PCAL + AEROGEL Calibration in the ZEUS Detector

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Abstract

A new calibration of the photon calorimeter and AEROGEL Cherenkov detectors in the luminosity system in ZEUS is performed. An introduction to the HERA accelerator and the ZEUS detector is given and the luminosity system is described in details. The calibration technique is explained and a series of methods to select pure Bethe-Heitler events is presented.

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1. Introduction

1.1. The HERA accelerator

The Hadron-Elektron-Ring-Anlage HERA was a lepton-proton collider at the Deutsche Elektronen Synchrotron DESY in Hamburg, operating from October 19, 1991, to June 30, 2007. The machine was operated with a nominal energy of the electron (positron) of 27.5 GeV and of the protons of 920 GeV leading to a center of mass energy of $\approx$318 GeV. Four experiments were installed at the four interaction points of the HERA ring, in two of them (ZEUS and H1) the protons were colliding head-on with the electrons. The protons and electrons were travelling in bunches separated by about 29 m (corresponding to 96 ns). Some of the bunches (called pilot bunches) had no corresponding bunch in the other beam, or were completely empty, and were used for background and pedestals studies. HERA underwent a major luminosity upgrade during a shut-down which began in 2000.

In the last months of its physics program, HERA was operated at different center of mass energies. The proton energy was decreased to 460 GeV from March 26 to June 1, 2007, referred to as low energy run (LER) period, and to 575 GeV from June 1 to June 30, 2007, referred to as medium energy run (MER) period. The time span before March 26, 2007, during which HERA was run with a proton energy of 920 GeV, is referred to as high energy run (HER) period.

1.2. The Luminosity measurement

The ZEUS experiment was a multipurpose detector designed to measure the products of the electron-proton collisions at HERA. It surrounded the interaction region with different detector systems to determine relevant quantities of the reactions, like for instance the exact position of the vertex or the energy and momentum of the produced particles. The central ZEUS detector had a size of 10x10x12 m^3 and a mass of about 3600 tons.

The luminosity is a key quantity to measure cross sections in collider experiments. The ZEUS experiment employed the precisely calculable Bethe-Heitler process, $ep \rightarrow ep\gamma$ (see Fig. 1), to determine the luminosity.

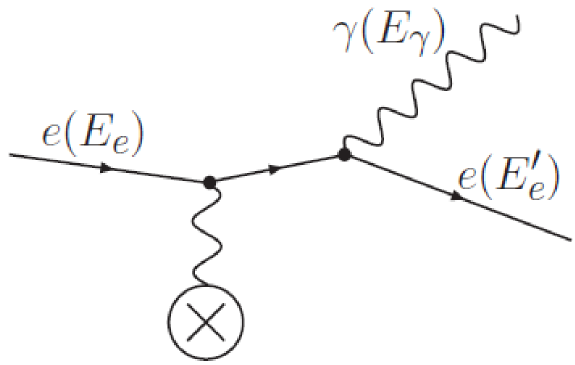

Figure 1 – Feynman diagram of a lowest-order QED Bethe-Heitler process at HERA

2. The Luminosity System

2.1. Photon measurement

The photon and the electron from a Bethe-Heitler process inside the ZEUS detector were generally radiated at very small angles with respect to the direction of the incoming electron. Therefore, both the electron and the photon left the detector through the beampipe in the direction of the electron beam.
The photon, unaffected by magnetic fields, traveled straight down the beampipe and left it through an exit window located 92m behind the nominal interaction point (see Fig. 2). Its energy and position were measured by the photon calorimeter which was installed 105.5 m from the interaction point [1,2].

