Validation of Geant4 physics via calorimeter test-beams in geant-val

D. Konstantinov, L. Pezzotti, A. Ribon

CERN, EP-SFT

28th Geant4 Collaboration Meeting
Hokkaido University, 25-29 September 2023

Outlook

- Our activity to include into geant-val calorimeters test-beams taken from HEP-experiment was introduced at the 2022 Geant4 Collaboration Meeting [slides]

- We maintain and develop several validation tests exploiting detectors from

  - the LHC experiments:
    ATLAS Tile Calorimeter, ATLAS Hadronic Endcap Calorimeter, ATLAS LAr barrel Calorimeter, CMS High-Granularity Calorimeter (soon)

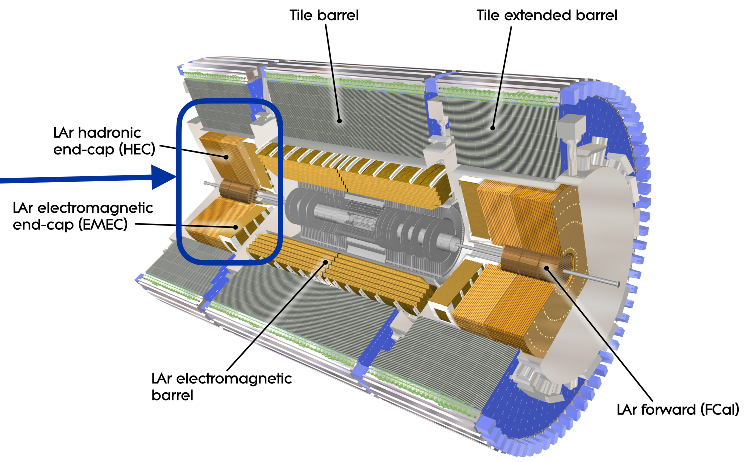
  - future Higgs factories detectors prototypes:
    CALICE SiW Calorimeter, Dual-Readout fiber calorimeters

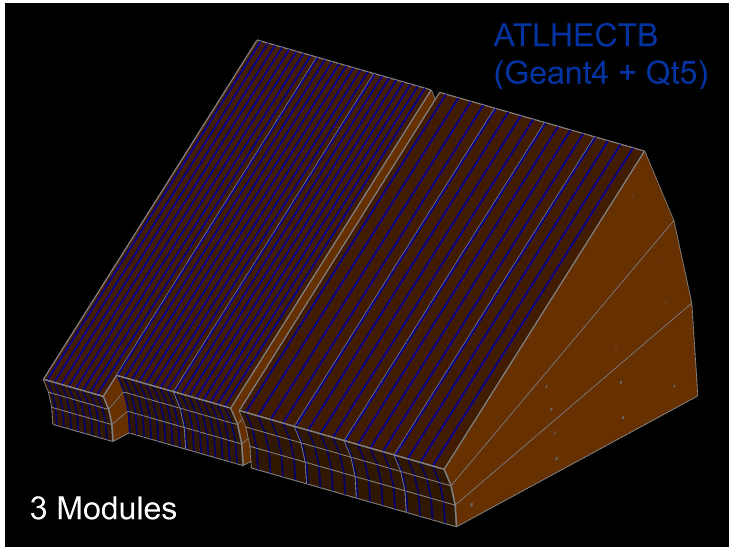
Outlook

- Our activity to include into geant-val calorimeters test-beams taken from HEP-experiment was introduced at the 2022 Geant4 Collaboration Meeting [slides]
- We maintain and develop several validation tests exploiting detectors from
  - the LHC experiments:
    ATLAS Tile Calorimeter, ATLAS Hadronic Endcap Calorimeter, ATLAS LAr barrel Calorimeter, CMS High-Granularity Calorimeter (soon)
  - future Higgs factories detectors prototypes:
    CALICE SiW Calorimeter, Dual-Readout fiber calorimeters
- Today's topics:
  - Comparison of ATLAS calorimeters using Geant4 and FLUKA.CERN hadronic models
  - New custom solutions developed for the ATLAS simulation
  - Studies of the new FTF tunings on thick detectors
  - Preliminary results from the new ATLAS LAr barrel Calorimeter test

ATLAS Hadronic End-Cap Calorimeter

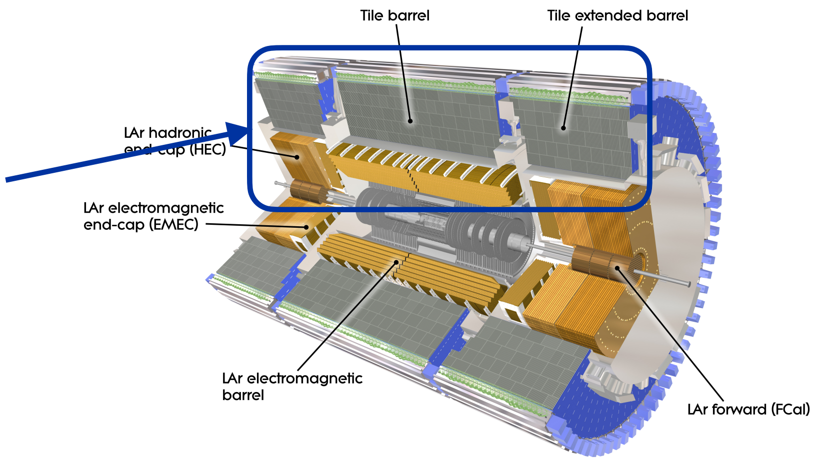
- The ATLAS HEC:
  - Covers the range $1.5 < |\eta| < 3.2$.
    Divided into two wheels (HEC1-2) each consisting of 32 azimuthal modules
  - It uses 8.5-mm-gap LAr sampling regions inserted between parallel copper plates, with 2.5 cm (HEC1) and 5.0 cm (HEC2) thickness
  - It has four longitudinal layers 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

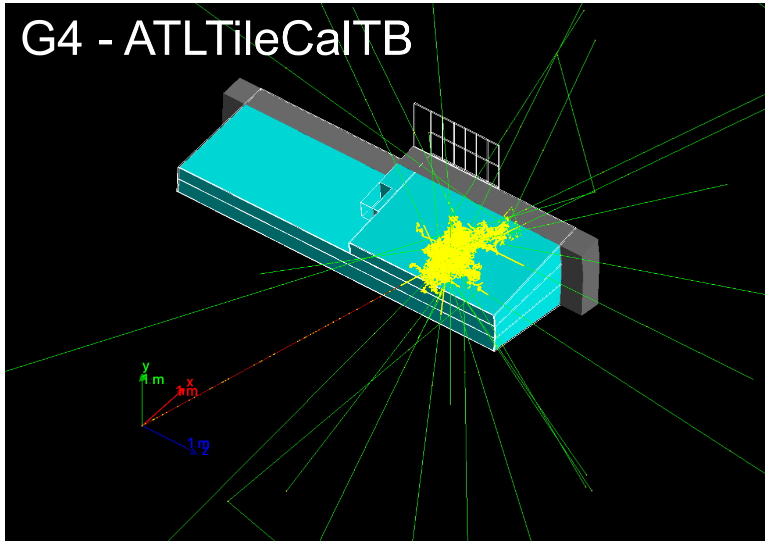




ATLAS Tile Calorimeter

- 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^+





The G4-to-FLUKA.CERN interface

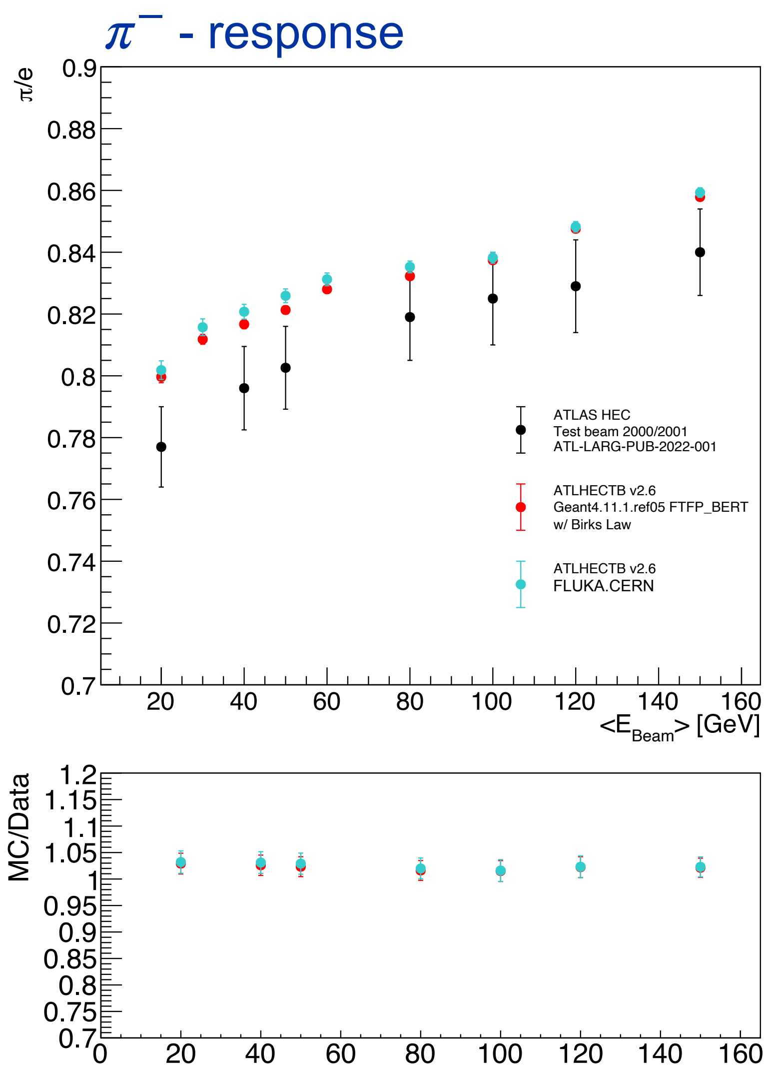
- We performed a quantitative comparison of the hadronic models provided by Geant4 (FTFP_BERT PL) and FLUKA.CERN
- See our documentation for a customized FTFP_BERT Physics Lists that uses the FLUKA.CERN Hadron Inelastic model
- Caveats:
  - User still needs to accept the FLUKA.CERN LICENSE
  - Only works with Geant4.11.1.ref05
  - Simulation must be run in single-threaded mode
- Used a custom FTFP_BERT Physics List that replaces the G4HadronPhysicsFTFP_BERT constructor with a new one that exploits the FLUKA.CERN interface

