Telescope Array search for EeV photons and neutrinos


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Telescope Array Collaboration

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Belgium, Japan, Korea, Russia, USA
Telescope Array surface detector

- 507 SD’s, 3 m² each
- 680 km² area
- 9 years of operation

Largest UHECR statistics in the Northern Hemisphere

Grigory I. Rubtsov for the Telescope Array collaboration

TA photon and neutrino search
$p$-induced EAS

$\gamma$-induced EAS

Photon-induced showers:
- arrive younger
- contain less muons
- multiple SD observables affected:
  - front curvature, Area-over-peak, number of FADC signal peaks, $\chi^2/d.o.f.$, $S_b$
Photon search: data and Monte-Carlo sets

- Data collected by TA surface detector for the nine years: 2008-05-11 — 2017-05-11
- $p$ and $\gamma$ Monte-Carlo sets with CORSIKA and dethinning


Cuts for both data and MC:
- 7 or more detectors triggered
- core distance to array boundary is larger than 1200m
- $\chi^2$/d.o.f. < 5
- $\theta < 60^\circ$
- $E_\gamma > 10^{18}$ eV ($E_\gamma$ is estimated with photon Monte-Carlo)

52769 events after cuts

Note: MC set is split into 3 equal parts: (I) for training the classifier, (II) for cut optimization, (III) for exposure estimate.
Photon search: list of relevant observables

1. Zenith angle, $\theta$;
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;


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 $b = 3$ and $b = 4.5$;


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. N. of peaks present in the upper layer and not in lower;
15. N. of peaks present in the lower layer and not in upper;
The Boosted Decision Trees (BDT) technique is used to build $p$-$\gamma$ classifier based on multiple observables.


root::TMVA is used as a stable implementation.


BDT is trained with Monte-Carlo sets: $\gamma$ (Signal) and $p$ (Background)

BDT classifier is used to convert the set of observables for an event to a number $\xi \in [-1 : 1]$: 1 - pure signal ($\gamma$), -1 - pure background ($p$).

$\xi$ is available for one-dimensional analysis. The cut on $\xi$ for the search is optimized using proton MC as a null-hypothesis.
Distribution of MVA estimator ($\xi$) for data and MC

log($E_\gamma$)>18.0

Entries 52769
Mean -0.1338
RMS 0.07948
Underflow 0
Overflow 0

log($E_\gamma$)>18.5

Entries 32700
Mean -0.1317
RMS 0.07903
Underflow 0
Overflow 0

log($E_\gamma$)>19.0

Entries 10070
Mean -0.1245
RMS 0.07469
Underflow 0
Overflow 0

log($E_\gamma$)>19.5

Entries 2279
Mean -0.153
RMS 0.07832
Underflow 0
Overflow 0

/PRELIMINARY/

data photon MC proton MC
Optimization of cut on $\xi$:

- The photon candidates are selected using the cut on $\xi$:
  $$\xi > \xi_{\text{cut}}(\theta)$$

- The cut is approximated as a quadratic function of $\theta$

- Cut is optimized in each energy range using proton and photon Monte-Carlo (cut optimization subsets)

- The merit factor is an average photon upper limit if the null-hypothesis is true (all protons)
Effective exposure

- Geometric exposure for $\theta \in (0^\circ, 60^\circ)$: \(12063 \text{ km}^2 \text{ sr yr}\)
- Effective exposure is estimated using photon MC assuming $E^{-2}$ primary spectrum

<table>
<thead>
<tr>
<th>$E_0$</th>
<th>quality cuts</th>
<th>$\xi$-cut</th>
<th>$A_{\text{eff}}$ km$^2$ sr yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{18.0}$</td>
<td>6.8%</td>
<td>6.5%</td>
<td>53</td>
</tr>
<tr>
<td>$10^{18.5}$</td>
<td>20.1%</td>
<td>7.9%</td>
<td>192</td>
</tr>
<tr>
<td>$10^{19.0}$</td>
<td>43.8%</td>
<td>16.0%</td>
<td>846</td>
</tr>
<tr>
<td>$10^{19.5}$</td>
<td>52.1%</td>
<td>34.0%</td>
<td>2138</td>
</tr>
<tr>
<td>$10^{20.0}$</td>
<td>64.7%</td>
<td>55.3%</td>
<td>4317</td>
</tr>
</tbody>
</table>
$E_\gamma > 10^{18}$ eV, zenith angle dependent cut on $\xi$: MC

