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Testing the declination dependency of the spectrum measured by the Pierre Auger Observatory

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The distribution of the arrival directions of cosmic rays observed by the Pierre Auger Observatory has a dipolar component that implies a flux dependence on declination. Previously, we showed that the spectrum built from events arriving with a zenith angle less than 60° is qualitatively consistent with the dipole. In this work, we go one step further and show that the Auger spectrum cannot reject the hypothesis of a declination-independent flux. By using events of up 80°, we extend the previous survey from +25° of declination to +45°, thus covering 85% of the sky.

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1. Introduction

An extragalactic origin of cosmic rays more energetic than 8 EeV is suggested by a dipolar structure superimposed in the otherwise isotropic distribution of arrival directions observed by the Pierre Auger Observatory [1]. This dipole was qualitatively consistent with a mild dependency of the Auger spectrum on declination up to $\delta = +25°$ [2], an expected agreement as both analyses are derived from the same event set. However, the connected but still different question of whether the Auger spectrum data rule out the hypothesis of a declination-independent flux remained open. This point was raised in a recent analysis of Telescope Array data [3]. In this work, we assess the sensitivity of the Auger spectrum to declination with a test that considers systematic uncertainties in most populated bins and the limited number of events in the most energetic bins. We extend our previous analysis to $\delta = +45°$ using two spectra that include events arriving with zenith angles up to 80°.

The Pierre Auger Observatory consists of a Surface Detector Array containing over 1600 surface detectors and a Fluorescence Detector comprising 27 telescopes. The surface detectors are organized into three nested triangular grids. The biggest array spaced 1500 m (SD-1500) extends over 3000 km^2 and contains an array spaced at 750 m in an area of 24 km^2 that, in turn, includes an array spaced at 433 m in 2 km^2. The Observatory operated in two phases, the first lasting 19 years from January 2004 to December 2022 and the second starting in January 2023. In Phase I, each surface detector contained only a water-Cherenkov detector [4], and in Phase II, each position was upgraded with a surface scintillator detector, a radio detector, a fourth PMT to the water-Cherenkov detector, and enhanced acquisition electronics [5]. In addition, an underground muon detector was installed in each position of the two smaller arrays. We used events acquired by the SD-1500 during Phase I to test declination.

This work is organized as follows. In the next section, we present two spectra acquired with the SD-1500; in section 3, we describe the method we applied to test the declination dependence; in section 4, we show the comparisons of different declination bands of SD-1500 spectra; we conclude in the last section.

2. Vertical and inclined spectra

Given its depth, particles of any inclination deposit a detectable signal in a water-Cherenkov detector. This feature allows the Surface Detector Array to reconstruct cosmic rays inclined less than 80°. However, showers in such a broad zenith angle range are quite different; more vertical showers have a near-symmetrical footprint on the surface and contain a lower proportion of muons than more inclined ones. Due to these differences, events tilted less and more than 60° are reconstructed differently [6, 7] and, therefore, separate spectra for *vertical* and *inclined* events are produced. While the vertical spectrum samples declinations from the south celestial pole to +25°, the inclined one covers from −85° to +45°, reaching more northern latitudes.

We report the vertical and inclined spectra from a minimum energy at which the probability that a cosmic ray triggers the array's data acquisition is more than 97%. This threshold is 2.5 EeV ($\log_{10}(E/\mathrm{EeV}) = 18.4$) for the vertical spectrum and 5 EeV ($\log_{10}(E/\mathrm{EeV} = 18.7$) for the inclined one. We increased this second threshold from 4 EeV ($\log_{10}(E/\mathrm{EeV}) = 18.6$) used in [8] to minimize

