Sensitivity of the Auger Observatory to ultra high energy photon composition through inclined showers

M. Ave\textsuperscript{1}, J. A. Hinton\textsuperscript{1,2}, R. A. Vázquez\textsuperscript{3}, A. A. Watson\textsuperscript{1}, and E. Zas\textsuperscript{3}

\textsuperscript{1}Department of Physics and Astronomy
University of Leeds, Leeds LS2 9JT, UK

\textsuperscript{2}Enrico Fermi Institute, University of Chicago,
5640 Ellis av., Chicago IL 60637, U.S.

\textsuperscript{3}Departamento de Física de Partículas,
Universidad de Santiago, 15706 Santiago de Compostela, Spain

Abstract

We report a calculation of the expected rate of inclined air showers induced by ultra high energy cosmic rays to be obtained by the Auger Southern Observatory assuming different mass compositions. We describe some features that can be used to distinguish photons at energies as high as $10^{20}$ eV. The discrimination of photons at such energies will help to test some models of the origin of ultra-high-energy cosmic rays.

1 Introduction

Uncovering the origin, composition and energy spectrum of the highest energy cosmic rays is one of the biggest challenges in astroparticle physics. The Pierre Auger project is the next step in the search for answers to intriguing questions about the origin of these particles \footnote{\textsuperscript{[1]}}. The Auger Southern Observatory will consist of 1600 water Cerenkov detector stations (each 10 m$^2$ x 1.2 m deep) on a hexagonal grid of 1500 m spacing overlooked by four detectors capable of detecting the fluorescence light emitted by the nitrogen molecules excited by the shower. The array covers a ground area of approximately 3000 km$^2$ at a mean altitude of 875 g cm$^{-2}$ ($\sim$ 1400 m), near Malargüe in Mendoza State, Argentina (lat = -35.2$^\circ$, long = -69.2$^\circ$). The Auger Southern Observatory will be able to measure the energy of the incoming cosmic ray using fluorescence detectors (FD) and thus calibrate the energy inferred from the surface detectors.

The proposal to use the Auger observatories to search for very inclined showers induced by ultrahigh energy neutrinos \footnote{\textsuperscript{[2]}} has led to an investigation of the characteristics of high energy showers at large zenith angles, i.e. showers arriving at zenith angles larger than $60^\circ$ \footnote{\textsuperscript{[3]}}. These showers would not be very different from vertical showers except for the fact that they develop in the upper part of the atmosphere. As a result the electromagnetic part of the shower, produced mainly from $\pi^0$ decay, is mostly absorbed well before the shower front reaches ground level. The muon front propagates through the atmosphere and it gets attenuated more slowly through pair production, bremsstrahlung, and hadronic interactions that reduce the muon energy and increase their probability to decay in flight. Therefore the muon energy spectrum at ground will have a low energy...
cutoff which increases as the zenith angle rises. As a result the average muon energy at ground level also increases. Although the bulk of the overall increase in the average muon energy with zenith is due to the rise of the cutoff, there is a smaller contribution due to the rise of the pion critical energy (the energy at which the pions are more likely to decay than to interact). These energetic muons travel making a small angle to the incoming cosmic ray direction but their trajectories are deflected by the Earth’s magnetic field. As a result the muon density patterns at ground are different from typical densities measured in vertical showers, reflecting the structure of the shower core and the geomagnetic field which acts as a kind of “natural magnetic spectrometer”.

This work outlines the sensitivity of the Auger Observatory to inclined air showers induced by ordinary cosmic rays, that is cosmic rays produced by protons, heavy nuclei, and photons. They constitute the background to neutrino detection but their observation also provides a significant increase in the aperture of the array and may improve mass composition studies [4]. Below, we predict the expected rate for the Auger Surface Array for zenith angles above 60° assuming different primary mass compositions: proton, iron and photons. Primary photons can interact with the geomagnetic field before reaching the top of the atmosphere [18]. This will have a major impact on the expected rate of detection for those primaries, as we will show. We can take advantage of this effect to outline a way to identify photon primaries at energies as high as $10^{20}$ eV.

