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

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Abstract

The Pierre Auger Observatory [1] has an unprecedented sensitivity to photons at energies above 10^{18} eV. Particularly the combination of ground array and fluorescence detection techniques offers a unique power to discriminate the primary particles based on different observables. Implications of photon searches extend from astrophysics to fundamental and particle physics. Current results and future prospects are reported.

Key words:
Pierre Auger Observatory, cosmic rays, upper limits, ultra-high energy photons

1. Introduction

In addition to the nuclear component of the Ultra-High Energy Cosmic Rays, a substantial photon flux, with fractions up to ~50% at the highest energies, is expected according to the predictions of the non-acceleration models [2]. Fractions at the level of ~ 0.1% [3] are expected from the decay of neutral pions produced in the interaction of nucleons with the cosmic microwave background (GZK effect). Discrimination between the different scenarios for the origin of the UHECR is possible, based on observables sensitive to the distinctive characteristics of extensive atmospheric showers. Deviation of data from expectations for showers induced by nuclear primaries can offer a clear signature for photons, detectable by fluorescence telescopes as well as by arrays of surface detectors. Hence, by combining both the detection techniques, the Pierre Auger Observatory hybrid instrument has an unique potential for these kind of searches. The detection of primary photons at these extreme energies will open a new window to the Universe, with large impact also on fundamental physics [4]. So far no observation of UHE photons has been claimed, but stringent limits on their fraction in the integral CR flux have been placed [5, 6]. These limits help to reduce uncertainties related to photon contamination in other air shower measurements like the determination of the primary composition and of energy spectrum and the derivation of the proton-air inelastic cross section.

2. Photon searches with the Pierre Auger Observatory

Showers induced by photon or nuclear primaries are expected to develop differently: distinctive characteristics of photon induced showers are a deeper shower maximum, X_{max}, and a smaller muonic component. The delayed development of photon showers is a consequence of the smaller multiplicity in electromagnetic interactions compared to hadronic interactions. Above 10 EeV the LPM effect becomes important and the development of photon induced showers is even further delayed with respect to the hadronic ones. The smaller cross sections for photonuclear and direct muon pair production are in turn responsible for the dominant electromagnetic component.

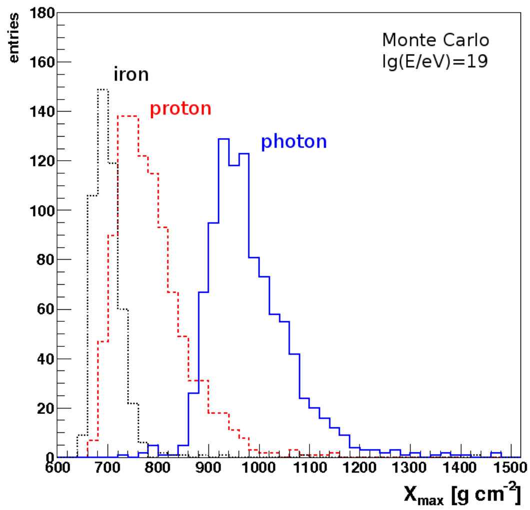

Figure 1: Discriminating observable for the Auger fluorescence detector: the depth of shower maximum, X_{max}. Distribution of X_{max} are shown for Monte Carlo events induced by photons (solid blue line), protons (dashed red line) and iron nuclei (dotted black line) at 10 EeV.

2.1. Searches with the Auger fluorescence detector

The key observable in searches for photon primaries with the Auger fluorescence detector is X_{max} itself. Since the fluorescence telescopes follows the longitudinal shower development, the derivation of the X_{max} position can be performed with very high accuracy. The procedure highly benefits from the small uncertainty in the geometry reconstruction of hybrid events, i.e. those events recorded by both the fluorescence telescopes and the ground array. In Fig. 1 the distribution of X_{max} , is plotted for Monte Carlo samples of showers induced by photons (solid blue line), protons (dashed red line) and iron nuclei (dotted black line) at 10 EeV. The difference between the average X_{max} value for showers induced by protons and photons at this energy is $\sim$ 200 g cm^{-2} . The shower-by-shower X_{max} resolution, obtained when information from the ground array is available, is $\sim$ 20 g cm^{-2} [7].

Based on the direct observation of the longitudinal shower profile by the Auger fluorescence detector a limit of 16% (95% c.l.) has been obtained on the photon fraction in the integral cosmic ray flux above 10 EeV (see Ref. [5]). For a sample of 29 high quality hybrid events, recorded in the period between January 2004 and February 2006, the measured depth of shower maximum has been compared to the theoretical expectations for showers of the same geometry and energy, but assuming a primary photon origin.

