Description of Hadron-induced Showers in Calorimeters using the GEANT4 Simulation Toolkit.

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***Abstract*—The longitudinal and lateral dimensions of hadron-induced showers are fundamental aspects of the simulation of LHC calorimeters. In segmented calorimeters it is important that showers are precisely described by the simulation programs, since the experiments often rely on the segmentation to improve the energy measurement. In the paper we review the current status of the agreement between data and simulation. For integrated quantities, such as response and resolution, there is generally very good agreement between data and GEANT4 ; shower shapes instead need additional attention and several studies are being performed in the GEANT4 collaboration to improve the agreement with data. The key aspects of the models having an impact on shower shapes will be reviewed and their agreement with experimental data assessed. Current limitations and possible solutions to improve the description of showers will also be discussed.**

I. INTRODUCTION

THE GEANT4 toolkit [1], [2] is a de-facto standard for the simulation of high energy physics experiments. All LHC experiments use GEANT4 to study in detail the expected performance of the detectors. Three of them regularly use GEANT4 to produce the large-scale simulated datasets to study the performance, calibration and tuning of the detector; and to develop the analysis algorithms used on real data.

One of the most challenging aspects to be simulated at LHC is the physics of jets. Jets are the most common objects at LHC and they are fundamental ingredients in both precision analyses and in new-physics searches. Jets are composite objects formed by a set of collimated particles (both in space and momentum): mainly photons (from neutral pion decays), charged pions and nucleons.

At LHC all calorimeters are segmented, at least in two main sections: an electromagnetic calorimeter, optimized to measure the energy of electrons and gammas; and a hadronic calorimeter, optimized to contain and measure hadron showers. Different materials and read-out technologies are used in different regions of the experimental apparatus and often the calorimeters are sub-divided in towers and cells. This segmentation can be exploited to improve the energy measurements (for example with the weighting techniques used by the ATLAS experiment); or even to distinguish the sub-structure of jets in terms of its content (energy flow techniques, used by the CMS experiment). It is thus clear that the precise description of the dimensions of hadron-showers is an important aspect for analyses based on these techniques to reduce the systematic error due to imprecise shower descriptions.

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For response and resolution GEANT4 shows an agreement with LHC data [3] that is satisfactory considering current understanding of the detectors. However, with the constantly improving performance of LHC detectors, the requirements on the simulation precision for shower shapes will become more and more challenging; a better description of shower shape will certainly be required.

On a longer time-scale, several prototype calorimeters being developed for a future Linear Collider are based on particle-flow techniques. They are already providing very valuable test-beam data and comparisons with GEANT4 . These future calorimeters require an unprecedented level of precision in describing hadron shower shapes and will provide valuable insight into the sub-structure of hadron showers and of processes that are important for shower development.

In this paper we discuss the current level of agreement between the simulation and available data. While for response and resolution the agreement between simulation and data for hadron-induced showers is at the level of a few percent, shower shapes are less precisely described and show an agreement at a level of 10-20%. An overview of the key aspects of the simulation responsible for the description of shower shape will be reviewed.

Three components of the simulation will be discussed:

- Cascade models at low energy
- String models at high energy
- The production, transport and absorption of neutrons

It has been shown that a fundamental ingredient to improve the description of the lateral development of showers is the use of an intermediate- and low-energy model that can describe the intra-nuclear cascading of hadrons in nuclear matter. The longitudinal development of hadron showers is mainly characterized by the hadronic physics at higher energies in the forward direction: quasi-elastic scattering and diffraction. Neutrons play a special role in the precise description of showers, since they may travel long distances in the calorimeters before being absorbed. In addition they have a special role in scintillator based calorimeters: the elastic scattering on hydrogen allows for an efficient sampling of their contribution in the showers.

II. STATUS OF THE SIMULATION

The GEANT4 simulation toolkit is used by all LHC experiments, in the past years a detailed validation of the simulation physics performance have been carried on to verify the predictions of the toolkit in comparison with experimental data.

