PROCEEDINGS OF SCIENCE

Measurement of UHECR energy spectrum with the Pierre Auger Observatory and the Telescope Array

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The measurement of the energy spectrum of ultra-high-energy cosmic rays (UHECRs) is of crucial importance to clarify their origin, acceleration mechanisms, and propagation processes in inter-Galactic and Galactic space. The Pierre Auger Observatory in Argentina and the Telescope Array (TA) in the US have reported their measurements of UHECR energy spectra observed in the southern and northern hemisphere, respectively. The Auger–TA energy spectrum working group was established in 2012 and has been working to understand the uncertainties in energy scale in both experiments, their systematic differences, and differences in the shape of the spectra. In previous works, we reported that there was an overall agreement of the energy spectra measured by the two observatories below 10 EeV while at higher energies, a remaining significant difference was observed in the common declination band. This time we revisit the energy scales of both experiments, including the fluorescence yield and the invisible energy corrections. Another new approach to investigate a possible source of energy systematic difference is to reconstruct simulated showers of common energy and zenith angle using the detector simulation and reconstruction programs of both experiments that are independently tuned and optimized for data from their own detectors. The results will be presented at the conference.

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1. Introduction

The origin of protons and nuclei with joule-scale kinetic energies – up to 10^{20} eV –, known as ultra-high energy cosmic rays (UHECRs), is one of the most intriguing unsolved problems in modern astrophysics. Discovering the origin of these particles would allow us to understand the most energetic phenomena occurring in the universe. The precise measurement of their energy spectrum, corresponding to the differential intensity dI/dE of the particles, is of particular importance because its absolute scale and its shape are closely related to the production rate in the sources, which in turn is related to the acceleration mechanisms at such extreme energies, as well as to the spatial distribution of the sources, which shapes the propagation that cosmic rays have to perform to be detected on Earth. The spectrum of cosmic rays above 10^{18} eV is known to be well described by a series of power laws, $dI/dE \propto E^{-\gamma}$, with a spectral index $\gamma \sim 3.2$–3.3 below the "ankle" feature around 5×10^{18} eV, hardening to $\gamma \sim 2.6$–2.7 beyond the ankle, and steepening to $\gamma \sim 5$ beyond $\simeq 5 \times 10^{19}$ eV. Recent observations at the Pierre Auger Observatory and at the Telescope Array have revealed an additional spectral feature, with the detection of a spectral index change around 10^{19} eV from $\gamma \sim 2.6$–2.7 to $\gamma \sim 3$.

The arrival of UHECRs at the Earth is so rare, about one event per square kilometer per year, that huge detection areas and long observation times are necessary. The two largest currently operational observatories, the Pierre Auger Observatory in Argentina and the Telescope Array (TA) in the United States, cover areas of 3000 km^2 and 700 km^2, respectively. Similar detection techniques are used by the two observatories, but their detailed characteristics and data reconstruction methods are rather different. A joint working group with members from both collaborations was formed in 2012 to discuss the technical details of the data analyses, and the results of its activities have been reported in the UHECR and ICRC conference series [1–3].

This time we revisit the energy scales of both experiments, including the fluorescence yield and the invisible energy corrections. Another new approach to investigate a possible source of energy systematic difference is to reconstruct MC showers with common energy and zenith angle using the detector simulation and reconstruction programs of both experiments that are independently tuned and optimized for data from their own detectors. In this contribution, we revisit the details of the Auger and TA data analysis, the systematic uncertainties in the energy determination, and the agreements and differences in the energy spectrum obtained by the two experiments.

2. Auger and TA detectors

Two types of extensive air shower detection techniques are used at the Pierre Auger Observatory and TA. Arrays of surface detectors (SDs), sampling the lateral profile of the showers at ground level, provide us with very large collection areas and exposure thanks to an almost 100% duty cycle. The SD arrays are overlooked by fluorescence detectors (FDs), sensitive to the fluorescence light isotropically emitted by atmospheric molecules along the shower particle track. The FD enables an almost calorimetric measurement of the cosmic-ray energy, and therefore an energy determination of the showers that is almost insensitive to details of hadronic interactions of cosmic rays in the atmosphere, which is rather uncertain because the center-of-mass energy of cosmic ray – atmospheric interactions is beyond the present accelerator energies.

