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First study and calibration of extended dynamic range PMTs and bases with muons using the Fermilab water tank

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Abstract

This document describes the results from muon data taking done on Fermilab water tank (FATII) during July 2001. New extended dynamic range PMTs were used for this data taking as well as one prototype of the 2-channel base from Orsay. Briefly, we found that a clear muon peak can be obtained using these new PMTs at low gain ($2x10^5$) under realistic conditions. We also demonstrate the relative calibration between the high and low gain channels of the PMT base using real data. In addition, we found that the photoelectron yield from vertical muons is 40-60 (depending on the PMT) without any optical coupling using a floppy dome. This yield goes up by almost a factor of two when the PMTs are glued to the floppy dome.

1 Introduction

The PMTs being used in the engineering array (EA) phase of the Pierre Auger observatory are high gain PMTs. For the production phase of the project, low gain PMTs will be used, with the standard operating gain of $2x10^5$. Until now, it has not been demonstrated that a clear muon peak can be observed at such a low gain under realistic conditions, and it is extremely important to do so.

During the middle of July 2001, we performed some data taking on FATII, a water tank at Fermilab. We used new low gain PMTs, and a prototype Hamamatsu production base provided to us by Joël Pouthas from IPN Orsay.

While the main purpose of this experiment was to show that muon calibration can be done using these low gain PMTs under realistic condition, we also had an opportunity to do a precise measurement of the photoelectron (PE) yield from a vertical muon, and to study the effect of optical coupling on the PE yield. In addition, we were also able to demonstrate the relative calibration between the high and low gain channels, again, under realistic conditions using muon data.

The details of data taking and analysis, and the results are described below.

2 The FATII Water Tank and DAQ system at Fermilab

The Fermilab water tank called hereafter FATII, is a full size surface detector prototype identical in size to the southern observatory tanks. It is composed of a cylindrical polyethylene tank of full dimensions, 10 m^2 surface area and about 1.5 m height. The tank interior is accessible through 3 hatches, above the location of the PMTs. The water is contained in a liner made of a laminate of polyethylene and Tyvek® identical to those used in the Engineering Array. This liner is equipped with dome kits with floppy windows intended for 8" PMTs. This liner was installed in the tank in March and filled with high resistivity (<18MΩ) purified and filtered water. The total volume of water enclosed is about 12,000 liters. The tank is linked to the control room via 30m long cables for providing the High Voltage supply and for transporting the signals back to the DAQ system. Four sets of plastic scintillating detector paddles were used to form an external trigger: each set consist of two scintillators about 30cm x 30cm, overlapping each other and used in coincidence. Two sets are installed above the tank, one in a central position, the other one on a rolling cart (see Figure 2.1). The tank is installed on a stand, which allows the installation of scintillator paddles underneath it. There are two sets of paddles under the tank, once in a central position, the other on the side.

A schematic diagram of the detector is shown in Figure 2.1.

The readout and trigger electronic is base on standard NIM and CAMAC modules as well as on a 4 channel digital oscilloscope Tektronics TDS3054. The CAMAC and the scope are controlled and readout using a GPIB bus via a PCI GPIB interface card from National

Instruments. The data acquisition program runs on Windows NT, it is written in C++, and uses Root. The data are saved on local disks as Root histograms and trees.

Two different triggers can be formed and used concurrently or independently. The trigger conditions are recorded using a coincidence register. One trigger that we will call hereafter Trigger1 or “external muon trigger”, is formed asking for a four-fold coincidence of hits in the central top and bottom scintillator paddles. This configuration detects quasi-vertical muons with a zenithal angle of 90°±15° traversing the tank within 30cm with respect to its center. The trigger rate is ~ 10^{-2} Hz. A second trigger, called Trigger 2 or “internal trigger”, requires a 2-fold coincidence of hits above a discriminator threshold on the 3 PMTs of the tank. It is in essence very similar to the muon calibration trigger that will be used in the final detectors.

