Searches for ultra-high-energy photons at the Pierre Auger Observatory

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The New Era of Multi-Messenger Astrophysics Conference

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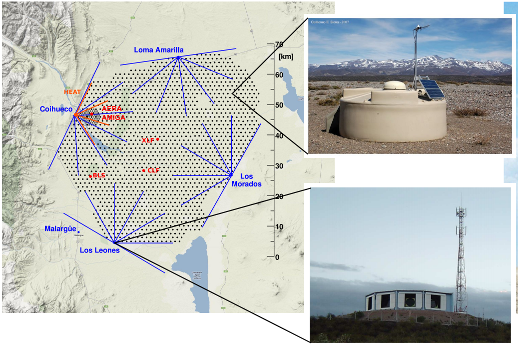
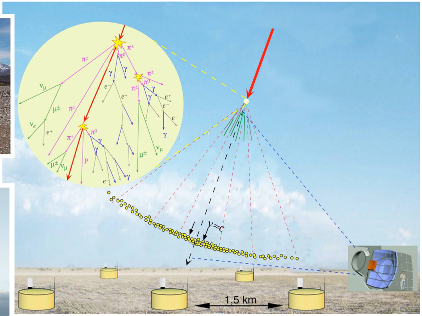
The Pierre Auger Observatory

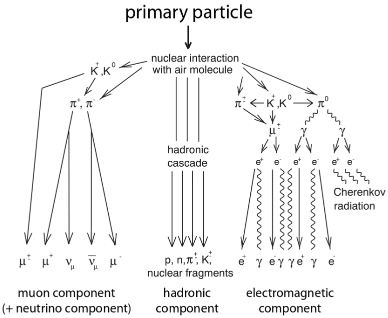


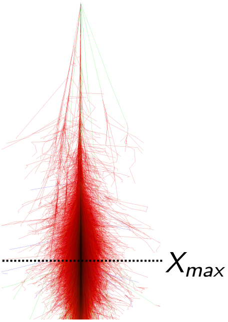


- Surface Detector (SD)
  - 1660 water Cherenkov detectors with spacing of 1.5 km ($3000\,\mathrm{km}^2$)
  - Measuring secondary particles of extensive air showers (EAS)
  - Duty cycle $\sim$ 100%
- Fluorescence Detector (FD):
  - 27 fluorescence telescopes at 4 sites
  - Measure nitrogen fluorescence light caused by EAS
  - Duty cycle $\sim$ 13%

Characterization of photon induced air showers (vs hadronic primaries):

- Delayed shower development $\rightarrow X_{max}$ (atmospheric depth of the shower maximum) on average $100 - 150\,\mathrm{g\,cm^{-2}}$ deeper
- Almost pure el.mag. shower, less muons





Photon searches at Auger

- Search for a diffuse flux of ultra-high energy (UHE) photons with the SD
  - Energy range: $> 10\,\mathrm{EeV}$
- Search for a diffuse flux of UHE photons with the hybrid detector
  - "Hybrid" $\hat{=}$ SD + FD
  - Energy range: $> 1\,\mathrm{EeV}$
- Search for point sources of UHE photons with the hybrid detector
  - Energy range: 0.2 EeV ... 3 EeV

Search for a diffuse photon flux with the SD

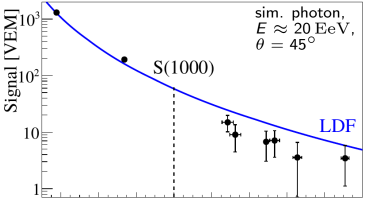
Analysis optimized for photon energies above 10 EeV.

Photon discriminating SD observables:

Lateral distribution function (LDF):

$$L_{LDF} = \log\left(\frac{1}{N}\sum\frac{S_i}{LDF(r_i)}\right)$$

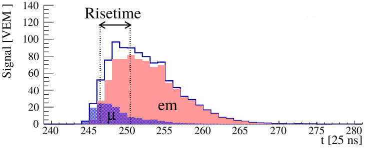
Comparison of signal S_i of each station to the typical signal at distance r_i



Risetime:

