# Recent Results from the High Resolution Fly's Eye Experiment

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The HiRes experiment has now completed data taking. We describe the experiment, the detector and atmospheric calibration and studies to improve precision of knowledge of air-fluorescence efficiency. The current results on the monocular and stereo spectrum and stereo-based composition measurements are summarized. Possible correlation of stereo data event directions with a subset of Bl-Lac objects is discussed.

## 1. Introduction

This paper describes the High Resolution Flys Eye (HiRes) experiment and introduces physics results on the spectrum, composition and anisotropy of ultra-high energy cosmic rays.

The HiRes experiment consists of two sites (HiRes I and II) 12.6 km apart, located at Dugway proving Ground in Utah. Each site consists of telescope units (22 at HiRes I and 42 at HiRes II) pointing at different parts of the sky. The detectors observe the full 360 degrees in azimuth but cover from 3 to 16.5 (Hires I) and from 3 to 30 degrees (HiRes II) in elevation angles. Since most cosmic ray events in this energy range are detected at distances of between 5 and 30 km from the detectors, higher elevation angles contribute little to the event rate. Each telescope consists of a 3.72 $m^2$ effective area mirror and a 256 phototube camera cluster in the mirror focal plane. The phototubes subtend a one degree by one degree field of view on the sky. The tubes view signals through a UV filter which cuts out light below 300 nm and above 400 nm (corresponding to the air-fluorescence spectral range).

## 2. Event Reconstruction

The arrival direction of the cosmic ray initiating the shower can be reconstructed monocularly, using the triggered tube pointing directions to determine the shower-detector plane, and the relative tube triggering times to determine the impact parameter and angle of the track within the plane. From this information, the impact parameter, zenith and azimuth angles can be easily calculated. Stereo reconstruction affords much better precision. If the shower is detected by both HiRes I and II and two shower-detector planes are determined for the event, the shower direction must lie along the intersection of the two planes. Because of the simplicity of the method, it is virtually impossible to get the shower direction and distance systematically wrong, once the pointing directions for the phototubes are accurately determined.

The largest data sample consists of events seen by HiRes I only, since this detector turned on three years before the completion of Hires II. Because of the limited elevation angle coverage of HiRes I monocular events are too short in angular spread for reliable determination of the geometry by timing alone. Experiment and simulation have shown that while the position of an EAS in the atmosphere will fluctuate, its shape has very little variation. This shape is well described by the Gaisser-Hillas function. To improve resolution for the HiRes I data, the expected form of the shower development (i.e. the shape of its longitudinal profile) is used to constrain the time fit. The HiRes II event sample has longer track lengths and the geometry can be well determined from timing alone. The profile constrained HiRes I fit has been carefully checked using both simulations and comparisons of reconstruction with stereo data for the subset of events where HiRes II was also triggered.

Once the geometry of the event is determined, the tube signals are used to determine the shower size in one degree angular bins on the sky (for

HiRes I), or in time bins corresponding to the FADC clock at HiRes II. Finally, combining the bin signal, corrected for atmospheric attenuation, with knowledge of the shower geometry, we calculate the size of the shower as a function of atmospheric depth. Cherenkov light scattered into the detector is subtracted in an iterative process. The depth of shower maximum, $X_{max}$, and shower energy $E$ are determined from the Gaisser-Hillas fit to the profile. The shower energy is proportional to the integral of the Gaisser-Hillas function after corrections are made for missing energy due to neutral particles or high-energy muons hitting the earth´s surface. The missing energy correction ($\sim 10\%$)is weakly hadronic model dependent.

An example of a longitudinal shower profile of a stereo event is shown in Fig. 1.

## 3. Detector Calibration

The energy scale of air-fluorescence detectors depends on a number of factors including the air-fluorescence efficiency, the effect of scattering in the atmosphere, the gain and efficiency of the phototubes and the reflectivity of the mirrors. The absolute calibration of the phototubes is done with a portable Xenon light source whose stability is better than 2% [1]. The source is mounted in the center of the mirror and illuminates the PMT cluster uniformly. The source is moved from mirror to mirror and its intensity is separately calibrated using photoelectron statistics, NIST-traceable photodiodes and HPD tubes. The night to night relative gain of the phototubes is monitored using a YAG laser whose output is sent out to all the mirrors via quartz optical fibers. In addition a portable laser positioned at 4 km from each mirror is used to cross-check the end to end detetector calibration. Mirror reflectivity is measured separately using a commercial UV reflectometer. The tube and mirror calibration constants are known to a 10% accuracy.

