Geant4 Validation on Test-Beam Calorimetry Data

L. Pezzotti, A. Ribon, D. Konstantinov
on behalf on the **CERN EP-SFT Group**

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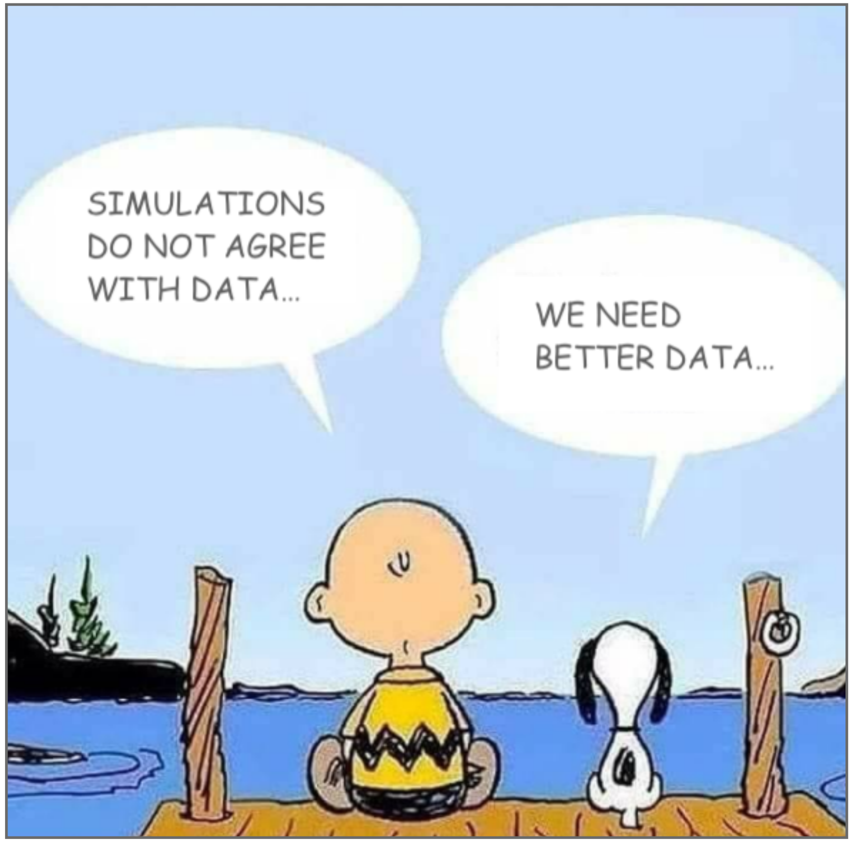

Partially based on Instruments 2022, 6, 41

instruments
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Article

Including Calorimeter Test Beams in Geant-val—The Physics Validation Testing Suite of Geant4

Lorenzo Pezzotti [1,*], Andrey Kiryunin [2], Dmitri Konstantinov [3], Alberto Ribon [1], Pavol Strizenec [4]
and on behalf of the Geant4 Collaboration

A SIMULATION TOOLKIT

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**).

Need new validation studies to foresee the Geant4 performance @Run3

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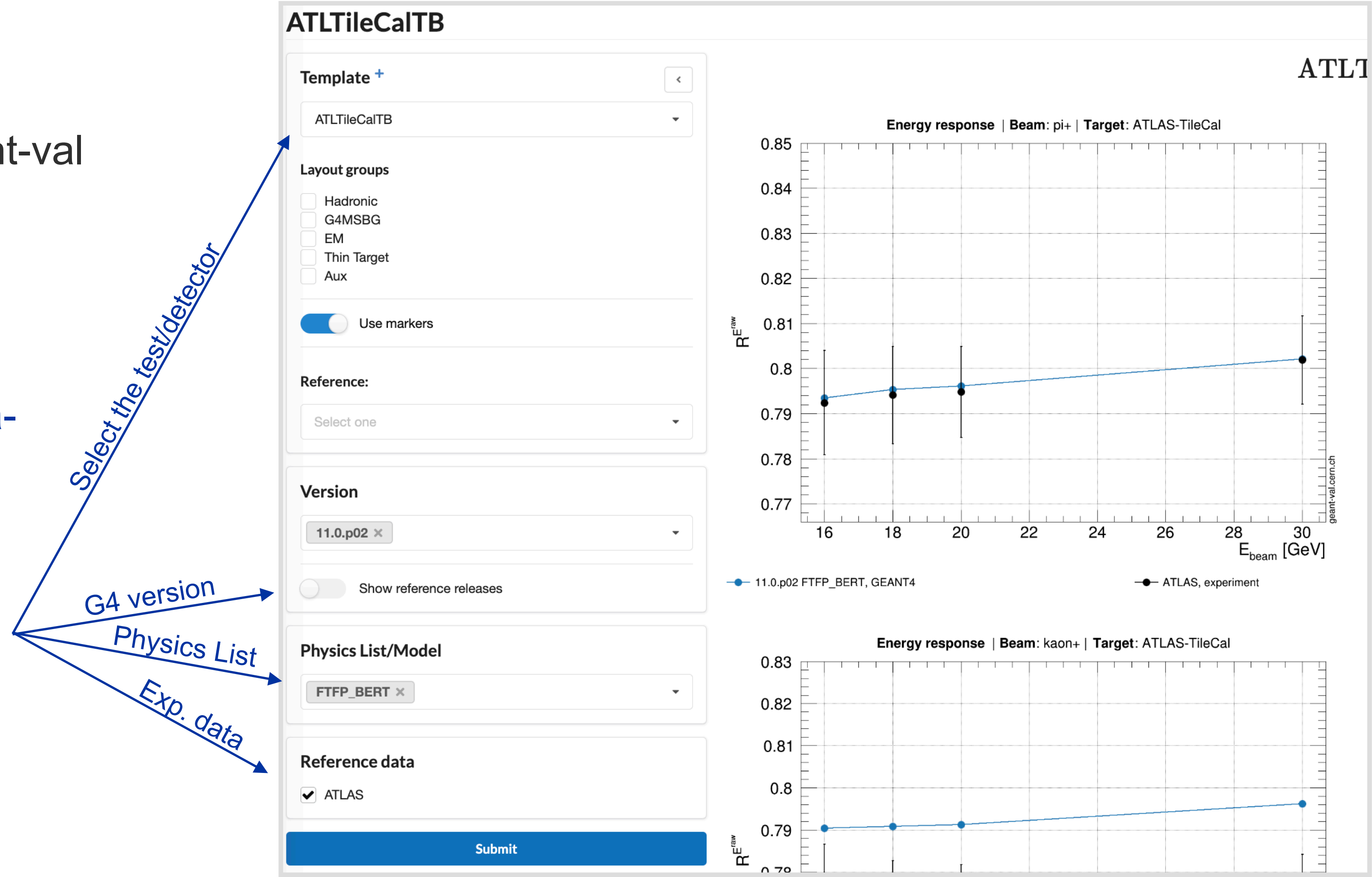
Need new validation studies to foresee the Geant4 performance @Run3

- 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].

