Considerations for the Optimal Use of the Milagro PMTs

Richard Miller, Stefan Westerhoff and David Williams

February 22, 1998

Abstract

We have examined how the deployment of the Milagro PMTs effects the capability of the experiment in two key areas: muon detection and angular resolution. These have always been key factors in determining the ultimate sensitivity of the experiment. We conclude the muon detection capabilities provided by the igloos are redundant with the hadron layer, and that the sensitivity of the detector to muons can be improved by deploying a larger hadron layer, rather than building igloos. The timing information provided by the hadron layer also appears to be of sufficient quality to benefit the angular reconstruction. Hence, a larger hadron layer can also be expected to improve the angular resolution. We conclude that Milagro will be a more sensitive detector if we build an expanded hadron layer instead of building igloos.

1 Introduction

We take as the baseline Milagro design the option ratified in the December 1997 vote of institutional representatives: 450 shower layer tubes, 198 hadron layer tubes, 162 igloos, and $\approx$86 shower tanks. As noted in the discussions leading up to that vote, any variations on that design are basically a zero-sum game. We do not have the resources to buy significantly more phototubes, although we might be able to eke out another 20. While there is some possibility that we might submit a future proposal for substantially more tubes, the point of this memo is to address the best use of our *present* resources.

We consider an alternative to the baseline design in which we do not build any igloos. The questions then become, "Where might we deploy those 162 tubes, and to what benefit?" and, "What would we be giving up?" There are three places we might put them: in the shower layer, in the hadron layer, and in shower tanks. We have not had a chance to study the benefits to be expected from shower tanks, and so we concentrate here on the Milagro pond. One possibility is to put more tubes in the air shower layer; another is to expand the hadron layer.

The baseline hadron layer of 198 tubes is 18 by 11, where 18 by 9 of those tubes are mounted on the back of the igloo tubes, and there is an additional row to the side of the igloos on the east and west. With additional tubes available, this layer could be expanded in the same horizontal plane by the addition of rows of 11 tubes at the north and south end, bringing the hadron layer to 20 by 11. Further expansion (keeping the standard grid spacing) requires placing the tubes at a shallower depth. The next row surrounding the 220 tubes would need to be about 1.5 m shallower. Adding this slightly shallower row all around would bring the hadron layer to 22 by 13, or 286 tubes, an increase of 88 compared to the baseline design. The extra 88 tubes would use just over half of the tubes which would become available if we don't build the igloos. Since any additional tubes beyond this would be yet another 1.5 m shallower, or 3 m above the base hadron layer, they would actually be closer to the shower layer. Hence we adopt the 286 tube hadron layer as our alternative design for study of this layer.

The studies we have done are based on showers thrown in the atmosphere with CORSIKA and a detector simulation with GEANT. We believe the GEANT detector simulation to be the most complete and accurate developed to date, although we would be the first to admit that it still has some shortcomings. While we have not duplicated the studies here with other Monte Carlo programs, in other cases where results have been compared between programs (in particular with the EAShower/MilagroSim combination), there is reasonable agreement. In particular, prior studies of muon signals in the hadron layer using MilagroSim have obtained the same qualitative behavior.

One of the areas in which there is still substantial uncertainty in simulating the detector is the reflectance of materials in the pond and the transmission of the water. In the next section, we discuss the choice of values used and the motivation for those choices. In subsequent sections, we will endeavor to discuss how uncertainties in these quantities may impact the conclusions.

We use the "quality factor," which is the ratio of the relative signal strength to the square root of the relative background strength, in many cases as a figure of merit for comparing various options. In the case where the background is sufficiently large to be Gaussian,[1] it is the factor by which the significance of a signal is changed, so quality factors larger than 1 represent improvements in the experimental sensitivity. In the case of making a cut, it is thus the ratio of the efficiency of the cut for γ rays compared to the square root of the efficiency of the cut for background (protons, in our simulations). In the case of increasing the number of events, such as by lowering the threshold, it is the factor by which γ rays are increased divided by the square root of the factor by which protons are increased. For a set of changes which are independent – uncorrelated from one another – the quality factors can multiplied together to obtain the quality factor for the set.

2 Scattering and Reflection in the Milagro Pond

The important parameters describing the water and the optical properties of the materials in the pond are only poorly known and not yet measured directly. We adopted the following "best guesses" in the current MC version:

- 5 % reflectivity of the cover material

The reflectivity of the cover material under water has been checked by Cy Hoffman in lab measurements, which show that 5 % is at least not far from the truth.

- 10 m maximum (*i.e.* above 400 nm) absorption length, with wavelength dependence as measured by Michael Schneider

Cy Hoffman *et al.* have set a lower limit on the absorption length in the Milagrito igloo water by measuring the shape of the pulse in the igloos, deriving 10 m absorption length and concluding that the attenuation length measurements by Michael Schneider are dominated by scattering.

The lab test also shows that – as expected – total internal reflection considerably increases the reflection wherever the cover is not in contact with the water. This may be the case for a large part of the pond. The GEANT MC takes into account total internal reflection, but as we do not know for what fraction of the pond we have air between the cover and the water, running the MC with the two extremes, no internal reflection and internal reflection (default) all over the pond, seems to be the most reasonable approach for the moment.

