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ABSTRACT

The surface detector array of the Pierre Auger Observatory can detect neutrinos with energy E_ν between 10^{17} eV and 10^{20} eV from point-like sources across the sky south of $+55^\circ$ and north of -65° declinations. A search has been performed for highly inclined extensive air showers produced by the interaction of neutrinos of all flavors in the atmosphere (downward-going neutrinos), and by the decay of tau leptons originating from tau neutrino interactions in Earth's crust (Earth-skimming neutrinos). No candidate neutrinos have been found in data up to 2010 May 31. This corresponds to an equivalent exposure of ~ 3.5 years of a full surface detector array for the Earth-skimming channel and ~ 2 years for the downward-going channel. An improved upper limit on the diffuse flux of tau neutrinos has been derived. Upper limits on the neutrino flux from point-like sources have been derived as a function of the source declination. Assuming a differential neutrino flux $k_{\text{PS}} \cdot E_\nu^{-2}$ from a point-like source, 90% confidence level upper limits for k_{PS} at the level of $\approx 5 \times 10^{-7}$ and 2.5×10^{-6} GeV cm $^{-2}$ s $^{-1}$ have been obtained over a broad range of declinations from the searches for Earth-skimming and downward-going neutrinos, respectively.

Key words: astroparticle physics – cosmic rays – neutrinos – telescopes

1. INTRODUCTION

The nature and production mechanisms of ultra-high energy cosmic rays (UHECRs), with energies above 10^{18} eV, are

still unknown (Nagano & Watson 2000; Bhattacharjee & Sigl 2000; Halzen & Hooper 2002). The observation of UHECRs makes an associated flux of ultra-high energy cosmic neutrinos (UHE ν s; Becker 2008) very likely. All models of UHECR production predict neutrinos as a result of the decay of charged pions generated in interactions of cosmic rays within the sources themselves (“astrophysical” neutrinos), and/or in their propagation through background radiation fields (“cosmogenic” neutrinos; Berezhinsky & Zatsepin 1969; Stecker 1973). In fact, charged pions, which are photoproduced by UHECR protons interacting with the cosmic microwave background radiation, decay into UHE ν s. However, the predicted flux has large

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uncertainties, since it depends on the UHECR spectrum and on the spatial distribution and cosmological evolution of the sources (Becker 2008; Ahlers et al. 2010; Kotera et al. 2010). If UHECRs are heavy nuclei, the $\text{UHE}\nu$ yield is strongly suppressed (Ave et al. 2005).

The observation of UHE neutrinos would open a new window to the universe. Neutrinos travel unaffected by magnetic fields and can give information on astrophysical regions that are otherwise hidden from observation by large amounts of matter. The discovery of astrophysical neutrino sources would shed light on the long-standing question of the origin of cosmic rays, and clarify the production mechanism of the GeV–TeV gamma rays observed on Earth (Gaisser 1995; Alvarez-Muñiz & Halzen 2002).

The Pierre Auger Observatory (Abraham et al. 2004)—located in the province of Mendoza, Argentina, at a mean altitude of 1400 m above sea level ($\sim 875 \text{ g cm}^{-2}$)—was designed to measure extensive air showers (EAS) induced by UHECRs. The fluorescence detector (Abraham et al. 2010a) comprises a set of imaging telescopes to measure the light emitted by excited atmospheric nitrogen molecules as the EAS develops. A surface detector (SD; Allekotte et al. 2008) measures EAS particles on the ground with an array of water-Cherenkov detectors (“stations”). Each SD station contains 12 tonnes of water viewed by three $9''$ photomultipliers. Arranged on a triangular grid with 1.5 km spacing, 1660 SD stations are deployed over an area of $\sim 3000 \text{ km}^2$, overlooked by 27 fluorescence telescopes.

