Resolution of a Forward Calorimeter prototype

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Abstract

To study the properties of high energy reactions where photons and partons are involved, the ALICE-FoCal collaboration is developing a forward calorimeter to measure photons in electromagnetic showers. These showers occur when a highly energetic photon, electron or positron interacts with matter and it decays via pair production or brehmsstrahlung. We are interested in showers that are not initiated by neutral pion decay but ones with direct photons. The aim of this thesis is to determine the resolution of the forward calorimeter prototype in detecting these 'pure' electromagnetic showers.

Contents

1 Introduction **4**

2 Literature **5**
2.1 Quantum Chromo Dynamics 5
2.2 Electromagnetic Showers 5
2.2.1 Brehmsstrahlung 6
2.2.2 Pair Production 6
2.2.3 Important Quantities 7
2.2.4 Simplified Shower 8
2.3 Electromagnetic Calorimetry 9
2.3.1 Forward Calorimeter (FoCal) 9

3 Description of Forward Calorimeter **10**
3.1 Design 10
3.2 Material 11
3.3 Chips 11
3.4 Available data 11

4 Method **12**
4.1 Up to now 12
4.1.1 Radial Profiles 12
4.1.2 Longitudinal Profiles 12
4.1.3 Calibration factors 13
4.2 Hit Distributions 13
4.2.1 Resolution 13

5 Analysis Results **14**
5.1 Hit Distributions 14
5.2 Relative Sigma values 16

6 Conclusion **19**

7 Discussion **20**

1 Introduction

Particle physics is the part of physics that studies the fundamental particles and fundamental forces. These are better known as the elementary particles, which are the smallest building blocks in the universe, and the fundamental interactions, which cause interactions between these elementary particles. If we consider protons for example, we see that they are not elementary particles. That is because they have a sub-structure, protons are made of multiple elementary particles. In a simplified view a proton consists of three elementary particles, two up-quarks and one down-quark, but in reality it is much more complicated than that.[3]

Especially for higher energies protons and other hadrons, particles that are made out of multiple quarks, need to be described by parton distribution functions. These are functions for every different type of constituent of the hadron describing the fraction of the longitudinal momentum they carry with respect to the total longitudinal momentum. At small fractions of the longitudinal momentum, also called at low-x, the functions are experimentally unconstrained.[3] This means there is still a lot to be learned about these distributions at low-x. The aim of the FoCal detector is to get better insight in the low-x part of these parton distribution functions. In order to achieve this the FoCal detector is designed to very precisely measure direct photons that are produced in electromagnetic showers. By observing the high energy photons we can get more insight in the quark-gluon plasma, the strongly interacting matter which can only exist at extremely high temperatures (and consequently high energies), because photons are continuously produced by strong interactions between quarks and gluons.

In this thesis we will be concerned with energetic photons, electrons and positrons that enter the FoCal prototype. These particles will start electromagnetic showers, which produce more and more of these particles that will all be detected by the FoCal prototype.

2 Literature

2.1 Quantum Chromo Dynamics

Like we said in the introduction the constituents of protons, and in general all hadrons, are not a static number of quarks, but have to be described by parton distribution functions. The quarks are constantly interacting with each other via the strong interaction which is mediated by the gluon particles. Quantum Chromo Dynamics (QCD) is the field of physics that studies this strong interaction. Besides the quarks themselves, the gluons are also continuously interacting with the quarks via the strong interaction. Therefore the constituents of a hadron are continuously interacting and thus popping out of existence and back into existence. The constituents of a proton are always changing and to describe the structure of hadrons we have to use these so-called parton distribution functions. The area that the FoCal detector will be studying is indicated in Figure 1.

