Gamma Ray Astronomy with Air Shower Arrays

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Abstract.
Detectors such as Milagro and ARGO-YBJ reconstruct the energy and arrival direction of very high energy (VHE) photons incident on the earth's atmosphere from measurements of the secondary particles in the air shower which the primary photon generates. These detectors operate continuously and with a wide field of view, allowing them to study all VHE gamma ray sources that pass overhead on a daily basis. This makes them ideal for monitoring time varying sources such as active galactic nuclei and for searching for transient sources such as gamma ray bursts. The Milagro detector is currently operating in the Jemez Mountains near Los Alamos, New Mexico and ARGO is under construction in Yangbajing,Tibet. The current status and future plans of both Milagro and ARGO are discussed and recent results from Milagro are presented.

INTRODUCTION

Astrophysical gamma rays have been directly detected to energies up to tens of GeV. Since the gamma ray flux typically falls as the inverse of energy squared or cubed, satellite and balloon experiments to date have had too small an area and time exposure to be sensitive above these energies. When a primary energetic photon enters the earth's atmosphere, it interacts producing secondary particles, which in turn interact and produce more particles. The result of this process is an atmospheric "air shower" of particles. At energies of about 100 Gev to 10 TeV, the shower particles, mainly electrons, positrons, and photons, increase in number down to a depth of a few hundred g/cm^2 after which they decrease exponentially. By the time this shower reaches sea level, at a depth of about 30 radiation lengths, it contains only a small remnant of shower particles which, depending on the primary energy, may be spread over an area of about a square kilometer. Ground level detectors which are sensitive to these products of the shower are used to indirectly measure properties of primaries whose flux is too small for direct detection.

Ground level air shower characteristics vary widely from event to event for primaries with identical properties. On an event by event basis, it usually not even possible to tell whether the shower was generated by a primary photon or a much more abundant cosmic ray nucleus. Cosmic rays, whose arrival is isotropic due to interstellar magnetic fields, are therefore the major source of background in such measurements. The success of ground based experiments thus depends strongly on the ability to find characteristics which differentiate between these two types of primaries.

Air cerenkov telescopes operate on cloudless moonless nights and view the cerenkov

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light created throughout the atmosphere by relativistic shower particles. The cerenkov image is thus a projection of the full shower which, as first shown by the Whipple experiment in 1989 [1], by virtue of the clumpiness of hadron showers compared with photon showers, can be used to reject a large fraction of cosmic ray generated showers.

In order to continuously monitor the full overhead sky, to search for transient sources such as gamma ray bursts or to study the time variation of “steady” sources, air shower arrays are used. In these methods only the air shower particles which survive to detection altitude are measured by detectors which are shielded from low energy photons. These detectors can thus monitor the full overhead sky at all times. Since they only sample a small surviving part of the shower, it has been more difficult in these methods to discriminate between primary types.

Because it is expensive to cover large areas with particle detectors, such experiments usually sparsely cover with counters a small fraction of a large area. Since the number of surviving particles goes down with decreasing primary energy, these experiments typically have been sensitive to photons with energy above 50 to 100 TeV. A few experiments claimed detection of sources at these energies during the 1980s, but these have not been confirmed. Possible time variation of sources makes definite interpretation of these results difficult.

A new generation of experiments uses a combination of high altitude and large area coverage to lower the threshold of the method enough to overlap with direct detection measurements. The principles of such VHE photon detectors are discussed in the following section. The Milagro experiment, which is currently taking data, and the ARGO-YBJ experiment, which will begin a run with one segment later this year, will be discussed in this paper. Milagro has already demonstrated the power of this technique. Both experiments are developing gamma hadron separation methods which will, if successful, make this technique even more powerful. The rest of this paper discusses the status of both these experiments, discusses their future plans, and presents some recent results from the Milagro experiment.