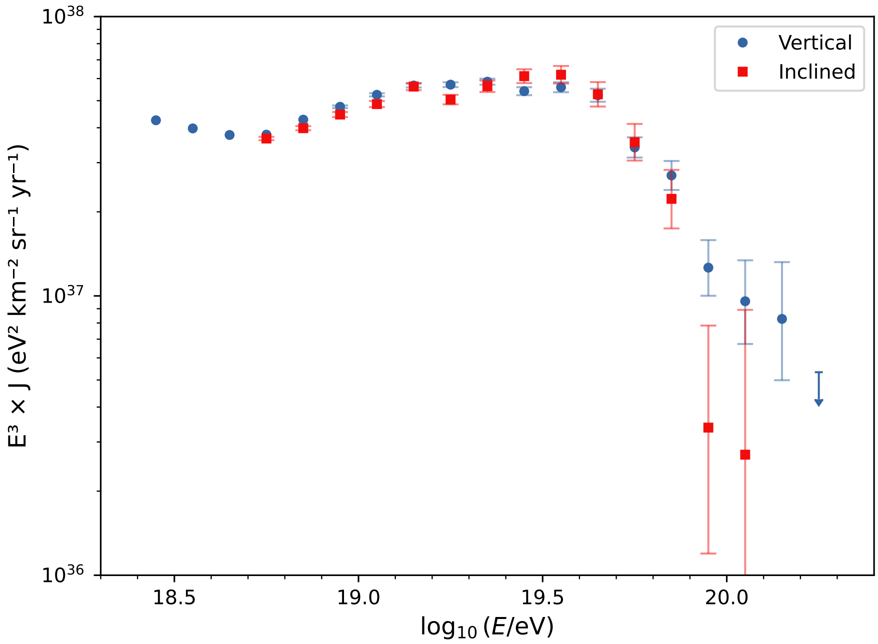

Figure 1: Spectra measured by the Surface Detector Array spaced at 1500 m using events arriving with zenith angle less than 60° (*vertical* spectrum) and between 60° and 80° (*inclined* spectrum). The error bars correspond to statistical uncertainties .

the impact of subthreshold events which are needed to correct the flux by the detector response. For the vertical spectrum, we used events observed from January 1, 2004, until August 31, 2018, and for the inclined, we extended the end date to August 31, 2021. These data are subsets of Phase I spectra that will be presented after the energy calibration is updated for the full data set. The array's exposure is robustly calculated at full efficiency based purely on geometrical considerations. The vertical and inclined spectra exposures are $60400 \pm 1800\,\mathrm{km}^2$ sr yr and $17850 \pm 540\,\mathrm{km}^2$ sr yr respectively. To ensure that the energy is well reconstructed, we selected for both spectra events in which the detector with the highest signal has all its six neighboring detectors functioning. We show the vertical and inclined spectra corrected by detector response in figure 1.

The inclined spectrum is, on average, 5% below the vertical one. These systematic differences usually found between spectra measured with different techniques can be explained mainly by a bias in the reconstructed energy. We reconciled the two spectra using a simultaneous fit previously used to combine the vertical SD-1500 and SD-750 spectra [9]. We fitted both spectra only in their common declination band from −85° to +25°. In this process, we fixed the vertical spectrum and allowed the inclined one to move by adjusting the energy calibration parameters. The best fit corresponds to reducing the calibration parameters 1.6 times their statistical uncertainties, increasing the energy of the inclined events 2% at 5 EeV followed by a linear decrease of 6% per energy decade. Figure 2 shows the simultaneous fit of the vertical and inclined spectra and the resulting combined spectrum that includes all the spectral features previously reported by Auger, namely, the ankle, the in-step, and the suppression at the high-energy end. The two spectra were consistent (p-value of ~ 0.5). A forthcoming paper will provide details of the SD-1500 spectra combination.

