

## Deliverable Report

# Adequation of GEANT4 simulation of hadronic showers in different media

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# AIDA

Advanced European Infrastructures for Detectors at Accelerators

Seventh Framework Programme, Capacities Specific Programme, Research Infrastructures,  
Combination of Collaborative Project and Coordination and Support Action

## DELIVERABLE REPORT

# ADEQUATION OF GEANT 4 SIMULATION OF HADRONIC SHOWERS IN DIFFERENT MEDIA

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### Abstract:

AIDA has contributed to the validation and further development of Geant 4 shower simulation models through the provision of mechanical and electronics as well as software infrastructure to support carrying large test beam campaigns and analysing the recorded data. The report gives a brief account of the measures, highlights some results and guides to more detailed documentation.

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## Executive summary

*Experiments at LHC and LC pose increasing demands on precision in modelling the interactions of high-energy particles with the detector material and in particular the evolution of hadronic showers. The trend to high granularity calorimeters amplifies the challenge. In the past years, shower simulation models, as implemented in the Geant4 software toolkit, have been continuously improve and refined. Test beam data recorded with highly granular prototypes developed and built within the CALICE collaboration are now the main source for experimental validation of the models.*

*AIDA has contributed to this validation effort by supporting the analysis of existing data and by improving the infrastructure for the construction and operation of new prototypes, which extend the range of tested technologies to tungsten absorbers and gaseous read-out. Altogether, during the period of AIDA this has led to the publication of seven refereed journal papers and five preliminary conference results documented in analysis notes on the subject of validation of Geant 4 shower models.*

*This deliverable report explains the relationship between the AIDA activities and these published validation results, and it gives some highlights to illustrate the current status of adequateness of the simulation models. These include classical measurements such as longitudinal and transverse shower profiles, but also new observables like the charged track multiplicity of particles generated with the hadronic cascade. For more global observables, the agreement between data and simulation is typically better than 5%, and in more detailed comparisons the data are reproduced with about 10% accuracy. The Geant4 toolkit is an important ingredient to physics analysis e.g. at the LHC and has also become a quantitative tool for detector design and optimisation, including hadronic calorimetry.*

## 1. INTRODUCTION

High energy physics experiments at the large hadron collider (LHC) and at a future linear electron positron collider (LC) pose increasing demands on precisely simulating multi-jet final states. Next to understanding QCD parton showers and jet fragmentation, modelling hadronic interactions in the detector material and the propagation of hadronic showers in the calorimeters is crucial for obtaining accurate predictions of experimental observations and thus maximising the sensitivity to underlying fundamental quantities or possible deviations due to new phenomena.

Over the past decade, the feedback from test beam experiments carried out with prototypes for the calorimeters of the large LHC experiments has spurred considerable improvements in the shower simulation models as implemented in the Geant 4 software toolkit. More recently, the trend towards development of calorimeters, which are more finely segmented in three dimensions, has amplified the challenge. This had originally been motivated by the so-called particle flow approach adopted by the planned LC detectors for the reconstruction of their final states particle by particle, but it is now also inspiring plans for the upgrades of LHC calorimeters.

Test beam data recorded with highly granular prototypes developed and built within the CALICE collaboration are now the main source for experimental validation of the models. AIDA has contributed to this validation effort by supporting the analysis of existing data and by improving the infrastructure for the construction and operation of new prototypes, which extend the range of tested technologies to tungsten absorbers and gaseous read-out. Altogether, during the period of AIDA this has led to the publication of seven refereed journal papers and five preliminary conference results documented in analysis notes on the subject of validation of Geant 4 shower models.

This deliverable report explains the relationship between the AIDA activities and these published validation results, and it gives some highlights to illustrate the current status of adequateness of the simulation models.

## 2. CALICE AND AIDA

### 2.1. CALICE TEST BEAM PROGRAM

The CALICE collaboration develops highly granular electromagnetic and hadronic calorimeters (ECAL and HCAL, respectively) for experiments at a future linear colliders such as the ILC or CLIC. In this framework several large prototypes have been constructed and exposed to test beam, including a variety of absorber materials and active read-out technologies.

Before the start of AIDA, data with a tungsten ECAL with either silicon or scintillator read-out were available, and with a steel HCAL with scintillator read-out, which had been recorded at CERN and Fermilab in the years 2006-08, and first analysis results had been published.

