Telescope Array search for EeV photons

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Abstract. We present the results of a search for point sources of photons with energies higher than 1 EeV based on the Telescope Array surface detector data for 9 years. No significant excess of photon signal over UHECR background was found. The photon-flux upper limits were set for each direction in the Telescope Array field of view as well as for stacked directions of dwarf spheroidal galaxies.

1. Introduction
Telescope Array [1, 2] is the largest cosmic-ray experiment in the Northern Hemisphere. It is located at 39.3° N, 112.9° W in Utah, USA. The observatory includes a surface detector array (SD) and 38 fluorescence telescopes grouped into three stations. The SD consists of 507 stations that contain plastic scintillators each of 3 m² area (SD stations). The stations are placed in the square grid with the 1.2 km spacing and covers the area of ∼ 700 km². The TA SD is capable of detecting EAS in the atmosphere caused by cosmic particles of EeV and higher energies.

In the present study, we use 9 years of TA SD data for blind and target search for point sources of UHE photons. We utilize the statistics of the SD data, which benefits from high duty cycle in comparison to measurements based on fluorescence observations. The full Monte-Carlo (MC) simulation of proton-induced and photon-induced EAS events allows us to perform the photon search up to the highest accessible energies, \( E \gtrsim 10^{20} \) eV. As the main tool for the present photon search we use a multivariate analysis based on a number of the SD parameters that make possible to distinguish between photon and hadron primaries.

An extensive air shower (EAS) initiated by a photon, significantly differs from hadron-induced shower: the depth of the shower maximum \( X_{\text{max}} \) for a photon shower is larger, a photon shower contains less muons and as a consequence has more curved front (see Ref. [3] for the review). The TA SD stations are sensitive to both muon and electromagnetic component of the shower and therefore may be triggered by both hadron-induced and photon-induced EAS.

2. TA SD data and Monte-Carlo
The data and Monte-Carlo sets used in this study are the same as in the recent TA search for diffuse photons [4]. We use the TA SD data set obtained in 9 years of observation, from May 11, 2008 to May 10, 2017. During this period, the duty cycle of the SD was about 95% [5].

For the Monte-Carlo sets, we simulate separately showers induced by photon and proton primaries for the signal and background estimation respectively, using the CORSIKA code [6]. The high energy nuclear interactions are simulated with QGSJET-II-03 model [7], the low energy nuclear reactions with FLUKA package [8] and the electromagnetic shower component with...
EGS4 model [9]. The usage of the PRESHOWER package [10] that takes into account the splitting of the UHE photon primaries into the Earth’s magnetic field allows us to correctly simulate photon-induced EAS up to the 100 EeV primary energy and higher. The thinning and dehinning procedures with parameters described in Ref. [11] are used to reduce the calculation time.

The multivariate analysis is based upon the observables calculated in the reconstruction procedure together with several additional parameters, which are related to both shower front, lateral distribution function (LDF) and the muon content of EAS. Some of the observables are utilizing the features of the experiment’s SD technical design, such as the double-layered scintillators. The full list of 16 parameters used in the present photon search is the same as in the TA SD search for diffuse photons [4] and the TA SD composition study [12].

For each MC and data event we also define the “photon energy” parameter $E_\gamma$ which is the expected energy of the primary particle assuming it is a photon. This energy parameter is calculated as the function of the zenith angle and the $S_{800}$ parameter, the signal at the distance of 800 m from the shower core. For proton MC events, as well as for the majority of data events, the $E_\gamma$ parameter is not the actual primary energy but merely a parameter needed for the consistent comparison of proton events and possible photon events.

3. Analysis

The analysis method used in this study to distinguish between photon and proton events is a boosted decision tree (BDT) classifier built with the 16 observable parameters discussed in the previous section. The BDT is trained to separate proton MC events from photon MC events. Both proton and photon MC sets are split into three parts with equal amount of events in each: one for training the classifier, the second one for testing the classifier and the last one for the calculation of proton background and photon effective exposure, respectively. We train the classifier separately in five photon energy ranges: $E_\gamma > 10^{18}$ eV, $E_\gamma > 10^{18.5}$ eV, $E_\gamma > 10^{19}$ eV, $E_\gamma > 10^{19.5}$ eV and $E_\gamma > 10^{20}$ eV. As a result of the BDT procedure, the 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 – positive $\xi$ values.

The photon flux upper limit is defined as:

$$F_{\text{UL}} = \frac{\mu_{\text{FC}}(N_{\text{bg}}, N_{\text{obs}})}{A_{\text{eff}}}$$

where $N_{\text{obs}}$ is the number of photon candidate events, $N_{\text{bg}}$ is the estimated number of background events, $\mu_{\text{FC}}$ is the upper bound of the respective Poisson mean for the given confidence level, defined according to Ref. [13], and $A_{\text{eff}}$ is the effective exposure of the experiment for photons.

