Telescope Array search for ultra-high energy photons and neutrinos

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Telescope Array Collaboration

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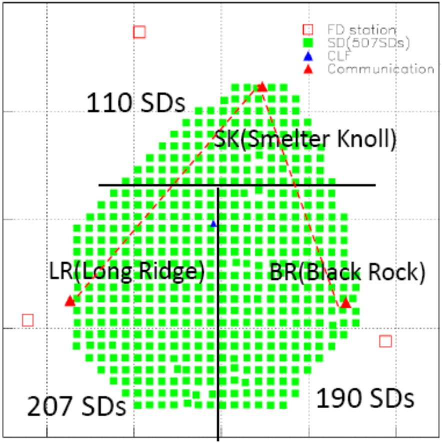
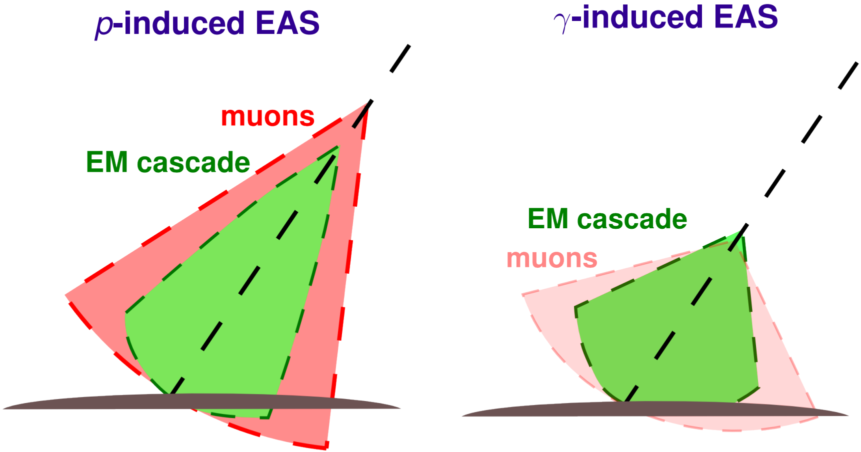
Belgium, Czech Republic, Japan, Korea, Russia, USA

Telescope Array surface detector



- 507 SD's, 3 m^2 each
- 680 km^2 area
- 9 years of operation (this analysis)

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

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 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)

52769 events after all cuts expect lightning cut

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

Lightning-induced air showers

- It is shown that there are triggers of TA SD associated with the downward propagating ladders in lightning flushes.
  - Multiple SD triggers are observed within one millisecond

    Phys.Lett. A 381 (2017) 2565.
  - The results of Lightning Mapping Array (LMA) at TA site

    Journal of Geophysical Research: Atmospheres, 123, (2017) 6864-6879
- The lightnings induce electromagnetic showers, which may be identified as photons. At least five candidates of this sort passed the cuts, see *GR, ICRC'2017* for details.
- We use the National Lightning Detector Network (NLDN) data on lightnings at the location of TA SD.

  We appreciate Vaisala Inc's academic research policy
- Both data and Monte-Carlo events are removed within $\pm$10 min from NLDN events. An associated loss of exposure is only 0.66% of the total exposure time.

52362 events after all cuts

Photon search: list of relevant observables

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 $b = 3$ 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. 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;

Multivariate analysis

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

  Pierre Auger Collaboration, ApJ, 789, 160 (2014)

