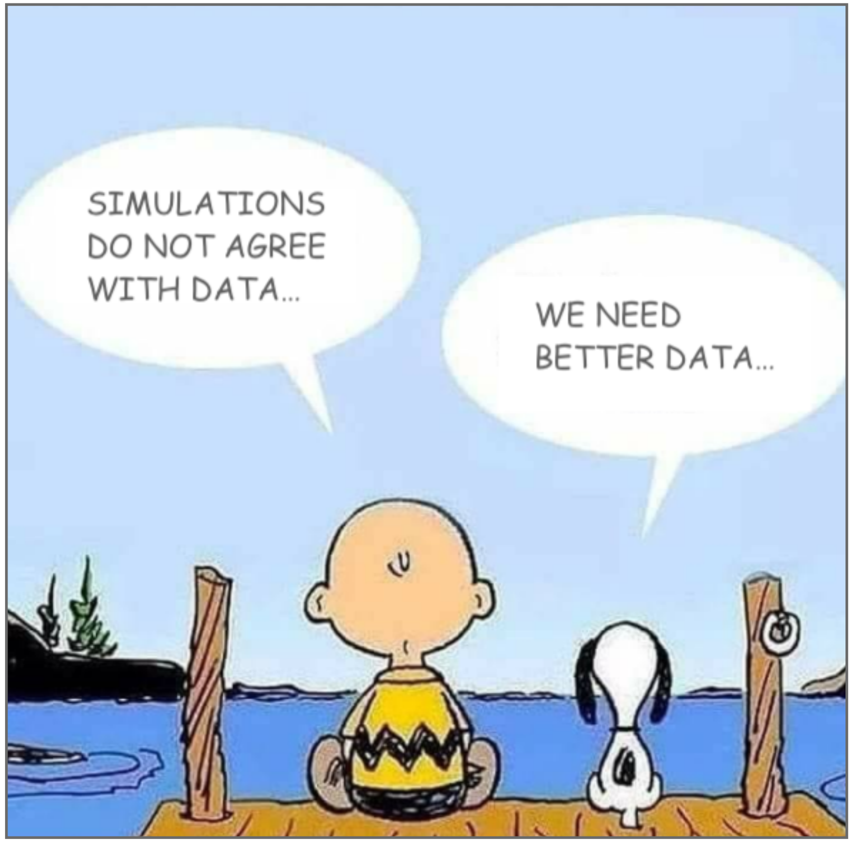
Physics validation of Geant4 via calorimeter test-beams, and their inclusion in geant-val

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



GEANT4
A SIMULATION TOOLKIT

27th Geant4 Collaboration Meeting
Rennes - 26-30 September 2022

instruments MDPI

Article

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

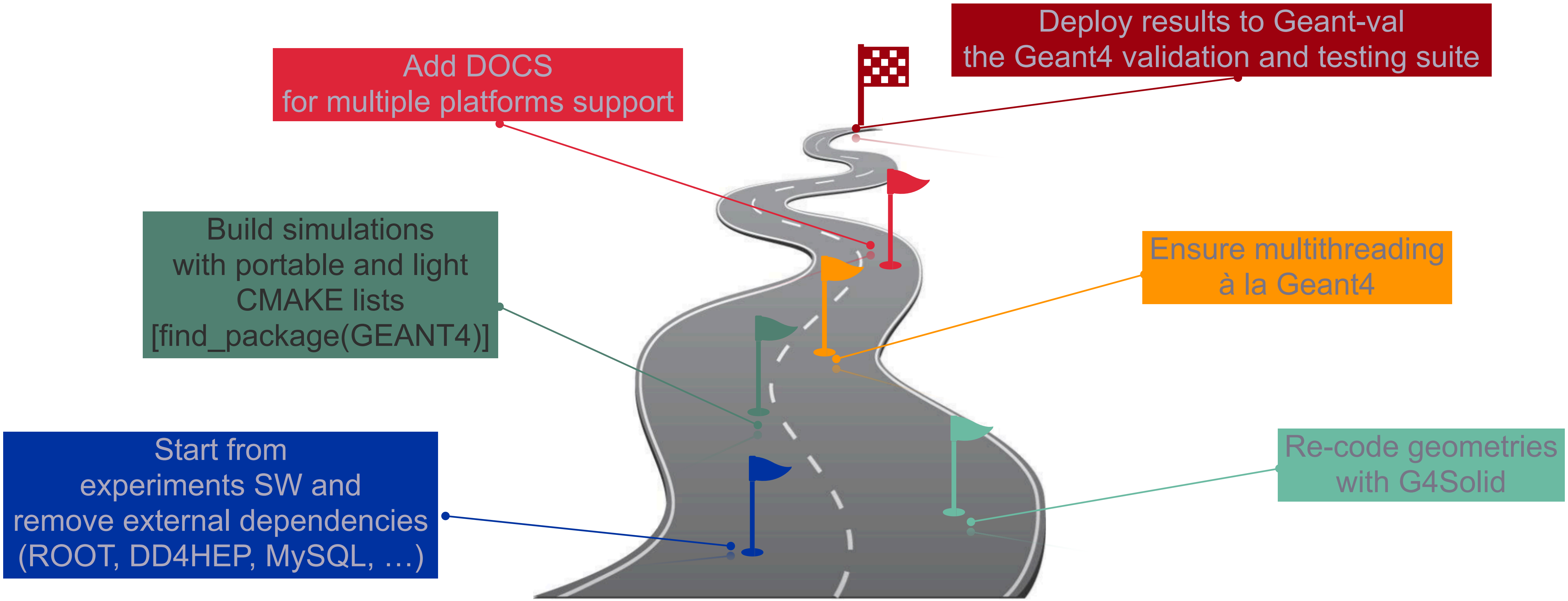
Lorenzo Pezzotti [1,*], Andrey Kiryunin [2], Dmitri Konstantinov [3], Alberto Ribon [1], Pavol Strizenec [4]
and on behalf of the Geant4 Collaboration

Partially based on [Instruments 2022, 6, 41]

Geant4 validation program exploiting beam tests

- In May 2021, the CERN EP-SFT Group started a new validation program on calorimeters beam tests.
  - Lead by the Hadronic WG under the supervision of Alberto Ribon.
- Currently focusing on:
  - ATLAS Hadronic Endcap Calorimeter (HEC) — *Completed*
  - ATLAS Tile Calorimeter (TileCal) — *Completed*
  - The 2020 Dual-Readout fiber calorimeter (em-sized) — *Ongoing*
  - CALICE SiW (em-sized, beam test involving π^-) — *Completed*
  - CMS High-Granularity Calorimeter (HGCAL) — *To be done*
  - One CALICE hadronic prototype (likely Fe/Scintillator) — *To be done*

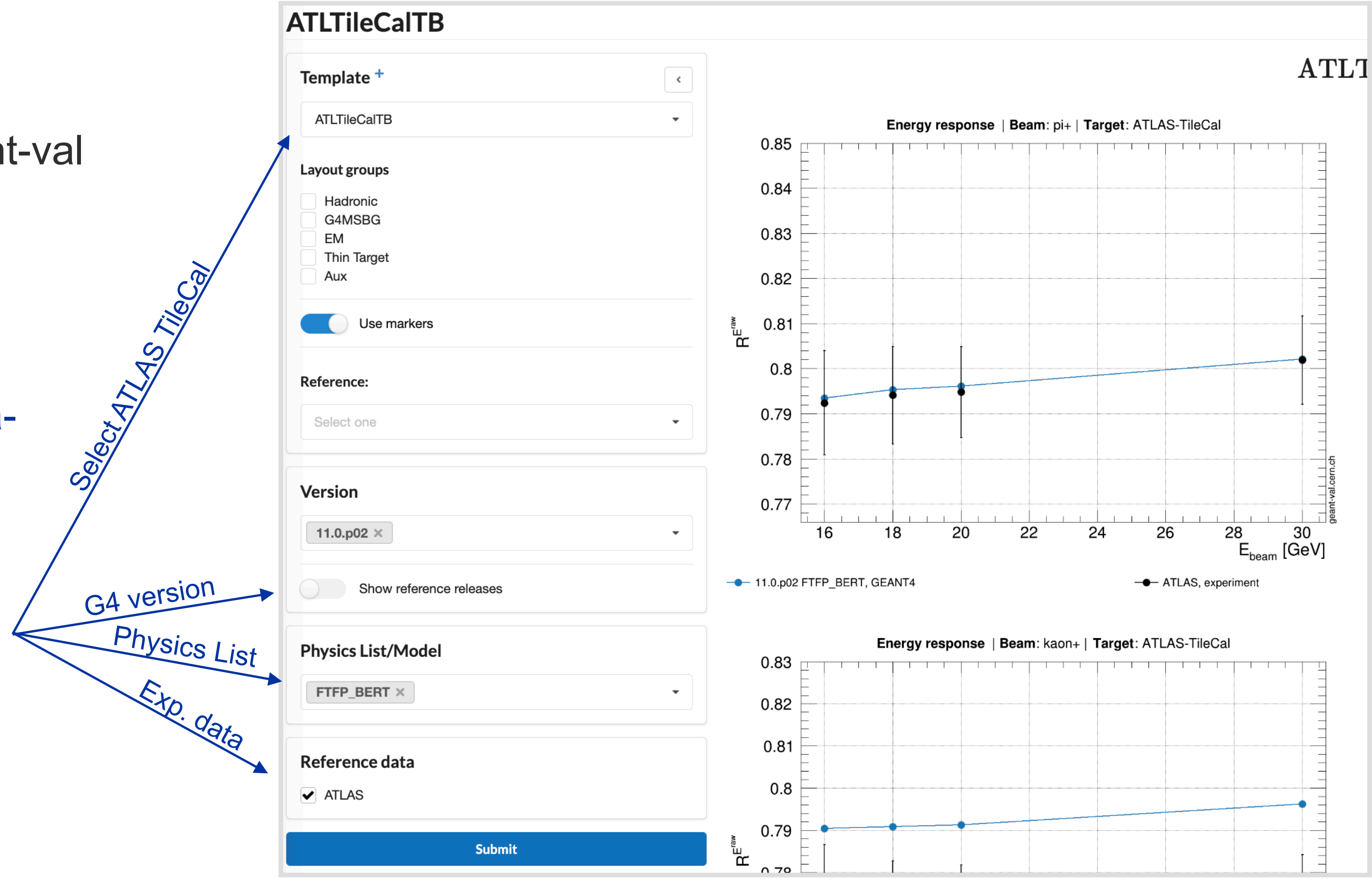
From experiments to geant-val, a winding road



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.



Geant-val usage

- **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.

