Performance of an digital Electromagnetic Sampling Calorimeter

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September 5, 2012

Abstract

The aim of this document is to show the performance of an digital Electromagnetic Sampling Calorimeter. First of all you could find a short information about the interactions in general. Electromagnetic interactions are the subsection of the interactions and the second main part of this report. Such aspects as electromagnetic showers and ECAL were affected. There are some introductory facts about tools after that. But everything revolves around the results of the analysis and comparison of some files that describe different simulations processes. And at the end you could find this results and their interpretation.

Contents

1 Introduction

This report is a summary of my work during the summer student program 2012 at DESY in Hamburg. First of all I affect such theme as interactions. They are fundamental aspect of nature. But my report strongly connects with the subsection of the interactions. That's why I consider more fully the electromagnetic interactions. Such important things as Electromagnetic Showers and ECAL haven't forgotten. Throughout all my work I used some tools. This tools are ROOT and Marlin. And it means that I should say a few words about them. But my main goal was to understand the behavior of the charged particles in the ECAL. I analysed files with different parameters such as incoming Energy of the beam, absorber and the size of the Pixel for this purpose. Energy range was from 1 GeV to 500 GeV for 50×50 μm and from 1 GeV to 400 GeV for 100×100 μm. I compared the digital and the analog signal. I did all this exercises using Tungsten as the absorber and after that I used Rhenium. At the end of my report I want to show you the main results of my work, their description and explanation.

1.1 Interactions

Interactions are processes in which particles respond to the force due to the presence of other particles or the particles decay into other particles. Neglecting gravity, which has no measurable effects on the scale of particle interactions, there are three basic types of interactions: Electromagnetic, Strong and the Weak Interactions.

1.2 Electromagnetic Interactions

Fundamental electromagnetic interactions occur between any two particles that have electric charge. Electromagnetic decay processes can often be recognized by the fact that they produce one or more photons. Theoretical calculations agree with experimental results to a very high precision for processes in which the electromagnetic interaction is dominant.
Typical electromagnetic interactions in high-energy physics are:

- Coulomb scattering (e.g. electron-nucleon scattering)
- Bhabha scattering (electron-positron scattering)
- Möller scattering (electron-electron scattering)
- Compton scattering (photon-electron scattering)
- Bremsstrahlung (photon emission in deceleration or acceleration)
- Pair creation ($\gamma \to e^+e^-$)
- Decay of π^0
- Annihilation ($e.g., e^+e^- \to \gamma\gamma$)

2 Electromagnetic Showers

Electrons and photons are the main components of an electromagnetic Shower. Pair production is the formation or materialization of an electron and a positron, from a pulse of electromagnetic energy traveling through matter, usually in the vicinity of an atomic nucleus. The intense electric field near the nucleus can cause the photon to decay into an electron and a positron. Electrons and positrons behave exactly the same way in a detector as far as a shower is concerned. Consider an electron or positron with several GeV of energy traversing in some material. For energies above 100 MeV, the electrons lose energy almost entirely through bremsstrahlung. The emitted photons carry off a large fraction of the electrons initial energy. For photons with energy greater than 100 MeV the major interaction is pair production, which gives another energetic electron or photon. Electromagnetic shower is confined to smaller regions in solids that are dense. If the material is made up of atoms with a high atomic number then the greater nuclear charges can produce greater accelerations and so the cascade process can develop more readily than it would in a material with a lower atomic number.

The parameters of EM shower are:

- Radiation length (X_0)
- Critical Energy (E_c)
- Moliere Radius ($r_{Moliere}$)
- Shower Max S_{max}

$$X_0 = \frac{716.4A}{Z(Z+1)\ln(287/\sqrt{Z})} * \frac{1}{\rho}$$

$$E_{c,solid/liquid} = \frac{610MeV}{Z+1.24}$$

$$E_{c,gas} = \frac{710MeV}{Z+0.92}$$

$$r_{Moliere} = 21.2MeV\frac{X_0}{E_c}$$

$$S_{max} = \ln(\frac{E_{incoming}}{E_c})$$

Here I want to explain what these parameters mean. ρ is the density of matter. Z is the Number of Protons. Radiation length (X_0) shows us when the energy has been reduced to 1/e and characterizes the shower depth. Critical Energy (E_c) is the energy, where Ionization takes over. Moliere Radius ($r_{Moliere}$) is the radius which contains 90 % of the shower and characterizes the width of the shower. Shower Max shows us the peak of the shower.

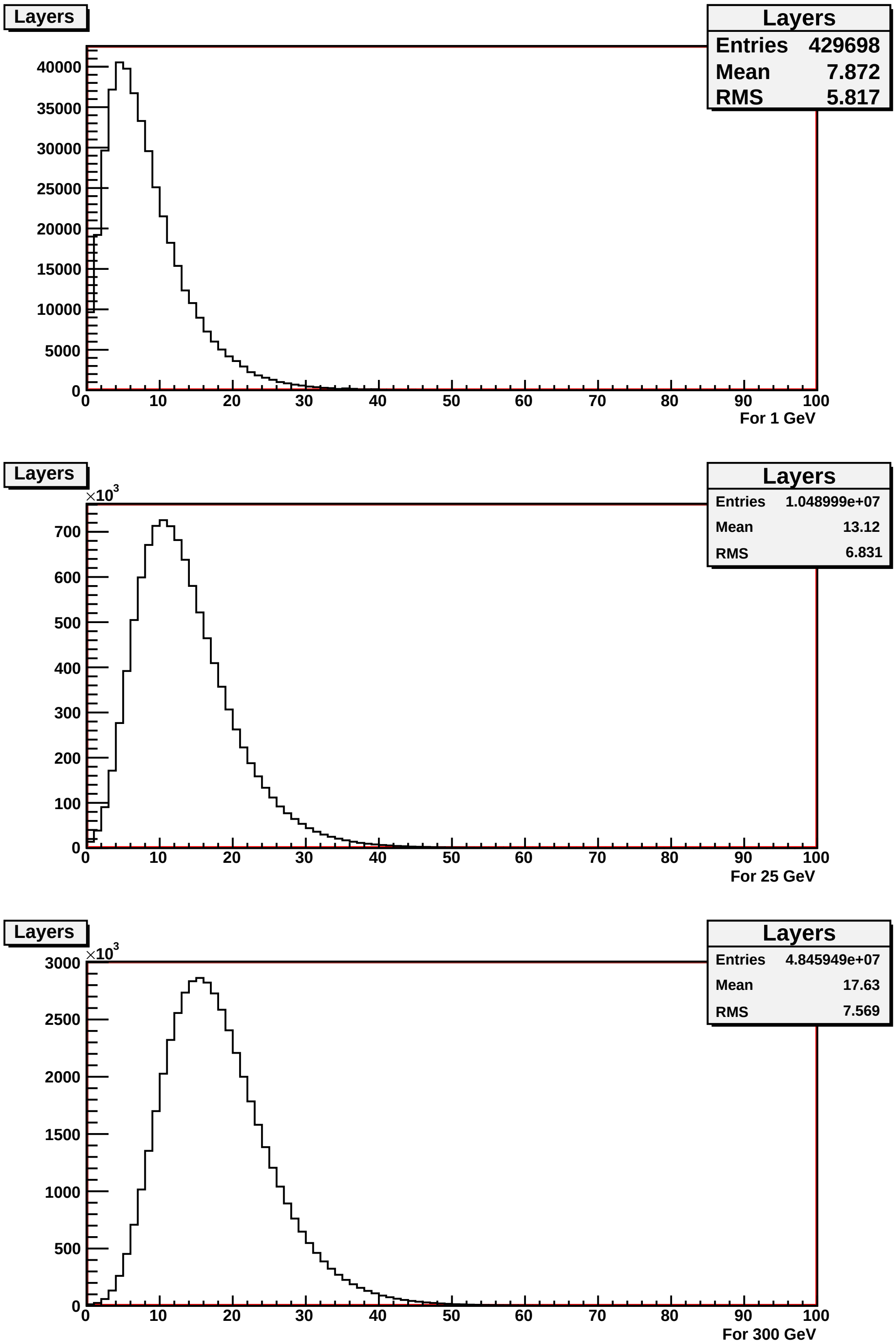


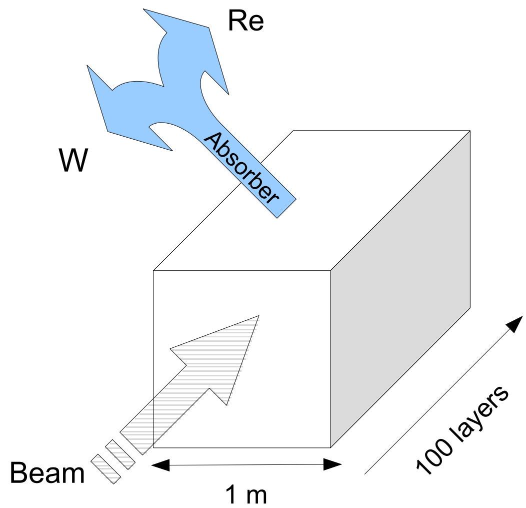
Figure 1: Shower Shapes for 50×50 μm Pixels. Absorber is Tungsten.

