The MINOS light injection spectra at low light levels

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First Year Report

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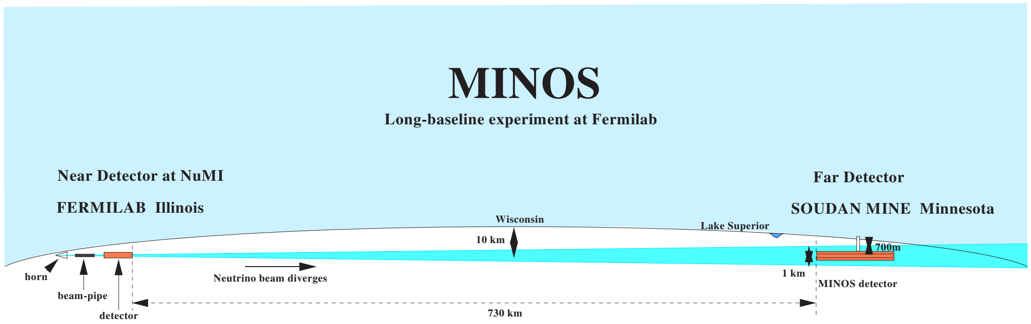

Figure 1: The MINOS experiment.

1 Overview of the MINOS experiment

For some time now there has been tentative, and recently not so tentative, evidence for neutrino oscillations. The MINOS experiment, Main Injector Neutrino Oscillation Search, was designed to give the most concrete evidence yet for the existence or otherwise of neutrino oscillations.

MINOS is a long baseline neutrino oscillation experiment. In brief, a beam of neutrinos is produced in the Main Injector at Fermilab and is aimed towards the Soudan mine in Minnesota some 730 kilometres, see Figure 1. There are two detectors in the beam line, the far detector in the Soudan mine and the near detector on site at Fermilab. Neutrino oscillations can cause changes in the neutrino event rate at the far detector, as extrapolated from measurements taken at the near detector. They can also cause differences in the characteristics of the events at the near and far detectors.

1.1 The Detectors

There are three MINOS detectors in total. The largest of these if the Far Detector in the Soudan mine. There is also the Near Detector at Fermilab which is used in comparison with the far detector. The final detector is the Calibration Detector which is currently in use at CERN. As its name implies the Calibration Detector is used to calibrate the other MINOS detectors.

The Far Detector is a 54 kt magnetised iron calorimeter, with an active detector of scintillator. It consists of eight metre wide octagons of one-inch thick steel planes sandwiching planes of scintillator. There are a total of 486 of these layers, meaning the length of detector is 31m. To increase the granularity, of the detector each scintillator plane is made of 192 strips, each of which is 4cm wide. Both ends of these scintillator strips are coupled, through clear fibres, to photo-multiplier tubes.

The Near Detector is a scaled down version of the Far Detector. The 2 detectors are designed to be as similar as possible to minimise systematic effects in the comparison between them. Due to the differences in flux and neutrino energy spectra, there are some unavoidable differneces between the detectors.

The Calibration Detector is a small scale version of the other detectors. It is discussed in detail in a later section.

2 The MINOS Calibration System

As with all detectors the MINOS detectors need to be acurately calibrated. Without a full understanding of all aspects of both detectors, the power gained from the ability to compare the near and far measurements is lost because of ambiguity in the relationship between the outputs of each detector.

The MINOS detectors are large tracking calorimeters. As such, the purpose of calibration is to determine the energy deposited by particles which interact with the detector. The standard way of calibrating calorimeters is to use beams of known energy pions, or similar particles, and measure the response of the detector. This is not a possibility for the MINOS detectors,thus a different method of calibration has been adopted.

The overall goal of the calibration system is to determine the ADC counts produced by a minimum ionising particle, MIP, which deposits energy in the scintillator strips. This can be done by studying muons that pass through the calorimeter in order to get the relationship between ADC counts and Muon Energy Unit (MEU). The advantage of using muons is that, muons of the same energy always look the same in the detector. Therefore energy measurements in MEU's from the near and far detector can be directly compared. This is a measurement that will be performed at the near detector by looking at beam muons of a known energy. At the far detector cosmic ray muons will be used. This measurement will also be made using the Calibration Detector at CERN for both cosmic ray muons and beam muons.

To try and remove as many of the systematic differences in this measurement as possible there are also two other forms of calibration. These calibration methods are incremental with the muon calibration, as each addresses a separate part of the readout chain. The first of these calibration methods is charge injection. Charge is injected at the base of the PMTs, so it simulates a signal from the phototube. By varying the amount of charge injected it is possible to map the ADC response. The relationship between injected charge and ADC is initially linear, but at high values of charge the ADCs saturate and a plateau value is reached. The charge injection calibration is used to correct for the non linearaties in the electronics downstream of the PMTs.

The other form of calibration is light injection calibration. Light is injected on either side of the scintillator strips. The response of the system to this light can then be measured, and factors such as the gain of the phototubes can be accounted for. For futher description of the light injection system, see the Mini-module and Calibration Detector sections.

