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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 is a very large calorimeter with an effective area for the detection of unaccompanied hadrons of 2000 m^2 and a thickness of 6 meters (7 interaction lengths and 16 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 1.35 meter of water) is used to establish calorimeter penetration by single hadrons without accompanying shower particles and the hadron energy is estimated from the response of the PMTs located below 6 meters of water.

Criteria developed to select candidate single hadrons are described and distributions of observed signals are compared with simulations of the response of Milagro to single hadrons incident upon the pond.

1 Introduction

Single hadrons, unaccompanied by any shower particles, are an upper limit to the number of protons surviving at observation level without interaction. As the energy of the single hadron increases the limit approaches the true flux of surviving hadrons. A measurement of unaccompanied hadron flux as a function of energy can be used to infer the spectrum of primary cosmic ray protons over a wide energy range and in principle could determine the bend in the proton spectrum in the 100s of TeV energy range(F. Siohan et al.,1978 and T.K. Gaisser et al., 1977).

Single hadrons in Milagro are energetic hadrons which are incident upon the Milagro pond without accompanying shower particles. These energetic hadrons produce a nuclear-electromagnetic cascade in the water. The transverse extent of these cascades is limited in the shower layer to a narrow bundle and the main beam of Cherenkov light is only about a meter and half wide for nearly vertical hadrons. The Milagro trigger requires that 50 or more tubes are hit. This 50 tube trigger is satisfied by single hadrons by some of the emitted Cherenkov light travelling nearly horizontally in the water and illuminating photo-multipliers(PMTS) away from the core of the cascade. This nearly horizontal light is produced by Cherenkov emission from multiply scattered low energy electrons in the cascade. Monte Carlo simulations of energetic single hadrons incident upon the pond with energies greater than 10 GeV show that these cascades satisfy the trigger requirements. This light, generated at the cascade, travels with speed of light in water(4.5 nanoseconds per meter). This feature provides a clean method for selecting triggers due to single hadrons. An estimate of the energy of the single hadron is obtained from the sum of the total number of photo-electrons detected in the top and the bottom layer, pesumtop(pt)+pesumbot(pb), called x hereafter.

We present a preliminary comparision of single hadron data with simulations which provides a validation of the method.

2 Method of Singleh hadron selection

The procedure to select out single hadron(SH) triggers consists of the following steps: (1) Find the tube with maximum number of photoelectrons detected(pes) in the top layer (maxtube), (2) calculate the time delay, t_i(ns), of all hit tubes with respect to the time of the maxtube and the distance of the tubes from the maxtube r_i (meters). (3) calculate the difference between t_i and the time it takes for light to travel in water to the tube from the maximum tube, [t_i-4.5 r_i] and require its absolute value to be less than 20 ns and (4) calculate the fraction of hit tubes satisfying this condition to the total number of hit tubes, f. If f is greater than 0.9, the event is a good single hadron candidate. When this selection is applied to the data, about 0.5 percent of the events are selected.

A further selection is applied to make sure that the single hadron penetrated both layers and its trajectory was well

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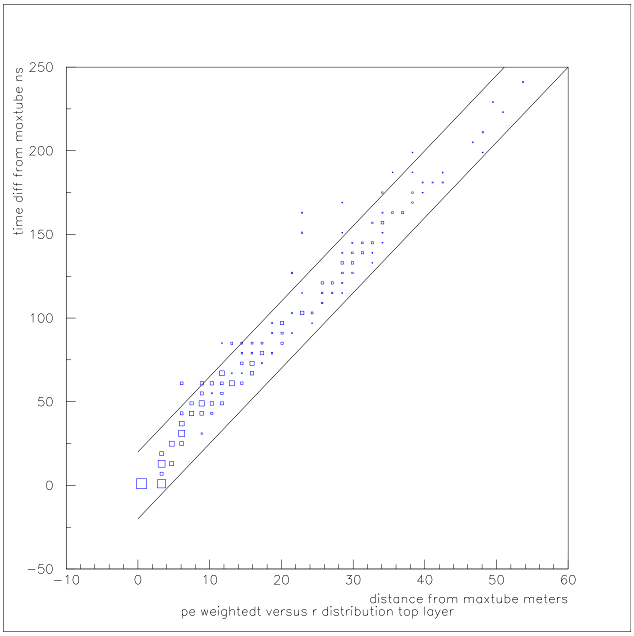

