

Search for EeV photon–induced events at the Telescope Array

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We report on the updated results on the search for photon-like-induced events in the data, collected by Telescope Array's Surface Detectors during the last 14 years. In order to search for photon-like-induced events, we trained a neural network on Monte-Carlo simulated data to distinguish between the proton-induced and photon-induced air showers. Both reconstructed composition-sensitive parameters and raw signals registered by the Surface Detectors are used as input data for the neural network. The classification threshold was optimized to provide the strongest constraint on the photons' flux.

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1. Introduction

Establishing limits on the ultra-high-energy cosmic photon flux is of importance for verifying theoretical models of evolution of astrophysical objects [1–3] and for the search for new physics [4–6]. Recently, several experiments reported evidence for the detection of ultra-high-energy photon-induced events from GRB 221009A [7–11]. How such photon-like particles have reached the Earth is yet unknown, and this observation may point to physics beyond the standard model [12–14]. This motivates for a search of photon-like-induced events in the Telescope Array’s data.

Telescope Array [15, 16] is a hybrid detector located in Utah, USA. Its Surface Detectors (SD) comprise of 507 scintillation detectors, arranged in a rectangular grid covering an area of 680 km². All stations are calibrated in real time and register signals with 20 ns time resolution in conventional units called “minimal ionizing particles”. SD have two scintillation layers and, when triggered, the data from consecutive 128 time bins is read out and saved for further analysis.

Unlike the fluorescence detectors, SD operate almost under all weather conditions. Therefore, they have bigger exposure time than the fluorescence detectors, which is important for establishing limit on the photon flux. This is the primary reason, for which the present work leverages only SD.

The data provided by solely SD is not as rich as by a combination of fluorescence and surface detectors, making it harder to discern photon- and proton-induced events. This drawback can be resolved by using machine learning to identify photon-like induced events. In this report, we present the updated results on the search for photon-like-induced events, using a neural network for the analysis of Telescope Array’s SD data collected during the last 14 years.

2. Monte-Carlo simulation

For training a neural network, we used Monte-Carlo simulation of the data. Namely, SD responses have been simulated for proton and photon air shower primaries. Elements heavier than protons were not employed, because they may be easily distinguished from photon-induced events. Moreover, the exact composition of ultra-high-energy cosmic rays is unknown. Hence using only protons as air shower primaries, besides photons, provides the most conservative and reliable results.

For the simulation of Monte-Carlo data, we used CORSIKA [17] with QGSJET II-03 [18] and FLUKA [19] for high and low energy hadronic interactions, correspondingly, and EGS4 [20] for electromagnetic interactions. Thinning and dethinning procedures were used during the simulation. Detectors’ response was obtained using GEANT4 [21] based look-up tables. We used real-time array configuration and calibration tables, which allows for the simulated data to be processed by reconstruction algorithms in the same way as the real experimental data. The proton’s energy spectrum was chosen to coincide with the experimentally expected one, while for photons the spectrum was proportional to the inverse energy.

3. Reconstruction and quality cuts

Before analyzing the events with a neural network, they were processed via standard algorithmic reconstruction procedure [22]. It is based on a joint fit of air shower’s geometry and lateral

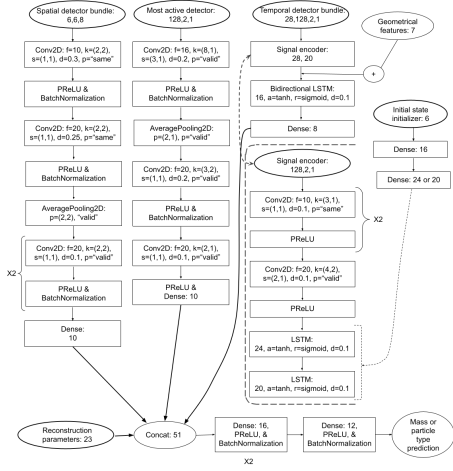


Figure 1: Architecture of the neural network. Arrows show the data flow.