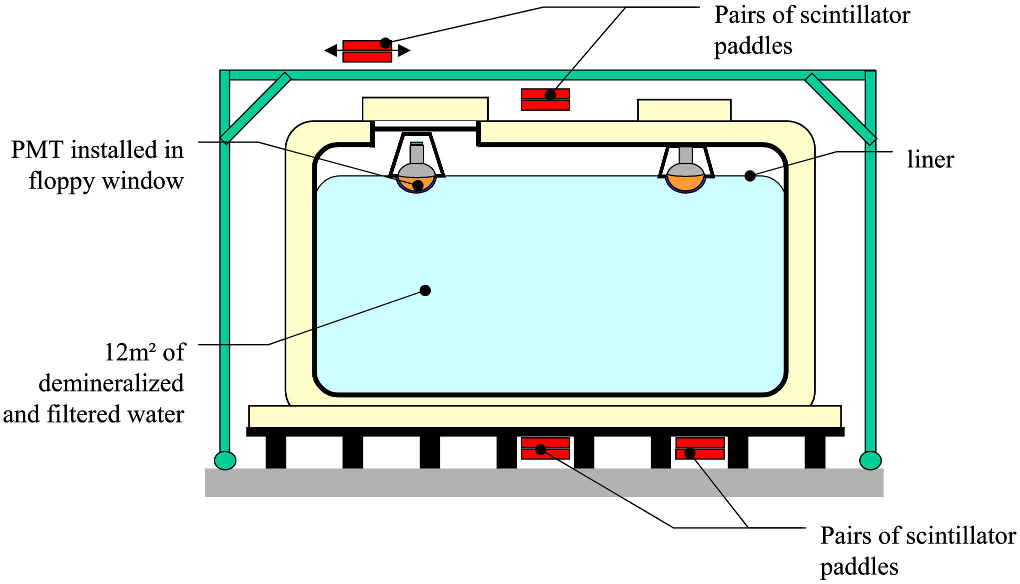

Figure 2.1 A schematic of the Fermilab water tank prototype FATII.

3 The PMTs and the bases

For the data taking, we used three different kinds of PMTs. One of them was a MACRO ETL PMT. This is a high gain, well-measured PMT. It was operated at very high gain, so that a single PE could be easily observed, and as a result, the PE yield from a vertical muon can be determined precisely. A passive MACRO base was used for this PMT.

The second PMT was a new, low gain Hamamatsu (R5912MOD) PMT. A prototype production base provided by IPN Orsay was used. The base provided both the anode and the amplified dynode signals.

The third PMT was a new low gain ETL PMT. The production version of the base for this PMT was not available, so we used a passive base built at UCLA during the course of PMT testing, and only the anode signal was available.

Photonis was not used because the domes in the Fermilab tank are designed for 8-inch PMTs.

4 The measurements

In this section, we describe the various measurements done and their results.

4.1 Photoelectron yield from a vertical muon

In order to precisely determine the number of photoelectrons from a vertical muon for a given PMT at a given gain, one must measure the average charge output from a single photoelectron from that PMT under the same conditions. Then the number of photoelectrons is determined in a straightforward manner by measuring the average charge output from a vertical muon.

We used a high gain MACRO ETL PMT in order to determine the photoelectron yield. This PMT could be operated at a very high gain, and as a result, a clear single PE peak could be observed without the need for any amplification, which introduces noise.

First, using an LED with filters in a dark box, we measured the single PE distribution for this PMT at 1883 volts. This voltage was high enough to give a single PE distribution well separated from pedestal, allowing us to determine the gain of the PMT precisely. The corresponding single PE spectrum is shown in Figure 4.1.1.

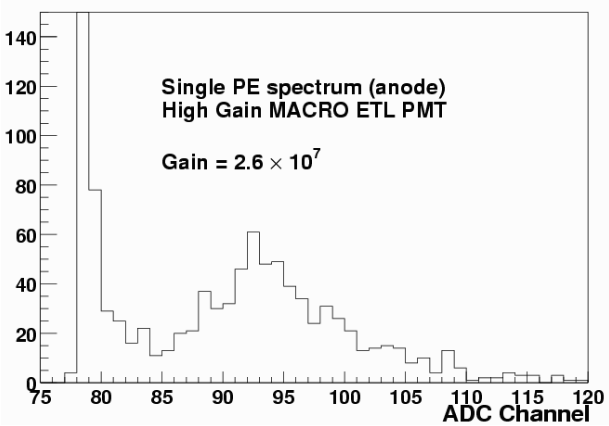

Figure 4.1 .1 Single photoelectron spectrum from high gain MACRO PMT used to measure the photoelectron yield. The PMT was operated at the same gain (2.6×10^7) gain in the tank. One ADC channel = 0.25 pC.

After determining the gain of this PMT inside the lab, it was installed in the water tank. At the same time, the new low gain ETL and Hamamatsu PMTs were also installed in the water tank, resulting in three different kinds of PMTs in the three domes. No optical coupling was applied between the PMTs and the floppy domes.

The gain curves for all three PMTs were known from measurements done in the lab. The MACRO PMT was operated at a gain of 2.6×10^7, identical to the gain used to obtain the single PE distribution. The new ETL and the new Hamamatsu PMTs were both operated at a (anode) gain of 1×10^6. These gains are much higher than the standard operating gain (2×10^5) for the new PMTs, but the goal of this part of the data taking was only to measure the PE yield. Demonstration of muon peak at low gain follows in the next section.

While installing the PMTs, they were all oriented in the optimum position with respect to magnetic field, that is, with pin 20 towards local magnetic north. The orientation was, however, only approximate.

