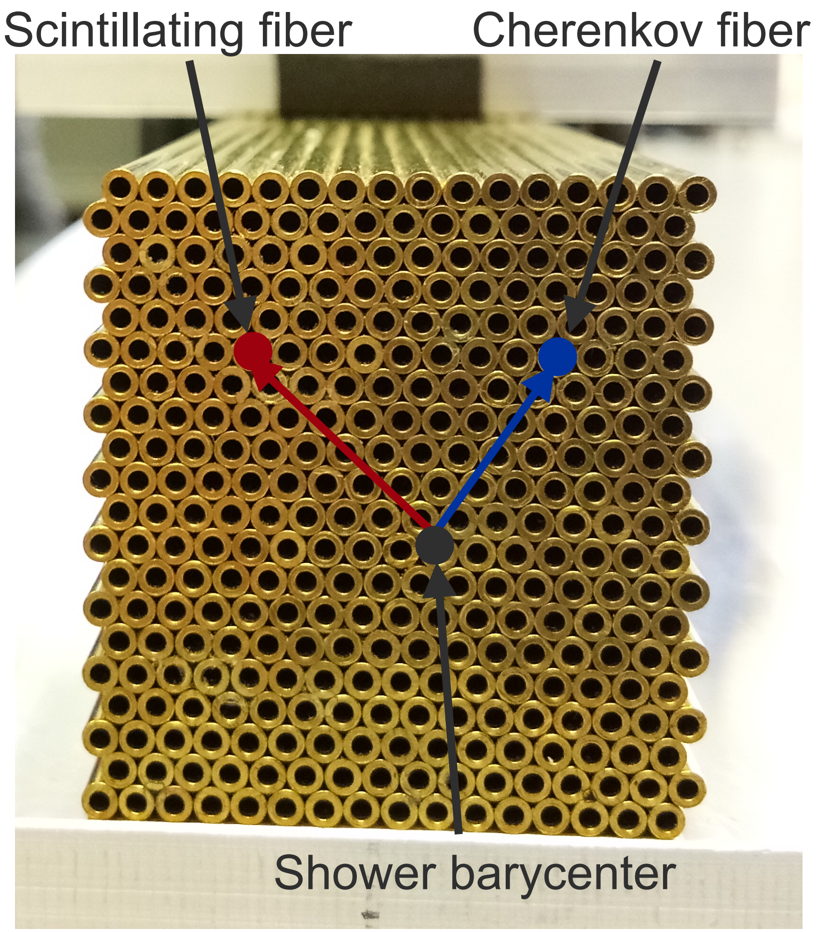
Front end board housing 64 SiPM



Readout Boards CAEN A5202

Dual-Readout Calorimeter: e^+ shower shape

- Tested with e^+ beam at CERN-SPS-H8 beam line with energies 10-125 GeV (highly affected by π^+ contamination).
- Lateral profile, *i.e.* the average signal carried by a fiber located at a distance r from the shower barycenter.
- Measurement:
  - For every event, and for every fiber we populate a scatter plot (signal *vs.* distance).
  - Lateral profiles are extracted as average values for every x-bin.



More details on SiPM calibration in R. Santoro [talk] at this Conference.

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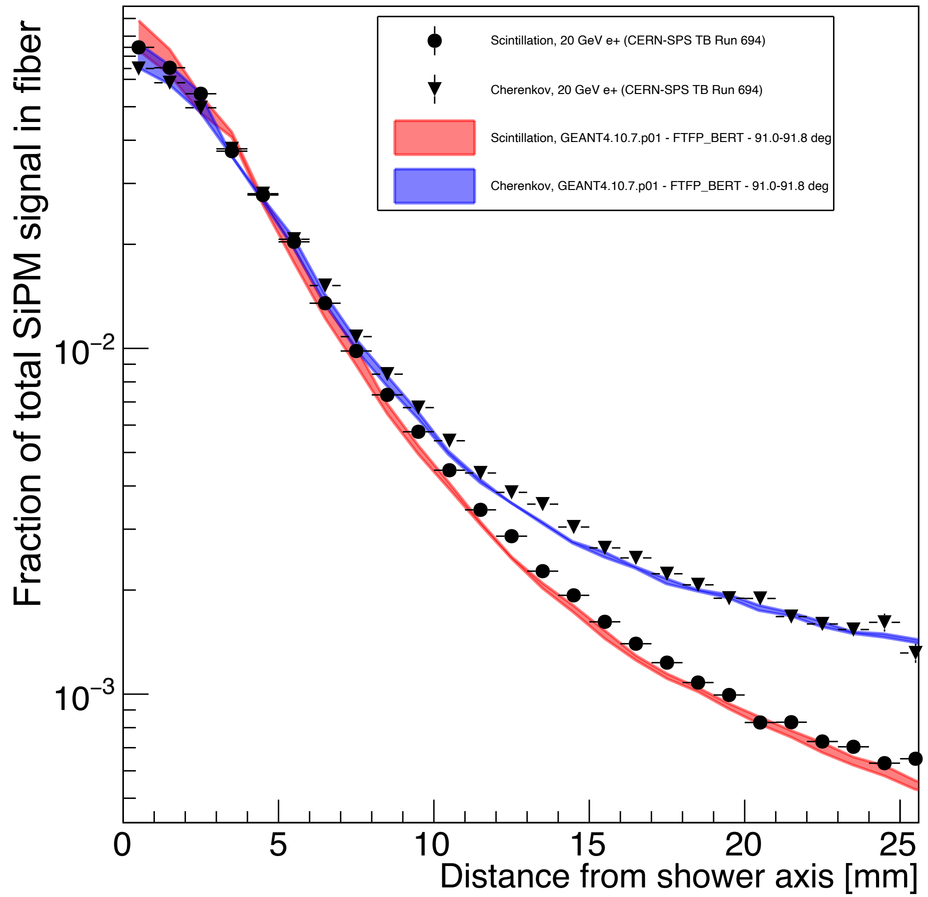
CERN SPS 20 GeV e^+ - GEANT4



We would like to thank the IDEA Dual-Readout Group for granting early access to unpublished data.

Take home messages

- GEANT4 needs experiments and experiments need Geant4.
- CERN EP/SFT recently validated new Geant4 releases in close contact with ATLAS, CALICE and Dual-Readout Calorimetry Groups.
- Future activity will tackle the inclusion of the ATLAS Tile Calorimeter, a CALICE hadronic-calorimeter and the future Dual-Readout Calorimetry test-beam results into geant-val.
- Geant-val is an open project to assist developers in large validation campaigns while distributing results to the HEP Community
  → *anyone is invited to try it out!*
- Consider collaborating with Geant4 for next validation studies [Alberto.Ribon@cern.ch - lorenzo.pezzotti@cern.ch]