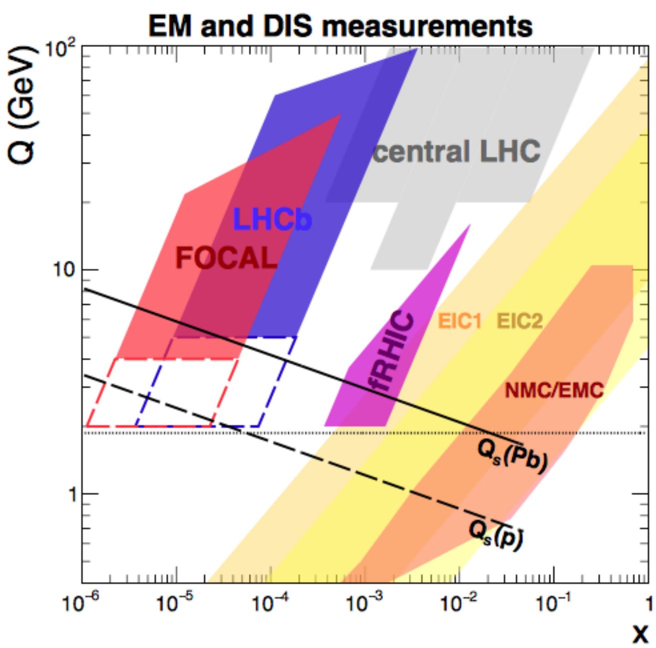

Figure 1: The kinematic reach of the FOCAL detector and several other detectors. Image taken from FOCAL project presentation.[3]

2.2 Electromagnetic Showers

When an energetic photon, electron or positron enters the calorimeter, it will move through the absorber material, in our case Tungsten, interact with it and therefore slow down, resulting in the particle losing some of its energy.

We are measuring highly energetic particles and at these energies energy-loss is predominantly caused by the following two processes, brehmsstrahlung and pair production.

2.2.1 Brehmsstrahlung

Charged particles, in our case electrons and positrons, enter the absorber, so consequently they will collide with the absorber material. This happens through radiative collisions[4], especially with the electric fields of the nuclei. Because of the interaction with the electric field of the nuclei, the particle will accelerate and decelerate. In doing so, the particle will radiate photons which carry energy and this is how the particle itself loses energy. A schematic view of this process is given in Figure 2.

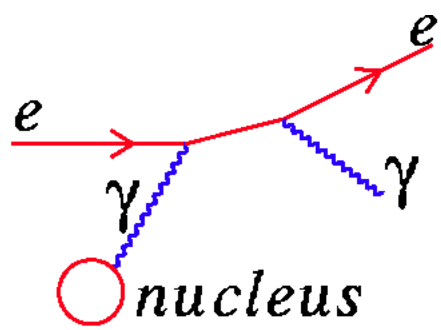

Figure 2: Brehmsstrahlung.

2.2.2 Pair Production

Pair production is the process where an energetic photon decays into an electron and a positron. In free space this process would need two incoming photons in order to satisfy energy conservation. But in our case the photon is in vicinity of a nucleus, from the absorber material, which increases the total energy of the incoming particles, making pair production possible. Thus we can have pair production from a single photon as illustrated in Figure 3. Pair prodcution from two photons is seen in Figure 4.

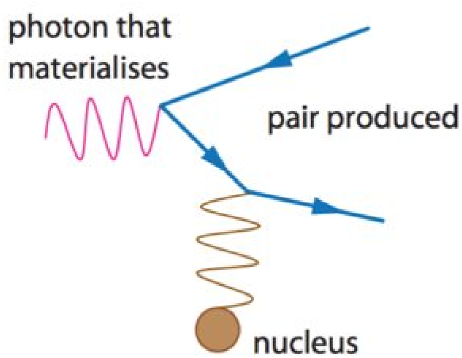

Figure 3: Pair production from one photon in the vicinity of a nucleus.

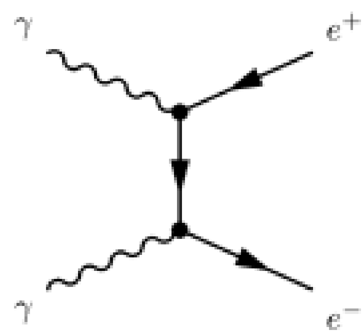

Figure 4: Pair production from two photons.

2.2.3 Important Quantities

With these processes some very important quantities introduce themselves. Evidently it is important to know when and how often these processes occur. This is impossible to know exactly, because the interactions of the particles with matter are poisson-distributed, so they happen at somewhat random times, and particles can scatter in very many angles. Therefore electromagnetic showers will be very chaotic, but there is a very well-defined structure to them, because we measure high energy particles, so resulting particles will mainly go in the direction of the incoming particles. Important quantities that desrcibe this structare are the Molière radius and the radiation length. These depend on the material the particle is moving through.
The Molière radius is a measure for the spread of the shower in the transverse direction of the incoming particle. It is important that this quantity is low in order to get a rather narrow shower. The narrower the shower the smaller our

detection area has to be. Therefore it is useful to choose a material with a low Molière radius in order to keep the detector small for financial and practical reasons.
The radiation length is for electrons/positrons the average distance it travels losing $1/e$ of its energy, for a photon it is 7/9 of its mean free path.[1]

