

GEANT4 physics evaluation with testbeam data of the ATLAS hadronic end-cap calorimeter

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Abstract. The validation of GEANT4 physics models is done by comparing experimental data from beam tests of modules of the ATLAS hadronic end-cap calorimeter with GEANT4 based simulations. Various physics lists for the simulation of hadronic showers are evaluated. We present results of studies of the calorimeter performance parameters (like energy resolution and shower shapes) as well as results of investigations of the influence of the Birks' law and of cuts on the time of development of hadronic showers.

1. Introduction

GEANT4 [1] is a package for simulating the passage of particles through matter. It provides variety of tools for detector response simulations, including: geometry description, particle transportation, physics models, visualization and so on. Nowadays it is used by many experiments and in many application areas.

The ATLAS collaboration works with the GEANT4 toolkit since its first production releases in 1999. A lot of efforts have been put over these years by the collaboration to evaluate electromagnetic and hadronic physics models of GEANT4, to follow up their development and to optimise corresponding simulations [2]. Part of the validation work is based on the comparison of GEANT4 predictions with experimental results obtained during various beam tests of ATLAS calorimeter modules. The validation includes comparisons of relevant calorimeter performance parameters like the energy dependence of the response, resolution and shower shapes.

The group of the ATLAS hadronic end-cap calorimeter (HEC) is actively involved in tests and validations of GEANT4 [3, 4]. In this talk the latest results of physics evaluation with HEC testbeam data are presented. Three points will be addressed: a) comparison of different hadronic physics lists, b) study of the saturation of the response in the liquid argon, c) consideration of the time structure of hadronic showers.

2. Hadronic end-cap calorimeter and its beam tests

The ATLAS hadronic end-cap calorimeter [5] is a liquid argon (LAr) sampling calorimeter with parallel copper absorber plates. The HEC is structured in two wheels (HEC1 and HEC2), each wheel consisting of 32 modules. Annular spacers define 8.5 mm gaps between the absorber

plates. The thickness of the copper absorber plates is 2.5 cm for HEC1 and 5.0 cm for HEC2. The calorimeter has four longitudinal layers. The total thickness of the calorimeter is ~ 103 radiation lengths X_0 or ~ 10 absorption lengths λ .

During the years 2000-2001, the serial production calorimeter modules were exposed to test beams as part of the standard quality control procedure during HEC construction. The beam tests have been carried out in the H6 beam line of the CERN SPS, using secondary and tertiary beams. In total more than 2200 runs were taken at different impact points. Each run consisted of typically 20 000 triggered events. The energy ranged 6-150 GeV for electrons, 10-200 GeV for charged pions and 120, 150, 180 GeV for muons. More details, as well as data analysis results can be found in [6].

3. GEANT4 simulations of the HEC testbeam

For GEANT4 based simulations of the HEC testbeam, the special code (running out of the standard ATLAS software) was prepared. Energy scans with electrons and with negatively charged pions were simulated. Usual statistics was typically 5000 events per beam energy.

GEANT4 version 9.0 (released in June 2007) was used for the present simulations. And the range cut of $30 \mu\text{m}$ was applied.

3.1. Hadronic physics lists

Different physics lists are provided by the GEANT4 package for simulations of hadronic showers. For the current comparison with the HEC testbeam data, three of them are selected:

- QGSP physics list is based on theory-driven models: it uses the quark-gluon-string model for interactions and a pre-equilibrium decay model for the fragmentation
- QGSP-BERT physics list includes the Bertini cascade model (a theoretical hadronic model for intra-nuclear transport) below ~ 10 GeV
- QGSP-BERT-HP physics list uses high precision data-driven modeling for low energy neutrons

Estimates of the time needed to simulate charged pions show, that QGSP-BERT based simulations are ~ 1.7 times slower than simulations with the QGSP physics list. Usage of precise neutron models significantly slows down simulations: QGSP-BERT-HP is almost five times slower than QGSP.

3.2. Birks' law

Recombination effects in the liquid argon lead to the saturation of the response for particles with large dE/dx . Phenomenologically this effect can be described by the Birks' law [7]:

$$\Delta E' = \Delta E \frac{A}{1 + \frac{c}{\rho} \frac{\Delta E}{\Delta x}}, \quad (1)$$

where $\rho = 1.396 \text{ g/cm}^3$ is the LAr density and parameters of the Birks' formula have the following values: $A = 1$, $c = 0.0045 \text{ g}/(\text{MeV cm}^2)$.

