Search for ultra-high energy photons using the Pierre Auger Observatory

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1. Introduction

Photons are one of the theoretical candidates for ultra-high energy cosmic rays (UHECR) with energies larger than 10^{18} eV. A large fraction ($\sim 50\%$) of photons in the cosmic-ray spectrum at the highest energies is indeed predicted within several "top-down" models to explain the origin of cosmic rays. Severe constraints to these models were imposed by previous photon searches above 10^{19} eV [1]. A smaller contribution of typically (0.01 - 1)% above 10^{19} eV [2] is additionally expected as the product of the photoproduction of pions with the microwave background (GZK effect [3,4]). The Pierre Auger Observatory [5] has reported a suppression of the cosmic ray energy spectrum beyond $10^{19.6}$ eV [6] which is consistent with the predicted GZK cut-off for protons but could also be due to the photon disintegration of heavy nuclei or due to a limit in the maximum particle energy reached at the sources. The observation of a photon flux compatible with this theoretical prediction could provide an independent proof of the GZK process. The upper limits on the photon fraction were extended to 2 EeV in [7] using the hybrid detection mode provided by the Pierre Auger Observatory. The analysis was based on the measurement of the depth of the shower maximum, $X_{\max}$, since photon induced showers are expected to develop deeper in the atmosphere compared to hadrons. In addition, they are also characterized by a smaller number of secondary muons and a more compact "footprint" at the ground.

In this work, based on [8], the search for EeV photons with hybrid events is improved by: (i) combining observables of the fluorescence detector and the surface array for a better photon-hadron discrimination; (ii) extending the energy range down to 1 EeV; and (iii) determining bounds on the flux of photons.

2. Photon search

The Pierre Auger Observatory, located in Malargüe, Argentina, consists of a surface array (SD) [9] of 1660 water Cherenkov stations spread over an area of 3000 km^2 and overlooked by 27 air fluorescence telescopes [10]. The SD samples the density of the secondary particles of the air shower at the ground while the fluorescence detector (FD) observes the longitudinal development of the shower. The analysis presented in this work uses *hybrid* data (detected by at least one FD telescope and one SD station) collected between January 2005 and September 2010. Due to the FD duty cycle ($\sim 13\%$) the event statistics is reduced compared to the SD-only detection mode. However, the hybrid detection technique provides a precise geometry and energy determination with the additional benefit of a smaller energy threshold for detection (around the EeV range).

To improve the photon-hadron discrimination power we complement the previous analysis, based on the $X_{\max}$ measurement, with an SD observable, S_b, defined in [11] as

$$S_b = \sum_i S_i \left(\frac{R_i}{R_{\text{ref}}}\right)^b \tag{1}$$

where the sum runs over the triggered stations, S_i is the recorded signal in the station at distance R_i from the hybrid reconstructed axis and R_{ref} is a reference distance equal to 1000 m for this analysis. The exponent b is chosen equal to 4 for maximizing the separation power between photons and hadrons. The S_b parameter combines the different amplitude of the signal in the surface detector and the sharper lateral distribution function (i.e. the signals recorded in the SD stations as a function of distance from the axis) expected for photon induced showers. Events with zenith angle smaller than 60° and with a good geometry reconstruction are selected

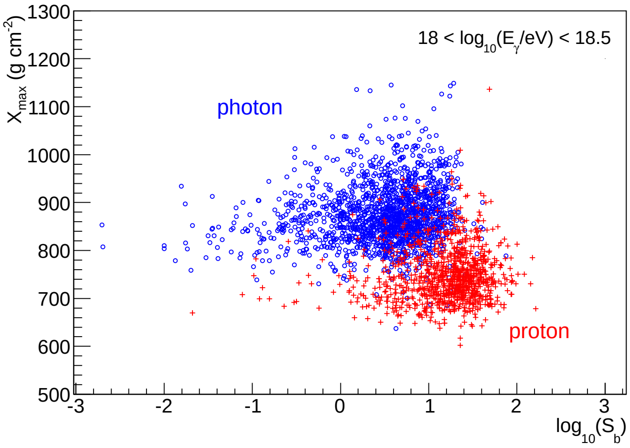

Figure 1. Scatter plot of $X_{\rm max}$ vs $\log_{10}(S_b)$ for proton (red crosses) and photon (empty blue circles) simulated showers with energy between 10^{18} and $10^{18.5}$ eV.

