Energy Spectra with the Milagro Detector

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I Introduction

The Milagro telescope is a ground based water Cherenkov air shower array for the observation of multi-TeV gamma rays and cosmic rays. It consists of a central 60m x 80 m pond with a 200m x 200m array of 174 "outrigger"tanks surrounding it. The central pond consists of an air shower layer of 450 PMTs located under 1.4 m of purified water and a bottom muon layer of 273 PMTs located 5m below the surface. The air shower layer and the outrigger tanks locate the shower core and provide timing measurements to reconstruct the shower direction and provide the trigger. The muon layer is used to detect penetrating muon and hadrons and provide means of distinguishing between gamma-ray and hadron induced showers. A procedure developed to estimate energies of primaries which trigger Milagro on an event by event basis is described in briefly in section II. Using this procedure, energy spectra of gamma-rays from the Crab nebula and spectra of Milagro background triggers have been determined in the energy range 1 to 100 TeV. The measured spectra are compared with those measured by ACT techniques and direct measurements of cosmic ray spectra.

II Energy Calculation

The event by event estimation of energies in Milagro is based upon simulations carried out using the GEANT program for detector simulations and CORSIKA package for Cherenkov air shower simulations. The energy algorithm is based upon correlation of incident energy with core distance (r_{core}), zenith angle (θ), and number of PMT's hit in the upper layer of Milagro's main pond (N_{AS}) and in the outrigger array (N_{OR}). The energy parameter is given by

$$p = \frac{N_{AS}}{cos(\theta)} + \bar{w}N_{OR} \quad (1)$$

is fit to a function of the form

$$E_{ij}(p) = \{\alpha_{ij} + \beta_{ij}p\}\, e^{\gamma_{ij}p+\Gamma_{ij}p^2} \quad (2)$$

where $E_{ij}(p)$ gives the fit energy in each i-th zenith angle and j-th core distance bin, $\bar{w}$ is the average weight assigned to each outrigger to account for irregular spacing, and the constants α_{ij}, β_{ij}, γ_{ij}, and Γ_{ij} are determined from the Monte Carlo data fits in each energy bin. Through this procedure we are able to produce a reliable energy estimation method over an energy range from approximately 1 up to 100 TeV, with energy resolutions approaching 35% at high energies for gamma ray primaries. Figure 1 shows the distribution of fractional deviation from true energy for gamma ray showers, for fitted energies between 20 and 50 TeV. The distribution shows a Gaussian distribution with a width of about 35% and asymmetric tail. The energy dependence of the energy resolution is given in figure Figure 2a. Figure 2b shows that median fit energy estimates the true energy well above 2 TeV. Figure 3 show a scatter plot of fit energy vs. true energy.

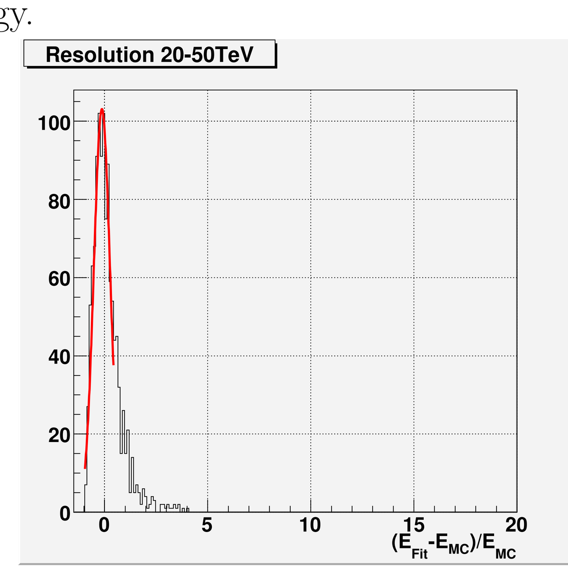
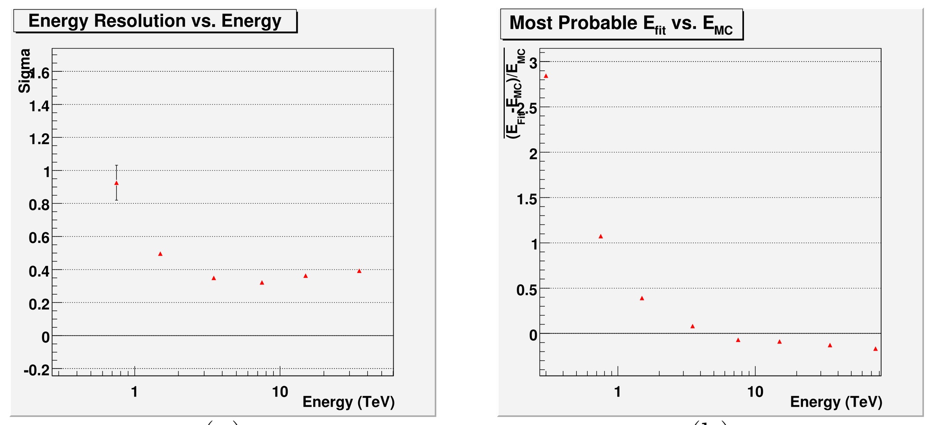


Figure 1: Energy Resolution between 20.0 TeV and 50.0 TeV. Resolutions are fit to a Gaussian distribution. For this figure $\sigma = 0.374$ and $\bar{x} = -0.07$



(a) (b)

Figure 2: Gaussian fit parameters (see 1) vs. Monte Carlo energy.

