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Latest results from the searches for ultra-high-energy photons and neutrinos at the Pierre Auger Observatory

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The Pierre Auger Observatory is the largest air-shower experiment in the world, offering an unprecedented exposure not only to ultra-high-energy (UHE, $E > 10^{17}$ eV) cosmic rays, but also to UHE neutral particles, specifically photons and neutrinos. Since the beginning of data taking almost 20 years ago, a number of searches for UHE photons and neutrinos using the different detector systems of the Observatory have been carried out. These searches led to some of the most stringent upper limits on the diffuse—i.e., direction-independent, unresolved—fluxes of photons and neutrinos in the UHE regime. These limits severely constrain current models for the origin of UHE cosmic rays and underline the capabilities of the Pierre Auger Observatory and its leading role in the context of multimessenger astronomy at the highest energies. In this contribution, we give an overview of the current activities concerning searches for UHE photons and neutrinos in the data from the Pierre Auger Observatory. The latest results of the searches for diffuse fluxes of photons and neutrinos will be shown. Furthermore, the follow- up searches for UHE photons and neutrinos in association with transient events, such as gravitational wave events, will be summarized. In addition, future perspectives in view of the ongoing *AugerPrime* detector upgrade will be discussed, which will further improve the sensitivity of the Pierre Auger Observatory to neutral particles at the highest energies.

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1. Introduction

One of the main goals of current efforts in multimessenger astronomy is to understand the nature and origin of ultra-high-energy (UHE, referring to the energy range above $\sim 10^{17}$ eV) cosmic rays. In this context, UHE photons and neutrinos play a crucial role: they appear as "by-products" in all scenarios aiming at explaining where and how UHE cosmic rays are produced, originating either directly at the cosmic-ray sources ("astrophysical" photons and neutrinos) or during the propagation through the Universe ("cosmogenic" photons and neutrinos). Photons and neutrinos themselves are complementary messengers: Photons trace the local Universe up to Mpc scales, due to interactions with the cosmic background fields limiting their reach, while neutrinos can traverse the whole Universe. In addition, they can also serve as cosmic probes of fundamental physics and open a window to new physics, for example in the context of super-heavy dark matter or violations of Lorentz invariance. As is the case with UHE cosmic rays, also the fluxes of UHE photons and neutrinos are far too small for direct detection using, e.g., satellite experiments. However, neutral particles entering the Earth's atmosphere can initiate extensive air showers like charged cosmic rays, making indirect detection possible. Therefore, a cosmic-ray observatory measuring air showers can, by construction, also be a photon observatory and even a neutrino observatory, complementing specialized instruments and adding valuable information to multimessenger studies.

The Pierre Auger Observatory [1], located near the town of Malargüe in the Argentinian *Pampa Amarilla*, is such a cosmic-ray observatory. A key feature of the Observatory is the hybrid concept, combining a Surface Detector array (SD) with a Fluorescence Detector (FD). The SD consists of about ~1660 water-Cherenkov detectors, covering a total area of about 3000 km^2. The SD is overlooked by 27 fluorescence telescopes, located at four sites at the border of the array. The SD samples the lateral shower profile at ground level, i.e., the distribution of secondary particles as a function of the distance from the shower axis, with a duty cycle of ~100 %, while the FD records the longitudinal shower development in the atmosphere above the SD. The FD can only be operated in clear, moonless nights, reducing the duty cycle to ~15 %. For a more detailed description of the detector systems of the Observatory, including its various enhancements, see [1].

2. Searches for UHE Photons and Neutrinos

The biggest challenge when searching for UHE photons and neutrinos is to distinguish air showers initiated by these particles from those induced by the vast background of primary protons and heavier nuclei in cosmic rays.

