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# Telescope Array search for EeV photons

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We present the results of a search for photons with energies higher than 1 EeV based on Telescope Array surface detector data for 9 years. The results are the limits for point source flux of photons for all directions in the Northern hemisphere.

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## 1. Introduction

Ultra-high energy photons are an important tool for studying the high-energy Universe. A plausible source of the EeV energy photons is ultra-high-energy cosmic rays (UHECR) undergoing the GZK-process [1, 2] or pair-production process on the cosmic background radiation. There also exists a class of so-called top-down models of UHECR generation that efficiently produce UHE photons [3–5]. The search for the UHE photons has been shown to be the most sensitive method of heavy dark matter indirect detection [6, 7]. Among other fundamental physics scenarios that could be tested with UHE photons are photon-ALP mixing [8] and Lorenz invariance violation [9–13].

Telescope Array [14, 15] (TA) is the largest cosmic-ray experiment in the Northern hemisphere. It is capable of detecting extensive air showers in the atmosphere from cosmic particles of EeV energies and higher. The experiment is located in Utah, USA and has operated since May 2008. It includes a surface detector (SD) and three groups of fluorescence telescopes. The surface detector consists of 507 scintillator stations, each of 3 $\mathrm{m}^2$ area, placed on the square grid with 1.2 km spacing and covering an area of $\sim 700\mathrm{km}^2$.

In the present study, we use 9 years of TA SD data to perform a blind search for the point sources of UHE photons. The full Monte-Carlo simulation of proton and photon extensive air shower (EAS) events allows us to perform the photon search up to the highest accessible energies: $E > 10^{20}$ eV. As the main technique for the present photon searches we use multivariate analyses based on a number of SD observables that makes it possible to distinguish between photonic EAS events and hadronic ones.

While searches for diffuse ultra-high energy photons have been performed by several EAS experiments [16–25], as well as by the Telescope Array [26, 27]. A search for point-sources of photons at these energies was made by the Pierre Auger observatory using hybrid data [28, 29]. In the present paper we perform a search for point sources of photons using the surface detector data in five energy ranges, namely $E > 10^{18}$, $E > 10^{18.5}$, $E > 10^{19}$, $E > 10^{19.5}$ and $E > 10^{20}$ eV.

## 2. Data set and simulations

We use the Telescope Array surface detector data set obtained with 9 years of observation from 2008-05-11 to 2017-05-10. During this period the duty cycle of the detector was about 95% [30, 31].

The Monte-Carlo simulations used in this study reproduce the 9 years of TA SD observations. We simulate separately showers induced by photon and proton primaries for the signal and background estimation respectively, using the CORSIKA code [32]. The high energy nuclear interactions are simulated with the QGSJET-II-03 package [33], the low energy nuclear reactions with the FLUKA package [34] and the electromagnetic shower component with EGS4 package [35]. The usage of the PRESHOWER package [36] that takes into account the splitting of the UHE photon primaries into the Earth's magnetic field allows us to correctly simulate the photon induced EAS up to the 100 EeV primary energy and higher. The thinning and dethinnig procedures with parameters described in Ref. [37] were used to reduce the calculation time.

We simulated 2100 CORSIKA showers for photon primaries and 9800 for proton primaries in $10^{17.5} - 10^{20.5}$ eV energy range. The showers from these libraries are processed by the code simulating the the real time calibration surface detector response by means of GEANT4 package [38]. For photons, each CORSIKA event is thrown at the random locations within the surface detector multiple times. As a result, a set of 57 millions photon events with an $E^{-2}$ differential spectrum was obtained. The proton Monte-Carlo set used in this study contains approximately 210 millions of events. The details of proton Monte-Carlo simulation are described in Refs. [30, 31]. The format of the Monte-Carlo events is the same as for real events, therefore both data and Monte-Carlo are processed by one and the same reconstruction procedure [37].

## 3. Reconstruction

Each data and MC event is reconstructed by the joint fit of shower front geometry and lateral distribution function (LDF) that allows us to determine arrival direction, core location, signal density at an 800 m distance from the core and Linsley front curvature parameter $a$.

