Astronomy of ultra-high energy neutral particles with the Pierre Auger Observatory

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Abstract. The Pierre Auger Observatory is a hybrid detector of Ultra High Energy Cosmic Rays (UHECRs) especially suitable for primary energies above $10^{18}$ eV. Auger is also sensitive to primary neutral particles, namely photons, neutrinos and neutrons. Neutral cosmic rays propagate along a straight line and are not deflected by magnetic fields, in contrast to charged cosmic rays. This opens the possibility of doing “astronomy” by directional pointing. The most accepted astrophysical models predict the production of neutral particles both in their sources or in physical processes during the propagation of charged particles. We perform independent analyses for different types of neutral particles. No significant evidence of the presence of these particles has been observed in data collected from 2004 up to now; therefore we present upper bounds to their fluxes.

1. The Pierre Auger Observatory

The Pierre Auger Observatory [1] is a detector of UHECRs (above $10^{18}$ eV) using a large ground array of 1660 surface detectors (SD) combined with 27 air fluorescence telescopes (FD) deployed at 4 sites overlooking the SD. It is located outside the city of Malargüe, Argentina, and covers an extension of around 3000 km$^2$ over a nearly flat surface at a mean altitude of 1400 m above sea level. The FD only works on clear moonless nights, which translates in $\sim$12% of duty cycle while the SD provides data $\sim$100% of lifetime. UHECR are detected through their induced Extensive Air Showers (EAS). The SD samples the density of the secondary particles at the ground while the FD observes the shower longitudinal development in the atmosphere. Hybrid events combining simultaneous information from the two detectors provides data of unprecedented quality.

2. Photons

Differently from nucleon primaries, photons induce EAS mostly through electromagnetic interactions. Photons showers are thus expected to have a larger depth of shower maximum $X_{\text{max}}$ and to contain fewer secondary muons. The search of photons presented here is based on hybrids events which provide a precise geometry and energy determination with the additional benefit of allowing to reduce the energy detection threshold to about $10^{18}$ eV. To improve the photon-hadron discrimination power over measurements of $X_{\text{max}}$ only, the differences in the lateral distribution functions for photons and hadrons measured by the SD have been
considered by analyzing the observable, $S_b$ defined in [2]. To reject misreconstructed profiles, only time periods with the sky not obscured by clouds, and with a reliable measurement of aerosol absorption [3] are selected. On the SD side we require at least 4 active stations within 2 km of the hybrid reconstructed axis which prevents an underestimation of $S_b$ due to missing or temporary inefficient detectors. To increase the separation power, a Fisher analysis [4] is trained with $\sim 30000$ photon and proton Monte-Carlo (MC) showers accounting for realistic operating conditions of the detector. Photon-like events are selected by applying an “a priori” cut at 50% of photon detection efficiency. The expected background contamination is about 1% at low energy $E_\gamma \in (10^{18}, 10^{18.5})$ eV decreasing with energy.

Applying the method to hybrid data collected between Jan 2005 and Sept 2010 with zenith angle smaller than 60°, 6, 0, 0, 0 and 0 candidates are found for energies above 1, 2, 3, 5 and 10 EeV which is consistent with the expectation of nuclear primaries under the assumption of mixed composition. Upper limits on the integral photon flux ($\Phi^{\text{95\% C.L.}}_\gamma$) become $8.2 \cdot 10^{-2}$ km$^{-2}$ sr$^{-1}$ yr$^{-1}$ above 1 EeV and $2.0 \cdot 10^{-2}$ km$^{-2}$ sr$^{-1}$ yr$^{-1}$ above 2, 3, 5 and 10 EeV as shown in [5]. Results are shown in figure 1. Total systematic uncertainties affecting the analysis becomes (+20%, -64%) above 1 EeV and (-15%, -36%) for the remainder energy thresholds.

**Figure 1.** Upper limits on the UHE photon flux compared to previous limits from Auger [6, 7] and other experiments [8, 9, 10] together with predictions from the GZK [11] and top-down models [11, 12].

3. Neutrons
Neutron primaries induce undistinguishable EAS from proton ones. Nevertheless, unlike protons, they travel unaltered by magnetic fields along straight lines an average distance of $9.2E/\text{EeV}$ kpc before decaying. Since the radius of the galaxy is approximately 15 kpc, the observatory is able to perform neutron astronomy by looking for excess arrival directions in narrow solid angles.
Using quality events collected by the SD during stable acquisition periods from 1 Jan 2004 to 30 Oct 2010, we perform into three energy bands \([1 - 2], [2 - 3], E \geq 1 \text{ EeV}\) two analyses (see [13] for details):

- **First**, a blind search for localized excesses over the highest exposed regions \(\delta < 15^\circ\). The background expectation is obtained assuming an isotropic CR distribution and parametrizing the zenith angle distribution of the observed events to smooth out statistical fluctuations. The sky is overpixelized using HEALPix [14] and the Li-Ma significance [15] is evaluated for each target revealing no candidate point on the sky. As an example, figure 2 shows the sky map of the flux upper limits for the energy region \(E \geq 1 \text{ EeV}\).