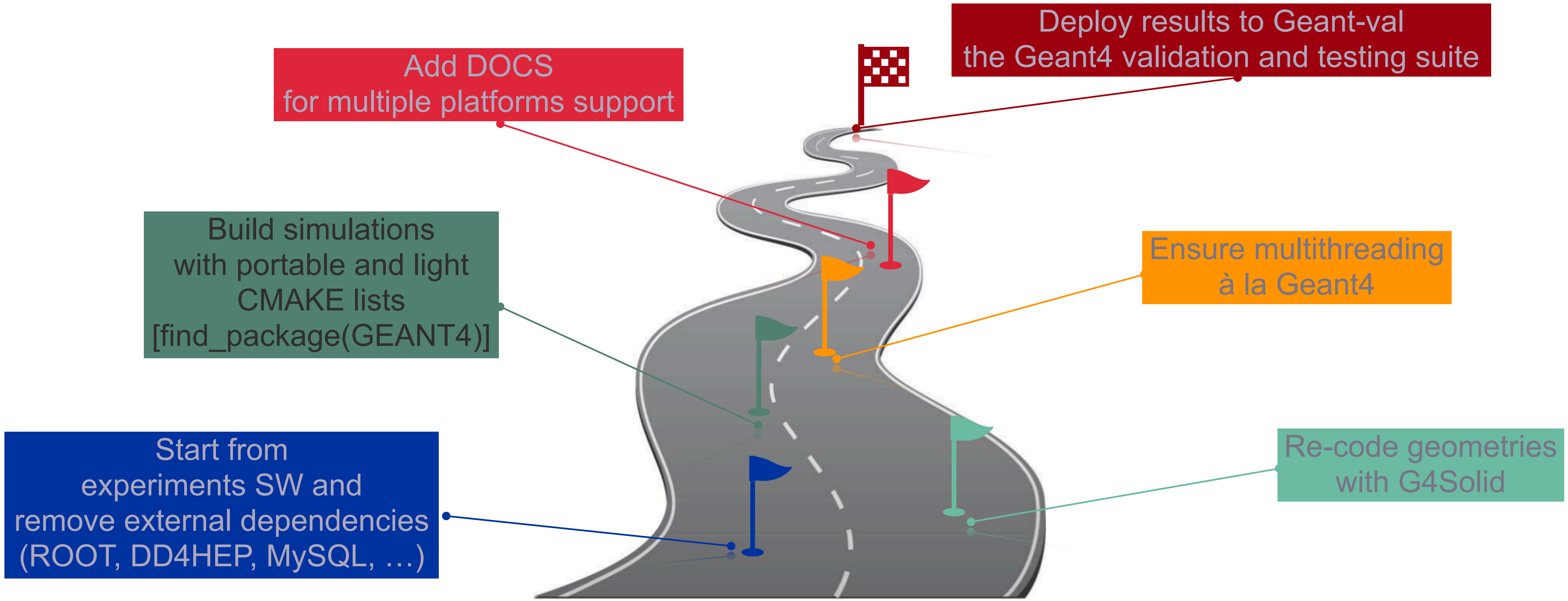
Geant-val - geant-val.cern.ch

Geant-val is the Geant4 validation and testing suite.

- $\simeq 40$ tests currently hosted on geant-val from almost every Geant4 domain.
- For the Community, it allows to:
  - Deploy results on a common data-base and fetch the information via a web-interface.
- Results in the following deployed on geant-val.

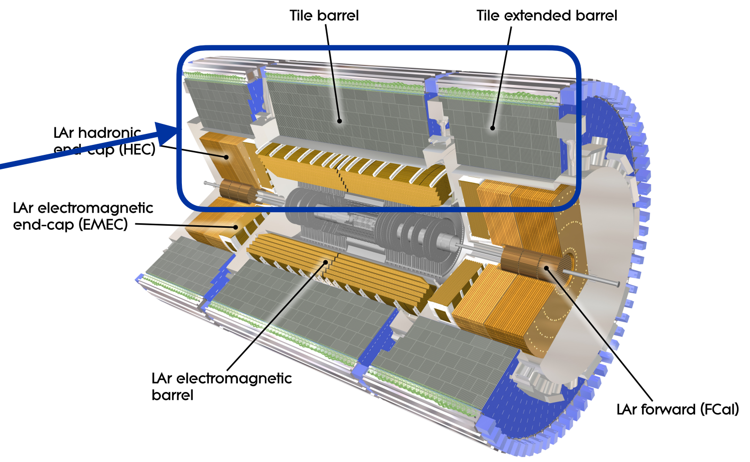


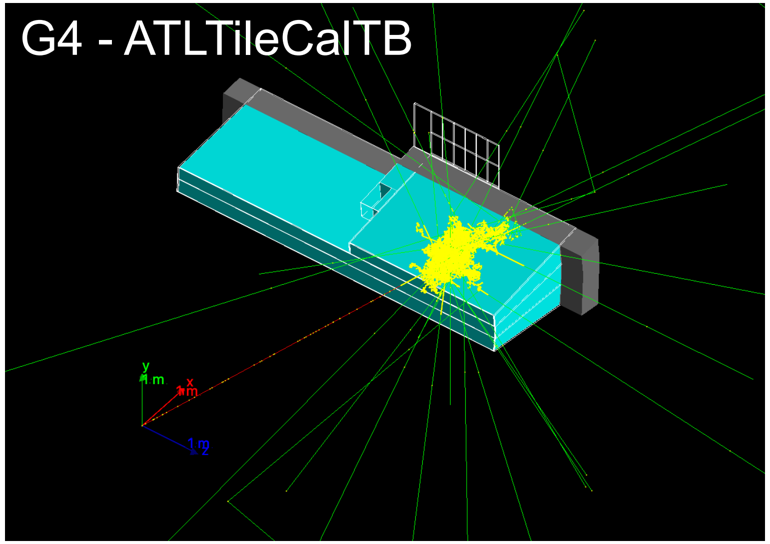
From experiments to geant-val, a winding road



ATLAS Tile Calorimeter beam test

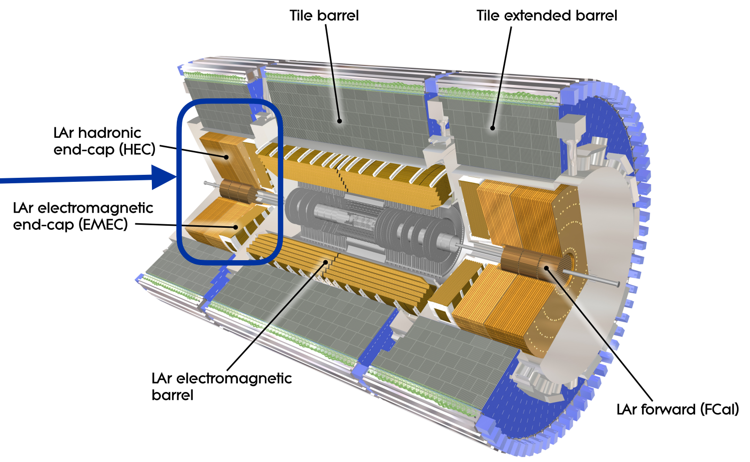
- ATLAS TileCal:
  - Mostly used to reconstruct hadronic jets in the range $|\eta| < 1.7$ thanks to 3 cylinders containing 64 modules each.
  - Measures light in scintillating tiles immersed in iron.
    Readout is grouped in pseudo projective cells with each layer readout by two PMTs.
  - Each barrel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