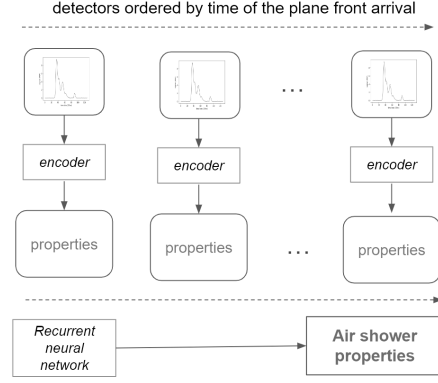


Figure 2: Schematic architecture of the temporal detector bundle.

distribution function, providing an estimate of such parameters as S_{800} , reconstructed shower core, e.t.c. Additionally, we estimated the energy of the primary particle as if it was a photon.

To ensure good quality of the events, the following cuts have been imposed:

- Reconstructed zenith angle is below 55° ;
- At least 7 detectors were triggered;
- Reconstructed position of the shower cover is within the detectors array and at least 1200 meters away from its boundary;
- Joint fit was done with a suitable accuracy, $\chi^2/d.o.f. < 5$.

The same reconstruction procedure and quality cuts were applied to the real experimental data. Additionally, we have excluded the events, whose registration time is within a 10-minute interval, related to the lightnings registered by the National Lightning Detection Network [23] at the location of SD. This has been done, since the Terrestrial Gamma-Ray Flashes are known to produce electromagnetic showers similar to the photon-induced events [24].

4. Neural Network architecture

For identifying photon-like induced events in the experimental data, we trained a neural network to distinguish between the Monte-Carlo simulated proton-induced and photon-induced events. Neural network's architecture, presented in figure 1, is identical to the network used for mass composition analysis of SD data [25], with the hyperparameters optimized for the given task. It contains the following four main components.

(1) *Spatial detector bundle.* This part of the neural network is designed to extract geometrical features of an event. It takes as input the array of 6x6 SD, centered around the reconstructed position of the shower's core. For each of these detectors, its geometrical position, integral registered charge,

and activation times are provided. For the detectors that were not triggered in an event, the data is filled with zeros. So formed data is passed through two-dimensional convolution layers to extract useful geometrical features of an event.

(2) *Waveform with the largest integral charge.* For each event, we identify a detector with the largest registered integral signal. One may consider the corresponding waveform as a one-dimensional image with 2 channels, that is, of shape (128,2). By passing it through several convolution layers, we extract specific characteristics of the waveform with the largest integral charge.

(3) *Temporal detector bundle.* The general scheme of data processing in this section of the neural network is presented in figure 2. First, all of the detectors triggered in an event are ordered according to their activation times. Further, the waveforms registered by each of these detectors are processed by an *encoder*. The *encoder* takes a waveform as input, passes it through a series of convolution and recurrent layers, and outputs lower-dimensional waveform features. This results in a time-order sequence of signal features. Finally, this sequence is analyzed by an LSTM layer, which outputs the characteristics of an event.

(4) *Reconstruction parameters.* We use the reconstructed event's characteristics, such as estimated energy, primary particle's incoming direction, S_{800} and others (see [26] for the full list of such parameters) as an additional input to the neural network.

The features from all of the above-mentioned neural network blocks are concatenated and passed through three fully-connected (dense) layers. The output of the last layer is a number, $\xi \in [0; 1]$, representing neural network's confidence that the corresponding event is photon-like.

To avoid overfitting, in particular to Monte-Carlo data as opposed to real experimental data, we introduced additive Gaussian noise into the data and used dropout layers. Moreover, to account for fluctuations in the SD apparatus, we introduced a Gaussian-like kernel for smoothing the waveforms, registered by SD.

To search for photon-like induced events, one needs to minimize the number of false-positive identification cases, that is, the number of proton primaries identified as photon primaries by the neural network. For this purpose, we implemented the following features.

(1) The weights for proton-induced events were set to 5, while for the photon-induced events the weights are 1. This forces the neural network to pay more attention to proton-induced events and thus improve their identification accuracy.