Figure 2. Flux upper limits celestial map (in units of \(\text{km}^{-2}\text{yr}^{-1}\)) in Galactic coordinates for \(E \geq 1 \text{ EeV}\). Refer to [13] for other energy maps.

- **Second**, a targeted search of excess in the direction of selected bright gamma-ray sources from the Fermi LAT Point Source Catalog [16] and the H.E.S.S. Source Catalog [17]. We define the excess in a solid angle \(\Omega\) around one source as: \(S = N_s/\sqrt{N_{\text{iso}}}\) where \(N_s\) is the difference between the observed and the expected \((N_{\text{iso}})\) number of events in the target region around the source. To improve the signal over background we perform a stacking analysis on sets with the ten brightest sources (in flux observed on Earth) of each catalog as described in [13]. The stacked excess signal reads: \(S_{\text{stacked}} = \sum N_s/\sqrt{\sum N_{\text{iso}}}\). The result is shown in table 1, which reveals no significant excess.

Table 1. Stacked excess Signal \((S_{\text{stacked}})\) for each set of sources of the neutron analysis.

| Energy Bin [EeV] | IFGL | HESS |
|------------------|------|------|
| \([1 - 2]\)      | 2.07 | -0.75 |
| \([2 - 3]\)      | 0.51 | -0.40 |
| \(E \geq 1\)     | 2.35 | -0.89 |
4. Neutrinos

Due to the nature of the weak interaction, neutrinos can interact either deep in the atmosphere (down-going) or in the Earth crust (Earth-skimming), where hadronic primaries can not penetrate. In both cases, the distinguishing signature for neutrino events is the presence of very inclined showers produced close to the ground (young). Two independent analyses have been carried out for both down-going neutrinos with reconstructed zenith angles $\theta_{\text{rec}} \in (75^\circ, 90^\circ]$ and for Earth-skimming with zenith $\theta_{\text{rec}} \in [90^\circ, 95^\circ]$.

![Single flavour neutrino limits (90% CL)](image)

**Figure 3.** Differential and integrated upper limits at 90% CL to the diffuse flux of UHE$\nu$s together with other experiments [18, 19] and cosmogenic models [20, 21].

Additionally to a high value of $\theta_{\text{rec}}$, an inclined shower usually exhibits elongated patterns at the SD along the azimuthal shower direction. A length ($L$) and a width ($W$) are assigned to the pattern and we place a cut on the ratio “$L/W$”. The apparent speed ($V$) of the shower front triggering station to station is also a useful variable for inclined showers discrimination. Regarding young shower selection, deep showers exhibit a relative large fraction of electromagnetic component leading to large signals in time. The Time over Threshold (ToT) local trigger [22] and the Area (integrated signal) over Peak (AoP) are variables sensitive to such signals. For the down-going analysis a Fisher method [4] is used to improve identification power. Table 2 summarises the set of cuts applied for the selection of deep inclined showers.

For the Fisher training a set of MC neutrino showers of all flavours interacting through charged (CC) and neutral (NC) current has been simulated. To account for all possible background effects, we use a subset of real data as background training sample. Applying the method to data collected by the SD between 1 Jan 2004 and 31 May 2010, no candidates were found [23]. Assuming a differential flux $J_{\nu}(E_\nu) = kE_\nu^{-2}$ we place upper limits at 90% CL for the single-flavour Earth-skimming neutrinos of $k < 2.8 \cdot 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ in
Figure 4. Upper limits (90% C.L.) for the integral flux of neutrinos from a point-like source as a function of source declination.

Table 2. Inclined and young shower selection for Earth-skimming and Down-going neutrino analyses. Speed \( (V) \) in units of m ns\(^{-1}\).

| Selection  | Earth-skimming | Down-going |
|------------|----------------|------------|
| N° Stations \( \geq 3 \) | N° Stations \( \geq 4 \) | \( L/W > 5 \) |
| Inclined \( 0.29 < V < 0.31 \) | \( V < 0.313 \) | \( RMS(V)/V < 0.08 \) |
| RMS(V) \( < 0.08 \) | \( \theta > 75^\circ \) |
| Young     | ToT fraction > 0.6 | AoP based Fisher |

the energy range \( E_{\nu} \in [1.6 \cdot 10^{17}, 2.0 \cdot 10^{19}] \) eV and for single-flavour down-going neutrinos of \( k < 1.7 \cdot 10^{-7} \) GeV cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) in the energy range \( E_{\nu} \in [1 \cdot 10^{17}, 1 \cdot 10^{20}] \) eV. The results, accounting for systematic uncertainties using the method described in [24], are shown in figure 3.

Additionally, the SD of the Pierre Auger Observatory is sensitive to point-like sources of neutrinos over a broad declination range spanning north of \( \delta \sim -65^\circ \) and south of \( \delta \sim 55^\circ \). The point source exposure and the derived limit at each \( \delta \) are evaluated in the same energy region and in a similar way as the diffuse exposure but avoiding to integrate over the solid angle [25].

Figure 4 shows the upper limits for both analyses as a function of declination.
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