

Directional Search for Ultra-High-Energy Photons Using the SD-1500 Array of the Pierre Auger Observatory

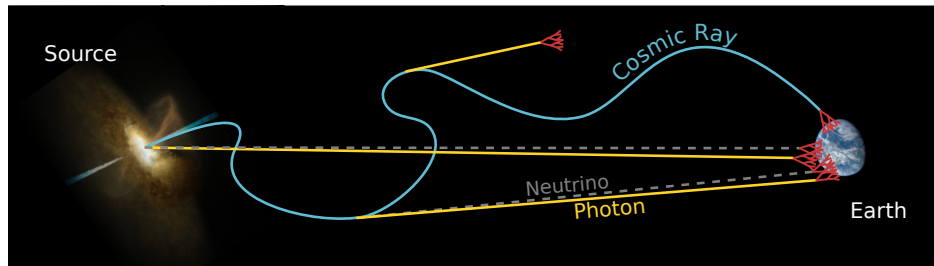
ISCRA (Erice, Sicily, Italy)

Tim Fehler ([email](#)), Marcus Niechciol, Markus Risse
Center for Particle Physics Siegen, University of Siegen, Germany



01 Aug 2026

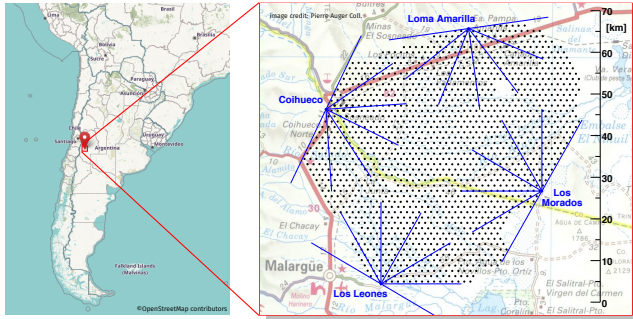
UHE photons as messengers of the Universe



Searching for **ultra-high-energy (UHE) photons** (here $> 10^{18}$ eV, discovery pending)

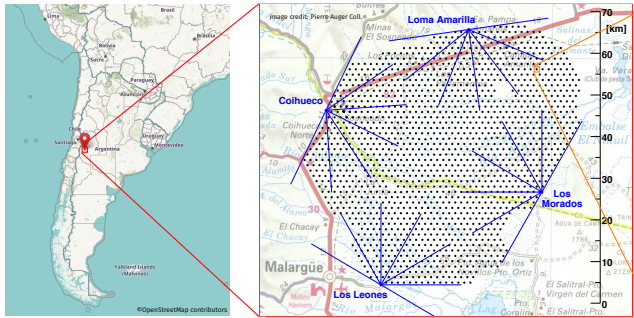
- ▶ Probing origin and nature of **UHE cosmic rays** (effective horizon ~ 10 Mpc at 10^{18} eV)
- ▶ Sensitive to physics **beyond the Standard Model**
- ▶ **Multimessenger observations** at the highest energies

Pierre Auger Observatory



- ▶ Largest **cosmic-ray observatory** worldwide, energy range 10^{17} to $> 10^{20}$ eV
- ▶ **Argentina, Malargüe** (Lat.: 35.1° S), 1400 m a.s.l.
- ▶ Indirect detection via **extensive air showers**
- ▶ **SD-1500 array**: “footprint of shower”, 1660 water-Cherenkov detectors (WCD) over 3000 km^2 , continuously operating since 2004

Pierre Auger Observatory



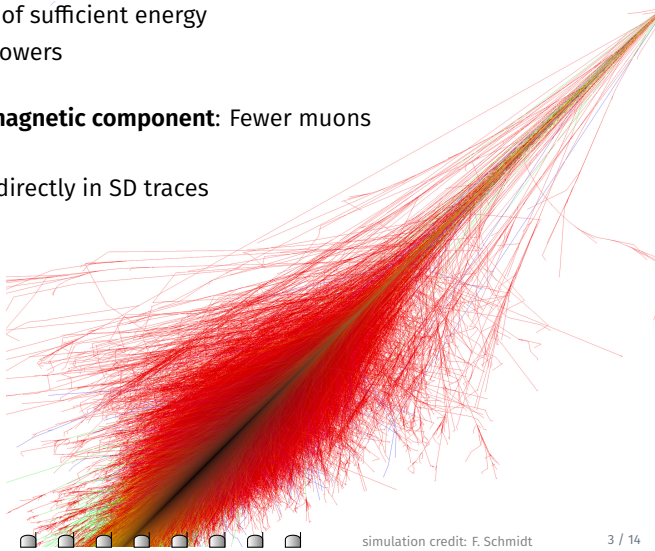
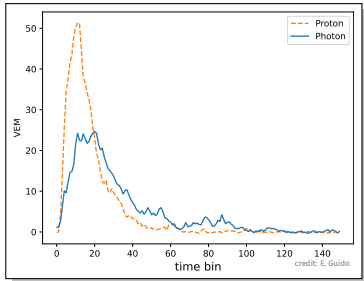
Surface Detector (SD) station