2.1 Electromagnetic Calorimeter

Shower is used to measure the energy of the particles in a collision. The electromagnetic calorimeter is a device used to measure the energy of the shower and hence the incident particle. Each device consists of alternate layers of metal radiator to enhance shower production and an active substance to sample energy loss. The calorimeter readout maybe digital or proportional. In a digital calorimeter the active region is finely divided into channels to provide a yes or no signal. In a proportional calorimeter the analog signals from the active regions are summed to produce a signal that is proportional to the total energy. The response of a given detector to two identical incident particles is different because of the statistical fluctuations of the shower development. A reasonable size for the shower detector implies that the radiation length of the material must be small. This in turn requires a high-Z material. There are two classes of such shower detectors:

- Homogeneous Calorimeters
- Heterogeneous or Sampling Calorimeters

The energy resolution for sampling calorimeters depends on the thickness of the absorber.



Pixels	Readout	Absorber	Active area
50x50	digital	W	15 µm
100x100	digital	W	15 µm
50x50	analog	W	300 µm
50x50	digital	Re	15 µm

Approximate scheme of the Calorimeter

2.2 ECAL

In a sampling electromagnetic calorimeter (ECAL), the energy deposited is proportional to the number of charged particles created in the shower, itself proportional to the incident energy of the particle. Two approaches are hence possible to measure the incident energy: by measuring the number of charged particles (digital approach) or by measuring the energy deposited (analogue approach). The motivation for using digital over analogue lies in the fluctuations occurring in the measured quantity. Only fluctuations in the development of the shower are expected if we are able to truely count charged particles. The energy deposited is however subject to additional fluctuations. Here I want to show you one Energy profile with Landau fitting function. I used this fitting function because Landau distribution is the nature distribution of the particles.

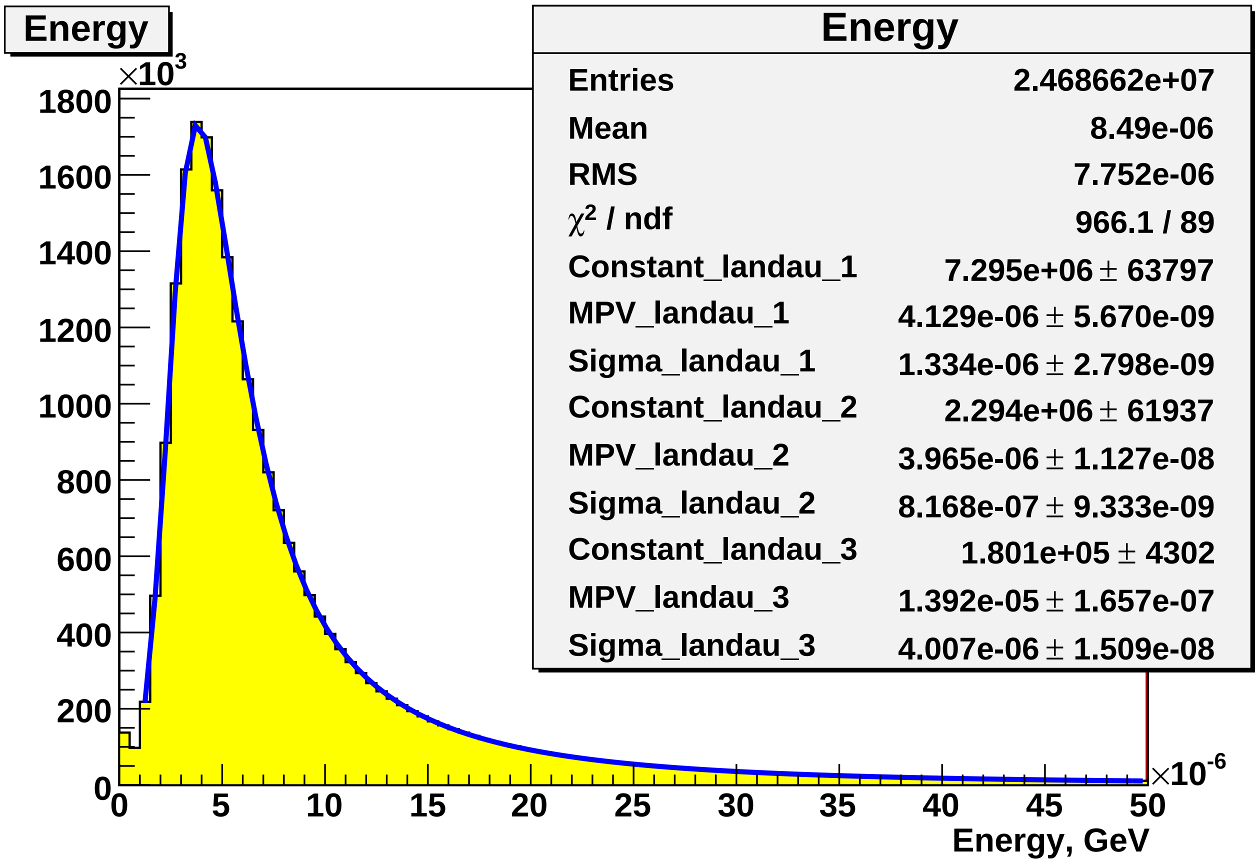


Figure 2: Energy Profiles with Landau fit for 50×50 μm Pixels (Incoming Energy is 60 GeV)

3 The tools: Marlin and ROOT

3.1 Marlin

Some common word about Marlin. Marlin is a C++ software framework for ILC software. It uses the LCIO data model and can be used for all tasks that involve processing of LCIO files, e.g. reconstruction and analysis. The idea is that every computing task is implemented as a processor (module) that analyzes data in an LCEvent and creates additional output collections that are added to the event. In my case I've updated the default Processor and added the special properties in it. The main purpose of Marlin is to facilitate the modular development of reconstruction and analysis code based on LCIO.

3.2 LCIO

LCIO (Linear Collider I/O) is a persistency framework and event data model for linear collider detector studies. It is used in both simulation studies and analysis frameworks. Using a common persistency format and event data model allows to easily share results and compare reconstruction algorithms.

3.3 ROOT

ROOT is a framework for data processing. You can use ROOT for the manipulations with data. You can:

- Save data. ROOT provides a data structure that is extremely powerful for fast access.
- Access data. It is really easy to use ROOT-files.
- Process data. Powerful mathematical and statistical tools are provided to operate on your data. You can fit whatever you want.
- Show results. Results are best shown with histograms, scatter plots, fitting functions, etc. ROOT graphics may be adjusted real-time. High-quality plots can be saved in PDF or other formats.

4 Results

In this section I want to show you the results of my work and try to explain them. First of all I want to speak about dependence between hits and incoming Energy of the beam. On this plots we can see that the dependence between Hits and incoming Energy is linear in all cases. Hits rise simultaneously with the rising of Energy. This is exactly what one would expect. But it should also be pointed out that the high-energy dependence is no longer linear, which is well seen in the graphs. This is due to the increasing fluctuations.

4.1 Linearity

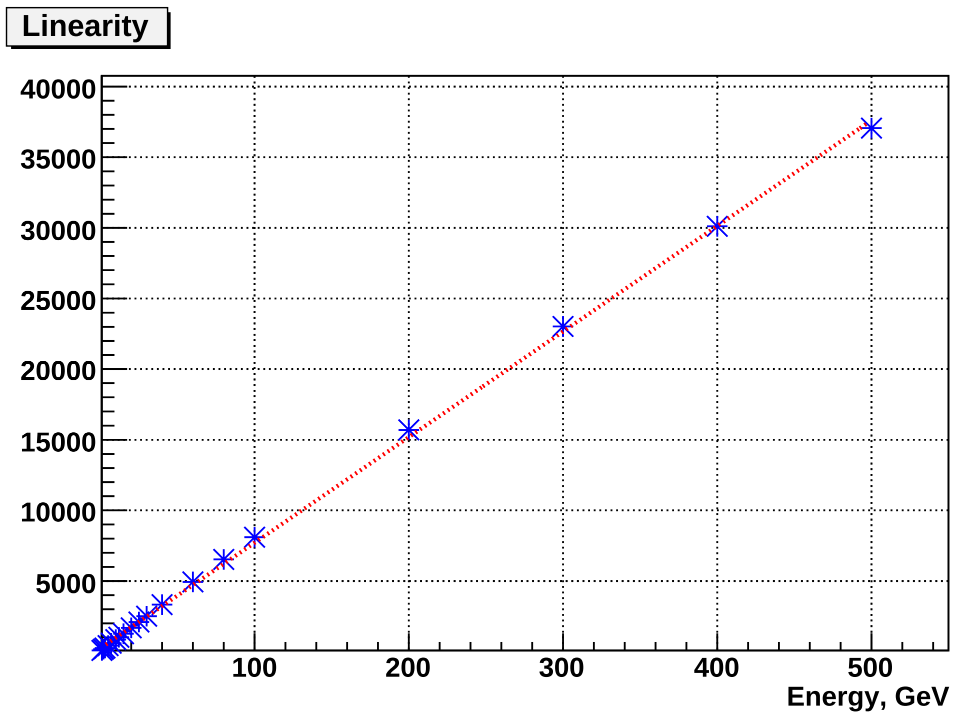


Figure 3: Linearity for 50×50 μm Pixels. Hits vs incoming Energy. Absorber is Tungsten.