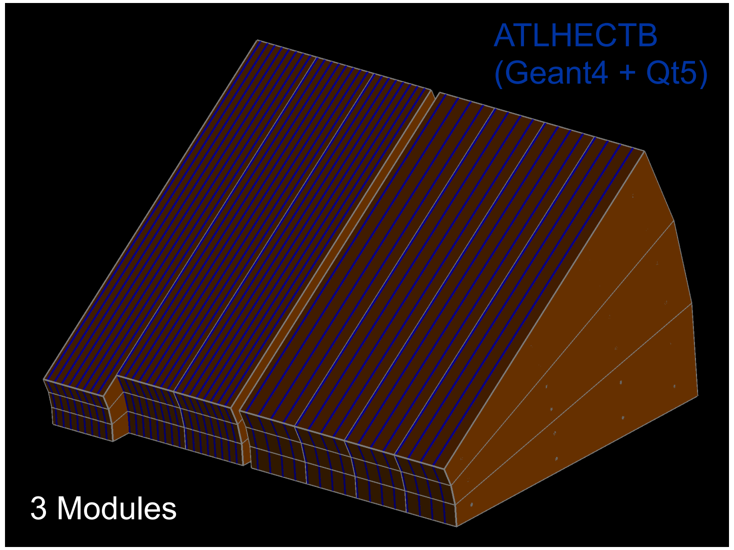




ATLAS Hadronic End-Cap Calo beam test

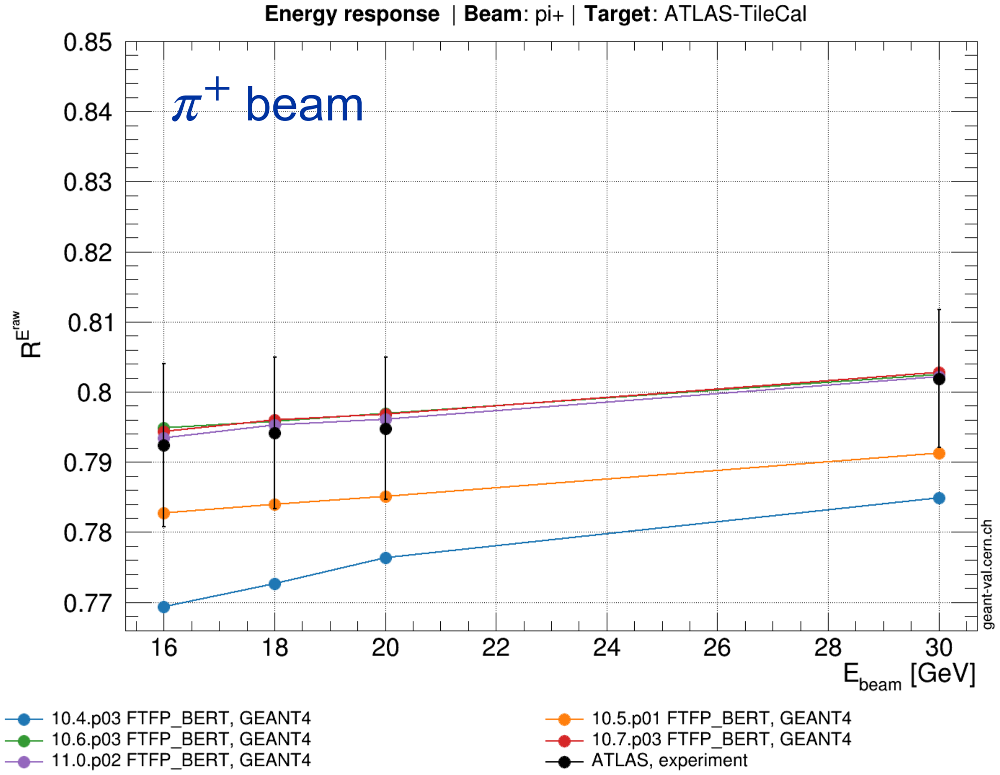
- The ATLAS HEC:
  - Covers the range $1.5 < |\eta| < 3.2$. Divided into two wheels (HEC1-2) each consisting of 32 azimuthal modules.
  - It uses 8.5-mm-gap LAr sampling regions inserted between parallel copper plates, with 2.5 cm (HEC1) and 5.0 cm (HEC2) thickness.
  - It has four longitudinal layers 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 $\phi-$wedges.
  - Involving e^-, μ^- and hadrons with $6 \leq E_{Beam} \leq 200$ GeV.





Hadronic response - FTFP_BERT (2017-2021)

- ATLAS TileCal FTFP_BERT regression testing:
  - Hadronic response (π/e) properly described by FTFP_BERT for G4 10.6, 10.7, 11.0.
  - Constant increase in the hadronic response (π/e) observed from G4 10.4 to 10.5 to 10.6.



Experimental data from ATLAS article

Hadronic response - G4 11.0 PL comparison

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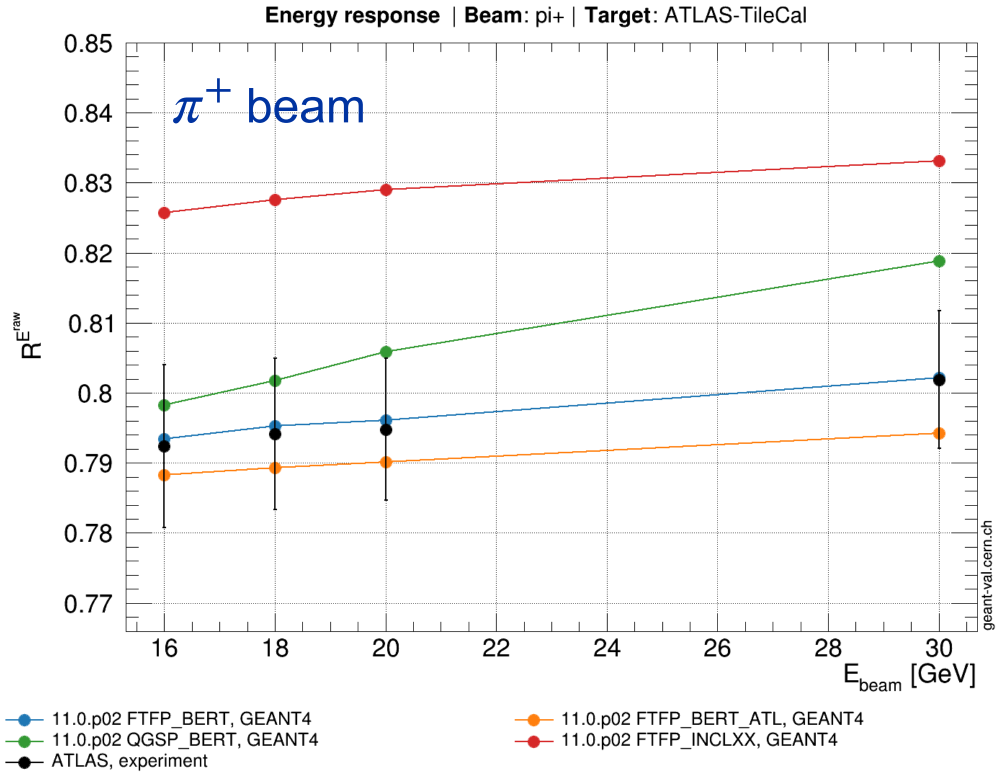
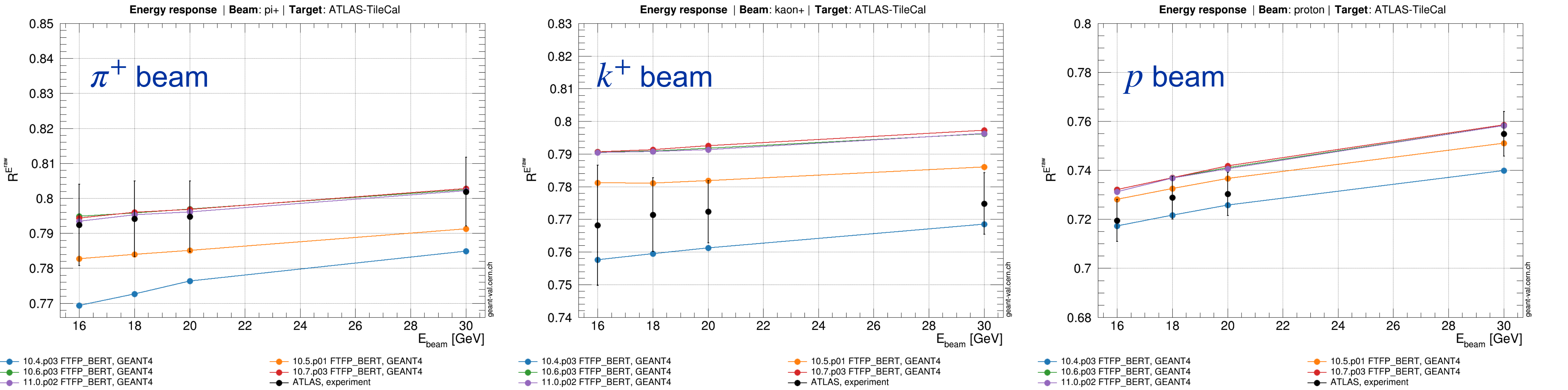
- ATLAS TileCal G4 11.0 PL comparison:
  - Current description is in good agreement with data for FTFP_BERT and FTFP_BERT_ATL.
  - FTFP_INCLXX producing shower responses $\simeq 5\ \%$ higher than the experimental reference.



