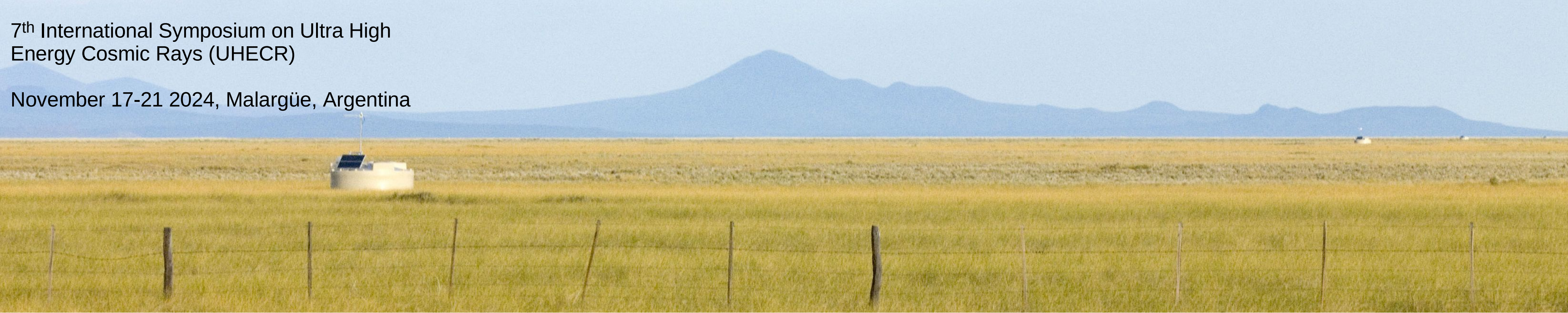
Searches for ultra-high-energy photons with the Pierre Auger Observatory

Nicolás González[1,2,3] for the Pierre Auger Collaboration[4]

[1] Università degli studi di Torino (UniTo)
[2] Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino
[3] Instituto de Tecnologías en Detección y Astropartículas (CNEA-CONICET-UNSAM), Argentina
[4] Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina
Full author list available at https:/www.auger.org/archive/authors_2024_11.html



7th International Symposium on Ultra High Energy Cosmic Rays (UHECR)

November 17-21 2024, Malargüe, Argentina

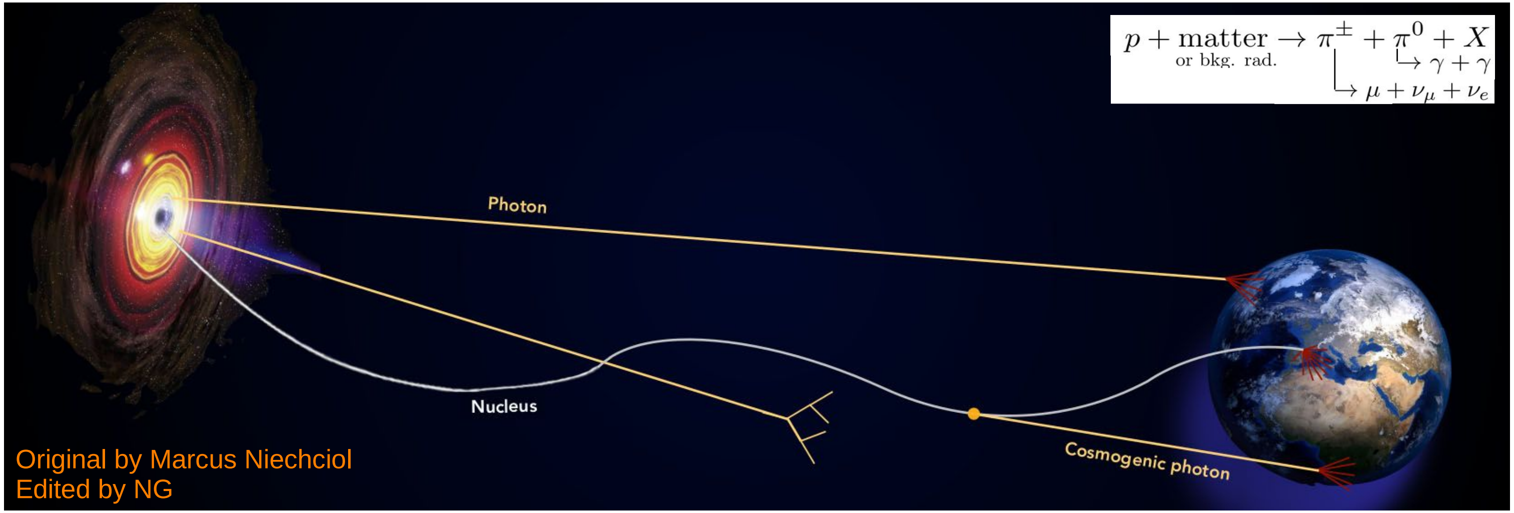
Neutral particles are probes of the Universe

► Produced in cosmic-ray acceleration sites (astrophysical fluxes), during cosmic-ray propagation (cosmogenic fluxes) or in the decay of dark matter particles

► Photons trace the local Universe while neutrinos travel through cosmological distances, both without deflection → complementary messengers of astrophysical steady and transient phenomena

► Elusive particles → need for ground arrays with large exposures

see J. Álvarez-Muñiz talk about neutrinos later in this session!

