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A New Background Rejection Technique for the Milagro Gamma-Ray Detector

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Abstract: A new background rejection technique that significantly increases the sensitivity of the Milagro detector has been developed. This technique, combined with other improvements, improves the sensitivity of the Milagro detector by more than a factor of 2.5 over the previous technique [1]. This new technique differentiates between hadronic and gamma-ray showers by looking at the fundamental differences in the shower parameters between these two types of showers and how they register in the detector. These shower parameters include the number of Muons presented in the EAS, the size of the EAS, and some shower reconstruction parameters. This technique resulted in discoveries of localized TeV gamma-ray sources from the Galactic plane [2]. Details of the new technique along with an all-sky TeV gamma-ray map –using this technique– will be presented.

Introduction

Milagro is a water-Cherenkov detector at an altitude of 2630m capable of continuously monitoring the overhead sky. The Milagro detector is composed of a central 80m x 60m x 8m (depth) pond with a sparse 200m x 200m array of 175 "outrigger" tanks surrounding it. The central pond is instrumented by 723 photo multiplier tubes (PMTs) that are submerged in 24 million liters of purified water which acts as the detection medium for the secondary particles in an air shower. The 723 PMTs are split into two layers: the top "air shower" layer consists of 450 PMTs and is under 1.4m of water, and the bottom "muon" layer has 175 PMTs and is located 6m under the surface of the water. The outrigger array extends the physical area of Milagro from 5000m^2 to 40,000m^2, thus improving the core location and angular resolution of the detector by providing a longer lever arm with which to reconstruct events. Extensive air showers initiated by charged cosmic-ray particles out number those of cosmic gamma rays by a factor of $\sim$1000 at the altitude of Milagro. A successful detection of a celestial gamma-ray signal requires the proper identification and rejection of this large cosmic-ray background.

Identification and Rejection of Hadronic Events

It is well known that extensive air showers induced by hadronic cosmic rays contain many more muons (from pion decay) and hadrons than EAS induced by gamma rays of comparable energies. The atmospheric overburden at the Milagro site is 20.5 radiation lengths and 8.3 interaction lengths. The muon layer in Milagro is located under 6m of water (corresponding to 17 more radiation lengths and 7.2 interaction lengths). This means that all EM charged particles that enter the pond get absorbed before reaching this layer. On the other hand, muons with energies as low as 1.2 GeV can penetrate and radiate Cherenkov light near the PMTs of the muon layer. These penetrating muons and hadrons will result in bright compact clusters of light in this layer. Using Monte Carlo simulations we estimate that 79% of all proton showers that trigger Milagro contain a muon and/or a hadron that enters the pond, while only 6% of gamma ray induced air showers contain a muon and/or a hadron that enters the pond.

A new parameter has been developed to parameterize the "clumpiness" in the muon layer. This parameter, A$_4$, is given by[3, 4]:

$$A_4 = \frac{(f_{top} + f_{out}) \times N_{fit}}{mxPE} \quad (1)$$

where

- f_{top} is the fraction of the air shower layer PMTs hit in an event.

- f_{out} is the fraction of the outriggers hit in an event.

- N_{fit} is the number of PMTs that entered in the angle fit.

- $mxPE$ is the number of photoelectrons (PEs) in the muon layer PMT with the highest hit.

The first part in the numerator of A_4 carries information about the size of the shower, while N_{fit} carries information about how well the shower was reconstructed. mxPE carries information about the clumpiness in the muon layer. Figure 1 shows A_4 distributions for different types of showers. The A_4 distribution of Monte Carlo cosmic-ray events are shown in red, Monte Carlo gamma-ray events are shown in blue, and data in black. The green line represents the Quality Factor[1] as a function of A_4. The A_4 distribution for gamma-ray events extends to larger values of A_4 because these showers contain fewer penetrating particles, such as muons and hadrons, which produce localized light in the bottom layer to give large values of mxPE without greatly increasing the number of hit PMTs. Requiring events to have $A_4 \geq 3.0$ rejects 96.5% of the simulated cosmic-ray-induced air showers that trigger Milagro and 96.3% of the data (for this data sample), and retains 32% of the gamma-ray-induced air showers. This results in a predicted Q-factor of 1.7 comparing Monte Carlo cosmic-ray events to Monte Carlo gamma-ray events, and 1.66 comparing the data to Monte Carlo gamma-ray events.

