

THE MUON CONTENT OF EXTENSIVE AIR SHOWERS
WITH $E \geq 2 \times 10^{17}$ EV.

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Abstract The Fly's Eye experiment and the Michigan muon array are operating in coincidence, simultaneously measuring the energy, depth of shower maximum, and muon content of high energy ($E \geq 2 \times 10^{17}$ eV) extensive air showers. We present the experimental data from both detectors and find no large systematic biases which may affect a primary composition measurement. We also show that the lateral distribution of muons is in good agreement with the previous lateral distribution parameterization given by the Yakutsk experiment.

Introduction The Fly's Eye experiment is currently examining the depth of shower maximum distributions of cosmic rays to provide a measurement of the primary composition in the EeV energy range (G. L. Cassiday et al. 1989, G. L. Cassiday et al. 1990). Additional sensitivity to the primary composition can be gained by simultaneously measuring the muon content along with the depth of shower maximum and primary energy. We have therefore begun examining Fly's Eye extensive air shower events which occur in coincidence with muon events observed by the Michigan muon array.

The experimental apparatus used in this measurement has been described elsewhere (R. M. Baltrusaitis 1985, G. L. Cassiday et al. 1990b). The muon array currently has 1280 m² muon detection area, arranged into 8 detector banks surrounding the Fly's Eye 2 detector. The Fly's Eye 1 detector is located on top of Little Granite Mountain, 3.4 km. to the southwest of the muon array. Between 2/7/88 and 3/31/89 the two experiments logged 746.8 hrs of coincident running time, yielding 580 Fly's Eye 1 events (fully reconstructed monocular) with muon array information, and 288 Fly's Eye 1 and 2 events (fully reconstructed stereo) with muon array data. Stereo events are chosen for analysis because these events have improved core position and angular resolution reconstruction over the monocular data.

A muon event is recorded when a minimum of 15 muon detectors are struck out of the

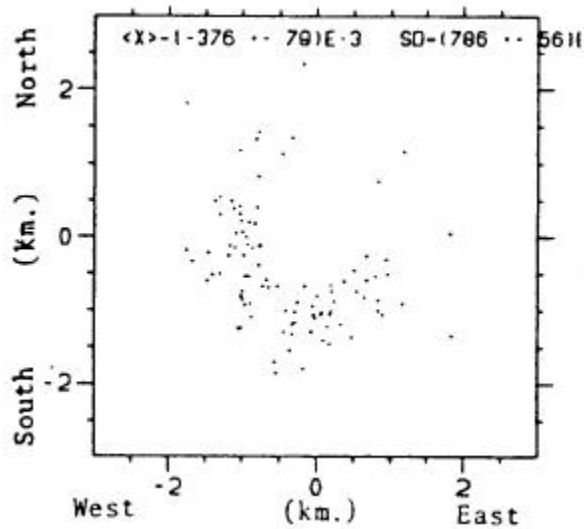


Figure 1: Core positions of coincidence events determined by the Fly's Eye Experiment. Axes are distance from the center of the muon array in km.

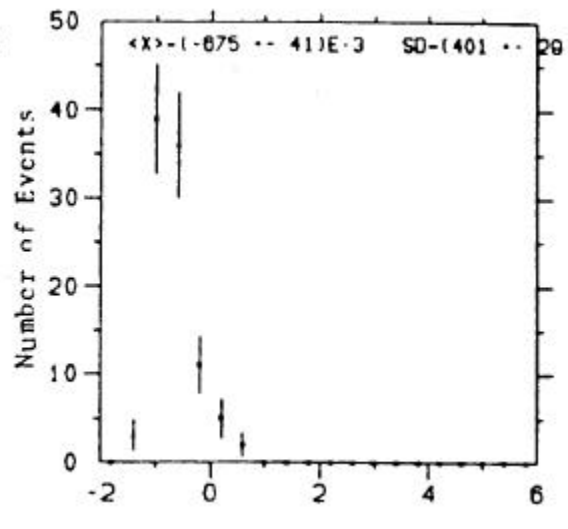


Figure 2: Energy Spectrum of coincidence events. Horizontal axis is $\log(E)$ where E is measured in EeV.

four inner muon patches within a 2 μ s time window. These events are analyzed by fitting a plane wave to the muon arrival times at the muon detectors. Detector hits with large deviations from the expected arrival time predicted from the wavefront fit to the majority of the detectors are discarded. This procedure removes approximately 4-8 random muon hits per coincident event. The remaining muon detector hits are then refit to a plane wave to determine the direction of the muon wavefront. After the refit, we require a minimum of 15 muon detectors per event. This requirement eliminates low detector multiplicity events (< 15 true muon hits) which have triggered the muon array due to a coincidence with random detector noise.

