

# Results from the HiRes Experiment

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**Abstract.** The High Resolution Fly’s Eye (HiRes) Experiment has been in operation in monocular mode since 1997 and in stereo mode since late 1999. The published HiRes monocular spectrum is consistent with the GZK Suppression at  $10^{19.8}$  eV and observes an ankle structure at  $10^{18.5}$  eV. The preliminary stereo spectrum is consistent with the monocular spectrum. Various anisotropy studies with both monocular and stereo data have yielded null results. However, a possible correlation between HiRes stereo events taken before Jan., 2004 and BL-Lac objects has been reported, but remains to be verified or refuted by the analysis of the Hires data taken after Feb., 2004. Composition studies of Hires stereo data shows a predominantly light composition in the energy range  $10^{18.0} - 10^{19.3}$  eV. We also report on the result of the proton-air cross section measurement from the tails of the  $X_{MAX}$  distribution.

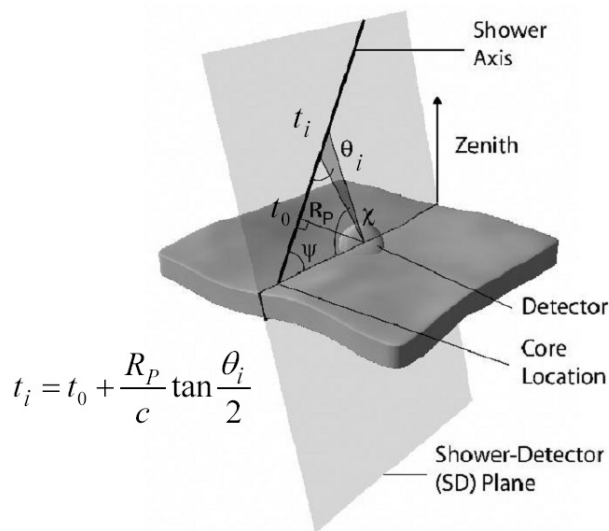
## 1. Introduction

The High Resolution Fly’s Eye (HiRes) Experiment is a collaboration between University of Utah, Columbia University, Rutgers University, University of New Mexico, University of Montana, the Los Alamos National Laboratory (LANL), University of Tokyo, and the Institute for High Energy Physics (IHEP) in Beijing, China. The experiment itself is located on the U.S. Army Dugway Proving Ground in the West Desert of Utah. The observatory is divided into two sites located 12.6 km apart. The HiRes-1 site, located at Little Granite Mountain, consists of 22 mirrors viewing nearly  $360^\circ$  in azimuth and  $3 - 17^\circ$  in elevation. and has been in operation since June of 1997. The HiRes-2 site, located at Camel’s Back Ridge, comprises 42 mirrors viewing  $360^\circ$  in azimuth and  $3 - 31^\circ$  in elevation, and began regular operation by December 1999.

All 64 HiRes mirror units employ the same basic optical design. Fluorescence light from distant air showers are collected using a  $\sim 2$  m diameter spherical mirror ( $3.72 \text{ m}^2$  effective collection area) onto a  $16 \times 16$  array of photo-tubes in a hexagonal close-packed arrangement. Each photo-tube pixel covers a  $1^\circ$  cone of the sky, and each mirror covers  $16^\circ$  in azimuth and  $14^\circ$  in elevation. While the solid angle viewed by each mirror is similar to that of the original Fly’s Eye, the  $1^\circ$  represents a factor of five improvement in resolution. Since air showers are approximately line sources of light, this improvement results in a five-fold increase in the signal-to-noise ratio for the individual pixels, which, when combined with the reduction in pixel size, allows HiRes to see the highest energy air showers at more than 30km away, which gives roughly an order-of-magnitude improvement in the detector aperture over that of the Fly’s Eye. Additional details of the detectors and associated electronics are given elsewhere (see, for example, [1, 2]).

