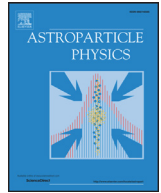




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Constraints on the diffuse photon flux with energies above 10^{18} eV using the surface detector of the Telescope Array experiment



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ABSTRACT

We present the results of the search for ultra-high-energy photons with nine years of data from the Telescope Array surface detector. A multivariate classifier is built upon 16 reconstructed parameters of the extensive air shower. These parameters are related to the curvature and the width of the shower front, the steepness of the lateral distribution function, and the timing parameters of the waveforms sensitive to the shower muon content. A total number of two photon candidates found in the search is fully compatible with the expected background. The 95% CL limits on the diffuse flux of the photons with energies greater than $10^{18.0}$, $10^{18.5}$, $10^{19.0}$, $10^{19.5}$ and $10^{20.0}$ eV are set at the level of 0.067, 0.012, 0.0036, 0.0013, $0.0013 \text{ km}^{-2}\text{yr}^{-1}\text{sr}^{-1}$ correspondingly.

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1. Introduction

The 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 approximately 700 km² area and three fluorescence detectors. The purpose of this Paper is to present the limits on diffuse photon flux with energies greater than 10^{18} eV based on nine years of surface detector operation.

Several limits on ultra-high-energy diffuse photon flux have been set by independent experiments, including Haverah Park, AGASA, Yakutsk, Pierre Auger and TA observatories [3–13], but no evidence for primary photons has been 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] as well as the properties of astrophysical sources and their evolution in the scenario of Greisen–Zatsepin–Kuzmin [16,17] cutoff. The flux of ultra-high-energy photons is the most pronounced signature for the heavy decaying dark matter searches [18,19]. Moreover, the results of the photon search severely constrain the parameters of Lorentz invariance violation at Planck scale [20–24]. 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 [25,26] (see Ref. [27] for a particular mechanism).

2. Data set and simulations

We use the TA surface detector data set covering nine years of observation from May 11, 2008 to May 10, 2017. The surface detector (SD) has been collecting data for more than 95% of time during that period [28,29].

Air showers induced by primary photons differ significantly from the hadron-induced events (see e.g. [30] for a review). The TA SD stations contain two layers of 1.2 cm thick plastic scintillators with an area of 3 m² which detect both muon and electromagnetic

components of the extensive air shower and therefore are sensitive to showers induced by primary photons (see Ref. [31] for discussion).

We employ Monte-Carlo simulations of TA SD events induced by simulated proton and photon-induced extensive air showers. The proton induced simulated event set is used as a background while the photon set is used as a signal. We produce simulated events by CORSIKA [32] with EGS4 [33] model for electromagnetic interactions, PRESHOWER code [34] for interactions of photons in geomagnetic field, QGSJET II-03 [35] and FLUKA [36] for high and low energy hadronic interactions. The showers are simulated with thinning ($\epsilon = 10^{-6}$) and the dethinning procedure is used to recover small scale structure of the shower fluctuations [37]. The proton Monte-Carlo set is simulated with the primary energy spectrum of HiRes experiment [38] and is validated by a direct comparison with the TA SD data [39]. The classification method of the present Paper requires high Monte-Carlo statistics at each energy range. Therefore, an additional high-energy proton Monte-Carlo set is simulated with a starting energy of $10^{18.5}$ eV, which is used for energy ranges above $10^{19.5}$ eV. The photon set is simulated following E^{-1} power spectrum and then sampled in each energy range according to E^{-2} spectrum for compatibility with the assumptions of the photon searches performed by other groups.

Detector response is accounted for by using look-up tables simulated with GEANT4 [40]. Real-time array configuration and detector calibration information of the nine years of TA SD observations are used for each simulated 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 [39]. The statistics of the proton MC set is 5.5 times larger than the number of the observed events.

