

Comparison of data with Monte Carlo simulations at the ATLAS barrel Combined Testbeam 2004

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Abstract. The scheme adopted as baseline by ATLAS for the calibration of hadrons depends strongly on the quality of the description of the data by simulations. In 2004, the calorimeters of the ATLAS barrel region have been exposed to a testbeam in order to evaluate the energy response of pions for the energies ranging from 1 to 350 GeV. For the energy region from 3 to 9 GeV a data analysis with the full systematic uncertainty is available. The data has been compared extensively to GEANT4 simulations. Several combinations of physical models—the so called “physics lists”—are provided by the GEANT4 collaboration and have been evaluated. The best overall description of data is achieved with the physics list QGSP_BERT which describes the energy response of pions within a few percent. QGSP_BERT has been adopted by ATLAS for the simulation of the first data.

Introduction

In 2004 the calorimeters of the ATLAS barrel region have been exposed to a testbeam to evaluate the energy response of pions for energies from 1 to 350 GeV. This data has been compared extensively to simulations. An evaluation of the agreement of the simulations with the data is crucial, since the calibration scheme which ATLAS has adopted as baseline for the hadronic calibration depends strongly on the quality of the simulations since corrections for the non-compensating nature of the calorimeter and for dead material are calculated using MC simulations. An accurate description of the geometry of the testbeam has been simulated with the simulation framework GEANT4. Several physics lists, compilations of models to simulate the interaction of particles of a certain type and a certain energy with matter are provided by the GEANT4 collaboration and their agreement with the data has been evaluated.

1. The Combined Testbeam 2004

In the ATLAS barrel Combined Testbeam 2004 (CTB) a slice of all the sub-detectors of the ATLAS barrel region has been put into the CERN SPS H8 beam line (see fig. 1). Pion beams with energies from 1 GeV to 350 GeV have been shot on the detectors to probe the energy response of the calorimeters. The ATLAS Inner Detector consists of a pixel, a silicon strip detector (SCT) and a transition radiation straw tube tracker (TRT). The calorimeters are liquid argon/lead for the electromagnetic part (LAr) and scintillator tiles/iron for the hadronic part (TileCal). The electromagnetic calorimeter consists of three longitudinal segments (front, middle and back), its electrodes have an accordion shape. A presampler is positioned upstream to correct for the energy which is deposited in the dead material before the calorimeters. The hadronic calorimeter

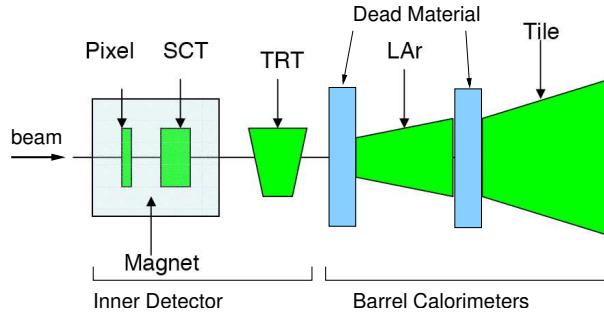


Figure 1: Sketch of the detectors in the ATLAS barrel Combined Testbeam 2004 (CTB). The beam passes the Inner Detector consisting of the Pixel detector, the silicon strip detector (SCT) and the transition radiation straw tube tracker (TRT) before entering the calorimeters. The liquid argon (LAr) calorimeter and the Tile calorimeter are mounted on a rotating table which allows to change the η -position of the calorimeters. The two main areas of dead material (for pions) are before the LAr calorimeter and between the LAr and the Tile calorimeter.

