# Validating Geant4 and its FLUKA.CERN interface against calorimeters beam tests

*Lorenzo* Pezzotti[1,*], *Gabrielle* Hugo[1], *Dmitri* Konstantinov[1,2], and *Alberto* Ribon[1] on behalf of the Geant4 Collaboration

[1]CERN

[2]University of Virginia

**Abstract.** The Geant4 Collaboration is leading a long-term validation program to port calorimeter test-beam simulations and results into geant-val, the Geant4 validation and testing suite. New results including Geant4 regression testing and physics list comparison are presented and discussed. Moreover, the new Geant4-to-FLUKA.CERN interface recently allowed detailed comparisons between the hadronic models in Geant4 and the FLUKA.CERN Monte Carlo codes. The interface is described and some geant-val results obtained with it are presented here for the first time.

## 1 Geant4 and geant-val

The Geant4 simulation toolkit [1–3] is a general-purpose Monte Carlo code capable of simulating radiation-matter interactions happening at an energy scale from O(100) eV to TeV, with some models for DNA and silicon simulation which can go down to eV scale, and neutrons that can be tracked down to thermal energies. Geant4 is currently used in biomedical, astroparticle, atmospheric, nuclear and sub-nuclear applications. At CERN, Geant4 is the toolkit backing all the simulations for the four big experiments at the Large Hadron Collider (LHC). Among all the computing activities such experiments perform, full simulation of the experiments with Geant4 is the most CPU-intensive. This situation will continue at the Run4 High-Luminosity operation as pointed out by the ATLAS Experiment's conservative Run4 CPU projection, showing that the Monte Carlo full-simulation will account for 24% of the computing budget [4]. At the same time, Geant4 applications in particle physics are increasingly oriented towards detector design at future Higgs factories where the precision physics envisaged calls for higher resolution experiments and more precise simulations with respect to the LHC standards. Therefore, the evolution of Geant4 points to faster simulation with more reliable physics models.

Physics models reliability in Geant4 is tested against experimental data with geant-val, the Geant4 validation and testing suite [5]. Geant-val facilitates the execution of time-consuming tests maximizing the usage of CERN computing resources and stores results in a database for long-term preservation. A web application (available at geant-val.cern.ch) allows the creation of comparison plots on demand, typically by comparing results from different Geant4 releases (regression testing) or physics models (physics lists' comparison). Hadronic models validation in geant-val stands on two pillars: thin target testing, allowing validation of secondary particles production in isolated hadronic processes, and calorimeter testing, allowing complete validation of the hadronic showering development in realistic environments. In the last three years, a long-term campaign to port test-beam simulation and results into geant-val [6] was carried on and selected results will be presented in Sect. 2. In Sect. 3 a new Geant4-to-FLUKA.CERN interface will be described and finally in Sect. 4 the first results comparing the two Monte Carlos will be described.

## 2 Results from the ATLAS Tile Calorimeter test-beam

The Tile Calorimeter is the ATLAS barrel hadronic calorimeter covering the region $|\eta| < 1.7$. It is a sampling calorimeter composed of eleven longitudinal rows of scintillating plastic tiles sandwiched within iron slabs. The ATLAS geometry includes three cylindrical calorimeters: the central "long-barrel" one, along with two "extended-barrel" cylinders featuring a higher $\eta$ coverage. The light produced by the scintillating tiles is brought to traditional photo-multipliers positioned at the back of the calorimeter by wave-length-shifting optical fibers. The fibers grouping into the same photo-multiplier defines the pseudo-projective readout cells for the entire calorimeter. A more extensive detector description is given at [7] and not repeated here for brevity.

Two Tile Calorimeter long-barrel modules and one extended-barrel module stacked together, as shown in Fig. 1 (left), are regularly tested with the CERN Super-Proton-Synchrotron (SPS) particle beams. The 2017 test-beam and its data analysis campaign [7] measured the calorimeter $\pi/e$ response by dividing the energy of the calorimeter cells calibrated to the electromagnetic scale