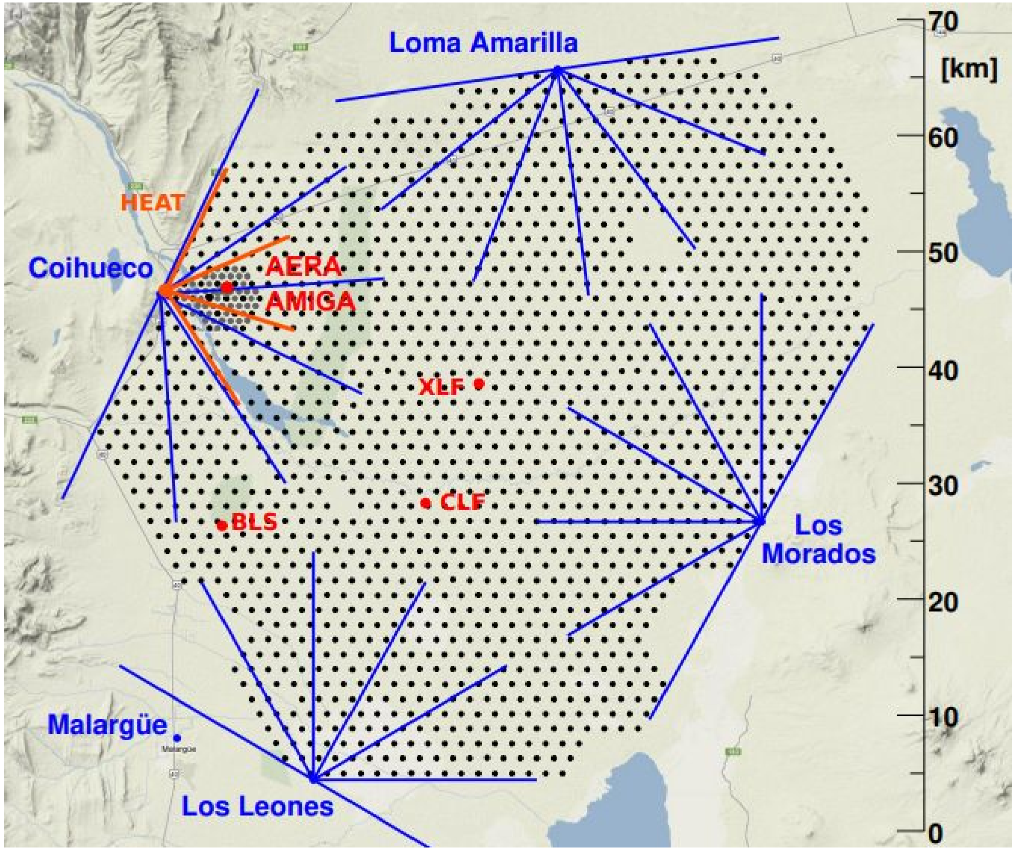


Nucl. Instrum. Meth. A 798 (2015) 172-213
ICRC2023 016

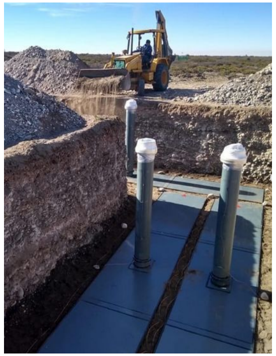
The Pierre Auger Observatory

Surface detector (SD)
- 1500 m array
1600 stations (3000 km^2)
- 750 m array
61 stations (25 km^2)
- 433 m array
19 stations (2 km^2)

Extensions:
- Radio antennas (AERA)
- Atmospheric monitoring facilities (CLF, XLF, Lidar)



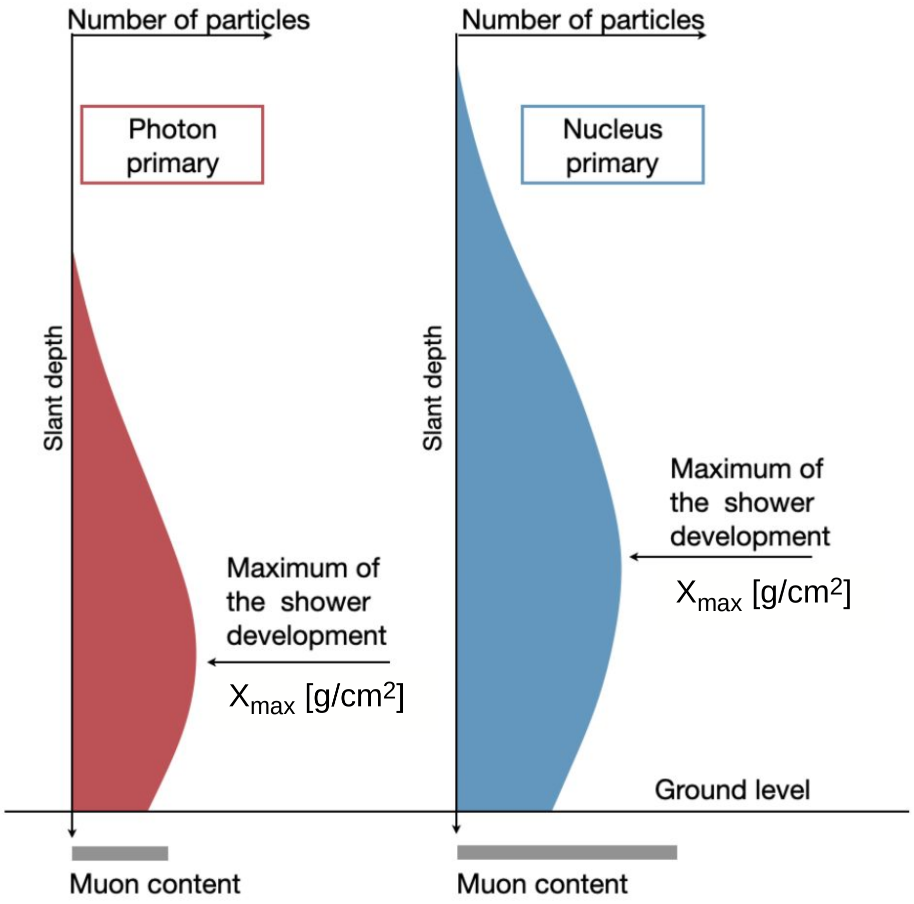
Unprecedented exposure to photons above 5.10^{16} eV



Underground muon detector (UMD)
41 (19) stations spaced by 750 m (433 m)

Fluorescence detector (FD)
27 telescopes across 4 sites

How can we identify a photon primary?

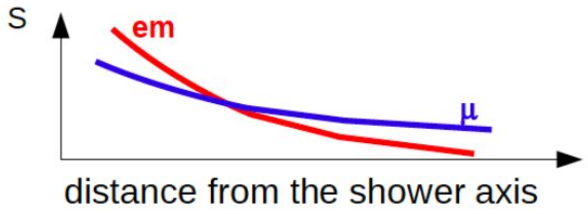


Air showers initiated by photon primaries follow a nearly pure electromagnetic (EM) development

► Deeper X_{max} due to lower multiplicity of EM interactions

► Less muon production due to suppressed $\pi^{\pm}$ generation channels

→ steeper lateral spread of signals and smaller footprint



► We exploit these features in all our searches

Diffuse and directional photon searches

Our searches can be classified in three classes:

► **Diffuse**: Searches for an unresolved, direction-independent, flux of γ/ν

- ► Tailored in different energy ranges
- ► Exploiting different detection techniques

► **Point-source**: Searches for a flux of γ/ν in the direction of catalogued sources or regions

- ► Dedicated to different type of sources
- ► Sensitive to geometry resolution

► **Follow-up**: Searches for a flux of γ/ν in space-time coincidence to significant astrophysical events (e.g., gravitational waves)

- ► Similar to point-source searches but with time dependence of the exposure (Earth’s rotation)

Photon search at 5.10^{16} eV – 2.10^{17} eV

SD+UMD

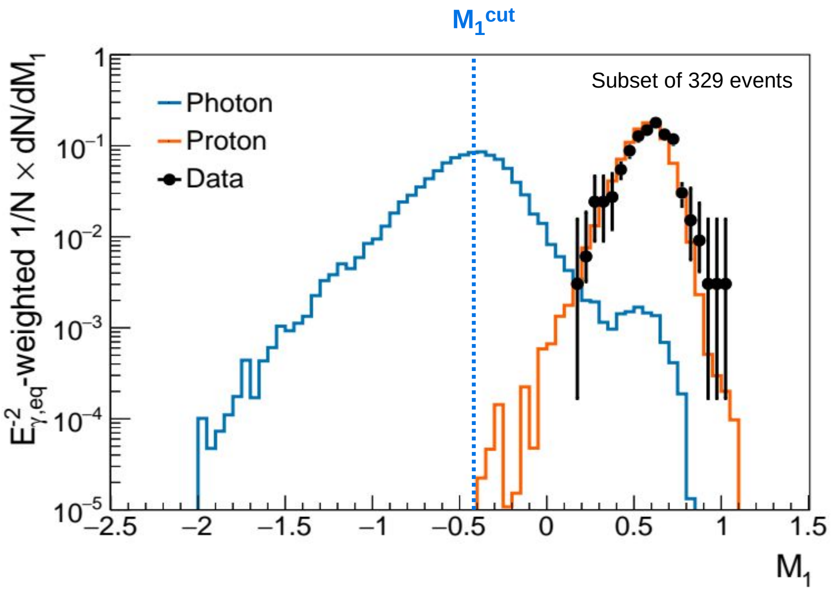
$$M_1 = \log_{10}\left(\sum_i \frac{\rho_\mu^i}{\rho_\mu^{\mathrm{p}}} \times \frac{r_i}{200\,\mathrm{m}}\right)$$

