Abstract: To investigate energy ordering effects close to the most energetic cosmic rays, a measurement of Energy-Energy-Correlations (EEC) has been performed with the data of the surface detector of the Pierre Auger observatory. The measurement includes the ultra high energy cosmic rays (UHECRs) with energies above $E > 60$ EeV arriving within a small solid angular region around UHECRs with $E > 60$ EeV. The measured EEC distribution is compared to the expectation for isotropic arrival directions of UHECRs.

Keywords: Pierre Auger Observatory, UHECRs, Magnetic Fields, UHECR Sources, Energy-Energy-Correlations

1 Introduction

The origin of ultra-high energy cosmic rays (UHECRs) is unknown. While there are strong hints that UHECRs are accelerated in discrete sources [1] and that the source distribution follows the large scale structure of the universe [2, 3], it has not been possible so far to identify individual sources. The main obstacle has been that galactic and extragalactic magnetic fields (GMF & EGMF) deflect the UHECRs as they propagate. On the other hand, the deflection offers a chance to constrain these magnetic fields. In many source and magnetic field scenarios, a characteristic energy-ordering of the arrival directions relative to the source position is expected.

The Energy-Energy-Correlation (EEC) distribution is an observable that is sensitive to such energy-ordering effects and was recently proposed as an observable sensitive to turbulent cosmic magnetic fields [4]. The EEC is a quantity originally developed in high energy physics analyses for testing strong interaction phenomena (e.g. [5, 6, 7]).

2 Energy-Energy-Correlations

In this section the EEC is introduced and its properties are studied for a scenario in which the arrival directions are isotropically distributed.

2.1 Definition

The EEC distribution is calculated as described in [4], except from one adjustment accounting for the field of view of the Pierre Auger observatory.

Firstly, regions of interest (ROI) are defined as cones with an opening angle of $0.2$ rad, centered around each UHECR with an energy above 60 EeV. A cone jet-algorithm is then applied to these ROIs:

1. The “center of mass” of the UHECRs within each ROI is calculated using the arrival directions weighted by the UHECR energies and the inverse exposure at each arrival direction.

2. Each ROI is moved to the corresponding center of mass.

3. The algorithm concludes after three iterations.

The Energy-Energy-Correlation $\Omega$ is calculated for every pair of UHECRs within each ROI using

$$\Omega_{ij} = \frac{(E_i - \langle E_i(\alpha_i) \rangle) \cdot (E_j - \langle E_j(\alpha_j) \rangle)}{E_i \cdot E_j}.$$  (1)

Here $E_i$ is the energy of an UHECR $i$ with an angular distance $\alpha_i$ to the center of the ROI. $\langle E_i(\alpha_i) \rangle$ is the average energy of all UHECRs at the angular distance $\alpha_i$ from the centers of the ROIs.

The angular distribution of the EEC is determined by averaging over all $\Omega_{ij}$ calculated in all ROIs. Each $\Omega_{ij}$ is
taken into account twice, once at the angular distance $\alpha_i$ and once at $\alpha_j$.

### 2.2 Isotropic Expectation

Here we evaluate the EEC distribution for a scenario in which the arrival directions are isotropic. Later, we will compare this to the distribution obtained from data (see section 3.3 below).

An isotropic set is realized using 18744 directions and the same energy spectrum as the Auger data above 5 EeV. To achieve this, the original energies of the actual events (see section 3.1) are reassigned to new directions according to the acceptance [8] of the Pierre Auger Observatory.

The average EEC distribution of 100 isotropic data sets is shown in Figure 1 as the black triangular symbols. The error bar denotes the RMS of these realizations. In this distribution two distinct features can be seen.

Firstly, there is a plateau at larger angles which is characteristic of the energy range and spectrum used. The level can be estimated by removing the angular dependence from (1) and calculating the expectation value

$$\langle \Omega_{ij} \rangle = \left( 1 - \langle E \rangle \left( \frac{1}{E} \right) \right)^2. \quad (2)$$

Secondly, an increase towards smaller angles is observed. This is caused by the jet algorithm used for the determination of the ROI (see section 2.1), which leads to a systematic overdensity of the most energetic events near the center of the ROIs. This effect increases the average value of the EEC at smaller angles.

A signal of energy-ordering of events would be a broader increase of the distribution, beyond that seen for isotropic sets, near the center of the ROI. The shape will depend on the scale of the ordering.

### 3 Data Analysis

The Pierre Auger Observatory is a hybrid air shower detector located in Malargüe, Argentina. The Surface Detector (SD) consists of a 3000 km$^2$ array of 1660 surface detectors overlooked by the 27 fluorescence telescopes of the Fluorescence Detector (FD) grouped at 4 sites on the array boundary. This allows for complementary measurements of the lateral distribution of air shower particles at ground level by the SD and the longitudinal development of the air shower by the FD.

#### 3.1 Event Selection

For the measurement of the EEC, all events with energies above 5 EeV measured between 1 January 2004 and 31 December 2010 SD are used. These event energies are above the so-called spectral ankle [9], and can thus be reasonably hypothesized to be of extragalactic origin [10].

The following additional cuts are applied to the SD data set:

- A reconstructed zenith angle of less than 60°.
- The SD tank with the highest signal has to be surrounded by 6 operating tanks during the time the UHECR is measured.
- Time periods in which the data acquisition was unstable are excluded. These are associated to unavoidable problems in the construction phase, or more generally to hardware instabilities [11].