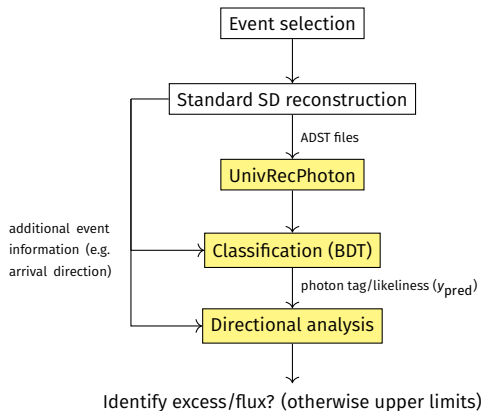
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Detecting UHE photons

- ▶ ~ 100% detection efficiency for UHE photons of sufficient energy
- ▶ Vastly dominant background: hadronic air showers
→ **Classification problem**
- ▶ Photon-induced showers **shaped by electromagnetic component**: Fewer muons (N_μ), deeper shower maximum ($X_{\max}$)
- ▶ **Challenge**: These properties only show up indirectly in SD traces



Search for directional excess of “photon-like” events



Key properties / design choices:

- ▶ Only **SD data** (greater statistics)
- ▶ Full **Phase-I data set** (2004–2022)
- ▶ Built on top of standard reconstruction
- ▶ **Modular design**

- ▶ *Almost all air showers can be sufficiently described by a handful of parameters.*
- ▶ **Consequence:** Model of the signal evolution in WCDs at arbitrary positions relative to the shower axis

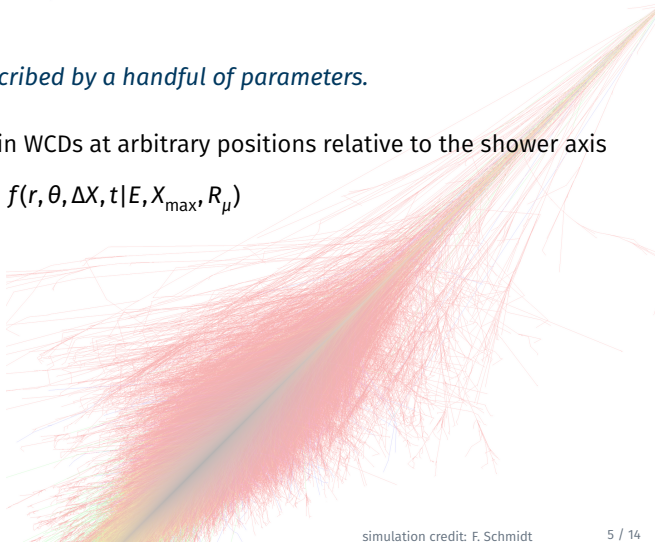
$$S_{\text{pred}}(t) = f(r, \theta, \Delta X, t | E, X_{\text{max}}, R_{\mu})$$

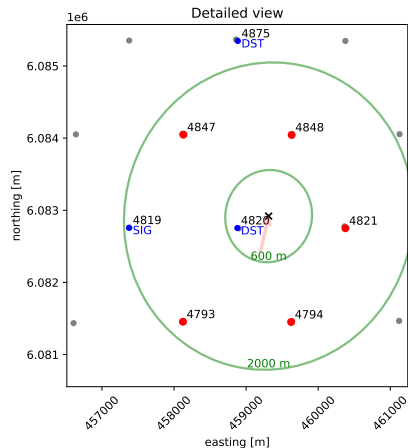
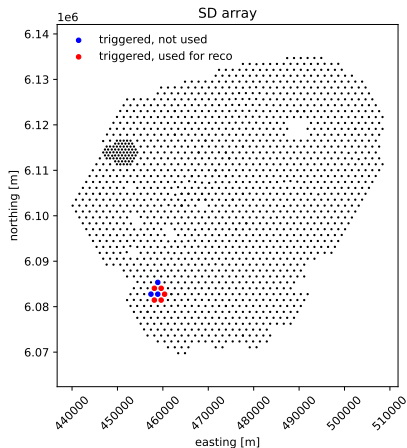
M. Ave et al., Astroparticle Physics **87**, 23–39 (2017)

