Evidence for Declination Dependence of Ultrahigh Energy Cosmic Ray Spectrum in the Northern Hemisphere

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Abstract

The energy of the ultrahigh energy spectral cutoff was measured, integrating over the

* Deceased

northern hemisphere sky, by the Telescope Array (TA) collaboration, to be $10^{19.78\pm0.06}$ eV, in agreement with the High Resolution Flys Eye (HiRes) experiment, whereas the Pierre Auger experiment, integrating over the southern hemisphere sky, measured the cutoff to be at $10^{19.62\pm0.02}$ eV. An 11% energy scale difference between the TA and Auger does not account for this difference. However, in comparing the spectra of the Telescope Array and Pierre Auger experiments in the band of declination common to both experiments ($-15.7° < \delta < 24.8°$) we have found agreement in the energy of the spectral cutoff. While the Auger result is essentially unchanged, the TA cutoff energy has changed to $10^{19.59\pm0.06}$ eV. In this paper we argue that this is an astrophysical effect.

Keywords: cosmic ray, spectrum, declination dependence, telescope array, surface detector

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1. Introduction

The spectra of ultrahigh energy cosmic rays (UHECR) measured by the TA [1, 2, 3, 4], Auger [5, 6, 7], and HiRes [8] experiments all exhibit similar features: a hardening of the spectrum in the middle of the 10^{18} eV decade, called the ankle, and a drastic cutoff of the spectrum in the upper 10^{19} eV decade [1]. For the TA SD and HiRes, the cutoff occurs at $10^{19.78\pm0.06}$ [1, 2] and $10^{19.75\pm0.05}$ eV [8], respectively, while for the Auger spectrum, the cutoff is at $10^{19.62\pm0.02}$ eV [9, 10]. The existence of a cutoff was predicted by K. Greissen [11], and by G. Zatsepin and V. Kuzmin [12], and is called the GZK effect. It occurs if ultrahigh energy cosmic rays are either protons or nuclei, and is due to interactions with the cosmic microwave background radiation. An alternative cause could be if the maximum energy of the cosmic ray sources is lower than the GZK cutoff energy of $10^{19.7}$ - $10^{19.8}$ eV.

When adjusting the energy scales of the three above-mentioned experiments one finds that the spectra line up below $10^{19.4}$ eV if the Auger energy scale is increased by 11%. This figure is within the quoted systematic uncertainty of the three experiments. One could also lower the energy scales of TA and HiRes by this amount to achieve the same result. Figure 1 shows the spectra of the three experiments, with this energy scale adjustment made to the Auger result. It should be noted that the TA SD spectrum measurement shown in Figure 1 extends over 7 years of data from

[1] In this paper, we characterize spectral features by fitting the spectra to a broken power law function of 4 parameters, which include the normalization constant, the break point, and the power indices before and after the break point.

May 11, 2008 to May 11, 2015, uses 23,854 events above $10^{18.2}$ eV with zenith angles from 0 to 45°, and it is calculated using methods described in [3].

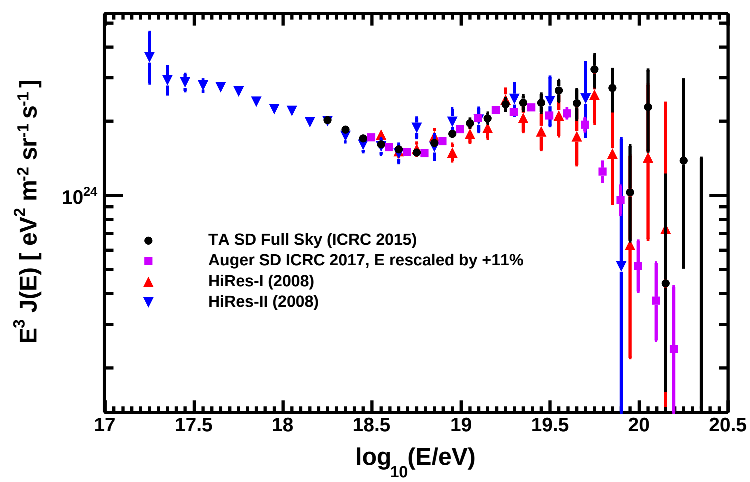


Figure 1: Energy spectra measured by the TA SD [13], Auger [5], and HiRes [8] experiments using their standard techniques. Auger energy has been increased by 11% to match the energy scale of TA SD and HiRes in the ankle region.