## 4. Atmospheric measurements and calibration

There are three components of the atmosphere that are of importance to air-fluorescence mea-

surements: the molecular atmospheric density profile, the aerosol component and the presence and distribution of clouds in the detector aperture [2]. The molecular component is stable, exhibiting small seasonal dependence. We use radiosonde balloon data from the Salt Lake City airport ($\sim 100$ km away) to correct for daily and seasonal density variation.

Aerosols can vary in horizontal and vertical profile on short time scales. We monitor the aerosols by firing steerable UV lasers from both HiRes I and HiRes II detector sites. The other detector triggers on light scattered out of the laser beam by a combination of molecular (Rayleigh) and aerosol scattering. Since the molecular component is well know we subtract out this contribution and we determine the VAOD, the vertical aerosol optical depth, on an hourly basis [2]. The various laser measurements allow us to reconstruct the horizontal scattering length and the exponential scale height of the aerosols.

Clouds can be detected by a number of techniques, including visual observation, IR temperature measurements of the night sky seen by the mirrors, and the characteristic enhancement of light scattering out of a laser beam as it sweeps through a cloud.

## 5. Air Fluorescence Efficiency

A number of experiments have measured the air-fluorescence efficiency, using radioactive sources or electron beams [3]. Most recently, a subset of the Hires collaboration (the E-165 collaboration) has performed an experiment at SLAC to determine the air-fluroescence efficiency more precisely [4]. The current data is in good agreement with the energy deposited in the gas via the $dE/dX$ curve.

The shape of the shower profile as determined by air fluorescence was also measured by this group in a follow-up thick target experiment [5]. The comparison of the fluorescence signal as a function of radiation length into a shower with a fit to GEANT predictions for 28.5 GeV electrons shows good agreement. In this case, the SLAC electron beam interacted in an Alumina air equivalent target.
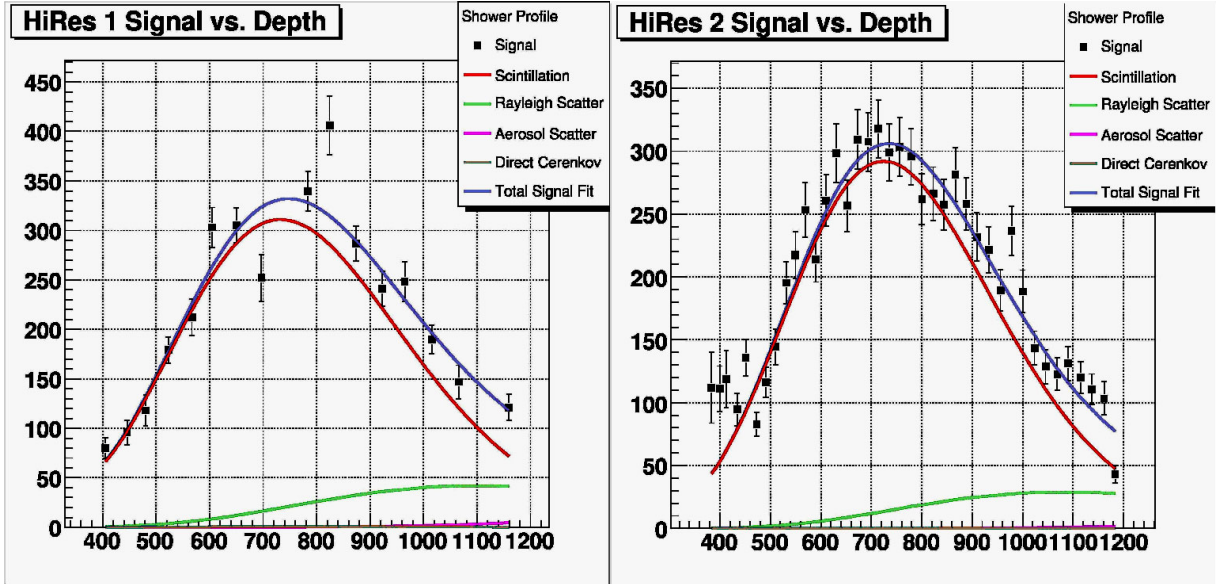
Figure 1. Typical shower profile measured by HiRes I and HiRes II.