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

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

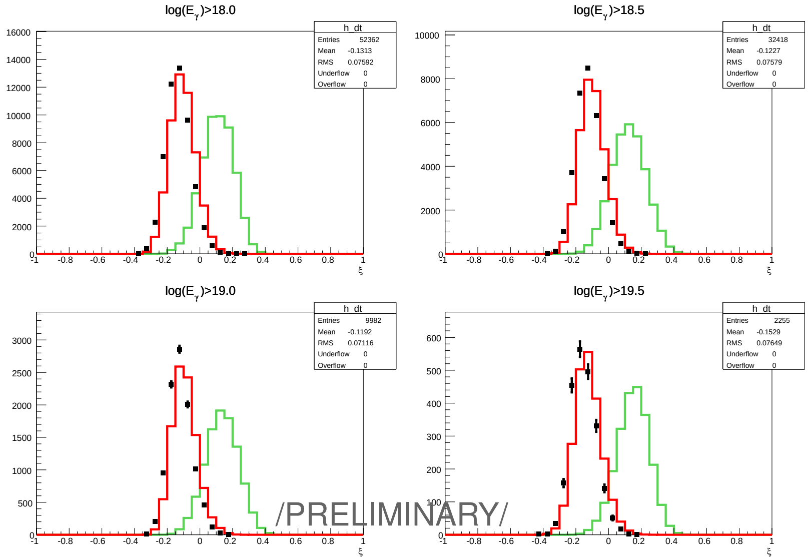
- BDT is trained with Monte-Carlo sets:

  γ (Signal) and *p* (Background)

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

- ξ is available for one-dimensional analysis. The cut on ξ for the search is optimized using proton MC as a null-hypothesis.

Distribution of MVA estimator (ξ) for data and MC



data photon MC proton MC

Optimization of cut on ξ

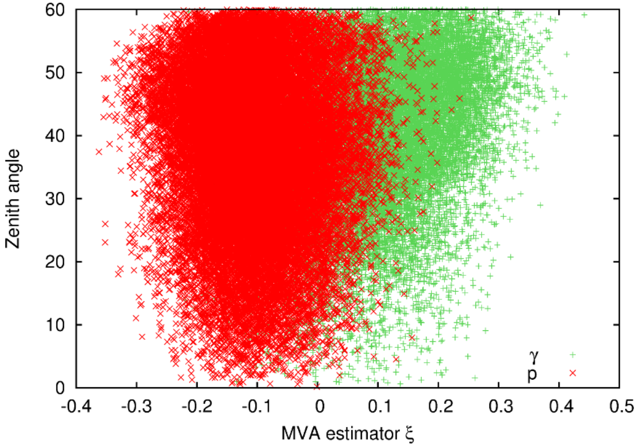
- The photon candidates are selected using the cut on ξ: $\xi > \xi_{cut}(\theta)$
- The cut is approximated as a quadratic function of θ
- Cut is optimized in each energy range using proton and photon Monte-Carlo (cut optimization subsets)
- The merit factor is an average photon upper limit if the null-hypothesis is true (all protons)

Effective exposure

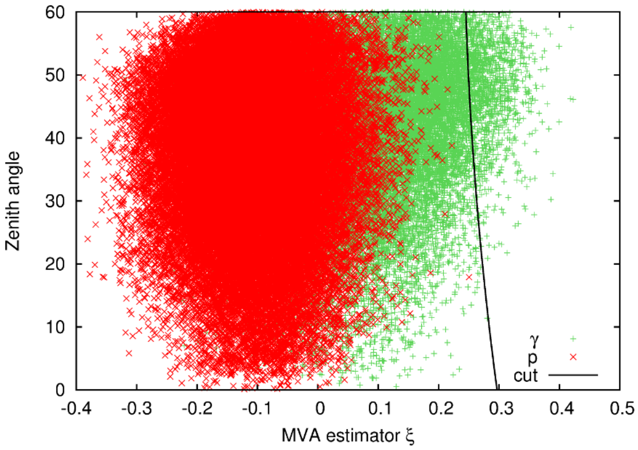
- Geometric exposure for $\theta \in (0^\circ, 60^\circ)$: **12060 km^2 sr yr**
- Effective exposure is estimated using photon MC assuming E^{-2} primary spectrum

