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Photon/hadron separation with the AUGER Observatory

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Abstract. Photons of ultra-high energy would be a strong evidence in favour of a ”top-down” production mechanisms; on the other hand their mean free path in the intergalactic medium becomes non-negligible above 10^{20} eV. At such energies the first steps of the electromagnetic shower in the atmosphere are affected by the LPM suppression, resulting in a delayed longitudinal profile. This could be observed directly with the Fluorescence Detector (X_{max} values well beyond 1000 g/cm^2), or indirectly with Surface Detector (steeper lateral distribution, more curved shower front); globally the Auger Observatory could be sensitive to a photonic fraction of a few percent in cosmic rays above a few 10^{19} eV. Moreover the geomagnetic conversion of photons before entering the atmosphere would produre a characteristic anisotropy of the effect with respect to the direction of the magnetic field in the region of the site, different from possible sky anisotropies.

1 Introduction

The origin of ultra-high energy cosmic rays (UHECR) is still unknown. Identifying their nature would greatly help to answer the question. Charged particles (protons and nuclei) are expected from *bottom-up* mechanisms (astrophysical acceleration), while large fluxes of photons (and neutrinos) are a characteristic signature of *top-down* mechanisms (decay of ultramassive objects) ending up into a large number of pions.

Due to their interaction with the radiation background in the intergalactic medium (pair production), photons are strongly absorbed above 1 TeV; however, their mean free path increases at ultra high energy and amounts to a few 10 Mpc above 10^{20} eV, comparable to the GZK range of the protons.

Up to 10^{19} eV, photons are expected to produce atmospheric showers like protons or nuclei, with a slightly slower longitudinal development and a lower muonic component; both are measured in AUGER. But the first steps of the hadronic cascade are affected by modelling uncertainties (extrapolation from measurements on accelerators), comparable to the expected differences. We want here to concentrate on new features appearing at UHE in electromagnetic interactions: the LPM effect (suppression of pair production and bremsstrahlung in matter), and the magnetic conversion of photons in earth's field. By a numerical coincidence, both effects combine in the AUGER energy range; this provides a specific signature of the photons (Bertou et al., 2000).

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2 Electromagnetic Effects at Ultra High Energy

2.1 LPM effect

The Landau-Pomeranchuk-Migdal (LPM) effect (Landau and Pomeranchuk, 1953; Migdal, 1956) is a suppression of the electromagnetic processes above a characteristic energy×density product: $E_{LPM} = m^2c^3\alpha X_0/4\pi\hbar = 7.7\,\text{TeV/cm}\ X_0$. At the density of the upper atmosphere, E_{LPM} is of the order of (10^{19} eV. The density increases gradually when the cascade goes down; however, the descent in energy is faster, and only the first steps are above LPM threshold.

2.2 Geomagnetic Conversion of Photons

It was pointed out by McBreen and Lambert (McBreen and Lambert, 1981) using a theoretical review of electromagnetic interactions in extreme conditions by T. Erber (Erber, 1966), that γ-rays with energy above 10^{19} eV have a large probability to convert into an e^+e^- pair in the magnetic field of the Earth before entering the atmosphere. Then the electron and the positron radiate strongly in the field and produce a large number of photons; some of them may also give secondary pairs. As a result, instead of a unique photon, there is a electromagnetic “preshower” entering the upper atmosphere. The probability of conversion depends on the parameter $E_\gamma/2m_ec^2 \times B_\perp/B_{cr}$, where $B_\perp$ is the field trans-

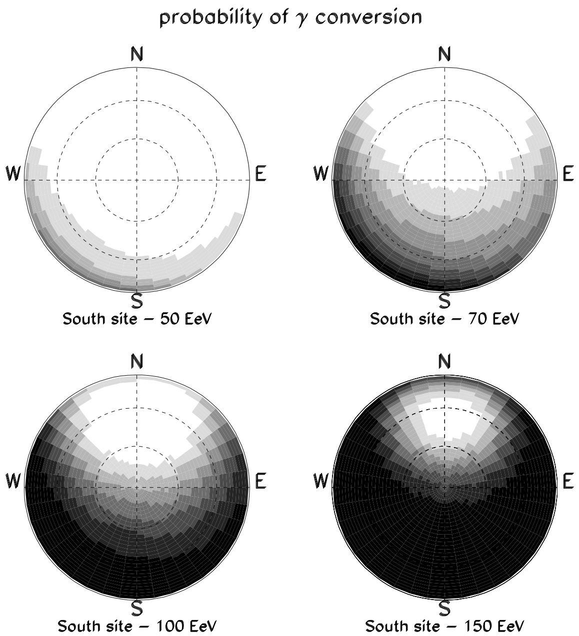

Fig. 1. Map of the photon conversion probability as a function of the direction, at the southern site of AUGER: eight equidistant levels from 0 (white) to 1 (black). The radial coordinate is $2\sin(\theta/2)$, so that the area on the plot is equal to the solid angle in steradians. The dashed circles correspond to zenith angles θ=30 and 60 deg.