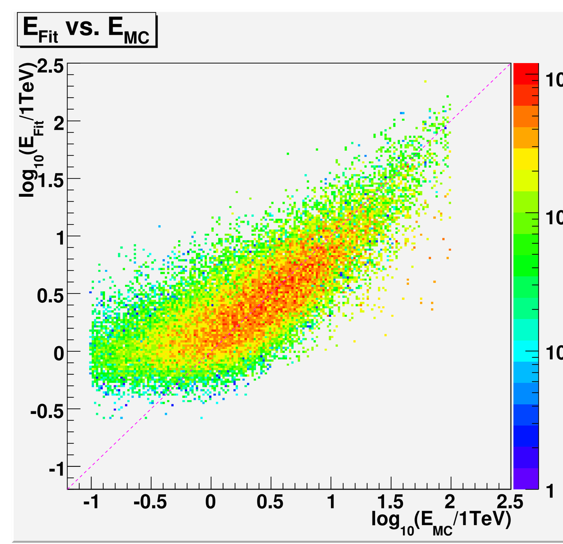


Figure 3: Fit Energy vs. Monte Carlo Energy for γ-rays

III Determination of Spectra

Spectra are fit through a χ^2 minimization process designed to account for asymmetries in the energy resolution. In the Milagro analysis each event is assigned a weight according to the probability that a given air shower originated from a proton or a gamma ray. An excess weight for each energy bin is measured, and significance for these excesses is calculated. For each measured energy bin a predicted number of weights can be computed from detector simulations through,

$$W_i = \int_0^{45^\circ} d\theta \int_{0.1TeV}^{\infty} dE\, \{\epsilon(\theta) f_i(E,\theta) j(E) A(E,\theta) W(E,\theta)\} \quad (3)$$

where $f_i(E)$ is the probability that an event of true energy E will be reconstructed with an energy inside of the i-th fit energy bin, $j(E)$ is the form of the assumed spectrum (usually a power law), $A(E,\theta)$ is the Milagro effective area and $W(E,\theta)$ the average weight for a given energy and zenith angle. For a fixed set of parameters in $j(E)$ a different set of predicted excess events may be determined. Minimization of the χ^2 value, given by

$$\chi^2 = \sum_{i=1}^{n_{bins}} \left\{ \frac{W_i^{(measured)} - W_i}{\sigma_i} \right\}^2 \quad (4)$$

with respect to the excess measured from a source give the optimum fit to the data.

IV Energy Spectrum of Background Triggers

Using the method briefly described in section III and setting $W(E,\theta)$ to unity, we estimate a power law spectrum of the form $I_0\,(E/10TeV)^{-\gamma}$, assuming background triggers are generated by proton primaries. We obtain $I_0 = 5.56\text{x}10^{-4} TeV^{-1} sr^{-1} s^{-1} m^{-2}$ and $\gamma = -2.70 \pm 0.08$. The spectral index derived from the analysis of background triggers in Milagro is in reasonable agreement with those of direct measurement from JACEE [3] and RUNJOB [4]. The calculation of estimated energies in this analysis of background triggers uses the energy algorithm for gamma ray triggers, hence it is preliminary. The spectrum obtained for Milagro background is shown in figure 4, where the flux axis is in arbitrary units. A more realistic analysis using an energy algorithm based on proton and helium Monte Carlo's is currently underway to obtain primary cosmic ray spectra.

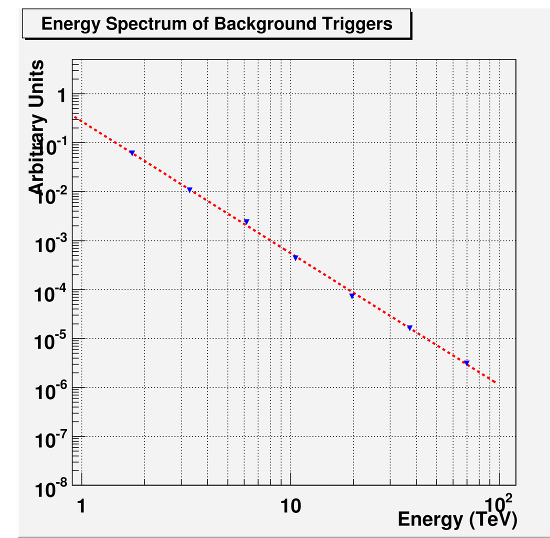


Figure 4: Cosmic ray spectrum as measured with Milagro shown by the blue points (the statistical error bars are smaller than the size of the points shown). The dashed red line represents the fit obtained through χ^2 minimization.