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 ” [41] along with the arrival direction,

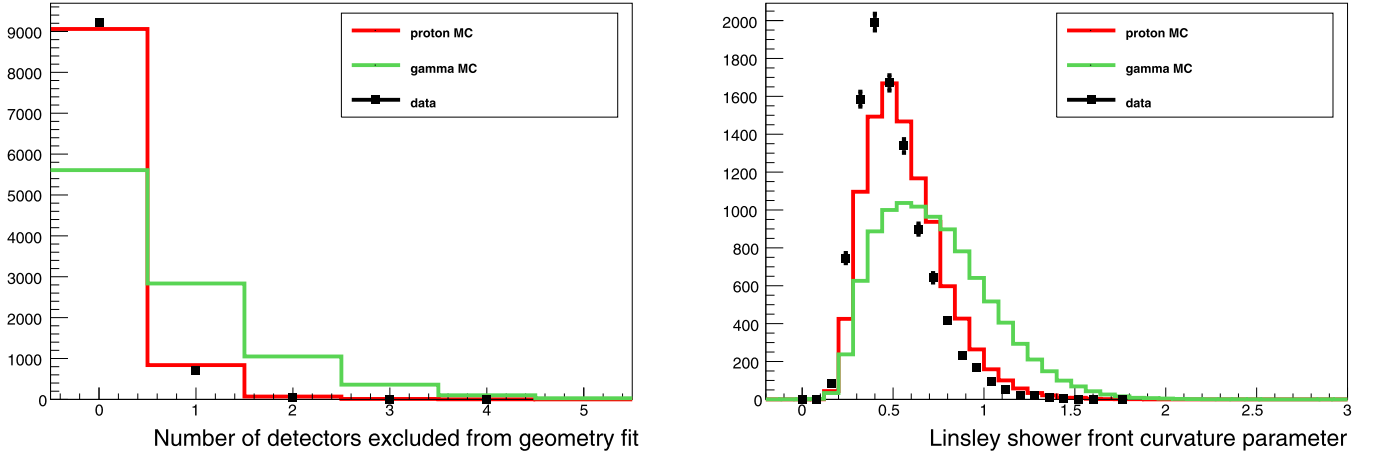


Fig. 1. Distributions of the two observables with the strongest γ -p separation power for data (black) compared with proton and photon-induced Monte-Carlo events for $E > 10^{19}$ eV (solid red - protons, dashed green - photons).

core location and signal density at 800 m $S \equiv S_{800}$. The same reconstruction procedure is applied to both data and MC events.

Reconstruction of each data and MC event results in a set of 16 observables, which are described in [42]. The following observables are 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 obtained from the fit of the shower front with the AGASA-modified Linsley time delay function [43];
4. Area-over-peak (AoP) of the signal at 1200 m [44];
5. AoP slope parameter [45];
6. Number of stations with Level-1 trigger [1];
7. Number of stations excluded from the fit of the shower front due to large contribution to χ^2 ;
8. $\chi^2/d.o.f.$;
9. S_b parameter for $b = 3$; S_b is defined as b th moment of the LDF:

$$S_b = \sum_i [S_i \times (r_i/r_0)^b], \quad (1)$$

where S_i is the signal of i th station, r_i is the distance from the shower core to a given station, $r_0 = 1000$ m. The sum is calculated over all triggered non-saturated stations. The S_b is proposed as a composition-sensitive parameter at [46];

10. S_b parameter for $b = 4.5$;
11. The sum of signals of all stations of the event;
12. An average asymmetry of signal at upper and lower layers of the stations defined as:

$$\mathcal{A} = \frac{\sum_{i,\alpha} |s_{i,\alpha}^{upper} - s_{i,\alpha}^{lower}|}{\sum_{i,\alpha} |s_{i,\alpha}^{upper} + s_{i,\alpha}^{lower}|}, \quad (2)$$

where $s_{i,\alpha}^{upper|lower}$ is the FADC value of upper or lower layer of i th station at α th time bin. The sum is calculated over all triggered non-saturated stations over all time bins of the corresponding FADC traces;