verse to the direction of the photon, and $B_{cr} = m_e^2\, c^2/e\,\hbar \simeq 4 \times 10^9$ T is the "critical field"; then, this effect is expected to depend on the direction of observation with respect to the Earth frame (see for example Fig. 1). Such a dependence is a very strong signature of primary photons.

2.3 Differences between Converted and Unconverted Photons

In the atmosphere, showers induced by a unique photon above a few 10^{19} eV develop slowly, with large shower-to-shower fluctuations, because the LPM suppression affects mainly the first steps, and there is a positive correlation between them (if the first interaction is delayed, the density for the next ones is larger, then the delay is self-amplifying). On the contrary, if the photon is converted, the atmospheric shower begins with a large set of photons, electrons and positrons below the LPM energy, and undergoes a "normal" development; moreover statistical compensations reduce the fluctuations. The anomaly of an unconverted photon is generally larger than the normal shower-to-shower fluctuation, and also larger than the modelling uncertainties in the shower development (see Fig.2). As a consequence, even a few unconverted photons could appear as clear anomalies compared to a large background of hadronic showers.

Fig. 2. Profiles of fluorescence ($\theta < 70$ deg, $50 < E < 100$ EeV). Solid line: unconverted photons; dashed: magnetically converted photons; dotted: protons

3 Discriminating observables

The discrimination may be done either directly from the fluorescence profile, or indirectly from the ground observables related to the "age" of the shower (lateral steepness, curvature and time structure of the front). We used here a sample of simulated proton and photon showers, with a primary energy between 30 and 300 EeV, and a zenith angle θ between 0 and 80 deg.

3.1 Fluorescence profile

When fitting a Gaisser-Hillas function to the observed profile, both the primary energy and the position X_{max} of the maximum can be estimated (see Fig.3). X_{max} may be poorly defined is it is beyond the ground level (870/$\cos\theta$ g/cm^2 for AUGER): in that case we just estimate an extrapolation, which is actually below the true value; the primary energy is also strongly underestimated. It is clear that a condition such that $X_{max} > 1100$ g/cm^2 isolates very efficiently a large fraction of the unconverted photons from protons and nuclei. After this selection, the distribution of estimated energy is concentrated at lower values and reflects well the transition energy range (50 to 150 EeV in the Southern site).

The determination of X_{max} may be degraded when accounting for the limited angular range of observation and the measurement errors (not simulated in this study); however differences as large as 200 to 400 g/cm^2 should remain clearly visible. If 10 % of the cosmic rays around 10^{20} eV are photons, AUGER could see about one such unambiguous anomaly per year. Moreover, in the transition energy range, the abnormal profiles would exhibit a characteristic anisotropy (concentration around the local field direction), giving a nice signature for photons.

3.2 Ground Array observables

The lateral expansion of the shower is correlated to its longitudinal development: the spread of electromagnetic component increases as long as the core remains active (at least 500 g/cm^2 beyond the maximum of the longitudinal profile); on the other hand the muons are produced early and their space distribution flattens continuously, independently of the electromagnetic development. The characteristics of the front depend mainly on the slant depth $X/\cos\theta$; anomalies appears as significant deviations to the values expected at a given value of θ (which is measured with a good precision).

