Journal of Physics: Conference Series

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To cite this article: E Santos and Pierre Auger Collaboration 2019 *J. Phys.: Conf. Ser.* **1181** 012060

26th Extended European Cosmic Ray Symposium IOP Publishing
IOP Conf. Series: Journal of Physics: Conf. Series 1181 (2019) 012060 doi:10.1088/1742-6596/1181/1/012060

Searches for ultrahigh-energy neutrinos from gravitational wave events with the Pierre Auger Observatory

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Abstract. With the advent of the multi-messenger astronomy era, neutrinos open a unique window to the Universe allowing one to relate the most violent phenomena with the production and origin of the highest energy cosmic rays at distances beyond the GZK horizon. Neutrinos with $E > 0.1$ EeV of all flavors can be detected with the Surface Detector array of the Pierre Auger Observatory by means of their interaction in the atmosphere (downward-going ν) or in the Earth crust (Earth-skimming ν). The Pierre Auger Collaboration has searched for neutrino candidates in coincidence with gravitational wave events detected by LIGO/Virgo. Up to the present moment no neutrino candidates were found in any of these searches, which allows us to put competitive limits on the energy radiated in ultra-high energy neutrinos. The most stringent limits to the neutrino spectral fluence arise from the binary neutron star merger event GW170817 at a $D_s \sim 40$ Mpc. The non-detection of neutrinos from this event is compatible with the predictions of a short GRB observed at a large off-axis angle.

1. Introduction

The detection of the first gravitational wave transient GW150914, by the Advanced LIGO detectors, on September 14, 2015, at $09:50:45$ UTC, marked the beginning of a new era. Its signal matched Einstein's predictions of General Relativity for a gravitational wave with $E_{GW} = 3.0^{+0.5}_{-0.5}\, M_{\odot}c^2$ produced by the merger of a binary black hole system at a luminosity distance of $D_s = 410^{+160}_{-180}$ Mpc [1]. Since then, several other events were detected by the Advanced LIGO/Virgo observatories [2, 3, 4] motivating astronomical multi-messenger observations to detect any other counterparts of these events. Presently, the most exciting results come from the event GW170817, detected both by the Advanced LIGO and Advanced Virgo Observatories on August 17, 2017, at $12:41:04$ UTC. It was due to a binary neutron star inspiral in the host galaxy NGC 4993, just at $D_s = 40^{+8}_{-14}$ Mpc, which makes it the closest, most precisely localized and brightest event detected so far [5]. Only 1.7 s after the coalescence, the *Fermi*-GBM independently detected the short gamma-ray burst GRB 170817A associated to the merger. An unprecedented broadband follow-up carried out by tens of Collaborations worldwide resulted in the positive detection of several counterparts of the event GW170817 / GRB 170817A across the electromagnetic spectrum ranging from the radio to X-rays [4]. Additionally, several models predict that ultra-high energy cosmic rays and high-energy neutrinos could be produced in such mergers of compact objects [6, 7, 8]. If this is the case, neutrinos are the messengers by excellence of these interactions [9, 10]. Since they are neutral particles with extremely low cross-sections they can propagate through distances beyond the GZK horizon, while keeping their direction unaffected by the presence of matter and magnetic fields, allowing them to point back at their source.

Neutrinos of all flavors with $E > 0.1$ EeV can be detected by the Pierre Auger Observatory, located in the Argentinian province of Mendoza at ~ 1400 m a. s. l., ($X_{\text{ground}} = 880$ g cm^{-2}). The Pierre Auger Observatory uses a hybrid detection technique combining a Surface Detector (SD) array, which samples the lateral density of particles at the ground, with a Fluorescence Detector (FD), which measures the fluorescence light produced by the excitation of the nitrogen molecules in the atmosphere. The SD array covers an area of 3000 km^2 with 1600 water-Cherenkov stations disposed in a triangular grid of 1.5 km spacing, while the FD is composed by four buildings placed at the array periphery, housing 6 telescopes each [11].

In this paper, the results of the neutrino searches done by the Pierre Auger Observatory in coincidence with gravitational wave events are presented.

