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Updated results on Ultra-High Energy Neutrinos with the Pierre Auger Observatory

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The Pierre Auger Observatory is the world's largest cosmic-ray observatory. Updated results on the search for ultra-high energy (UHE) neutrinos with Auger data are presented. The search method and the detection channels are introduced and neutrino flux limits are given in the energy range 0.1 – 100 EeV. Finally the sensitivity to point-like sources of ultra-high energy neutrinos over a broad range of declinations is demonstrated.

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1. Introduction

All the scenarios invoked to explain the origin of ultra-high energy cosmic rays (UHECR) predict, along with the nuclear component, the presence of primary neutrinos. The expected flux depends primarily on the chemical composition of the primaries and on the nature, cosmological evolution and spatial distribution of astrophysical sources [1, 2, 3, 4].

A guaranteed flux of UHE neutrinos is expected from the interaction of UHECRs with the cosmic background radiation. In particular, cosmic rays above $\sim 5 \times 10^{19}$ eV may exceed the threshold for resonant $\Delta+$ particle production (protons), via the so-called Greisen-Zatsepin-Kuz'min (GZK) effect [5], or may undergo photo-disintegration (heavier nuclei). These unstable secondaries decay into pions and subsequently into photons and neutrinos. Neutrinos point back to the sites of production, revealing details of the sources and of their acceleration mechanisms. In particular they can traverse large amounts of matter without interacting and they could probe cosmological distances, providing a complementary view of the UHECR origin.

Ultra-high energy neutrinos of all flavors can induce extensive atmospheric showers that could be detected by the surface detector of the Pierre Auger Observatory [6] in the EeV range and above. Identification of neutrinos is possible, by observing deviations of the recorded data from expectations for showers induced by nuclear primaries.

The Pierre Auger Observatory, the world's largest cosmic-ray observatory, has a unique potential for this kind of search. The Observatory is taking data stably since January 2004. It consists of a surface detector (SD) [7] with 1660 water-Cherenkov stations extending over 3000 km^2 on a triangular grid (1.5 km spacing), and a fluorescence detector (FD) [8] overlooking the array with 27 fluorescence telescopes deployed at four sites,

So far no neutrino observation has been claimed, but stringent limits on the diffuse flux of primary neutrinos in the EeV energy range and above have been placed and published in Refs. [9, 10, 11, 12, 13]. These limits put severe constraints on non-acceleration models [14] and favor astrophysical scenarios for the origin of the highest energy cosmic particles.

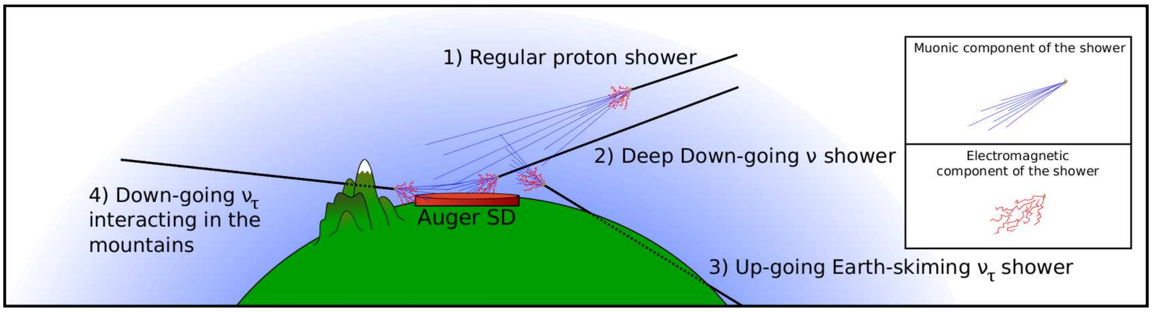

Figure 1: Sketch of the different types of inclined showers that can be detected by the surface detector of the Pierre Auger Observatory. 1) regular showers induced by nuclear primaries, 2) and 4) downward-going showers induced by neutrinos, and 3) upward-going neutrinos interacting in the Earth's crust. From Ref. [13].

