Analysis of inclined air showers and search for ultra-high energy neutrinos and photons with the Pierre Auger Observatory

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Abstract. The Pierre Auger Observatory distinguishes itself by its capability to detect showers arriving at the ground with zenith angles up to 90°, and provides a unique tool to search for primary photons and neutrinos in ultra-high energy cosmic rays. From a dedicated analysis of inclined air showers with zenith angles larger than 60°, we present the updated cosmic-ray energy spectrum above $4 \times 10^{18}$ eV and a measurement of the muon number in inclined showers at ground level. We also present the latest results on the search for UHE neutrinos and photons, reporting updated upper limits on the diffuse fluxes of ultra-high energy neutrinos and photons in the sub-EeV range and above. In addition we report the sensitivity of the Surface Detector to neutrinos from point-like sources.

1. Introduction
Inclined air showers are conventionally defined as those induced by cosmic rays arriving with zenith angles $\theta > 60°$. They are characterized by the dominance of secondary energetic muons at ground. Their analysis is of great interest because it enhances the exposure of existing air shower detectors up to about 30% with respect to that achieved with vertical showers only, extending the field of view to sky directions otherwise inaccessible. Since inclined showers are mainly composed of muons, their study provides a direct measurement of the muon content at ground level and as a consequence, they can be used to study mass composition and to test high-energy hadronic interaction models. In addition, inclined showers constitute the main background against which the search for high-energy neutrino-induced showers has to be performed.

The composition of primary ultra-high energy cosmic-ray (UHECR) flux in the range above EeV is still unknown. Some theoretical models predict the existence of ultra-high energy (UHE) neutrinos and photons. In this energy range, they are expected to be produced in the same scenarios of cosmic ray production. In conventional models they are expected to be produced in interactions of cosmic rays within their sources or in their propagation through the cosmic microwave background (CMB) radiation [1, 2]. Exotic scenarios predict larger fractions of UHE neutrinos and photons [1, 3]. Therefore, the identification of these UHE astroparticles would be a great step towards the understanding of the origin of UHECRs.

The Pierre Auger Observatory [4] was conceived to characterize the properties of nucleonic UHECRs with energies above $10^{18}$ eV by measuring the extensive air showers induced in the...
Figure 1. Left panel: Shower size $N_{19}$ as a function of the FD energy. The solid line is the calibration fit to $N_{19} = A(E/10^{19}\text{eV})^B$ with $A = (2.13 \pm 0.04 \pm 0.11 \text{(sys)})$ and $B = (0.95 \pm 0.02 \pm 0.03 \text{(sys)})$. Prediction of $N_{19}$ vs FD energy based on simulation results of proton QGSJETII (···) and iron EPOS1.99 (- - -) is shown for comparison. Right panel: The cosmic ray flux $J(E)$ above $4 \times 10^{18} \text{eV}$ derived from inclined events with zenith angles $62^\circ < \theta < 80^\circ$.

Earth’s atmosphere. It is a hybrid detector that combines two detection techniques: a surface array of Cherenkov detectors (SD) and a network of fluorescence telescopes (FD). In particular, the design of the surface stations allows one to detect inclined particles, converting the SD into a fully efficient instrument to detect showers with zenith angles up to 90° at energies above $4 \times 10^{18} \text{eV}$. Apart from this first goal, its technical characteristics turn it into a unique tool to detect showers induced by primary UHE $\nu$’s and $\gamma$’s in the sub-EeV range and above.

The paper is organized as follows. In Sec. 2, the latest results from the analysis of inclined showers detected by the Pierre Auger Observatory are reported. In Sec. 3, the updated upper limit on the diffuse flux of UHE-$\nu$ and the sensitivity to neutrinos from point-like sources are shown. Finally, bounds on the photon flux obtained from hybrid data are presented in Sec. 4.

2. Analysis of Inclined Showers

Inclined showers generate asymmetric and elongated signal patterns in the SD with narrow pulses in time, typical for a muonic shower front. These events are selected using a chain of quality cuts and triggers, mainly based on conditions of space-time compatibility of the event with a plane front [5]. After event selection, the arrival direction of the cosmic-ray is determined from the relative arrival times of the shower front at the triggered stations by fitting a shower front model. The shower size $N_{19}$, which is proportional to the total number of muons and scales only with the primary energy and mass, is reconstructed using special techniques, in which a set of muon densities at the ground derived from simulations is compared with experimental data [6]. The reconstruction chain has been validated with simulations [6], resulting in an angular resolution above 4 EeV better than 0.5° with systematic uncertainty in both zenith and azimuth angles less than 0.05°, and in a resolution in $N_{19}$ better than 20% with a systematic uncertainty less than 3%.

The energy of each event is obtained by calibrating $N_{19}$ with the FD energy from a set of high-quality hybrid events observed simultaneously with FD and SD as described in [7] and illustrated in Fig. 1 (left). The calibration also provides a direct measurement of the number of muons in the shower as a function of energy. This quantity is sensitive to the cosmic ray composition and to hadronic interactions in the showers (see Fig. 1 (left)). The number of muons estimated from data exceeds that in proton showers simulated with QGSJETIII by a factor 2.1 and in iron showers simulated with EPOS1.99 by a factor 1.23, without showing a
significant energy dependence in either case [6]. As demonstrated in the analysis, none of the current models, neither for proton nor for iron primaries, are able to predict as many muons as are observed in data.