## 2. HiRes Data Analysis

While the main goal of the HiRes experiment is to make stereoscopic observations, the 2.5 year earlier start of the HiRes-1 detector means that the HiRes-1 monocular data set contains significantly higher statistics than the available stereo data. In fact, the monocular data set represented the largest exposure for highest energy cosmic rays at the time of this workshop (April 2005). The HiRes-2 site, with its  $3 - 31^\circ$  field of view, can reliably measure cosmic ray showers accurately in monocular mode down to  $10^{17.2}$  eV, so that the HiRes-2 monocular data set has the lowest energy reach. For both monocular datasets, the shower trajectory is obtained in two steps illustrated in Figure 1(a): first a shower-detector plane (SDP) is constructed from the pattern of hit photo-tubes, and next timing information is used to determine the impact parameter,  $R_P$ , and incline angle,  $\psi$ , within the SDP. In the case of the HiRes-1 monocular data, the limited elevation coverage necessitated the inclusion of the assumption of a the standard Gaisser-Hillas shower profile [3] integrated into the timing fit. This Profile-Constrained Fitting (PCF) technique [4] compensates for the limited track lengths seen by HiRes-1. However, the PCF is well motivated by previous experimental measurement of the shower profile by the HiRes Prototype/MIA experiment.

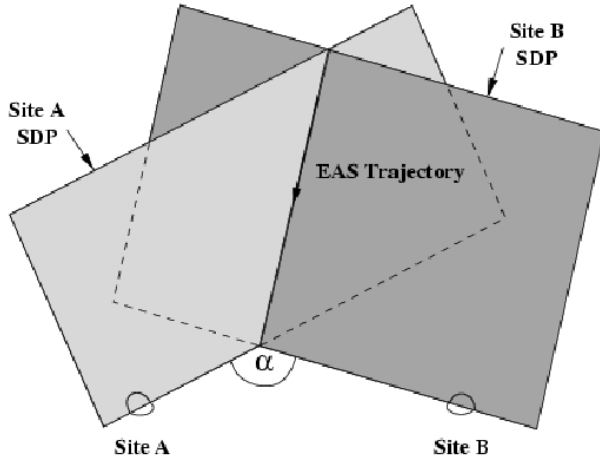


**Figure 1.** Illustration of monocular event reconstruction: (a) determination of the shower-detector plane (SDP) from hit photo-tubes, and (b) fitting the arrival times to find the impact parameter,  $R_P$ , and incline angle,  $\psi$ .

The analysis of the stereo dataset, using the intersection of the two shower-detector planes as illustrated in Figure 2, provides of course the best quality reconstruction, especially in providing an independent means of checking Monte Carlo (MC) resolution predictions, a particularly powerful feature for the composition measurement. However, the stereo overlap between the two sites decreases rapidly below  $10^{18.5}$  eV. For this reason, the stereo data set is limited in its composition and anisotropy measurements down to about  $10^{18}$  eV, and spectrum measurements down to  $10^{18.5}$  eV. In particular, the aperture calculation for the stereo dataset becomes increasingly sensitive to details of the aerosol variations and changes in energy calibration below  $10^{19}$  eV.

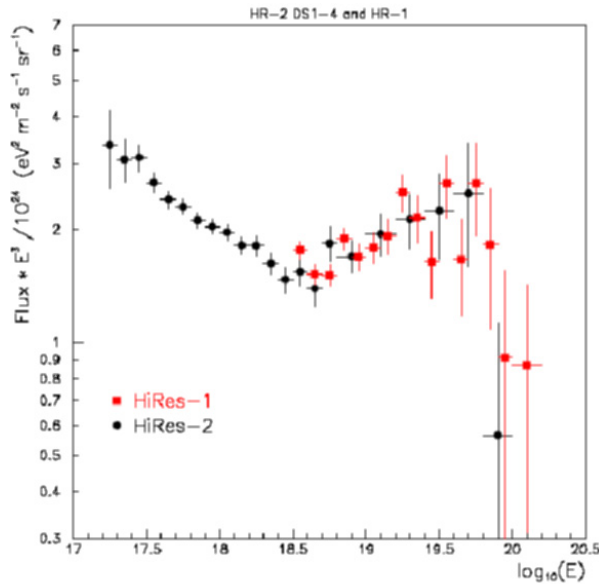
## 3. Spectrum Results

The combined monocular spectrum (from HiRes-1 and HiRes-2 monocular measurements) was first published in reference [5]. A more recent spectrum and fits to various models were given in a separate presentation [6]. We show here the most recent spectrum (As of April 2005) in Figure 3. This spectrum clearly shows two spectral features expected from attenuation from the cosmic microwave background: (a) the GZK suppression (from photo-pion production)[7]