THE AIR SHOWER ARRAY METHOD

Individual counters in an air shower array will be triggered by the large flux of low energy muons resulting from the abundant GeV cosmic rays. In order to trigger on air showers, a minimum number of counters are therefore required to detect particles within a short time window, usually up to a few hundred nanoseconds. A large central core of particles typically follows a trajectory which is a continuation of that of the primary particle. Extending laterally from the core is an almost planar cone of particles of thickness on the order of 10 ns near the core but with time spread increasing with distance from the core.

The measured counter hit times are fit to a cone to determine the incidence direction of the primary particle. Measurement of the core location, as determined from the lateral signal size distribution, allows fitting the conical shape and improves angular resolution. The lateral distribution of the deposited energy also gives a measure of the primary particle energy. Knowledge of the core location is vital for this measurement, since without this it is difficult to tell the difference between the distribution of a low energy shower near the core and a high energy one far from it.

Since the isotropic TeV cosmic ray background is large, there are several basic methods used to search for a photon signal from a source:

- Angular resolution: Since the background is isotropic, the better the detector angular resolution, the smaller the region over which one looks for signal, and therefore the smaller the average background contribution.
- Gamma - hadron separation: Hadron induced air showers tend to be clumpier than those due to photons. They are also more likely to include hadrons and muons. Although shower fluctuations make it impossible to identify the primary on an event by event basis, one can find parameters on which to select in order to decrease the number of hadrons in any sample relative to the number of photons.
  For a given bin size with a mean number of expected background events B, the significance (in number of standard deviations) of M measured events is approximately given by $(M-B)/\sqrt{B}$. (A more precise formulation takes into account the the fact that the measurement, regardless of its source, has in this case fluctuated to the value M [2].) The gain from imposing some cut can then be quantified by the quality factor Q defined as $Q = [(M_C - B_C)/\sqrt{B_C}]/[(M-B)/\sqrt{B}]$ where the subscript C identifies the same parameters with the selection cuts imposed.
  For purpose of comparison with numbers presented below, air cerenkov experiments allow elimination of over 99% of hadrons while keeping over 50% of photons for a quality factor of about 9.
- Triggring with other experiments: A detector which covers a large region of the sky with a large number of small angular resolution bins will suffer from statistical upward background fluctuations in random bins. If another experiment is used to fix a location or time bin, the probability of such fluctuations are reduced by the number of bins that would have had to be searched without this information. For example, for gamma ray bursts we refer to the triggered versus untriggered searches, where the sensitivity will be better in the former case.

Because only a small remnant of the shower is detected, these experiments rely heavily on Monte Carlo computer simulations of shower development and detector response. Although accelerator measurements for proton - proton interactions at these energies exist, they do not include the forward going particles, which go unmeasured down the accelerator beam-pipe, but which carry the energy forward and determine the major properties of the air shower. In addition, nucleus - nucleus interactions at these energies still remain largely unmeasured. In spite of these problems, the uncertainties due to particle interaction models are often small compared with the uncertainties in the details of detector properties. It is therefore especially important here to compare data and simulation predictions of event properties.

THE MILAGRO EXPERIMENT

The main part of the Milagro experiment is an instrumented, water-filled, man-made 60m x 80 m x 8m pond located at an altitude of 2630 m in the Jemez Mountains near Los Alamos, New Mexico. The pond is instrumented with two layers of photomultiplier tubes (PMTs): 450 PMTs on a 25 by 18 grid of 2.8 meter squares at a depth of 1.4 meters below the water surface, and 273 PMTs on a 19 by 12 grid at a depth of 6 meters. When an air shower hits the detector, relativistic charged particles emit cerenkov radiation along a 41 degree cone. Because of the counter depth and cerenkov angle, a single PMT is sensitive to charged particles anywhere in the local grid square. Photons, which are typically about 5 times as numerous as charged particles in these showers, either pair produce or Compton scatter in the 1.4 m of water, transferring energy to detectable charged particles. The net result is that light from about half of the particles entering the the pond is detected, in contrast to a fraction of a percent for standard air shower arrays.

