Search for ultra-high energy photons with the Telescope Array surface detector

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for the Telescope Array collaboration

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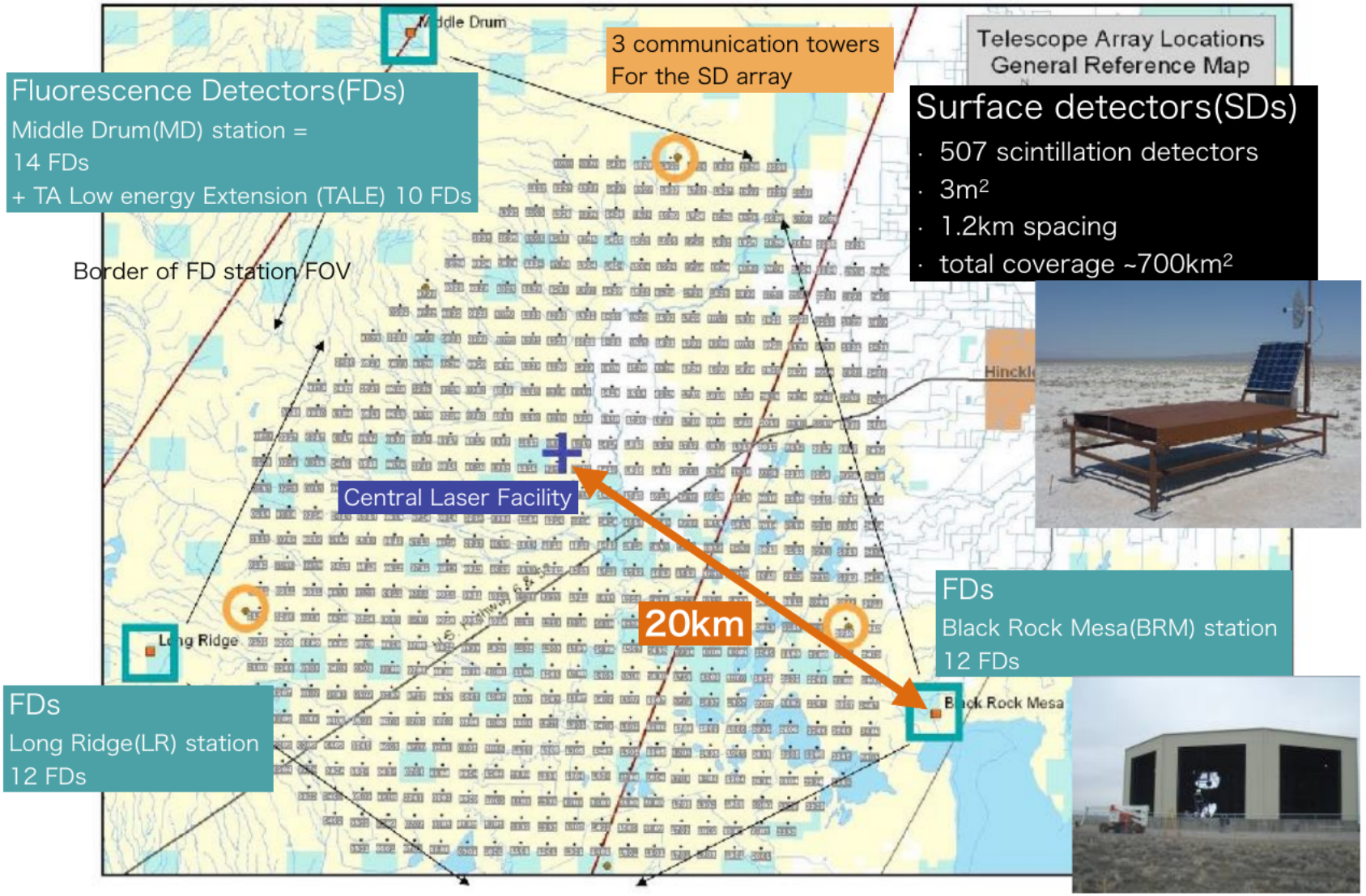
- Telescope Array experiment
- Technique of photon search — multivariate analysis
- Search for diffuse UHE photons

  TA, Astropart.Phys. 110, 8, 2019
- Blind search for point sources of UHE photons

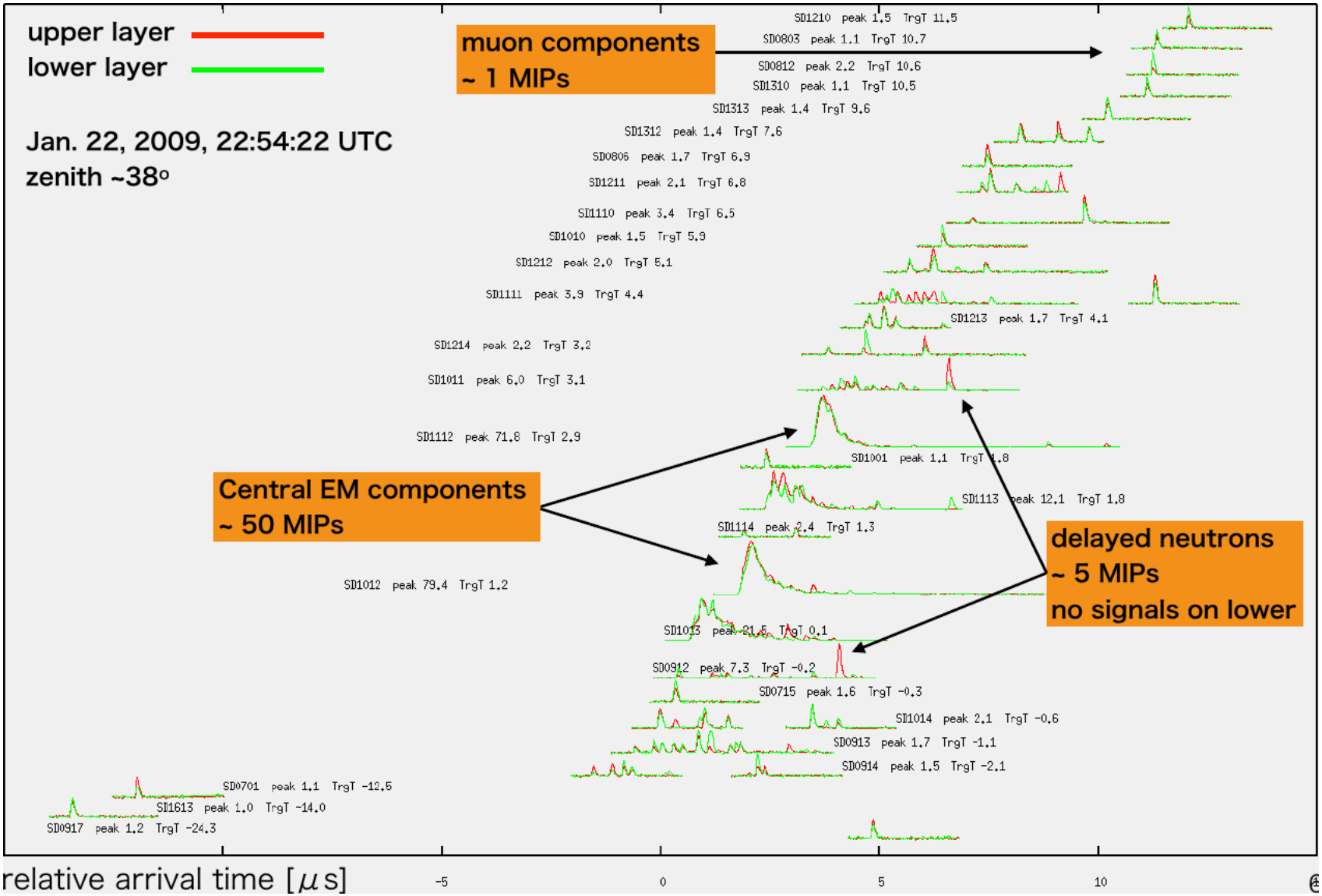
  TA, arXiv:1904.00300
- Target search for UHE photons from dwarf galaxies