**Figure 2.** Illustrations of Stereo event reconstruction by intersection of the two shower-detector planes.

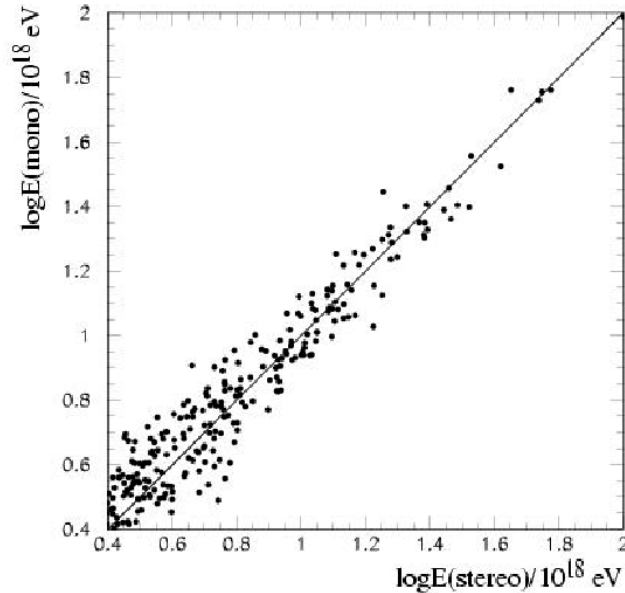
near  $10^{19.8}$  eV and the associated *pile-up* just below, and (b) the ankle structure at  $10^{18.5}$  eV consistent with previous measurements [8].



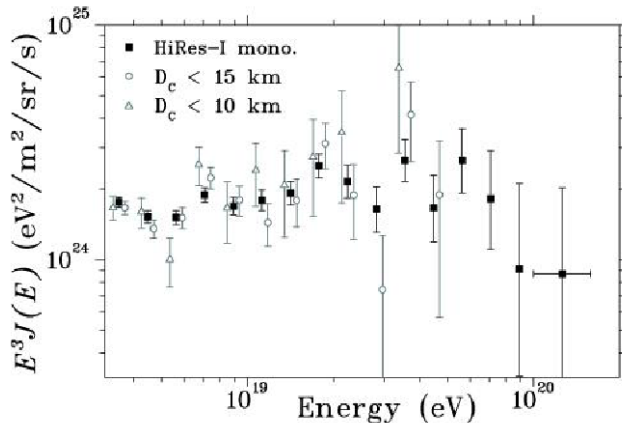
**Figure 3.** The HiRes monocular spectrum (4/2005) showing an ankle structure at  $10^{18.5}$  eV consistent with previous measurements [8] and a suppression at  $10^{19.8}$  eV consistent with the GZK Effect[7].

The HiRes spectrum results are inconsistent with the AGASA results in three respects: (1) The HiRes spectrum is not consistent with the single power-law continuation beyond the GZK threshold seen in the AGASA spectrum. (2) The flux observed by HiRes is about 30-50% lower than that measured by AGASA, and (3) HiRes sees the ankle structure at  $10^{18.5}$  eV. To investigate possible causes of these discrepancies, a number of systematic checks have been made by HiRes. We discuss here two examples of such checks, the first being a mono-stereo comparison to validate the HiRes-1 PCF reconstruction using data seen in coincidence between HiRes-1 and HiRes-2, which is shown in Figure 4. This plot shows excellent agreement between energies obtained from the PCF geometry and those found using the stereo geometry. We also checked the reliability of the aperture calculation by restricting the analysis of both data and Monte Carlo to those events with core locations within 10 and 15 km. By artificially limiting the

detector aperture, the energy-dependence of the aperture is significantly flattened. The resulting spectra, shown in Figure 5, are in good agreement with the standard spectrum produced without the core distance cuts.



**Figure 4.** Scatter-plot of energies obtained from the HiRes-1 monocular PCF method versus those obtained from the stereo geometry for the subset of HiRes-1 monocular data seen in coincidence. The agreement seen between these energies provides a validation for the PCF method used for HiRes-1 monocular analysis.