Example:

1. Create config files, json files (with metadata), and submit jobs on HTCondor

params.conf

```
!PHYSLIST=FTFP_BERT, QGSP_BERT
!CONST:ENERGY_UNIT=GeV
PARTICLE | ENERGY | PHYSLIST | NEVENTS
pi- | 20. | PHYSLIST | 50000
pi- | 30. | PHYSLIST | 50000
pi- | 40. | PHYSLIST | 50000
pi- | 50. | PHYSLIST | 50000
pi- | 60. | PHYSLIST | 50000
pi- | 80. | PHYSLIST | 50000
pi- | 100. | PHYSLIST | 50000
pi- | 120. | PHYSLIST | 50000
pi- | 150. | PHYSLIST | 50000
pi- | 180. | PHYSLIST | 50000
pi- | 200. | PHYSLIST | 50000
e- | 20. | PHYSLIST | 50000
e- | 40. | PHYSLIST | 50000
e- | 50. | PHYSLIST | 50000
e- | 80. | PHYSLIST | 50000
e- | 100. | PHYSLIST | 50000
e- | 119.1 | PHYSLIST | 50000
e- | 147.8 | PHYSLIST | 50000
```

template.conf

```
/run/initialize
/gun/position -9 172 0 cm
/gun/direction 0 0 1
/gun/particle %PARTICLE%
/gun/energy %ENERGY% %ENERGY_UNIT%
/run/setCut 1.0 mm
/run/beamOn %NEVENTS%
```

run.sh

```
#!/bin/bash

# Environment variables
export PHYSLIST="%PHYSLIST%"

# Execute
ATLHECTB -m ATLHECTB.mac -pl %PHYSLIST%
-t 2
```

```
python mc-config-generator.py submit -t ATLHECTB -d OUTPUT -v 10.7.p01 -q "testmatch" -r
```

2. Run analysis:

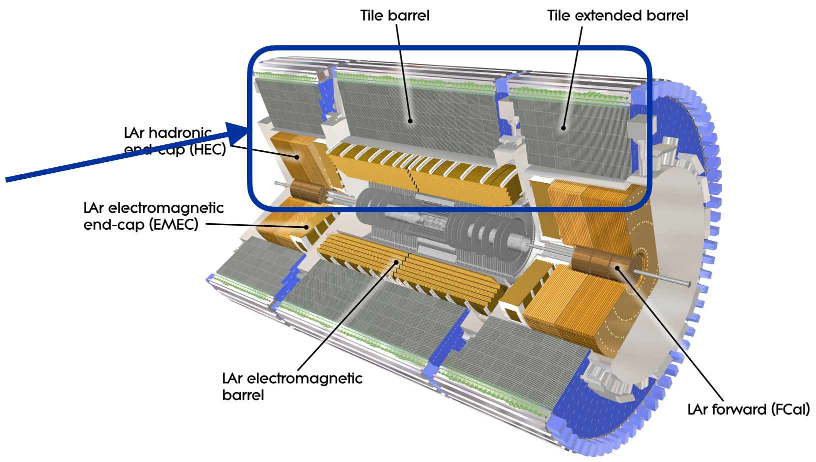
```
python mc-config-generator.py parse -t ATLHECTB -d OUTPUT
```

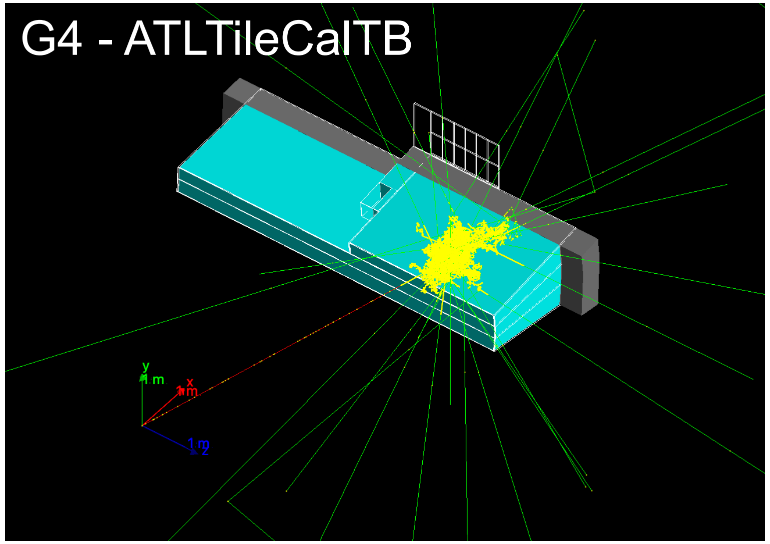
3. Deploy jsons on geant val database:

```
find . -name '*.json' | while read i; do curl -H "Content-Type: application/json"
-H "token: askauthor" --data @$i https://geant-val.cern.ch/upload; echo; done
```

ATLAS Tile Calorimeter beam test

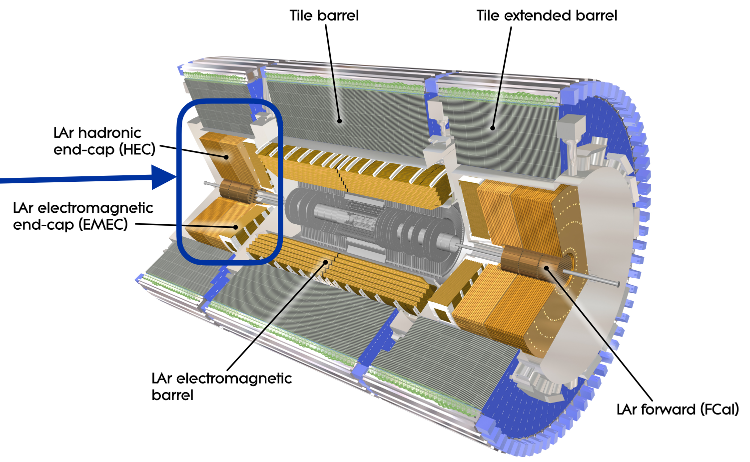
- ATLAS TileCal:
  - Mostly used to reconstruct hadronic jets in the range $|\eta| < 1.7$ thanks to 3 cylinders containing 64 modules each.
  - Measure light in scintillating tiles immersed in iron.
    Readout is grouped in pseudo projective cells with each layer readout by two PMTs.
  - Each barrel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



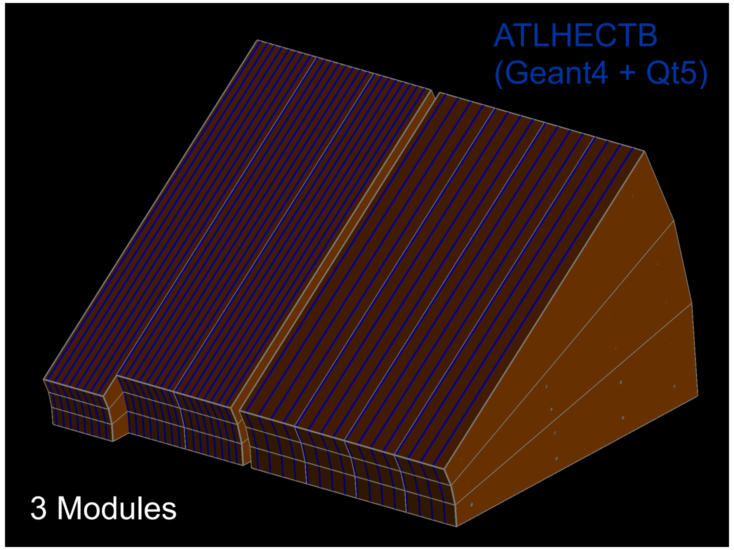


ATLAS Hadronic End-Cap Calo beam test

- 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 $\simeq 9.7\lambda_{int}$.

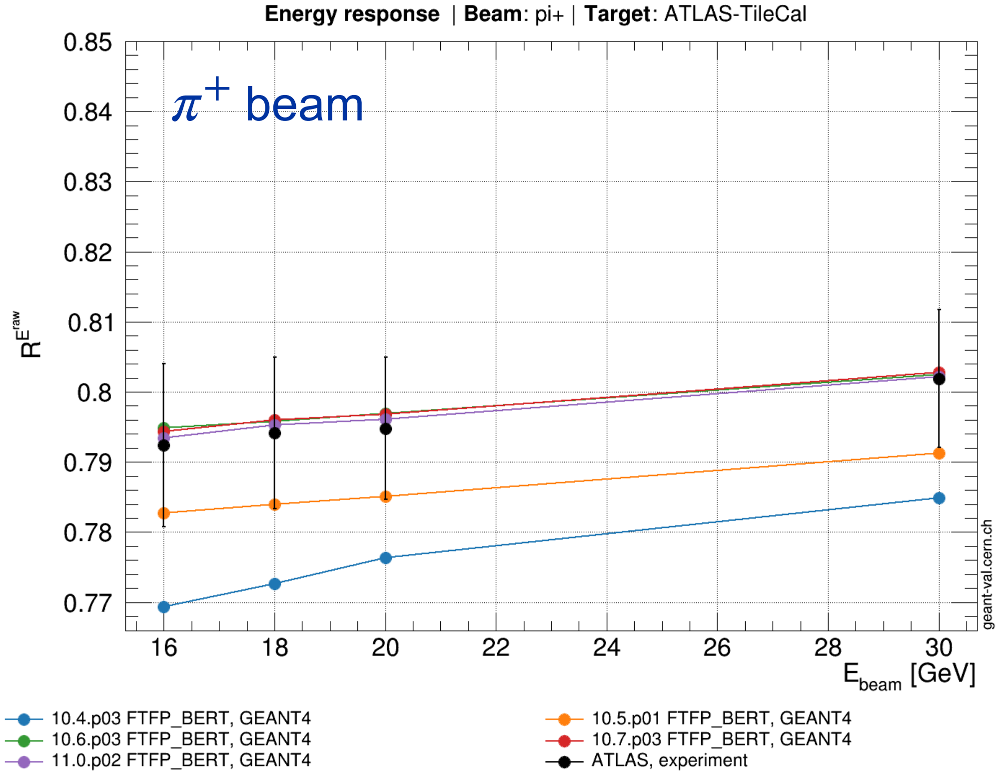


- HEC beam test:
  - Tested in 2000-2001 at CERN-SPS-H6 beam line.
  - Tests performed with 3 $\phi-$wedges.
  - Involving e^-, μ^- and hadrons with $6 \leq E_{Beam} \leq 200$ GeV.