To study the influence of this effect on the calorimeter performance parameters, all simulations were done twice: without taking into account the Birks' law and when corresponding energy corrections at each step of simulations were switched on.

3.3. Time structure of hadronic showers

To study the time structure of showers, information about the time of energy depositions in calorimeter cells were kept during simulations. In Figure 1 the visible energies in LAr are shown as functions of the deposition time for 100 GeV pions. It is seen that time profiles of hadronic showers have rather long tails for all studied physics list. And QGSP-BERT clearly predicts slower showers than two other physics lists. Late energy depositions (after 100 ns) amount to 4.1, 1.3 and 0.9 % of the total energy for QGSP-BERT, QGSP and QGSP-BERT-HP, respectively. Long tails of time profiles given by the QGSP-BERT physics lists (if one compares with QGSP-BERT-HP) seem artificial and can be related to neutron modeling as it is implemented in this physics list.

Under conditions foreseen at the Large Hadron Collider (high luminosity, 25 ns interval between bunch crossings), calorimeter signals cannot be integrated over the full time of development of hadronic showers. Readout of calorimeter channels is fast. To model the experimental situation, the following procedure was applied to simulated signals.

For each calorimeter channel in each event a time profile is convoluted with a shaping function corresponding to this channel. (Example of such a function for one of HEC channels is shown in Figure 2.) Reconstructed signal in this case is the amplitude of a convoluted profile at the peak position of a shaping function. Peak positions for different HEC channels are distributed between 50 and 70 ns. Effectively this procedure means the integration of time profiles over a few tens of nanoseconds.

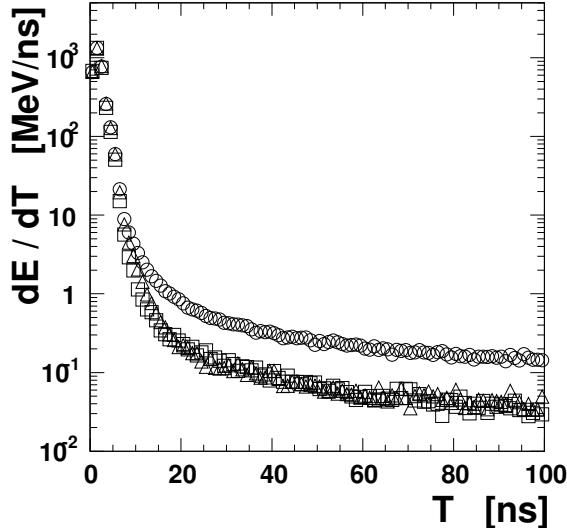


Figure 1. Visible energy in the HEC for 100 GeV charged pions as a function of the time of energy depositions. Squares — QGSP, circles — QGSP-BERT, triangles — QGSP-BERT-HP predictions (with the Birk's law switched on).

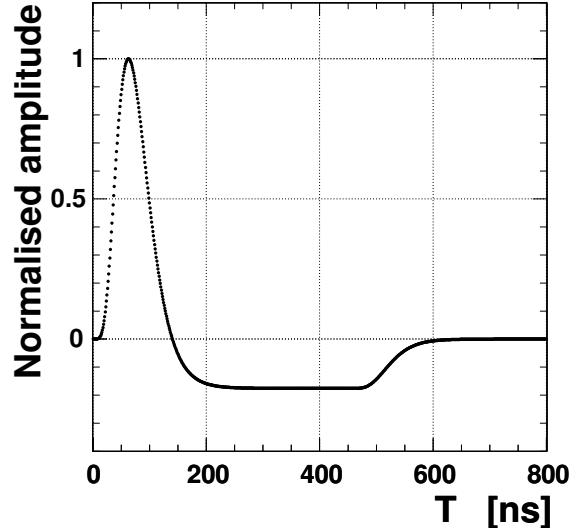


Figure 2. Shaping function for one of HEC channels.

To evaluate the significance of these cuts on the time of shower development, results obtained with the described procedure are compared with results after the integration of signals over the full time interval (i.e. obtained without any time cut).

3.4. Reconstruction and analysis

The analysis of the simulated data followed rather closely the experimental procedure [6]. An energy independent electromagnetic scale factor (obtained by the analysis of electron samples) was applied for the energy reconstruction. Clusters of fixed size were used, i.e. the same set of cells was selected for energy measurements in all events and for all beam energies. The use of clusters of fixed size for the energy reconstruction allowed the evaluation of the electronics noise (including possible correlations between channels). To compare the experimental and simulated data, known spread of the noise was subtracted from the resolution of the experimental data.