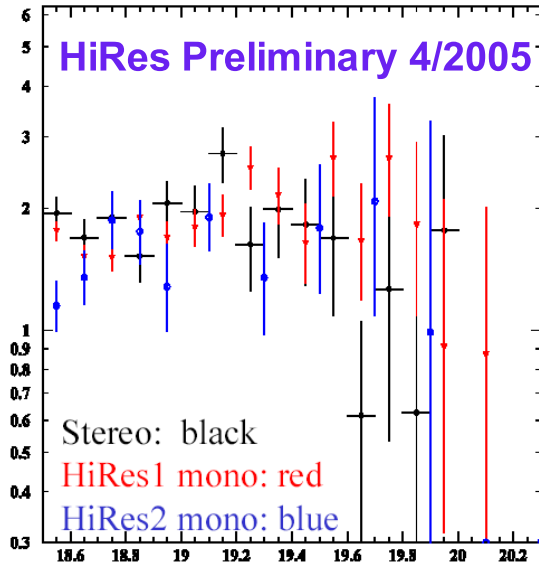


**Figure 5.** HiRes-1 monocular spectra obtained using artificial core-distance cuts of 10 and 15 km, respectively. Both are in good agreement, as shown, with the standard results.

Figure 6 shows the preliminary HiRes stereo spectrum (as of April, 2005). This analysis is still in progress. In particular, the overall normalization remains under intensive study because of the sensitivity of the aperture calculation to details in the simulation by such conditions as the hour-by-hour aerosol levels and detector thresholds. It should, however, be noted that the stereo spectrum agrees with the monocular spectrum in particular with respect to the paucity of events above the GZK threshold.

#### 4. Anisotropy Results

Several studies have been performed to search for both small- and large-scale anisotropy using the HiRes-1 monocular data. All have yielded null results. The studies have included searches for point-sources [9] as well as cross-correlation with the AGASA doublets and triplet[10, 11].



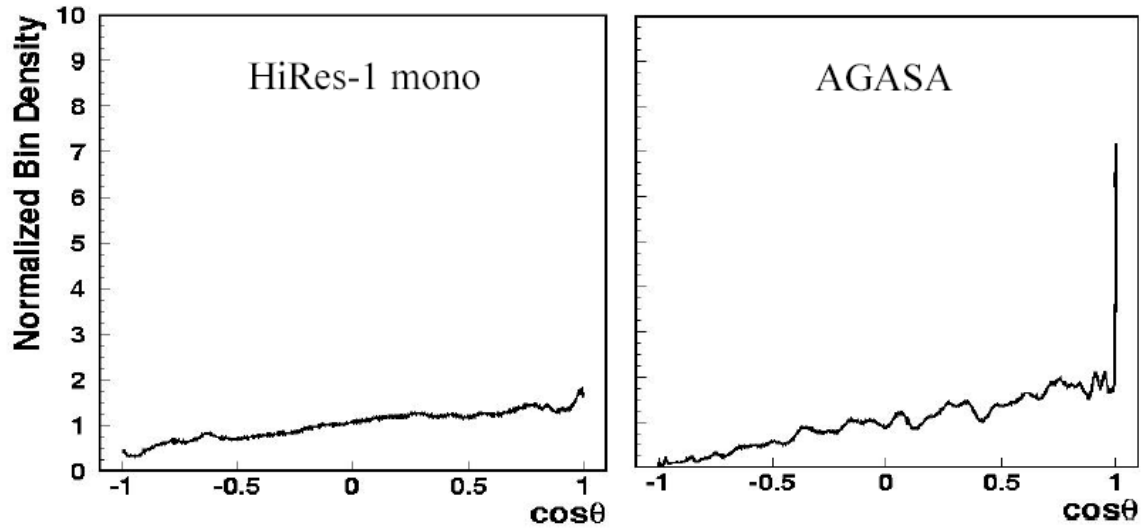
**Figure 6.** Preliminary HiRes (as of April 2005) stereo spectrum. It agrees with the monocular spectrum in particular in the small number of events seen beyond the GZK threshold.

