Photon physics with Auger

Piotr Homola[1], for the Pierre Auger Collaboration

***Abstract*— The composition of ultra-high energy (UHE) cosmic rays above 10^{18} eV remains uncertain ever since they were discovered. While the most likely candidates for cosmic rays at highest energies are hadrons, most of the scenarios if not all of them predict also a photon component in the cosmic ray flux. Observing this component will be of vital importance not only for the cosmic ray physics it will also open a new research window with possible impact on astrophysics, cosmology, particle and even fundamental physics. The southern Pierre Auger Observatory, the world's largest new-generation cosmic ray detector, is currently the best scientific instrument to search for UHE photons. In this paper the current status of this search is reported including the newest Auger Collaboration upper limits for the fraction of photons in cosmic-ray flux. The perspectives are outlined for the photon search after the northern part of the Observatory is completed. An increased potential of photon search with the two observatory sites with significantly different local magnetic field is also discussed.**

I. Introduction

The ultra-high energy (above 10^{18} eV) cosmic rays, although discovered decades ago, are still poorly understood. Their origin, propagation and composition are uncertain. Seriously considered candidates for UHE particles include protons, heavier nuclei, photons and neutrinos. This paper summarizes the capabilities and first results of the Pierre Auger Observatory [1] concerning the contribution of photons to the observed flux of UHE cosmic rays. The UHE photons, if discovered, would open a new and valuable channel of multimessenger observations of the Universe.

There are two main classes of theoretical scenarios aiming at the explanation of highest energy cosmic ray origin. Both of them predict that photons should contribute to the UHE cosmic-ray flux. The first class, so-called "bottom-up" models, is based on conventional acceleration mechanisms. Charged particles can be accelerated to high energies in relativistic shocks nearby astrophysical objects like radiogalaxies or active galactic nuclei or during catastrophic events like collisions of galaxies. After escaping from the shock region the accelerated particles propagate through the Universe and interact with different types of background radiation. Among the products of these interactions are photons and neutrinos due to the GZK-type [2] process of resonant photo-pion production of UHE nucleons and cosmic microwave background. The "GZK photons" are expected to contribute to the cosmic-ray flux observed at Earth on the level of 0.1% [3]. The other class of cosmic-ray origin scenarios, so-called "top-down" or "exotic" scenarios, describe mainly decay processes of hypothetic supermassive X-particles which could originate in early Universe or at present as a result of decay or annihilation of early Universe relics like domain walls, cosmic strings or topological defects. The masses of X-particles should be larger than 10^{23} eV and their consecutive decays should result in substantial fluxes of photons and neutrinos seen among cosmic rays. The predicted photon fractions of the total cosmic-ray flux vary in different scenarios, but for the energies as large as 10^{20} eV they can reach even $\sim$50% [4]. This is much more than in case of conventional models. The difference in photon predictions from the two classes of models offers a unique possibility to verify the theory: identification of photons or specifying the upper limits for their flux or fraction should allow a discrimination between the "bottom-up" and "top-down" scenarios or even to narrow down the favored class to only few models.

[1]Institute of Nuclear Physics PAN, ul. Radzikowskiego 152, 31-452 Kraków, Poland, Piotr.Homola@ifj.edu.pl

II. UHE photons: simulations

Since cosmic rays above 10^{15} eV can be observed only indirectly through the extensive air showers, in order to identify cosmic-ray photons, a set of well-observable shower features characteristic for photon primaries is required. These can be found only through precise simulations of photon-induced air showers. An important process that should be simulated in case of photon primaries is the so-called *preshower* effect. Highest energy photons (E $> 10^{19}$ eV), in the presence of the geomagnetic field, can convert into e^+e^- pair which, in turn, emit secondary bremsstrahlung photons [5]. As a result, instead of one high energy photon, a bunch of lower energy particles, mainly photons and a few electrons, reaches the top layers of the atmosphere. Such a cascade is called a preshower since it originates and develops before the extensive air shower. The effect of pre-cascading depends on the energy of primary photon and on the component of the geomagnetic field transverse to the primary's motion. The latter dependence implies directional asymmetry of the effect intensity and dependence on the location of the observatory. A typical preshower originated by a photon of energy around 10^{20} eV and arriving more or less perpendicular to the local magnetic field starts around 1000 km a.s.l. and consists of one e^+e^- pair and $\sim$500 photons [6]. All the preshower particles can be regarded with a good approximation as propagating along the primary trajectory and arriving to the top of the atmosphere at the same time [6]. After entering the atmosphere, each of the preshower particles initiates an air subshower and the superposition of these subshowers is observed as one extensive air shower. The results presented in this paper were obtained with use of CORSIKA [7] and AIRES [8] programs which both include procedures that simulate the preshower effect.