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**

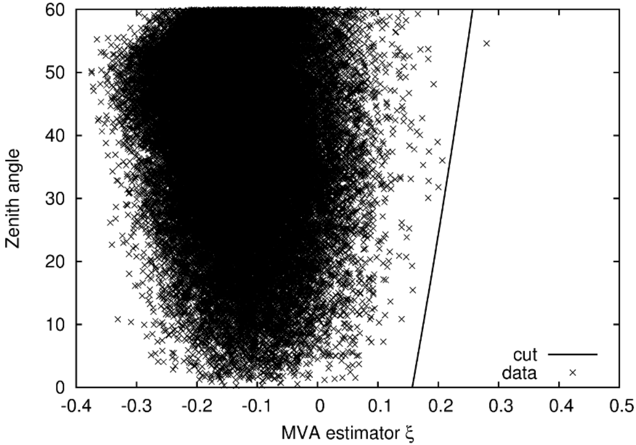
$E_\gamma > 10^{18}$ eV, zenith angle dependent cut on ξ: MC



$E_\gamma > 10^{18}$ eV, zenith angle dependent cut on ξ: MC



$E_\gamma > 10^{18}$ eV, zenith angle dependent cut on ξ: data



1 photon candidate event

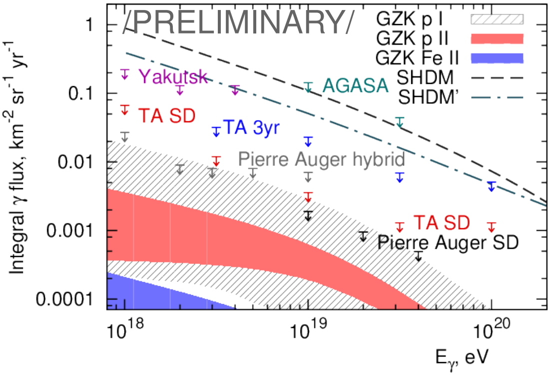
Photon candidate events

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: $\sim$0.5 events in each energy range.
- The background estimate depends on composition and hadronic model. To stay conservative, zero background is assumed in the analysis.

Results: photon flux limits

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
$\bar{n}$ <	5.14	3.09	3.09	3.09	5.14
A_{eff}	77	255	852	2351	4055
F_γ <	0.067	0.012	0.0036	0.0013	0.0013



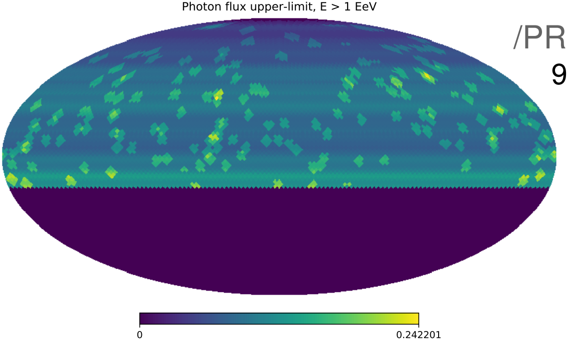
models from J. Alvarez-Muniz et al. EPJ Web Cong. ***53****, 01009 (2013)*

Search for point sources of the ultra-high-energy photons

- The skymap is pixelized into 12288 directions with HEALpix
- An independent search with the cut optimization is performed in circles centered in each of the pixels; radius = angular resolution
- Angular reconstruction for photons:

E_γ, eV	ang. resolution 68%
$10^{18.0}$	3.00°
$10^{18.5}$	2.92°
$10^{19.0}$	2.64°
$10^{19.5}$	2.21°
$10^{20.0}$	2.06°

Point-source photon flux upper-limits



/PRELIMINARY/
95% C.L.

