Single hadrons in Milagro and the Spectrum of Cosmic Ray Protons

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Abstract

Single unaccompanied hadrons can be used to probe the shape and intensity of the primary cosmic ray proton spectrum. The Milagro detector can be used as a very large calorimeter with an effective area of 2000 m^2 and a thickness of 7 meters (7 interaction lengths and 15 radiation lengths) to sample primary protons which survive to Milagro level without interacting in the atmosphere. The response of the shower layer (PMTs located below about 2 meters of water) is used to establish calorimeter penetration by single unaccompanied hadrons and the hadron energy measured from the response of the PMTs located below 7 meters of water. A data set from three years of operation can be used to establish the presence of a bend in the proton spectrum if it is below 500 TeV. Results from simulation, which illustrate the method, and some preliminary experimental results showing feasiblity using data from Milagrito will be presented.

1 Principle of the Technique:

At high energies (energies above a few TeV) most cosmic rays produce air showers at the Milagro altitude of 750 gm/cm^2. Energetic hadrons in the shower which retain a significant fraction of the energy of the incident cosmic ray are located within few meters of the core of the shower. A fraction $\exp(\frac{-x}{\lambda(E)})$ will survive without any interaction in slant depth x and they will not have a shower associated with them. The interaction length $\lambda(E)$ for proton air inelastic cross sections can be calculated from a knowledge of the p-p total cross section and the elastic slope parameter using Glauber techniques (Gaisser et al., 1987). A measurement of the energy spectrum of the surviving hadron flux can be used to estimate the energy spectrum of primary protons and search for a possible cut-off in the spectrum above 100 TeV which has so far eluded detection (Swordy, 1993).

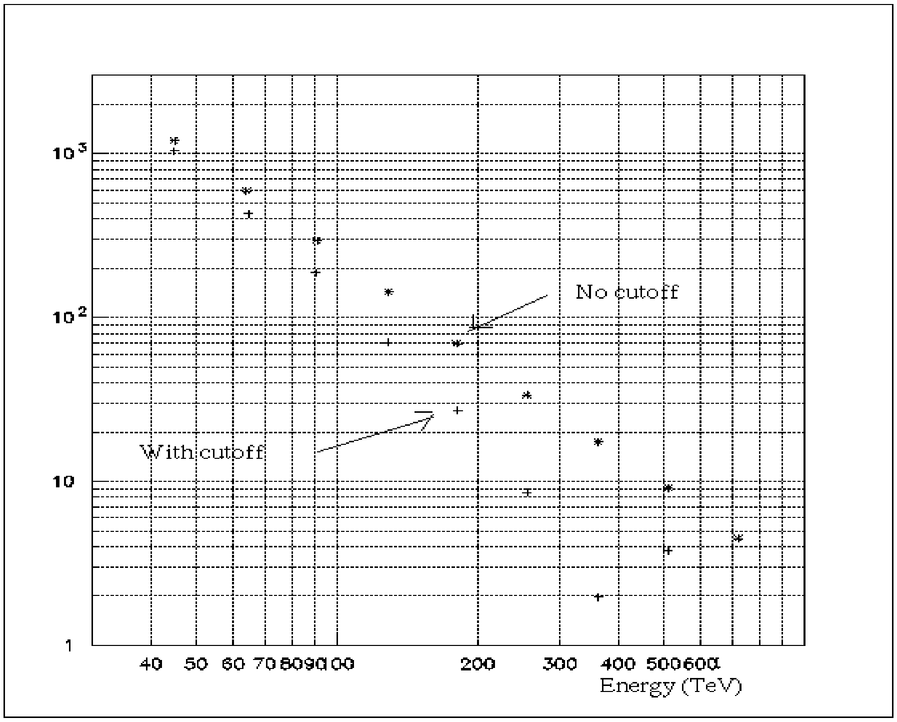
As the fraction of surviving hadrons is small ($\sim 10^{-4}$), a very large and reasonably deep calorimeter to detect these hadrons and measure their energies is required. In addition, events with accompanying shower particles must be rejected. The Milagro TeV gamma ray telescope satisfies these requirements. Its bottom layer, which is about 2000 m^2 in area and whose PMTs can collect the Cherenkov light produced by the cascade produced by energetic hadrons in about 7 meters depth of water (7 λ_{int} and 15λ_{rad}) can be considered a calorimeter to measure energetic surviving hadrons and its top layer can be used to ensure lack of shower accompaniment.