*e-mail: lorenzo.pezzotti@cern.ch

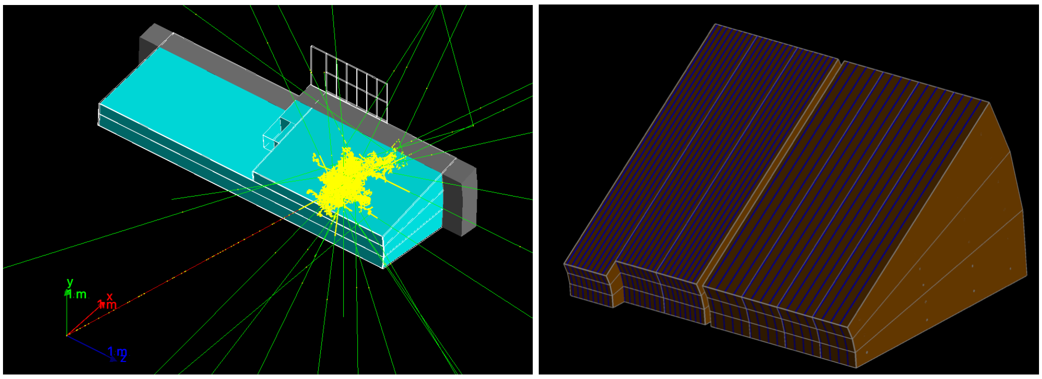

**Figure 1.** (Left) Test beam geometry as reproduced in Geant4 for the Tile Calorimeter beam tests. (Right) Graphical representation of the three $\phi$-modules from a section of the ATLAS HEC (HEC1+HEC2) as simulated with Geant4.

by the energy of the incident beam ($R^{E^{raw}}$). Of particular interest was the possibility of disentangling the contributions from $\pi^+$, $K^+$ and $p$ in the energy range 16-30 GeV by tagging the hadron type using three auxiliary Cherenkov counters positioned upstream of the calorimeter. The TileCal test-beam simulation was ported to geant-val and the Geant4 hadronic models tested against it.

Fig. 2 shows the results for the three hadron types separately and indicates a difference for the response to $\pi^+$ and $p$ up to $\simeq$ 10%. This difference arises from the electromagnetic fraction content within the showers induced by $\pi^+$ and $p$ beams: while in $\pi^+$-induced showers processes like $\pi^+ + n \rightarrow \pi^0 + p$ make possible events in which a large fraction of the beam energy is transformed into the electromagnetic component, such events are prohibited for $p$-induced showers due to baryon number conservation. While at the LHC such particles are included in collimated hadronic jets with no possibility to disentangle their contributions, this result represents an ideal benchmark for Geant4.

Fig. 2 also shows the regression testing for the FTFP_BERT Physics List (PL), the recommended choice in high-energy-physics applications, which combines the Fritiof (high-energy) hadronic string model with the (low-energy) Bertini hadronic intra-nuclear cascade model with an overlapping range between 3 – 6 GeV. Overall, Geant4 agrees well with the experimental data and the difference in the response to $\pi^+$, $K^+$ and $p$ is well reproduced. Also visible is a constant increase in the response to simulated hadronic showers from the Geant4 release 10.4 (2017) to 10.7 (2020) and a decrease in the more recent 11.2 (2023). Such a regular testing of the evolution of Geant4 physics predictions is vital for the toolkit development.

## 3 Geant4 interface to FLUKA.CERN hadron-nucleus inelastic interactions

An interface to the FLUKA.CERN hadron inelastic interaction physics is available in Geant4 from the 11.2 release onward [8]. This interface remarkably extends the range of physics options available to the Geant4 user community, giving access to models developed and benchmarked over decades independently from those of Geant4. It encompasses the FLUKA PEANUT nuclear interaction model [9–11], which handles hadron-nucleus interactions from threshold (or 20 MeV for neutrons) to 20 TeV. PEANUT includes a Glauber–Gribov cascade for modelling the multiple collisions of each hadron with the nuclear constituents, a Generalized IntraNuclear Cascade (GINC) with transition to a preequilibrium stage, and finally the evaporation, fragmentation, fission and final deexcitation. Photonuclear reactions are also supported. Via this interface, the FLUKA.CERN models can be accessed from any Geant4 application. In addition to the interface itself, examples demonstrating its use are included in Geant4, both at the single interaction level via an event generator and at the physics list level. The physics list encompasses hadron inelastic physics from FLUKA, while all other components such as elastic scattering, neutron treatment below 20 MeV, electromagnetic physics and particle transport rely on the Geant4 implementation. Fig. 3 illustrates the use of the FLUKA.CERN interface in event generator mode, displaying the spectra of protons and neutrons from the interaction of 7 TeV protons on natural carbon. Conversely, Sect. 4 presents an example application of the FLUKA.CERN interface using a Physics List. This section details an inter-comparison of Geant4 and FLUKA results against test-beam data from the ATLAS Experiment.