## 6. Cosmic Ray Spectrum

Because of the different turn-on times of HiRes I and HiRes II and the different elevation angle coverage of the two detectors, we have three different data sets in the analysis: HiRes I monocular, HiRes II monocular, and HiRes stereo data. HiRes I monocular has the largest statistics and utilizes the profile constrained monocular timing reconstruction technique [6]. This has an effective physics threshold of near 3 EeV, determined by rapidly worsening energy resolution below this threshold. HiRes II, in contrast, has a physics energy threshold of near 0.2 EeV, set by rapidly changing aperture below this energy. The stereo data has an effective energy threshold of 2 EeV, again set by the onset of a rapidly decreasing aperture below this energy. The monocular aperture grows with energy and must be carefully simulated [7]. The most recent monocular spectrum from HiRes I and II is shown in Fig. 2. The spectrum clearly exhibits an ankle with a spectral minimum near 3-5 EeV and a depletion of events above 80 EeV consistent with the GZK feature

[8]. Details of the analysis and the physical interpretation of the ankle and GZK suppression features can be found in reference [7].

From the point of view of geometrical reconstruction, the most reliable spectral data comes from the stereo data set. However, since the stereo aperture is the intersection of two monocular apertures, the aperture calculation is more complex and the aperture drops very rapidly below 2 EeV. Fig. 2 shows the stereo spectrum superimposed on the monocular spectra. There is excellent agreement between the two.

One of the advantages of stereo reconstruction is that the same shower is measured by two different detectors. This allows us to check the energy resolution of the sytem, without relying so much on simulations. The distribution of energies of showers where the energy had a separate determination in HiRes I and HiRes II has a Gaussian distribution and its width is consistent with expectations from simulation. The inferred HiRes II energy resolution is $\sim 15\%$.

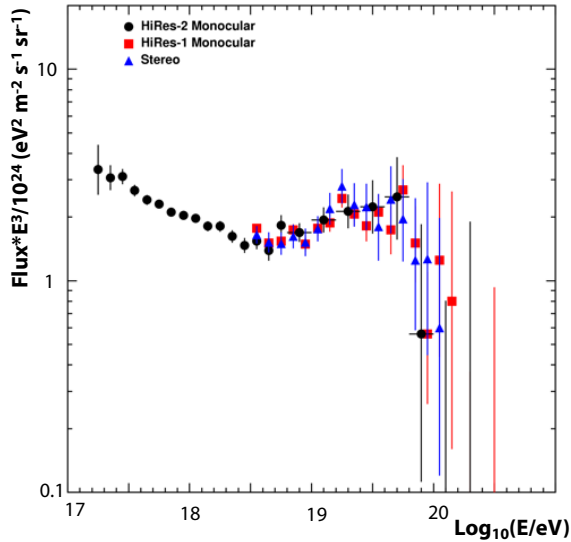Since the stereo spectrum exhibits significant

Figure 2. Monocular and Stereo Spectra. Blue symbols correspond to Stereo data

structure (the ankle and the GZK cutoff), it is important to establish that this structure is not the result of systematics in the determination of the stereo aperture. To study this, we define a "fully efficient" stereo aperture, where both HiRes I and HiRes II detectors will trigger with maximal efficiency. This is done by defining, for each energy bin, a maximum $R_p$ from each detector, such that for showers with smaller impact parameters will always trigger both detectors. Data points will then fall into the "fully efficient" region of the aperture. The resultant stereo spectrum is consistent with the ordinary stereo aperture and exhibits the same features.

The observed features are independent of the way we define the stereo aperture. Note that the stereo spectrum figures do not have final cloud free aperture cuts and hence are preliminary.

## 7. Cosmic Ray Composition

The distribution of shower maxima ($X_{max}$) is known to be sensitive to the composition of cos-

mic rays. Both the elongation rate and the absolute position of the mean $X_{max}$ and its fluctuations about the mean carry information about the primary composition [9]. While the detailed interpretation is hadronic model dependent, a measure of the systematic uncertainties can be garnered by comparing the predictions of a variety of hadronic models, from QGSJET and SYBILL to DPMJET [10]. The elongation rate, or slope of the mean $X_{max}$ per decade of energy, is essentially model independent up to energies of 30 to 50 EeV and the variation in absolute mean $X_{max}$ position are in agreement to within 25-30 g/cm$^2$ in this energy region. Since the separation between a pure Fe and a pure p spectrum is about 70-100 g/cm$^2$, qualitative information about the nature of the primary particles can certainly be derived using this technique.

