Physics Validation of the Simulation packages in a LHC-wide effort

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Abstract

In the framework of the LCG Simulation Physics Validation Project, we present comparison studies between the Geant4 and FLUKA shower packages and LHC subdetector test-beam data. Emphasis is given to the response of LHC calorimeters to electrons, photons, muons and pions. Results of ”simple-benchmark” studies, where the above simulation packages are compared to data from nuclear facilities, are also shown.

INTRODUCTION

Hadronic physics is notoriously a very broad and difficult field, mainly because the underlying theory, Quantum Chromodynamics (QCD), cannot produce predictions for observables whose dominant energy range is outside the perturbative high-energy regime. The only current viable approach, in these cases, is to use different simplified models, whose approximated validity is often restricted to particular incident particles, target material types, and interaction energies. By using a proper set of these models it is often possible to cover different regions of interest.

In Geant4 [1] a large set of hadronic models are available, and users can choose and combine them according to their needs, in terms of application, precision, and computing time. To ease such a choice, a certain number of “educated guess” Physics Lists, each being a complete and consistent collection of different models, are provided according to use cases.

The goal of this paper is to report about the validation of some of these Geant4 Physics Lists (LHEP, QGSC, QGSP, QGSP_BIC, QGSP_BERT: see [2] for more information), and also of FLUKA simulation engine [3], in the context of the LHC experiments. We will focus here only on the hadronic physics validation (the electromagnetic physics has been already validated at the percent level).

There are two complementary approaches to the physics validation of simulation results: one is based on thin-target setups with simple geometries, that allow to test, in a clean and simple environment, single interactions or effects; the other one relies on calorimeter test-beam setups, in which the observables are the convolution of many complex processes and interactions.

We will treat here some of the work that has been carried out in the context of the LCG (LHC Computing Grid Simulation) Physics Validation Project [4], starting first with three thin-target tests, and then with three calorimeter test-beams.

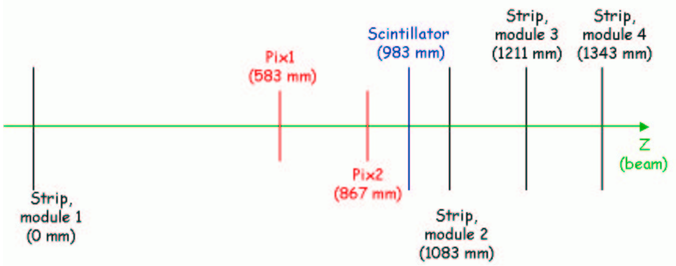

Figure 1: Pixel test-beam setup.

PIXEL TEST-BEAM

A test-beam with $180\,GeV/c$ positive pions on silicon sensors of the ATLAS Pixel tracker detector has been made at CERN in 2001 [5]. The setup is presented in Fig.1. It consists of a telescope of four microstrip planes (each double sided), two pixel detector planes (to test two different chips), and a scintillator counter. The pixel detectors have $50\,\mu m$ pitch in one dimension, $400\,\mu m$ in the other, and thickness of $280\,\mu m$.

In a run dedicated to the study of hadronic interactions, the trigger required an energy deposition in the scintillator corresponding to at least three minimum-ionising particles. A total of about $800\,000$ interaction events were collected. Only those events in which at least three clusters have been reconstructed in each of the three downstream microstrip planes (in both sides) are further considered in the analysis.

The analysis procedure consists of four steps.

First, tracks are reconstructed in the three microstrip planes downstream of the pixel planes. Second, the interaction vertex is reconstructed. Third, the cluster (defined as a contiguous set of pixels each having a charge deposit above a given threshold) closest in the transverse plane to the interaction is selected, and it is further considered only if it has a large energy deposition, as expected for heavy nuclear fragments, of very short range, which are produced in hadronic interactions. Fourth, the cluster properties of such selected interaction clusters are finally considered.