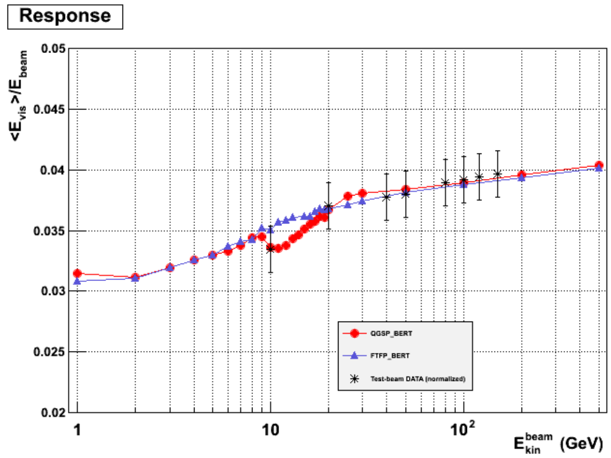

Fig. 1. Ratio between energy released in the active material and beam energy for a sampling copper-liquid argon calorimeter. The ratio is shown as a function of the beam kinetic energy for impinging negative pions. The data from ATLAS-HEC test-beam are compared to the predictions of QGSP_BERT (red) and FTFP_BERT (blue) physics lists. Simulations obtained with GEANT4 version 9.5.β (June 2011).

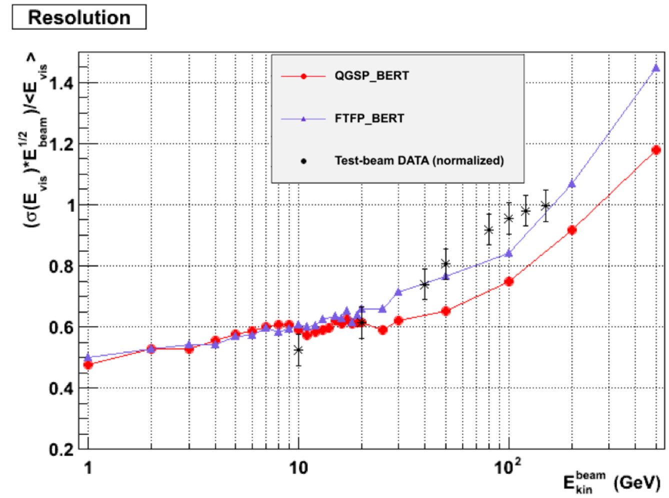

Fig. 2. Energy resolution for a sampling copper-liquid argon calorimeter. The resolution is shown as a function of the beam kinetic energy for impinging negative pions. The data from ATLAS-HEC test-beam are compared to the predictions of QGSP_BERT (red) and FTFP_BERT (blue) physics lists. Simulations obtained with GEANT4 version 9.5.β (June 2011).

After only 2 years of data taking the quality of collected data at LHC allows for a detailed validation of the full simulation chain (from the generator to the implementation of the various detector elements in the simulation). To better understand the role of the detector simulation and disentangle the other simulation elements, the test-beam data still play a fundamental role.

Calorimeters, giving their importance for all physics analysis, have been studied in detail with test-beam data exposing modules to beams of different particles. Hadrons (mainly pions and protons) can be used to study the performance of the simulation making a direct comparison between experimental data and Monte Carlo predictions.

Predictions for the most important observables: response (e/pi ratio), resolution and shower shapes (both longitudinal and lateral) are compared to data to validate in details the different aspects of the simulation.

The precise measurement of the top-quark mass and compositeness searches require a precision at the 1% level in the simulation of the response for calorimeters up to energy of 1 TeV. All calorimeters used at LHC are non-compensating, thus the energy released by an electron (used to calibrate the calorimeter) and by a hadron of the same initial energy are different.

Figure 1 shows the GEANT4 predictions compared to the test-beam measurements for a sampling calorimeter with copper as absorber and liquid argon as active material.

The data are from ATLAS Hadronic End Cap calorimeter [7]. The simulation is a simplified version of the test-beam setup in which the sampling fraction and dimension of the calorimeter are realistic, but the details of the geometry and the read-out chain are not implemented[1]. To take into account these differences the test-beam data are *corrected* with a multiplication factor (the value of which being close to 1) such that the ratio between data and the simplified simulation is the same, for all data points, as the ratio between data and the detailed simulation.

These studies confirm what has been observed by both ATLAS and CMS experiments: recent versions of GEANT4 match the required precision (at the level of per-cent) for the description of the response. The precision is not so satisfactory for the ATLAS iron scintillating tiles calorimeter for which the simulation predicts a higher response of 3-5%. Possible causes of this discrepancy are currently under study (the role of neutrons and their scattering in scintillator is the main area of study together with the effect of the Birks' saturation).

One of the most important conclusions of the test-beam studies is the fundamental role of theory-based model to precisely describe the data. In Figure 1 the data are shown by the black stars, simulations obtained with two distinct *physics lists* are shown with the colored lines: QGSP_BERT in red and FTFP_BERT in blue.

