

# Search for Ultra-High Energy Photons with the Pierre Auger Observatory

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## Abstract

One of key scientific objectives of the Pierre Auger Observatory is the search for ultra-high energy photons. Such photons could originate either in the interactions of energetic cosmic-ray nuclei with the cosmic microwave background (so-called cosmogenic photons) or in the exotic scenarios, e.g. those assuming a production and decay of some hypothetical super-massive particles. The latter category of models would imply relatively large fluxes of photons with ultra-high energies at Earth, while the former, involving interactions of cosmic-ray nuclei with the microwave background - just the contrary: very small fractions. The investigations on the data collected so far in the Pierre Auger Observatory led to placing very stringent limits to ultra-high energy photon fluxes: below the predictions of the most of the exotic models and nearing the predicted fluxes of the cosmogenic photons. In this paper the status of these investigations and perspectives for further studies are summarized.

## Keywords

cosmic rays; ultra-high energy photons; upper limits to UHE photon fluxes

## 1 Introduction

So far, photon structure is most efficiently studied with the accelerator instruments, where available energies reach TeV. There is, however, some potential in exploring the cosmogenic photons as well. Despite the cosmic photon fluxes being extremely low in comparison to accelerator data, different physics mechanisms are involved at the production sites and during the subsequent propagation to the Earth. This gives prospects for a complementary study on photons. Also the energies of cosmogenic photons can be higher than in accelerators. Gamma astronomers report on power-law spectra of  $\gamma$ -rays extending without a cut-off or a spectral break to tens of TeV [1] and plan building instruments capable of detecting photons of energies up to 300 TeV [2]. But these are not the largest photon energies expected on Earth. Within the research concerning ultra-high energy cosmic rays (UHECR), i.e. particles with energies exceeding  $10^{18}$  eV, all the prominent scenarios predict photon fluxes reaching the Earth. One distinguishes two major classes of UHECR models: “bottom-up”, based on the acceleration and subsequent interaction of nuclei; and “top-down”, based on a decay or annihilation of hypothetical supermassive particles (see [3] for a review). The two classes differ significantly in the predicted fractions of photons among UHECR:  $< 1\%$  the former and even up to c.a. 50% the latter. Hence, determining the UHECR mass composition, including identification of photons or setting upper limits on their fluxes, is an effort towards distinguishing between the two major classes which should give a hint on photon production and properties at the highest energies. Moreover, it is worth emphasizing that any result on UHE photons, including non-observation, is meaningful for the foundations of physics at the highest energies, allowing constraints on e.g. Lorentz invariance violation (LIV) [4], QED nonlinearities [5], space-time structure [6] or the already mentioned “top-down” scenarios.

The searches performed so far have not confirmed the existence of UHE photons, resulting in setting upper limits to photon fluxes and fractions [7–11]. In this paper we summarize the recent advances

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in UHE photon search performed based on the data collected by the largest cosmic-ray instrument: the Pierre Auger Observatory [12, 13] resulting in setting the most stringent upper limits. The summary is based on Refs. [14], [15], and [16]. We also briefly sketch an outlook on the further possible efforts, complementary to the current searches, based on the cascade approach.