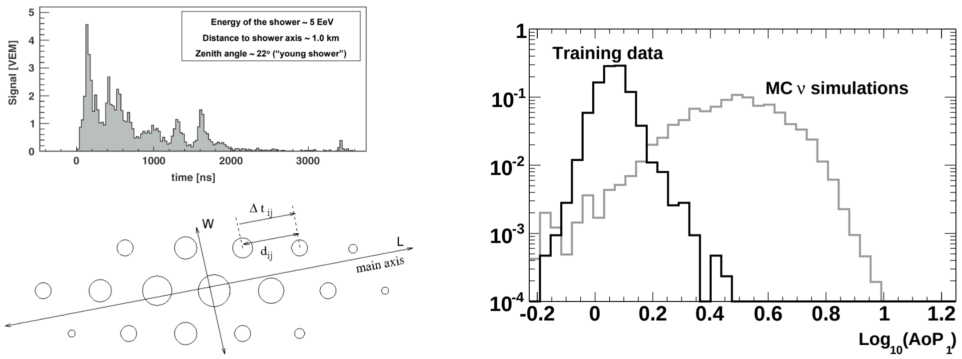

Figure 2: Left panel: signal expected in a surface detector station from a young shower (top). Footprint of an inclined shower on stations of the surface detector array (bottom), the radii of circles being proportional to their recorded signals. Right panel: logarithm of the ratio Area over Peak for the signal in the first station in training data (black histogram) and in simulated neutrino events (gray histo gram) [13].

2. Detection channels at the Pierre Auger Observatory

Fig. 1 is a pictorial representation of the different types of inclined showers that can be detected by the surface detector of the Pierre Auger Observatory. Along with 1) regular showers, 2) downward-going (DG) neutrino events are showers induced by neutrinos of all flavors which interact in the atmosphere via either charged or neutral current interaction. In particular 4) tau neutrinos interacting in the mountains, produce a downward-going tau lepton that can decay close to the detector, initiating a shower. Tau neutrinos can also interact in the Earth's crust producing, via charged current interactions, a tau lepton which in turn can emerge and decay in the atmosphere, giving 3) an Earth-skimming upward-going (UG) event.

In inclined hadronic showers only a tight front of muons reaches the ground after traversing large atmospheric depths. It is detected within a few tens of nanoseconds (old shower). For the case of a deeply interacting neutrino event, the early region of the shower front still contains an electromagnetic component, giving a signal spread over hundreds of nanoseconds (young shower), similar to the one shown in Fig. 2 top left. Thus the observation of a significant electromagnetic component at ground level in inclined events is the key to separating neutrino candidates from the large background of showers induced by proton or nuclear primaries.

2.1 Earth-skimming event search

Events with zenith angles between 90° and 95° and with detector stations passing the time-over-threshold (ToT) trigger [7] are selected. A fraction of ToT stations larger than 60% is required to select showers induced by neutrinos. A cut on the ratio of the area of the detected signal to its peak value (AoP) is also applied in order to reject muon triggers. The data sample is then searched for events with an elongated footprint, defined by a large ratio of track length over track width (Fig. 2 bottom left), and with a propagation speed at ground close to the speed of light [9, 10]. The search is performed on data from January 2004 through May 2010, corresponding to about 3.5 years of full SD exposure [12].

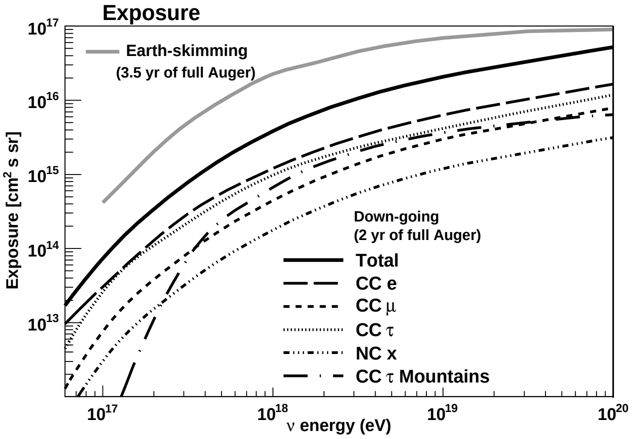

Figure 3: Exposure of the surface detector to upward-going (Earth-skimming) and downward-going neutrino induced showers (equivalent to 3.5 yr and 2 yr of full Auger SD, respectively). From Ref. [13].

2.2 Down-going event search

The downward-going candidates can be searched for in a broader range of zenith angles, between 75° and 90°. Observables characterizing young showers are identified based on recorded traces. The Fisher discriminant method [15] is used to optimize the background rejection based on the combination of 10 variables: the AoPs of the first four triggered stations, their squares, their product, and an early-late shower asymmetry parameter. In Fig. 2 right panel, the logarithm of the Area over Peak ratio of the first station is plotted for training data (black histogram) and for simulated neutrino events (gray histogram). A sub-sample of data, corresponding to about 1.2 years of the full surface array, is used for training the method. The data sample for a blind search corresponds to about 2 years of full SD exposure [11].

3. Upper limits on diffuse neutrino flux

The exposure for the UG and DG channels is shown in Fig. 3. Different strategies were applied for optimizing the calculation for each of the channels with respect to the effective surface array aperture, to be folded with the ν interaction probability and the ν identification efficiency. For details on the calculations see Ref. [10, 11, 13].