For the identification of primary photons, one can exploit the fact that the development of photon-induced air showers in the atmosphere is dominated by electromagnetic interactions, leading to air showers developing deeper in the atmosphere with a smaller muon component, compared to air showers induced by protons and nuclei. In the following, we will briefly discuss the most recently updated analysis based on data from the 1500 m SD array only [2], focussing on primary energies above 10^{19} eV. A review of all photon searches performed at the Pierre Auger Observatory using the different detector systems and targeting different energy ranges can be found in [3]. The SD-only analysis is based on two observables, L_{LDF} and Δ (see Fig. 1). The two observables relate

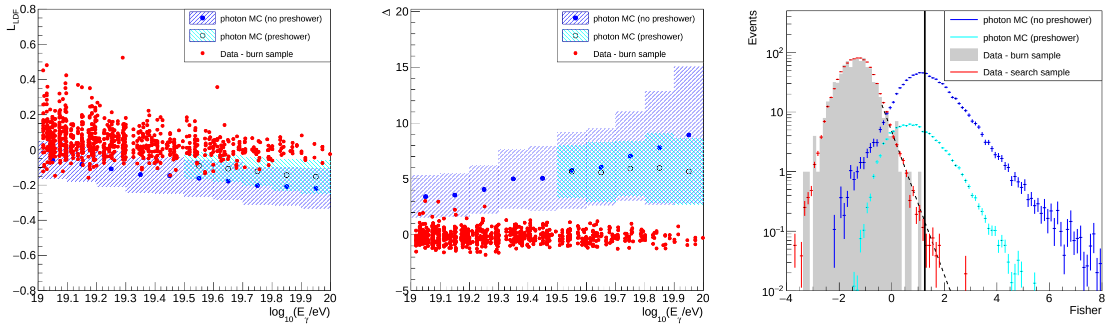

Figure 1: Search for photons with energies above 10^{19} eV: distributions of the observables $L_{\rm LDF}$ (left) and Δ (center); distribution of the Fisher discriminant and results of the application to data (right); for details, see [2].

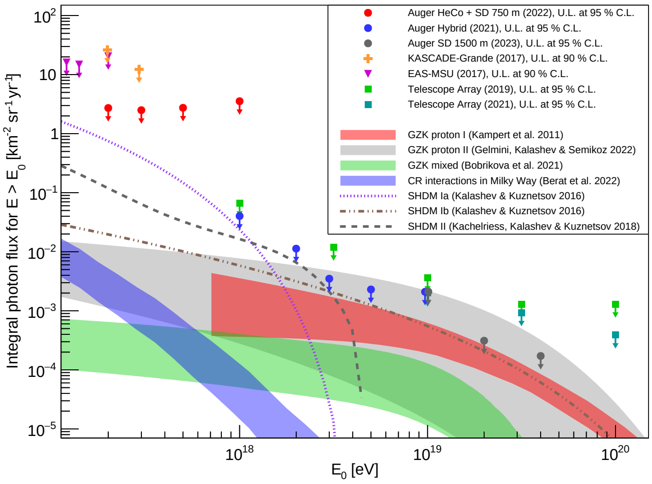

Figure 2: Current upper limits on the integral photon flux determined from data collected by the Pierre Auger Observatory (red, blue and gray circles); shown are also upper limits published by other experiments as well as the expected photon fluxes under different theoretical assumptions and scenarios; for details, see [3].