► **The observable** M_1 combines the high-energy muon densities, ρ_μ^i, measured at a distance r_i from the shower axis

► **The photon candidate cut** is a threshold value, M_1^{cut}, ensuring 50% photon selection efficiency

► **The background contamination** is the fraction of cosmic-ray events below M_1^{cut}

► 10^{-5} contamination assuming a pure-proton background (the most photon-like species)



► Data set spans 15 months → ~ 0.6 km² sr yr

► No events below the photon candidate cut

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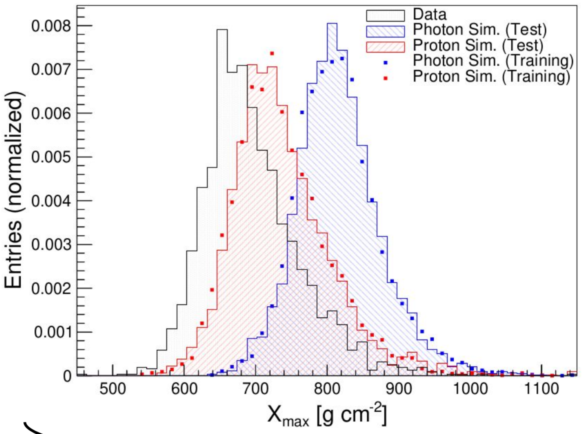
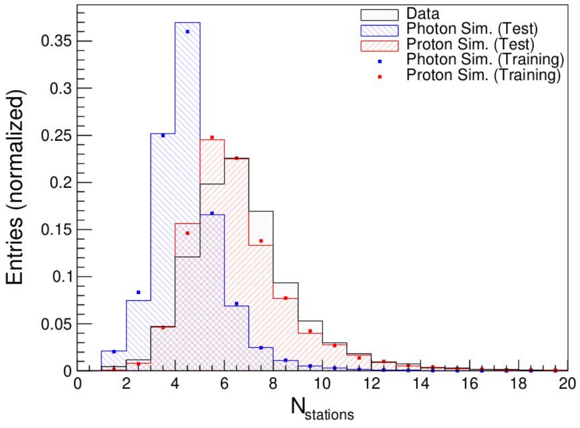
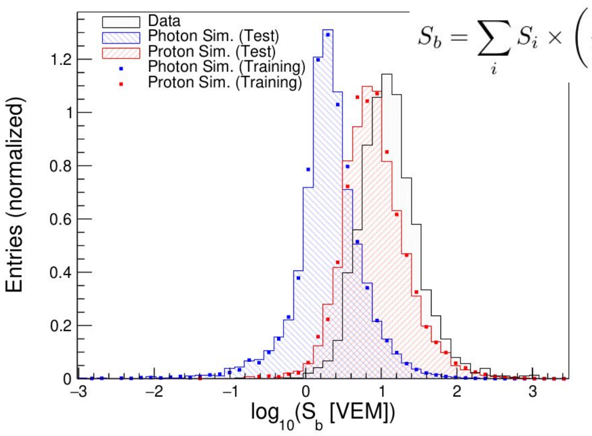
Photon search at 2.10^{17} eV – 10^{18} eV

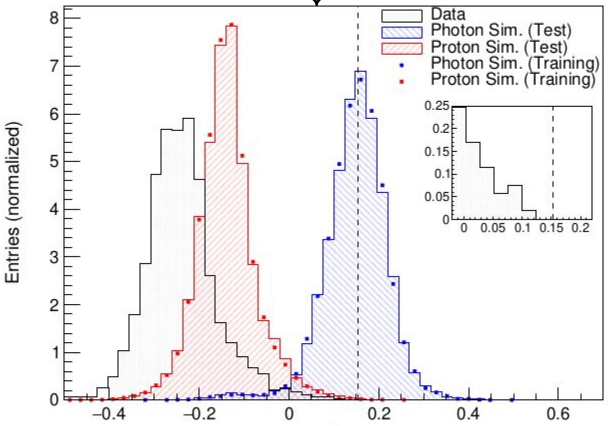
SD+FD







$$S_b = \sum_i S_i \times \left(\frac{R_i}{1000\,\mathrm{m}}\right)^b$$



Boosted decision trees observable

► X_{max} measured with FD, number of triggered stations and S_4 combined into a single observable with a boosted decision trees method.

► ~10^{-4} background contamination, i.e., 2 background events in data set, with 50% signal efficiency photon candidate cut

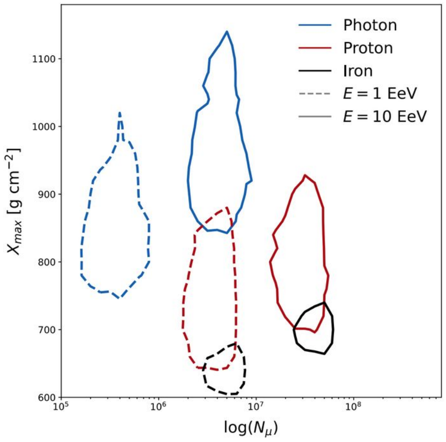
► Data set spanning 5.5 years → ~2.5 km² sr yr

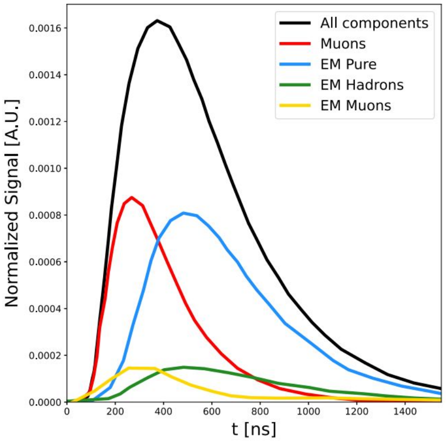
► No photon candidate events

Phys. Rev. D 110, 06205 (2024)

Photon search at 10^{18} eV – 10^{19} eV

SD+FD





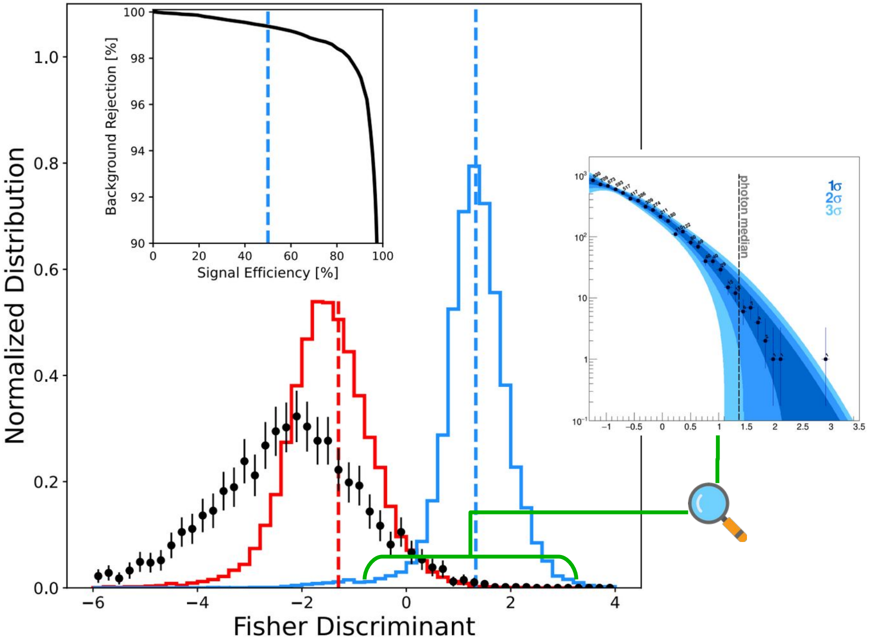
► X_{max} measured with the FD. F_μ is a proxy of the muon content extracted from the SD signals