With the help of AIDA, a versatile tungsten HCAL structure was provided for test beam experiments with scintillator as well as gaseous read-out, and different gaseous read-out elements, based on resistive plate chambers (RPCs) and micro-mesh amplification structures (MICROMEAS) have been built and included in the test beam set-ups for data taking in the years 2011-12. The set-ups are shown in Figure 1.

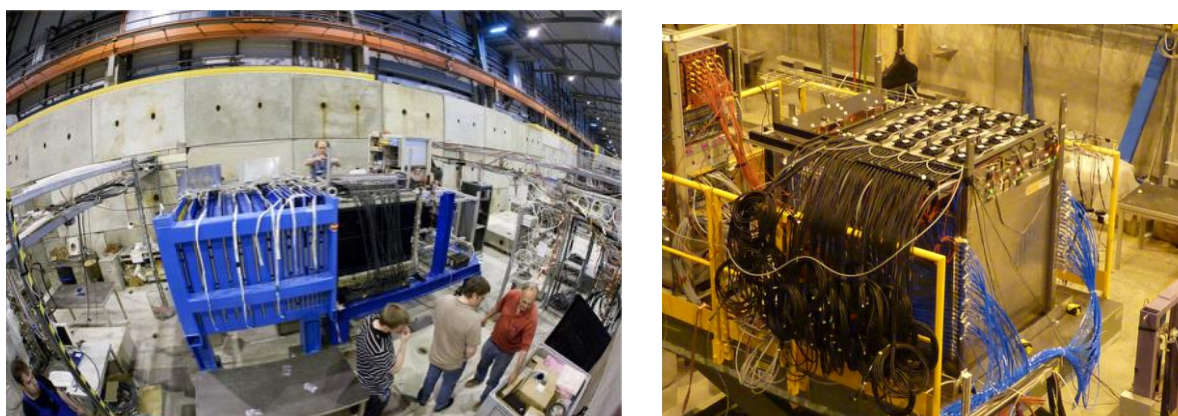


Figure 1: CALICE test beam set-ups at the SPS: tungsten HCAL (left) with tail catcher, steel HCAL with RPC read-out (right)

### 2.2. AIDA CONTRIBUTIONS

Several measures [1] in AIDA contributed directly or indirectly to the test-beam based Geant 4 validation effort:

- The **analysis software framework** created in AIDA and further developed in AIDA (WP 2) is used by CALICE and provides an efficient environment for simulation and reconstruction.
- The **transnational access** mechanism was used to support a wide participation of different user groups in the test beam campaigns at CERN (WP 6) or at DESY (WP 5).
- **Mechanical infrastructure** and support (WP 9) was provided. A platform was built which did not only host the tungsten absorber structure, but also the racks for read-out and supply, and cable trays, which enabled the transfer of the complete set-up after

commissioning in a staging area into the beam enclosure without extra re-cabling effort (Figure 2). In addition, a versatile tail catcher absorber structure was constructed which was instrumented with existing scintillator or RPC planes for the different test beam campaigns.

- Electronic components were provided (WP 9) to support the read-out of a dedicated **fast timing** installation. The tungsten timing test beam (T3B) detection elements (scintillator tiles, see Figure 2, or a small RPC), together with an event-wise reconstruction of the point of first interaction, using the standard read-out, enabled measurements of hit timing as a function of position along and transverse to the shower axis.
- The RPC and micromegas-based read-out elements of the semi-digital (SD) HCAL were equipped with HARDROC2 ASICs and thus strongly benefitted from the **development of the ROC ASIC family** started in EUDET and continued in AIDA (WP 9).
- AIDA supported the provision of a **gas system** for SDHCAL operation (WP 9).
- The **data acquisition system (DAQ)** used by both SDHCAL technologies was based on developments made in the framework of EUDET and continued in AIDA (WP 8).