A. Photon shower signatures

For detailed discussion of the characteristics of photon-induced showers the reader is referred to Ref. [9] and the references therein; only a short review of basic information is given below. The occurence of preshower and the directional dependence of this effect considerably influence the air shower development and properties. Without preshowering, an UHE photon initiates an air shower that develops significantly deeper (even by several hundreds of g/cm^2) in the atmosphere than in case of proton primary. Also the fluctuations of shower maximum depth (X_{max}) are larger for showers induced by UHE photons. This is due to the LPM effect [10] which suppresses the interaction cross section of electromagnetic particles with air. This suppression increases with primary energy and with density of the medium. At densities of the upper atmosphere the LPM effect starts to be important for photons of energies above 10^{19} eV. The properties of an air shower are different when the primary photon initiates a preshower above the atmosphere. Since in most cases the preshower particles have energies smaller than 10^{19} eV, they are not affected by the LPM effect and the resultant air shower develops faster than in case of non-converting photon primary, but with maximum still deeper than for a proton primary. It was investigated elsewhere (see Ref. [9] and the references therein) that X_{max}, its fluctuations and directional dependence allow for distinction between the photon and proton primaries. While X_{max} can be determined mainly with the air fluorescence technique, there are other photon signatures that should be seen with the array of particle counters at the ground. Out of these signatures, the most important one is the significantly reduced content of muons (N_μ) due to almost purely electromagnetic character of a photon-induced shower at the beginning of its development. For the purpose of this work we introduce below two more signatures that are partially dependent both on X_{max} and N_μ and which can be observed by the surface array.

Radius of curvature of the shower front Let's consider an imaginary planar shower front, a particle counter localized within this front at distance r from the shower core and shower particles that originate at height H and reach the selected front plane (see Fig. 1). For geometrical reasons, the particles hitting the plane at a distance r are delayed with respect to those moving along the shower axis. Therefore, the actual shower front is expected to be curved. A good approximation of its shape is a sphere. We note that the delay mentioned above decreases with increasing H. Consequently, the radius of front curvature R_c is sensitive to the depth of shower development: the air showers developing deep in the atmosphere (e.g. like those initiated by a photon, without pre-cascading) will form a front with R_c smaller than in case of showers developing earlier. Since photon-induced showers are expected to develop extraordinarily deep (in case no preshower effect occurs) compared to the other primaries, small R_c observed on ground should serve as a good primary photon signature.

Risetime of the signal in the surface detector Correspondingly, the time of arrival of particles originating within a certain pathlength ΔH is larger at lower altitudes (see Fig. 1). Automatically, the risetime of the signal recorded by the detector is longer for showers developing deep in the atmosphere. This in turn makes the risetime another promising signature of primary photons. In the studies presented throughout this paper the risetime $t_{1/2}(1000)$ denotes the time it takes to increase from 10% to 50% of the total shower signal reconstructed for 1000 m distance from the shower core and located along the line given by the projections of the shower axis onto the ground.