There is no theory for the interaction of hadrons with matter valid for all energies and particle species. A *physics list* is a collection of models covering the full energy range for a given application. For high energy physics experiments, and in particular for calorimeters, GEANT4 encourages the use of physics lists based on theoretical or phenomenological models. Both QGSP_BERT and FTFP_BERT use an intra-nuclear cascade model at low energy (the GEANT4 implementation of the Bertini cascade code [9]) and a quark-gluon string model at high energy (the well-known Fritiof model [10] for FTFP_BERT and the GEANT4 quark-gluon-string model for QGSP_BERT).

The differences between the two physics lists are mainly on the energy ranges where the models are applied: in the case of FTFP_BERT the cascade code is used below 5 GeV and the

[1] Only the two main read-out effects have been implemented: the recombination in the liquid argon, similar to the Birks' effect, is implemented and the energy deposits are requested to be in a given time windows. The systematic error connected to the choice of the parameters has been studied varying their values and has been verified to be small.

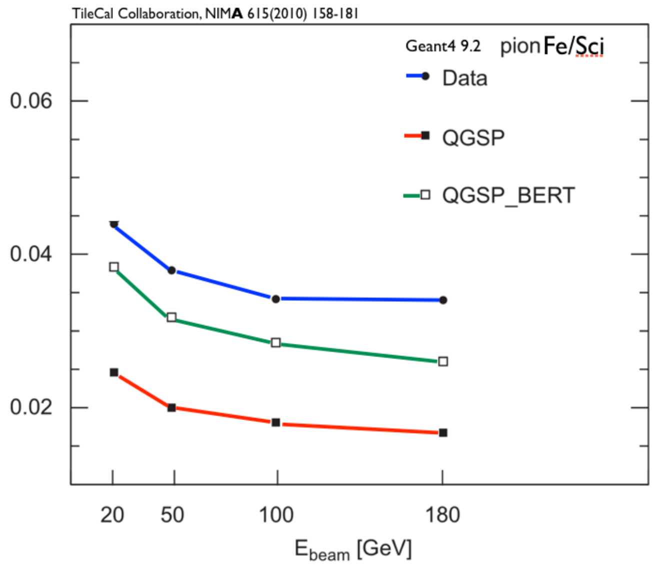

Fig. 3. Lateral leakage for the Tile calorimeter. The ratio between the energy released in the module displaced with respect to the beam axis and the central module is shown as a function of beam energy. The modules are about 30 cm wide. Test-beam data are in blue, QGSP_BERT is shown in green and a physics list without a cascade model is shown in red.

string model is used starting from 4 GeV [2]. For QGSP_BERT the use of Bertini is extended up to 9.9 GeV, the QGS model is used starting from 12 GeV, a parametrized model (based on the GHEISHA code) is used between 9.5 and 25 GeV. The parametrised models have several limitations: based on sampling of experimental data, they lack theoretical justifications. Their predictive power is limited (giving good results only for observables and materials used in the tuning itself) and they do not enforce energy-momentum conservation.

The effect of the use of the parametrized model is clearly visible in Figure 1: the response as a function of the primary energy shows an unphysical discontinuity corresponding to the *transition* energies. This has been extensively discussed elsewhere [11].

One of the most important achievements of the GEANT4 collaboration in the last year was the extension of the Fritiof model down to 3 GeV, thanks to improvements the FTFP_BERT physics lists is now free from the use of parametrized models. Both ATLAS and CMS agree that Fritiof based physics list best describes test-beam and collision data.

At LHC the requirement on the precision in the description of the hadronic energy resolution is less stringent with respect to the response. For the physics analysis using the hadronic decay of the W boson it is required a precision of the simulation at the level of 10%. Figure 2 shows a qualitative comparison between the test-beam data and the GEANT4 simulation as a function of the beam energy for single pions. The simulation predicts less fluctuations with respect to the data. FTFP_BERT predictions are closer to the data. The approximated setup used for these study (and in particular the absence of the simulation of noise) is too simplistic for these kind os studies and additional work is needed. Both ATLAS and CMS studies performed with detailed simulations agree that GEANT4 predicts smaller values for resolution of 3-10% with respect to data.

While this level of agreement can be considered adequate at LHC, it will not be the case for calorimetry at future linear colliders. In addition the fluctuations play a role also for shower shapes fluctuations. Improvements in the description of fluctuations will improve both the description of resolution and shower shapes.

