



## Comparison of preshower characteristics at Auger South and North

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**Abstract:** Due to geomagnetic cascading, the properties of air showers initiated by photons above  $10^{19}$  eV depend strongly on the arrival direction and on the geographical location of the experimental site. This offers the possibility of a complementary search for such ultra-high energy photons with observatories located at sites with significantly different local geomagnetic field. In this paper we compare the characteristics of photon showers at the southern and northern sites of the Pierre Auger Observatory. The complementarity of the shower features seen by the two sites is demonstrated. We study how this complementarity can be used to search for ultra-high energy photons.

### Introduction

Substantial fluxes of cosmic-ray photons at ultra-high energy (UHE), above  $10^{19}$  eV, are predicted by non-acceleration (top-down) models of cosmic-ray origin (for example, see [2]). At a smaller level, UHE photons are also expected to be produced in acceleration (bottom-up) models [4]. So far, upper limits on the photon flux were set (see [15] and references therein). The large exposure expected to be collected during the next years, in particular by the Pierre Auger Observatory [12], will enormously increase the sensitivity for detecting UHE photons [13].

Contrary to the case of hadron primaries, UHE photons around  $10^{20}$  eV can interact with the geomagnetic field before entering the atmosphere [10] producing a bunch of lower energy particles. This process is commonly called geomagnetic cascading or preshower and leads to a dramatic change of the air shower development for primary photons (see [7] and references therein). The probability of magnetic  $e^+e^-$  pair production (“photon conversion”) and, in case of conversion, the synchrotron emission by the produced electrons depend on the particle energy and on the transverse component of the local magnetic field [3, 6]. This implies

the dependence of the expected properties of the photon-induced shower on the primary arrival direction within the local coordinate system and on the geographic location of the experiment [10].

In this work we study how the preshower characteristics affects the properties of air showers for the conditions of the southern part of the Auger Observatory (“Auger South”) situated in Malargue (Argentina) at  $69.2^\circ$  W,  $35.2^\circ$  S and its northern part (“Auger North”) planned in Colorado (USA) at  $102.7^\circ$  W,  $37.7^\circ$  N. The geomagnetic field vector differs significantly between these two sites: at Auger South, the magnetic field of  $\sim 24.6 \mu T$  points upward to  $\theta \sim 55^\circ$ ,  $\phi \sim 87^\circ$  while at Auger North, the magnetic field of  $\sim 52.5 \mu T$  points downward from  $\theta \sim 25^\circ$ ,  $\phi \sim 262^\circ$ .<sup>1</sup> It is also considered how the different properties of photon-showers at the two sites can be used to perform a complementary search for UHE photons.

While the study is performed for the specific case of the two Auger sites, the general findings hold for any two sites with sufficiently different local magnetic field conditions.

<sup>1</sup> Azimuth is defined in this work counterclockwise from geographic East. For instance,  $\phi = 0^\circ$  means East,  $\phi = 90^\circ$  North etc.

## Conversion of an UHE energy photon at Auger South and North

A key parameter to characterize the fate of an UHE photon in the Earth's magnetic field is the conversion probability  $P_{\text{conv}}$ . Given the local differential probability of a photon to convert into an electron pair,  $P_{\text{conv}}$  results from an integration along the particle trajectory. Small values of  $P_{\text{conv}}$  indicate a large probability of the UHE photon to enter the atmosphere without conversion and to keep its original identity. In turn, UHE photons would almost surely undergo geomagnetic cascading for values of  $P_{\text{conv}}$  close to unity.

$P_{\text{conv}}$  depends on the experimental site, the photon energy, and the direction of the particle trajectory in the local coordinate system of zenith  $\theta$  and azimuth  $\phi$ ,  $P_{\text{conv}} = f(\text{site}, E, \theta, \phi)$ . Thus, for a chosen site and a fixed primary photon energy, sky maps within the local coordinate system  $P_{\text{conv}} = f(\theta, \phi)$  can be produced to study the pattern of UHE photon conversion. As an example, in Figure 1 two such sky maps are shown for two different geographical locations, Auger South and Auger North, and for one primary energy of 100 EeV. One can see significant differences in  $P_{\text{conv}}$  between the two sites for a given direction in terms of local coordinates. As expected, small conversion probabilities are found for sky regions around the pointing direction of the local magnetic field vector.