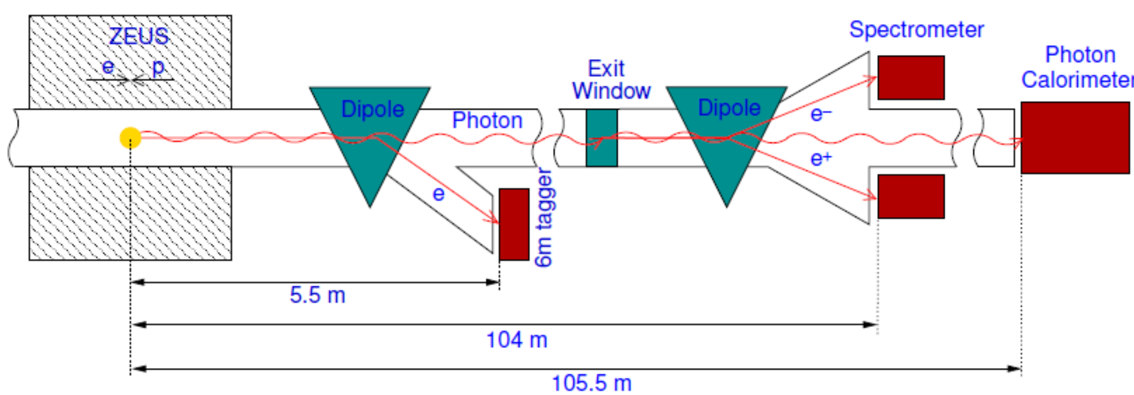

Figure 2 – Schematic view of the ZEUS luminosity system

The photon of the BH was measured by two independent systems, the photon calorimeter (PCAL) and the spectrometer (SPEC).

The photon calorimeter was a lead-scintillator sampling calorimeter with a depth of $24X_0$, read out by two photomultipliers. It was shielded against synchrotron radiation by an active filter system consisting of two carbon absorber in series, each with a depth of $2X_0$ (see Fig. 3). Behind each absorber an AEROGEL Cherenkov detector was installed which was read out by one photomultiplier. These detectors enabled an estimation of the amount of energy absorbed in the filters in front of the calorimeter and therefore provided better resolution of the energy measurement.

The main advantage of the use of the silica AEROGEL as the Cherenkov radiators is that it is completely 'blind' to the synchrotron radiation. This is due to its low refraction index of 1.030 which corresponds to Cherenkov energy threshold for electrons of 1.62 MeV. In case of the ZEUS experiment the synchrotron radiation penetrating the filter has the critical energy of about 140 keV and its spectrum extends up to 1−2 MeV. Therefore, only a small fraction of photons can give rise to a signal via the Compton Effect. On the other hand, the high energy BH photons generate electromagnetic cascades in the filter. The typical energy of the shower particles is about 20 MeV, which is much above the silica AEROGEL Cherenkov threshold. This shows that the interactions of the bremsstrahlung photons in the filter can be easily detected [3].