Although the primary goal of the SD is to detect UHECRs, it can also identify UHE neutrinos. Neutrinos of all flavors can interact at any atmospheric depth through charged or neutral currents and induce a “downward-going” (DG) shower. In addition, tau neutrinos can undergo charged current interactions in the Earth crust and produce a tau lepton which, after emerging from the Earth surface and decaying in the atmosphere, will induce an “Earth-skimming” (ES) upward-going shower. Even if tau neutrinos are not expected to be produced at the astrophysical source, approximately equal fluxes for each neutrino flavor should reach the Earth as a result of neutrino oscillations over cosmological distances. Neutrino candidate events must be identified against the overwhelming background of showers initiated by standard UHECRs (protons or nuclei) and, in a much smaller proportion, photons (Abraham et al. 2010b). Highly inclined (zenith angle $\theta > 75^\circ$) ES and DG neutrino-induced showers will present a significant electromagnetic component at the ground (“young” showers), producing signals spread over hundreds of nanoseconds in several of the triggered SD stations. Inclined showers initiated by standard UHECRs are, by contrast, dominated by muons at ground level (“old” showers), with signals typically spread over only tens of nanoseconds.

Thanks to the fast sampling (25 ns) of the SD digital electronics, several observables sensitive to the signal time structure can be used to discriminate between young and old showers, allowing for detection of $\text{UHE}\nu$ s. Candidates for $\text{UHE}\nu$ s are searched for in inclined showers in the ranges $75^\circ < \theta < 90^\circ$ and $90^\circ < \theta < 96^\circ$ for the DG and ES analysis, respectively.

2. LIMITS ON THE DIFFUSE FLUX OF UHE TAU NEUTRINOS

An upper limit on the diffuse flux of tau neutrinos from the search for ES events in data through 2008 April 30 (~ 2 years of exposure with a full SD array) was reported in Abraham et al. (2009). Here, the search is extended to data until 2010

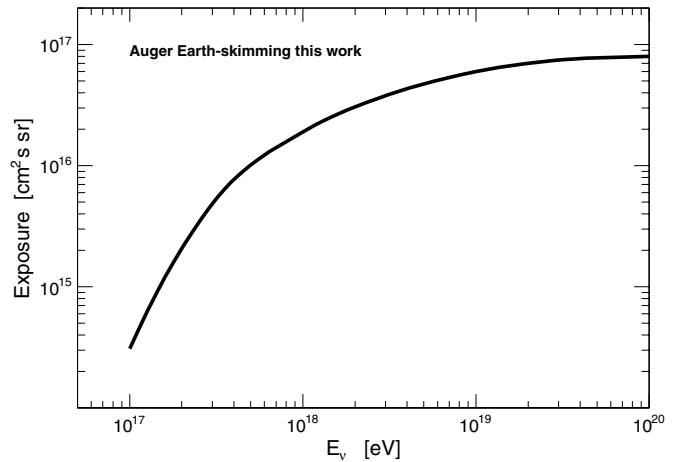


Figure 1. Exposure of the surface detector of the Pierre Auger Observatory for Earth-skimming neutrino initiated showers as a function of the neutrino energy, for data collected between 2004 January 1 and 2010 May 31.

May 31 (~ 3.5 years of exposure with a full SD array), and an improved limit is obtained. A preliminary report of this result was presented in Guardincerri et al. (2011).

Details of the neutrino selection procedure, of the calculation of the detector exposure for ES showers, and of sources of systematic uncertainties are given in Abraham et al. (2009). The neutrino selection criteria were optimized with an early data set collected between 2004 November 1 and December 31. By using data rather than Monte Carlo simulations, all possible detector effects and shower-to-shower fluctuations, which constitute the main background to $\text{UHE}\nu$ s and may not be well reproduced by simulations, are taken into account. The neutrino selection established with the training sample was then applied to a “blind search sample” of data collected between 2004 January 1 and 2010 May 31 (excluding 2004 November and December). The blind search sample is equivalent to ~ 3.5 years of data collected by a fully efficient SD array, i.e., with all stations working continuously. The time evolution of the SD array, which was growing during the construction phase, as well as the dead times of individual stations, was accounted for in this calculation. The integrated exposure for detection of ES tau neutrinos as a function of energy is shown in Figure 1. No neutrino candidates were found in the blind search. Assuming a differential spectrum $\Phi(E_\nu) = dN_\nu/dE_\nu = k \cdot E_\nu^{-2}$ for the diffuse flux of $\text{UHE}\nu$ s and zero background (Abraham et al. 2009; Abreu et al. 2011a), a 90% confidence level (CL) upper limit on the integrated flux of tau neutrinos is derived:

