Study of Cosmic Rays Above 0.3 EeV Using Fly's Eye-Muon Array Coincidences

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ABSTRACT

The Fly's Eye (FE) and the Michigan Muon Array (MA) simultaneously detect Extensive Air Showers (EAS) from EeV Energy primaries. Combining data from both experiments during analysis yields a reliable measurement of Depth of Shower Maximum (X_{max}), and gives a measurement of the Muon Lateral Distribution (MLD) $< 1km$ from the Shower core. The MLD densities agree with previously measured values.

I. INTRODUCTION

The FE and the Michigan Muon Array (FEMA) have been operating in coincidence since 1988. Together, they detect EAS from primaries with $E > 10^{17}eV$ landing in the vicinity of the Muon Array triggering > 15 of 512 muon counters buried in 8 Patchs of 64 counters each $3m$ below the surface. The FE detects EAS via the Atmospheric Fluorescence technique.[1] The Michigan Muon Array[2] detects EAS muons in coincidence with the Utah Array (now disabled),[3] and with the Chicago Air Shower Array (CASA).[4]

Results from a subset of FEMA data have been presented previously.[5] The events used were detected by FE1, FE2 and the Muon Array (Stereo-MA) with 93 surviving quality data cuts from the period 2/88-3/89. The triple coincidence was required for reliable EAS reconstruction. Here we present results from FE1-MA coincidences. The Muon data providė the Shower direction and FE1 data provide the Shower Core distance (R_{core}). Coincident data from 10/88-11/89 are presented.

II. EVENT RECONSTRUCTION

II.A Geometry

The FE Shower Plane (Figure 1), represented by a unit vector $\overrightarrow{N_{FE}}$, is determined by minimizing $\sum \vec{r_i} \cdot \overrightarrow{N_{FE}}$ where $\vec{r_i}$ is the i^{th} FE tube's direction vector pointing towards the EAS path. The plane direction is known typically to $\pm 2°$. The shower impact parameter, R_p, and angle in the plane, ψ, are determined by the arrival times t_i of the fluoresence photons at the FE PMTs with plane angles χ_i. The photon arrival time is

$$t_i = t_0 + R_p \tan\left(\left(\pi - \psi - \chi_i\right)/2\right)/c \tag{1}$$

where t_0 is the time the EAS front passes through the FE origin. Geometric resolution degrades with smaller FE track lengths (the angle subtended by the first and last FE tubes detecting the EAS) making a fit to R_p, ψ unreliable.

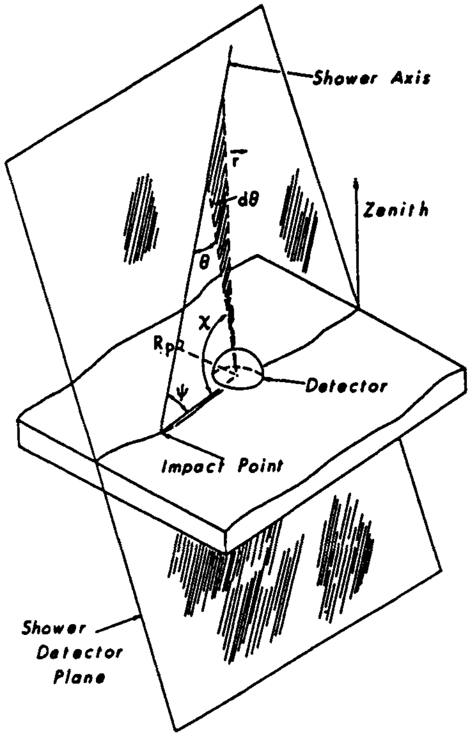

Figure 1. Geometry of EAS viewed from the FE.

To circumvent the problem, Array data are used to obtain the shower direction (giving ψ). Since the FE plane is known to $\pm 2°$, we constrain the direction fit to lie within the FE plane. Determining R_p is now found from a 2-D linear fit (Eqn 1).

The resolution is found by comparing a subset of data reconstructed via the Stereo technique where the geometry is found by the intersection of FE1 and FE2 Shower Planes. Figures 2,3 show the difference between FE1-MA and Stereo Zenith angles and R_p values. Overall, the FE1-MA resolution is better than shown because on average, Stereo-MA coincidence data have lower muon occupancy and are at larger R_{core} distances than the FE1-MA sample.

Figure 4 shows the Track Length distribution for FE1-MA and FE1-only events. FE1-MA has a higher reconstruction efficiency at small Track Lengths.

II.B Longitudinal Profile (LP)

The FE measures the EAS LP. A phenomenological gaussian fit of form

$$N_e(X_i) = N_{max} \exp\left(\frac{-(X_i - X_{max})^2}{2\sigma_X^2}\right) \tag{2}$$

where N_{max} is the Shower Maximum and σ_X is the Shower Width, is fit to the FE PMT signals appropriately corrected for solid angle, scattering, and attenuation of both Cherenkov and fluorescence light.