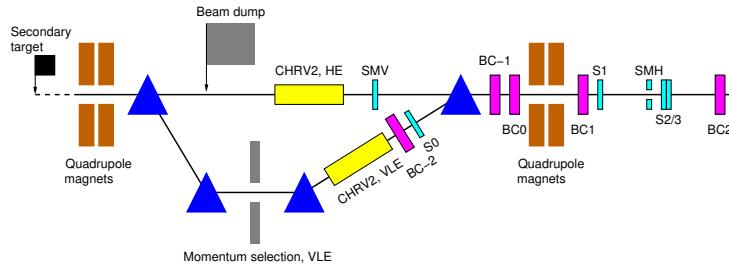


Figure 2: Sketch of the layout of the high energy (HE) and the very low energy (VLE) beam lines for the CTB.

is an iron structure with pockets where scintillator tiles are put. It consists of three longitudinal segments (A, BC and D). The calorimeters were mounted on a rotating table which allowed to change their η -position. For the pion beams, two dead material regions were of importance: the material upstream of the LAr calorimeter (about 0.5λ) for low energy pions, and the dead material region between the LAr and the Tile calorimeter (about 0.5λ) for high energy pions.

In fig. 2 the layout of the high energy (HE) and the very low energy (VLE) beam lines is shown. In the analysis of the VLE data, several analysis cuts have been applied to achieve a good rejection of muons passing through the HE beam line and electron/pion (e/π) separation. The rejection of high energy muons used mainly the timing information of the calorimeters, since these muons are passing directly through the HE beam line and produce their signal earlier or later than the particles which follow the VLE beam line. The effect of muons from pion decays is small and has been included in the systematic uncertainties. The e/π -separation used the signal from the TRT and the Čerenkov detector in the VLE beam line. To achieve a clean pion beam, strong purification cuts had to be applied which lead to a large event rejection of about 100.000 to 1000 events.

In the high energy region, the beam energies 20, 50, 100 and 180 GeV have been analyzed. Electrons are also separated from pions using the TRT. Besides electrons, the pion beam can also

Table 1: Four selected physics lists and their main constituent models. The models are the *quark gluon string* model (QGS), the *Fritiof* model (FTF), the *low energy parametrization* model (LEP) and the *Bertini cascade* model (BERT). For each physics list, the energy region for all models which are used is given. In the overlap region a random decision which model is used is taken.

physics list	low energy region	high energy region
QGSP	$0 \text{ GeV} < \text{LEP} < 25 \text{ GeV}$	$\text{QGS} > 12 \text{ GeV}$
QGSP_BERT	$0 \text{ GeV} < \text{BERT} < 9.9 \text{ GeV}$ $9.5 \text{ GeV} < \text{LEP} < 25 \text{ GeV}$	$\text{QGS} > 12 \text{ GeV}$
FTFP	$0 \text{ GeV} < \text{LEP} < 5 \text{ GeV}$	$\text{FTF} > 4 \text{ GeV}$
FTFP_BERT	$0 \text{ GeV} < \text{BERT} < 5 \text{ GeV}$	$\text{FTF} > 4 \text{ GeV}$

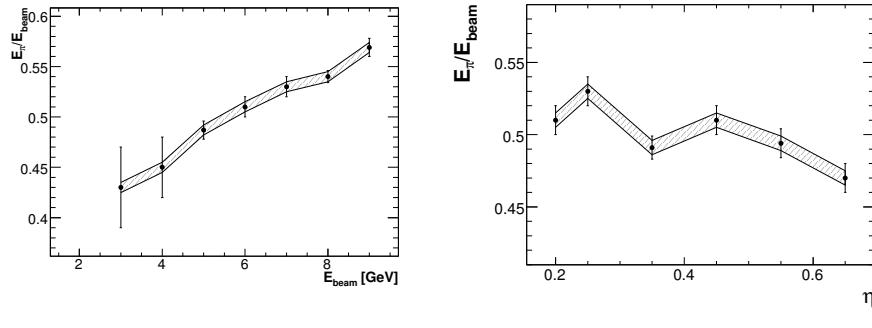
contain protons. With the instruments in the beam line pions and protons cannot be separated on an event by event basis. Using the amount of energy deposited in the straws of the TRT can be used to estimate the fraction of the protons in the beam for each beam energy. For the VLE data negative pion beams have been used. There was therefore no proton contamination. The proton fraction has shown to vary from 0% to 75% for the beam energies of 20 GeV to 180 GeV respectively. For the comparisons of data with simulations, simulations of both pions and protons have been produced and mixed according to the estimated fractions of pions and protons. These pion-proton mixes have been compared to data.