Telescope Array experiment

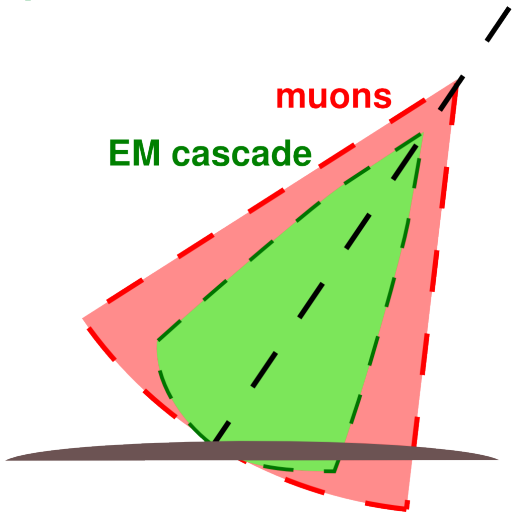


More than 11 years of operation
Largest UHECR statistics in the Northern Hemisphere

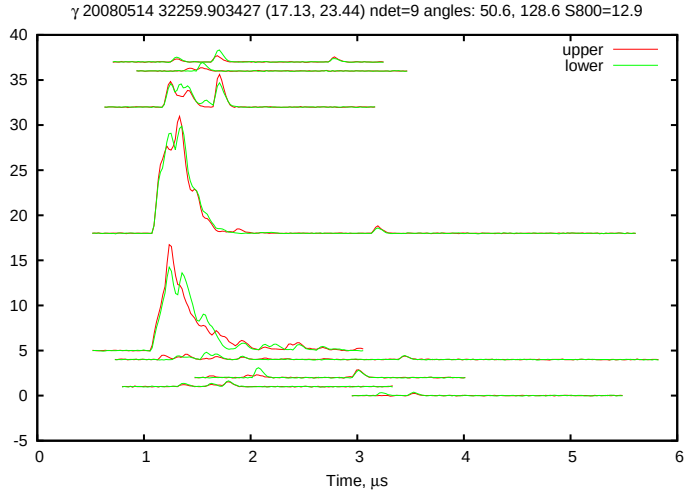
Sample of TA surface detector event

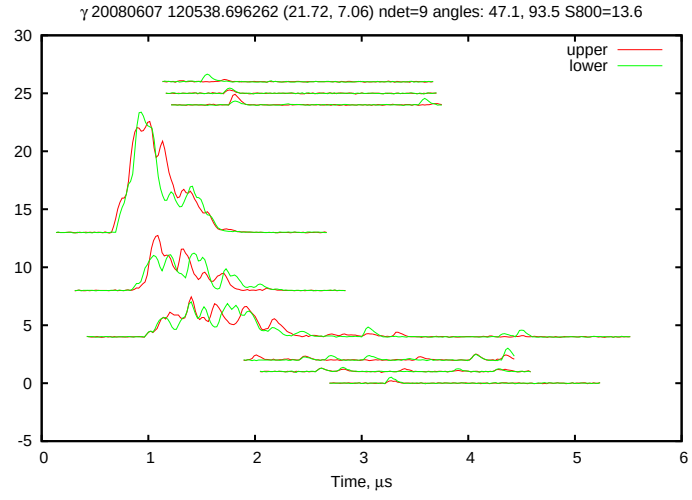


p-induced EAS



γ-induced EAS





Photon-induced showers:

- arrive younger
- contain less muons
- multiple SD observables affected: **front curvature, Area-over-peak, $\chi^2/d.o.f.$, etc.**

Data and Monte-Carlo sets

- Data collected by TA surface detector for the 9 years:
  2008-05-11 — 2017-05-10
- 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
- $\chi^2/\text{d.o.f.} < 5$
- $\theta < 60^\circ$
- $E_\gamma > 10^{18}$ eV (E_γ is estimated with photon Monte-Carlo)
- remove events coincident with lightnings (lightning events mimics γ-induced events)

52362 events after cuts

Photon search: list of relevant SD observables

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

   Pierre Auger Collaboration, Phys.Rev.Lett. 100 (2008) 211101
3. AoP LDF slope parameter;
4. Number of detectors hit;
5. N. 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 $b = 3$ and $b = 4.5$;

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

Machine learning for multivariate analysis.

- The Boosted Decision Trees (BDT) technique is used to build p-γ classifier based on multiple observables.