3 The Mini-Module Results

Last summer the MINOS calibration system was tested at CERN using the 'mini-module' in the T11 test beam. This module was designed as a miniature version of the MINOS detectors. It consists of 16 planes of solid scintillator sandwiched by planes of steel and had a cross section of 20.5 x 17.0cm. Each plane of scintillator was sub-divided into 4 strips, which were 4.1cm wide and 1.0cm thick. Green wavelength shifting fibre was embedded in the scintillator to transport light out of the mini-module. On one side of the mini-module these fibres were readout by a Hamatasu M64, a 64 pixel photomultiplier tube, and on the other side by four 16 pixel photomultiplier tubes, Hamamatsu M16's. The signals from the PMTs were then digitised in an ADC and read out to disk. A photo of the steel and scintillator of the mini-module is shown in Figure 2

Calibration was provided through a specially designed light injection system. Blue light from an ultra bright LED was transported down clear optical fibres to the light injection manifolds, LIMs. These are boxes through which the wavelength shifting fibre was passed. In these LIMs the light from clear optical fibre could be distributed evenly across the green fibres. This system was designed so that the injected light took the same route as light from a particle passing through the calorimeter.

The bright LED could be pulsed at variable rate, width and height. Using this system, the amount of light supplied could be varied. The LED was also connected to a PIN diode, to measure the light level it produced. A PIN diode was used because the response of the PIN diode is very linear with respect to light level. So by plotting PIN diode against ADC value it is possible to draw a gain curve for all of the different pixels. From these gain curves the number of photoelectrons at each ADC value can be determined.

The PMTs are sensitive to a lower light level than the PIN diode. This means that at low light levels you need a separate way of calculating the light level from the

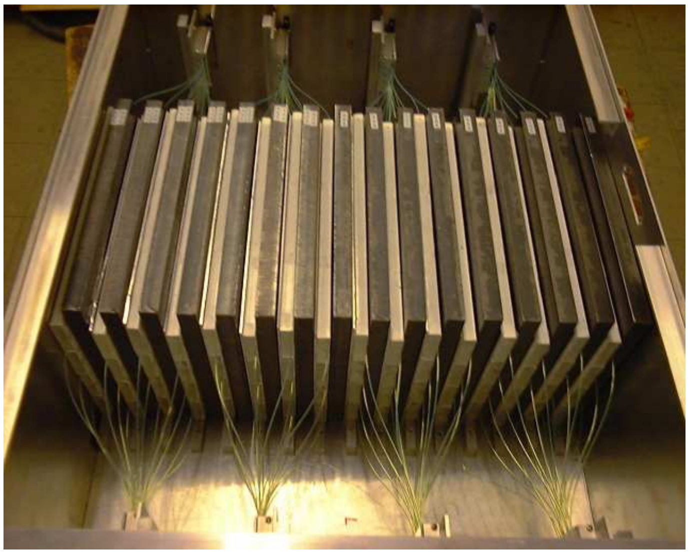

Figure 2: A photograph showing the steel and scintillator planes of the mini-module

ADC distribution. A fitting function was developed for these low light level spectra. A typical spectra is shown in Figure 3.

To explain the features of these spectra, it is necessary to have some understanding of how a photomultiplier tube works. In brief, photons are incident on the photocathode of the tube where they produce photoelectrons. These electrons are then accelerated through a series of dynodes, which provides the multiplication stage of the process. The electrons are collected at the anode, where they produce a signal pulse.

One important feature of these spectra is the distinct pedestal. Random fluctuations in the PMTs and other amplification stages causes a small amount of current to be detected by the ADC. This means that the measurement of zero light has a finite width. So the number of entries in the pedestal is a measure of the number of times no photoelectrons were produced at the photocathode.

For low light levels incident on the photocathode one would expect that the number of photoelectrons produced to be 0,1,2,3,... following a Poisson distribution. The formula for the Poisson distribution is:

$$P(\lambda, n) = \lambda^n e^{-\lambda}/n!$$

where $\lambda = mean\ no.\ of\ photons\ incident.$

and $n = no.\ of\ photoelectrons\ produced.$

The number of electrons incident on the first dynode will also be small, so the number of electrons produced here should also follow a Poisson distribution. If you consider each individual electron that is incident on the successive dynodes the number of electrons produced will also follow a Poisson distribution. However the signal that the ADC receives is the combination of all these effects. Which can be approximated by a Gaussian distribution of ADC counts for each photoelectron.

If one looks again at Figure 3, above the pedestal is the single photoelectron peak, at 175 ADCs. The higher photoelectron peaks are not visible as the Gaussian gets wider for each additional photoelectron, so they are washed out. It is also possible to see a slight bump between the pedestal and the single photoelectron peak. This peak is thought to be due to photons traveling through the photocathode, and producing photoelectrons at the first dynode. If a photoelectron is produced here it will miss out one level of multiplication. The ratio of the pedestal subtracted ADC values of the single p.e peak and this dynode peak, should therefore be the multiplication factor at the first dynode.

Using this information, a fitting function was produced that could be used to determine the gain of the system. That is the number of ADC counts per photoelectron, which is also the position of the single photoelectron peak. An example of a fitted spectra is shown in Figure 4.

There are a number of ways to test the accuracy of the fitting function. One very simple method is to compare the mean p.e from the fit, to that obtained from the number of entries in the pedestal. The ratio of pedestal to total entries should, according to the Poisson distribution, be $e^{-\lambda}$. Table 1 is a comparison of these two methods for four pixels.