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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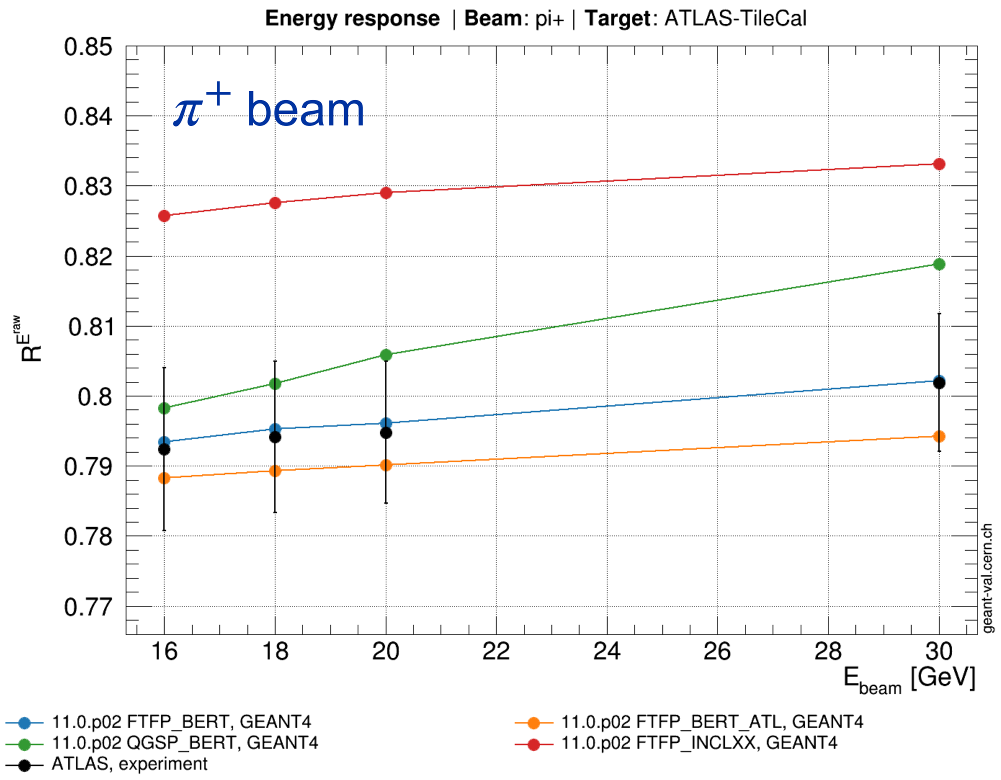
  - Constant increase in the hadronic response (π/e) observed from G4 10.4 to 10.5 to 10.6.

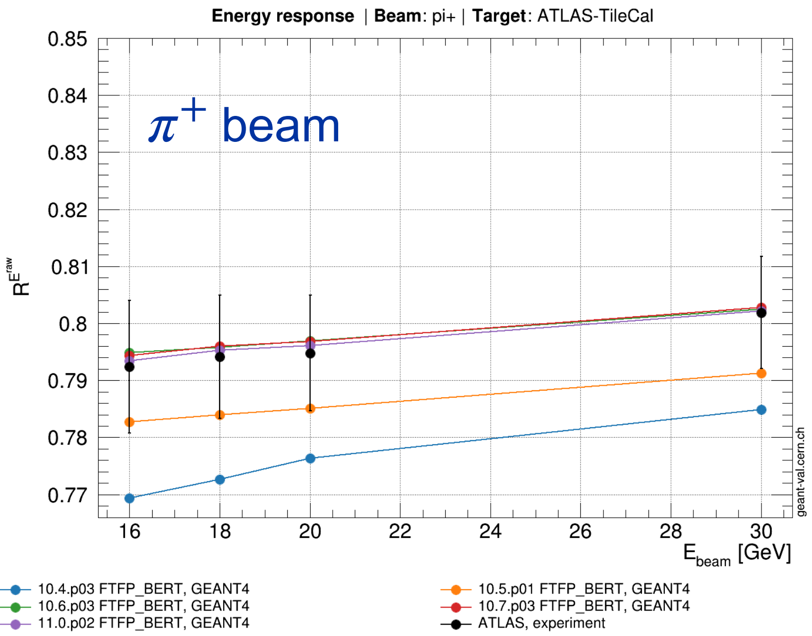
- ATLAS TileCal G4 11.0 PL comparison:
  - Current description is in good agreement with data for FTFP_BERT and FTFP_BERT_ATL.
  - FTFP_INCLXX producing shower responses $\simeq 5\,\%$ higher than the experimental reference.

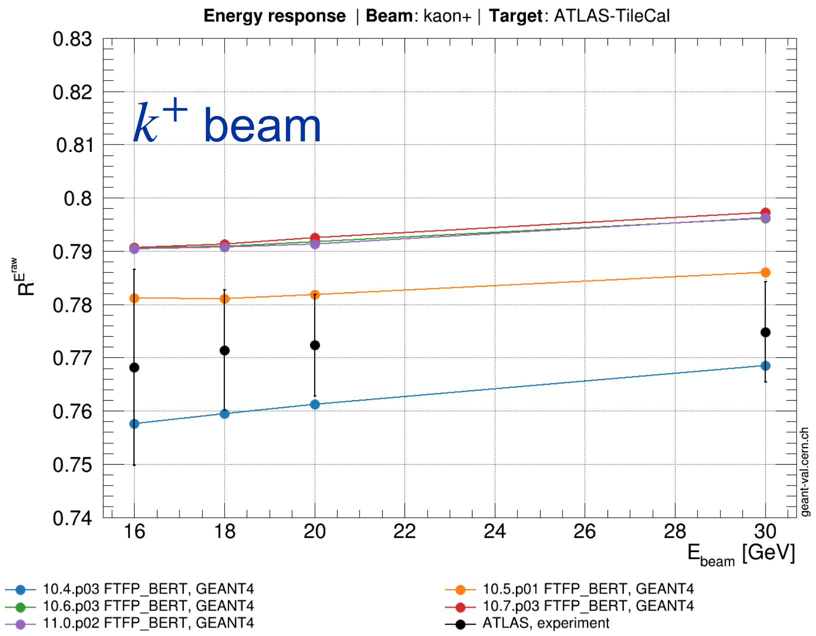


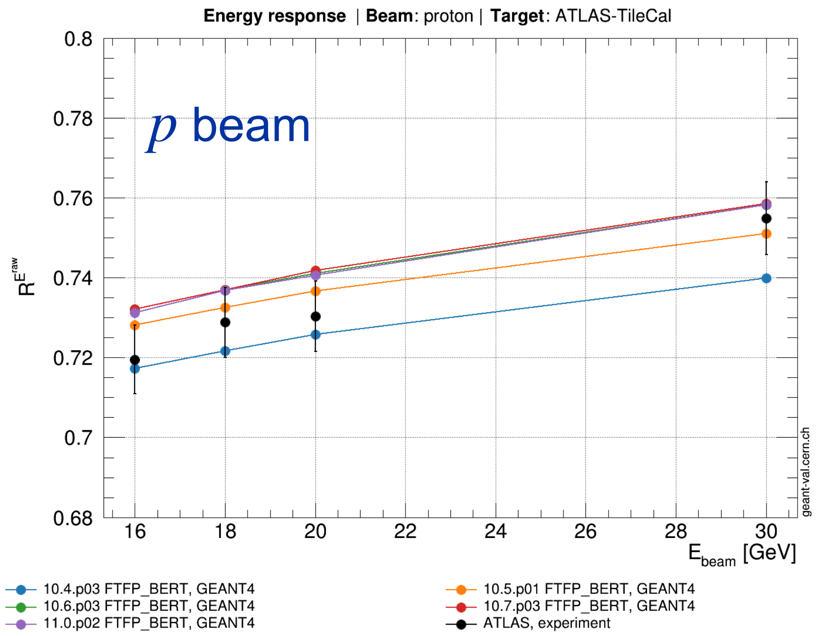
Experimental data from ATLAS article

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)

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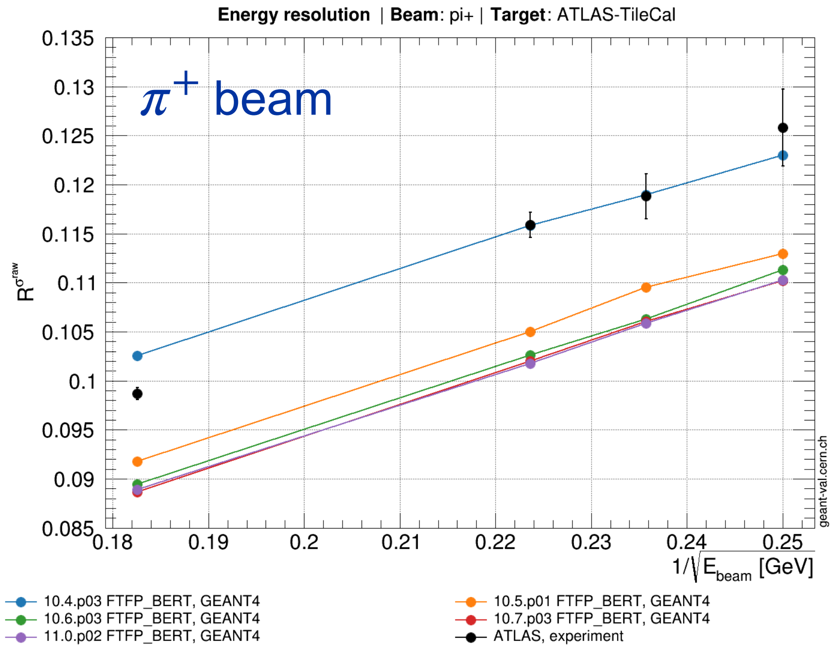
    Currently FTFP_BERT is $\simeq 20\,\%$ off w.r.t. ATLAS.