  TA, Astropart. Phys. 110, 8 (2019); PRD 99, 022002 (2019)

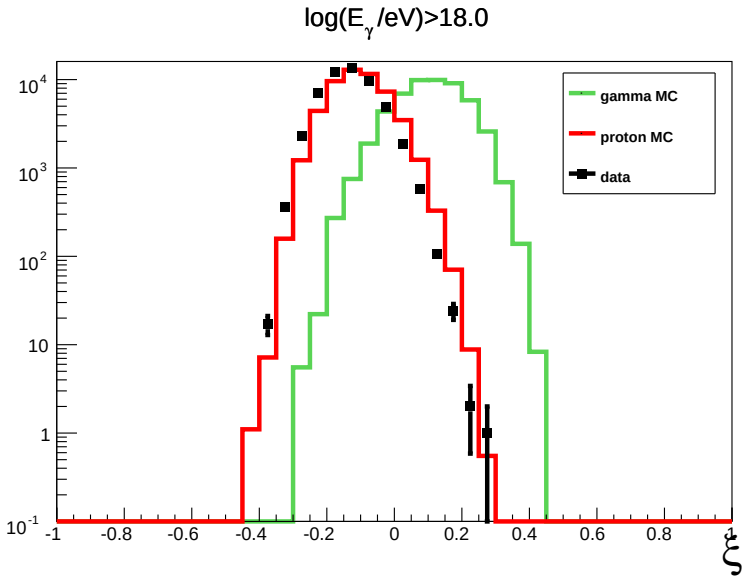
- root::TMVA is used as a stable implementation.

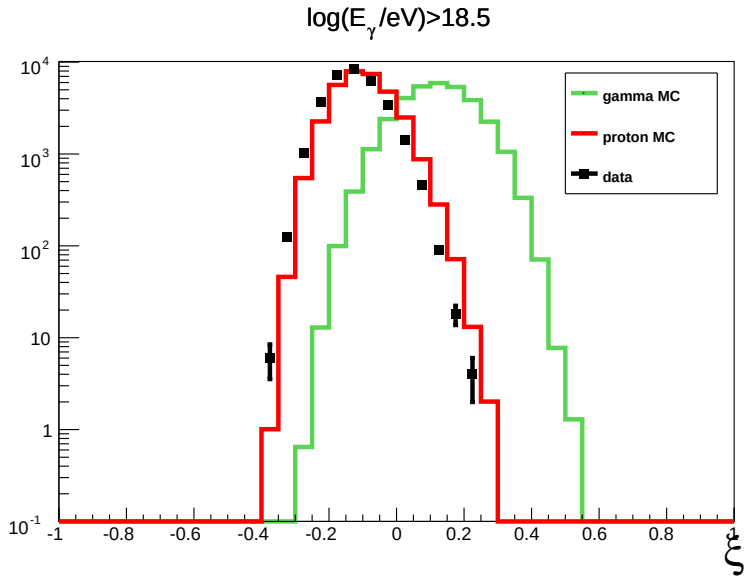
  PoS ACAT 040 (2007), arXiv:physics/0703039

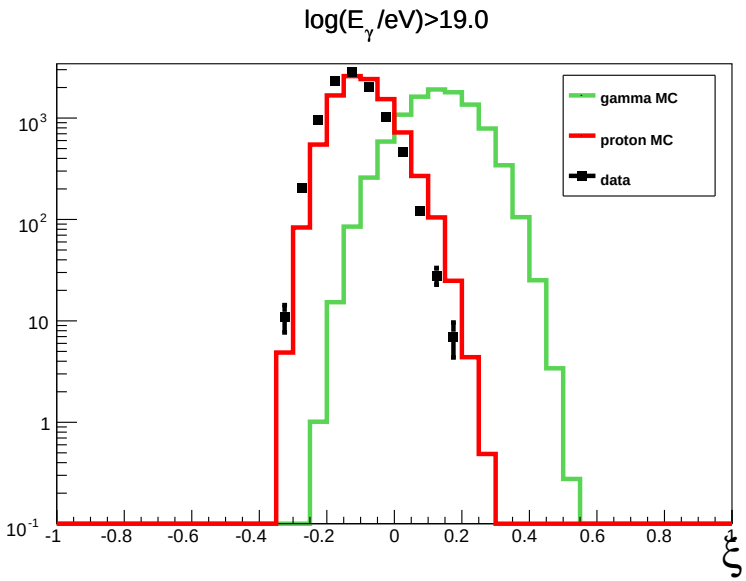
- BDT is trained with Monte-Carlo sets: γ (signal) and p (background)*
- BDT classifier is used to convert the set of observables of each event to a number $\xi \in [-1 : 1]$
- ξ is available for one-dimensional analysis.

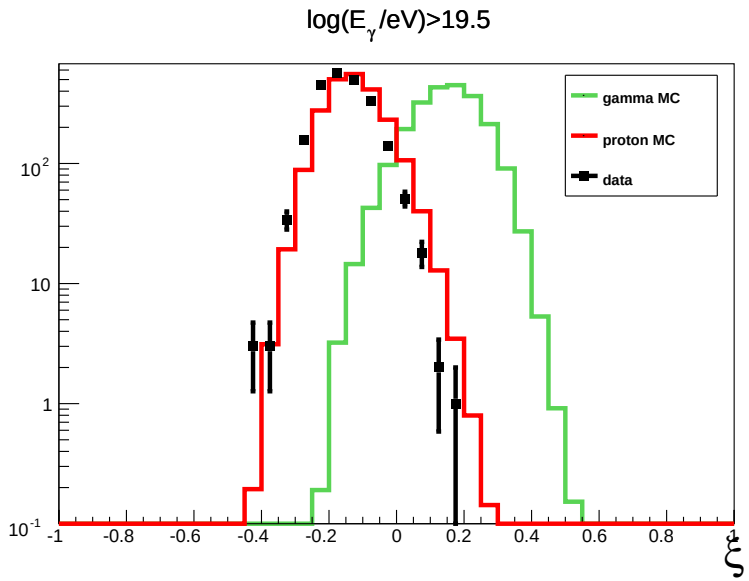
* MC set is split into 3 equal parts: (I) for training the classifier, (II) for ξ-cut optimization, (III) for exposure estimate.