Because a large fraction of showers which trigger the experiment have cores outside the detector, energy resolution of the existing experiment is poor. This will improve with the addition of counters outside the pond currently in progress and described below. In absence of such knowledge, one simulates detector rates for assumed primary spectra and thereby find bounds on possible primary energy distributions.

A Results from Milagrito

The Milagro prototype, Milagrito, consisted of 228 PMTs whose depths ranged during the run from 1.0 to 2.0 meters and took data from February 1997 to May 1998. This allowed study of the water cerenkov method, comparison of computer calculations with measured data, and was also an experiment in its own right.

Lessons learned from the experimental method include:

- The optimum depth at which to set the counters to maximize time resolution. This was done by comparing Δ_{EO} for data recorded at different water depths.
- The necessity of blocking almost horizontal moving photons. Such cerenkov photons can induce late signals in far away PMTs which have not been previously hit by other shower particles. These were eliminated from Milagro by putting baffles around the PMTs.
- Comparisons of the monte carlo with data showed cosmic trigger rates [3] and zenith angle distribution [4] could be accurately calculated. The angular resolution as seen by Δ_{EO}, the difference between fit arrival angle calculated using two independent sets of PMTs interleaved like the light and dark squares of a checkerboard, is also well simulated [4]. The resulting point spread function is close to that determined from the cosmic ray shadow the moon casts [5].

The Milagrito measurements included:

- Study of the shadowing of cosmic rays by the moon [5] and the sun: This measurement allows study of the detector resolution, study of the earth's magnetic field, study of the solar magnetic field, and a search for anti-particles in cosmic rays.

- Study of solar energetic particle emission events [6]: This showed the sensitivity of the detector's individual PMT rates to changes in the GeV cosmic ray flux and its resulting usefulness as a large area neutron monitor type detector.
- Detection of Markarian 501 [3] which showed the usefulness of this method for studying time varying sources.
- The possible detection of a TeV gamma ray burst seen by BATSE [7]: This showed the power of this method which allows uninterrupted study of the full overhead sky.

Some additional studies, including an untriggered gamma ray burst search and study of other sources are in progress. Still other analyses, although possible with Milagrito data, will probably not be performed because data from the full detector is now available.

STATUS OF MILAGRO

The full Milagro pond detector began an engineering run in July of 1999 and commenced regular data taking in December of 1999. The trigger, a hardware sum requiring at least 50 PMTs above 1/4 equivalent photoelectrons in a 150 ns time window, fires at a rate of ~ 1.5 KHz. Except for a down period during the Los Alamos fire, it has run with a duty cycle better than 95%.

A fit to the shower cone is performed off line using PMTs with pulse height greater than 2 equivalent photoelctrons. PMTS whose timing is far from the fit are removed in an iterative procedure. The number of PMTS surviving in the fit, N_{FIT} is typically required to be greater than 20. The median energy of cosmic ray triggers is 1.8 TeV and the angular resolution for showers whose core is inside the pond is 0.75°.

Photon hadron separation currently uses the clumpiness of hadronic showers versus that of purely electromagnetic ones as observed in the bottom layer PMTs. The parameter X_2 is defined as the ratio of the number of bottom layer PMTs with a pulse height greater than 2 photoelectrons ($NHIT_{BOT}$) divided by the maximum pulse height in equivalent photoelelectrons of a bottom layer PMT ($PEMAX_{BOT}$). A large value of X_2 indicates a less spiked distribution and cutting on $X_2 > 2.5$ provides a quality factor of 1.8 as determined from the monte carlo. The simulation currently does not completely match the data (Figure 1) and the cut appears to be more effective than predicted, as can be seen in the Crab data presented below.

The fraction of the sky to which Milagro is sensitive can be seen in Figure 2, which presents the exposure for 60 days of data.

The efficacy of the X_2 cut can be seen in the preliminary Milagro Crab signal (Figure 3) based on 1.35 years of exposure, which has an excess of 1.0 σ above background (8,749,562 events with an expected background of 8,746,621) for no gamma hadron cuts, increasing to 4.8σ (787,503 events with an expected background of 783,059) when the $X_2 > 2.5$ cut is applied. This would correspond to Q=4.8 if statistical fluctuations could be ignored. Milagro accumulates approximately 10 Crab photons per day.