Tests of A_4 on the Crab Nebula

The Crab Nebula acts as a standard candle for gamma-ray astronomy due to its long-term, unchanging energy emission through many wave-
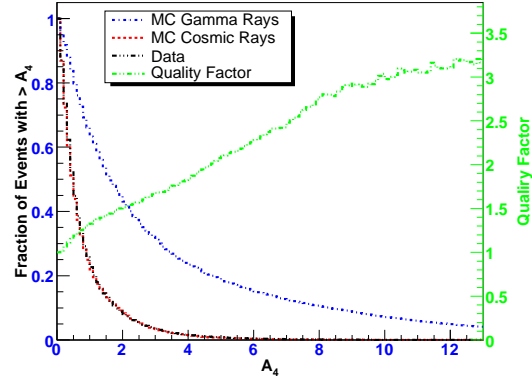

Figure 1: Distribution of A_4 for different types of showers. The A_4 distribution of Monte Carlo cosmic-ray events are shown in red, Monte Carlo gamma-ray events are shown in blue, and data in black. The green line represents the Quality Factor as a function of A_4.

lengths. Thus, the performance of A_4 is best verified on this source. 1.7 years of data was searched for a TeV gamma-ray signal from the Crab Nebula where the $A_4 \geq 3.0$ was applied. 2074 signal events were observed over the 60637 background events. This corresponds to 3.42% signal-to-background ratio and statistical significance of 8.02 σ. when a harder A_4 cut of 12 was applied on the same data set, 44 signal events where observed on top of the 75 background events. This corresponds to 60% signal-to-background ratio and statistical significance of 5.6 σ. Although there was a $\sim 30\%$ loss in statistical significance of the Crab Nebula when the harder A_4 cut was applied, the main advantage of applying this cut is the higher S/B ratio achieved with this cut compared to that with the soft A_4 cut.

1. The Quality Factor (Q) is a measure of the relative increase in significance of a signal for a given selection criterion. For a large number of events, Q is given by:

$$Q = \frac{\epsilon_s}{\sqrt{\epsilon_b}} \quad (2)$$

Where ϵ_s and ϵ_b are the efficiencies for retaining the signal and background events, respectively.

A_4 Weighting Analysis

The fact that one can achieve higher S/B ratios with no major loss in statistical significance when applying harder A_4 cuts led to the development of an alternative analysis method that weights events based on the relative probability that the event was due to a gamma-ray. Therefore, instead of counting all the events in an angular bin equally, a weighted sum of events is used in which events with higher values of A_4 are assigned higher weights. The significance is computed using the method described in Li & Ma [5], where background fluctuations are similarly estimated for the sum of the weights of the background sample, rather than the background event count. The statistical significance derived from this analysis was verified both by Monte Carlo simulation and through the study of statistical fluctuations in the background data sample. The values of the weights used in this analysis are determined from the predicted S/B ratio as calculated a priori from our detector simulation for an incident Crab-like spectrum.With this weighting scheme, this analysis is equivalent to a likelihood ratio method estimation in the limit that the background is large, which is true for the Milagro data.

Figure 2 shows a map of the statistical significance around the Crab Nebula with the new A_4 weighting analysis method applied. The statistical significance at the location of the Crab in this map is $11.32\,\sigma$.

The weighted analysis enhances the contribution of higher A_4 events that are, on average, higher energy gamma rays. The median energy with this analysis is 12 TeV for a Crab-like spectrum with a differential photon spectral index of $E^{-2.6}$. By comparison, a previously published Milagro analysis had a median energy of 3-4 TeV [1]. The angular resolution improves from $0.72°$ to $0.5°$ when this analysis method is used.

Conclusions

The combination of the installation of the outrigger array, the adoption of the A_4 discriminant, and the event weighting increases the sensitivity of Mi-
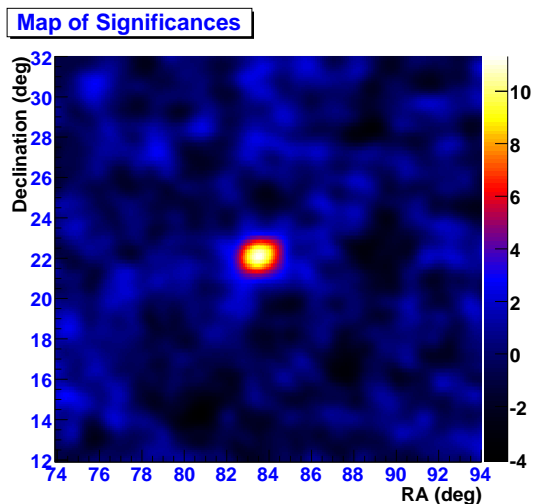

Figure 2: Map of the statistical significance around the Crab Nebula with the new A_4 weighting analysis method applied. The statistical significance at the location of the Crab in this map is $11.32\,\sigma$.

lagro as compared to previous analysis by ~ 2.5 times as confirmed by observation of the Crab.

Acknowledgments

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