PROCEEDINGS OF SCIENCE

# Multi-Messenger astrophysics with the Pierre Auger Observatory

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The Pierre Auger Observatory is sensitive to ultra-high energy neutral particles, such as photons, neutrinos, and neutrons, and can take part in Multi-Messenger searches in collaboration with other observatories. Photons and neutrinos are searched by exploiting the design of the Pierre Auger Observatory and profiting from the different properties of the induced showers caused by different particles. Diffuse and point source fluxes of photons and neutrinos are searched for. Furthermore, photon and neutrino follow-ups of the gravitational wave events observed by the LIGO/Virgo Collaboration are conducted. The Pierre Auger Observatory is also used to search for neutrons from point-like sources. In contrast to photons and neutrinos, neutrons induce air showers that cannot be distinguished from those produced by protons. For this reason, the search for neutrons from a given source is performed by searching for an excess of air showers from the corresponding direction. All these searches have resulted in stringent upper limits on the corresponding fluxes of the considered particles, allowing, together with the results obtained by other experiments, to shed some light on the most energetic phenomena of our Universe. An overview of the Multi-Messenger activities carried out within the Pierre Auger Collaboration is presented.

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## 1. Introduction

The complementary information from cosmic rays, neutrinos, high energy gamma rays, gravitational waves and neutrons provides insights into the properties of the corresponding astrophysical sources. After the detection of the first gravitational wave [1], Multi-Messenger astronomy underwent a significant boost. The later discovery of gravitational waves from a binary neutron star merger [2] was coupled with a combined search for high energy gamma rays [3] and neutrinos [4] in which the Pierre Auger Observatory took part. The importance of Multi-Messenger searches in the comprehension of astrophysical sources became evident with the detection of a high energy neutrino from the blazar TXS-0506+056 in coincidence with a flare of high energy gamma rays in 2017 [5]. The analysis of archival data allowed the identification of an enhanced neutrino emission from this source between 2014 and 2015 [6].

Multi-Messenger analyses are currently on-going within the Pierre Auger Collaboration. The design of the Pierre Auger Observatory allows the performance of searches for photons and neutrinos by exploiting the different properties of cosmic ray, neutrino and photon induced showers. Searches for neutrons from point-like sources are also performed by searching for excesses of air showers from given directions.

## 2. Search for photons

Ultra-high energy photons can originate from the decay of neutral pions produced in the interaction of protons with the Cosmic Microwave Background (CMB) photons and from the interaction of protons within the sources or their local environment. In addition to this “bottom-up” scenario, a large flux of ultra-high energy photons is expected in “top-down” models, which assume that ultra-high energy cosmic rays are the decay products of super-heavy particles. Limits on the flux of ultra-high energy photons can provide a discrimination between these two different scenarios. Considering that the attenuation length of EeV photons is about 4.5 Mpc, the maximum distance from which photons at those energies can be detected is limited. Air showers induced by ultra-high energy photons can be identified by relying on their reduced muon content and deeper depth of the shower maximum $X_{\rm max}$. The $X_{\rm max}$ separation allows to use the Fluorescence Detector (FD) [7] to discriminate between photon and hadron showers. The reduced muon content, on the other hand, makes the lateral distribution function (LDF) for photons steeper than that for hadrons, making photon showers detectable also with the Surface Detector (SD) [7]. The number of triggered SD stations $N_{\rm stat}$ is tipically smaller for photon showers [8]. Furthermore, the rise of the signal in the SD stations for photon showers is slower than that for hadron showers.

### 2.1 Search for diffuse fluxes of photons

For energies above 10 EeV, photon showers are searched for with the SD in the zenith angle range $30^\circ < \theta < 60^\circ$. Data taken from 1 January 2004 to 30 June 2018 are used. Two discriminating observables, one based on the LDF and the other based on the risetime of the SD signals, are used to perform a Principal Component Analysis (PCA) [9]. After the application of the selection cut on the PCA variable 11 data events are left. Since the background hypotesis could not be excluded for these events [9], an upper limit on the photon flux at 95% confidence level was derived. For energies below 10 EeV, the smaller number of SD stations with a signal does not allow discrimination between photon and hadron showers. However, the $X_{\max}$ measured by the FD can be used as a discriminating observable because of the increased statistics of the events. The zenith angle range considered for these energies is $0^\circ < \theta < 60^\circ$. The discrimination is performed by using $X_{\max}$, $N_{\text{stat}}$ and a SD observable sensitive to the difference in LDF, which are used in the training of a Boosted Decision Tree (BDT). The search for photon showers can be extended below 1 EeV by using the data from the infill array [7] and the measurement of $X_{\max}$ from the High Elevation Fluorescence Telescopes (HEAT) [7]. The data used for this analysis are those from 1 June 2010 to 31 December 2015. Only one event is observed above the selection cut on the BDT output variable. This number is consistent with the number of events expected from background, therefore an upper limit on the integral photon flux at 95% confidence level for the energy thresholds 0.2, 0.3, 0.5 and 1 EeV was derived. The upper limits on the photon flux at 95% confidence level are shown in Figure 1.