$$k < 3.2 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}. \quad (1)$$

Systematic uncertainties in the exposure were taken into account in the upper limit by using a semi-Bayesian extension (Conrad et al. 2003) of the Feldman–Cousins approach (Feldman & Cousins 1998). The limit, shown as a horizontal line in Figure 2, is valid in the energy range $1.6 \times 10^{17} \text{ eV} \leq E_\nu \leq 2.0 \times 10^{19} \text{ eV}$, where $\approx 90\%$ of neutrino events would be detected for an E_ν^{-2} flux. Also shown is the 90% CL upper limit in differential form, where the limit was calculated independently in each energy bin of width 0.5 in $\log_{10} E_\nu$. The integrated and differential limits from the search for DG neutrinos (Abreu et al. 2011a) at the Pierre Auger Observatory, based on a “blind search sample” of data collected from 2007 November 1 until 2010 May 31 (equivalent to ~ 2.0 years of exposure with the full SD array), are also shown in Figure 2, together with limits from the IceCube

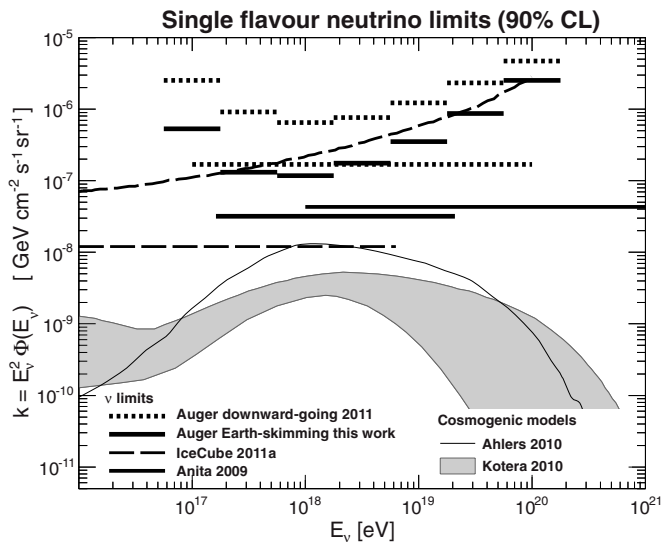


Figure 2. Differential and integrated upper limits at 90% CL on the single flavor E_ν^{-2} neutrino flux from the search for downward-going and Earth-skimming neutrinos at the Pierre Auger Observatory. Integrated upper limits are indicated by horizontal lines, with the corresponding differential limits being represented by segments of width 0.5 in $\log_{10} E_\nu$. Limits from the IceCube Neutrino Observatory (Abbasi et al. 2011a) and from the ANITA experiment (Gorham et al. 2010) are also shown after proper rescaling to account for single flavor neutrino flux and different energy binning. Predictions for cosmogenic neutrinos under different assumptions (Ahlers et al. 2010; Kotera et al. 2010) are also shown, although predictions almost one order of magnitude lower or higher exist.

Neutrino Observatory (Abbasi et al. 2011a) and the ANITA experiment (Gorham et al. 2010). The shaded area in Figure 2 brackets the cosmogenic neutrinos fluxes predicted under a wide range of assumptions for the cosmological evolution of the sources, for the transition between the galactic and extragalactic component of cosmic rays, and for the UHECR composition (Kotera et al. 2010). The corresponding number of cosmogenic neutrino events expected in the blind search sample ranges between 0.1 and 0.3, approximately. For the diffuse flux of cosmogenic neutrinos predicted in Ahlers et al. (2010), 0.6 neutrino events are expected at the Pierre Auger Observatory with the integrated exposure of the present analysis, to be compared with 0.43 events expected in the 333.5 days of live time of the IceCube-40 neutrino telescope (Abbasi et al. 2011a). The current bound to a cosmogenic neutrino flux with energy dependence as in Ahlers et al. (2010) and shown in Figure 2 is four times larger than the predicted value. With the current selection criteria the exposure accumulated in ~ 10 more years with the Pierre Auger Observatory may exclude this cosmogenic neutrino flux at 90% CL. Note that the maximum sensitivity of the Pierre Auger Observatory, obtained for $E_\nu \sim 10^{18}$ eV, matches well the peak of the expected neutrino flux.

