PROCEEDINGS OF SCIENCE

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.

38th International Cosmic Ray Conference (ICRC2023)
26th of July - 3rd of August, 2023
Nagoya, Japan

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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 for 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 km^2. All stations are calibrated in real time and register signals with 20 ns time resolution in conventional units called "minimal ionizing particles". Each SD has 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, SDs 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 SDs.

The data provided by solely SDs 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

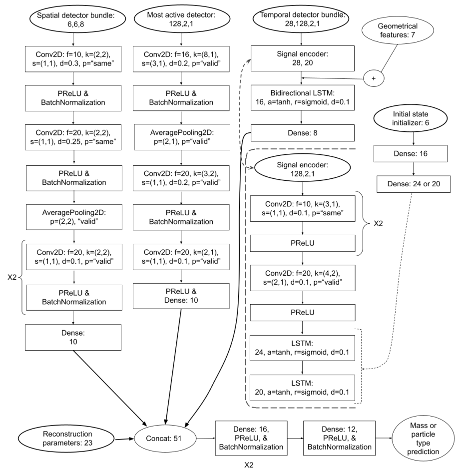

Figure 1: Architecture of the neural network. Arrows show the data flow.

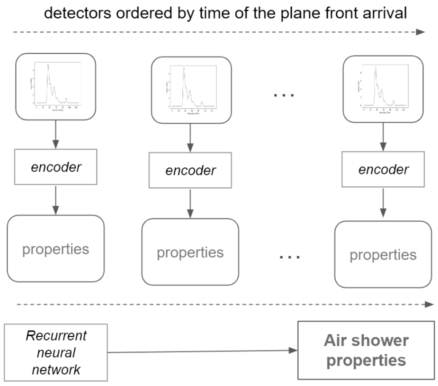

Figure 2: Schematic architecture of the temporal detector bundle.

distribution function, providing an estimate of such parameters as Linsley front curvature, reconstructed position of the 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: *(1)* reconstructed zenith angle is below 55°; *(2)* at least 7 detectors were triggered; *(3)* reconstructed position of the shower core is located within the detectors array and at least 1200 meters away from its boundary; and *(4)* joint geometry and lateral distribution profile 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 at the location of SDs.

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 [23], 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 an array of 6x6 SDs, 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 this waveform.

(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 a recurrent layer, namely, by a long short-term memory 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 [24] 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 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* [25]. 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. The latter were weighted to yield the spectrum proportional to E^{-2}, which is close to the one expected experimentally. The resulting histogram is shown in figure 3.

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

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

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

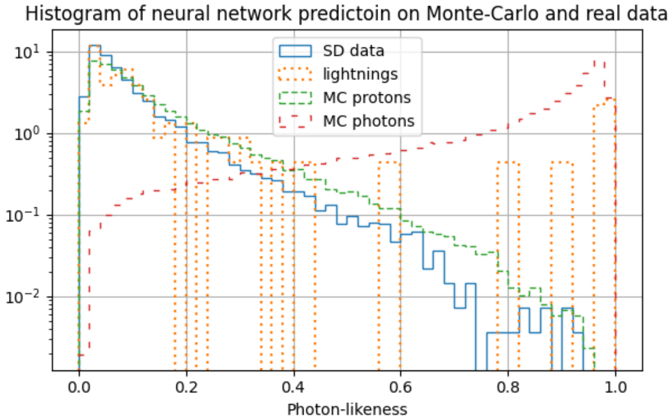

Figure 3: Comparison of the neural network's predictions for SD data, lightnings, and Monte-Carlo proton-induced and photon-induced events.

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 shifted to the right (photon-like) side. 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 SDs, depicted in 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. For each of the energy ranges, the optimal classification threshold has been established independently, on a separate Monte-Carlo data set. The resulting limits on photons' flux are presented in table 1 and are depicted on figure 4. We would like to note that the number of observed photon-like-induced events in SD data is within the 95% confidence level of the expected false-photon identifications. Thus, we do not see evidence for photon-like-induced events in TA SD data.