## 4 Results from the ATLAS Hadronic Endcap test beam

The ATLAS Hadronic Endcap Calorimeter (HEC) [12] is used to reconstruct hadronic jets in the range $1.5 < |\eta| < 3.2$. To fit in the forward ATLAS region, it adopts a wedge-shaped design with 32 azimuthal modules rotating around the beam pipe. The HEC is part of the ATLAS Liquid Argon (LAr) calorimetric system as LAr is used in 8.5-mm-thick active gaps interspersed in copper plates. Two wheels make the entire calorimeter: an innermost wheel (HEC1) uses 2.5-cm-thick copper plates, and is followed by a second wheel (HEC2) in which the absorber thickness is increased to 5.0 cm. The total length is 9.7 $\lambda_{int}$. The readout scheme consists of 88 channels grouped in

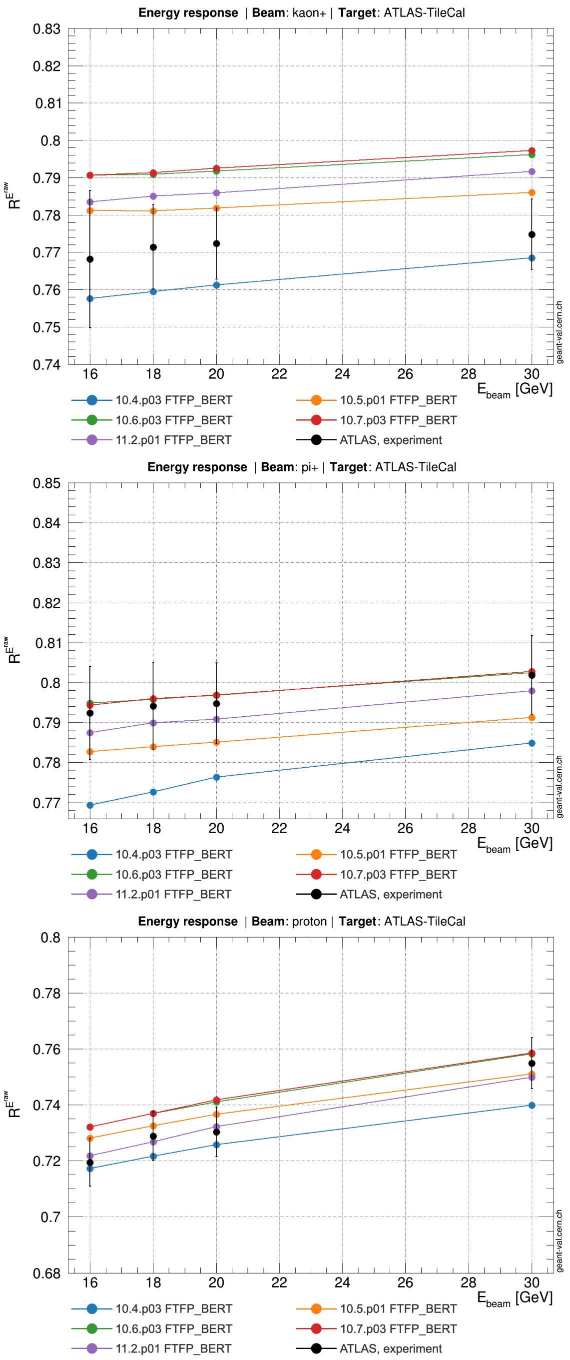


**Figure 2.** The ATLAS Tile Calorimeter response in the energy range 16-30 GeV for $K^+$ (up), $\pi^+$ (center) and $p$ (down). Experimental results from [7] are compared with the FTFP_BERT Physics List of Geant4 release 10.4 (2017), 10.5 (2018), 10.6 (2019), 10.7 (2020) and 11.2 (2023). Simulation results from geant-val testing.