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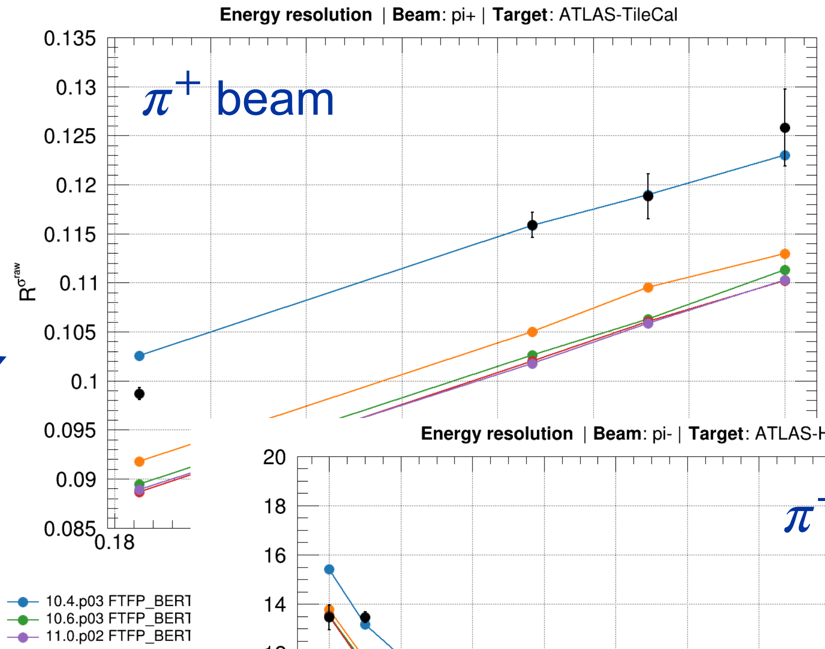
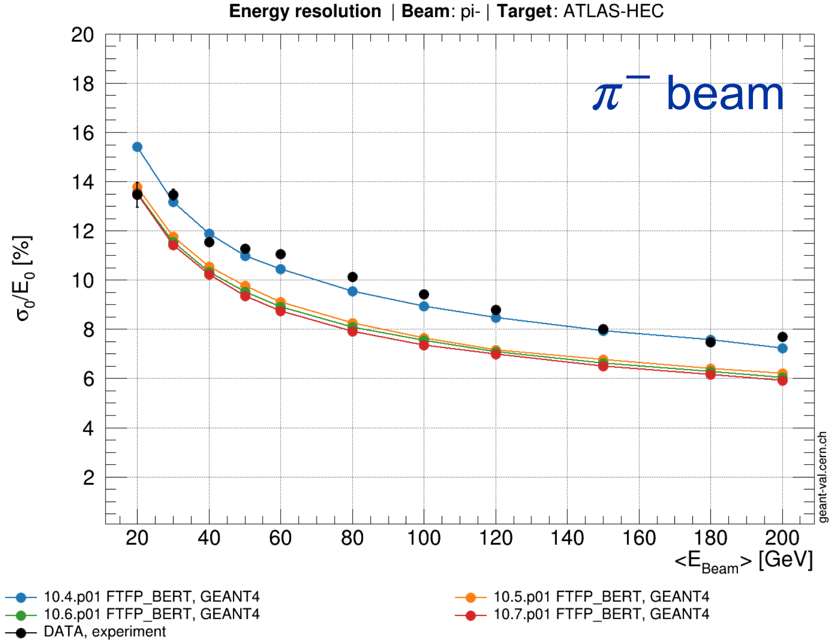
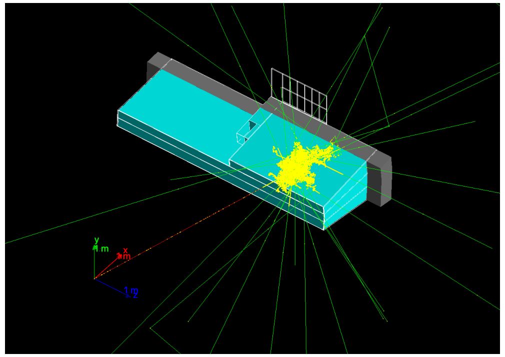
- ATLAS HEC FTFP_BERT regressione testing:
  - Geant4 validation study on the ATLAS HEC shows the same pattern w.r.t. ATLAS.

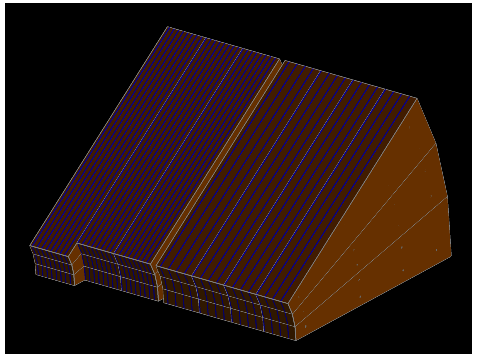
TIleCal

HEC









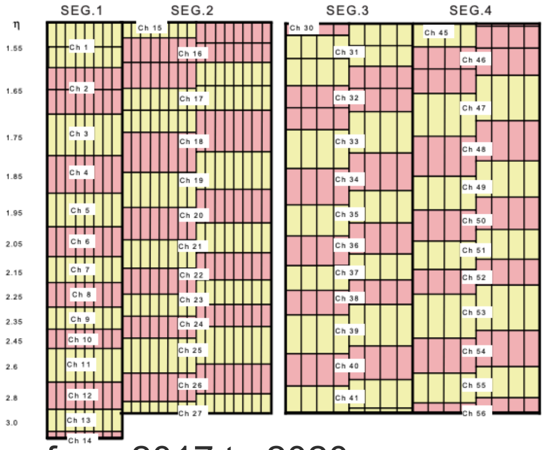
Experimental data from ATLAS article

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}.

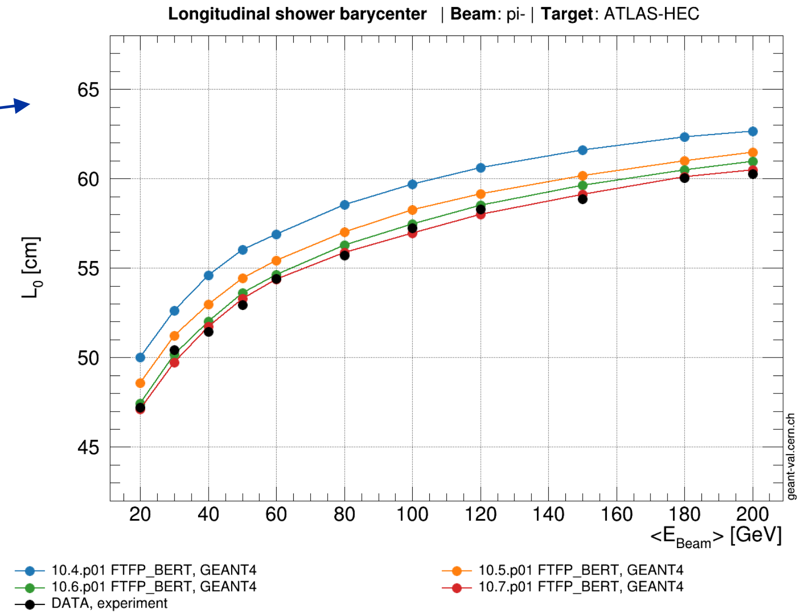
HEC longitudinal structure

HEC layer	Number of LAr gaps	HEC length [cm]	HEC length [λ_{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.

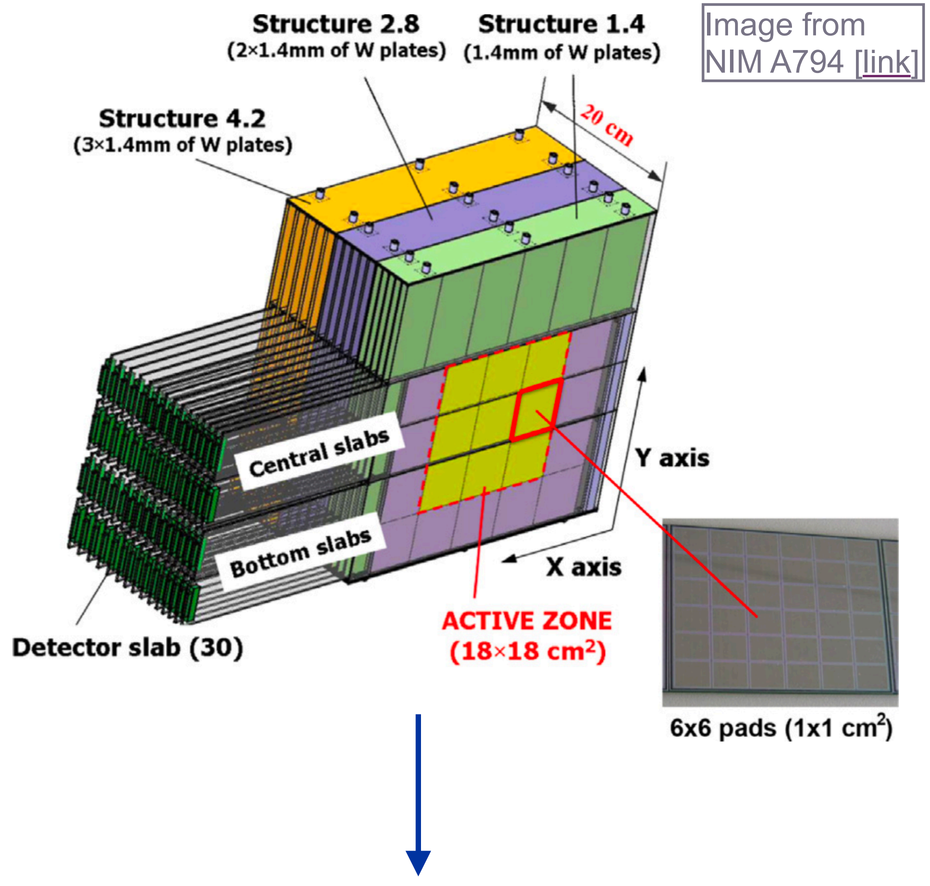
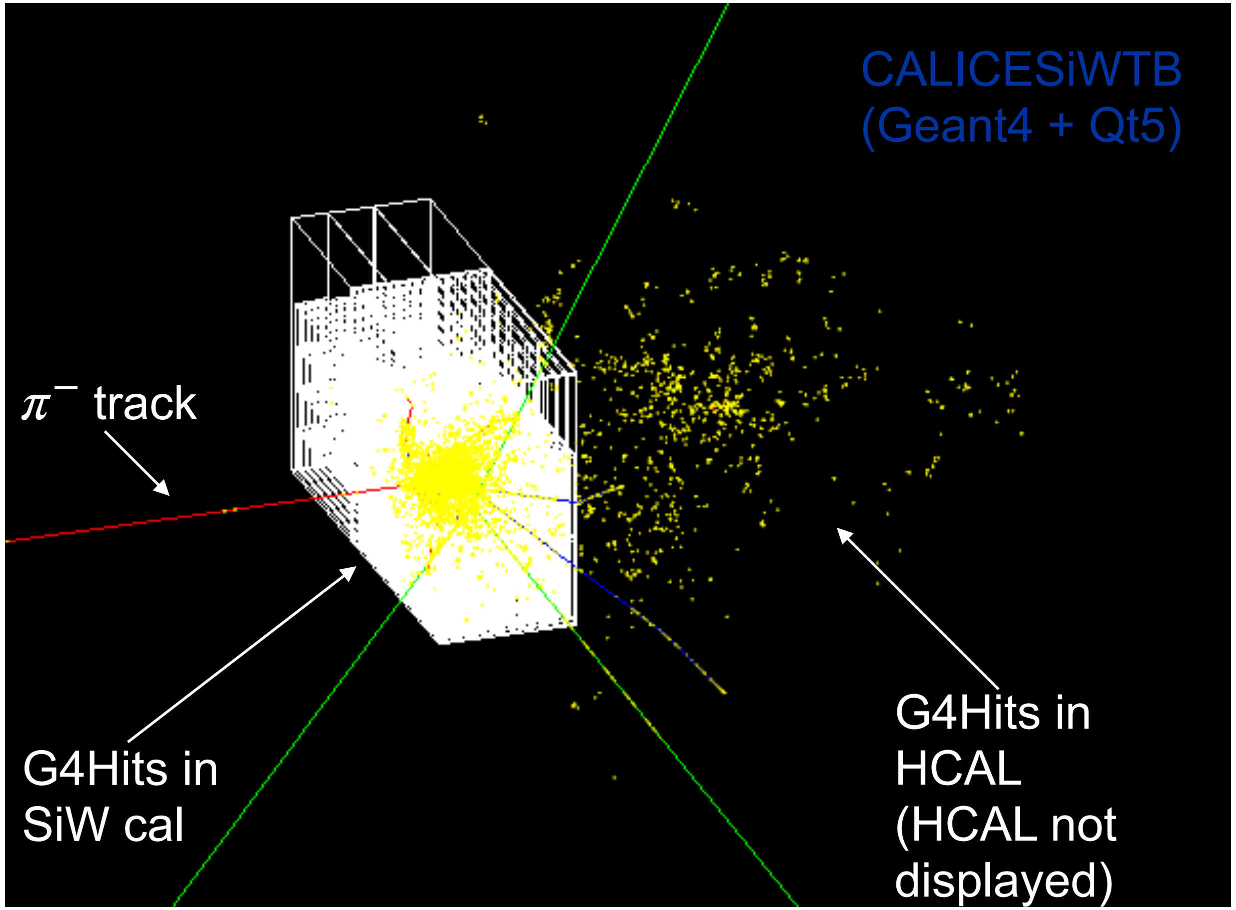