The exposure for the Earth-skimming channel is higher due to the larger data sample and due to the larger density of the Earth's crust where ν interactions can occur, compared to the atmosphere. The difference is partially compensated by the sensitivity of the downward-going channel to all the neutrino flavors as well as the broader angular range of the search. In general, the neutrino identification efficiencies depend on many parameters like the energy of the primary neutrino (DG) or tau lepton (UG), the neutrino flavor and type of interaction (DG), the depth in the atmosphere of the ν interaction (DG) or the altitude above ground of the tau decay point (UG). The efficiencies

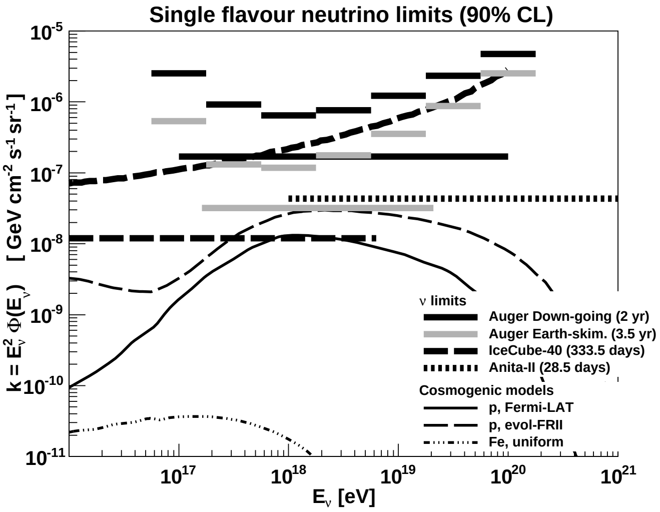

Figure 4: Integrated and differential upper limits (at 90% C.L.) on the normalization of the diffuse flux of UHE neutrinos for the Earth-skimming and downward-going channels (search period equivalent to 3.5 and 2 years of full Auger exposure, respectively). From Ref. [13]

are estimated through Monte Carlo simulations of the first neutrino interaction, the development of the shower in the atmosphere and the surface detector response.

The dominant sources of systematic uncertainties for DG neutrinos come from the hadronic models and the neutrino induced shower simulations (+9%, -33%), and from the neutrino interaction cross-section (±7%) [11]. For the UG channel, they are dominated by the tau energy losses (+25%, -10%), the shower simulations (+20%, -5%) and the ground topography (+18%) [10, 12].

Assuming a differential spectrum $\Phi\,(E_\nu\,) = dN_\nu\,/dE_\nu = k \times E_\nu^{-2}$ [GeV^{-1} cm^{-2} s^{-1} sr^{-1}], the integrated limit on the normalization of the diffuse neutrino flux is $k < 3.2 \times 10^{-8}$ ($k < 1.7 \times 10^{-7}$) [GeV cm^{-2} s^{-1} sr^{-1}] for the upward-going (downward-going) channel, for no candidates and no expected background events. In Fig. 4 the integrated limits are shown along with predictions of different theoretical models of UHE neutrino production. Limits are shown also in differential form, assuming that the diffuse neutrino flux behaves as E^{-2} in energy bins of 0.5 in $\log_{10} E_\nu$, and no background events. The achieved sensitivity is maximum in the energy range $0.16 - 20$ EeV ($0.1 - 100$ EeV) for UG (DG) neutrinos, see Ref. [11, 12, 13].

3.1 Combined limits

Updated limits on the UHE neutrino flux for the UG, DG channels have recently been published in [16]. The analysis is extended using Auger data up to 31 December 2012, corresponding to almost six years of full Auger SD exposure. Moreover, for the first time, the limits have been combined. Individual searches have been performed in three different zenith angle ranges ($> 90^\circ$ for UG, $75^\circ - 90^\circ$ for DG-high and $60^\circ - 75^\circ$ for DG-low). The relative contributions of the UG, DG-high and DG-low channels to the total expected event rate assuming a flux behaving with neutrino energy as E_ν^{-2} , are 0.73, 0.23 and 0.04, respectively. For details on the exposure calculation and treatment of systematic errors, see Ref. [16].

