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Stereo HiRes Spectrum Measurements

P. SOKOLSKY[1], FOR THE HIRES COLLABORATION
[1]*University of Utah, Salt Lake City UT 84112 U.S.A.*
ps@cosmic.utah.edu

Abstract: While monocular measurements of the UHECR flux with the HiRes detector give the largest statistical significance and the largest range of energies available, the stereo spectrum has the best geometrical reconstruction and the best energy resolution, though it has a higher energy threshold. The stereo spectrum for the full HiRes data set is presented and compared to the monocular spectra.

Introduction and Motivation

The High Resolution Fly's Eye (HiRes) detector was designed to view UHECR showers in stereo. Showers viewed independently from two sites spaced 12 km appart have excellent precision in geometrical reconstruction. Independent energy measurements from two sites allows a verification of the calculated energy resolution of the detector. This is critical because an energy dependent energy resolution or non-gaussian tails on the energy resolution functions can distort the measurement of a steeply falling spectrum. The stereo technique has a physics threshold of near $3\dot{1}0^{18}$ eV because the detector aperture begins to decrease very rapidly below this value. Monocular reconstruction is less precise but has a much more slowly changing aperture at low energies and thus a lower threshold. The geomtrical and energy reconstruction can be cross-checked for the sample of events seen in both stereo and mono. The stereo spectrum, while more limited in statistics and energy reach gives the stablest geometrical and energy reconstruction and hence is important in understanding the systematic errors due to other issues such as atmospheric corrections and aperture calculations.

Analysis Techniques

For the subset of events observed in stereo, the geometrical reconstruction is essentially determined by the intersection of the two shower-detector planes. Here the shower-detector planes are found by fitting a plane to the direction vectors of the phototubes which were triggered at each detector. Even better precision is found by combining the shower time information with this simple geometrical fit. Once the stereo geometry is determined, the shower profile is reconstructed independently for HiRes I and HiRes II using similar binning techniques to those used in the monocular analysis.

With the geometry determined, the photo-electron count is converted to a shower size at each atmopheric depth, using the known geometry of the shower, and corrected for atmospheric attenuation. We integrate the resulting function of slant depth X (using the determined values of N_{max} and X_{max}) and then multiply by the average energy loss per particle to give the visible shower energy. A correction for energy carried off by non-observable particles to give the total shower energy ($\sim 10\%$)[1] is then applied.

Comparison of energies determined in stereo for HiRes I and Hires II alone confirm the adequacy of the energy resolution estimates from the detector Monte Carlo (see Fig. 1).

The detector Monte Carlo is also used to calculate the detector aperture. Simulated events generated by the Corsika program were subjected to the same reconstruction algorithm and cuts applied to the data. To verify the reliability of this calculation, we compared, at different energies, the zenith angle and impact parameter distributions, which define

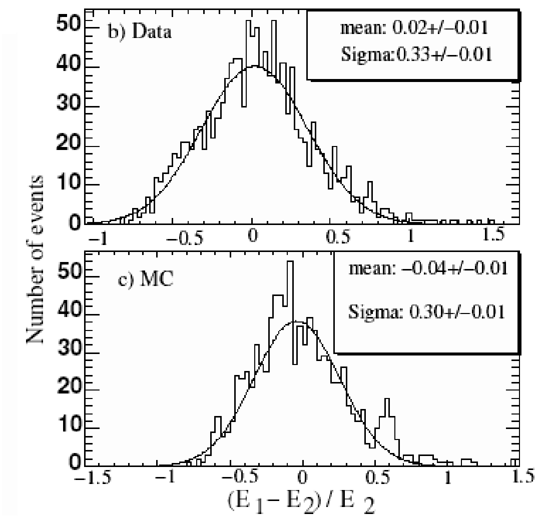

Figure 1: Distribution of energy differences for HiRes I and HiRes II divided by the HiRes II energy for events seen in stereo. Top panel - data. Bottom panel - Monte Carlo prediction.

the detector aperture. The MC predictions for these are very sensitive to details of the simulation, including the detector triggering, optical ray-tracing, signal/noise, and the atmospheric modeling. Good agreement is found for both stereo and mono distributions (see Fig. 2).

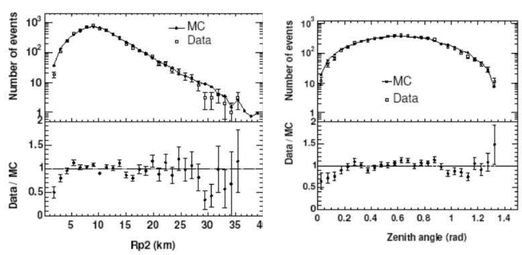

Figure 2: Comparison of data and Monte Carlo predictions for the impact parameter and zenith angle distribution of events.