III. Shower shape description

The precise description of the lateral and longitudinal profiles of hadronic showers are of fundamental importance at future imaging calorimeters. Never the less also with the limited granularity of LHC calorimeters an adequate simulation of shower profiles is needed.

The simulation of longitudinal profile of hadrons is important to correctly predict the effect of the punch-through in the muon spectrometers and study the effect on trigger rates. In addition experiments use *weighting techniques* to calibrate the energy of jets. These methods use simulations to extract correcting factors that depend on the longitudinal profile.

The peculiarities of the hadrons lateral profile is used for the identification of e, pions and taus. Finally CMS uses particle flow algorithms to improve the jet-energy scale that rely on the ability to identify single showers. Description of the hadron shower shapes are particularly challenging aspects for any simulation code, since a precise description of each hadronic interaction is needed to describe the full shower profiles: small discrepancies for single interactions are amplified with the evolution of the shower.

A. Lateral shower shape

The coarse segmentation of LHC calorimeters allow only for a limited comparison between test-beam data and simulation. Typically the leakage from a calorimeter module to the neighbor one is measured. Figure 3 shows such a comparison in the case of the ATLAS hadronic barrel calorimeter TileCal (an iron-scintillating tiles, sampling calorimeter).

A stack of three modules was exposed at pion beams of different energies. The energy released in the down most module is compared to the energy released in the central module where the beam is impinging. The measurement is thus sensitive to the halo of the hadronic shower (each module is about 30 cm wide) [6]. Data are shown with the blue line, only about 4% of the energy is released in the lateral module.

A direct comparison with GEANT4 simulations is shown. The red line shows the predictions obtained with the physics list QGSP that uses a string model at high energy (above 25 GeV) and only parametrized models at lower energies. No cascade code is used in QGSP and a poor description of the lateral shower profile is obtained.

The green line shows the predictions obtained with the QGSP_BERT physics list that enables the Bertini code below

[2]In the region where models overlap, one of the two is randomly chosen at each interaction. At the lower limit the cascade code is used 100% of the times. Its use is reduced linearly down to 0% at the higher limit where the high-energy model is used for all the interactions.