Fig. 1. Figure 1: Distribution of hits along the speed of light in water line for a selected single hadron candidate

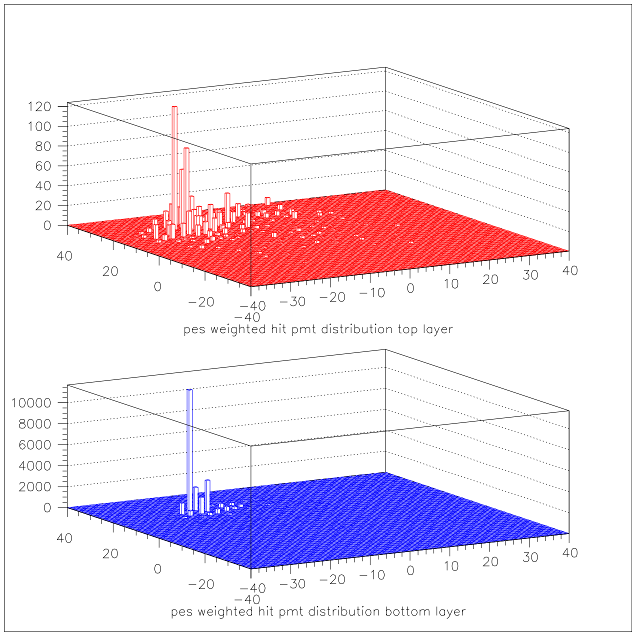

Fig. 2. Figure 2: Two dimensional display of pes weighted hit tubes in the top and bottom layers

contained within the pond. Simulations showed that with this selection we select single hadrons of energy above 100 Gev with high efficiency.

A plot of t_i versus r_i for a typical selected single hadron event is shown in Figure 1. The figure clearly shows that hits away from the maxtube lie along the speed of light in water line.

The distribution of hit pmts in the top and bottom layer weighted by the pes for each tube is shown in Figure 2 for the same selected hadron candidate. A clear indication of the collimated cascade structure is seen in the figure.

3 Energy determination

Single protons with energy greater than 50 GeV with a spectral index of -2.9 and with zenith angles less than 15 degrees were incident on Milagro were simulated. For each selected event we plot the relation between log10(x) and log10(E), where E is the energy of the proton in GeV in Figure 3.

The observed correlation is fitted to a straight line and the result is

$$x = 126E^{0.69\pm0.03} \tag{1}$$

For later use we call the exponent δ.

4 Observed single hadron spectrum

We are currently outputting single hadron files selected requiring that the fraction of hits in the speed of light in water band are greater than 90 percent of the total hits. For each of these events we estimate their zenith angle by geometry

