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Telescope Array search for EeV photons

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We present updated results of the search for the ultra-high energy photons with primary energies greater than 10 EeV. The data of the Telescope Array Surface Detector collected over 11 years are used in this work. The method is based on the machine learning classifier, which is trained on both the reconstructed composition-sensitive parameters of the event and the calibrated waveform signals at each triggered station of the Surface Detector.

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1. Introduction

The Telescope Array (TA) experiment [1, 2] is a hybrid detector operating in Utah, USA. The TA Surface Detector (TA SD) is an array of 507 stations covering an area of 680 km^2 placed in a square grid with 1.2 km spacing. Each SD station registers particles of extensive air showers (EAS) at the ground level with two layers of 1.2 cm thick plastic scintillator. SD station is solar powered and wirelessly connected to one of the three communication towers. The purpose of this *Talk* is to present updated limits on the diffuse photon flux with energies greater than 10^{19} eV obtained using novel neural-network classifier and the data of the 11 years observations of the TA SD.

The limits on the ultra-high-energy diffuse photon flux have been set in many independent experiments, including Haverah Park, AGASA, Yakutsk, Pierre Auger and Telescope Array observatories [3–14], while no evidence for primary photons found at present. The upper limit on the photon flux from Southern and Northern hemisphere point sources is set by the Pierre Auger Observatory [15] and TA [16]. Photon flux limits are used to constrain the parameters of top-down models [17] and the properties of the astrophysical sources and their evolution in the scenario of Greisen-Zatsepin-Kuzmin [18, 19] cut-off. Moreover, the results of the photon search severely constrain the parameters of Lorentz invariance violation at the Planck scale [20–24]. Finally, photons with energies above $\sim 10^{18}$ eV might be responsible for ultra-high-energy cosmic ray events correlated with BL Lac type objects on the angular scale significantly smaller than the expected deflection of protons and nuclei in cosmic magnetic fields and thus suggesting neutral primaries [25, 26] (see Ref. [27] for a particular mechanism).

2. Data set and simulations

We use Telescope Array surface detector data set covering eleven years of observation from 2008-05-11 to 2019-05-10. Surface detector has been collecting data for more than 95% of time during that period [28].

The structure of the extensive air showers induced by the primary photons is significantly different from the structure of the hadron-induced events (see e.g. [29] for a review). The photon-induced events develop deeper in the atmosphere and contain less muons. As a consequence they have larger shower front curvature, longer duration of the signal at scintillator and difference in multiple other observables [13]. The 1.2 cm thick plastic scintillator responds to both muon and electromagnetic components of the shower and therefore TA SD is sensitive to showers, induced by primary photons (see Ref. [30] for discussion).

The results of this *Talk* employ Monte-Carlo simulations reproducing the observations at the TA SD. The proton induced simulated shower set is used as a background while the photon set is used as a signal. We produce simulated events by CORSIKA [31] with EGS4 [32] model for electromagnetic interactions, PRESHOWER code [33] for interactions of photons in geomagnetic field, QGSJET II-03 [34] and FLUKA [35] for high and low energy hadronic interactions. The showers are simulated with thinning and the dethinning procedure is used to recover small scale structure of the shower fluctuations [36].

Detector response is accounted for by using look-up tables simulated with the GEANT4 [37]. Each simulated event uses real-time array configuration and detector calibration information. The

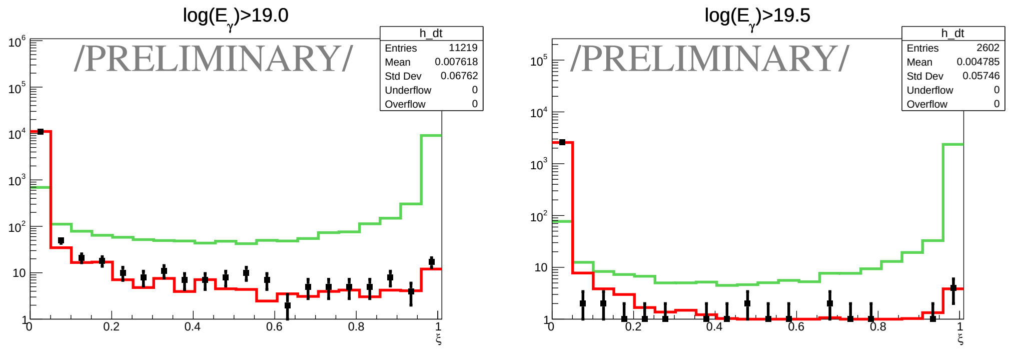

Figure 1: Distribution of the ξ parameter for data (black) compared with proton and photon-induced Monte-Carlo events (red - protons, green - photons).

format of the Monte-Carlo (MC) events is the same as the format of the real data and therefore all the analysis procedures are applied to both in the same way [36].