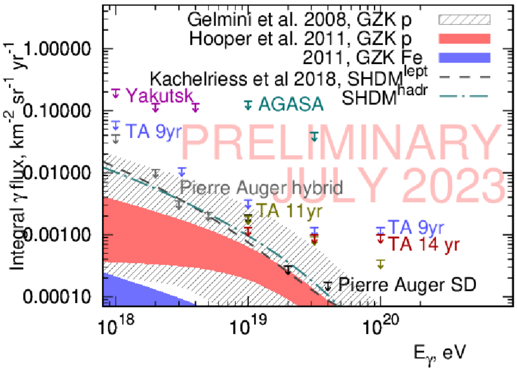

Figure 4: Photon flux limits obtained by various collaborations.

Energy, eV	Effective exposure, $km^2 \cdot sr \cdot yr$	Number of photon candidates, expected background	observed in data	Upper photon flux limit, $km^{-2} \cdot sr^{-1} \cdot yr^{-1}$
$10^{19.0}$	2366.5	0.0	0	$1.3 \cdot 10^{-3}$
$10^{19.5}$	2974.0	0.304	0	$1.0 \cdot 10^{-3}$
$10^{20.0}$	4933.8	0.78	1	$1.0 \cdot 10^{-3}$

Table 1: Resulting photon flux limits.

Acknowledgments

The Telescope Array experiment is supported by the Japan Society for the Promotion of Science(JSPS) through Grants-in-Aid for Priority Area 431, for Specially Promoted Research JP21000002, for Scientific Research (S) JP19104006, for Specially Promoted Research JP15H05693, for Scientific Research (S) JP19H05607, for Scientific Research (S) JP15H05741, for Science Research (A) JP18H03705, for Young Scientists (A) JPH26707011, and for Fostering Joint International Research (B) JP19KK0074, by the joint research program of the Institute for Cosmic Ray Research (ICRR), The University of Tokyo; by the Pioneering Program of RIKEN for the Evolution of Matter in the Universe (r-EMU); by the U.S. National Science Foundation awards PHY-1806797, PHY-2012934, PHY-2112904, PHY-2209583, and PHY-2209584 as well as AGS-1613260, AGS-1844306, and AGS-2112709; by the National Research Foundation of Korea (2017K1A4A3015188, 2020R1A2C1008230, & 2020R1A2C2102800) ; by the Russian Science Foundation grant 22-22-20063, IISN project No. 4.4501.18, by the Belgian Science Policy under IUAP VII/37 (ULB), by National Science Centre in Poland grant 2020/37/B/ST9/01821. This work was partially supported by the grants of the joint research program of the Institute for Space-Earth Environmental Research, Nagoya University and Inter-University Research Program of the Institute for Cosmic Ray Research of University of Tokyo. The foundations of Dr. Ezekiel R. and Edna Wattis Dumke, Willard L. Eccles, and George S. and Dolores Doré Eccles all helped with generous donations. The State of Utah supported the project through its Economic Development Board, and the University of Utah through the Office of the Vice President for Research. The experimental site became available through the cooperation of the Utah School and Institutional Trust Lands Administration (SITLA), U.S. Bureau of Land Management (BLM), and the U.S. Air Force. We appreciate the assistance of the State of Utah and Fillmore offices of the BLM in crafting the Plan of Development for the site. We thank Patrick A. Shea who assisted the collaboration with much valuable advice and provided support for the collaborations efforts. The people and the officials of Millard County, Utah have been a source of steadfast and warm support for our work which we greatly appreciate. We are indebted to the Millard County Road Department for their efforts to maintain and clear the roads which get us to our sites. We gratefully acknowledge the contribution from the technical staffs of our home institutions. An allocation of computing resources from the Center for High Performance Computing at the University of Utah as well as the Academia Sinica Grid Computing Center (ASGC) is gratefully acknowledged.

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