The article is organized as follows: in section 2 we describe the procedure to calculate the expected rate for the Auger array above 60° for primary protons, giving the expected values for the energy resolution, core error reconstruction, and multiplicity of stations as a function of the energy: a detailed explanation of the procedure can also be found in [3]; in section 3 we describe the effect of the geomagnetic interactions in inclined air showers initiated by photon primaries; in section 4 we present the expected rate for three primary mass compositions (protons, iron and photons). Finally in section 5 we end up with some conclusions.

2 A simulation of inclined events and their analysis

The effect of the magnetic field on inclined showers makes the density patterns at ground level dependent on zenith and azimuth angles, in addition to their dependence on assumptions that must be made about energy, mass composition and interaction model as is usual in the the case for vertical showers. The work presented here relies on the model of the muon density patterns produced by inclined showers under the influence of the Earth’s magnetic field described in [3]. This model approximates the magnetic distortions of circularly symmetric muon density patterns generated by simulation in the absence of magnetic effects. Moreover the model has revealed relatively simple energy scaling functions for the density patterns once the zenith and azimuthal angles are determined [3]. The model provides a simple and continuous average muon density function which simplifies fitting procedures and allows us to simulate the expected sensitivity of the Auger Surface Array for showers with zenith angle above 60°. The magnetic field at
Malargüe has been taken to have an intensity $B = 26 \mu T$, an inclination of $\beta_i = -33.18^\circ$ (pointing in the upward direction) and a declination $\beta_d = 6.88^\circ$ (eastward). A northern site with a larger intensity and higher inclination would have a different distortion pattern and results are expected to be slightly different particularly in relation to azimuthal angle distributions.

We have simulated a subarray containing 91 detectors arranged in five concentric hexagons and showers are assumed to fall in the central region to save computing time. Results obtained in this subarray are then scaled up to the total array surface of 3000 km$^2$. This approximate approach has two important implications. The subarray “radius” ranges between $r_{sub} \sim 6.5$ and 7.5 km. This implies that in the transverse plane the maximum distance to shower axis is $r_{sub} \cos \theta$ which can be rather small for high zenith angles (for example for a zenith of 75$^\circ$ the subarray stops sampling at about 1.8 km). As a result the number of tanks that have a signal in the total array will be severely underestimated for high zenith and high energy showers. Another implication is that no edge effects are taken into consideration but this is not expected to affect much neither the shower rate nor most of our results because a large fraction of the showers will fall well within the array.

With the help of AIRES [7] (version 2.2.1) and this model, we have generated libraries with average muon density maps for inclined showers between 60$^\circ$ and 88$^\circ$ in steps of 2$^\circ$, and for all azimuth angles in steps of 5$^\circ$, at a constant energy of $10^{19}$ eV. Muon density profiles for different primary energies are obtained using the appropriate scaling factor which depends on primary composition and hadronic model considered [6]. In this work we consider the QGSJET98 [8] as the high energy hadronic interaction model. To account for the detector response to muons of different energy and impact angle we have used the WTANK [9] program based on the GEANT CERN package [10]. As was previously shown in [3] for Haverah Park detectors, the signal of very inclined muons in water Čerenkov tanks can be greatly enhanced by direct light and muon interactions, which are included in these simulations. Between 60$^\circ$ and 70$^\circ$ the electromagnetic component, from $\pi^0$ decay, was directly calculated using Monte Carlo simulation with AIRES and treated as a small correction to the tank signals, which is ignored for $\theta > 70^\circ$.