Experimental data from ATLAS article

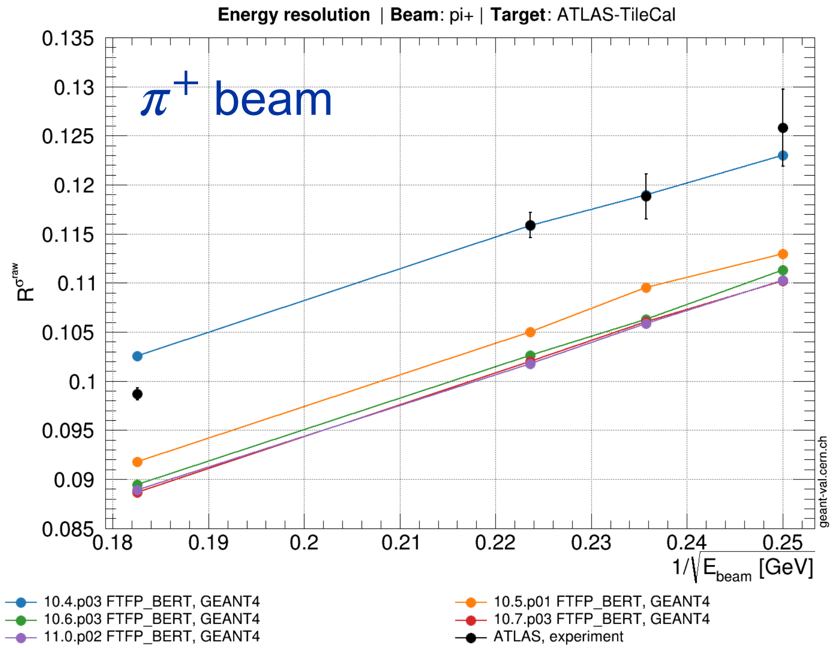
Hadronic response - π^+, k^+, p

- Excellent work by ATLAS to disentangle contributions from π^+, k^+ and p in the ATLAS TileCal:
  - Visible difference in the response to p and π^+: (my opinion) 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.



Hadronic resolution - FTFP_BERT (2017-2021)

- ATLAS TileCal FTFP_BERT regression testing:
  - π^+ response fluctuations in good agreement with data for G4 10.4.
  - We observe a constant reduction of the response fluctuations from 10.4 to 10.5 to 10.6.
    Currently FTFP_BERT is $\simeq 20\,\%$ off w.r.t. ATLAS.



Experimental data from ATLAS article

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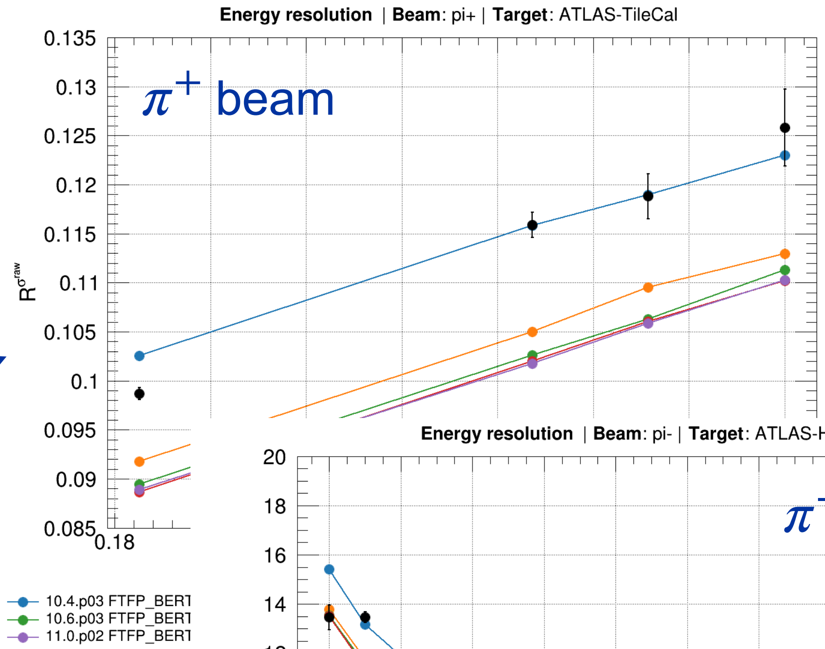
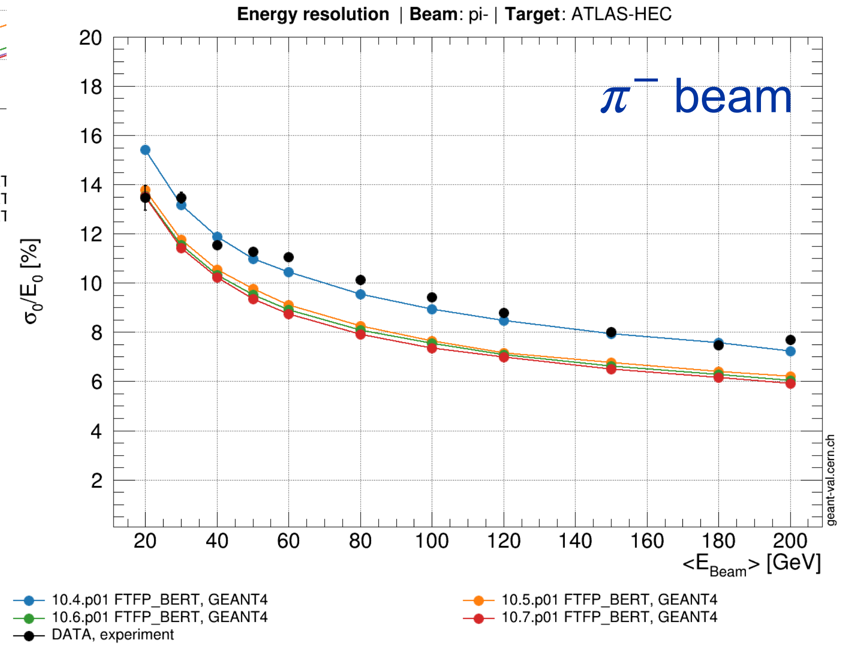
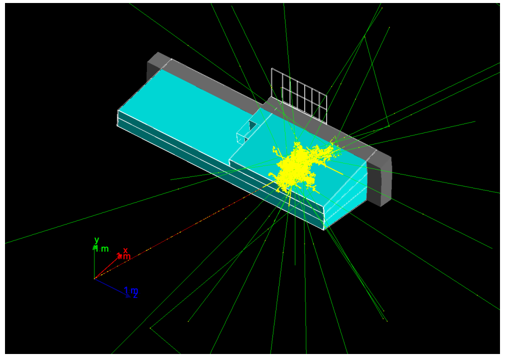
TIleCal

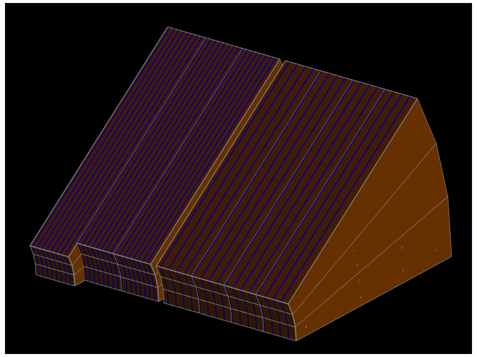


- **ATLAS HEC FTFP_BERT regressione testing:**
  - Geant4 validation study on the ATLAS HEC shows the same pattern.

HEC







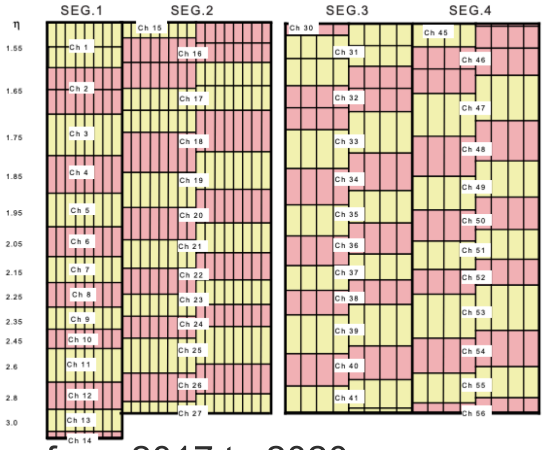
Experimental data from ATLAS article

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}.