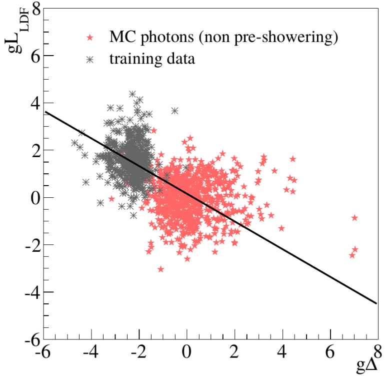
$$\Delta = \frac{(\sum\delta_i)}{N}, \quad \delta_i = \frac{t_{1/2} - t_{bench}}{\sigma_{t_{1/2}}}$$

Normalized residual of signal risetime $t_{1/2}$ and a parameterized data benchmark t_{bench}

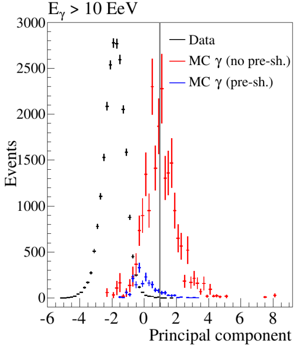


[ICRC 2015]

Search for a diffuse photon flux with the SD



- Energy- and zenith-normalized observables gL_{LDF} and $g\Delta$ complement each other in terms of separation power between simulated photon showers and the bulk of data



- Projection on common principal component (PC) axis to combine the observables
- Photon candidate cut at the median of the photon distribution

[ICRC 2015]

Search for a diffuse photon flux with the SD

Analysis results:

Count events with PC $>$ photon candidate cut as "photon candidate events"

- 4 photon candidate events above 10 EeV
- 2 photon candidate events above 20 EeV
- 0 photon candidate events above 40 EeV

$\rightarrow$ Upper limits (at 95% CL) on the diffuse photon flux $F_\gamma^{95\%} = \frac{N_\gamma^{95\%}}{\langle \mathcal{E} \rangle}$

$$\left(\begin{array}{l} N_\gamma^{95\%}\text{: Feldman-Cousins upper limit at 95\% CL} \\ \langle \mathcal{E} \rangle\text{: spectrum-weighted average exposure} \end{array} \right)$$

$$F_\gamma^{95\%}(E_\gamma > (10, 20, 40)\,\mathrm{EeV}) = (1.9, 1.0, 0.49) \times 10^{-3} km^{-2} yr^{-1} sr^{-1}$$

[ICRC 2015]

Search for a diffuse photon flux with the hybrid detector

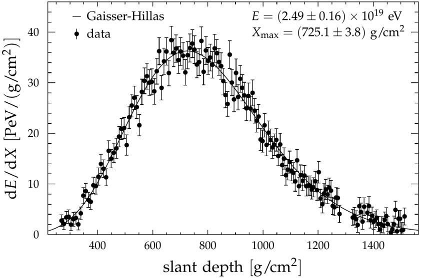
Extend photon search down to 1 EeV with the Auger hybrid detector:

- Energy and axis reconstruction with help of the FD
- Lower duty cycle of FD, but higher particle flux at lower energies

Photon discriminating hybrid observables:

Maximum of the Gaisser-Hillas ($\mathcal{GH}$) fit to the longitudinal profile:

$$X_{max} = X|_{\mathcal{GH}(X)=max(\mathcal{GH}(X))}$$



LDF:

$$S_4 = \sum S_i \left(\frac{r_i}{1000m}\right)^4$$

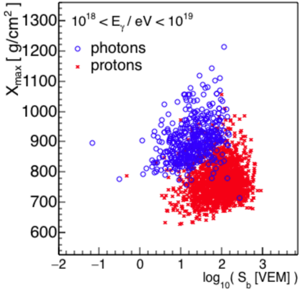
Sum over signal in each SD station weighted by distance to shower axis

$$N_{Stations}$$

Number of triggered SD stations

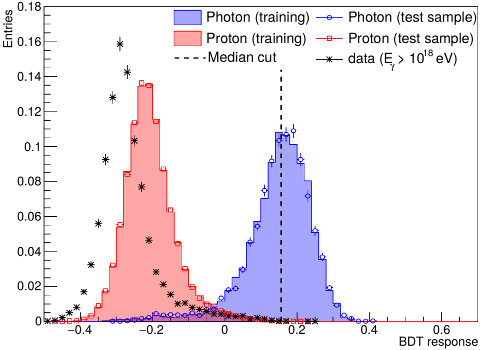
[JCAP 2017; PRD 2014]