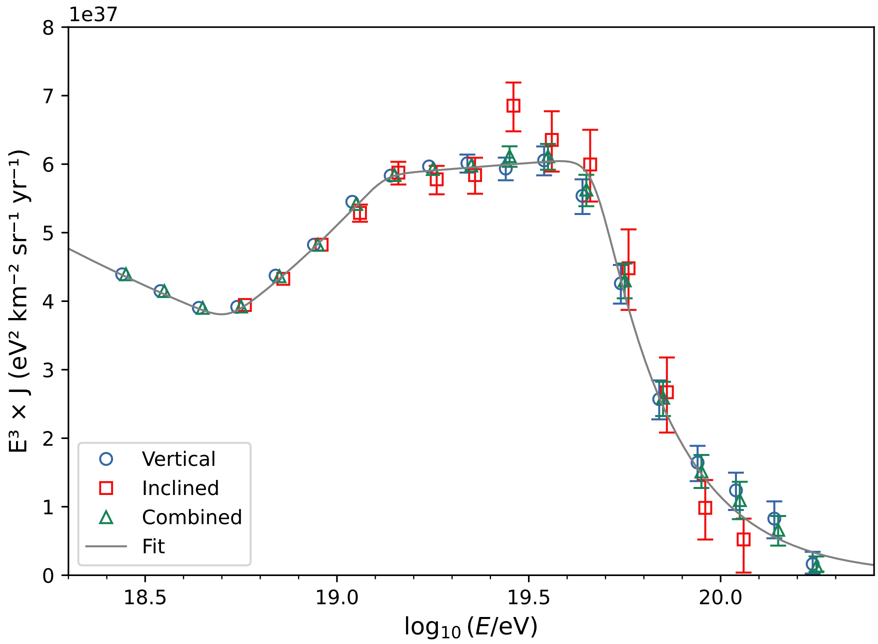

Figure 2: Simultaneous fit of the vertical and inclined spectra. The combined spectrum obtained from the fit is shown with white crosses.

3. Spectra comparison method

We developed a method to compare spectra that considers two distinct features: systematic uncertainties and scarcity of events. These relate to two opposite limits. Systematic uncertainties are considered in bins with many events, and a custom method different from the traditional chi-square test is applied for bins with few events. We first compared the data of two spectra in the same energy bin and then combined the outcomes of all bins into a single global test. We applied the formalism of hypothesis testing for the comparison, assuming the null hypothesis that both spectra sample the same physical flux.

We measured the flux by binning the data in energy bins of size $\log_{10}(E) = 0.1$. The flux measured bin i is,

$$J_i = \frac{c_i\, k_i}{\varepsilon\, \Delta E_i}. \tag{1}$$

with k_i the number of events in the bin, ε the exposure, ΔE_i the bin width, and c_i a correction factor between 0.9 and 1. The factor c_i compensates for a bias in J_i introduced by the statistical fluctuations of the measured energy and the trigger efficiency. The statistical uncertainty in J_i is propagated from the confidence interval of the Poisson variable k_i. The large number of available events results in statistical errors of less than 1% in the bins of lowest energy.

For bins with more than 100 events in total, considering the two spectra, we run a chi-square test that accounts for systematic uncertainties. These tests are valid as the Poisson distribution in the number of events can be well approximated by a normal distribution. Systematic uncertainties in the measured flux J_i must be considered when they become comparable to statistical uncertainties. If ignored, any slight deviation between the fluxes of two spectra would be considered statistically significant instead as an effect of the unavoidable systematic biases present in the measurement process.

The systematics in the measured flux, ranging from 25% to 60% depending on energy, are dominated by the propagation of the systematics in the reconstructed energy of the events. We avoided most systematics by only comparing two declination bands of the same spectrum since the energy bias impacts them very similarly. However, some remaining small systematics between bands must be accounted for in the comparison. A source of these systematics is, for example, any zenith angle dependence of the reconstructed energy or the assumed unfolding corrections. We assumed a systematic uncertainty uncorrelated between bands of 1%, a negligible fraction of the total systematic uncertainty of the measured flux. We accounted for systematic uncertainties in each bin by adding in quadrature the statistical and the uncorrelated systematic uncertainties, $\sigma^2 = \sigma^2_{stat} + \sigma^2_{sys}$. We used the test statistic corresponding to a chi-square test,

$$\chi^2_i = \frac{(J_i - J'_i)^2}{\sigma^2_i + \sigma'^2_i}, \tag{2}$$

with J_i and J'_i the measured fluxes in the compared bands and σ^2_i and σ'^2_i their corresponding total uncertainties. We calculated a p-value p_i from the test static using the upper tail of a chi-square distribution with one degree of freedom. Figure 3 shows the p-values for comparing the north and south bands of the vertical spectrum that will be presented in the next section.

For bins with few entries, the normal approximation to the distribution of the number of events is no longer valid, and therefore, the chi-square test cannot be applied. A deviance statistic derived from a Poisson likelihood could be used to overcome this limitation. While this approach avoids resorting to a normal approximation, the p-values are still calculated using a chi-square distribution, which is only exact for normal variables. Instead, we apply a binomial test that computes exact p-values. The binomial test considers the total events in bin i considering the two bands, $n_i = k_i + k'_i$, with k_i and k'_i the number of events in each band. Empty bins in both bands cannot be compared, but those in which only one of the bands is empty are included. The test considers the probability p_b that an event is observed in the first band. Assuming the null hypothesis that both bands sample the same flux, this probability is given by exposure of the first band over the total exposure of the two bands considering unfolding factors,

$$p_b = \frac{\varepsilon_1/c_1}{\varepsilon_1/c_1 + \varepsilon_2/c_2}. \tag{3}$$

For bands of similar exposure, $p_b \sim 0.5$, i.e., a single event has about the same probability of being observed in any band. The number of events in the first band (k_i) follows a binomial distribution with n_i trials and Bernoulli probability p_b. The statistic of the binomial test is k_i. The p-value p_i is calculated as the probability that k_i is more extreme than the observed value considering the two tails of a binomial distribution. Since the test statistics k_i are discrete, so are the p-values derived from them. We did not consider the systematics in a bin with few entries as the statistical contribution dominates the total uncertainty.