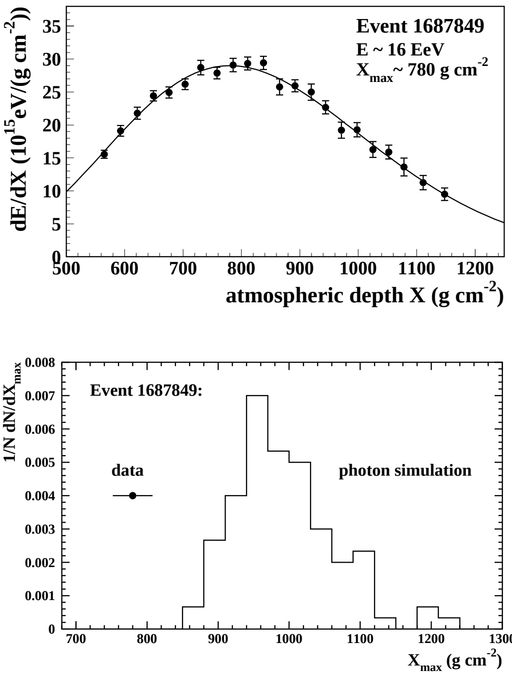

Figure 2: Upper panel: longitudinal shower profile of a typical event recorded by the Auger fluorescence detector. Lower panel: data point with statistical uncertainty along with X_{max} distribution from photon simulations. Figures from Ref. [5].

In Fig. 2 (upper panel) the reconstructed longitudinal profile is plotted for a typical event recorded by the Auger fluorescence detector. In the lower panel the data point is plotted along with the corresponding photon simulations. The difference between data and average photon X_{max} value corresponds to 2.9 in units of standard deviations, i.e. a photon origin is unlikely for this event. The probability for each event to be a photon has been then combined to derive the upper limit on the primary photon fraction. This limit has been the first derived by the use of the fluorescence technique, improving on and confirming the limits derived previously by ground array data.

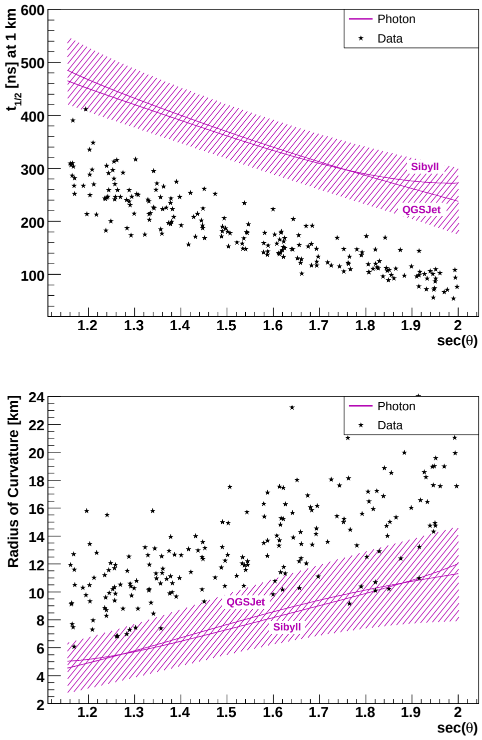

Figure 3: Discriminating observables for the Auger ground array: upper panel the signal risetime $t_{1/2}$, lower panel the radius of shower front curvature. The parameterization of the mean behavior for 20 EeV primary photons is plotted as a function of shower zenith angle along with a sample of real events. The deviation of the observed values from those expected for primary photons is evident. Figures from Ref. [6].

2.2. Searches with the Auger surface detector

The results of the search for UHE photons with the Auger surface array data, recorded between January 2004 and December 2006, have been published in Ref. [6]. A limit to the photon flux is derived by comparing photon-like events to the well known experimental exposure. The discriminating observables, connected to shower X_{max} and muon content, are: the risetime of the signal at 1000 m from shower core and the estimated shower front curvature. A detailed Monte Carlo study has been performed to characterize the behavior of photon induced showers. The distribution of arrival times of particles in the shower front is expected to become more dispersed for deeply penetrating events. The delay of the arrival times of particles at ground with respect to a planar shower front approximation is expected to increase with increasing X_{max} .

In Fig. 3 signal risetime (upper panel) and radius of shower front curvature (lower panel) are shown for a subset of the data along with photon simulations. The deviation of real data from photon expectations is evident. A combination of both the observables is obtained via principal component analysis. A cut is then set *a priori* at the median of the distribution of the simulated photon sample. No event in the large statistics dataset is found to be photon-like and the limit on the photon fraction is placed at the level of 2% (95%c.l.), see Fig. 6.

