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D. Barret, F. Casoli, T. Contini, G. Lagache, A. Lecavelier, and L. Pagani (eds)

UPPER LIMITS ON THE ULTRA HIGH ENERGY PHOTON FRACTION WITH THE PIERRE AUGER OBSERVATORY

Cécile Roucelle for the Pierre Auger collaboration[1]

Abstract. We use the Pierre Auger Observatory to set an upper limit on the photon fraction in UHECR. With a restricted set of hybrid events, we present an upper limit of 16% (at 95% confidence level) for cosmic rays above 10^{19}eV. Using the surface detector (SD) we can also make an attempt towards a very promissing result in this field. The first result obtained with an hybrid analysis is summarized here. A surface detector stand alone analysis is also discussed.

1 Introduction

One of the key observables to distinguish between model predictions on the origin of the highest energy cosmic rays is the fraction of photons in primary cosmic rays. In non-acceleration models (so called "top-down" models), a significant fraction of the generated UHECR is expected to be photonic (Gelmini 2005). the photon induced atmospheric showers are expected to have a specific signature.

We report here a first analysis based on data recorded by the Auger observatory (Auger coll. 2004). The first upper limit derived here is based on the direct observation of air shower longitudinal profile and makes use of the hybrid detection technique developped by Auger (Mostafa 2005). It relies on the shower development maximum measurement (so called X_{max}), which is a discriminant observable for photon primaries as explained in section 1. We show in section 4 that surface detector observables can also be used for photon searches purposes. This information can lead to a statistically powerful stand alone analysis with the surface detector. This SD-data analysis has to deal with several subtleties which are presented there.

2 Specificities of photon showers

The atmospheric air shower coming from photons have a significantly different behaviour from their hadronic counterparts. Several effects lead to significant differences in shower development and composition.

Muon richness: photon showers, dominated by an electromagnetic cascade are expected to produce much less secondary muons. This also changes the shower front shape that can be exploited in SD analysis (see section 4).

LPM effect: above $\simeq$ 10^{19} eV the primary photon interaction cross section is attenuated (Landau Pomerandchuk (1953) Migdal (1956)), delaying the first stages of the development of photon initiated showers. This results in deeper development (and as a result a larger value of X_{max}) for photons than for nuclei induced showers.

Conversion in geomagnetic field: photon interaction with the geomagnetic field (for energies above $10^{19.7}$eV) leads to a preshowering effect before entering the atmosphere. As a consequence, it modifies the stage of development of a photon induced shower as we detect it. The conversion probability depends on both energy

[1] LPNHE - Laboratoire de Physique Nucléaire et de Hautes Energies IN2P3 - CNRS - Universités Paris VI et Paris VII, Paris. e-mail : roucelle@lpnhe.in2p3.fr

and transverse magnetic field. A detailed study (Bertou et al, 2000) has led to the conclusion that an anisotropy induced by this effect (related to the differences in conversion probability with arrival directions) could be a possible independent signature of photon origin of the showers. The conversion effect is accounted for but not used as a signature in the analysis based on hybrid events. This effect can also be accounted for in a pure SD analysis as well, but will not be discussed here.

3 Upper limit on photon fraction given with Xmax : study based on hybrid events

The data are taken with a total of 12 fluorescence telescopes (Auger Collaboration, ICRC 2005a) situated at two different telescope sites, during the period from January 2004 to February 2006. The number of active tanks for the surface detector (*SD*) grew from $\simeq 150$ to $\simeq 950$ during this period. Details on the selection, reconstruction accuracy and systematic effects can be found in (Auger Collaboration, 2006). After quality cuts 29 events are kept for the analysis.The principle of the analysis is to evaluate the probability for each event to be a photon, comparing one event to its dedicated photon simulation. These probabilities are thereafter combined (Risse 2004) to lead to an upper limit on the primary photon fraction. An example is given on fig 1. An event whose primary energy is reconstructed at 11 EeV has its X_{max} evaluated at $744\,\mathrm{g.cm}^{-2}$. This measurement has to be compared to te corresponding X_{max} distribution expected for primary photons. As explained in section 1, proton initiated showers, with $< X^{\gamma}_{max} >= 1020\,\mathrm{g.cm}^{-2}$, are expected to reach their maximum developpemnt well below proton induced ones. Shower-to-shower fluctuations are large due to the LPM effect (the rms of the distribution is $80\,\mathrm{g.cm}^{-2}$) and dominate the measurement uncertainty. For the 29 events kept for this analysis, the derived upper limit (see fig. 1 right) on the photon fraction is 16% (95% CL) above 10^{19}eV. This limit improves the existing limits above 10^{19}eV.