M. Ave et al., Astroparticle Physics **88**, 46–59 (2017)

M. Stadelmaier et al., Phys. Rev. D **110**, 023030 (2024)

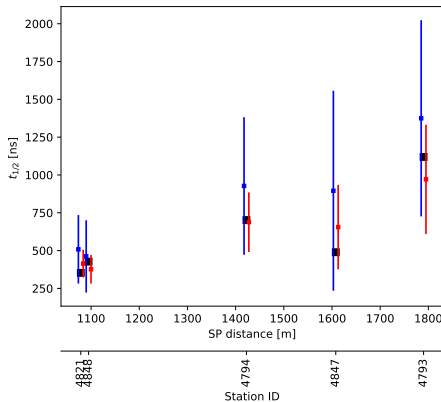
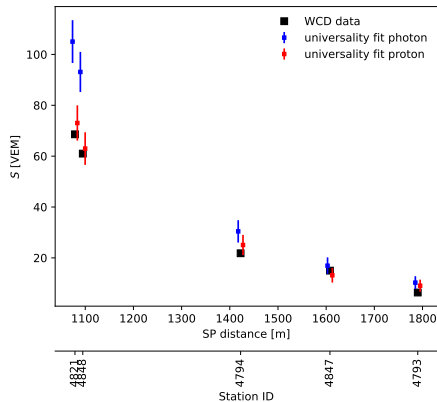
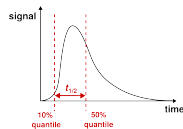
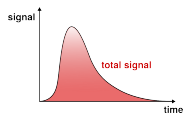
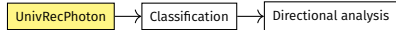
- ▶ R_{μ} : proxy for muon number N_{μ}





MC "truth": Proton primary, $E_{MC} = 2.13 \times 10^{19}$ eV.

Universality reconstruction module



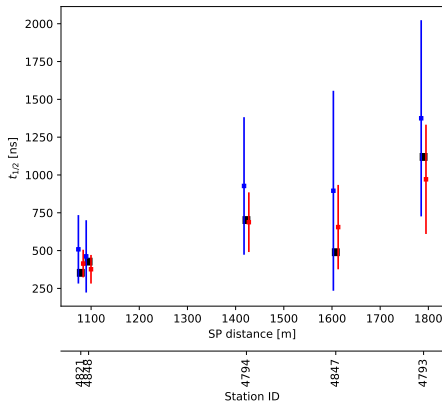
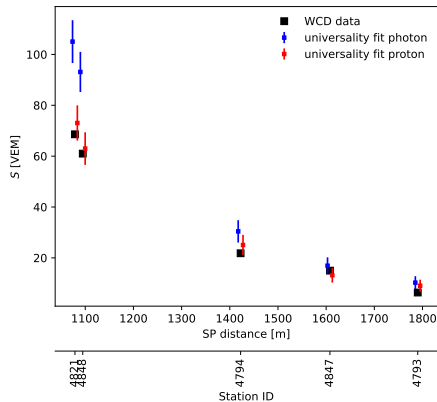
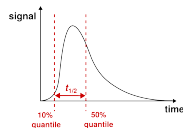
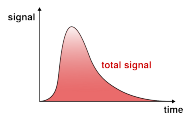
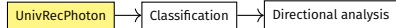
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 GPSSecond: 1104122008
 UTC Timestamp:
 2015-01-01 04:33:12.000
 Zenith: 20.6 deg
 Azimuth: 257.0 deg

Photon hypothesis:
 $\lg(E/\text{eV}) = 19.884$
 $X_{\text{max}} = 931.9 \text{ g cm}^{-2}$
 $R_{\mu} = 0.352$
 $\lg(L_{\text{sig}}) = -33.3$
 $\lg(L_{\text{time}}) = -35.2$

Proton hypothesis:
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- ▶ **XGBoost**¹ library, version 3.0.4
- ▶ photon (sig) 97 163 events
proton (bkg) 188 471 events

- ▶ Offline v4r0p2, CORSIKA 7.7420, EPOS-LHC
- ▶ $18.0 < \lg(E_{\text{MC}}/\text{eV}) < 20.0$
- ▶ 80% for training / validation, 20% for testing