2. Neutrino detection with the Pierre Auger Observatory

Each water-Cherenkov station of the SD array consists of a cylindrical polyethylene tank of 3.6 m diameter and 1.2 m height filled with 12 000 liters of purified water, and it is equipped with three $9''$ photo-multiplier tubes (PMT) placed at the top. The signals of the PMTs are sampled by flash analogue to digital converters (FADC) with a frequency of 40 MHz [11]. These features make possible the detection of hadronic air showers with $E > 4$ EeV with zenith angles up to 80° [11, 12, 13].

Hadron primaries interact early in the atmosphere generating large numbers of secondary particles which, in order to be detected by the ground detectors, need to cross a mass overburden which grows with zenith angle as $X/\cos\theta$. This makes that the shower front of showers with $\theta > 60°$ is dominated by muons, as most of the electromagnetic component gets absorbed in the atmosphere. Thus, inclined air showers detected by the SD array, those with $60° < \theta < 80°$, typically present very flat shower fronts and narrow time distributions. Neutrinos, on the other hand, have much smaller cross-sections and can interact deeper, much closer to the ground. In this case, the FADC time traces of the SD stations would present a broad time structure, indicative of that of a "young" shower, with a high content of electromagnetic particles [14], as it is depicted in figure 1.

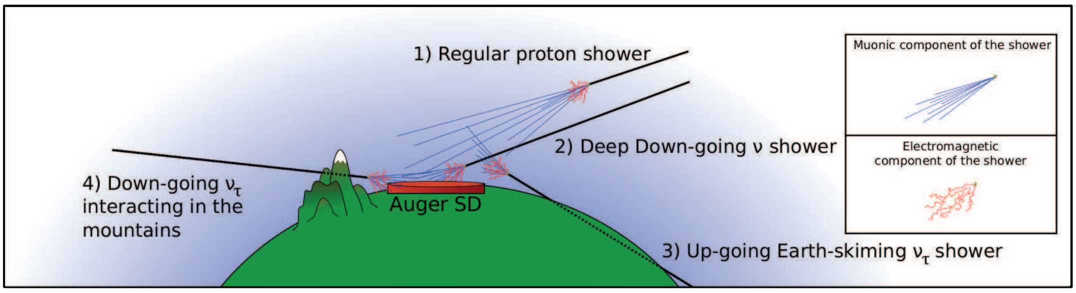

Figure 1. Different types of inclined showers which can be detected by the SD of the Pierre Auger Observatory [14]. 1) A common proton induced shower interacting high in the atmosphere. 2) A deep down-going neutrino shower interacting close to the ground. 3) An Earth-skimming ν_τ interacting in the Earth's crust generating a shower. 4) A down-going ν_τ crossing through the Andes and producing a τ which decays near the SD.

The discrimination of the neutrino signals from the hadronic background relies on the value of the Area over Peak (AoP) of the triggered stations, defined as the ratio of the integral of the FADC trace to its peak value, normalized to 1 for the average signal produced by a single muon [14].

Neutrino searches can be performed either in the Downward Going (DG), or in the Earth-skimming (ES) channels. The DG channel is subdivided into two regimes, the Downward Going Low (DGL), which is used for events with zenith angles between 60° and 75°, and the Downward Going High (DGH) for $75° < \theta < 90°$. In the DG channels the neutrino searches use a Fisher discriminant which combines up to 10 variables using the AoP of 4 (4 or 5) early (central) stations in the DGH (DGL) selections as described in detail in [15]. Finally, the ES channel applies for events in the zenith angle range $90° < \theta < 95°$, and it dominates the exposure of the Pierre Auger Observatory to neutrinos. The ES selection requires a minimum of three stations, a high eccentricity of the elliptic shape of the triggered area on the ground and an apparent speed of the trigger times between station pairs with an average value very close to c with a small spread [15]. This channel is only sensitive to tau neutrinos, and it is the one which presents the highest selection efficiency, as it is demonstrated in figure 2.