► Estimated by matching the measured signal in SD stations to S_{pred} which is a decomposition in EM and muonic components ($S_{i,comp}$)

$$S_{\text{pred}} = \sum_{i=1}^{4} S_i = \sum_{i=1}^{4} f_i(F_\mu) S_{i,\text{comp}}$$

► Data set spans 12 years → ~1,000 km² sr yr

► 22 photon candidate events but consistent with the background contamination of 30 ± 15 events estimated with data



Nicolás Martín González

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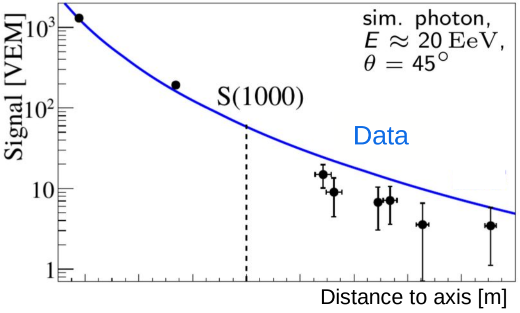
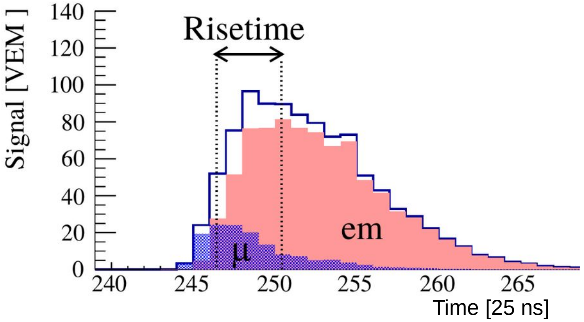
Photon search at > 10^{19} eV

SD

Steeper lateral spread of particles (LDF)

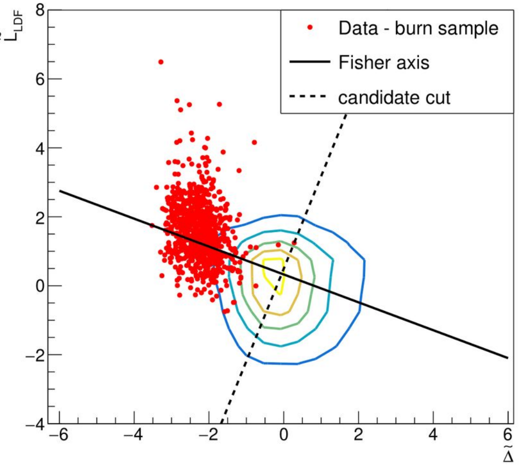


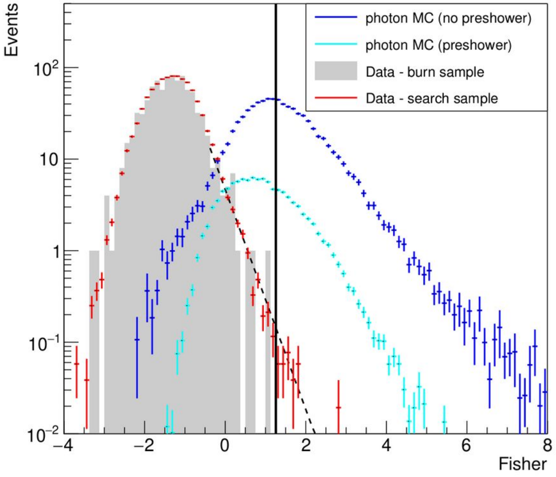
Longer signal risetime



$$L_{\mathrm{LDF}} = \log_{10}\left(\frac{1}{N}\sum_{i=1}^{N}\frac{S_i}{S_{\mathrm{LDF}}(r_i)}\right)$$

$$\Delta = \frac{1}{N}\sum_{i=1}^{N}\frac{t_{1/2}^{i} - t_{1/2}^{\mathrm{bench}}}{\sigma_{t_{1/2}}^{i}}$$





► Benchmarks $t_{1/2}^{\mathrm{bench}}$ and S_{LDF} obtained with data
→ method free of cosmic-ray composition assumptions

► Data set spans 16 years → 17,000 km² sr yr

► Fisher analysis trained with photon simulations and a subset of data

► 16 photon candidate events, but compatible with the background contamination

Universe 8 (2022) 579
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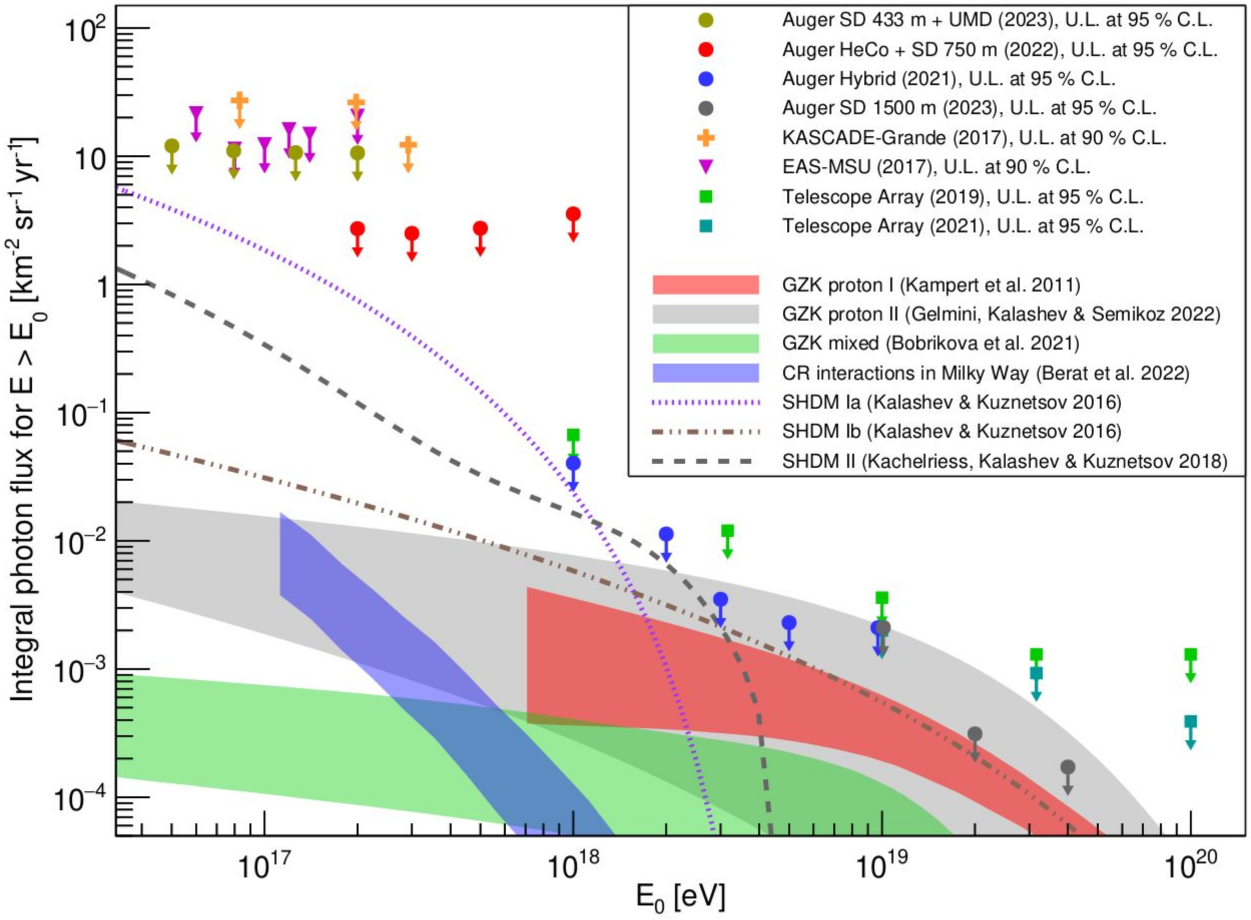
Upper limits to ultra-high-energy photons