the measured total signals in the individual SD stations and the measured risetimes of the signals to a *data benchmark*, describing the average of all of the SD data (assumed to be overwhelmingly constituted by primary nuclei). The use of the average behavior of all SD data in the two quantities removes the need for assumptions on the composition of the background, which is not known in detail at the highest energies. The two observables are combined in a Fisher discriminant analysis, with the burnt sample—about 2 % of the full data sample which do not enter the final analysis—used as the background and photon simulations as the signal (see also Fig. 1). The analysis is applied to SD data collected between 1 January 2004 and 30 June 2020. Overall, 16 events from the data sample pass the photon candidate cut, which is consistent with the expectation from background. No primary photon could therefore be unambiguously identified. The resulting upper limits on the integral photon flux are shown in Fig. 2, together with upper limits determined from other experiments as well as the expected photon fluxes under different theoretical assumptions and scenarios. The upper limits determined by the Pierre Auger Observatory are the most stringent ones to date, over a wide energy range spanning from 2×10^{17} eV to the highest energies. First results from an extension to even lower energies in the 10^{16} eV range, using a dense 433 m SD sub-array and underground muon detectors, are shown in another contribution at this conference [4]. More "exotic", top-down models have been strongly constrained by the present limits—a number of such models were, in fact, already ruled out by previous results published by the Pierre Auger Collaboration. On the other hand, the predictions from some cosmogenic models, for example involving interactions of UHE cosmic rays with the cosmic microwave background, are within reach. For a more detailed discussion of the astrophysical significance of these limits, see [3].

Searching for UHE neutrinos in air-shower data means, in a nutshell, searching for inclined showers with an electromagnetic component. Protons and nuclei initiate air showers high in the atmosphere. At large zenith angles, the electromagnetic component is fully absorbed within the atmosphere, and only muons arrive on the ground. Neutrinos, with their smaller interaction cross section, can also initiate showers close to the ground, so that the electromagnetic component can still be measured even at large zenith angles. This leads to a unique signature that can be efficiently detected with the SD. Another search channel comes from Earth-skimming τ neutrinos interacting in the Earth's crust, producing a τ lepton that enters the atmosphere from below and initiates a slightly upgoing air shower close to the ground—another unique signature. All searches for UHE neutrinos at the Pierre Auger Observatory look for these signatures. The analyses are, based on the zenith angle, categorized either into the Earth-skimming channel (ES, zenith angles between 90° and 95°) or the down-going channel (DG, zenith angles between 60° and 90°). The latter is further divided into a number of sub-channels based on the number of triggered SD stations (N_{stations}) and the zenith angle. Using the combined results of all search channels, upper limits on the diffuse flux of UHE neutrinos have been obtained using data from the 1500 m SD array collected between 1 January 2004 and 31 December 2021 [5, 6]. As examples, we show the results of the data unblinding in two search channels in Fig. 3. In the ES channel, the average area-over-peak $\langle \mathrm{AoP} \rangle$, defined as the ratio of the integral of the time trace in a SD station to its peak value, averaged over all triggered stations in an SD event, is used as the discriminating observable. In the DG channel, specifically the sub-channel with $N_{\mathrm{stations}} \in [7, 11]$, the analysis is again based on the AoP values, but in this case, several observables that carry information on the time spread of the signals in the SD stations are constructed from the individual AoP values and subsequently combined in a Fisher discriminant analysis. From the non-observation of any neutrino event in any of the search channels, upper limits on the diffuse flux of neutrinos are determined. Assuming a (single flavor) neutrino flux of the form $\phi = k \times E_\nu^{-2}$, an upper limit on the normalization k, for the energy range between 10^{17} and 2.5×10^{19} eV, was obtained at 3.5×10^{-9} GeV cm^{-2} s^{-1} sr^{-1}. Upper limits can also be determined for energy bins of width 0.5 in $\log_{10}(E_\nu \,/\, \mathrm{eV})$ as an effective way of characterizing the energy dependence of the sensitivity. For the Pierre Auger Observatory, the best sensitivity is achieved at energies around 10^{18} eV. The upper limits are shown in Fig. 4, together with upper limits determined by IceCube and ANITA, as well as the expected neutrino fluxes under different theoretical assumptions and scenarios. Using these results, we can constrain several classes of models of neutrino production, both cosmogenic and astrophysical. In particular, cosmogenic models involving a pure-proton composition and a strong evolution of the sources with redshift are strongly constrained and even excluded due to the non-observation of neutrinos so far.

