Ultra-high energy photon studies with the Pierre Auger Observatory

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***Abstract*. While the most likely candidates for cosmic rays above 10^{18} eV are protons and nuclei, many of the scenarios of cosmic ray origin predict in addition a photon component. Detection of this component is not only of importance for cosmic-ray physics but would also open a new research window with impact on astrophysics, cosmology, particle and fundamental physics. The Pierre Auger Observatory can be used for photon searches of unprecedented sensitivity. At this conference, the status of this search will be reported. In particular the first experimental limits at EeV energies will be presented.**

***Keywords*: UHE photons, upper limits, Auger**

I. Introduction

The composition of ultra-high energy cosmic rays (UHECR), i.e. those above 10^{18} eV, is still unknown. The Pierre Auger Observatory [1], the newly completed giant air shower detector, with its unprecedented event statistics, brings us closer than ever to resolving this issue. One of the theoretical candidates for UHECR are photons. The first photon searches based on Auger data resulted in upper limits on photon fractions and fluxes [2], [3]. So far, no primary CR photons were identified, the most significant upper limit on the photon fraction is 2% for photons of energies above 10 EeV, based on the data collected by the surface array of particle counters of the Pierre Auger Observatory. This limit severely constrains the family of 'top-down' models [4] which predict large photon contributions (up to 50%) to the observed CR flux. A smaller contribution with typical values around ∼0.1% is expected in 'bottom-up' models. Here, so-called 'GZK-photons' originate during the propagation of charged particles by photo-pion production with background radiation.

Until now, all UHE photon limits were placed at energies larger than 10 EeV. In this work the first limits for photons of energies down to 2 EeV are presented, based on the data collected by the Pierre Auger Observatory.

II. Data set and selection cuts

The Pierre Auger Observatory collects data with two independent techniques: a surface array of water Cherenkov detectors (Surface Detector - SD) and a network of fluorescence telescopes (Fluorescence Detector - FD). The analysis presented in this work concerns the *hybrid* data (i.e. events recorded by both detectors) collected between December 2004 and December 2007.

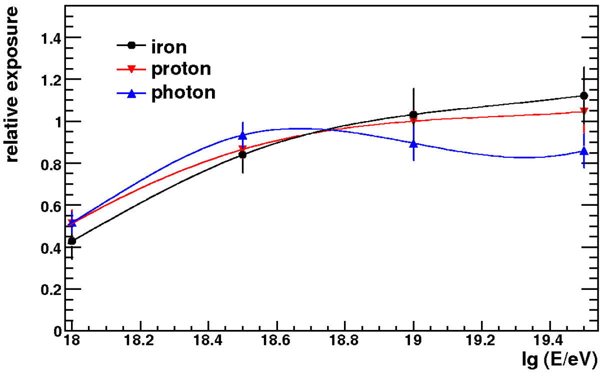

Fig. 1. Relative exposure to primary photons, protons and iron nuclei, normalized to protons at 10 EeV, after applying the quality and fiducial volume cuts with the requirement of the hybrid trigger (see text). In order to guide the eye polynomial fits are superimposed to the obtained values.

The hybrid data statistics are reduced comparing to the pure SD data because of the limited FD duty cycle (∼13% of the total time). On the other hand, the advantage of the hybrid technique is the direct observation of the longitudinal shower profile, reaching also to lower energies.

The requirements for the hybrid event selection include a good quality of shower longitudinal profiles (e.g. enough FD phototubes triggered, good quality of the profile fit, small contamination of direct Cherenkov light) and the shower maximum $X_{\max}$ within the FD field of view (see Ref. [5] and references therein). It has been proven before [2] that $X_{\max}$ is a powerful discriminating variable for photon searches (photon-induced showers in general reach their maxima deeper in the atmosphere than showers initiated by nuclei) and we make use of this fact here.

To avoid biases introduced by the above requirements a set of energy dependent fiducial volume cuts was introduced: nearly vertical showers and those landing too far from the detector were rejected from the analysis. Technical details and a complete list of the data selection cuts with explanations can be found in Ref. [5].

After applying the selection criteria the acceptances for photon and nuclear primaries are similar in the energy region of interest. This is shown in Fig. 1. The presented shower simulations were performed with CORSIKA [6] using QGSJET01 [7] and FLUKA [8] interaction models and processed through a complete detector simulation and reconstruction chain [9]. The application of all the cuts resulted in a data sample of $n_{\rm total}(E_{\rm thr})$ = 2063, 1021, 436 and 131 events above the predefined energy thresholds: $E_{\rm thr}$ = 2, 3, 5 and 10 EeV respectively. To account for the efficiency dependence on the primary energy, fiducial volume cut correction factors $\epsilon_{\rm fvc}(E_{\rm thr})$ = 0.72, 0.77, 0.77 and 0.77 were introduced for $E_{\rm thr}$ = 2, 3, 5 and 10 EeV respectively. These corrections are conservative and independent of the assumptions on the actual primary fluxes (see Ref. [5] for details).

