Telescope Array search for EeV photons

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for the Telescope Array Collaboration

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Telescope Array Collaboration

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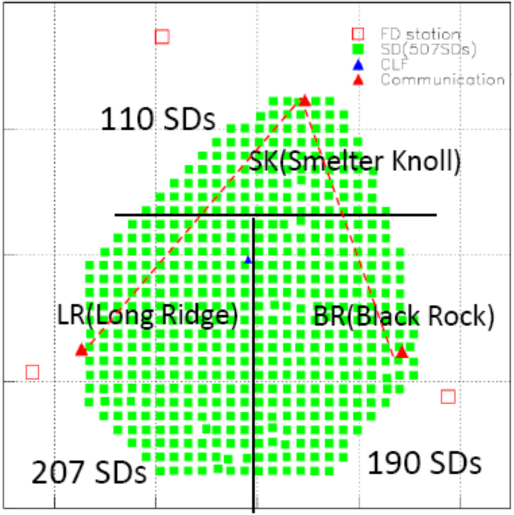
Belgium, Czech Republic, Japan, Korea, Russia, Slovenia, USA

Telescope Array surface detector



- 507 SD's, 3 m^2 each
- 680 km^2 area
- operating since May 2008

Largest UHECR statistics in the Northern Hemisphere

Photon search strategy

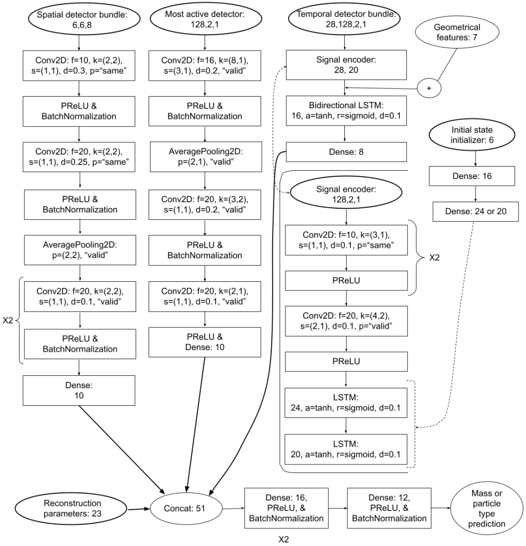
Photon-induced showers:

- develop deeper in the atmosphere $\Rightarrow$ arrive younger
- contain less muons $\Rightarrow$ SD waveforms are less compressed

We use the neural-network classifier trained on both the

- **time-resolved waveforms**
- and derived features: front curvature, Area-over-peak, number of FADC signal peaks, $\chi^2/d.o.f.$, S_b

p-γ classifier based on neural network



Input:

- incidence time and integral signal for 6x6 SD stations
- time-resolved signals for all triggered stations ordered by the front arrival time
- composition-sensitive event features

TA, Phys.Rev.D 99 (2019) 02200

Output:

- The value $\xi \in [0, 1]$ for an event. ξ is close to 0 for proton-induced showers and to 1 for γ-induced.

p-γ classifier: list of event features

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;

Pierre Auger Collaboration, Phys.Rev.Lett. 100 (2008) 211101

5. AoP LDF slope parameter;
6. Number of detectors hit;
7. N. of detectors excluded from the fit of the shower front;
8. $\chi^2/d.o.f.$;
9. $S_b = \sum S_i \times r_i^b$ parameter for $b = 2.5, 3.0, 3.5, 4.0$ and $b = 4.5$;

Ros, Supanitsky, Medina-Tanco et al. Astropart.Phys. 47 (2013) 10

10. The sum of signals of all detectors of the event;
11. Asymmetry of signal at upper and lower layers of detectors;
12. Total n. of peaks within all FADC traces;
13. N. of peaks for the detector with the largest signal;

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

Photon search with p-γ classifier

- The p-γ classifier is trained with two Monte-Carlo sets:
  - γ-induced events (Signal)
  - proton-induced events (Background)
- The output of the classifier for each event is a number $\xi \in [0:1]$: 1 – pure signal (γ), 0 – pure background (p).
- We call “photon-candidates” events with $\xi > \xi_{cut}$.
- The optimal value of ξ_{cut} is obtained by the requirement of the strongest sensitivity in case null-hypothesis is valid, i.e. all events are protons.

Photon search: data and Monte-Carlo sets

- Data collected by TA surface detector for the 11 years:
  2008-05-11 – 2019-05-10
- *p* and γ Monte-Carlo sets with CORSIKA and dethinning

Stokes et al, Astropart.Phys.35:759,2012

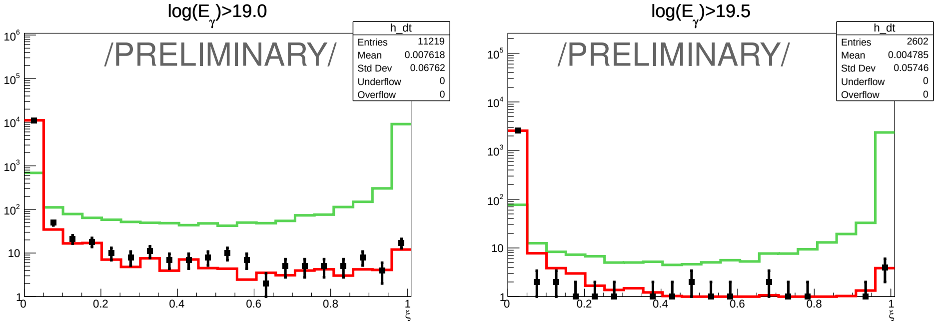
Cuts for both data and MC:

- 7 or more detectors triggered
- core distance to array boundary is larger than 1200m
- χ^2/d.o.f. < 5
- $\theta < 55^\circ$
- $E_\gamma > 10^{19.0}$ eV (E_γ is estimated with photon Monte-Carlo)
  - or $E_\gamma > 10^{18.5}$ eV for training Monte-Carlo sets

11327 events after cuts

MC set is split into 3 parts: (I) 80% of events, for training the classifier, (II) for testing and cut optimization, (III) for exposure estimate.

Distribution of classifier result (ξ) for data and MC



data photon MC proton MC

Efficient separation of proton and photon-induced events.

Effective exposure

- Geometric exposure for $\theta \in (0^\circ, 55^\circ)$: **13221 km^2 sr yr**
- Effective exposure is estimated using photon MC assuming E^{-2} primary spectrum

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**

- Efficiency of photon candidate selection ($\xi > \xi_{cut}$) has substantially grown 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.

TA Collaboration, Astroparticle Physics 110 (2019) 8

Photon candidate events for $E_0 > 10^{19.0}$ eV

energy cut	event date and time	comment
$E_0 > 10^{19.0}$ eV	2010-10-04 16:58:42	
	2011-07-27 08:06:15	
	2011-09-16 19:40:56	
	2012-05-01 00:59:15	
	2012-07-06 01:49:11	
	2012-09-07 01:55:45	
	2013-08-27 22:38:37	
	2014-07-31 21:19:19	
	2014-08-14 09:46:58	
	2014-08-23 02:39:15	
	2014-09-27 07:54:35	
	2015-07-19 01:03:04	
	2017-09-12 18:32:59	
	2018-08-02 15:25:51	
	2018-10-03 04:03:48	
	2019-04-30 22:43:17	

Photon candidate events for $E_0 > 10^{19.0}$ eV

energy cut	event date and time	comment
$E_0 > 10^{19.0}$ eV	2010-10-04 16:58:42	**TGF candidate event**
	2011-07-27 08:06:15	**TGF candidate event**
	2011-09-16 19:40:56	**TGF candidate event**
	2012-05-01 00:59:15	
	2012-07-06 01:49:11	**TGF candidate event**
	2012-09-07 01:55:45	**TGF candidate event**
	2013-08-27 22:38:37	**TGF candidate event**
	2014-07-31 21:19:19	**TGF candidate event**
	2014-08-14 09:46:58	
	2014-08-23 02:39:15	**TGF candidate event**
	2014-09-27 07:54:35	**TGF candidate event**
	2015-07-19 01:03:04	**TGF candidate event**
	2017-09-12 18:32:59	**TGF candidate event**
	2018-08-02 15:25:51	**TGF candidate event**
	2018-10-03 04:03:48	**TGF candidate event**
	2019-04-30 22:43:17	**TGF candidate event**

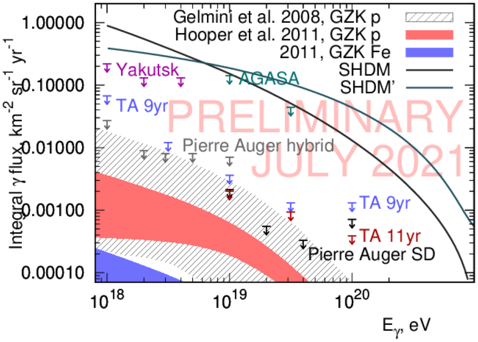
Terrestrial Gamma-Ray Flashes candidate events are time correlated with the lightnings registered by National Lightning Detection Network.

TA collaboration, JGR Atmospheres (2020)
J. Remington, talk 828, this conference

- 2 photon-candidate events observed
- 0.8 events expected from proton MC

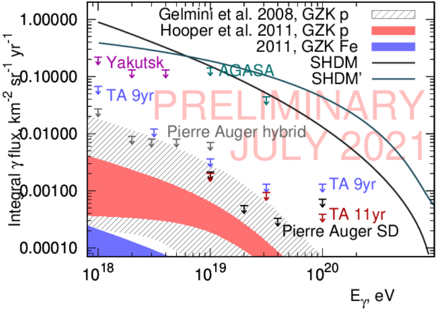
Results: photon flux limits

E_0, eV	$10^{19.0}$	$10^{19.5}$	$10^{20.0}$
γ candidates	~~16~~ 2	~~11~~ 1	~~5~~ 0
$\bar{n}$ $<$	6.72	5.14	3.09
A_{eff}	3428	5546	7875
F_γ $<$	2.0×10^{-3}	9.3×10^{-4}	3.9×10^{-4}



Conclusions

- The search for photons in the TA SD 11 years data is performed with the novel neural-network classifier.
- Diffuse photon flux limits above $10^{19.0}$ eV are presented.



- The TGF-induced events are classified as the photon candidates.

see talk 828 by J. Remington, this conference