Vertical muon data were collected under these conditions. The vertical muons were selected by requiring coincidence among the pairs of trigger paddles on the top and at the bottom of the tank. The resulting charge spectra from the anode signals of the three PMTs are shown in Figure 4.1.2 .

The number of photoelectrons corresponding to a vertical muon, without any optical coupling, is: 37.6 for MACRO, 58.6 for Hamamatsu and 44.7 for ETL. Since the gains of these three PMTs were known independently, these are three independent measurements of the PE yield. The sources of differences in PE yields include: different quantum efficiencies, different collection efficiencies, different qualities of contact between the PMT and the floppy dome (since no optical coupling was used) etc. Still, the smallest PE yield seen is 37.6.

Note that the above PE yields are based on the knowledge of absolute PMT gain.

It is also interesting to calculate the number of PEs assuming that the width of the gaussian comes entirely from the statistical fluctuations at the photocathode. In that case, the number of PE = $(\text{mean/sigma})^2$. Using this method, the PE yield from the three PMTs is: 24.5 (MACRO), 21 (Hamamatsu) and 16.8 (ETL).

Clearly, using this method, we ***underestimate*** the number of PEs by more than a factor of two, depending on the PMT. The reason for this underestimate is that the width of the gaussian also includes the excess noise factor (ENF) of the PMT, and any physical noise. Therefore, this is not a reliable method of measuring the PE yield.

4.2 Can we observe muons at a gain of $2\text{x}10^5$?

So far, all the field measurements of the muon signals have been done when the PMTs were being operated at a high gain ($>10^6$). In the production phase, Auger will be using new low gain PMTs, and they will be operated at a gain of $2\text{x}10^5$. It is, therefore, critical to demonstrate that a muon signal can easily be observed at such a low gain.

In order to demonstrate this, we proceed in two steps. First we show some data taken with vertical muons, and then we show data taken without any trigger paddles. The latter is similar to data taking in the real experiment.

4.2.1 Vertical muon data with low gain Hamamatsu PMT:

In this section, we show some data taken with the low gain Hamamatsu PMT. This data was taken by triggering on vertical muons, using scintillator paddles.

The PMT base used for this data taking was the 2-channel base from IPN Orsay. The base provided both an anode and an amplified dynode signal. The PMT was operated at a gain of $2\text{x}10^5$, the proposed operating gain in Auger.

Both the anode and the amplified dynode signals are shown in Figure 4.2.1.1. There is no clear muon peak in the anode signal. However, a beautiful muon peak can be seen in the amplified dynode signal.

In real life, there won't be any scintillator paddles to trigger on muons. Therefore, we have to show that we can observe muons by triggering on the PMTs alone. This is described in the next section.