Image from NIM A794 [link]

9720 sensitive volumes

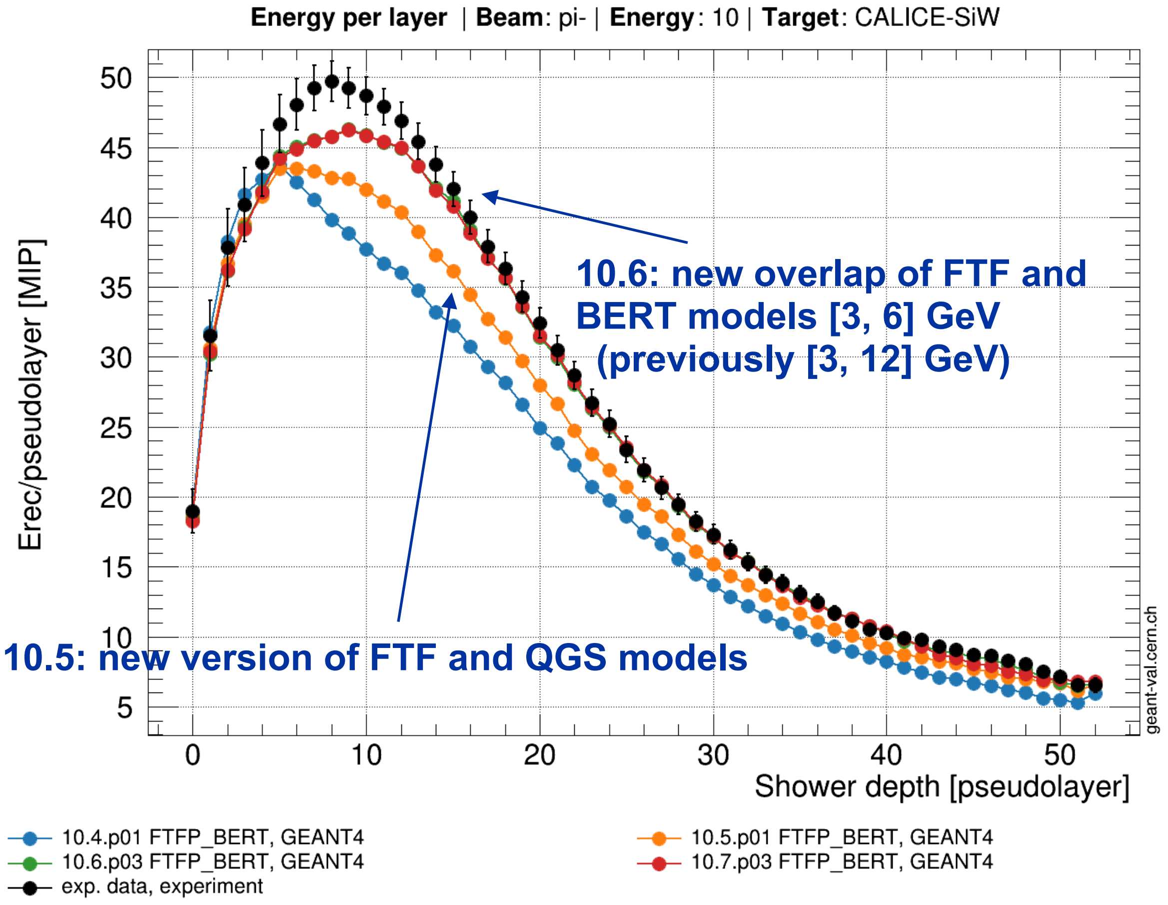
Tagging nuclear breakup events

- 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*.

