RESULTS ON ULTRA HIGH ENERGY COSMIC RAYS PRIMARY COMPOSITION AND SEARCH FOR PHOTONS WITH THE PIERRE AUGER OBSERVATORY

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The Pierre Auger Observatory is the world's largest instrument conceived to study the origin and nature of the highest energy cosmic rays, i.e. E $> 10^{18}$ eV. The "hybrid" design combines the ground array and the fluorescence detection techniques in order to characterize the extensive particle showers induced by the cosmic primaries in the Earth atmosphere. Data taking at the southern site has been running stable since 2004. Results on the UHECR primary composition studies are presented, focusing in particular on the search for photon primaries at these extreme energies.

1 Introduction

Composition studies are a key to understand the nature of the Ultra High Energy Cosmic Rays (UHECR). Measurements at the transition region from galactic to extra-galactic cosmic rays are especially crucial to clarify their origin and characterize their sources. Data collected at the Pierre Auger Observatory [1] suggest a mixed composition over the whole energy range [2]. Apparently in contrast, results from the different experiments are still compatible within the quoted systematics and the characterization of the astrophysical sources is still an open issue. Interpretation of the observations in terms of mass composition depends strongly on the assumed hadronic interaction models and related uncertainties [3]. Further improvement of the detection techniques and better knowledge of the experimental systematics, together with the increase of statistic are necessary. An overlap of the range of study between different experiments making use of complementary techniques will also be decisive.

A UHE photon component at the level of $\sim 0.1\%$ is also expected from the decay of neutral pions produced in the interaction of nucleons with the CMB [4]. Larger photon fractions (up to $\sim$50% at the highest energies) are predicted by the non-acceleration models [5]. 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 initiated by photons. So far no observation of UHE photons has been claimed, but stringent limits on their fraction in the integral CR flux have been placed. These limits also help to reduce uncertainties related to photon contamination in other measurements (i.e. derivation of energy spectrum [6], proton-air cross section [7]). The detection of primary photons at these extreme energies will in turn open a new window to the Universe, with large impact also on fundamental physics [8].

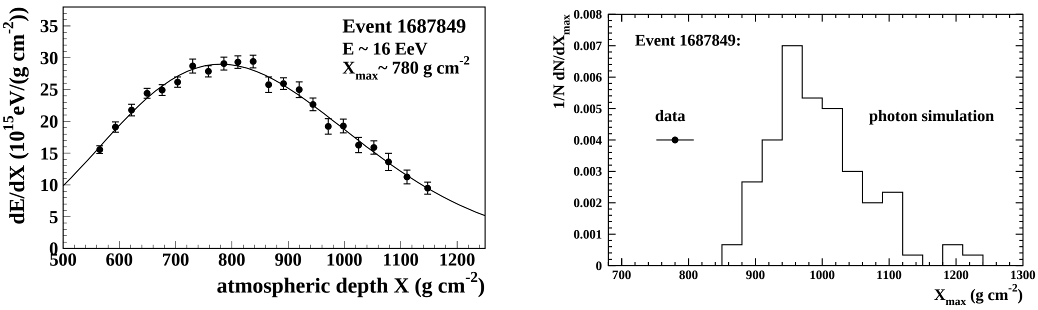

Figure 1: Left: longitudinal shower profile of a typical event recorded by the Auger fluorescence detector. Right: data point with statistical uncertainty along with $X_{\max}$ distribution from photon simulations. Figures from Ref. [9].

2 Photon searches with the Pierre Auger Observatory

Deviation of the recorded data from nuclear expectations can offer a clear signature detectable from both fluorescence telescopes and the surface detectors, using the most sensitive observables connected to the cascade development. By combining both the detection techniques, the Pierre Auger Observatory hybrid instrument has an unique potential for these kind of searches.

