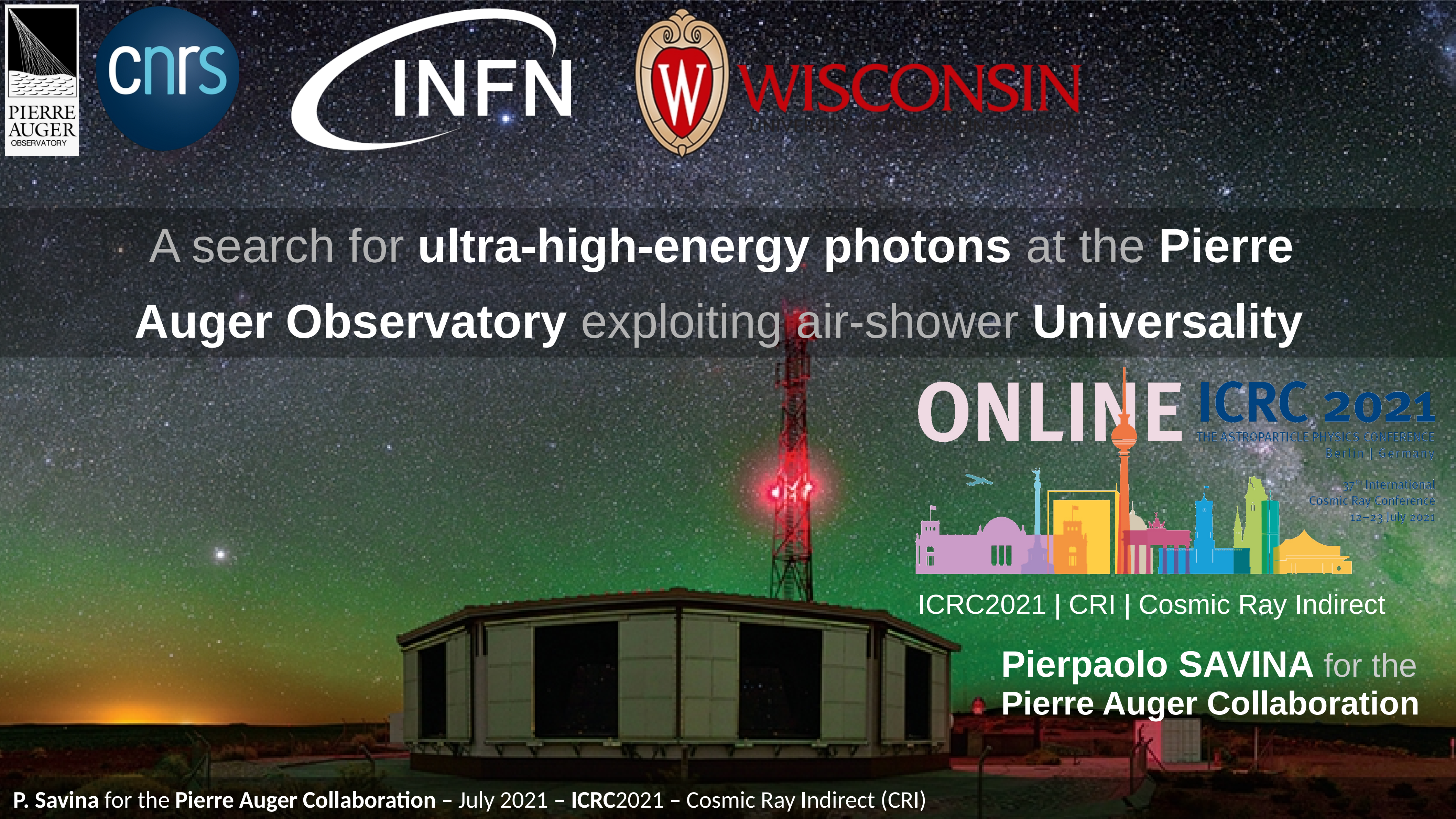


PIERRE AUGER OBSERVATORY

cnrs

INFN

WISCONSIN

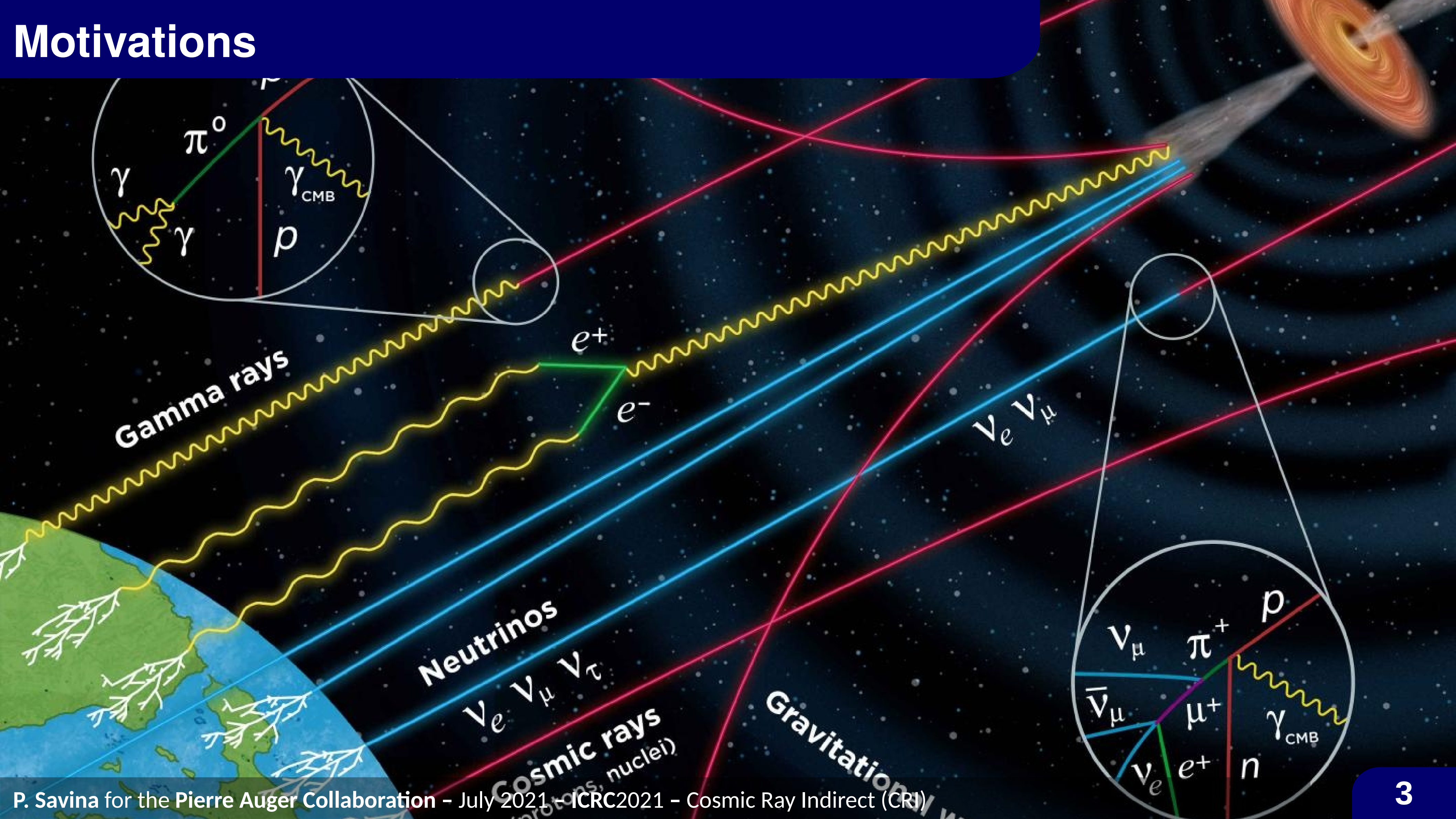
A search for **ultra-high-energy photons** at the **Pierre Auger Observatory** exploiting air-shower **Universality**

ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

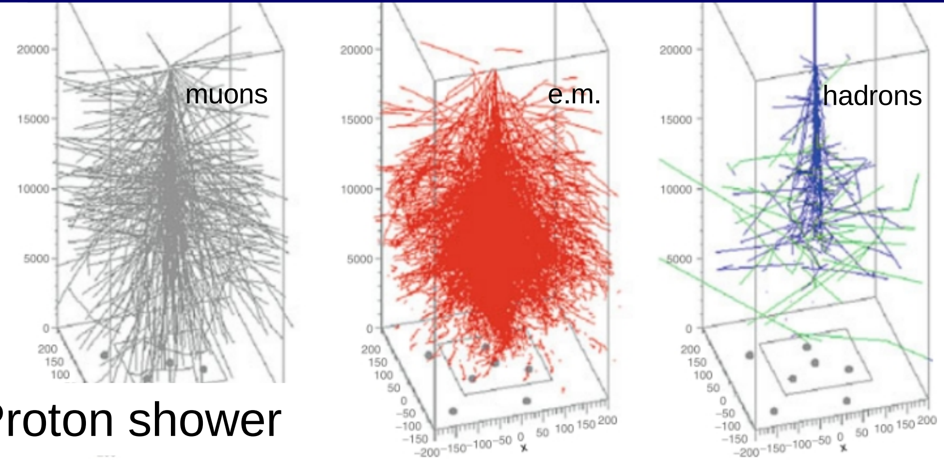
ICRC2021 | CRI | Cosmic Ray Indirect

Pierpaolo SAVINA for the
Pierre Auger Collaboration

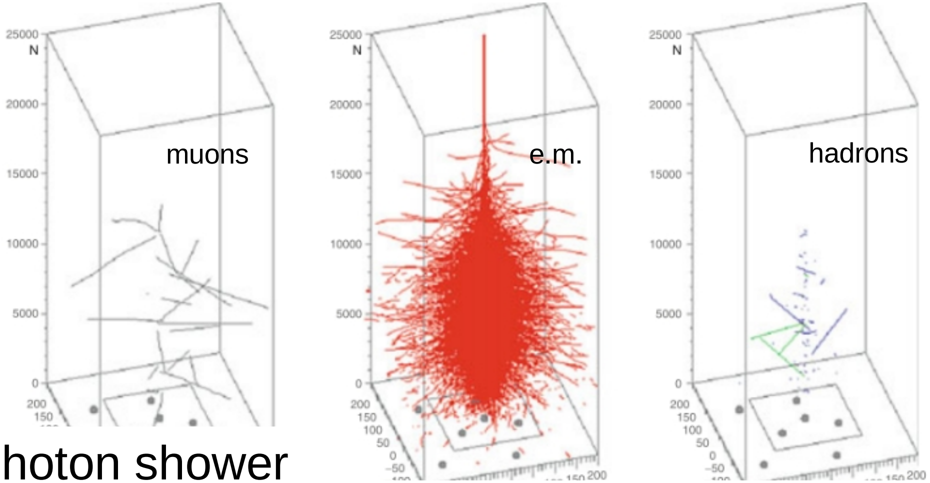
Motivations