3. SENSITIVITY TO POINT-LIKE SOURCES

The neutrino search at the Pierre Auger Observatory is limited to highly inclined showers, with zenith angles between 90° and 96° in the ES analysis, and between 75° and 90° in the DG analysis. Thus, at each instant, neutrinos can be detected only from a specific portion of the sky corresponding to these zenith angle ranges. A point-like source of declination δ and right ascension α (equatorial coordinates) is seen at our latitude ($\lambda = -35.2^\circ$), at a given sidereal time t , with a zenith angle $\theta(t)$

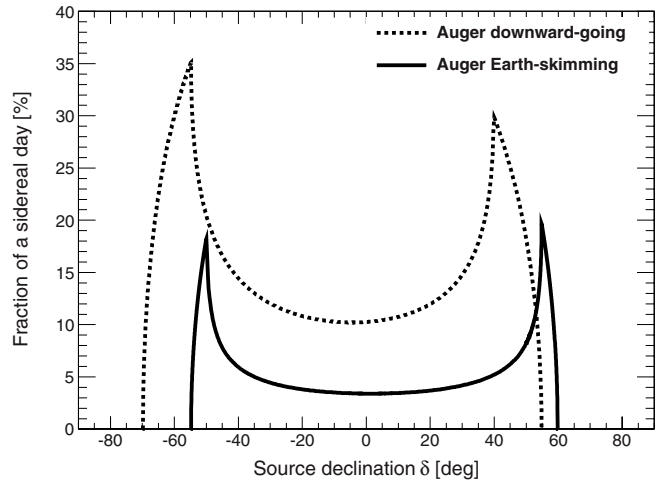


Figure 3. Fraction of a sidereal day having a point-like source at declination δ detectable by the Pierre Auger Observatory with the Earth-skimming and downward-going neutrino selection.

given by

$$\cos \theta(t) = \sin \lambda \sin \delta + \cos \lambda \cos \delta \sin(2\pi t/T - \alpha), \quad (2)$$

where T is the duration of one sidereal day. From Equation (2), the fraction of a sidereal day during which a source is detectable (i.e., within the zenith angle ranges for the ES and DG analyses) is shown in Figure 3; it depends only on the source declination. The SD of the Pierre Auger Observatory is sensitive to point-like sources of neutrinos over a broad declination range spanning north of $\delta \sim -65^\circ$ and south of $\delta \sim 55^\circ$. The regions of the sky close to the Northern ($\delta = 90^\circ$) and Southern ($\delta = -90^\circ$) Terrestrial Poles are not accessible by this analysis. As an example, Centaurus A ($\delta \sim -43^\circ$) is observed $\sim 7\%$ ($\sim 15\%$) of one sidereal day in the range of zenith angles corresponding to the ES (DG) search. The peaks in Figure 3 are a consequence of the relatively smaller rate of variation of the zenith angle with time for directions near the edges of the range accessible to this analysis.

The exposure of the SD as a function of the neutrino energy and of the source position in the sky, $\mathcal{E}(E_\nu, \delta)$, is evaluated by folding the SD aperture with the neutrino interaction probability and the selection efficiency for each neutrino channel. The procedure is identical to that used for the calculation of the exposure for a diffuse flux of UHE ν s (Abraham et al. 2009; Abreu et al. 2011a; Guardincerri et al. 2011), with the exception of the solid angle integration over the sky. The integration over the blind search time period takes into account the growth of the SD array during its construction phase and dead times of individual stations. For example, the exposure for the DG analysis is given by

$$\mathcal{E}(E_\nu, \delta) = \frac{1}{m} \sum_i \left[\omega_i \sigma_i(E_\nu) \int \int \int \cos \theta(t) \varepsilon_i(\mathbf{r}, E_\nu, \theta(t), D, t) dA dD dt \right], \quad (3)$$

where the integration is performed over the area A of the SD, the interaction depth D of the neutrino, and the search period. In Equation (3), m is the mass of a nucleon, $\sigma_i(E_\nu)$ is the neutrino-nucleon cross-section (Cooper-Sarkar & Sarkar 2008), and ε_i

is the neutrino selection efficiency, with the sum running over the three neutrino flavors ($\omega_i = 1$, corresponding to a 1:1:1 flavor ratio) and over the neutrino charged and neutral current interactions. The dependence of ε on several parameters (the point of impact at ground of the shower core, r , the neutrino interaction depth, its energy and zenith angle, and time) is also explicitly included in Equation (3). The dependence of the exposure on the source declination comes through $\theta(t)$ as obtained from Equation (2). When integrating over time, only those periods when the source is within the zenith angle range of the neutrino selection are considered. The exposure for ES neutrinos is derived analogously to Equation (3).