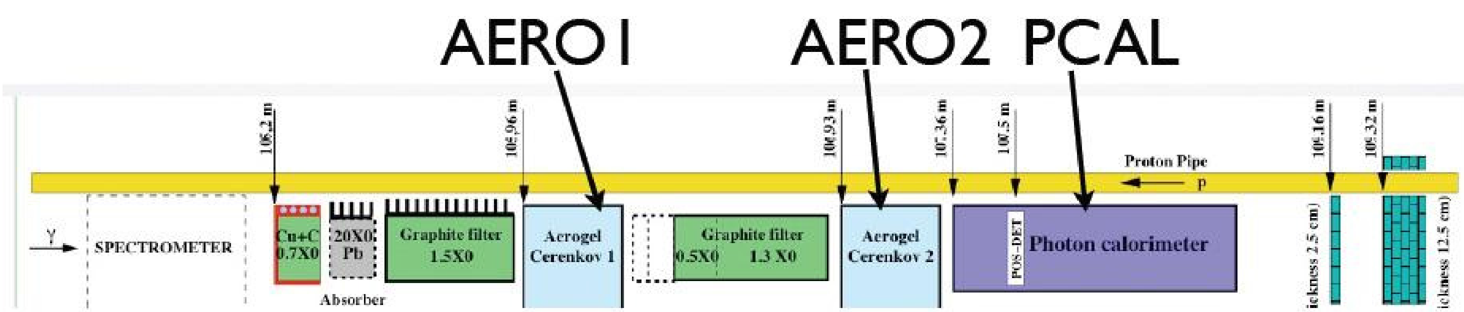

Figure 3 – Schematic view of the PCAL + AEROGEL system

Due to the high cross section of the BH process, more than one Bethe-Heitler process per bunch crossing was expected; pile-up events in which more than one photon hit the calorimeter had to be considered. Contributions from pile-up events to the luminosity measurements were reduced with the installation of the spectrometer in the HERA upgrade in 2000 and by tagging the positron with the 6m Tagger.
The spectrometer system is beyond the scope of this report, therefore we will proceed to explain the 6m Tagger.

2.2. Positron measurement

The so-called six meter tagger (6mT) was a $84 \times 24 \times 100\ \mathrm{mm}^3$ spaghetti type calorimeter that consisted of 70 cells ordered in 5 rows and 14 columns and was located 5.7 m from the interaction point in the backward direction (see Fig. 4). The magnetic field of the HERA magnet in which the 6mT was located, drove the low-angle scattered positrons to the tagger. The bending power of the dipole was such that positrons with energies between 4 – 7 GeV, originating for instance in a BH or photoproduction process, were deflected out of the nominal beam orbit and hit the 6m tagger [1].

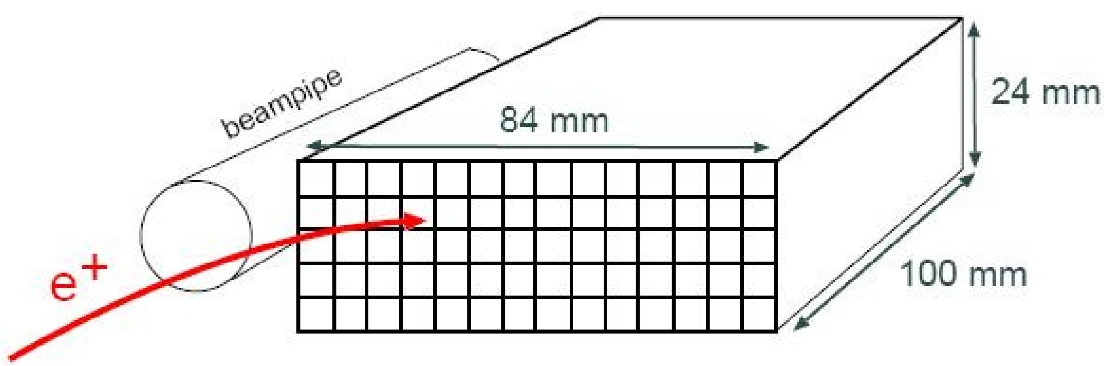

Figure 4 – Schematic drawing of the 6mT

As mentioned before, the 6mT was originally designed as part of the luminosity system (LUMI) for acceptance studies and it is also used for the determination of the total photoproduction cross section [1,4]. In this work it was used for the calibration of the PCAL + AEROGEL system.

3. Calibration process

To this day, the calibration of the calorimeter part of the LUMI system was done only for the PCAL without the AEROGEL detectors. Therefore, as mentioned above, the resolution was compromised due to the two carbon absorbers. Our goal in this work was to improve the energy resolution and redo the calibration using the AEROGEL detectors.

Initially, the calibration of the AEROGEL detectors was planned to be achieved with the PCAL Monte-Carlo. However, we intend to achieve the calibration using data collected by the LUMI system.