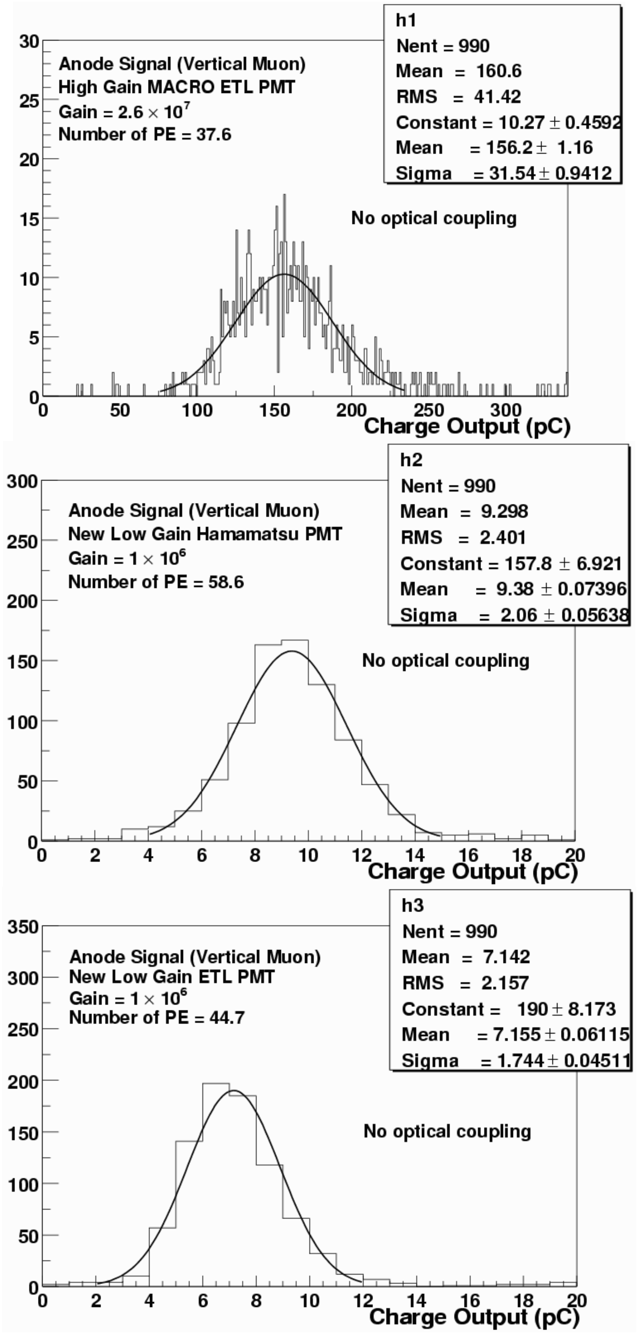

Figure 4.1.2 The signals from MACRO, Hamamatsu and ETL PMTs corresponding to vertical muons, without any optical coupling. The gains of all three PMT were known independently, so that PE yield from each PMT is an independent measurement.

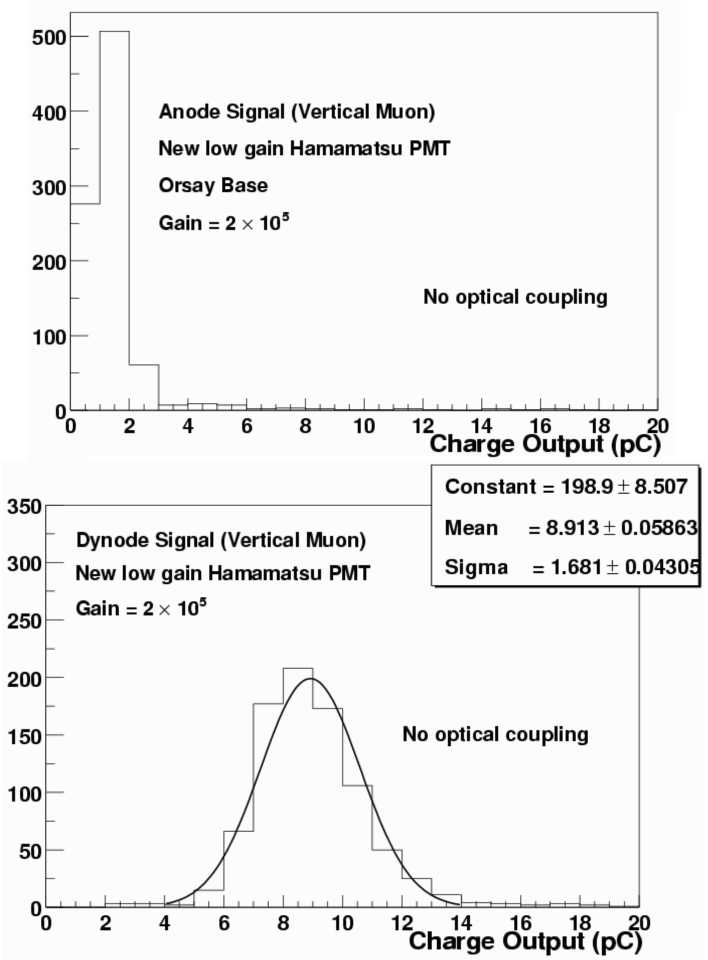

Figure 4.2.1.1 The anode and the amplified dynode signals from the low gain Hamamatsu PMT. The signals correspond to vertical muons. The PMT was operated at a gain of 2×10^5.