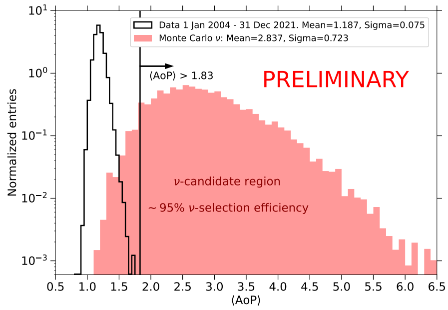

Figure 3: Results of the data unblinding for two search channels: ES channel (left); DG channel (right), in the sub-channel with $N_{\text{stations}} \in [7, 11]$; for details, see [5, 6]

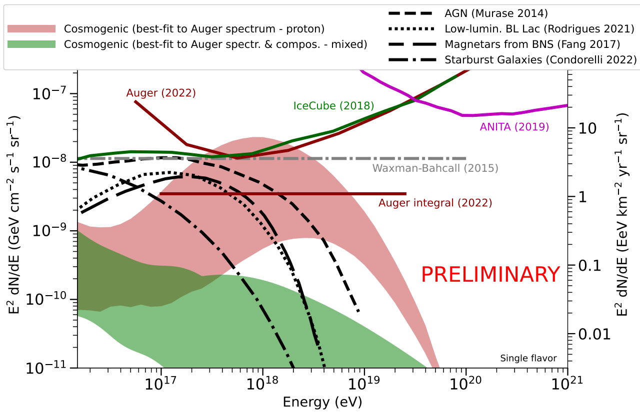

Figure 4: Upper limits on the diffuse flux of neutrinos, both integral (straight solid line) as well as differential (curved solid line); shown are also upper limits from IceCube and ANITA and the expected neutrino fluxes under different theoretical assumptions and scenarios, including ones based on Auger data (cf. [7]); for details, see, e.g., [5, 6].

A more detailed study of the constraints on the characteristics of the sources of UHE cosmic rays that can be derived from the limits on the neutrino flux is also shown at this conference [7].

3. Gravitational Wave Follow-Up Searches

The large exposure to UHE photons and neutrinos makes the Pierre Auger Observatory also an ideal tool for follow-up studies to gravitational wave (GW) and other transient events. Alerts received through the General Coordinates Network (GCN)[1] are routinely followed up based on the stand-alone searches discussed in the previous section. To highlight the capabilities of the Observatory as a multimessenger instrument, we mention the follow-up search for UHE neutrinos to the event GW170817, a binary neutron star merger [8]. Here, stringent upper limits on the neutrino fluence in the UHE regime could be set, due to the source of the GW being directly within the field of view of the ES channel at the time of the event. In the following, we briefly discuss a stacking analysis of all binary black hole mergers observed by LIGO and Virgo during the observation runs O1 to

[1] https://gcn.nasa.gov/

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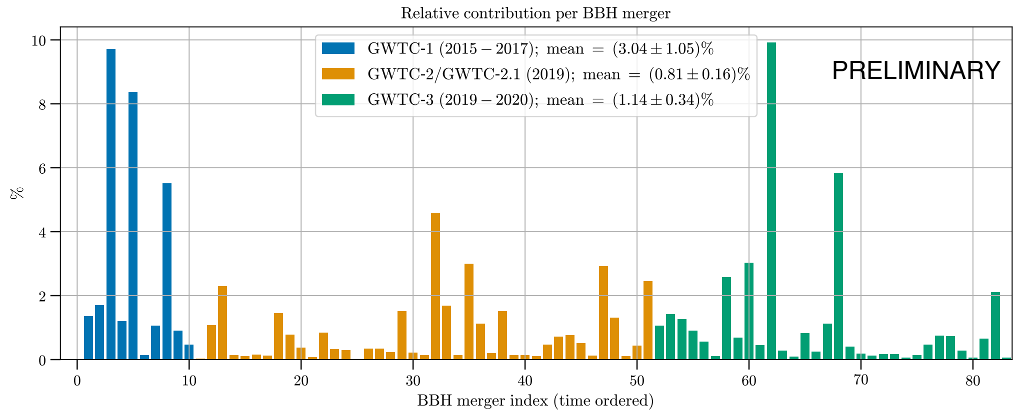

Figure 5: Relative contribution of each BBH merger to the 24-hour UHE-neutrino luminosity limit; the events are shown in chronological order with colors indicating the GW event catalog; for details, see [9].