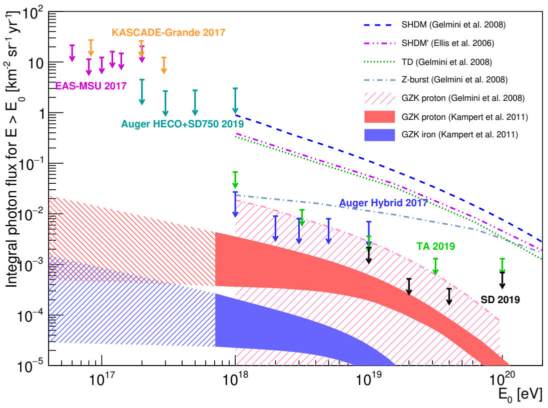

**Figure 1:** Upper limits on the photon flux at 95% confidence level obtained with the Pierre Auger Observatory. Predictions from models and other experimental results at 95% or 90% confidence level are also shown. Figure from [9].

## 2.2 Search for point-like sources of photons

In addition to the search for diffuse fluxes of photons, the Pierre Auger Collaboration performs also searches for ultra-high energy photons from point-like sources. To avoid large statistical penalties, the search for photons is performed considering twelve target sets, each consisting of a class of possible sources of ultra-high energy photons [10]. One of the classes is the Galactic center, where there is an indication of the presence of a PeV accelerator [11]. Since the signal from more than one source should be more significant than that from a single source, the possible sources of photons in each target set are combined in a “stacked analysis”. This analysis is performed by using the hybrid events, i.e. events detected by the FD and having at least one triggered SD station, in the energy range between $10^{17.3}$ eV and $10^{18.5}$ eV with a zenith angle smaller than $60^\circ$ collected from 1 January 2005 to 31 December 2013 [10]. The targets considered in this search are those within the maximum distance given by the attenuation length of the photons at the energies of interest. Similarly to the search for diffuse fluxes of photons described in section 2.1,

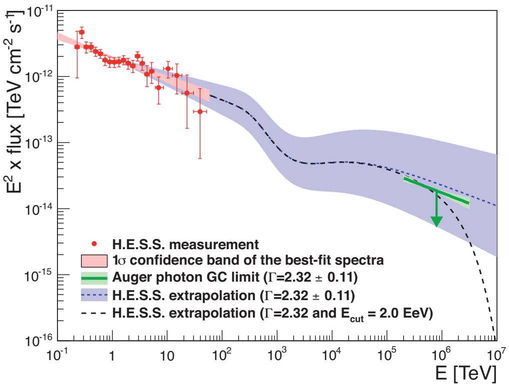

**Figure 2:** Photon energy spectrum from the region of the Galactic center as measured by the H.E.S.S. Collaboration [11] (red points) together with the extrapolations in the EeV range (dashed lines) and the Auger upper limit (green line). Figure from [10].

the discrimination between hadron and photon showers is provided by a selection cut defined using the BDT method. Sources within a given target set are weighted according to their electromagnetic flux and their exposure to the Pierre Auger Observatory. Weights are normalized in order to sum to 1 in each target set. Given a set with $N$ targets, any target $i$ is assigned with a p-value $p_i$, which is defined as the Poisson probability of having a number of events equal to or greater than the one actually measured. The p-values from the different targets are then used to obtain the combined p-value for both unweighted and weighted target sets. No evidence of a statistical significance larger than $3\sigma$ was found, therefore an upper limit on the photon flux from the target with the smallest p-value in each target set was calculated assuming a power law spectrum of $E^{-2}$ [10]. Focusing on the region of the Galactic center and using a spectral index of 2.32, which is the same as measured by the H.E.S.S. Collaboration [11], the upper limit shown in Figure 2 was derived. This upper limit constrains the allowed parameter space for the photon flux at EeV energies.

### 2.3 Photon follow-up of gravitational wave events

Recently, a follow-up of gravitational wave events has been performed within the Pierre Auger Collaboration by searching for photons with energies above 10 EeV in temporal coincidence with the gravitational wave events observed by the LIGO/Virgo Collaboration. Photon showers are searched for with the SD by using the standard photon search described in section 2.1 in both the time window between 500 s before and after the merger and the 24-hour period after the merger. Close and well localized gravitational wave sources are selected to reduce background and account for the attenuation length of photons. Among the selected gravitational wave sources, only four are found to have some overlap with the SD field of view during the 1 day period. The selection criteria used in this analysis are described in [12]. No candidate photon showers were found in coincidence with these events. Under the assumption of a $E_\gamma^{-2}$ energy spectrum, a preliminary upper limit on the photon spectral fluence at 90% confidence level was set for each source. The preliminary upper limits on the photon spectral fluence for the four sources considered in this analysis are shown in Figure 3.

