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The Search for Ultra-High Energy Neutrinos through Highly Inclined Air Showers in the Pierre Auger Observatory

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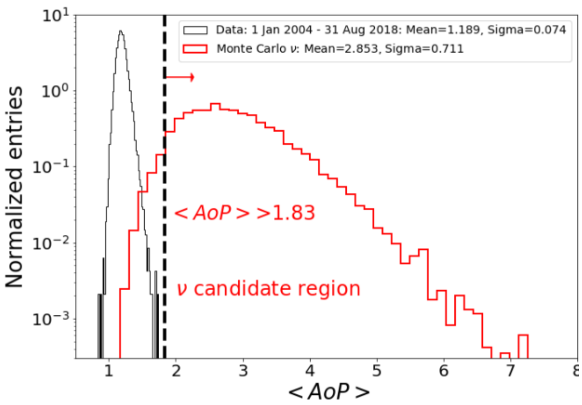
Abstract. The Surface Detector of the Pierre Auger Observatory for the detection of ultra-high energy cosmic rays, an array of 1600 water-Cherenkov stations in a triangular grid with 1500 m separation between stations, has also the capability to detect neutrinos with energy above 10^{17}eV. The identification, through the special characteristics of highly inclined showers, is efficiently performed for neutrinos of all flavours interacting deep in the atmosphere at large zenith angles as well as for τ-neutrinos skimming the Earth crust. In this talk I review the status of the neutrino search at the Observatory using about 15 years of data. Restrictive upper bounds on the neutrino flux from diffuse sources and from point-like steady sources were stablished, placing strong constraints on several models of neutrino production at EeV energies and on the properties of the sources of ultra-high-energy cosmic rays. Unrivaled sensitivity in searches for transient sources has been also achieved.

1. Introduction

The Pierre Auger Observatory is an enormous cosmic ray detector placed in Argentina, close to the city of Malargüe in Mendoza province. Extensive air showers induced by cosmic rays are captured by different techniques using the two main detectors of the observatory [1]. The Surface Detector (SD) is a 3000 km^2 array of 1600 water-Cherenkov stations in a triangular grid with 1.5 km separation. Lower energy showers are detected with 60 more stations forming a denser 750 separation grid. The SD stations scan the shower particles at ground where the signals left by the particles crossing the tanks are digitized. The Fluorescence Detector (FD) has 27 telescopes distributed in 4 sites overlooking the array. The FD observes the longitudinal development of the shower in the atmosphere which is used for composition studies. Importantly, FD is also employed for energy callibration of SD events. The upgrade of the observatory AugerPrime, now in the final phase of construction, includes scintillators plates over the tanks to improve the capability to distinguish the electromagnetic (EM) from the muonic component of the shower for composition studies. The upgrade also includes the installation of anntenas to detect radio-waves from inclined showers, and underground muon detectors.

Accumulating data from the last 15 years, the Auger Observatory has achieved outstanding results allowing to answer the fundamental questions on the origin and nature of ultra-high energy (UHE) cosmic rays. The observed spectrum features: low energy ankle, second knee, ankle, and a new instep feature, just before the suppression of the flux at the highest energies [2] constitute a detailed picture of the cosmic ray spectrum in 4 energy decades. The depth of shower maximum and its fluctuations indicates a change in composition from light to heavy nuclei as increasing the energy above the ankle [3]. The dipolar anisotropy in arrival directions found in data suggest an extragalactic origin of the UHE cosmic rays [4]. Auger is also providing intringuing results on hadronic physics. The number of muons in showers is found to be significantly higher than expected. As the measured fluctuations are not in disagreement with models, the muon deficit of the models should be related to an acumulative effect during the shower development and not at the first interaction [5].

Neutrinos can generate extensive air showers at UHE as do cosmic rays [6]. The Pierre Auger Observatory has the capability to identify the events induced by neutrinos by looking for deep showers at large zenith angles [7]. Most of the sensitivity in the EeV range come from Earth-skimming tau-neutrinos [8]. Since 2008 the Auger Observatory has been routinely searching for neutrino events [9-15]. UHE neutrinos are expected to be produced along with UHE cosmic rays in their sources (astrophysical neutrinos) and in the propagation of cosmic rays through the cosmic microwave background (cosmogenic neutrinos). The precise flux depends on many aspects: cosmic ray composition, injection spectrum, maximum energy achived, and cosmological model. The flux of cosmogenic neutrinos provide an independent probe of the source properties and of the origin of the spectrum suppression at the highest energies.