[1] Even in the case of looking for a few seconds' burst from a particular direction, the background is ≈1 Hz in the source bin, and Milagro is approximately in this regime.

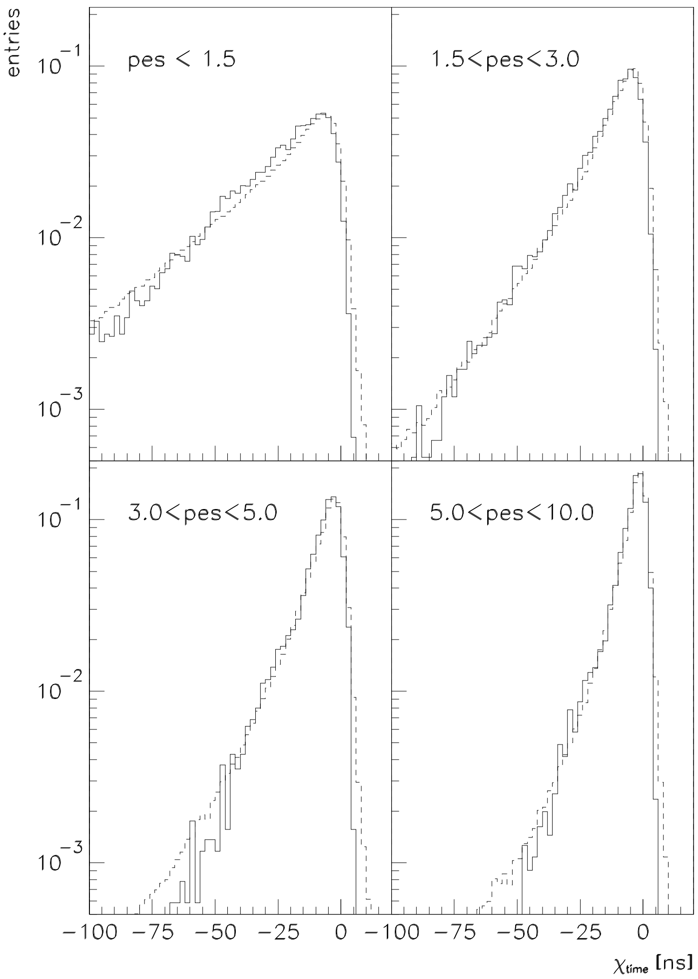

Figure 1: χ_{time}-distribution for various PE levels. The solid line represents the MC, the dotted line is experimental data.

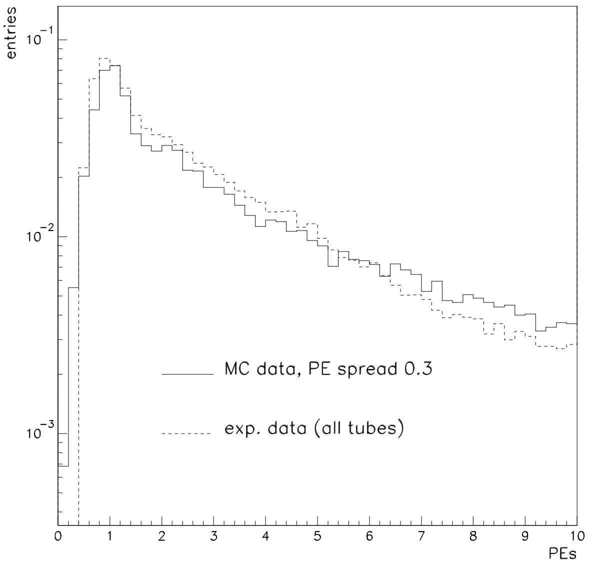

Figure 2: PE distribution for MC (solid line) and data (dashed line). The data have been calibrated using ADC lookup tables (Andrew Smith). "PE spread 0.3" refers to the fact that the PMT has been assumed to have an amplitude spread of 30% at 1 PE.

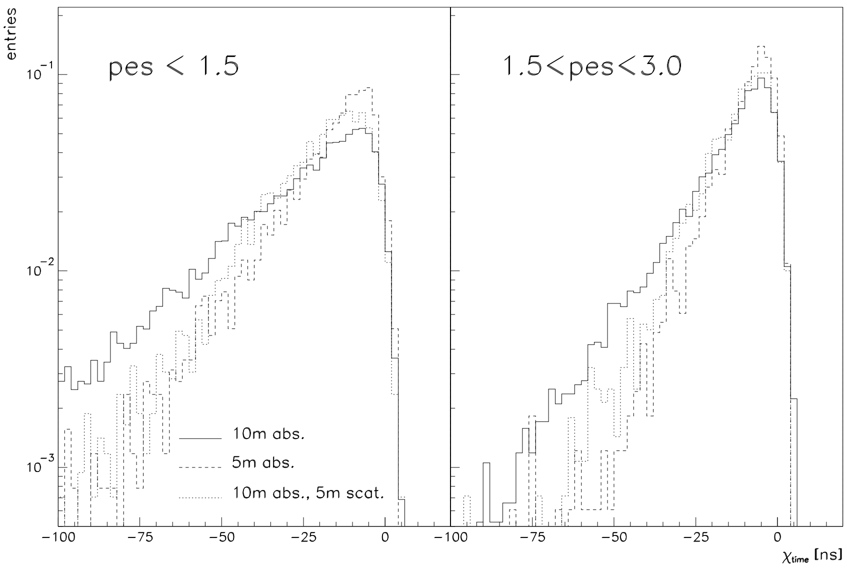

Figure 3: Comparison of the χ_{time}-distribution of the two lowest PE levels with 10 m absorption length (solid line), 5 m absorption length (dashed line), and 10 m absorption length plus isotropic scattering with 5 m (max.) scattering length (dotted line).