2.2.4 Simplified Shower

To understand how a electromagnetic shower would evolve in a detector it is good to look at a simplified 2D view of electromagnetic showers. Following the restrictions mentioned in an article about electromagnetic cascades, in order to get a simple model of this process.[5] These restrictions say that the shower starts with a single incoming particle, with an energy much higher than a critical energy, below which ionization is the dominant energy-loss process. Furthermore particles with an energy below this critical energy will not radiate anymore and lose its extra energy via collisions. And the last restriction is that the particles will radiate once every radiation length. According to these restrictions the resulting process would look like Figure 5, with one decay every time step for t=0, t=1 etc. In reality a shower will look much more complicated and diverse without these restrictions. A somewhat more realistic, but still a very simple example, is shown in figure 6.

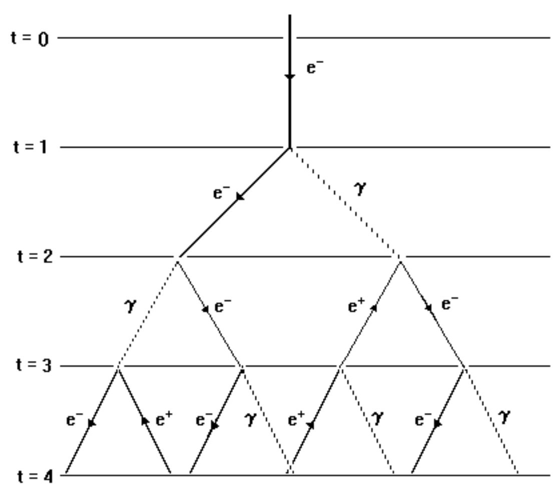

Figure 5: Electromagnetic shower following given restrictions.

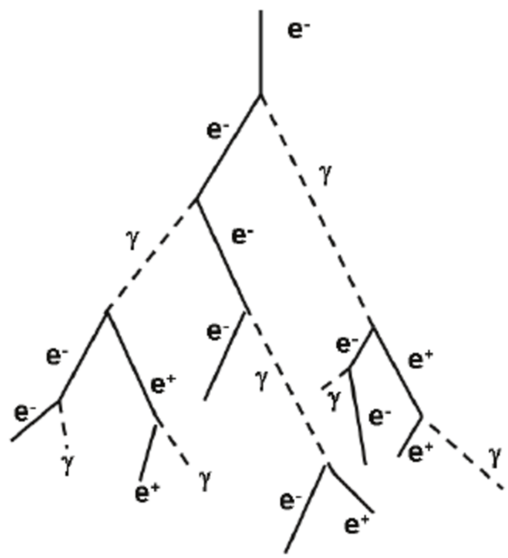

Figure 6: Somewhat more realistic electromagnetic shower.

2.3 Electromagnetic Calorimetry

Electromagnetic calorimeters are detectors that measure the energy of passing particles. The FoCal prototype we are using is a forward calorimeter that doesn't measure the energy deposited, but rather whether a pixel is excited or not by a passing photon.

2.3.1 Forward Calorimeter (FoCal)

To measure the electromagnetic showers we will be studying a forward calorimeter has been developed, the FoCal prototype. Its called a forward calorimeter, because it measures particles at very low scattering angles, so mainly in the forward direction, as seen from the incoming particle. It is a hybrid sampling electromagnetic calorimeter, it is made of two alternating layers, absorbing layers and detection layers. FOCAL has high granularity which is needed because we don't measure energy but we measure hits. Therefore we have to be able to distinguish two different showers that are close to each other. To be able to detect this high granularity is needed.