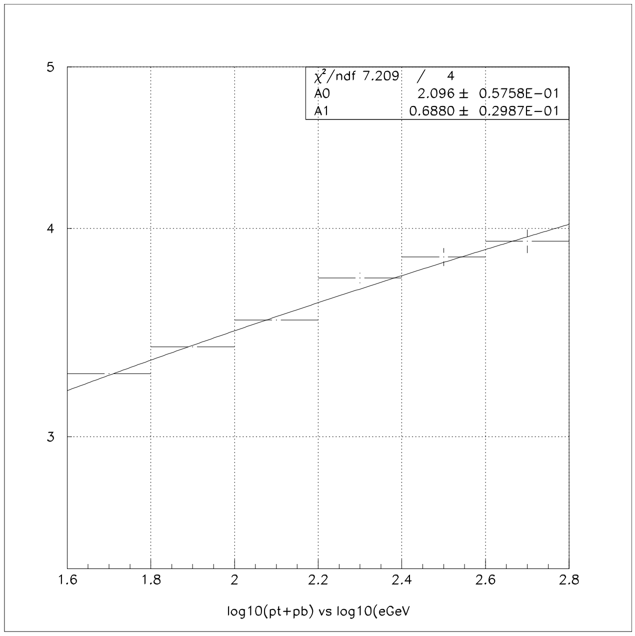

Fig. 3. Figure 3: Correlation of observed total pes and true energy in GeV

of the cascade as seen in top and bottom layers. We further require that the zenith angle so determined is less than 25 degrees. This should give us a sample of unaccompanied single hadrons in the pond. The observed spectrum of sum of total photoelectrons detected in the top and bottom layer, (pt+pb), of these selected events is given in Figure 4.

The fitted spectral index, is called β, where $\frac{dN}{dx}$ = B $x^{-\beta}$ and x =(pt+pb). This is obtained using sufficiently high val-

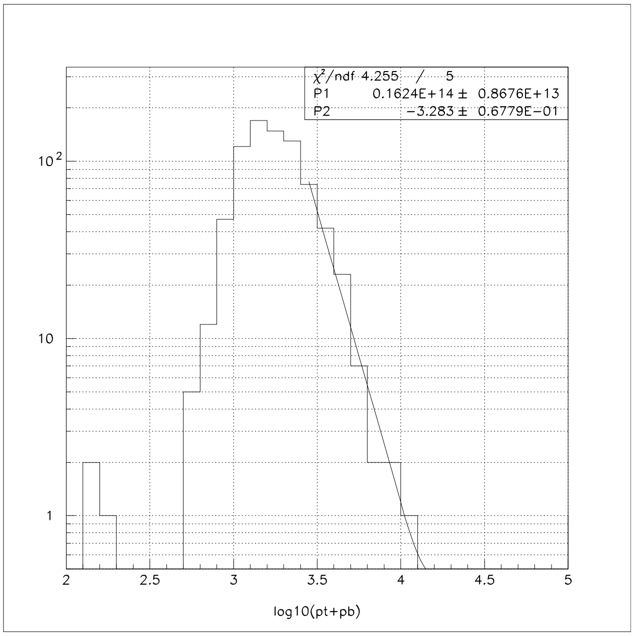

Fig. 4. Figure 4: Observed spectrum of total detected photoelectrons in top and bottom layer

ues of x so as not to be influenced by threshold effects clearly seen in Figure 2, and is found to be: 3.28±.07. What does this tell us about the spectral index of the energy spectrum of single hadrons that it corresponds to? This is addressed next.

5 The relation of spectral indices

Let the spectral index of the energy spectrum of the single hadrons incident upon Milagro be γ, so that we can write

$$\frac{dN}{dE} = KE^{-\gamma} \quad (2)$$

The relation between x and energy is taken from Monte Carlo (see Figure 1) and written as

$$x = AE^{\delta} \quad (3)$$

One can easily show that the relation between γ, δ and β is

$$\beta = \frac{\gamma}{\delta} - \frac{1}{\delta} + 1 \quad (4)$$

From this we estimate the spectral index of the incident single hadrons in data to be approximately -2.6 with an uncertainty of about ± 0.2. This value is quite reasonable and is what is expected from solution of the coupled cascade equations for the hadronic cascade in the atmosphere. In this energy range where we expect scaling to hold in the fragmentation region and where the interaction cross section is almost energy independent(T.K.Gaisser, 1990) one expects the single hadron spectral index to reflect that of the primary cosmic rays provided that the energy resolution of is reasonably symmetric. These unaccompanied hadrons originate mostly from primary protons and helium nuclei, whose spectral indices in the 100 GeV energy range are -2.75 and -2.64 respectively.

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