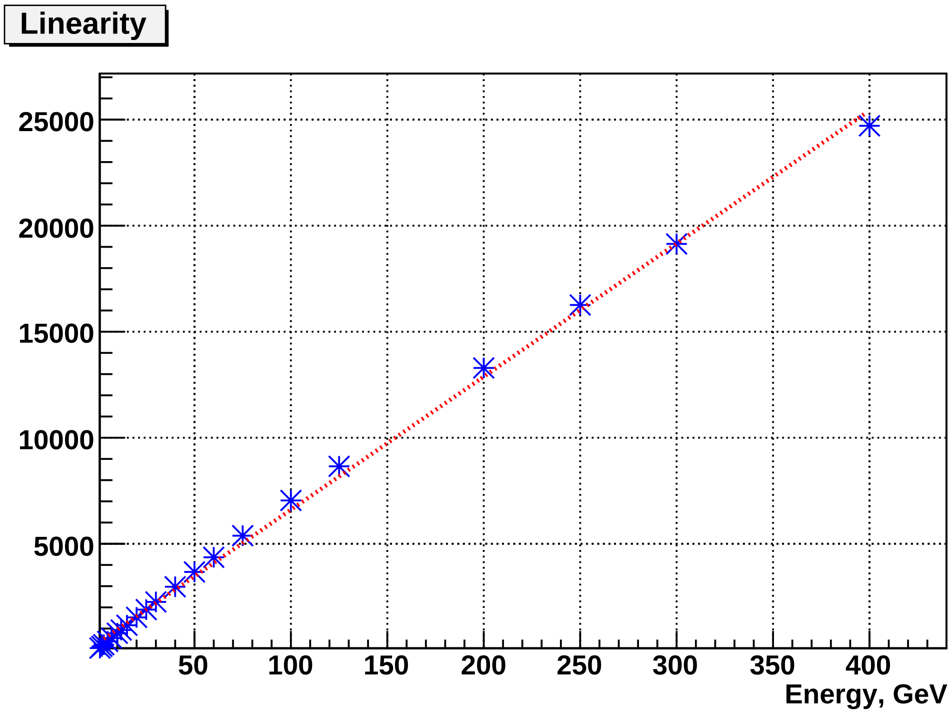


Figure 4: Linearity for 100×100 μm Pixels. Hits vs incoming Energy. Absorber is Tungsten.

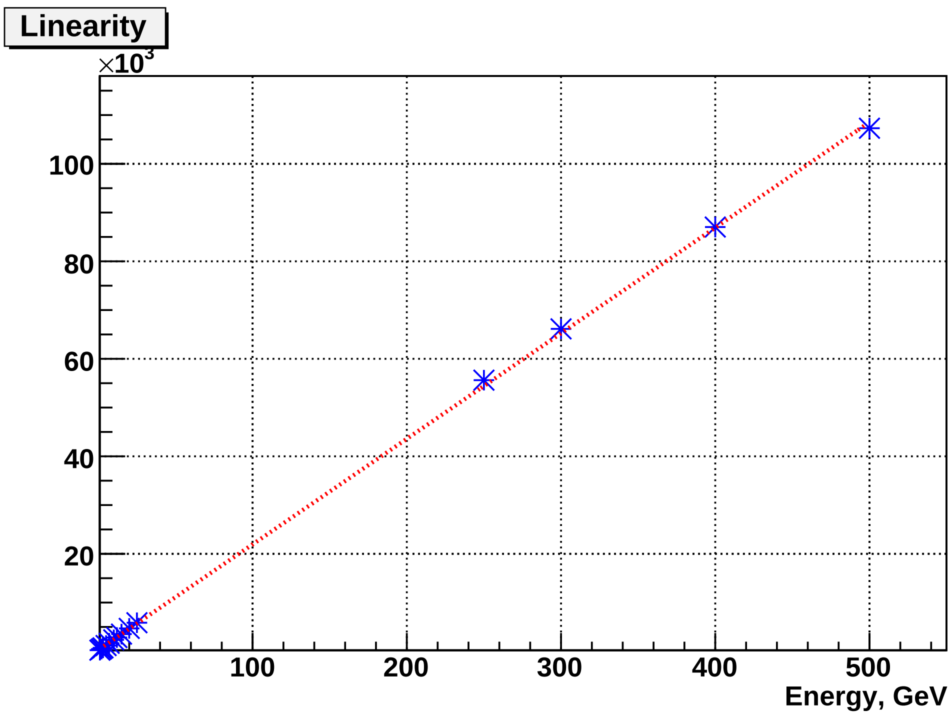


Figure 5: Linearity for 50×50 μm Pixels. Hits vs incoming Energy. Analog readout.

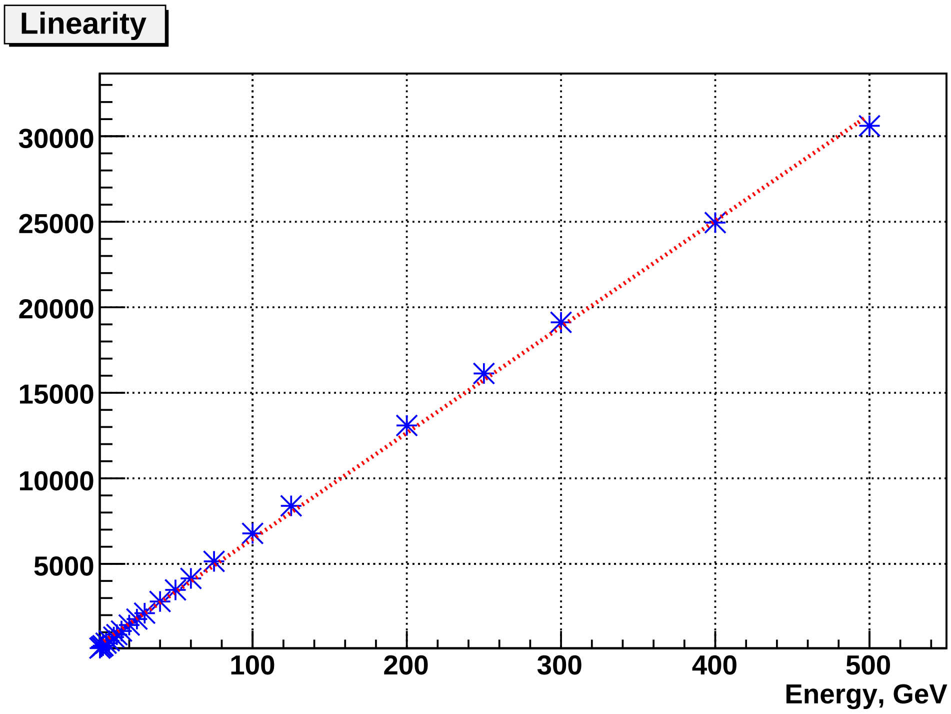


Figure 6: Linearity for 50×50 μm Pixels. Hits vs incoming Energy. Absorber is Rhenium.

4.2 Energy Resolution

$$\frac{RMS}{MEAN} = \frac{\alpha}{\sqrt{E}} + \beta$$
$$\frac{RMS}{MEAN} \approx \frac{\delta E}{E}$$
$$\alpha = p1, \beta = p0$$

Using these formulas, we could see that if we plot the dependence between 1/sqrt(E) and RMS/Mean and make a linear fit of it, we can get a constant α and β. Here we used 5 different amount of layers. There are 100, 50, 40, 30 and 20 layers