(2) For training the neural network, we used a special loss function called *focal loss* [27]. It allows to decrease the number of false-positive identification cases by forcing the neural network to pay more attention to events that are hard to classify.

(3) We trained an ensemble of neural networks and averaged their predictions. The introduction of such a "board of expert" allows to reduce the specifics of individual neural networks, and thus decrease the number of false-positive identifications.

5. Method

After training the neural network, one can plot the histogram of neural network's predictions for Monte-Carlo proton-induced and photon-induced events, figure 3. To get the optimal classifi-

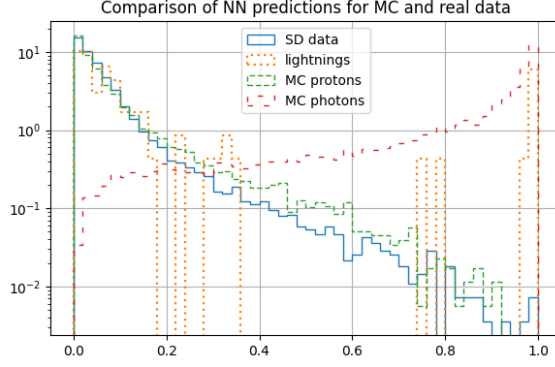


Figure 3: Comparison of the neural network’s predictions for SD data, lightnings, and Monte-Carlo proton-induced and photon-induced events.

cation threshold, note that we do not expect photon-induced events in the real experimental data. Correspondingly, to get the strongest limits on the photons flux, we minimize the following quantity:

$$\rho = \frac{N_{max}(\xi)}{E(\xi)}, \quad (1)$$

where ξ is the classification threshold, $E(\xi)$ is the photons’ efficiency (the fraction of true photon-induced events to the right of the classification threshold), and N_{max} is the maximal number of photon-like induced events, expected in experimental data at 95% confidence level. To evaluate N_{max} , we first count the number of false-photon identifications on the Monte-Carlo dataset for a given ξ . Further, this number is multiplied by the ratio of the number of experimentally registered events to that of the Monte-Carlo dataset, to yield the expected number of false photon-like-induced events in the experimental data. Finally, based on this value, we evaluate the N_{max} at the 95% confidence level.

For the described procedure to be correct, the histograms of neural network’s predictions on Monte-Carlo and experimental data should be the same. As we are using only proton-induced air shower, the histogram for the Monte-Carlo simulated data should be, in fact, slightly higher. As one can see from figure 3, this is indeed the case. Thus, the procedure is correct and provides a conservative limit on the photon flux.

To verify that the neural network’s predictions are reliable, we studied the neural network’s prediction on events that are correlated with lightnings registered near SD, figure 3. The corresponding histogram has a peak at $\xi \simeq 1$, which indicates that the neural network learned correctly to identify photon-like-induced events.

6. Results

To estimate the photons’ flux, we have calculated the effective SD exposure after taking into account the quality cuts on events, and dropping off events to the left of the classification threshold. The resulting limits on photons’ flux are depicted on figure 4. As one can see, our results are compatible with the limits obtained previously for 11 years of data collection.

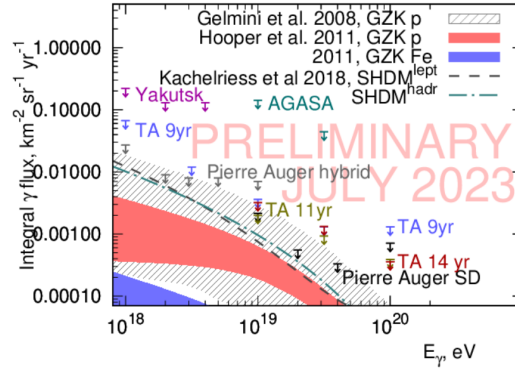


Figure 4: Photon flux limits obtained by various collaborations.

We would like to note that we observe 3 photon-like-induced events in SD data in the energy range of $10^{19} - 10^{19.5}$ eV. This is within the 95% confidence level of expected false-photon identifications. These events shall be studied more carefully before concluding whether they were indeed photon-induced.

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