We show in Fig.2 the comparisons between data and simulation results for FLUKA and for some Physics Lists of Geant4, for the two most important observables, that are, at least in first approximation, indipendent from the absolute normalization of the cluster charge that is not well known. We refer to the note [6] for more details. The conclusion is that both Geant4 and FLUKA describe reasonably well the test-beam data, more or less at the same level, although there are some discrepancies in some observables. Geant4 QGSP reproduces very closely the ratio of the charges (first plot in Fig.2), but the cluster (second plot in Fig.2) is narrower than the data; vice versa, FLUKA

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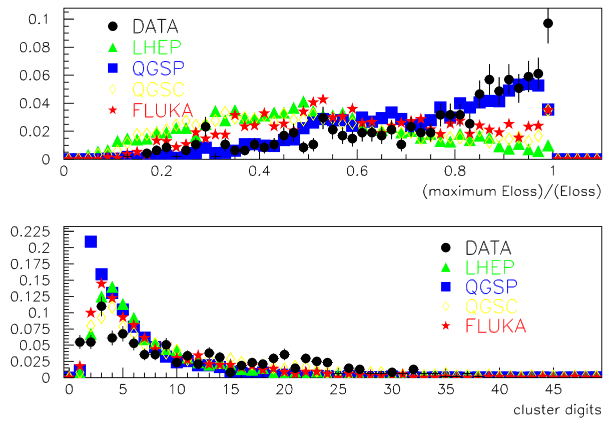

Figure 2: The upper plot shows the maximum energy in a single pixel of the cluster divided by the total cluster energy. The bottom plot shows the cluster size, i.e. the number of pixels in the cluster.

and, to less extend, also Geant4 LHEP and QGSC describe well the cluster size, but not so the charge ratio.

NEUTRON PRODUCTION CROSS-SECTIONS

Neutron production from proton bombardment, and in particular (p, xn) double-differential cross-section measurements, $d^2\sigma/d\Omega dE_n$, i.e. neutron spectrum at fixed angles, are an important benchmark for the validation of hadronic models. Here we consider measurements made at Los Alamos Meson Physics Facility (LAMPF) for proton beam energies of 113, 256, 597, and $800\,MeV$, and for angles of $7.5°$. $30°$, $60°$, $120°$ and $150°$ [7]. For details, plots and further references we invite to see the note [8]. The preliminary conclusions from the comparison of the simulation results with the experimental data are the following. While the Geant4 LHEP Physics List is clearly not suitable for the simulation of *(p,xn)* double-differential cross-sections, FLUKA and Geant4 QGSP_BERT and QGSP_BIC Physics Lists do all reproduce the double-differential cross-section data measured by Los Alamos at the level of $20\,\%$ to $50\,\%$.

IN-FLIGHT PION ABSORPTION

Data of thin-target experiments [9] [10] on in-flight π^+ and π^- absorption are compared with the Geant4 and FLUKA simulations. Pion beam energies are between $23\,MeV$ and $315\,MeV$, and targets are made of Al, Cu and Au. The in-flight pion absorption process can affect in particular the *e/h* ratio of calorimeters, as well as the energy resolution at low and medium energies, and therefore needs to be well understood for the simulation of LHC calorimeters. The preliminary results (that will be soon made available as a LCG application area note) show a generally good agreement between both simulation packages and the experimental data. Unfortunately, due to large uncertainties in the data, precise comparisons are not possible. Geant4 and FLUKA agree better with each other for intermediate weight materials like Cu. The discrepancies become larger for light materials like Al and for the heavy materials like Au. On the other hand, the multiplicity and type of the outgoing particles are qualitatively similar, indicating that the implementation of the processes is correct.

CALORIMETER TEST-BEAMS

We present here the results of the comparisons between Geant4 simulation, with LHEP and QGSP Physics Lists, with three different calorimeter test-beam data. It is important to verify the coherence of the simulation across different experiments and sub-detector technologies.

The first calorimeter test-beam setup is the ATLAS HEC (Hadron End-Cap) [11], which is a sampling calorimeter with copper as absorber and liquid argon as sensitive part.

The second calorimeter test-beam setup is the ATLAS Tilecal [12], which is the central (barrel and extended barrel) hadronic calorimeter, a sampling calorimeter made of iron as absorber and scintillator tiles as active medium.

The third calorimeter test-beam setup is the combined CMS ECAL+HCAL [13]. The electromagnetic part is a matrix of PbWO4 crystals, whereas the hadronic part is a sampling calorimeter made of copper as absorber and scintillator tiles as sensitive part. The whole apparatus is embedded in a magnetic field of max 3 Tesla.

The results are shown in Figures 3, 5, 4, 6, 7. For more details and results see [14].