FLUKAHadronInelasticPhysics.cc

```
void FLUKAHadronInelasticPhysics::ConstructProcess() {
  //...

  const auto helper =
          G4PhysicsListHelper::GetPhysicsListHelper();

  // FLUKA hadron - nucleus inelastic XS
  const auto flukaInelasticScatteringXS =
                     new FLUKAInelasticScatteringXS();

  // FLUKA hadron - nucleus model
  const auto flukaModel =
                     new FLUKANuclearInelasticModel();

  // PROTON
  build_G4_process_helpers::buildInelasticProcess(
                                 G4Proton::Proton(),
                                 helper,
                         flukaInelasticScatteringXS,
                                 flukaModel);


  //...
}
```

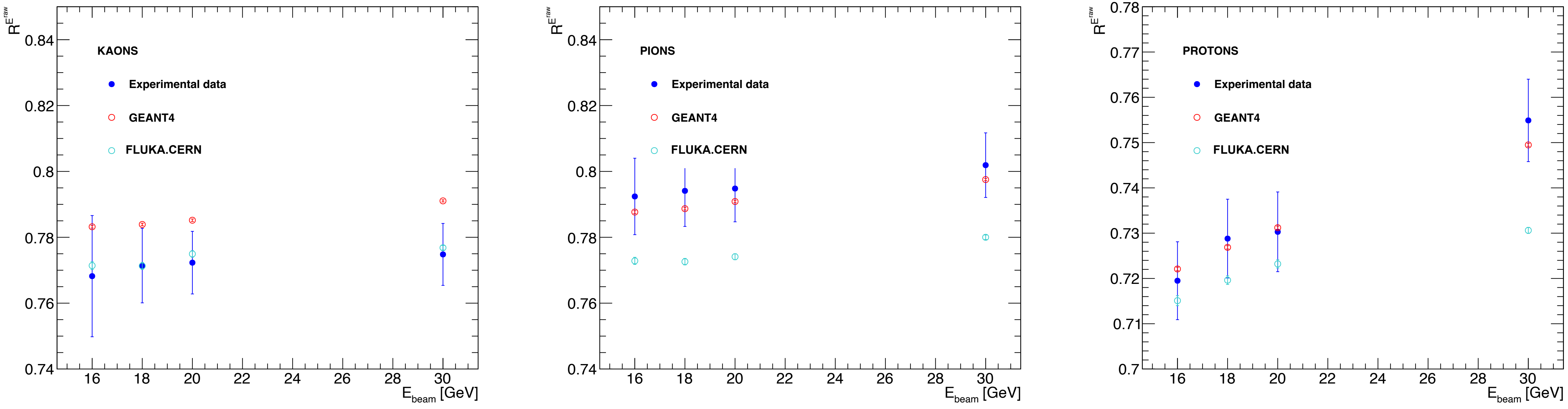
ATLAS HEC response

- 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
- Showing only the FTFP_BERT PL results, all results with other PLs are available at geant-val.cern.ch
- FLUKA.CERN and Geant4 are very close in the average signal produced
- They both scale well with E_{beam}, which likely means that the π^0 production is well modeled by both Monte Carlos



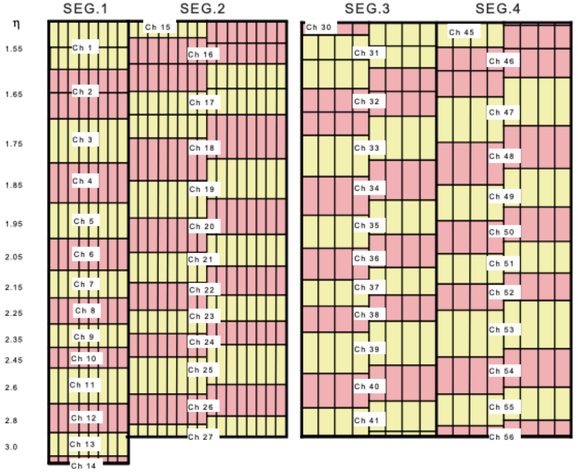
ATLAS TileCal response - π^+, k^+, p

- 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^+: due to the baryon number conservation law, high f_{em} processes (*e.g.* $\pi^+ + n \rightarrow \pi^0 + p$) are prohibited for p-induced events

