The Hybrid Energy Spectrum and Composition of Telescope Array's Middle Drum Detector and Surface Array

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Abstract: The Telescope Array experiment (TA) studies ultra high energy cosmic rays using a hybrid detector. Fluorescence telescopes measure the longitudinal development of the extensive air shower generated by a primary cosmic ray particle, while scintillation detectors measure the lateral distribution of secondary particles that hit the ground. The Middle Drum (MD) fluorescence telescope consists of 14 telescopes from the High Resolution Fly's Eye experiment (HiRes), providing a direct link back to the HiRes data and measurements. Using the scintillation detector data in conjunction with the MD data improves the geometrical reconstruction of the showers significantly, and hence, provides a more accurate reconstruction of the energy of the primary particle. In addition, the constraint of the core location by the surface array allows us to make a more precise measurement of the composition of the primary cosmic rays. The Middle Drum hybrid results are presented.

Keywords: Telescope Array, Hybrid, Energy Spectrum, Composition

1 Telescope Array

The Telescope Array (TA) experiment uses a hybrid detector to study cosmic ray particles with energies $> 10^{18}$ eV. It is comprised of three fluorescence detector (FD) sites, each with 12 - 14 fluorescence telescopes (38 in total). The FD sites surround an array of 507 scintillation surface detectors. Refurbished telescopes from the High Resolution Fly's Eye (HiRes) experiment were used in the northwestern FD site, located at the Middle Drum (MD) mountains.

The HiRes experiment produced the first observation of the GZK cut-off [1]. The use of the telescopes from HiRes at the MD site provides a direct link from that experiment to the Telescope Array. An energy spectrum comparison between the MD site and HiRes was performed and found that the two are in agreement [2].

2 Middle Drum Hybrid

This analysis used the MD FD data in conjunction with the surface detectors (SD). This is the next step in directly linking the HiRes measurement to the entire Telescope Array experiment.

The Middle Drum hybrid data is collected by time matching data from the MD and SD detectors, each operating in monocular mode. Events that trigger both detectors within a microsecond are kept. The photo-multiplier tube (PMT) trigger times from the FDs are fit to a model of the UHECR shower axis to obtain the shower detector plane (SDP). The location of the core of the shower can be calculated from the locations of the triggered SDs. This information, along with the trigger times of the SDs is used to constrain the geometry calculation from the FD analysis. The hybrid event reconstruction programs are described in detail in [3].

The MD hybrid energy calculation is done using the triggered times of the PMTs as well as the integrated pulse areas. The number of photons per track length per collection area for each PMT is plotted as a function of shower slant depth. This slant depth is calculated from the pointing directions of the PMTs and the initial calculated geometry of the shower. We fit this energy profile to the Gaisser-Hillas parametrization, which fits the maximum number of particles in the shower as well the slant depth of the shower at the shower maximum. The energy of the particle shower is calculated from integral of this curve. And, correcting for the missing energy from neutral particles in the shower, we calculate the energy of the primary particle.

Two measurements are shown here using the reconstructed information from the particle showers. An initial MD hybrid energy spectrum was calculated and has been shown [4]. In this paper, we show an updated hybrid energy spectrum including four years of MD hybrid data (2008-2012). This data set has excellent geometry resolutions, making it ideal for a composition analysis. We also show the results of initial composition studies using the MD hybrid shower maximum, X_{max} parameter to differentiate between light (proton-like), and heavy (iron-like) particles.

2.1 Resolutions

The resolutions of parameters in this analysis are calculated using Monte Carlo (MC) data. A set of MC data was thrown for the purpose of determining how well the reconstruction programs perform. The set was generated using protons, and contains $\sim$15,700 events.