In this study the errors due to physical fluctuations in the detectors and the digitization time of 25 ns were taken into account. The degradation of the signals due to the electronic chain is assumed to be negligible in comparison. The conditions are those of the southern site (earth field: 25 μT, incli-

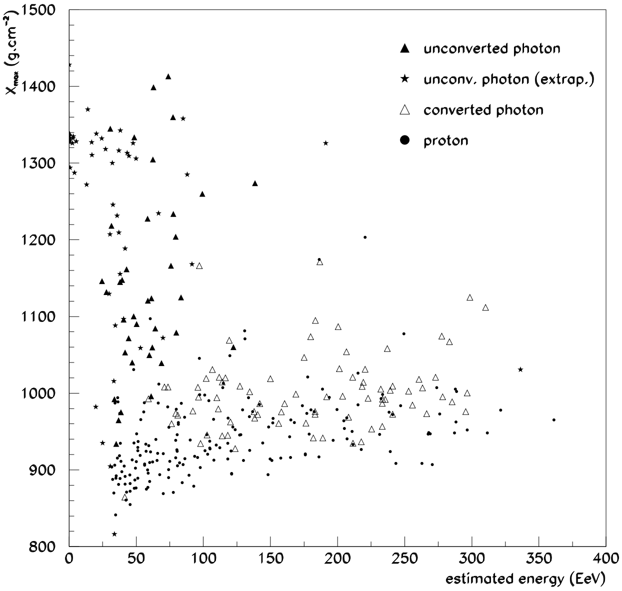

Fig. 3. Depth X_{max} of the maximum of the longitudinal profile vs amplitude (from a fit to a Gaisser-Hillas function), for protons, converted and unconverted photons. In the latter case, if the maximum is not visible (beyond the ground level), the results of the fit are represented by stars

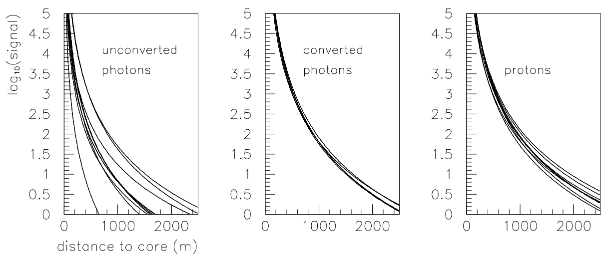

Fig. 4. Lateral distribution for almost vertical showers ($\theta < 20$ deg), normalized to energy.

nation 35 deg).

3.2.1 Lateral distribution

At any zenith angle, an unconverted photon shower gives a steeper distribution than a converted one, with larger fluctuations, for the same statistical reasons as the longitudinal profile. This is illustrated on Fig. 4 for nearly vertical showers actually, narrow profiles will be rejected by the trigger requirements,and the dispersion is attenuated at large θ, because all showers arrive at ground after their maximum.

3.2.2 Front structure

The curvature of the front is continuously decreasing with the longitudinal development. Basically, the first particles arriving at a given point are mainly high energy (ultra-relativistic) muons, produced at the early stage of the shower (hadronic cascade). As a first approximation, the front is a sphere centered on this region, propagating at the speed of light. Due to the electromagnetic component, the structure is more complicated, and the front is better described with a paraboloid close to the core, and a cone at large distances; the curvature remains a good indicator of the stage of development. The value of R is obtained here by fitting a spherical shape on the starting times of the signals in the ground stations (weighted by the square of their integrated amplitudes, in order to favour the central region); using a paraboloid gives practically the same result.

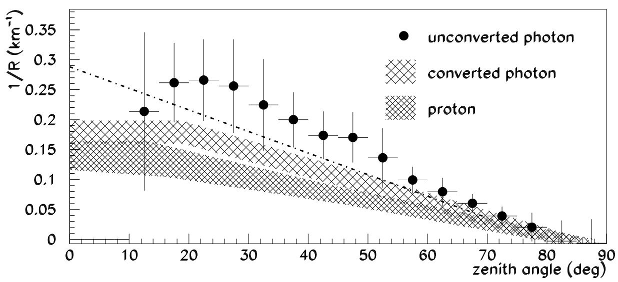

Fig. 5. Reconstructed front curvature $1/R$ as function of the zenith angle θ (error bars represent the dispersions).

Fig. 5 shows the distribution of the fitted value of $1/R$ vs θ for protons, converted and unconverted photons, after applying a realistic trigger condition (at least 4 ground stations with an integrated signal above 4 *vertical equivalent muons*) . The discrimination is slightly better than with the steepness, and extends over the full zenithal range, up to 80 degrees.

The *time shape* is also a well known discriminator between protons/nuclei and photons, even under LPM energies: both a large muon content and a late stage of electromagnetic development reduce the rise time; the difference is enhanced in the case of a high energy unconverted photon. A shape parameter may be defined as a early/late ratio of the time profiles, summed over the stations, with a time scale proportional to the distance from the shower axis. This simple and robust parameter appears to be very efficient.