The calibration will be performed separately for each run, HER, LER and MER. We will use the following formula for the calibration:

$$E_{\gamma} = aE_{AERO_1} + bE_{AERO_2} + cE_{\gamma}^{\mathrm{scint}} \tag{1}$$

, where E_{γ} is the energy of the photon, E_{AERO_1} and E_{AERO_2} are the ADC values of the AEROGEL detectors, $E_{\gamma}^{\mathrm{scint}}$ is the uncalibrated energy of the PCAL and a, b and c are parameters to be determined from the calibration. E_{γ} will be calculated from the assumption that the energy of the photon and the energy of the positron, must add up to the energy of the beam,

$$E_{\gamma} = E_{\mathrm{beam}} - E_{\mathrm{6mT}} \tag{2}$$

. To determine the calibration constants a, b and c, we use a χ^2 minimization method,

$$\chi^2 = \sum_{n=1}^{N} \frac{(\sum_{j=1}^{3} \alpha_j e_{j,n} - E_n^{\gamma})^2}{\sigma^2_{E_n^{\gamma}}} \quad \rightarrow \quad \frac{\partial \chi^2}{\partial \alpha_i} = 0 \tag{3}$$

, where α_j is the parameters vector, e_j is a vector containing the PCAL and AEROGEL energies and N is the number of events in each period. After differentiating we get,

$$\sum_{j=1}^{3} \alpha_j \sum_{n=1}^{N} \frac{e_{j,n} e_{i,n}}{\sigma^2_{E_n^{\gamma}}} = \sum_{n=1}^{N} \frac{E_n^{\gamma} e_{i,n}}{\sigma^2_{E_n^{\gamma}}} \tag{4}$$

. We can assume that the error on the energy of the photon $\sigma^2_{E_n^{\gamma}}$ does not change throughout the calibration period as we do the calibration for each period separately and therefore eliminate it from equation 4.

We define the following matrix and vector:

$$A_{ij} = \sum_{n=1}^{N} e_{j,n} e_{i,n} \qquad V_i = \sum_{n=1}^{N} E_n^{\gamma} e_{i,n} \tag{5}$$

, and calculate the calibration constants by inverting A_{ij}

$$A_{ij} \alpha_j = V_i \quad \Rightarrow \quad \alpha_j = (A^{-1})_{ij} V_i \tag{6}$$

.

4. Event Selection

For the calibration process we need to select only clean BH events. The selection was aimed primarily at a high purity of the data sample. The efficiency of the selection was not an issue due to the large statistics available for the analysis.

4.1. Bethe- Heitler energy window

As mentioned above, the 6mT accepted positrons only in a certain energy. As a consequence, photon energies were expected to lie in a certain energy range $\boldsymbol{E}_{\gamma}^{\text{BH mean}} - 2\boldsymbol{\sigma} < \boldsymbol{E}_{\gamma} < \boldsymbol{E}_{\gamma}^{\text{BH mean}} + 2\boldsymbol{\sigma}$ and only events with corresponding photon energies were expected (see Fig. 5).

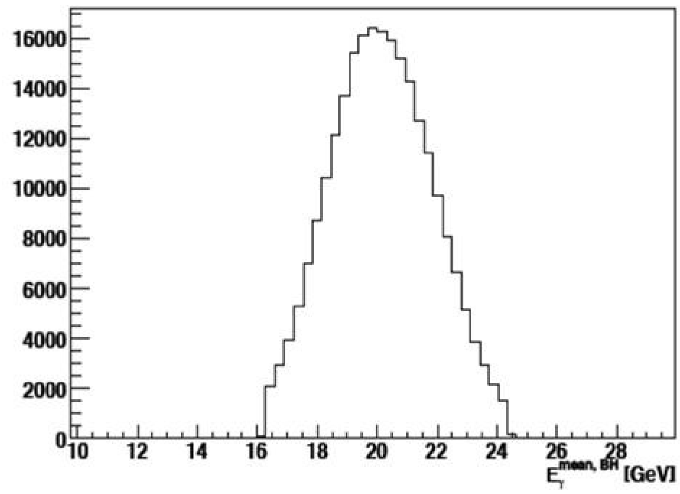

Figure 5 – Photon energy for clean BH events

4.2. AEROGEL Vs. PCAL correlation

Good BH photons, where the photon has energy which lies in the window shown above, should deposit energy in both AEROGEL detectors and in the PCAL. Moreover, we expect the energy deposited in the AEROGEL detector to be correlated with the energy we measure in the PCAL. By drawing the ADC values in each AEROGEL as a function of the uncalibrated energy in PCAL we can clearly see how the distribution of events is divided into events with real photons, depositing energy in both detectors, and events which can only be constructed as noise or background processes (such as synchrotron radiation).