We have also included scattering of Cherenkov photons in the current MC, but as the type and amount of scattering in the pond water is unknown and no direct evidence for scattering exists, we do not use this option as the default. However, as analysis techniques may be influenced by scattering, we will use this option to verify that our separation methods do not crucially depend on this.

Although the scattering length and absorption length are basically guesses, we can check whether the *Milagrito* version of the simulation code describes the data to a satisfying degree. We use a sample of 200 000 proton showers from 50 GeV to 20 TeV on a 2.7 spectrum with an 80 tube trigger, thrown over $200\,\mathrm{m} \times 200\,\mathrm{m}$, to compare two basic data distributions with the MC prediction, the χ_{time}-distribution for different PE levels (Fig. 1) and the PE distribution itself (Fig. 2).

The main features, such as the "late light" tail of the data (negative χ_{time}) are well described with the current set of parameters, and they also help to check alternatives (Fig. 3). It is *e. g.* not possible to reproduce the tail in the data by assuming a maximum absorption length of 5 m. This and further studies show that the main parameters creating "late light" are absorption length and – to a lesser degree – reflection at the pond bottom. Including isotropic scattering with 5 m scattering length in the current Milagrito MC also changes the χ_{time}-distribution, as shown.

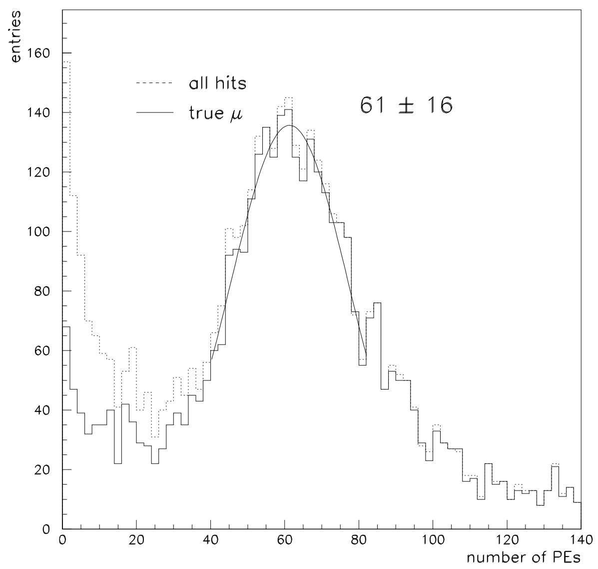

Figure 4: Number of PEs detected in igloos for 0.5 - 10 TeV proton showers. The solid line indicates (true) muons, the dotted line all hits. The Gaussian fit gives an average of 61 ± 16 PEs per muon.

The igloos are implemented with the Tyvek properties as described in Gaurang Yodh's memo on water tanks. The 10 m absorption length in the water produces the distribution of igloo pulses shown in Fig. 4. At first glance, the light yield of 61 PEs per muon would appear to be in contradiction with the value of 30 PEs measured by Morgan Wascko *et al.* (see The Igloo Page 8-11-97, linked from the Milagro Memos web page). However, the value of 30 PEs really means a pulse with total charge 30 times the charge from one photoelectron. The Milagro phototube and base combination exhibits substantial nonlinearity, even at relatively small pulse amplitudes. Several years ago, we measured about 30% nonlinearity between 1 and 10 PE (the 10 PE pulse has only about 7 times as much charge as the 1 PE pulse) for the Milagro tube we have at UCSC. Isabel Leonor has recently observed similar behavior in the laser calibration data. In fact, she finds that a pulse height corresponding to 30 PEs as measured by the adc method (similar to how the igloo pulses were measured) corresponds to about 60 PEs as measured by the laser calibration system with the occupancy method. The occupancy method relies on the correct calibration of the filter wheel, rather than the linearity of the phototube response, to scale pulses from 1 PE to higher light levels and should be a more reliable value. Hence, taking the tube nonlinearity into account, the 30 PEs measured for igloo pulses corresponds to about 60 actual PEs, and the igloo Monte Carlo is in excellent agreement with the data.

We emphasize that in order to verify the quality of the MC code, *direct* measurements of the detector parameters are required. Nevertheless, we do not yet observe major discrepancies between the Milagrito MC and the data, showing that the reasonable choice of water parameters shown above does not completely fail to describe the detector.

The water level used in the current version of the Milagro simulation is 7.0 m, with the air shower layer at a depth 1.5 m. The lower 220 tubes of the hadron layer are at a depth of 5.9 m.