## 2 Photon signatures

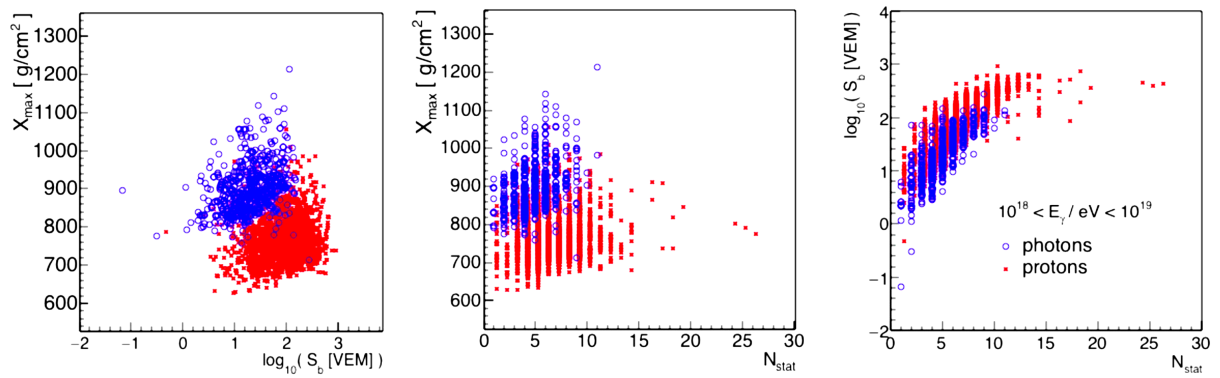
Investigations on cosmic rays of energies above  $10^{15}$  eV can be done only indirectly, through the interpretation of properties of extensive air showers (EAS) induced in the atmosphere by primary cosmic particles. The interpretation is made based on interaction models which incorporate cross section data from accelerators within the available energy range and assume extrapolations beyond this range. Obviously, the higher the primary energy under investigation, the higher the risk of being mistaken with the extrapolations being used to interpret the data. Another disadvantage and potential uncertainty is the progressing degeneracy of the information about primary particles and their first interactions in the atmosphere with the rise of subsequent generations of secondary particles. Thus, if there is some mistreatment in the models at the very beginning of an air shower creation and propagation, it might significantly affect the final outcome of the analysis. Keeping in mind all the theoretical assumptions implying the existence of uncertainties, an effort is being made to identify the ultra-high energy primary particles that initiate the largest air showers observed. The effort is based on using simulations to predict air shower properties, characteristic for primaries of different types and confronting these predictions with observations.

EAS initiated by UHE photons should possess two independent properties: significantly delayed development and reduced muon content [17]. The former signature is based on the assumption that at the highest energies the pair production formation length gets elongated so much that the destructive interference of the fields associated with the atoms and particles nearby the primary suppresses the pair production process in the upper atmosphere, thus delaying the first interaction and the consequent air shower development. This is so-called LPM effect [18], a standard in air shower modeling [20]. Here it is important to note that the LPM suppression is sensitive to the possible LIV effects including both increase and reduction of the pair production formation length [21]. While the former would strengthen the UHE photon discrimination power based on delayed air shower development, the latter would do the opposite: reduce or even invert the LPM effect, and hence make photon-induced air showers develop more similarly to those initiated by nuclei. The present state-of-the-art photon identification methods involving the expectation of a delayed development of an air shower induced by a photon assume the standard LPM effect, without any LIV effects.

The other expected property of photon-induced air showers, the low muon content  $N_\mu$ , is also founded on conventional physics assumptions concerning the photonuclear cross section  $\sigma_{\gamma-air}$ . Air shower muons are thought to originate mostly from the charged pion decays, and charged pions originate from hadronic interactions. Therefore the observed  $N_\mu$  should correspond to the size of a hadronic component of an air shower. If the interaction initiating an air shower is not hadronic, one would consequently expect that the hadronic component is initiated only by one of the secondary particles, thus its size and the corresponding  $N_\mu$  are smaller comparing to an air shower induced by a hadronic interaction. According to the standard extrapolations for a photon of energy  $E_\gamma = 10^{19}$  eV,  $\sigma_{\gamma-air}$  should be ca. 30 times smaller than the electron pair production cross section, although some existing models allow  $\sigma_{\gamma-air}$  to be only ca. 3 times smaller at the highest energies [17]. The energies of the secondary and virtual photons inside air showers are naturally lower than the primary energy and thus the  $\sigma_{\gamma-air}$  uncertainty is correspondingly lower. Since in any case one expects that primary photons at the highest energies would pair produce more readily than interact with air molecules, the hadronic component and  $N_\mu$  in the corresponding air showers will be in general smaller than in case of hadron-induced showers. The data collected so far by the Pierre Auger Observatory do not reveal muon-poor showers, just the opposite – the muon content seems to exceed the simulated values at the highest energies [22], which might point to a yet unconsidered physical source of uncertainty related to  $N_\mu$ .