Pixel	Fit Method	Pedestal Method
1	1.77	1.67
9	1.62	1.61
11	2.20	2.11
14	2.36	2.31

Table 1: A Table showing the number of photoelectrons counted by two method for four pixels.

Another test of both the stability of the fit and of the stability of the PMTs is to look at the relative change in gain from hour to hour. Light injection runs were made at regular intervals during the test beam time, so that there was always recent calibration data available. Figure 5 shows the relative change in gain for all pixels over a period of a few weeks. From here you can see that the system is stable to 2.4%.

3.1 Demonstration of 1% Calibration using the Light Injection System

Unfortunately the PIN diode taken to CERN for the mini-module di not work. To simulate the PIN diode, the total number of photoelectrons, calculated by $mean^2/RMS^2$, in the M64 was used in the place of the PIN diode. This value can then be used to create calibration constants for each of the pixels, so that they are scaled to the same level.

The procedure was carried out on a set of calibration runs spanning two weeks of run time. The results of this procedure are shown in Figure 6, where two histograms having one entry for each of the M16 phototubes, for each of 50 runs are shown. The upper plot shows the relative difference from run to run using the uncalibrated ADCs and the lower plot is after calibration. The figure shows that the calibration has achieved a 1% accuracy.

The success of the calibration is particularly evident when looking at the red histograms. These entries correspond to runs which occured just before and just after the phototube power supplies were swapped and a 15% change in the gain of one tube was observed. It is clear to see that the differences in the upper plot are removed after the corrections have been applied.

4 The Calibration Detector

At CERN this summer the Calibration Detector will be used in the T11 test beam. The Calibration Detector, Caldet, can be thought of as either a scaled down version of the other MINOS detectors, or as a scaled up version of the mini-module. It consists of 60 planes of 2.5 cm thick steel interlaced with 60 planes of 1cm thick scintillator planes. Each of the scintillator planes is subdivided into 24 strips. In half of the planes these strips run horizontally, the x view, and in the other half vertically, the y view. These strips provide a better granularity for the energy measurement. There is green wavelength shifting fibre embedded in the planes to transport the light produced. The light is taken from either end of the plane down optical fibres to the boxes which house the PMTs. Each pair of planes share 3 M16 multi-pixel phototubes at either end. These M16s are read out using the electronics which have been specially designed for the far detector. Essentially though, the electronics functions in a similar manner to those of the mini-module. The signals from the M16s, after some shaping, are digitised by an ADC and read out through the data acquisition chain. The readout is triggered by a PMT dynode signal greater than a threshold. As all of the pixels on a PMT share the same dynode, whenever there is a trigger, all of the pixels are readout. All of the components of the readout chain are the same as for the Far Detector, so the Caldet has proven to be a valuable test-bed before the Far Detector installation commences later this year.

The calibration system at the Caldet is the same as that of the other MINOS detectors. A pulser box contains 6 bright LEDs, each of these LEDs flashes a cone of fibres. These fibres then lead to the light injection manifolds, LIMs, which are at either end of the scintillator planes. Three fibres go to each of the LIMs. Inside the LIMs is a reflective surface which is designed to evenly distribute the light from the LED across a number of the green fibres from the plane. There are also fibres from the LEDs which go to PIN diodes to monitor the light level produced by the LEDs.

The only other fibre leaving the pulser box goes to the trigger PMT. This fibre is attached to its own separate LED that flashes whenever any of the other LEDs flash. This is necessary, particularly at low light levels, to flag which signals from the PMTs are due to the light injection. At high levels of light injection it is easy to determine which hits correspond to light injection. This can be done simply by looking at the ADC distribution or by using the PIN diode as the flag. Using the PIN is a more reliable way of distinguishing which hits are related to the light injection; however, at low light levels the PIN does not produce enough of a signal to be used as a flag. Also, it is not possible to tell by looking at the ADC distribution, as there is a pedestal present in these distributions. Most extra noise hits will be in the pedestal, due to the reading out of all 16 channels when 1 has a signal, so these rogue hits are not easily detectable. By increasing the number of entries in the pedestal, the distribution still looks like light, but at a lower level. This is because at low light levels you get very little contribution to the spectra from the 2 or higher photoelectron peaks. So with just the pedestal and single p.e. peak the light level can be made to look lower than it actually is. Using the trigger PMT signal you can tell which hits in the distribution are light injection related, and thus be able to fit the correct distribution. The reason that you can use the trigger PMT but not the PIN diodes is that the light level supplied to the trigger PMT is constant, regardless of the brightness with which the other LED is flashing.

The multi-pixel PMTs are very small. This means that when a fibre is pointing to one pixel some of the light from the fibre will shine on the adjacent pixels. If neighbour pixels were flashed simultaneously it would be hard to determine where the light came from. This is a particular problem as the level of this optical crosstalk varies according to pixel location. To minimise the effect of this, a maximum of 20 fibres across three PMTs are flashed at the same time. The fibres are connected to the PMT using a checkerboard pattern so that neighbour pixels are never flashed simultaneously.

Figure 7 shows the spectra of one M16 when light is injected. It is clear to see which pixels receive light from the light injection, and which only see the crosstalk.