12 input features

- ▶ $\max_y L_{\text{sig/time}}, \max_p L_{\text{sig/time}}$
- ▶ $\lg(E)_{\text{rec}}^y, \lg(E)_{\text{rec}}^p$
- ▶ $X_{\text{max, rec}}^y, X_{\text{max, rec}}^p$
- ▶ $R_{\mu, \text{rec}}^y, R_{\mu, \text{rec}}^p$
- ▶ $\sin^2(\theta)$
- ▶ N_{stations}

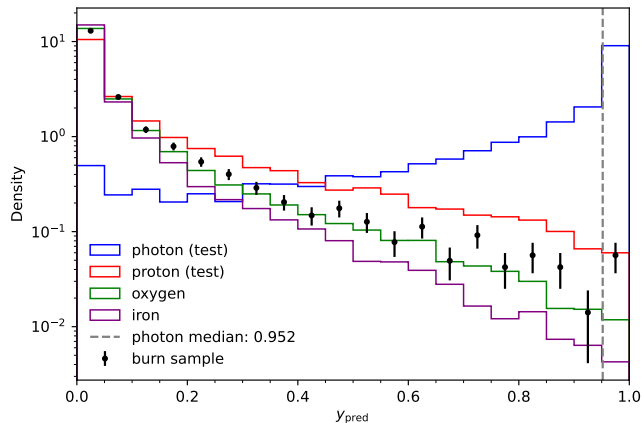
BDT

 $y_{\text{pred}} \in [0, 1]$

“photon tag”

¹T. Chen and C. Guestrin, in Proc. of SIGKDD '16 (2016), pp. 785–794

Test with SD-1500 burn sample



Photon-proton discrimination:

- **background rejection** at 50% signal efficiency:

$$0.99448 \pm 0.00037$$

- **area-under-curve** score:

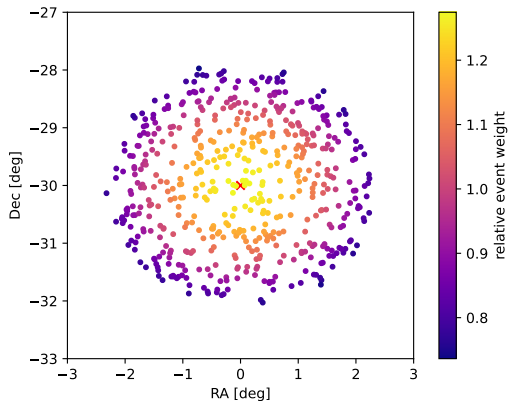
$$0.9588 \pm 0.0010$$

- **balanced accuracy** ($y_{\text{thres}} = 0.5$):

$$0.8931 \pm 0.0017$$

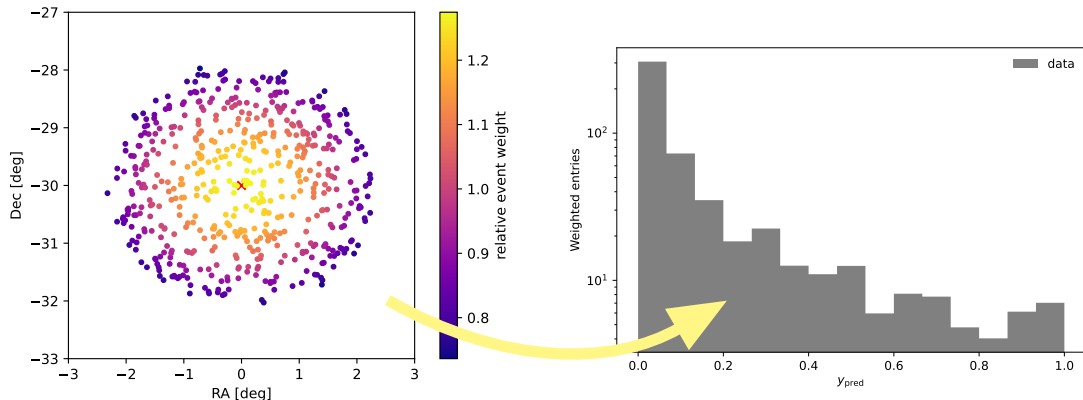
All metrics have been calculated above $\lg(E_{\gamma}/\text{eV}) = 19.0$ with energy spectra $\Phi \propto E^{-2}$.