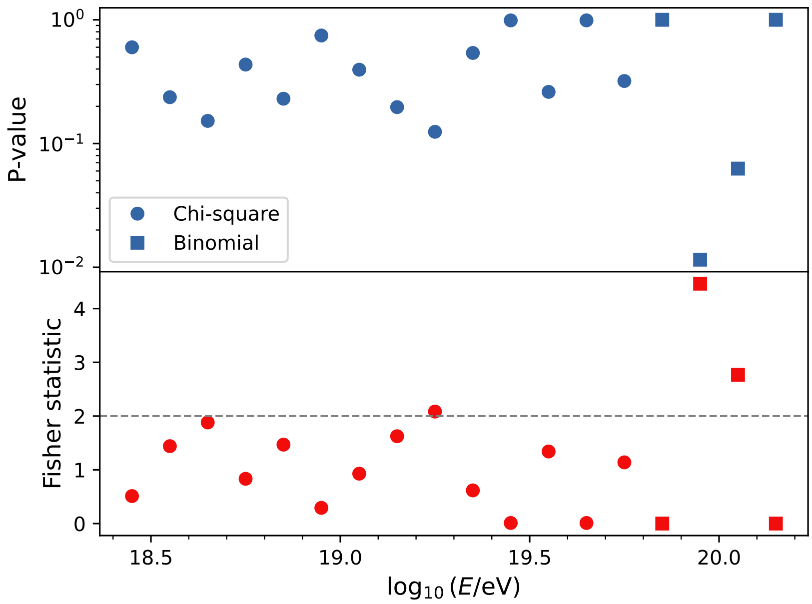

Figure 3: Probability values and related Fisher statistics for comparing the north and south bands of the vertical spectrum. Different markers indicate bins compared with chi-square and binomial tests. The mean value of the Fisher statistic is marked with a horizontal line.

We combined the p-values of the chi-square and binomial tests performed at the bin level with Fisher's method. This combination is based on the Fisher statistic defined as the sum over the bins $t = \sum t_i$, with the bin-level statistic defined from the corresponding p-value, $t_i = -2\log(p_i)$. The combined p-value is calculated as the probability that the statistic t is greater than the observed value t_{obs}. If the null hypothesis is true, a continuous p-value follows a uniform distribution between 0 and 1, and the related t_i follows a chi-square distribution with two degrees of freedom. This t_i uniform distribution is valid for the chi-square test but not for the binomial test, which has discrete bin p-values. Since the resulting distribution of t is not analytical, we calculated the combined p-value with Monte Carlo simulations using the software library in reference [10].

4. Comparison of declination bands

We split the vertical events according to their declinations in the three bands of similar exposure shown in figure 4. The southern band contains events with declinations from $-90°$ to $-42,5°$, the middle one from $-42.5°$ to $-17.3°$, and the northern one from $-17.3°$ to $+24.8°$. The exposures are 20495, 19931, and 20000 km^2 sr yr for the south, middle, and north bands, respectively. We compared declination bands in pairs to search for significant differences with the results in table 1. The number of degrees of freedom corresponding to the chi-square distribution of the Fisher statistic t is 36, twice the number of compared bins, and the observed test statistics t are comparable to the degrees of freedom. The p-values calculated numerically from Monte Carlo simulations are determined with $\sim 10^{-4}$ errors. The displayed significance is the quantile of a standard normal

