Telescope Array search for photons and neutrinos with the surface detector data

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We report on a search for ultra-high-energy photons with a multivariate analysis technique based on the properties of shower fronts of events observed by the Telescope Array surface detector. The revised constraints on the diffuse flux of the primary photons with energies greater than $10^{18.5}$ eV are presented. We also report the status of the search for the photon point sources and down-going neutrino in the Northern hemisphere.

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1. Introduction

Telescope Array (TA) experiment [1, 2] is a hybrid detector operating in Utah, USA. TA consists of a surface detector array of 507 plastic scintillators with 1.2 km spacing covering 700 km^2 area and three fluorescence detectors. The purpose of this *Talk* is to present the limits on photon flux with energies greater than $10^{18.5}$ eV based on 7 years of surface detector operation. Preliminary constraints on the ultra-high energy neutrino flux are also presented.

Several limits on the ultra-high-energy diffuse photon flux have been set by independent experiments, including Haverah Park, AGASA, Yakutsk, Pierre Auger and Telescope Array observatories [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13], but no evidence for primary photons found at present. The upper limit on a photon flux from Southern hemisphere point sources is set by the Pierre Auger Observatory [14]. Photon flux limits may be used to constrain the parameters of top-down models [15] and the properties of the astrophysical sources and their evolution in the scenario of Greisen-Zatsepin-Kuzmin [16, 17] cut-off. Moreover, the results of the photon search severely constrain the parameters of Lorentz invariance violation at Planck scale [18, 19, 20, 21, 22]. Finally, photons with energies above $\sim 10^{18}$ eV might be responsible for CR events correlated with BL Lac type objects on the angular scale significantly smaller than the expected deflection of protons in cosmic magnetic fields and thus suggesting neutral primaries [23, 24] (see Ref. [25] for a particular mechanism).

Ultra-high energy *neutrinos* may be generated by the decay of the charged pions produced as secondaries in GZK process [26], by beta-decay of unstable ultra-high energy nuclei or by some mechanism related to the new physics. Neutrino flux at ultra-high energies is constrained by air shower [27, 28, 29, 30], ice shower [31] and radio Cherenkov [32, 33, 34, 35, 36, 37] experiments (see [38] for a review). At lower (PeV) energies, neutrinos of astrophysical origin are discovered by IceCube [39].

2. Data set and simulations

We use Telescope Array surface detector data set covering seven years of observation from 2008-05-11 to 2015-05-11. Surface detector has been collecting data for more than 95% of time during that period [40].

Air showers induced by primary photons differ significantly from the hadron-induced events (see e.g. [41] for a review). The Telescope Array surface detectors contain plastic scintillators of 3 m^2 area which detect both muon and electromagnetic components of the extensive air shower and therefore are sensitive to showers induced by primary photons (see Ref. [42] for discussion).

The results of this *Talk* employ both proton and photon-induced simulated showers. We produce simulated events by CORSIKA [43] with EGS4 [44] model for electromagnetic interactions, PRESHOWER code [45] for interactions of photons in geomagnetic field, QGSJET II-03 [46] and FLUKA [47] 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 [48].