3 Description of Forward Calorimeter

In developing the forward calorimeter the aim is to achieve high granularity of the detection sensors and fast sampling rates to minimize the time data gets processed from detection to eventual storage. The high granularity is needed to get a high spatial resolution of the electromagnetic showers to precisely measure the position of incoming photons and to be able to distinguish between two different showers that are very close to each other. Fast sampling is also important, because a shorter trigger time will deliver better quality data. If the sampling time between triggers is too large you could for example get the data of two showers together in one trigger. Therefore these concepts are vital in designing the FoCal detector and help with the main challenge of the FoCal detector, which is studying the difference between electromagnetic showers and pion decays.[3]

3.1 Design

The FoCal detector is a hybrid sampling detector, it consists of layers made from two different materials, in this case Tungsten and Silicon. A sideways picture can be seen in Figure 7, here the detector is facing downward. Tungsten acts as the absorber, it is used to decrease the energy of the incoming particles, it will absorb the particles or slow them down. Silicon is used as the detection material, it detects whether a particle passes through the detector. The FOCAL detector consists of 24 detection layers. Every layer has 4 chips, so the detector has 96 chips in total. The layers are 4 mm in width, representing 0.97 radiation lengths, but between layers 21 and 22 a piece of Tungsten is placed that is 6.7 radiation lengths long.[1]

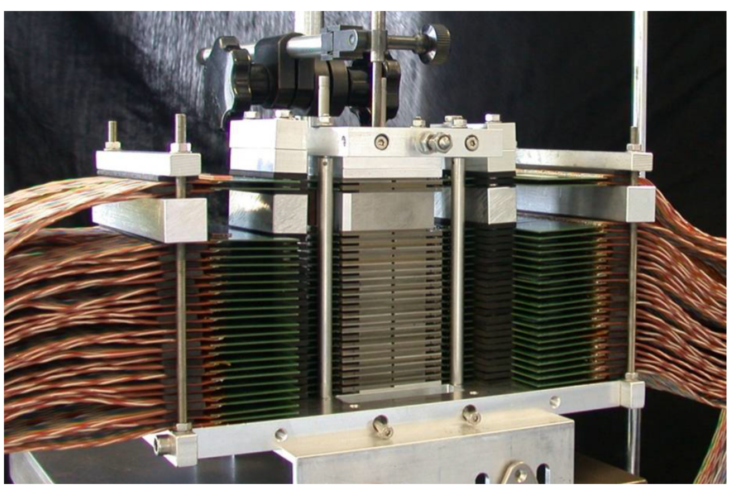

Figure 7: A sideways view of the FoCal prototype, the actual detector is the middle part.

3.2 Material

In the literature section about electromagnetic showers we introduced the notion of the Molière radius and the radiation length. With regard to these quantities Tungsten is chosen as the absorber material, because it has a very short radiation length and a very small Molière radius compared to other commonly used materials for electromagnetic calorimeters.[1] On top of that Tungsten has a good thermal conductivity, so it will disperse the heat generated by all the interactions, and as a consequence cooling elements are not needed to be added to the detector.[1] This all will keep the size of the detector reasonable.

3.3 Chips

The detection chips that are used for the construction of the FoCal prototype, the PHASE2/MIMOSA23 chips, are Monolithic Active Pixel Sensors or MAPS in short.[2] MAPS are high granularity detectors, they have a high precision in detecting the position of passing particles. The MIMOSA chip consists of 640 pixels by 640 pixels. The active detection area is 19.52 mm by 19.52 mm.[1] Therefore a full layer, 2 by 2 chips, is 39.04 mm by 39.04 mm in size. The largest distance between two points on the detector is one of the two diagonals across the square surface. This distance is approximately $\sqrt{39^2 + 39^2} \approx 55$ mm, so our maximum search radius is 55 cm, if we want to make sure we won't miss a single hit that is detected by the detector.

3.4 Available data

The data that we will be using for our data analysis is data taken from the Super Proton Synchotron (SPS), which is located at CERN. [8]. The data gathered here is data for electrons with energies of 30, 50, 100 and 244 GeV. There is also data available from the Deutsches Elektronen-SYnchrotron (DESY), but this data is for electrons with energies of 2, 3, 4 and 5.4 GeV. We are far more interested in the electrons with much higher energies, so we will be focusing our analysis on the data gathered at SPS.

4 Method

The data analysis that we need to do for our research will be done with the ROOT software. ROOT is a data analysis framework developed by CERN, that is primarily written in the programming language C++.[7] We will use the SPS data in order to look at the amount of hits measured by the detector every trigger.