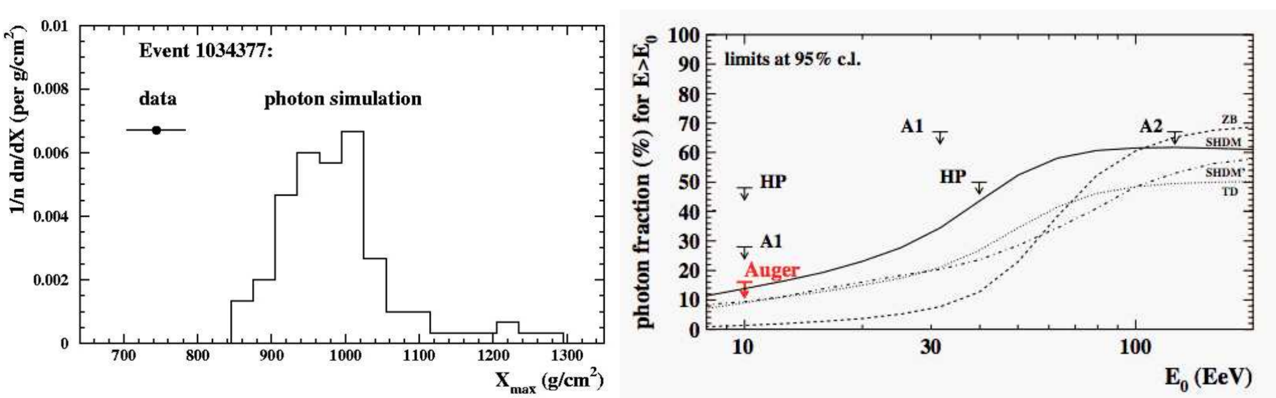

Fig. 1. (i) Example of X_{max} measured in an individual shower of 11 EeV compared to the distribution expected for photon showers (solid line). The X_{max} distribution for data sample is also shown (dashed line). (ii) Upper limits (@ 95% CL on UHECR photon fraction derived in the present analysis (Auger) and previously from AGASA (A1 & A2) (Shinozaki et al 2002, Risse et al 2005) and Haverah park (HP) (Ave et al 2002) compared to some estimates given for top down models (Gelmini et al 2005).

4 Toward a SD stand alone analysis

When the number of triggered surface detectors is large enough to perform a standard SD reconstruction (N > 4), it can provide several variables that are relevant for photon primary discrimination, e.g:

Rise time : for each triggered tank, we define a rise time as the time for the signal to go from 10% to 50% of its total value. We extract the rise time at 1000m interpolating between tanks and correcting for azimuthal asymmetry. Compared to nuclear primaries, where the risetime is relatively short due to the muon component of the shower (secondary muons do not suffer multiple scattering during the shower development as secondary electrons do), showers initiated by primary photons which have only few muons should exhibit a large risetime.

Curvature : the shower front shape is fitted to a sphere (expanding at the speed of light as the shower propagates) using the start times of the FADC traces of each station. Then the curvature for the event is defined as the inverse of the radius of the sphere at the shower core position on ground. As the photon initiated showers are expected to develop in general deeper in the atmosphere, the shower front curvature is expected to be larger for a photon primary than for nuclei.

As an example, for the specific event used on fig 1, the measured rise time and curvature data are compared to the simulated distributions in fig 2 left and 2 right. For this and the other SD reconstructed hybrid event, the SD observables are well separated from the predictions for primary photons. These results provide independent information to the photon limit derived above and support its conclusions. Moreover it can be seen from these plots that
The SD data statistics at energies above 10^{19}eV is considerably larger than the one available for hybrids (the duty cycle of the FD is only 10% of the SD). To exploit this appealing statistical power and hence better constrain primary photon fraction one can use a combination of these variables to even maximize the separation between photon simulations and data as they are not completely correlated.