13. Total number of peaks of FADC trace summed over both upper and lower layers of all stations participating in the event. To suppress accidental peaks as a result of FADC noise, we define a peak as a time bin with a signal above 0.2 vertical equivalent muons (VEM) which is higher than a signal of the 3 preceding and 3 consequent time bins;
14. Number of peaks for the detector with the largest signal;

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

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

Both data and MC events are selected by the following quality criteria:

- (a) Zenith angle: $0^\circ < \theta < 60^\circ$;
- (b) The number of stations triggered is 7 or more;
- (c) Shower core is inside the array boundary with the distance to the boundary larger than 1200 m;
- (d) Joint LDF and shower front fit quality, $\chi^2/d.o.f. < 5$;
- (e) $E_\gamma(S_{800}^i, \theta^i, \phi^i) > E_0$ eV for photon search, where $E_0 = 10^{18.0}, 10^{18.5}, 10^{19.0}, 10^{19.5}$, or $10^{20.0}$ eV is the lower limit of the energy range;
- (f) Event is not time-correlated with the lightnings in the Vaisala lightning database [47–49]. The details of the cut are given below.

The conditions (a)–(e) are the same as the quality cuts in the previous TA analysis [13], while the condition (f) is introduced in the present analysis. The details of the latter are provided below.

It was shown that some of the extensive air showers observed by the TA SD are produced by the terrestrial gamma-ray flashes (TGFs) [50,51]. Being initiated by the gamma-rays in the middle of the atmosphere, these cascades share many properties of the showers induced by the ultra-high-energy photons. Namely, the showers induced by TGFs contain no muons and possess large curvature of the front. In order to exclude possible photon candidates of the atmospheric origin we use the Vaisala lightning database from the U.S. National Lightning Detection Network (NLDN) [47–49]. We obtained the list of the NLDN lightning events located within a 15 miles radius of the Central Laser Facility of the TA in the time range of the study 2008-05-11–2017-05-10. The number of the events in the list is 31,622 and they are grouped in time in such a way that a total of 910 astronomical hours contain one or more lightning events. With condition (f), we remove the SD events which occur within 10 min time interval before or after the NLDN lightnings. The cut efficiently removes all the events known to be related to the TGFs with the cost of only 0.66% of the exposure time.