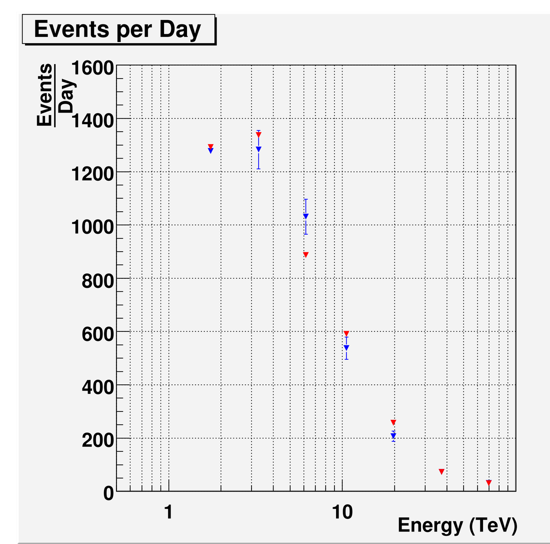


Figure 5: Event rates in individual energy bins, compared with expected event rates after minimization. (Blue points are the measurement, and the red represent the expected event rates)

V Crab Spectrum

For determining the gamma ray spectrum from the Crab we include hadron rejection cuts and gamma-hadron weights as outlined in section III. Through χ^2 minimization we obtain the spectrum to be $I_0 = (4.84 \pm 1.23)\text{x}10^{-10} TeV^{-1} m^{-2} s^{-1}$ with a spectral index of $\gamma = -2.78 \pm 0.14$ for a power law with I_0 normalized to 10 TeV and reduced χ^2 value of 2.31.

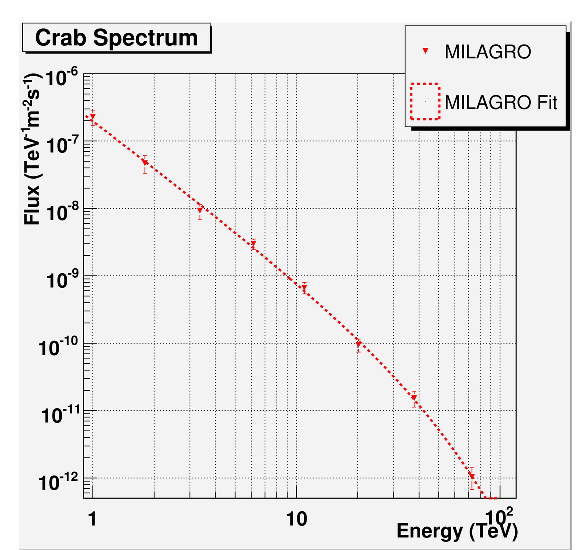


Figure 6: Milagro fit for the Crab Spectrum

A fit with the addition of an exponential cutoff,

$$j(E) = I_0 \left\{ \frac{E}{10TeV} \right\}^{\gamma} e^{-\frac{E}{E_c}} \quad (5)$$

gives the result $I_0 = (1.04 \pm 0.56)\text{x}10^{-9} TeV^{-1} m^{-2} s^{-1}$, $\gamma = -2.29 \pm 0.39$, with $E_c = 31.0 \pm 26.26 TeV$ and a reduced χ^2 value of 0.33, indicating a probable cutoff in the region above 10 TeV (See Figure 6). The Milagro results are consistent with the measurements of other experiments, and provides competitive measurements up to 100 TeV (see figure 7).

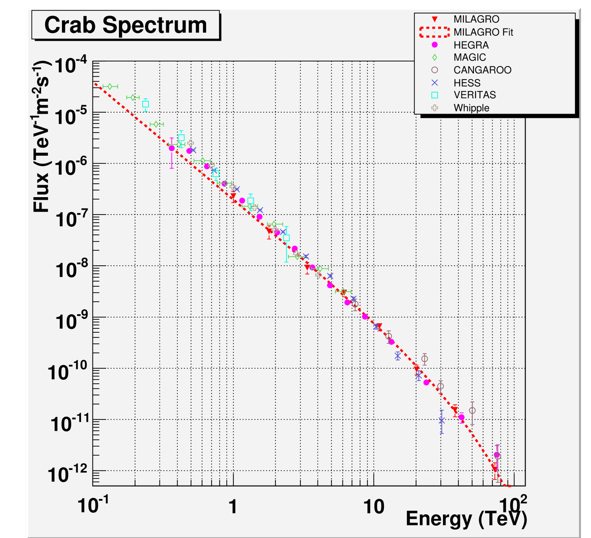


Figure 7: Milagro Comparison with selected experiments [2, 7, 6, 5, 1, 8]

VI Conclusions

We have developed a method for event by event determination of primary energy using MC based on CORSIKA and GEANT programs to simulate the experiment. We are able to measure energy spectra in the TeV energy range extending up to 100 TeV. Our result for the slope of the Milagro background is consistent with the most recent direct measurements of the cosmic ray spectrum. The measured Crab spectrum is in agreement with published results from HESS and HEGRA experiments and indicate a possible cutoff in the region between 10 and 50 TeV.

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