3 Muon Identification

We next examine both the efficiency and the collection area of the igloos and the hadron layer for detecting muons in air showers. We compare the 162 igloos of the baseline design to our alternative hadron layer of 286 tubes.

In order to compare the muon identification capability of the igloos and the hadron layer, we have to develop a technique to identify muons in the hadron layer. This is essentially a pattern recognition problem which may be best addressed by the use of neural networks. However, for the moment the goal here is not to come up with the best possible identification method, but rather with an easy criterion which is robust and simple. Muons in the hadron layer are characterized by tubes with rather large pulseheight, surrounded by tubes with fewer PEs. In contrast to γ-shower cores, they are a relatively local phenomenon. A simple method for finding muons with the hadron layer is to compare PEs in a single hot tube with the average PE values of its closest neighbors. Fig. 5 shows the PE value of hadron layer tubes with more than 10 PEs vs. the average PE level of its 8 closest neighbors, both for γ showers (top) and (true) muons in proton showers (bottom).

The plots indicate that as expected muons are defined by a very narrow distribution of the average PE level of the tubes surrounding the hot tube. Note that due to the geometry of the light cone, this average value is nevertheless well above zero. We apply the following selection criterion for muons in the hadron layer: any tube with more than 30 PEs (with no hotter tube within 2 tube distances) and an average PE level between 5 and 20 PEs for the 8 neighboring tubes is considered a muon. As a first step, we check the muon detection efficiency of this cut vs. the muon energy and compare it to the igloo layer muon efficiency, where an igloo with more than 10 PE is considered as being hit by a muon. Fig. 4 shows the pulse height distribution for muons in the igloos.

Figure 6 (a) shows the muon efficiency as a function of the muon energy, with the expected cutoff at approximately 1.5 GeV for both methods. Since we consider all muons crossing the plane of the extended hadron layer (*i.e.* $62\,\mathrm{m} \times 36\,\mathrm{m}$), the number of muons detected in the igloo layer is about two times smaller for geometrical reasons, although the muon detection efficiency of the igloos is essentially 1. Fig. 6 (b) compares the energy distribution of the total number of muons crossing the hadron layer plane to the distributions of the muons actually detected by the igloo and the hadron layer.

The next step is to evaluate the proton- and γ-shower efficiency for both layers for a cut that

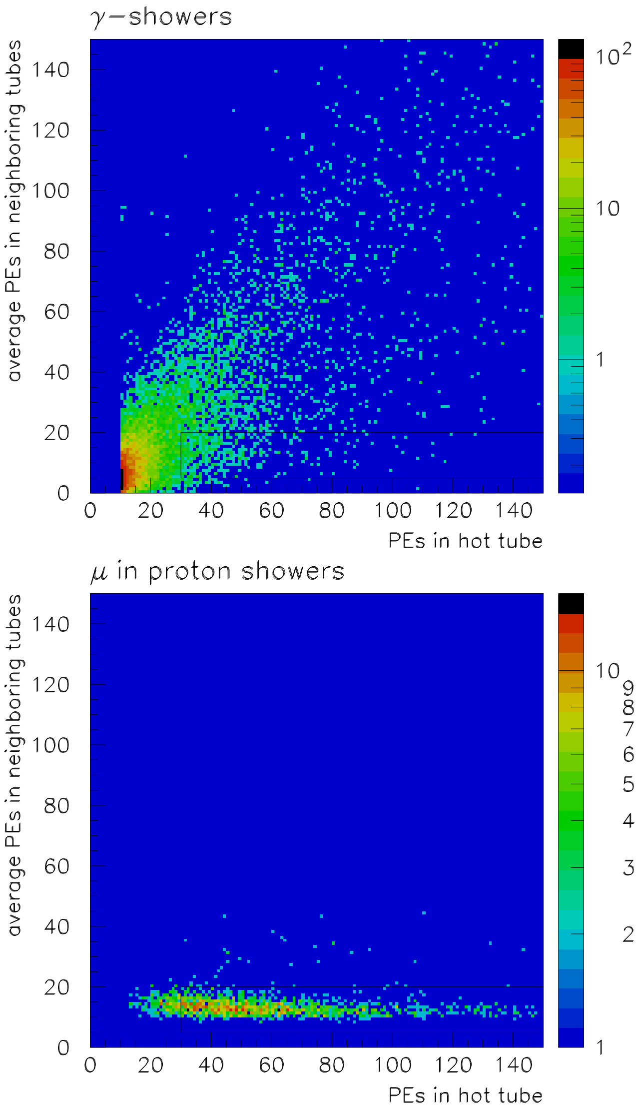

Figure 5: PE level of “hot” tubes (≥ 10) vs. the average PE level of their 8 neighboring tubes for γ showers and (true) muons in proton showers.