4.1 Up to now

Many people have developed, edited and added onto the analysis code for the data taken by the FoCal detector. The last addition to the code is the part that calculates the calibration factors of the chips in order to generate calibrated radial profiles and calibrated longitudinal profiles for the detector. We will make use of these calibration factors in generating the hit distributions.
Firstly the rough shower centre will be determined. Then for every layer quantities like the amount of hits, the amount of noise and the amount of working pixels will be determined and stored in files. These amounts are determined for many rings around the shower centre. The first ring is a circle around the shower centre with a radius of 0.1 mm. The next ring will be the area of the circle with a radius of 0.2 mm surrounding that inner circle. The first twenty rings are each time 0.1 mm outward of the previous rings making up a 2 mm radius circle. The remainder of the steps are 106 rings that are each time 0.5 mm outward of the previous ring. This is done to get a detailed look at what happens close to the shower centre, because the differences here are much more significant than in the tail of the distribution. All these rings together make up a searching radius of 55 mm, this is the length of the diagonal across the chips of one layer. This way every hit measured by the detector gets used and not a single hit is thrown away for the analysis.

4.1.1 Radial Profiles

The radial profiles are generated by calculating the density of hits for every step/ring. This density is calculated by dividing the amount of hits over the amount of working pixels and this density also gets converted in conventional units of measurement. That is we will get the amount of hits per mm^2 as the density that is plotted in the radial profile. Some translation of the plotting radius will also happen to show the density at a radius that represents a realistic point in the radial distribution.

4.1.2 Longitudinal Profiles

For generating the longitudinal profiles the data of the radial profiles will be retrieved. The densities from these radial profiles get integrated which will give back the amount of hits. Now adding these hits for every layer will give the total hits per layer. This is done for every layer and that way the longitudinal profiles are obtained, the amount of hits against the layer. But for the last three layers, these values will be shifted backwards, because of the thicker piece of Tungsten between layer 21 and 22.

4.1.3 Calibration factors

The longitudinal profiles will be fitted to the ideal gamma function that it should follow. The calibration factors are then calculated by dividing the value of the given chip divided by the fitted value of that chip. That way the sensitivity of the chips is calculated and with these factors the radial profiles and longitudinal profiles get generated again, but now with the calibrated amount of hits. This way we eventually get the calibrated longitudinal profiles.

4.2 Hit Distributions

In order to generate the hit distributions we basically have to count the amount of hits per trigger. Because the sensitivity of the chips is different everywhere we have to make use of the calibration factors to get the calibrated amount of hits. In order to compensate for dead areas in the chips, where the pixels are not working, we have to extrapolate the amount of hits for these areas. That way we get a rather accurate approximation of the amount of hits that did not get measured in the dead pixels and these will now be added to the total by extrapolation. Because we are working with small rings errors in these extrapolations will cancel out for the most part and the extrapolations therefore give a realistic amount of hits. The extrapolation is done by multiplying the calibrated amount of hits by the total amount of pixels of that given area divided by the amount of working pixels of that given area. This amount needs to be summed over all layers, and so we will get the following sum

$$\sum_{layers} N_{hits,calibrated} * \frac{N_{p,all}}{N_{p,working}} \tag{1}$$

for the total hits of one trigger. This sum has to be calculated for every single trigger. Then we will get the hit distribution by plotting the occurence of the amount of hits against the amount of hits.

4.2.1 Resolution

The resolution is the spread in the distribution of the amount of hits. So by calculating the hit distributions we can determine the width (or sigma) of the distribution. The relative width, the sigma value of the distribution divided by the energy, is a measure for the resolution of the detector.

5 Analysis Results

For our results we used the data taken from SPS. In our analysis we have taken every good run that was available from the SPS data. Following the method for generating the calibrated longitudinal profiles, I used the first step of this code to generate files with the amount of hits, noise and working pixels etc. for every ring around the shower centre stored in them. In the appendices you will find the radial profiles and longitudinal profiles generated with this code together with the calibration factors. The calibration factors that I have generated following this code is added in Figure 15 as an appendix.

5.1 Hit Distributions

Executing my part of the code, following the method as described earlier, resulted in the following hit distribution. The hit distributions for the energies 30, 50, 100 and 244 GeV can be seen respectively in Figures ref-ref, and together in Figure ref.