Distribution of MVA estimator ξ for data and MC



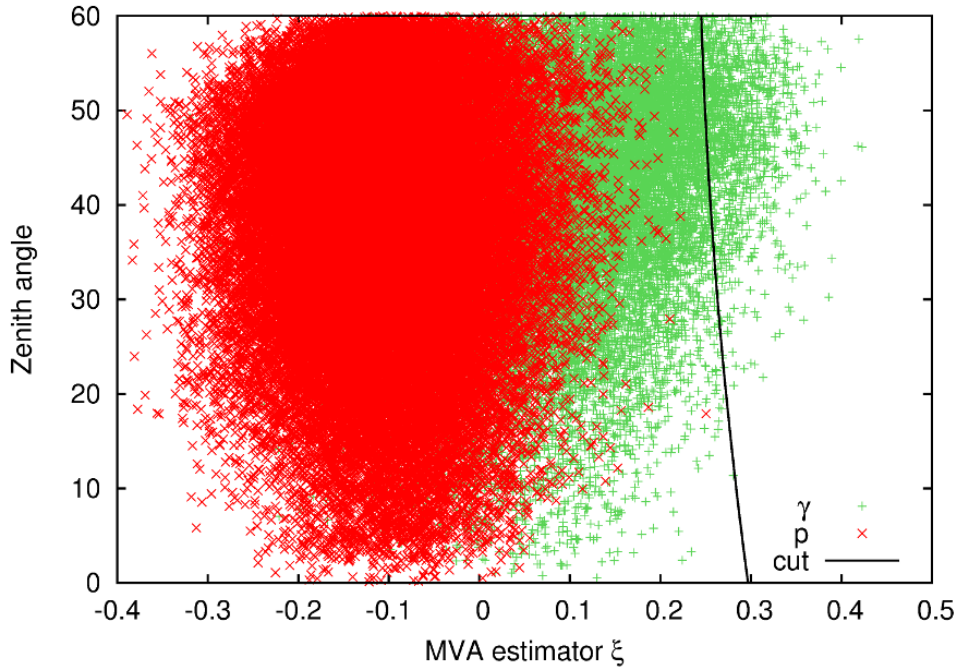






data proton MC gamma MC

TA MVA Search for diffuse UHE photons



- The photon candidates are selected using the cut on ξ: $\xi > \xi_{cut}(\theta)$
- Cut is optimized in each energy range using proton and photon Monte-Carlo
- The null-hypothesis is assumed for the cut-optimization (all events are protons)

Effective exposure for photons

- Geometric exposure for $\theta \in (0^\circ, 60^\circ)$ is **12060 km^2 sr yr**
- Effective exposure is estimated using photon MC assuming E^{-2} primary spectrum

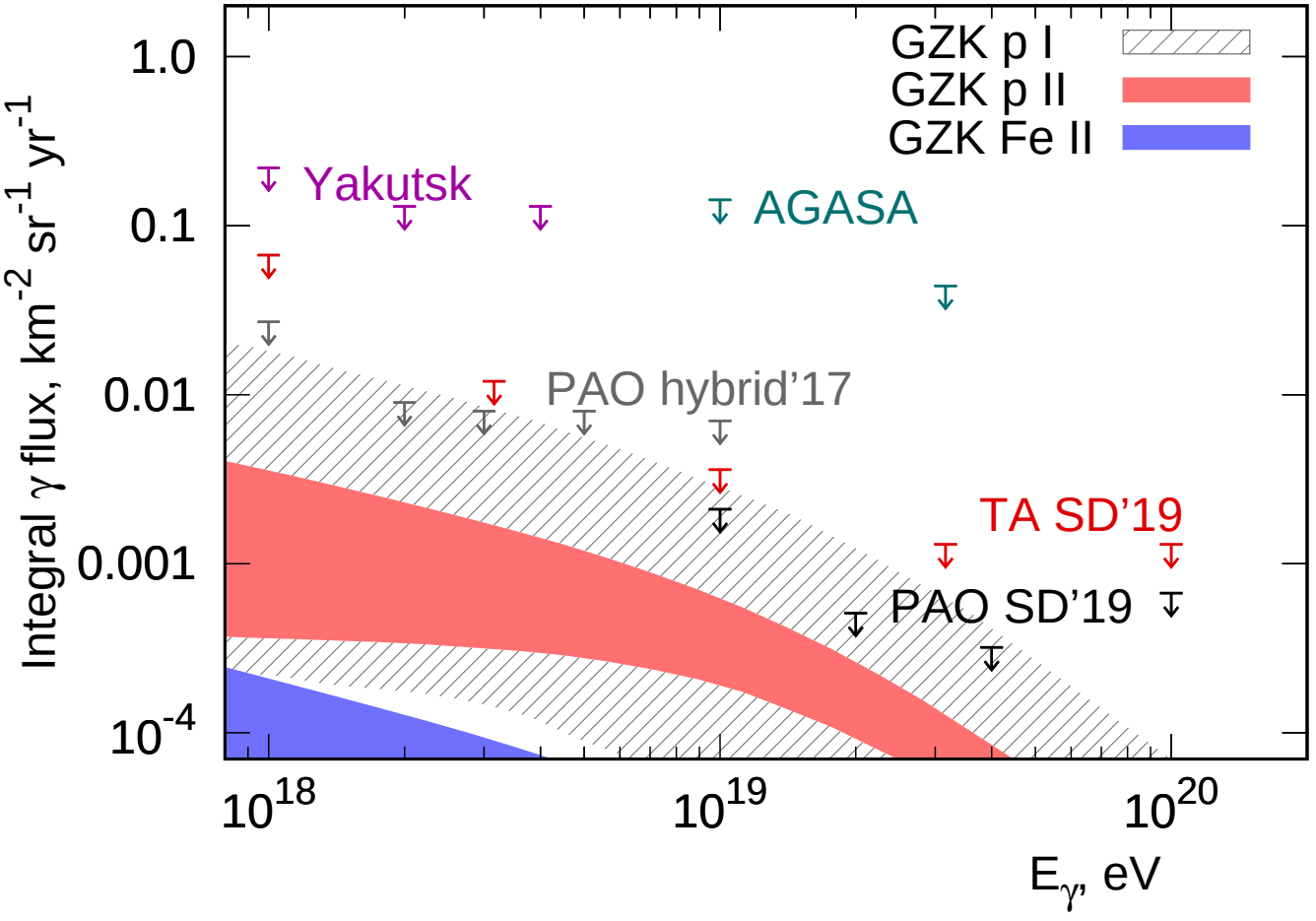
E_0	quality cuts	ξ-cut	A_{eff} km^2 sr yr
$10^{18.0}$	6.5%	9.8%	**77**
$10^{18.5}$	19.9%	10.6%	**255**
$10^{19.0}$	43.6%	16.2%	**852**
$10^{19.5}$	52.0%	37.2%	**2351**
$10^{20.0}$	64.2%	52.3%	**4055**

Photon candidate events

energy cut	event date and time
$E_0 > 10^{18.0}$ eV	2012-03-24 14:06:23
$E_0 > 10^{18.5}$ eV	none
$E_0 > 10^{19.0}$ eV	none
$E_0 > 10^{19.5}$ eV	none
$E_0 > 10^{20.0}$ eV	2012-03-24 14:06:23

- No thunderstorms in March 2012.
- Expected background from proton misclassification: ~ 0.5 events in each energy range.
- The background estimate depends on mass composition and hadronic model. To stay conservative, zero background is assumed.