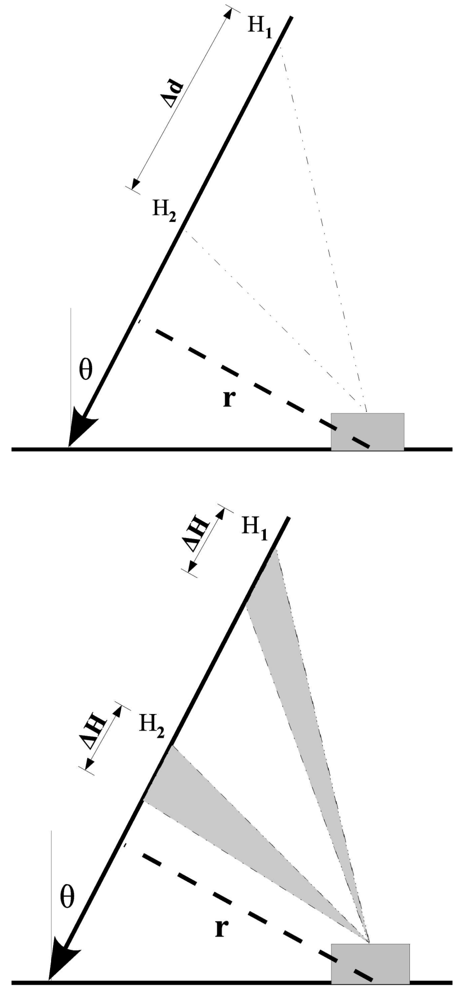

Fig. 1. Explanation of photon shower signatures: radius of curvature of the shower front (top) and risetime of the signal recorded by a surface detector (bottom). For details see the text. [12]

It should be noted that in realistic detection circumstances both R_c and $t_{1/2}(1000)$ are affected not only by the shower geometry but also by the history of its propagation. For instance, the shower muons should pass long distances without significant deflections which for showers with large muon content should result in larger R_c and shorter $t_{1/2}(1000)$. The reconstruction details and other information concerning these two observables can be found in Ref. [11] and [12].

III. Search for UHE photons: the Pierre Auger Observatory

Currently, the best instrument capable of detecting cosmic rays at highest energies (including, possibly, photons) is the Pierre Auger Observatory. The ∼3000 km^2 area near Malargüe, Argentina, covered by ∼1600 water Cherenkov detectors (so-called *tanks*) and 4 stations of 6 fluorescence telescopes each viewing the sky above the site[1] makes the Observatory the largest cosmic-ray instrument ever. Another part of the Observatory, to be located, for complementarity, on the northern hemisphere, is planned in Colorado, USA. Although the official inauguration of the Observatory took place in November 2008, the data has been taken since 2004 and its volume is already now larger than what was recorded by all the other UHE cosmic-ray experiments together. Apart from the scale, the other great advantage of the Pierre Auger Observatory is its hybrid detection technique: the surface array of particle counters and the telescopes detecting the fluorescence light induced by shower particles propagating through the atmosphere are the two independent ways to measure the shower properties. Having these two techniques working together enables better understanding of systematic errors related with each technique, a cross-calibration of the detectors, and, in consequence, a more precise reconstruction of shower arrival directions and primary energies.

Determination of composition of the highest energy cosmic rays is one of the main scientific goals of the Auger Collaboration. While hadrons are the main candidates for cosmic-ray primaries and the existing data seem to confirm this candidature, the magnitude of photon contribution is unknown. As mentioned above, all the models of cosmic-ray origin predict certain fractions of photons in the flux observed on Earth and these predictions differ significantly from each other. One of the Collaboration's tasks is the determination of the photon fractions at different energies or the relevant upper limits. This should enable discrimination between the existing theoretical models and get us closer to solving the mystery of the sources of the highest energy particles in the Universe.

A. *Upper limit for UHE photons with the Auger hybrid events*

In its first analysis concerning the UHE photons the Pierre Auger Collaboration studied the data set recorded during the period from January 2004 to February 2006 [13]. Only the hybrid events (recorded by both fluorescence and surface detectors) were considered. Several selection criteria had to be applied to the available data set in order to properly reconstruct shower properties and analyze the photon candidates. Main data quality cuts included: reconstructed event energy $> 10^{19}$ eV, minimum viewing angle of the shower direction $> 15°$, minimum number of triggered phototubes in the fluorescence detector ≥ 6, no observation disturbance by clouds, X_{max} within the telescope field of view. The latter

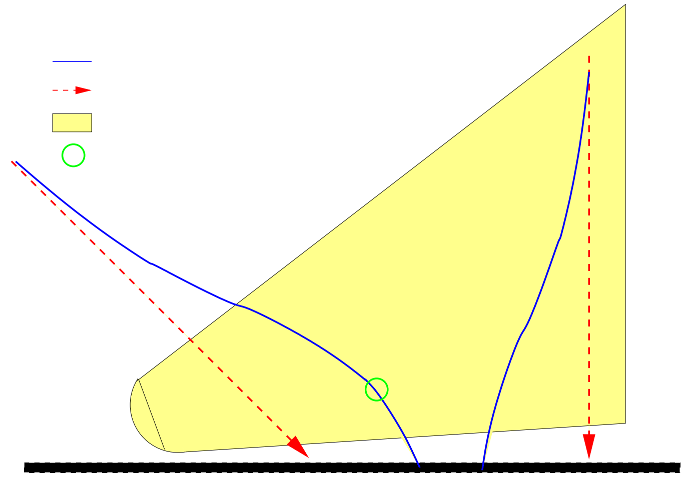

Fig. 2. Exemplary photon showers and the selection requirement of observing X_{max}. For further explanations see the text. [13]