4. Results

To evaluate GEANT4 physics models, the following calorimeter performance parameters are studied and presented in this talk: the energy resolution for charged pions, ratio e/π and longitudinal shape of hadronic showers.

4.1. Pion energy resolution

To get the energy resolution and response, Gaussian curves were fitted to the reconstructed energy distributions in the interval $\pm 3\sigma$ around the peak value E_0 . The parameters E_0 and σ from this fit were used to determine the resolution σ/E_0 .

The pion energy resolution as a function of the beam energy is presented in Figure 3 for the experimental data and for Monte Carlo (MC) simulations with different hadronic physics lists and the Birks' law switch. Comparison of the left-hand and right-hand plots show, that time cuts strongly influence the energy resolution. For the QGSP-BERT physics list, predicting slower hadronic showers, relative increase of 10-30 % (depending on the beam energy) is observed. For the QGSP and QGSP-BERT-HP lists the increase is at the level of $\sim 5\%$. This growth brings the energy resolution for QGSP-BERT and QGSP-BERT-HP closer to experimental values.

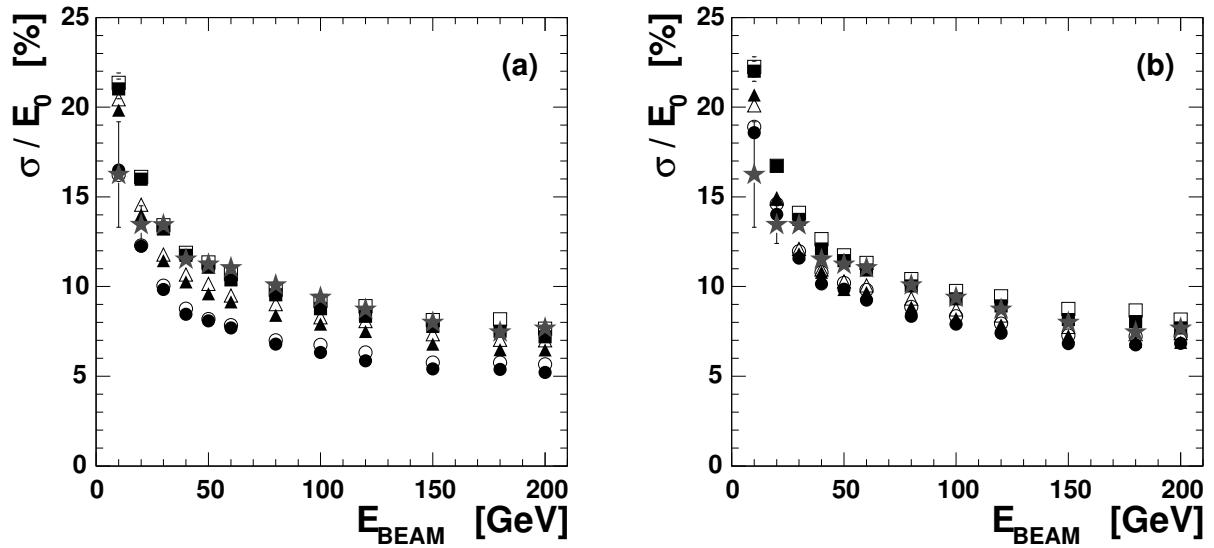


Figure 3. Energy resolution for pions as a function of the beam energy. Stars mark experimental values. Squares — QGSP, circles — QGSP-BERT, triangles — QGSP-BERT-HP predictions. For MC samples: open (full) symbols correspond to simulations with (without) the Birks' law; (a) — no time cut, (b) — after time cuts.

The energy dependence of the resolution can be parametrized by the following two-term

formula:

$$\frac{\sigma}{E_0} = \frac{A}{\sqrt{E_{BEAM}}} \oplus B, \quad (2)$$

where A and B are the sampling and the constant terms, respectively. Results, obtained for different simulations after applying time cuts, are summarised in Table 1. They are to be compared with experimental values: $A_{EXP} = 69 \pm 1 \%$, $B_{EXP} = 5.8 \pm 0.1 \%$.

Table 1. Sampling and constant terms of the pion energy resolution, as obtained from simulations after time cuts.