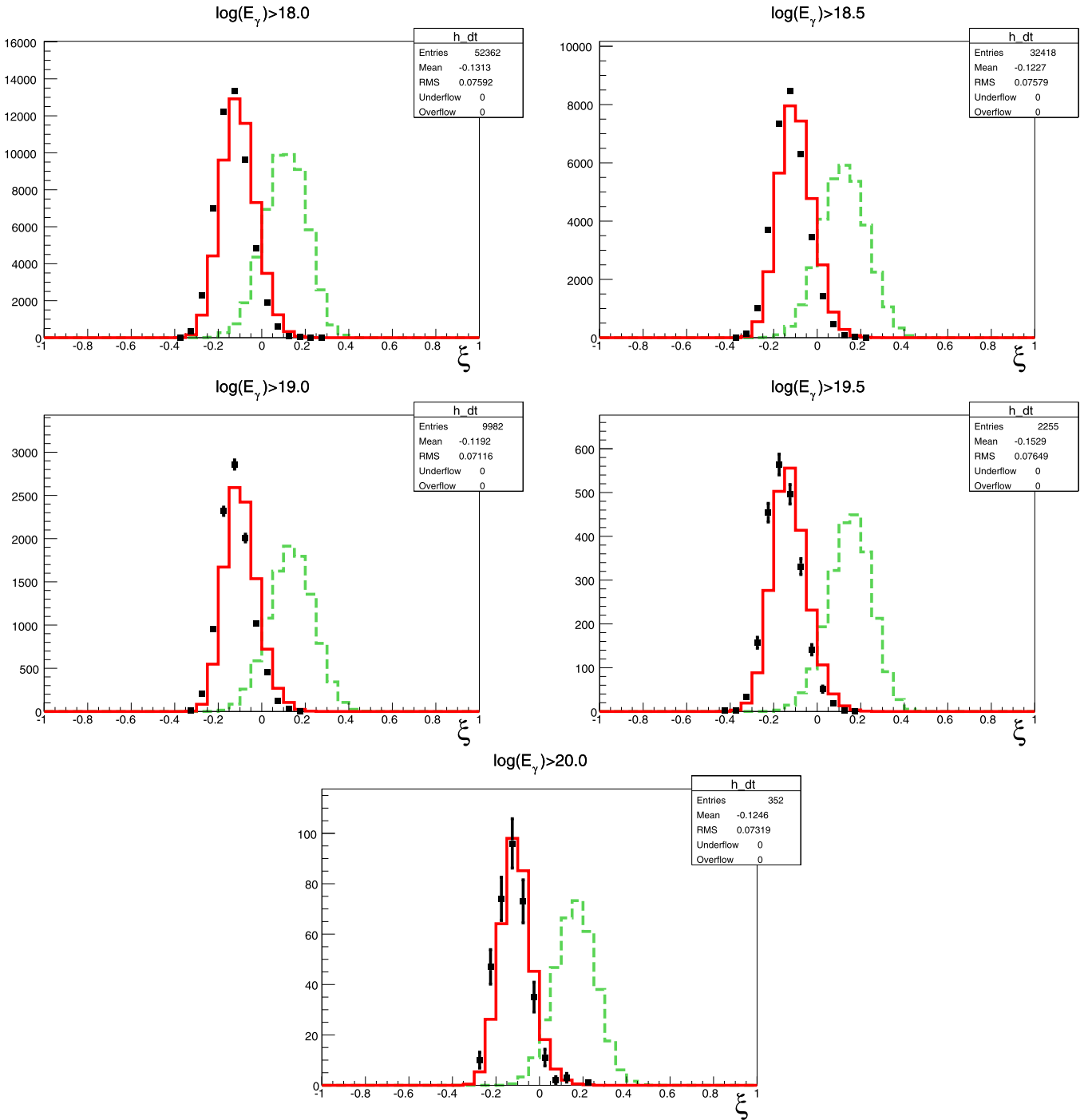


Fig. 2. Distributions of the ξ parameter for data (black) compared with proton and photon-induced Monte-Carlo events for the five energy ranges of interest (solid red - protons, dashed green - photons).

After the cuts, the data set includes 52,362 events. The number of events in proton and high-energy proton Monte-Carlo sets is 283k and 662k, correspondingly. The photon Monte-Carlo set includes 57k, 151k, 325k, 354k and 330k reconstructed events for the energy ranges defined with $E_0 = 10^{18.0}, 10^{18.5}, 10^{19.0}, 10^{19.5}$, and $10^{20.0}$ correspondingly.

3.1. Method

The analysis is based on a proton-photon classification procedure using the method of boosted decision trees (BDT). Follow-

ing the analyses of [14,45] we use the *TMVA* package [52] for *ROOT* [53] as an implementation of the method. The decision forest is constructed using the 16 observable parameters listed in the Section. 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 subsets of equal number of events: (I) for training the classifier, (II) for cut optimization, (III) for exposure estimate. For the photon search, the classifier is built independently for each energy range of interest $E > E_0$, where E_0 takes values of $10^{18.0}, 10^{18.5}, 10^{19.0}, 10^{19.5}$ and $10^{20.0}$ eV.

The distributions of the 16 parameters in the SD data are in a reasonable agreement with the proton MC, see individual param-

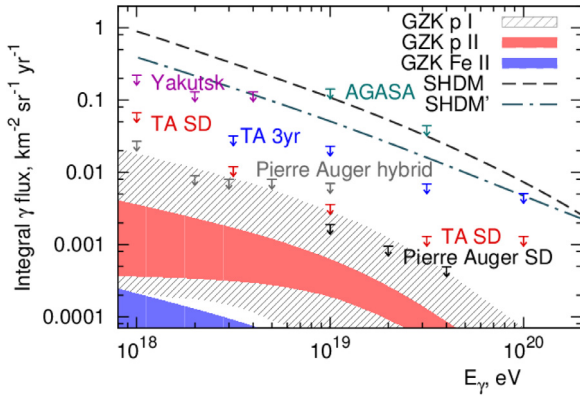


Fig. 3. The photon flux limit presented in this *Paper* (TA SD, red arrows) compared with the results from AGASA (light blue) [4], Pierre Auger Observatory SD (black) [10,11] and hybrid data (gray) [12], Yakutsk (magenta) [6] and previously published TA SD result (TA 3yr, dark blue) [13] and the predictions of some models [55–57].