► Most stringent limits across four decades in energy with 16 years of data

► Useful for constraining new physics, e.g., super-heavy dark matter models. **(see R. Aloisio talk, this session & O. Deligny invited review, this evening)**

► Start closing the gap to the smaller air-shower experiments

► Predictions from cosmogenic models of cosmic-ray propagation are within reach above 10^{18} eV

► Note that these are diffuse limits. What about direction and follow-up searches?

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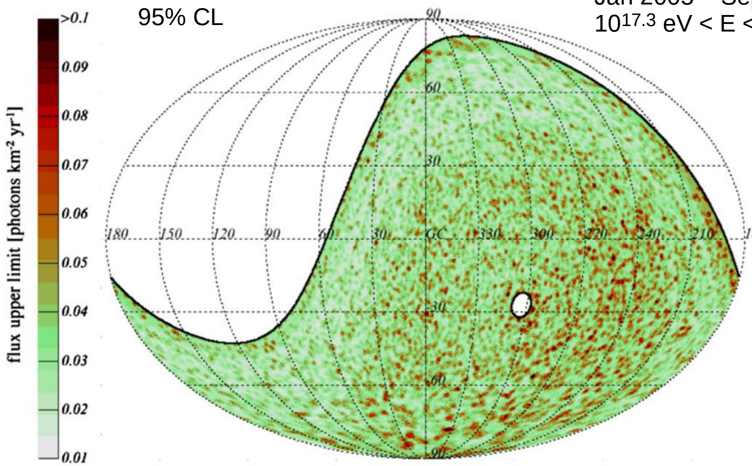
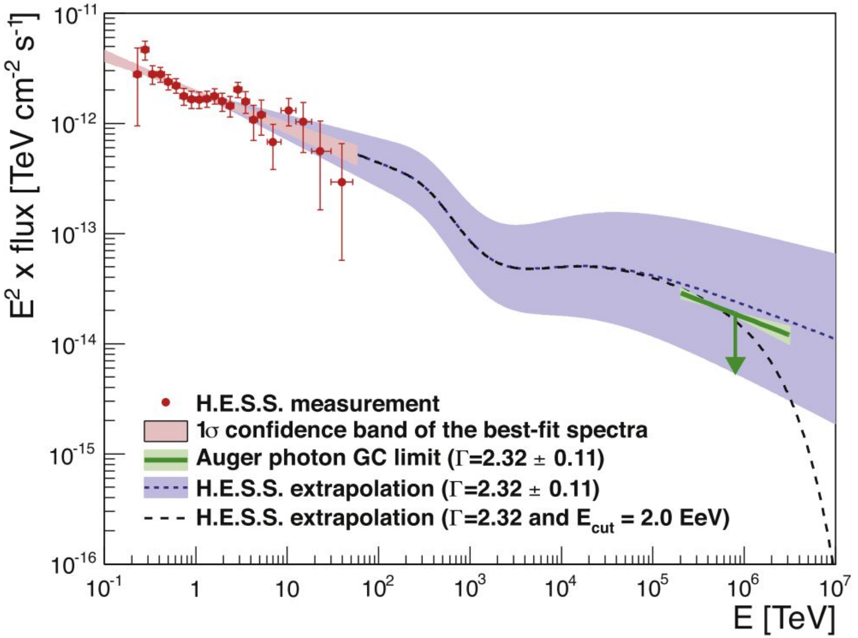
Directional searches





► SD+FD data was scanned using several observables combined with a boosted decision trees method

► No significant excess of photon-like events from any direction in the sky between -85° < δ < +20°

► Upper limits compatible with either:
- extragalactic sources farther than 5 Mpc
- transient or opaque Galactic sources

► Extrapolation of the HESS gamma-ray flux from Galactic center to EeV energies?

► Upper limit in the direction of the Galactic Center served to set a cut-off energy at 2.10^{18} eV

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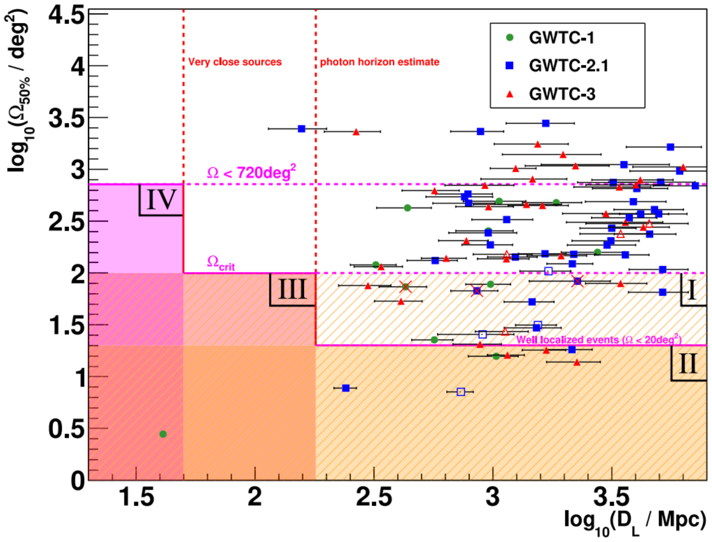
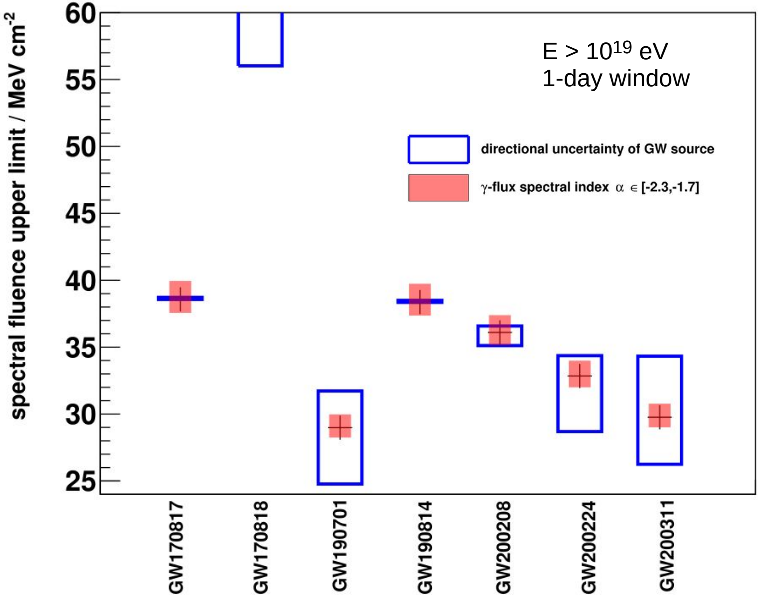
Multi-messenger follow-up studies

► The Pierre Auger Observatory takes part in the multimessenger-astronomy networks GCN/TAN and AMON.