Birks' law	Physics list	A [% \sqrt{GeV}]	B [%]
OFF	QGSP	68.1 ± 0.8	6.2 ± 0.1
	QGSP-BERT	57.1 ± 0.7	5.30 ± 0.09
	QGSP-BERT-HP	60.2 ± 0.7	5.4 ± 0.1
ON	QGSP	67.9 ± 0.8	6.9 ± 0.1
	QGSP-BERT	58.6 ± 0.7	5.83 ± 0.09
	QGSP-BERT-HP	59.6 ± 0.7	6.13 ± 0.09

When time cuts are applied and the Birks' law is taken into account, the sampling term of the pion energy resolution is well described by QGSP. At the same time, the constant term is predicted better by the QGSP-BERT and QGSP-BERT-HP physics lists. This means that these two lists give better prediction of the resolution at high beam energies. It is also seen that usage of the Birks' law does not change the sampling term, but leads to the increase of the constant term.

4.2. Ratio e/π

Ratio e/π is defined as a ratio of reconstructed energies E_0 in electron and in pion clusters at the same beam energy. Energy dependences of this ratio are presented in Figure 4 for the experimental data and for different MC simulations. As for the energy resolution, time cuts strongly influence the e/π -ratio for QGSP-BERT: 4-8 % increase is observed for this physics list after applying those cuts. For two other physics list the increase is smaller — 1-2 %. When the Birks' law is taken into account, ratio e/π also becomes larger: by 2-3 % for all physics lists.

To make comparison with experimental data more clear, ratio between simulated and experimental data for e/π can be studied (see Figure 5). After applying time cuts and with usage of the Birks' law, all three hadronic physics lists describe experimental values of the e/π -ratio rather good.

4.3. Longitudinal shape of hadronic showers

Longitudinally the HEC calorimeter is segmented into four layers. (Their thicknesses equal to 1.5, 2.9, 3.0 and 2.8 λ .) This allows to study the longitudinal development of hadronic showers. An appropriate variable is the fraction of energy in a layer with respect to the total energy. It can be defined in the following way:

$$F = \frac{< E_i >}{\sum_{i=1}^4 < E_i >}, \quad (3)$$

where E_i is the energy in a HEC layer within the reconstructed pion cluster.

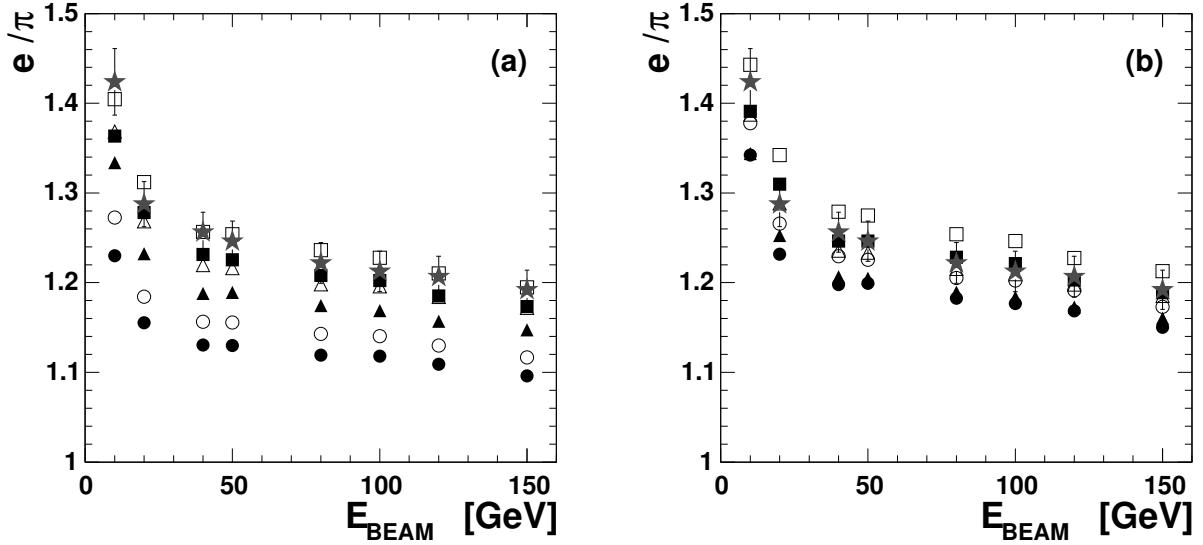


Figure 4. Ratio e/π as a function of the beam energy. Stars mark experimental values. Squares — QGSP, circles — QGSP-BERT, triangles — QGSP-BERT-HP predictions. For MC samples: open (full) symbols correspond to simulations with (without) the Birks' law; (a) — no time cut, (b) — after time cuts.