Those pixels which received between 0.1 and 3 photoelectrons, determined from the pedestal method, were fitted using the fitting function. An example of one these fits is shown in Figure 8. The most important information that these fits provide is the number of ADC counts per photoelectron. The gain of all the fitted spectra was put into a histogram, see Figure 9, the mean gain is $61.7 ADCs/p.e.$ It should be noted that this is only for a limited number of pixels, and data is needed on more pixels before an overall impression can be obtained. However this is approximately what one would expect, due to the fact that the gain of the highest gain pixel on each tube is set to 10^6. Taking $2fc/adc$ this corresponds to a gain of $80 ADCs/p.e.$ so an average gain of 75% of the maximum is not unreasonable.

4.1 Calculating the MIP Point

This gain information can also be used to calculate the the number of photoelectrons produced in each strip when a muon passes through it. At present we do not have enough muon data to calculate this for each individual strip. As a rough guide it is possible to calculate this value assuming that all the strips are identical. Muons were selected from the data using the condition that three or more planes must be hit, with the hits forming a track. The pedestal subtracted ADC value for these muon events is shown in Figure 10. The distribution is a Landau-like shape with a high tail, as one would expect for muons. To roughly calculate the number of photoelectrons produced per MIP, the mean of this distribution, taken from the fit, is divided by the mean of the gain histogram. This gives a value of 6.1 photoelectrons per MIP per strip.

5 Conclusions

The minimodule last year showed the validity of the light injection calibration system. Calibration to 1% was achieved using an independent light monitor. This work needs to be continued at the Calibration Detector, with all aspects of the calibration system that will be used in the other MINOS detectors.

The work going on at the Calibration Detector is still very much in the debugging phase of operation. More calibration data is needed from the light injection system, to gain a better understanding of the detector. Also, more muon data is needed before the strip to strip muon calibration data for the detector can be produced. There is still much to be done, but by the end of the summer the Calibration Detector will have provided lots of useful information for the MINOS collaboration.

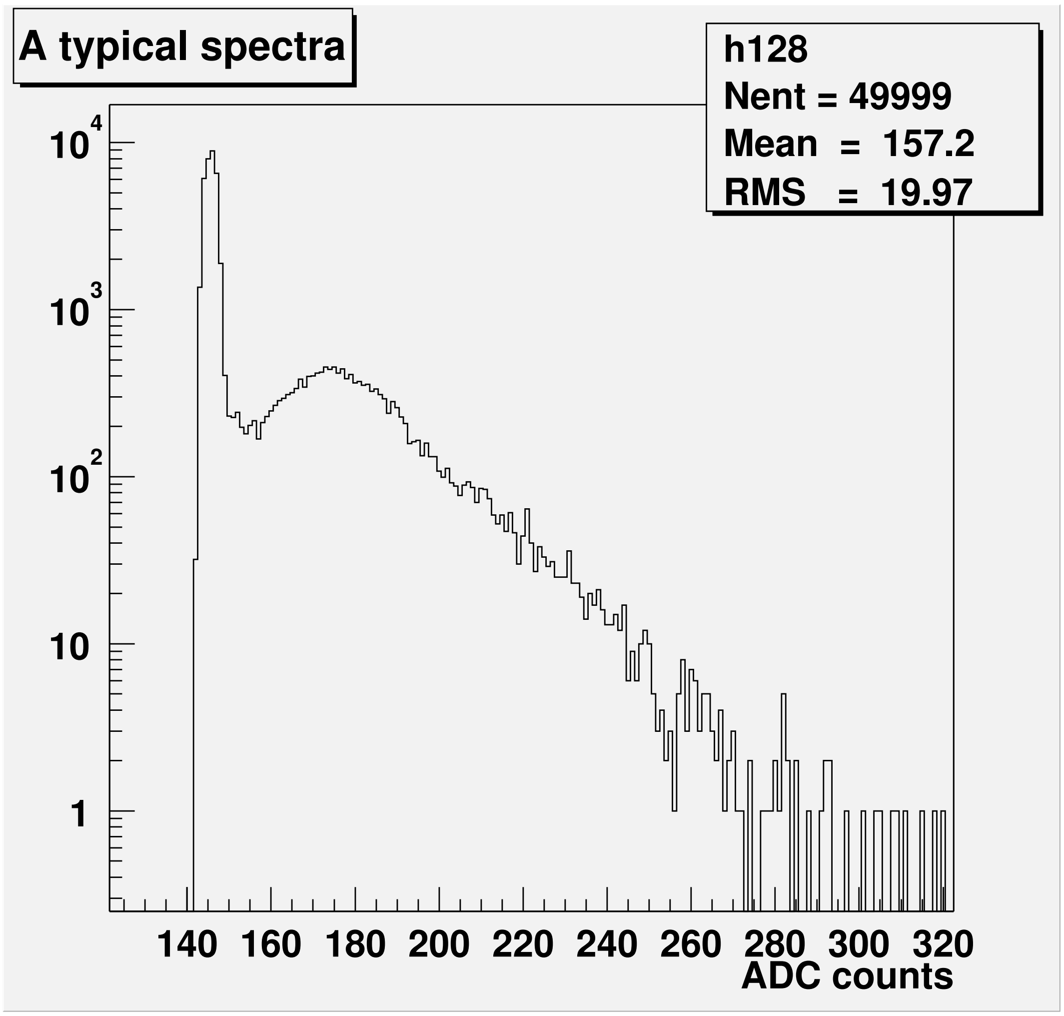

Figure 3: A low light level spectra.