These spectra show two outstanding features, good agreement in the ankle region and below, and the disagreement in the position of the high energy cutoff. These spectra were made by integrating over the northern sky by the TA and HiRes collaborations, and the southern sky by the Pierre Auger collaboration. As a result of this partial agreement and partial disagreement, suggestions have been made that the spectrum might be different in the two parts of the sky.

In order to understand the difference in cutoff energies, a working group was formed, under the auspices of the UHECR2016 Workshop, by the TA and Auger collaborations. Similar working groups for the 2012 and 2014 UHECR Workshops had addressed other spectral questions, such as the energy scale difference of the two experiments. The 2016 working group concentrated on measuring the spectrum of both experiments in the part of the sky seen by both experiments, declinations between $-15.7°$ and $+24.8°$, called the common declination band. Looking in the common region of the sky, one would expect the two experiments should get the same answer. The short answer is that, in the common declination band, the cutoff energies agree within uncertainties. While the change in the Auger spectrum is minimal, the energy of the cutoff in the TA spectrum is lower by a significant amount. The change seems to be astrophysical in nature.

This paper is organized as follows. Section 2 describes the TA and Auger spectra in the common declination band; Section 3 describes the difference in the TA spectra above and below $\delta = 24.8°$ and the search for systematic biases that might cause the difference, and in Section 4 we state our conclusions.

2. Spectra in the Common Declination Band

The Auger surface detector (SD), located in the region *Pampa Amarilla*, near Malargüe in Argentina, consists of about 1600 water tanks that detect Cherenkov light from air shower particles, and covers about 3000 km^2 in area. The TA SD, located near Delta, Utah, USA, consists of 507 scintillation counters that cover about 700 km^2. Figure 2 shows the exposures of the TA and Auger experiments as a function of declination [9, 10]. In the TA-Auger spectrum working group [9], as well as this work, we use the Auger vertical SD analysis results (events with zenith angles from 0 to 60°) and the TA SD analysis that uses events of zenith angles ranging from 0 to 55°. It should be noted that for the TA SD spectrum analysis that goes down to $10^{18.2}$ eV, we use events with zenith angles from 0 to 45°, [3], while above $10^{19.0}$ eV, we use same quality cuts as in [3], except the event zenith angles are allowed to go up to 55°. With these cuts, the number of events and the total exposure of the TA SD above $10^{19.0}$ eV are 2890 and 8300 $\mathrm{km}^2\,\mathrm{sr\,yr}$, respectively. The angular resolution of the TA SD above $10^{19.0}$ eV is better than 1.5°, and the energy resolution is better than 20% [4].

Even in the common declination band, the spectra could be different since each would be weighted by a different function of declination. To eliminate this possible difference, the working group has adopted a method of removing the declination weighting that had been invented previously by the anisotropy working group of the UHECR2014 Workshop and fully described in [10]. Defining the variable $\omega(\delta)$ to be the directional exposure as a function of declination, δ, the *1/ω method* can be summarized as follows [9]:

$$
\begin{aligned}
J_{1/\omega}(E) &= \frac{1}{\Delta\Omega\Delta E}\sum_{i=1}^{N}\frac{1}{\omega(\delta_i)}\ , \\
\Delta J_{1/\omega}(E) &= \frac{1}{\Delta\Omega\Delta E}\left\{\frac{\int_{\delta_{\min}}^{\delta_{\max}} \mathrm{d}\delta\cos(\delta)/\omega(\delta)}{\int_{\delta_{\min}}^{\delta_{\max}} \mathrm{d}\delta\,\omega(\delta)\cos(\delta)}\right\}^{1/2}\sqrt{N}\ .
\end{aligned}
\tag{1}
$$

In Equation (1), $J_{1/\omega}(E)$ and $\Delta J_{1/\omega}(E)$ are the differential flux and its statistical