for the analysis. To ensure a reliable profile reconstruction we require: a reduced χ^2 of the longitudinal profile fit to the Gaisser-Hillas function smaller than 2.5, a χ^2 of a linear fit to the longitudinal profile exceeding the Gaisser-Hillas fit χ^2 by at least a factor of 1.1, the $X_{\rm max}$ observed within the field of view of the telescopes, the Cherenkov light contamination smaller than 50% and the uncertainty of the reconstructed energy less than 20%. To reject misreconstructed profiles, only time periods with the sky not obscured by clouds and with a reliable measurement of the vertical optical depth of aerosols [12,13], are selected. On the SD side we require at least 4 active stations within 2 km from the hybrid reconstructed axis. This prevents an underestimation of S_b (which would mimic the behavior of a photon event) due to missing or temporarily inefficient detectors. For the classification of photon candidates we perform a Fisher analysis [14] trained with a sample of a total of ∼30000 photon and proton CORSIKA [15] showers generated according to a power law spectrum between 10^{17} and 10^{20} eV. QGSJET-II [16] and FLUKA [17] are used as hadronic interaction models. To carefully reproduce the operating conditions of the DAQ, time dependent simulations are performed according to the hybrid detector on-time [18]. The actual configurations of FD and SD and realistic atmospheric conditions are also taken into account. The correlation between $X_{\rm max}$ and S_b is shown in Figure 1 for well reconstructed photon (empty blue circles) and proton (red crosses) showers, in the energy interval between 10^{18} and $10^{18.5}$ eV. Photon-like events are expected to lie in the top-left part of the plot because of the deeper $X_{\rm max}$ and of the smaller S_b. A Fisher analysis is performed in bins of 0.5 in the logarithm of energy and, for the moment, using only proton showers since they are expected to be the main source of background for the photon search. The impact of a mixed composition assumption will be discussed later. The best performance of this combination of observables, compared to FD-only or SD-only, is reached at the lowest energies. Particularly at higher energies, the main contribution to the Fisher observable comes from $X_{\rm max}$. Photon-like events are selected by applying an "a priori" cut at 50% of the photon detection 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 hadron contamination is about 1% in the lowest energy interval (between 10^{18} and $10^{18.5}$ eV) and it becomes smaller for increasing energies. 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. We checked with simulations that the observed number of photon candidates is consistent with the expectation for nuclear primaries, under the assumption of a mixed composition. For the two events with the deepest $X_{\rm max}$ (both larger than 1000 g cm^{-2}) the hadronic background has been individually checked by simulating 1000 dedicated proton CORSIKA showers with the same energy, arrival direction and core position as reconstructed for the real events. The actual SD and FD configurations at the detection time are considered.

3. Photon upper limits

The 95% CL upper limits on the photon flux $\mathbf{\Phi}_\gamma^{95CL}$ integrated above an energy threshold E_0 is given by:

$$\mathbf{\Phi}_\gamma^{95CL} = \frac{N_\gamma^{95CL}(E_\gamma > E_0)}{\mathcal{E}_{\gamma,\rm min}}. \qquad (2)$$

where E_γ is the reconstructed energy assuming that the primary particle is a photon (i.e., the calorimetric energy measured by FD plus a correction of about 1% due to the invisible energy [19]), N_γ^{95CL} is the number of photon candidates above E_0 at 95% of confidence level and $\mathcal{E}_{\gamma,\rm min}$ is the exposure of the hybrid detector. To be conservative, in equation (2) we use the minimum value of the exposure above E_0 and a possible nuclear background is not subtracted for the calculation of N_γ^{95CL}. An additional independent sample of 20000 photon showers is used for determining the exposure of the hybrid detector using a procedure as the one discussed in [18]. Events are selected with the same criteria applied to data, and the final exposure is shown in Figure 2 for photon primaries after the

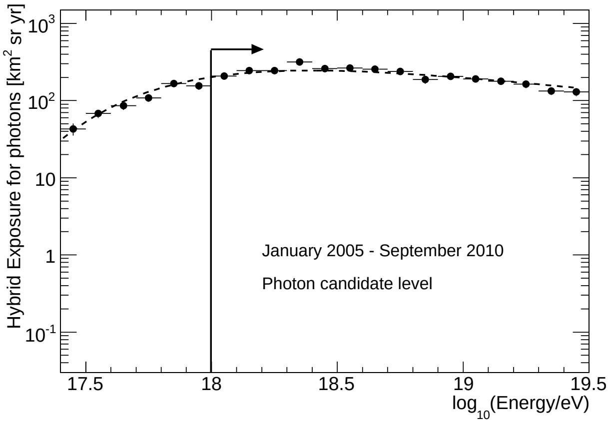

Figure 2. Exposure of the hybrid detector for photon primaries as a function of energy after all cuts.