Results: diffuse UHE photons flux limits



Telescope Array, Astropart.Phys. 110, 8, 2019

$E_\gamma >$, eV	$10^{18.0}$	$10^{18.5}$	$10^{19.0}$	$10^{19.5}$	$10^{20.0}$
γ candidates	1	0	0	0	1
$F_{\rm UL}(95\%CL)$	0.067	0.012	0.0036	0.0013	0.0013

Search for point sources of photons: motivation

The way to improve the photon search sensitivity:

Hadron background is highly isotropic

$\Downarrow$

Assume that photons are emitted by point source

$\Downarrow$

In angular vicinity of the source the **photon/hadron ratio** would be larger than in full TA field of view

$\Downarrow$

Easier to separate photons from hadrons!

Bonus!

Specific photon source hypotheses could be tested by search in certain directions stacked

- Dwarf spheroidal galaxies (heavy DM decay hypothesis)

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Features of γ point sources search: blind search

- Independent search for γ in each skymap direction
- The angular size of the each search region is equal to the γ **angular resolution:**

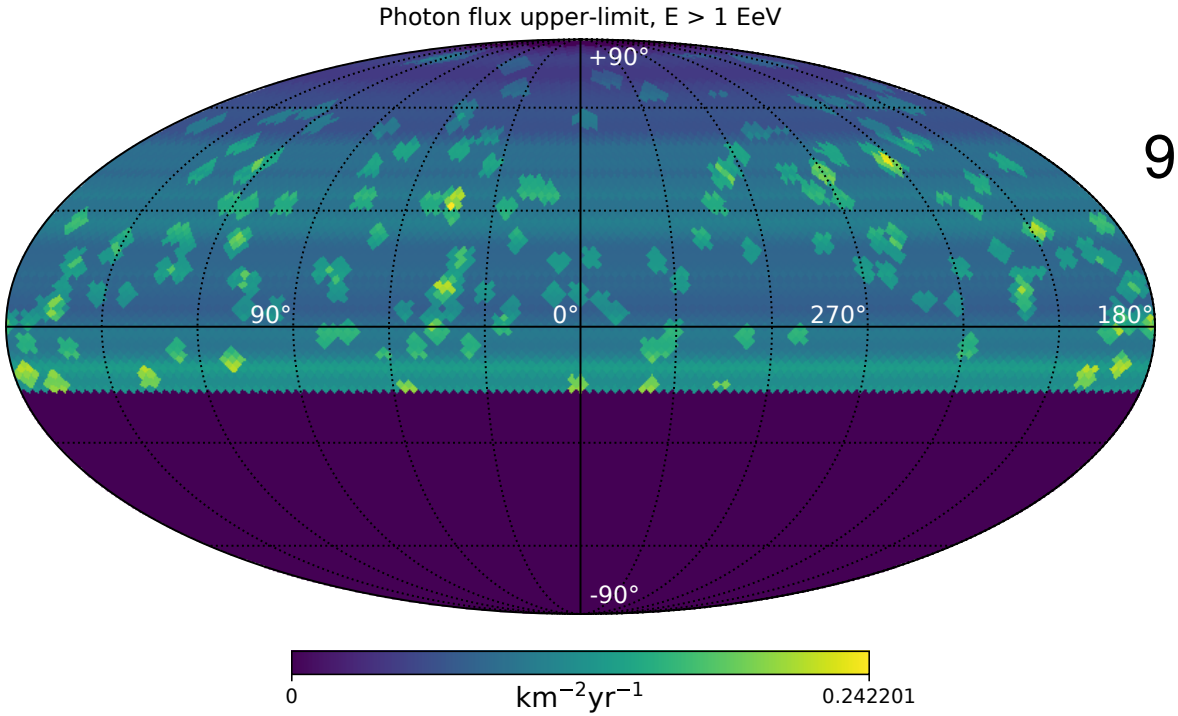
$E_\gamma \geq$, eV	$10^{18.0}$	$10^{18.5}$	$10^{19.0}$	$10^{19.5}$	$10^{20.0}$
ang.res.	3.00°	2.92°	2.64°	2.21°	2.06°

- The skymap is pixelized into 12288 directions with HEALpix (7720 in TA field of view)

Optimisation of MVA-cut for γ flux upper-limit:

- Assume the flux consists of protons only (null hypothesis): $F_{\text{total}} = F_{\text{p}}$
- Optimize the ξ-cut for the best upper-limit separately in each constant declination band $\delta_i \pm \text{ang.res.}$ using MC *p* and MC γ
- E^{-2} γ-spectrum is assumed

Results: point-source photon flux upper-limits



95% C.L.

$E_\gamma \geq$, eV	$\langle F_\gamma \rangle \leq$, km^{-2}yr^{-1}
$10^{18.0}$	0.094
$10^{18.5}$	0.029
$10^{19.0}$	0.010
$10^{19.5}$	0.0071
$10^{20.0}$	0.0058

Pierre Auger: $\langle F_\gamma \rangle \leq 0.035$ km^{-2}yr^{-1} (1° ang.res., $10^{17.3} \leq E \leq 10^{18.5}$ eV)