The recent outburst of Markarian 421 is still being analyzed by Milagro. The preliminary analysis of data from 17 January 2001 to 26 April 2001 shows a signal of 5.2σ significance (See Figure 4).

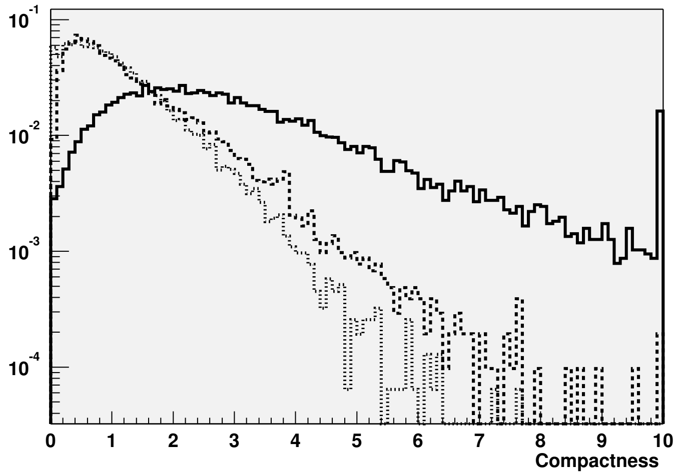

FIGURE 1. Data X_2 distribution (small dots, botom curve) and simulated distribution for photons (solid) and hadrons (large dots)

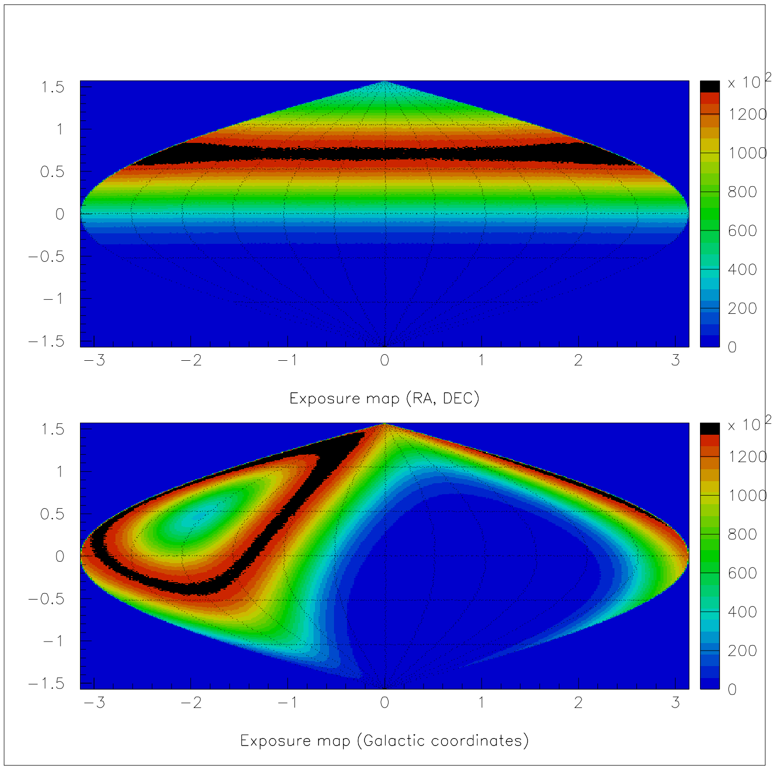

FIGURE 2. Milagro exposure for 60 days of data in bins of 0.5 degrees in declination by 1.0 degrees in -(right ascension) times cos(declination) (top), and in similar sized bins in galactic coordinates (bottom).

