Estimation of Cosmic Ray Flux in Milagro

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Introduction

This memo describes a detailed computation of the predicted cosmic ray flux as measured by Milagro. It has been proposed that the by quoting gamma-ray fluxes relative to the cosmic ray flux, the large systematic errors due to the unknown absolute efficiency of the Milagro detector can be avoided. Of particular importance is the measured flux from the Cygnus region. In this case, the predicted flux from GALPROP is anchored to the measured cosmic ray flux at the earth, so quoting our flux relative to the cosmic ray flux when comparing to the GALPROP is optimal. This study finds that the predicted flux with the current MC simulation is 58% of the measured flux.

Simulation and Data

The simulation used in the analysis was GEANT 4 v2.0 (current PRO). The absorption length was 30m and the scattering lengths was 50m. The parameter describing the angular distribution of the scattering was 0.99. The detector was simulated with white baffles, but no curtains. No air was included in the simulation between the cover and the surface of the water. The number of dead PMTs was fixed at 1%. The dead PMTs were randomly distributed throughout the pond. The PMT collection efficiency corrections were included (default in the current version of milinda) as well as noise and the simulation of the TOT-PE conversion.

Data from run 6620 was used in this analysis. This run was selected because the data was collected during a period where a good contact between the cover and the pond surface was known to exist. In this run, there were 5 dead or uncalibrated PMTs in the air shower layer.

Analysis

The computation of the cosmic ray flux was performed using the formulas derived in the memo by R.W. Ellsworth entitled *Calculation of Trigger Rates from the GEANT 4 Monte Carlo Data.* The computation included corrections for "r weighting" of the simulated MC events. Protons and Helium were simulated separately. Heavier elements were not simulated. The simulations used were thrown from 30 GeV to 100TeV and were thrown on an $E^{-2.7}$ spectrum. Weighting was used to simulate spectra with different spectral indices.

The specific trigger conditions at the time of the data collection can be difficult to obtain. In general, the VME trigger is not well simulated. See V. Vasileiou's recent memo for details. The events collected near threshold, while quite important in low energy analyses, are not important in the weighted analysis which places a heavy emphasis on the the larger events. For this reason, I do not attempt to simulate the actual trigger conditions, but rather I simulate an "offline trigger" that allows all events with "nTop>=85" to pass. This cut has an efficiency near unity for all trigger settings used in Milagro. Using an offline cut takes uncertainties in the trigger out of the cosmic ray rate computation.

There are two experiments that have performed direct measurements of the cosmic ray flux in our energy regime. The BESS experiment used a balloon based spectrometer to measure cosmic ray fluxes from a ~1 GeV up to ~500 GeV. The JACEE experiment, also balloon based, used an large area emulsion stack and measured fluxes from ~5 TeV to ~100 TeV. Both experiments quote fluxes for primary protons and Helium with errors of <~10% .

<u>BESS Flux:</u>
(from astro-ph/0403704)

$$\Phi_p = (1.37 \pm 0.06^{stat} \pm 0.11^{syst}) \times 10^4 \ (\mathrm{m^2\ sr\ s\ GeV})^{-1}$$
$$\gamma_p = -2.732 \pm 0.011^{stat} \pm 0.019^{syst}$$

$$\Phi_{He} = (7.06 \pm 0.94^{stat} \pm 1.17^{syst}) \times 10^3 \ (\mathrm{m^2\ sr\ s\ GeV/nucleon})^{-1}$$
$$\gamma_{He} = -2.694 \pm 0.041^{stat} \pm 0.044^{syst}$$

Converting to TeV gives:

$$\Phi_p = (0.0872 \pm 0.0038^{stat} \pm 0.0070^{syst}) \ (\mathrm{m^2\ sr\ s\ TeV})^{-1}$$
$$\gamma_p = -2.732 \pm 0.011^{stat} \pm 0.019^{syst}$$

$$\Phi_{He} = (0.00584 \pm 0.00078^{stat} \pm 0.00097^{syst}) \ (\mathrm{m^2\ sr\ s\ TeV/nucleon})^{-1}$$
$$\gamma_{He} = -2.694 \pm 0.041^{stat} \pm 0.044^{syst}$$

The BESS flux and spectrum are determined from a fit to data collected between ~1 GeV and ~500 GeV, so the characteristic energy scale (median energy in log space) of the measurement is ~25 GeV. When projecting these measurements to higher energy, the error in the spectral index translates into an error in the absolute flux. The Milagro energy scale (~3-4 TeV) is about 100 times higher than the typical energies used in the fit, so an error of 11% for protons and 32% for Helium must be added to the flux error.