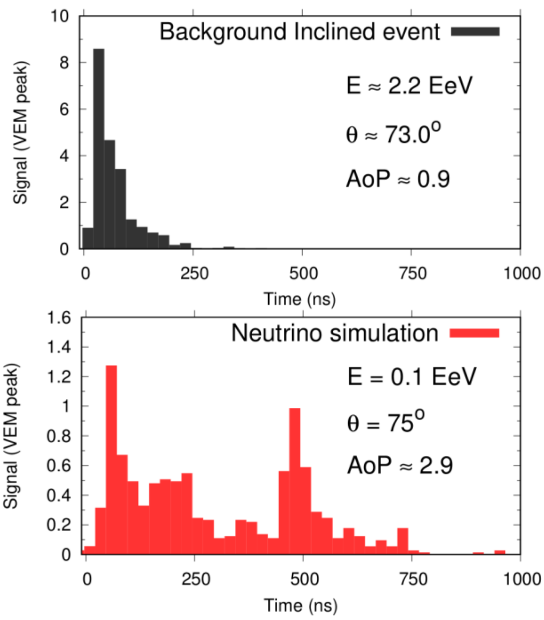


Figure 1. Top-left: Average area over peak (AoP) distribution of events for the selection of Earth-Skimming neutrino candidates. Time profile of the signal for a background inclined cosmic-ray real event (top-right) and for a simulated neutrino-induced inclined air shower close to the detector (bottom-right) [14].

2. Neutrino detection, exposures and limits

Neutrinos induced showers can be distinguished from the background by looking in the inclined direction with respect to the vertical to ground. For large zenith angles, as protons and nuclei initiate showers high in the atmosphere, the shower particles are atenuated and at the ground contains mainly muons with a small EM part. However, neutrinos can initiate showers much close to the detector where they look like young vertical showers with a large EM component. The SD can identify down-going (DG) neutrinos of any flavor interacting in the atmosphere and