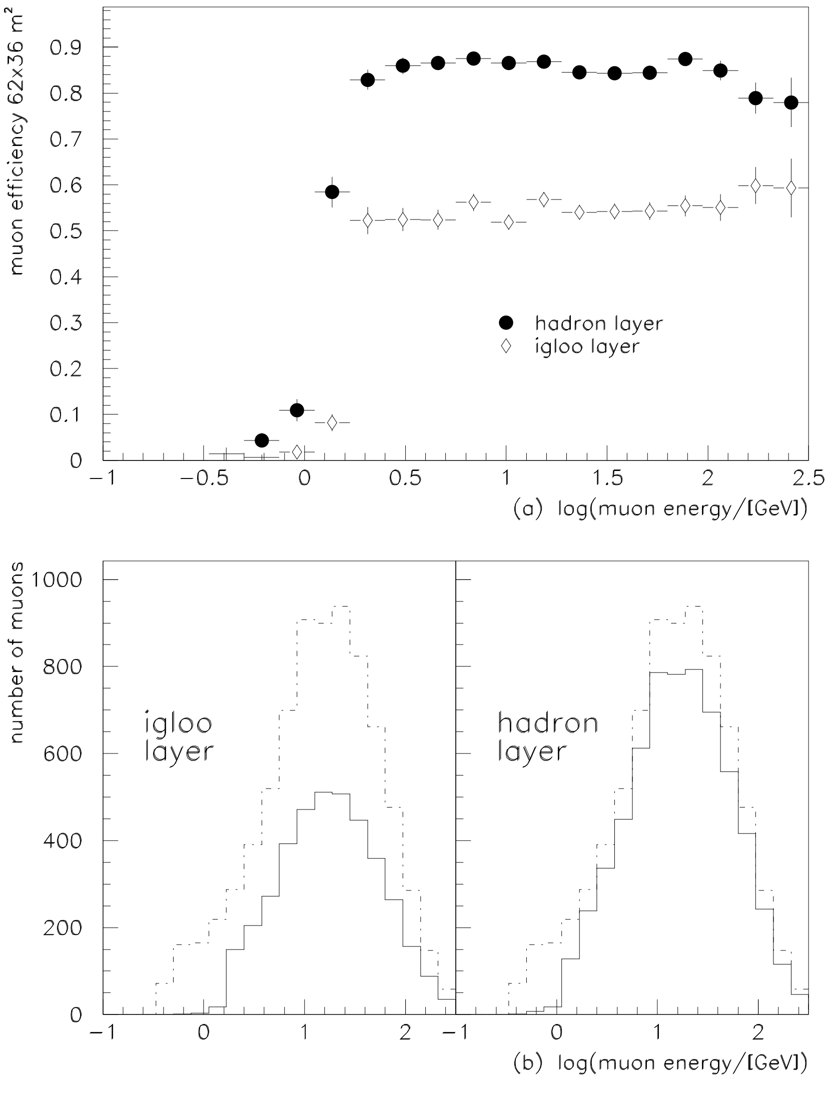

Figure 6: (a) Muon efficiency for the igloo and hadron layer as a function of muon energy. (b) Energy distribution of all muons crossing the hadron layer plane (dotted line) as compared to the energy distribution of muons detected by the igloo and hadron layers (solid lines).

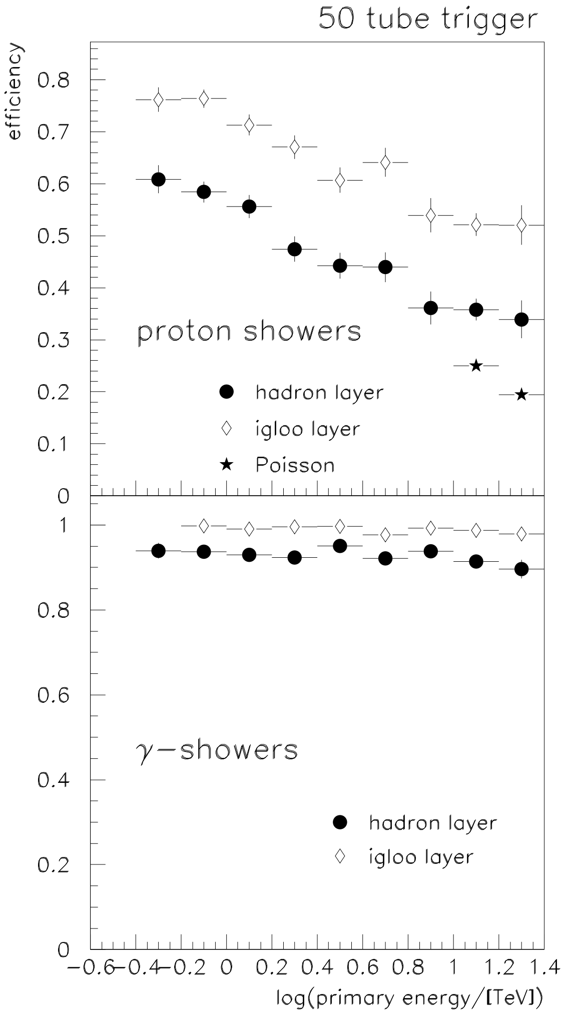

Figure 7: Fraction of proton and γ showers with *no* detected muon for the igloo layer and the hadron layer. For a cut that discards events with more than 1 detected muon as hadronic, this is also the proton and γ-shower efficiency for a muon-based γ/hadron separation. Also shown is the efficiency for high-energy proton showers that would be (incorrectly) inferred from the mean number of detected muons in the shower and assuming a Poisson distribution.

rejects showers with at least one detected muon as hadronic. We do this as a function of primary energy for showers from 500 GeV to 20 TeV, requiring a minimum of 50 tubes in the air shower layer (Fig. 7).