Search for a diffuse photon flux with the hybrid detector



- Comparison of simulated showers induced by photon and proton primaries in terms of S_4 and X_{max}

- Combine observables in boosted decision tree (BDT) classifier
- Add photon energy and zenith angle to BDT to account for dependencies



[JCAP 2017]

Search for a diffuse photon flux with the hybrid detector

Analysis results:

Photon candidate events

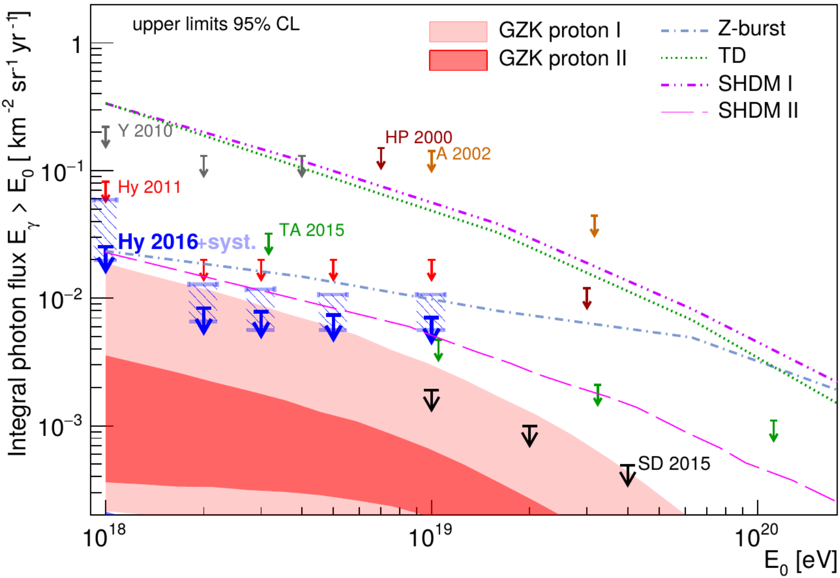
- 3 photon candidate events above 1 EeV
- 0 photon candidate events above 2 EeV

Upper limits:

$$F_{\gamma}^{95\%}(E_{\gamma} > (1, 2, 3, 5, 10)\,\mathrm{EeV}) = (27, 9, 8, 8, 7) \times 10^{-3} km^{-2} yr^{-1} sr^{-1}$$

[JCAP 2017]

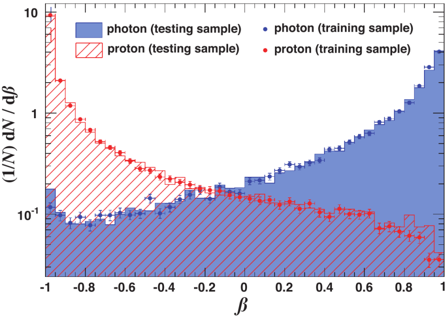
Limits to the diffuse photon flux above 1 EeV



[JCAP 2017]

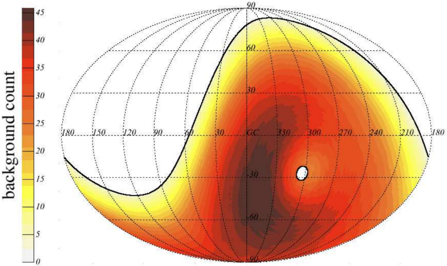
Search for point sources of UHE photons

- Use hybrid detector to allow for low energies (here down to 0.2 EeV) and directional reconstruction with precision $\sim 1^\circ$
- Photon-hadron discrimination method: BDT with 5 discriminating observables
- photon-candidate cut after an optimization between (Zech-)upper limits and signal efficiency



- Estimation of hadronic background using the scrambling technique (Cassiday et al. 1990):

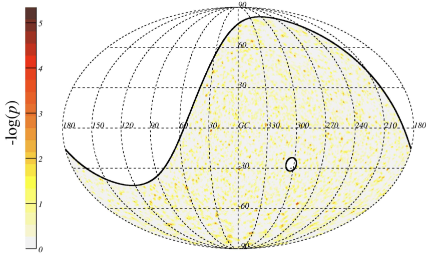
  Random assignment of arrival directions (horizontal coordinates) and times