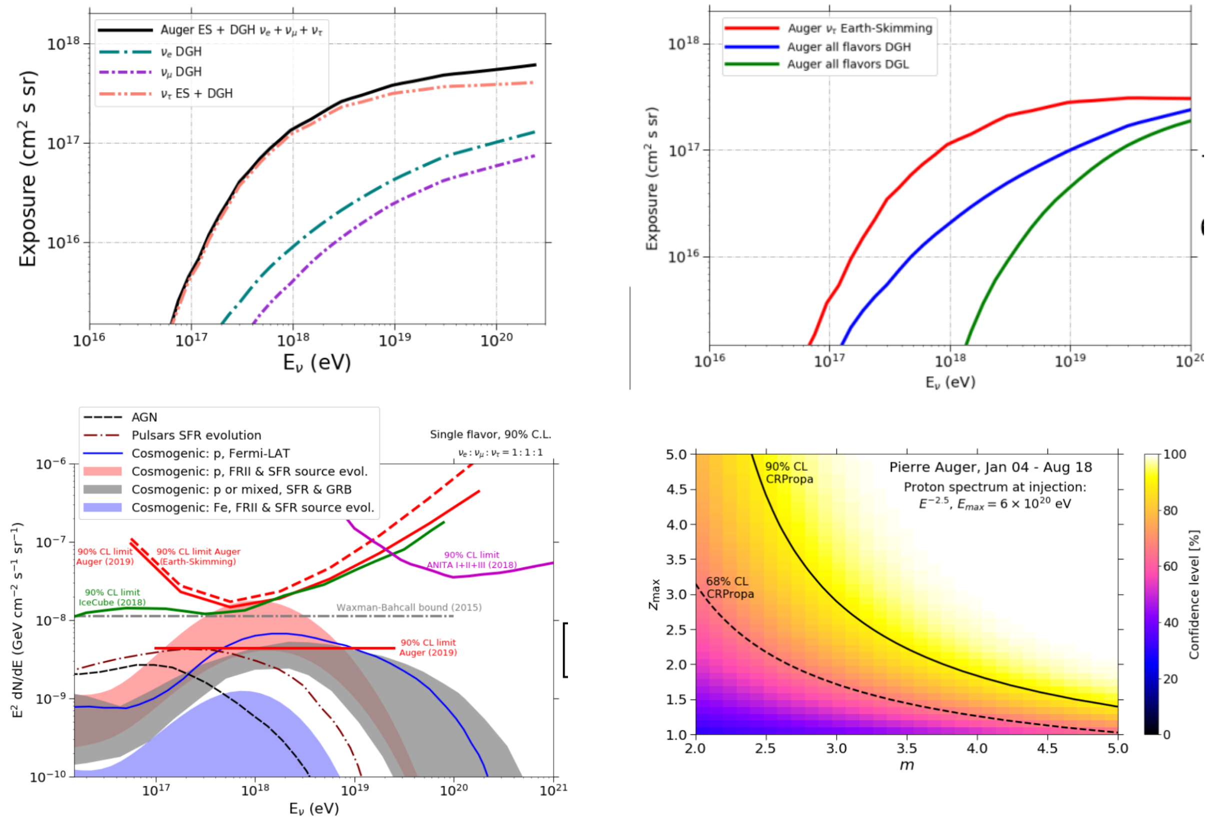


Figure 2. Top: Exposure of the SD (1 January 200431 August 2018) to UHE neutrinos for different detection channels and neutrino flavors (see text for details). Bottom-left: Upper limit (90% C.L.) to the diffuse flux of UHE neutrinos (red-flat line. See text for more details). Bottom-Right: Constraints on UHECR source evolution models parameterized as $(1 + z)^m$ for sources distributed homogeneously up to a maximum redshift z_{max} [14]

Earth-skimming (ES) tau-neutrinos near the horizontal direction interacting in the Earth-crust. In the ES channel, the tau lepton from the charge-current deep-inelastic interaction, leaves the Earth and immediatly decays in the atmosphere with the shower particles deviating laterally from the axis and hitting the ground. To identify neutrinos in SD, inclined showers are selected by the elongated footprint and the signal aparent speed closed to the speed of light. From the inclined showers the deep ones are chosen with a large Area-over-Peak (AoP) value typically reflecting the presence of a sizeable EM component in the showers. The background due to cosmic rays gives narrower signals with small AoP (see Fig. 1). In the ES channel the average value of AoP of the stations is considered as the only criteria to select young showers. The cut $\langle \text{AoP} \rangle > 1.83$ guarantee a 95 % efficiency over the inclined selection of Monte Carlo neutrinos as can be see in Fig.1. For DG neutrino search a multivariate Fisher analysis is applied.

The result of the search from january 2004 till august 2018 gives no neutrino candidate events for both DG and ES analysis of SD data.

2.1. Diffuse fluxes

For a given neutrino flux the number of expected events in SD is obtained by convolution with the exposure. For DG neutrinos the exposure is the integral of the detection efficiency times the neutrino-nucleon cross-section. The efficiency depends on the neutrino flavor, the type of