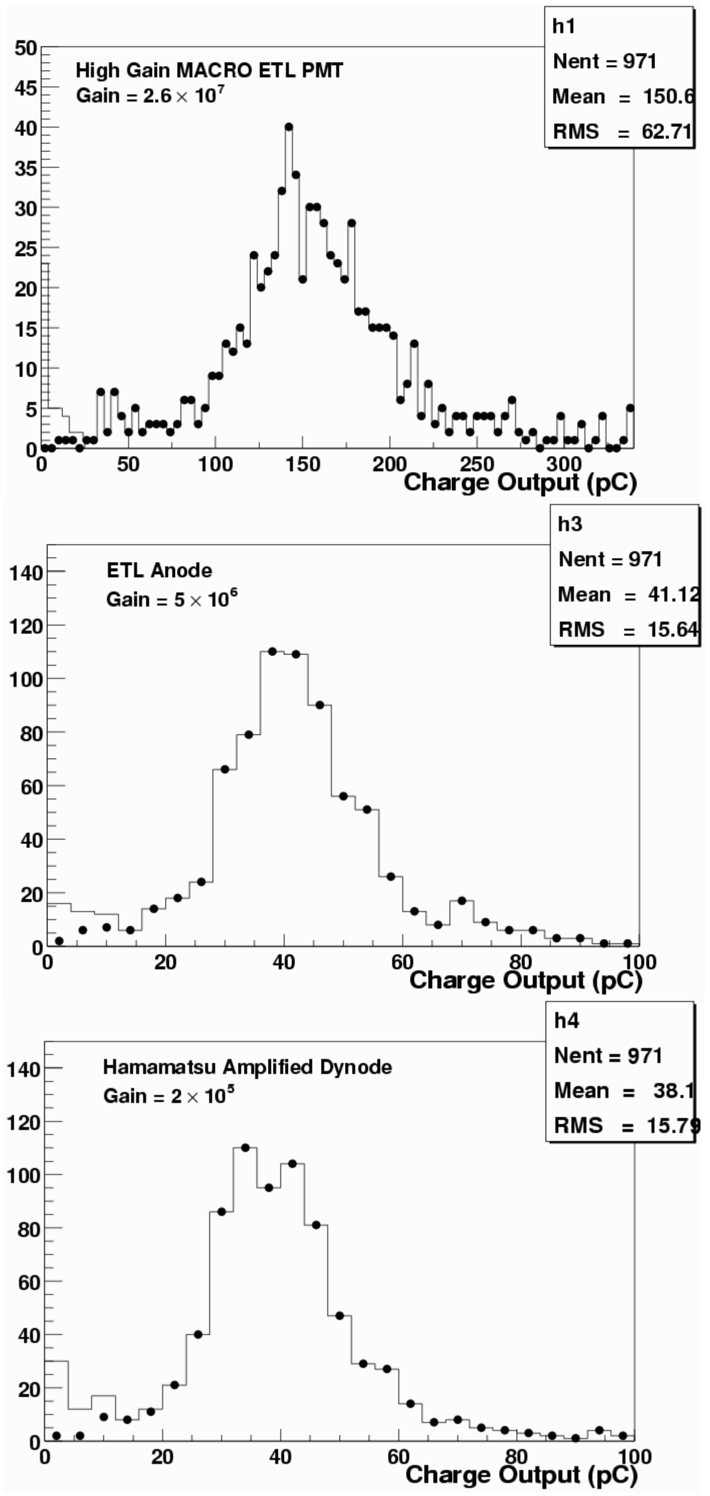

Figure 4.2.2.1 Comparison of scintillation-paddle triggered events to the PMT-triggered events from the same data set. The solid line corresponds to the events that triggered the scintillator paddles (i.e. muon events). The circles are the subset of these events that also passed the PMT coincidence trigger as described in the text. Clearly, the PMT coincidence trigger does not have any bias against muons.

4.2.2 Muon calibration with low gain PMTs without scintillator paddles

To demonstrate muon calibration using low gain PMTs without any scintillator paddles, we set up a PMT coincidence trigger. The trigger required any two of the three PMTs to fire in coincidence. The gains of the PMTs were 2.6×10^7 for MACRO, 5×10^6 ETL and 2×10^5 for Hamamatsu. For Hamamatsu, the amplified dynode channel was used in the trigger. For the MACRO and ETL PMTs, anode signal was used. The discriminator thresholds were set to: 20 mV for MACRO, 10 mV for ETL, 10 mV for Hamamatsu.

As a first step in observing the muons from this trigger, one has to make sure that the trigger thresholds are low enough that we don't bias against muons. We can do that using data from the trigger paddles.

Figure 4.2.2.1 shows the comparison between the scintillator paddle trigger and the PMT-coincidence trigger for the gains and thresholds described above. These data were taken using scintillator paddle trigger, and therefore they are muon events, although not necessarily vertical muons. For all these events, the PMT trigger information was also recorded, and one could check offline if an event passed the PMT coincidence trigger or not. The solid lines in Figure 4.2.2.1 correspond to the events that passed the scintillator paddle trigger. The circles correspond to the subset of these events that also passed the PMT coincidence trigger. Clearly, there is no visible bias against muons in the PMT coincidence trigger.

After making sure that our PMT coincidence trigger is not biased against muons, we collected some data under these trigger conditions, by requiring any two of the three PMTs to fire in coincidence. No trigger paddle information was used in forming this trigger. The raw signal distribution from the three PMTs is shown in Figure 4.2.2.2. The PMT signals are expressed in the units of photoelectron. This is easily done since the gain of each PMT was known. In the case of Hamamatsu amplified dynode, the relative gain was measured using large signals from real data, as described in section 4.2.3 below. Even in the real experiment, the gain of each PMT will be know from lab measurements, so this unambiguous unit for expressing PMT signals can be used in the Auger experiment as well. Already in the raw data, one can see the hints of a muon peak.

In order to get rid of the background, we applied two cuts to the data: (1) The signal from any given PMTs should be at least 20% of the total signal from the three PMTs, and (2) The total combined signal from the three PMTs must be at least 25 photoelectrons, which is only 20% of the total expected signal from a muon.