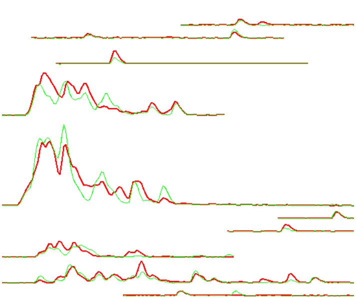
$E_\gamma \geq$, eV	$\langle F_\gamma \rangle \leq$, $\mathrm{km}^{-2}\mathrm{yr}^{-1}$	max. γ signif. (pre-trial)
$10^{18.0}$	0.094	2.72 σ
$10^{18.5}$	0.029	2.71 σ
$10^{19.0}$	0.010	2.89 σ
$10^{19.5}$	7.1×10^{-3}	2.76 σ
$10^{20.0}$	5.8×10^{-3}	3.43 σ

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

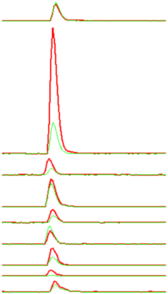
A. Aab et al. ApJ 789, 160 (2014)

Neutrino search strategy

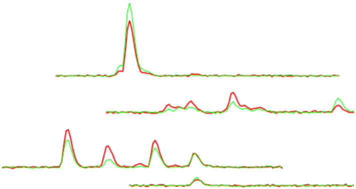
young shower, $\theta = 19.5^\circ$



old shower, 78.3°



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



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

upper layer lower layer

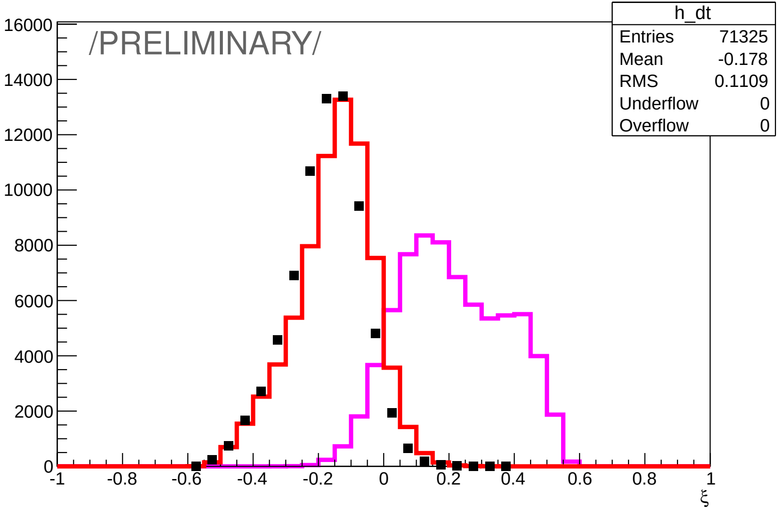
Method

- Cuts:
  - 5 or more detectors triggered
  - core distance to array boundary is larger than 1200m
  - χ^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 ξ is optimized in a similar to photon search way

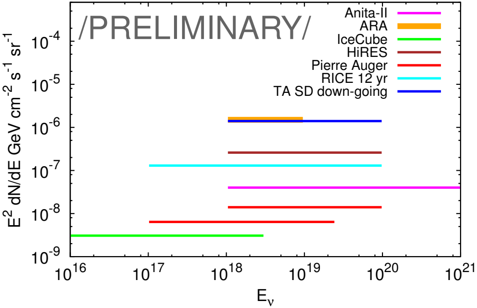
Distribution of MVA estimator (ξ) for data and MC



data neutrino MC proton MC

Results

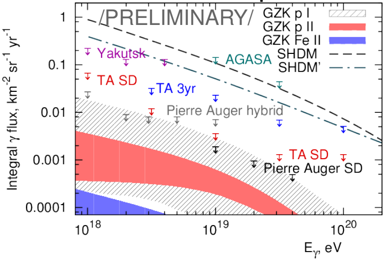
- 0 neutrino candidates after cuts, $\bar{n}_\nu < 2.44$ (90% C.L.)
- **Exposure:**
  - Geometric exposure for $\theta \in (45^\circ, 90^\circ)$: 8042 km^2 sr yr
  - probability to interact in the atmosphere: 1.4×10^{-5}
  - trigger, reconstruction and quality cuts efficiency $\sim 7\%$
  - ξ cut efficiency: $\sim 24\%$
  - total exposure (all flavors): $A = 1.9 \times 10^{-3}$ km^2 sr yr
- Single flavor diffuse neutrino flux limit for $E > 10^{18}$ eV:
  $E^2 f_\nu < 1.4 \times 10^{-6}\,\mathrm{GeV\,cm^{-2}s^{-1}sr^{-1}}$ (90% C.L.)