The presence of clouds during shower detection could change the efficiencies shown in Fig. 1. In particular, the reconstructed values of $X_{\rm max}$ could be affected in case the measured longitudinal profile is partially obscured by clouds. In consequence, the primary particle could be misidentified. Thus, events are qualified as photon candidates only when IR cloud cameras could verify the absence of clouds. The fraction of events passing this cloud cut was determined by individual inspection of subsets of the data sample to be $\epsilon_{\rm clc} = 0.51$.

III. The photon upper limits at EeV

To calculate the photon limit, the number of photon candidates n_γ has to be specified for all the considered values of $E_{\rm thr}$. This is done by constructing the photon candidate cut as the median of the $X_{\rm max}$ distribution for photons. The relevant efficiency correction is then $\epsilon_{\rm pcc} = 0.5$. The values of the median were extracted with dedicated simulations performed for primary photons with geometry and energy corresponding to all the potential photon candidates. A parametrization for the typical median photon depth of shower maximum is shown as a solid line in Fig. 2, where the $X_{\rm max}$ values are plotted versus the reconstructed event energies above the lowest considered threshold (2 EeV) for all the events with $X_{\rm max} \geq 800$ g cm^{-2} after executing all the cuts discussed before. Statistical uncertainties are typically a few percent in energy and $\sim$ 15-30 g cm^{-2} in $X_{\rm max}$ while systematic uncertainties are $\sim$22% in energy and $\sim$11 g cm^{-2} in $X_{\rm max}$. The photon candidates are located above the *pcc* line in Fig 2: $n_{\gamma-{\rm cand}} = 8, 1, 0, 0$ for the considered threshold energies $E_{\rm thr}$ = 2, 3, 5 and 10 EeV respectively. It has been checked that the observed number of photon candidates is within the expectations in case of nuclear primaries only. In Fig. 2 the 5% tail of the proton $X_{\rm max}$ distribution is shown. We therefore conclude that the observed photon candidate events may well be due to nuclear primaries only.

With the candidate number and the efficiency corrections defined above, the 95% c.l. upper limit for photon fraction can be calculated as

$$F_\gamma^{95}(E_{\rm thr}) = \frac{n^{95}_{\gamma-{\rm cand}}(E_{\rm thr})\frac{1}{\epsilon_{\rm fvc}}\frac{1}{\epsilon_{\rm pcc}}}{n_{\rm total}(E_{\rm thr})\epsilon_{\rm clc}} \qquad (1)$$

where $n^{95}_{\gamma-{\rm cand}}(E_{\rm thr})$ is the 95% c.l. upper limit on the number of photon candidates. $n^{95}_{\gamma-{\rm cand}}(E_{\rm thr})$ was

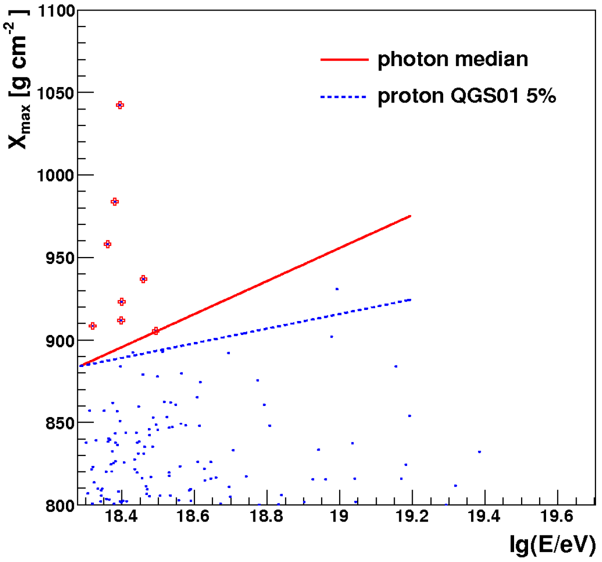

Fig. 2. Measured depth of shower maximum vs. energy for deep $X_{\rm max}$ events (blue dots) after quality, fiducial volume and cloud cuts. Red crosses show the 8 photon candidate events (see text). The solid red line indicates the typical median depth of shower maximum for primary photons.The dashed blue line indicates the 5% tail in the proton $X_{\rm max}$ distribution using QGSJET 01.

calculated using the Poisson distribution and conservatively assuming no background of nuclear primaries. The resultant 95% c.l. upper limits on the photon fractions are 3.8%, 2.4%, 3.5% and 11.7% for the primary energies above 2, 3, 5 and 10 EeV respectively.