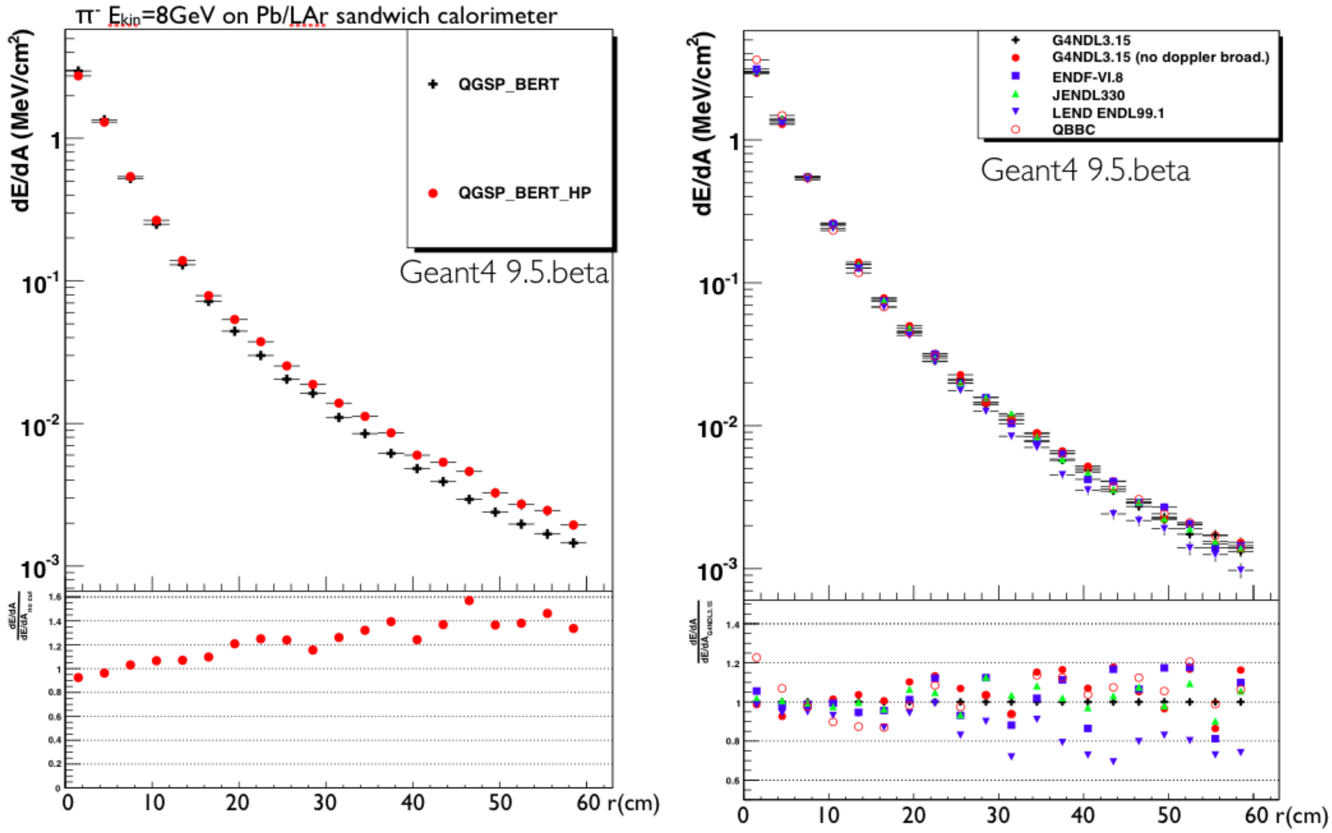

Fig. 4. Simulations of the radial profile of $E_{kin} = 8$ GeV pions impinging on a lead-liquid argon calorimeter. Left: comparison of a typical physics list for high energy physics experiments (black) with one with the high precision neutron simulation module (red). The ratio between the two is shown in the insert. Right: comparison between different international data libraries (G4NDL3.15 corresponds to ENDF-VII.0), two special cases are also included: full red circles shows the G4NDL3.15 without doppler broadening; open red circles shows the QBBC GEANT4 physics list.

9.9 GeV. The use of the cascade code substantially increases the energy released at higher radii.

Production and transportation of low energy neutrons is very important to describe the lateral evolution of showers. They can be transported at far distances losing energy mainly via elastic scattering. They are eventually absorbed and the excited nucleus releases energy emitting nucleons and gammas in the tens of MeV range. For scintillator based calorimeters, as in the case of the Tile Calorimeter, they can undergo elastic scattering with the hydrogen nuclei of the scintillator, these protons have high stopping power and leave a substantial signal in the active material.

In the physics lists used for high energy physics, neutrons with kinetic energies below 20 MeV are simulated only very roughly. To simulate multi-GeV hadron showers in a reasonable time these approximations cannot be avoided. The high precision (*HP*) extension is available in GEANT4 for the simulation of neutrons from thermal energies up to 20 MeV.

The HP model is based on international data-libraries and provides cross-sections and final states tables for the scattering of neutrons on almost 400 isotopes. The thermal motion of nuclei (Doppler broadening) is also taken into account.

The plot on the left side of Figure 4 shows the lateral profile of $E_{kin} = 8$ GeV pions impinging on a lead-liquid argon sampling calorimeter. The simulation is performed with GEANT4 version 9.5.β[3]. Two physics list are compared: the QGSP_BERT and its extension with the low-energy high precision neutron simulation (QGSP_BERT_HP).

The precise treatment of low energy neutrons has a clear impact on the lateral profile of showers with the energy density increasing up to 40% at high radii. It should be noted, however, that the energy released at high radii ($r > 20-30$ cm) is less than 1% of the energy of the core of the shower, the effect of low energy neutrons is thus visible mainly in the far halo of the hadronic shower.

The HP data library (called G4NDL) is based on the ENDF international library (starting with GEANT4 9.5.β, ENDF-VII.0), but recent developments in the HP package enable the use of alternative libraries (JENDL 3.30, ENDL 99.1, ENDF-VI.8). The differences between these are important only for specific applications in which the best description of the interaction of neutrons with a given isotope is needed. It is expected that all of them perform similarly for shower shape studies. This is confirmed in the right plot of Figure 4.

No large differences are seen between data libraries (with the exception of the experimental code based on ENDL 99.1, that shows more compact shower at high radius). For comparison also the QBBC physics list is shown. This is an experimental physics list and it has a treatment of low energy

[3]The HP package has been substantially improved in the last year and the new developments will be available in GEANT4 9.5.

