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Energy Spectrum of gamma rays from the Crab nebula from 1 to 100 TeV with the Milagro telescope

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Abstract: The Crab is a standard calibration source for TeV gamma ray astronomy. Its energy spectrum extends beyond 10s of TeV, however, an open question is does the spectrum cutoff and at what energy. We present new results from Milagro analysis of the energy spectrum of the Crab nebula up to 100 TeV with good statistical determination. A robust algorithm was developed to estimate the energies of gamma rays on an event by event basis. This energy algorithm is based upon correlation of incident energy with core distance, zenith angle and the number of PMTs hit in the air shower and outrigger layers of Milagro telescope as determined by simulations using CORSIKA and GEANT. The variables used for energy estimation are relatively independent of the quantities used to make the gamma/hadron separation cut. The energy algorithm is used to measure the spectral slope of the background cosmic ray triggers in the full 1 to 100 TeV energy range, which gives a fit with a single spectral slope of -2.71 ± 0.03, showing that the algorithm works well over this energy range. The procedure is then used to obtain the energy spectrum for the Crab signal, which is found to fit well to a power law.

The Milagro γ-ray Observatory

The Milagro instrument consists of a 60 m x 80 m pond containing a total of 723 photomultiplier, with 263 tubes submerged at a depth of 6 m and 450 at a depth of 1.4 m. The photomultipliers in both layers are spaced 2.7 m for their nearest neighbor in a grid pattern (see figure 1). The main pond is surrounded by a 200 m x 200 m "outrigger" array, which consists of cylindrical water tanks with a radius of ≈ 1 m and a height of ≈ 0.75 m, each containing a single inverted photomultiplier tube. Milagro is located at an altitude of 2630 m, approximately 45 km northeast of Los Alamos, NM.

Energy Reconstruction

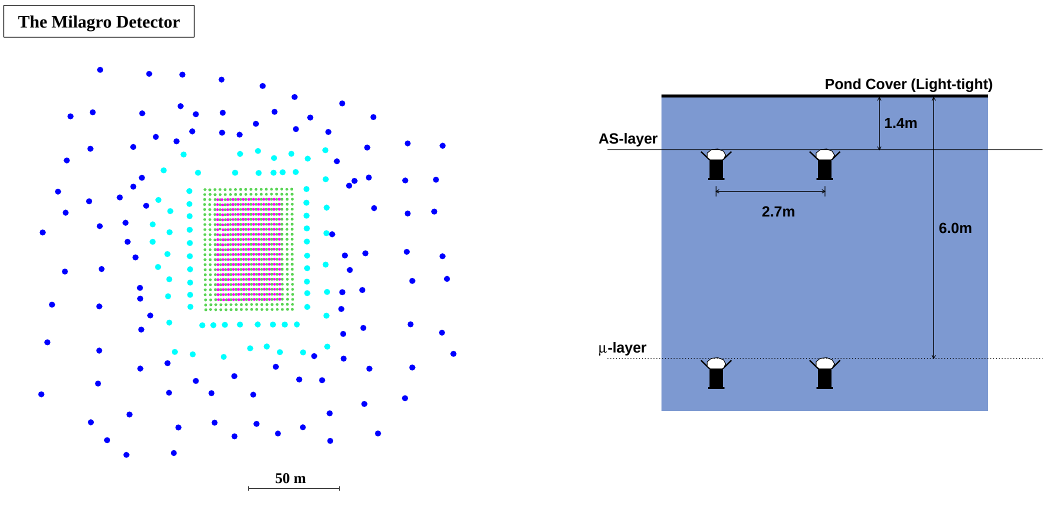
Event-by-Event energy reconstruction in Milagro is dependent upon the core distance of an extensive air shower (EAS) from the center of Milagro (r_c), the zenith angle of the primary particle (θ) and the detector response to the event, which is measured through the number of photomultipliers triggered in the air shower layer (N_{AS}) and outrigger array (N_{OR}). Though Monte Carlo simulations it has been determined that the parameter ξ given by

$$\xi = \frac{N_{\mathrm{AS}}}{\cos(\theta)} + \langle\omega\rangle\, N_{\mathrm{OR}} \qquad (1)$$

has a strong correlation with the energy of the primary particle. $\langle\omega\rangle$ is a weight introduced to correct for the relative triggering efficiency and spacing of the outrigger array and the AS layer.

The determination of energies is carried out using ξ by dividing the data into three 10° and one 15° zenith angle bins. The data is further partitioned into 6 r_c bins. From the Monte Carlo data the correlation with energy is determined independently for each bin and stored for the determination of event energies (see figure 2). Event energies are determined through

$$E_{\mathrm{fit}} = E_0 \left\{\frac{\xi}{\xi_0}\right\}^{\ln\left\{\frac{\xi_0}{\xi_1}\right\} \ln\left\{\frac{E_1}{E_0}\right\}} \qquad \xi_0 \leq \xi < \xi_1 \qquad (2)$$



(a) (b)

Figure 1: (a) Layout of the Milagro detector and (b) schematic of the Milagro Pond. The AS layer photomultiplier tubes are shown in green, the μ-layer tubes are shown in magenta, and the outrigger tubes are displayed in dark and light blue.