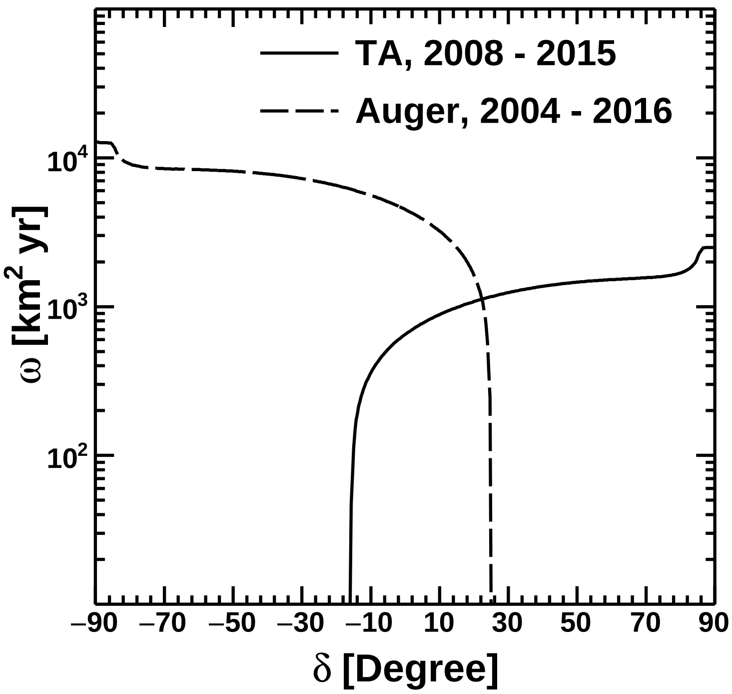


Figure 2: Directional exposures of the TA and Auger SDs as functions of the declination, for 7 years of the TA SD and 12 years of Auger data. Solid line shows the exposure for the TA SD with event zenith angles ranging from 0 to 55°, and the dashed line shows the exposure of the *Auger vertical* SD analysis that uses events with zenith angles ranging from 0 to 60°.

uncertainty (to first order), calculated using N events in the energy interval $E - \Delta E/2, E + \Delta E/2$, with the declination values $\delta_{min} < \delta_i < \delta_{max}$. The solid angle $\Delta\Omega = 2\pi \int_{\delta_{\rm min}}^{\delta_{\rm max}} {\rm d}\delta \cos(\delta)$ is that of the TA-Auger common declination band: $\delta_{\rm min} = -15.7°$, $\delta_{\rm max} = 24.8°$.

Figure 3 shows the energy spectra of TA and Auger in the common declination band, calculated using the $1/\omega$ method. When the spectra are fit to a broken power law function the cutoff energies agree at the $\sim$0.5 σ level [9].

3. Comparison of the TA spectra above and below $\delta = 24.8°$

Figure 4 shows two TA SD spectra, using events with zenith angles ranging from 0 to 55°, and declinations above and below 24.8°. The high and low declination

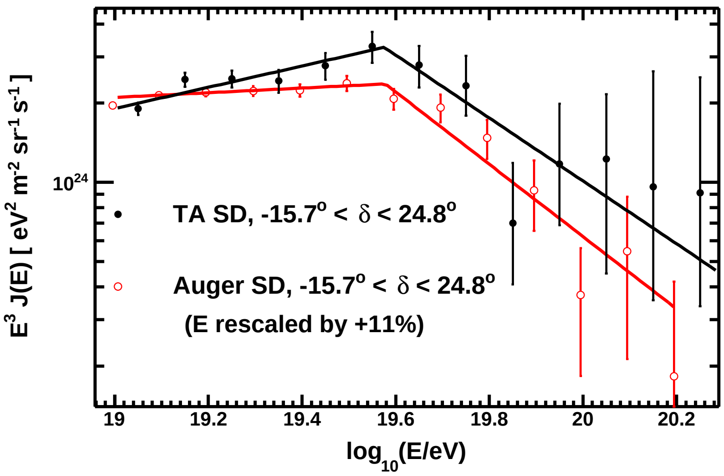


Figure 3: Energy spectra of TA and Auger in the common declination band.