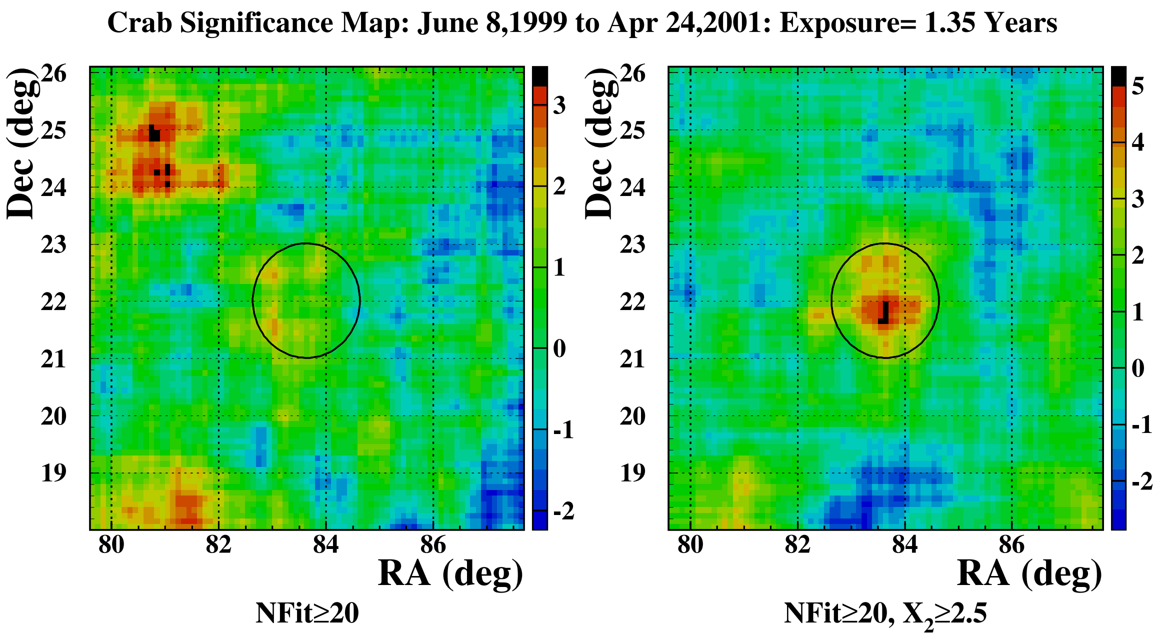

FIGURE 3. Preliminary Milagro background subtracted sky map in the region of the Crab for events with $N_{FIT} > 20$ and no X_2 cut (left), and with $X_2 > 2.5$ (right).