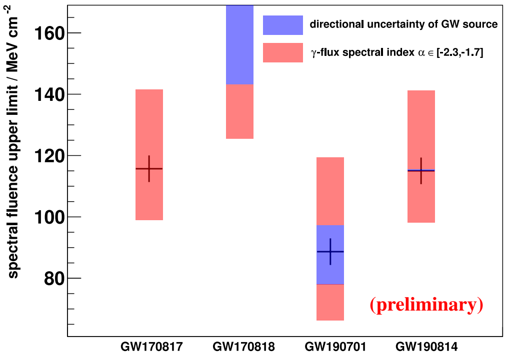

**Figure 3:** Preliminary upper limits at 90% confidence level on the spectral fluence for the four gravitational wave sources reported in the text. Figure from [12].

## 3. Search for neutrinos

Similarly to photons, ultra-high energy neutrinos can be produced from the interaction of protons within the sources, from the decay of charged pions produced in the interaction of protons with the CMB photons and from the interactions of protons with matter. Neutrinos can travel long distances without being absorbed, pointing directly to their sources and providing useful information about extragalactic sources. Ultra-high energy neutrinos are searched for by looking at inclined downward-going showers or nearly horizontal upward-going showers. Hadron showers with a zenith

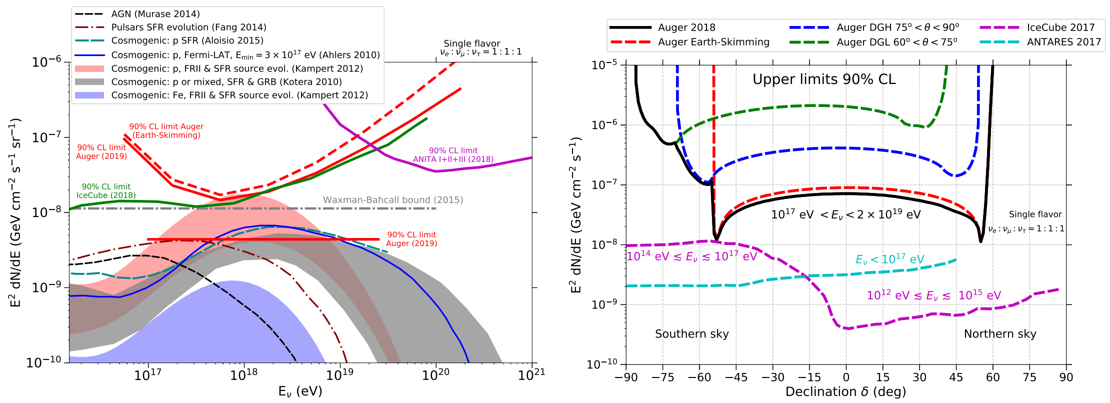

**Figure 4:** Integrated upper limit (solid straight red line) and differential upper limits (solid red line and the dashed red line) on the neutrino diffuse flux at 90% confidence level from the Pierre Auger Observatory together with the differential limits from other experiments and the expected neutrino fluxes from different cosmogenic and astrophysical models of neutrino production (left) and upper limits at 90% confidence level on the point-like neutrino flux as a function of the source declination $\delta$ obtained with the Pierre Auger Observatory together with the upper limits obtained by other experiments in different energy ranges (right). Figure on the left is from [13], while Figure on the right is from [14].

angle $\theta > 60°$ traverse large atmospheric depths, resulting in an almost complete absorption of their electromagnetic component. As a consequence, the SD stations are reached mainly by muons. Neutrinos, on the other hand, can interact deep in the atmosphere and produce showers with a large concentration of electrons and photons at ground. The resulting broader signal in the SD stations can be discriminated from that produced by hadron showers. Furthermore, tau neutrinos can interact in the Earth producing tau leptons that in turn decay and produce upward-going showers. The searches for inclined downward-going showers and nearly horizontal upward-going showers are performed with the SD in the zenith angle ranges $[60, 90]\,°$ and $[90, 95]\,°$, respectively.

### 3.1 Search for diffuse fluxes of neutrinos and neutrinos from point-like sources

Both inclined downward-going showers and nearly horizontal upward-going showers are searched for by defining a single discriminating variable. The search for diffuse fluxes of ultra-high energy neutrinos is performed by using data from 1 January 2004 to 31 August 2018. Since no candidate events were found, an upper limit on the diffuse neutrino flux can be derived. The upper limits on the neutrino flux at 90% confidence level obtained with the Pierre Auger Observatory are shown in Figure 4 (left).