The Pierre Auger Observatory is located at a latitude of 35.2°S near the town of Malargüe in the province of Mendoza, Argentina, at an altitude of 1400 m above the sea level. The SD array, which consists of 1600 water-Cherenkov tanks ($10\,\mathrm{m}^2 \times 1.2\,\mathrm{m}$) spread over a triangular grid with 1500 m spacing, covers $3000\,\mathrm{km}^2$ in area [4]. The Cherenkov light emitted by the charged particles in a detector is recorded by three photo-multiplier tubes (PMTs). Signals are digitized with an FADC at a sampling rate of 40 MHz. The FD consists of 24 telescopes installed at four sites (six telescopes each) located on the border of the array. Each telescope consists of a $3.5\,\mathrm{m} \times 3.5\,\mathrm{m}$ spherical mirror with a curvature radius of 3.4 m, and a camera with a 22×20 cluster of PMTs at the focal plane. The field of view of a telescope is 30° in elevation and 28.6° in azimuth. Signals from the FD PMTs are digitized with a 10MHz-12bit FADC. Details can be found in e.g. [1, 4].

The TA detector site is located near Delta, Millard County, Utah, U.S., centered at 39.3° N, 112.9° W at a mean altitude of 1400 m. An array of 507 scintillation counters on a square grid with 1.2 km spacing covers an area of $700\,\mathrm{km}^2$ [5]. A counter consists of two-layers of plastic scintillators of $3\,\mathrm{m}^2$ area and 1.2 cm thick. Wavelength-shifting fibers are embedded in the scintillators, which also reduces the position dependence of the detector response in the $3\,\mathrm{m}^2$ area. Two PMTs are equipped for a counter, one for each layer, and signals are digitized at 50 MHz. TA FDs are installed at three sites separated with a distance of ~ 30 km. Technical details are given in [5].

3. Energy measurements

3.1 Energy estimation from surface detector data

For both SD arrays, the signal that would be detected by a station located at a reference distance from the shower axis is used as the shower-size estimator. The reference distance, 1000 m for Auger is chosen so as to minimize the fluctuations of the shower size, and 800 m for TA to minimize the difference of the lateral distribution function between different nuclear types. The differences in reference distances stem from the detector type (water tanks, which is relatively sensitive to muons, vs scintillation counters sensitive to electrons) and the detector spacing (1500 m vs 1200 m). To take into account atmospheric attenuation for different zenith angles of cosmic-ray arrival directions, the Auger $S(1000)$ parameter of a shower of a given zenith angle θ is converted into S_{38}, the particle density that would have been observed had the shower arrived at $\theta = 38°$, by means of the *constant intensity cut* (CIC) method [6]. The corrected shower size is subsequently calibrated against the FD energies using a power-law function, $E = AS_{38}^{B}$. The statistical uncertainty in the energy scale arising from the fit of the two calibration parameters is below 1%. In TA, Monte Carlo simulations of showers are used to obtain an energy "lookup-table" so as to convert $S(800)$ into primary energy for each θ. A CIC-based energy determination has also been carried out: for TA the energies calculated by the two methods agree within 3% [7].

The Auger and TA energy spectra are presented in Figure 1[3, 6, 7]. Beyond the well-established "ankle", a hardening of the spectrum at $E \sim 5 \times 10^{18}$ eV where the spectral index $dI/dE \propto E^{-\gamma}$ changes from $\gamma = 3.2$–3.3 to $\gamma = 2.6$–2.7, the two spectra have also captured a steepening at around $E \sim 5 \times 10^{19}$ eV, above which the cosmic-ray intensity drastically falls off with $\gamma \sim 5$. The spectral shape and the position of the steepening in the TA spectrum can be fit by a "GZK scenario" in which a pure-proton composition is assumed. On the other hand, the Auger spectrum and composition data