Null results were also reported for possible dipole enhancements in the direction of several nearby objects including the Galactic Center, Centaurus A, and M87 [12]. We note in particular that we did not observe any small-scale auto-correlation such as that reported by AGASA [13, 14]. This result is shown in Figure 7, where error densities for the cosine of angles between pairs of events are plotted for events above  $4 \times 10^{19}$  eV for HiRes-1 monocular data (left) and for AGASA (right). In these plots, the error densities, for both experiments, were modeled as 2-D Gaussian distributions and included in the study by sampling these distributions. The original AGASA result did not take into consideration the error distributions. As can be seen in the plots, we were able to reproduce the AGASA enhancement, but did not see any corresponding effect in the HiRes-1 monocular data. A further simulation study established that the two data sets had comparable sensitivities.

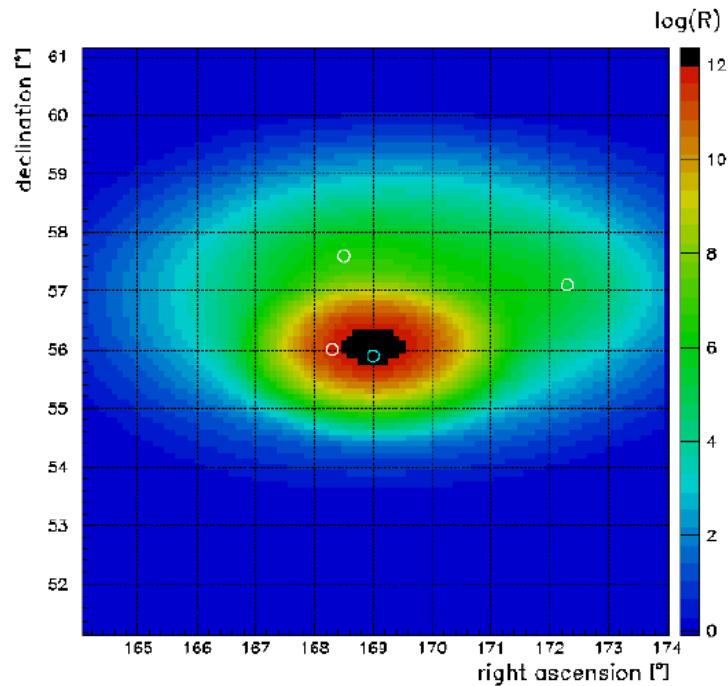
Anisotropy studies were also performed using the HiRes stereo dataset, which has better than  $0.6^\circ$  resolution in the arrival direction of the primary cosmic rays. An initial study showed the stereo events above  $10^{19}$  eV to be consistent with isotropy at all small angular scales [15]. A joint search for point sources with AGASA data showed one HiRes stereo event in coincidence with the AGASA triplet. This result is shown in Figure 8, which plots the relative likelihood ratio for the location of a point source that would give the both the AGASA triplet and the one HiRes event. However, a simulation study using  $10^4$  random, isotropic HiRes datasets with identical statistics yielded 47 sets which gave a coincidence with greater significance, consistent with a  $\sim 2.5\sigma$  fluctuation. Moreover, This chance probability of  $\sim 5 \times 10^{-3}$  does not take into consideration the statistical penalty associated with the *a posteriori* nature of the AGASA cuts, which would further weaken the significance of the observed overlap.

A possible correlation between HiRes stereo events and BL-Lacertae (BL-Lac) objects were first reported by Gorbunov *et al.*[16]. Using a binned analysis, the authors compared the positions of HiRes stereo events above  $10^{19}$  eV extracted from previous HiRes publications to those of the 156 “BL” objects in the Veron Catalog [17], and found 11 events HiRes events to lie within  $0.8^\circ$  of a “BL” object, with a chance probability estimated at  $\sim 10^{-3}$ . An independent analysis by the HiRes group using an unbinned maximum-likelihood method reproduced the apparent correlation with a chance probability of  $\sim 10^{-4}$ . A peculiar feature of this observation is that the correlation is consistent with the HiRes stereo angular resolution.

The HiRes BL-Lac correlation has been published [18] with data up to January of 2004. An



**Figure 7.** Histograms of the error densities of the cosine of angles between pairs of events above  $4 \times 10^{19}$  eV for HiRes-1 monocular data (left) and AGASA (right). No significant autocorrelation was seen by HiRes.