At this point we once again emphasize that the number of muons in air showers does not follow a Poissonian distribution. Naturally, this problem is more evident at higher energies, but even at 10 TeV it leads to a significant deviation from the true distribution. To illustrate this, Fig. 7 also shows the efficiency for high energy protons that would be inferred form the mean number of muons in the shower if we assume a Poissonian distribution, where the fraction of showers without muons is

$$f = e^{-\overline{N_\mu}}. \tag{1}$$

This effect is more dominant for showers on the pond and for higher energies. Fig. 8 shows the fraction of showers without muons at 10 TeV and 20 TeV as a function of distance to the core.

The analysis has shown that a hadron layer with 286 tubes outperforms the igloo layer in terms of muon based γ/hadron separation because of its larger muon sensitive area. It remains to be shown that by using the hadron layer we do not lose the ability of *muon counting*. Since the hadron layer tubes are not optically isolated, one might expect a somewhat poorer capability of separating several muons at close quarters. We address this problem in Fig. 9 which shows the mean number of detected muons versus the number of muons crossing the hadron layer plane. The statistics are poor at high muon multiplicity, but both methods are clearly able to resolve multiple muons.

Finally, Table 1 gives the proton and γ-shower efficiency (assuming a differential spectral index of 2.7) for events with more than 50 air shower tubes both for primary energies below and above 10 TeV.

	≤10 TeV		≥10 TeV	
	igloo	hadron	igloo	hadron
proton	0.70	0.51	0.53	0.35
γ	0.99	0.93	0.99	0.91
Q	1.18	1.30	1.36	1.54

Table 1: Proton and γ-efficiencies and quality factors for showers below and above 10 TeV.

As we noted above, we have not included scattering of light by the water in the simulations used to obtain these results. Simulations are underway, but not yet completed, which include scattering. It seems unlikely, however, that scattering will significantly change these results. Muons are identified in the hadron layer as a "hot tube" with some "fuzz" around it. Any muon reaching the hadron layer passes within 2 m or less of some tube, which is the hot one. The light only needs to travel a few meters to reach that tube, so even a scattering length as short as 5 m will not attenuate the pulse height in the hot tube too severely. Scattering may change the level of the surrounding fuzz a bit, but this can be taken into account in selecting the cuts.

4 Angular Reconstruction

The hadron layer also provides additional information, unattainable with the igloo layer, that may lead to improved angular resolution. To study this we have compared the χ_{time}-distribution of both the air-shower and hadron layer PMTs using the detector Monte Carlo. Fig. 10 shows these distributions resulting from the same sample of Monte Carlo γ showers discussed previously. Note that the RMSs of the hadron layer tubes are *at least* as good as those of the air-shower layer.

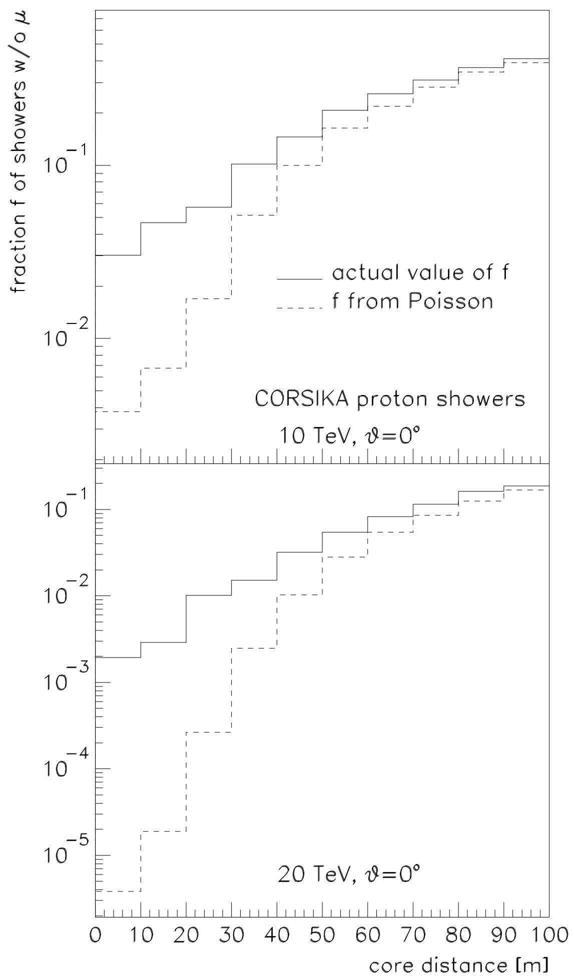

Figure 8: Fraction of showers without muons as a function of the distance of the core to the pond center.