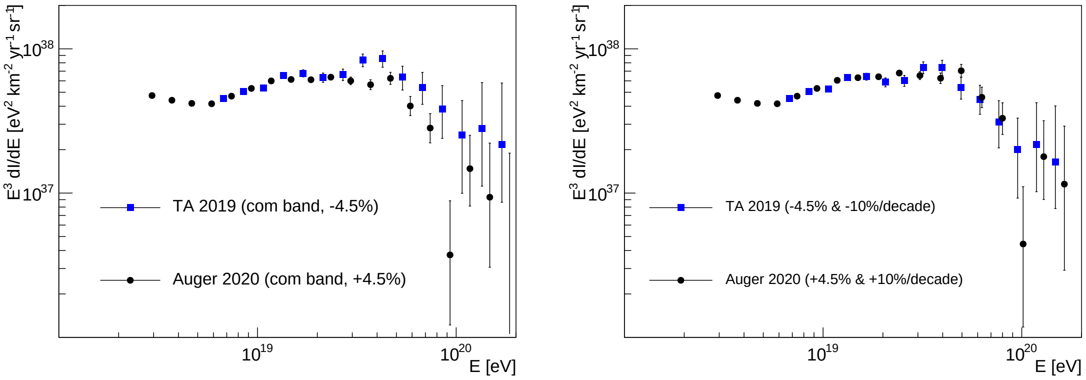

Figure 1: Left: Auger and TA spectra in the common declination band ($-15.7° < \delta < 24.8°$) with a constant shift ±4.5%, Right: with an energy-dependent shift $\pm 10\% \times \log_{10}(E/10^{19}\ \text{eV})$ for $E > 10^{19}$ eV.

are suggestive of cosmic rays getting heavier with energy. In this scenario, the steepening is caused by both the GZK effect and the maximal acceleration energy at the sources close to 10^{20} eV [8]. The origin of the high-energy steepening is currently one of the most important problems in cosmic-ray physics. A significant step-forward in this respect will be done by using the SD data to infer the mass composition up to the highest energies [9].

There is a systematic difference in the absolute energy scale between the two measurements at a level of ~ 9%. If we rescale the energies by +4.5% for Auger and −4.5% for TA, values well within the systematic uncertainties of both experiments, a better agreement of the spectra is seen. It is worth noting that the overall energy scale offset of 9% is significantly reduced once the differences in the energy assignments arising from the fluorescence yield and invisible energy models adopted by the two collaborations are subtracted as shown in Section 3.2.

When we compare, after the ±4.5% rescalings, the energy spectra in the declination band that is commonly accessible to the two observatories ($-15.7° \leq \delta \leq +24.8°$), the differences are smaller (left panel of Figure 1). However, the persistent differences require an additional energy rescaling in an energy-dependent way (±10%/decade for $E > 10^{19}$ eV) to get agreement (right panel of Figure 1). The Auger spectra in different declination bands are fully consistent within the accessible field-of-view [6, 8]. On the other hand, TA observed slightly different spectra in the northern and the southern part of the TA sky with different positions of the steepening at a 4.4σ confidence level [10]. No systematic and instrumental effects have been identified, and the difference remains after removing events of the TA "hotspot" located at $(\alpha, \delta) = (146.7°, 43.2°)$ with a 20° radius [11].

3.2 Tests with different energy determination of individual cosmic ray events

In the previous studies we shifted *data points* of energy spectra to compare the Auger and TA results after binning the event energies into histograms, after taking into account the effects of fluorescence yield or invisible energy corrections. This time we shifted *individual event energies* by applying different models including fluorescence yield or invisible energies, and energy assignments for SD events.

