Results from the Pierre Auger Observatory: Search for Photon primaries, Neutrinos and Point-sources

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1. Introduction

The Pierre Auger Observatory started collecting data in 2004 [1–3]. The Observatory uses hybrid measurements of air showers recorded by an array of 1660 water Cherenkov surface stations covering an area of 3000 km^2, together with 24 air fluorescence telescopes that observe the development of air showers in the atmosphere above the array during dark nights.

An infill array [4] with half the grid size has been completed and is currently taking data with a threshold of about $3{\cdot}10^{17}$ eV. Moreover, three high-elevation telescopes (HEAT) [5] have begun operation and, together with the infill array in the FOV of the telescopes, will allow us to extend the hybrid measurements further down to 10^{17} eV thus covering with full efficiency the region of the transition from galactic to extra-galactic cosmic rays. The deployment of buried muon detectors (AMIGA) [6] in the infill area is in progress and an extensive R&D program for radio and microwave detection of UHE air showers is under way. The construction of the Auger Engineering Radio Array (AERA) has started [7] and several GHz-antennas are installed and taking data [8].

These extensions and new technologies may enhance the performance and capabilities of the Auger Observatory in Argentina and, in parallel, will explore their potential for a future much larger ground based observatory.

2. Search for photons and neutrinos

The search for ultra-high energy primary photons and neutrinos is motivated by several arguments. From an astrophysical point of view, the evidence of their existence would open a new window on the most extreme Universe. The detection of neutrinos and photons, as eventually produced by the decay of charged and neutral pions respectively, would also provide an independent proof of the GZK-effect.

Independently of a positive or negative result, their search will help constraining astrophysical scenarios for the origin and the propagation of UHECR, exotic models (i.e., Super Heavy Dark Matter, SHDM, topological defects, TD, Z-burst, etc., see [9] for a review) and provide hints of fundamental and new physics (e.g. Lorentz Invariance Violation [10]).

2.1. Photons

Distinctive characteristics of photon induced showers are a deeper shower maximum, $X_{\max}$, and a poorer muonic component. The delayed development of photon showers with respect to hadronic ones is due to the smaller multiplicity in electromagnetic interactions, and it is further delayed by the LPM effect [11] above 10 EeV. A dominating electromagnetic component is expected due to the lower cross-sections both for photo-nuclear interactions and muon pair production.

Upper limits on the absolute photon flux were derived by relating the number of photon-like events to the well known experimental exposure [12]. 95% CL limits on the photon fraction of 2.0%, 5.1%, and 31% above 10, 20, and 40 EeV, are derived (see Fig. 1, SD).

The key observable in searches for photon primaries with the fluorescence detector is the depth of shower maximum, $X_{\max}$. The difference between the average $X_{\max}$ value for showers induced by protons and photons at this energy is ~ 200 g cm^{-2}, which is large compared to the $X_{\max}$ resolution of the hybrid detector, ~ 20 g cm^{-2} [?]. Observations in hybrid mode are possible also at energies below 10 EeV. By decreasing the energy threshold, the event statistics increases balancing, to some extent, the factor $\sim$10 smaller duty cycle compared to observations with the ground array alone.

To improve the photon-hadron discrimination power the previous hybrid analyses [13], based on the FD $X_{\rm max}$ measurement only, are complemented in [15] with an SD observable combining the amplitude of the signal in the Cherenkov stations and the slope of the shower lateral distribution function. For the classification of photon candidates a Fisher analysis based on a large statistics Monte Carlo training sample is performed. Photon-like events are selected by applying an "a priori" cut at 50% of the photon selection efficiency. This provides a conservative result in the upper limit calculation by reducing the dependence on the hadronic interaction models and on the mass composition assumption. With this choice the expected nuclear contamination is about 1% in the lowest energy interval (between 10^{18} and $10^{18.5}$ eV) and it becomes smaller for increasing energies.

To carefully reproduce the operating conditions of the DAQ, time dependent simulations are performed according to the hybrid detector on-time. The actual configurations of the FD and SD and realistic atmospheric conditions are also taken into account.

Applying the method to data, 6, 0, 0, 0 and 0 photon candidates are found for energies above 1, 2, 3, 5 and 10 EeV. The observed number of photon candidates is consistent with the expectation from nuclear primaries, within the assumption of a mixed composition. Upper limits on the integral photon flux of $8.2\cdot10^{-2}$ km^{-2} sr^{-1} y^{-1} above 1 EeV and of $2.0\cdot10^{-2}$ km^{-2} sr^{-1} y^{-1} above 2, 3, 5 and 10 EeV are derived [15].