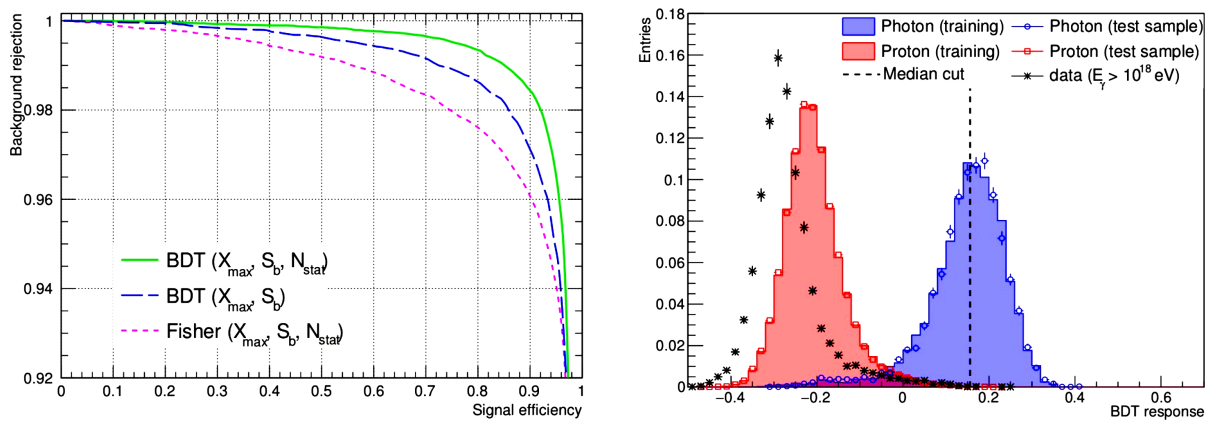
### 3 Diffuse photon flux and hybrid UHE photon limits with multivariate analysis

In this section we follow Ref. [15] to present the upper limits to diffuse UHE photon fluxes obtained using the hybrid detector of the Pierre Auger Observatory. The observables used for this analysis are tightly connected with the key photon signatures introduced in the previous section:  $X_{max}$  [g/cm<sup>2</sup>] – the depth in the atmosphere where an EAS reaches maximum of its development,  $N_{stat}$  – the number of triggered stations in an effective EAS footprint composed of the triggered stations, and  $S_b = \sum_i^N S_i (R_i/R_0)^b$ , where  $S_i$  and  $R_i$  are the signal and the distance from the shower axis of the  $i$ -th station,  $R_0 = 1000$  m is a reference distance and  $b = 4$  is a constant optimized to have the best separation power between photon and nuclear primaries in the energy region above  $10^{18}$  eV.  $S_i$  are measured in units of VEM (Vertical Equivalent Muon, i.e. the signal produced by a muon traversing the station vertically). Due to the standard LPM effect  $X_{max}$  in an EAS induced by a UHE photon is expected to occur deeper in the atmosphere than in the case of showers initiated by nuclei. On the other hand, the low muon content expected in showers initiated by UHE photons results in a lower trigger capability at larger distances, and consequently smaller  $N_{stat}$  and  $S_b$  when comparing to the footprints of hadron-induced EAS. The primary type discrimination power of the above three observables is illustrated in Fig. 1. The Boosted



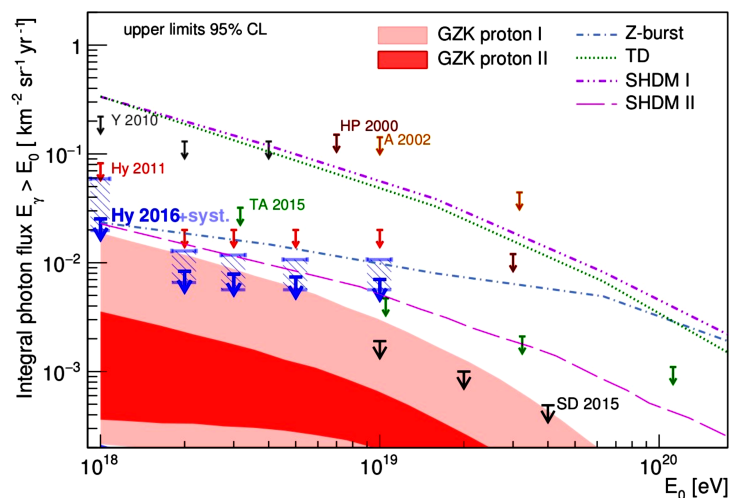
**Fig. 1:** Photon-proton discrimination power of the shower observables used for the UHE photon search in the hybrid detector of the Pierre Auger Observatory. [15]