Using these muon density libraries, and assuming an isotropic cosmic ray distribution consisting of protons, and a given parameterization of the measured spectrum, we have simulated artificial events in the energy range $10^{18.5}$-$10^{21}$ eV and in the zenith angle range 60$^\circ$-89$^\circ$. We have assumed a simple trigger condition demanding 5 stations with a density greater than 0.4 vertical equivalent muons (VEM) m$^{-2}$. For each artificial event the densities at each detector are fluctuated according to the Poisson fluctuations in the number of muons, and also according to the distributions of light fluctuations in the tank. These zenith angle dependent distributions include the response to the geometry of the muon tracks, the direct light contribution and the catastrophic muon energy losses, namely hard bremsstrahlung, pair production or hadronic interactions which become more important as the average muon energy rises, as obtained in detailed simulations using WTANK.

Following the steps of [3, 4] the shower parameters of these artificial events ($\theta, \phi$, impact
point position, and energy) are reconstructed as if they were real data. The procedure is based on a two-step fitting process using a maximum likelihood method which is iterated. Silent stations are taken into account in the fitting procedure. The arrival direction angles are first fitted to the signal times in the “triggered” detectors and then the energy and impact point are varied to make the average muon density map fit the actual “measured” densities in the tank. Curvature corrections to the arrival times are implemented once there is an estimate of the core location; the process is iterated three times for convergence. An example of a reconstructed event in the plane perpendicular to the shower direction is shown in Fig. 1, together with the contours of densities that best fit the data. In the figure the array is rotated in the shower plane such that the y-axis is aligned with the component of the magnetic field perpendicular to the shower axis. The asymmetry in the density pattern due to the geomagnetic field is apparent. As anticipated [2], in spite of a relatively moderate energy, common events can be rather spectacular having over twenty tanks triggered.

We have estimated the detection rate as a function of primary energy integrating over all zenith and azimuth angles, using the parameterization of the energy spectrum of [11]. This parameterization lies between the energy spectra recently reported by the AGASA group and the HiRes group [12], [13]. Assuming these parameterizations of the energy spectrum our predicted rate will increase (decrease) up to 20%. For self-consistency, the energy spectrum to be used in a practical application of the ideas outlined here should be the one derived from the Auger experiment using the fluorescence technique, as the spectrum derived by this technique has the advantage of being independent of assumptions of primary mass composition.

The results are shown in Fig. 2. The dashed line is the integral rate that could be expected in a 3000 km$^2$ array from the cosmic ray spectrum that has been assumed in this work. The continuous line represents the reconstructed spectrum. We have made quality cuts to the reconstructed events, namely the downward error in the energy was required to be less than 60% and the $\chi^2$ probability for the energy and time fits have been forced to be greater than 1% for the accepted events. The difference in normalization, which amounts to $\sim 20\%$, is due to the combined effect of the quality cuts, systematic effects and the effect of the finite energy resolution of the detector.

The number events expected per year, assuming a pure proton composition, is $\sim 1000$ above $10^{19}$ eV and $\sim 18$ above $10^{20}$ eV after making these quality cuts. It should be noted that these numbers are obtained using the parameterization of the energy spectrum of [11], where no Greisen-Zatsepin-Kuzmin (GZK) cutoff is indicated.

The multiplicity of detectors with a signal above 0.4 VEM m$^{-2}$ as a function of energy for the range of angles simulated is also shown in Fig. 2. For a given energy the multiplicity is much larger than for vertical showers. Two factors contribute to this effect: the reduction of the effective spacing between stations in the shower plane, and the flatter density profile of horizontal air showers compared to vertical.