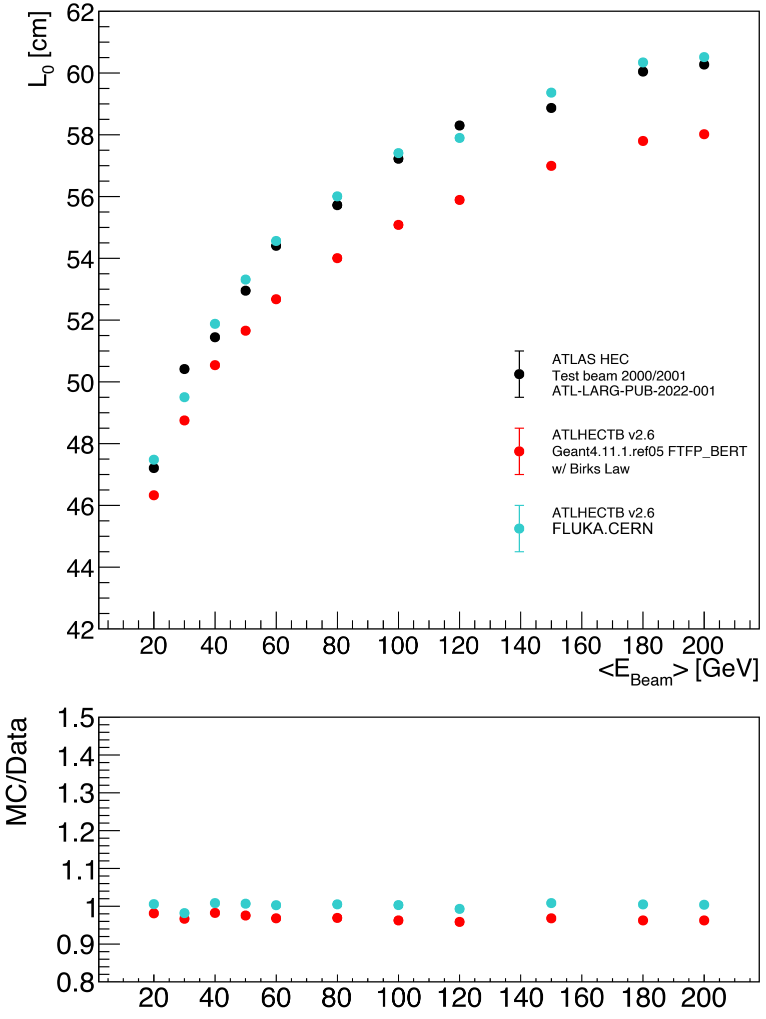


Hadronic shower shape

- 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}

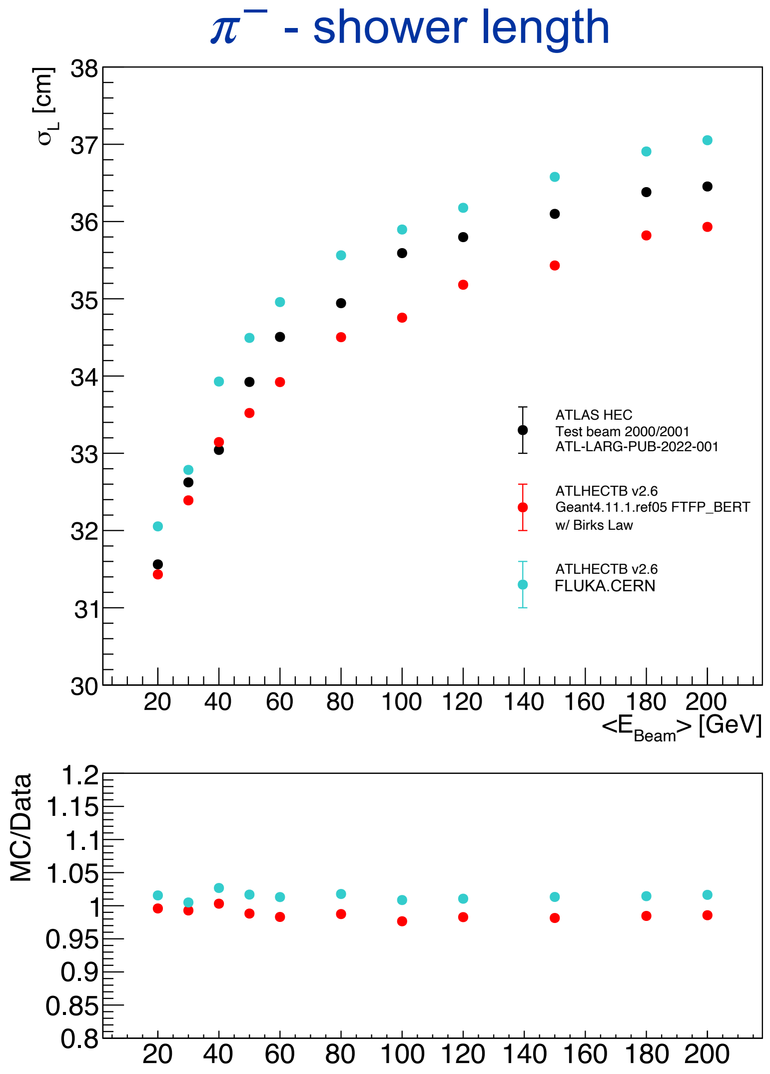


π^- - barycenter longitudinal position



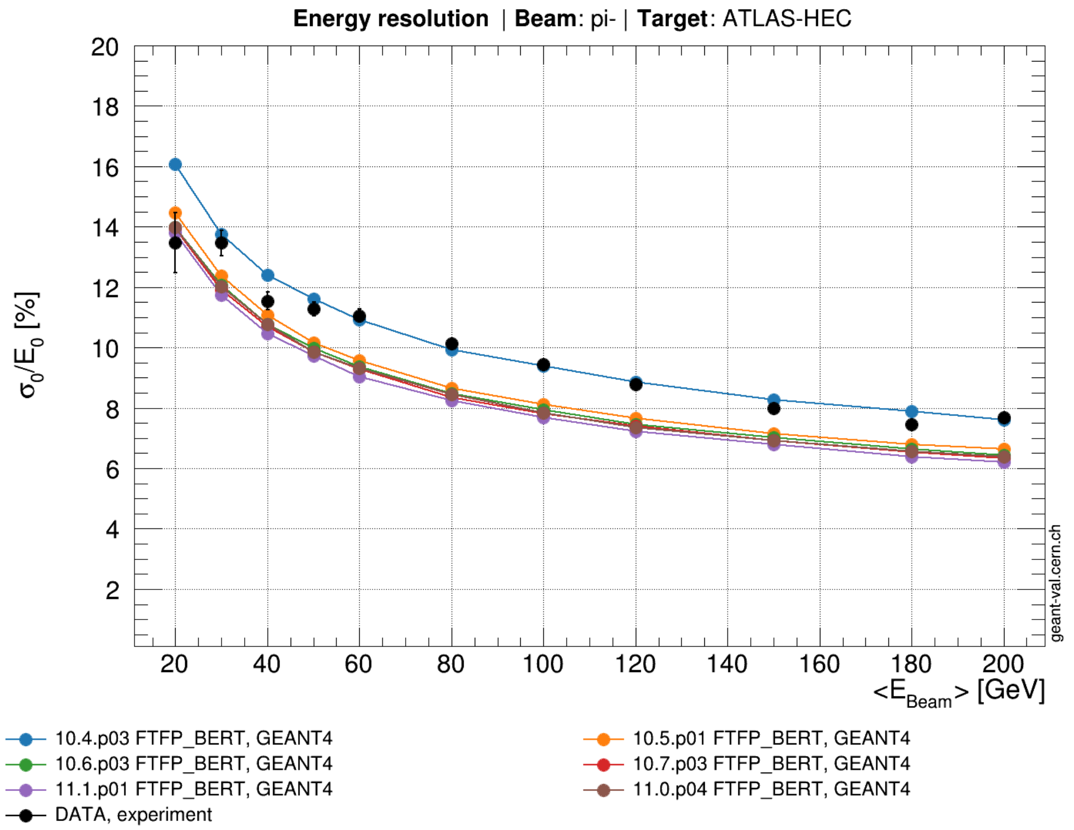
Hadronic shower shape

- 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}
- Average shower length:
  - Extracted as the RMS (σ_L) of the energy profile



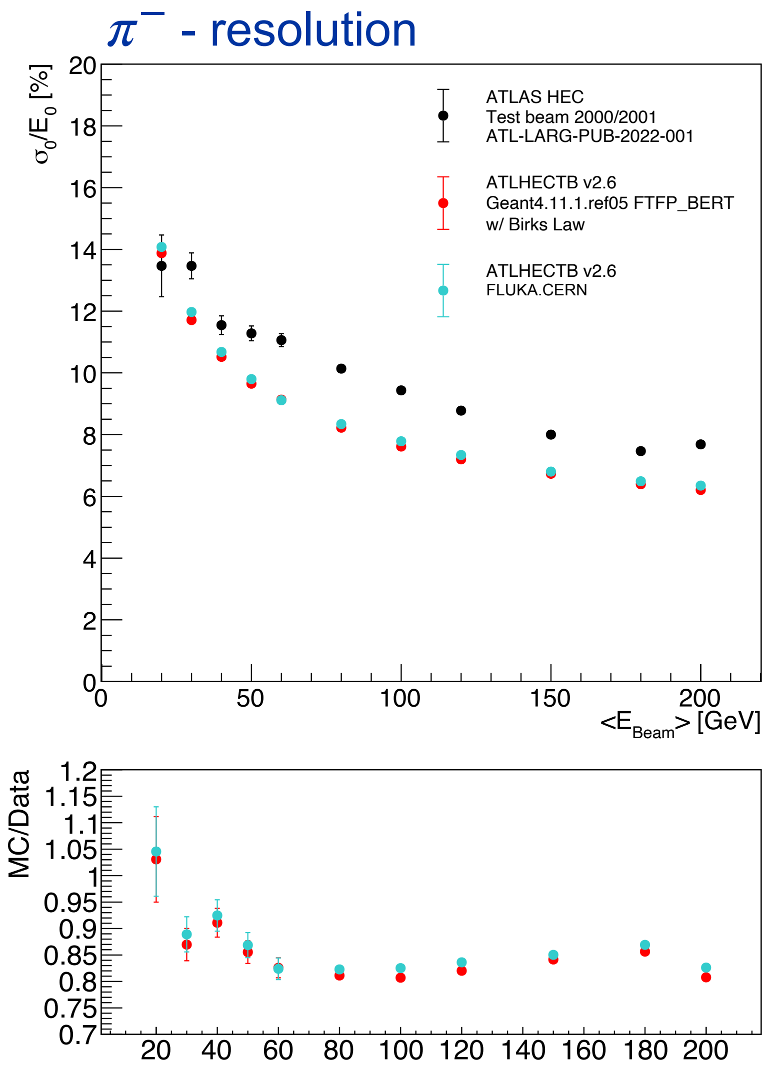
ATLAS HEC resolution

- σ/E extracted from a gaussian fit of the energy distributions
  - **ATLAS HEC** regression testing:
    - Geant4.10.4 (2017) was found to be in good agreement with ATLAS data
    - A big drop in the hadronic signal fluctuations happened between Geant4 10.4 and 10.5 (2018). Stable since then



ATLAS HEC resolution

- σ/E extracted from a gaussian fit of the energy distributions
  - **ATLAS HEC** regression testing:
    - Geant4.10.4 (2017) was found to be in good agreement with ATLAS data
    - A big drop in the hadronic signal fluctuations happened between Geant4 10.4 and 10.5 (2018). Stable since then
  - **ATLAS HEC** Geant4 vs. FLUKA.CERN:
    - Currently both Geant4 and FLUKA.CERN underestimate the HEC resolution by $\simeq 15\% - 20\,\%$
  - Similar results from the TileCal signal fluctuations



Testing alternative FTF tunes

Custom tunes studies for ATLAS and tests of existing tunes

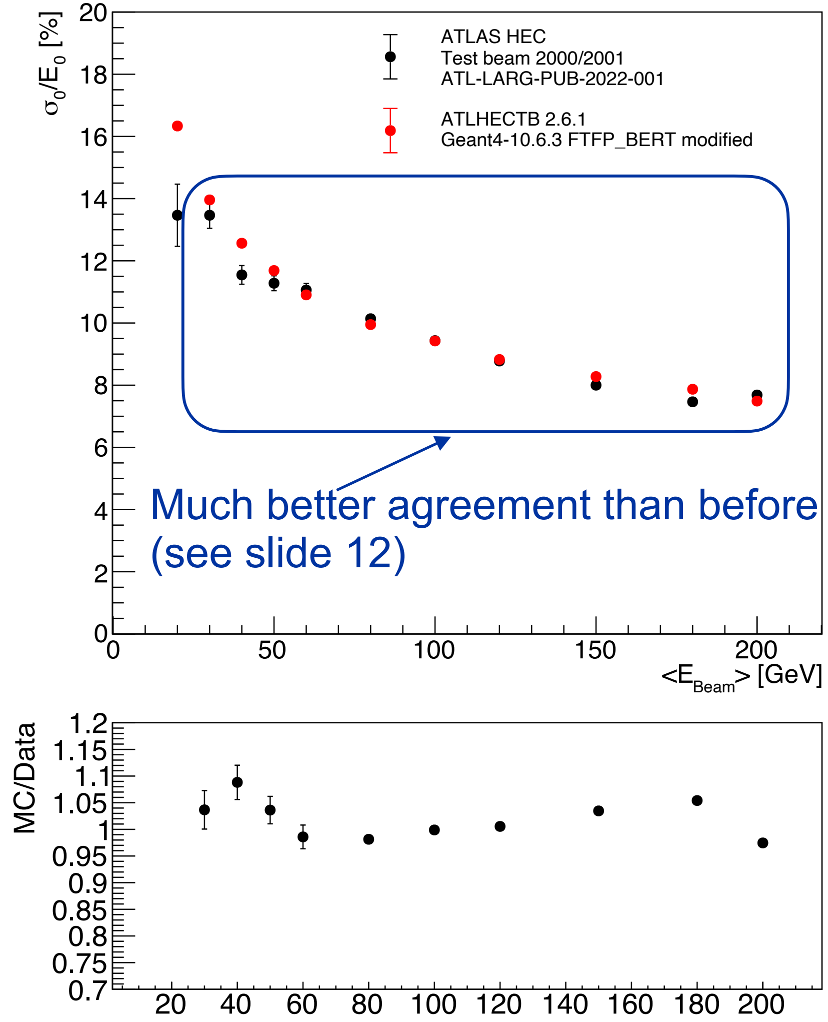
Changing FTF parameters

- ATLAS moved from Geant4-10.1 to Geant4-10.6 for the Run3 MC campaign → we need to improve the (too) narrow signal fluctuations
- We tried to achieve it by changing the FTF parameters (`G4FTFParameters.cc`) affecting the charge-exchange string-formation process and the nuclear destruction
- These changes:
  - increase the probability of having a charge-exchange process during the string formation
  - increase the probability of involving a neighboring nucleon during the Reggeon cascade
  - increase the excitation energy per wounded nucleon
- These changes only affect $\pi^{\pm}$-induced showers
- We studied their effect on ATLAS calorimeters using Geant4-10.6.p03