Inclined events recorded by the SD from 1 Jan 2004 to 31 Dec 2010 have been analyzed with the procedure outlined above, resulting in 5936 reconstructed events with 62 significant energy dependence in either case [6]. As demonstrated in the analysis, none of the uncertainty of the flux due to the calibration is by dividing the energy spectrum by the exposure is shown in Fig. 1 (right). The systematic uncertainty of the flux due to the calibration is \( \sim 13\% \) at 10 EeV, and the uncertainty due to the FD energy scale is \( \sim 22\% \). A power law \( E^{-\gamma} \) fitted to the spectrum between 6 and 40 EeV gives a spectral index \( \gamma_1 = (2.72 \pm 0.04 \pm 0.04 \text{ (sys.)}) \). A flux suppression above 40 EeV is observed, with a sharp break in the spectrum and a new spectral index \( \gamma_2 = (4.5 \pm 0.08 \pm 0.04 \text{ (sys.)}) \). The flux obtained from inclined showers agrees with the one obtained from vertical showers [8] within the systematic uncertainties.

3. Search for ultra-high energy neutrinos

UHE neutrinos can be detected and identified with the SD [9]. Earth-skimming \( \tau \) neutrinos (UG) are expected to be observed through the detection of “up-going” showers induced by the decay products of emerging \( \tau \) leptons after propagation and interaction via charged current of \( \nu_\tau \) inside the Earth. “Down-going” neutrinos (DG) of all flavours interacting via charged or neutral currents in the atmosphere, or \( \nu_\tau \) interacting via charged current in the mountains surrounding the surface array can induce a shower close to the ground potentially detectable by the SD.

The identification of \( \nu \)-induced showers in the background of showers initiated by hadronic UHECRs is based on a simple idea: \( \nu \)'s can penetrate large amounts of matter and generate “young” inclined showers at low altitude resulting in a thick and curved front with a significant electromagnetic (EM) component spread in time. In contrast, inclined showers induced by nucleonic UHE particles result in “old” muonic fronts narrower in time (see Sec. 2). Although the SD is not directly sensitive to the nature of the arriving particles, the time resolution of the digitized signal allows one to distinguish narrow signals in time from broad signals by using several observables that characterize the time structure of the signals.

Two different sets of identification criteria were designed to search for each kind of \( \nu \)'s. Searching for UG (DG) \( \nu \)'s in SD data collected from 1 Jan 2004 (1 Nov 2007) to 31 May 2010, no candidates were found [10]. Using the computed exposures and assuming a typical \( f_{\nu_\tau} = k \cdot E^{-2}_\nu \) differential \( \nu \) flux and a 1:1:1 flavour ratio, the updated single-flavour 90% C.L. limit based on UG \( \nu \)'s is: \( k < 3.2 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \) in the energy interval 0.16 - 20 EeV and the one based on DG is: \( k < 1.7 \times 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \) in 0.1 - 100 EeV (Fig.2).

Directional searches have also been carried out, given the good sensitivity of the SD to \( \nu \)'s from sources located in a large fraction of the sky [10]. For example assuming a point source flux as \( g_{\nu_\tau} = k^{PS} \cdot E^{-2}_\nu \) and a 1:1:1 flavour ratio, the single-flavour 90% C.L. upper limit for the case of the active galaxy Centaurus A based on UG neutrinos is \( k^{PS} \lesssim 8 \times 10^{-6} \text{ GeV cm}^{-2} \text{ s}^{-1} \).

4. Search for ultra-high energy photons

UHE photons can be detected at the Pierre Auger Observatory, after inducing showers with a deeper shower maximum \( X_{max} \) and a poorer muonic content than regular showers induced by hadronic primaries. This delayed development is due to the smaller multiplicity in EM interactions compared to hadronic ones, together with the LPM effect above 10 EeV. A dominant EM component is expected due to the lower cross sections for both photoproduction and direct muon pair production with respect to cross sections of EM processes.

The search for \( \gamma \)-induced showers can be done by using data recorded by the SD alone [11], with direct observations of the shower development from the FD alone [12], or combining
observables of both detectors. The latter procedure was recently updated to improve the photon-hadron discrimination and complement the previous analyses extending the energy region down to 1 EeV [13]. This new search is based on the $X_{\text{max}}$ measurement directly provided by the FD and on a new SD observable $S_b$ defined in [14]. Photon-like events are expected to have deeper $X_{\text{max}}$ and smaller $S_b$. The best performance of this combination of observables, compared to SD alone or FD alone, is reached at the lowest energies. Applying the new criteria to high-quality hybrid events, fulfilling $\theta < 60^\circ$ and with a good geometry reconstruction, in the period from 1 Jan 2005 to 30 Sep 2010, the photon candidates found were 6, 0, 0, 0 and 0 for energies above 1, 2, 3, 5 and 10 EeV (compatible with the 1% of nuclear contamination expected around 1 EeV). Using the computed exposure of the hybrid detector, the 95% C.L. upper limits on the integral photon flux is $8.1 \times 10^{-2}$ km$^{-2}$ yr$^{-1}$ above 1 EeV and $\sim 2.0 \times 10^{-2}$ km$^{-2}$ yr$^{-1}$ above 2, 3, 5 and 10 EeV. The results are shown in Fig. 3. Comparing these limits with the measured Auger spectrum [8], upper bounds on the fraction of photons of 0.4%, 0.5%, 1%, 2.6% and 8.9% are obtained for energies above 1, 2, 3, 5 and 10 EeV. This new analysis [13] improves significantly previous results at the lower energies, complement the previous constrains on top-down models and is approaching the GZK regime, where UHE-$\gamma$ are predicted by bottom-up models.

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