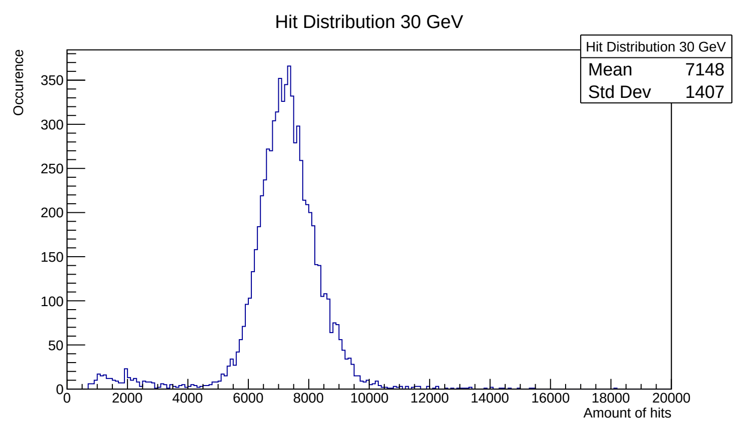

Figure 8: 30

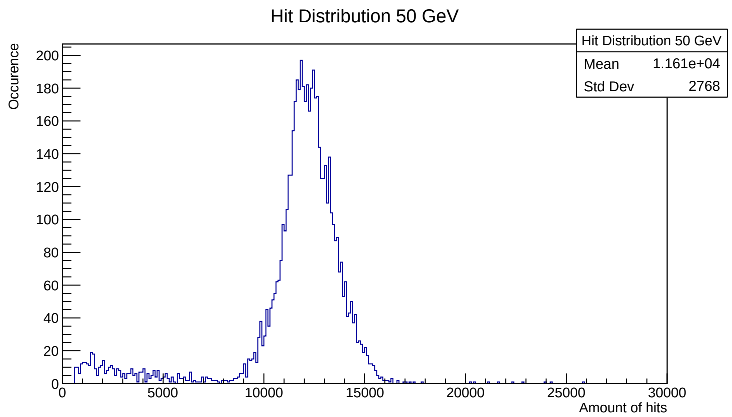

Figure 9: 50

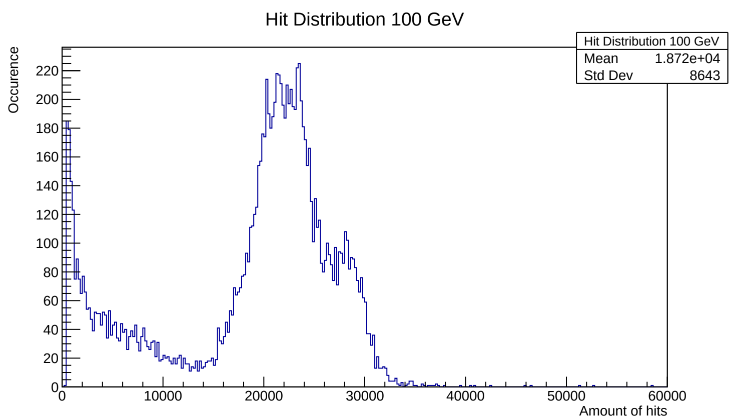

Figure 10: 100

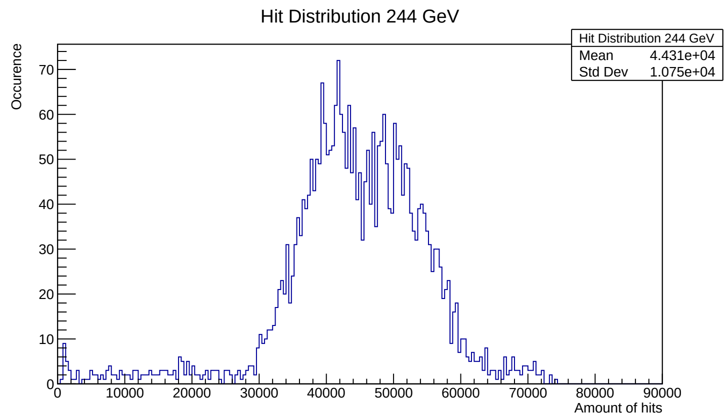

Figure 11: 244

In Figure 12 I have plotted all four distributions together. Here you can clearly see that the distributions get wider if the energy gets higher. The height of the distribution is not of importance, because the values are closer together for lower energies the peak will be higher for these energies. But the height also depends on the amount of data which is available for the given energy. Overall the distributions look very similar. The higher the energy the more the distributions seems stretched out.