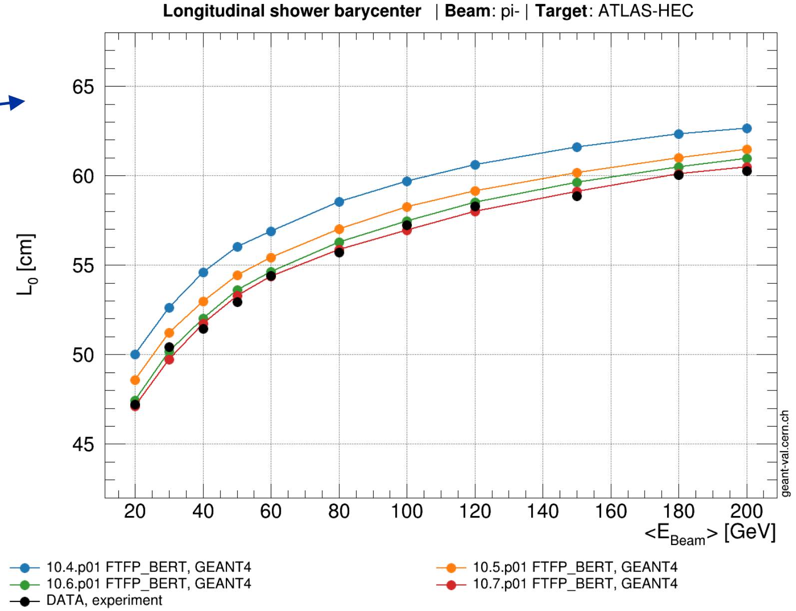
HEC
longitudinal structure

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 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.

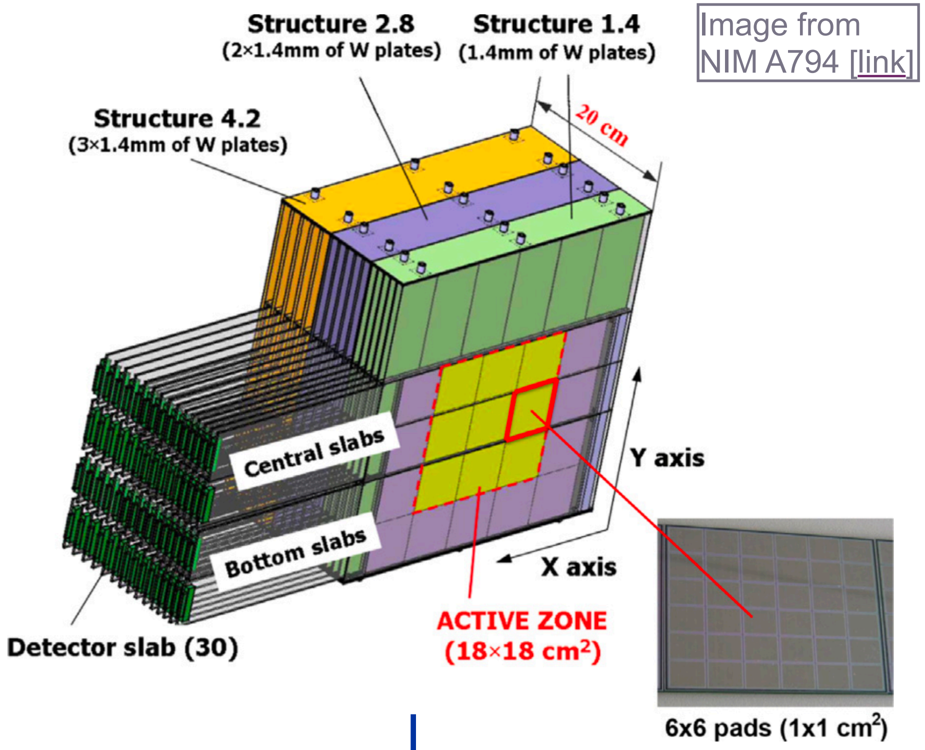
FTFP_BERT evolution from 2017 to 2020



CALICE SiW Calorimeter beam test

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

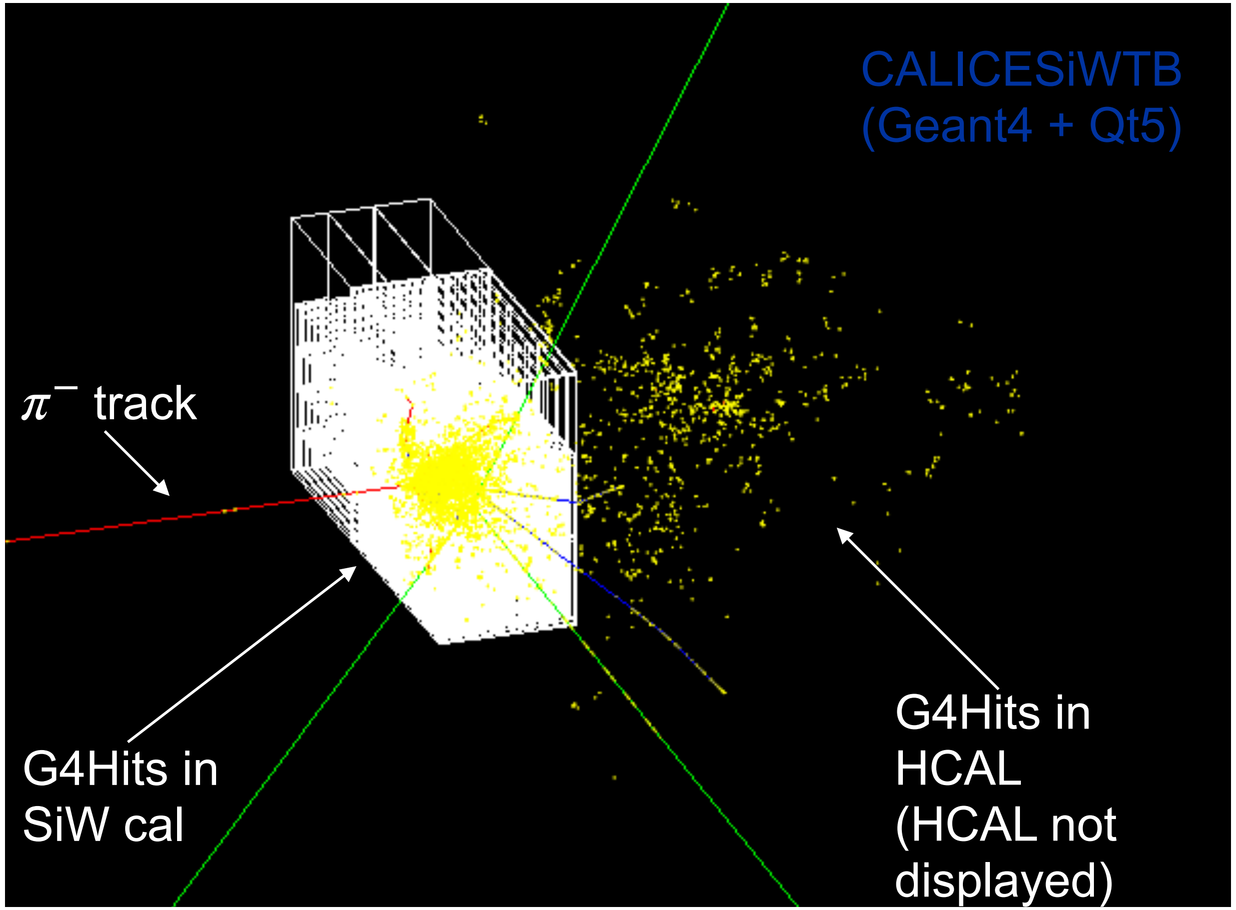
Image from NIM A794 [link]



