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# Correlation between UHECRs measured by the Pierre Auger Observatory and Telescope Array and neutrino candidate events from IceCube

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**Abstract.** We present the results of three searches for correlations between ultra-high energy cosmic ray events (UHECRs) measured by Telescope Array and the Pierre Auger Observatory and high-energy neutrino candidate events from IceCube. Two cross-correlation analyses of UHECRs are done: one with 28 “cascades” from the IceCube ‘high-energy starting events’ sample and the other one with 12 high-energy “tracks”. The angular separation between the arrival directions of neutrinos and UHECRs is scanned. The same events are also used in a separate search stacking the neutrino arrival directions and using a maximum likelihood approach. We assume that UHECR magnetic deflections are inversely proportional to the energy with values 3°, 6° and 9° at 100 EeV to account for the various scenarios of the magnetic field strength and UHECR charges. A similar analysis is performed on stacked UHECR arrival directions and the IceCube 4-year sample of through-going muon-track events that was optimized for neutrino point source searches.

## 1. Introduction

The sources of ultra-high energy cosmic rays (UHECRs) have not been identified yet. The CRs do not point back to their sources as they are deflected by magnetic fields en-route to Earth. Since both CR composition at ultra-high energies and the magnetic field strength are poorly known, this deflection cannot be computed precisely. If the CR composition is light, i.e. mainly protons, the magnetic deflection is a few degrees at energies above a few tens of EeV. Secondary particles including neutrinos are produced in the sources by the interactions between the CRs and ambient photon and matter fields. Neutrinos arrival directions point back to their origin,



even though they are hard to detect. This work describes a joint analysis by the IceCube, Pierre Auger and Telescope Array Collaborations of possible correlations between the arrival directions of high-energy neutrinos and UHECRs.

## 2. The IceCube Neutrino Telescope

IceCube is a cubic-kilometer neutrino detector embedded in the ice at the South Pole [1] between depths of 1450m and 2450m. Different IceCube data sets are considered here. The first, called high-energy cascades, is a set of cascades<sup>1</sup> detected between May 2010 and May 2014 in a search for high-energy events where the interaction occurs within the detector [2]. These 39 cascades are part of the HESE (High-Energy Starting Events) set with deposited energy range of  $\sim 30\text{--}2000$  TeV. A second set of events referred to as high-energy tracks (energy above  $\sim 70$  TeV) consists of the 7 tracks<sup>2</sup> of the HESE sample [2] which start inside the detector and have energies and directions making them more likely to be of extraterrestrial origin and 9 through-going muon tracks found in a search of a diffuse up-going  $\nu_\mu$  flux [3]. The third data set used is called the 4-year point-source sample [4] and consists of events with sub-degree median angular resolution detected between May 2008 and May 2012. The set includes about 400,000 events. It is dominated by the background of up-going atmospheric neutrinos from the Northern hemisphere and high-energy atmospheric muons from the Southern hemisphere with possible contribution of neutrinos of astrophysical origin.

## 3. The Pierre Auger Observatory

The Pierre Auger Observatory, located in Malarge, Argentina [5, 6], consists of surface and air fluorescence telescopes designed to perform complementary measurements of air showers created by UHECRs. The data set used for the present analysis includes 231 events with  $E > 52\text{EeV}$  and zenith angles smaller than  $80^\circ$  recorded by the surface detector array from January 2004 to March 2014 [7]. The exposure determined by geometrical considerations for the period analyzed amounts to  $66,452\text{ km}^2\text{ sr yr}$ . The angular resolution is better than  $0.9^\circ$ . The absolute energy scale has a systematic uncertainty of  $\sim 14\%$  and the energy resolution is  $\sim 12\%$ .