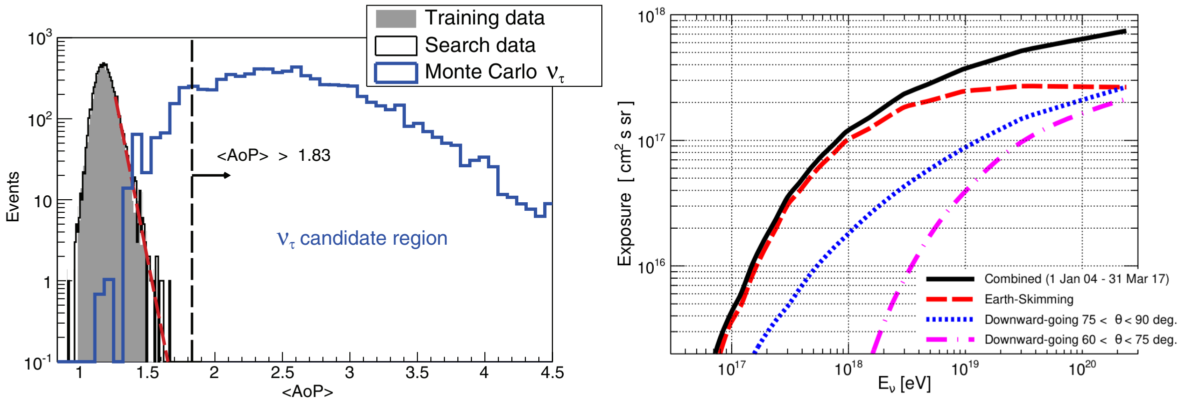

Figure 2. Left: Neutrino discrimination for the Earth-skimming channel. The cut in $\langle \text{AoP} \rangle$ (dashed line) ensures that there is less than one background event in 50 years of observation time. The selection efficiency for the Earth-skimming channel is 95% [15]. Right: Total exposure (black solid line) as a function of the neutrino energy and contributions of the ES (dashed red), DGH (blue dotted line) and DGL (chained magenta line) channels assuming equal fluxes for all neutrino flavors [16].

2.1. *Point-like sources*

The arrival directions of the events detected by the SD are calculated by the relative arrival time of the shower front to the triggered stations. The angular resolution of inclined events with $\theta < 80°$ is better than 2.5°, and improves with the number of triggered stations and the energy of the shower [12].

At the latitude of Auger, $\lambda = -35.2°$, a source with equatorial coordinates (α, δ) observed at a given sidereal time t is described, for a given zenith angle $\theta\,(t)$, by

$$\cos\theta\,(t) = \sin\lambda \sin\delta + \cos\lambda \cos\delta \sin\left(2\,\pi\, t/T - \alpha\right), \tag{1}$$

where T is the duration of the sidereal day. Hence, the study of point-like neutrino sources is only possible within certain declination ranges, as it is illustrated in figure 3.

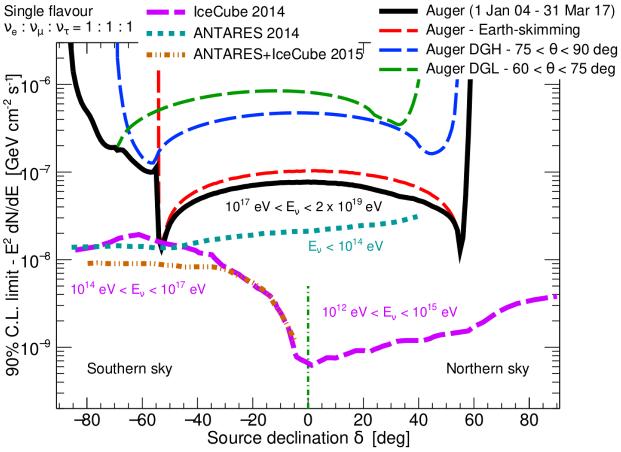

Figure 3. Upper limits at 90% C.L. for the sensitivity of the several neutrino channels as a function of the declination, namely: ES (red dashed line), DGH (blue dashed line), DGL (green dashed line), and the total exposure (black solid line) [16].

For the ES channel, the sky coverage of the Auger array ranges from $-54.5°$ to $59.5°$ in declination, while for the DG channels, it is possible to increase the declination range in the southern sky to $-84.5°$.