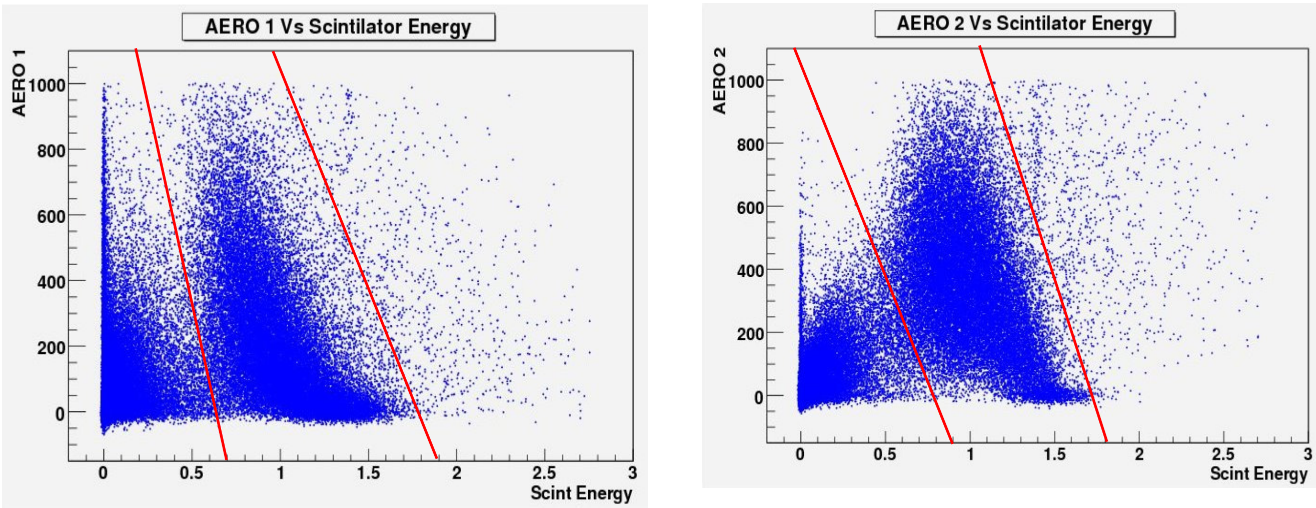

Figure 6 – AEROGEL ADC Vs. PCAL un-calibrated energy

To choose only good BH events for the calibration we reject all events outside the lines shown in Fig. 6. The resulting distributions can be seen in Fig. 7.