Changing FTF parameters

- ATLAS moved from Geant4-10.1 to Geant4-10.6 for the Run3 MC campaign → we need to improve the (too) narrow signal fluctuations
- We tried to achieve it by changing the FTF parameters (`G4FTFParameters.cc`) affecting the charge-exchange string-formation process and the nuclear destruction
- These changes:
  - increase the probability of having a charge-exchange process during the string formation
  - increase the probability of involving a neighboring nucleon during the Reggeon cascade
  - increase the excitation energy per wounded nucleon
- These changes only affect $\pi^{\pm}$-induced showers
- We studied their effect on ATLAS calorimeters using Geant4-10.6.p03

π^{-} - resolution



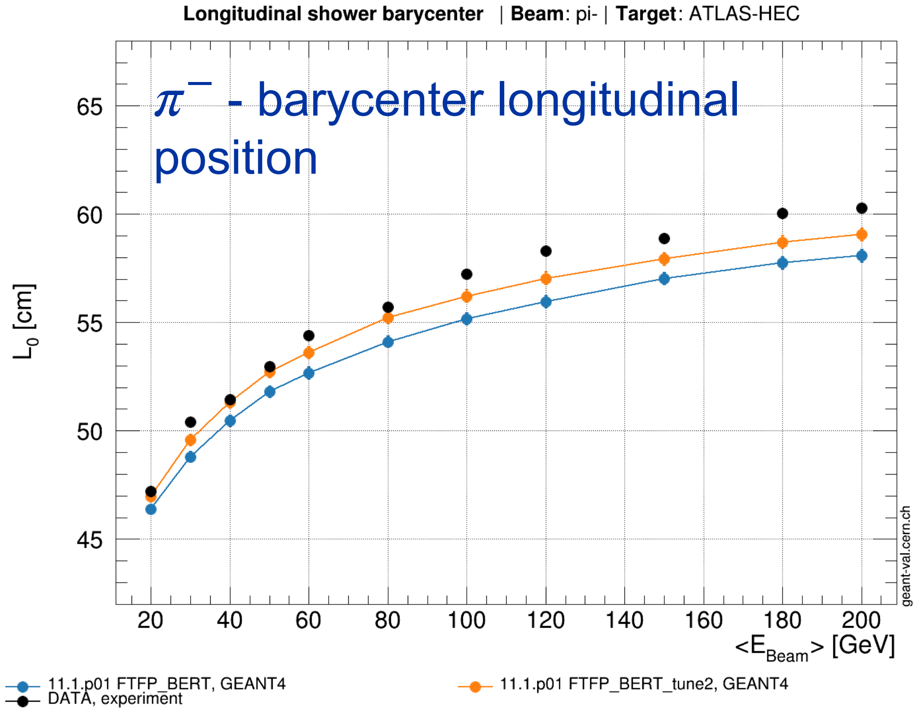
Alternative FTF tunes

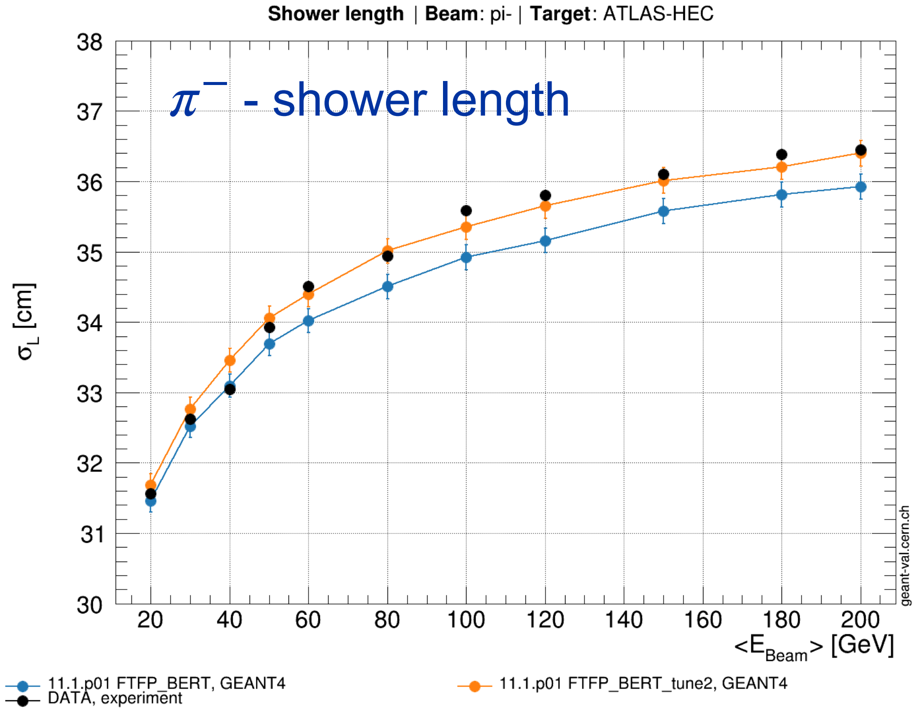
Geant4-11.1 introduced alternative FTF-model tunes selectable via the `G4FTFTunings` singleton

- FTF tunes were extracted by J. Yarba, several examples reported in her presentation at the HSF Detector Simulation WG meetings
- Currently, 4 tunes are available: default (index=0), baryon-tune2022-v0 (index=1), pion-tune2022-v0 (index=2), combined-tune2022-v0 (index=3)
- From the release notes:
  Currently, the feature is mostly meant for use in internal tests, further study and development
- These alternative tunes are obtained as best parameters to maximize the MC agreement with **thin** target experimental data
  - We studied their impact on **thick** targets

Testing alternative FTF tunes on calorimeters

- Alternative tunes do not lead to significant changes in most calorimeter results
- We observed a small improvement in the hadronic shower shape using the ATLAS HEC





- However, such improvements are not confirmed in other tests (see next slide)

CALICE SiW Calorimeter beam test

- We studied the hadronic shower shape more precisely using the highly-granular calorimeters for future Higgs factories by CALICE
- 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