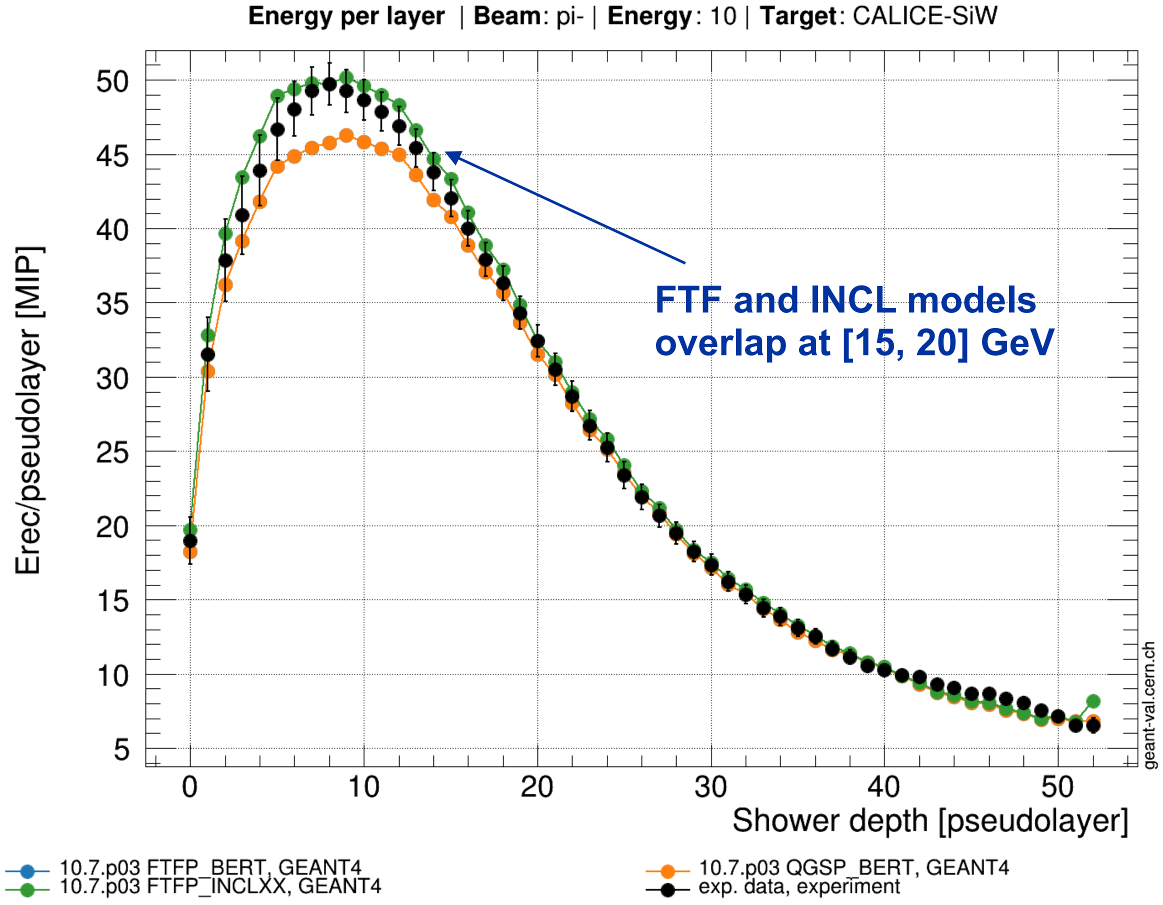


CALICE SiW: longitudinal energy distributions

10 GeV π^-, exp. data from NIM A794



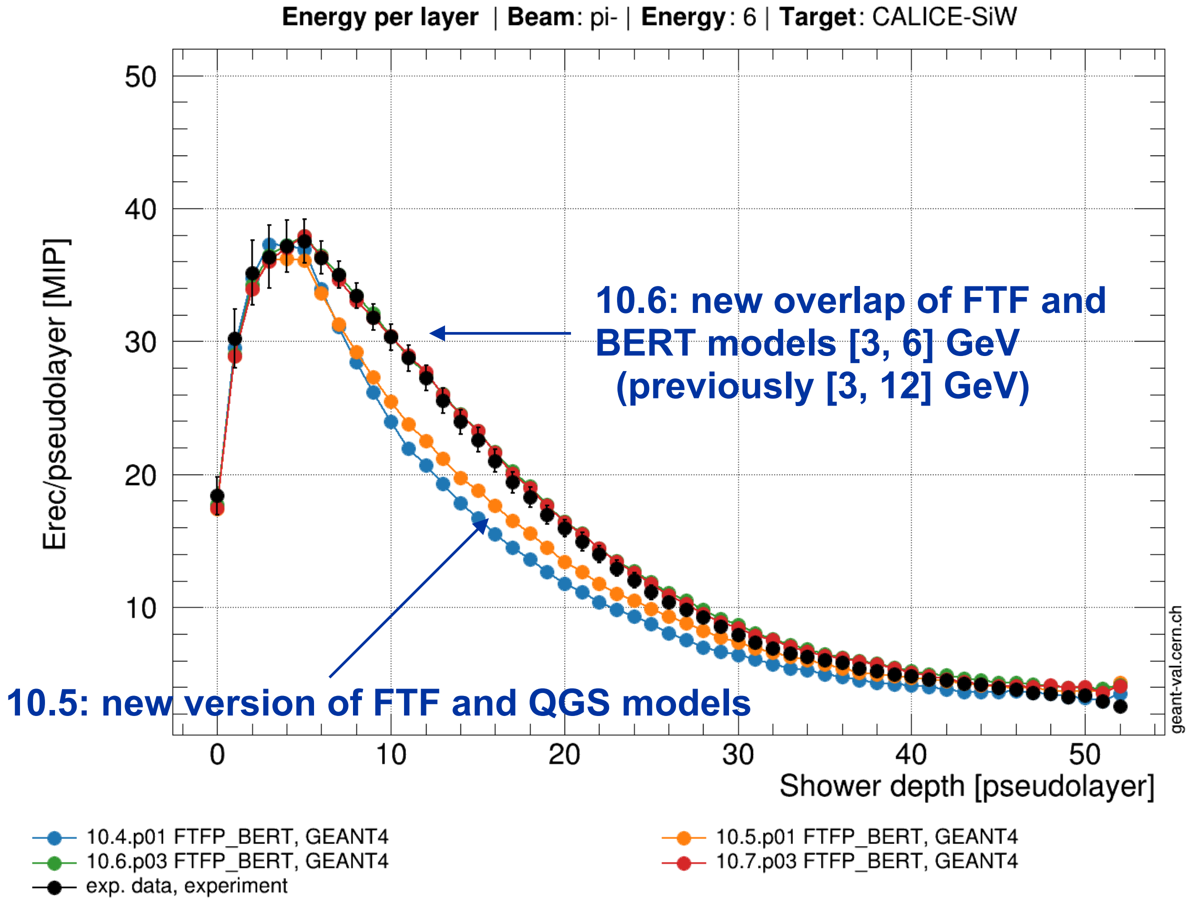
***FTFP_BERT** Physics List regression testing 2017-2020*



Physics Lists comparison - Geant4.10.7.p03

CALICE SiW: longitudinal energy distributions

6 GeV π^-, exp. data from NIM A794



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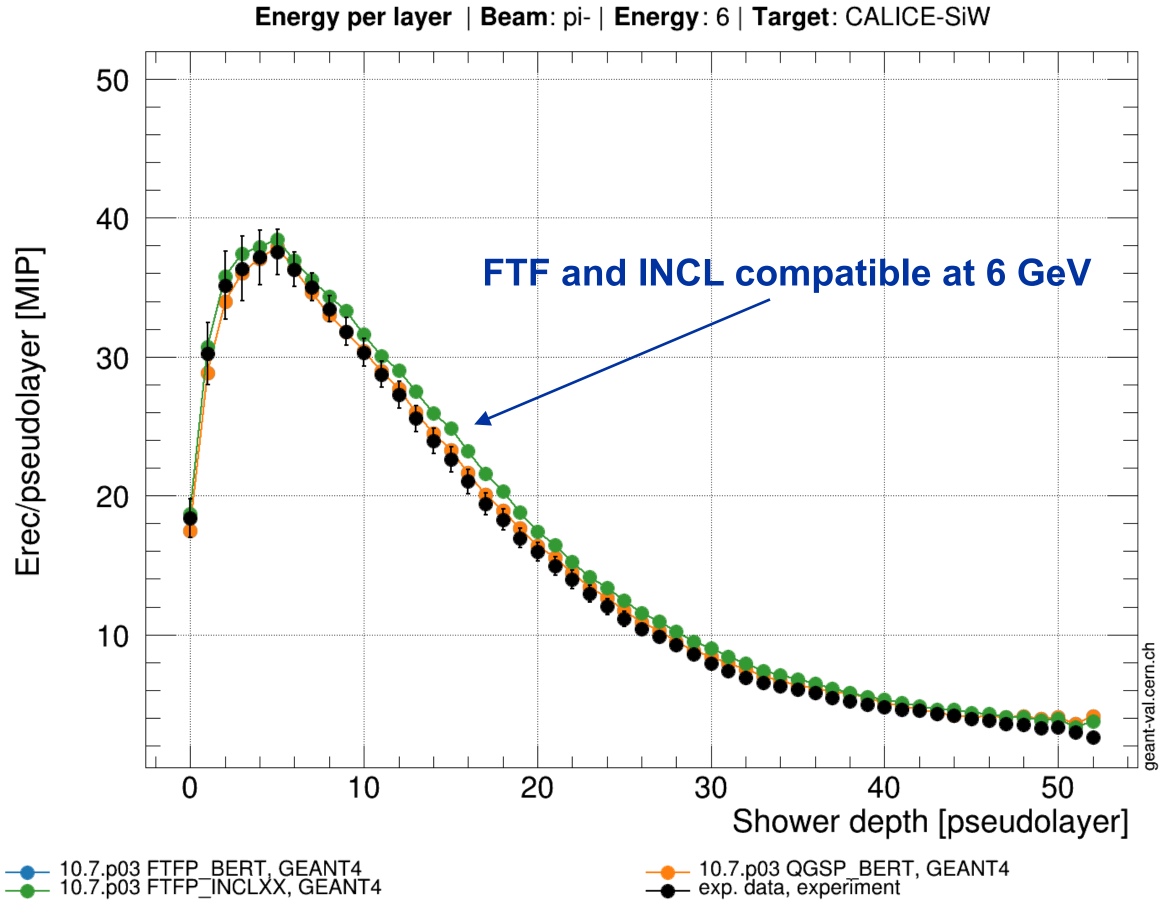
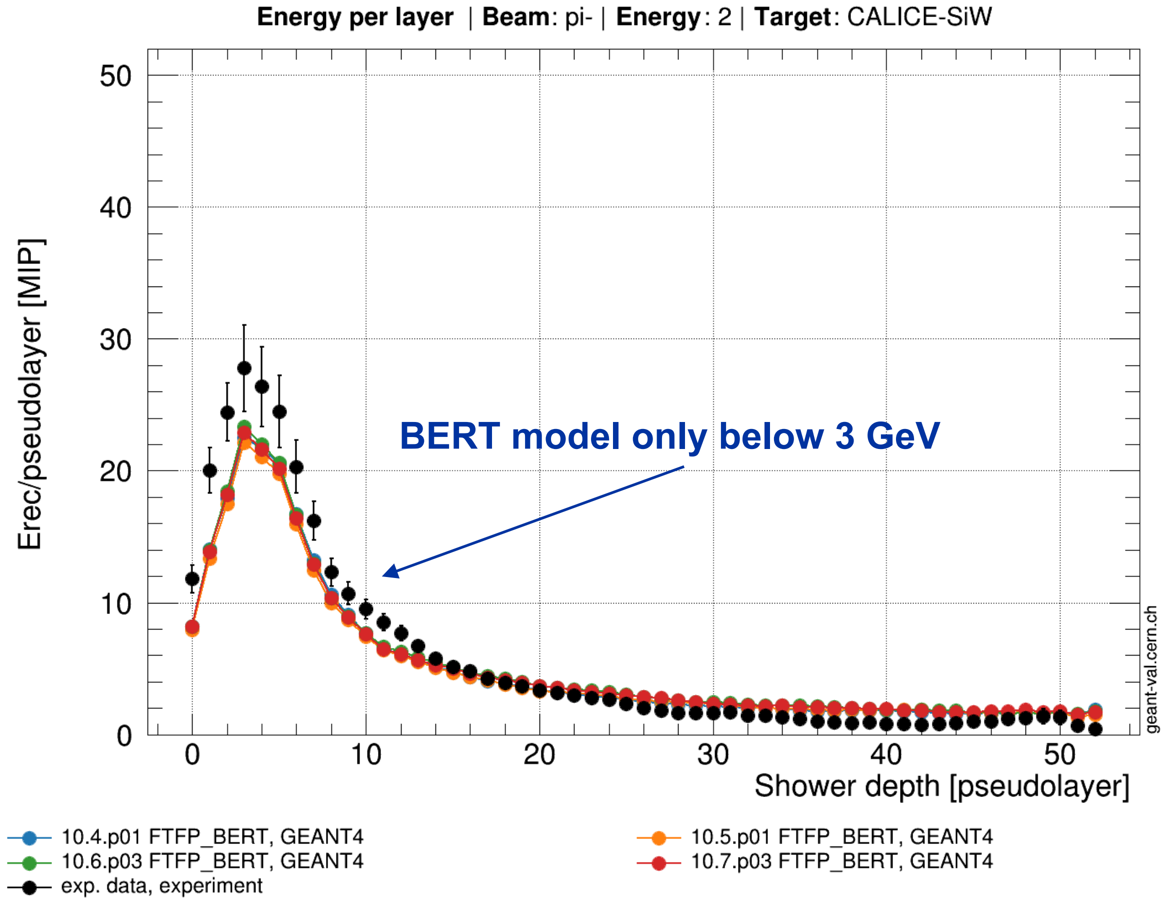