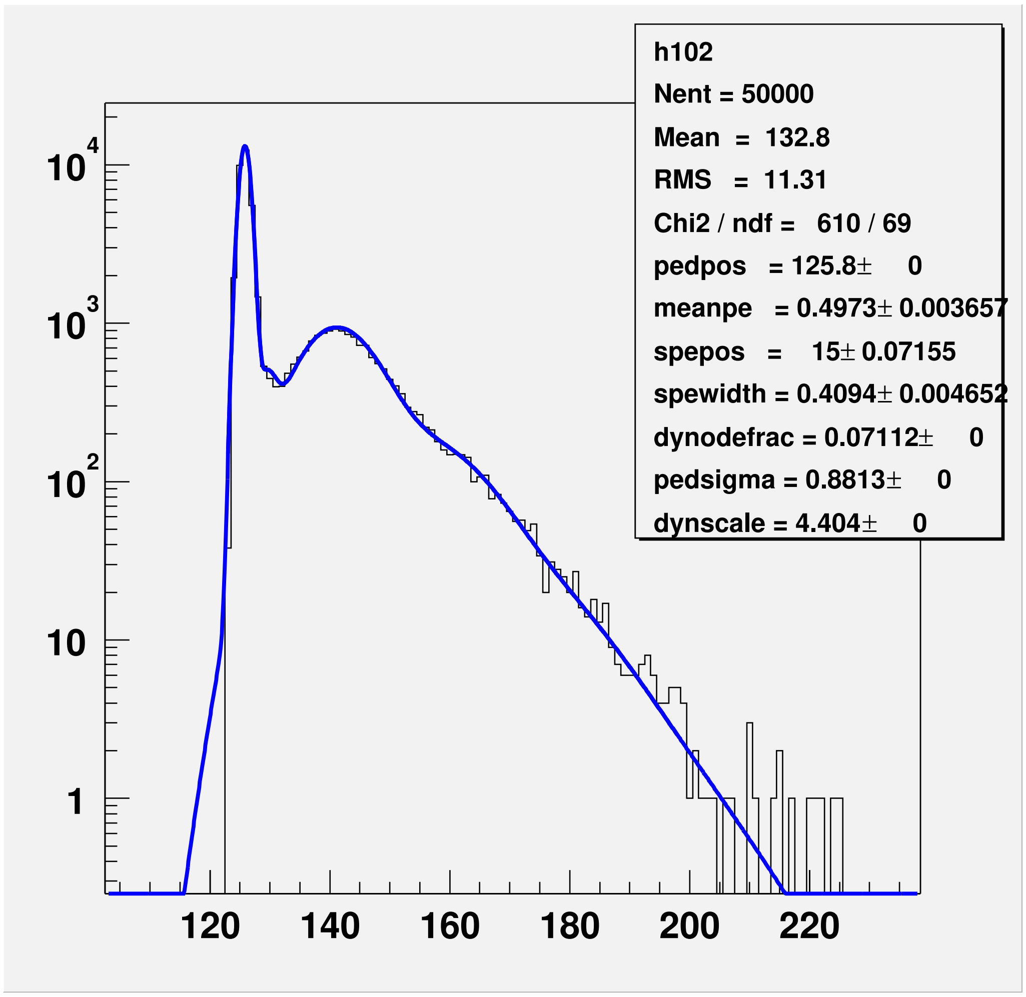

Figure 4: A low light level fitted spectra.