A. Aab et al. ApJ 789, 160 (2014)

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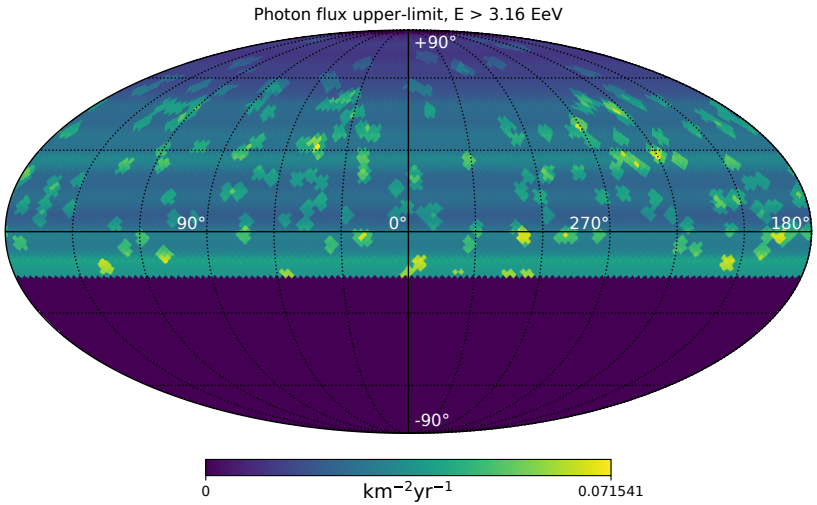
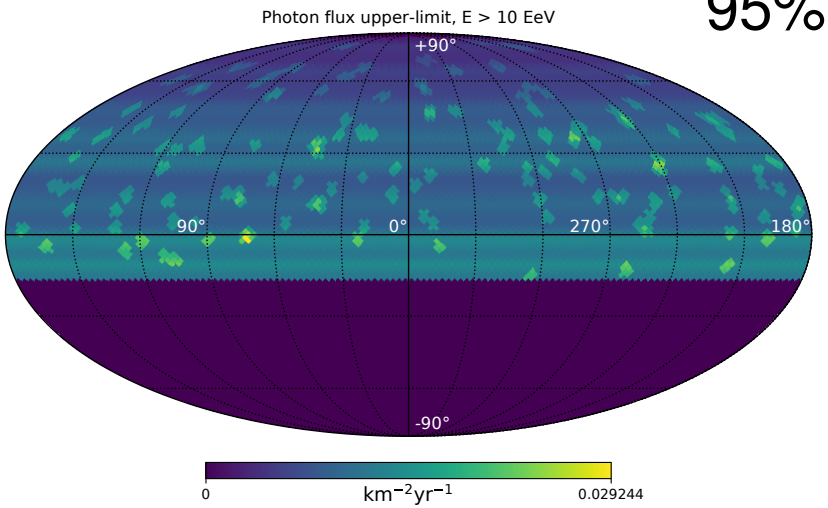
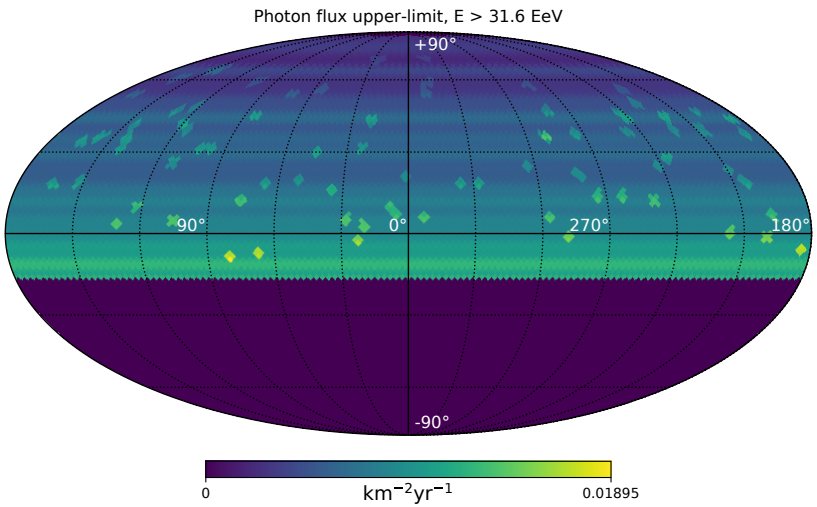
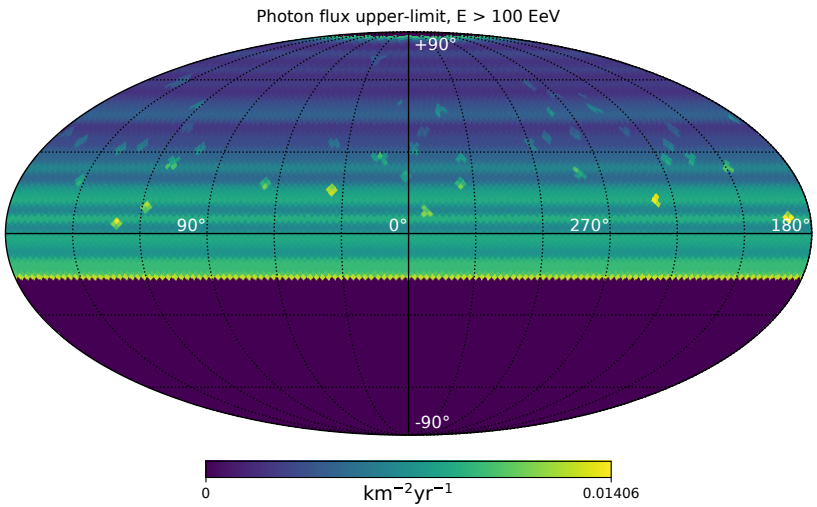