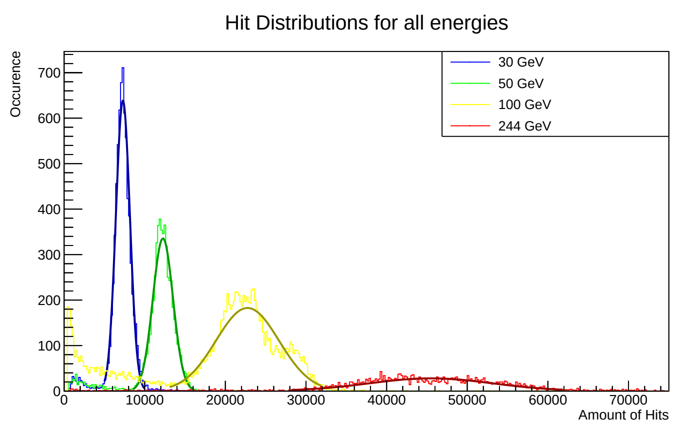

Figure 12: allemaal

5.2 Relative Sigma values

From the hit distributions we can now get the sigma value and derive the resolution of the detector from this. The values for the resolution, the sigma values of the distribution divided by the energy, are plotted against the energies in

Figure 13.[1] Here the red line is a fitted straight line through these four points. This plot is on a logarithmic scale in both directions, so the line doesn't seem straight because of that. We see that the values follow the line rather good, but at 100 GeV the value is a little high. The actual values are 28.9559, 25.0457, 39.1047 and 31.554 for respectively 30, 50, 100 and 244 GeV.

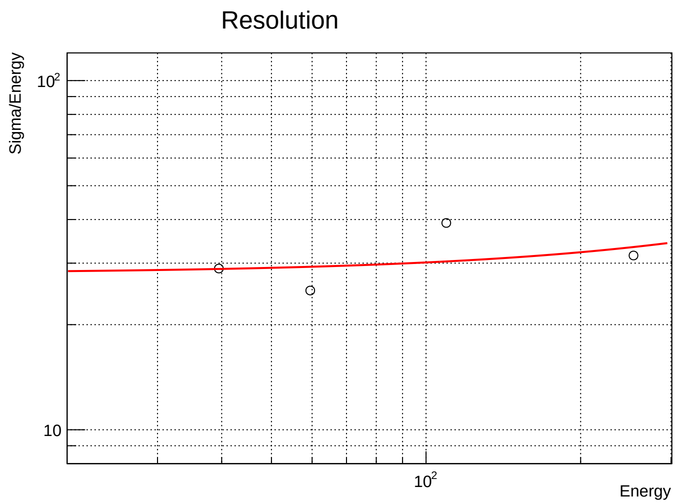

Figure 13: Energies are in GeV.

It is therefore useful to look at the ratio of these values compared to the fitted value, these can be found in Figure 14.[2] And as we suspected the ratio for the data for 100 GeV diverges the most from the value of 1. Nevertheless the other values are not more than 15 percent away from each other, which is nice to see.

[1]The data points are shifted a little to the right, they have to be at the points 30, 50, 100 and 244 GeV on the x-coordinate.

[2]Here the data points are shifted to the right as well.

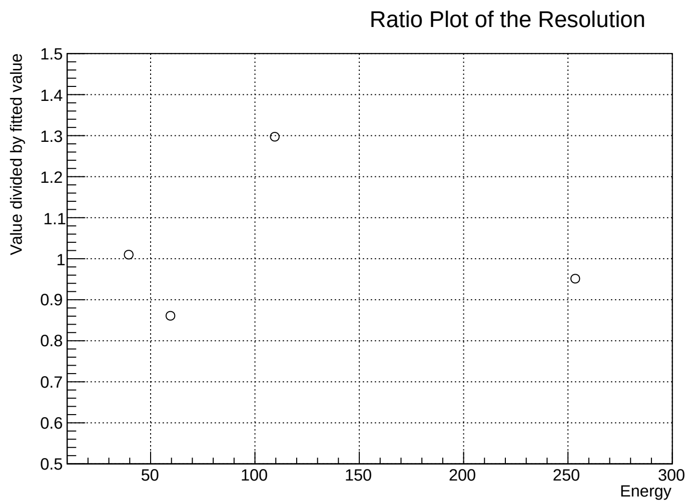

Figure 14: Ratio Plot of the Resolution. Here the relative sigma value of the distribution is plotted against the energy. Energies are in GeV.