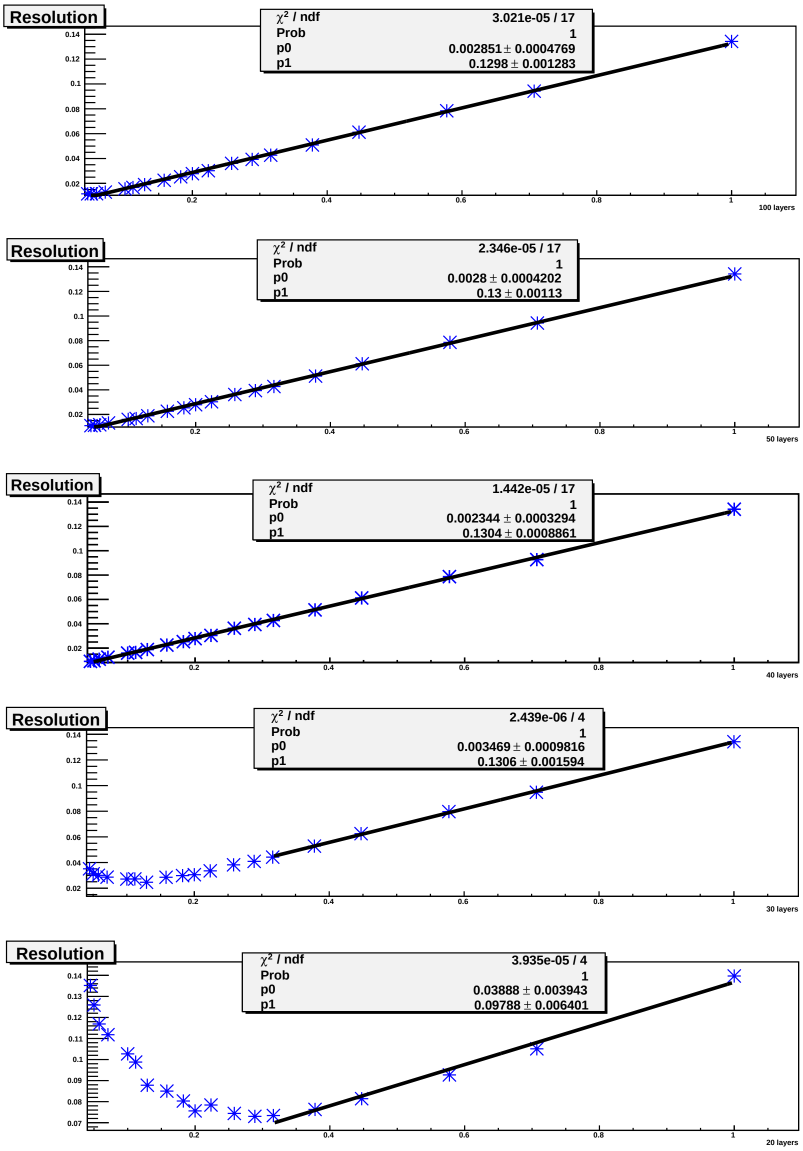


Figure 7: Energy Resolution for different amount of using layers 50×50 μm Pixels. Hits. Absorber is Tungsten.

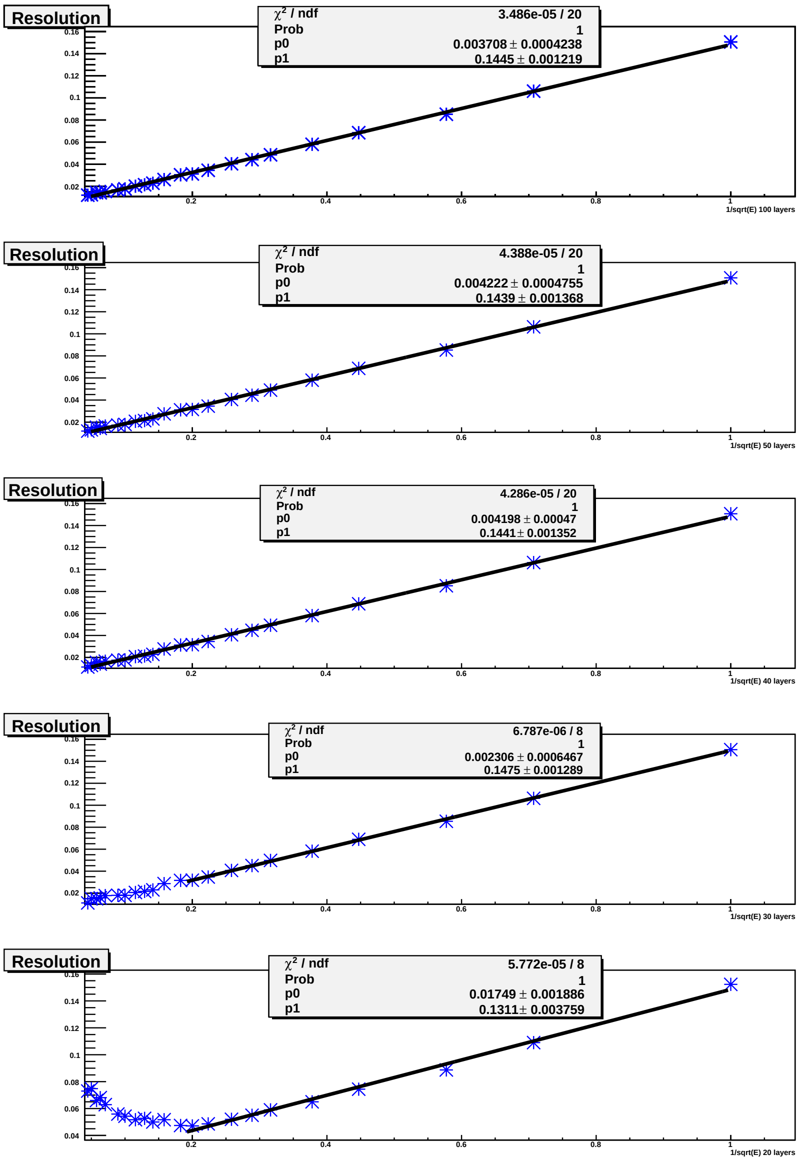


Figure 8: Energy Resolution for different amount of using layers 50×50 μm Pixels. Hits. Absorber is Rhenium.

Here we can notice that resolution become worse when we use a lower amount of layers. For 30 and 20 layers we have a strong leakage, hence the poor behaviour at high energies. When we use all 100 layers we can analyze all information because we don't lose any Hits. And we can notice that resolution is better for Tungsten and for digital readout.

Table 1: Resolution

Amount of layers	W 50×50 α,β	W 100×100 α,β	W analog 50×50 α,β	Re 50×50 α,β
100 layers	0.1298, 0.0028	0.1179, 0.006	0.21, 0.001	0.1445, 0.0037
50 layers	0.13, 0.0028	0.1182, 0.0058	0.2102, 0.001	0.1439, 0.0042
40 layers	0.1304, 0.0023	0.1202, 0.0047	0.2092, 0.0018	0.1441, 0.0042
30 layers	0.1306, 0.003	0.1212, 0.014	0.2106, 0.018	0.1432, 0.005

4.3 Hits vs Particles

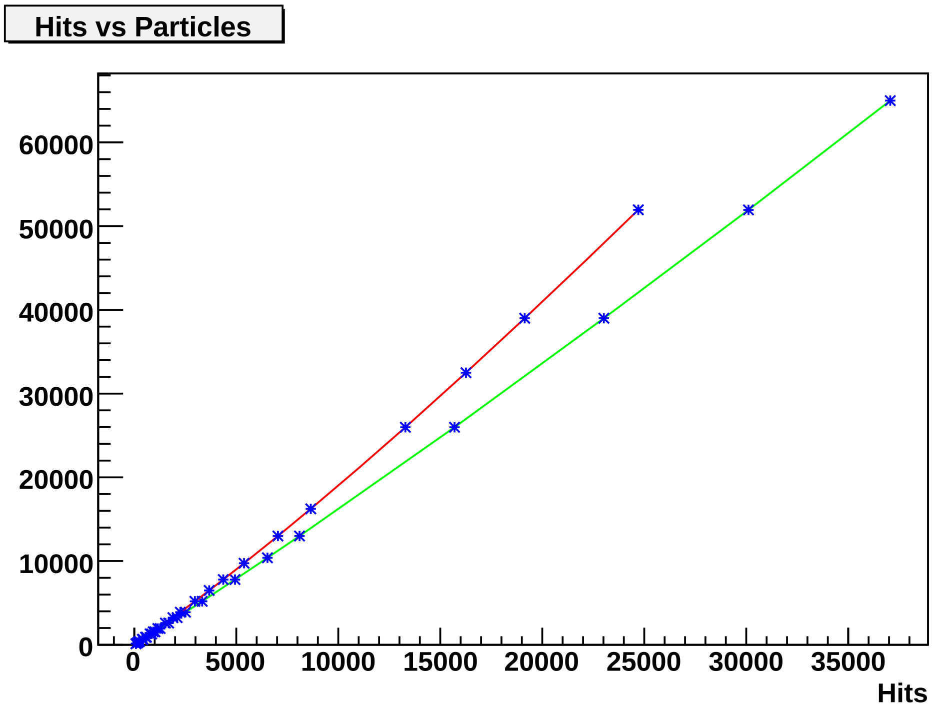


Figure 9: Hits vs Particles. Red one is for 100×100 μm Pixels, green one is for 50×50 μm Pixels. Absorber is Tungsten.