How to recognize photon-induced showers

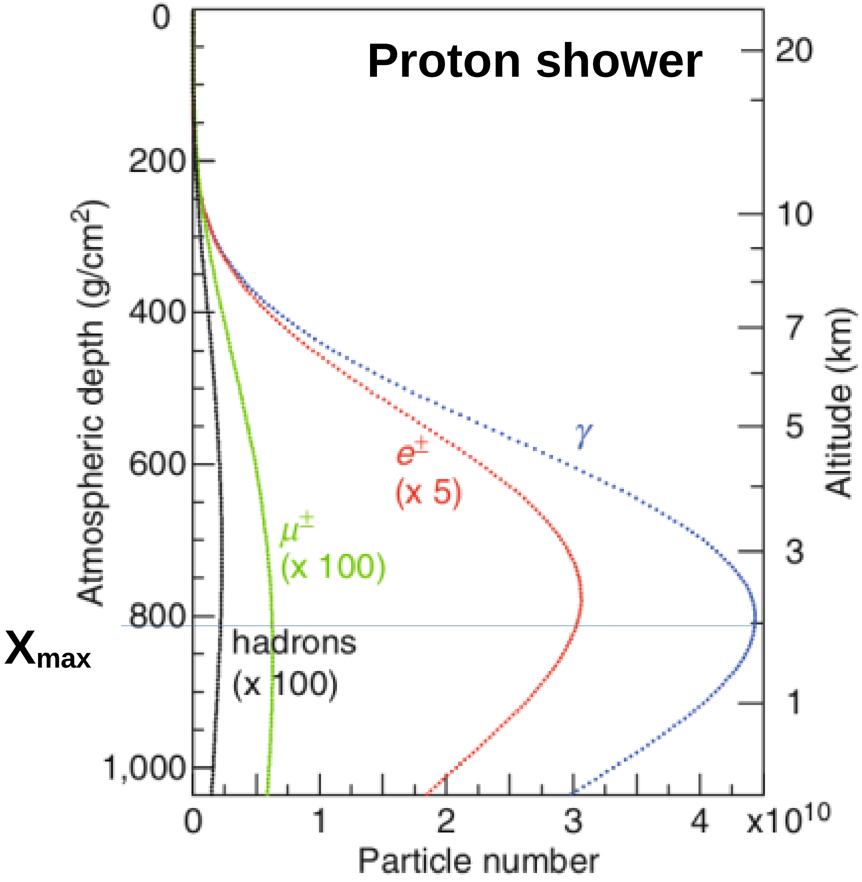


Proton shower



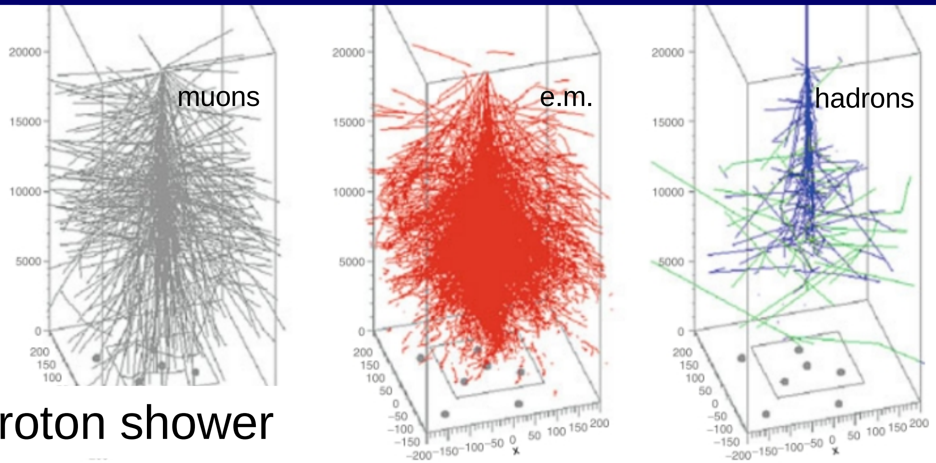
Photon shower

[R. Engel, Handbook of Particle Detection and Imaging, Springer-Verlag, 2012]