Disclaimer: *This slide and the following depict realistic toy data.*



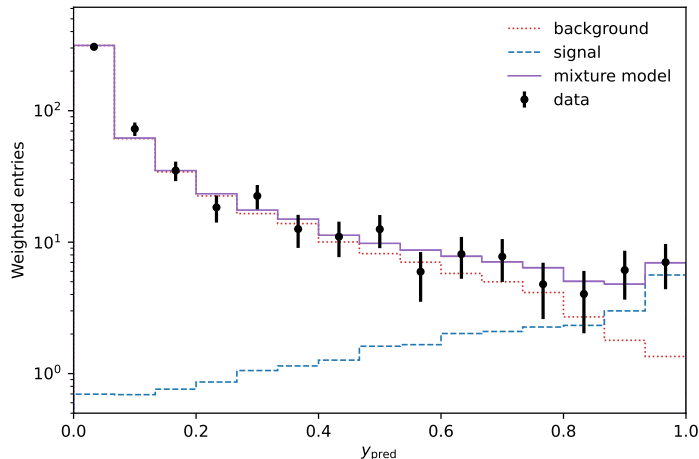
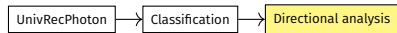
$$w(\Delta\theta) \propto \exp(\kappa \cdot \cos \Delta\theta)$$

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Analyzing one search direction: Template fitting



Signal template

MC photon sample

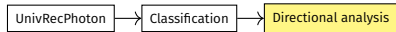
Background template

Distribution of y_{pred} for data outside search window

Results: $\hat{\tau}_{\text{sig}} = 27.1^{+9.3}_{-8.2}$, $Z = 4.16$, $-\log_{10}(p) = 4.81$

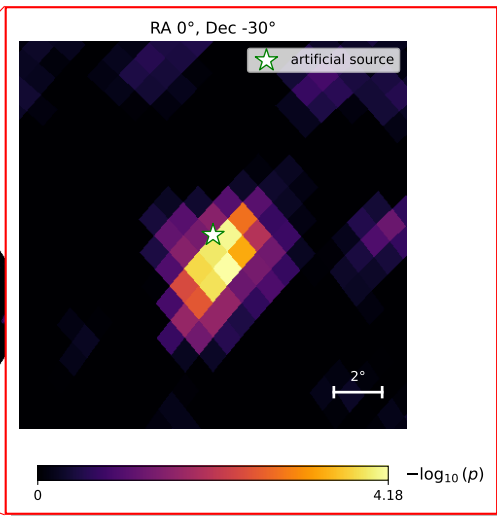
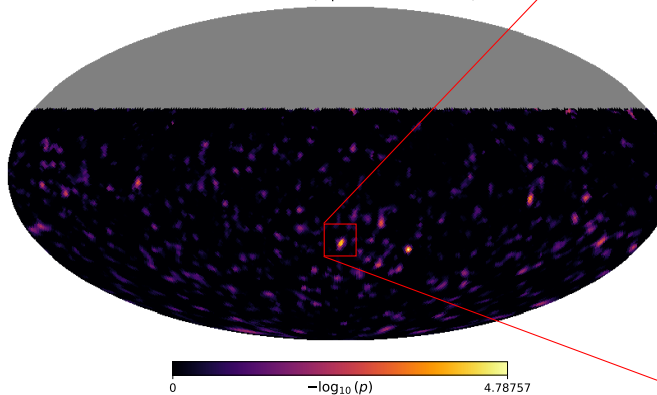
Following method of H. Dembinski and A. Abdelmotteleb, Eur. Phys. J. C 82, 10.1140/epjc/s10052-022-11019-z (2022)

Toy scenario: full-FOV scan



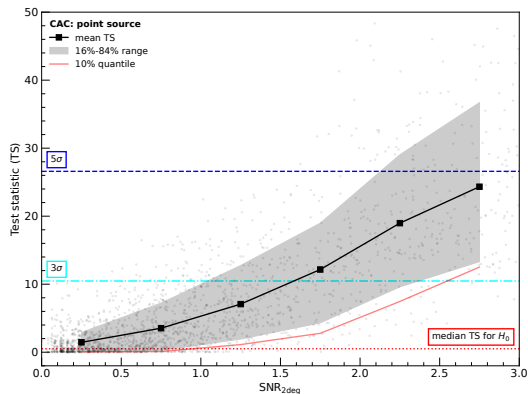
- ▶ 80 **signal** events (E^{-2} spectrum, realistic smearing)
- ▶ 1 000 000 **background** events (Auger spectrum/exposure)

Mollweide view (equatorial coordinates)