The event reconstruction procedure of the Fly's Eye experimental data has been described elsewhere (R. M. Baltrusaitis et al. 1985). In the analysis presented here, we define R_p of the reconstructed event as the distance of closest approach of the air shower core to the FE 2 detector (located at the center of the muon array). In order to compare the muon lateral distribution measured in this experiment with previous parameterizations (which depend upon the energy E and R_p), we require $\Delta E/E < 0.4$, and $\Delta R_p/S_p < 0.4$. After these cuts a total of 99 coincident events are left for analysis. These events have an average of 36.4 muon counters hit per event.

Data Distribution Characteristics The core position location and energy distribution of the coincident events, measured by the Fly's Eye detectors, are shown in Figures 1 and 2. Core locations are distributed randomly about an annular ring centered about the muon array and the FE 2 detector. The lack of events on the inside of the ring is due to cuts imposed on the Fly's Eye stereo reconstruction to discard events which are biased by Cerenkov light contamination at FE 2. The energy distribution of these events is a narrow distribution centered about 0.21 EeV. An examination of coincidence events with marginally triggering muon content (< 15 true muon hits) reveals that these events have

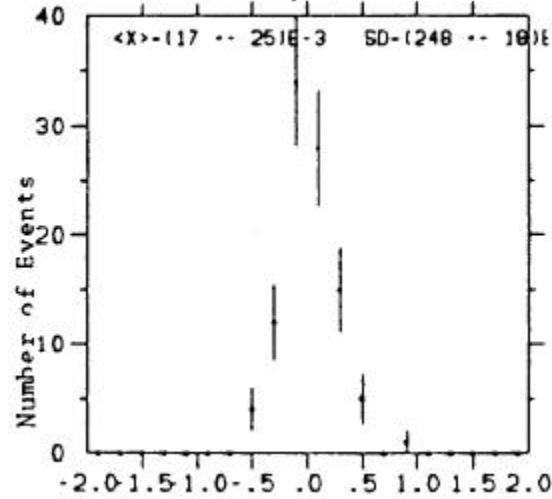


Figure 3: Comparison of experimental muon density with Yakutsk parameterization at 1 km. from the core. Horizontal axis is $\log(\rho_1^{\text{expt}}(1000)/\rho_1^{\text{Yakutsk}}(1000))$.

higher average energies and larger $\langle R_p \rangle$ than the selected data set. This implies that the muon array trigger is fully efficient at small R_p for primaries with $E \geq 2 \times 10^{17}$ eV. We therefore expect that the coincidence event data sample will trigger efficiently on both heavy and light primary nuclei.

We can demonstrate the consistency of the coincident muon density with previous measurements by the Yakutsk group. In Figure 3 we plot the distribution of differences between the muon density predicted by the Yakutsk lateral distribution parameterization (M. N. Dyakonov et al. 1987) at 1 km. with the experimental measurement extrapolated to this distance. We have adjusted the Yakutsk formula to account for the difference in atmospheric depth between the Yakutsk experiment (depth=1020 gm/cm²) and the Fly's Eye depth (870 gm/cm²):

$$\rho_1(R_p) = \hat{e}(E(\text{EeV}))^{0.87} R_p^{-0.75} (1 + R_p/R_0)^{0.75-b_1},$$

$$\hat{e} = 1309 \exp((1 - \sec \theta)870/440),$$

$$b_1(\theta, E_0) = b_0 - b_1(1 - \cos \theta) + b_2 \log(E(\text{EeV})),$$

$$b_0 = 3.26, b_1 = 2.28, b_2 = 0.09, R_0 = 280\text{m}.$$

The mean of the distribution is

$$\langle \log(\rho_1^{\text{expt}}(1000) / \rho_1^{\text{Yakutsk}}(1000)) \rangle = 0.017 \pm 0.025$$

implying agreement to within 4%. We note that our agreement with this parameterization w also implies that the energy calibration of the Fly's Eye detector at 2×10^{17} eV is in good agreement with the Yakutsk energy calibration at this energy.