This results in a set of $N_{events} = 18744$ UHECRs.

#### 3.2 Experimental Uncertainties

In this section the relevant experimental uncertainties of the Pierre Auger Observatory are discussed and propagated to the EEC analysis. The error propagation is performed either by variation of the data itself, if possible, or with Monte Carlo (MC) data of isotropic arrival directions. Since the EEC distribution depends on the total number of events in the data set, this number is fixed for all the studies performed below.

#### 3.2.1 Energy Resolution

Events with energies larger than 3 EeV are measured by the SD with an energy resolution of 14.8% [13]. To model the effect on the EEC distribution the energies of the events are varied or “smeared” by a Gaussian with this width. By varying all Auger events, including those below 5 EeV, events may cross the imposed threshold from above or from below. Due to the steep spectrum, this variation will slightly increase the number of events exceeding the threshold. To keep the number of events fixed, events are randomly removed.

This variation of the energies is performed 100 times and each time the EEC distribution is calculated. The RMS of these distributions then is considered to be the statistical uncertainty resulting from the energy resolution.

#### 3.2.2 Angular Resolution

The angular resolution of the SD is better than 1° for energies above 5 EeV [12], where the angular resolution is given in terms of the 68% quantile of a two-dimensional Gaussian distribution. The angular resolution is propagated in the same way as in section 3.2.1. The RMS of 100 data sets gives the statistical uncertainty resulting from the angular resolution.

#### 3.2.3 Absolute Energy Scale

The energy measurement of the SD is calibrated using the fluorescence detector of the Pierre Auger Observatory [9].
There is a systematic uncertainty of 22% on the overall energy scale. In order to keep the number of UHECRs constant the corresponding uncertainty has been studied using 100 isotropic MC data sets of 70000 UHECRs above 3 EeV. The MC set has a spectrum according to [9] and the geometrical coverage of the Pierre Auger observatory given in reference [8], using a latitude of $-35^\circ$ S for the observatory site. In a second step, the following three types of data sets are produced:

- For the nominal value of energy, the first $N_{\text{events}}$ above 5 EeV are taken from each data set.
- All energies are shifted up by 22%, then the first $N_{\text{events}}$ above 5 EeV are taken from each data set.
- All energies are shifted down by 22%, then the first $N_{\text{events}}$ above 5 EeV are taken from each data set.

The average of the EEC distributions of the unshifted data sets is taken as the mean value and the average of the shifted EEC distributions as the uncertainty of the mean. The relative uncertainties of this MC study are used to quantify the effect of a systematic shift of the energy scale.

### 3.2.4 Detector Acceptance

The detector acceptance has no direct influence on the measurement of the EEC distribution, but the effects are important for a comparison with models of UHECR propagation like the one performed in section 2.2. At energies larger than 5 EeV the Pierre Auger observatory has reached full trigger efficiency [11], so a geometrical acceptance model [8] can be assumed. Historically, data was taken while the Observatory was being constructed. The effect from the growing SD before 2008 and from bad periods of operation is much smaller than the uncertainty from the angular and energy resolutions. Therefore it is sufficient to use a geometrical acceptance model for MC comparisons.

### 3.3 Measurement of the Energy-Energy-Correlations

The measurement of Energy-Energy-Correlation in the data set as defined in section 3.1 is shown in Figure 1 by the red circular symbols.

The statistical uncertainty has been determined as described above (sections 3.2.1 and 3.2.2). The arrival directions and the energies of the UHECRs have been varied simultaneously by their respective uncertainty. The RMS of the average distribution is the statistical uncertainty denoted by the error bars. The systematic uncertainty is calculated as described in section 3.2.3, by varying the energy scale of isotropic MC data sets. It is denoted by the blue error band.

For comparison the expectation from isotropically arriving UHECRs with the same energy spectrum as the data set is shown as the black triangular symbols. The error bars indicate the RMS of 100 realizations.

![Figure 1: Measurement of the EEC distribution by the Pierre Auger Observatory (red circular symbols). The error bars denote the statistical uncertainty from angular and energy resolution effects, the band denotes the systematic uncertainty from the overall energy scale. For comparison an EEC distribution from a simulated data set with isotropic arrival directions is shown (black triangular symbols). The error bars denote the RMS of 100 realizations.](image)

### 3.4 Discussion

As can be seen in figure 1 the measured EEC distribution is compatible with the expectation from isotropic arrival directions. This means, in particular, that in this analysis no energy-ordered deflections are observed near the most energetic UHECRs. Such a distribution can be caused either by a high source density for an isotropic source distribution or by large deflections of the UHECRs in cosmic magnetic fields.

### 4 Conclusions

The observable $\Omega$ of the Energy-Energy-Correlations has been used to investigate the strength of energy-ordering effects close to the most energetic UHECRs above $E = 60$ EeV. The measurement presented in this contribution includes UHECRs above 5 EeV arriving within regions of interest (ROI), each of size 0.2 rad, near the most energetic events. The average value of $\Omega$ has been measured as a function of the angular distance in each ROI. In this measurement no energy ordering has been found.

### References

[13] R. Pesce, for the Pierre Auger Collaboration, paper 1160, these proceedings