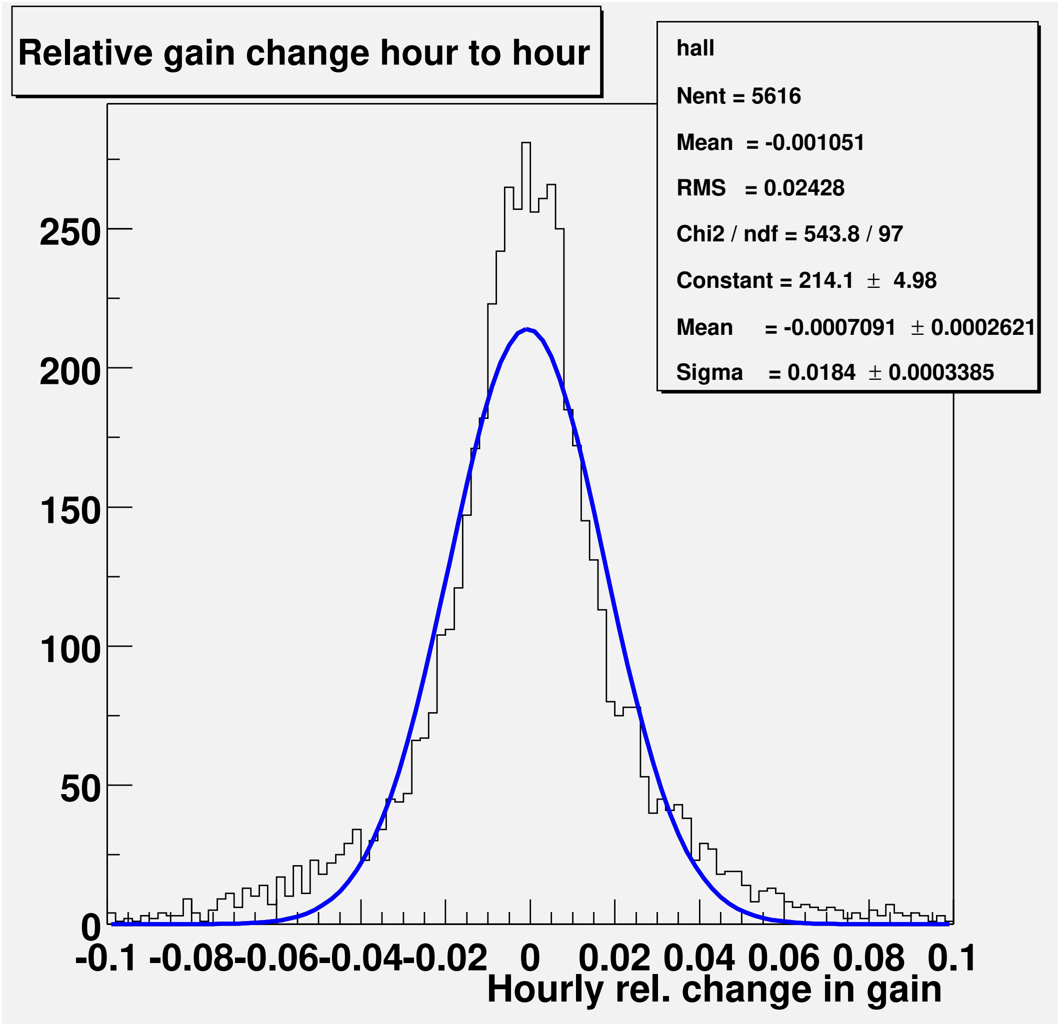

Figure 5: Relative stability of the gain.

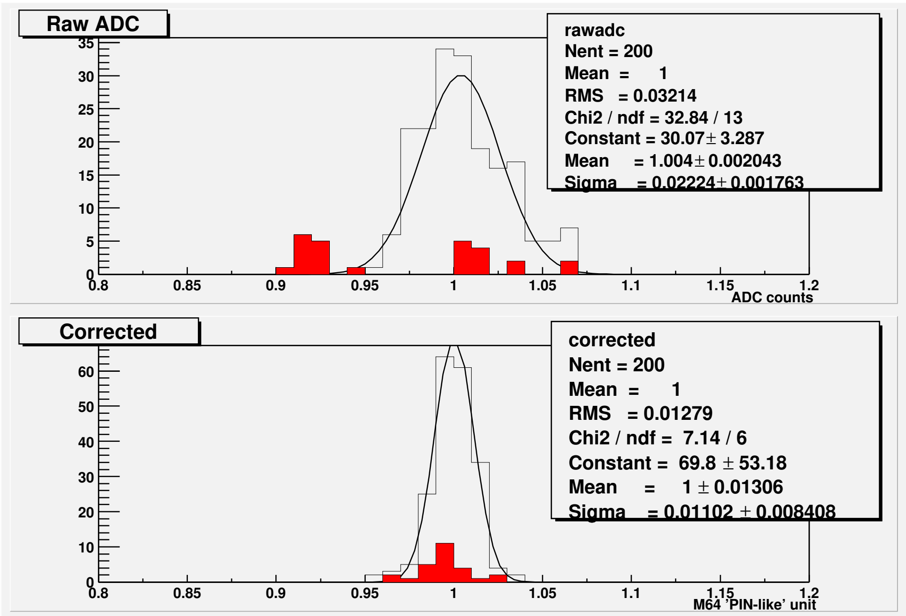

Figure 6: Proof that the Light Injection calibration system works! Relative change in the M16s before and after calibration. The red shaded areas correspond to runs just before and just after the power supplies to the phototubes were changed. As can be seen the calibration corrects for the obvious differences in the upper plot.