Changes in the detector configuration during data taking, due to the dead times of the SD stations, and to the increase of the array size during the construction phase, may introduce a dependence of the exposure on the right ascension. In particular, fluctuations in the number of stations cause a small diurnal variation, but this effect is only apparent in solar time. When averaged over a large number of sidereal days, as in this analysis, the modulation in right ascension caused by this effect is less than 1% (Abreu et al. 2011b). For this reason, the dependence of the exposure on α has been neglected in the evaluation of the upper limits.

Due to the finite resolution of the SD on the reconstruction of the variables used in the selection of neutrino-induced showers, events close to the edges of the zenith angle range for the neutrino selection may be wrongly rejected (or wrongly accepted). In the exposure as given in Equation (3) we account for this effect by evaluating the selection efficiency ε through Monte Carlo simulations.

Several other sources of systematic uncertainties on the exposure have been investigated (Abraham et al. 2009; Abreu et al. 2011a). For the DG analysis, the major contributions in terms of deviation from a reference exposure come from the knowledge of neutrino-induced shower simulations (+9%, -33%), of the neutrino cross-section ($\pm 7\%$), and of the topography ($\pm 6\%$). Only uncertainties compatible with the conventional NLO DGLAP formalism of ν cross-section calculation—see Cooper-Sarkar & Sarkar (2008) for details—have been considered. We have not accounted for gluon saturation models that would give rise to considerable smaller ν cross-sections (as small as a factor ~ 2 at 10^{18} eV; Henley & Jalilian-Marian 2006; Armesto et al. 2008), and hence to a larger systematic uncertainty than the one quoted here. For the ES analysis, the systematic uncertainties are dominated by the tau energy losses (+25%, -10%), the shower simulations (+20%, -5%), and the topography (+18%, 0%).

4. LIMITS ON THE FLUX OF UHE NEUTRINOS FROM POINT-LIKE SOURCES

The expected number of neutrino events in an energy range $[E_{\min}, E_{\max}]$ from a point-like source located at a declination δ is given by

$$N_{\text{expected}}^{\text{pointsource}}(\delta) = \int_{E_{\min}}^{E_{\max}} F(E_\nu) \mathcal{E}(E_\nu, \delta) dE_\nu, \quad (4)$$

where $F(E_\nu)$ is the flux of UHE ν s from the source. No candidate events were selected using the ES and DG analyses. Under the conservative assumption of zero background, a 90% CL upper limit on the neutrino flux from point-like sources is derived. To set the upper limit, a differential flux $F(E_\nu) = k_{\text{PS}}(\delta) \cdot E_\nu^{-2}$ was assumed, as well as a 1:1:1 neutrino flavor ratio. Systematic

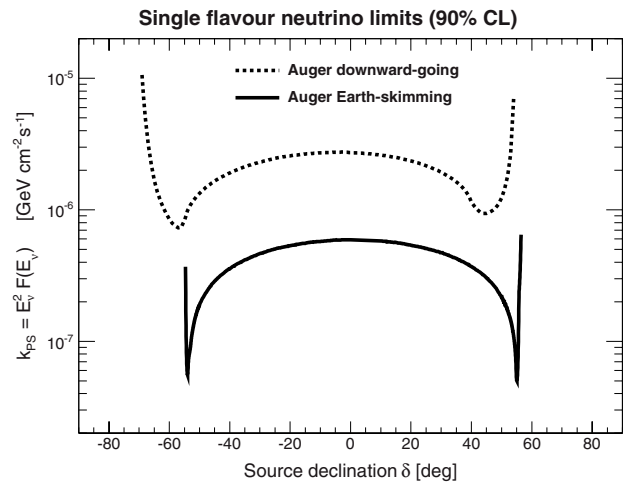


Figure 4. Upper limits at 90% CL on a single flavor E_ν^{-2} flux from a specific point-like source as a function of the source declination. The bounds from the Earth-skimming and downward-going neutrino analyses hold for a neutrino energy range 10^{17} – 10^{20} eV (see text for details).

uncertainties on the exposure were calculated using the semi-Bayesian approach described above in Section 2.