2. The simulation framework

The simulations of the CTB have been done with GEANT4, a framework for the simulation of the interaction of particles with matter. Several physics lists are provided by the GEANT4 developers. A physics list defines for all particle types and energy ranges the physical processes and models which are used to simulate the interactions of particles with matter. In table 1 four physics lists and the most important models for the development of hadron showers and their energy ranges are shown. The simulations have been done with GEANT4.7 QGSP_BERT and with GEANT4.91 QGSP_BERT, FTFP and FTFP_BERT. GEANT4.91 is presently the newest version of the simulation framework (Dec. 2007), GEANT4.7 dates from Feb. 2007. GEANT4.91 has improvements of the quasi-elastic and the elastic scattering of nucleons and the multiple scattering.

3. Analysis of the very low energy region for various pseudo-rapidities and comparison with simulations

A full scan from of the beam energies from 3 to 9 GeV and a pseudo-rapidity of $\eta = 0.20$ to 0.65 has been analyzed and a full systematic error analysis has been done[1]. For this data set, the Pixel and the SCT were not available. In this data set the amount of muons from the high energy beam lines was particularly high and therefore it was in addition to the requirements mentioned in sec. 1 necessary to require that in the last layer of the Tile calorimeter a signal compatible with noise is detected. As an example, in fig. 3 the energy response at pseudo-rapidity $\eta = 0.45$ for the beam energies from 3 to 9 GeV and the uniformity for a beam energy of 6 GeV as a function of the pseudo-rapidity are shown. The bars at each point show the uncertainty of the reconstructed energy. The uncertainty ranges from about 8% at 3 GeV to about 1% at 9 GeV. The error is dominated by the statistical uncertainty. The band denotes the uncertainty on the beam energy scale. The energy response is slowly decreasing with the pseudo-rapidity η and



(a) Energy response of pions for $\eta = 0.45$ as a function of the pion energy
 (b) Energy response of pions with a beam energy of 6 GeV as a function of η

Figure 3: Examples of the results of the analysis of the VLE data. The energy response for $\eta = 0.45$ as a function of the beam energy (a) and the uniformity over η for a beam energy of 6 GeV (b) are shown. The band around the points denotes the uncertainty on the beam energy scale.

increases with the energy.

For the analyzed η - and energy-scans, the ratio of the energy response of the simulation performed with GEANT4.91 and QGSP_BERT and the data have been calculated. Examples for 3, 6 and 9 GeV are shown in fig. 4. The energy response of the data is described by QGSP_BERT within a few percent.

Examples of the ratio of the resolution of the energy response in simulations and data is shown in fig. 5. The resolution is in the simulations about 10% to 20% too narrow.

4. Analysis of the very low and the high energy data at fixed pseudo-rapidities and comparison with simulations

Fig. 6 shows as example the distributions of the total deposited energy of 100 GeV pions for the data and simulations. The distributions do not have a Gaussian shape. This is not expected, since a part of the energy is deposited in the dead material regions before and between the electromagnetic and hadronic calorimeters. The width of the distribution of GEANT4.7 QGSP_BERT is narrower than in the data. The widths of the distributions of the total deposited energy simulated with GEANT4.91 are wider, such that they agree better with data. The use of the Bertini cascade model causes a shift of the distribution to higher energies which leads to a better agreement with data.

4.1. Linearity and resolution

In fig. 7a the linearities for the energies from 2 to 180 GeV of the simulations done with QGSP, QGSP_BERT, FTFP and FTFP_BERT are compared to data¹. No systematic uncertainty is included in this comparison. It can be seen, that the Bertini cascade model increases the energy response in the simulations. QGSP_BERT shows the best overall performance for the linearity (within 4%). In particular at low energies, the Fritiof model is not in good agreement with data.