► Follow-up photon searches in time and directional coincidence with 10 selected GWs from LIGO/VIRGO:
- close-by to avoid attenuation (III, IV)
- well-localized to look for new physics (I, II)





► Addopted discrimination strategy based on LDF steepness (L_{LDF}) and SD time structure (Δ)

► First ever limits on the photon emission from GWs at UHE

► < 20% energy transferred to UHE photons above 4.10^{19} eV from nearby neutron star merger GW170817

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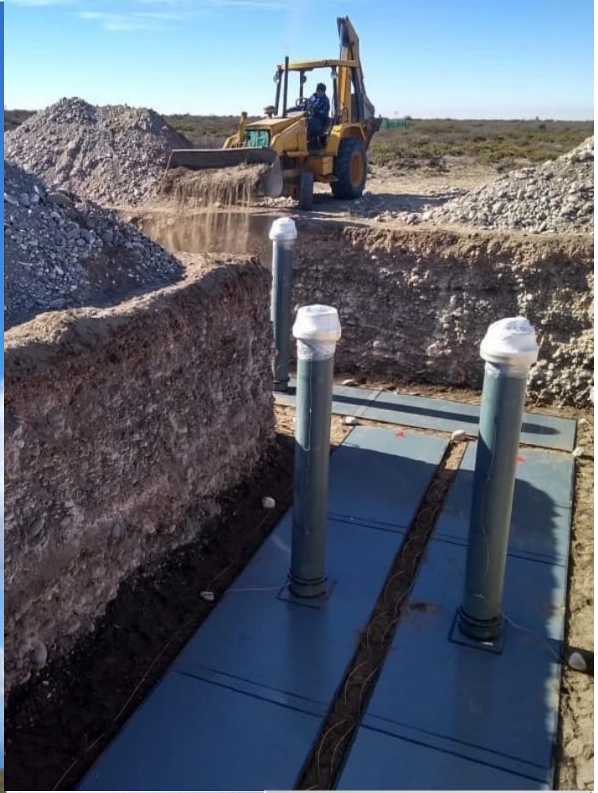
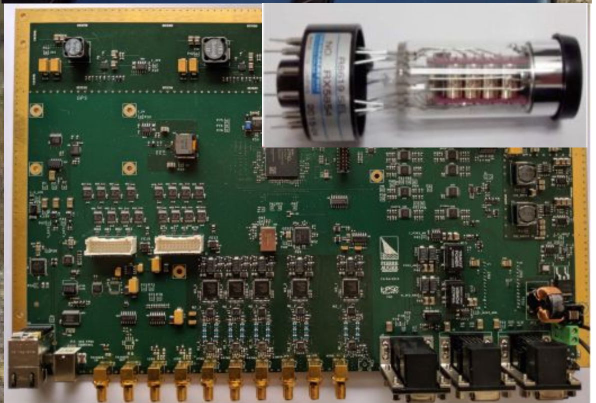
The AugerPrime Upgrade





Multi-hybrid air-shower detection:

► Faster electronics (SDEU) and larger dynamic range (SPMT) to measure high particle densities closer to the core

► 433 and 750 m arrays equipped with 3 x 10 m^2 UMD stations

► 4 m^2 plastic surface scintillation detectors (SSD)

► Measure radio emission from air showers with antennas (RD)

Aiming at a better separation between air-shower components

see D. Schmidt talk, Thursday morning

Summary

► Unrivalled exposure to photons: most stringent flux limits across four decades in energy above 5.10^{16} eV

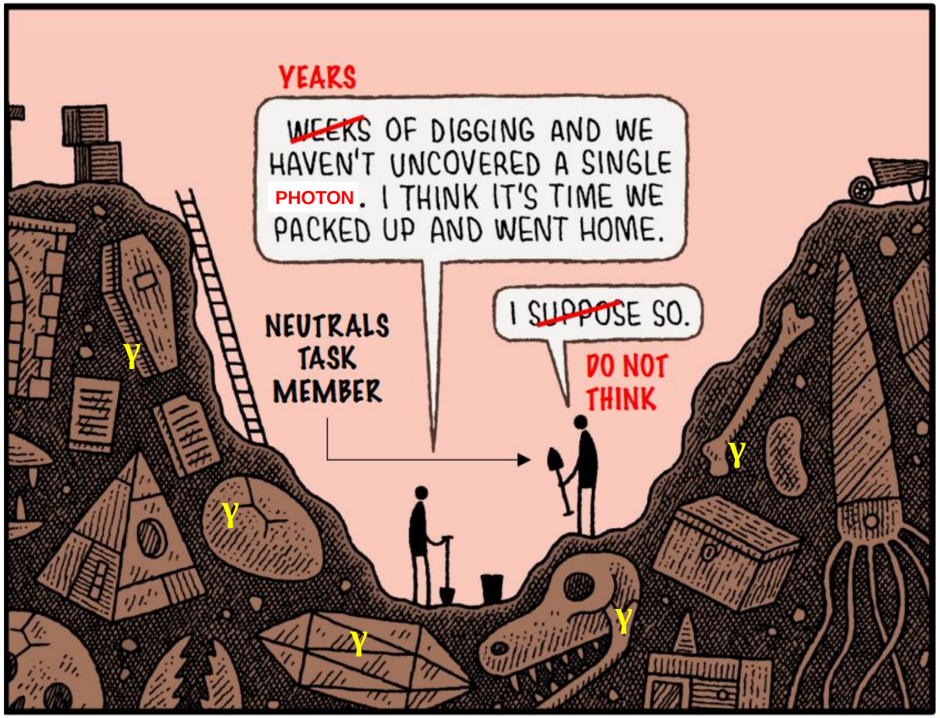
► Upper limits can be used to constrain the parameter space of cosmogenic and super-heavy dark matter models

► The Pierre Auger Observatory is a key actor in the UHE multi-messenger astronomy thanks to its large sky coverage

→ thorough follow-up searches to transients

► The AugerPrime upgrade will unlock a better air-shower component separability

→ better constrains to photon fluxes or even the first detection at UHE!