Grigory I. Rubtsov for the Telescope Array collaboration

TA photon and neutrino search
$E_\gamma > 10^{18}$ eV, zenith angle dependent cut on $\xi$: MC

Grigory I. Rubtsov for the Telescope Array collaboration

TA photon and neutrino search
$E_\gamma > 10^{18} \text{ eV}$, zenith angle dependent cut on $\xi$: data

1 photon candidate event
## Photon candidate events

<table>
<thead>
<tr>
<th>energy cut</th>
<th>event date and time</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_0 &gt; 10^{18.0}$ eV</td>
<td>2011-09-16 19:40:56</td>
<td></td>
</tr>
<tr>
<td>$E_0 &gt; 10^{18.5}$ eV</td>
<td>2011-09-16 19:40:56</td>
<td></td>
</tr>
<tr>
<td>$E_0 &gt; 10^{19.0}$ eV</td>
<td>2011-07-27 08:06:15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2011-09-16 19:40:56</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2012-07-06 01:49:11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2014-09-27 07:54:35</td>
<td></td>
</tr>
<tr>
<td>$E_0 &gt; 10^{19.5}$ eV</td>
<td>2011-07-27 08:06:15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2011-09-16 19:40:56</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2012-09-07 01:55:45</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2014-09-27 07:54:35</td>
<td></td>
</tr>
<tr>
<td>$E_0 &gt; 10^{20.0}$ eV</td>
<td>2011-07-27 08:06:15</td>
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<tr>
<td></td>
<td>2013-08-27 22:38:37</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2014-08-23 02:39:15</td>
<td></td>
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<tr>
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<td>2014-09-27 07:54:35</td>
<td></td>
</tr>
<tr>
<td>energy cut</td>
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<td>comment</td>
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<td>------------------</td>
<td>----------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>$E_0 &gt; 10^{18.0}$ eV</td>
<td>2011-09-16 19:40:56</td>
<td>BURST event</td>
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<tr>
<td>$E_0 &gt; 10^{18.5}$ eV</td>
<td>2011-09-16 19:40:56</td>
<td>BURST event</td>
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<td>BURST event</td>
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<td>2011-09-16 19:40:56</td>
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<tr>
<td>$E_0 &gt; 10^{19.5}$ eV</td>
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<td>BURST event</td>
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<td>2011-09-16 19:40:56</td>
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<td>BURST event</td>
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<td>2011-07-27 08:06:15</td>
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<tr>
<td></td>
<td>2013-08-27 22:38:37</td>
<td>γ candidate</td>
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<td></td>
<td>2014-08-23 02:39:15</td>
<td>γ candidate</td>
</tr>
<tr>
<td></td>
<td>2014-09-27 07:54:35</td>
<td>BURST event</td>
</tr>
</tbody>
</table>

"BURST events" – multiple SD triggers within one millisecond found to be associated with lightnings

*J. Belz talk CRI251; TA collaboration, Phys.Lett. A 381 (2017) 2565*
## Results: photon flux limits

<table>
<thead>
<tr>
<th>$E_0$, eV</th>
<th>$10^{18.0}$</th>
<th>$10^{18.5}$</th>
<th>$10^{19.0}$</th>
<th>$10^{19.5}$</th>
<th>$10^{20.0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ candidates</td>
<td>10</td>
<td>10</td>
<td>40</td>
<td>40</td>
<td>42</td>
</tr>
<tr>
<td>$\bar{n} &lt;$</td>
<td>3.09</td>
<td>3.09</td>
<td>3.09</td>
<td>3.09</td>
<td>6.72</td>
</tr>
<tr>
<td>$A_{\text{eff}}$</td>
<td>53</td>
<td>192</td>
<td>846</td>
<td>2138</td>
<td>4317</td>
</tr>
<tr>
<td>$F_\gamma &lt;$</td>
<td>0.059</td>
<td>0.016</td>
<td>0.0037</td>
<td>0.0014</td>
<td>0.0016</td>
</tr>
</tbody>
</table>

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**Note:** This graph is preliminary and subject to further analysis.
Neutrino search strategy

**young shower, $\theta = 19.5^\circ$**

**old shower, $78.3^\circ$**

- Neutrino-induced showers are young while very inclined
- Waveform has many peaks