¹ In this analysis a different run period compared to the VLE analysis described in sec 3 has been used. Here, a cut in the last Tile layer was not necessary.

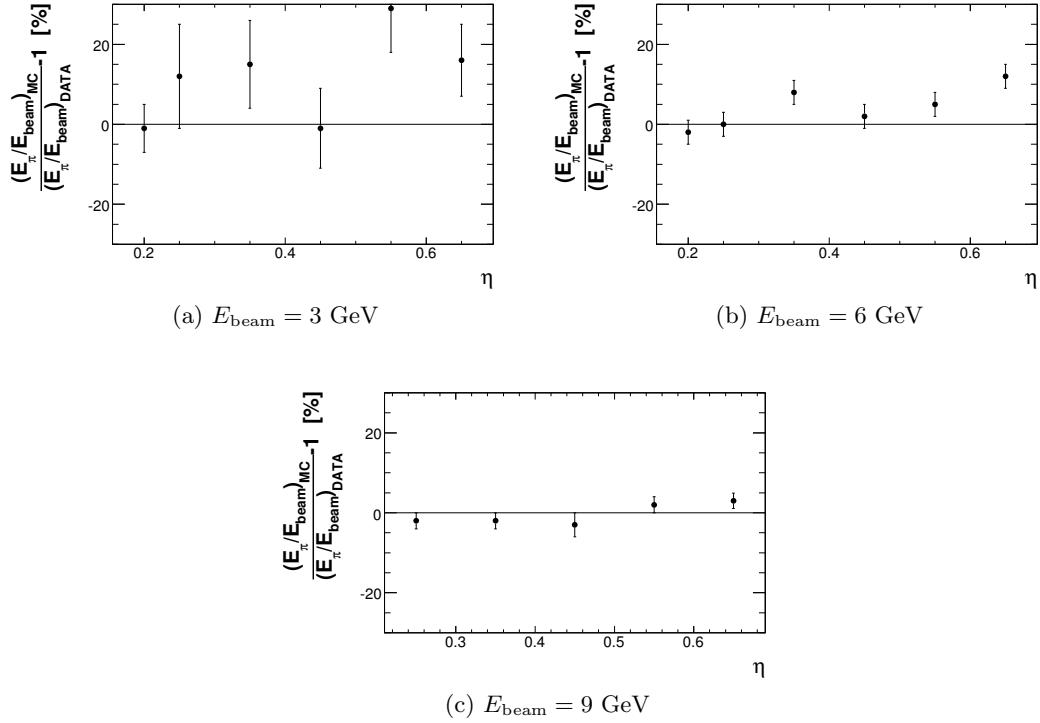


Figure 4: Ratio of the energy response of the simulation and the data for η -scans for the beam energies 3, 6 and 9 GeV.

In fig. 7b the resolution for the energies from 2 to 180 GeV are shown for data and simulations with QGSP, QGSP_BERT, FTFP and FTFP_BERT. Physics lists using the Bertini cascade model have a resolution which is too narrow compared to data. The ones without are in better agreement with the data. The disagreement between data and simulations is about 10 to 20%.

4.2. Energy sharing between LAr and Tile calorimeter

Fig. 8 shows the energy sharing between the LAr and the Tile calorimeter for 100 GeV pions. The energy distribution in fig. 8a has a peak at about 0 caused by the events which start to shower after the LAr calorimeter and a broader peak for events which start to shower in the LAr calorimeter. It can be seen that the physics lists using the QGS model are shifted to higher energies. Fritiof describes the energy distribution in the LAr calorimeter better. The Tile calorimeter (see fig. 8b) shows as well two peaks. The one at lower energies comes from events which started to shower before the Tile calorimeter, the peak at higher energies is consists of events which start to shower in the Tile calorimeter. Simulations with QGSP produce too many events with small energies in the Tile calorimeter and too few with high energy. The shower produced with QGSP is too short. Using the Bertini cascade (QGSP_BERT) makes the showers longer, but they are still too short compared to data. FTFP describes well the first peak in the Tile calorimeter, but is shifted to lower energies for the second peak (similar to QGSP). The Bertini cascade shifts the first peak of FTFP_BERT to higher energies compared with data. The high energy peak is well described by both physics lists with the Bertini cascade, FTFP_BERT and QGSP_BERT.