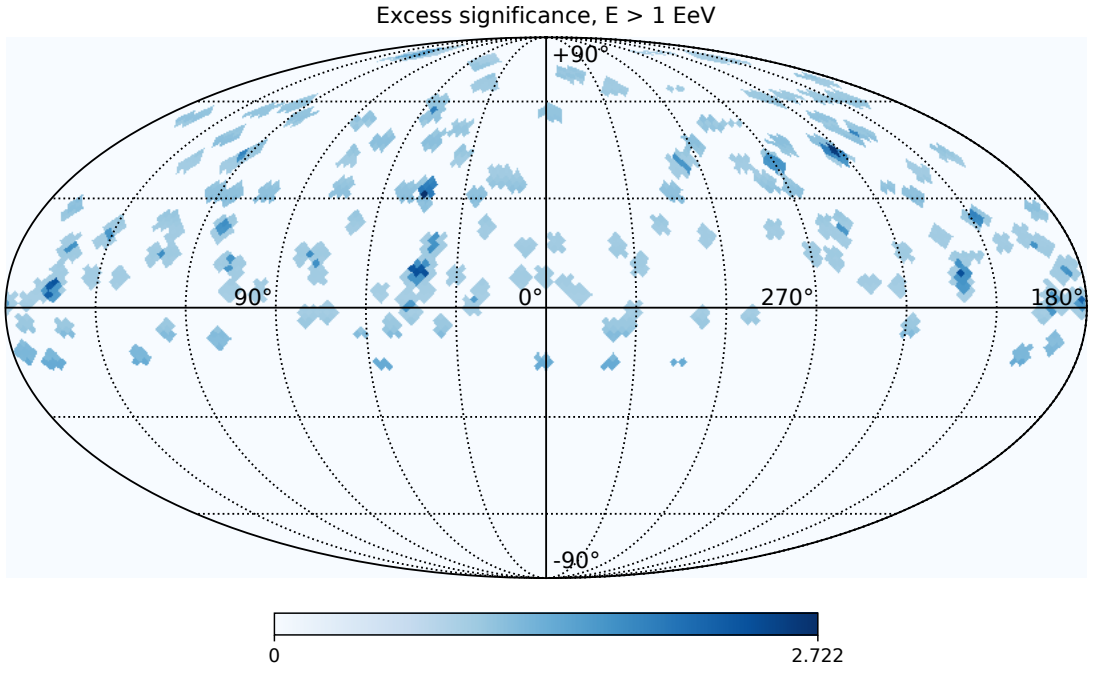


The results for all points are available in a table form with paper

Telescope Array, arXiv:1904.00300

It can be used to constrain models of UHECR sources.

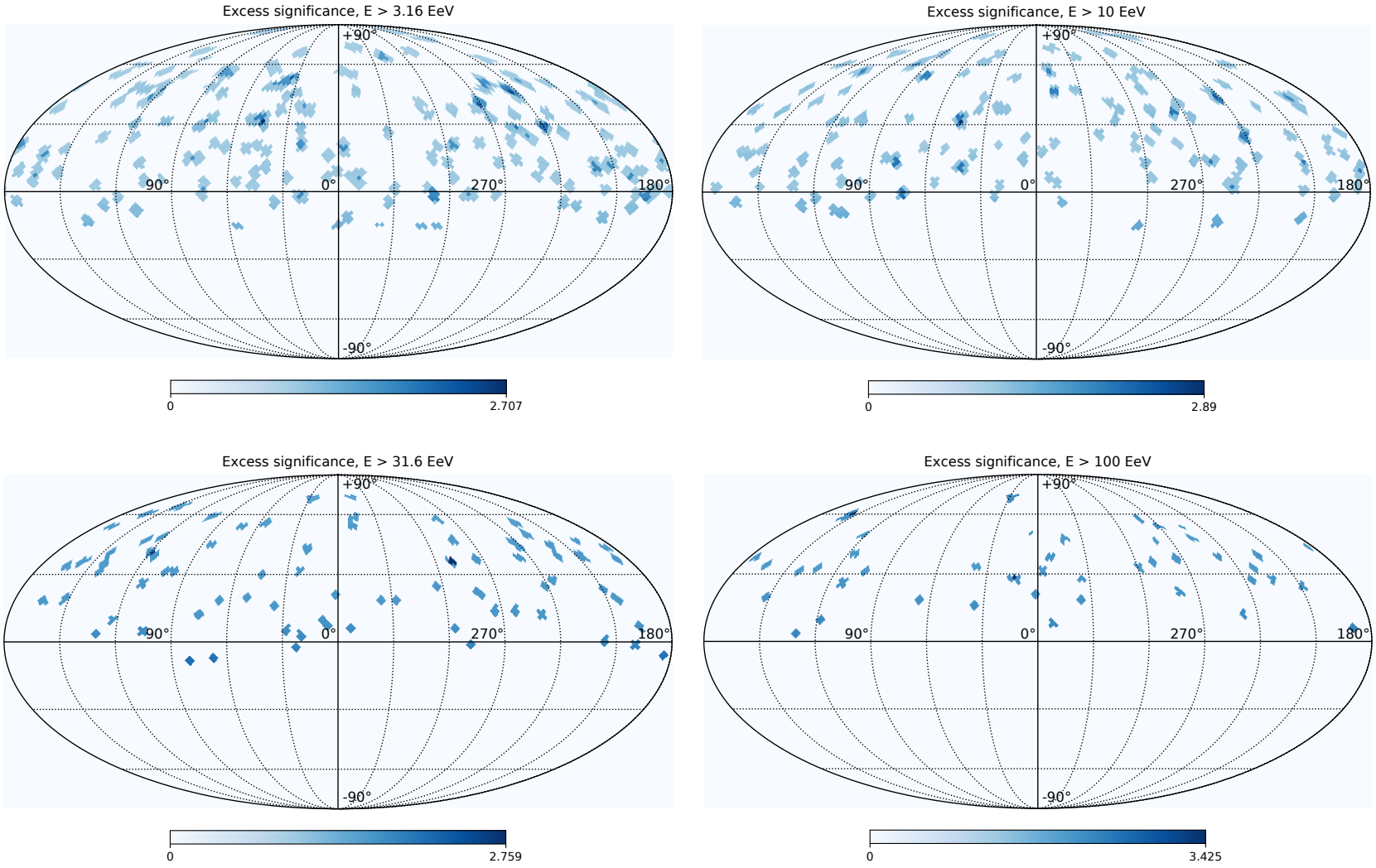
Results: photon excesses significance



$E_\gamma \geq$, eV	max. γ signif. (pre-trial)
$10^{18.0}$	2.72 σ
$10^{18.5}$	2.71 σ
$10^{19.0}$	2.89 σ
$10^{19.5}$	2.76 σ
$10^{20.0}$	3.43 σ

The excesses are insignificant, given the large number of trials

Results: photon excess significance



Though not significant enough, the largest excess is 3.43 σ for

$E_\gamma \geq 10^{20.0}$ eV located at $\{\alpha = 155.3°, \delta = 60.4°\}$

Target search for photons from dwarf galaxies

Probe for the possible decay of heavy dark matter (HDM)

- HDM decay produce significant amount of photons in any model

  M. Kachelriess et al., PRD 98, 083016 (2018)

- DM is abundant in dwarf galaxies (Galactic Center is outside the TA field of view)
- Target source set: 21 dwarf galaxies — satellites of Milky Way

  V. Bonnivard et al., MNRAS 453 (2015), 849

- Search for γ in stacked skymap pixels of dwarf galaxies (pixel size = γ **ang.res.**)

Results

No evidence for photon signal ($N_{\gamma}^{\text{cand.}} = 0$ at all energies)

E_{γ}, eV	$10^{18.0}$	$10^{18.5}$	$10^{19.0}$	$10^{19.5}$	$10^{20.0}$
F_{UL}^{γ}, $\text{km}^{-2}\text{yr}^{-1}$	0.15	0.057	0.014	0.0076	0.0052