9720 sensitive volumes

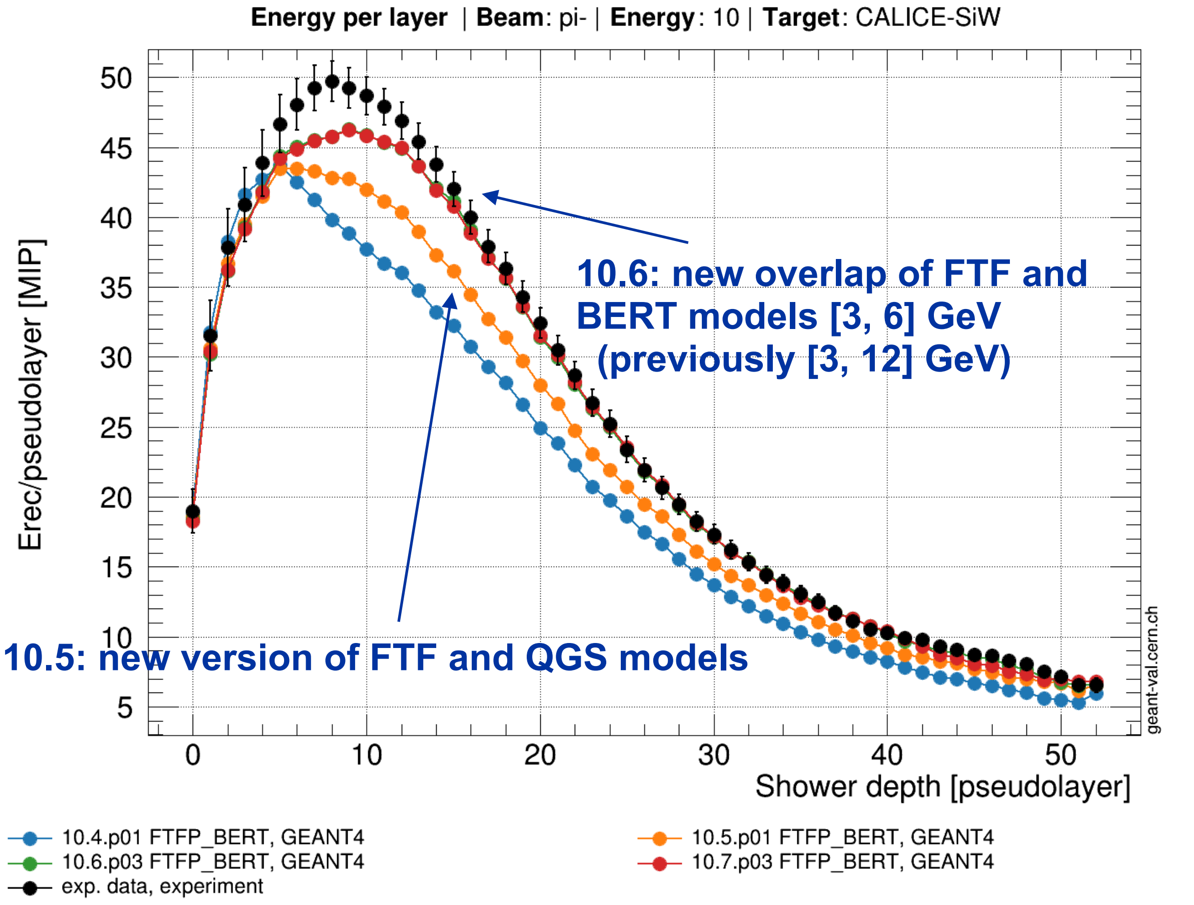
Tagging nuclear breakup events

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

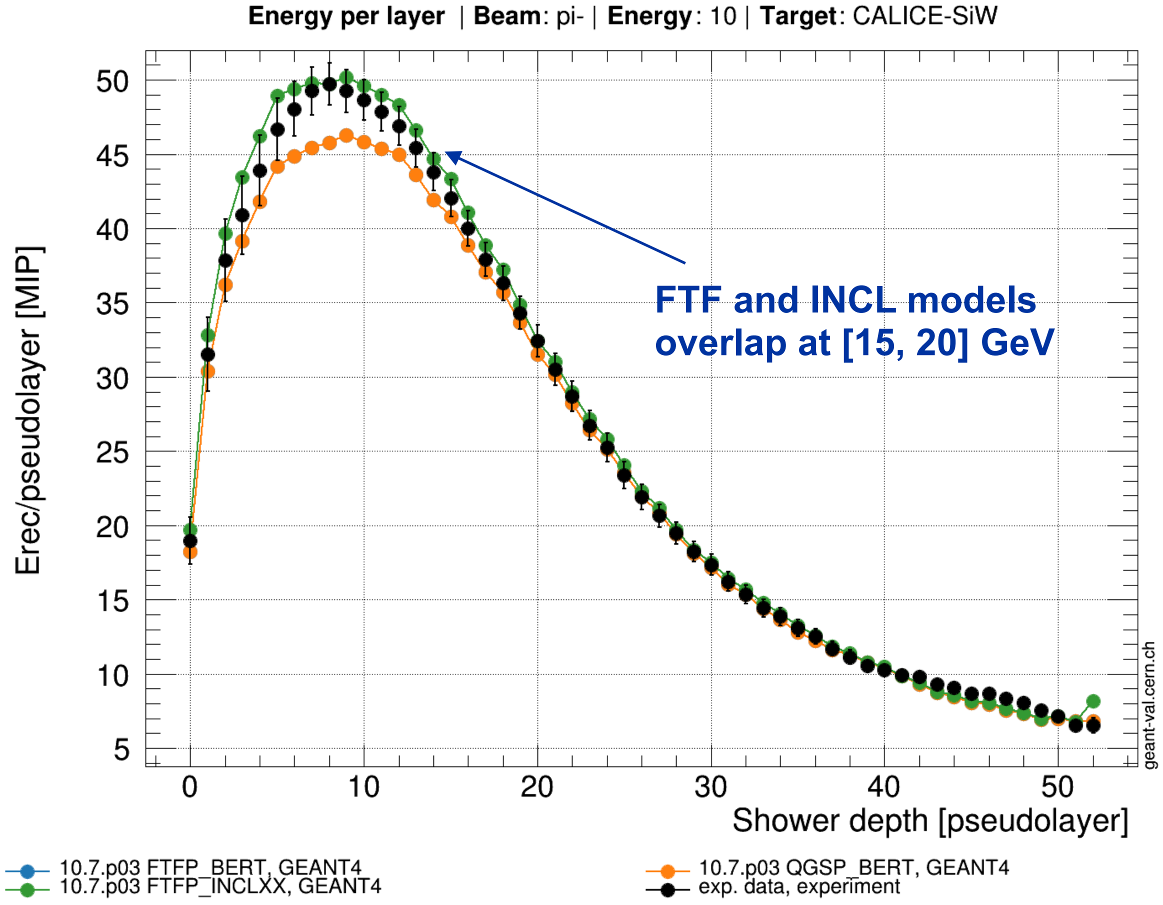


CALICE SiW: longitudinal energy distributions

10 GeV π^-, exp. data from NIM A794



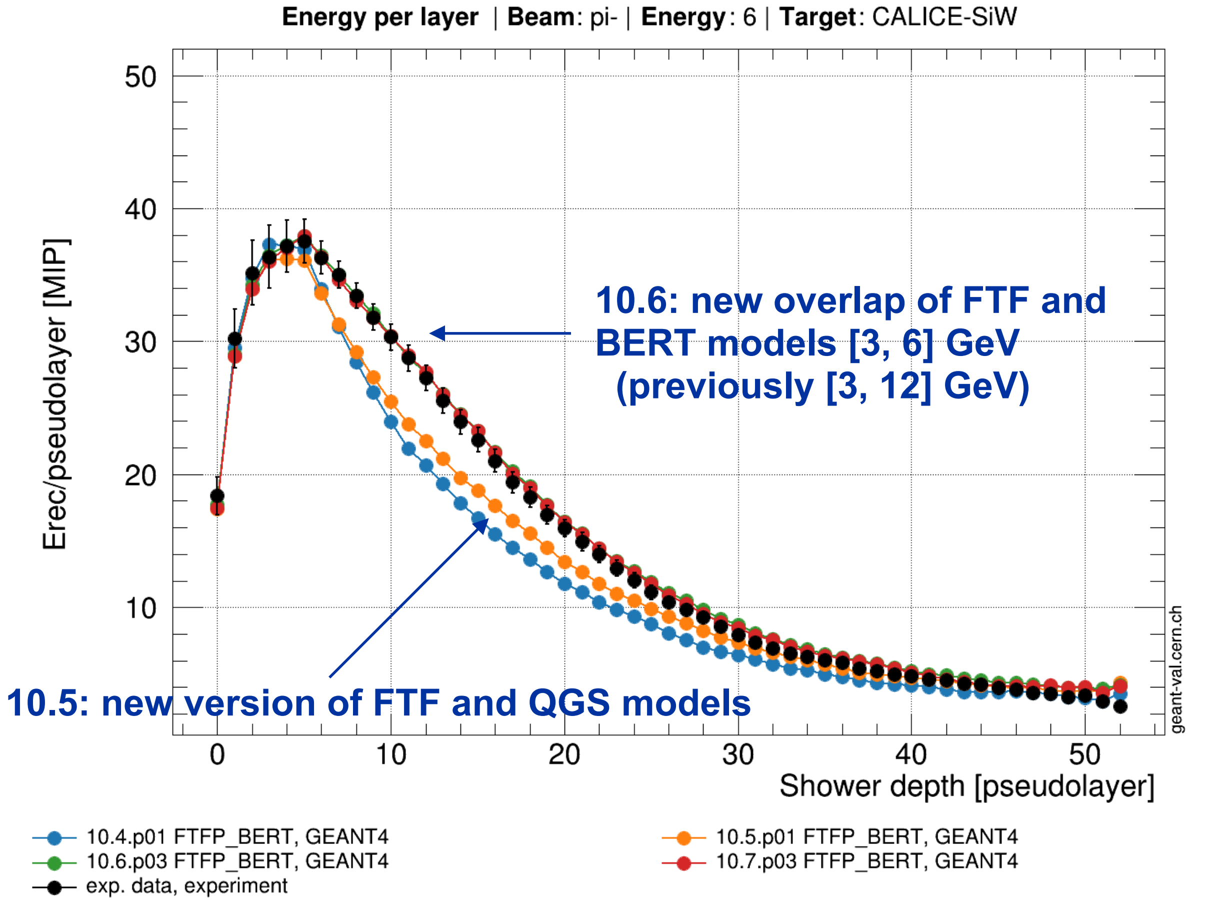
FTFP_BERT Physics List regression testing 2017-2020