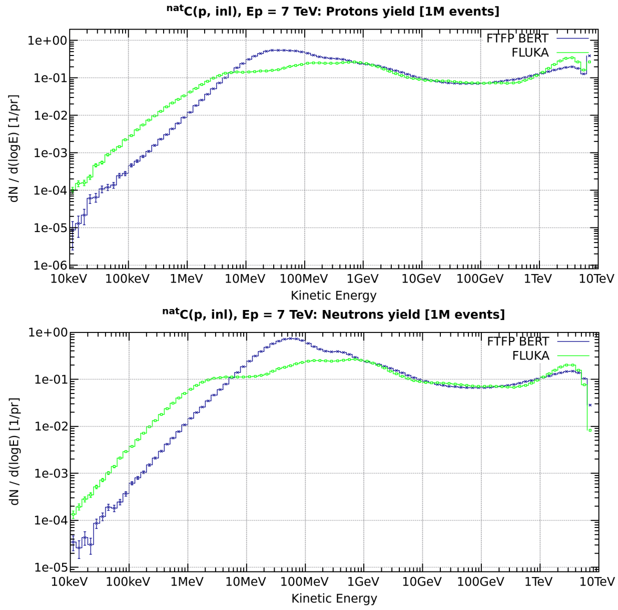


**Figure 3.** Proton (up) and neutron (down) secondaries from the interaction of 7 TeV protons on natural carbon. Results obtained with the Geant4 FTFP_BERT Physics List are compared with the ones from the FLUKA.CERN hadron inelastic process used via the Geant4 interface.

semi-projective cells which easily determines the $\eta$ direction of impinging particles. The readout cell size amounts to $\Delta\eta \times \Delta\phi = 0.1 \times 2\pi/64$ up to $|\eta| < 2.5$ and $0.2 \times 2\pi/32$ for $|\eta| > 2.5$. Readout cells are divided longitudinally into 4 layers.

During the HEC construction, a section of the full detector composed of 3-$\phi$ wedges, was tested with the CERN SPS beams in 2000-2001. Secondary and tertiary beams from the SPS have been used to study the calorimeter performance with electrons, muons and pions within the energy range $6 \leq E_{beam} \leq 200$ GeV. The results found allowed a detailed characterization of the detector performances and a test bed for Geant4 simulation.

The HEC test-beam simulation was recently ported to geant-val, Fig. 1 (right), and the simulation output was compared to a summary of the detector performance in beam testing [13]. Test-beam setup and data analysis treatment are explained in [13]. In the following, we report the first comparison of Geant4 (development version 11.1.ref05, similar to 11.2.beta) and FLUKA.CERN (release 4-3.3) hadronic models over this experimental benchmark.

The $\pi/e$ ratio, i.e., the ratio of the response to negatively charged pions and electrons, was measured by dividing the reconstructed energy for $\pi^-$ events by the one obtained for $e^-$ events with approximately the same energy. Fig. 4 (up) shows its value in the energy range 20 – 160 GeV and compares the experimental reference with Geant4 simulations with and without the FLUKA.CERN interface that substitutes the hadronic inelastic models with the FLUKA.CERN one. Currently, simulated results emerging from the two hadronic models overestimate up to