The experiment measures an upper limit to the primary flux of cosmic ray protons. This upper limit approaches the true flux as energy increases because the probablity of rejection of events with small accompaniment increases with energy. Thus contamination from events with accompaniment will make the estimated proton spectrum steeper than the true spectrum at low energies (below a TeV) and then at higher energies (greater than 10 TeV) the spectral slope would more accurately reflect the true slope of primary protons. A cutoff in the primary proton spectrum above 100 TeV should manifest itself as a steepening in the slope of the measured spectrum. The contribution to this unaccompanied flux from higher A nuclei can be shown to be small at these high energies.

2 Estimate of Number of Events:

The expected event rate can be estimated using measured values of the primary proton flux and calculated values of the proton-air inelastic cross section as a function of energy. Most of the single hadron flux comes from near zenith. For this calculation protons and alpha primaries were both included. Figure 1 shows integral spectrum of expected number of events of surviving hadrons for a 3000 m^2 area calorimeter. Two sets of points are shown corresponding to no steepening of the primary cosmic ray proton spectrum upto the knee, $\sim$ 1 PeV (designated no cutoff) and to a steepening of the spectrum at 100 TeV with an increase in spectal slope of 0.5 (designated cut off). These numbers are also consistent with previously meaured fluxes of unaccompanied particles at mountain level (Siohan78). The integral spectra for single hadrons in Milagro with an area of 2000 m^2 and an operation time of 3 years, corresponds to collecting 400 events above 60 TeV with no cut-off, and only 290 events above the same energy with a cut-off at 100 TeV. A steepening of slope in the surviving hadron spectrum would be observable, indicating a steepening of the spectrum of primary protons in cosmic rays.

In addition to events attributable to single hadrons, high energy muons can produce cascades due to catastrophic energy loss, such as muon bremmstrahlung. This contribution can be shown to be less than a few percent of the single hadron rate and the zenith angle distribution of events due to muons will be much flatter than that of single hadrons. The muon generated events can be estimated from observed zenith angle distribution of cascades.



Integral number of events versus energy (TeV)

Figure 1: Integral spectrum for number of events expected for a 3000m^2 detector in three years. Ordinate is N($\geq$ E)

3 Some Results from Milagrito:

The Milagrito detector, which was a one layer Milagro prototype with 1.5 m of water above PMTs, operated for about a year. We made a preliminary search for single hadrons in Milagrito. Single hadrons should produce a large quantity of localized light in the region of the cascade developed by the energetic hadron. Simulation of single hadron cascades shows that in addition to localized large pulse-heights near the core of the cascade, a large number of other PMTs were lit up with low pulseheights from light produced by particles in the cascade due to multiple scattering of low energy electrons in the cascade. A study of timing distributions of these lit tubes with respect to the timing of the largest tube showed time delay of these hits to be what would be expected for light travelling at the speed of light in water. In a plot of time versus position of each tube with respect to the hottest tube can be fitted with a straight line which corresponds to speed of light in water. An example of this behaviour on a time versus distance scatter plot for 1 TeV simulated single hadron events is shown in Figure 2. Single hadrons were selected from Milagrito data by requiring that 90 percent of all hits lie in a band around the speed of light in water line. A relatively clean sample of single hadrons was obtained. Figure 3 shows a lego plot of a selected single hadron event selected using the cut on delay times. The figure shows pulse heights in terms of equivalent number of photo-electrons (pes) for each tube(z axis) and (x,y) location of the tube. The figure clearly shows a localized cascade due to the energetic hadron.