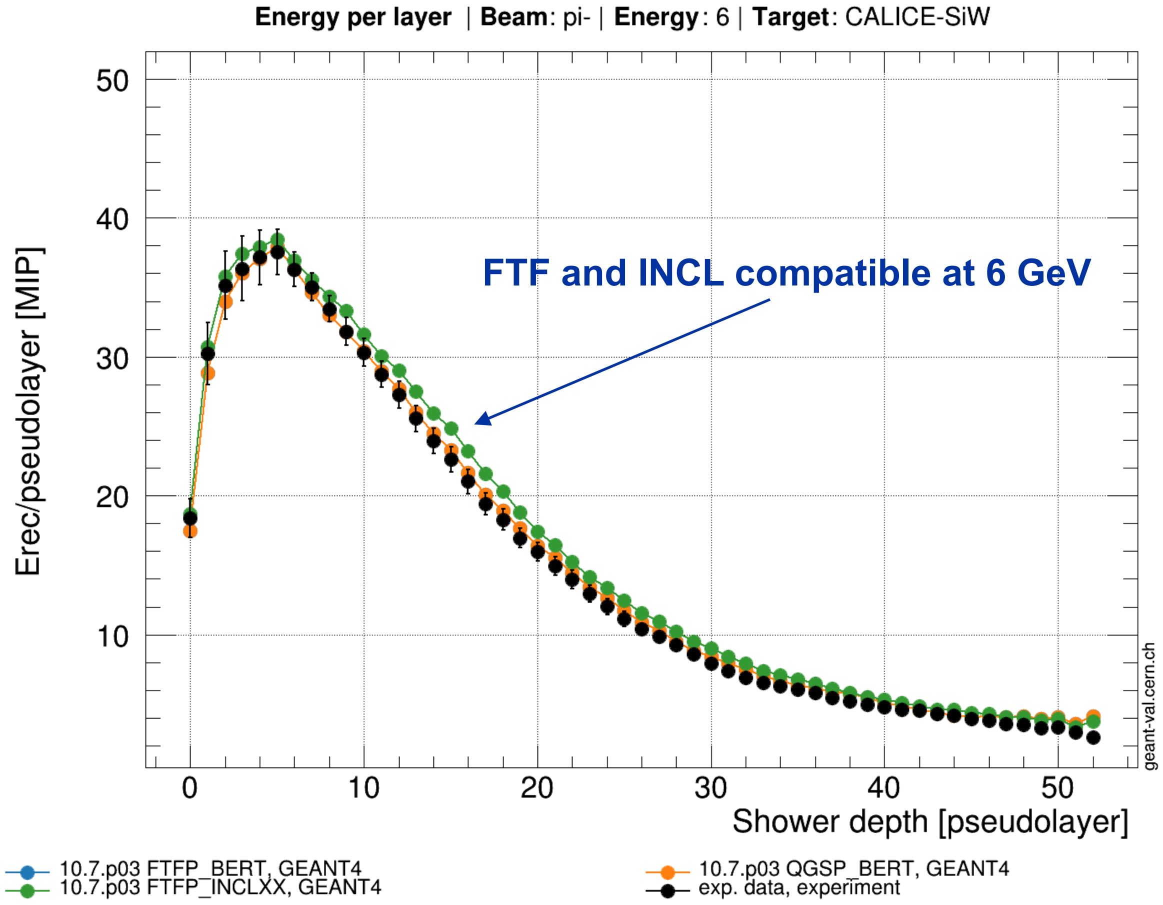
Physics Lists comparison - Geant4.10.7.p03

CALICE SiW: longitudinal energy distributions

6 GeV π^-, exp. data from NIM A794



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

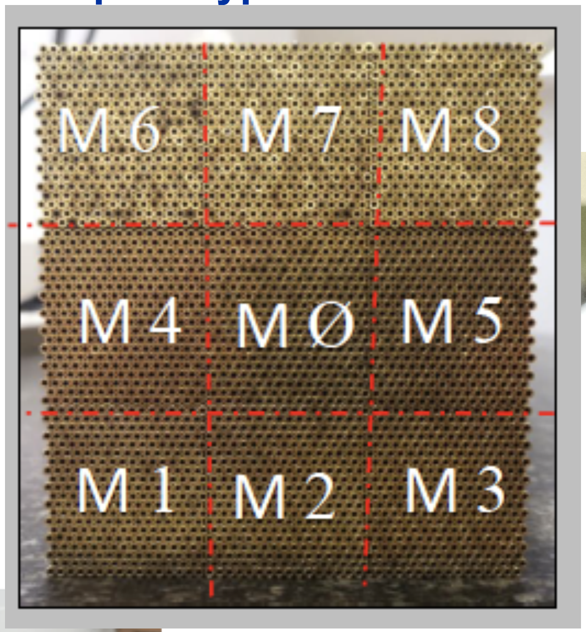


Physics Lists comparison - Geant4.10.7.p03

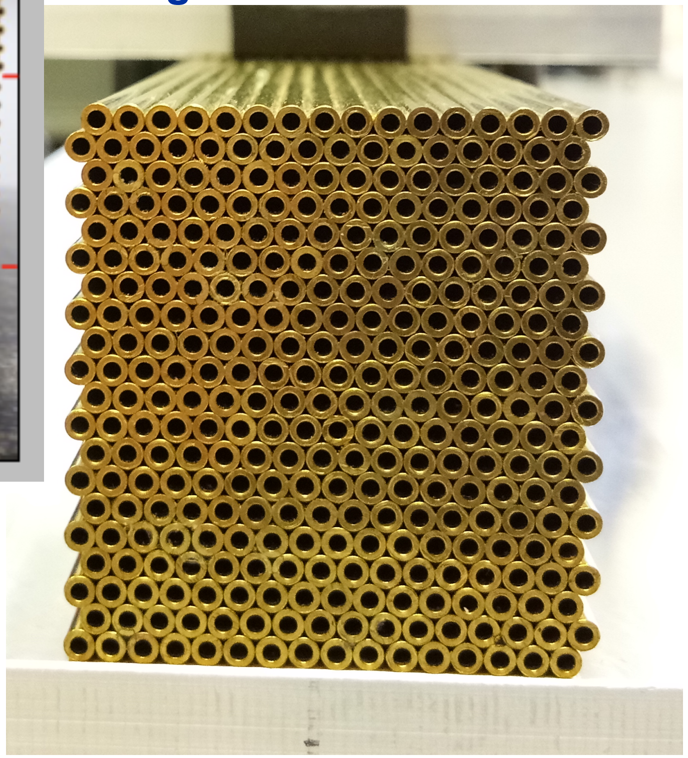
The Bucatini Dual-Readout Calorimeter within Geant4

- The 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.