The measurement errors on the lateral distribution, the curvature and the time shape are not strongly correlated. Then combining the Groud Array discriminating variables provide an powerful isolation of unconverted photons. With a duty time 10 times larger than the optical observations, they offer the best chance to detect a small photon component.

4 Distinguishing photons from neutrinos

Abnormally slow shower developments are expected also from weak interacting particles, and may be exploited to detect neutrinos with AUGER (Cappelle et al., 1998; Billoir, 1999). In that case the position X_0 of the first interaction is uniformly distributed in the available range in X, and X_{max} is close to $X_0 + \Delta X(E)$, where $\Delta X(E)$ is the normal po-

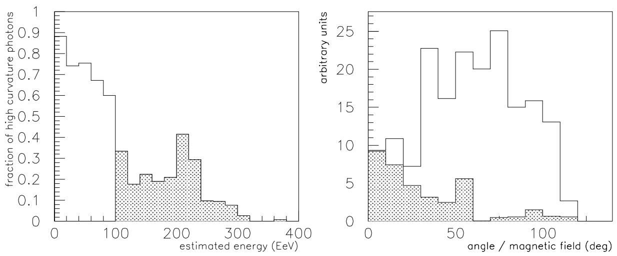

Fig. 6. Energy distribution and anisotropy of photons discriminated by high curvature ($\theta < 70$ deg.). Left side: fraction of high curvature photon showers vs reconstructed energy. Right side: angle with respect to the magnetic field (shadowed area: reconstructed energy above 100 EeV).

sition of the maximum at energy E: if abnormal values of X_{max} are due to neutrinos, very high values of X_{max} should also be observed at large θ; this is not expected with photons.

An independent confirmation of the presence of photons could be obtained through the anisotropy in the earth frame, depending on the energy, which may be distinguished from an intrinsic anisotropy of the incident flux. For example, we can select highly curved showers (above the dash-dotted line on Fig. 5) and consider their distribution in *reconstructed* energy (including the bias on unconverted photons): Fig.6 shows that the angular distributions of the high and low energy subsets are significantly different, even with a few events. This difference would be still visible with a background of protons and/or nuclei: whatever the incident distribution, it is widely smeared by Earth rotation, and it cannot produce an accumulation around the direction of the local magnetic field, which makes a large angle with the polar axis of the Earth.

On the northern site (earth field: 50 μT, inclination 65 deg), the transition energy would occur at a lower energy, where the differences between converted and unconverted photons are smaller; on the other hand, the available statistics would be higher. Again the field direction is far away from the axis of the Earth.

5 Conclusion

The thresholds for LPM effect in the upper atmosphere and magnetic conversion of photons in the geomagnetic field are comparable. As a result, a single unconverted photon and a photon converted into in a preshower with the same total energy behave quite differently: the preshower has a "normal" development, with moderate fluctuations, and it is not very different from a proton induced shower, so that the separation can be obtained on a statistical basis only, with systematical uncertainty due to the modelling of ultra high energy hadronic interactions; on the contrary, an unconverted photon gives a much slower and more fluctuating development, which can be highly different from the proton/nucleus pattern.

This can be seen directly with the fluorescence detector on the longitudinal profile (abnormally deep maximum, up to 1500 g/cm^2 and more), or through discriminating variables computed from the ground array measurements: lateral shape, curvature and thickness of the front. In both cases, a few significantly "abnormal" events could suffice to provide a good signature for photons. Although the longitudinal profiles may be more spectacular, the best statistical significance is given by the ground array. The level of sensitivity is about ten photons above 30 EeV. This is a small fraction of the expected total rate of events in AUGER (about 300 per year above 30 EeV). If the statistics is large enough, the photonic hypothesis may be confirmed by the energy distribution of the abnormal events, and the anisotropy in the Earth frame (accumulation around the direction of the local magnetic field). Moreover the intensity and zenith angle of the field in the two sites is different: this could help to get rid of analysis artefacts.

The Pierre AUGER Observatory is well designed to detect photons in the UHE cosmic rays, around 10^{20} eV (or to confirm their presence if some candidates are found in the next future at existing fluorescence detectors). Because it is a hybrid detector, it provides several independent criteria, allowing cross-checks and model independent evidences. Its sensitivity at highest energies, where photons could become abundant in "top-down" scenarii, is at the level of a small fraction (less than 10%) of the total flux. Taking also into account its neutrino capability, AUGER will give crucial tests on the origin of UHECR.

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