3. Reconstruction and event features

The reconstruction of each event is performed with a joint fit of the geometry and lateral distribution function (LDF). The fit determines the Linsley shower front curvature parameter "a" along with the arrival direction, core location and signal density at 800 meters $\mathcal{S} \equiv S_{800}$. The reconstruction procedure is identical for the data and MC events.

For each real event "i" the energy of hypothetical photon primary $E_\gamma^i = E_\gamma(\mathcal{S}^i, \theta^i, \phi^i)$ is estimated. E_γ^i is the average energy of the primary photon, inducing the shower with the same arrival direction and $\mathcal{S}$. The look-up table for $E_\gamma(\mathcal{S}, \theta, \phi)$ is constructed using photon MC set.

The following cuts are applied to both data and MC events:

(a) Zenith angle cut: $0° < \theta < 55°$;

(b) The number of detectors triggered is 7 or more;

(c) Shower core is inside the array boundary with the distance to the boundary larger than 1200 meters;

(d) Joint fit quality cut, χ^2/d.o.f.< 5;

(e) $E_\gamma(S_{800}^i, \theta^i, \phi^i) > E_0$, where E_0 is lower limit of the energy range. E_0 takes values of $10^{19.0}$, $10^{19.5}$ and $10^{20.0}$ eV in the present analysis. The training of the classifier is performed with $E_0 = 10^{18.5}$.

Additionally, we exclude the events with the arrival times correlated with the lightnings registered by the National Lightning Detection Network [38–40] at the location of TA SD. There is an evidence that Terrestrial Gamma-Ray Flashes induce the electromagnetic showers similar to the photon-induced events [41, 42].

Reconstruction of each data and MC event results in a set of the following features used as an input of the neural-network classifier along with the time-resolved signals at SD stations (waveforms) [43]:

1. Zenith angle, θ;
2. Signal density at 800 m from the shower core, $S(800)$;
3. Linsley front curvature parameter, a;
4. Area-over-peak (AoP) of the signal at 1200 m [44];
5. AoP slope parameter [45];
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 $b = 2.5, 3.0, 3.5$ and 4.5 [46];
10. The sum of signals of all detectors of the event;
11. An average asymmetry of signal at upper and lower layers of the detectors;
12. 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.
13. Number of peaks for the detector with the largest signal;

14-15. Total number of peaks present in the upper layer and not in lower (and vice versa).

3.1 Method

In present *Talk* novel neural-network classifier is employed. The architecture of the classifier includes convolutional and recurrent neural networks and is explained in [50]. The classifier uses both time-resolved signals for all triggered SD stations of the event and composition-sensitive event features listed in Section. 3. The classifier is trained using the proton Monte-Carlo set as a background and the photon as a signal. The Monte-Carlo set is split into three parts: (I) for training the classifier, (II) for cut optimization, (III) for exposure estimate.

The result of the classifier is a single parameter ξ^i for each event "i" which by it's definition lies in range $0 \leq \xi^i \leq 1$. The histograms of ξ-parameter for data and simulated events with reconstructed photon energy greater than $10^{19.0}$ eV and $10^{19.5}$ eV are shown in Figure. 1.

The photon candidates are selected with the cut on ξ

$$\xi > \xi_{cut} \,. \tag{1}$$

The cut is optimized with the part II of MC with the merit factor defined as an average photon flux upper limit assuming the null-hypothesis is valid: all events in the data set are protons.