eter distributions in [42]. The *TMVA* classifier ranks the variables according to importance parameter, which indicates relative contribution of each parameter to separation power. In the present study, all the parameters show an importance value between 4% and 9% with the strongest separation power for the number of detectors excluded from the geometry fit (9%) and Linsley shower front (7%) curvature. The histograms of these two parameters for data and simulated events for the energy range $E > 10^{19}$ eV are shown in Fig. 1. The result of the BDT classifier is a single parameter ξ^i for each event “ i ” which by definition has a bounded range $-1 \leq \xi^i \leq 1$. The ξ -parameter is finally used for a one-parametric composition analysis. The histograms of the ξ -parameter for data and simulated events for the five energy ranges of interest are shown in Fig. 2. The histograms indicate general compatibility of the data with the proton Monte-Carlo, while a shift to the smaller ξ values may be observed. The latter corresponds to either moderately heavier hadronic primaries or hadronic model uncertainty, see discussion of the latter in [42].

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

$$\xi > \xi_{cut}(\theta). \quad (3)$$

The cut function is approximated as a quadratic polynomial of θ . The cut is optimized with the part II of the MC with the merit

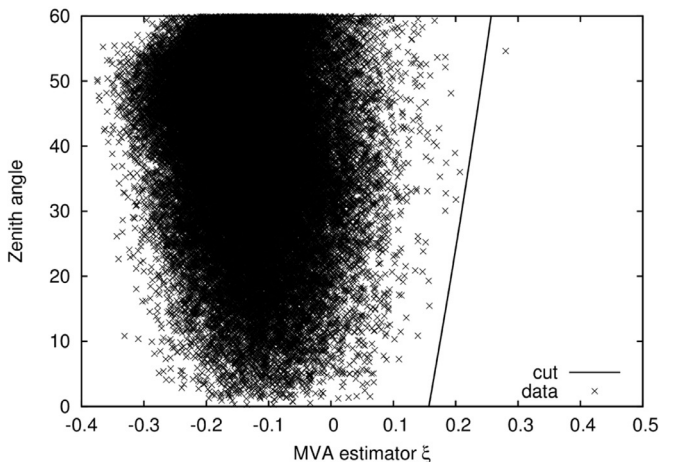
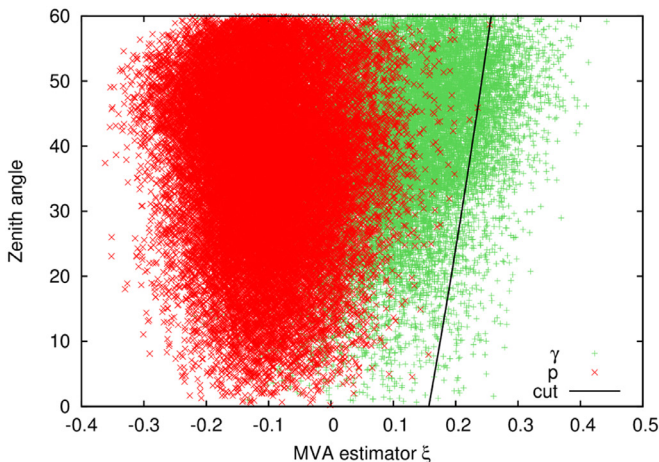


Fig. 4. Left panel: The scatter-plot of ξ and zenith angle for proton (red dots) and photon (green dots) Monte-Carlo sets along with the optimal ξ -cut (black line) for the energy range $E > 10^{18}$ eV. Right panel: the same ξ -cut applied to the data set.