As a shower becomes inclined the earliest and latest tanks that are above threshold can be quite far apart corresponding to different depths in shower development. Due to the additional atmosphere traversed an attenuation can be expected for the late arriving
Figure 1: Density map of a proton simulated event of $10^{19.6}$ eV at a zenith angle of $77^0$ in the plane perpendicular to the shower axis. Recorded muon densities are shown as circles with radii proportional to the logarithm of the density. The positions of the best-fit and simulated impact points are indicated by a star and a cross respectively. Densities in VEM m$^{-2}$ are marked and, in brackets, the actual number of inclined muons that produced each signal. The $y$-axis is aligned with the component of the magnetic field perpendicular to the shower axis. Contour levels for 2, 5, 10 and 20 muons per station are shown for the fit. Detectors not triggered are indicated by an empty circle. The original energy was $\log_{10}(E/eV) = 19.52$ and the reconstructed $\log_{10}(E/eV) = 19.6 \pm 0.06$. The original and reconstructed zenith angles are $\theta = 77^0$ and $76.5^0 \pm 0.3$ respectively.
particles. This was studied for muon distributions which is the dominant component in inclined showers in [3, 4] and for electron distributions in [15]. If the number density of muons changes significantly over such a distance it can represent a significant correction to the densities derived in our work. It should be remarked that no attenuation of the shower particles across the array, has been taken into account in this work. As it is shown in [3], such attenuation effects become important at extreme zenith angles $> 87^\circ$, but for most of the zenith angle interval discussed in this article the attenuation, which is less important than in the vertical case, can be ignored in a first approximation. As an example, simulations show that for a 30$^\circ$ shower, water Cherenkov density at 1000 m from the shower core in the shower plane is attenuated by a $\approx 30\%$ when reaching ground level. At 70$^\circ$ this factor is less than 15%. The main reason for this is that in the vertical direction the signal is dominated by electromagnetic particles from $\pi^0$ decay, while in the horizontal direction the signal at ground level is dominated by high energy muons and secondary electromagnetic particles from decaying muons. The scale of the attenuation is roughly determined by the interaction length, which for photons and electrons is orders of magnitude smaller than that for muons.

We should also point out that in spite of using average density maps, statistical fluctuations of the shower densities are considered in this work. These are complicated effects that include fluctuations in the ratios of energy transported by charged and neutral pions in the hadronic interactions as well as fluctuations in depth of maximum. As obtained in simulations it typically represents a 20% effect on the overall muon number density normalization for proton primaries and it is rather independent of primary energy [3]. Much of the fluctuation corresponds to the first interaction. In the left panel of Fig. 3 we show the energy resolution for two energy ranges. Two factors contribute to the energy resolution calculated in this work: the variation of the number of muons at ground due to shower to shower fluctuations ($\approx 20\%$ for all energies) and the muon size reconstruction error (which evolves from 20% at $10^{19}$ eV to 10% at $10^{20}$ eV). Hence, at $10^{20}$ eV the energy resolution is dominated by shower to shower fluctuations. The errors in the reconstruction of the impact points of the analysed events are also shown in Fig. 3. As an example it is $\sim 70$ m at 60$^\circ$ and it has a small variation with zenith angle due to the different effective spacing of the detectors when projected on to the transverse shower plane.

3 Inclined showers induced by primary photons

The recent analysis of inclined data obtained at Haverah Park has opened a new window to establishing bounds on photon composition at ultrahigh energies [4]. As photon showers have far fewer muons than hadron showers, the expected rate of inclined showers created by photons detected with a surface array is reduced relative to the rate from protons or nuclei primaries. This is because the detection of horizontal showers induced by photons and hadrons by surface detectors is practically only sensitive to the muon component. The determination of the spectrum of cosmic rays through vertical shower measurements
Figure 2: Integral spectrum of events per year that trigger the Auger surface array, before and after energy reconstruction, assuming proton composition and adopting QGSJET as the high energy interaction model. The average multiplicity in the number of stations above threshold and its spread is also shown for two ranges in the arrival zenith angle indicating that the multiplicity is increasing as the zenith rises. Hardly any reduction is observed at high energies. This is an artificial effect because of the limited number of stations simulated. Because we are using a reduced subarray, the tank multiplicity given here should be considered as a lower bound (see text).
using the fluorescence technique, which is fairly independent of the primary composition together with the inclined shower rate thus allow measurements of composition [3, 4]. Following a similar procedure to that described in the previous section we obtain in this section the predicted integral spectrum for photon primaries for the Auger Observatories. There are a number of potential problems that could compromise the capabilities of the Auger Observatories to establish bounds or measure photon composition through inclined event rates, namely the Landau-Pomerančuck-Migdal [16] effect, the rise in the photoproduction cross section [17] and the interactions of photons with the geomagnetic field of the Earth [18, 19, 20]. We discuss these effects in detail to show to what extent it can be expected that the Auger detector will be sensitive to photon primaries.