The X_{max} distribution is physically interesting, since it is related to the chemical composition of incident primaries. It has been previously measured via the FE Stereo method.[6] Since the Array data give a better direction over FE1-only data, improvements in the LP parameters are expected. Figure 5 shows the X_{max} distribution for the FE1-MA data and the FE1-only data. For the new data, $\langle X_{max}\rangle = 643 \pm 9 \pm 20 gmcm^{-2}$ which agrees with the published Stereo value of $\langle X_{max}\rangle = 656 \pm 5 \pm 20 gmcm^{-2}$ for showers with $\langle E\rangle = 0.3EeV$ (the average Energy for the FE1-MA dataset). The FE1-only data give $\langle X_{max}\rangle = 774 \pm 16 gmcm^{-2}$ which is over $100 gmcm^{-2}$ deeper (and is in agreement with known FE1-only X_{max} systematic errors).

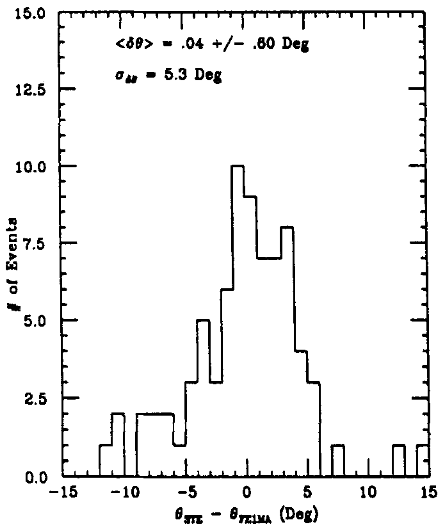

Figure 2. $\theta_{STE} - \theta_{FE1-MA}$

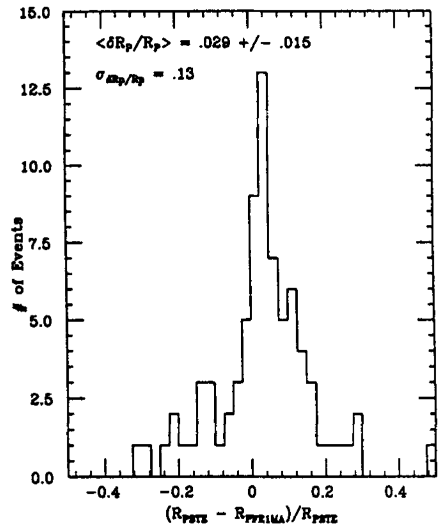

Figure 3. $\left(\frac{R_{P_{STE}} - R_{P_{FE1-MA}}}{R_{P_{STE}}}\right)$.

II.C Muon Lateral Distribution

Since the Muon array has no pulse height information, counters registering a trigger have ≥ 1 muon. For constant muon density over a Patch (valid for large R_{core}), the muon density is given by

$$\rho_\mu(R_{core}) = \frac{-log_e(1 - n_{hit}/N_{live})}{Area \cos\theta} \tag{3}$$

where n_{hit} and N_{live} are the number of counters in the Patch which register triggers and which are 'live' respectively, and $Area \cos\theta$ is a single counter's effective Area. Each Patch is sensitive to densities typically ranging from $.01m^{-2}$ to $1.6m^{-2}$, although ρ_μ of a typical FE1-MA event only varies by a factor of 2 to 3 over the 8 Patches.

The Yakutsk group have parameterized the MLD as a function of Energy and Zenith angle.[7] It is a modified Greisen form[8] relating muon Size to primary Energy and Zenith angle. For the FE overburden, the Yakutsk MLD becomes

$$\rho_\mu(R_{core}, E, \theta) = 1309 \exp\left(\frac{(1 - \sec\theta)870}{440}\right) E^{0.87} R_{core}^{-0.75} \left(1 + \frac{R_{core}}{280m}\right)^{0.75 - b_\mu} \tag{4}$$

where

$$b_\mu(\theta, E) = 3.26 - 2.28(1 - \cos\theta) + 0.09 \log E. \tag{5}$$

Figure 6 histograms the ratio of the measured ρ_μ to that expected from the Yakutsk MLD. The mean of the distribution implies the two agree to $\pm$ 5 %. This comparison was presented previously from Stereo-MA coincidence data. That

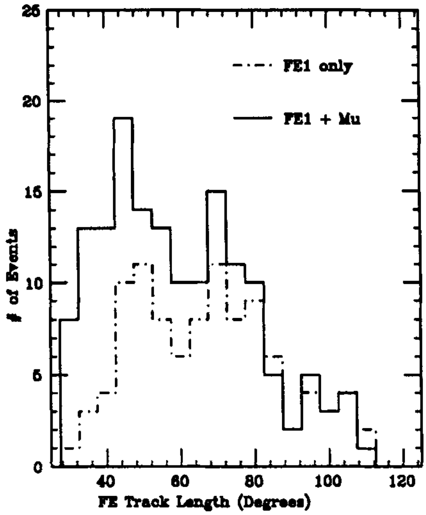

Figure 4. Track length distribution of FE1-MA (solid) and FE1-only events (dashed). More events at small track length now survive quality cuts. The 2 distributions agree at large track length where FE-only data are good.