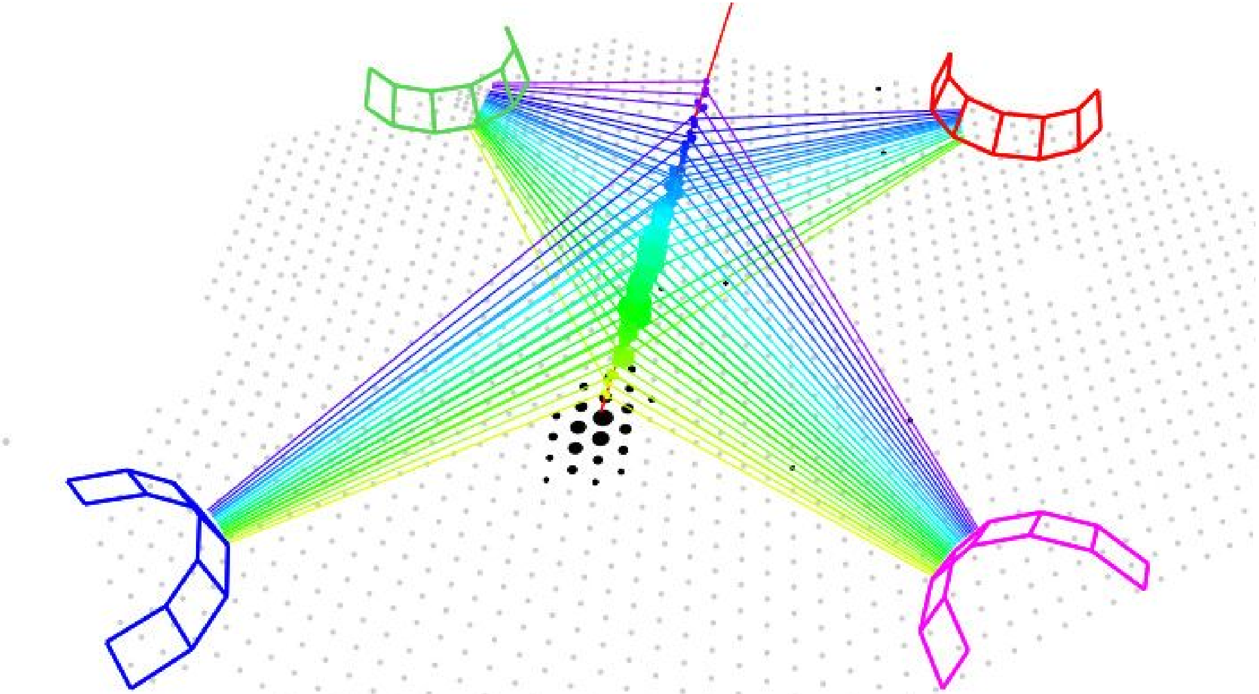


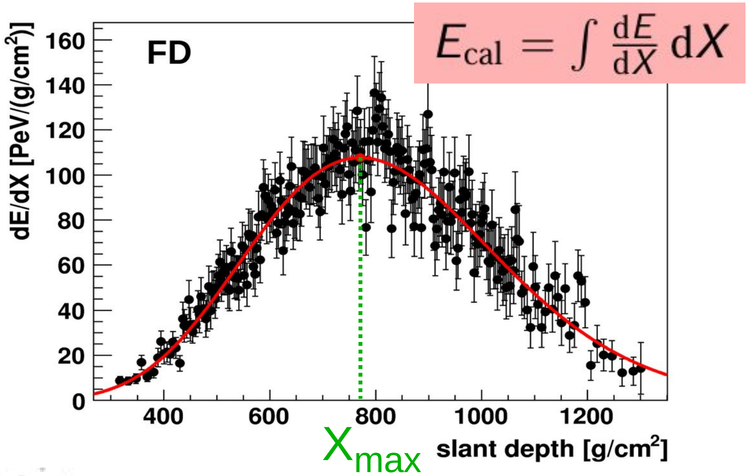
[Tom Gauld, Department of mind-blowing theories, Canongate Books, 2020]

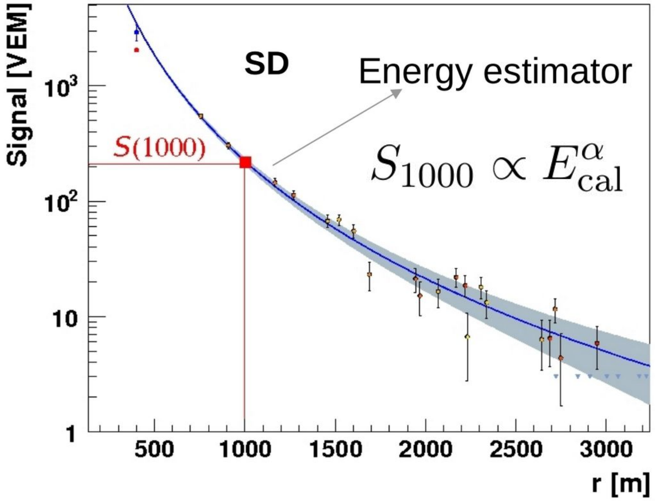
Edited by the Neutrals task

Backup

Hybrid Detection of Air Showers







- ► Primary energy from the FD measurements
- ► SD energy estimator calibrated against FD → SD-only reconstruction
- ► Maximum of shower development, X_{max}, is sensitive to the mass composition

Observables used in directional searches

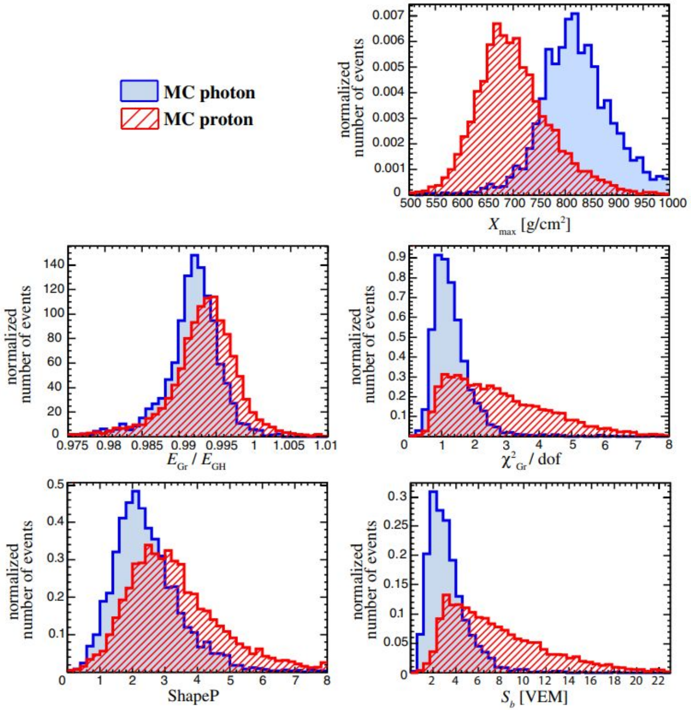


Figure 1. Distributions of photon (full blue) and proton (striated red) simulations of the introduced observables. The distributions are shown as examples for the energy range between $10^{17.6}$ eV and 10^{18} eV and zenith angle between 0° and 30°.

$$S_b = \sum_{i=1}^{N} \left[S_i \cdot \left(\frac{r_i}{1000\,\mathrm{m}} \right)^b \right]$$

$$\text{Shape P}(r, \theta) = \frac{S_{\text{early}}(r, \theta)}{S_{\text{late}}(r, \theta)}.$$

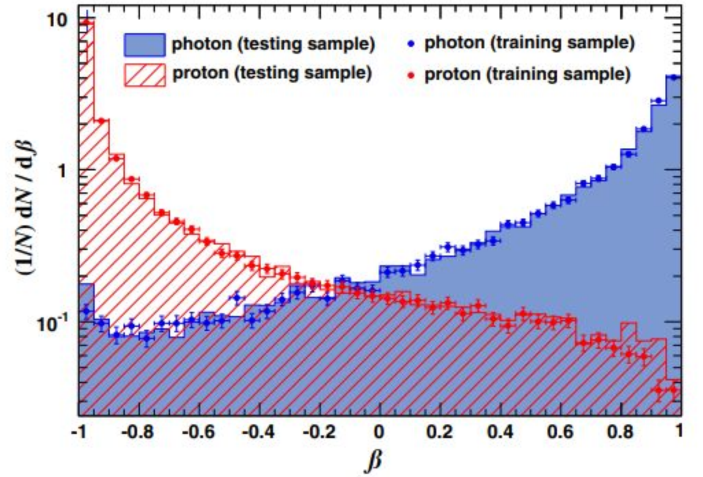
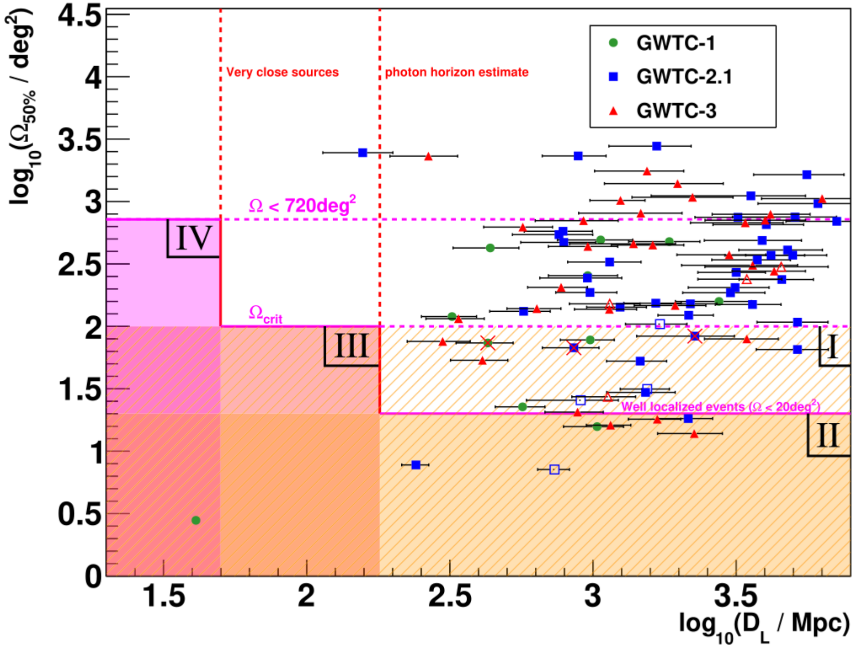