Table 1

Contribution of the cuts to an effective exposure in the energy ranges of interest. The value represents the ratio of the exposure after the given cut to the exposure before cut.

E_0	Quality cuts (a)-(f)	ξ -cut	A_{eff}^γ , km ² yr sr
$10^{18.0}$	6.5%	9.8%	77
$10^{18.5}$	19.9%	10.6%	255
$10^{19.0}$	43.6%	16.2%	852
$10^{19.5}$	52.0%	37.2%	2351
$10^{20.0}$	64.2%	52.3%	4055

Table 2

95% CL upper limits on the number of photons in the data set \bar{n}_γ and on the photon flux F_γ (km⁻²yr⁻¹sr⁻¹), b is an expected number of background photon candidates obtained with proton MC.

	E_0 , eV				
	$10^{18.0}$	$10^{18.5}$	$10^{19.0}$	$10^{19.5}$	$10^{20.0}$
γ candidates	1	0	0	0	1
b	0.55	1.01	0.97	0.80	0.49
$\bar{n} <$	5.14	3.09	3.09	3.09	5.14
A_{eff}	77	255	852	2351	4055
$F_\gamma <$	0.067	0.012	0.0036	0.0013	0.0013

factor defined as an average photon flux upper limit in the case of null-hypothesis that all events in the data set are protons. The ξ -cut for $E > 10^{18}$ eV is shown in Fig. 4 along with the Monte-Carlo (left panel) and data (right panel).

4. Photon search results

The geometrical exposure for the considered SD observation period with $0^\circ < \theta < 60^\circ$ and the boundary cut is given by

$$A_{geom} = 12060 \text{ km}^2 \text{ sr yr}. \quad (4)$$

After the cuts, the effective exposures A_{eff}^γ for different E_0 values are given in Table 1.

No photon candidates are found in the data set for $E_0 = 10^{18.5}$, $10^{19.0}$ and $10^{19.5}$ eV. There is one candidate for each of the two energy ranges $E_0 = 10^{18.0}$ and $10^{20.0}$ eV. An upper limit on a mathematical expectation of the number of photons is determined following Ref. [54]. The flux upper limits are given by the relation

$$\bar{n}_\gamma = F_\gamma A_{eff}^\gamma. \quad (5)$$

The resulting 95% CL photon diffuse flux upper limits are summarized in Table 2 and are shown along with the results of other ex-

periments in Fig. 3. As one may see from Table 2 the number of photon candidates is compatible with the background expectation b obtained with the proton Monte-Carlo.

Let us discuss the impact of the possible systematic uncertainties. The result may be affected by the systematics of the hadronic model as well as by the primary hadronic composition different from proton assumed in simulations. Both the sources of systematics act in a similar way by changing the background set used for training and optimization of the cut. That is, the proton Monte-Carlo is used to build a classifier and to define a criteria for photon candidates. Let us note, however, that given the classifier we are not using the proton Monte-Carlo in the final one-dimensional analysis. In particular, the number of photon candidates expected from the background b (see Table 2) is not used for calculating the limit. The use of zero-background approximation makes the result conservative with respect to the systematics of the hadronic model and primary composition. On the other hand, the better the data to Monte-Carlo agreement the better the sensitivity of the method and the stronger the flux limits. We assume that the classifier used in the Paper is pretty close to optimal based on the reasonable agreement between data and proton Monte-Carlo, see Fig. 2.

5. Conclusion

The use of the multiple observables within the multivariate classifier and the wide range of zenith angles ($0^\circ < \theta < 60^\circ$) along with the nine years statistics allowed us to improve significantly over the previous TA SD constraints on the diffuse photon flux. The photon flux limits of the present Paper are the most strict among the ones obtained in the Northern Hemisphere and complement the limits set by Pierre Auger Observatory in the Southern Hemisphere with the hybrid [12] and SD data [11]. The TA photon flux limits come close to the values of the flux predicted in certain models of cosmogenic photons.

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