Figures 3 and 5 refer to the pion energy resolution for the Geant4 Physics Lists LHEP and QGSP, respectively. Good description of the calorimeter hadronic energy resolution is important for several physics studies at LHC, in particular for hadronic channels ($Z/W \rightarrow$ *jet*+*jet*), and to understand the detector missing transverse energy resolution. Above about $30\,GeV$ there is a good agreement, at the level of $\sim 10\,\%$, between simulation and data. Below $30\,GeV$ the data have large uncertainties (not shown in the figure), so it is not possible to draw any conclusion: further work is required in this energy region.

Figures 4 and 6 show the e/π ratio for LHEP and QGSP, respectively. The e/π ratio plays an important role on those physics analyses that rely on the tails of distributions, for instance the quark compositeness search. There is an excellent agreement between simulation and data, at the level of $\sim 5\%$ for QGSP Physics List.

Figure 7 shows the longitudinal shower shape. Hadron shower profiles have an impact on different aspects: on particle identification (e.g. e/π and *e / jet* separation), on the estimation of energy losses in dead regions of a detector, and on offline calorimeter compensation. It turns out that Geant4 showers are shorter (and narrower) than the real ones, especially for QGSP Physics List.

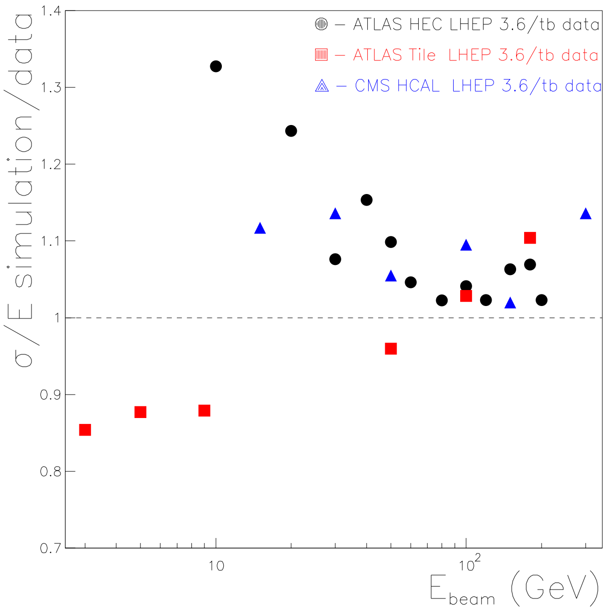

Figure 3: Ratio between the LHEP simulation and test-beam data for the pion energy resolution as a function of energy.

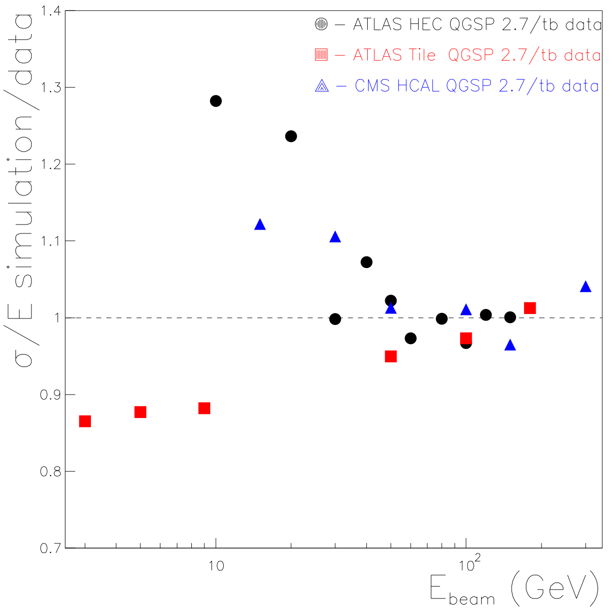

Figure 5: Ratio between the QGSP simulation and test-beam data for the pion energy resolution as a function of energy.