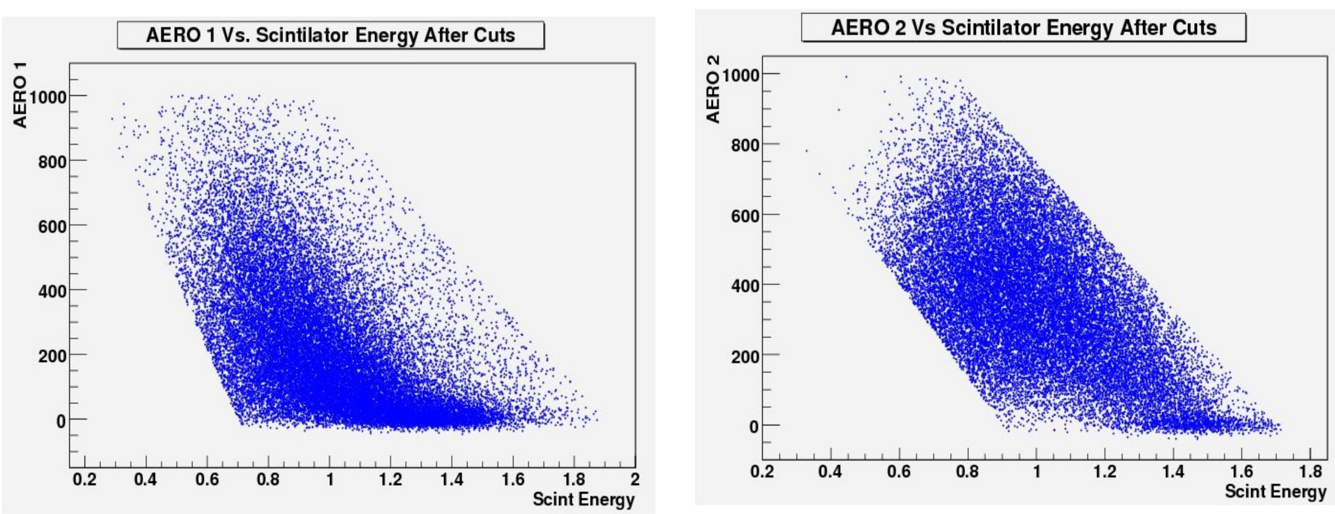

Figure 7 – AEROGEL ADC Vs. PCAL un-calibrated energy after applying cuts

4.3. A good positron in the 6m tagger

Selecting a good BH event requires a series of selection cuts on positron hitting the 6m tagger. Following is a list of cuts applied to the 6mT hits in order to select only those BH positrons whose energy can be reconstruct accurately.

Events having ADC counts corresponding to non-physical energy values were found in the data taken with the 6m tagger. In order to avoid such corrupted events, a cut over the ADC value $(0 \leq \mathrm{ADC} \leq 4095)$ was applied.

Positron hits in the 6mT were required to be in rows 1 and 2 since the 6mT trigger was changed during data taking to include only those two rows (see blue rectangle in Fig. 8).

Previous studies [2] showed that 95% of the energy deposited by a positron hitting the 6mT lies in a 3×3 cell matrix around the hottest cell. The energy used in this calibration process was therefore taken from that matrix (see yellow square in Fig. 8). Thus events where the hottest cell lied in the outer columns and rows were rejected since the shower was not contained in the 6mT and the energy of the positron could not have been accurately reconstructed.

The 6mT had two noisy cells, cells 52 and 54 (see Fig. 8). The energy in these cells was distorted and therefore unusable. To fix the reconstructed energy in events where the 3×3 matrix includes the noisy cells a previously trained neural network was used [5].