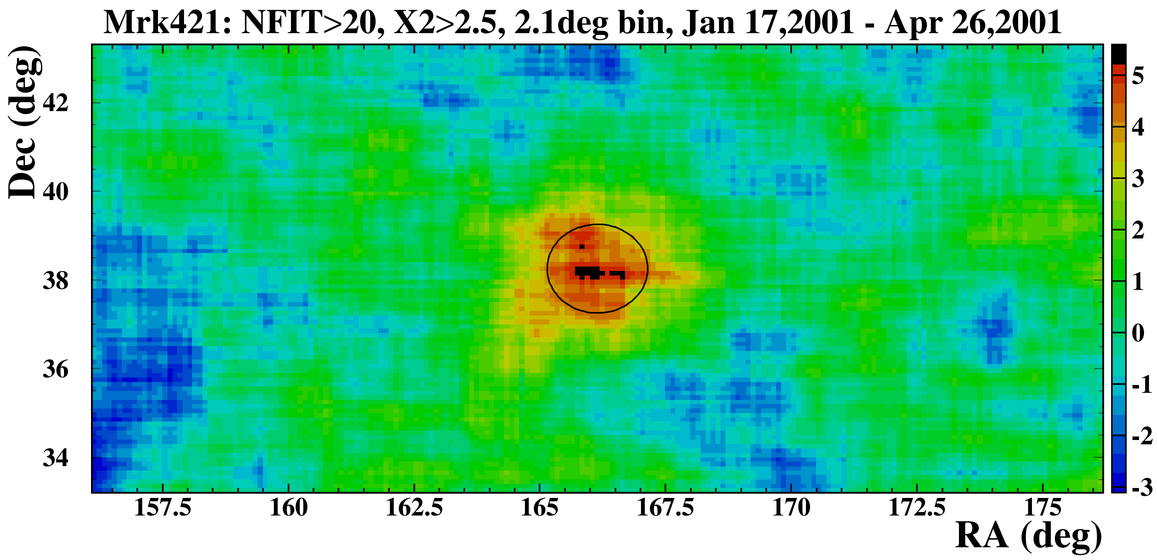

FIGURE 4. Preliminary Milagro background subtracted sky map in the region of Markarian 421.

As Milagro continuously monitors the full overhead sky, studies of the Crab and other galactic sources, studies of AGNs and search for gamma ray bursts are all in progress, as is a search for VHE emission from the galactic plane. Milagro sensitivity to gamma ray bursts is similar in fluence to that of BATSE (Figure 5). Note that this figure does not include any gammma hadron separation or the improvement with the planned outriggers, discussed below. Other cosmic ray studies currently in progress include those of the sun

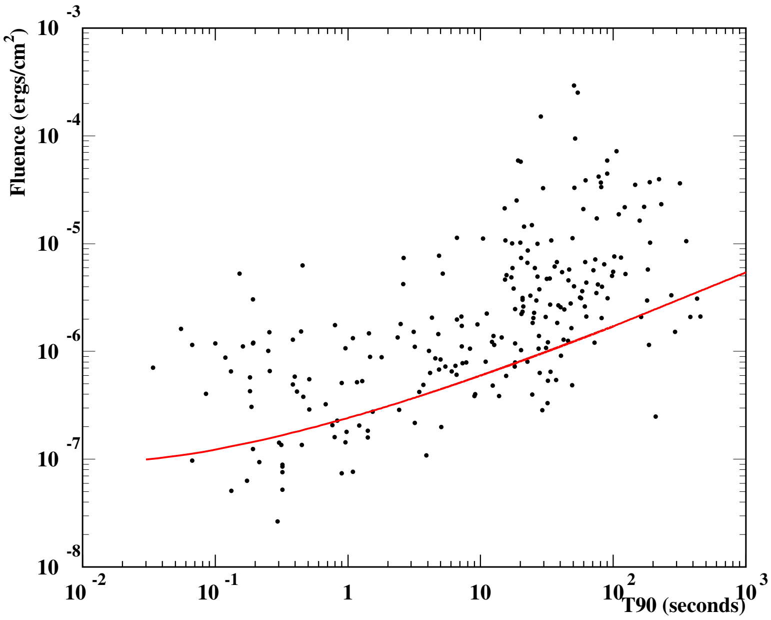

FIGURE 5. Milagro sensitivity to gamma ray bursts compared with BATSE detected events.

and moon shadows, of cosmic rays by measuring surviving unaccompanied hadrons, and of solar energetic particle events. Taking advantage of the fact that, unlike optical detectors, Milagro can monitor the sun and its vicinity, a search is also underway for VHE photons from annihilating relic neutralinos which could be trapped by the solar gravitational field.

FUTURE MILAGRO PLANS

The Milagro energy threshold is currently determined by the muon background rate. If the N_{HIT} cut is lowered, the trigger rate is overwhelmed by non-vertical muons whose cerenkov light can fire many PMTs. The Milagro angular resolution, about 0.75 degrees for on-pond showers which allow the cone shape and sampling corrections to the fit, is appreciably worse (Figure 6) for showers whose core is off the pond. Milagro can tell little about primary energy from the shower it measures without knowledge of the core position. For all of these reasons, a array of 176 counters is being deployed in an area about 10 times that of Milagro centered on the Milagro pond. The construction began in the summer of 2000 and is on-going. With these counters in place, angular resolution is expected be better than 0.9 degrees for showers as far as 200 meters from the pond center, energy resolution is expected to be about 50% for showers of energy above ~ 2 TeV, and the air shower size threshold can be lowered significantly.