3.1 General features of inclined photon showers

The dominant process for muon production in an electromagnetic cascade is photoproduction:

\[ \gamma + \text{nucleus} \rightarrow \text{hadrons} \]  

When photoproduction occurs the reaction products are essentially like those of a pion-nucleus interaction. Muons originate from the decay of the produced pions and kaons and their progeny in the resulting hadronic subshowers. The cross section for photoproduction has been measured up to \( \sim 10^4 \) GeV [21, 22] for the incident photons in the laboratory frame. Above the resonance region (see Fig. 1) the cross section is about 100 \( \mu \)barns per nucleon, and rises slowly for photon energies above \( \sim 10 \) GeV. The corresponding cross section on an air nucleus is \( \sim 1.1 \) mb, obtained by scaling \( \sigma_{\gamma A} \sim A^\alpha \sigma_{\gamma p} \) where \( \alpha \sim 0.9 \).
The ratio of the pair production to the photohadronic cross section gives the probability of a hadronic interaction to occur. This ratio is at 10 GeV:

\[ R = \frac{\sigma_{\gamma \rightarrow \text{hadrons}}}{\sigma_{\gamma \rightarrow e^+e^-}} \approx 2.8 \times 10^{-3} \]  

The ratio grows with the incident photon energy, because of the rise in the photoproduction cross section, and it is expected to be \( \sim 10^{-2} \) at \( 10^{19} \) eV. Fig. 4 shows the measured photoproduction cross sections at different energies, together with the standard parameterization used by the AIRES code and a recent parameterization given by Block et al. from a combined analysis of \( pp, p\gamma \) and \( \gamma\gamma \) interactions. As pointed out in ref. [17], the photoproduction cross section is close to the saturation limit at the HERA energies and cannot grow with energy faster than the currently used parameterizations. Therefore, the Block et al. parameterization may be considered as an upper limit to the photoproduction cross section. Other potential sources of muons are smaller than this. Muon pair production, in which a pair of electrons is replaced by a pair of muons is suppressed by a factor \( m_e^2/m_{\mu}^2 \approx 2 \times 10^{-5} \). Hadron production by electrons also contributes less than photoproduction because the process has to occur through exchange of a virtual photon, and the energies of the produced hadrons are small. The probability of photoproduction versus pair production is further enhanced at high
energies when the Landau-Pomeranchuk-Migdal (LPM) effect takes place \[^{[16]}\]. The LPM effect is a collective effect of the electric potential of several atoms and it tends to suppress the pair-production and bremsstrahlung cross sections for energies above a given value \(E_{\text{LPM}}\), which is inversely proportional to the medium density. It starts to become relevant for the development of photon induced air showers at primary energies above \(10^{19}\) eV for vertical showers \[^{[24]}\], a value somewhat above \(E_{\text{LPM}}\). This energy rises for large zenith angles corresponding to shower development higher up in the atmosphere where the air is thinner. We have found from simulations using AIRES code that for the zenith angle range being discussed, the LPM effect has a mild impact on the total number of muons produced by photon showers (< 25% at a zenith angle of 60°).

It has been shown before that to a very good approximation the number of muons produced by a proton and iron primary rises with energy according to a simple scaling law \[^{[3]}\]:

\[
N_\mu = N_0 \left( \frac{E}{10^{19}} \right)^\beta,
\]

where \(N_0\) (the normalization, here taken at \(10^{19}\) eV) and \(\beta\) (a constant parameter of order 0.9) are fixed numbers for a given zenith angle, hadronic interaction model and mass composition. The approximation is also valid for photon primaries although a number of differences are worth a brief discussion.