band cutoffs, of significances 6.9 and 6.4 σ, evaluated using the same technique as in [3], have been found at $10^{19.85^{+0.03}_{-0.03}}$ and $10^{19.59^{+0.05}_{-0.07}}$ eV, respectively. The ratio of cutoff energies in the two declination bands is a factor of 1.82 and the cutoff energies are 4.0 σ different. Also, one should note, that the second break points of TA and Auger spectra are in agreement in the common declination band, while the second break point of the high declination TA SD spectrum result ($\delta > 24.8°$) is higher than the second break point of both TA SD full sky average and HiRes spectra shown in Figure 1. We calculate the global chance probability of this occurrence using isotropic Monte Carlo (MC), which assumes that the spectrum follows the TA SD full sky average result. A MC trial, of the same size as data, is counted as a success if it satisfies the following set of conditions: (i) second break points of both $\delta > 24.8°$ and $\delta < 24.8°$ subsets are at least as significant as those in the data and are at least 4.0 σ different, (ii) the second break point of the $\delta < 24.8°$ subset is within 1 σ of the second break point of the Auger spectrum (Figure 3), and (iii) the second break point of the $\delta > 24.8°$ subset is higher than the weighted average of the TA SD full sky and HiRes second break points (Figure 1). A total of 2351 random MC sets, out of 10^7 generated, have satisfied this criteria, resulting in a 3.5 σ global chance probability.

It is also interesting to ask whether this effect is due to the TA hotspot [17], a circular region of event excess (of significance 3.4 σ) centered at $(\alpha, \delta) = (146.7°, 43.2°)$ with a 20° radius. The hotspot circle is almost totally above the 24.8° dec-

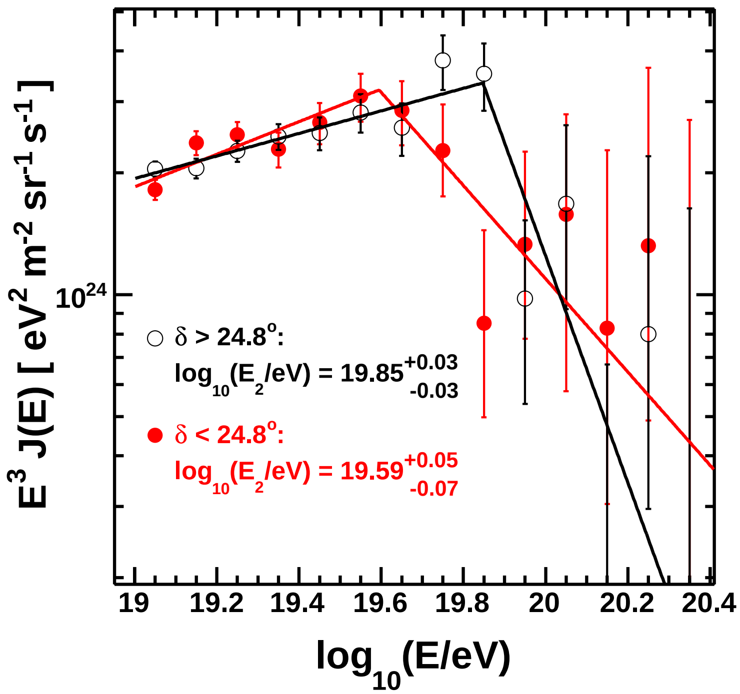


Figure 4: TA SD spectrum results for two declination bands using events with zenith angles from 0 to 55°. Black points: $24.8^\circ < \delta < 90^\circ$, red points : $-15.7^\circ < \delta < 24.8^\circ$. Superimposed are broken power law fit results for each of the declination bands. Second break points ($\log_{10}(E_2/\mathrm{eV})$) are $19.85^{+0.03}_{-0.03}$ and $19.59^{+0.05}_{-0.07}$ for the high and low declination bands, respectively. There is a $4.0\,\sigma$ difference between the second break points of the two spectra. The minimization of the binned log-likelihood function (Equation 39.16 in [14]) was carried out using MINUIT [15, 16] program, and asymmetric errors of the second break point energies were determined, taking into account the correlations with the remaining 3 fit parameters, using MINOS procedure of MINUIT [15].

lination used to divide the sky in the current analysis. If we cut out events inside the hotspot circle the difference of the two second break points is reduced to 3.0 σ. So the hotspot contributes, but may not be the entire effect. At the location of the hotspot, there is an additional 4.0 σ spectrum anisotropy effect [18] above $10^{19.2}$ eV of 30° radius, that might also be contributing here.