Decision Tree (BDT) multivariate analysis method has been applied to the available data set using  $X_{max}$ ,  $N_{stat}$  and  $S_b$ . The BDT method has been chosen after examining several variants, as illustrated in the left panel of Fig. 2, leading to the optimal selection cut suitable for  $E_\gamma > 10^{18}$  eV (Fig. 2, right panel). The few photon candidates found in this way were checked to be consistent with the proton background



**Fig. 2:** The variants of the multivariate analysis method considered for the diffuse photon flux studies (left) and the selection cut on the response of the optimum variable (right). [15]

which led to determining the new hybrid upper limits to photon fluxes, as seen in Fig. 3. The new limits



**Fig. 3:** The newest hybrid upper limits to the diffuse photon fluxes based on the Pierre Auger Observatory data (blue arrows) and the corresponding uncertainties (dashed regions around the arrows) compared to the theoretical predictions (check Ref. [15] for references) and to the limits provided by other experiments. [15]

are more stringent in comparison to previous ones (see Ref. [9]), and the uncertainties of the limits are specified for the first time. The strong constraints on the “top-down” models can be concluded under the assumptions explained in Sections 1 and 2. For the first time also the photon flux predictions from one of the “bottom-up” scenarios (“GZK proton I”) are constrained below  $E_\gamma=10^{19}$  eV. The reader is referred to Ref. [15] for details and references.

#### 4 Directional blind search

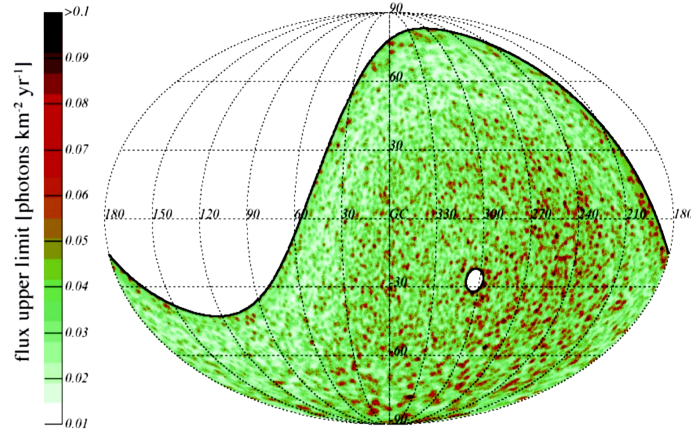
Complementing the diffuse photon flux study, the Pierre Auger Observatory performed also the blind search for arrival directions where photon excesses could be observed [14]. While the diffuse flux study aims at identifying all the photon candidates regardless their arrival directions, the directional blind search tries to identify photon candidates grouping directionally, and thus pointing to possible photon sources. The sensitive search for point sources was performed within a declination band from  $-85^\circ$  to  $+20^\circ$ , and in an energy range from  $10^{17.3}$  eV to  $10^{18.5}$  eV, where the photon fluxes are not precluded by the diffuse photon search. No photon point source has been detected and an upper limit on the photon flux has been derived for every direction. In the study the method to derive a skymap of upper limits to the photon fluxes of point sources (Fig. 4) was specified.

