FERMILAB-CONF-05-274-E-TD

29th International Cosmic Ray Conference Pune (2005) **00**, 101–106

Upper limit on the primary photon fraction from the Pierre Auger Observatory

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Based on observations of the depth of shower maximum performed with the hybrid detector of the Auger Observatory, an upper limit on the cosmic-ray photon fraction of 26% (at 95% confidence level) is derived for primary energies above 10^{19} eV. Additional observables recorded with the surface detector array, available for a sub-set of the data sample, support the conclusion that a photon origin of the observed events is not favoured.

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 primary cosmic-ray photons. In non-acceleration ("top-down") models a significant fraction of the generated particles are photons [1]. Air showers initiated by photons at energies above 10^{19} eV are in general expected to have a relatively large depth of shower maximum $X_{\max}$ and fewer secondary muons compared to nuclear primaries. Previous upper limits on the photon fraction were derived from surface array data of the Haverah Park and AGASA experiments [2, 3, 4].

We report an analysis of data recorded by the Auger Observatory [5]. The photon upper limit derived here is based on the direct observation of the longitudinal air shower profile and makes use of the hybrid detection technique: $X_{\max}$ is used as discriminant observable. The information from triggered surface detectors in hybrid events considerably reduces the uncertainty in shower track geometry.

For a sub-set of the event sample used in this analysis, a variety of surface detector observables is available. The additional discrimination power of these observables is demonstrated.

2. Data

The data are taken with a total of 12 fluorescence telescopes [6], situated at two different telescope sites, during the period January 2004 to April 2005. The number of deployed surface detector (SD) stations [7] grew from $\sim$200 to $\sim$800 during this time. For the analysis, hybrid events were selected, i.e. showers observed both by (at least one) surface tank and telescope [8]. Even for one triggered tank only, the additional timing constraint allows a significantly improved geometry fit to the observed profile which leads to a reduced uncertainty in the reconstructed $X_{\max}$. The following criteria are applied for event selection:

- to maximize the reconstruction quality: geometry and profile fits succeeded, $X_{\max}$ observed, track length in field of view >400 g cm^{-2}, minimum viewing angle >18°, primary photon energy $\lg E/\mathrm{eV}>19.0$;
- to achieve comparable detector acceptance to photon and nuclear primaries: primary zenith angle $>35°$, distance of telescope to shower axis <24 km + $f(E)$, with $f(E) = 12$ km$\cdot(\lg E/\mathrm{eV}-19.0)$.

The reconstruction is based on an end-to-end calibration of the fluorescence telescopes [9], on monitoring data of local atmospheric conditions [10, 11], and includes an improved subtraction of Cherenkov light [12] and reconstruction of energy deposit profiles for deriving the primary energy. The decreased fraction of missing energy in primary photon showers is accounted for. In total, 16 events with energies above 10^{19} eV are selected.

The total uncertainty $\Delta X_{\max}^{\rm tot}$ of the reconstructed depth of shower maximum is composed of several contributions which, in general, vary from event to event. A conservative estimate of the current $X_{\max}$ uncertainties gives $\Delta X_{\max}^{\rm tot} \simeq 40$ g cm^{-2}. Among the main contributions, each one in general well below $\Delta X_{\max}$ =15 g cm^{-2}, are the statistical uncertainty from the profile fit, the uncertainty in shower geometry, the uncertainty in atmospheric conditions such as the air density profile, and the uncertainty in the reconstructed primary energy, which is taken as input for the primary photon simulation.

For each event, high-statistics shower simulations are performed for photons for the specific event conditions. Possible cascading of photons in the geomagnetic field is simulated with PRESHOWER [13]. Shower development in air, including the LPM effect [14], is calculated with CORSIKA [15]. The Particle Data Group extrapolation of the photonuclear cross-section [16] and QGSJET 01 [17] as hadron event generator are adopted.