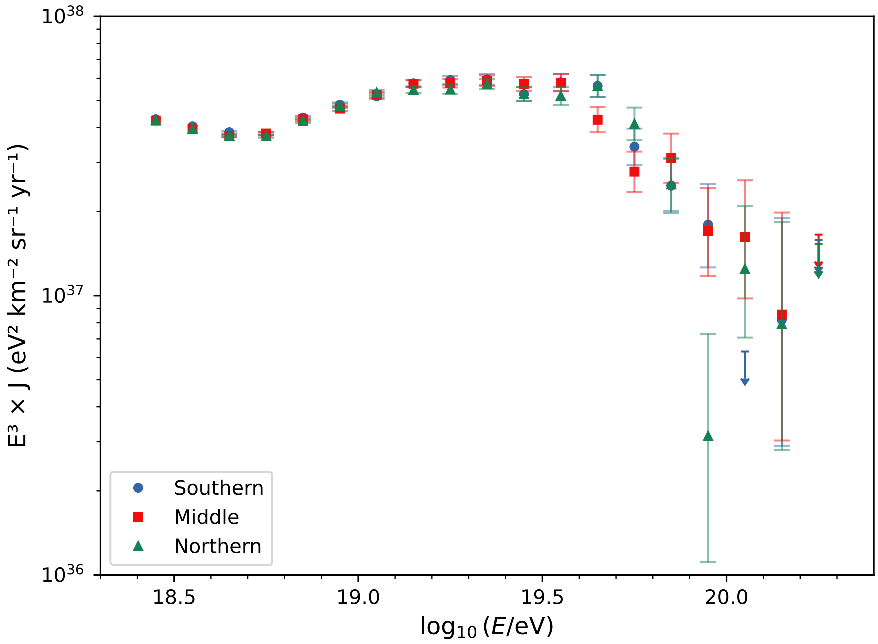

Figure 4: Flux in three different declination bands of the vertical spectrum used to test declination dependence up to +25°.

variable corresponding to a probability equal to unity minus the global p-value. The data of the three vertical bands agree with each other within uncertainties.

We extended the testing of the declination dependency of the flux up to +45° using the inclined spectrum. We split the events in a broad band from −85° to +25° overlapping the sky accessible with the vertical spectrum and a northern band from +25° to +45°. We show the spectra of these two bands in figure 5. We applied the same test for the vertical bands and obtained an observed Fisher statistic t_{obs} = 30.0 for 28 degrees of freedom. The numerical p-value is 22.0%, and the related significance is 1.23 σ, indicating that the two inclined bands' data are consistent.

Bands	t_{obs}	p-value	Significance
Southern-Middle	37.0	34.1%	0.95 σ
Middle-Northern	40.6	21.5%	1.24 σ
Northern-Southern	42.8	14.8%	1.45 σ

Table 1: Comparison of declination bands of the vertical spectrum.

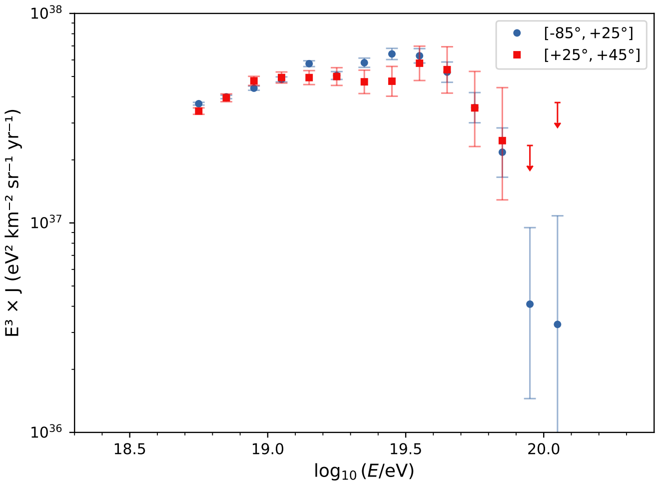

Figure 5: Flux in two different declination bands of the inclined spectrum used to test declination dependence up to +45°.

5. Conclusions

We presented two spectra measured with the surface detector of the Auger Observatory spaced at 1500 meters containing events arriving with less than 60° and between 60° and 80° of zenith angle, respectively. We showed that the two spectra are consistent with each other after shifting the energy of inclined events by a magnitude consistent with systematic uncertainties in the energy. We investigated the sensitivity of the vertical and inclined spectra to the declination dependency of the flux expected according to the dipole in arrival directions by splitting the events of the vertical and inclined spectra in declination bands. We compared these bands with a hypothesis test that considers 1% systematic uncertainty in the measured flux and that it is exact for bins with few events. We found the spectra do not have the sensitivity to reject the hypothesis of a flux independent of declination up to a declination of +45°.

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