6 Conclusion

The results we got for the hit distributions follow the distribution pattern that we expected. These distributions are gaussian distributed and the mean of the distribution shifts forward with higher energies. The width of the distribution also increases, but this is expected since the relative width stays more or less the same.
At the higher energies it is clearly visible that there is a dip in the middle of the peak. This is something that should not happen as we expect smooth distributions. The cause of this is unknown to me and I will have to look into this further as I haven't found an explanantion for this phenomenon yet.
Furthermore we see that that the distribution for 100 GeV has a tail at the start. This tail is caused by data of pion decays and should therefore not be seen here as we excluded the data from pion decays. These tails showed themselves at first at all energies, but as we can see these tails have disappeared almost completely in the distributions for the other energies. This lets us see that we have taken the right approach, but along the way some wrong data has been used for the 100 GeV data.
The relative sigma values are very consistent with each other, only the value for 100 GeV is a little deviant, what means that overall the hit distributions represent what really happens very well.
Thus the resolution of the detector is good, but it could be a lot better seeing that the distributions are very wide. In reality the resolution is better than we have seen now, because there are still many things to be improved in the method we used in determining the resolution.

7 Discussion

In this thesis we aimed to determine the resolution of the FoCal prototype. This is determined with the hit distributions for the different energies. As seen in the results we get distributions which we expected, gaussian distributed with a sigma value that grows with the energy. The relative sigma values are relatively close together, varying up to about 10 percent of the mean (except for 100 GeV). But the hit distributions are rather wide. A detector with more active areas could be the solution to get more correct estimates of the amount of hits is needed to solve this. A new forward calorimeter is already being developed, so improvements in the quality of the data are in progress.

Besides that improvements in the code have to be made. I have already stumbled upon some problems that need to be reconsidered. Chips that don't work at all, where all pixels are dead, now contribute nothing and there is still no correction for this. In our method this problem also arises for rings with no working pixels. A possible way of fixing this is by interpolating between layers. Furthermore the code has to be cleaned up and get more intuitive names to work with to make problem solving a whole lot easier.

Documentation of the code is also very important to do after this. Then others can work more easily with the code and it can be applied to the analysis of the new detector.

So improving the code and using the new detector not only the resolution will be a lot better, but capturing the electromagnetic showers will become much more accurate which hopefully leads to more insight in the behavior of highly energetic photons.

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Appendices

Appendix Calibration Factors

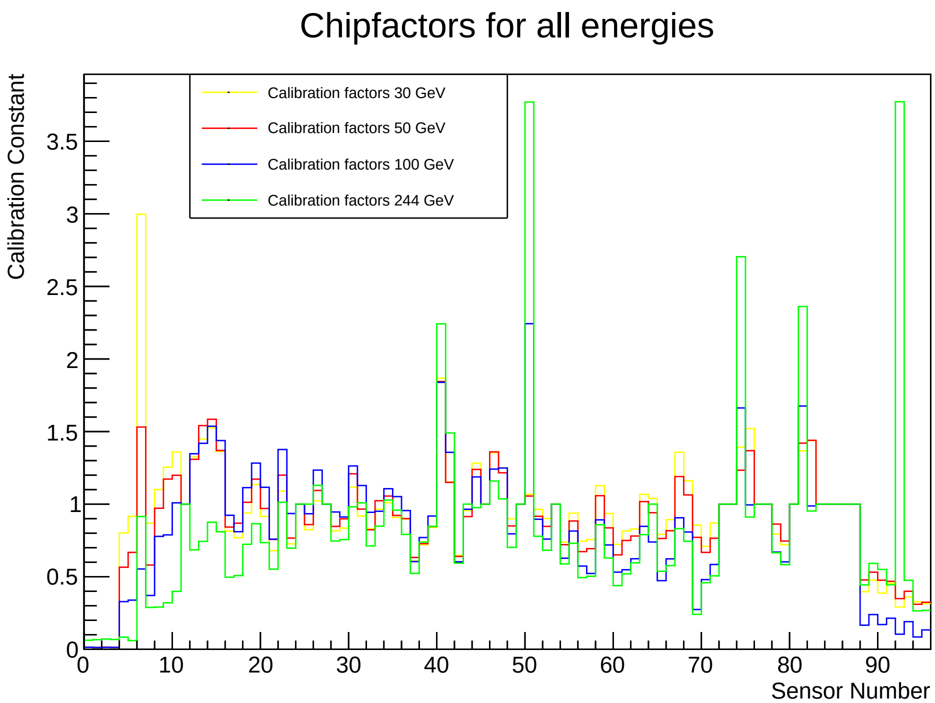

Figure 15: Calibration factors.