It is clear from Fig. 1 that cuts on the local shower arrival direction can be introduced to select regions of the sky where  $P_{\text{conv}}$  is larger (or smaller) at one site compared to the other site. A possible photon signal could then show up with *different* signatures at the two sites for the *same* selection cuts.

### Air showers initiated by converted and unconverted photons

It is well known that unconverted photon showers, contrary to converted, have a considerably delayed development due to the LPM effect [9, 11]. Additionally, event-by-event fluctuations can be extraordinarily large due to a positive correlation of the suppression of the cross-section with air density. To demonstrate how this effect can be seen at

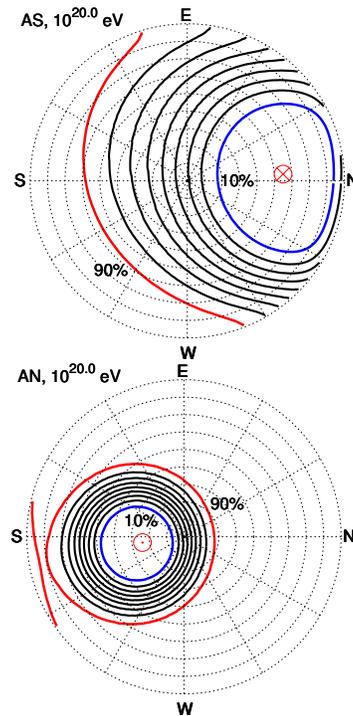


Figure 1: Exemplary sky maps of conversion probabilities at  $\lg(E/\text{eV})=20.0$  for Auger South (AS, top) and Auger North (AN, bottom). Contour lines are given for the conversion probability with a step-size of 10%. Azimuthal directions are labeled (“E” for East etc.). Zenith angles are given as concentric circles of  $10^\circ$  steps ( $\theta = 0^\circ$  in the center). The pointing direction of the local magnetic field vector at ground is indicated for a specific site.

two different locations, detailed simulations were carried out with CONEX [14, 1], which reproduces well CORSIKA [5] results. All the primaries were simulated at energies of  $10^{20}$  eV with two different local arrival directions and two different observation sites: Auger North and South. 1000 photon events per each combination of site and arrival direction were simulated, and hadron showers (simulated with QGSJET 01 model [8]) were added for comparison. The resulting distributions of depth of shower maximum  $X_{\text{max}}$  are shown in Figure 2. In the upper panel all the primaries arrived from geographic North at  $45^\circ$  zenith. For this particular direction the photon conversion probability is large at Auger North ( $> 99.9\%$ ) and small

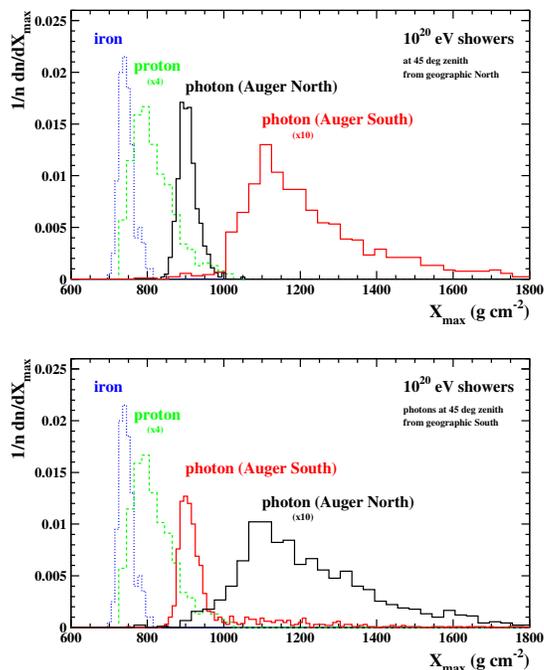


Figure 2: *Upper panel:*  $X_{\max}$  distributions of different primaries arriving from local geographic North). *Lower panel:* same as in upper panel, but the photon simulations were performed with the azimuth changed by  $180^\circ$  (photons arriving from local geographic South). If indicated, distributions were scaled.

at Auger South (0.4%). Consequently, most of the photons at Auger North convert and have a depth of shower maximum  $200\text{--}300\text{ g cm}^{-2}$  smaller than the (mostly unconverted) photon showers at Auger South. As expected, also fluctuations are much smaller at Auger North in this example. The opposite behavior can be seen for the arrival direction with the azimuth changed by  $180^\circ$  (lower panel of Fig. 2). As expected from Figure 1, the  $X_{\max}$  distribution of photons at Auger South is now peaked at smaller values, while the distribution at Auger North is dominated by the large  $X_{\max}$  values from unconverted events.