## 4. Telescope Array

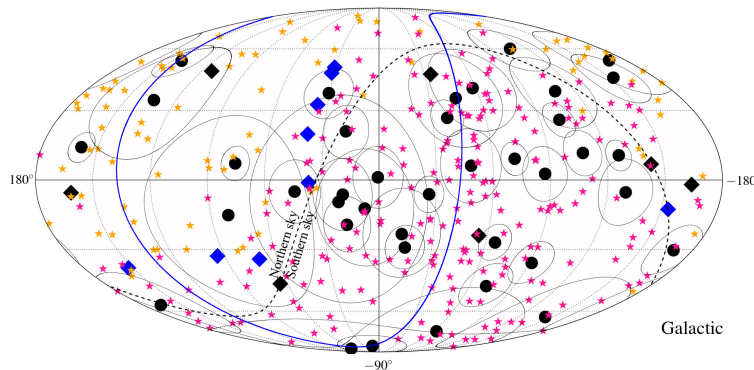
The Telescope Array (TA) is located in Utah, USA [8] and similarly detects extensive air showers generated by UHECRs. The UHECR sample considered in the present analysis consists of 87 events with  $E > 57\text{EeV}$  and zenith angles smaller than  $55^\circ$  collected between May 2008 and May 2014 by the surface detector array. A subset of events has been published in [9]. The total exposure is around  $9,500\text{ km}^2\text{ sr yr}$ . The angular resolution is better than  $1.5^\circ$ . As with the Auger the energy scale of the surface detector array is cross-calibrated with the fluorescence telescopes. The energy resolution is better than 20% with a systematic uncertainty on the absolute energy scale of 21%.

## 5. The searches

This section describes three different analyses. A cross-correlation and a stacking likelihood analysis are done on the sample of high-energy cascades and high-energy tracks and the UHECRs. Cascade and track-like events are considered separately since, due to their different angular resolutions, the angular distance at which a signal (if any) can be detected would be different. A third analysis is performed on stacked UHECRs and the IceCube 4-year point-source sample. The magnetic deflections of CRs have to be accounted for in the likelihood tests. For simplicity, we model individual deflections as a 2-dimensional Gaussian distribution with

<sup>1</sup> The result of  $\nu_e$  and  $\nu_\tau$  charged-current, and all flavor neutral-current interactions.

<sup>2</sup> Moun tracks from  $\nu_\mu$  charge current interactions.



**Figure 1.** Map in Galactic coordinates of the arrival directions of the IceCube cascades (black dots) and tracks (diamonds), as well as the UHECRs detected by the Pierre Auger Observatory (magenta stars) and Telescope Array (orange stars). The circles around the showers indicate angular errors. The black diamonds are the HESE tracks while the blue diamonds are the tracks from the through-going muon sample. The blue curve indicates the Super-Galactic plane.

the energy dependent standard deviation  $\sigma_{MD}(E_{CR}) = D \times 100 \text{ EeV}/E_{CR}$ , and we consider the values  $D = 3^\circ, 6^\circ$  and  $9^\circ$  (the latter is used only for the likelihood test with the high-energy cascades and high-energy tracks). These values are reasonable test values as shown by a backtracking simulation of the detected UHECRs in the galactic magnetic field models of Pshirkov et al [10] and Jansson and Farrar [11], presented in [12].

### 5.1. UHECR correlation searches with high-energy cascades and tracks

The arrival directions of the high-energy tracks and cascades in IceCube, and of the UHECRs measured by Auger and TA are shown in Fig. 1. Two different analyses are performed with these data sets: a cross-correlation and a stacking likelihood analysis.

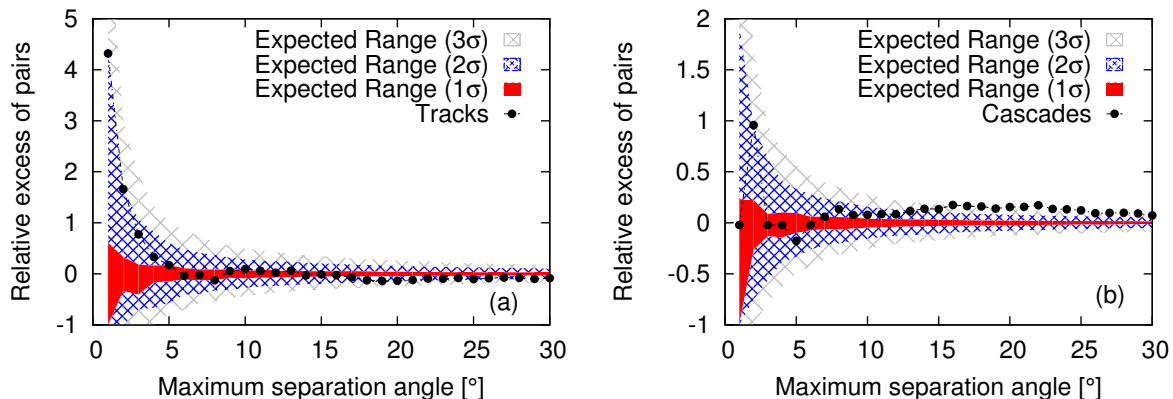
**Cross-correlation analyses:** The method computes the number of UHECR-neutrino pairs as a function of their angular separation  $\alpha$ ,  $n_p(\alpha)$ , and compares it to the expectation from an isotropic distribution of arrival directions of CRs. Unlike the likelihood method, there is no assumption made about the exact magnetic deflection and an angular scan is performed between  $1^\circ$  and  $30^\circ$  with a step of  $1^\circ$ .