An important question remains, is the high-δ and low-δ difference in cutoff energies a result of a systematic bias, or is it astrophysical in nature. We now describe searches carried out to find a possible systematic bias. We compared the energies reconstructed by our SD to those of the same events reconstructed in hybrid mode by the TA fluorescence detectors (FDs). TA has FDs located at three sites around the SD, and looking inward over the SD area. There are 48 fluorescence telescopes in the TA FD system. In hybrid observation mode, timing of SD counters is used to help determine the geometry of UHECR air showers, but not in the energy determination. The energy is determined from the profile of the shower development in the atmosphere. TA hybrid reconstructions have resolutions of less than 1° in angle and better than 10% in energy [19, 20, 21]. For comparison, TA SD event reconstructions have resolutions of about 1.5° in direction and 20% in energy [4]. Figure 5 shows the ratio of SD/hybrid energies as a function of energy and declination. No systematic bias in energy reconstruction is apparent in this figure.

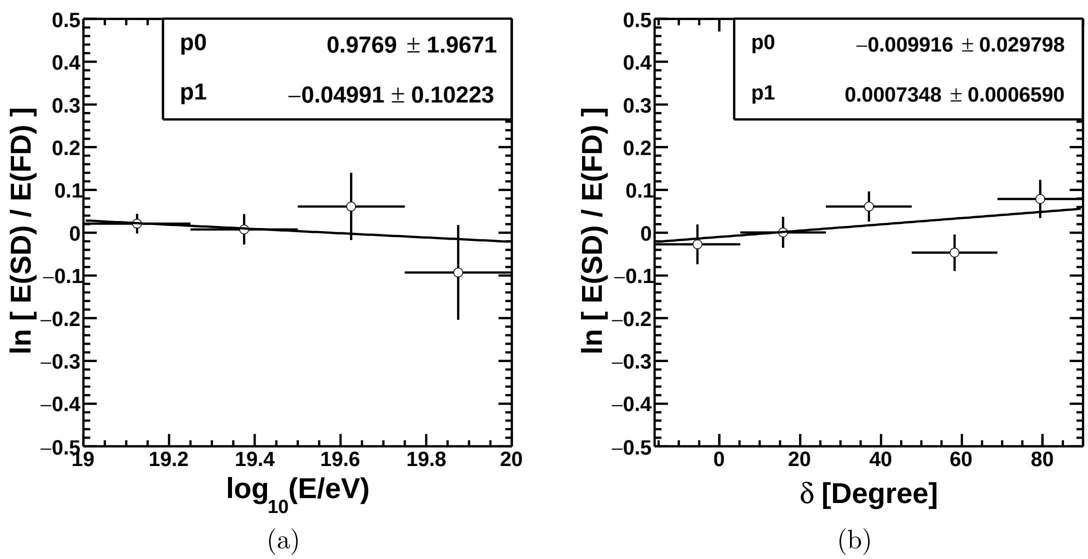
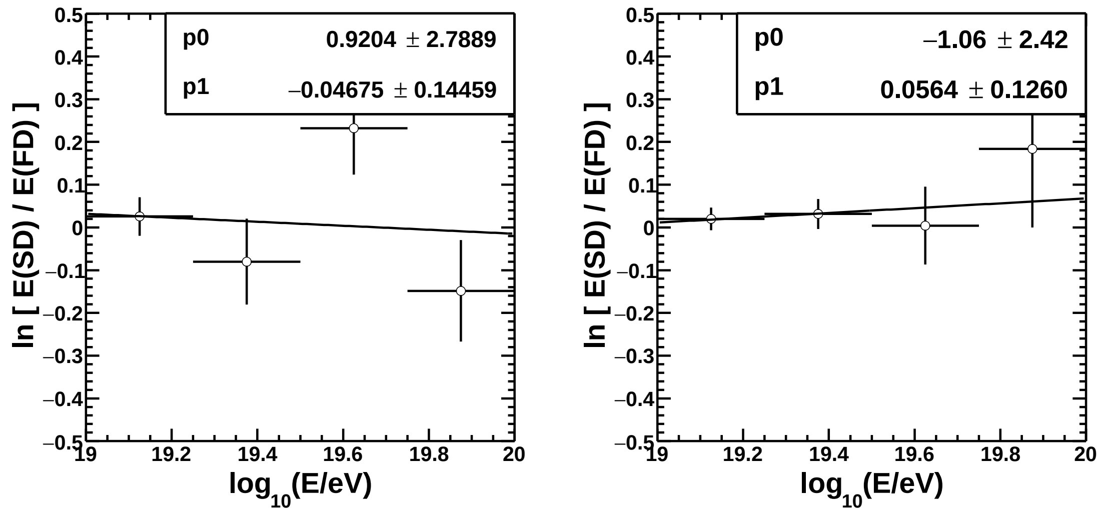