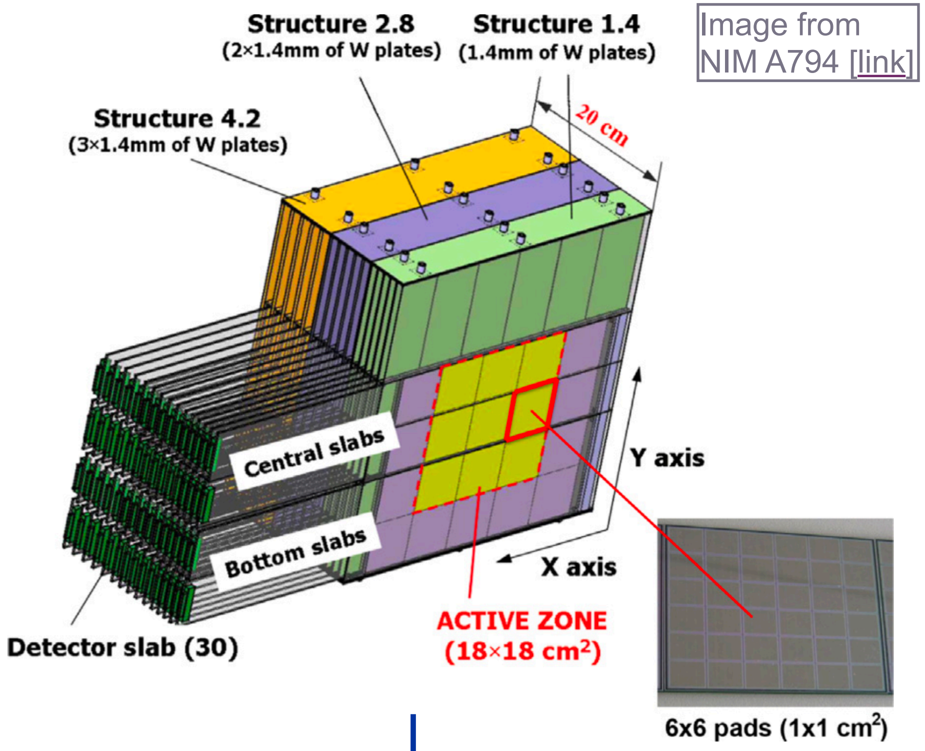
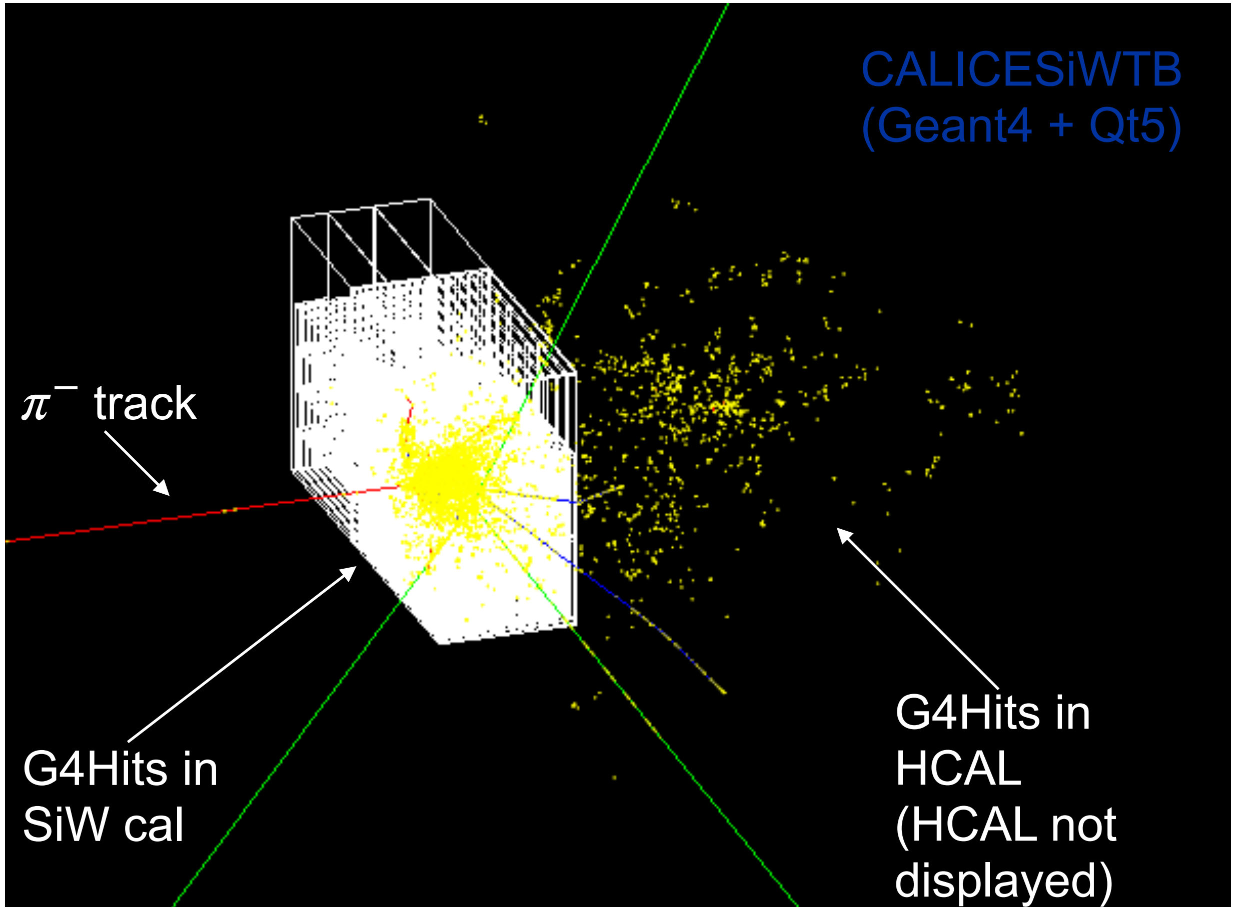


Image from NIM A794 [link]

9720 sensitive volumes

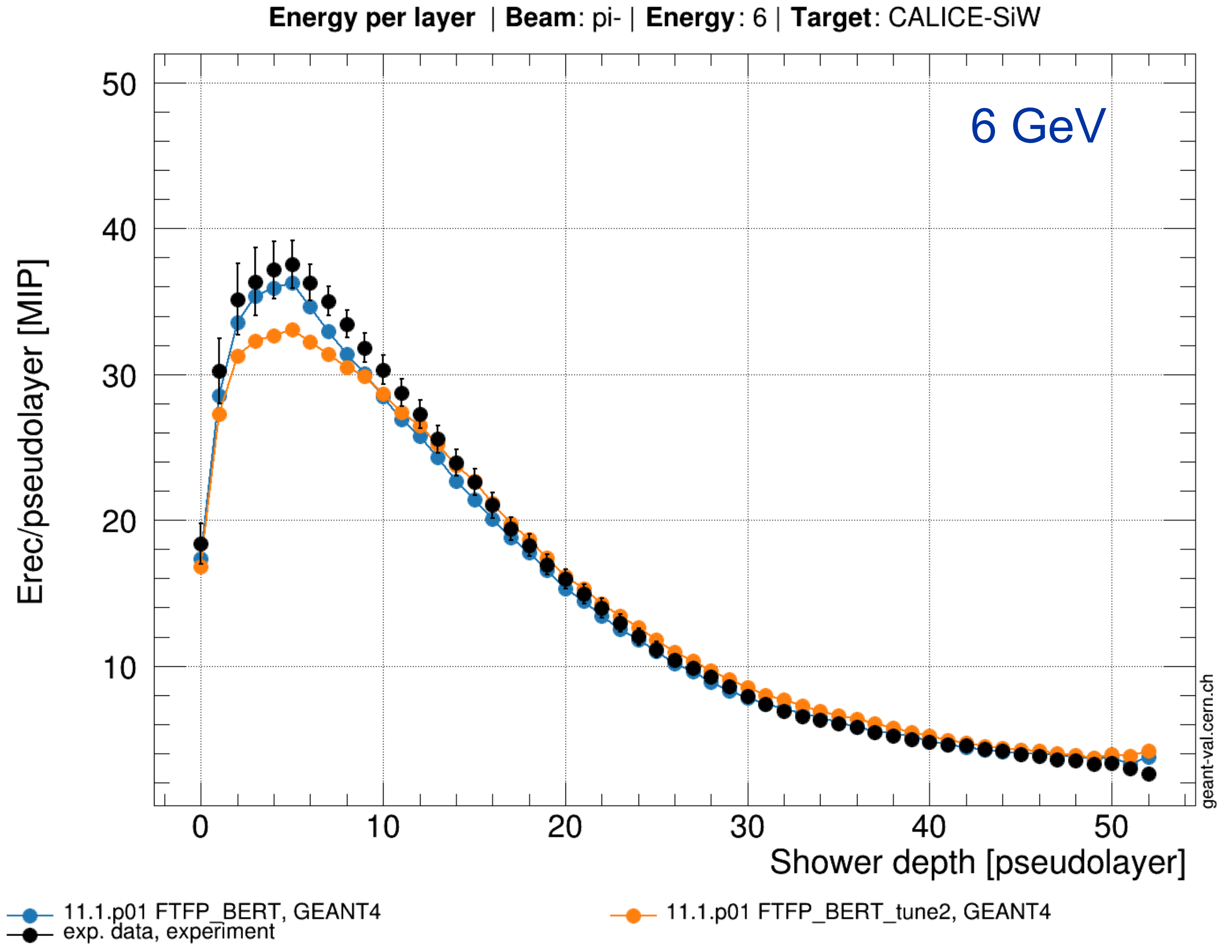
Tagging nuclear breakup events

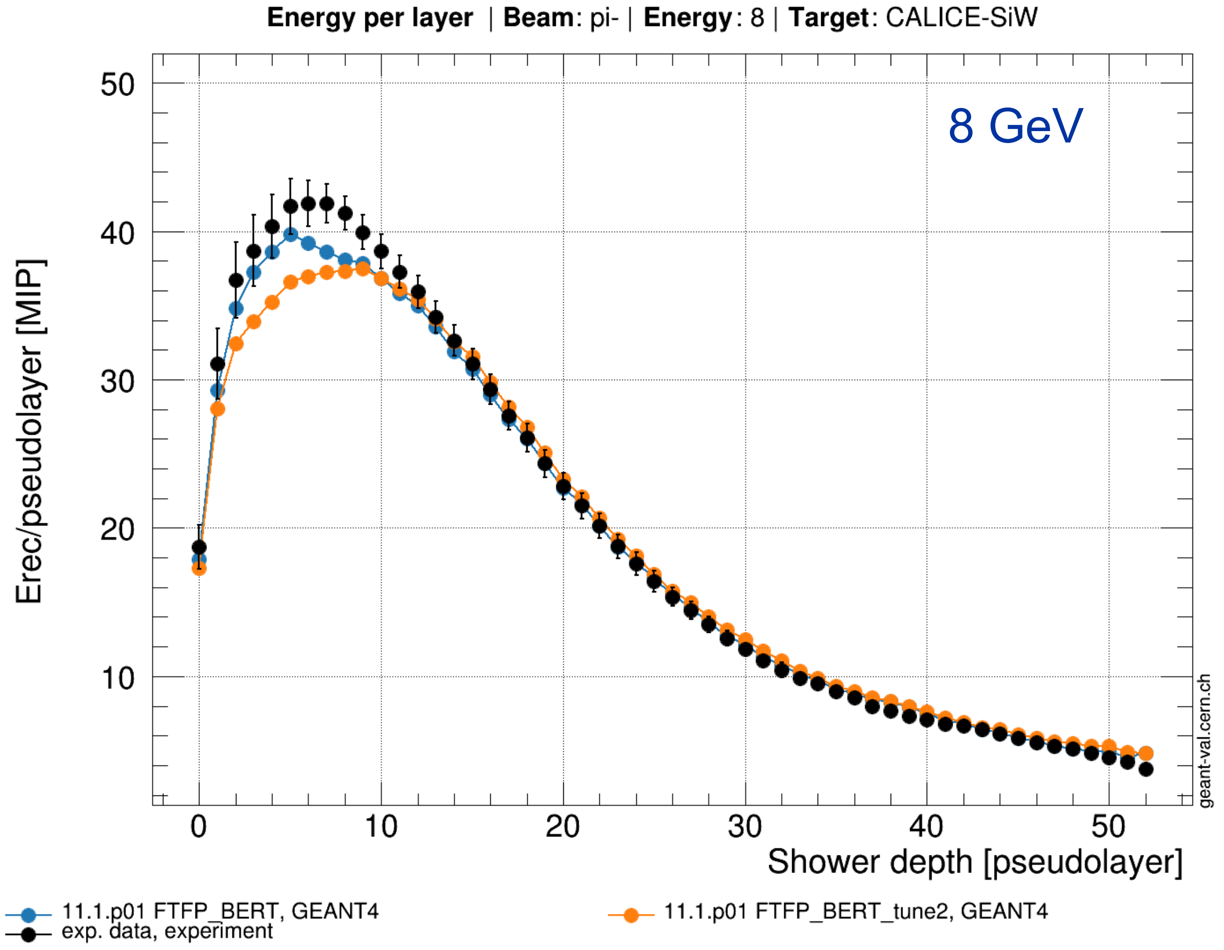
- Beam tests performed at FNAL in 2008 with 2, 4, 6, 8 and 10 GeV π^- to study the first development stages of hadronic showers
- Energy depositions in each cell calibrated in MIP units (extracted with μ^- runs)
- Events with a single nuclear breakup are tagged and used for later analysis
- Starting 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