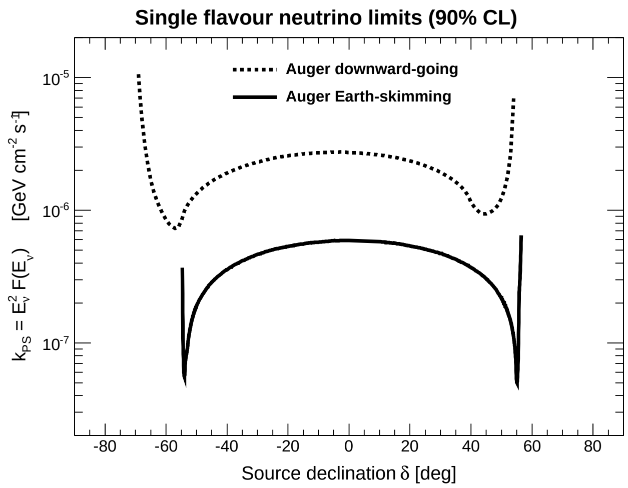

Figure 5: Upper limits on single flavor neutrino flux from a point-like source as a function of the source declination. The bounds are given at 90% confidence level. From Ref. [12]

The combined Auger limit is $k < 1.3 \times 10^{-8}$ [GeV cm^{-2} s^{-1} sr^{-1}] over the energy interval $0.1 - 100$ EeV. This limit is below the Waxman-Bahcall bound on neutrino production in optically thin sources [17] and is beginning to constrain model predictions, for instance those assuming pure proton primaries at the source [3]. A power-law extrapolation (following E_ν^{-2}) to ultra-high energies of a neutrino flux compatible with the observation of two candidates at PeV energies reported by the IceCube Collaboration [18] is excluded at 90% CL.

4. Sensitivity to point sources

The Pierre Auger Observatory is sensitive to UHE neutrinos from astrophysical point-like sources over a broad range of declinations. The absence of candidates in the searches for diffuse neutrino fluxes described in Sec. 3 allows us to place limits on the neutrino fluxes coming from sources in the surface detector field of view.

Assuming a differential spectrum $\Phi\,(E_\nu) = k_{PS}(\delta) \times E_\nu^{-2}$, the 90% CL upper limits on neutrino flux from a point-like source are derived for the upward-going and downward-going analyses as a function of the source declination δ.

The Auger SD covers declinations north of -65° and south of $+55^\circ$. The polar regions are not accessible by these analyses. The sensitivity to neutrinos originated at a given point source is a function of the local sidereal time, and the shape of the upper limits is mainly determined by the amount of time a source lies within the field of view for the UG or DG analyses.

Limits for k_{PS} are obtained at the level of 5×10^{-7} (2.5×10^{-6}) [GeV cm^{-2} s^{-1}] for the searches for UG (DG) neutrinos, over a broad plateau spanning $\sim 100^\circ$ in declination. The upper limits are derived in the same energy ranges as in Sec. 3, with a negligible dependence on source declination. The derived limits, shown in Fig. 5, are currently the best published in the EeV region, see Ref. [12].

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References

[1] G. Gelmini, O. Kalashev, and D. V. Semikoz, *JCAP* **11** (2007) 002

[2] V.S. Berezinsky et al. *Phys. Lett. B* **28** (1969) 423

[3] M. Ahlers et al., *Astropart. Phys.* **34** (2010) 106

[4] K. Kotera, D. Allard, A. V. Olinto *JCAP* **10** (2010) 013

[5] K. Greisen, *Phys. Rev. Lett.* **16** (1966) 748. G. T. Zatsepin and V. A. Kuz'min, *Sov. Phys. JETP Lett.* **4** (1966) 78

[6] Pierre Auger Collaboration [J. Abraham et al.], *Nucl. Instrum. Meth. A* **523** (2004) 50

[7] Pierre Auger Collaboration [J. Abraham et al.], *Nucl. Instrum. Meth. A* **613** (2010) 29

[8] Pierre Auger Collaboration [J. Abraham et al.], *Nucl. Instrum. Meth. A* **620** (2100) 227

[9] Pierre Auger Collaboration [J. Abraham et al.], *Phys. Rev. Lett.* **100** (2008) 211101

[10] Pierre Auger Collaboration [J. Abraham et al.], *Phys. Rev. D* **79** (2009) 102001

[11] Pierre Auger Collaboration [P. Abreu et al.], *Phys. Rev. D* **84** (2011) 122005

[12] Pierre Auger Collaboration [P. Abreu et al.], *Astrophys. J. Lett.* **755** (2012) L4

[13] Pierre Auger Collaboration [P. Abreu et al.], *Adv. in High Energy Phys.* **2013** (2013) 708680

[14] P. Bhattacharjee and G. Sigl, *Phys. Rep.* **327** (2000) 109

[15] R. Fisher, *Annals of Eugenics* **7** (1936) 179

[16] P. Pieroni for the Pierre Auger Collaboration, 33^{rd} ICRC, Rio de Janeiro, Brazil (2-9 July 2013)

[17] E. Waxman and J.N. Bahcall, *Phys. Rev. D* **59** (1998) 023002; *Phys. Rev. D* **64** (2001) 023002

[18] IceCube Collaboration, *Phys. Rev. Lett.* **111** (2013) 021103