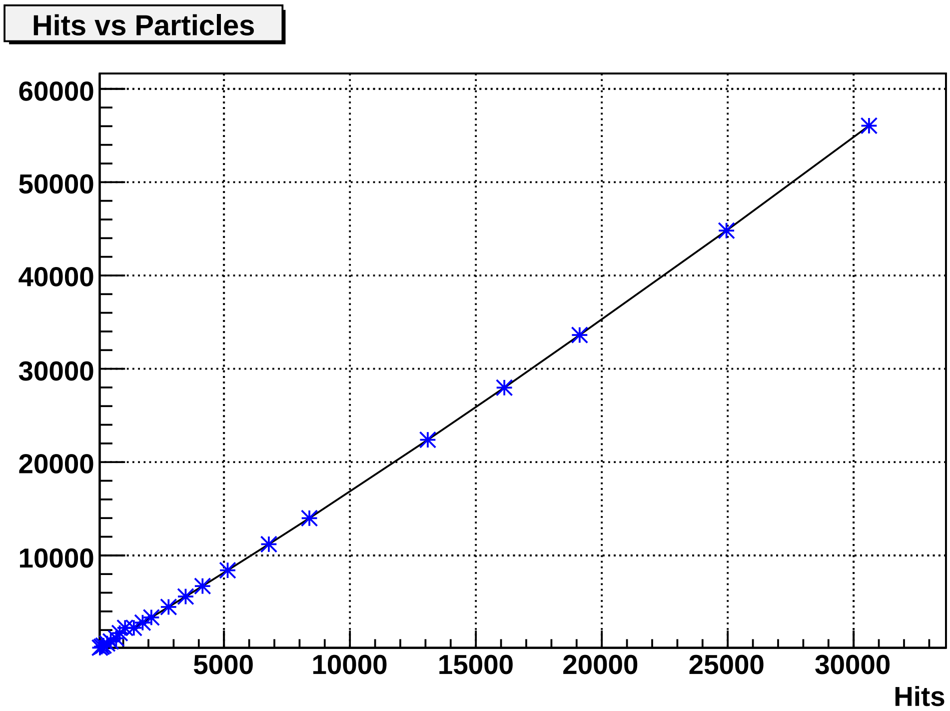


Figure 10: Hits vs Particles. 100×100 μm Pixels. Absorber is Rhenium.

Hits vs Particles have a linear dependence. We can see it on the upper plots. There are two reasons of this behavior. The first reason for leakage. The second reason is that one digital hit can have more than one particle.

4.4 Single Hits/All Hits and Multiple Hits/All Hits

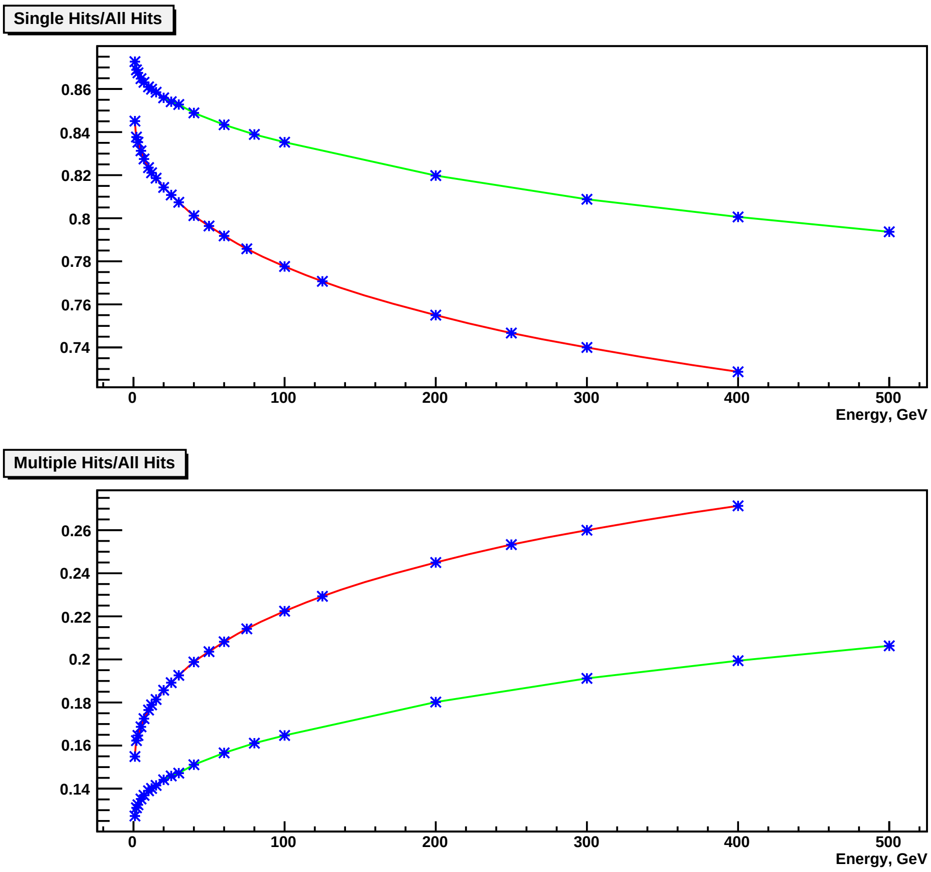


Figure 11: Single Hits/All Hits and Multiple Hits/All Hits. Red one is for 100×100 μm Pixels, green one is for 50×50 μm Pixels. Absorber is Tungsten.

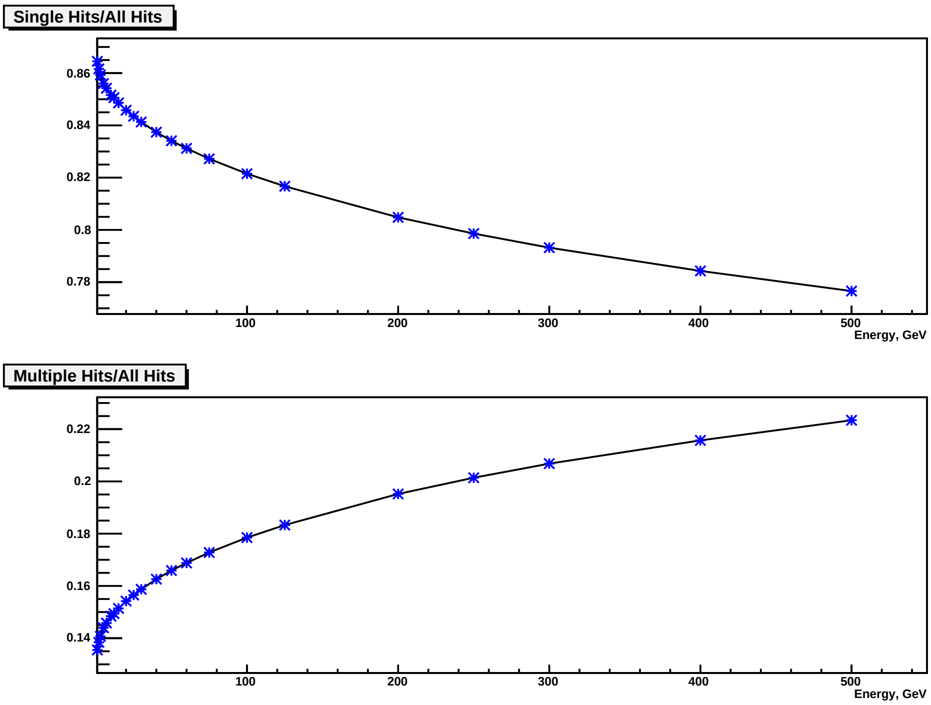


Figure 12: Single Hits/All Hits and Multiple Hits/All Hits for 50×50 μm Pixels. Absorber is Rhenium.

Single hit is equal for one particle going through calorimeter. Multiple hit is a hit which has more than one particle. Here we can notice that part of Single Hits decrease with the Energy rising. For 50×50 μm Pixels the situation is better than for 100×100 μm Pixels. But there are no specific differences between Rhenium and Tungsten.