We have shown that the MD hybrid analysis improves the resolutions in the geometrical parameters by an order of magnitude, and in energy by a factor of two when compared to the MD monocular resolution [3]. Figure 1 shows the distributions of the differences between the thrown and reconstructed in-plane angle, impact parameter, and energy. The in-plane angle and impact parameters are key variables for determining the geometry of a particle shower. The energy resolution is shown for energies $18.5 < Log_{10}(E)[\text{eV}] < 19.0$ because this is the range in which the MD hybrid detector is optimized. The energy resolution here is 7.1%, which is significantly better than the MD monocular resolution of 26% [3], or the SD monocular resolution of $\sim$ 25% [5]. The resolution in the other energy ranges is also very good: in the energy range of $18.0 < Log_{10}(E)[\text{eV}] < 18.5$, the energy resolution is 9.8% compared with 35% for the MD, and $\sim$ 30% in the SD monocular resolutions; in the energy range of $Log_{10}(E)[\text{eV}] > 19.0$, the energy resolution is 5.6%, improved over 19%, and $\sim$ 18% in the MD and SD monocular cases, respectively [3, 5].

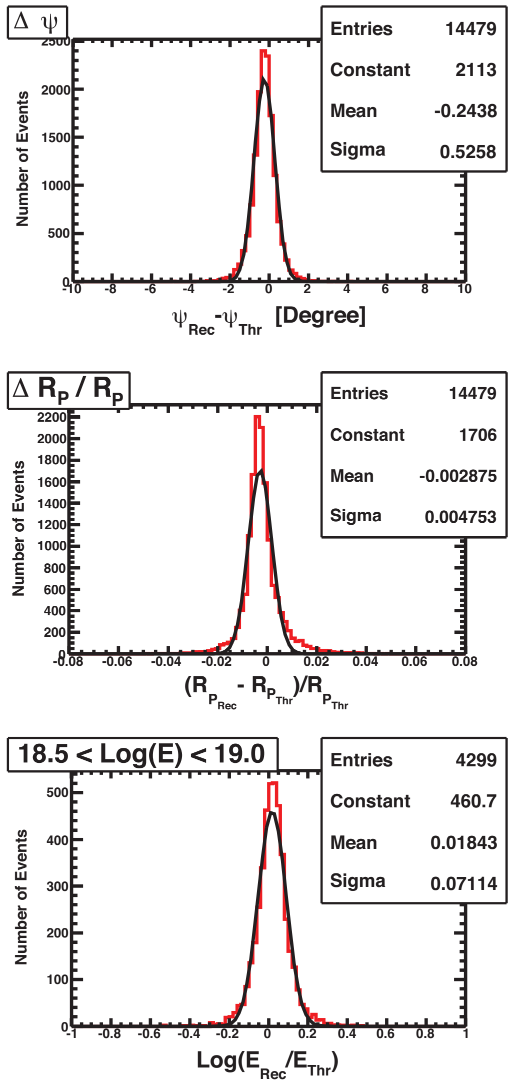

Fig. 1: Middle Drum Hybrid Resolutions: Shown are the Middle Drum Hybrid Impact Parameter, R_P, resolution (top); the Middle Drum Hybrid In-Plane Angle, Ψ, resolution (middle); and the Middle Drum Hybrid Energy resolution for the optimized energy range: $18.5 < Log_{10}(E) < 19.0$ (bottom). In each case, the red histogram shows the Monte Carlo data, while the black line shows the gaussian fit to the data.

2.2 Data-MC Comparison

The simulated MC showers are also used to calculate the detector aperture which is necessary for making an energy spectrum measurement. In order to ensure that the aperture calculation is representative of reality, the MC must represent the data accurately. We use Data / Monte Carlo comparisons to make these determinations. The MC data was thrown using the HiRes energy spectrum as input, with the intention of creating an accurate MC set. Figure 2 shows the distribution of the in-plane angle for the data and the MC. Figure 3 shows the distribution of the impact parameter for both the data and the MC. In both cases, the MC is normalized to the number of data events, and the MC distributions are in good agreement with the data.

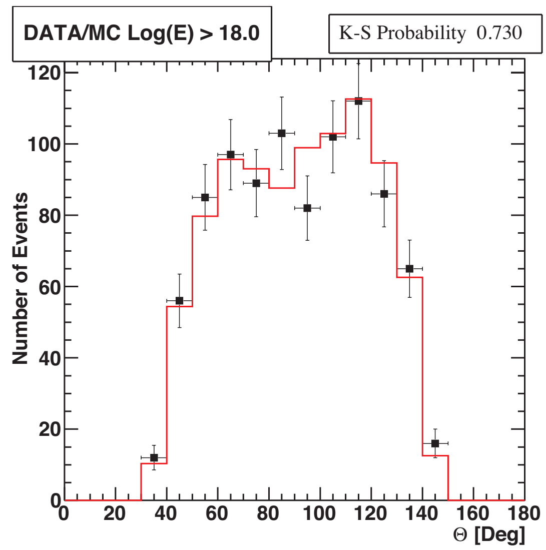

Fig. 2: Middle Drum Hybrid Data / Monte Carlo Comparison: Shown is the Middle Drum Hybrid In-Plane Angle, Ψ, from the data (black points) compared to the Monte Carlo (red histogram).