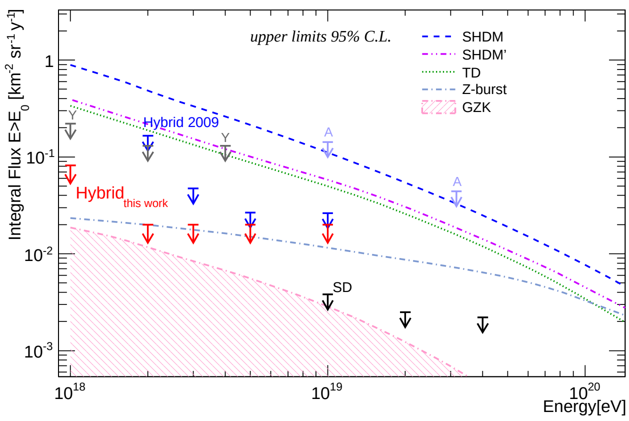

Figure 3. Upper limits on the photon flux above 1, 2, 3, 5 and 10 EeV derived in this work (red arrows) compared to previous limits from Auger (SD [1] and Hybrid 2009 [7]), from AGASA (A) [20] and Yakutsk (Y) [21]. The shaded region and the lines give the predictions for the GZK photon flux [2] and for top-down models (TD, Z-Burst, SHDM from [2] and SHDM' from [22]). The Hybrid 2009 limits on the photon fractions are converted to flux limits using the integrated Auger spectrum.

Fisher analysis and the "a priori" cut discussed before. To reduce the impact of statistical fluctuation, a fit of a Gamma function to the exposure values has been performed and is shown as a dashed line. The arrow indicates the energy region of interest for the analysis presented in this work. Upper limits on the integral photon flux of $8.2 \cdot 10^{-2}$ km^{-2} sr^{-1} y^{-1} above 1 EeV and $2.0 \cdot 10^{-2}$ km^{-2} sr^{-1} y^{-1} above 2, 3, 5 and 10 EeV are derived. They are shown in Figure 3 compared to previous experimental results (SD [1], Hybrid 2009 [7], AGASA [20]) and Yakutsk [21] and to model predictions [2,?]. The Hybrid 2009 limits on the photon fraction are converted to flux limits using the integrated Auger spectrum [6]. The bounds corroborate previous results disfavoring exotic models also in the lowest energy region. Comparing the flux limits on the measured Auger spectrum [6], upper bounds to 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.

We studied the robustness of the results against different sources of uncertainty. Increasing (reducing) all $X_{\rm max}$ values by the uncertainty $\Delta X_{\rm max} = 13$ g cm^{-2} [23] changes the number of photon candidates above 1 EeV by +1 (-2) not affecting the higher energies. As a consequence, this leads to an increase of ∼10% (decrease of ∼ 25%) of the first point of the upper limits. The uncertainty on the shower geometry determination corresponds to ΔS_b ∼5%, changing the number of photon candidates by ±0 (+1) above 1 EeV. The overall uncertainty on the hybrid exposure calculation for photons is about 5%. It includes the uncertainty due to on-time calculation (∼4%), input spectra for Monte Carlo simulations and dependence of the trigger efficiency on the fluorescence yield model (∼2%). Another source of systematic uncertainties is the energy scale which has been estimated to be about 22% [24]. An increase (reduction) of the energy scale, keeping the energy thresholds E_0 fixed, would change the upper limits by +14% (-54%) above 1 EeV and by +6% (-7%) above 2, 3, 5 and 10 EeV. This is a consequence of a different number of photon candidates ($^{+1}_{-4}$ in the first bin, unchanged in the others) and of the exposure ($^{-6\%}_{+7\%}$).

As the photon induced showers have an almost pure electromagnetic nature, no significant impact is expected when using another hadronic interaction model. However, since the Fisher analysis is also driven by the hadronic showers, we performed the same analysis using a sample of proton CORSIKA showers with QGSJET 01 [25]. In this case the separation capability improves by about 20% because this model predicts shallower $X_{\rm max}$ and a larger number of muons for proton showers. The number of photon candidates is then reduced by 1 above 1 EeV. The same effect is obtained when a 50% proton - 50% iron mixed composition assumption is used in the classification phase. The impact on the exposure is about a few percent.

4. Conclusions and Outlook

Using more than 5 years of hybrid data collected by the Pierre Auger Observatory we obtain an improved set of upper limits on the photon flux, in an energy region not covered by the SD-alone, and we extend the range of these limits down to 10^{18} eV. The derived limits on the photon fraction are 0.4%, 0.5%, 1.0%, 2.6% and 8.9% above 1, 2, 3, 5 and 10 EeV, significantly improving previous results at the lower energies, where limits well below the 1% level are reached now. These bounds also help reduce the systematic uncertainties on primary mass composition, energy spectrum and proton-air cross section measurements in the EeV range. The photon search conducted in this work benefits from the combination of complementary information provided by the fluorescence and surface detectors. While the focus of the current analysis was the low EeV range, future work will be performed to improve the photon-hadron separation also at higher energies using further information provided by the SD.

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