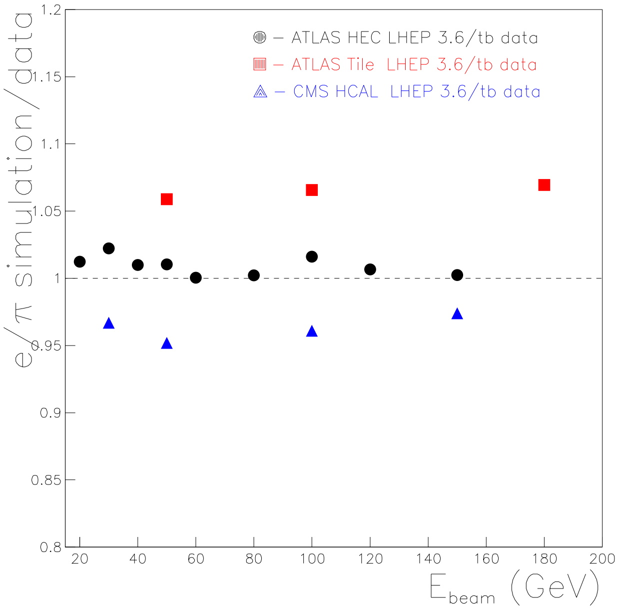

Figure 4: Ratio between the LHEP simulation and test-beam data for the e/π ratio as a function of the energy.

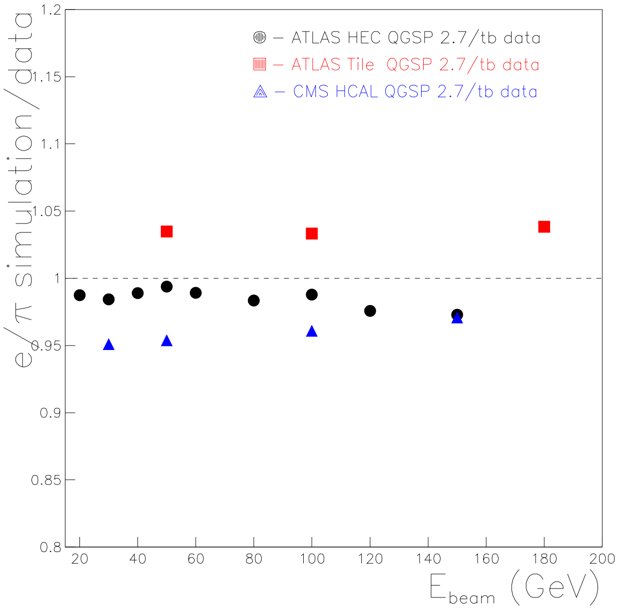

Figure 6: Ratio between the QGSP simulation and test-beam data for the e/π ratio as a function of the energy.

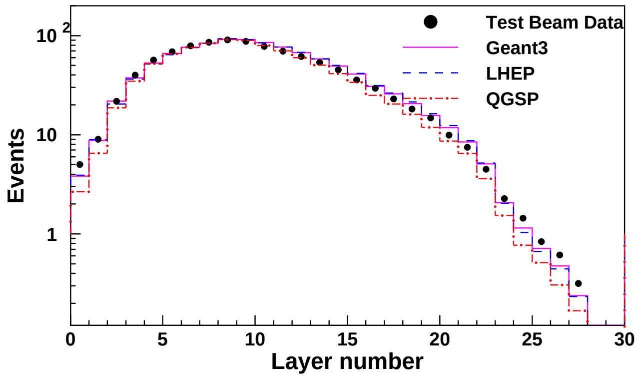

Figure 7: Longitudinal shower profile in the CMS HCAL for $100\,GeV$ pions.

CONCLUSIONS

We have presented several validation tests for Geant4 Hadronic Physics, some of which also showing the comparison with FLUKA simulation. This work concludes the first round of hadronic physics validation, with good results. The conclusion is that Geant4 LHEP and QGSP Physics Lists are in good agreement with experimental data, for most observables, and in particular for the calorimeter energy resolution and for the e/π ratio, essentially matching the physics requirements [15]. These are coming from the demand that the dominant systematic uncertainties for all physics analyses should not be due to the imperfect simulation. Longitudinal and transverse shower shapes, however, are not reproduced very well by Geant4, in particular for QGSP Physics List. Given the importance of shower shapes for the physics of LHC, a large part of the future activity of the LCG Simulation Physics Validation Project will be devoted to improve the agreement between simulation and data for these observables. This effort will rely also on new experimental data sets that have been collected in recent test-beams. Another area of interest, in progress, is the one of Geant4 background radiation studies in the LHC caverns, and the first results will be soon compared with the ones based on FLUKA simulation.

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