Physics Lists comparison - Geant4.10.7.p03

CALICE SiW: longitudinal energy distributions

2 GeV π^-, exp. data from NIM A794



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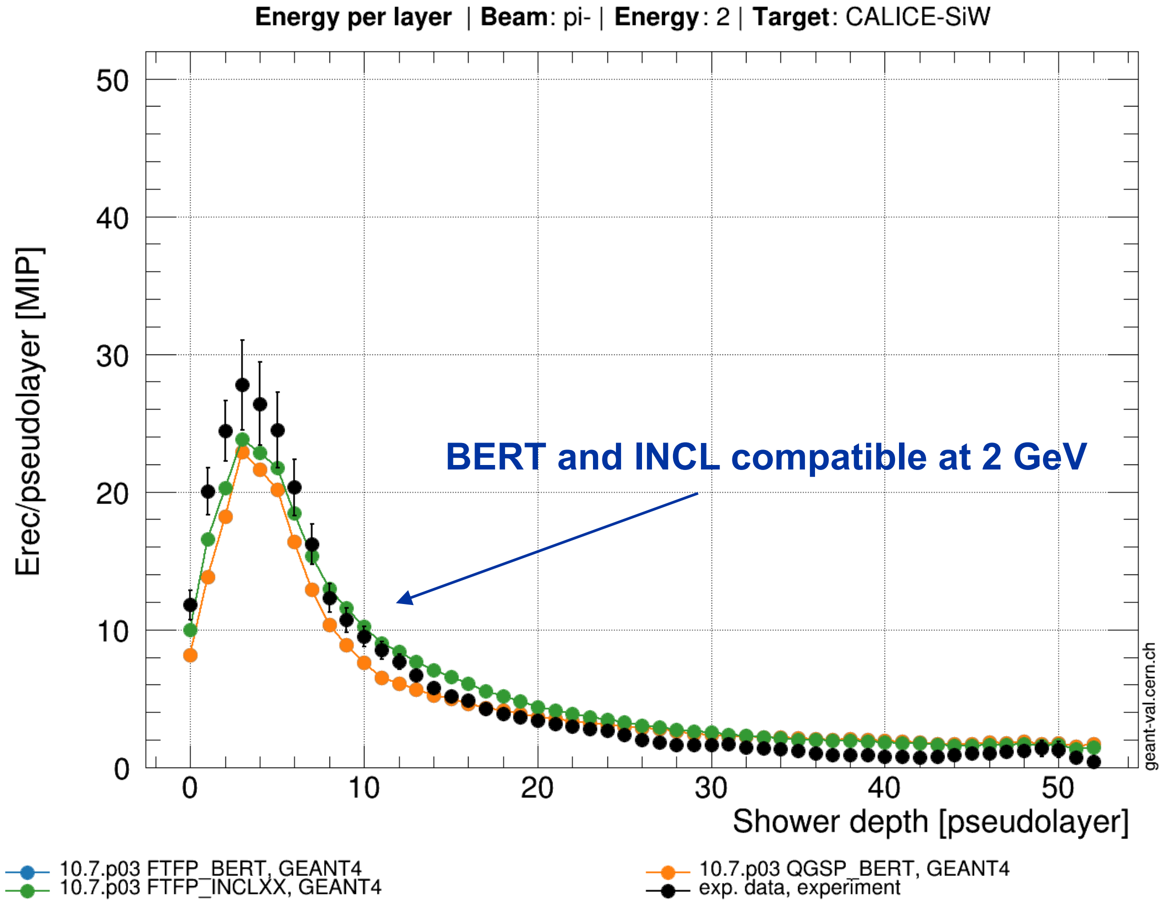
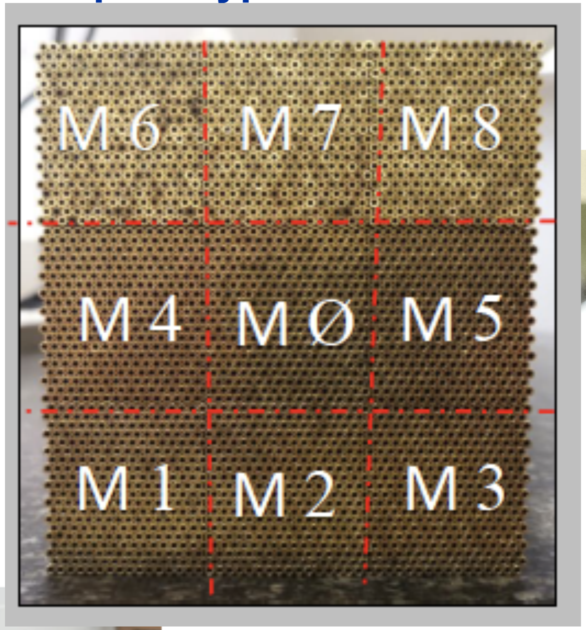


Physics Lists comparison - Geant4.10.7.p03

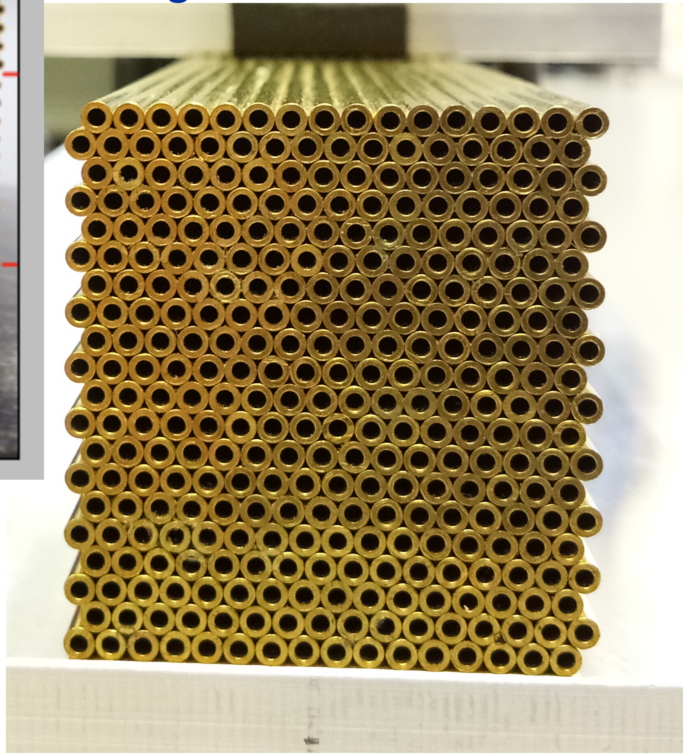
The Bucatini Dual-Readout Calorimeter within Geant4

- 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.

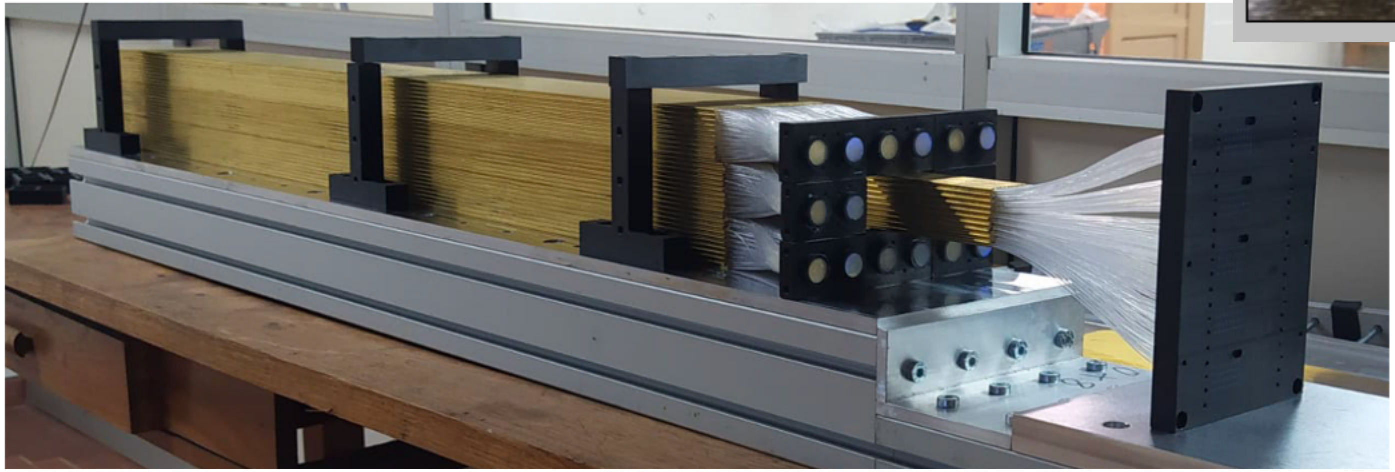
Full prototype - 9 towers



A single tower



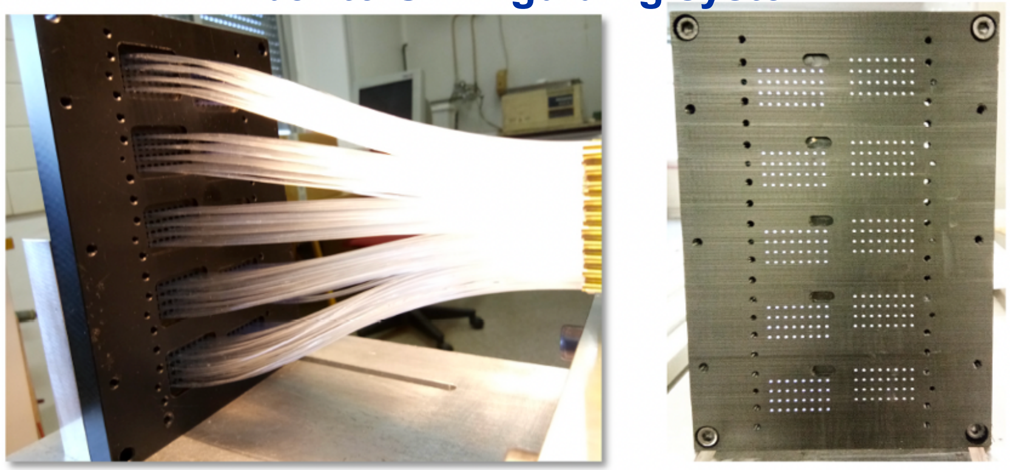
Prototype rear end

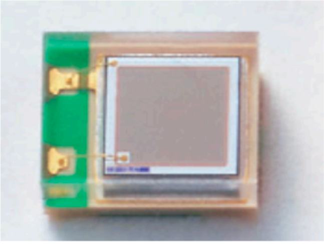


Towards superior Geant4 EM validation

- 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.