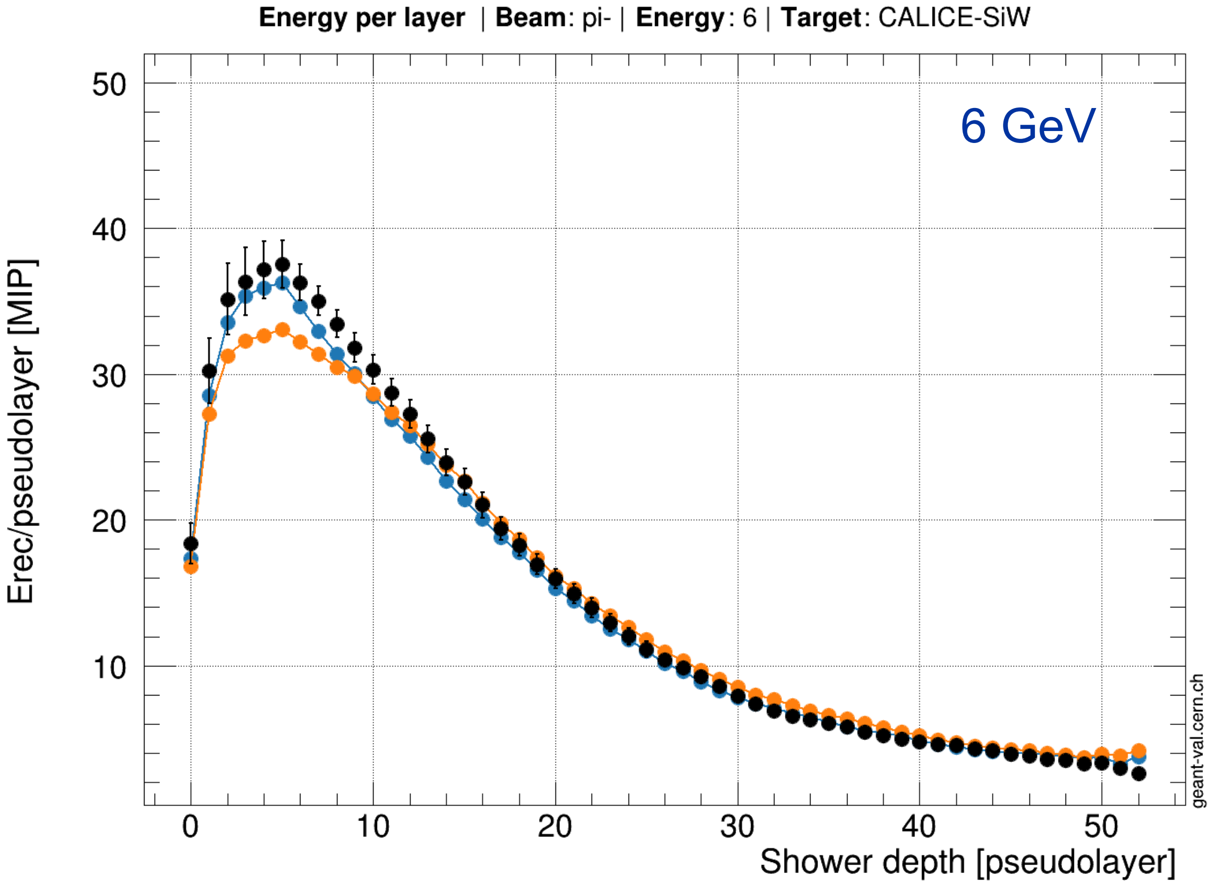
π^- - exp. data from NIM A794

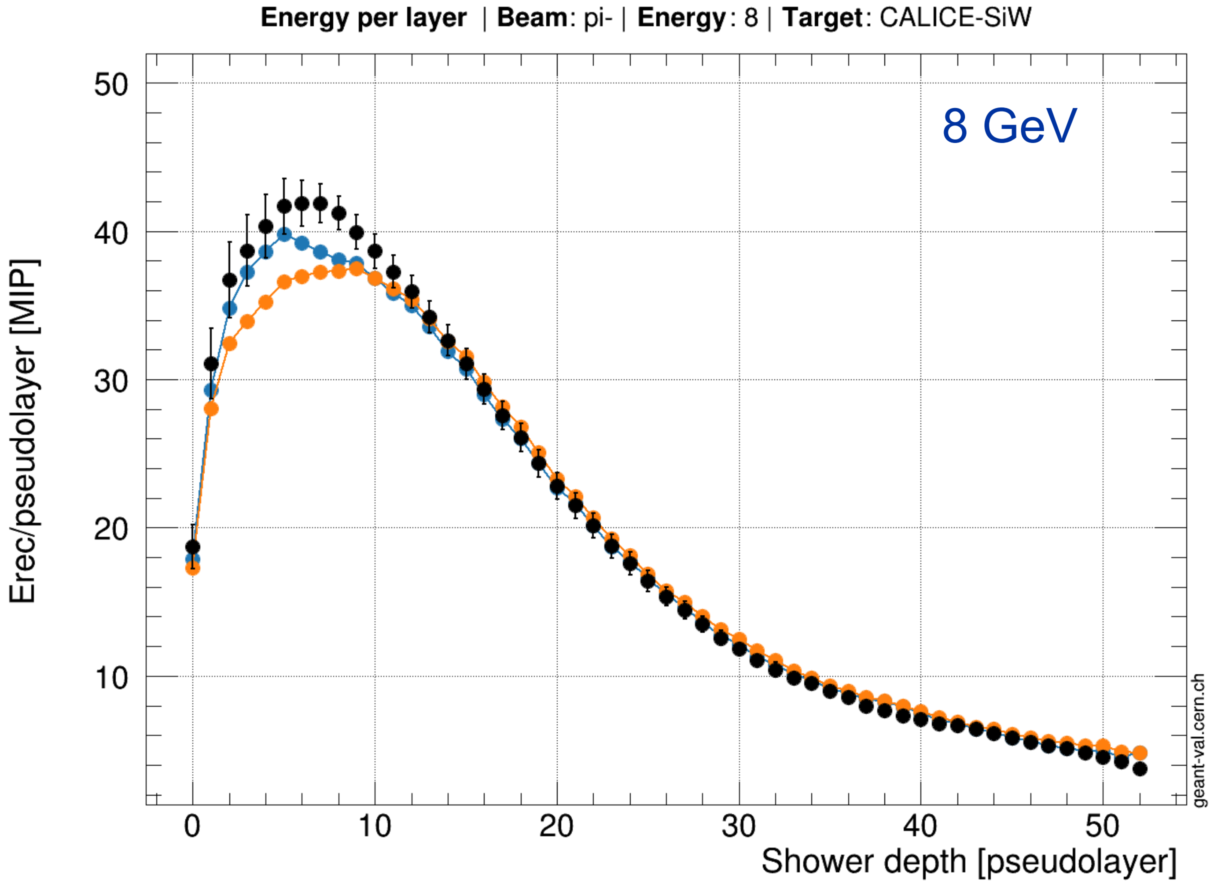




CALICE SiW: longitudinal energy distributions

π^- - exp. data from NIM A794



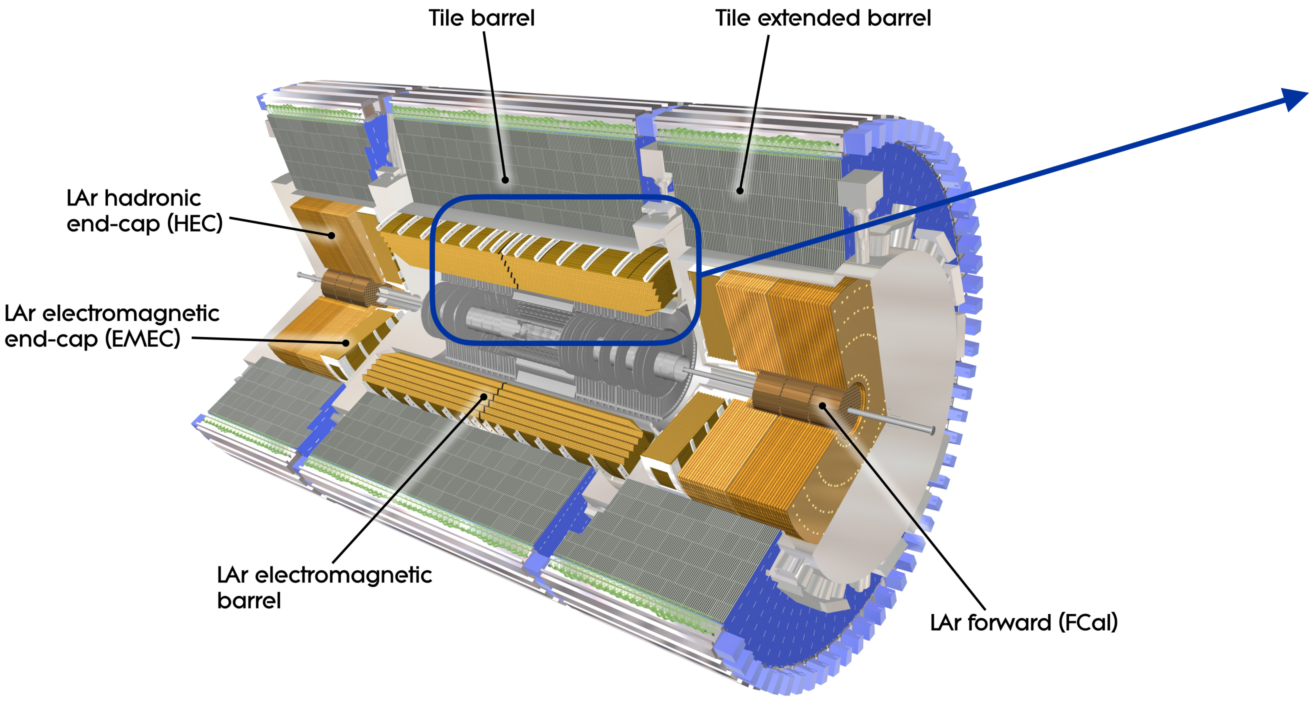


- When the shower shape is tested more precisely, the FTF tune2 does not lead to a better agreement with data

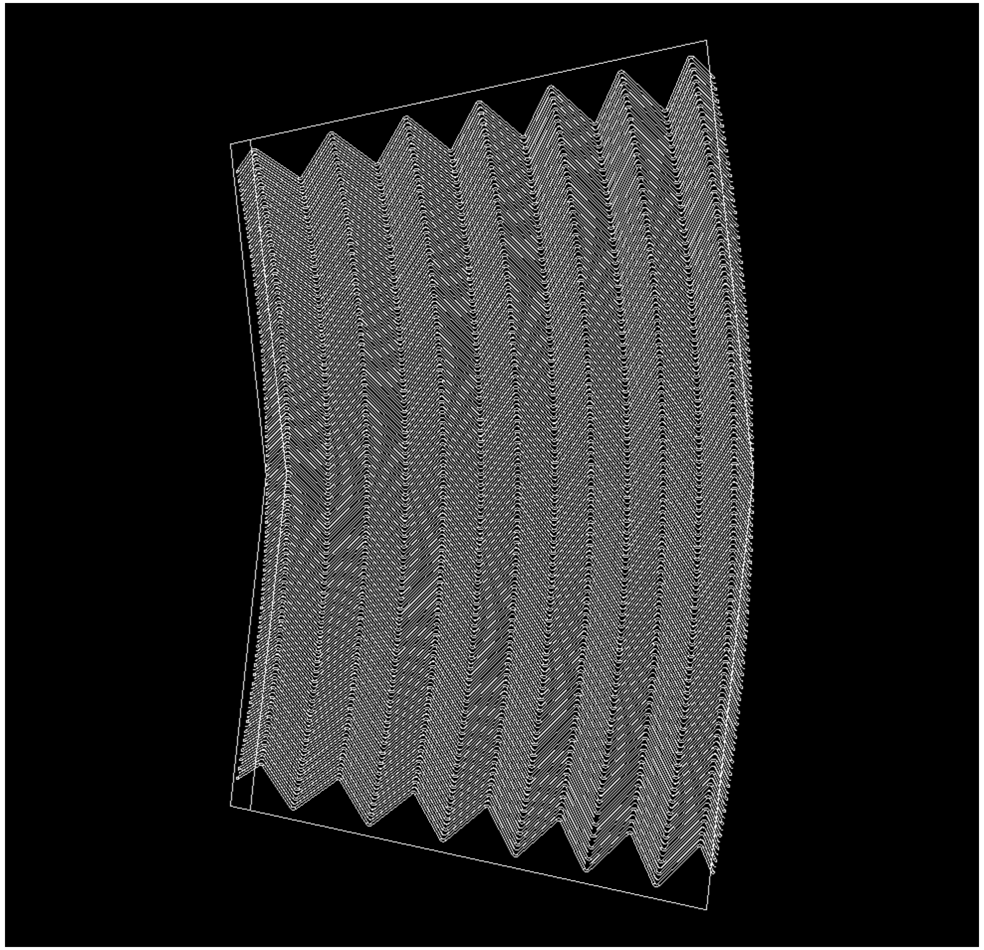
Preliminary results from the Geant4 ATLAS LAr barrel test

An ATLAS LAr barrel test for geant-val