4.5 Shower Profile

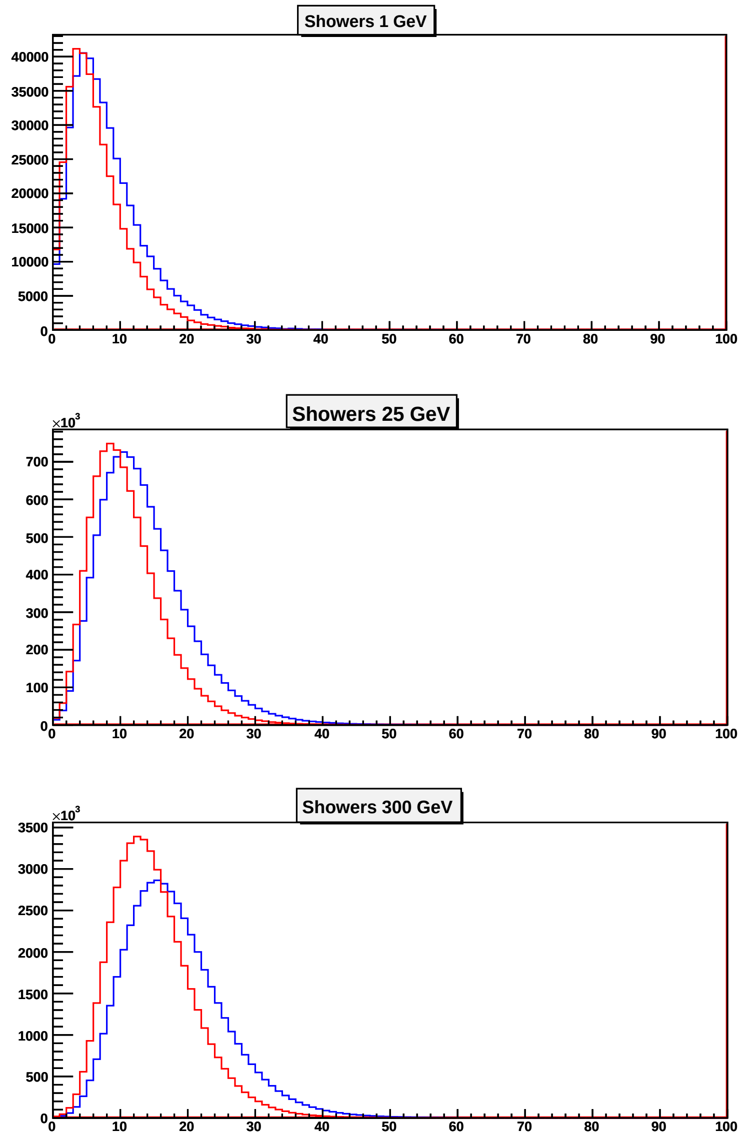


Figure 13: Shower Shapes for 50×50 μm Pixels. Red one is Rhenium, Blue one is Tungsten.

If we compare the Shower Shapes for Re and W we'll see that Re is better absorber than W because Shower Max is lower for Re. Shower in Rhenium is more compact than in Tungsten.

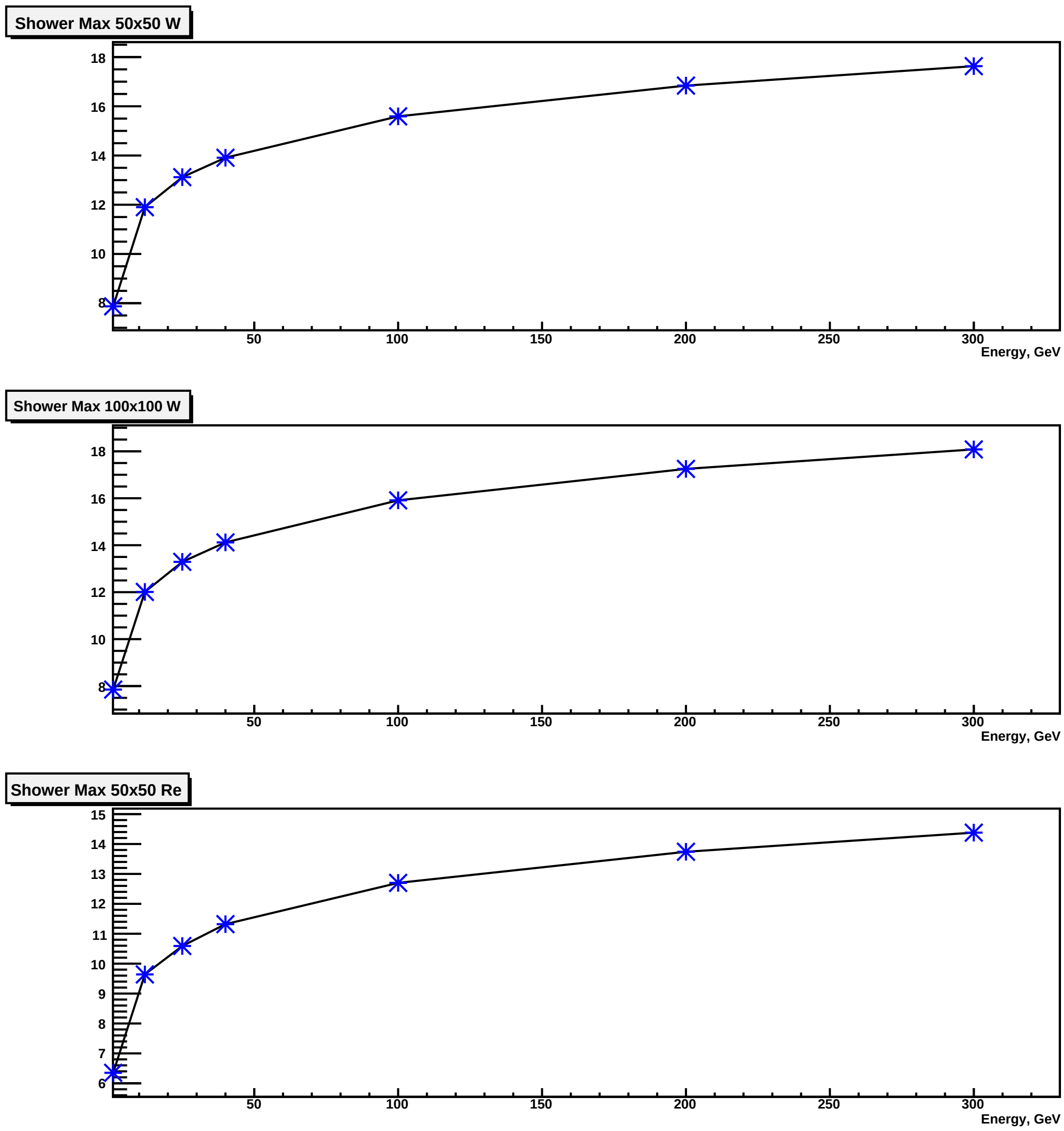


Figure 14: Shifting of the Shower Max with the Energy

Here we can notice that all graphs have the same behavior. It can be concluded that the behavior of the Shower Max does not depend on the material.

4.6 Energy Profile for Hits

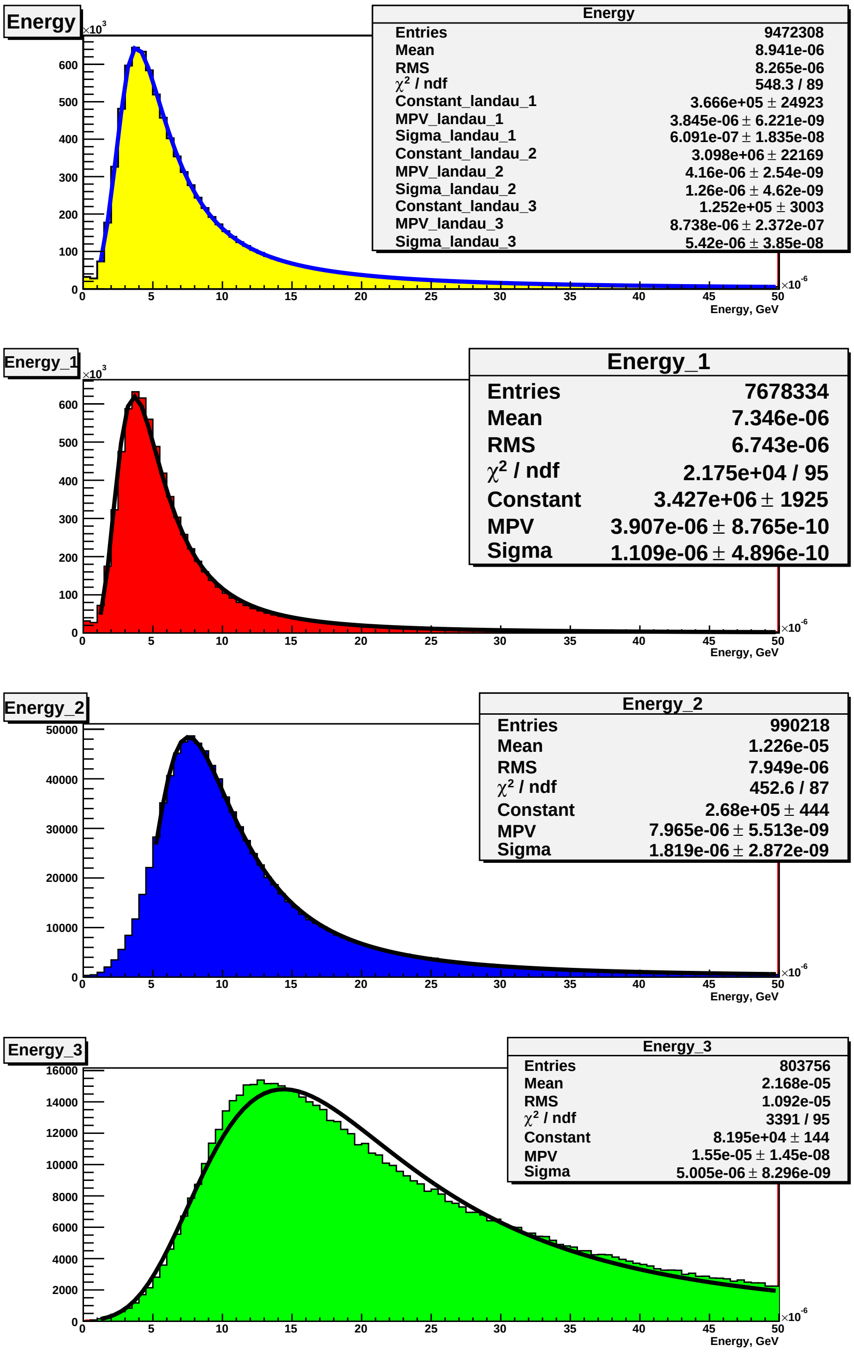


Figure 15: Energy Profile with Landau fit for 100×100 μm Pixels. Absorber is Tungsten.