A simulation study of the detector acceptance to photons and nuclear primaries has been conducted. For the chosen cuts, the ratio of the acceptance to photon-induced showers to that of nuclear primaries (proton or iron nuclei) is $\epsilon = 0.88$. A corresponding correction is applied to the derived photon limit.

3. Results

Fig. 1 shows as an example an event of 11 EeV primary energy observed with $X_{\max} = 744$ g cm^{-2}, compared to the corresponding $X_{\max}$ distribution expected for primary photons. With $<X_{\max}^{\gamma}>= 1020$ g cm^{-2}, photon showers are on average expected to reach maximum at depths considerably greater than observed. Shower-to-shower fluctuations are large due to the LPM effect (rms of 80 g cm^{-2}) and well in excess of the measurement uncertainty. For all 16 events, the observed $X_{\max}$ is well below the average value expected for photons. The $X_{\max}$ distribution of the data is also displayed in Fig. 1.

The statistical method for deriving an upper limit follows that introduced in [4]. In brief, for each event a χ^2 value is derived by comparing the observed $X_{\max}$ to the prediction from photon shower simulations. Accounting for the limited event statistics, the chance probability $p(f_\gamma)$ is calculated to obtain data sets with χ^2 values larger than observed as a function of the hypothetical primary photon fraction f_γ. The upper limit $f_\gamma^{\rm ul}$, at a confidence level α, is then obtained from $p(f_\gamma \geq \epsilon f_\gamma^{\rm ul}) \leq 1 - \alpha$, where the factor $\epsilon = 0.88$ accounts for the different detector acceptance to photon and nuclear primaries.

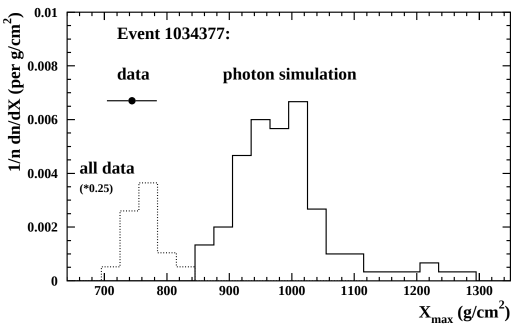

Figure 1. Example of $X_{\max}$ measured in an individual shower of 11 EeV (point with error bar) compared to the $X_{\max}$ distribution expected for photon showers (solid line). Also shown the $X_{\max}$ distribution of the data sample (dashed line; normalization changed as indicated).

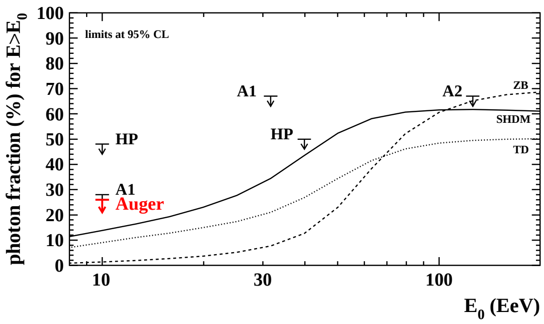

Figure 2. Upper limits (95% CL) on cosmic-ray photon fraction derived in the present analysis (Auger) and previously from AGASA (A1) [3], (A2) [4] and Haverah Park (HP) [2] data compared to some estimates based on non-acceleration models [1].

For the Auger data sample, an upper limit on the photon fraction of 26% at a confidence level of 95% is derived. In Fig. 2, this upper limit is plotted together with previous experimental limits and some estimates based on non-acceleration models. The presented 26% limit confirms and improves the existing limits above 10^{19} eV.