For each MC and data event we also define the "photon energy" parameter, $E_\gamma$, which is the energy of this event in the assumption that the primary particle was a photon. This energy is estimated as the function of the zenith angle and the $S_{800}$ parameter, from photon MC simulations [26].

We apply the following set of the quality cuts for both MC and data events:

1. Zenith angle cut: $0^\circ < \theta < 60^\circ$ ;
2. The number of detectors triggered is 7 or more
3. Shower core is inside the array boundary with the distance to the boundary larger than 1200 m;
4. Joint fit quality cut: $\chi^2/\text{d.o.f.} < 5$.

We also use the additional cut to eliminate the events induced by lightnings. To make this clean-up we use the list of lightning events detected in the area of TA SD in the time of observation provided by Vaisala lightning database from the U.S. National Lightning Detection Network (NLDN) [39, 40].

## 4. Method

For the search for point sources of photons we use the boosted decision trees (BDT) method that was previously successfully used in TA searches for diffuse photons [27] and neutrinos [41] as well as in the SD mass composition analysis [42]. The detailed description of the search procedure along with the results is given in the work [43]. The BDT classifier is built using the *TMVA* package [44] for ROOT [45] and the 16 shower observable parameters sensitive to the sort of primary particle:

1. Zenith angle, $\theta$;
2. Signal density at 800 m from the shower core, $S_{800}$;
3. Linsley front curvature parameter, $a$;

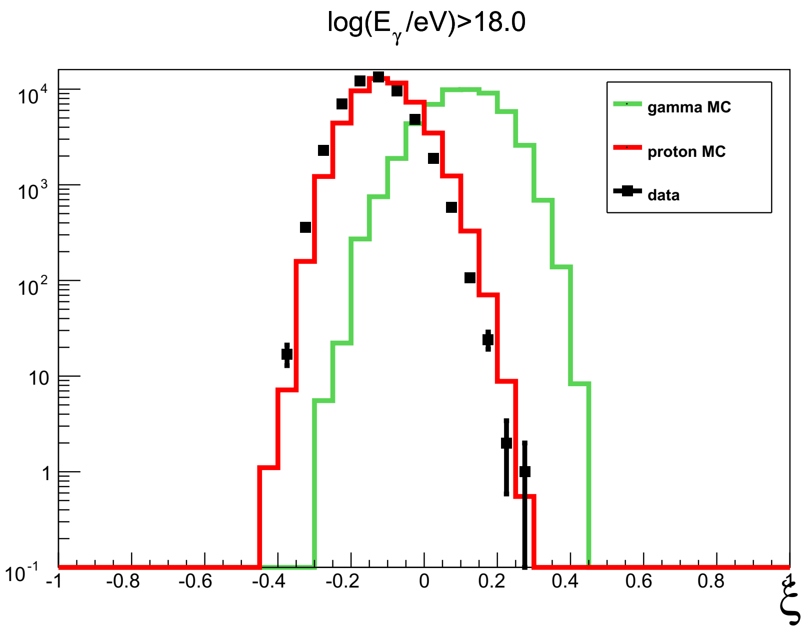

**Figure 1:** Distribution of the $\xi$ parameter for data (black) compared with proton and photon-induced Monte-Carlo events (red - protons, green - photons).

4. Area-over-peak (AoP) of the signal at 1200 m [46];
5. AoP slope parameter [47];
6. Number of detectors hit;
7. Number of detectors excluded from the fit of the shower front;
8. $\chi^2/d.o.f.$;
9. $S_b$ parameter for $b = 3$; $S_b$ is defined as $b$-th moment of the LDF:

$$S_b = \sum_i \left[ S_i \times (r_i/r_0)^b \right] , \tag{4.1}$$

   where $S_i$ is the signal of $i$-th station, $r_i$ is the distance from the shower core to a given station, $r_0 = 1000\,\mathrm{m}$. The sum is calculated over all triggered non-saturated stations. The $S_b$ is proposed as a composition-sensitive parameter in Ref. [48].