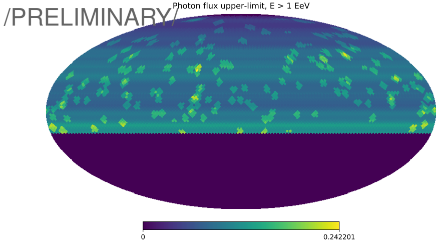


Conclusions

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

- Diffuse and point-source photon flux upper limits above $10^{18.0}$ eV are presented.





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

The development and application of the multivariate analysis method is supported by the

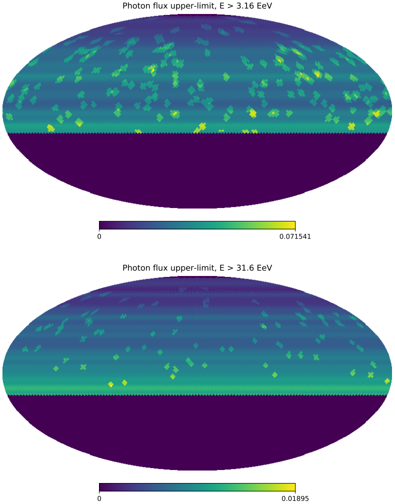
RSF | Russian Science Foundation

Backup slides

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

Results: point-source photon flux upper-limits

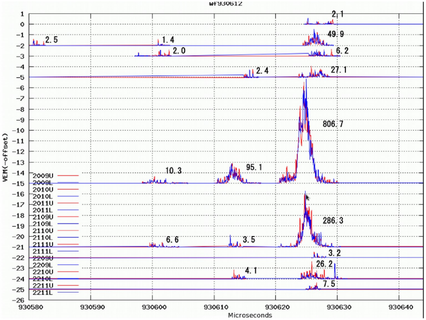


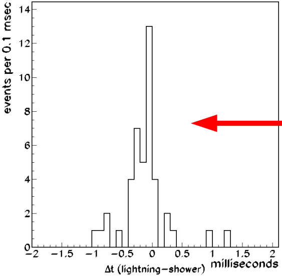
/PRELIMINARY/

95% C.L.

Plot: T. Okuda

TA Observation: "Burst" Events

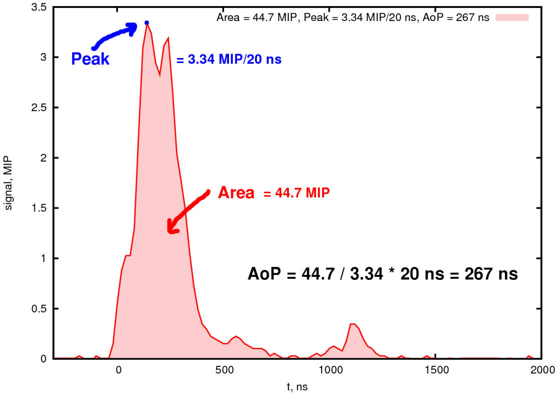




- 5 year data (2008-2013)
- 10 surface detector bursts seen
  - 3 or more SD triggers, $\Delta t < 1$ msec
  - Occasional $\Delta t \sim 10\ \mu$sec
- "Normal" SD trigger rate < 0.01 Hz. *These cannot be cosmic ray air showers*.
- Found to have close time/space coincidence with *U.S. National Lightning Detection Network* (NLDN) activity.
- Abbasi et al. *Phys. Lett.* **A 381** (2017).