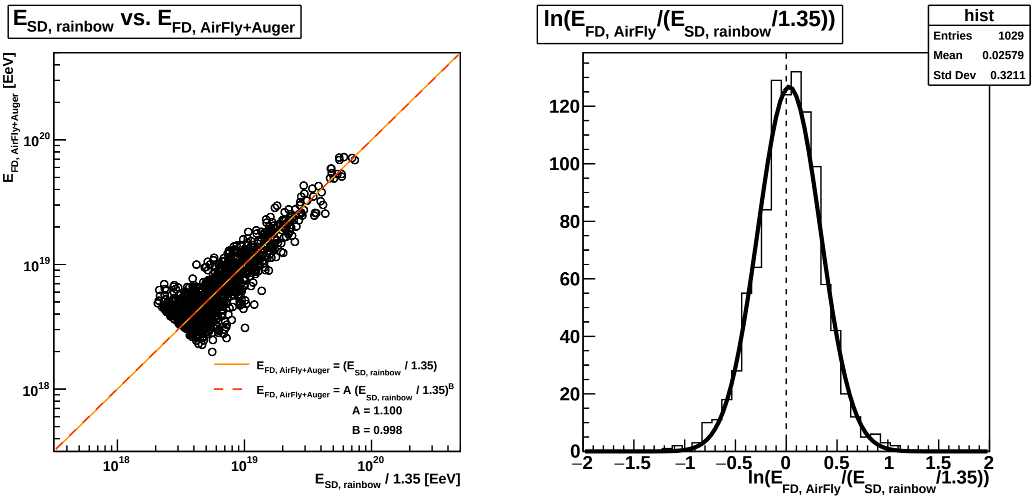

Figure 2: Correlation of energies determined by TA SD and FD applying the fluorescence yield model based on AirFly [12] and the invisible energy used in Auger. The rescaling factor of the MC energies ($E_{\mathrm{SD,rainbow}}$) is 1/1.35 and has to be compared with 1/1.27 obtained when the TA models for the fluorescence yield and invisible energy are used. The difference between the two rescaling factors is 6%.

For FD event energy reconstruction, Auger uses the fluorescence yield model by AirFly [12] with an uncertainty of 4%. For correction of invisible energies for FD events Auger uses an empirical formula almost independent of hadronic interaction models derived from the FD-SD hybrid data. TA uses a fluorescence yield model based on the absolute yield measurement by Kakimoto [13] and emission spectrum from the FLASH experiment [14], and the formula for individual energy correction was derived from CORSIKA simulated showers assuming proton primaries and the QGSJet II-03 model of hadronic interactions. When the Auger fluorescence yield and invisible energy correction formula are applied to TA reconstruction, the event energies are shifted by 6% on average (Figure 2). Event energies are also changed if we apply a different invisible energy correction. Further change may be induced by the energy conversion method, i.e. the shower attenuation correction – TA uses the energy-lookup-table for $S(800)$ and zenith angle, and Auger uses an empirical method to convert $S(1000)$ based on the CIC approach.

The energy spectrum comparisons were always made in the spectrum data points by taking into account this average effect, and this time, for the first time, comparisons are made using the energy spectrum obtained with event energies individually assigned using the different models at the time of energy reconstruction. The results are presented in Figure 3. The results are fully consistent with the previous studies by the spectrum data point shifting.

4. Shower reconstruction of commonly simulated showers

Unexpected energy shifts may be caused by “over-tuning” of the reconstruction programs developed by the experiments. An air shower reconstruction program is generally developed using simulated showers using a Monte Carlo package such as CORSIKA [15], and tuned so that the primary energy and arrival direction given to the shower generator are reproduced with desired

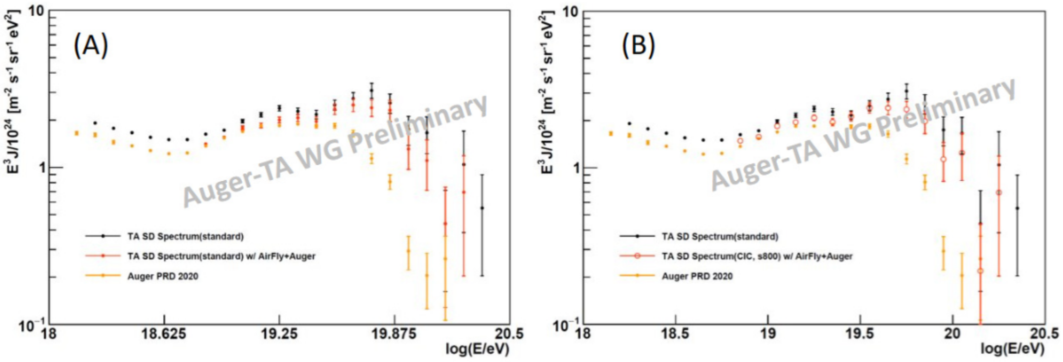

Figure 3: TA and Auger spectra, where TA energies are reconstructed using the same fluorescence yield and invisible energy correction. Left: using the TA standard energy *look-up table*. Right: using the shower attenuation effect calculated with the constant intensity cut method with the standard particle density a 800 m from the shower core.