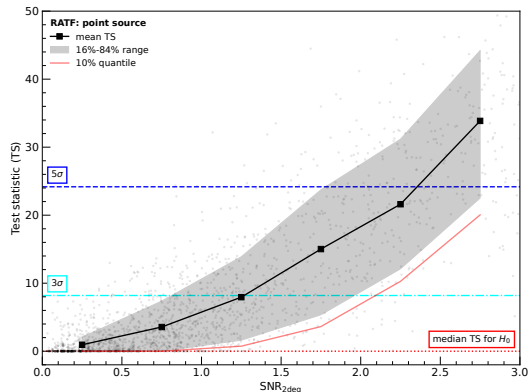


Point source with $\Phi \propto E^{-2}$, $\lg(E/\text{eV}) > 18.5$

Old method ($\rightarrow$ cut-and-count)



This work



$$\text{SNR}_{2\text{deg}} = n_{\text{sig}} / \sqrt{n_{\text{bkg}}} \text{ within } 2^\circ \text{ top-hat window}$$

Takeaway Points

- ▶ UHE photons are important **puzzle pieces** in **astrophysics at the highest energies**
- ▶ Developed novel **universality-based reconstruction and classification** algorithm for extensive air showers
- ▶ Plan **targeted search and full-FOV scan** using refined template fitting method

Thank you!

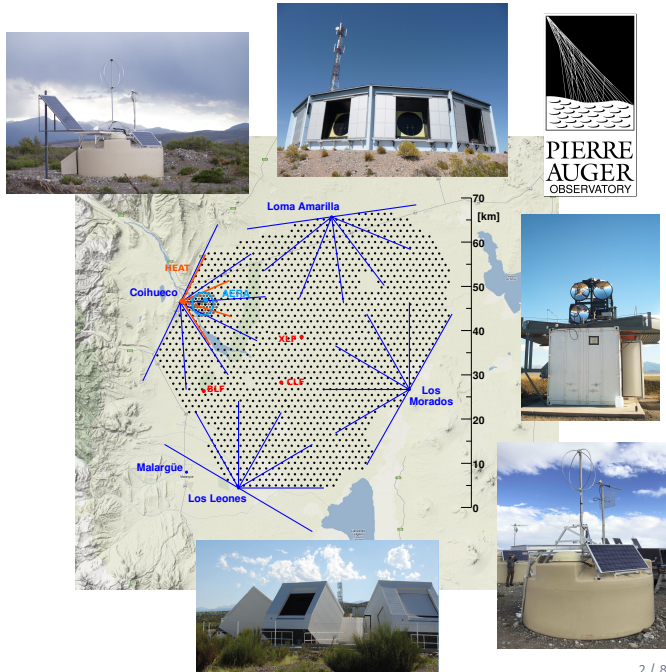


- ¹M. Ave et al., “A generalized description of the signal size in extensive air shower detectors and its applications”, *Astroparticle Physics* **87**, 23–39 (2017).
- ²M. Ave et al., “A generalized description of the time dependent signals in extensive air shower detectors and its applications”, *Astroparticle Physics* **88**, 46–59 (2017).
- ³M. Stadelmaier et al., “Model of the response of surface detectors to extensive air showers based on shower universality”, *Phys. Rev. D* **110**, 023030 (2024).
- ⁴T. Chen and C. Guestrin, “XGBoost: a scalable tree boosting system”, in *Proc. of SIGKDD '16* (2016), pp. 785–794.
- ⁵H. Dembinski and A. Abdelmotteleb, “A new maximum-likelihood method for template fits”, *Eur. Phys. J. C* **82**, 10.1140/epjc/s10052-022-11019-z (2022).
- ⁶Pierre Auger Coll., “The Pierre Auger Cosmic Ray Observatory”, *NIMA* **798**, 172–213 (2015).

Pierre Auger Observatory

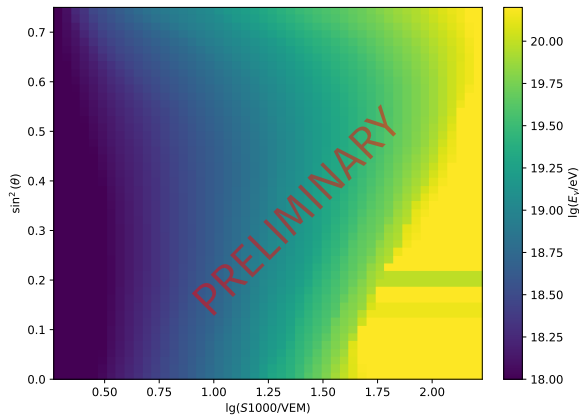
- ▶ Largest **cosmic-ray observatory** in the world
- ▶ Located near Malargüe, Argentina
- ▶ Energy range: 10^{17} eV to $> 10^{20}$ eV
- ▶ **Hybrid detector**
 - ▶ **Surface detector (SD) array**
 - ▶ **Fluorescence detector (FD)**
- ▶ Auxiliary detector systems (infill arrays, radio antennas, ...)
- ▶ Atmospheric monitoring (LIDAR, laser facilities, ...)
- ▶ **AugerPrime upgrade**
 - ▶ Primary mass estimate on shower-by-shower basis