SD observable: Area over peak

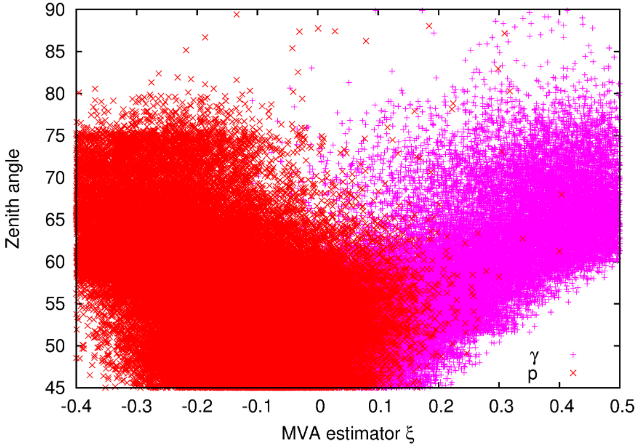
- Consider a surface station time-resolved signal



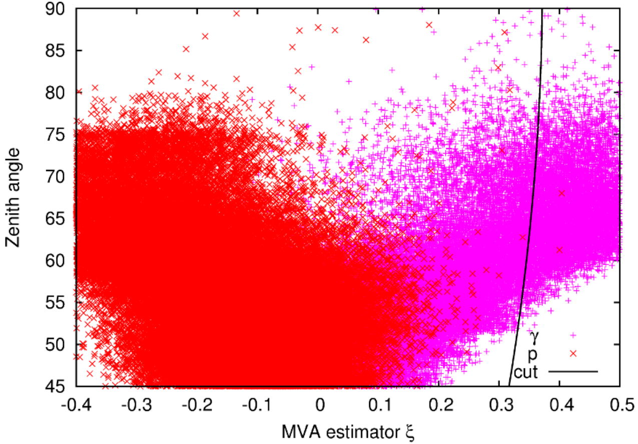
- Both peak and area are well-measured and not much affected by fluctuations

- First introduced by Pierre Auger Collaboration in the context of neutrino search

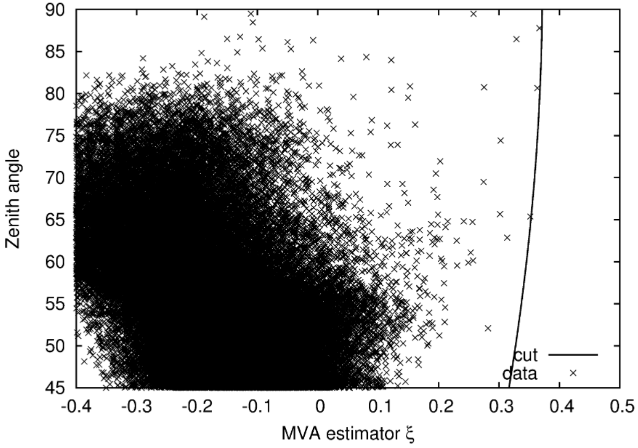
$E_\nu > 10^{18}$ eV, zenith angle dependent cut on ξ: MC



$E_\nu > 10^{18}$ eV, zenith angle dependent cut on ξ: MC



$E_\nu > 10^{18}$ eV, zenith angle dependent cut on ξ: data



0 neutrino candidate events

Event reconstruction: fit functions

- Joint 7-parametric fit: x_{core}, y_{core}, θ, ϕ, S_{800}, t_0, a

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

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

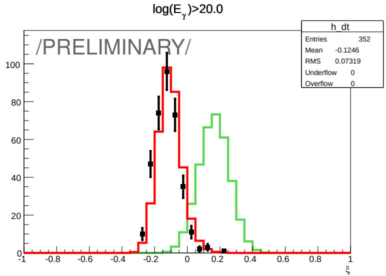
$$S(r) = S_{800} \times LDF(r)$$

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

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

$$\eta = 3.97 - 1.79(\sec(\theta) - 1)$$

Distribution of ξ for data and MC 10^{20} eV



data photon MC proton MC