The gamma hadron separation capabilities of Milagro are just beginning to be understood and exploited. In addition to X_2, the two dimensional $\mathrm{NHIT_{BOT}}$ and $\mathrm{PEMAX_{BOT}}$ space is being studied. Additional parameters which can be used include the shower signal rise time and the lateral signal distribution for both top and bottom PMT layers.

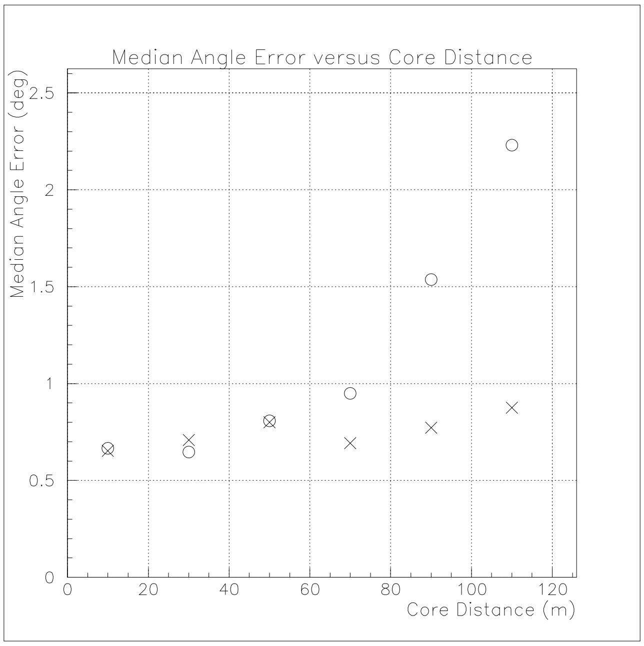

FIGURE 6. Milagro angular resolution as a function of core distance from the pond center with (X's) and without (circles) outriggers.

Early studies already show the possibility of significant improvement in quality factor. The future of Milagro is thus a bright one.

ARGO-YBJ

The ARGO-YBJ experiment [8], a Chinese - Italian collaboration, uses resistive plate chambers (RPCs) to provide a 6700 m^2 active area at an altitude of 4300 m in Yangbajing, Tibet. This allows detection of primaries with energies as low as 20 GeV and brings the sensitivity down to about 1/10 the Crab flux from 100 GeV to 20 TeV. An overall trigger rate of 20 KHz (with a 15 pad trigger) and an angular resolution of about 0.4 degrees for 100 pad multiplicity events is expected.

Each RPC is constructed of 10 pads of size 0.60 m by 0.56 m. The plan is to cover 92% of a 78m by 74 m central carpet, and an additional 20 % of the remaining area inside a 111m by 99 m rectangle. Photons will be converted by a layer of 0.5 cm lead covering the RPCs.

Gamma hadron separation using the the radial distribution, expected to be steeper for photons, local lateral fluctuations in the signal, expected to be larger for protons, and a neural network analysis [9] is expected to give a quality factor of about 1.8 retaining 80% of photons.

From February to May of 1998 a 51 m^2 area with 91% active area was tested with the following results [10], all consistent with expectations for the final detector listed above:

- 1.3 ns time resolution

- Δ_{EO} about 2 degrees for 100 pad multiplicities.
- Resolution for 35 pad multiplicity events goes down from 8 degrees to 5 degrees with the addition of the lead layer.

Construction of an 800 m^2 area began in October of 2000 and is expected to begin taking data sometime in 2001. The full central carpet is expected to be completed by the end of 2003 and the outer ring by 2004 [11].

CONCLUSIONS

The current generation of VHE gamma ray air shower detectors is coming into its own. Milagro has shown that the method works and the advantages of a method which can continuously monitor the full overhead sky. ARGO will provide significant overlap with existing satellite detector energies. A qualitative change in the power of air cerenkov experiments occurred when a powerful gamma-hadron separation technique was introduced. Milagro is already using some separation techniques, but improvements are possible in both experiments and should lead to major improvements.

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