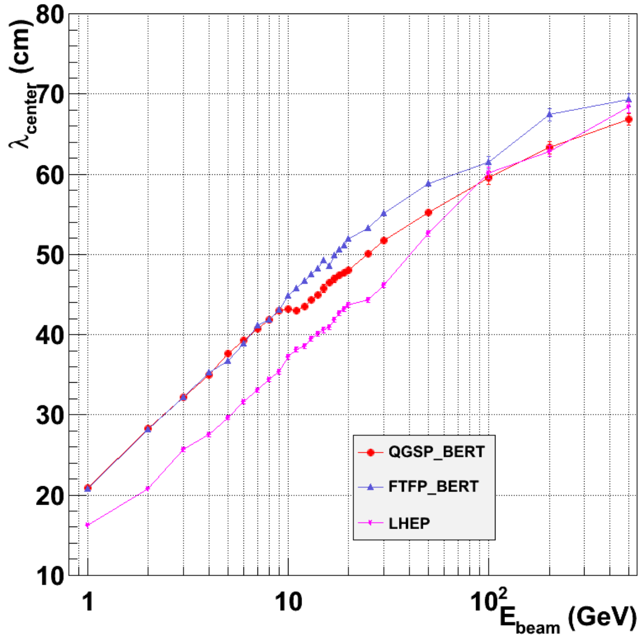

Fig. 5. Simulation of pion induced showers in an iron-scintillator calorimeter obtained with GEANT4 version 9.5.β. The shower depth (left) and shower length (right) of three different physics lists (LHEP , FTFP_BERT , QGSP_BERT) are compared.

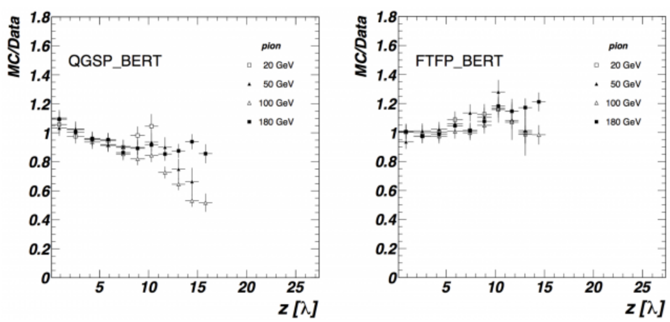

Fig. 6. Monte Carlo-data ratio for the energy deposit as a function of the shower depth. Left: simulations obtained with the QGSP_BERT physics list; right: simulations obtained with the FTFP_BERT physics list. Courtesy of the TileCal collaboration [12].

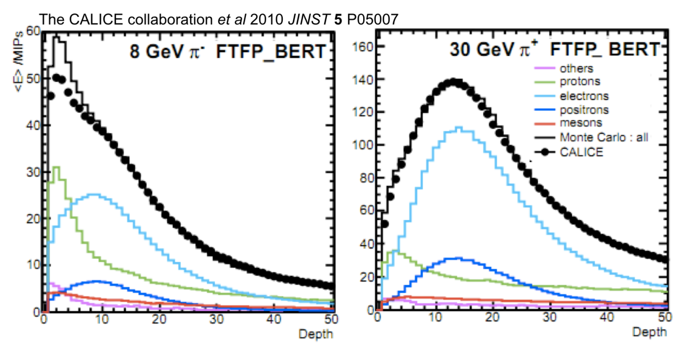

Fig. 7. Longitudinal profile obtained by the CALICE collaboration with the test-beam data of a tungsten, silicon digital calorimeter. Pions beam with two energies are shown: 8 GeV (left) and 30 GeV (right). The simulation is obtained with GEANT4 version 9.3 and the FTFP_BERT physics list. For the simulation the contribution to the shower profile of each particle species in the profile is also shown. Courtesy of the CALICE collaboration [5].

neutrons with a precision that is in between the default and the high precision description. This physics lists predicts higher energy in the core of the showers and agrees with the others in the far tail[4].

At thermal energies the motion of nuclei has to be taken into account for the correct calculation of the reaction energy. This process (Doppler broadening of the cross sections) is very CPU intensive. A special simulation with the QGSP_BERT_HP physics list with no Doppler broadening has been performed. The lateral shower profile is not affected by temperature effects.

This is an interesting result since it opens the possibility to use high precision neutron simulation while limiting the impact on CPU performances.

[4]It should be stressed that this particular physics list has not been developed for high energy physics experiments. It should thus be of no surprise that it does not agree with the other, it has been included in this study only for its special treatment of neutrons.