We have simulated batches of 100 photon induced air showers using AIRES code at different zenith angles and energies, in the absence of magnetic field, using the two different extrapolations of the photoproduction cross sections which are shown in Fig. 4, namely the standard parameterization of AIRES and the parameterization of ref \[^{[17]}\]. In Fig. 5 we plot the average number of muons generated by a photon as a function of energy for different zenith angles as obtained in the simulation. We note that the absolute number of muons of a photon shower is less than that of a hadron shower as expected from the ratio of probabilities in Eq. 2. However the number of muons in a photon-induced shower rises with energy faster than in a proton shower so that differences between the two become smaller as the energy rises. This is also qualitatively expected from the behaviour of the photoproduction cross section with energy. We also show for comparison an approximate scaling law using \(\beta = 1.2\) which we have used before as a conservative estimate \[^{[3, 4]}\].

We can observe in Fig. 5 a steepening kink of the curve at the highest energies. This is due to the LPM effect which makes the showers develop deeper and further enhances the ratio \(R\). The rise in \(R\) is a potential problem for the method. If the average number of muons in a photon shower becomes sufficiently close to that of a proton shower, no conclusion could be extracted regarding photon composition since a photon shower that photoproduces in the first interaction is practically undistinguishable from a proton shower of the same energy.

On the other hand, the difference in the number of muons produced for the two parameterizations used for the photoproduction cross section is small which gives an idea of the uncertainty involved in this calculation (see Fig. 4). This is not surprising since it is clear that the number of muons in a photon shower is dominated by processes at lower energies closer to the region where data constrain the cross section.

Fluctuations in the number of muons in photon-induced showers are rather different from
Figure 5: Number of muons produced in inclined showers as a function of primary energy for proton showers (upper continuous line) and photon showers for 60°, 70°, 80°, from top to bottom, using the standard AIRES parameterization (continuous) and the Block et al. parameterization (dashed). Also shown for $\theta = 60^\circ$ is the $\beta = 1.2$ parameterization used in our previous work (dotted line).
ordinary cosmic ray showers. If the first interaction of the incident photon happens to be hadronic (probability $R \sim 0.01$ at $10^{19}$ eV) then the shower is indistinguishable from a hadronic shower. We can thus expect a distribution for the total number of muons in a photon shower with a long tail in the region of showers with large number of muons, close to those of a proton shower. These non-gaussian tails can affect the detection rates and for that reason we have implemented fluctuations in the number of muons in photon shower using the distributions obtained in the simulations.

3.2 Interactions with the geomagnetic field

It was pointed out in [18, 19, 20] that photons above $10^{19}$ eV have a large probability to convert into an electron-positron pair in the presence of the Earth magnetic field before entering the atmosphere. The strength of this interaction depends on $E B_\perp$ where $E$ is the photon energy and $B_\perp$ is the transverse magnetic field. Therefore the probability of interaction will depend on the direction of the incoming photon with respect to the Earth frame. For a given zenith angle it is a maximum when the photon trajectory intercepts the Earth’s magnetic axis, which roughly corresponds to the geomagnetic south at the Malargüe site. This is because at a given distance to the center of the Earth the dipole field is strongest along the magnetic axis. For the same reason it is clear that the field will be largest for higher zenith angles. This azimuthal asymmetry was also pointed out by Stanev and Vankov [19] and by Bertou et al. [20] to be a potential way to establish a photon contribution in the highest energy cosmic rays.

The point we want to make is that this interaction reduces the potential problems that could arise because of the increase in the photoproduction cross section and therefore “safeguards” the method of using the inclined shower rate for composition studies also for the highest energies. If such an interaction is deemed to happen an electron-positron pair is created that will radiate strongly by synchrotron radiation. A large number of photons is thus produced and some of them may give secondary pairs provided they still have sufficient energy. Instead of a single particle entering the upper atmosphere we end up with a spectrum of gammas and one or a few electron positron pairs adding up to the primary photon energy.