Since the search for diffuse neutrinos is performed in the zenith angle range $[60, 95]\,°$, neutrinos from point-like sources can be searched for at a certain instant only from the region of the sky defined by this range. The three zenith angle ranges into which the analysis is divided correspond to different fields of view for the neutrino search. No candidate events were found in data taken from 1 January 2004 to 31 August 2018, therefore upper limits on the neutrino flux from point-like sources can be derived. The upper limits as a function of the source declination are shown in Figure 4 (right).

### 3.2 Neutrino follow-up of gravitational wave events

The neutrino follow-up of gravitational wave events is performed by applying the standard neutrino search in the same time windows mentioned in section 2.3. Inside these two time windows, the search is limited to the periods when the 90% confidence level region of the source localization in the sky is in the SD neutrino field of view of the Pierre Auger Observatory. Since no candidate events were found, upper limits on the neutrino spectral fluence were derived. The upper limits at 90% confidence level for the neutrino follow-up performed together with the IceCube and ANTARES Collaborations [4] on the neutrino spectral fluence for the gravitational wave event GW170817 [2] during the time window of 500 s before and after the merger and the 14-day period after the merger are shown in Figure 5.

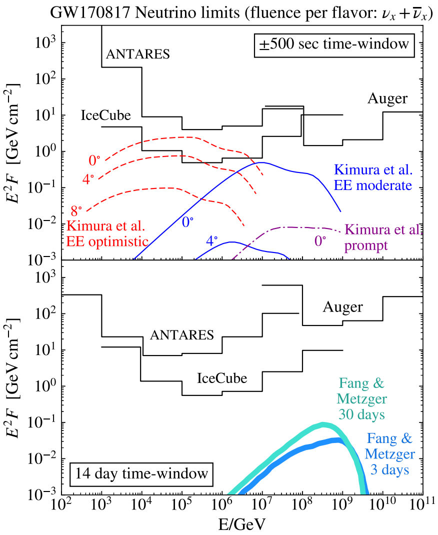

**Figure 5:** Upper limits at 90% confidence level on the neutrino spectral fluence from GW170817. Predictions from neutrino emission models are also shown. Figure from [4].

## 4. Search for neutrons

Considering their mean decay path length, neutrons with energies of a few EeV should allow to identify sources within most of our galaxy. Air showers produced by neutrons cannot be distinguished from those produced by protons, therefore a flux of neutrons from a given direction can be identified only by searching for an excess of air showers from that direction. Since the production of neutrons is associated to that of photons, the search for neutrons is performed in a similar way as that for photons from point-like sources on a total of eleven target sets consisting of nine classes of possible sources of photons plus the Galactic center and the Galactic plane combined in a stacked analysis [15]. SD events with a zenith angle $\theta < 60^\circ$ in the period from 1 January 2004 to 31 October 2013 [15] are used. Since no evidence of excess of a neutron flux was found from any of the target sets, an upper limit on the neutron flux was derived for each target set [15].

## References

[1] B. P. Abbott et al., *Phys. Rev. Lett.* **116** (2016) 061102, [1602.03837].
[2] B. P. Abbott et al., *Phys. Rev. Lett.* **119** (2017) 161101, [1710.05832].
[3] B. P. Abbott et al., *Astrophys. J. Lett.* **848** (2017) L12, [1710.05833].
[4] A. Albert et al., *Astrophys. J. Lett.* **850** (2017) L35, [1710.05839].
[5] M. G. Aartsen et al., *Science* **361** (2018) eaat1378, [1807.08816].
[6] M. G. Aartsen et al., *Science* **361** (2018) 147–151, [1807.08794].
[7] A. Aab et al., *Nucl. Instrum. Meth. A* **798** (2015) 172-213, [1502.01323].
[8] P. Abreu et al., *Astropart. Phys.* **35** (2011) 266-276 [erratum: *Astropart. Phys.* **35** (2012) 681-684], [1111.6645].
[9] J. Rautenberg [for the Pierre Auger Coll.], PoS(ICRC2019)398, [1909.09073].
[10] A. Aab et al., *Astrophys. J. Lett.* **837** (2017) L25, [1612.04155].
[11] A. Abramowski et al., *Nature* **531** (2016) 476, [1603.07730].
[12] P. Abreu et al., PoS(ICRC2021)973.
[13] A. Aab et al., *JCAP* **531** (2019) 022, [1906.07422].
[14] A. Aab et al., *JCAP* **11** (2019) 004, [1906.07419].
[15] A. Aab et al., *Astrophys. J. Lett.* **789** (2014) L34, [1406.4038].