<u>JACEE Flux:</u>
(ApJ 502:278)

$$\Phi_p = (0.111 \pm 0.008^{s}) \ (\mathrm{m^2\ sr\ s\ TeV})^{-1}$$
$$\gamma_p = -2.80 \pm 0.04$$

$$\Phi_{He} = (0.00786 \pm 0.00024) \ (\mathrm{m^2\ sr\ s\ TeV/nucleon})^{-1}$$
$$\gamma_{He} = -2.68 \pm 0.04$$

The flux measured by JACEE is about 30% higher than the BESS flux for both species and are barely consistent (~2 sigma). The spectral index measurements are in reasonable agreement. These spectra are the result of a fit to data that range from 5-100 TeV which is closer to the typical Milagro event energies. The energy scale of the JACEE fit (median energy in log space) is ~22 TeV or ~5 times the Milagro median energy. Projecting the errors in the spectral indices by a factor of 5 yields an uncertainty of 7% for both protons and Helium.

The CAPRICE balloon experiment also made measurements in the relevant energy interval, but the energy range was lower than that of BESS and had larger error, so data from CAPRICE are not presented here.

In the Milagro data, I measure a rate of 692 events/s passing the offline trigger criteria. The dead time for this period was 9%, so the inferred event rate is 760/s.

Before proceeding with the computation of predicted event rate from the detector simulation, it is important to confirm that the simulated data is thrown with a broad enough set of parameters so that all the triggers are simulated. Events are simulated with energies ranging from 30 GeV to 100 TeV and zenith angles ranging from 0 deg to 70 deg. These events are thrown over an circular area with a 1000m radius. In the 4 attached plots, I show the predicted trigger rate plotted vs throw radius cut, throw angle cut and minimum and maximum throw energy. I conclude from these plots that the throw area, angle cut and the minimum energy cut do not impact this analysis. The maximum energy cut of 100 TeV seems to exclude a small number of triggers from the highest energy events.

The predicted cosmic ray "offline trigger" rate in Milagro is:

R_{JACEE} (He)	$= 117 \pm 9$	R_{BESS}(He)	$= 88 \pm 34$
R_{JACEE}(Proton)	$= 321 \pm 32$	R_{BESS}(Proton)	$= 246 \pm 35$
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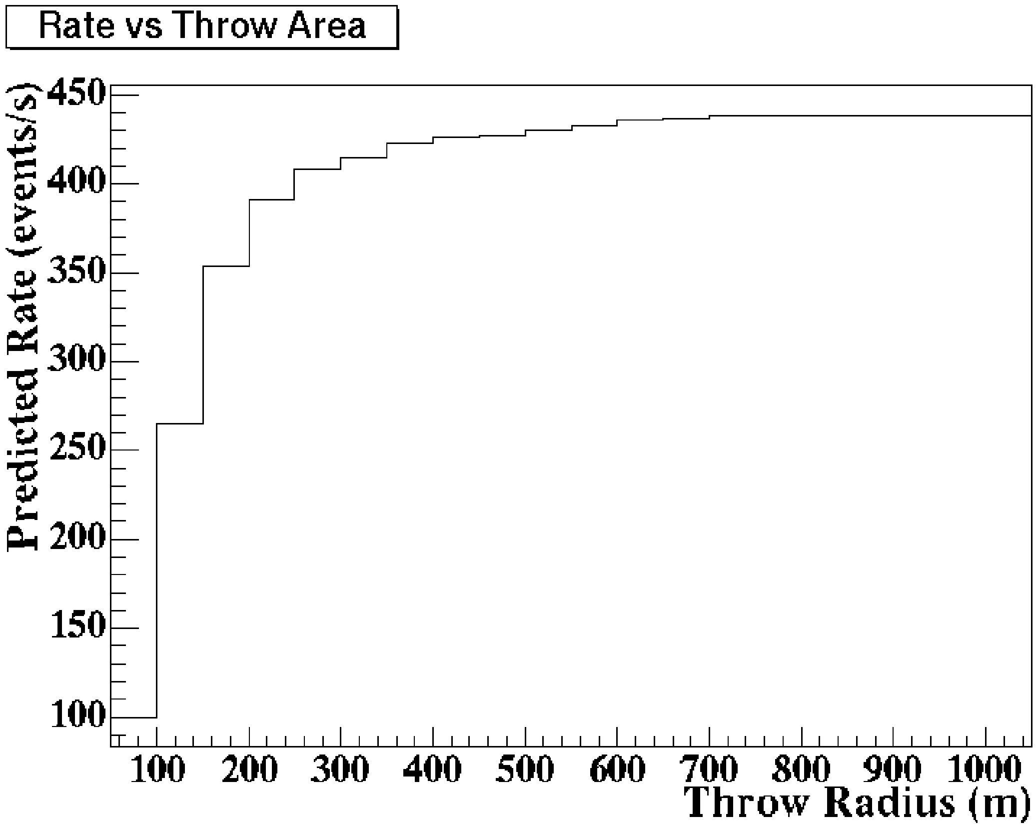
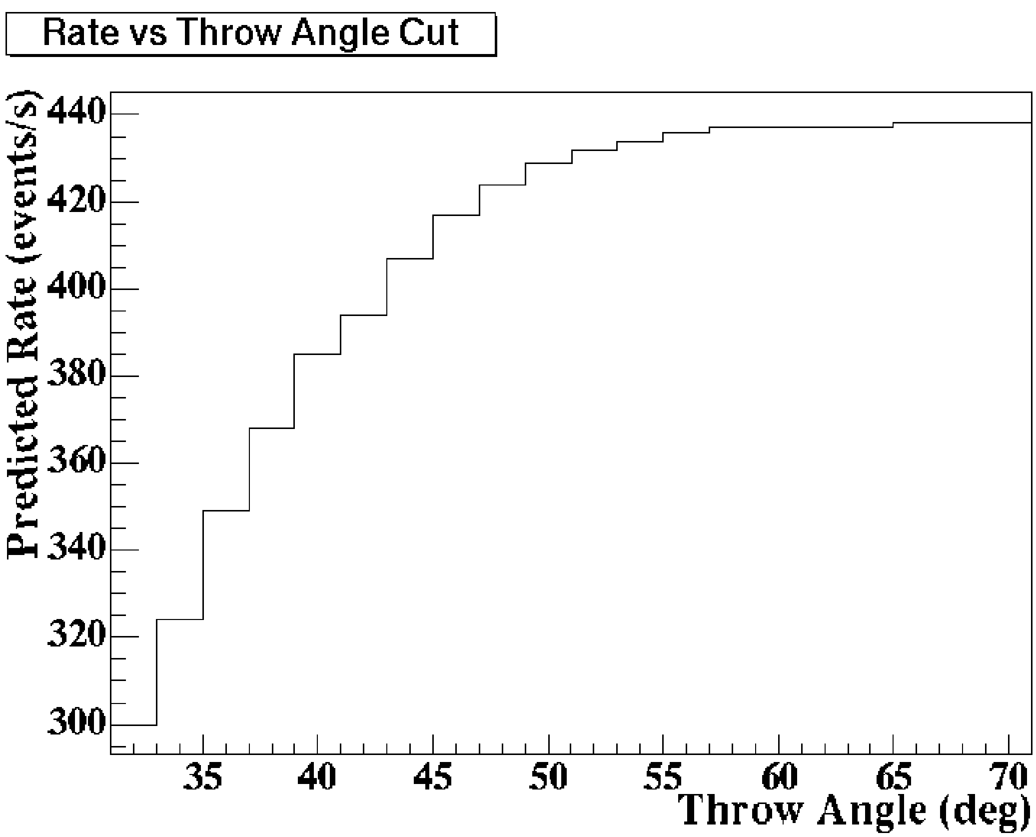
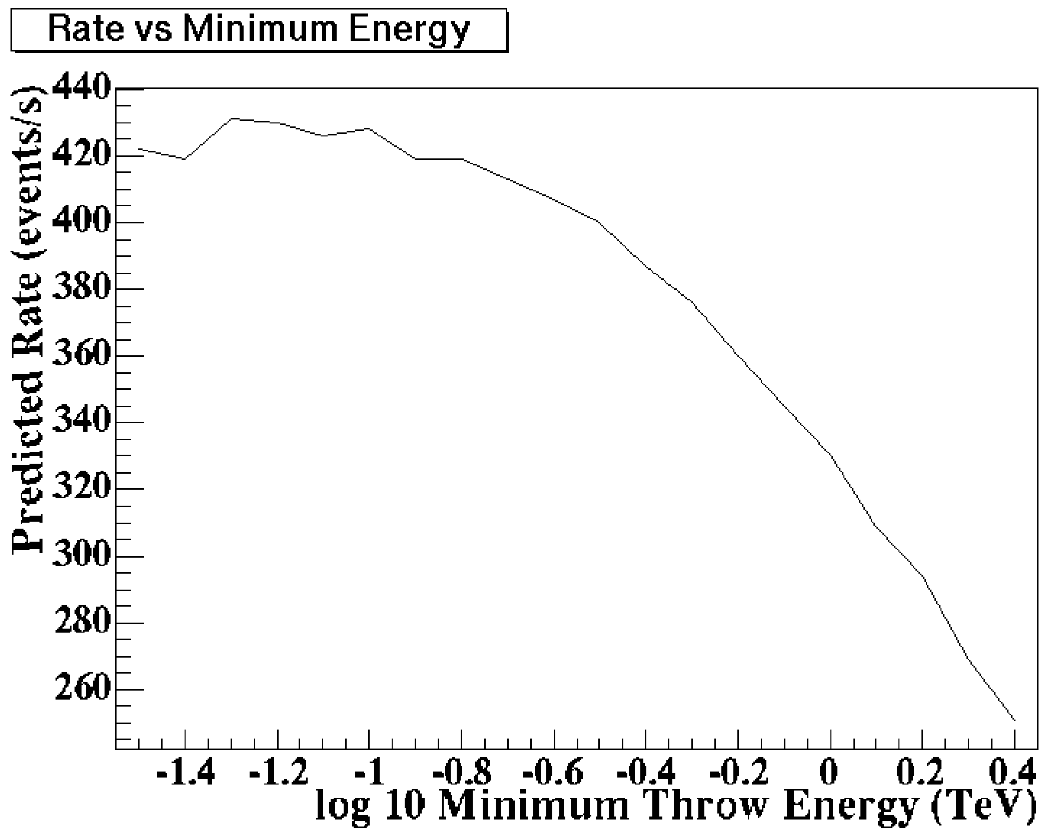
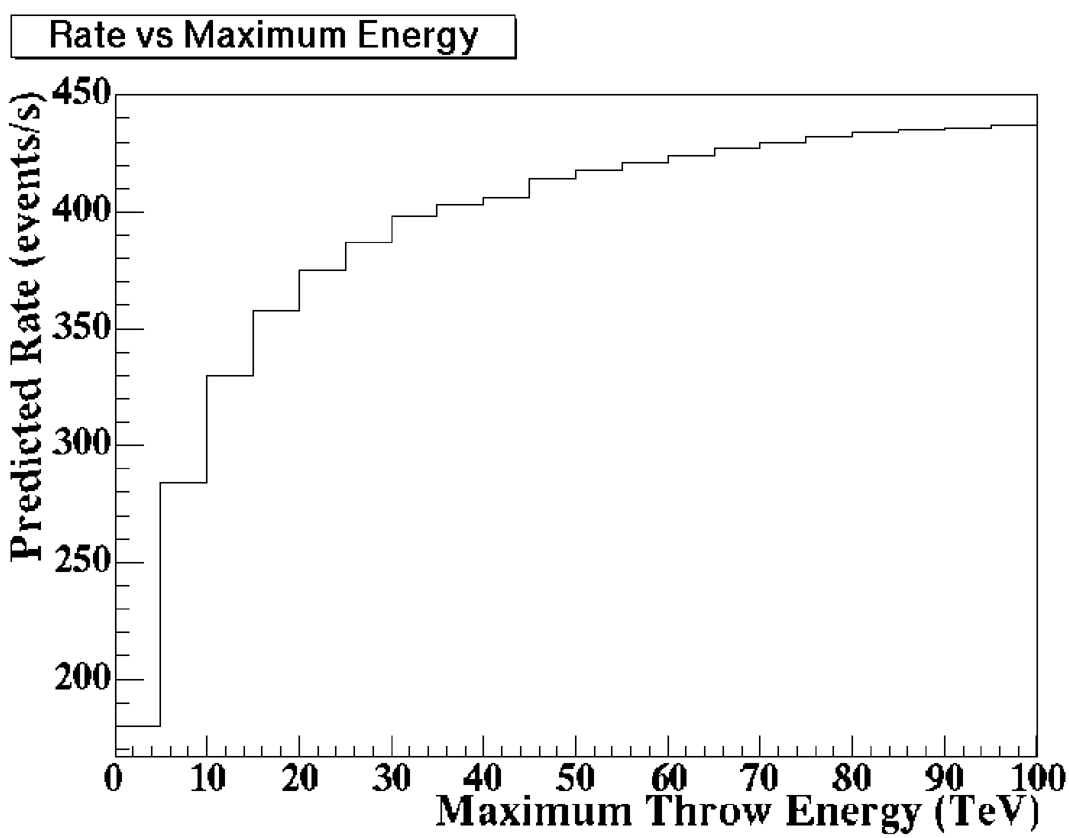
	438 ± 33 ev/s		334 ± 49 ev/s