condition is visualized in Fig. 2. Photon-induced showers start deep in the atmosphere and it may happen that nearly vertical events reach the ground before being fully developed - hence they have to be excluded from the analysis. Another limitation concerns the maximum distance of the shower impact point to the viewing telescope. Deeper X_{max} of a photon-induced shower means that the light emitted from the shower maximum towards the telescope passes through the air of higher density and hence it is more attenuated than in case of nuclear primaries which typically reach their maxima at larger altitudes. The increased attenuation implies a shorter maximum distance between the shower and the telescope.

After applying all the cuts, 29 events were left for the analysis. The investigated photon signature was X_{max}. Dedicated simulations (see also [19] for details on the method) with reconstructed parameters of each event (energy, arrival direction) as the input were performed. By comparison with the recorded data, the probability was determined that a particular event was initiated by a photon primary. Since in case of all the events the probabilities of photon origin were small (2 or more standard deviations from the data) an upper limit to the photon fraction could be determined. The result was 16% with the confidence level (CL) of 95%.

For details concerning the data selection, distributions of cut variables and analysis of the data the reader is referred to Ref. [13].

B. *Upper limits for UHE photons with the Auger surface detector events*

Another analysis was based on the events detected only by the Auger surface detector (SD) in the period between 1 January 2004 and 31 December 2006. Since SD works 24 h a day, the statistics of events is much (∼10 times) larger than in case of the hybrid events study. The most relevant and easily observable photon signatures for events recorded by the SD are R_c and $t_{1/2}$ defined above. The analysis was restricted to the events with reconstructed primary energies $\geq 10^{19}$ eV and arrival directions with zenith angles

[1]The fluorescence telescopes can operate only during clear, moonless nights.

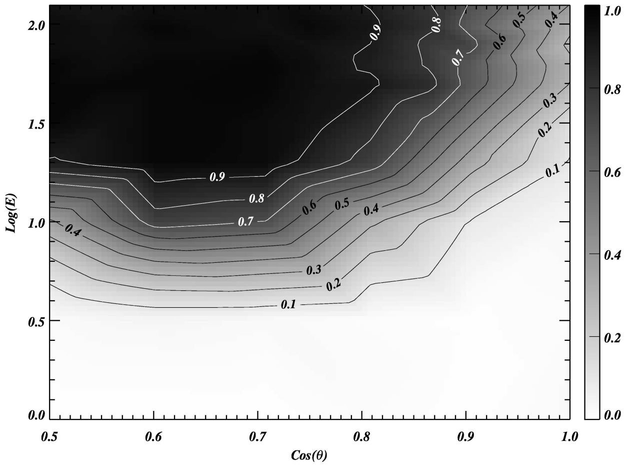

Fig. 3. Photon detection and reconstruction efficiency in the surface detector of the Pierre Auger Observatory. [12]

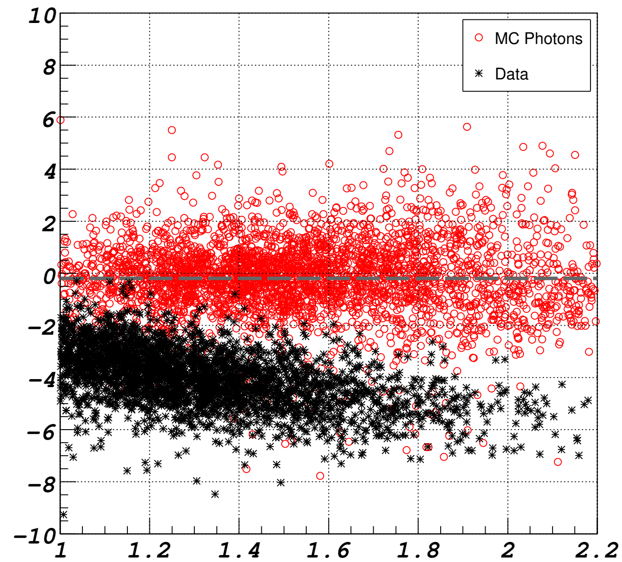

Fig. 4. The deviation of data and MC photons from the principal component as a function of energy. No data points above the line (mean of the MC photon distribution) means the lack of photon candidates. [12]