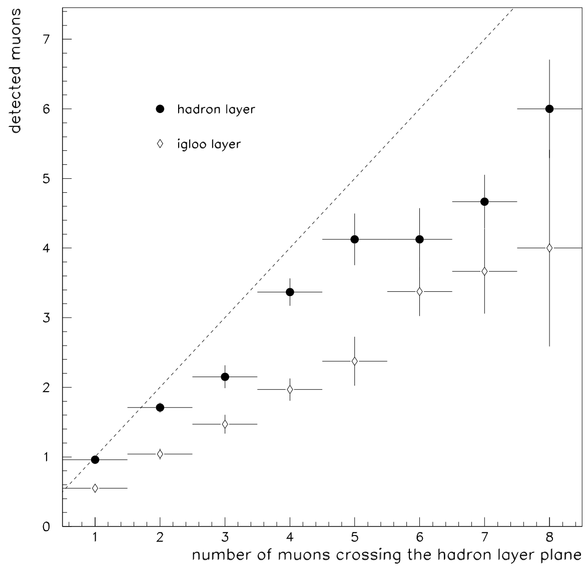

Figure 9: Number of detected muons vs. number of muons crossing the hadron layer plane for igloos and hadron layer.

In addition, for the γ-ray spectrum studied here, the occupancy is 15% higher for hadron layer tubes than it is for air-shower layer tubes. It should be possible, therefore, to include hadron layer tube hits into shower-angle reconstruction and get, at a minimum, the *same* benefit as hits in the air-shower layer. If algorithms can be developed to take advantage of the hadron layer hits in angle fitting (*i.e.* non-flat array) then this second layer becomes, at some level, equivalent to increasing the PMT coverage on the air-shower layer. Of course the hadron layer has the additional advantages of muon recognition, the potential for additional non-muon-based γ/hadron separation, and calorimetric measurements.

We should note that this result seems to be at odds with the Milagro DOE proposal. Fig. 3.3.4.d of that document shows the optimal angular resolution at the shallowest depth of 1 m, with worse resolution at depths of 1.5 and 2 m. We do not understand the source of this difference, but it may have to do with how the number or spacing of the tubes was varied as the depth of the air-shower layer was varied. It may also be an artifact of a simplification used in that simulation: The number of Cherenkov photons thrown was reduced by a factor of the tube area over the grid cell area, and every thrown Cherenkov photon was assumed to hit the tube in the cell where it landed. Note that in this procedure, every particle which has more than about 4 cm of path length produces at least one Cherenkov photon and hits a tube. This is certainly not the case in reality for tubes at 1 m depth, since the Cherenkov cone in most cases does not open up enough in one meter to intercept a tube. Another simulation, done a few years ago by Tom Yang, indicated that the resolution was best at a depth of about 3 m, degrading slowly deeper than that.

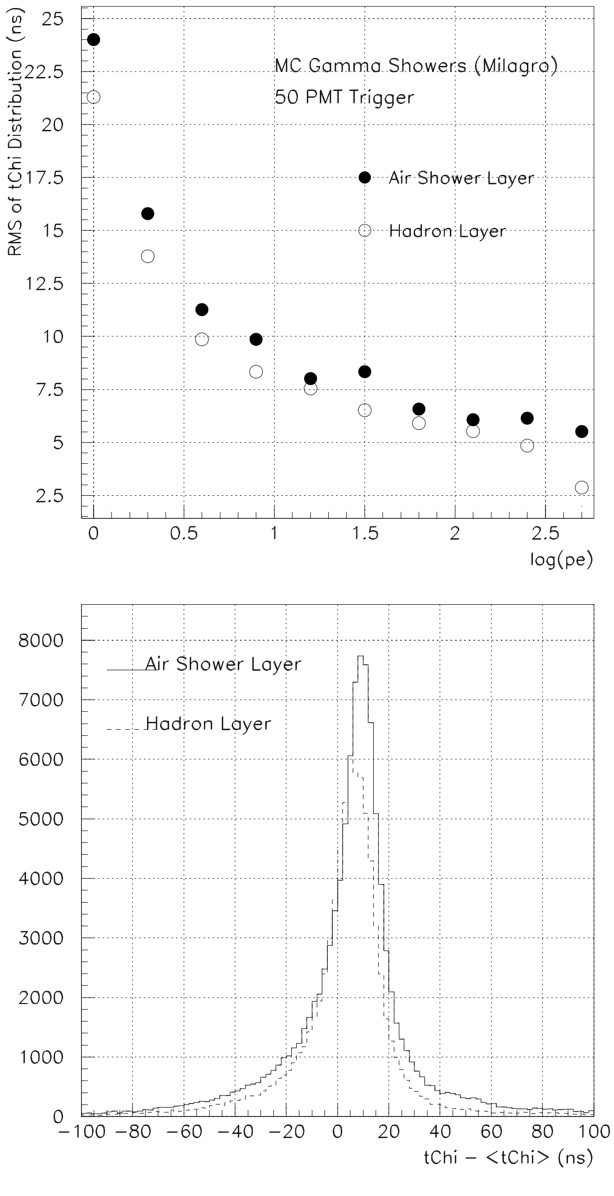

Figure 10: Top: RMS of $\chi_{\rm time}$-distributions as a function of PE (note the log scale). Bottom: $\chi_{\rm time}$-distributions (independent of PE) relative to mean-$\chi_{\rm time}$ of each event

5 Maximal Air-Shower Layer

From time to time, folks have speculated whether we might be better off putting all of our tubes in the air-shower layer, and just going all out for the best possible angular resolution. As discussed in the previous section, an expanded hadron layer may essentially give us that, with muon identification as well. Using all our tubes, we could put twice as many in the air-shower layer. (To the extent that the hadron layer timing is as good as the air-shower layer, we would essentially have this situation over the central two-thirds of the pond, if we opt for the larger hadron layer.) We have not done simulations of a shower layer with 900 tubes. However, it is instructive to make some back-of-the-envelope estimates of what we might expect. Since civil construction is out of the question, these tubes would cover the same area with twice the density as the present air shower layer.