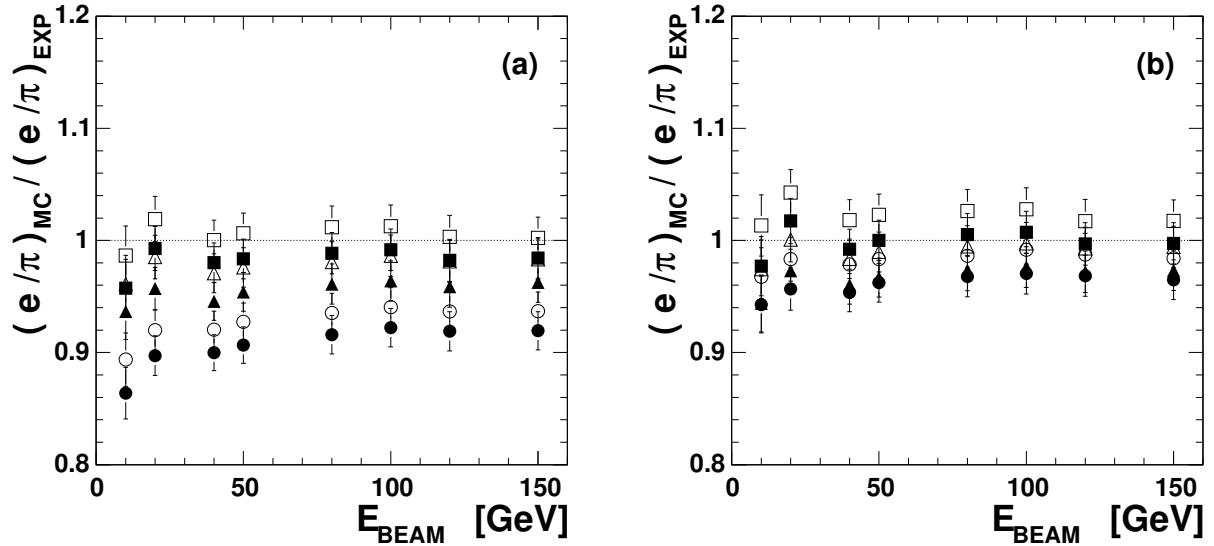


Figure 5. Ratio between simulated and experimental data for e/π as a function of the beam energy. Squares — QGSP, circles — QGSP-BERT, triangles — QGSP-BERT-HP predictions. Open (full) symbols correspond to simulations with (without) the Birks' law; (a) — no time cut, (b) — after time cuts.

These energy fractions are presented in Figure 6 as functions of the beam energy. The ratio between simulated and experimental data is shown as well (Figure 7). Approximately half of the pion signal is deposited in the second layer of the calorimeter. And this is described within a few percent by all three physics lists. At the same time QGSP predicts more energy in the first layer and significantly less energy in the third layer. This means that hadronic showers in this model start earlier and are more compact. The QGSP-BERT and QGSP-BERT-HP physics

lists give better description of longitudinal profiles of hadronic showers (except the lowest beam energy of 10 GeV).