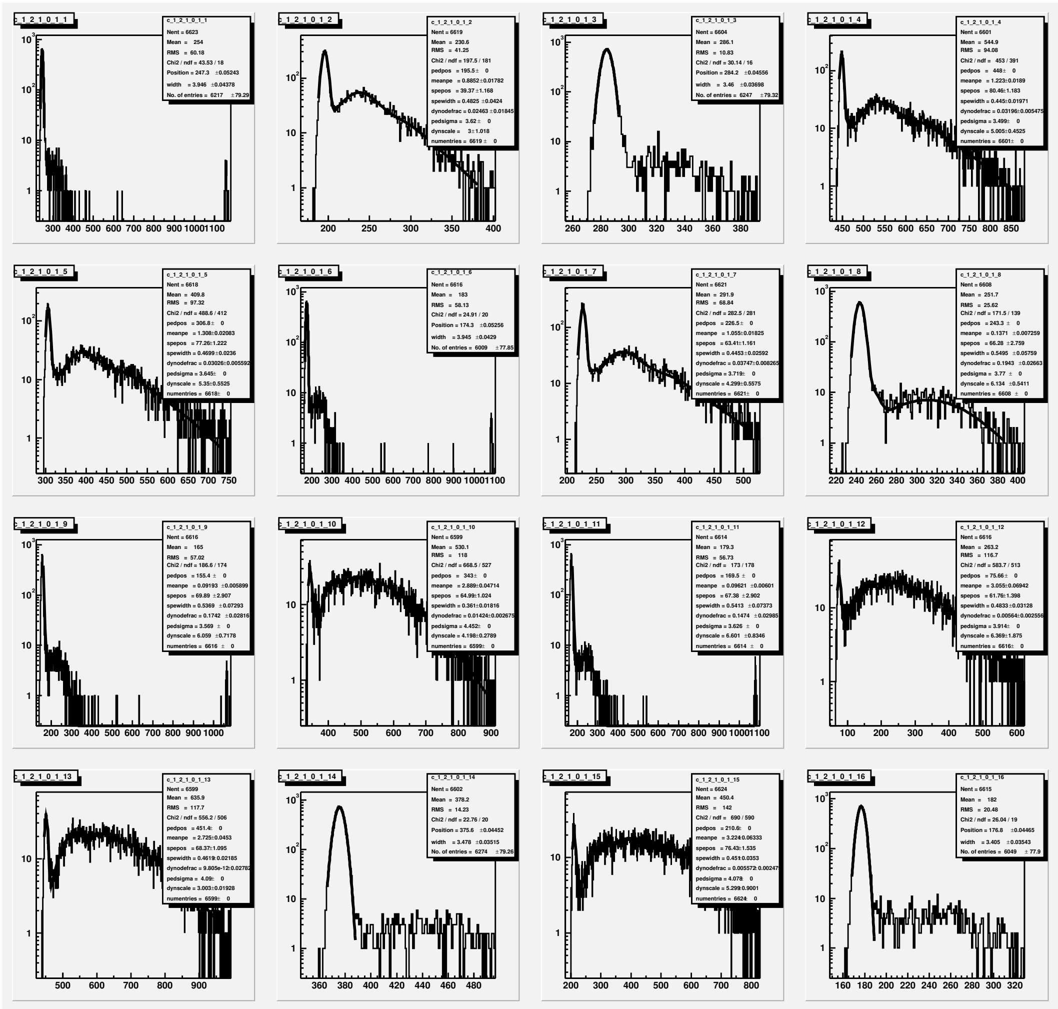

Figure 7: An M16 light injection spectra demonstrating the checkerboard pattern.