Figure 5: Ratio of SD energy to FD energy for events seen in common by both detectors, (a) plotted versus event energy, (b) plotted versus declination δ. Solid lines are fits to a linear function, where p_0 is the constant offset and p_1 is the slope. Values of p_1 being smaller than or comparable to their fitting uncertainties indicate that there are no significant energy reconstruction biases.

We performed the same comparison of SD to hybrid energies making cuts on zenith angle θ and declination δ. Cutting at $\theta = 30°$ to form two approximately equal statistical samples (Figure 6), we observe no systematic bias in the ratio of SD/FD energy reconstructions. We place an upper limit of ~10%/decade on a possible bias in the energy scale of the TA SD.

In a second test, we note that cutting at 24.8° in declination is really selecting events according to their zenith and azimuthal angles. This cut is symmetric about a



(a) (b)

Figure 6: Ratio of energies reconstructed by SD and FD, for the samples of events seen by the two detectors in common. Each sample is formed by restricting the events to a certain zenith angle range: (a) $0 < \theta < 30°$. (b) $30 < \theta < 55°$.

north-south axis. This direction is also one of the two main axes of the arrangement of TA SD counters. Figure 7a, is a scatter plot of events in zenith vs. azimuthal angles, where the u-shaped curve in black is the dividing line, $\delta = 24.8°$.

Events represented by red open circles are south of 24.8°, and events represented by black points are to the north of 24.8°. If we artificially rotate the function for the u-shaped curve by 90°, to look east, the resulting scatter plot is shown in Figure 7b. Here we are looking along the other main axis of the TA SD arrangement. If we compare the spectra of the events represented by red open circles to that for events represented by black points, we are carrying out the exact same process in looking at higher and lower declinations. We know what should be the result, since we are looking in the direction the sky rotates: the energies of the cutoff should be identical. Figure 8 shows the spectra of the black and blue regions of the sky, and the cutoff energies are the same.

4. Summary

The three cosmic ray spectra measured by HiRes, Auger, and TA, integrated over their respective fields of view, are in a good agreement below $10^{19.4}$ eV, after an