We impose the additional constraint $\Delta X_{\text{max}}/X_{\text{max}} < .25$ on the data sample when examining characteristics of the X_{max} distributions, decreasing the number of coincident

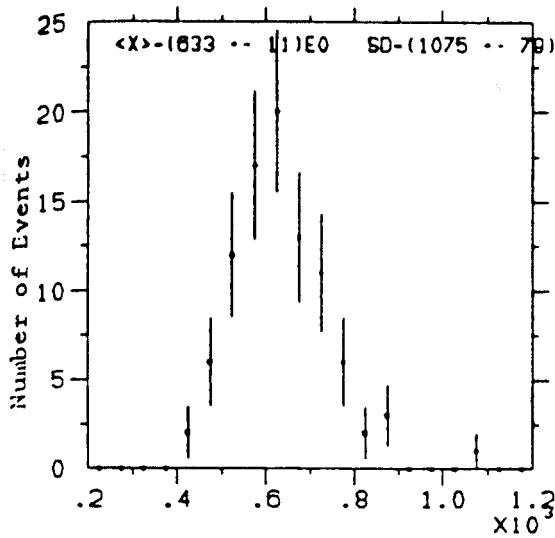


Figure 4: X_{\max} distribution of coincident events. Horizontal axis is depth in gm/cm^2 .

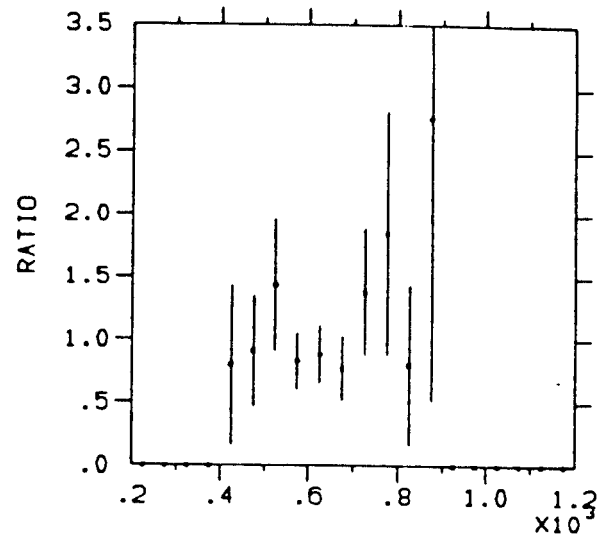


Figure 5: Ratio of coincidence data X_{\max} distribution to uncorrelated stereo data X_{\max} distribution. Horizontal axis is depth in gm/cm^2 .

events in the data sample to 93. Figure 4 shows the X_{\max} distribution of these events. Coincident events have $\langle X_{\max} \rangle = 633 \pm 11 \text{ gm}/\text{cm}^2$ and $\sigma_{X_{\max}} = 107.5 \pm 8 \text{ gm}/\text{cm}^2$, Y_s consistent with the X_{\max} distribution of uncorrelated stereo events with identical geometrical and resolution constraints to the coincidence events. Figure 5 shows the ratio of the coincident X_{\max} distribution to this uncorrelated stereo event distribution. The ratio has been normalized so that perfect agreement will yield a ratio of 1. Within the statistical limitations, the muon coincidence requirement does not result in a systematic bias in the X_{\max} distribution.

Summary The Fly's Eye and Michigan muon array can provide a unique, simultaneous measurement of the shower energy, muon content, and shower development curve of extensive air showers. The next step in the analysis of the data is to use a Monte Carlo simulation to examine the sensitivity of the simultaneous measurement of X_{\max} and N_i to the primary composition. We will present the results of the continuing analysis at the Adelaide conference.

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