As you can see the total Energy Profile consists of 3 different profiles. First one consists only of hits when NMCContribution is equal to 1, second, when NMCContribution is equal to 2 and third, when NMCContribution more than 2. I've fitted them with help of Landau fit because it is the nature property of particles. NMCContribution it is condition of how many particles there are per hit.

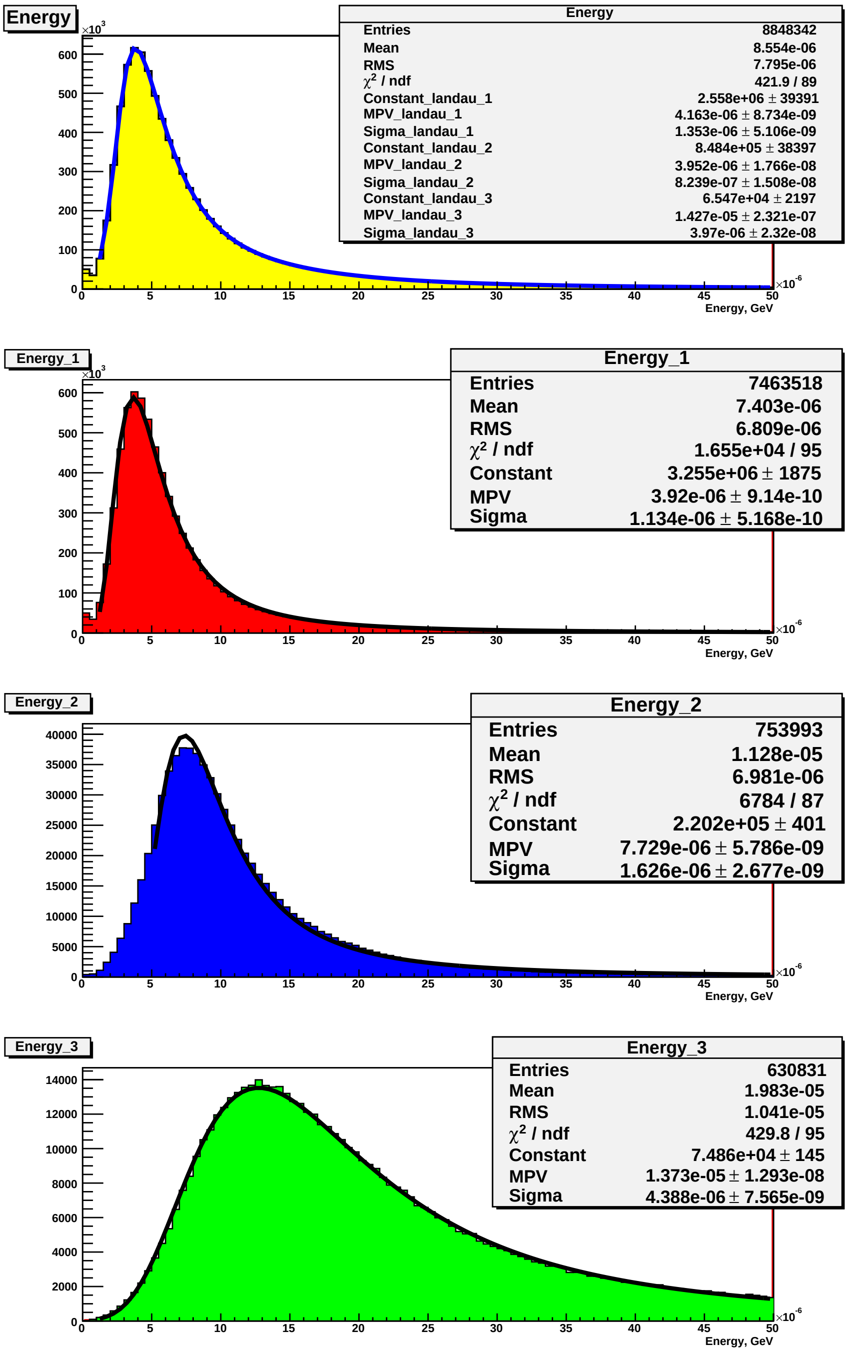


Figure 16: All Energy Profiles with Landau fit for 50×50 μm Pixels. Absorber is Rhenium.

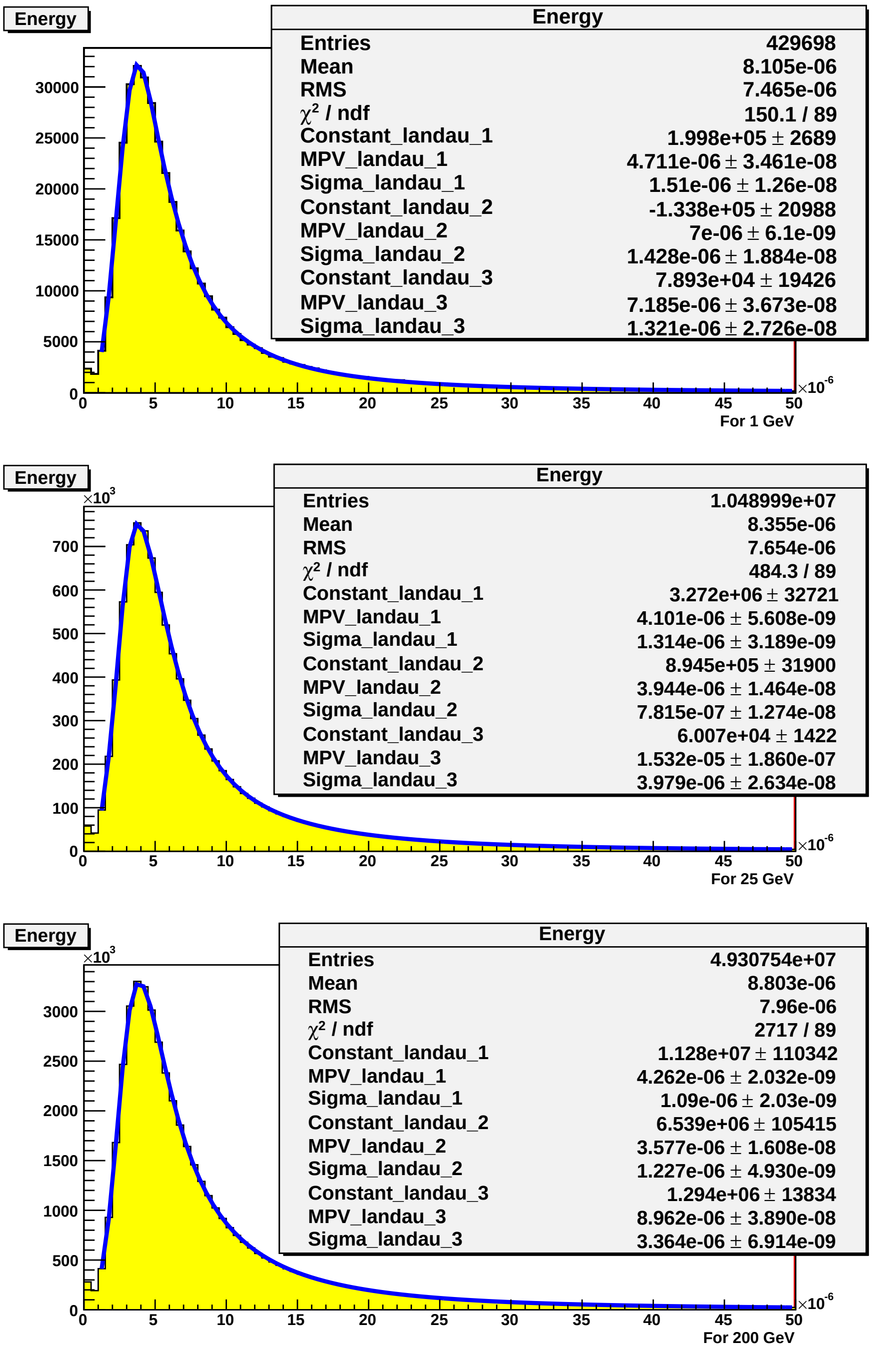


Figure 17: All Energy Profiles with Landau fit for 50×50 μm Pixels. Absorber is Tungsten.