The robustness of these results was checked against different sources of uncertainties. The variation of the selection criteria within the experimental resolution essentially does not affect the results. The effective total uncertainty in $X_{\rm max}$ for this analysis amounts to $\sim$16 g cm^{-2} (see Ref. [5] for details). Increasing (reducing) all the reconstructed $X_{\rm max}$ values by 16 g cm^{-2} increases (reduces) the number of photon candidates only for the two lowest energy thresholds: 2 and 3 EeV. The corresponding variations of the photon upper limits are: $F_\gamma^{95}(E_{\rm thr} = 2$ EeV$) = 4.8\%$ (3.8% – no variation) and $F_\gamma^{95}(E_{\rm thr} = 3$ EeV$) = 3.1\%$ (1.5%).

IV. Discussion

The current upper limits on photon fractions compared to theoretical predictions are plotted in Fig. 3. The Auger hybrid photon upper limits above 2, 3, and 5 EeV placed with this analysis are the first photon upper limits below 10 EeV. The limit above 10 EeV is an update of the previous Auger hybrid limit published in Ref. [2]. The predictions of 'top-down' models were tested here in a new energy range and the constraints from the Auger SD limits were confirmed by data taken with the fluorescence technique. It should be noted that the presented limits together with the one published in Ref. [2] are the only ones based on fluorescence data. It is also worth mentioning that the previous 10 EeV SD

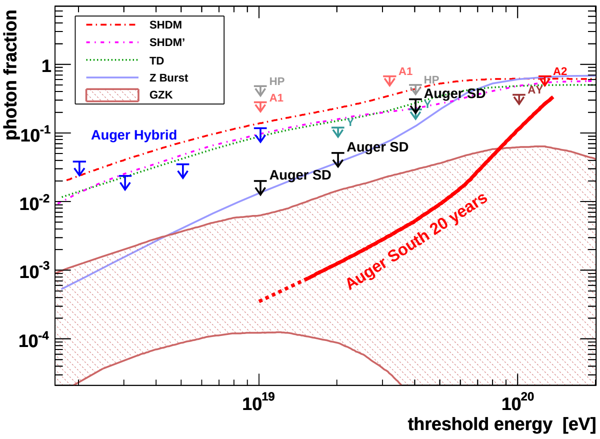

Fig. 3. Upper limits on the photon fraction in the integral cosmic-ray flux from different experiments. The limits from the Auger surface detector are labeled 'Auger SD' and the limits from this work – 'Auger Hybrid'. The thick red line indicates sensitivity of the southern site of the Auger Observatory to the photon fractions after 20 years of operation. The other lines indicate predictions from 'top-down' models and the shaded region shows the expected GZK photon fraction. The labels shown here are explained in [5].

limit only marginally constrains the photon prediction at lower energies: even for $E_{\rm thr} = 5$ EeV as many as 75% events have the energies in previously untested 5-10 EeV range.

The new limits reduce uncertainties related to the contamination of photons at EeV energies in other analyses of shower data. For instance, the possible contamination from photons was one of the dominant uncertainties for deriving the proton-air cross-section (see e.g. [10]). This uncertainty is now reduced to $\sim$50 mb for data at EeV energies, which corresponds to a relative uncertainty of $\sim$10%. Photon contamination is important also in the reconstruction of the energy spectrum or determination of the nuclear primary composition.

In future photon searches, the separation power between photons and nuclear primaries can be enhanced by adding the detailed information measured with the surface detectors in hybrid events.

V. Perspectives

The current exposure of the Pierre Auger Observatory is already a factor $\sim$4 larger than the exposure used for the 2% photon limit at 10 EeV. Hence, the Observatory starts to be sensitive to photon fractions within the predicted range of GZK photons and specific GZK scenarios will be tested by UHE photon searches for the first time. Within 20 years of operation the southern part of the Observatory the detection of photon events at fractions below $\sim$0.1% (above 10 EeV) will be at hand (see Fig. 3). The sensitivity to UHE photons will be significantly strengthened with the advent of the northern site of the Observatory in Colorado (USA). This site is planned to cover a surface a factor 7 larger than the one in Argentina.

The northern site of the Observatory will bring another opportunity related to the UHE photon search. Thanks to the difference between the local geomagnetic fields at the two sites a possible detection of UHE photons at Auger South may be confirmed in an unambiguous way at Auger North by observing the well predictable change in the signal from geomagnetic cascading of UHE photon showers [11].

The photon upper limits placed by the Auger Collaboration also address fundamental physics questions. The GZK photons are expected to be absorbed on scales of a few Mpc by pair production with background photons if Lorentz symmetry holds. On the other hand, violation of Lorentz invariance could lead to the observation of an increased photon flux. The new constraints placed on the violation of Lorentz invariance based on our photon limits are substantially more stringent than previous ones [12]. A future *detection* of UHE photons will further impact fundamental physics and other branches of physics (see e.g. [13]).

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