The distributions of the signals from the three PMTs after these cuts are shown in Figure 4.2.2.3. The circles show the data from PMT coincidence trigger. The fit function used was a sum of three gaussians. The signal from a vertical muon for each PMT is also shown as a solid line histogram.

Clearly, a distinct muon peak can be seen from each PMT. Note that no trigger paddle information was used in obtaining these plots.

However, the peaks thus obtain are not simply from single through going muons. There is a peak on the left hand side of the muon peak, which probably comes from stopped tracks. Also, there is a tail on the right hand side of the muon peak, which comes from a broad gaussian distribution (the third gaussian in the fit). This distribution could either come from small EM showers, or from the case when more that one muon enters the tank within the digitizing period.

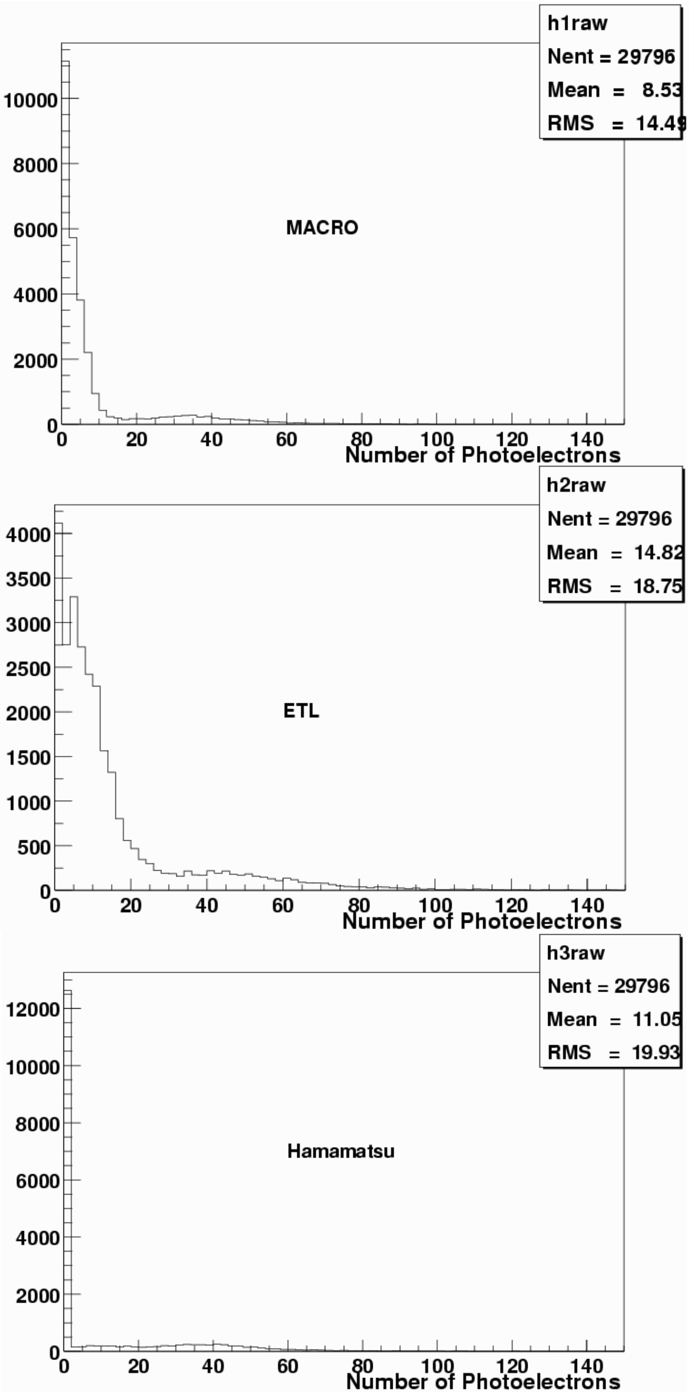

Figure 4.2.2.2 The raw signal distribution from MACRO, ETL and Hamamatsu amplified dynode. The signal is expressed in the units of photoelectrons. This can be easily done since the gain of each PMT was known (and will be known for each PMT in Auger experiment).