B. Longitudinal shower shape

Figure 5 shows the longitudinal shower shapes obtained with the simulation of an iron-scintillator sampling calorimeter. The position of the shower center (right) and he second moment of the shower longitudinal profile (right) are obtained with GEANT4 version 9.5.β as a function of the beam energy.

The observables are defined as:

$$\lambda_{center} = \frac{\sum_c E_c z_c}{\sum_c E_c} \tag{1}$$

$$< \lambda^2 > = \frac{\sum_c E_c \lambda_c^2}{\sum_c E_c} \tag{2}$$

The sums are extended to all cells with energy deposited, λ_c is the position of the cell c along the beam axis measured with respect to the shower center.

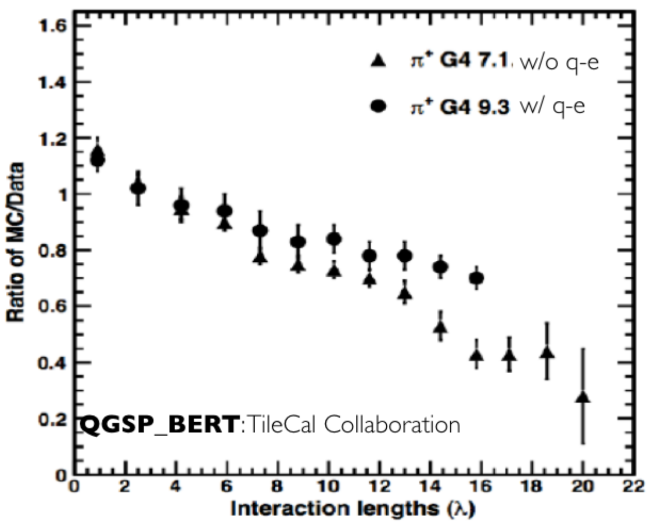

Fig. 8. Monte Carlo-data ratio for the energy deposit as a function of the shower depth. The simulations, obtained with the QGSP_BERT physics list show the effect of the implementation of quasi-elastic process. Showers get substantially longer. Courtesy of TileCal collaboration.

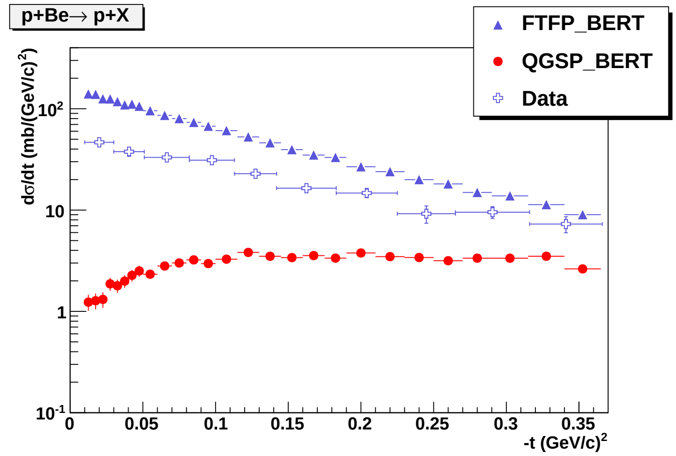

Fig. 9. Differential cross section, as a function of the transferred four-momentum, for the target diffraction process. Protons of $p = 450$ GeV/c impinging on a beryllium target collected by the HELIOS experiment are compared to GEANT4 version 9.5.β simulation. Results obtained with the qurk-gluon-string (QGSP_BERT) and Fritiof (FTFP_BERT) models are shown.

Three different physics lists are shown: FTFP_BERT , QGSP_BERT and, for comparison, the fully paramtrised list LHEP (based on the GHEISHA models). The use of theory and phenomenology models predicts longer and more penetrating showers, at higher energies the FTFP_BERT physics list predicts the longest and most penetrating showers.

The most precise comparison with data of the longitudinal profile with LHC calorimeters has been obtained by the ATLAS hadronic barrel calorimeter during a test-beam in which the beam was impinging on the calorimeter modules from the side [6]. From the energy deposits in a row of cells a profile measurement up to 20 λ_I can be obtained. Figure 6 shows the ratio Monte Carlo over data for the energy deposited as function of the shower depth. The simulations are obtained with GEANT4 version 9.4.p02. On the left plot the results obtained with the QGSP_BERT physics list are shown. For all considered beam energies the simulation predicts too short shower, about 10-20% shorter at 10 λ_I. The plot on the right shows the results obtained with the FTFP_BERT physics list. In this case the profile is better reproduced, but in this case the simulation predicts longer shower with respect the data.