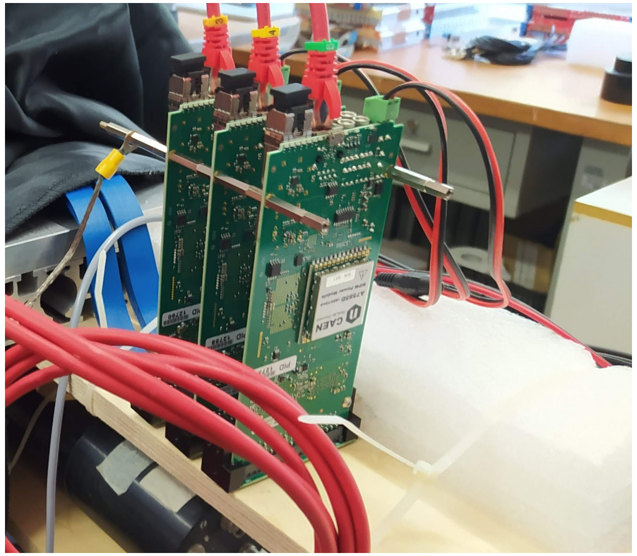
Fiber-to-SiPM guiding system





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

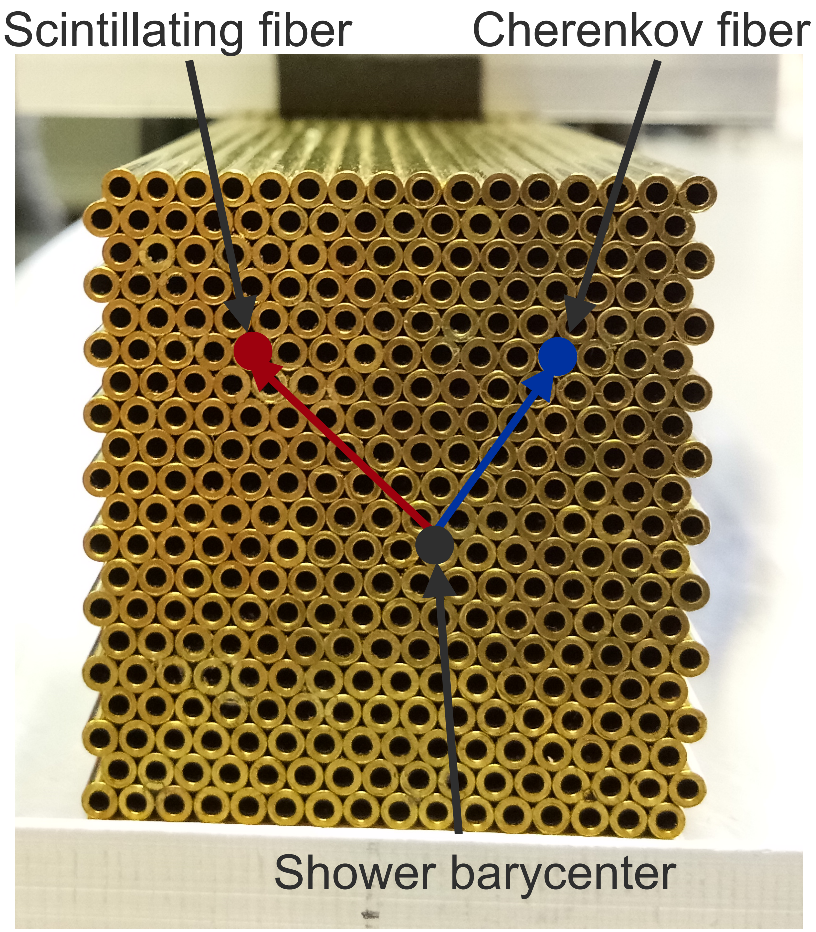
Front end board housing 64 SiPM



Readout Boards CAEN A5202

Dual-Readout Calorimeter: e^+ shower shape

- Tested with e^+ 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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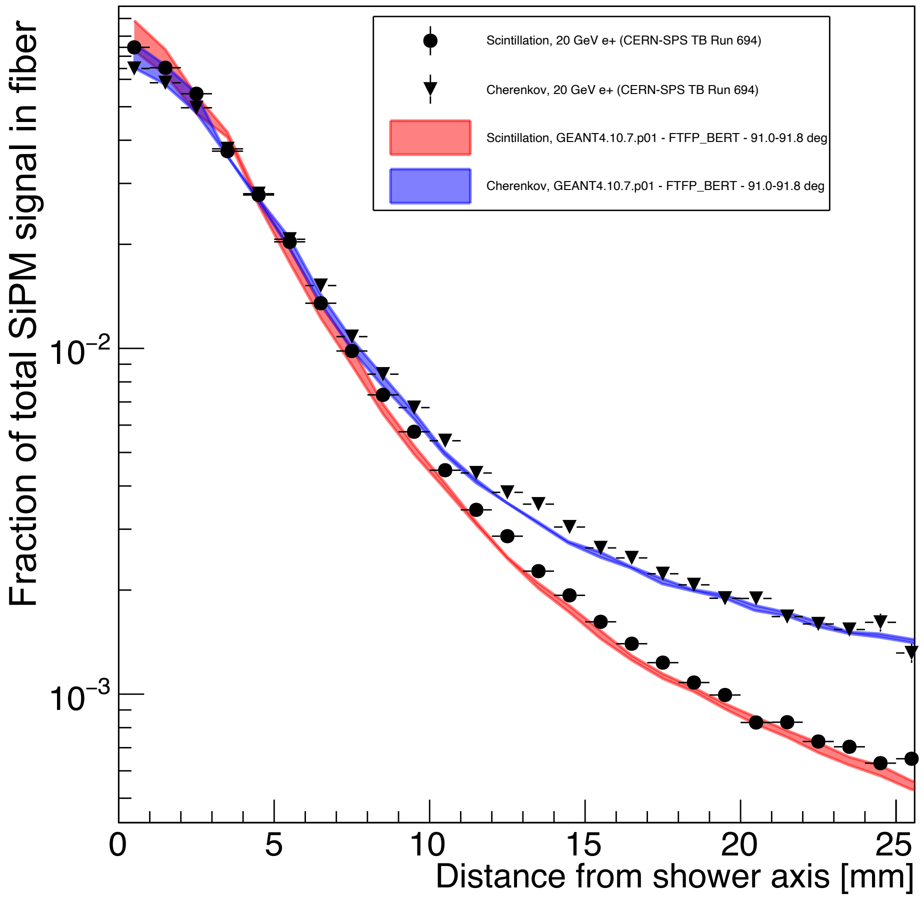
CERN SPS 20 GeV e^+ - GEANT4



Feedback from beam test validation

- Experiments perform Geant4 validation, often using old-releases and few physics lists:
  - 2021 article from ATLAS TileCal uses only G410.1 and FTFP_BERT_ATL (because so was ATHENA in 2017!).
  - 2019 article from CALICE RPC-steel calorimeter uses G410.1 release.

Eur. Phys. J. C (2021) 81:549
https://doi.org/10.1140/epjc/s10052-021-09292-5

THE EUROPEAN PHYSICAL JOURNAL C

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Regular Article - Experimental Physics

Study of energy response and resolution of the ATLAS Tile Calorimeter to hadrons of energies from 16 to 30 GeV

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

ELSEVIER

Analysis of testbeam data of the highly granular RPC-steel CALICE digital hadron calorimeter and validation of GEANT4 Monte Carlo models

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- Collaboration with Experiments leads to better understanding of our and their SW:
  - ATLAS recognized recent EP-SFT activity as excellent collaboration with Geant4 [slide].

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Calorimeter Test Beam Integration to Geant Val

Geant4 validation program

Automatically validate Geant4 using hadronic and electromagnetic calorimeters test-beam data

Lorenzo Pezzotti & Alberto Ribon

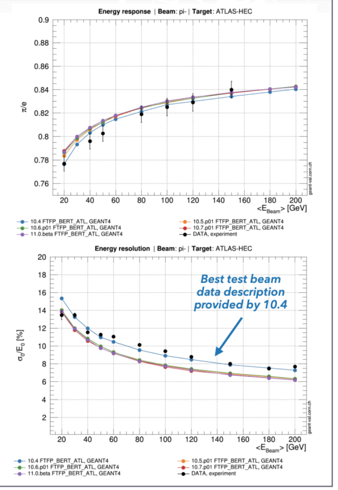
ATLAS data considered:

- Hadronic Endcap Calorimeter (HEC)
- Tile Calorimeter (TileCal)

Workflow:

1. Port the ATLAS HEC simulation into a new standalone Geant4 simulation
2. Perform Geant4 validation against the ATLAS HEC test-beam data
3. Porting the application into the Geant Val testing suite

Excellent example of collaboration between ATLAS and Geant4!



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  - 2021 article from ATLAS TileCal uses only G410.1 and FTFP_BERT_ATL (because so was ATHENA in 2017!).
  - 2019 article from CALICE RPC-steel calorimeter uses G410.1 release.

- Collaboration with Experiments leads to better understanding of our and their SW:
  - ATLAS recognized recent EP-SFT activity as excellent collaboration with Geant4 [slide].

- Calorimetry Collaborations for future colliders benefit from Geant4 collaboration to facilitate funds granting:
  - Remarked at the latest CALICE Collaboration meeting.

Eur. Phys. J. C (2021) 81:549
https://doi.org/10.1140/epjc/s10052-021-09292-5
THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Study of energy response and resolution of the ATLAS Tile Calorimeter to hadrons of energies from 16 to 30 GeV

ELSEVIER
Contents lists available at ScienceDirect
Nuclear Inst. and Methods in Physics Research, A
journal homepage: www.elsevier.com/locate/nima

Analysis of testbeam data of the highly granular RPC-steel CALICE digital hadron calorimeter and validation of GEANT4 Monte Carlo models

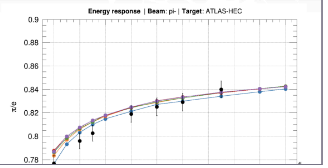
Calorimeter Test Beam Integration to Geant Val

Geant4 validation program

Automatically validate Geant4 using hadronic and electromagnetic calorimeters test-beam data

Lorenzo Pezzotti & Alberto Ribon

ATLAS data considered:



IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

This meeting

CALICE

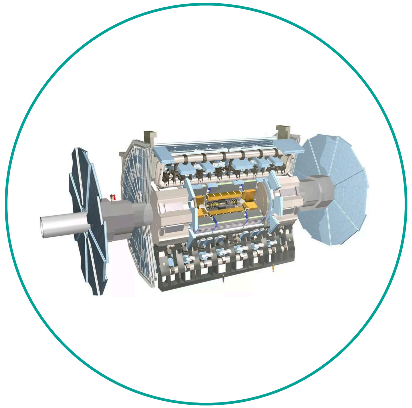
- 80 registered participants
  - A hybrid meeting with 25 registered on-site participants
  - Thanks to the conveners for having compiled the agenda
- Interesting scientific program
  - First feedback on 2021/22 beam tests, more to come
  - Retightening the links with GEANT4 team

Conclusion

G4 ADOPTION

- Building experiments SW stacks
- $\mathcal{O}(10^{11})$ event productions (CMS, ATLAS @Run2)
- 50-100 publications/year (LHC experiments)
- Tuning PLs to experiments' needs

🙂



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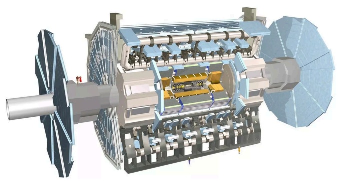

G4 VALIDATION

- Provide inputs on G4 usage
- Systematic testing over decades
- Feedback to models' developers
- Geant-val integration
- Reproduce test-beams in G4