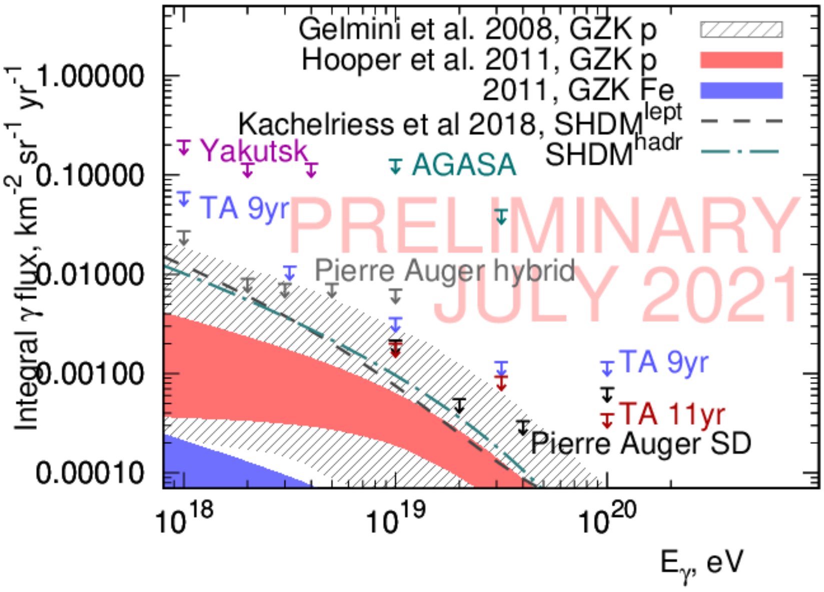

Figure 2: Photon flux limit presented in this *Talk* (TA SD) compared with the results from AGASA [4], Pierre Auger Observatory SD [10, 14] and hybrid data [11], Yakutsk [6], TA SD 9 years result [13], and the predictions of cosmogenic photon flux in certain models of [47, 48]. The prediction of super-heavy dark matter (SHDM) model is shown for leptonic and hadronic decay channels [49]. The mass of SHDM particle is 1000 EeV and the lifetime for this mass is mostly constrained by Auger hybrid photon limits. The lines correspond to the flux in the TA field of view, which is inferior to the flux in the Southern Hemisphere.

4. Photon search results

Geometrical exposure for the considered SD observation period with $0^\circ < \theta < 55^\circ$ and boundary cut is given by

$$A_{geom} = 13221 \text{ km}^2 \text{ sr yr} . \tag{2}$$

The effective exposure after the cuts A^{γ}_{eff} is given in Table 1.

E_0	quality cuts	$\xi > \xi_{cut}$	A_{eff} km^2 sr yr
$10^{19.0}$	43.7%	**59.4%**	**3428**
$10^{19.5}$	52.0%	**80.7%**	**5546**
$10^{20.0}$	64.3%	**92.7%**	**7875**

Table 1: Contribution of the cuts to an effective exposure at the energy ranges of interest. The value represents a ratio of the exposure after the given cut to the exposure before cut.

Implementation of novel neural-network classifier substantially increased the efficiency of the photon candidate selection ($\xi > \xi_{cut}$) compared to the previous analysis with BDT classifier (16.2%, 37.2% and 52.3% for $\log_{10} E_0 = 19.0, 19.5$ and 20.0, correspondingly) [13].

An upper limit on a mathematical expectation of number of photons is determined following Ref. [51] in the assumption of zero background. The latter assumption is conservative. For reference we calculate the expected number of false positive photon candidates b using proton Monte-Carlo. The flux upper limits follow from the relation

$$\bar{n}_\gamma = F_\gamma A^\gamma_{eff} \,. \quad (3)$$

The number of photon candidates and resulting 95% CL photon diffuse flux upper limits are summarized in Table 2 and are compared to the results of other experiments in Figure 2.

E_0, eV	$10^{19.0}$	$10^{19.5}$	$10^{20.0}$
γ candidates	2	1	0
b	0.8	0.4	0.05
$\bar{n}\ <$	6.72	5.14	3.09
A_{eff}	3428	5546	7875
$F_\gamma\ <$	2.0×10^{-3}	9.3×10^{-4}	3.9×10^{-4}

Table 2: The preliminary number of γ candidates, background expectation b estimated with proton Monte-Carlo, 95% CL upper limits on the number of photons in the data set $\bar{n}_\gamma$ and on the photon flux F_γ ($\mathrm{km}^{-2}\mathrm{yr}^{-1}\mathrm{sr}^{-1}$).

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