3 Energy Spectrum Measurement

The energy spectrum, or the differential flux of cosmic rays, is calculated by taking the number of data events per energy bin and dividing by the exposure and energy interval for that bin.

The exposure is calculated by multiplying the aperture per energy bin by the on-time for the detector. The aperture for the detector is calculated from the MC simulations. The simulated set is generated within a particular area (in this case, a circle with radius 25 km centered at the middle of the SD array). The aperture is the area of this circle multiplied by the solid angle and the fraction of simulated events that are reconstructed by the detector.

The MD hybrid energy spectrum measurement is shown in figure 4. It is compared to the energy spectra as measured by the MD monocular data set as well as the SD monocular data set. The spectra are in reasonable agreement.

4 Composition Measurement

The X_{max} parameter, or depth of the shower maximum, is particularly useful for composition analysis. Light, proton-like showers tend to penetrate deep into the atmosphere before interacting, with a greater uncertainty on the distance before its first interaction. This results in a larger X_{max} val-

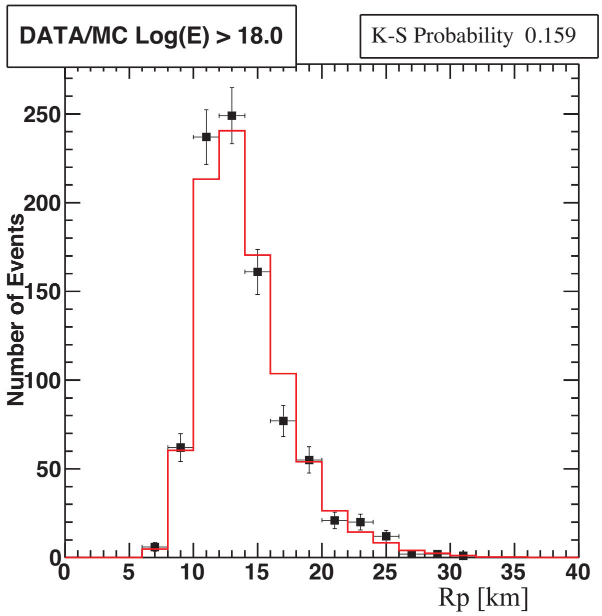

Fig. 3: Middle Drum Hybrid Data / Monte Carlo Comparison: Shown is the Middle Drum Hybrid Impact Parameter, R_P, from the data (black points) compared to the Monte Carlo (red histogram).

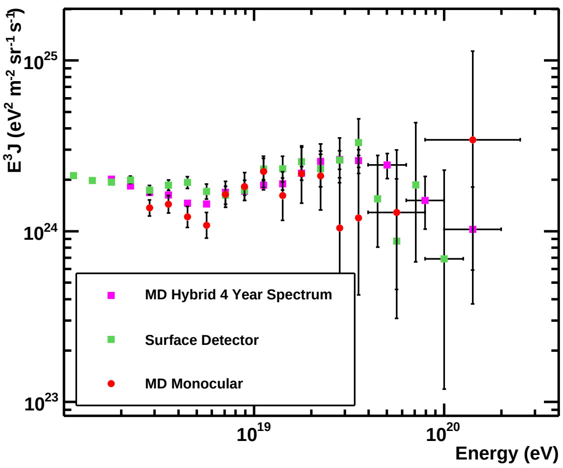

Fig. 4: The Middle Drum Hybrid Energy Spectrum (red circles) compared with the spectrum measured by the surface array (purple squares) and the MD monocular spectrum (green squares).

ue with a wider distribution. On the other hand, heavier particles tend to interact right away and with higher multiplicity, resulting in a smaller X_{max} value and a narrower distribution. The MD hybrid composition analysis uses these factors to try to distinguish whether the actual data agrees more closely with the light or heavy particles.