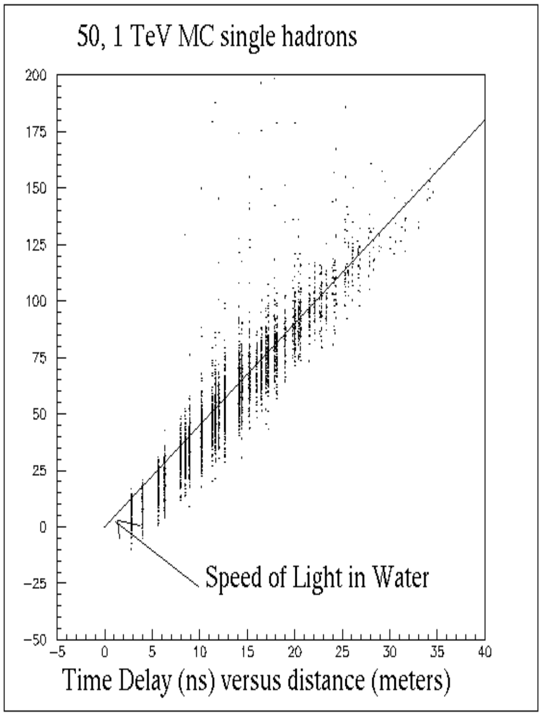


Figure:2 Time delay(x) versus distance from the high-pulse height tube(y), for 1 TeV MC protons. The line represents speed of light in water.

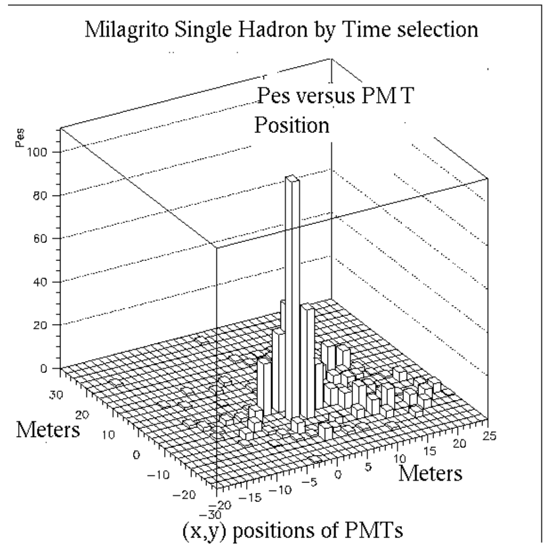


Figure 3: A typical single hadron selected from data. Lego plot of pulse heights

The observed photo-electron(pes) spectrum for single hadrons selected from data by the techinque described above is compared with that obtained from simulation in Figure 4. The x axis is the logarithm of the total number of pes detected in Milagrito. The simulation imposed the same trigger cuts as the data and generated events for surviving hadrons from cosmic ray protons with a threshold well below trigger level and on a spectrum with slope of -2.7. The reasonable similarity between the shapes of these two distributions indicates that the criteria for picking out single hadrons works. The number of total pes in the current simulation have about a systematic uncertainty of 30 percent. Further work is in progress to minimize this uncertainty.

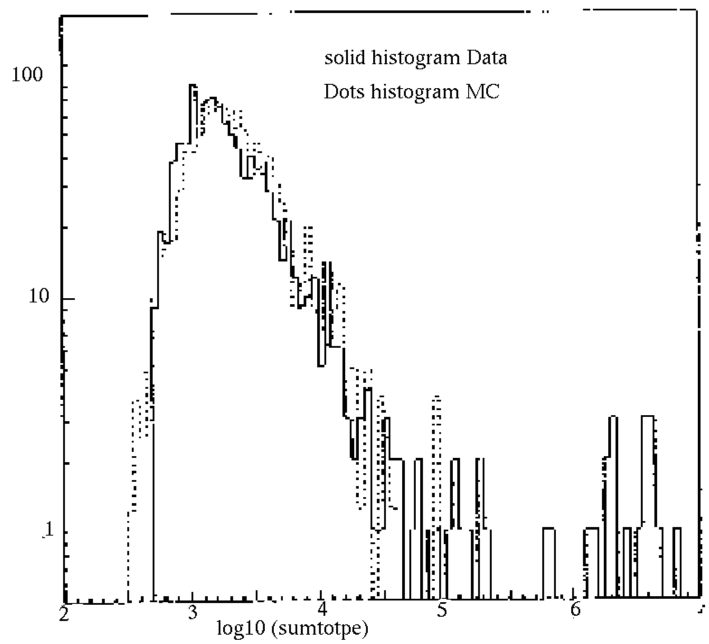


Figure 4: Comparision of MC and Data single had spectra
Solid histogram is data and dashed is MC

4 Concluding Remarks

Milagro has just begun operation. We will study the data to determine the best method to pick out triggers due to single hadrons in Milagro and also develop special triggers to select single hadrons. This study of single hadrons should complement the composition studies we plan to do using a Wide Angle Cherenkov Telescope(WACT) array (Atkins99).

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