Figure 2. MVA response value β for photon and proton primaries using BDTs. During evaluation the MC sample is split half into a training (filled circles) and half into a testing sample (solid line).

Short time-window in follow-up analysis



$$(D_{\mathrm{L}} < \infty \text{ and } \Omega_{50\%} < 100\,\mathrm{deg}^2)_{\mathrm{s}} \text{ “class I”}$$
$$(D_{\mathrm{L}} < \infty \text{ and } \Omega_{50\%} < 20\,\mathrm{deg}^2)_{\mathrm{l}} \text{ “class II”}$$
$$(D_{\mathrm{L}} < 180\,\mathrm{Mpc} \text{ and } \Omega_{50\%} < 100\,\mathrm{deg}^2)_{\mathrm{l}} \text{ “class III”}$$
$$(D_{\mathrm{L}} < 50\,\mathrm{Mpc} \text{ and } \Omega_{50\%} < 720\,\mathrm{deg}^2)_{\mathrm{l,s}} \text{ “class IV”}.$$

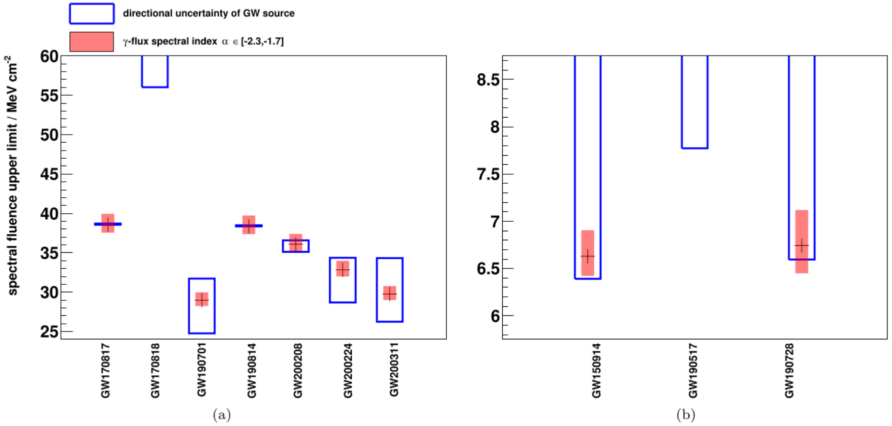
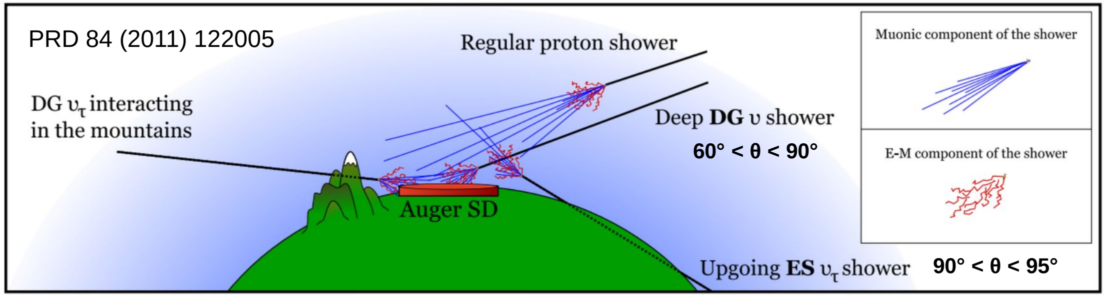


Figure 4. Upper limits (at 90% CL) on the spectral fluence of UHE photons from the selected GW sources for the searches in (a) the long and (b) the short time window. The limits for the most likely direction and a spectral index of $\alpha = -2$ are marked by the cross. The blue (empty boxes) error bars correspond to the variation of the upper limits due to the directional uncertainty of the source. Red (shaded boxes) error bars show the impact of a variation of the spectral index. For contours which are partly outside the field of view, the blue error bars grow to infinity (e.g., in the case of GW170818). While in the case of GW170818 in (a), the most likely direction is close to the edge of the field of view, yielding a large upper limit of 109 MeV cm^{-2}, no limit could be placed on the most likely direction of GW190517 in (b) as it was not inside the observed zenith-angle range during the short time window.

How can we identify a neutrino primary?



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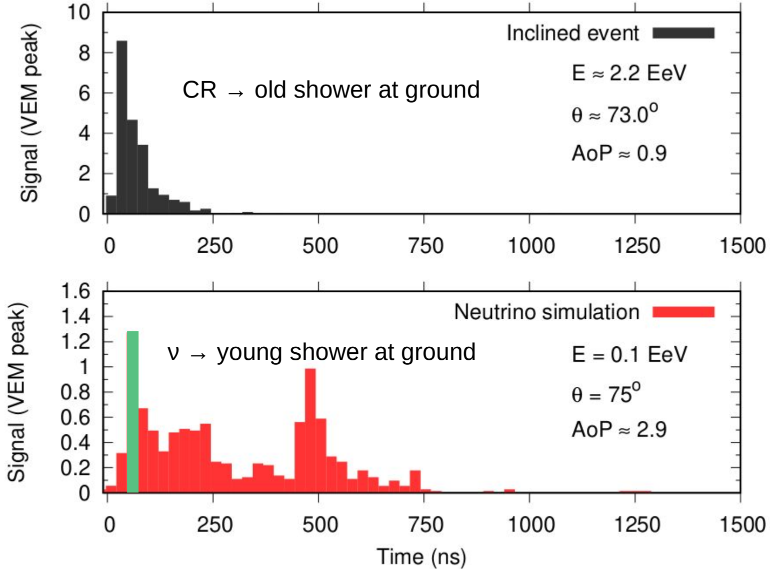

► Background composed by muon-dominated hadronic showers (EM component absorbed in the atmosphere)

► Down-going (DG) channel: ν interacting deep in the atmosphere. Sensitive to all flavors

► Earth-skimming (ES) channel: ν_τ interacting in Earth's crust. τ lepton initiating an up-going shower close to the ground

► Discrimination relies on the different SD signal shapes between hadronic and neutrino events → **Area**-over-**Peak**