From the above example it is clear that for the same local directions, the expected features of photon showers can be very different at two different sites.

There are other shower observables, especially from ground arrays, that were shown (or are expected) to differ between converted and unconverted photons. However, as discussed in Ref. [7], a study of  $X_{\max}$  distributions provides us with most relevant information for investigating possible complementary features of both sites.

## UHE photon scenarios and their observation at Auger South and North

The complementarity between the preshower characteristics at Auger North and South can be taken as an advantage when searching for the presence of the photon component in the cosmic-ray flux at highest energies. Photons can manifest themselves at Earth within different scenarios. One of such scenarios, a diffuse photon signal, is considered below as an example. The other possibilities, e.g. a signal from a source region or the absence of photons are discussed in Ref. [7].

An isotropic primary flux with the all-particle energy power law spectrum with index  $-2.84$  is assumed. Such a spectrum is consistent with the first estimate from the Auger South Observatory [16]. We assume protons and photons as primaries and the input fraction of photons as a function of primary energy follows the results from a topological defect model in [4]. For each Auger site, we simulated  $\sim 1000$  events above  $\lg(E/\text{eV}) = 19.6$  with zenith angles between  $30\text{--}75^\circ$  and random azimuth. We accounted for a detector resolution of  $25\text{ g cm}^{-2}$  in  $X_{\max}$  and 10% in primary energy. The zenith angle range was chosen similar to that in the analysis of Auger data for the first photon limit [13]. For other details and specifications the reader is referred to Ref. [7].

In Figure 3 we show average  $X_{\max}$  as a function of energy. We restricted the azimuth range in this plot to the local *northern* sky by requiring an azimuth between  $30\text{--}150^\circ$ . In this region of the sky, photon conversion starts at Auger North at smaller energies than at Auger South.

As expected, there are considerably fewer events with large  $X_{\max}$  (e.g. exceeding  $1000\text{ g cm}^{-2}$ ) at Auger North, for the same overall cuts applied to the data at both sites. Additionally, the larger average  $X_{\max}$  at Auger South is accompanied by sig-

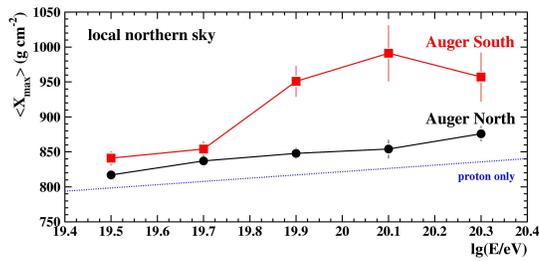


Figure 3: Average  $X_{\max}$  vs. energy for the local northern sky (for definition see the text) at Auger North and at Auger South. For comparison, values corresponding to a pure proton flux are also shown using the model QGSJET 01 (dotted blue line).

nificantly increased shower fluctuations (for a reference plot see Ref. [7]). An observation of such different characteristics at Auger North and South would be an unambiguous confirmation of a photon signal detection.

The above conclusions are not changed for the cosmic ray spectrum with the GZK cut-off. For a discussion and a quantitative example of applying a simple cut-off to the power law energy spectrum the reader is referred to Ref. [7].

## Conclusion

The difference of conversion probabilities is a convenient and effective parameter to estimate the complementarity between two sites for searching for UHE photons. Regarding the two sites of the Pierre Auger Observatory, Auger North and Auger South, significant differences in the preshower features of UHE photons exist. These differences in the preshower characteristics result in different rates of (un-)converted photons from the same (both in local and astronomical coordinates) regions of the sky. Air showers initiated by converted and unconverted photons can be well distinguished by current experiments. The main difference is related to the position of depth of shower maximum  $X_{\max}$ , which is typically  $\sim 200\text{--}300\text{ g cm}^{-2}$  smaller for converted photons.

For a variety of UHE photon flux scenarios (diffuse photon flux; photons from source regions; absence of photons), the different preshower characteristics

at the experimental sites can be used for a complementary search for UHE photons. Most important, 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 UHE photon showers.

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