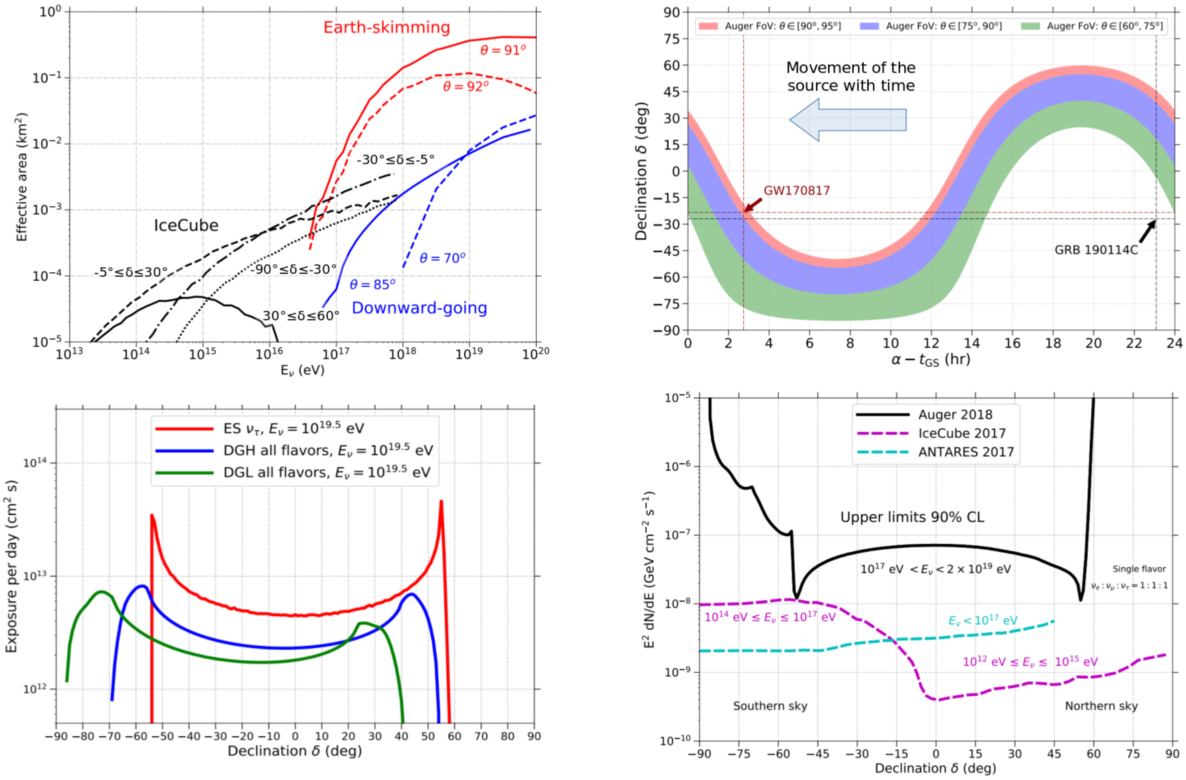


Figure 3. Top-left: Instantaneous effective areas for different neutrino detection channels and selected zenith angles (θ) compared to those of IceCube. Top-right: Instantaneous field of view of SD for different neutrino detection channels as a function of the hour angle. Bottom-left: Average exposure per day for different detection channels for the period 1 May 2008 to 31 Aug 2018. Bottom-right: Upper limits (1 Jan 200431 Aug 2018) at 90% C.L. on the single flavour point-like flux of UHE neutrinos as a function of the source declination δ. Limits from IceCube (2008-2015) and ANTARES (2007-2015) are also shown [15]

interaction, energy, arrival direction, the impact point of the shower core on the ground, the depth in the atmosphere where the neutrino interacts, and on the time. For the ES channel, the calculation of the exposure is even more elaborated as it also includes the probability of having the tau-lepton emerging from the Earth and the tau-decay probability.

The SD is mostly sensitive to tau-neutrinos through the ES channel (see the exposures in Fig. 2). In fact, in the case of equal fluxes of neutrino flavors with E^{-2} spectrum, 86 % of the events will be due to tau neutrinos, most of them through the ES channel,

Having zero neutrino candidates, the 90 % C.L. limit to the diffuse flux of UHE neutrinos is calculated assuming equal fluxes of neutrino flavors at Earth with E^{-2} spectrum. The limit is shown as the red flat line in Fig. 2. The bounds from IceCube and ANITA detectors are shown for comparison. Also shown are a neutrino flux from AGN and various representative models of cosmogenic neutrinos with different composition, injection spectra and evolution of the sources. The limit already constraints cosmogenic neutrino scenarios where the sources have strong evolution with redshift and accelerate only protons.

A more detailed study of the constraints to the parameter space for the cosmogenic models acelerating only protons is performed. The non observation of neutrino events in data disfavor a significant region of the parameter space, above the solid black curve in the plot of the redshift evolution of the sources parameter m and the maximum redshift (lower-right panel in Fig 2).