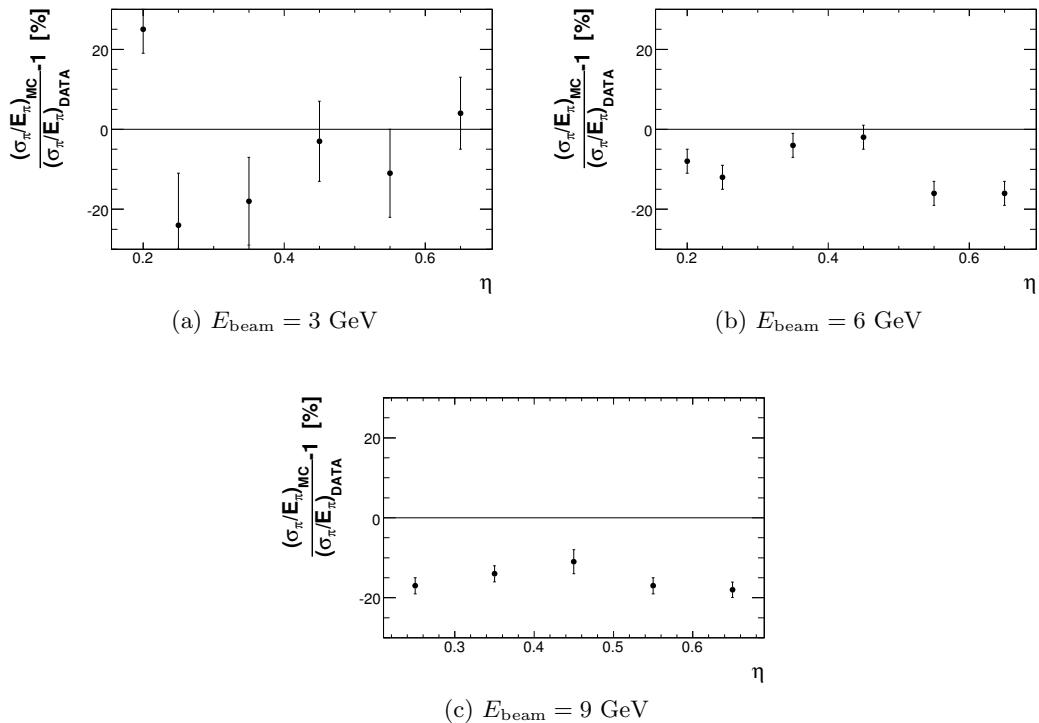


Figure 5: Ratio of the resolution of the energy response of the simulation and the data for η -scans for the beam energies 3, 6 and 9 GeV.

4.3. Barycenter of the showers

In fig. 9 the distribution of the barycenters along the shower axis of the pion showers is shown. Three regions (peaks) can be identified: the first one below 1000 mm, the second one between 1000 and 1500 mm and the third one above 1500 mm. The first peak is formed by events where most of the energy is deposited in the LAr calorimeter. The second peak is formed by events where most of the energy is deposited in the Tile calorimeter. The third peak is created by events where the shower is nearly completely contained in the Tile calorimeter.

Simulations with QGSP produce too many events where the barycenters are too early. Using the Bertini cascade (QGSP_BERT) less events with a barycenter which is too low and more events with a larger barycenter are observed, but it is still not in agreement with the data. FTFP follows the data well, all three peaks are well described. FTFP_BERT shifts the barycenter to higher values, especially for the first peak.