In this computation, the errors due to the spectral index projection from the energy scale BESS and JACEE to the Milagro energy scale were combined in quadrature with the flux errors reported by the experiments. There is a ~2 sigma discrepancy between the measurements from the 2 experiments. The fractional error on the JACEE measurement is almost half of the fractional error of the BESS experiment. Both experiments give results that are much lower than the measured Milagro rate. The ratio between the predicted rate based on the JACEE flux and the Milagro measured rate is 0.58 ± 0.04. Inclusion of heavy elements (beyond Helium) and higher energy events (greater than 100 TeV) will increase the predicted flux, but certainly not by enough to account for the large discrepancy. It is also important to note that the current simulation also predicts a gamma-ray flux from the Crab (based on measurements by ACTs) that are 60%-70% of the observed rate. The simulation predicts 6-7 events/day for the standard cuts while the detector records about 10 events/day. The fact both the proton and gamma-ray simulations predict lower event rates than observed by roughly the same factor is evidence that the simulation is some how underestimating the efficiency of the Milagro detector.


Rate vs Throw Area
Predicted Rate (events/s)
450
400
350
300
250
200
150
100
100
200
300
400
500
600
700
800
900
1000
Throw Radius (m)


Rate vs Throw Angle Cut
Predicted Rate (events/s)
440
420
400
380
360
340
320
300
35
40
45
50
55
60
65
70
Throw Angle (deg)


Rate vs Minimum Energy
Predicted Rate (events/s)
440
420
400
380
360
340
320
300
280
260
-1.4
-1.2
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
log 10 Minimum Throw Energy (TeV)


Rate vs Maximum Energy
Predicted Rate (events/s)
450
400
350
300
250
200
0
10
20
30
40
50
60
70
80
90
100
Maximum Throw Energy (TeV)