Pierre Auger Coll., NIMA 798, 172–213 (2015)

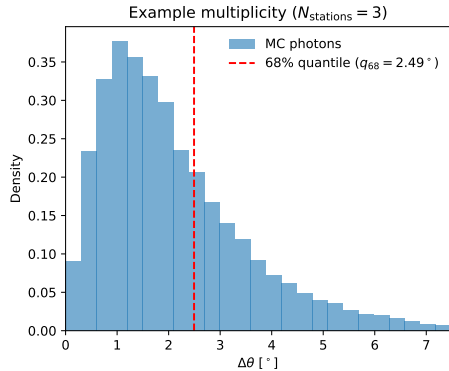
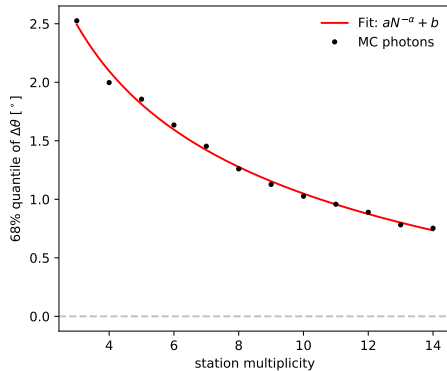


PIERRE
AUGER
OBSERVATORY

Problem: Energy reconstruction designed for nuclei primaries, inherent bias for photons

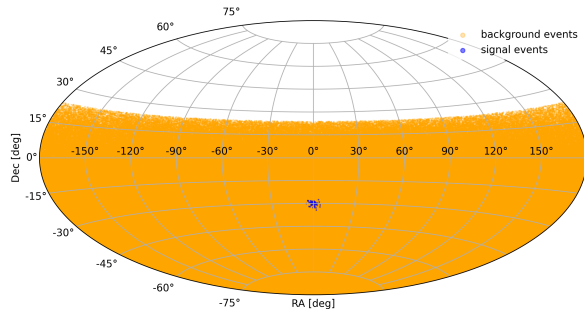


Angular displacement based on station multiplicity

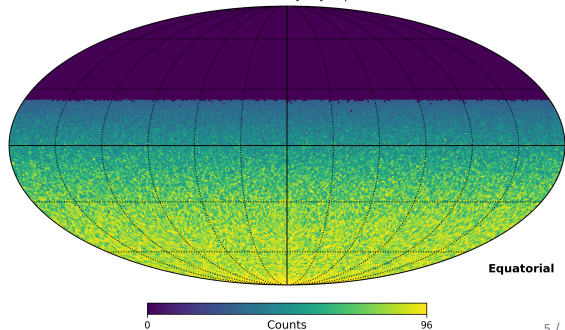


Typical scenario

- ▶ 1 000 000 **background** events
 - ▶ Set of $(\lg(E_\gamma/\text{eV}), y_{\text{pred}})$ drawn from SD-1500 burn sample
 - ▶ Isotropic distribution accounting for Auger exposure during Phase I
- ▶ 80 **signal** events (*single source*)
 - ▶ Photon simulations
 - ▶ E_{MC}^{-2} spectrum, starting at $10^{18.5}$ eV
 - ▶ Realistic signal smearing