Conclusions

The calorimeters from the barrel region of ATLAS have been exposed to a testbeam (CTB). A data analysis with the full systematic uncertainty is available for 3 to 9 GeV. The pion response is described within a few percent by simulations with the physics list QGSP_BERT, but the energy resolution is about 10 to 20% too narrow compared to data. The Bertini cascade model increases the energy response, but makes the resolution of the energy response narrower. The barycenter of showers simulated with QGSP is too early compared to data. This is improved by using the Bertini cascade (QGSP_BERT), but the barycenter is still too early compared to the

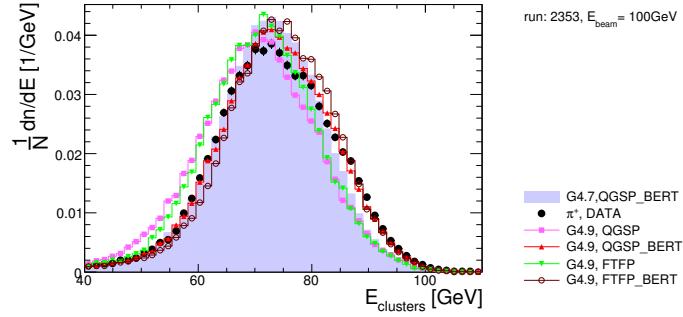


Figure 6: Total deposited energy for 100 GeV pions in the data and in selected physics lists. The width of the distribution of GEANT4.7 QGSP_BERT is narrower than data. With the physics lists from GEANT4.91 the distributions have a width which is comparable to data. The physics lists where cascade models are used the distribution of the total deposited energy is shifted to higher energies, which is in better agreement with the data.

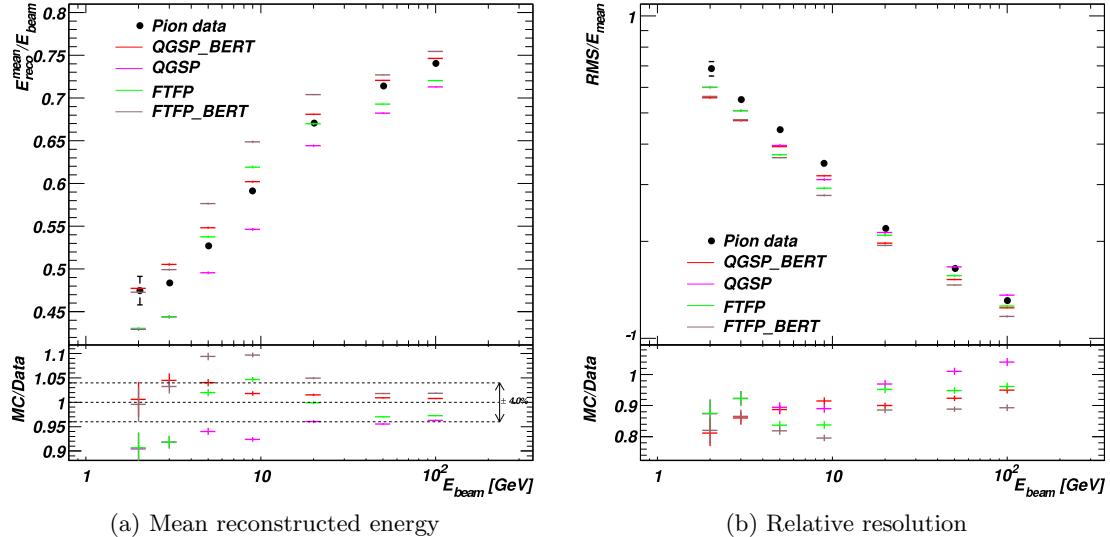


Figure 7: Fig. (a) shows the mean reconstructed energy (a) with respect to the beam energy as reconstructed in data and simulations with the physics lists QGSP, QGSP_BERT, FTFP and FTFP_BERT. The Bertini cascade model increases the energy response. QGSP_BERT shows the best overall performance for the linearity (within 4%). Fig. (b) shows the relative resolution of simulations with the physics lists QGSP, QGSP_BERT, FTFP and FTFP_BERT and of data. The Bertini cascade model makes the resolution narrower (too narrow compared to data). A disagreement of about 10 to 20% in resolution is seen between simulation and data.

data. The Fritiof physics list (FTFP) describes well the distribution of the barycenter of the showers. Adding the Bertini cascade to the Fritiof physics list (FTFP_BERT) produces showers where the barycenter is too late.