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2.2. Point like transient sources

With the SD it is also possible to look for neutrinos from transient sources in different directions of the sky. The field of view (FoV) of the different neutrino search channels are shown in Fig.3 (upper-right panel) as they correspond to different zenith angles. The SD covers a broad declination range between $-85°$ and $60°$. Notice in figure that the LIGO/Virgo GW170817 event [16] was in the FoV just on time.

Being sensitive to point-like sources, the absence of candidates is converted to an upper limit. This limit is calculated using the directional exposure. The sensitivity in each directions is evaluated in terms of the effective area (upper-left panel in Fig. 3) which depends on the neutrino flavor, interaction and search channel, and also on the position of the source. The effective area is maximum when the source is in the ES FoV (red curves). The rate of detected events is obtained by integration of the efective area times the neutrino flux.

2.3. Point like steady sources

For the case of steady sorces the effective are is integrated over a given time interval to obtain the exposure. This is shown in the lower-left plot of Fig. 3, where the largest exposure is found for sources at declination between $-55°$ and $55°$ because they remain longest in the ES FoV.

Similarly as for the case of the diffuse flux, upper limits are obtained when zero event candidates are found. There is a good sensitivity at EeV energies in a broad range in declination (see lower-right plot in Fig. 3)). The best limits correspond to sources at declination $\delta = -53°$ and $\delta = 55°$ where they spend more time in the ES FoV (see Fig. 3).

3. Conclusions

The Surface Detector of the Pierre Auger Observatory is a highly efficient neutrino detector. As no neutrino events were found analyzing data up to August 2018, very restrictive limits to the UHE neutrino flux in the EeV range has been established. The observatory is also sensitive to steady sources of EeV neutrinos in the Northern Hemisphere and to transient sources if they are in the field of view of the ES channel. This have permitted to search for neutrinos in coincidence with GW events, which makes the Auger Observatory a key detector in multi-messenger astronomy at EeV energies [17].

References

[1] Aab A et al [The Pierre Auger Collaboration] 2015 *Nucl. Instrum. Meth.* A **798** 172
[2] Novotny V on behalf of the Pierre Auger Collaboration 2021 *Proc. 37th Int. Cosmic Ray Conf.* PoS(ICRC2021)
[3] Yuskov A on behalf of the Pierre Auger Collaboration 2019 *Proc. 36th Int. Cosmic Ray Conf.* PoS(ICRC2019)
[4] Menezes R on behalf of the Pierre Auger Collaboration 2021 *Proc. 37th Int. Cosmic Ray Conf.* PoS(ICRC2021)
[5] Aab A et al 2021 *Phys. Rev. Lett.* **126** 152002
[6] Berezinskii V S and Smirnov A Yu 1975 *Astrophysics and Space Science* **32** 461
[7] Capelle K S, Cronin J W, Parente G and Zas E 1998 *Astropart. Phys.* **8** 321
[8] Bertou X, Billoir P, Deligny O, Lachaud C and Letessier-Selvon 2002 *Astropart. Phys.* **17** 183
[9] Abraham J et al [Pierre Auger Collaboration] 2008 *Phys. Rev. Lett.* **100** 211101
[10] Abraham J et al [Pierre Auger Collaboration] 2009 *Phys. Rev.* D **79** 102001
[11] Abraham J et al [Pierre Auger Collaboration] 2011 *Phys. Rev.* D **84** 122005
[12] Abreu P et al [Pierre Auger Collaboration] 2012 *Astrophys. J. Lett.* **755** L4
[13] Aab A et al [Pierre Auger Collaboration] 2015 *Phys. Rev.* D **91** 092008
[14] Aab A et al [Pierre Auger Collaboration] 2019 *JCAP* **10** 022
[15] Aab A et al [Pierre Auger Collaboration] 2019 *JCAP* **11** 004
[16] Albert A et al [ANTARES, IceCube, Pierre Auger and LIGO Collaborations] 2017 *Astrophys. J.* **8850** L35
[17] Ruehl P on behalf of the Pierre Auger Collaboration 2021 *These proceedings*