- We ported to a standalone Geant4 simulation the last test-beam code of the ATLAS LAr barrel Calorimeter
- This (very) complex geometry is a good benchmark to test the speeding-up solutions in em-physics



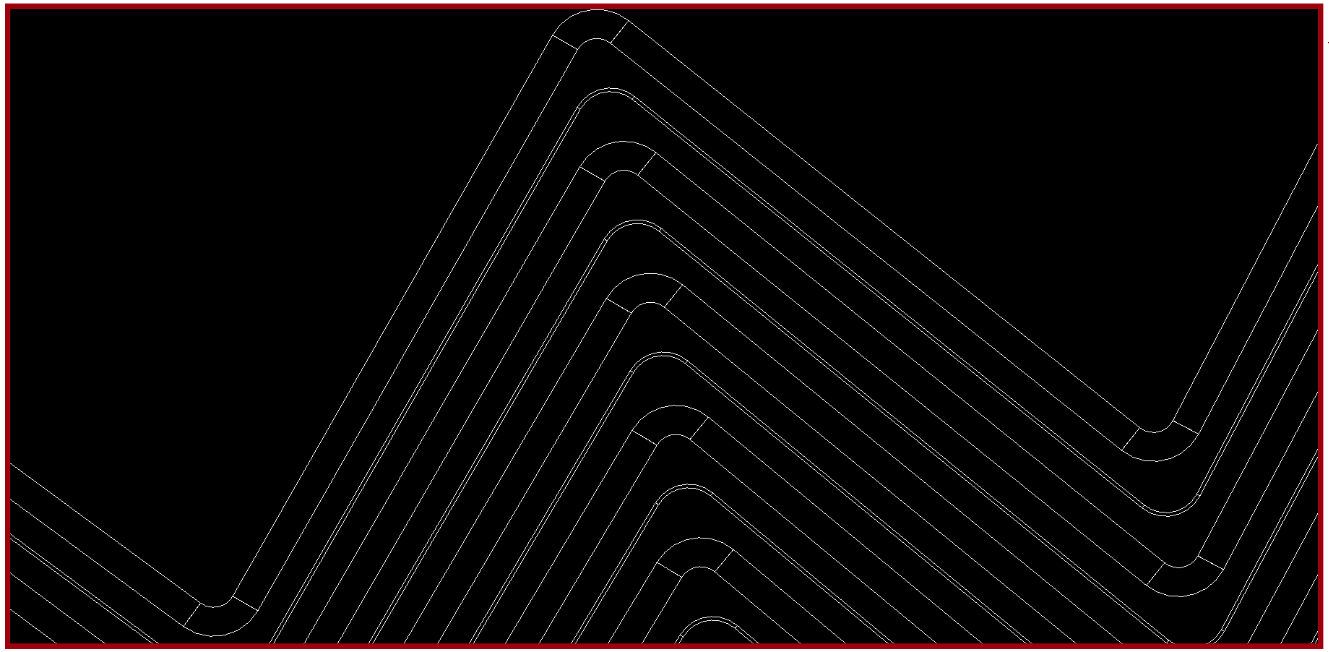
A single LAr module



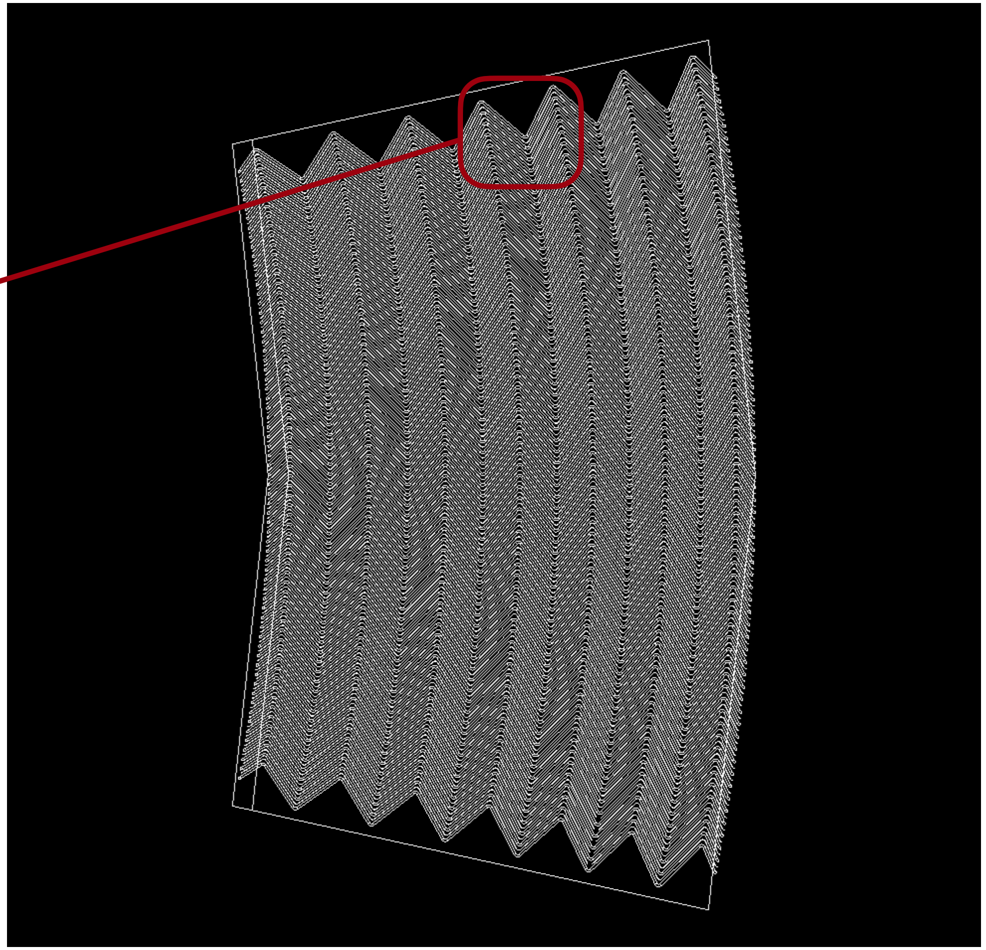
An ATLAS LAr barrel test for geant-val

- We ported to a standalone Geant4 simulation the last test-beam code of the ATLAS LAr barrel Calorimeter
- This (very) complex geometry is a good benchmark to test the speeding-up solutions in em-physics