Based on the direct observation of the longitudinal shower profile by the Auger fluorescence detector a limit of 16% (95% c.l.) was obtained on the photon fraction in the integral cosmic ray flux above 10 EeV (see Ref. [9]). A sample of high quality reconstructed events was selected from the bulk of recorded data. The measured discriminant observable, the depth of shower maximum $X_{\max}$, was compared to the theoretical expectations for showers of the same geometry and energy, but assuming a primary photon origin. In Fig. 1 (left) the reconstructed longitudinal profile is plotted for a typical event. In the right panel the data point is plotted along with the corresponding photon simulations. The difference between data and average photon $X_{\max}$ value is $\sim 200\ \mathrm{g\,cm^{-2}}$, which corresponds to a deviation of 2.9 in units of standard deviations, i.e. a photon origin is unlikely for this event.

The results from the search for UHE photons with the Auger ground array have been published in Ref. [10]. The sensitive observable was in this case a combination of the risetime of the signal at 1000 m from shower core and the estimated shower front curvature. A detailed Monte Carlo study was performed to characterize the behavior of photon induced showers. A limit to the photon flux was derived by comparing photon-like events to the well known experimental exposure. The limit on the photon fraction was placed at the level of 2% (95%c.l.), see Fig. 4. In Fig. 2 shower front curvature and signal risetime are shown for data and photon simulations.

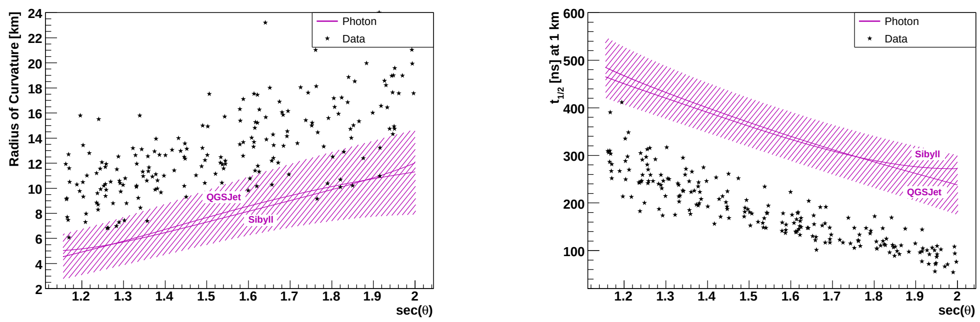

Figure 2: Shower front curvature (left) and signal risetime (right) for events recorded with the Auger surface detector (black) along with parameterizations from simulations of photon induced showers. Figures from Ref. [10].

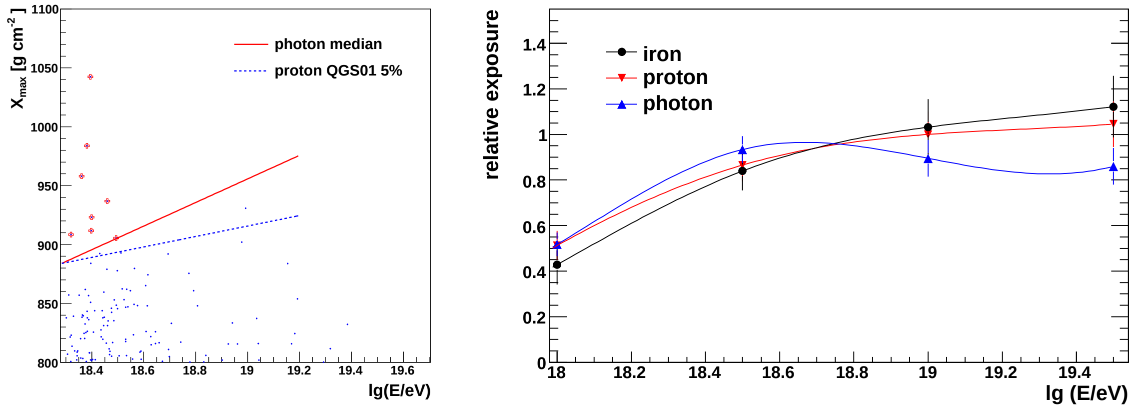

Figure 3: Left: closeup of the scatter plot of $X_{\max}$ vs energy for all events (blue dots) with $X_{\max}$ above 800 g cm^{-2} and energy above 2 EeV, all cuts applied. Red crosses show the 8 photon candidate events (see text). The solid red line indicates the typical median depth of shower maximum for primary photons. The dashed blue line results from simulations of primary protons. A fraction of 5% of the simulated proton showers had $X_{\max}$ values larger than indicated by the line. Right: relative exposure to primary photons, protons and iron nuclei normalized to protons at 10 EeV. Polynomial fits are superimposed to the obtained points. Figures from [11].