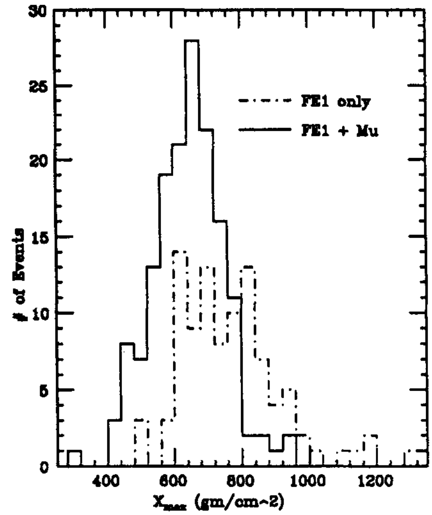

Figure 5. The X_{max} distribution for the 2 data sets. The FE1-MA distribution is consistent with previously measured values.

data required an extrapolation to the density at $1km$, since showers observed in Stereo require $R_{core} \geq 1km$. FE1-MA data give a direct comparison of the ρ_{μ} for $R_{core} < 1km$ (the range of values used by the Yakutsk group in the parameterization). Figure 7 shows a scatterplot of EAS cores in the Array horizontal plane for events passing quality cuts.

III. Conclusions and Future Directions

We have demonstrated that FE1-MA showers landing outside the Array can be reconstructed with reliable geometries and significantly improved X_{max} values. This doubles the useful set of FEMA data and gives a MLD measurement at $< 1km$. The new measurement is consistent with the Yakutsk MLD extrapolated to the FE depth and to $0.3EeV$.

Future upgrades to the Array and the FE include increasing the number of muon Patches from 8 to 16, expanding CASA to 1089 stations, and installing the Fly's Eye High Resolution (HiRes) prototype[9] which will consist of 4 mirrors each with 256 tubes and each covering a different portion of the atmosphere overlooking the Arrays. All upgrades are scheduled to be completed by the end of 1990.

Current plans are to use HiRes-CASA coincident events whose core falls inside CASA. This requirement insures $\pm 1°$ error in direction and $\pm 10m$ error in core position. The expected trigger rate above $0.03EeV$ for showers landing inside the $0.25km^2$ area is $> 1700yr^{-1}$.

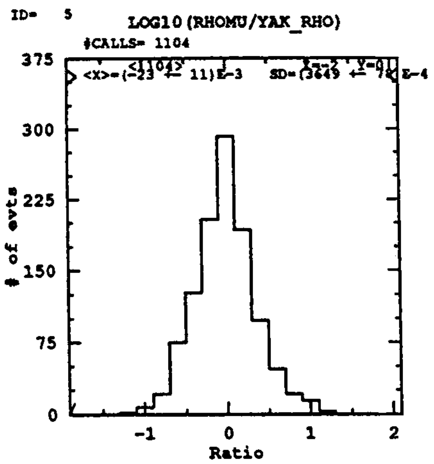

Figure 6. $\log_{10}\left(\frac{\rho_\mu^{Observd}(R_{core})}{\rho_\mu^{Yakutsk}(R_{core})}\right)$

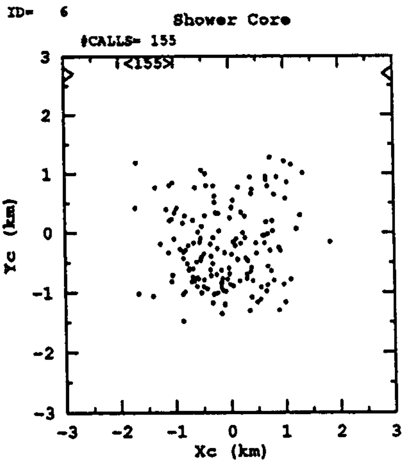

Figure 7. Core positions (km).

The actual coincidence rate will be significantly higher, since many events outside the Array boundary will be detected by both experiments. Events detected with HiRes will have Shower Plane angles good to 0.6° and the timing accuracy will be $20nsec$ compared to the current FE resolution of 2° and $50nsec$ respectively. So, events landing outside the Array will conservatively have angular and relative R_p resolutions of $0.6° \times 2.5°$ and $< 5\%$ respectively. These are assuming an improvement in Array angular resolution by a factor of 2 due to the longer baseline from the 8 additional muon Patches, and a slight improvement in R_{core} from improved FE timing.

Accepting events $< 1km$ from the Array center gives a collecting area that is a factor of 12 larger than the contained collecting area.

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