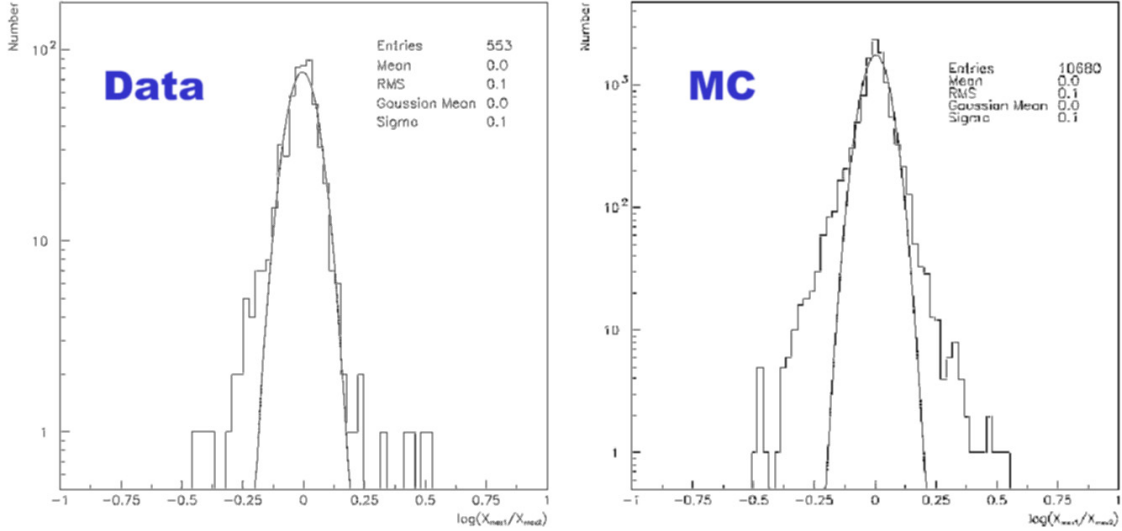
**Figure 8.** Sky-map, in the vicinity of the AGASA triplet, of the Relative likelihood ratio for the location of a point source that would give the both the AGASA triplet and the one HiRes event. Because of its smaller uncertainty, the point nearest the centroid of the distribution is the HiRes event.

independent dataset containing roughly 2/3 the exposure of the first dataset will be collected between February 2004 and the end of HiRes operations in April 2006. This new dataset will be analyzed separately to either confirm or refute this correlation.

## 5. Composition and Cross-Section Results

The shower maximum depth ( $X_{MAX}$ ) from the HiRes stereo dataset has also been used in both a composition study of UHE cosmic rays above  $10^{18}$  eV and to measure the proton-air cross