In order to look at both particle types, a second MC set was thrown using iron as the primary cosmic ray particle. It was generated in the same way as the proton set and reconstructed with the same programs as the data. This set is described in detail in [3].

Figure 5 shows the overall distributions of the X_{max} parameters for the proton MC, iron MC, and the data. All Events with calculated energies above $10^{18.0}$ eV were used in this figure. A Kolmogorov-Smirnoff test was performed to compare the data to each MC set. The probability for each test is shown on the figure, and a p value > 0.05 indicates good agreement between the two sets.

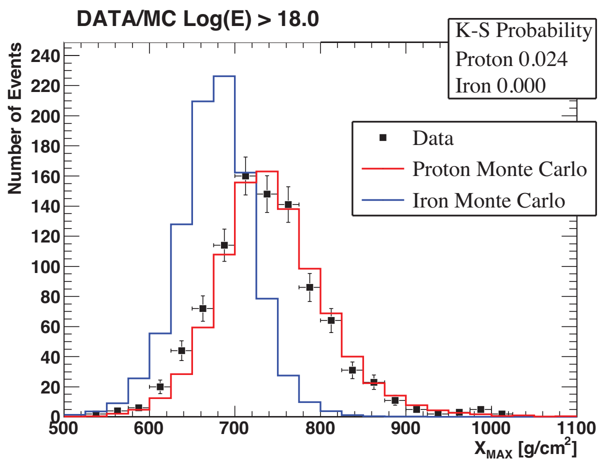

Fig. 5: The Data / Monte Carlo comparisons of the shower maximum (X_{max}): the distribution of measurements is shown for the data (black points with error bars) with the proton Monte Carlo (red histogram), and the iron Monte Carlo (blue histogram). The MC has been normalized to the area of the data. The K-S Probability for the iron MC is less than the single precision limit, meaning that the value of the must be smaller than 10^{-37}.

A second composition study was done using the X_{max} parameter. Figure 6 shows the average X_{max} value for each 10^{th} decadal energy bin for the data plotted with the same information for each of the MC sets. The average values for the MC sets were fit to lines which are seen in the figure. The MD hybrid data points are much more closely aligned with the proton MC line.

5 Summary

We have previously shown that the MD hybrid energy spectrum is in agreement with the MD monocular energy spectrum [2], which links the entire TA experiment to the High Resolution Fly's Eye experiment. Using the two detector types in hybrid also significantly improves the resolutions on the reconstructed parameters over the monocular reconstructions, and results in a better energy spectrum measurement. We have also shown that the initial MD hybrid com-

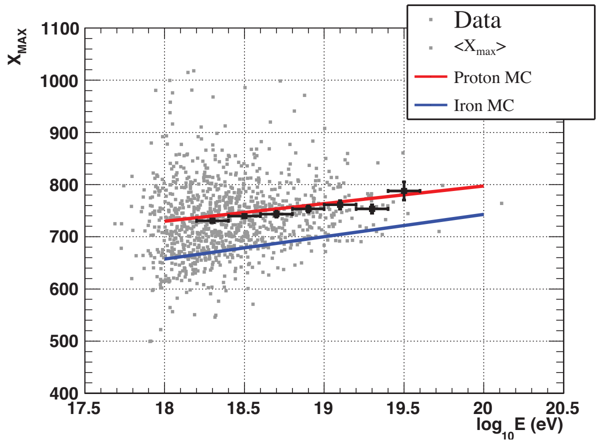

Fig. 6: Middle Drum hybrid composition result: the $<X_{max}>$ values for each data event are plotted as a function of energy overlaid with the proton and iron "rails". The pink points are a scatter plot of the X_{max} of the real data as a function of energy. The black data points with error bars represent the $<X_{max}>$ values binned by energy. The dotted "rail" is the fitted line to the proton MC set $<X_{max}>$ values, while the solid "rail" is the fitted line to the iron MC $<X_{max}>$ values.

position measurements indicate that UHECR at the highest energies are light, or proton-like.

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