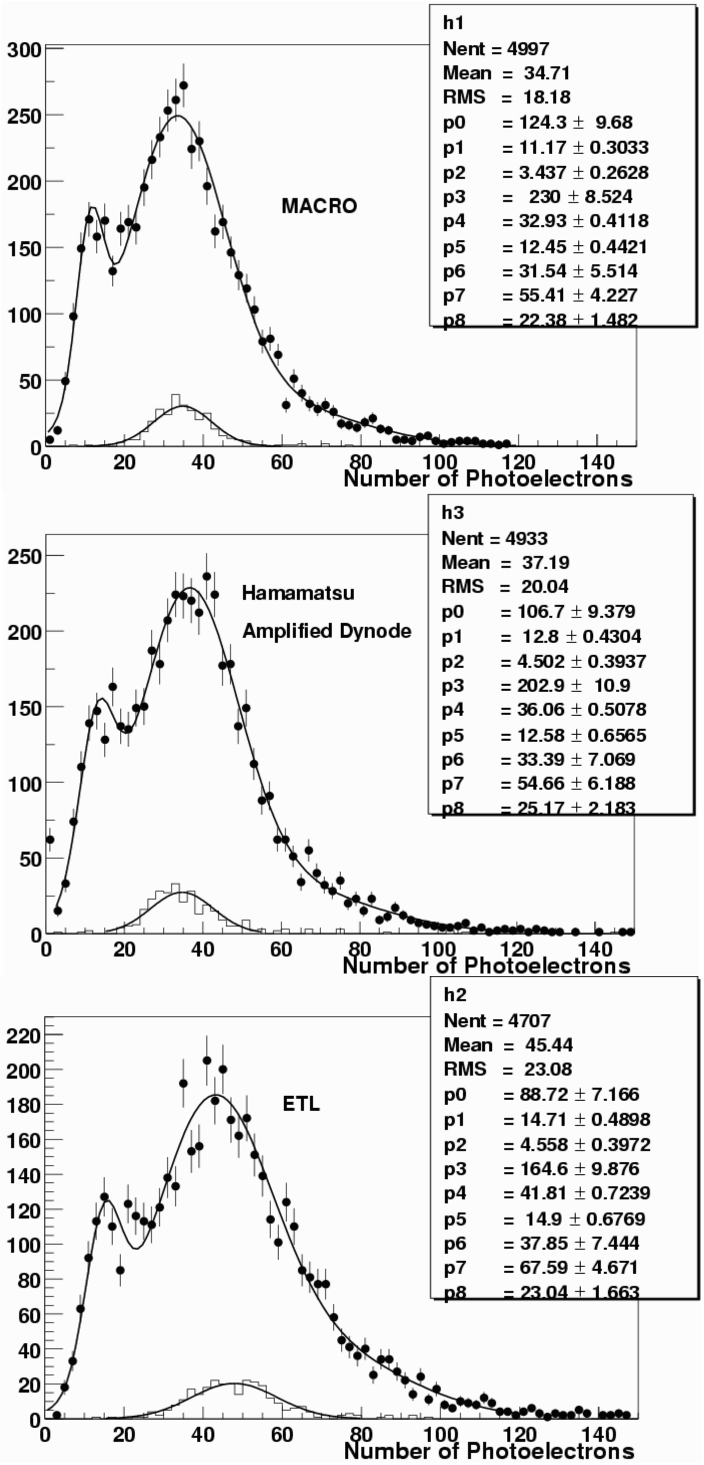

Figure 4.2.2.3 The circles show the signal distribution from the three PMTs after requiring that the signal from each PMT be at least 20% of the total signal (from the three PMTs) and that the total combined signal from the three PMTs be at least 25 PE (20% of the expected muon yield). The fit function is the sum of three gaussians. The solid line histogram is vertical muon signal from the corresponding PMT, obtained using trigger paddles.

4.2.3 Relative Calibration between Anode and Amplified Dynode Channels

In the Auger experiment, muon calibration data would come from the amplified dynode channel, while the high-energy shower data would come from the anode. Therefore, the relative gain between the anode and the amplified dynode channels will have to be measured. This can be accomplished by looking at the signals that are small enough not to saturate the amplifier, but large enough to appear distinctly above pedestal on the anode channel.

We attempted to obtain this relative calibration from the events that gave a relatively large signal (> 100 pC) on the amplified dynode channel. The distribution of the ratio of the amplified dynode signal to that from the anode is shown in Figure 4.2.3.1. The width of the distribution mainly arises from the fact that even these "large" signals give rise to very small charge on the anode, and as a result there is significant relative error on the anode signal measurement, and we did not have many large signal events.

However, even with our small sample of such events, the average ratio between the high gain (amplified dynode) and low gain (anode) channels is 33. This is in good agreement of the expected average ratio of 32. The actual ratio, of course, will very from PMT to PMT.