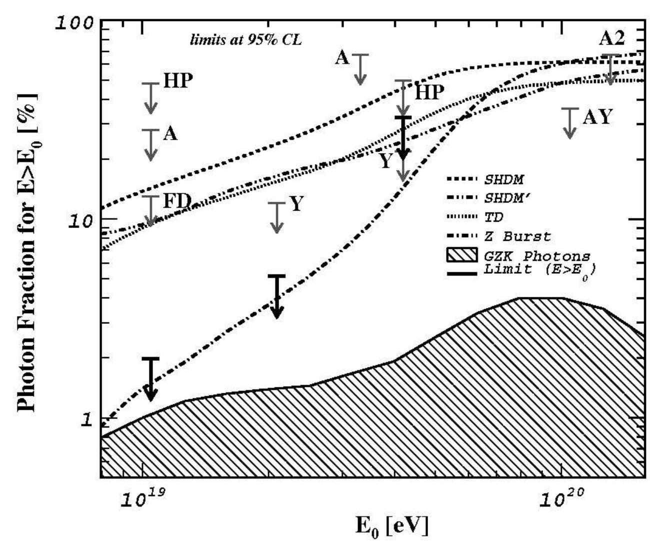

Fig. 5. Upper limits for the photon fraction based on the Pierre Auger Observatory data. The limits are compared with the predictions from the exotic scenarios (SHDM, TD and ZB from Ref. [3], SHDM' from Ref. [16]) and with the expectation bound for the photons originated from the GZK processes (from Ref. [3]). The thickest arrows denote the Auger results based only on the surface detector data and the label FD stays for the Auger photon limit based on the hybrid events. The previous experimental limits are also shown (HP: Haverah Park [17]; A1, A2: AGASA [18], [19]; AY: AGASA-Yakutsk [20]; Y: Yakutsk [21]). [12]

θ of 30−60° ($0.5 < \cos\theta < 0.87$; see the relevant plot in Fig. 3). For the selected energy threshold and with the applied quality cuts (see Ref. [12] for more details) the total number of events above 10, 20 and 40 EeV in the analyzed sample was, respectively, 2761, 1329 and 372 with the assumption of primary photons. If the primary hadrons are assumed the respective quantities are 570, 145 and 21. Different quantities of events are due to different energy reconstruction methods required for primary hadrons and photons ([14], [12]). 5% of the selected data were processed with the principal component analysis [15] by combining the information on R_c and $t_{1/2}$. The principal component axis was selected so that the variance of the sample is maximized. The deviation from the principal component axis for all the data and its dependence on the energy is plotted in Fig. 4. The data (black crosses) are compared to the photon MC simulations (open circles). The events above the mean for the MC photon distribution were to be regarded as photon candidates. But, as can be seen in Fig. 4, there are no such events. This enabled placing the following upper limits for photon fractions: 2.0% for $E > 10^{19}$ eV, 5.1% for $E > 2 \times 10^{19}$ eV and 31% for $E > 4 \times 10^{19}$ eV. The corresponding numbers for the limits of photon fluxes are 3.8 $\times\ 10^{-3}$, 2.5 $\times\ 10^{-3}$ and 2.2 $\times\ 10^{-3}\text{km}^{-2}\text{sr}^{-1}\text{yr}^{-1}$. All the limits were calculated at 95% CL. All the upper limits for UHE photon fractions calculated by the Pierre Auger Collaboration are summarized in Fig. 5. The comparison is made to the predictions of some representative exotic models of cosmic-ray origin, the expected bound for the photons originated from the GZK processes and the upper limits from other analyzes. It's clear from the plot that the Auger limits constrain seriously the exotic models. The future increase of statistics can bring either the more stringent upper limits or the identification of photons. The first case may discredit completely the exotic models while the latter one, provided the photon fraction is measured precisely enough, may point to a single model or specific family of scenarios.