**Likelihood stacking analyses:** Stacking a set of sources is a common way of enhancing the statistical weight of multiple weak signals to enhance the discovery potential. Since neutrinos are not deflected on their way to Earth, neutrino arrival directions are stacked. An unbinned likelihood method is used, with the log of the likelihood function defined as:

$$\log \mathcal{L}(n_s) = \sum_{i=1}^{N_{\text{Auger}}} \log \left( \frac{n_s}{N_{\text{CR}}} \mathcal{S}_{\text{Auger}}^i + \frac{N_{\text{CR}} - n_s}{N_{\text{CR}}} \mathcal{B}_{\text{Auger}}^i \right) + \sum_{i=1}^{N_{\text{TA}}} \log \left( \frac{n_s}{N_{\text{CR}}} \mathcal{S}_{\text{TA}}^i + \frac{N_{\text{CR}} - n_s}{N_{\text{CR}}} \mathcal{B}_{\text{TA}}^i \right), \quad (1)$$

where  $n_s$ , the number of signal events, is the only free parameter and  $N_{\text{CR}} = N_{\text{Auger}} + N_{\text{TA}}$  is the total number of UHECRs.  $\mathcal{S}_{\text{Auger}}^i$  and  $\mathcal{S}_{\text{TA}}^i$  are the signal probability density functions (PDFs). The Auger signal PDF has the following form:

$$\mathcal{S}_{\text{Auger}}^i(\vec{r}_i, E_i) = R_{\text{Auger}}(\delta_i) \cdot \sum_{j=1}^{N_{\text{src}}} S_j(\vec{r}_i, \sigma(E_i)), \quad (2)$$



**Figure 2.** Relative excess of pairs,  $[n_p(\alpha)/\langle n_p^{\text{iso}}(\alpha) \rangle] - 1$ , as a function of the maximum angular separation between the neutrino and UHECR pairs, for the analysis done with the track-like events (a) and with the cascade events (b). The  $1\sigma$ ,  $2\sigma$  and  $3\sigma$  fluctuations expected from an isotropic distribution of arrival directions of CRs are shown in red, blue and grey, respectively.

where  $\vec{r}_i$  is the angular position of the  $i^{\text{th}}$  UHECR event,  $R_{\text{Auger}}(\delta_i)$  takes into account the Auger detector response, e.g. the relative exposure for given event declination  $\delta_i$  and  $N_{\text{src}}$  is the number of stacked sources, 39 for the cascades and 16 for the tracks. The last term,  $S_j(\vec{r}_i, \sigma(E_i))$  is the value of the normalized directional likelihood map for the  $j^{\text{th}}$  source (i.e., the  $j^{\text{th}}$  neutrino) taken at  $\vec{r}_i$  and smeared with a Gaussian with standard deviation  $\sigma(E_i)$ , which is defined as:

$$\sigma(E_i) = \sqrt{\sigma_{MD}^2(E_i) + \sigma_{\text{Auger}}^2}, \quad (3)$$

where  $\sigma_{\text{Auger}} = 0.9^\circ$ . The signal PDF for Telescope Array  $S_{\text{TA}}^i$  has the same form as Eq. 2, but the relevant parts are replaced with the Telescope Array equivalents, namely  $R_{\text{Auger}}(\delta_i)$  is replaced by the Telescope Array relative exposure  $R_{\text{TA}}(\delta_i)$  and the angular resolution is  $\sigma_{\text{TA}} = 1.5^\circ$ . The background PDFs,  $B_{\text{Auger}}^i$  and  $B_{\text{TA}}^i$ , represent the probabilities of observing a cosmic ray from a given direction assuming an isotropic flux. Therefore they are taken to be the Auger and TA normalized exposures.

The log-likelihood of Eq. 1 is maximized with respect to  $n_s$  and the ratio of the maximum likelihood w.r.t the case where  $n_s = 0$  is taken as the test statistic [12].