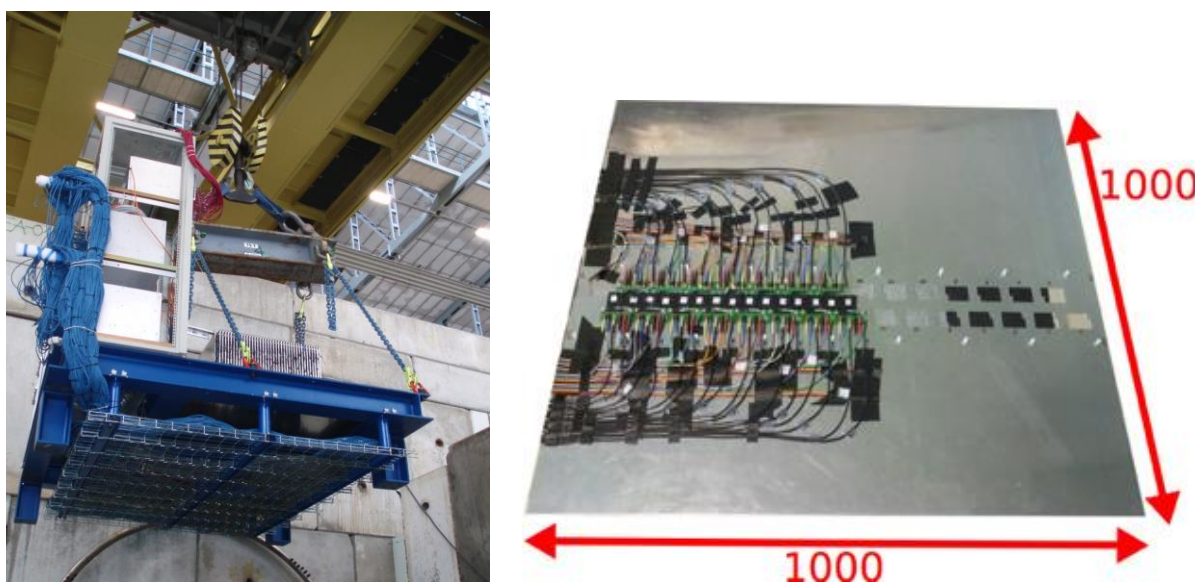


Figure 2: Platform for tungsten HCAL structures and peripherals (left), view of the high precision timing installation T3B (right).



### 3. PUBLISHED RESULTS

We include in this overview results, which are directly related to the validation of Geant4 shower simulation models. Additional ones have been released, e.g. on response and energy resolution of the SDHCAL, but have not been compared to simulations yet.

#### 3.1. JOURNAL PAPERS

Based on data taken before the start of AIDA:

- **Hadronic energy resolution of a highly granular scintillator-steel calorimeter using software compensation techniques;** 2012\_JINST\_7\_P09017 [2]
- **Track segments in hadronic showers in a highly granular scintillator-steel hadron calorimeter;** 2013\_JINST\_8\_P09001 [3]
- **Validation of GEANT4 Monte Carlo Models with a Highly Granular Scintillator-Steel Hadron Calorimeter;** 2013\_JINST\_8\_P07005 [4]
- **Shower development of particles with momenta from 1 to 10 GeV in the CALICE Scintillator-Tungsten HCAL;** 2014\_JINST\_9\_P01004 [5]
- **Testing Hadronic Interaction Models using a Highly Granular Silicon-Tungsten Calorimeter** e-Print: arXiv:1411:7215, submitted to NIM [6]
- **Pion and proton showers in the CALICE scintillator-steel analogue hadron calorimeter;** e-Print: arXiv:1412.2653 submitted to JINST [7]

Based on data taken during the period of AIDA:

- **The Time Structure of Hadronic Showers in Highly Granular Calorimeters with Tungsten and Steel Absorbers;** JINST 9 (2014) P07022 [8]

#### 3.2. CALICE ANALYSIS NOTES

CALICE releases preliminary results for presentation at conferences in the form of CALICE analysis notes, which undergo an internal peer review process and are publicly available. In general, the results therein are frozen until they are replaced by a final journal paper.

Based on data taken before the start of AIDA:

- **Parametrisation of hadron shower profiles in the CALICE Sc-Fe AHCAL;** CALICE analysis note CAN-048 [9]
- **Analogue, Digital and Semi-Digital Energy Reconstruction in the CALICE AHCAL;** CALICE analysis note CAN-049 [10]
- **Extraction of h/e and calorimeter response from fits to the longitudinal shower profiles in the CALICE Sc-Fe AHCAL;** CALICE analysis note CAN-051 [11]

Based on data taken during the period of AIDA:

- **Shower development of particles with momenta from 10 to 100 GeV in the CALICE scintillator-tungsten HCAL;** CALICE analysis note CAN-044 [12]
- **Tracking within Hadronic Showers in the SDHCAL prototype using Hough Transform Technique;** CALICE analysis note CAN-047 [13]

The analysis of test beam data for the purpose of validation of shower simulations is complex and time-consuming. In particular, the understanding of the detector response in terms of simulations must first be validated using the well understood and precisely simulated interactions of muons and electrons, before physics conclusions on the adequateness of hadronic shower models can be drawn. Therefore the above lists contain still mostly results from the earlier data taking periods. However, it is to be expected that a similar number of publications will result from the more recent data and appear in the next few years.