3. First limits in the EeV range with hybrid data

Observations in hybrid mode (i.e. observed by both the fluorescence and surface detectors) are also possible at energies below 10 EeV. Decreasing the energy threshold increases the event statistics, which to some extent balances the factor ~10 smaller duty cycle compared to observations with the ground array alone. A high quality hybrid data sample is selected, from data recorded between December 2004 and december 2007, by applying a set of reconstruction quality, fiducial volume and cloud cuts (for details see Ref. [8]). The quality criteria ensure the high accuracy in the shower geometry and longitudinal profile reconstruction. Events with large contamination of direct Cherenkov light and with X_{max} outside of the field of view are rejected. The criterion of X_{max} being observed can introduce a bias against the deeply penetrating photon primaries. To reduce the dependence of the detector acceptance on composition, a set of energy dependent fiducial volume cuts is applied, which rejects showers at small zenith angles and showers landing too far from the detector. The presence of clouds may affect the reconstruction of the longitudinal profile towards deeper X_{max} values. Clouds can in particular obscure the early parts of the shower profile, so that the remaining profile would be similar to that of deeply penetrating photon events. Therefore data are selected only when any disturbance by clouds can be excluded by the monitoring devices information.

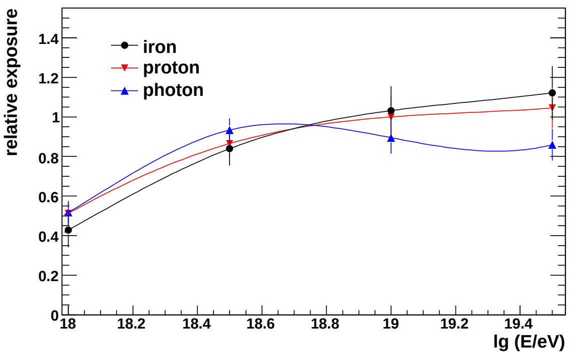

Figure 4: Relative exposure after trigger, quality cuts, and fiducial volume cuts for primary photons, protons and iron nuclei (normalized to protons at 10 EeV). Polynomial fits are superimposed to the obtained points. Figures from Ref. [8].

A detailed study of the detector efficiency as a function of energy for different primary particles has been performed with a high statistics CORSIKA sample [9]. In Fig. 4 the energy-dependent relative exposure obtained after trigger, quality cuts, and fiducial volume cuts for primary photons, protons and iron nuclei (normalized to 10 EeV protons) is shown. The acceptance for photons is close to the acceptance for nuclear primaries, and the relative abundances are preserved to a good approximation at all energies. An correction factor, conservative and independent of assumptions about the actual primary fluxes, is derived and applied to the selected data. For details see Ref. [8].

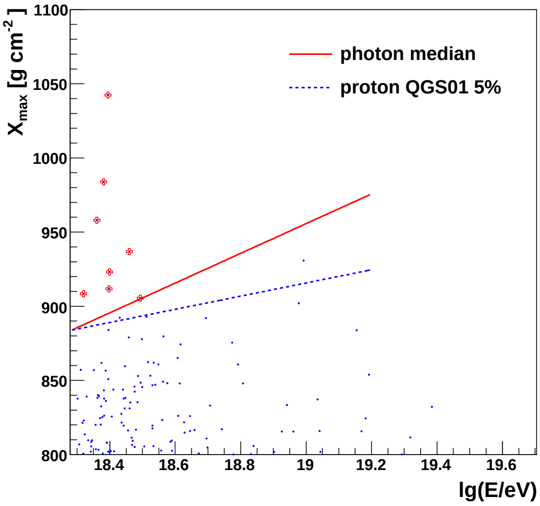

Figure 5: Closeup of the scatter plot of X_{max} vs energy for all events (blue dots) with X_{max} above 800 g cm^{-2} and energy above 2 EeV, all cuts applied. Red crosses show the 8 photon candidate events (see text). The solid red line indicates the typical median depth of shower maximum for primary photons. The dashed blue line results from simulations of primary protons. A fraction of 5% of the simulated proton showers has X_{max} values larger than indicated by the line. Figures from Ref. [8].

Applying the selection cuts to the data, there remain $n_{total}(E^{\gamma}_{thr})$ = 2063, 1021, 436 and 131 events with energies greater than E^{γ}_{thr} = 2, 3, 5 and 10 EeV respectively. The label γ in E^{γ}_{thr} indicates that the missing energy correction for photons [10] has been applied. Accepting only events where any disturbance by clouds can be excluded reduces the sample by a factor ~ 2. The closeup of the X_{max} vs energy plot for all the selected events with X_{max} above 800 g cm^{-2} and energy above E^{γ}_{thr} = 2 EeV, after quality, fiducial volume and cloud cuts, is shown in Fig. 5. Events with large X_{max} values are of interest, in particular events having X_{max} above the photon median value are deemed as "photon candidates". The observed X_{max} of all the photon-like events is compared with expectations from photon induced showers of the same geometry and energy.