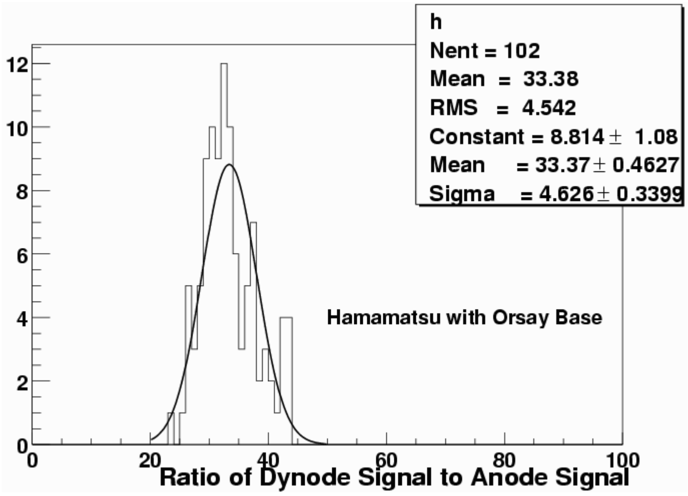

Figure 4.2.3.1 Ratio of the signals from amplified dynode channel and the anode channel for events that yielded more that 100 pC on the amplified dynode channel.

5 Effect of Optical Coupling on PE Yield

During our study, we were also able to study the effect of optical coupling on the PE yield. We used RTV to couple the Hamamatsu PMT to the floppy dome. The gain of the PMT, the trigger conditions, and the orientation of the PMT were kept constant before and after applying the coupling. Therefore, any change in the PE yield is attributable to the optical coupling.

Figure 5.1 shows the amplified anode charge distributions before and after applying the optical coupling. A 92% increase in the PE yield can be observed when the

PMT is coupled to the floppy dome with RTV. While most of the increase in the light yield is simply from a better optical coupling, some of it might also arise from an effective enlargement of the photocathode area when the RTV is applied, because it can flow around the edges the dome and cover a somewhat large area of the glass bulb than the dome alone.

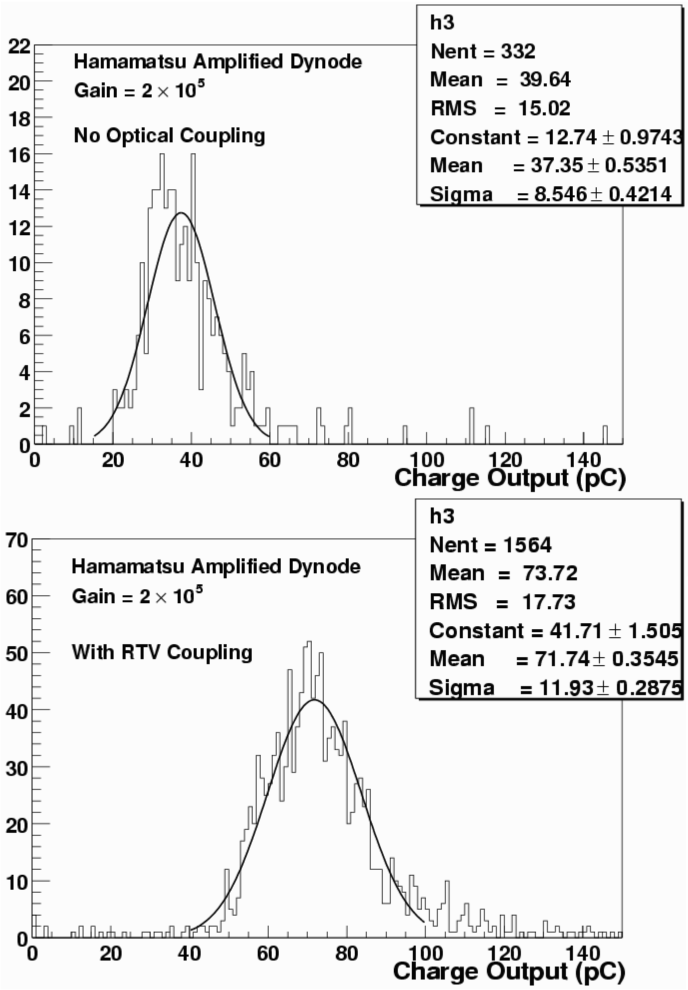

Figure 5.1 Charge distributions from muons before and after the optical coupling between the PMT and the floppy dome. The average PE yield goes up by 92% when optical coupling is applied.

6 Summary

From our studies using the FATII water tank in Fermilab, we have demonstrated that the muon signals can easily be observed on the amplified dynode channel even at a low gain of 2×10^5. We have also shown that the relative gain between the anode and the amplified dynode channels can easily be measured from data in the field.

Using the PMT balancing technique, we were able to obtain a muon peak without any trigger paddles. In addition to the muon peak, there is evidence of small balanced pulses below the muon peak that might possibly come from stopped tracks. Also, there is a component possibly from small showers. A sum of three gaussian functions, corresponding to these three components fits reasonably well to this distribution.

We also measured the PE yield from a vertical muon. Without any optical coupling to the floppy dome, we get 38-60 PEs, depending on the kind of PMT used. Use of RTV optical coupling (same as used in Malargue) between the PMT and the floppy dome increases the light yield by 92%.