Detector response is accounted for by using look-up tables simulated with GEANT4 [49]. Real-time array configuration and detector calibration information are used for each simulated
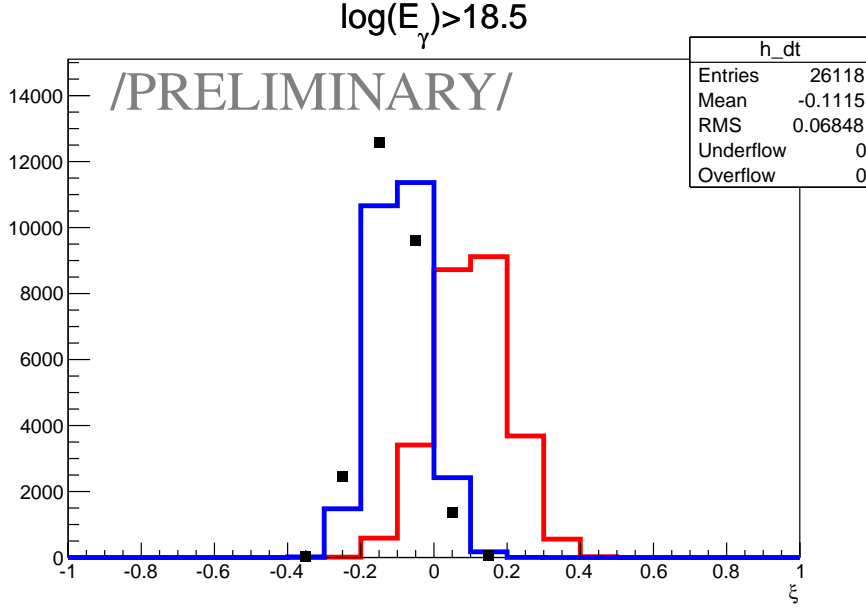
Figure 1: Distribution of the ξ parameter for data (black) compared wit proton and photon-induced Monte-Carlo events (blue - protons, red - photons).

event. Monte-Carlo (MC) events are produced in the same format as real events and the analysis procedures are applied in the same way to both [48].

3. Reconstruction and observables

We reconstruct each event with a joint fit of the geometry and lateral distribution function (LDF) and determine Linsley shower front curvature parameter "a" along with the arrival direction, core location and signal density at 800 meters $\mathscr{S} \equiv S_{800}$. One and the same reconstruction procedure is applied to both data and MC events.

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

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

  i. Zenith angle cut: $0° < \theta < 60°$;

  ii. The number of detectors triggered is 7 or more;

  iii. Shower core is inside the array boundary with the distance to the boundary larger than 1200 meters;

  iv. Joint fit quality cut, $\chi^2/\text{d.o.f.} < 5$;

  v. $E_\gamma(S^i_{800}, \theta^i, \phi^i) > 10^{19}$ eV.

Reconstruction of each data and MC event results in a set of the following observables used for construction of a multivariate classification method:

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 [50];

5. AoP slope parameter [51];

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 $b = 3$ [52];

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

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

3.1 Method

The analysis is based on the proton-photon classification procedure using the method of boosted decision trees (BDT). Following the analyses of [14, 51] we use the *TMVA* package [53] for ROOT as an implementation of the method. The decision forest is constructed using 15 observable parameters listed in Section. 3. The BDT is trained using the proton Monte-Carlo set as a background and the photon Monte-Carlo as a signal. The Monte-Carlo set is split into three equal parts: (I) for training the classifier, (II) for cut optimization, (III) for exposure estimate. The classifier is built independently for each energy range of interest $E > E_0$, where E_0 takes values of $10^{18.5}, 10^{19.0}, 10^{19.5}$ and $10^{20.0}$ eV.