Fig. 3 shows the elongation rate from the stereo data [11]. Also included in this figure are lower energy data from an earlier hybrid experiment [12]. Above 1 EeV, the data is consistent with a light, mainly protonic composition. However, this HiRes data is based on the first two years of operation and runs out of statistics above 30 EeV. We have recently analyzed a much larger sample of stereo events, with stringent shower profile quality cuts. These golden events yield an extension to the elongation rate to nearly 100 EeV . HiRes $X_{max}$ data is consistent with a light composition to the highest energies.

## 8. Anisotropy

Many studies of the anisotropy of ultra-high energy cosmic rays using the HiRes monocular and stereo data set have been performed. No significant large-scale anisotropies have been found in the data [13]. Here we mention an intriguing small scale anisotropy in the stereo data, which was first pointed out by Gorbunov et al. [14].

Tyniakov et al. have suggested that well identified Bl-Lac objects are attractive candidates for cosmic ray acceleration [15]. Initial binned analysis of HiRes stereo data directions relative to the Veron catalogue of Bl-Lacs with a magnitude < 18 cut yielded a marginally significant correlation within the angular resolution of the HiRes
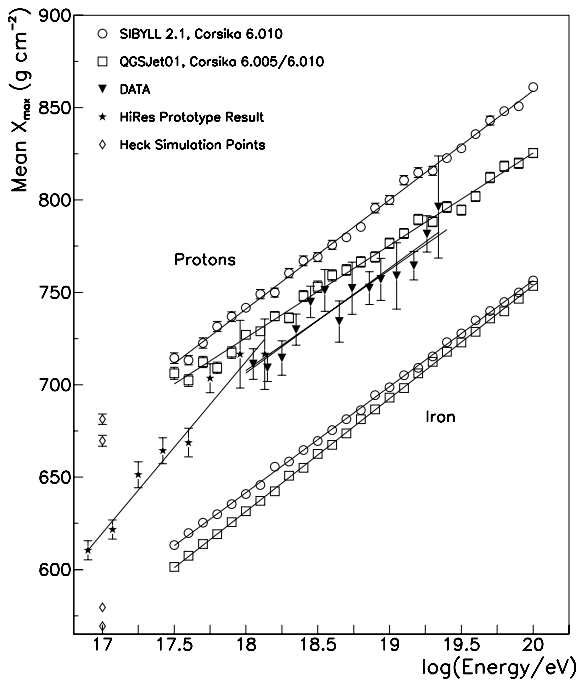
Figure 3. HiRes stereo data elongation rate. Also shown is the result from the HiRes prototype/MIA experiment

## 9. Conclusions

The HiRes experiment has completed data taking as of March, 2006. HiRes I has currently the worlds largest air-fluorescence data set on cosmic rays with energies $> 3$ EeV and has been accumulating data for $\sim 9$ years. HiRes II has been accumulating data for six years and has an extensive data set ranging down to .2 EeV. The HiRes stereo data set is now in the final analysis phase. The current stereo spectrum strongly confirms the presence of the ankle and GZK cutoff features seen in the monocular data. Stereo data indicate a light composition from above 1 EeV all the way to the GZK cutoff energy region. Previous suggestions of a correlation between cosmic ray arrival directions and a catalogue of Bl-Lac objects have been weakly confirmed, but additional analysis of independent data is needed to establish an objective probability for this correlation.

With the funding of the Telescope Array Experiment in Millard County, Utah, the equipment used in the HiRes experiment will acquire a new life as it will be refurbished and moved to this location. It will be used to provide one of the three air-fluorescence sites for the main hybrid array and will also be used to extend the low energy threshold of the experiment to 300 PeV.

detector. We have done a detailed maximum likelihood analysis of this correlation and have broadened the target catalogue to include HP (high polarization) Bl-Lacs as well [16]. With no energy cut, we find evidence for $\sim 22$ such objects being correlated with observed cosmic ray directions within the .6 degree Hires stereo resolution with an estimated probability of $10^{-5}$. Significant questions about tuning of the original selection of Bl-Lacs remain and an independent data set will shortly be analyzed to confirm or refute this apparent correlation.

If the correlation holds up, it will certainly be very interesting since only neutral particles can show a correlation within the intrinsic angular resolution of the detector and, given the $\sim 100$ Mpc distances to Bl Lacs, it is very unlikely that photons would survive.

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