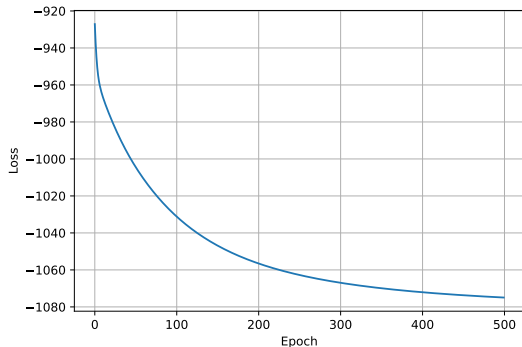


Event Density Skymap

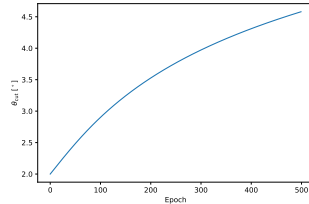


Hyperparameter optimization for directional analysis

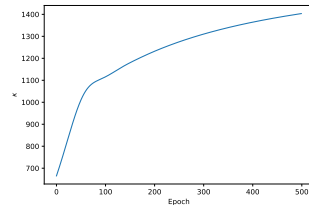
- ▶ Made $S/\sqrt{B}$ a fully differentiable function of $(\theta_{\text{cut}}, \kappa, E_{\text{thr}})$
- ▶ Maximize on an ensemble of toy scenarios via gradient descent for a specific signal topology



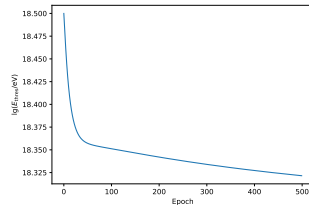
θ_{cut}



κ

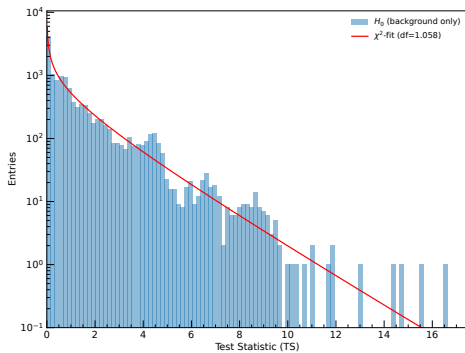


$\lg(E_{\text{thr}}/\text{eV})$

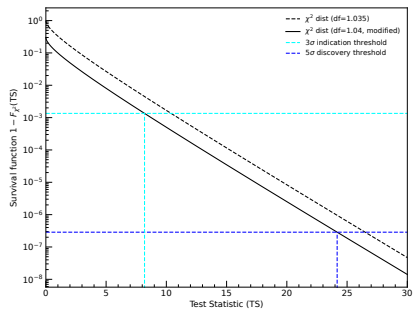
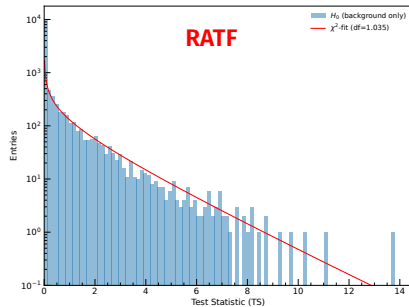


TS thresholds for directional analysis

cut-and-count



RATF



Photon flux in toy scenario

Integrated photon flux above threshold energy (E_{thres}):

$$F(E > E_{\text{thres}}) = \frac{N_{\text{events}}}{\int_{E_{\text{thres}}}^{\infty} \epsilon(E) g(E) dE},$$

with directional exposure $\epsilon(E)$ and normalized photon energy spectrum $g(E)$.

Assuming $\epsilon(E, \theta) \approx \epsilon(E)$ for the photon detection efficiency:

$$F(E > E_{\text{thres}}) = \frac{N_{\text{events}}}{T \cdot A_{\text{geom}} \cdot D_{\text{sid}} \cdot \langle \epsilon \rangle},$$

with the **directional acceptance factor per sidereal day** $D_{\text{sid}} = \int_0^{T_{\text{sid}}} \cos \theta(t) \Theta(\theta_{\text{limit}} - \theta(t)) dt$ and the **energy-averaged efficiency** $\langle \epsilon \rangle = \int_{E_{\text{thres}}}^{\infty} g(E) \epsilon(E) dE$.

- ▶ For detector latitude $\lambda = -35.3^\circ$, source declination $\delta = -30^\circ$, maximum zenith angle $\theta_{\text{limit}} = 60^\circ$: $D_{\text{sid}} \approx 0.289$
- ▶ For energy threshold $E_{\text{thres}} = 10^{18.5}$ eV, energy spectrum $g(E) \propto E^{-2}$: $\langle \epsilon \rangle \approx 0.854$
- ▶ $N_{\text{events}} = 80$, $A_{\text{geom}} = 3000 \text{ km}^2$, $T = 17 \text{ yr}$

$$\Rightarrow F(E > E_{\text{thres}}) \approx 6.006 \times 10^{-3} \text{ km}^{-2} \text{ yr}^{-1}$$

Disclaimer: This does not account for fact that effective area only reached full size in 2008.