To be able to perform this SD-stand alone analysis several subtelties specific to the photon showers have nevetheless to be dealt with :

(i) event reconstruction and triggering are not fully efficient at 10^{19}eV for photonic showers, compared to those initiated by nuclei which the experiment has been designed for. We thus have to compute a specific acceptance of the SD to photon induced showers and correct for this difference when working on a photon fraction in UHECR.

(ii) Due to its very particular development, the detection of an extensive air shower initiated by a photon primary would lead to an underestimation of its primary energy if "classical" energy reconstruction is used (i.e. designed for nuclei initiated shower, see Auger Collaboration, ICRC 2005b). The development of a specific energy converter accounting for the shower development has been performed to achieve a resolution comparable to the current "classical" energy estimator (ie. 25%).

Thanks to this specific photon reconstruction approach and the exploitation of SD observables that are sensitive to the shower development stage and its muon content, we can exploit SD data to perform an independant study which can lead to very low upper limits on the photon fraction. This independant analysis is still under discussion among the collaboration and results are to be published in the next few months.

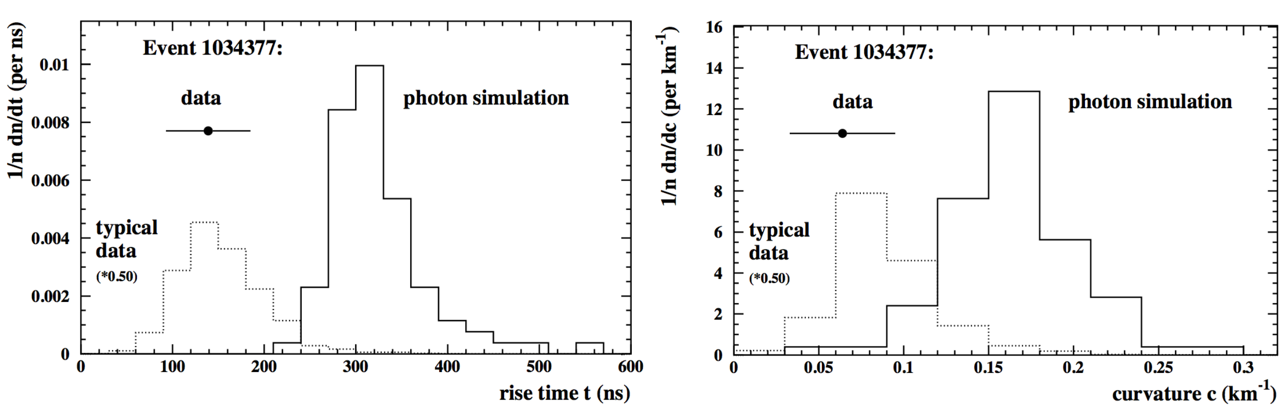

Fig. 2. Example of risetime (on the left panel) and curvature (on the right panel) measured in an individual shower (same as fig 1) compared to the distributions expected for photon showers for these variables (solid line). The typical ditribution from SD event is also given (dashed line; normalisation changed as indicated)

Conclusion

We can currently establish a photon fraction of 16% (95% CL), improving existing limits above 10^{19}eV. The number of hybrid events will improve in the next years, and even lower primary photon fractions will be accessible for testing with this hybrid study. The SD will also provide another upper limit in the near future. Accepting non-hybrid SD events will immediately increase our statistics accumulation by a factor of 10. As a consequence, It can lead to very low upper limits on the photon fraction in UHECR. Several observables like rise time of the signal in the tanks and curvature give very promising discriminating power for photons and a combination of these will be used. Specific reconstruction of events has nevertheless to be made for photon showers as the development of photon showers is very late compared to their nucleic counterparts. The obtention of this experimental result will be a crucial improvement as some theoretical models predict very high photon fractions at the highest energies (see fig 1 right). All these studies rely on extrapolations of the photonuclear cross-section at highest energies which must be considered with care. Nevertheless, studies about these systematics show that only a dramatic change on the cross section would prevent us from giving a constraint on several top-down models.

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