accuracy. A detailed detector Monte-Carlo is also required since we cannot use the CORSIKA outputs directly as inputs for reconstruction, because we can only use detector outputs like waveforms from phototubes that are inevitably distorted by response functions or due to limited acceptance. Auger and TA reconstruction programs were tuned using their own CORSIKA showers with their own settings (CORSIKA *input data cards*), including the low-energy threshold for particle tracking, atmospheric modeling, and many others. To estimate the impact of this, both Auger and TA generated CORSIKA showers with pre-determined common fixed energies and zenith angles (10^{19}, $10^{19.5}$ and 10^{20} eV and $\theta = 0, 32$ and 56 degrees) with their own "standard" settings unchanged. Then we exchanged the generated proton and iron showers and reconstructed the exchanged showers as well as their-own showers using the both Auger and TA reconstruction programs. This time we only exchanged one event for each energy and zenith angle, and reused it many times by randomly assigning shower impact points in the detection area of 3000 km^2 for Auger and 700 km^2 for TA.

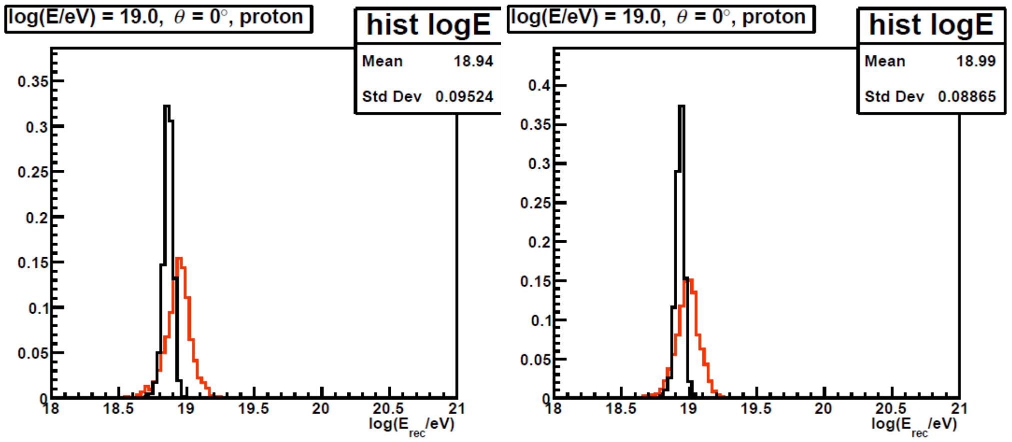

Figure 4: The energy of an example TA-simulated proton shower (left) and an example Auger-simulated proton shower (right) as reconstructed using the Auger program (black) and the TA program (red).

The results are shown in Figure 4. We found general agreement between the Monte-Carlo input energies and reconstructed energies for proton showers. One possible origin of slight bias is a potential incompatibility of the de–thinning process. In shower generation both Auger and TA employ the `THIN` option of CORSIKA to reduce the computation time needed to simulate showers with energies $\gtrsim 10^{19}$ eV, and separately developed a "de-thinning" program to split the CORSIKA thinned output to individual particles, which is necessary to use the particle information for detector simulation before passing it to the reconstruction process. Since the TA de-thinning program is tuned for TA-generated showers, caution has to be used when it is applied to showers of different settings like tracking threshold energy for low-energy particles. We will investigate this using more showers in detail.

5. Summary

We revisited the energy scale used to reconstruct the shower energies of the Auger and TA collaborations. We calculated the energy spectra using different energy reconstructions by changing the fluorescence yield, the invisible energy, the attenuation correction and by using the individual shower energies rather than by shifting the energy spectrum data points. The size of the energy shifts found in this study was fully consistent with the expectation from the previous studies. Using a common/unified parameter set between the UHECR experiments is still in discussion. We also studied the performances of the reconstruction programs using common energies and zenith angles with other parameters unchanged from the Auger and TA standard setting. Here we only presented limited number of proton showers, and we'll use not only protons but also iron showers or of different primaries.

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