The result of the BDT classifier is a single parameter ξ^i for each event "i" which has a bounder range by definition $-1 \leq \xi^i \leq 1$. The ξ-parameter is finally used for one-parametric composition analysis. The histogram of ξ-parameter for data and simulated events with reconstructed photon energy greater than $10^{18.5}$ eV is shown in Figure. 1.
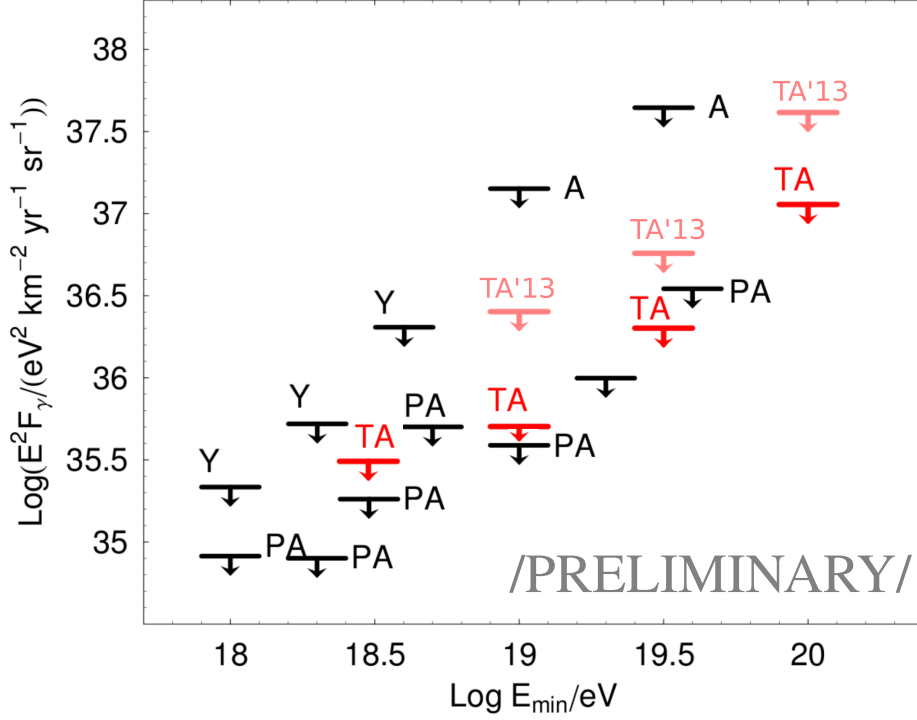
Figure 2: Photon flux limit presented in this *Talk* (TA) compared with the results from AGASA (A) [4], the surface detector of the Pierre Auger Observatory (PA) [10], Yakutsk (Y) [6] and TA ICRC'2013 (TA'13) [13]

The photon candidates are selected with the zenith angle dependent cut on ξ

$$\xi > \xi_{cut}(\theta). \tag{3.1}$$

The cut function is approximated as a quadratic polynomial of θ. The cut is optimized with the part II of MC with the merit factor defined as an average photon flux upper limit in the case of null-hypothesis: all events in the data set are protons.

Geometrical exposure for the considered SD observation period with $0° < \theta < 60°$ and boundary cut is given by

$$A_{geom} = 9340 \text{ km}^2 \text{ sr yr}. \tag{3.2}$$

The effective exposure after the cuts A_{eff} is given in Table 1.

E_0	$n_{det} \geq 7$	χ^2 and energy cuts	ξ-cut	A_{eff} km^2 sr yr
$10^{18.5}$	11.5%	80.3%	11.2%	**96**
$10^{19.0}$	55.2%	79.2%	16.1%	**656**
$10^{19.5}$	78.3%	71.2%	27.9%	**1448**
$10^{20.0}$	91.0%	73.0%	44.6%	**2760**

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

4. Results

After the cuts there are no photon candidates found in the data set. Therefore an upper limit on a mathematical expectation of number of photons is $\bar{n}_\gamma < 3.09$ at (95% CL). The flux upper limits follow from the relation

$$\bar{n}_\gamma = F_\gamma A_{eff}. \tag{4.1}$$

The 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. A comparison of the limits with the prediction of different scenarios of the photon origin [38] will be shown at the conference.

	E_0, eV			
	$10^{18.5}$	$10^{19.0}$	$10^{19.5}$	$10^{20.0}$
γ candidates	0	0	0	0
$\bar{n} <$	3.09	3.09	3.09	3.09
A_{eff}	96	656	1448	2760
$F_\gamma <$	0.032	0.0047	0.0021	0.0011

Table 2: Preliminary 95% CL upper limits on the number of photons in the data set $\bar{n}$ and on the photon flux F_γ (km^{-2}yr^{-1}sr^{-1}).

The implementation of the multivariate classifier permits to extend zenith angle search range w.r.t. the preceding TA study and to enhance the effective exposure significantly.

Along with the diffuse flux limits, the status of the search for down-going neutrino and the point sources of photons in the Northern hemisphere will be presented at the conference.

Acknowledgment

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