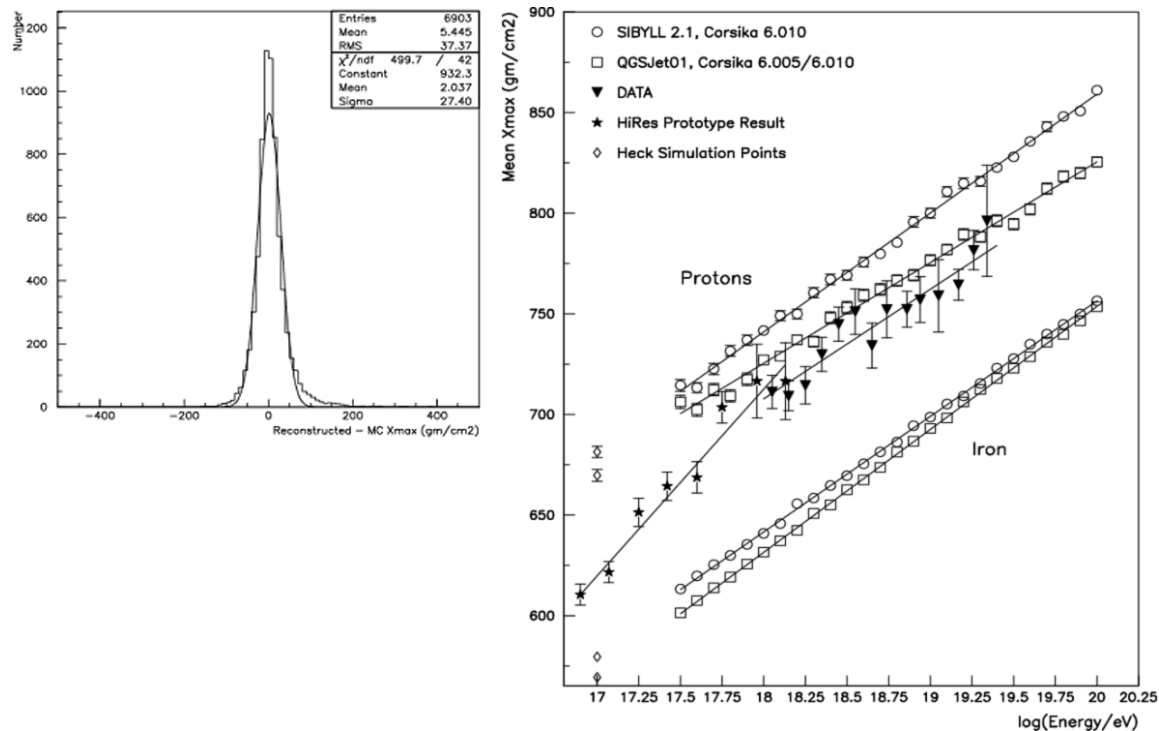
section at  $10^{18.5}$  eV. The stereoscopic nature of the HiRes experiment offers the unique advantage of redundant  $X_{MAX}$  measurements. The difference between the two measurements can be used to check the reliability of the Monte Carlo simulations. Figure 9 shows the distributions of the fractional difference between the  $X_{MAX}$  values measured from HiRes-1 and HiRes-2 detectors, shown for both data (left) and Monte Carlo simulations (right). The vertical axes in these plots are in log scale. The two distributions have essentially identical widths which serves to validate the  $X_{MAX}$  resolution derived from simulations.



**Figure 9.** Distributions of the fractional difference between the  $X_{MAX}$  values measured from HiRes-1 and HiRes-2 detectors, shown for both data (left) and Monte Carlo simulations (right).

The simulated  $X_{MAX}$  resolution of about  $30 \text{ g/cm}^2$  is shown in the left panel of Figure 10. The first composition results for the average  $X_{MAX}$  measured by HiRes as vs. energy has been published [19]. These results are shown together with the lower-energy results from the HiRes/prototype-MIA hybrid measurements in the right panel of Figure 10 along with model predictions for proton and iron. The published HiRes results, which spans the energy range of  $10^{18.0} - 10^{19.3}$  eV, and consistent with a constant and predominantly light composition. The indications come from constant mean depth of shower max and width of shower profiles. The elongation rate,  $(dX_{MAX}/d \log E)$ , is also approximately parallel to the models also indicative of constant composition. In contrast the HiRes Prototype-MIA results are consistent with a composition transition in the energy range just below this. These measurements indicate a transition from predominantly heavy below  $10^{17}$  eV to a predominantly light composition at  $10^{18}$  eV.

Lastly, the stereo data has also been analyzed to extract the proton-air cross-section by fitting the slope of the exponential tail of the  $X_{MAX}$  distribution for values greater than  $700 \text{ g/cm}^2$ . This analysis uses essentially a reverse Monte-Carlo deconvolution to fit for the exponential slope,  $\lambda_{p-air}$ , of the distribution of the interaction depth of the primary cosmic rays in the atmosphere. From a fitted value of  $\lambda_{p-air} = 52.7 \text{ cm}^2/\text{g}$ , a cross-section of  $456 \pm 17(\text{stat.}) + 39(\text{sys.}) - 11(\text{sys.}) \text{ mb}$  was obtained for  $E = 10^{18.5}$  eV. Details of this analysis can be found in reference [21].



**Figure 10.** Left: Distribution reconstruction error in  $X_{MAX}$  from simulation showing a resolution of  $\sim 30 \text{ g/cm}^2$ . Right: the average measured  $X_{MAX}$  for UHE cosmic rays plotted as a function of energy for both the HiRes stereo data[19] and for the HiRes/prototype-MIA hybrid measurement[20].

## 6. Acknowledgments

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