Search for ultrahigh energy photons and neutrino at Telescope Array observatory

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Telescope Array surface detector

- 507 SD’s, 3 m$^2$ each
- 680 km$^2$ area
- 7 years of operation

Largest UHECR statistics in the Northern Hemisphere
Photon-induced showers:
- arrive younger
- contain less muons
- \( \Rightarrow \) multiple SD observables affected:
  - front curvature, Area-over-peak, number of FADC signal peaks, \( \chi^2 / d.o.f., S_b \)
Data and Monte-Carlo sets

- Data collected by TA surface detector for the seven years: 2008-05-11 — 2015-05-11
- $p$ 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
- $\theta < 60^\circ$
- $E_\gamma > 10^{18.5}$ eV ($E_\gamma$ is estimated with photon Monte-Carlo)

26118 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. Linsley front curvature parameter, $a$;
2. Area-over-peak (AoP) of the signal at 1200 m;
   

3. AoP LDF slope parameter;
4. Number of detectors hit;
5. Number of detectors excluded from the fit of the shower front;
6. $\chi^2 / d.o.f.$;
7. $S_b = \sum S_i \times r^b$ parameter for $b = 3$;
   

8. The sum of signals of all detectors of the event;
9. Asymmetry of signal at upper and lower layers of detectors;
10. Total n. of peaks within all FADC traces;
11. N. of peaks for the detector with the largest signal;
12. N. of peaks present in the upper layer and not in lower;
13. 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 ($E_\gamma$) > 18.5**
  - Entries: 26118
  - Mean: -0.1115
  - RMS: 0.06848
  - Underflow: 0
  - Overflow: 0

- **Log ($E_\gamma$) > 19.0**
  - Entries: 7849
  - Mean: -0.1036
  - RMS: 0.05734
  - Underflow: 0
  - Overflow: 0

- **Log ($E_\gamma$) > 19.5**
  - Entries: 1748
  - Mean: -0.1357
  - RMS: 0.07247
  - Underflow: 0
  - Overflow: 0

- **Log ($E_\gamma$) > 20.0**
  - Entries: 259
  - Mean: -0.1264
  - RMS: 0.1019
  - Underflow: 0
  - Overflow: 0
The photon candidates are selected using the cut on $\xi$:

$$\xi > \xi_{\text{cut}}(\theta)$$

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

Cut is optimized in each energy range using proton Monte-Carlo

The merit factor is an average photon upper limit in the case of null-hypothesis (all protons)
Effective exposure

- Geometric exposure for $\theta \in (0^\circ, 60^\circ)$: $9340 \text{ km}^2 \text{ sr yr}$
- Effective exposure is estimated using photon MC assuming $E^{-2}$ primary spectrum

<table>
<thead>
<tr>
<th>$E_0$</th>
<th>$n_{det} \geq 7$</th>
<th>$\chi^2$ and energy cut</th>
<th>$\xi$-cut</th>
<th>$X_{\text{eff}}$ km$^2$ sr yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{18.5}$</td>
<td>11.5%</td>
<td>80.3%</td>
<td>11.2%</td>
<td>96</td>
</tr>
<tr>
<td>$10^{19.0}$</td>
<td>55.2%</td>
<td>79.2%</td>
<td>16.1%</td>
<td>656</td>
</tr>
<tr>
<td>$10^{19.5}$</td>
<td>78.3%</td>
<td>71.2%</td>
<td>27.9%</td>
<td>1448</td>
</tr>
<tr>
<td>$10^{20.0}$</td>
<td>91.0%</td>
<td>73.0%</td>
<td>44.6%</td>
<td>2760</td>
</tr>
</tbody>
</table>
Zenith angle dependent cut on $\xi$: MC

Grigory I. Rubtsov for the Telescope Array collaboration

TA photon and neutrino search
Zenith angle dependent cut on $\xi$: MC

Grigory I. Rubtsov for the Telescope Array collaboration

TA photon and neutrino search
Zenith angle dependent cut on $\xi$: data
### Results: photon flux limits

<table>
<thead>
<tr>
<th>$E_0$</th>
<th>N. cand</th>
<th>$\tilde{N}$ (95% C.L.)</th>
<th>$\chi_{\text{eff}}$</th>
<th>$F &lt; \frac{\text{km}^{-2}\text{sr}^{-1}\text{yr}^{-1}}{}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{18.5}$</td>
<td>0</td>
<td>3.09</td>
<td>96</td>
<td>0.032</td>
</tr>
<tr>
<td>$10^{19.0}$</td>
<td>0</td>
<td>3.09</td>
<td>656</td>
<td>0.0047</td>
</tr>
<tr>
<td>$10^{19.5}$</td>
<td>0</td>
<td>3.09</td>
<td>1448</td>
<td>0.0021</td>
</tr>
<tr>
<td>$10^{20.0}$</td>
<td>0</td>
<td>3.09</td>
<td>2760</td>
<td>0.0011</td>
</tr>
</tbody>
</table>

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*models from J. Alvarez-Muniz et al. EPJ Web Conf. 53, 01009 (2013)*

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Comparison with the other experiments

Neutrino search strategy

- Neutrino produces very inclined young shower

**young shower, \( \theta = 19.5^\circ \)**

- long, many peaks

**old shower, 78.3°**

- one peak

- Down-going \( \nu \) search based on MVA is in progress
The method works for neutrino. Complete analysis is in progress.
Conclusions and outlook

- A new technique for photon search based on the multivariate analysis
- Photon flux limits above $10^{18.5}$ eV

Ongoing searches:
- photon point sources
- down-going neutrino, $E > 10^{18}$ eV
- TALE SD photon search, $E > 10^{17}$ eV
- Next: searches with TAx4
Backup slides
Event reconstruction: fit functions

- Joint 7-parametric fit: $x_{core}, y_{core}, \theta, \phi, S_{800}, t_0, a$

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

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

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

\[
t_0(r) = t_0 + t_{\text{plane}} + a \times 0.67 \left( 1 + r/R_L \right)^{1.5} LDF(r)^{-0.5}
\]

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

\[
\eta = 3.97 - 1.79(\sec(\theta) - 1)
\]
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

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 than 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