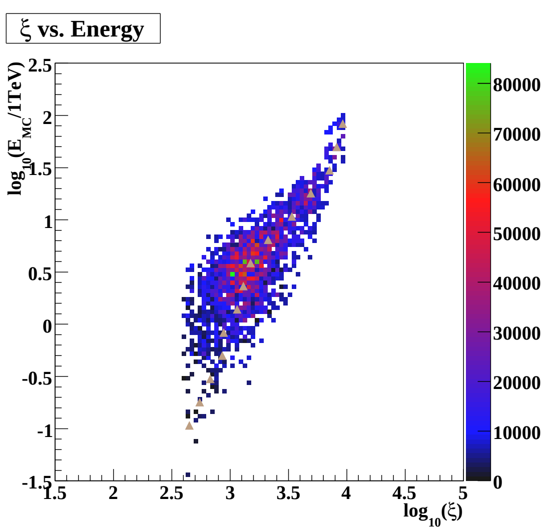


Figure 2: ξ vs. Energy for the fourth r_c and third θ bin. These correspond to events within r_c and θ. The beige points correspond to the median ξ value as a function of energy which are stored for the event-by-event reconstruction of energy.

where ξ_0 and ξ_1 are the median values of ξ as determined from the parameter distributions at energies E_0 and E_1 respectively.

Thorough this method the determination of the energy of γ-ray primaries is possible with energy resolutions approaching 37% at high energy. At lower energies resolution functions are asymmetric making a number of corrections necessary.

Using this technique a spectral fit was preformed for the determination of the cosmic ray spectrum between 1 TeV and 100 TeV, yielding a spectral index of $\gamma = -2.71 \pm 0.03$ in good agreement with that of direct measurements of the all particle spectrum within this energy range [1].

Spectral Reconstruction

Following the procedure outlined in [1] spectra are reconstructed through a χ^2 minimization process with respect to the parameters of an assumed spectrum, where the number of predicted events are compared to the measured events. The number of predicted events in Milagro are given by,

$$\widetilde{N}_j(\vec{\gamma}) = \int_{0^\circ}^{45^\circ} d\theta \int_{0.1}^{120} dE' \epsilon(\theta) f_j(E') \cdots$$
$$\cdots \vartheta(\vec{\gamma}, E') A_{\text{eff}}(E', \theta) w(E', \theta) \quad (3)$$

where the integration is carried out over the zenith angle and true energy (E') with $\epsilon(\theta)$ as the exposure of a particular source as a function of the zenith, $\vartheta(\vec{\gamma}, E')$ as the assumed differential spectrum as a function of energy, as $w(E', \theta)$ the weight distribution computed for γ-rays from Monte Carlo as a function of zenith angle and energy, and $ga\vec{m}ma$ are the parametesr of the assumed spectrum. The resolution function $f_j(E')$, is defined as the probability that an event with true energy between E' and $E' + dE'$ will be reconstructed within the j-th fit energy bin, is included to correct for systematic effects associates with the energy estimation algorithm. The χ^2 function is simply given by

$$\chi^2(\vec{\gamma}) = \sum_{i=1}^{N} \left\{ \frac{\widetilde{N}_i(\vec{\gamma}) - N_i}{\sigma_i} \right\}^2 \quad (4)$$

where the minimization is preformed with respect to the parameters of the assumed spectrum ($\vec{\gamma}$). The vector γ contains the parameters spectal index and intensity. The weights for transit of the crab nebula as a function of energy are given in figure 3a, each point is set at an energy that is corrected for the effects of asymmetric energy resolution.

The Crab Nebula

The spectrum of the Crab Nebula has been measured in the energy range from 1 TeV to 100 TeV. Preliminary resulst show that our measurement is in agreement with the previous observations made in the same energy range. At the conference, we will present our analysis of 1346 days of data. Preliminary results are shown in figure 3.

Acknowledgments

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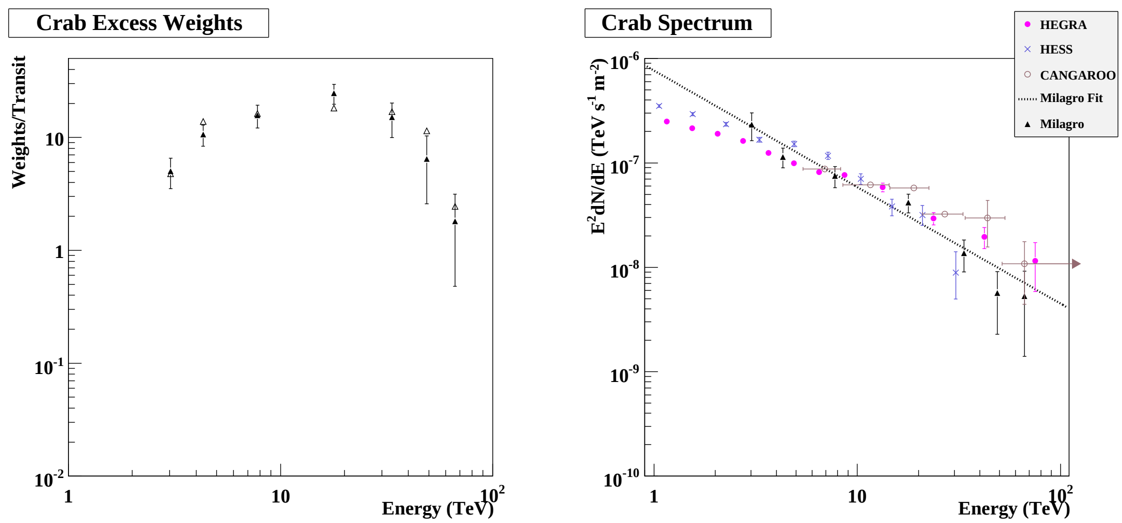
References

[1] B. T. Allen, et al., Measurement of the Crab Spectrum with Milagro, Journal of Physics Conference Series 60 (2007) 321.



(a) (b)

Figure 3: Preliminary results on the Crab energy spectrum. (a) Excess weights as a function of energy, with the number of expected weights computed for the fit spectrum shown to the right. (b) Comparison of the spectrum fit to Milagro data and other IACT experiments.