Since the tubes cover the same area, we have twice as many samples of the same part of the shower, and we can expect twice as many hits on average from any given shower as in the baseline design. These hits would have roughly the same lateral distribution as the hits on the baseline design tubes. Twice as many hits, with the same lateral extent, would be expected to improve the statistical error on the angular reconstruction by a factor of $\sqrt{2}$. Assuming the statistical error is dominant (a best case scenario), this improvement in the angular resolution reduces the background by a factor of 2, and the quality factor is

$$\mathrm{Q} = \frac{1}{\sqrt{0.5}} = \sqrt{2} = 1.4. \tag{2}$$

This is assuming that we kept the same trigger threshold (in terms of energy; twice the threshold in turns of tube multiplicity) in order to keep the overall trigger rate the same.

It is trickier to estimate the effect of taking advantage of the denser sampling to turn down the trigger threshold. Consider taking all showers with NFIT > 20 in either case. Since the 20 hits can be spread over a smaller area in the case of the denser layer, they can have less lever arm in the reconstruction (see the discussion in section 3.1.3.2 of the Milagro DOE proposal). Hence, for the same timing resolution, the angular resolution at a given value of NFIT should be worse in the denser shower layer. On the other hand, there is a fraction of large showers with NFIT > 450 in the denser layer, which would be better reconstructed (by at most a factor of $\sqrt{2}$, as argued in the previous paragraph) than in the baseline design.

Ignoring both of these effects for the moment and assuming that the angular resolution for the ensemble of triggered showers with a certain number of tubes hit is the same in both cases, what does that imply for the quality factor? We can estimate the change in rate by comparing the trigger rate at 50 tubes and 25 tubes in the baseline design, *i.e.* we assume that a 25 tube trigger in the baseline design gives us the same rate as a 50 tube trigger would in the doubly dense alternative. We use a sample of 60000 events thrown on an $\mathrm{E}^{-2.7}$ differential spectrum between 0.5 and 10 TeV, with zenith angles from zenith to 45^o, and with cores thrown over a $300\,\mathrm{m} \times 300\,\mathrm{m}$ area.[2] The number of 50 tube triggers for γ's is 2501 and for protons is 2789; the number of 25 tube triggers is 5074 for γ's and 5472 for protons. The quality factor is then roughly

$$\mathrm{Q} = \frac{\frac{5074}{2501}}{\sqrt{\frac{5472}{2789}}} = 1.45. \tag{3}$$

[2]To the extent that the rate change from 50 tubes to 25 tubes is independent of zenith angle, this is legitimate. We should really integrate the effective areas as a function of zenith angle over the path of a source. Here, we are just trying to get a feel for the numbers.

For a harder γ-spectrum, the quality factor would be less, since we would gain relatively more background than signal by lowering the trigger threshold.

In summary, doubling the density of the shower layer compared to the baseline design by putting all of the tubes in that layer would probably yield a quality factor of around 1.4 to 1.5. This would come at the expense of any muon detection and at the ability to locate cores any significant distance off the pond. It appears that we can get most of this benefit from an expanded hadron layer, while still leaving tubes for outrigger detectors in order to locate cores off the pond.

6 Solar Physics

We presume that the expanded muon collection area offered by our alternative hadron layer will yield improved sensitivity for solar physics, just as it results in better muon detection in air showers. While the lack of igloos may make it harder to trigger for solar physics, we have found in Milagrito that we trigger very effectively on muons by simply lowering the coincidence requirement. A trigger requirement of four or five hadron layer tubes, with the possible additional requirement that one have a large pulse height, should prove to be an effective trigger. Although we have not studied this question, it seems reasonable that any inefficiency of a slightly more complicated trigger will probably be more than compensated by the larger area.

7 Summary

We have shown that it is possible to use an expanded 286 PMT hadron layer to achieve substantially better the muon identification and quality factors than for the igloos. The gain is a little less than a factor of two in identified muons, and there is room for reality to be less forgiving than the simulation and still end up with a significant improvement. There is also room for improvement of the muon identification algorithms, so the potential is not only on the down side. An expanded hadron layer also promises to improve the angular resolution, by providing more timing information to be used in the angular reconstruction.

Since the only purpose of the igloos is muon identification, if that task can be done as well or better by putting PMTs into the hadron layer instead, it makes sense to do so. The expanded hadron layer we have studied would only use 88 of the 162 igloo tubes, leaving an additional 74 to be used in outrigger tanks or as spares. This would allow tubes for approximately 150 outriggers, with about ten spares.

We conclude that Milagro will be a better, more sensitive experiment if we dispense with the igloos and expand the hadron layer to 286 tubes. We propose that the collaboration make this decision.