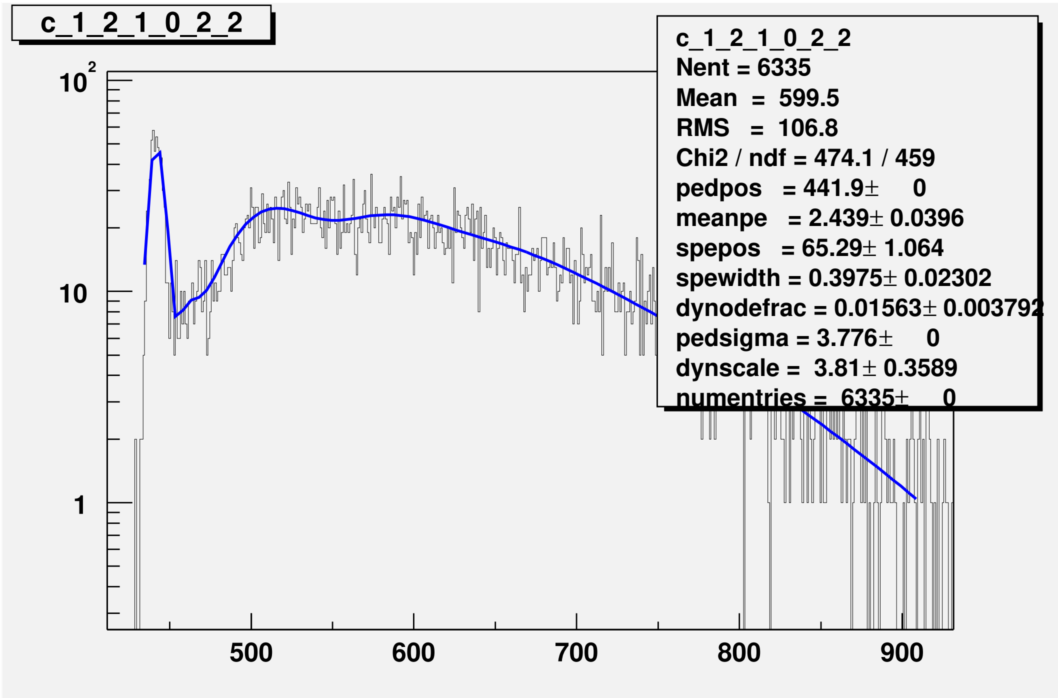

Figure 8: An example fit from the Calibration Detector

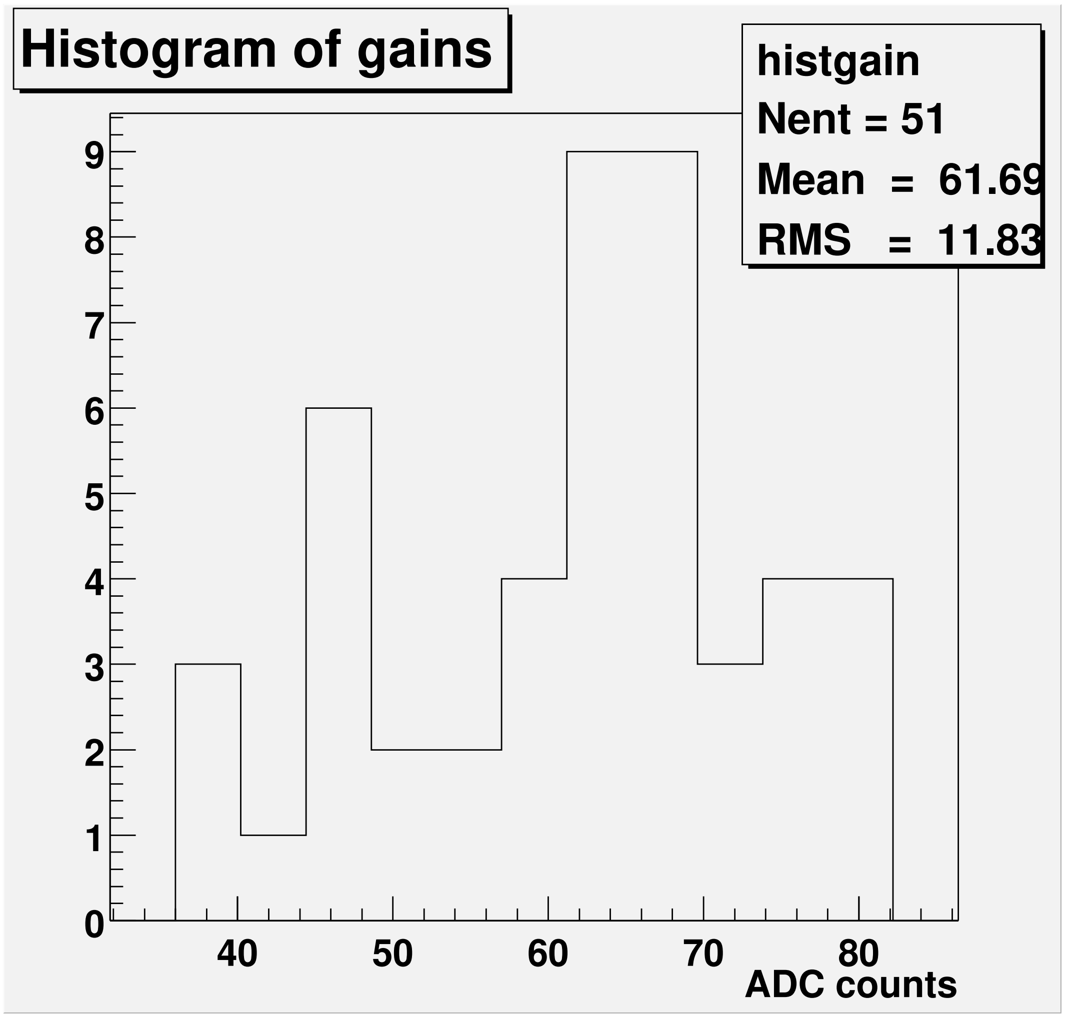

Figure 9: Distribution of gain for selected pixels.

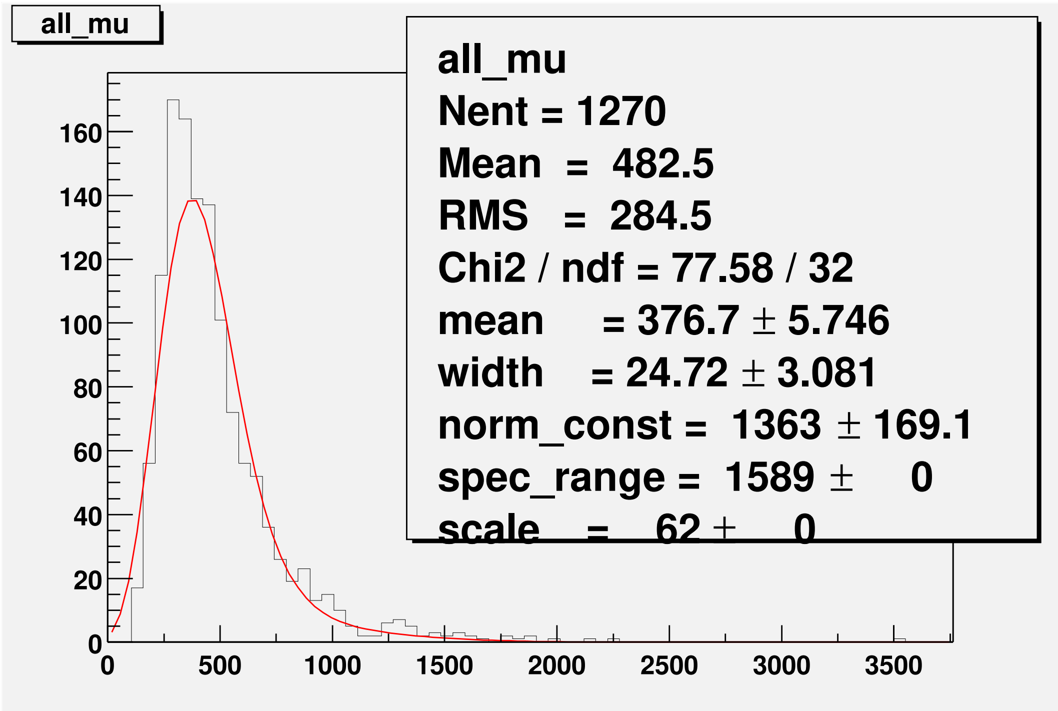

Figure 10: Distribution of pedestal subtracted ADCs for muon events.