4. Discrimination power of surface array observables

In 5 out of the 16 selected events, the number of triggered surface detectors is large enough to perform a standard SD reconstruction [7]. Several observables can be used for primary photon discrimination [18], e.g.:

- *rise time:* For each triggered tank, we define a rise time as the time for the integrated signal to go from 10% to 50% of its total value. By interpolation between rise times recorded by the tanks at different distances to the shower core, the rise time at 1000 m core distance is extracted after correcting for azimuthal asymmetries in the shower front. Compared to nuclear primaries, where the rise time is relatively short due to muons that do not suffer from multiple scattering as shower electrons do, rise times in muon-poor photon showers are expected to be significantly larger.
- *curvature:* The shower front shape is fitted to a sphere (expanding at 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 in general develop deeper in the atmosphere, the shower front curvature is expected to be larger than that of nuclear primaries.

As an example, for the specific event shown in Fig. 1, the measured rise time and curvature data are compared to the simulated distributions in Figs. 3 and 4. For this and the other SD reconstructed hybrid events, the SD observables are well separated from the predictions for primary photons. These results provide independent information to the photon limit derived by the hybrid analysis. They support the conclusion that a photon origin of the observed events is not favoured.

The SD data statistics at these energies is considerably larger than the hybrid statistics, as the duty cycle of the fluorescence telescopes is ∼10%. To exploit the excellent statistical power, which will allow us to test

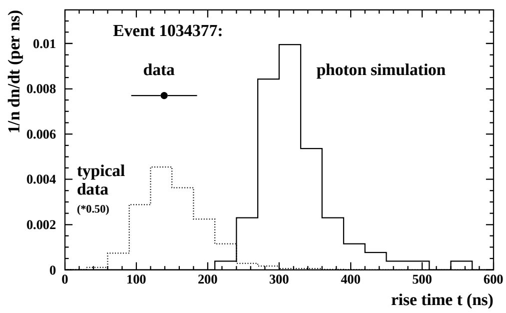

Figure 3. Example of rise time measured in an individual shower (same as in Fig. 1) (point with error bar) compared to the $X_{\max}$ distribution expected for photon showers (solid line). The typical data distribution from SD events at comparable zenith angle is also given (dashed line; normalization changed as indicated).

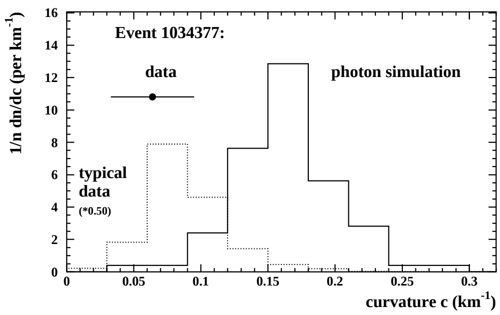

Figure 4. Example of curvature measured in an individual shower (same as in Fig. 1) (point with error bar) compared to the $X_{\max}$ distribution expected for photon showers (solid line). The typical data distribution from SD events at comparable zenith angle is also given (dashed line; normalization changed as indicated).

hypothetical primary photon fractions that are significantly smaller, current studies are performed on subtleties specific to an SD-only analysis: (i) event trigger and reconstruction are not fully efficient for photons at 10^{19}eV; (ii) the primary energy estimation is mass dependent, which could lead to a selection bias.

5. Outlook

The photon bound derived in this work is mainly limited by the small number of events. The data statistics of hybrid events will considerably increase in the near future, and much lower primary photon fractions can be tested. Moreover, the larger statistics will allow us to increase the threshold energy of 10^{19} eV chosen in the present analysis to energy ranges where even larger photon fractions are predicted by some models.

The discrimination power of surface detector observables will be further exploited. If hybrid detection is not required then statistics is significantly increased. Ways to reduce a possible selection bias in SD-only analyses are being investigated. Also, the technique introduced in [2] where event rates of near-vertical and inclined showers are compared to each other, can be further developed.

The uncertainty in extrapolating the photonuclear cross-section to highest photon energies imposes a systematic uncertainty in photon shower simulations both for fluorescence light and ground particle observations [19, 4]. Related systematic studies are ongoing.

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