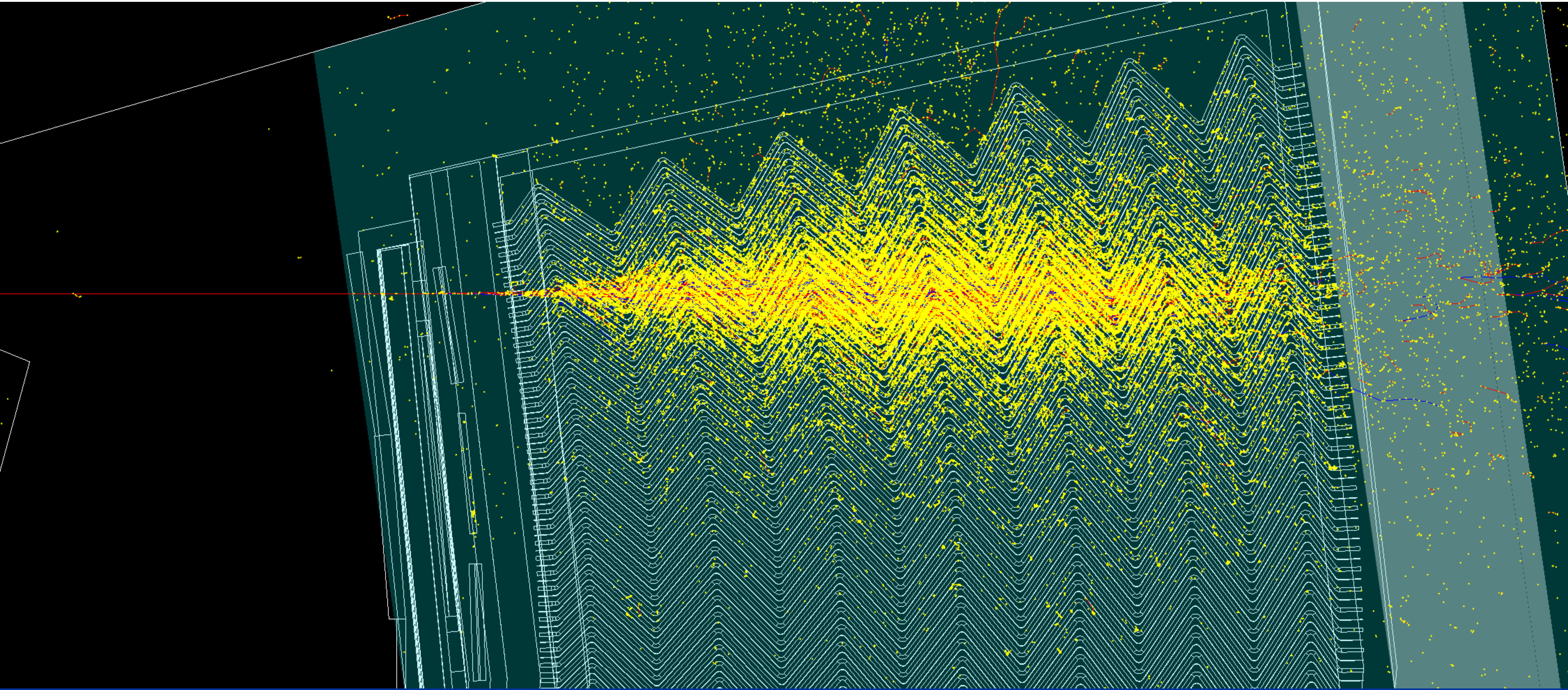
The Accordion geometry



A single LAr module

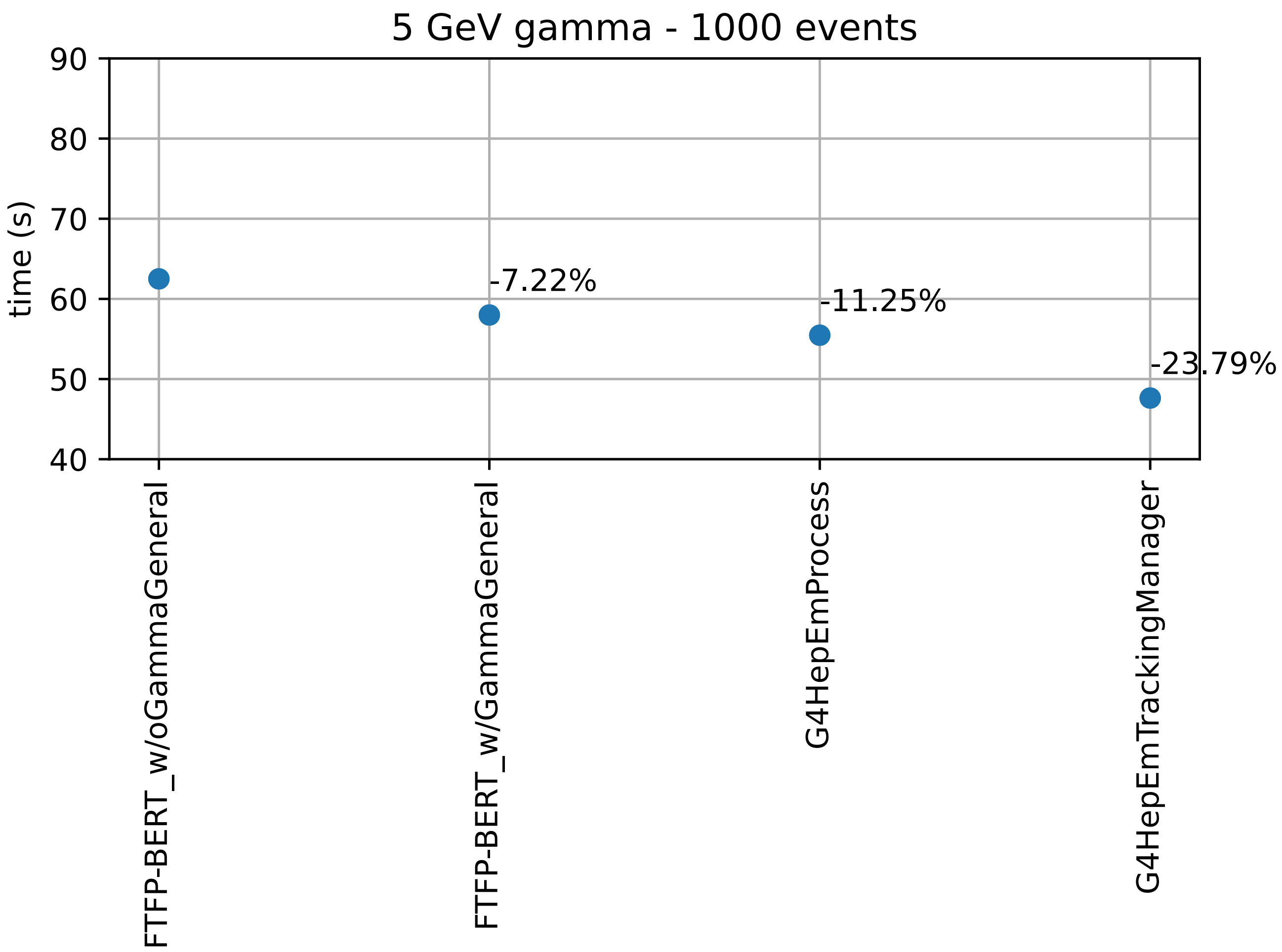


100 GeV e^- in the ATLAS LAr barrel



Testing speedup solutions

- 1000 events, 5 GeV γ in the ATLAS LAr geometry:
  - Using Geant4-11.1
  - CPU: Apple M1 Pro @3.2 GHz, using a single thread.
  - No SensitiveDetector, no hit, no SteppingAction
  - Note:
    GammaGeneral process is not included in G4HepTrackingManager nor in G4HepEmProcess



Summary and next steps

- Recent results:
  - FLUKA.CERN hadronic model was found to be in good agreement with FTFP_BERT PL
  - Alternative FTF tunings usually do not lead to better description of thick target data
  - Speedup solutions from em-physics modeling are being tested on the ATLAS LAr barrel geometry
- Next steps:
  - CMS HGCAL beam tests
- Our Geant-val tests were selected as benchmarks for R&D activities:
  - Celeritas and Adept/ATLAS-Adept
  - Julia interface (Geant4.jl) by Pere Vila

Backup

mc-config-generator 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

```
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
```

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
```