The imaging calorimeters under construction and testing for the future linear collider have unprecedented segmentation with very small cells. The test-beam data of the CALICE prototypes are thus of extreme value to study the details of the shower profiles providing up to 50 measurement points[5]. Comparison between data and simulation (GEANT4 version 9.3, FTFP_BERT physics lists) are shown, for two beam energies, in Figure 7.

The agreement between data and simulation is satisfactory at high energy, while the simulation reproduces less precisely for the low energy beam. The disagreement is particularly visible at the beginning of the shower, with an overestimation of the energy deposited by protons produced in the first interactions.

This last fact, together with the differences between QGSP_BERT and FTFP_BERT observed in the case of Tile Calorimeter, suggest to study in detail the high energy string model model. A first important improvement is available from GEANT4 version 9.3 thanks to the introduction of the quasi-elastic component of the inelastic interactions. The effect of quasi-elastic scattering, in which the primary conserves a substantial fraction of the initial momentum, can be seen in Figure 8: showers get substantially longer. The *forward* physics components of the inelastic interaction of hadrons with matter (quasi-elastic; target and projectile diffractions) thus plays an important role in the description of longitudinal shower profile.

Only few experiments have studied in detail the properties of these interactions. The proton-induced target diffraction of nuclei has been studied by the HELIOS experiment and a comparison with its data and GEANT4 simulation has been performed [4][6].

The differential cross-section of target-diffraction events as a function of the transferred four-momentum for experimental data and GEANT4 simulation is shown in Figure 9. Protons of $p = 450$ GeV/c impinge on at beryllium target.

There is poor agreement between simulation and experimental data. Only the Fritiof model is able to reproduce the shape of the experimental distribution. Additional tuning of the models' parameters is needed to improve the description of the diffraction process, in order to better describe the longitudinal profiles.

IV. CONCLUSIONS

The precise description of both the longitudinal and the lateral profile of hadron-induced showers is an important

[5]The CALICE tungsten, silicon digital calorimeter is a 5 λ_I long calorimeter, thus significantly shorter than the Tile Calorimeter.

[6]A second experiment, NA22, has performed measurement of meson induced target and projectile diffraction. The extension of this validation to NA22 is being performed.

requirement for the simulation of high energy physics experiments. The GEANT4 toolkit, used for the simulation of LHC experiments, provides a rich set of alternatives to simulate the interaction of hadrons with matter.

Among them Fritiof model at high energy, the Bertini cascade model at intermediate and low energies and the pre-equilibrium and de-excitation models are the ones that better describe test-beam and collision data.

The recent developments and extensions of the high energy Fritiof model and the Bertini cascade models allow for the creation of the FTFP_BERT physics list. Starting from GEANT4 version 9.5.β (released in May 2011), this physics lists reduces to the minimum the use of parametrized models and gives the best results to reproduce calorimetric observables (response, resolution, shower shapes).

The longitudinal and lateral profiles agree with test-beam data, at the level of 10-20%. While this level of agreement may be adequate for the current LHC analysis, improvements are needed to describe the highly granular CALICE calorimeters and reduce the systematic errors on jet measurements for the future analysis of LHC.

Several studies are ongoing to understand the origin of these descripancies and improve the simulation. In this paper we have discussed some of the aspects being addressed.

The Bertini cascade is a fundamental ingredient to improve the description of the lateral profile of showers. The low-energy neutrons have an important role in describing the tails of the lateral profile. GEANT4 provides a high precision optional module to describe such interactions that is substantially improved in GEANT4 release 9.5 (December 2011).

The use of the HP extension increases the CPU usage, but this can be reduced removing the Doppler broadening without reducing the physics performance.

The Fritiof model has been substantially improved in the recent past. The quasi-elastic and the diffraction processes play a role in the longitudinal evolution of showers, the comparison with the HELIOS data shows that only Fritiof can reproduce the experimental shape of the target-diffraction cross-section. However the cross-section is overestimated of a factor of about 2. Tuning of the model's parameters is foreseen to improve the description of the forward physics components of the inelastic scattering of hadrons with matter.

In conclusion, starting with GEANT4 version 9.4 the FTFP_BERT physics list is the recommended physics list to describe calorimeters at the level of few percent for all typical observables. For increased precision in the simulation of low-energy neutrons an optional module (HP) can improve the description of the lateral shower shape.

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