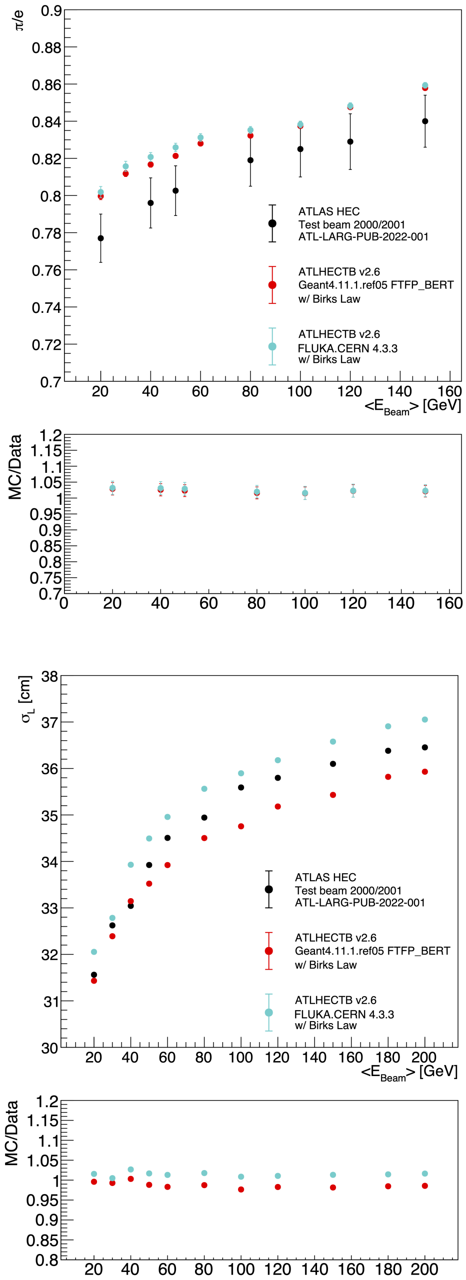


**Figure 4.** The ATLAS HEC $\pi/e$ ratio as measured in beam testing, simulated by Geant4 uniquely and in combination with the FLUKA.CERN interface; read text for details (up). The HEC longitudinal profile root mean squared as measured in test beam, simulated by Geant4 uniquely and in combination with the FLUKA.CERN interface; read text for details (down). Simulated results from geant-val testing.

a few percent the experimental reference; the agreement of the two models in describing the average simulated signal at every energy is remarkable.

The HEC longitudinal segmentation into four layers with lengths of 1.45, 2.75, 2.87 and 2.66 $\lambda_{int}$ allows studying the hadronic shower length in beam testing. In particular, the energy profile was defined as the energy fraction deposited in each layer reconstructed as $F_i =< E_i > /E_{sum}$ with $E_{sum} = \sum E_i$. The root mean squared (RMS) of the profile represents an indirect measurement of the shower length: the longer the shower the higher the RMS, and vice-versa. Fig. 4 (down) shows the shower longitudinal profile RMS at several beam energies for $\pi^-$-induced shower. It is evident how the shower becomes longer while the beam energy is increased. Over-imposed to the experimental reference, we report the simulation results as obtained with Geant4 with and without the FLUKA.CERN interface. Interestingly, Geant4 hadronic models lead to shower lengths underestimating the ATLAS results, while the FLUKA.CERN hadronic model overestimates it, especially for energies above 120 GeV.

## References

[1] S. Agostinelli et al., Geant4 - A Simulation Toolkit, Nucl. Instrum. Meth. A 506 250-303 (2003). https://doi.org/10.1016/S0168-9002(03)01368-8

[2] J. Allison et al., Geant4 Developments and Applications, IEEE Trans. Nucl. Sci. 53 270-278 (2006). https://doi.org/10.1109/TNS.2006.869826

[3] J. Allison at al., Recent Developments in Geant4, Nucl. Instrum. Meth. A 835 186-225 (2016). https://doi.org/10.1016/j.nima.2016.06.125

[4] ATLAS, ATLAS Software and Computing HL-LHC Roadmap, CERN-LHCC-2022-005, LHCC-G-182, Geneva (2022). https://cds.cern.ch/record/2802918

[5] L. Freyermuth et al., Geant-val: a web application for validation of detector simulations, EPJ Web of Conferences 214, 05002 (2019). https://doi.org/10.1051/epjconf/201921405002

[6] L. Pezzotti et al., Including Calorimeter Test Beams in Geant-val—The Physics Validation Testing Suite of Geant4, Instruments, 6, 41 (2022). https://doi.org/10.3390/instruments6030041

[7] J. Abdallah et al., Study of energy response and resolution of the ATLAS Tile Calorimeter to hadrons of energies from 16 to 30 GeV, Eur. Phys. J. C 81, 549 (2021). https://doi.org/10.1140/epjc/s10052-021-09292-5

[8] G.Hugo et al., Latest FLUKA developments, in Proc. SNA+MC 24, Paris, France (2024).

[9] Ferrari, A. & Sala, P. The Physics of High Energy Reactions in Proc. Workshop on Nuclear Reaction Data and Nuclear Reactor Physics, Design and Safety (World Scientific, 1998), 424.

[10] Ballarini, F. et al. The physics of the FLUKA code: Recent developments. Advances in Space Research. 40, 1339–1349 (2007).

[11] Battistoni, G. et al. Overview of the FLUKA code. Annals of Nuclear Energy 82, 10–18 (2015).

[12] D.M. Gingrich, D.M. et al., Construction, assembly and testing of the ATLAS hadronic end-cap calorimeter, J. Instrum 2 P05005 (2007).

[13] ATLAS, Performance of the ATLAS Hadronic End-cap Calorimeter in beam tests: Selected results, ATL-LARG-PUB-2022-001, CERN, Geneva (2022). https://cds.cern.ch/record/2811731