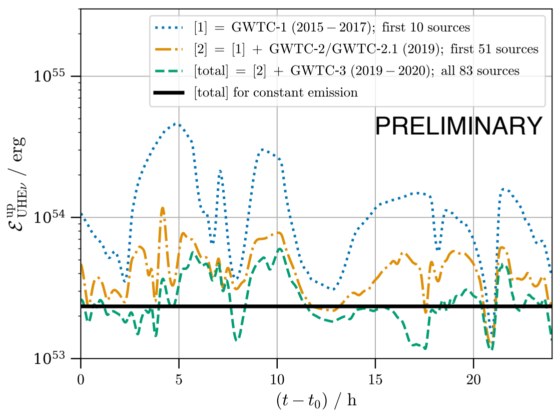

Figure 6: Results of the stacking analysis in the 24-hour time window [9]. Solid line: upper limit on the total energy emitted in UHE neutrinos. Dashed lines: partial results when only a subset of the available sources is taken into account.

O3 [9]. The aim of this analysis is to probe the UHE neutrino luminosity of such mergers from the non-observation of any UHE neutrino event. As a benchmark model, a universal and constant UHE-neutrino luminosity for all BBH mergers is assumed, with an E_ν^{-2} spectrum. The neutrinos are assumed to be emitted isotropically during two different hypothetical emission periods after each merger of 24 h and 60 d. The analysis is then based on the total number of neutrinos that can, under these assumptions, be expected to be collected from all sources, only taking into account observational parameters related to the source position and its luminosity distance. Also factored in is the time-dependent exposure of the SD to the individual sources in the two time windows. The relative contribution of each BBH merger to the stacking analysis in the 24 h time window is shown in Fig. 5. The results of this analysis, given in terms of an upper limit on the UHE-neutrino luminosity, taking into account all 83 BBH merger events observed by LIGO/Virgo during the three observation runs, is 2.7×10^{48} erg s^{-1} for the 24 h period and 4.6×10^{46} erg s^{-1} for the 60 d period. The corresponding limits on the total energy emitted in UHE neutrinos are 2.3×10^{53} erg

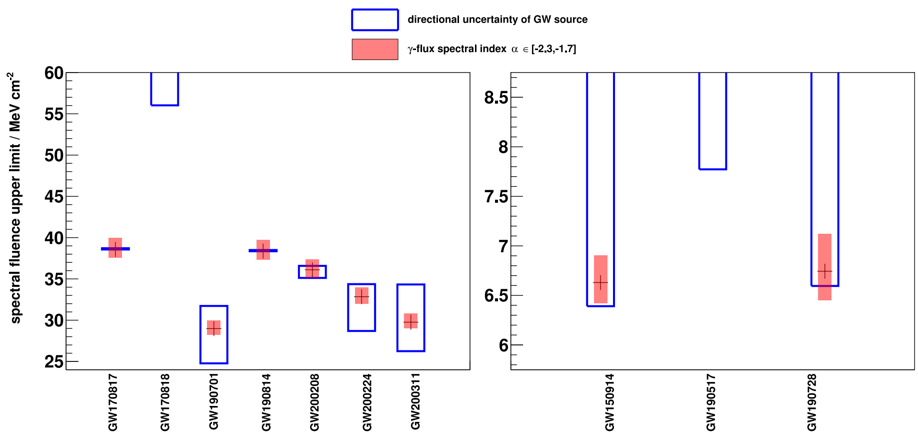

Figure 7: Upper limits on the spectral fluence of UHE photons from the selected GW sources in the long (left) and the short time window (right); the empty blue and shaded red bars correspond to the variation of the upper limits due to the directional uncertainty of the source and the impact of a variation of the spectral index (between −2.3 and −1.7), respectively; for details, see [10].