## 4. SELECTED HIGHLIGHTS

A comprehensive review of the adequateness of Geant4 shower simulation models (see e.g. [14]) would be beyond the scope of this deliverable report. We restrict ourselves to illustrate the status with a few highlights selected from the results obtained in connection with AIDA.

### 4.1. CLASSICAL OBSERVABLES: SHOWER SHAPES

As a first example we show the longitudinal shower profile measured for pions of 80 GeV energy in the CALICE scintillator steel HCAL in Figure 3. The fine granularity of the detector allows for reconstruction of the location of the first hard interaction event by event such that the profile can be measured as a function of distance from shower start. The resulting profiles are thus not convoluted with the large spread of initial penetration depth but much narrower and make it easier to assign different – early or late – parts to different physics sub-processes occurring in the cascade. Such decomposition is also shown in the figure.

The largest discrepancies between data and simulation have persisted for quite some time in the transverse profiles of hadronic showers. However, with recent model improvements also here the disagreement is reduced to a level below 5% for pions, and proton data are almost perfectly matched, as shown in Figure 3. It is noteworthy that also the event-to-event fluctuations of the shower shapes are well described.

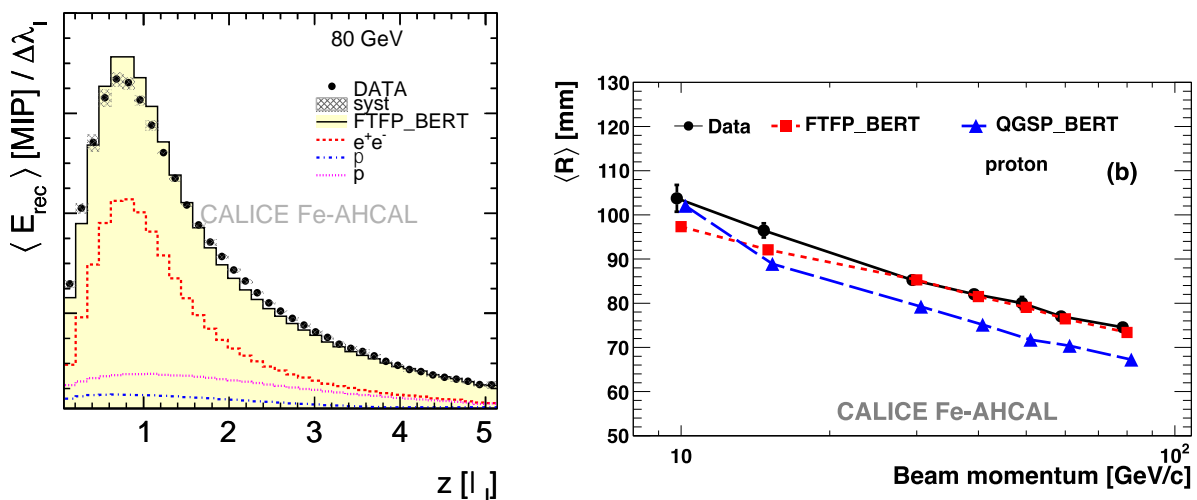


Figure 3: Longitudinal shower profile of pions, measured from the point of first interaction, with simulation and indication of sub-components (left); mean radial shower extension as a function of energy for protons, compared with different simulation models (right).

### 4.2. NOVEL OBSERVABLES: SUB-STRUCTURE AND TIMING

High granularity calorimeters can resolve the internal sub-structure of hadronic showers; a feature that is made use of in particle flow reconstruction and that is to be modelled adequately, too. Charged track segments have been observed in all CALICE prototypes, and quantitative results on track multiplicity and track length have been compared to simulations for the scintillator as well as for the gaseous HCAL, see for example Figure 4. For such detailed comparisons, the agreement with simulations is not perfect, but for the recent, more

theory-driven models it is far better than it used to be for the more phenomenological parameterisations that were in use up to a few years ago.

The slow propagation of low-energetic neutrons produced in the shower cascade induces delayed signals in the calorimeters, which lead to irreducible pile-up backgrounds, e.g. at the LHC or at CLIC. Thus an adequate model description of the hadron shower evolution with time is important for the conception of detectors and readout electronics. Using the T3B set-up, the time of the first energy deposition as a function of distance from the shower axis could be measured and compared with simulations, see Figure 4. For heavy, neutron-rich absorber materials such as tungsten the so-called high performance (HP) versions of the shower models, which include detailed simulation of neutron propagation and absorption, have to be used in order to obtain accurate predictions. For lighter materials such as steel, this is not an issue.