To study this effect we have devised a Monte Carlo to simulate the cascading of photons in the geomagnetic field. The photon is injected at 20000 km from the top of the atmosphere along the incoming direction and tracked in steps of 100 km. The values of the interaction length for pair production are taken from [25]. Fig. 6 shows the probability of conversion for photons at different energies, zenith and azimuth angles. When a photon is converted, the resulting electron and positron are tracked in steps of 2 km, and the number and energy of the photons emitted via synchrotron radiation is calculated using the spectral distribution in [25]. The photons produced by magnetic bremsstrahlung are tracked and the probability of conversion calculated in each step. In this way, we obtain the spectrum of electrons, positrons and gammas at the top of the atmosphere.

The relevant parameter for the inclined shower rate is the total number of muons in the shower. When the photon converts in the magnetic field the number of muons at ground
Figure 6: Probability of photon conversion in the geomagnetic field as a function of azimuth angle for four different energies and eight different zenith. In each graph the eight curves are displayed corresponding, from bottom to top, to zenith angles from 10° to 80° in steps of 10°. An azimuth angle of 0° corresponds to a photon arriving from the geomagnetic north.
will be given by a sum over the contribution of the corresponding particle distribution:

\[ N_\mu = \sum_i N_0 \left( \frac{E_i}{10^{19}} \right)^\beta, \]

where \( E_i \) is the energy of particle \( i \). Meanwhile for an unconverted photon it is given by Eq. 3. Since the slope parameter in this equation, \( \beta \), is greater than one the number of muons is reduced when the photon interacts with the Earth’s magnetic field relative to when it does not.

It is of some interest to comment on a few facts about this conversion procedure. The strength of the Earth’s magnetic field is such that efficient conversion starts at energies of order \( 10^{20} \) eV. When the photon energy is well above this energy, the photon is always converted, giving rise to a sort of universal photon spectrum. The shape of the resulting spectrum is governed by magnetic bremsstrahlung and it is independent of the primary energy and only mildly dependent on the arrival direction; only the total number of particles changes as can be seen in Fig. 7 for two different primary energies. The spectrum displays a low energy tail and a maximum at around \( 10^{19} \) eV and can be parameterized by:

\[ \frac{dN_{em}}{d\log E} = k \left[ \frac{E}{E_c} \right]^\gamma \left[ 1 + \frac{E}{E_c} \right]^{-\delta}, \]

where \( \gamma = 0.24, \delta = -1.7, E_c = 10^{19.76} \) eV, and \( k \) is a normalization constant which due to energy conservation scales linearly with the primary photon energy. At very high energies there is a sharp cutoff in the spectrum due to the fact that all photons of such energies convert in the magnetic field. Thus at very high energies, when the photons convert, we can equivalently talk about an effective slope parameter of (Eq. 3) \( \beta_{eff} = 1 \).

At this point we can use the method described in the previous section to generate artificial events in the Auger array. We use the conversion probability for the photon showers to predict their behavior. These events are then reconstructed as if they were protons, and an equivalent energy \( (E_p) \) is calculated.

It is interesting to note that, as a coincidence, the energy at which photon conversion becomes efficient is also that at which the LPM effects start to show up in shower development, \( \approx 10^{19} \) eV [24] for a vertical air shower. When a photon is converted a quick look at the spectrum shown in Fig. 7 shows that most of the particles that will reach the top of the atmosphere and initiate the shower will be below the LPM threshold. The magnetic field of the Earth shields the atmosphere and the probability that showers develop in the atmosphere with strong LPM suppression becomes very small. The effective shielding is strongest at high zenith angles because the energy at which the LPM effect starts to take up is higher.