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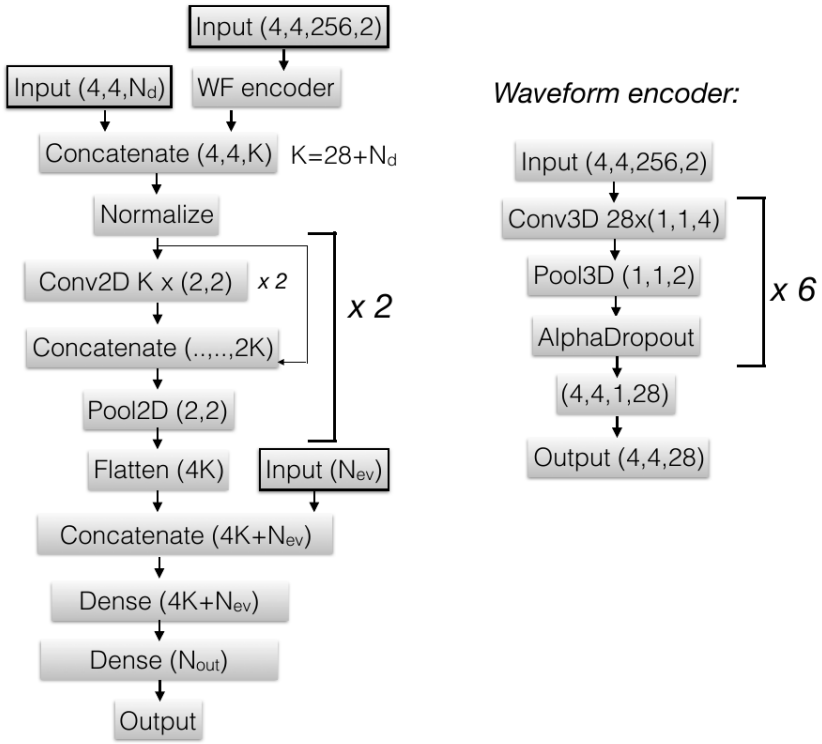
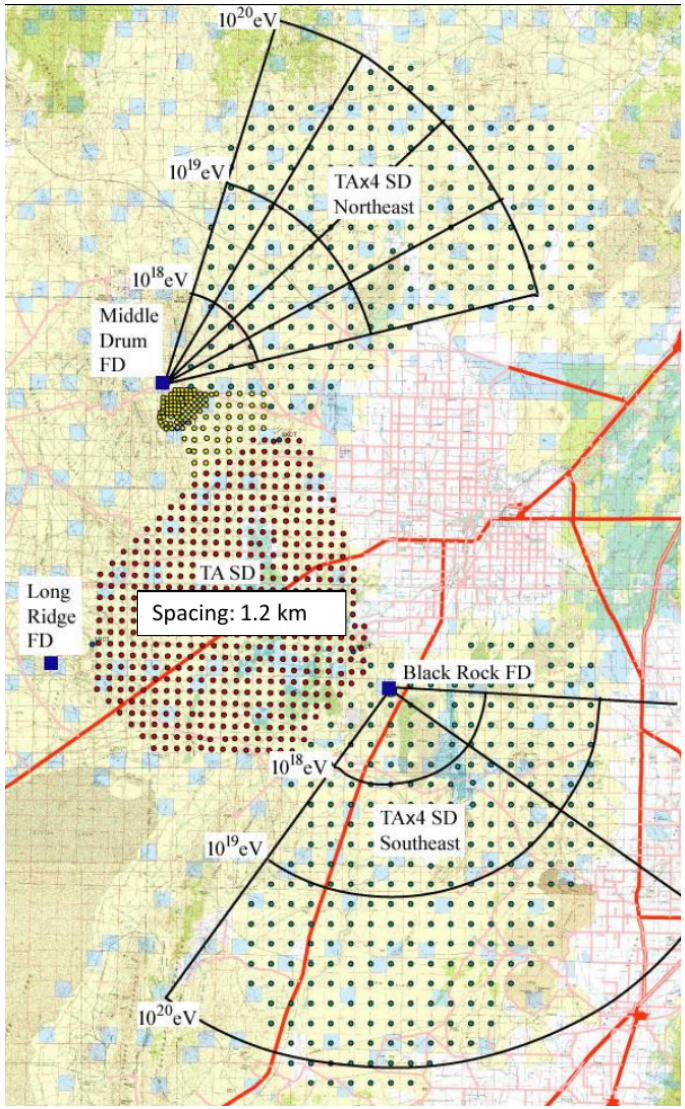
Plans

Improve γ-search sensitivity with recently developing Neural Net



Telescope Array, PoS(ICRC2019)30

Increase γ-search exposure with recently deploying TAx4 SD detector



Conclusions

- **Search for diffuse photons**
  - The diffuse upper-limits for photons with $E > 10^{18}$ eV were set
  - No significant evidence for photons was found
  - The limits are starting to probe cosmogenic photons area
- **Search for point sources of photons**
  - The directional upper-limits for photons with $E > 10^{18}$ eV were set
  - The directional upper-limits for $E > 10^{18.5}$ eV were set for the first time
  - No significant evidence for photon signal was found in blind search
  - The results can be used to constrain UHECR sources models
  - The photons from staked dwarf galaxies were searched — no candidates were found
  - The flux upper-limits for dwarf galaxies can be used to constrain heavy dark matter models

Thank you!

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Thank you!

Backup slides

Impact of possible proton MC systematics

- QGSJet II-03 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: tighter ξ-cut and underestimation of photon exposure
  2. protons are farther to photons than data: looser ξ-cut and extra photon candidates in the data set
- In both cases the flux upper-limits stay conservative

Monte-Carlo: photon angular resolution

The geometry reconstruction of events is crucial for point source search.

There is a bias in zenith angle θ reconstruction.

We correct all data and MC events for the mean value of this bias:

$$\langle \theta_{\text{rec.}} - \theta_{\text{true}} \rangle$$

Angular reconstruction for photon primaries (used in this search)

E_γ, eV	$\langle \theta_{\text{rec.}} - \theta_{\text{true}} \rangle$	ang. resolution
$10^{18.0}$	-2.25°	3.00°
$10^{18.5}$	-2.24°	2.92°
$10^{19.0}$	-2.16°	2.64°
$10^{19.5}$	-2.06°	2.21°
$10^{20.0}$	-1.72°	2.06°