In the present upper-limit calculation we assume the “null hypothesis”, i.e. that there is actually no photons and any excess counts from the expected background, $N_{\text{obs}} - N_{\text{bg}}$, is considered as a fluctuation of background, where $N_{\text{bg}}$ itself is set to zero to obtain conservative limit. The separation between photon and proton primaries is defined by a cut on MVA-variable $\xi$ optimized separately for every direction studied. We pixelize the sky in equatorial coordinates $\{\alpha, \delta\}$ using the HEALPix package [14] into 12288 pixels ($N_{\text{side}} = 32$). For the pixel “i” with the center $\{\alpha_i, \delta_i\}$ the corresponding data set contains events located inside a spherical cap region around the pixel center within an angular distance that equals to the experiment’s angular resolution at the respective energy. To find the minimum value of $F_{\text{UL}}^i$, as a function of $\xi_0$, we optimize the cut position assuming $N_{\text{bg}} = 0$ and the null hypothesis: $N_{\text{obs}} = N_p(\xi > \xi_0)$, where $N_p(\xi > \xi_0)$ is the number of protons passing the $\xi$-cut. As the cut $\xi_0$ position for the pixel $i$ is fixed, the actual upper-limit value is calculated using the definition (1) with $N_{\text{bg}}^i = 0$ and $N_{\text{obs}}^i = N_{\text{data}}^i(\xi > \xi_0)$, where $N_{\text{data}}^i$ is the number of the
Photon flux upper-limit, $E > 1\ E_{eV}$

$0.242201\ km\ 2\ yr^{-1}$

Figure 1. Maps of point-source photon flux upper limits (95% C.L.) for various photon energies plotted in equatorial coordinates.

4. Results
The photon-flux upper limits at 95% C.L. for each pixel in the Telescope Array field of view and for various photon energies are shown in Fig. 1. The values of the limits averaged over all pixels are presented in Table 1 together with maxima pre-trial significances over proton background. The highest pre-trial excess significance, $3.43\sigma$ ($N_{bg} = 0.036$ and $N_{obs} = 2$), appears in the highest energy bin $E_{\gamma} > 10^{20}\ eV$, at $\{\alpha = 155.3^\circ, \delta = 60.4^\circ\}$ pixel. However, post-trial significances are less than 1$\sigma$ in all energy bins.

Target search for UHE photon signal from dwarf galaxies is performed. Dwarf galaxies are expected to be dark-matter abundant and gas-deficit, which makes it a plausible candidate to search for heavy dark matter decay footprints. The dwarf galaxy set is the 21 sources as proposed in [15], the search is performed in stacked skymap pixels of dwarf galaxies with the pixels size equal to the TA SD $\gamma$ resolution. As a result, no evidence for photon signal is found at all energies ($N_{cand.} = 0$), that allows one to impose upper limit on the UHE photon flux from dwarf galaxies, as listed in Table 2. The derived result may be used to constrain the lifetime of heavy dark matter.
\[ E_{\gamma}, \text{eV} \quad (F_{\gamma}) \leq, \text{km}^{-2}\text{yr}^{-1} \quad \text{max. \gamma signif. (pre-trial)} \]

| \( E_{\gamma} \) | \( (F_{\gamma}) \leq \) | \( \text{max. \gamma signif. (pre-trial)} \) |
|----------------|--------------------|-------------------------|
| \( > 10^{18.0} \) | 0.094 | 2.72 \( \sigma \) |
| \( > 10^{18.5} \) | 0.029 | 2.71 \( \sigma \) |
| \( > 10^{19.0} \) | 0.010 | 2.89 \( \sigma \) |
| \( > 10^{19.5} \) | \( 7.1 \times 10^{-3} \) | 2.76 \( \sigma \) |
| \( > 10^{20.0} \) | \( 5.8 \times 10^{-3} \) | 3.43 \( \sigma \) |

Table 1. Point-source photon-flux upper limits averaged over all pixels in TA FOV together with the maximum pre-trial significance of the photon excess over proton background.

\[ E_{\gamma}, \text{eV} \quad F_{\gamma}^{UL}, \text{km}^{-2}\text{yr}^{-1} \]

| \( E_{\gamma} \) | \( 10^{18.0} \) | \( 10^{18.5} \) | \( 10^{19.0} \) | \( 10^{19.5} \) | \( 10^{20.0} \) |
|----------------|-----------|-----------|-----------|-----------|-----------|
| 0.15           | 0.057     | 0.014     | 0.0076    | 0.0052    |

Table 2. Point-source photon-flux upper limits for the stacked directions of dwarf spheroidal galaxies as a function of energy.

5. Discussion
The upper limits are set on the fluxes of photons from each particular direction in the sky in the TA field of view, according to the experiment’s angular resolution with respect to photons. The point-source photon-flux upper limits derived in the present study can be used to constrain various models of astrophysics and particle physics. The models that could be probed with the present photon point-source flux limits include cosmogenic photon generation models as well as top-down models of ultra-high energy photons production such as heavy decaying dark matter.

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