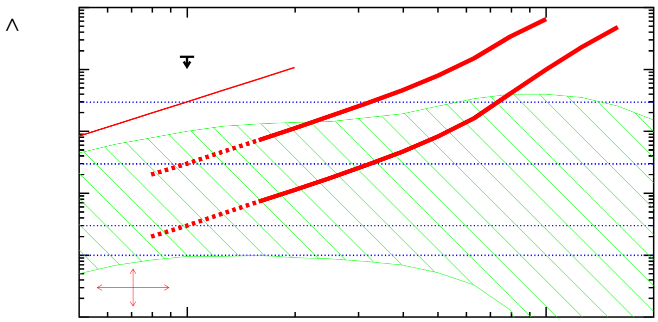

Fig. 6. Sensitivity of the southern site of the Pierre Auger Observatory to the UHE photon upper limits as a function of threshold energy. For comparison, the predictions for the GZK photons from primary nucleon sources following a spectrum with flux suppression are shown (as given in Ref. [3]). The uncertainty of the sensitivity is indicated at the lower left corner. The theoretical minimum numbers of events needed to exclude the fractions represented by the horizontal dotted lines are indicated on the right hand side of the plot. At around 10^{19} eV (dashed lines) additional threshold effects may become increasingly important for the array. [9]

A separate analysis performed by the Pierre Aguer Collaboration provided the upper limit for ultra-high energy tau neutrinos [22].

IV. Outlook

With the completed southern and northern parts of the Pierre Auger Observatory, the available statistics of data will soon enable further interesting investigations related with UHE photons. Some highlights are presented below.

A. GZK photons

Even in case the exotic scenarios have to be abandoned, one still should expect to detect photons produced through the GZK processes. The capability of the southern Auger Observatory to detect these showers can be drawn out from the plot shown in Fig. 6. The plot shows the predicted sensitivity of the southern site of the Observatory to the upper limits for photons as a function of threshold energy. The predictions for the GZK photons from primary nucleon sources following a spectrum with flux suppression (as given in Ref. [3]) are also shown. In case no photon candidates are seen in the data, the upper limits, on the plot represented by the thick lines, could be set. The lines are given for a short- and long-term perspective. At around 10^{19} eV (dashed lines) additional threshold effects may become increasingly important for the array. In addition, the possible limits from the hybrid data are shown. The theoretical minimum numbers of events needed to exclude the fractions represented by the horizontal dotted lines are attached to each line on the right hand side of the plot (see Ref. [9] for details). It can be seen that the limit of 1% at the energies larger than 10^{19} eV can be reached within the next few years of operation of the southern site of the Observatory, while the fractions typical for the GZK photons (0.1% or less) may not be observed within the whole period of the site's operation. However, with the successful completion of the northern part of the observatory, the chance for observations of the GZK photons will be significant.

B. Photonuclear cross section constraints

Another promising issue is related with the possibility of constraining the predictions of photonuclear cross section at the highest energies. The process of reconstruction of shower properties depends heavily on simulations. This introduces a major uncertainty to the results, especially in case of hadron primaries where simulations at the highest energies have to rely on models extrapolated even over several orders of magnitude. In case of photon primaries the beginning of shower development is ruled mostly by the electromagnetic processes which are understood much better than the hadron dynamics. This means a smaller reconstruction uncertainty for photon-induced showers and in consequence a most efficient way to constrain the cross-sections of high-energy interactions initiating the shower. For a photon primary, the photonuclear interactions at the beginning of shower development significantly influence the main shower properties characteristic for photon primaries (e.g. the muon content is increased). Therefore, assuming effective identification of photon events, the measurements of photon signatures would offer a unique chance for constraining the models of photonuclear interactions. The first analysis in this direction was published in Ref. [23].