3. Neutrino searches in coincidence with gravitational wave events

The Pierre Auger Observatory participates in several multi-messenger studies, among which is the neutrino follow-ups of gravitational wave events. Currently Auger has participated in the neutrino searches in temporal and spatial coincidence of the gravitational wave events GW150914, the candidate event LVT151012, GW151226, and the GW170817 / GRB 170817A [17, 18]. A brief description of these events is summarized in table 1.

Table 1. List of gravitational wave events followed-up by the Pierre Auger Observatory. SNR represents the signal-to-noise ratio of the gravitational wave events [3, 4]. BBH stands for Binary Black Hole merger and BNS stands for Binary Neutron Star inspiral.

Event	Date and time of detection	D_s/Mpc	$E_{GW}/M_\odot c^2$	SNR	Category
GW150914	Sep. 14, 2015, 09 : 50 : 45 UTC	410^{+160}_{-180}	$3.0^{+0.5}_{-0.5}$	23.7	BBH
LVT151012	Oct. 12, 2015, 09 : 54 : 43 UTC	1000^{+500}_{-500}	$1.5^{+0.3}_{-0.4}$	9.7	BBH
GW151226	Dec. 26, 2015, 03 : 38 : 53 UTC	440^{+180}_{-190}	$1.0^{+0.1}_{-0.2}$	13.0	BBH
GW170817	Aug. 17, 2017, 12 : 41 : 04 UTC	40^{+8}_{-14}	> 0.025	32.4	BNS

The neutrino searches were performed in the energy range of $[0.1\,\text{EeV}, 25\,\text{EeV}]$, a complementary energy region to the searches done by IceCube/ANTARES [19]. Two time windows were used: one of ±500 s around the time of the merger, to look for neutrinos coming from the prompt phase of gamma-ray bursts [20, 21], and an extended one of 1 day (14 days) after the merger of binary black hole (binary neutron star) systems, to search for longer lived processes [21].

Since the ES channel dominates the exposure of the Auger SD array to neutrinos while presenting the lowest background, it is desirable that the source position at the time of the merger lies in this region. From all the events followed by Auger, the event GW170817/GRB 170817A was the best located one since the source could be observed during the whole ±500 s time window in this channel, one reason more to highlight this event in a dedicated sub-section. Also, the events GW151226 and LVT151012 had some overlap with the ES channel during a part of the ±500 s time window. Finally, all the three binary black hole merger events GW151226, LVT151012 and GW150914 could be observed in the DGH channel during the ±500 s, and their follow-up could be carried on during a fraction of the 1 day time window. No neutrino candidates were found during the ±500 s and 1 day time windows [17].

3.1. The binary neutron star merger event GW170817/GRB 170817A

Thanks to the several electromagnetic counterparts, this was the most precisely located event at the equatorial coordinates $\alpha\,(2000) = 13^h09^m48^s.085$, $\delta\,(2000) = -23°22'53''.343$ [4]. Neutrino searches in the energy range of GeV to EeV in coincidence with GW170817/GRB 170817A were performed by the most sensitive neutrino observatories ANTARES, IceCube and Auger [18]. The sky map of these neutrino searches, as well as their results are shown in figure 4.