Finally 8, 1, 0, 0 photon candidate events are found with energies greater than 2, 3, 5 and 10 EeV, respectively (red crosses in Fig. 5). Their number is used to obtain the upper limit to the photon fraction in the data sample above E^{γ}_{thr} after accounting for the corresponding efficiencies. The limit is largely independent of uncertainties related to hadronic interaction models and conservative as no nuclear background is subtracted. A simulation study has been performed in order to find out whether primary photons appear to be required to explain the photon candidates. The conclusions are that observations are compatible with the expectations from nuclear primaries.

Upper limits of 3.8%, 2.4%, 3.5% and 11.7% on the fraction of cosmic-ray photons above 2, 3, 5 and 10 EeV are obtained at 95% c.l.. The total uncertainty in X_{max} is ~16 g cm^{-2}. This includes the systematic uncertainty (~11 g cm^{-2}), the energy scale uncertainty (~7 g cm^{-2}) and the uncertainty related to the high-energy extrapolation of the photonuclear cross-section ($\sim$10 g cm^{-2}). Increasing (reducing) *all* reconstructed $X_{\max}$ values by this amount changes the limits to 4.8% (3.8%) above 2 EeV and 3.1% (1.5%) above 3 EeV, while the limits above 5 and 10 EeV are unchanged. Uncertainties connected to the variation of the selection cuts within the experimental resolution don't affect the derived limits.

The new hybrid limits [8] (Auger HYB) and surface array limits [6] (Auger SD) are shown in Fig. 6 along with other experimental results, model predictions and GZK bounds (see Ref. [8] and references therein). The thick red line (Auger South 20 years) is an estimate of the sensitivity to UHE photons of the southern Auger site after 20 years of operation, see Ref. [4].

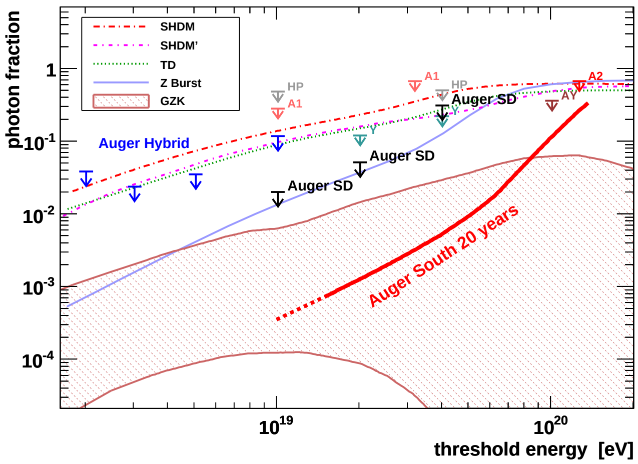

Figure 6: Upper limits on the photon fraction in the integral cosmic-ray flux for different experiments: AGASA (A1, A2), AGASA-Yakutsk (AY), Yakutsk (Y), Haverah Park (HP). In black limits from the Auger surface detector (Auger SD) [6], in blue the new Auger hybrid limits above 2, 3, 5, and 10 EeV (Auger Hybrid), see Ref. [8] and references therein. Lines indicate predictions from top-down models. The shaded region shows expected GZK bounds [3]. The solid red line (Auger South 20 years) is an estimate of the sensitivity to UHE photons of the southern Auger site after 20 years of operation, see Ref. [4].

4. Conclusions

The Pierre Auger Observatory already demonstrated its unique potential for UHECR photon searches. The published limits favor astrophysical scenarios for the origin of the highest energy particles putting severe constraints to the alternative non-acceleration models. The new hybrid limits are the first ones at energies below 10 EeV and, together with limits derived in Ref. [5], the only ones obtained so far from fluorescence observations (all other limits coming from ground arrays). The derived photon bounds provide a test of model predictions in different energy ranges and using different experimental techniques thus giving an independent confirmation of the model constraints. They help to reduce systematic uncertainties in the measurement of the primary composition and in other analyses regarding air showers, namely the energy spectrum [11] and the proton-air inelastic cross section [12]. The limits also support fundamental physics. In particular constraints on Lorentz invariance violation have improved on by several orders of magnitude [13].

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. The construction of the northern Auger site will allow the extension of the total collection area of a factor 8, highly incrementing the statistics and achieving the full sky coverage. Photon fractions below 0.1%, as expected due to the interaction of primary nuclei with the cosmic microwave background, will be soon in reach.

Acknowledgments

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