

# Measurement of the Crab Spectrum with Milagro

B.T. Allen<sup>1</sup> and G.B. Yodh<sup>1</sup> for the Milagro Collaboration

<sup>1</sup>Department of Physics and Astronomy

University of California, Irvine

Irvine, CA 92697-4575

E-mail: btallen@uci.edu

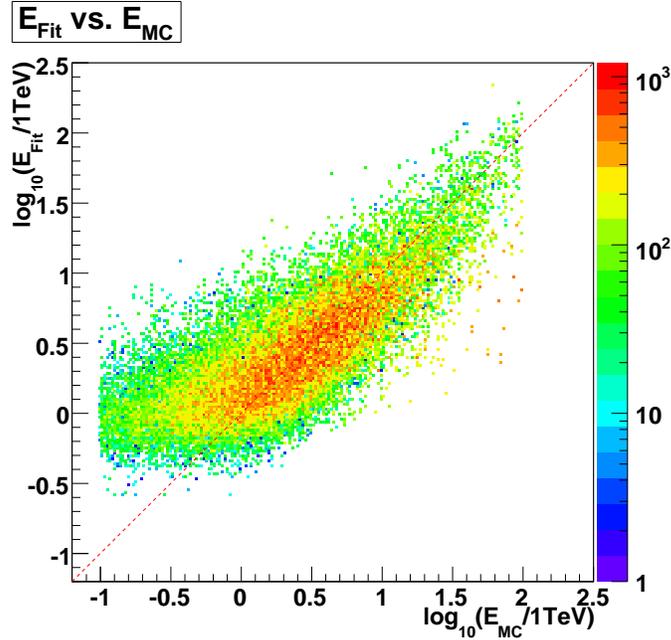
**Abstract.** Through use of new algorithms for estimating  $\gamma$ -ray and cosmic ray primary energies of events in Milagro we determine the energy spectra of gamma rays from the Crab nebula and spectra of Milagro background triggers have been determined in the energy range 1 to 100 TeV. The measured spectra are compared with those measured by ACT techniques and direct measurements of cosmic ray spectra.

## 1. 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 ( $\theta$ ), 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  $p = N_{AS}/\cos(\theta) + \bar{w}N_{OR}$  and is fit to a function of the form  $E_{ij}(p) = \{\alpha_{ij} + \beta_{ij}p\} e^{\gamma_{ij}p + \Gamma_{ij}p^2}$  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  $\alpha_{ij}$ ,  $\beta_{ij}$ ,  $\gamma_{ij}$ , and  $\Gamma_{ij}$  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.

## 2. Determination of Spectra

Spectra are fit through a  $\chi^2$  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  $W_i = \int_0^{45^\circ} d\theta \int_{0.1TeV}^{\infty} dE \{\epsilon(\theta)f_i(E, \theta)j(E)A(E, \theta)W(E, \theta)\}$  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,  $W(E, \theta)$  the average weight for a given energy and zenith angle, and  $\epsilon(\theta)$  is the exposure time as a function of zenith angle. For a fixed set of parameters in  $j(E)$  a different set



**Figure 1.** Fit Energy vs. Monte Carlo Energy for  $\gamma$ -rays

of predicted excess weights may be determined. Minimization of  $\chi^2$  with respect to the excess measured from a source give the optimum fit to the data.

### 3. Energy Spectrum of Background Triggers

Using the method briefly described in section 2 and setting  $W(E, \theta)$  to unity, we estimate a power law spectrum of the form  $I_0 (E/10\text{TeV})^{-\gamma}$ , assuming background triggers are generated by proton primaries. We obtain  $I_0 = 5.56 \times 10^{-4} \text{TeV}^{-1} \text{sr}^{-1} \text{s}^{-1} \text{m}^{-2}$  and  $\gamma = -2.70 \pm 0.08$ . The spectral index derived from the analysis of background triggers in Milagro is in agreement with those of direct measurement from JACEE [3] and RUNJOB [4]. This preliminary analysis assumes all background triggers are induced by a primary cosmic ray proton. A more realistic analysis based on proton and helium Monte Carlo is currently underway in order to obtain primary cosmic ray spectra.

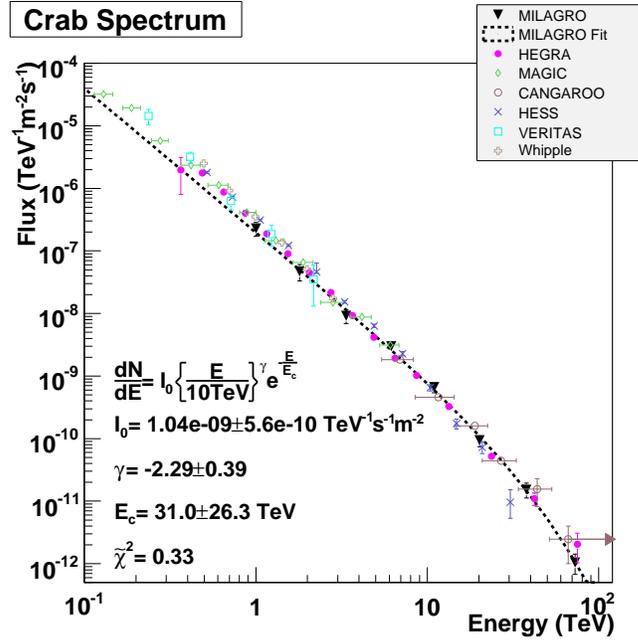
### 4. Crab Spectrum

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

A fit with the addition of an exponential cutoff, gives the result  $I_0 = (1.04 \pm 0.56) \times 10^{-9} \text{TeV}^{-1} \text{m}^{-2} \text{s}^{-1}$ ,  $\gamma = -2.29 \pm 0.39$ , with  $E_c = 31.0 \pm 26.3$  TeV and a reduced  $\chi^2$  value of 0.33, indicating a probable cutoff in the region above 10TeV. The Milagro results are consistent with the measurements of other experiments, and provides competitive measurements up to 100TeV (see figure 2).

### 5. Conclusions

We have developed a method for event by event determination of primary energy using MC based on CORSIKA and GEANT programs used to simulate the experiment. We are able to



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

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 recent direct measurements of the cosmic ray spectrum. The measured Crab spectrum is in agreement with published results from other experiments and indicates the existence high energy cutoff at  $31.0 \pm 26.3$  TeV.

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