This is fortunate because, as Fig. 8 shows, if a high energy photon reaches the top of the atmosphere, the number of muons produced in the corresponding shower could become rather large and close to that of proton induced showers.
Figure 7: Differential energy spectrum of electromagnetic particles resulting of the cascading in the geomagnetic field of primary photons at two different primary energies $10^{21}$ eV (continuous) and $10^{22}$ eV (dashed).
4 Composition analysis with HAS

In Fig. 8 we show the integral energy spectra obtained from the artificial events under three different assumptions for the primary composition (protons, iron, and photons) using the cosmic ray parameterization given in [11]. In all the cases the artificial events are generated with muon density maps obtained for each specific primary, and then reconstructed as if they were protons, obtaining an equivalent energy \( E_p \). For primary photons we have calculated the spectra switching on (off) the interaction with the geomagnetic field. We show the prediction assuming the Block et al. photoproduction cross section and a parameterization used in [4]. This parameterization is based on AIRES simulations but the authors set the value of \( \beta \) to be 1.2 to be conservative.

Three important features are clear in this picture:

- The expected rate for primary photons above \( 10^{20} \) eV is reduced 30% when geomagnetic interactions are taken into account.
- The two photoproduction cross sections used predict a rate for photon primaries \( \sim 10 \) times smaller compared to the predictions for other hadronic primaries.
- Geomagnetic interactions modify the slope of the spectrum for primary photons at energies above \( 10^{19.6} \) eV.

According to current wisdom and partly because of the geomagnetic effect the uncertainty on the photoproduction cross sections at high energies has a small effect on the muon number at ground level. The predicted distortion of the longitudinal shower development for photon primaries because of the LPM effect is reduced because of the geomagnetic interactions. Assuming that the vertical flux is well measured independently of mass composition, as expected to be achieved with a fluorescence detector, the rate of inclined showers could be used to impose strong constraints on primary photon composition assuming a given hadronic model.

The hadronic model uncertainty can change the normalization of the spectra shown in Fig. 8. Therefore this method is not adequate to impose constraints on both mass composition and hadronic models at the same time. It should be used in combination with vertical measurements on mass composition using the same hadronic model. However, the differences in muon densities between the different hadronic models available are \( \approx 20\% \), which is comparable to the difference between densities produced by proton and iron primaries, and therefore, these primaries cannot be resolved by using the overall rate measurements. Nevertheless the difference between photon and hadronic primaries are much larger than 20% so that this method can, on its own, impose severe constraints on the photon content of the highest energy cosmic rays.

Currently the ultra high energy data suggest a mostly hadronic composition [4, 26], and the inclined showers rate is well described by proton primaries at energies above \( \sim 10^{19} \) eV. If there is a change of composition to a photon dominance at higher energies, the rate of inclined showers will be much lower. After a few years of operation of the Auger
Figure 8: Integral $E_p$ spectrum of events per year triggering the Auger Surface Array ($\theta > 60^\circ$) for three assumptions of primary composition. The expected spectra for converted and unconverted photons are also displayed. The two sets of spectra are calculated using two different assumptions of the rise with energy of the number of muons produced in photon showers.
Observatory these features will help to establish bounds on the flux of photons at energies as high as $10^{20}$ eV.

5 Conclusions

Inclined showers will be seen in the Auger Observatory as spectacular events with as many as 30 or 40 hit detectors. We have calculated the approximate rate of inclined showers with zenith angle exceeding 60° expected to be observed at the Pierre Auger Observatory. This rate increases the aperture of the observatory by almost a factor 2. Assuming a pure proton composition, there will be over 1000 well reconstructed events above $10^{19}$ eV, with a mean error energy $\sim 25\%$. The rate is sensitive to composition. If photons were dominant at high energy, the rate would be an order of magnitude smaller than if they were protons or nuclei allowing for a clear discrimination of the two cases. Uncertainties in the physics at very high energies have implications for our results on the detailed quantitative predictions but these uncertainties have little impact on the previous conclusions.

There are other signatures of the presence of photons (see for instance ref. [20]). Surely the combination of the inclined shower rate measurements together with vertical flux determinations and detailed analysis of the expected photon signatures will be a great step in the establishment of the overall photon rate at very high energies with the forthcoming data from the Auger experiment.

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