**Results:** In Fig. 2 we show the results obtained applying the cross-correlation method to the data. For the sample of high-energy tracks, the maximum departure from the isotropic expectation of CRs (fixing the positions of the neutrinos) obtained is at an angular distance of  $1^\circ$ , where 0.38 pairs are expected on average and 2 pairs are detected. The post-trial  $p$ -value is 28%. For the high-energy cascade events, the smallest pre-trial  $p$ -value occurs at an angular distance of  $22^\circ$ , for which 575 pairs are observed while 490.3 are expected on average. The post-trial  $p$ -value is  $5 \times 10^{-4}$  with respect to expectations of an isotropic flux of CRs. As an a posteriori study, we also evaluated the significance under the hypothesis of an isotropic distribution of neutrinos, fixing the UHECR arrival directions (note that this alternative hypothesis preserves the degree of anisotropy in the arrival directions of CRs that is suggested by the TA hot spot [13] or the excess around Cen A reported by Auger [7]). The post-trial  $p$ -value is  $8.5 \times 10^{-3}$ .

For the likelihood stacking analysis, the most significant deviation from the isotropic flux is found for the magnetic deflection parameter  $D = 6^\circ$  for the cascade sample. The observed pre-trial  $p$ -value is  $2.7 \times 10^{-4}$ . Using a conservative method to estimate the trial factor [12], the post-trial  $p$ -value is found to be  $8.0 \times 10^{-4}$ . For this search the post-trial  $p$ -value with respect to the isotropic neutrino flux hypothesis is  $1.3 \times 10^{-3}$  ( $\sim 3\sigma$ ). We see that for both

the cross-correlation and the likelihood stacking analyses, the  $p$ -values obtained under the null hypothesis of isotropic neutrinos turn out to be larger than the ones obtained under the null hypothesis of isotropic CRs, the differences reflecting the extent to which the original  $p$ -values, from the isotropic cosmic-ray hypothesis, are due to an alignment of the neutrinos with the known clustering of the cosmic rays.

### 5.2. Stacking search for neutrino point-sources in the 4 year point-source sample

The neutrino data set used for this analysis is the IceCube point-source data set. A stacking analysis is done but in this case (as opposed to the previous one) the stacked sources are the measured positions of UHECRs. An unbinned likelihood method is performed where the log likelihood is defined as:

$$\log \mathcal{L}(n_s, \gamma) = \sum_{i=1}^{N_\nu} \log \left( \frac{n_s}{N_\nu} \mathcal{S}_i^{\text{tot}} + \left( 1 - \frac{n_s}{N_\nu} \right) \mathcal{B}_i \right), \quad (4)$$

where  $n_s$  is the number of signal events in the sample and  $\gamma$  is the spectral index of the neutrino source candidates, assumed to collectively follow an unbroken power-law spectrum  $\propto E^{-\gamma}$ .  $N_\nu$  is the total number of astrophysical neutrino candidate events in the sample.  $\mathcal{S}_i^{\text{tot}}$  is the signal PDF for the stacked sources and  $\mathcal{B}_i$  is the background PDF. The log-likelihood,  $\log(\mathcal{L})$  is maximized w.r.t.  $n_s$  and  $\gamma$  and the TS is defined as in section 5.1.

Only UHECRs above  $E_{th} = 85$  EeV have been considered. The value of  $E_{th}$  was decided using the procedure described in [12]. Applying the method to the actual data, all observations are found to be compatible with the background only hypothesis. The smallest post-trial  $p$ -value is 25% for the hypothesis of  $D = 3^\circ$ , with a fitted excess of  $\sim 123$  events and  $\gamma = -3.24$ . The analysis with  $D = 6^\circ$  yields a  $p$ -value larger than 50%.

## 6. Conclusions

Three analyses have been performed to investigate correlations between UHECRs detected by the Pierre Auger Observatory and Telescope Array with various samples of IceCube neutrino candidates. The results obtained are all below  $3.3\sigma$ . There is a potentially interesting result in the analyses performed with the set of high-energy cascades when compared to assumed isotropic arrival directions of CRs. If we compare the result to an isotropic flux of neutrinos (fixing the positions of the CRs) to consider the effect of anisotropies in the arrival directions of CRs (such as the TA hot spot), the significance is  $\sim 2.4\sigma$ . These results were obtained with relatively few events and we will update these analyses in the future with increasing statistics to follow their evolution.

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