3 First limits on the photon fraction at EeV energies

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 has been selected applying a set of reconstruction quality, fiducial volume and cloud cuts (for details see Ref. [11]). 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 2 EeV is shown in Fig. 3 (left). Events with large $X_{\max}$ values are of interest, in particular events having $X_{\max}$ above the photon median value have been deemed as "photon candidates". The observed $X_{\max}$ of all the photon-like events has been compared with expectations from photon induced showers of the same geometry and energy. 8, 1, 0, 0 photon candidate events have been found with energies greater than 2, 3, 5 and 10 EeV, respectively (red crosses in Fig. 3 left panel). Their number, compatible with expectations from nuclear background, has been used to obtain an upper limit to the photon fraction in data by accounting for the corresponding cut efficiency. The limit is conservative and model independent as no nuclear background is subtracted.

A detailed study of the detector efficiency as a function of energy for different primary particles has been performed. 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, see Fig. 3 (right). A correction factor, conservative and independent of assumptions about the actual primary fluxes, has been derived and applied to the selected data [11].

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 have been obtained at 95% c.l.. Uncertainties connected to the variation of the selection cuts within the experimental resolution don't affect the derived limits. The total uncertainty in $X_{\max}$ is ∼16 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. The new hybrid limits [11] (Auger HYB) and surface array limits [10] (Auger SD) are shown in Fig. 4 along with other experimental results, model predictions and GZK bounds.

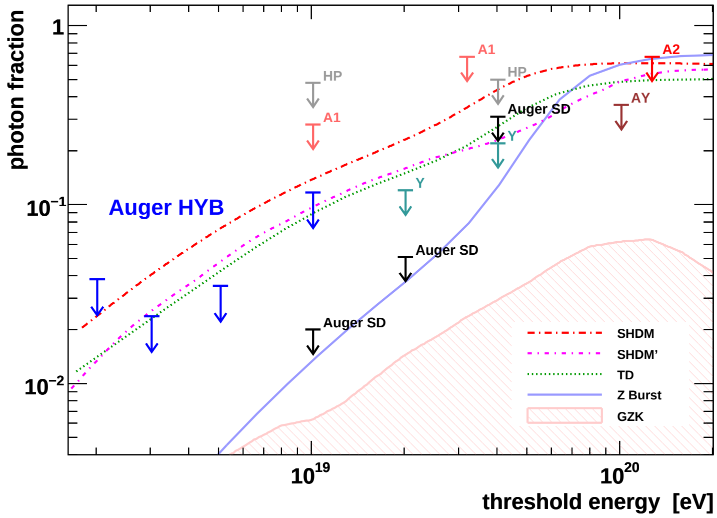

Figure 4: Upper limits on the photon fraction in the integral cosmic-ray flux for different experiments: AGASA (A1, A2), AGASA-Yakutsk (AY), Yakutsk (Y), Haverah Park (HP). In black limits from the Auger surface detector (Auger SD) [10], in blue new hybrid limits above 2, 3, 5, and 10 EeV (Auger HYB) [11]. Lines indicate predictions from top-down models. The shaded region shows expected GZK bounds [4]. Figure taken from Ref. [11].

4 Conclusions

The Pierre Auger Observatory already demonstrated his unique potential both for UHECR composition studies and UHE photon searches. 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. When completed by the northern site its collection area will increase of a factor 8 and gain unprecedented statistics at the highest energies. Photon fractions at the level of 0.1% (as expected from GZK precess) will be in reach.

Acknowledgments

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