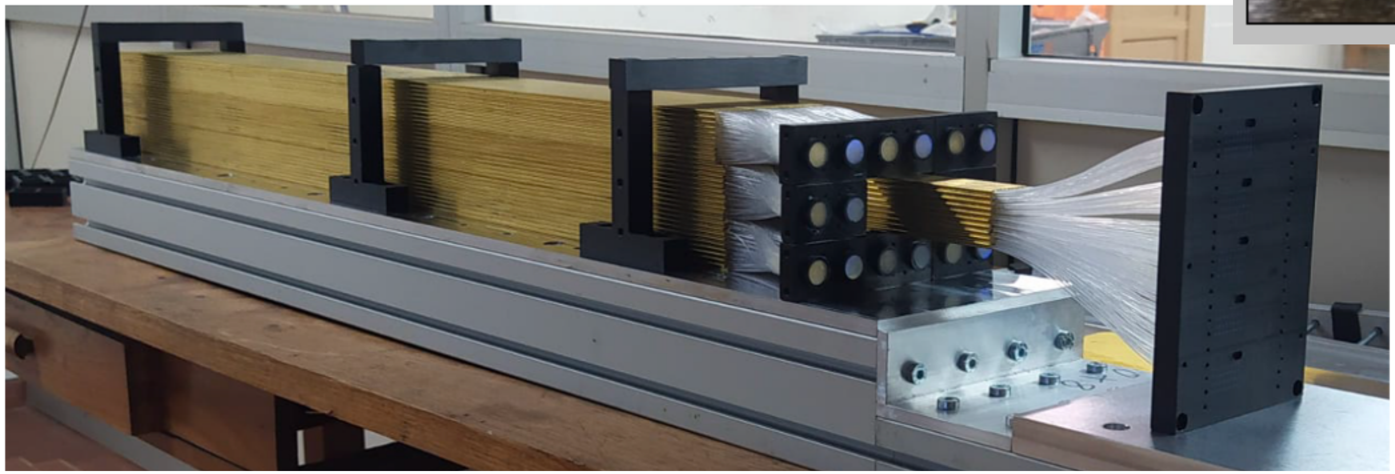
Full prototype - 9 towers



A single tower

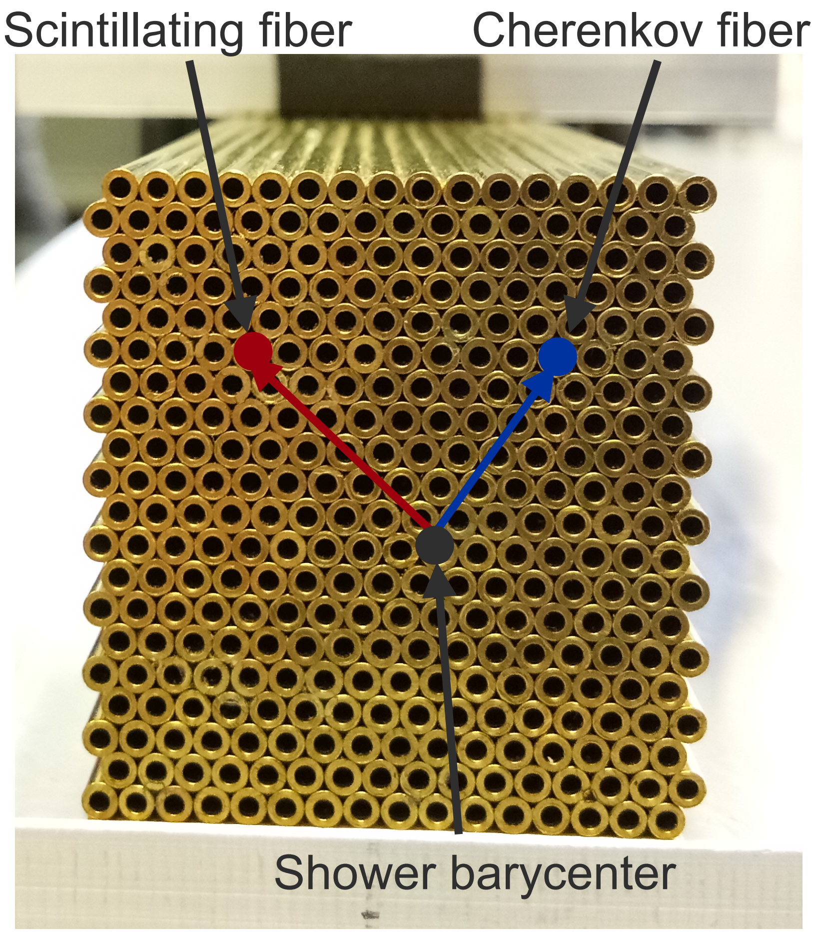


Prototype rear end



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.



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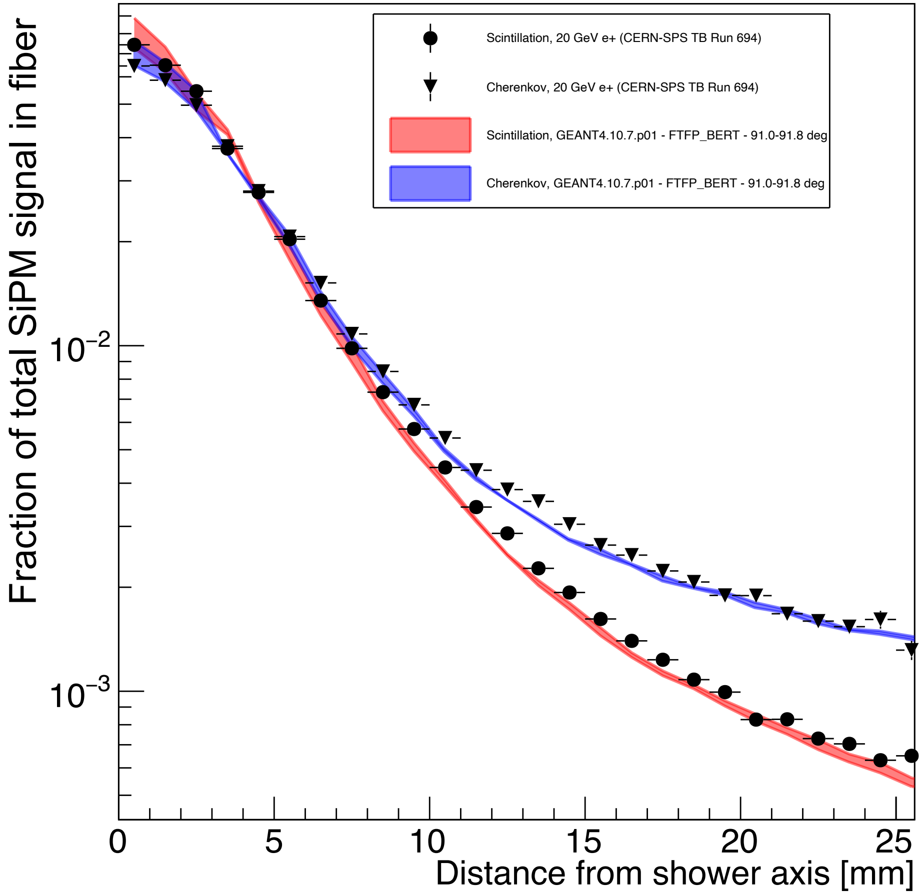
CERN SPS 20 GeV e^+ - GEANT4



Possible extension: Fluka hadronic models

- Recent G4/FLUKA.CERN collaboration is ongoing to create a G4 interface to FLUKA hadronic models (FLUKA PEANUT).

  Goals:

  - Give direct access to any G4 simulation to FLUKA hadronic models (might be extended to ion-nucleus models). At the moment targeting FORTRAN code, implementation of hadronic models in C++ (FLUKA++/FLUKA5) is a future step.
  - N.B. registration to FLUKA and agreement to FLUKA license is needed.

- A Geant4 example is in preparation (to be included in G4-11.2) to show how to access FLUKA.CERN hadronic cross sections and inelastic final-states from a Geant4 application.

- *Hadronic calorimeters tests housed on geant-val will soon be tested against FLUKA hadronic models with no additional efforts!*

Take home messages

- **GEANT4 needs experiments and experiments need Geant4.**
- 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!*
- The benefit involves much more than better physics models, *e.g.*:
  - We are close to a prototype to use external hadronic models in a single Geant4 application.
  - Having a validated Geant4 standalone simulation of your detectors let us test our GPU-offloading solutions on your needs.
  - We can adapt out speeding up solutions, especially in EM-physics, to your use-cases.
- Consider collaborating with Geant4 for next validation studies [Alberto.Ribon@cern.ch - lorenzo.pezzotti@cern.ch].