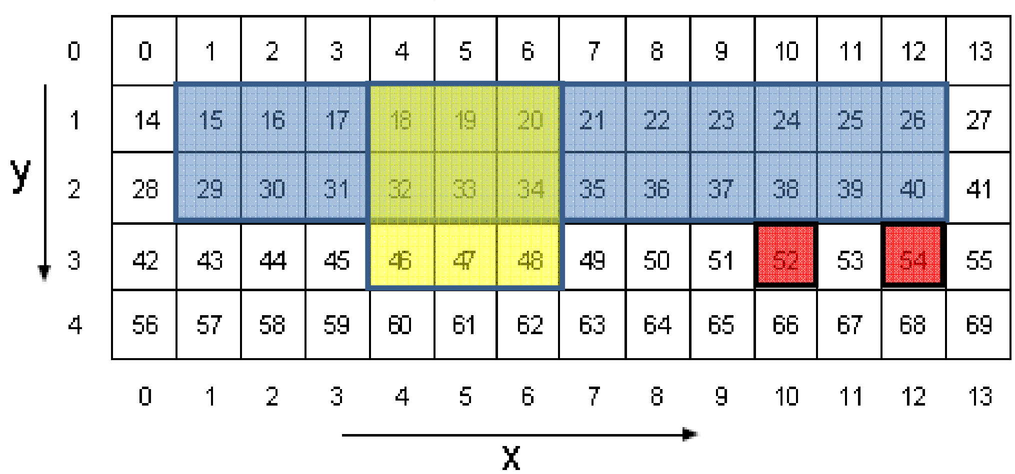

Figure 8 – 6mT layout

The data contained about 2 - 3% pre-showered events. These are events where the positron started the electromagnetic cascade before hitting the tagger and the result is a rather uniform distribution of energy in the tagger. Fig. 9 shows an example of such an event. In order to reject these “splash”, events we apply a cut on the ratio of the 3×3 matrix and the 5×5 matrix around the hottest cell, $\frac{\boldsymbol{E}(3\times3)}{\boldsymbol{E}(5\times5)} \geq 0.65$ [4].

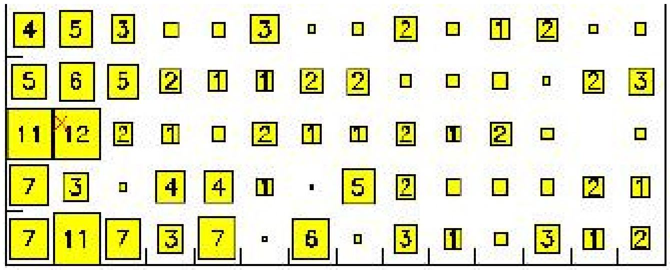

Figure 9 – An example to a “splash” event

As mentioned above, the positron hitting the 6mT is bent by a dipole magnet. As a result, we expect to find a correlation between the energy of the positron and the position it hit in the tagger. We plotted the energy of the positron as a function to its X position and found a very clear band corresponding to BH positrons (see Fig. 8). Therefore, we reject all events which lie outside the band marked by the red lines [1,4].

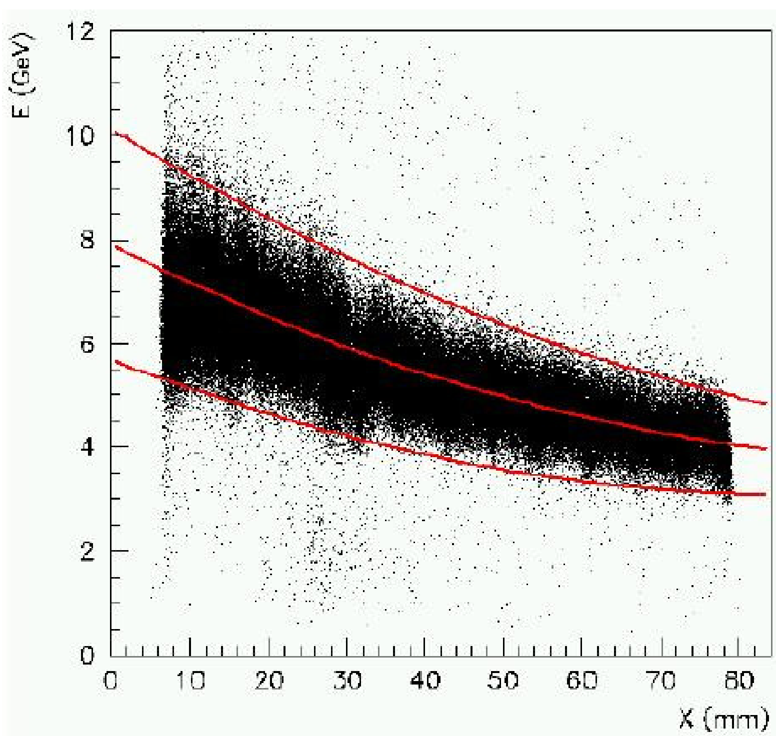

Figure 10 – Energy Vs. X position of positron. The lines correspond to the expected limits of BH events

5. Results and Summary

In Fig. 9 we plot the energy of all the photons in Bethe-Heitler events in the HER period as measured by the PCAL (old calibration) and by the PCAL + AEROGEL detectors (new calibration).