C. Cross-checking the photon signal using directional dependence of the preshower effect

The directional dependence of the preshower effect mentioned at the beginning of this paper can be helpful in the identification of photons. A good signature of photon contribution in the observed set of events should be the directional asymmetry of X_{max} and related observables. Photons arriving from directions nearly parallel to the local magnetic field vector **B** (small transverse component of **B**) will have small chance to convert into e^+e^- pair and start a preshower. This means the subsequent air showers will develop deep in the atmosphere. On the other hand, if the arrival direction of the primary photon is nearly perpendicular to **B**, the probability of conversion is high, and, consequently, X_{max} is expected at a shallower atmospheric depth. Correspondingly, if two observational sites with significantly different local magnetic fields are available, a different distributions of X_{max} are expected for the same local sky window observed at the two locations. The study of this effect for the two sites of the Pierre Auger Observatory was published in Ref. [24]. Based on the probability distributions of the preshower effect at the two sites, certain parts of the local skies can be selected for which the differences in the photon-induced air shower properties are especially pronounced. A simulation example of N_μ vs. X_{max} scatter plot for such a selection at the two Auger sites is shown in Fig. 7. The assumptions made for the presented simulations include uniform distribution of sources, standard energy spectrum without cutoff and 1% photon fraction. The data recorded with Auger North.

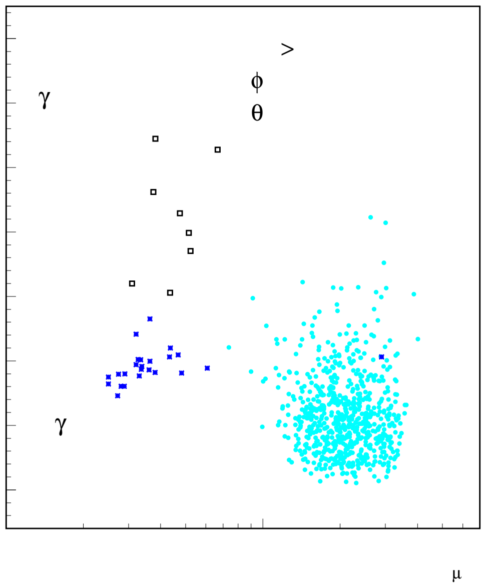

Fig. 7. Dependence of the N_μ vs. X_{max} scatter plot on the geographical location of the observatory. Photon-induced showers observed in Malargüe (Auger South - AS) should have deep maxima with large fluctuations (small conversion probability) while the photons of the same energies and arriving from the same directions to the observatory in Colorado (Auger North - AN) will most likely start preshowers that induce showers with shallower and less fluctuated maxima. For a further explanation see the text.

cutoff of the spectrum will not change the conclusions of this paragraph but the number of events will be smaller. In the presented example a total exposure of the southern part of the Auger Observatory is taken as 1.5×10^5 L (= sr×km^2×yr) and 5×10^5 L for the northern part. The final quality cuts in primary energy and arrival direction are shown in the plot. As can be seen, the observation of the events with the same local arrival directions at the two sites should give clearly separated group of points. The local field vectors at the chosen locations are different both in strength and direction: in Malargüe the field of ∼24.6 μT points upward to zenith angle $\theta \sim 55°$ and azimuth $\phi \sim 87°$, while in Colorado the field of ∼52.5 μT points downward from $\theta \sim 25°$ and azimuth $\phi \sim 262°$[2] Due to the different local magnetic field vectors the photons arriving from the selected directions to the observatory located in Malargüe will have small chance for conversion and the respective air showers should have large and strongly fluctuated values of X_{max} (open squares). For the same local directions and the observatory in Colorado the photon conversion probability is large and hence the expected values of X_{max} and their fluctuations are smaller. The results of simulations for proton-induced showers are shown for comparison. The earlier mentioned clear separation between photon- and proton-induced showers is worth noting. With use of plots similar to the one in Fig. 7 the photon signal detected at Auger South could be confirmed and cross-checked by the data recorded with Auger North.

[2]The azimuths in this paper are counted from geographic East in the counter-clockwise direction.

V. Conclusion

The available simulations show that distinction between hadron- and photon-induced showers is possible with a number of shower observables. So far there is no evidence for photon primaries among the showers recorded in all the relevant experiments, especially by the Pierre Auger Observatory - the largest UHE cosmic-ray observatory ever. The upper limits for UHE photon fraction and flux constrain seriously the exotic models of cosmic-ray origin which commonly predict significant photon contribution to the observed flux. With the rapid increase of UHE cosmic-ray event statistics expected in the future from the two sites of the Pierre Auger Observatory, the observation of very small fractions (∼ 0.1%) of UHE photons originated form the GZK processes will be possible. Detection of such photons would offer a new observation window of the Universe making a contribution to the multimessenger tracing of the highest energy processes known.

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