Comparing the flux limits to the measured Auger spectrum [**?**, **?**], upper bounds on the fraction of photons of about 0.4%, 0.5%, 1.0%, 2.6% and 8.9% are obtained for energies above 1, 2, 3, 5 and 10 EeV. The limits are shown in Fig. 1, (Hyb 2011) along with previous experimental results. The presented limits on the photon flux in UHECR favor astrophysical scenarios for the origin of the highest energy particles putting severe constraints on alternative non-acceleration models [9].

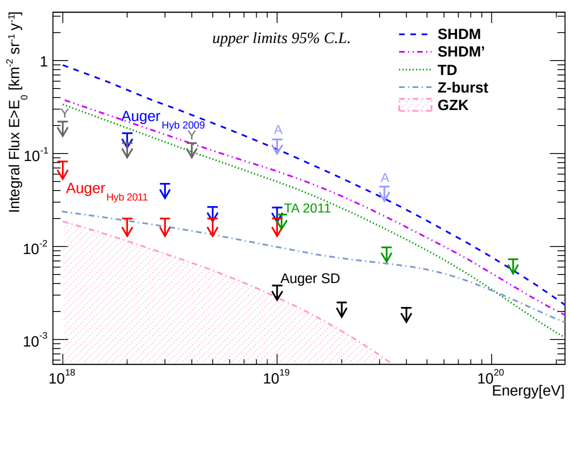

Figure 1. Upper limits on the integral photon flux [15] along with the previous ones by the Pierre Auger Observatory. See [14] for a complete list of references to experiments results and predictions.

2.2. Neutrinos

Ultra high energy neutrinos of all flavours can induce extensive atmospheric showers that could be detected both by the Pierre Auger Observatory fluorescence and surface detectors [16–18].

Tau neutrinos can interact in the Earth crust producing, via charged current, a tau lepton which in turn can emerge and decay in the atmosphere, giving an Earth skimming upward-going (UG) event. If the decay occurs in flight over the detector, it may initiate a detectable air shower. Down-going (DG) events are showers induced by neutrinos of all flavours which interact in the atmosphere both via charged and neutral current.

The main challenge from the experimental point of view is to identify neutrino-induced showers in the large background of showers initiated by nuclear primaries. The observation of a significant electromagnetic component, at ground level, in events with very inclined arrival direction is the key to separate neutrino candidates from nuclear background.

Among events with zenith angles between 90° and 95° the selected candidates must exhibit elongated footprint at the ground, defined by a large length over width ratio, and mean propagation speed at ground close to the speed of light, for details see Refs. [19,20]. The downward-going candidates were searched in a broader range of zenith angles, $75° - 90°$.

The analysis methods were applied to data collected with the Auger surface detector, the exposure for UG (DG) neutrinos being equivalent to 3.5 (2) years of the full Auger SD. No candidate neutrino event was found in the collected data. Based on this, the corresponding limits on

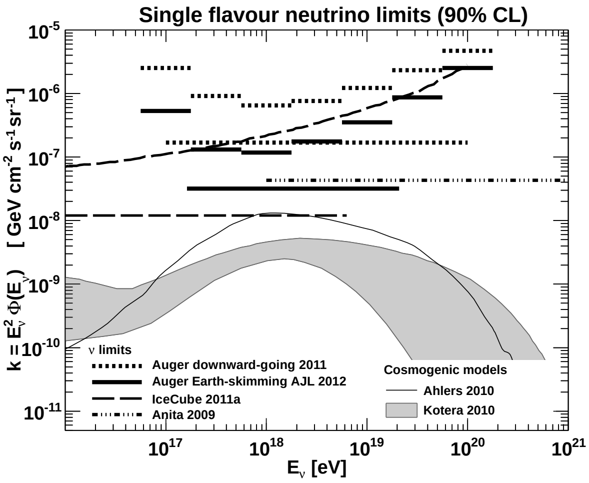

Figure 2. Differential and integrated upper limits at 90% CL on the single flavour E_ν^{-2} neutrino flux from the search for downward-going and Earth-skimming neutrinos at the Pierre Auger Observatory. Integrated upper limits are indicated by horizontal lines, with the corresponding differential limits being represented by segments of width 0.5 in $\log_{10} E_\nu$. See Ref. [20] for a complete list of experiments results and predictions.

the diffuse flux of UHE for UG and DG neutrinos were derived. The total exposure of the Auger surface detector was computed with MC simulations, by folding the real time SD array aperture with the interaction probability and the method identification efficiency, for details see [21].