**neutrino shower, $\theta = 78.6^\circ$**

**upper layer** | **lower layer**
Method

- Cuts:
  - 5 or more detectors triggered
  - core distance to array boundary is larger than 1200m
  - $\chi^2$/d.o.f. < 5
  - $45^\circ < \theta < 90^\circ$
  - no energy cut

  197250 events after cuts

- Multivariate analysis is used
  - The set of observables is the same as for photon search (Energy is replaced with $S_{800}$)

- Method: Boosted decision tree trained with inclined proton (background) and all-flavor down-going neutrino (signal) Monte-Carlo

- The cut on $\xi$ is optimized in a similar to photon search way
Distribution of MVA estimator ($\xi$) for data and MC

/data neutrino MC proton MC/
Results

- 0 neutrino candidates after cuts, $\bar{n}_\nu < 2.44$ (90% C.L.)

**Exposure:**
- Geometric exposure for $\theta \in (45^\circ, 90^\circ)$: $8042 \text{ km}^2 \text{ sr yr}$
- Probability to interact in the atmosphere: $1.4 \times 10^{-5}$
- Trigger, reconstruction and quality cuts efficiency $\sim 7\%$
- $\xi$ cut efficiency: $\sim 24\%$
- Total exposure (all flavors): $A = 1.9 \times 10^{-3} \text{ km}^2 \text{ sr yr}$

- Single flavor diffuse neutrino flux limit for $E > 10^{18} \text{ eV}$: $E^2 f_\nu < 1.4 \times 10^{-6} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ (90% C.L.)
Conclusions

- The search for photons and neutrino in the TA SD 9 years data is performed with the multivariate analysis method.

- Photon and down-going neutrino diffuse flux limits above $10^{18.0}$ eV are presented.

- The lightning-induced events are classified as the photon candidates.
Backup slides
TA Observation: “Burst” Events

- 5 year data (2008-2013)
- 10 surface detector bursts seen
  - 3 or more SD triggers, $\Delta t < 1$ msec
  - Occasional $\Delta t \sim 10 \, \mu$sec
- “Normal” SD trigger rate < 0.01 Hz.
  These cannot be cosmic ray air showers.
- Found to have close time/space coincidence with *U.S. National Lightning Detection Network* (NLDN) activity.
Consider a surface station time-resolved signal

Both peak and area are well-measured and not much affected by fluctuations

First introduced by Pierre Auger Collaboration in the context of neutrino search
$E_\nu > 10^{18}$ eV, zenith angle dependent cut on $\xi$: MC
$E_{\nu} > 10^{18}$ eV, zenith angle dependent cut on $\xi$: MC
$E_\nu > 10^{18} \text{ eV}$, zenith angle dependent cut on $\xi$: data

0 neutrino candidate events
Impact of possible proton MC systematics

- Proton MC is used for MVA estimator training and cut optimization

- Systematics in proton MC affects the method sensitivity
  1. protons are closer to photons that data: exposure is underestimated
  2. data are closer to photons than protons: extra photon candidates in the data set

- In both cases the flux limits stay conservative
Joint 7-parametric fit: $x_{core}, y_{core}, \theta, \phi, S_{800}, t_0, a$

$$f(r) = \left( \frac{r}{R_m} \right)^{-1.2} \left( 1 + \frac{r}{R_m} \right)^{-(\eta-1.2)} \left( 1 + \frac{r^2}{R_1^2} \right)^{-0.6}$$

$$LDF(r) = f(r)/f(800 \text{ m})$$

$$S(r) = S_{800} \times LDF(r)$$

$$t_0(r) = t_0 + t_{plane} + a \times 0.67 (1 + r/R_L)^{1.5} LDF(r)^{-0.5}$$

$$R_m = 90.0 \text{ m}, \ R_1 = 1000 \text{ m}, \ R_L = 30 \text{ m}$$

$$\eta = 3.97 - 1.79 (\sec(\theta) - 1)$$
Distribution of $\xi$ for data and MC $10^{20}$ eV

\begin{figure}
\centering
\includegraphics[width=\textwidth]{plot.png}
\caption{Distribution of $\xi$ for data and MC $10^{20}$ eV.}
\end{figure}

\begin{tabular}{|c|c|c|c|}
\hline
\% & Data & Photon MC & Proton MC \\
\hline
\hline
\end{tabular}