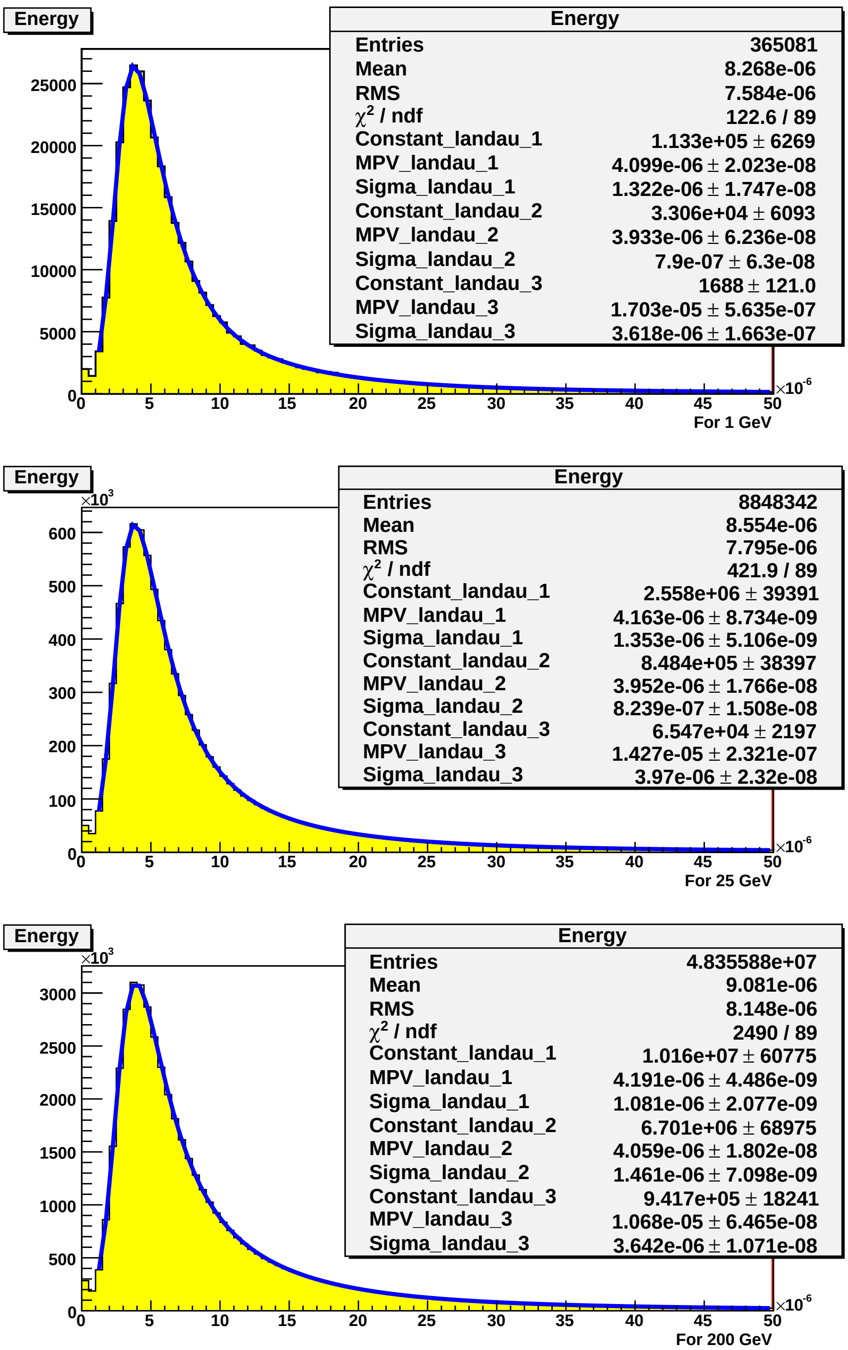


Figure 18: All Energy Profiles with Landau fit for 50×50 μm Pixels. Absorber is Rhenium.

Here we can see that mean of the energy of the particles isn't strongly changes with the incoming energy. This is also true for Tungsten and for Rhenium. And it is quite expected. Dimensions to ensure complete absorption of the energy of the beam is weakly dependent on its energy. Transverse dimensions of the shower are weakly dependent from the energy.

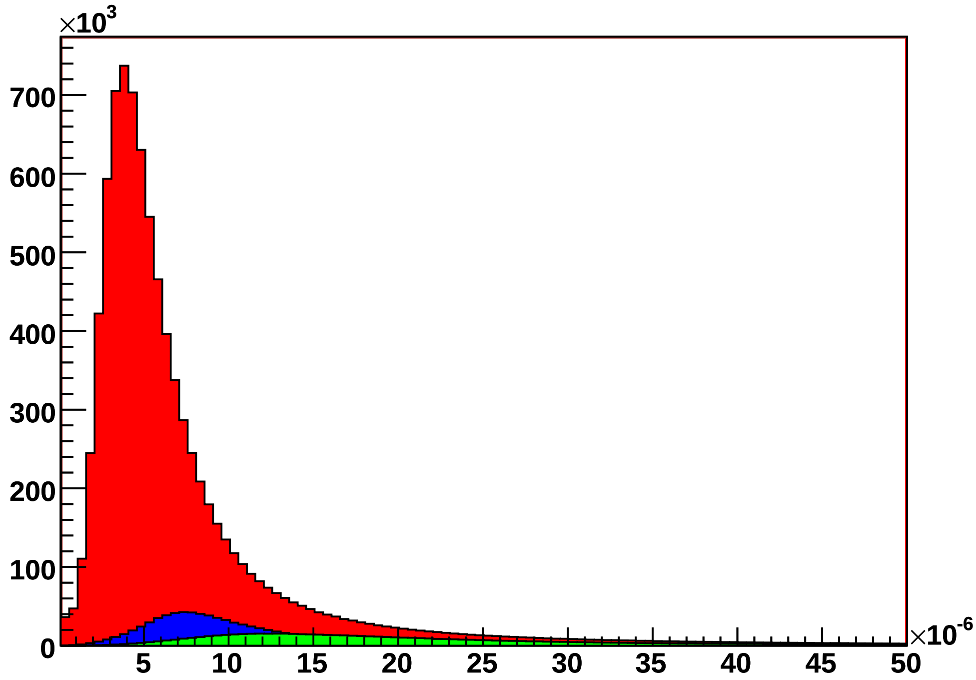


Figure 19: Energy Profiles for 50×50 μm Pixels (incoming energy is 25 GeV) (no stack)

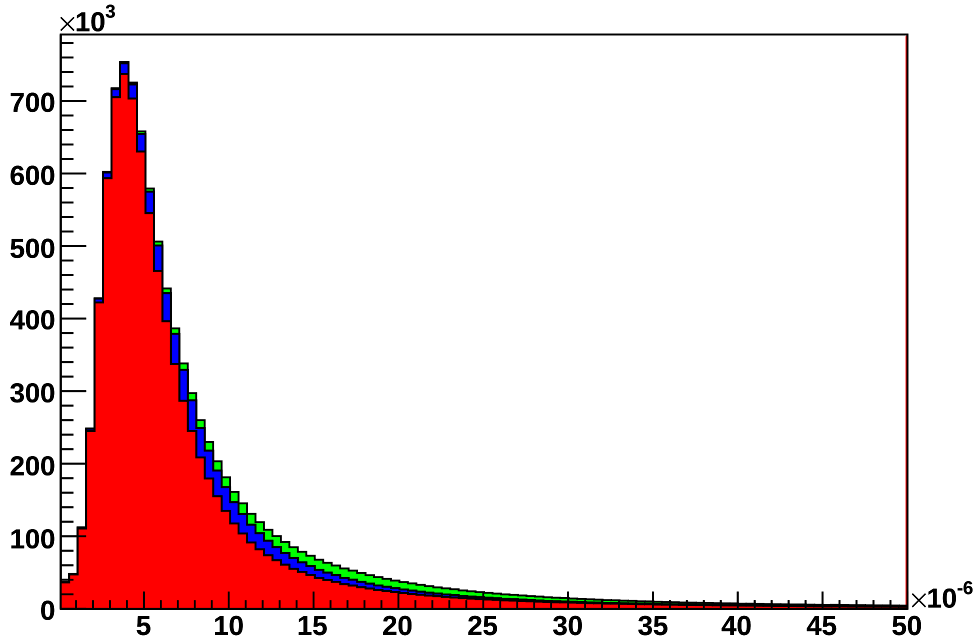


Figure 20: Energy Profiles for 50×50 μm Pixels (incoming energy is 25 GeV) (stack)

5 Acknowledgments

I would like to thank greatly my supervisor Marcel Stanitzki for his support, tolerance, understanding and helpful discussions during my work at DESY.

References

[1] http://root.cern.ch

[2] http://ilcsoft.desy.de/Marlin

[3] http://www2.warwick.ac.uk/fac/sci/physics/staff/.../material/detectors/calorimetry.pdf *Marcel Stanitzki*