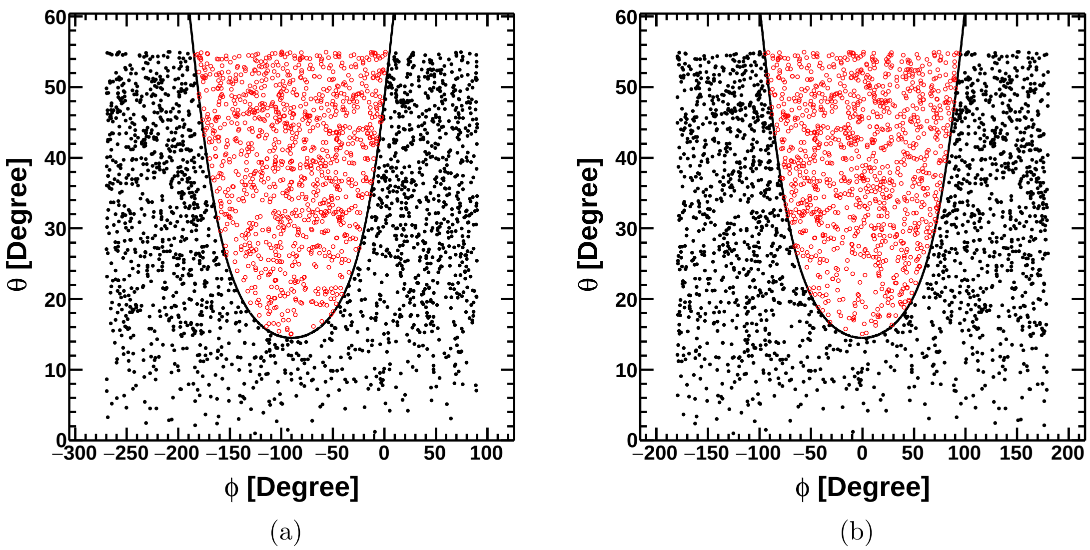


Figure 7: Scatter plots of event zenith angle (θ) vs azimuthal angle (ϕ), in local sky coordinates. (a) Events within the u-shaped region, shown by open red circles, have declinations $\delta < 24.8°$. Events outside of the u-shape region, shown as black filled circles, have declinations $\delta > 24.8°$. (b) Modification of the declination cut in (a) by artificially moving the u-shaped contour by $+90°$ in ϕ. Now events within (red open circles) and outside (black filled circles) the u-shape region no longer correspond to the declinations above and below $\delta = 24.8°$.

upward scaling of Auger energies by 11%, which is within the systematic uncertainty of both experiments. Both TA and HiRes have the same energy scale, and observe the cutoff at the same energy in the Northern hemisphere. The Auger cutoff energy, which pertains mostly to the Southern hemisphere, occurs at a lower energy. We have found that restricting the TA SD and Auger spectrum measurements to a common declination band, $-15.7° < \delta < 24.8°$, brings the TA SD and Auger cutoff energies into agreement, while the TA SD measurement outside of the common declination band, $\delta > 24.8°$, differs by a factor of 1.82 from the TA SD measurement in the common declination band. Additionally, in the high declination region the cutoff energy is higher than that seen by HiRes and TA over the whole sky. The statistical significance of the difference is 4 σ, and corresponds to a 3.5 σ chance probability.

The tests described above, and others we have performed, have failed to identify a source of systematic bias in our measurement of the spectra above and below 24.8° in declination. Furthermore, they reinforce the idea that our reconstruction of UHECR events' energies and directions is robust.

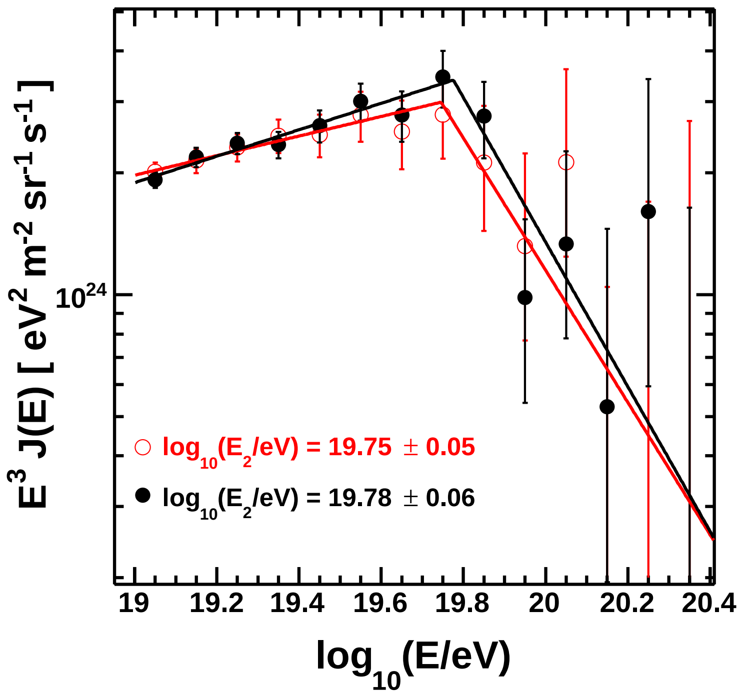


Figure 8: TA SD spectrum results for two artificial cuts. Black points correspond to the energy spectrum of events outside of the u-shaped contour of Figure 7b and red open circles are spectrum made using events inside of the contour. Superimposed are two broken power law fit results to these spectra, showing that their second break points E_2 are in agreement.

We conclude that we have an evidence (at the 3.5 σ level) for a change in the energy spectrum of ultrahigh energy cosmic rays in the northern hemisphere of the sky. Since this is not a 5 σ observation, we must await the collection of further TA data for confirmation of this effect. The TAx4 project [22] is funded to increase the area of the TA SD by a factor of 4 by placing new SD counters in two areas adjacent to the TA SD, and to add two new FD stations to overlook the new TAx4 SD areas.

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