One can clearly see a vast improvement between the two measurements. With the old PCAL energy a lot of events are being overestimated and this results in a non Gaussian energy distribution. The energy distribution after the calibration is the expected symmetric Gaussian shape with better resolution and the right mean.

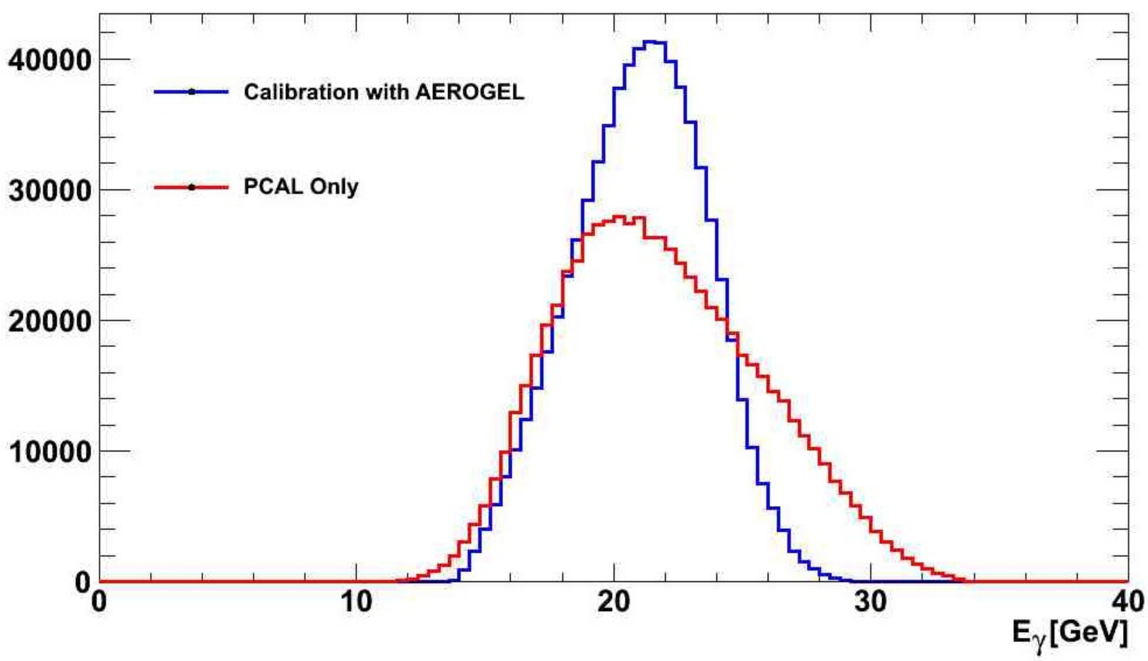

Figure 11 – Photon energy as measured by the PCAL and by the PCAL + AEROGEL

The calibration constants are

$$\begin{aligned} \boldsymbol{a} &= 0.00681085 \\ \boldsymbol{b} &= 0.0101021 \\ \boldsymbol{c} &= 15.7308 \end{aligned} \tag{7}$$

. The ideal way to check the validity of our result is to compare to the much more accurate spectrometer data, but we did not have access to that information. Maybe in the future the check will be made.

Future steps will be to implement this calibration in the Zeus Data Chain and to use it in future analysis, like in the measurement of the total photo-production cross section.

6. References

1. A. Stern – Measurement of the W dependence of $\sigma_{tot}(\gamma p)$ with the ZEUS detector at HERA (2008)
2. M. Schröder – Calibration of the ZEUS 6m tagger (2008)
3. http://www-zeus.desy.de/~figiel/posters/poster_v1.pdf
4. http://www-zeus.desy.de/~schmidke/ZEUS_ONLY/sigtot/sigtot.html
5. O. Gueta – “sigma tot and the 6m-tagger” talk on SFE+QCD work group meetings 2009-08-13, part of an MSc. thesis to be submitted to Tel-Aviv University

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