#### 5 Targeted search

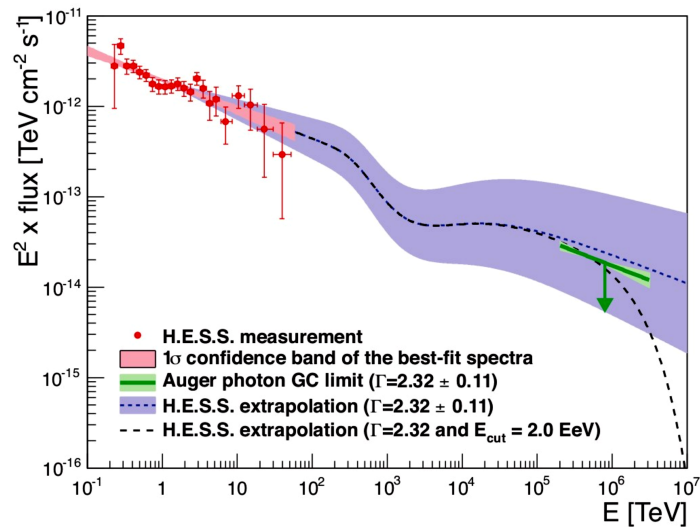
To reduce the statistical penalty of many trials from that of a blind directional search in Ref. [16] several Galactic and extragalactic candidate objects were grouped in classes and analyzed for a significant photon excess above the background expectation. No evidence for photon emission from candidate sources was found and the corresponding particle and energy flux upper limits were given. These limits significantly constrain predictions of EeV proton emission models from non-transient Galactic and nearby extragalactic sources, as illustrated for the particular case of the Galactic center region (Fig 5).

#### 6 Summary and Outlook

In this report the status of the ultra-high energy photon search at the Pierre Auger Observatory is summarized with emphasis on the recent advances, including the searches for the diffuse UHE photon flux,



**Fig. 4:** Celestial map of photon flux upper limits in photons  $\text{km}^2\text{yr}^{-1}$  illustrated in Galactic coordinates. [14]



**Fig. 5:** Photon flux as a function of energy from the Galactic center region. Measured data by H.E.S.S. are indicated, as well as the extrapolated photon flux at Earth in the EeV range, given the quoted spectral indices ([1]; conservatively the extrapolation does not take into account the increase of the  $p$ - $p$  cross section toward higher energies). The Auger limit is indicated by a green line. A variation of the assumed spectral index by  $\pm 0.11$  according to systematics of the H.E.S.S. measurement is denoted by the light green and blue band. A spectral index with cutoff energy  $E_{\text{cut}}=2.0 \times 10^6$  TeV is indicated as well. [16]

emission from discrete sources and targeted photon search. Although none of the searches performed so far proved an existence of ultra-high energy photons, the diffuse, directional and grouped upper limits to photon fluxes provide valuable astrophysical constraints. The end of the road to discovering UHE photons in the Pierre Auger Observatory has not yet been reached. The new substantial amount of data of increased sensitivity to primary mass will be acquired within the next several years with the AugerPrime upgraded detectors [13] which could lead either to identification of photons or to further constraints on the “bottom-up” predictions.

The UHE photon search can be continued also with alternative methods. UHE photon sensitivity comparable to the Pierre Auger Observatory is possible e.g. with the Cherenkov Telescope Array [23]. Considering  $\gamma$ -ray detection technique for the UHE photon search implies using an alternative set of observables, unreachable by standard cosmic-ray arrays. The first studies in this direction point to a chance for a very precise identification of a photon primary or photon pre-shower, even event-by-event [24, 25].



Another interesting scenario involving UHE photons and their interactions is based on questioning some of the assumptions underlying the physical interpretation of the presently reported non-observation of UHE photons. In these scenarios (e.g. LIV with rapid photon decay) UHE photons produced at astrophysical distances have very short lifetimes and have a negligible chance to reach Earth [26–29]. On the other hand, the experimental verification of such models would be possible only if there is a chance to observe at least partly the products of UHE photon interactions: extensive cascades of cosmic rays. Such a chance should then be determined for the scenarios leading to UHE photon cascading in order to proceed with the experimental effort. Alternatively one could also think of a global cosmic-ray analysis strategy dedicated to hunting for large scale time correlations independently of the expectations from the existing theoretical models.

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