Several sources of systematic uncertainties were taken into account and their effect on the exposure evaluated. In particular the dominating systematic uncertainties are due to the lack of knowledge of the calculation of τ energy losses, the neutrino cross section at ultra-high energy.

Assuming a differential neutrino flux $\sim k\ E^{-2}$, 90% C.L. limits on neutrino flux were obtained, see Fig. 2. The limit on Earth skimming tau neutrinos, in the range 0.16-20.0 EeV, is $k < 3.2\ 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} [20]. For down-going neutrinos in the range 0.1-100.0 EeV, $k < 1.7\ 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} [19].

The sensitivity of the Pierre Auger Observatory to point-like sources of neutrinos with UHE has been obtained by evaluating the exposure as a function of source declination. The search for neutrinos was performed over a broad declination range, north of $\sim -65°$ and south of $\sim 55°$, and for neutrino energies between 10^{17} eV and 10^{20} eV. Assuming a differential neutrino flux $\sim k_{PS}\ E^{-2}$ from a point-like source, 90% confidence level upper limits for k_{PS} at the level of $\sim 5 \cdot 10$ and $2.5 \cdot 10$ GeV cm^{-2} s^{-1} have been obtained for Earth-skimming and downward-going neutrinos, respectively [20].

3. Astrophysics

One of the keys to understanding the nature of UHECRs is their arrival direction distribution over the sky. This distribution depends on the location of the UHECR sources, as well on the UHECR mass composition and large-scale magnetic fields, both Galactic and extragalactic. Despite significant efforts, none of these issues is well understood at present.

Observation of the suppression of the CR flux at the highest energies and its interpretation in terms of the GZK-effect suggest that the sources of UHECRs are located within about 100 Mpc. At these scales the matter distribution in the Universe is inhomogeneous, and so must be the distribution of the UHECR sources. If propagation of UHECRs at these distances is quasi-rectilinear, anisotropies would be expected, showing variations at large angular scales and possibly point sources.

The Pierre Auger Collaboration in fact reported [22] directional correlations of UHECR at E ¿ 5.5 10^{19} eV with AGN from the Véron-Cetty-Véron catalog [23] within 75 Mpc on an angular scale of 3.1° at the 99% CL.

The analysis including data up to June 2011 is shown in Fig.3. A total of 28 of 84 events show a correlation on a 3.1°-scale with a nearby AGN. The overall correlation strength thus decreased from (62 ± 10)% initially to (33 ± 5)%. The chance probability of observing such a correlation from a random distribution remains below 1%. The superimposed black symbols show in addition the averages of 10 independent consecutive events. The first bin is an upward fluctuation by about 3 σ from the mean of all events while the rest of the dataset does not show any peculiarity.

Evidently, more data is needed to draw a definite conclusion.

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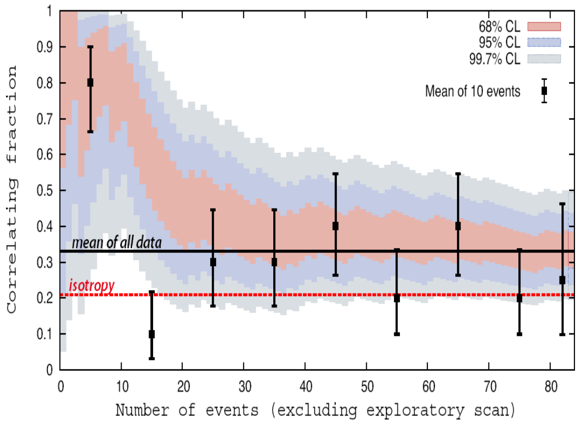

Figure 3. The most likely value of the degree of correlation $p_{data} = k/N$ is plotted as a function of the total number of time-ordered events (excluding those used for the exploratory scan). The 68%, 95% and 99.7% confidence level intervals around the most likely value are shaded. The horizontal dashed line shows the isotropic value $p_{iso} = 0.21$ and the full line the current estimate of the signal $p_{data} = 0.33 \pm 0.05$. The black symbols show the correlation fractions bins of independent 10 consecutive events.

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