10. $S_b$ parameter for $b = 4.5$;
11. The sum of signals of all detectors of the event;
12. An average asymmetry of signal at upper and lower layers of the detectors;
13. Total number of peaks over both upper and lower layers of all detectors hit. To suppress accidental peaks as a result of FADC noise we define a peak as a time bin with a signal above 0.2 VEM which is higher than a signal of 3 preceding and 3 consequent time bins.

| $E_\gamma$, eV | ang. resolution |
|---|---|
| $> 10^{18.0}$ | 3.00° |
| $> 10^{18.5}$ | 2.92° |
| $> 10^{19.0}$ | 2.64° |
| $> 10^{19.5}$ | 2.21° |
| $> 10^{20.0}$ | 2.06° |

**Table 1:** Angular resolution of TA SD for photon primaries at various energies.

14. Number of peaks for the detector with the largest signal;

15. Total number of peaks present in the upper layer and not in lower;

16. Total number of peaks present in the lower layer and not in upper.

The BDT is trained with the proton MC as a background and the photon MC as a signal. Both proton and photon MC sets are split into three equal parts: one for training the classifier, the one for testing of classifier, and one for the calculation of the proton background and photon effective exposure, respectively. We train the classifier separately in five photon energy ranges: $E_\gamma > 10^{18}$, $E_\gamma > 10^{18.5}$, $E_\gamma > 10^{19}$, $E_\gamma > 10^{19.5}$ and $E_\gamma > 10^{20}$ eV. As a result of the BDT procedure, a single multivariate analysis (MVA) parameter, $\xi$, is assigned to each MC and data event. $\xi$ is defined to take values in the range $-1 < \xi < 1$, where proton-induced events tend to have negative $\xi$ values, and photon-induced events have positive $\xi$ values. An example of the resulting $\xi$ distribution of the MC events from testing sets and data events for the $E_\gamma > 1$ EeV energy range is shown in Fig. 1.

In the search for photon point sources the photon candidates are defined with the $\xi$-cut optimized separately in each constant declination band of the sky. We optimize the cut using proton and photon MC and assuming a photon-flux upper limit in the case of null-hypothesis: all events in the data set are protons. We pixelize the sky in equatorial coordinates into 12288 pixels using the HEALPix package [49]. For the pixel "$i$" with the center $\{\alpha_i, \delta_i\}$ the corresponding the data set contains the events located inside the spherical cap region around the pixel center within an angular distance equal to experiment angular resolution at the respective energy (see Tab. 1).

## 5. Results

An upper limit on the mathematical expectation of the number of photons is determined following Ref. [50]. The flux upper limits follow from the relation $\bar{n}_\gamma = F_\gamma A_{eff}$. The 95% CL photon flux upper-limit for each point in the Telescope Array field of view for $E_\gamma > 1$ EeV is shown in Fig. 2. The values of the limits for various photon energies averaged over all points are presented in Table 2. Although there are some photon candidate events found at some points, the excess of these events over the proton background is not significant, given a penalty for the scanning of the skymap.

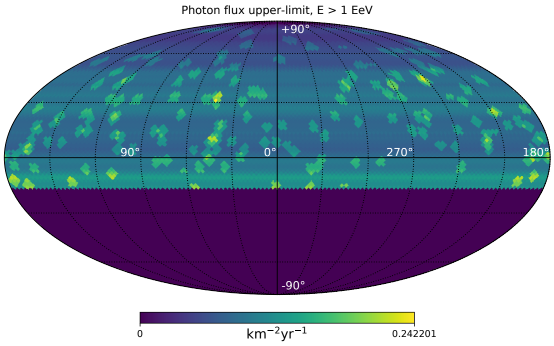

**Figure 2:** The map of point-source photon flux upper-limits for $E_\gamma > 1$ EeV plotted in equatorial coordinates.

| $E_\gamma \geq$, eV | $\langle F_\gamma \rangle \leq$, km$^{-2}$yr$^{-1}$ |
|---|---|
| $10^{18.0}$ | 0.094 |
| $10^{18.5}$ | 0.029 |
| $10^{19.0}$ | 0.010 |
| $10^{19.5}$ | $7.1 \times 10^{-3}$ |
| $10^{20.0}$ | $5.8 \times 10^{-3}$ |

**Table 2:** The point-source photon flux upper-limit averaged over all points in the TA field of view.

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