and 2.4×10^{53} erg, respectively. The result for the 24 h period is also shown in Fig. 6, together with partial results when only selected catalogs are taken into account. The variations with time after the merger in this limit reflect both the changing exposure of the detector with time during the assumed emission period as well as the distance of each individual source. The limits obtained by combining all catalogs exhibits smaller variations than the limits derived from just a subset of the sources, as the contributions of all sources are averaged out, leading to a more stable upper limit.

In addition to the follow-up searches for neutrinos, also corresponding follow-up searches for photons are performed [10]. While the overall detection efficiency is larger for photons, compared to primary neutrinos, their identification poses a challenge due to the larger background (see Sec. 2). To keep the expected background at a reasonable level and the significance of a possible photon signal high, not all GW events are followed up. The decision regarding which GW events are followed up is based on their distance and localization. While we focus on the most promising—close and/or well-localized—sources, we still keep an open window for unexpected discoveries. Under these criteria, 23 GW events from the three GW catalogs published by LIGO/Virgo would qualify to be followed up. Out of these 23 GW events, only 10 had at least partial overlap with the field of view of the SD—since the follow-up search is based in the stand-alone photon search with the SD described before—in either of the two time windows studied here, ±500 s around the time of the merger and +1 d after. Among the seven GW events followed up in the longer time window is the binary neutron star merger event GW170817. No photon candidate events have been observed for any of the 10 GW events studied in the respective time windows—in fact, no air-shower event at all has been observed in these time windows from the directions of the GW events. Taking into account the directional exposure, upper limits on the UHE-photon fluence can be derived (cf. Fig. 7). While no assumption on the time dependence of the photon flux is made, the extrapolation of the flux limits (derived for the time of transit of the source through the field of view of the detector) to the full time window is done under the assumption that the average flux during the period for which the source has been in the field of view is representative for the whole time window. The limits on the spectral fluence depend on the exact direction of the GW event and on the assumed spectral shape of the UHE photon flux, here assumed to be a simple power law. In Fig. 7, the uncertainties due to the source localization and due to the assumptions on the spectral index are shown separately. In the longer time window, all localization regions were fully covered by the field of view of the SD except for GW170818. All three GW sources in the short time window have contours which partly leak out of the field of view of the SD. For GW190517, also the most likely source direction is outside of the field of view. The upper limits on the UHE photon fluence from a GW event are typically at the level ~7 MeV cm^{-2} (for the short time window) and ~35 MeV cm^{-2} (for the long time window). Due to the proximity of the binary neutron star merger GW170817, the energy of the source transferred into UHE photons above 40 EeV can be constrained to be less than 20 % of its total gravitational wave energy.

4. Summary and Outlook

The Pierre Auger Observatory offers an unprecedented exposure not only to UHE cosmic rays, but also to UHE photons and neutrinos. Stringent upper limits on the diffuse flux of UHE photons and neutrinos have been obtained and thorough follow-up searches for these particles to GW and other transient events have been performed. Overall, these results underline that the Pierre Auger Observatory is a key actor in multimessenger astronomy at the highest energies. The Observatory is currently undergoing a major detector upgrade, dubbed *AugerPrime*, which will only strengthen this role. A key part of this upgrade is equipping all water-Cherenkov detectors of the SD with additional scintillators, with the goal of increasing the composition sensitivity through a better disentangling of the different shower components, which will also be beneficial for the searches for UHE photons and neutrinos. In addition, the detector stations will be equipped with radio antennas to measure the radio signals emitted by an air shower, and the electronics of the SD stations have been replaced to achieve a better time resolution and a larger dynamic range. All of these efforts combined will significantly improve the upper limits or, in the best case, lead to the first unambiguous detection of a primary photon or neutrino at ultra-high energies.

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