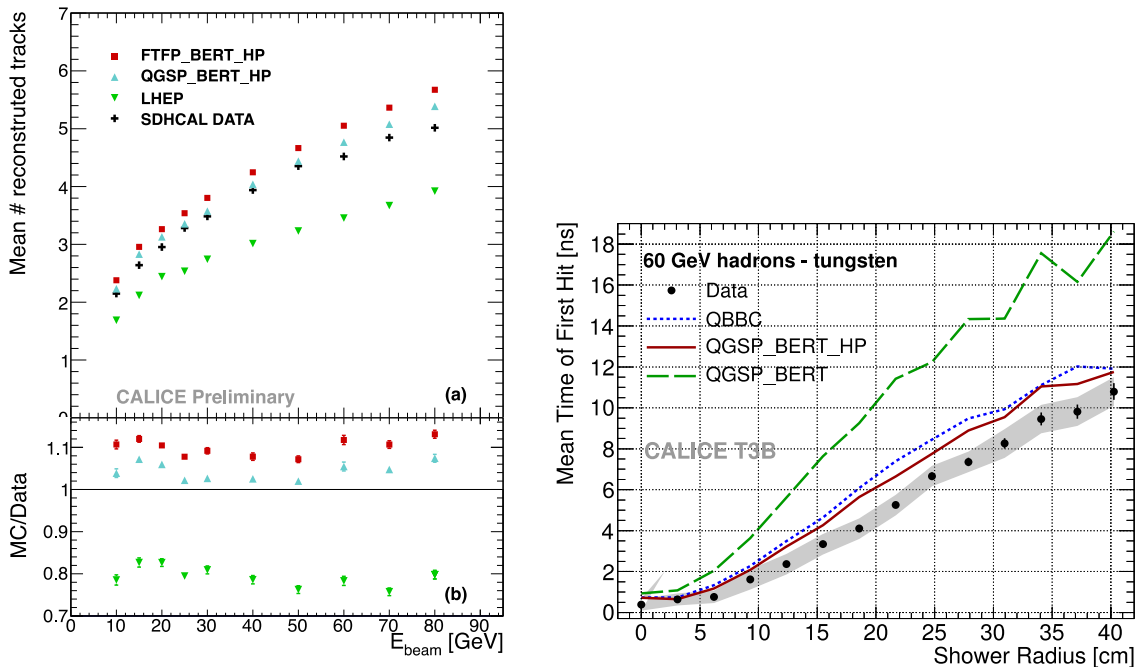


Figure 4: Mean number of reconstructed tracks in pion showers, as a function of primary particle energy (RPC SDHCAL data, left); mean time of first hit as a function of distance from the shower axis (scintillator tungsten HCAL, right).

## 5. CONCLUSION AND FUTURE PLANS

Significant progress has been made over the past years in the achieving adequate descriptions of hadronic showers in terms of theory-driven simulation models. Validation through test beam experiments, carried out in the framework of detector development for the LHC and for linear colliders, is vital in this continued effort. For more global observables, the agreement between data and simulation is now typically better than 5%, and in more detailed comparisons the data are reproduced with about 10% accuracy. The Geant4 toolkit is an important ingredient to physics analysis e.g. at the LHC and has also become a quantitative tool for detector design and optimisation, including hadronic calorimetry.

In the next few years, it is planned to finalise the analyses of the CALICE data taken during the period of AIDA. In particular, a detector simulation will be established that models the response of the semi-digital gaseous detectors also in dense shower core regions and simultaneously describes data recorded with muons, electrons and different types of hadrons. This will then be used to validate hadron shower models for detectors with gaseous readout, which have a different sensitivity to the various sub-components of showers, e.g. to neutrons, than scintillators or silicon pads. Moreover, data taking with the SDHCAL will continue, and the new generation of prototypes constructed with the support of AIDA will be exposed to test beams, too. The ECAL has a four times finer granularity and will probe showers with even higher spatial resolution than before, and the scintillator HCAL readout features single hit timing and will enable the study of timing correlations within shower propagation. From these data unique and important guidance for the further refinement of the shower simulations can be expected.

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## **ANNEX: GLOSSARY**

<b>Acronym</b>	<b>Definition</b>
ASIC	Application-specific integrated circuit
CLIC	Compact linear collider
ECAL	Electromagnetic calorimeter
HCAL	Hadronic calorimeter
ILC	International linear collider
SDHCAL	Semi-digital HCAL