In Figure 4, the 90% CL upper limits on k_{PS} derived from the ES and DG analyses are shown as a function of source declination. Limits for k_{PS} at the level of $\approx 5 \times 10^{-7}$ and 2.5×10^{-6} $\text{GeV cm}^{-2} \text{s}^{-1}$ were obtained over a broad range of declinations from the searches for ES and DG neutrinos, respectively.

The shape of the declination-dependent upper limits is largely determined by the fraction of time a source is within the field of view of the ES or DG analyses (cf. Figure 3), and, to a lesser extent, by the zenith angle dependence of the exposure.

The upper limits are derived for neutrinos in the energy range 1.6×10^{17} eV– 2.0×10^{19} eV for the ES analysis, and in the energy range 1×10^{17} eV– 1×10^{20} eV for the DG analysis, with a negligible dependence of these energy intervals on the source declination. These are the best limits around 1 EeV.

The IceCube Neutrino Observatory and the Antares Neutrino Telescope have also searched for UHE ν s from point-like sources (Abbasi et al. 2011b and Adrián-Martínez et al. 2011, respectively). The bounds obtained by these two experiments apply to energies below the Auger energy range.

Limits for the particular case of the active galaxy Centaurus A, a potential source of UHECRs, are shown in Figure 5, together with constraints from other experiments. The predicted fluxes for two theoretical models of UHE ν production—in the jets (Cuoco & Hannestad 2008) and close to the core of Centaurus A (Kachelriess et al. 2009)—are also shown for comparison. The expected number of events in our blind search samples for a flux like in Cuoco & Hannestad (2008) is about 0.1 and 0.02 for the ES and DG selection, respectively, the expected number for Kachelriess et al. (2009) being one order of magnitude smaller.

5. SUMMARY

The sensitivity of the Pierre Auger Observatory to point-like sources of neutrinos with UHE has been obtained. Highly inclined EAS produced by the interaction of neutrinos of all flavors in the atmosphere and by the decay of tau leptons originating from tau neutrino interactions in the Earth's crust were searched for, and differentiated from the background of standard UHECRs thanks to the distinctive time structure of the signals measured by the SD array. The search for neutrinos was

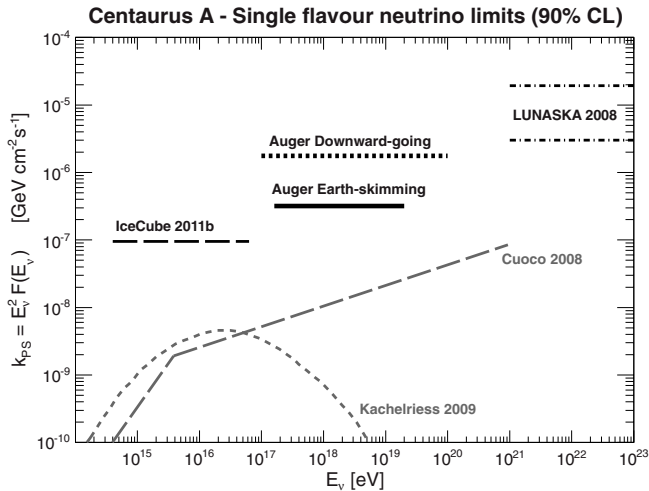


Figure 5. Upper limits at 90% CL on a single flavor E_{ν}^{-2} flux from the active galaxy Centaurus A from the Earth-skimming and downward-going neutrino analyses, together with bounds from the IceCube Neutrino Observatory (Abbasi et al. 2011b) and LUNASKA (James et al. 2011). The predictions for two models of UHE ν production—in the jets (Cuoco & Hannestad 2008), and close to the core of Centaurus A (Kachelriess et al. 2009)—are also shown.

performed over a broad range of declination, north of $\sim -65^{\circ}$ and south of $\sim 55^{\circ}$, and for neutrino energies between 10^{17} eV and 10^{20} eV.

No neutrino candidates were found in data collected through 2010 May 31, and an improved upper limit on the diffuse flux of tau neutrinos was correspondingly placed. Also, the exposure for neutrino fluxes from point-like sources was evaluated as a function of source declination. Upper limits at 90% CL for neutrino fluxes from point-like sources were established, which are currently the most stringent at energies around and above 1 EeV in a large fraction of the sky spanning more than 100° in declination.

The successful installation, commissioning, and operation of the Pierre Auger Observatory would not have been possible without the strong commitment and effort from the technical and administrative staff in Malargüe.

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