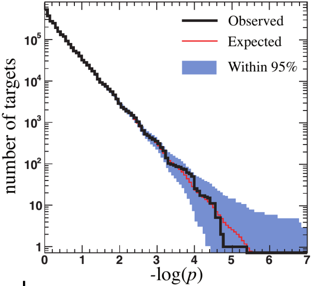


[ApJ 2014]

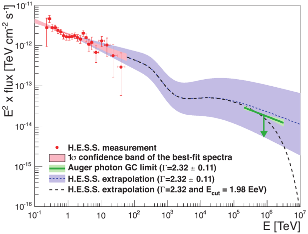
Search for point sources of UHE photons

Blind search: pixelized map with 526,200 target areas
$\rightarrow$ no statistical excess of photon-like events from any direction





Targeted search: grouping of 364 astrophys. targets into 12 target classes to reduce penalty factor
$\rightarrow$ No significant excess from any target class (lowest penalized p-value of 0.22 for Cen A)
$\rightarrow$ Constraint for extrapolation of H.E.S.S. measurements of the galactic center

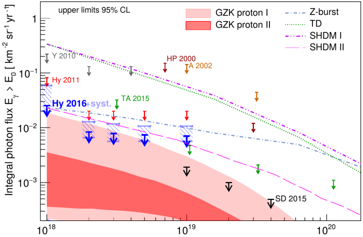


[ApJL 2017; ApJ 2014]

Summary

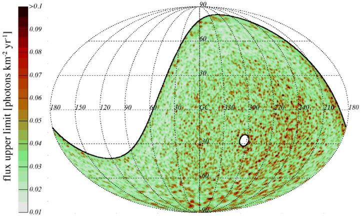
Search for a diffuse photon flux:

- Photon energies $> 1\,\text{EeV}$
- No unambiguous identification of photon primaries
- Upper limits on diffuse photon flux:



Directional photon search:

- No excess of photon-like events found both in an all-sky blind search and from a set of 12 selected target classes
- Directional upper limits on photon flux:



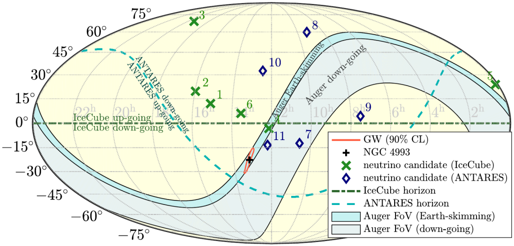
- Not presented here: Follow-up analyses on gravitational wave events at Auger with UHE neutrinos and (in prep.) photons

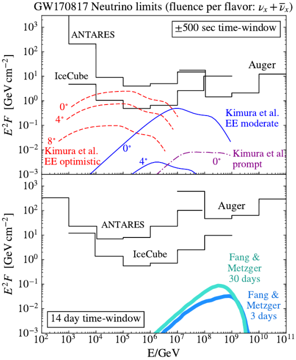
[JCAP 2017; ApJ 2014]

Backup

Neutrino follow-up search on NS-NS merger GW170817

- neutrino follow-up search analysis with Auger
- extends ANTARES and IceCube energy range to $E > 10^{18}\,\mathrm{eV}$
- no ν candidate detection $\Rightarrow$ upper limits on ν fluence
- Auger ν candidates would be highly significant due to negligible background





[ApJL 2017]

Systematic uncertainties of upper limits (hybrid analyisis)

Systematic uncertainties $\rightarrow$ variation of upper limits

Example:
UL for $E_\gamma > 1\,\mathrm{EeV}$

Detector systematic uncertainties		
Source	Syst. uncert.	$\mathrm{UL}^{0.95}$ change ($\mathrm{E}_\gamma > 1$ EeV)
Energy scale	$\pm$ 14%	(+18, -38)%
X_{max} scale	$\pm$ 10 g/cm^2	(+18, -38)%
S_b	$\pm$ 5%	(-19, +18)%
Exposure	$\pm$ 6.4%	(-6.4, +6.4)%

[JCAP 2017]