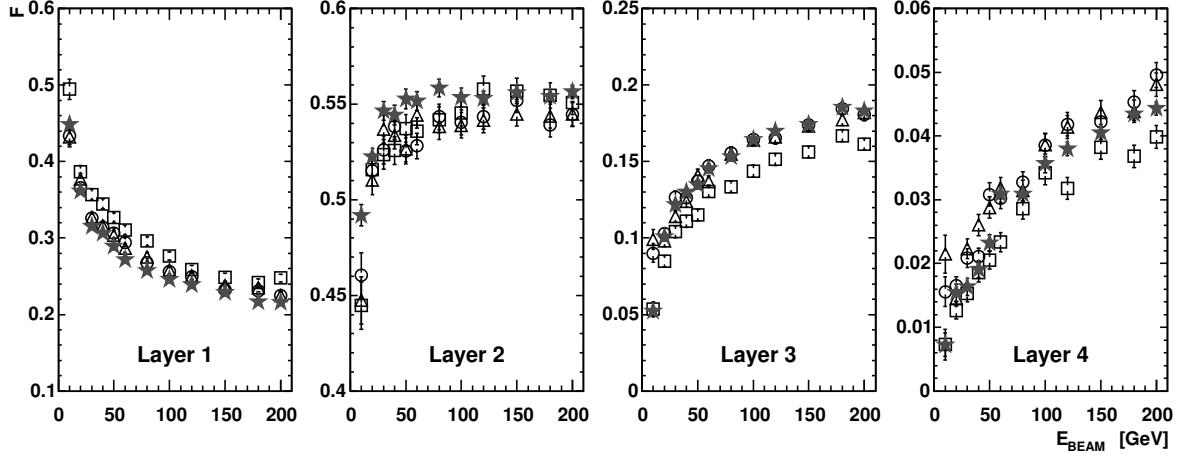


Figure 6. Fractions of the pion shower energy in the various longitudinal layers as a function of the beam energy. Stars mark experimental values. Squares — QGSP, circles — QGSP-BERT, triangles — QGSP-BERT-HP predictions. MC samples: with the Birk's law and after time cuts.

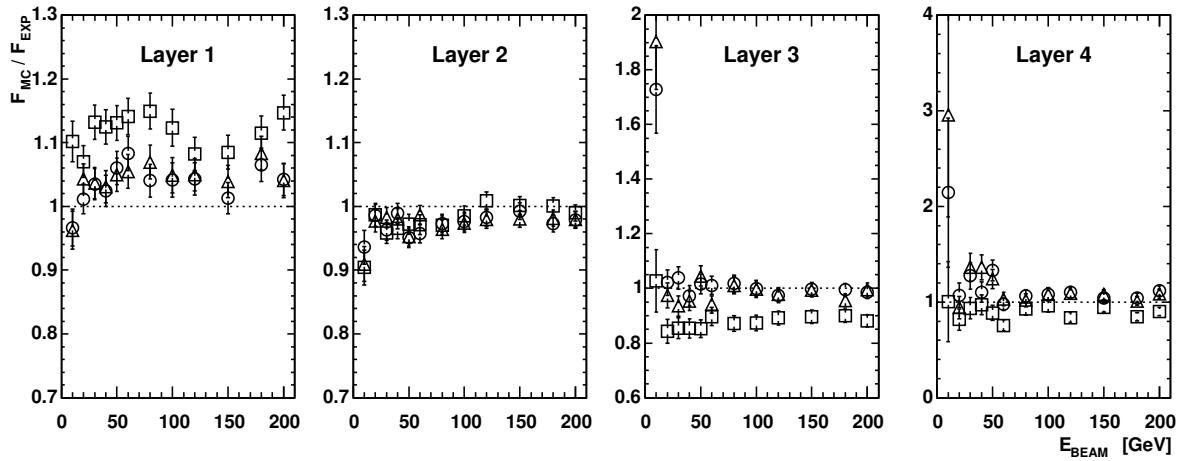


Figure 7. Ratio between simulated and experimental data for the pion energy fractions in the various longitudinal layers as a function of the beam energy. Squares — QGSP, circles — QGSP-BERT, triangles — QGSP-BERT-HP predictions (with the Birk's law and after time cuts).

Additional studies show, that longitudinal profiles do not depend, whether the Birk's law is switched on or off during simulations. Cuts on the time of development of hadronic showers practically do not influence the fraction of energy in HEC layers.

5. Conclusions

GEANT4 based simulations of the HEC testbeam were carried out with different physics lists, namely: QGSP, QGSP-BERT and QGSP-BERT-HP. Influence of the Birk's law and time cuts

on the calorimeter performance parameters was investigated. Comparison with experimental results, obtained during beam tests of HEC modules, was done.

Applying cuts on the time of development of hadronic showers (following the experimental procedure of signal measurements in calorimeter cells) has influence on the energy resolution and response for charged pions. Usage of the Birks' law increases the e/π -ratio and the constant term of the pion energy resolution.

After applying time cuts and with the Birks' law switched on: the better description of studied experimental parameters, in total, is given by the QGSP-BERT and QGSP-BERT-HP physics lists. Agreement in the e/π -ratio, close predictions of the resolution at high beam energies and good description of longitudinal profiles of hadronic showers are achieved for these two physics lists.

There are still some open questions. They are addressed to GEANT4 experts. Among them are such requests as a better description of the sampling term of the energy resolution for charged pions with BERT-based physics lists and improvement of the neutron physics in QGSP-BERT.

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