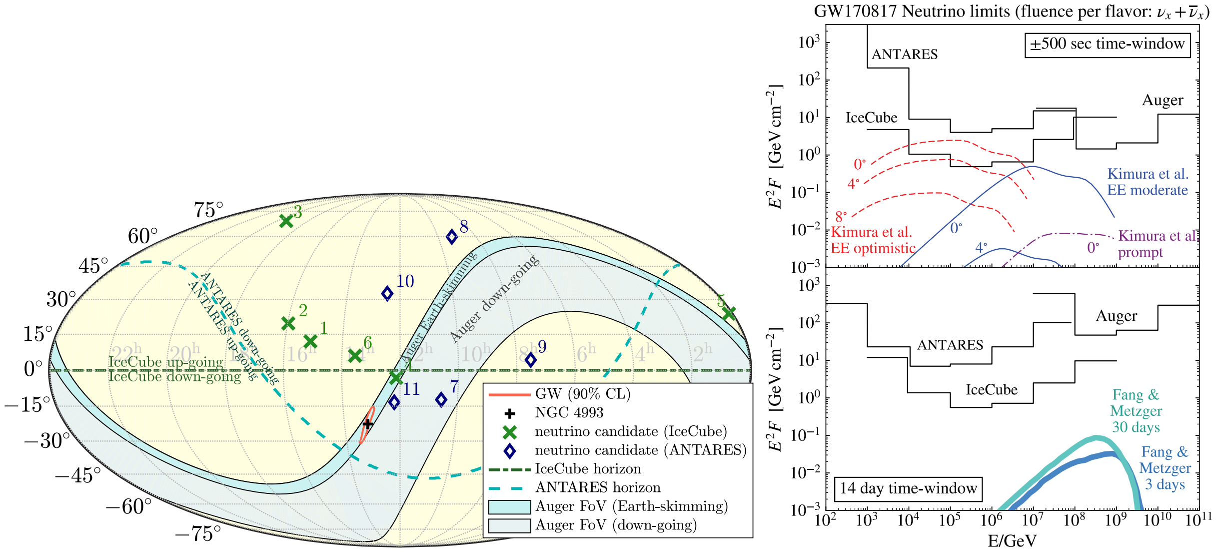

Figure 4. Left: Sensitive sky areas of ANTARES, IceCube and Auger at the time of the event GW170817 in Equatorial Coordinates. The red contour marks the 90% C.L. location of the event GW170817 [1, 18]. Right: Upper limits at 90% C.L. of the neutrino spectral fluence from the event GW170817 for a ±500 s time window (top panel) and in the following 14 days after the trigger (bottom panel). Some model predictions for the neutrino emission scaled to a distance of 40 Mpc are also shown in the plot.

In Auger, the whole ±500 s time window was observed in the ES channel field of view, the most sensitive channel to ultra-high energy neutrinos. In this period, the source of GW170817 transited from $\theta \sim 93°.3$ to $\theta \sim 90°.4$ as seen from the center of the array. The performance of the SD array (which is monitored each minute) was very stable, with an average number of active stations amounting to $\sim 95.8\% \pm 0.1\%$. No inclined showers passing the ES channel selection were detected. The estimated number of background events in this 1000 s window is $\sim 6.3 \times 10^{-7}$, for the cuts applied in the ES channel [15]. Assuming neutrinos are emitted steadily during this period, with an energy spectrum of E^{-2} [17], the non-detection of candidates allows us to put limits to its fluence (see figure 4 right). In the following 14 days searches were carried out both in the ES and DG channels. From the Auger coordinates, the zenith angle of the optical counterpart of the event oscillates daily between $\theta \sim 11^\circ$ to $\theta \sim 121^\circ$. The source is visible in the ES channel for $\sim 4\%$ $(90^\circ < \theta < 95^\circ)$ of the day, in the DGL channel for $\sim 10.5\%$ $(60^\circ < \theta < 75^\circ)$, and in the DGH for 11.1% $(75^\circ < \theta < 90^\circ)$. No significative counterpart was found in any of the searches with any of the observatories, a result which is compatible with the expectations of a GRB observed off-axis or with a low luminosity GRB [18].

4. Conclusions

With the functioning of the LIGO/Virgo systems, and with the upcoming gravitational wave detectors, it is foreseeable an increase of the detection of gravitational wave events from nearby sources. The detection of neutrino candidates from gravitational wave events would allow to better understand the processes by which these ultra-high energy neutrinos, and possibly ultra-high energy cosmic rays are produced. Also, in the case of the non-detection of any other counterparts, it could help to better constrain the position of these sources in the sky with a precision, ranging from less than ~ 1 deg^2 to the order of 10 deg^2 [17]. The Pierre Auger Observatory, along with the neutrino detectors IceCube and ANTARES is committed in continuing the rapid searches of neutrino candidates from the follow-up of future gravitational wave events.

Acknowledgments

We wish to acknowledge the financial support from a number of funding agencies in the participating countries, listed at https://www.auger.org/index.php/about-us/funding-agencies. This work is funded by the MEYS under the project LTT 18004 and LM 2015038 and by the Czech Science Foundation under the project 14-17501S.

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