As a result from the extensive comparisons of the simulations with the data the physics list

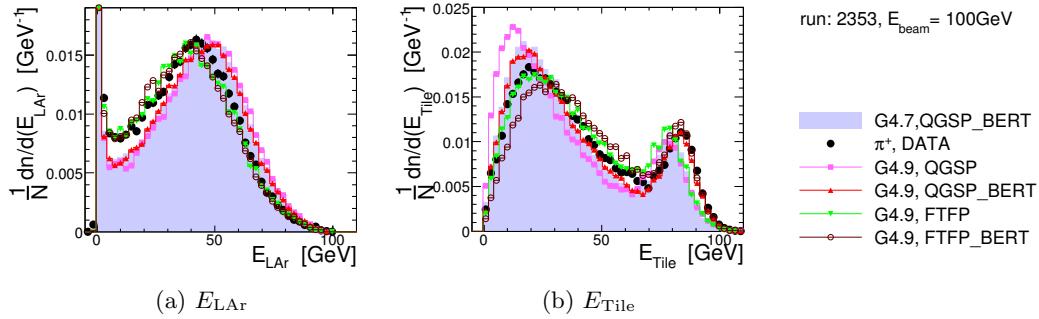


Figure 8: Energy sharing between the LAr and the Tile calorimeter for 100 GeV pions. In (a) the simulations with the physics lists using the QGS model are shifted to higher energies. Fritiof describes the energy distribution in the LAr calorimeter better. Simulations with QGSP produce too many events with small energies in the Tile calorimeter (b) and too few with high energy. Using the Bertini cascade (QGSP_BERT) produces less events with a low energy and more with a high energy, but still too few compared to data. FTFP describes well the first peak in the Tile calorimeter, but is shifted to lower energies for the second peak (similar to QGSP). The Bertini cascade shifts the first peak of FTFP_BERT to higher energies compared with data. The high energy peak is well described by both physics lists with the Bertini cascade, FTFP_BERT and QGSP_BERT.

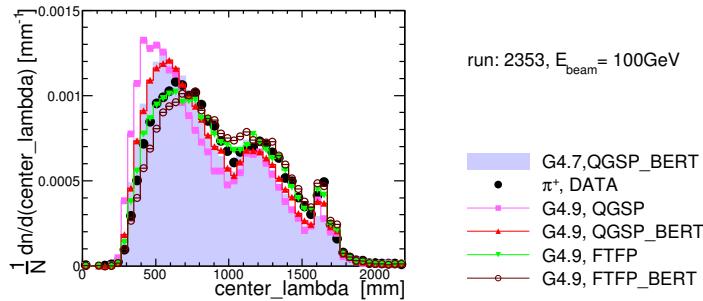


Figure 9: The barycenter (center_lambda) along the axis of showers of the showers produced by 100 GeV pions. The distribution has three peaks. The first is produced by events where most of the energy is deposited in the LAr calorimeter, the second is produced by events depositing most of the energy in the Tile calorimeter and the third peak is produced by events whose shower is nearly completely contained in the Tile calorimeter.

QGSP_BERT has been identified to describe the data best. It therefore has been chosen for the simulation of the first ATLAS data.

References

- [1] Cavasinni V, Giangiobbe V and Santoni C 2008 *Study of the response of the central electromagnetic and hadronic calorimeters to pions of energies from 3 to 9 GeV*. Geneva, CERN, ATL-COM-TILECAL-2008-001, 36 p