Because the stereo aperture has a more rapid dependence on energy at lower energy, we define a set of geometrical cuts such that only the fully efficient part of the stereo aperture is used. This is done by determining, as a function of energy, the maximum impact parameter distance to an event below which the trigger is fully efficient (see Fig. 3). Only events in this geometrical range are used for the "fully efficient" stereo aperture. The "fully efficient" aperture is nearly identical to the normal stereo aperture at high energies but is significantly smaller near detector threshold. We determine the required cuts using the detector Monte Carlo. Since this cuts out events with marginal triggering, this set of cuts also insures that the aperture is largely insensitive to atmospheric variations.

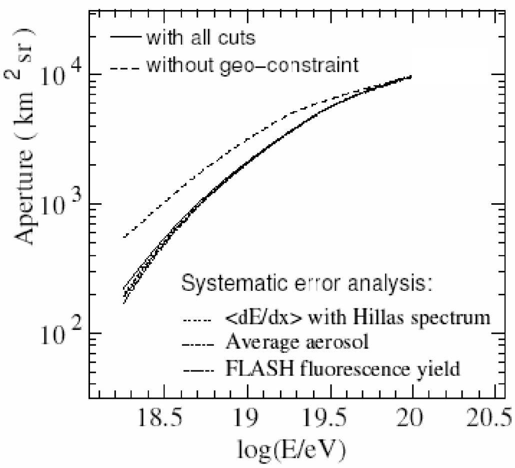

Figure 3: Stereo aperture for normal and "fully efficient" aperture. Dashed curve ("without geo constraints) represents the normal aperture. Other curves represent the "fully efficient" aperture and its variation under changes in various assumptions.

Flux

We present the stereo spectrum for essentially the full HiRes data set for the "fully efficient" aperture (see Fig. 4). The ankle structure and the expected GZK cutoff are clearly seen. We fit two power laws to the spectrum with a floating break point. The slope below the ankle is -3.33 ± 0.18 while the slope above the ankle is -2.75 ± 0.25. These are in excellent agreement with the slopes measured by the monocular reconstruction. The spectrum for the normal aperture is essentiall indistinguishable from the "fully efficient" one.

The largest systematic uncertainties are the absolute calibration of the photo-tubes ($\pm 10\%$), the

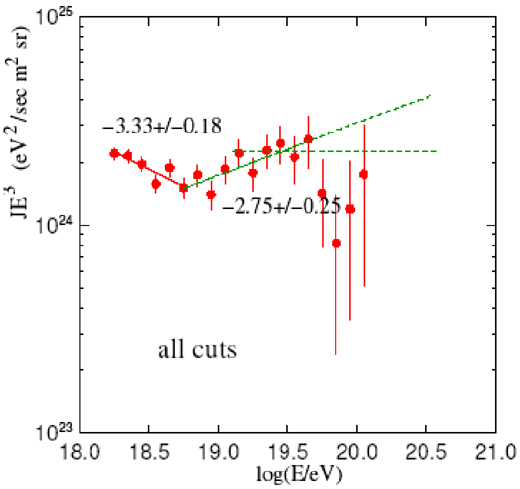

Figure 4: Stereo spectrum for "fully efficient" aperture showing result of two power law fits with floating break point.

yield of the fluorescence process ($\pm 10\%$), the correction for unobserved energy in the shower ($\pm 5\%$)[1], [2], and the modeling of the atmosphere.

Significance of cut-off

We estimate the significant of the cut-off near $6\dot{1}0^{19}$ eV by comparing the number of events observed to the expected number in the case of a continuing spectrum with a slope of -2.75 and with a continuing spectrum with a slope of -3.00. For the first case, we expect 37.4 events for 11 events observed above an energy of $10^{19.7}$. In the second case, we expect 29.8 events. This represents a 4.3 and 3.4 sigma effect, respectively.

Comparison to Monocular Spectra

The stereo spectrum was recalculated with exactly the same assumptions (fluorescence yield, dE/dX, missing energy, atmospheric and detector calibration constants, etc.) that were used in the published monocular spectra. Use of the older versions of these values yield a shift in energy by about ten percent. Fig. 5 shows the comparison of this stereo spectrum with the two monocular spectra. Agreement is very good.

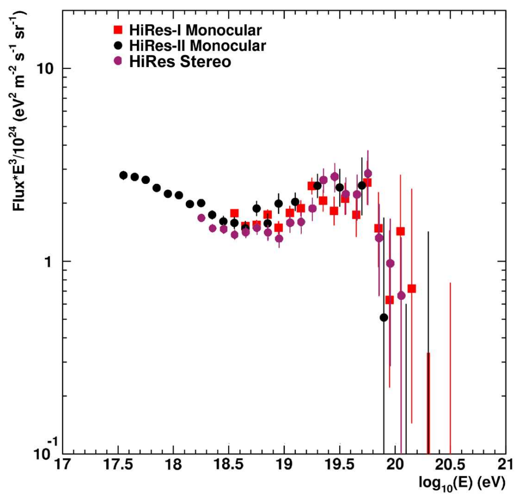

Figure 5: Comparison of stereo aperture with HiRes I and HiRes II monocular spectra. Stereo data has been re-analyzed with the same calibration and other assumptions that were used in the older monocular analysis.

Acknowledgements

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