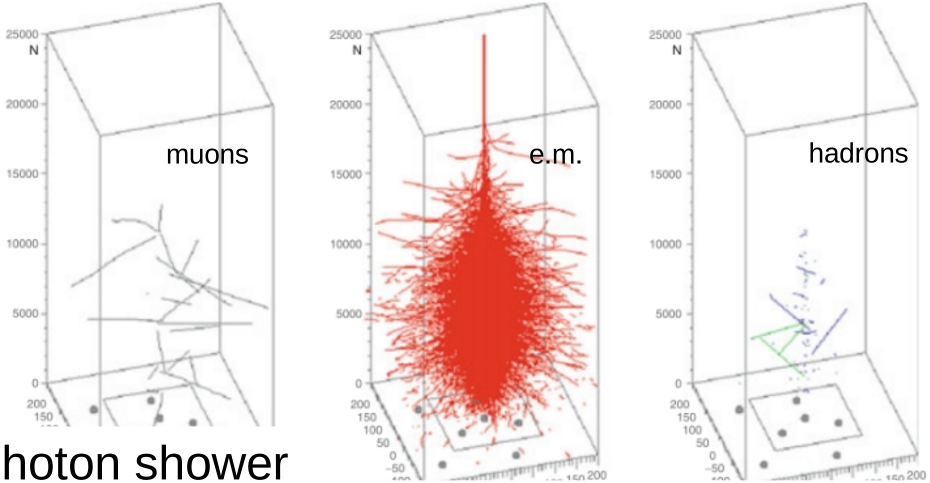


e.m. component dominant.
longitudinal profile characterized by
that of the e.m. component.

How to recognize photon-induced showers

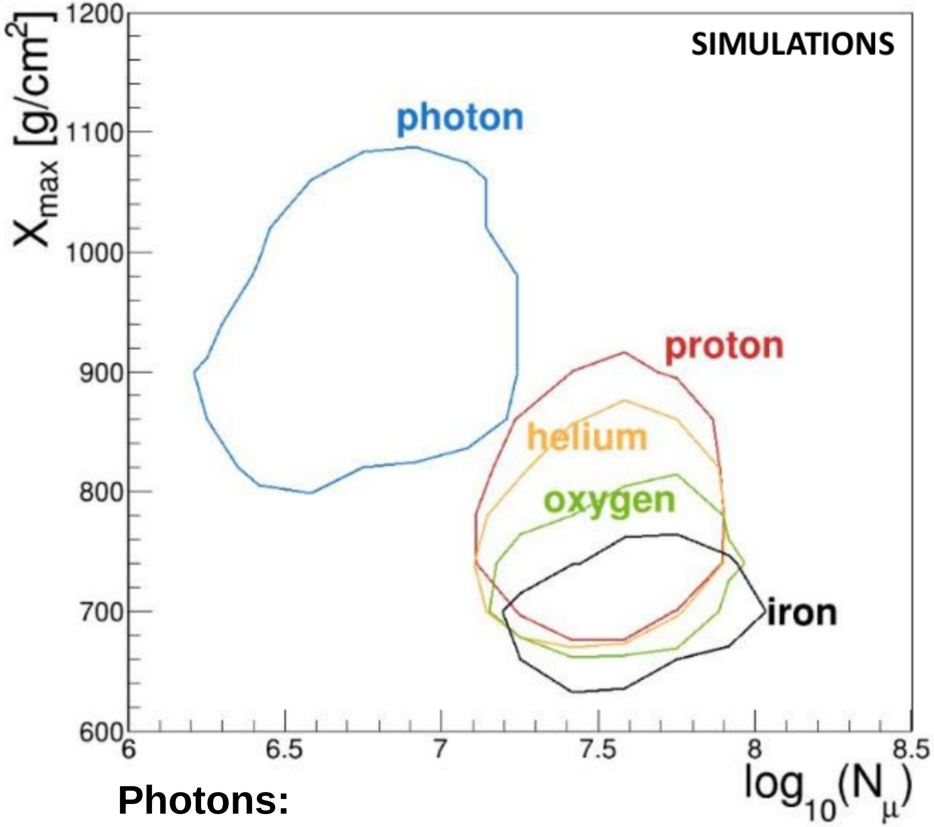


Proton shower



Photon shower

[R. Engel, Handbook of Particle Detection and Imaging, Springer-Verlag, 2012]



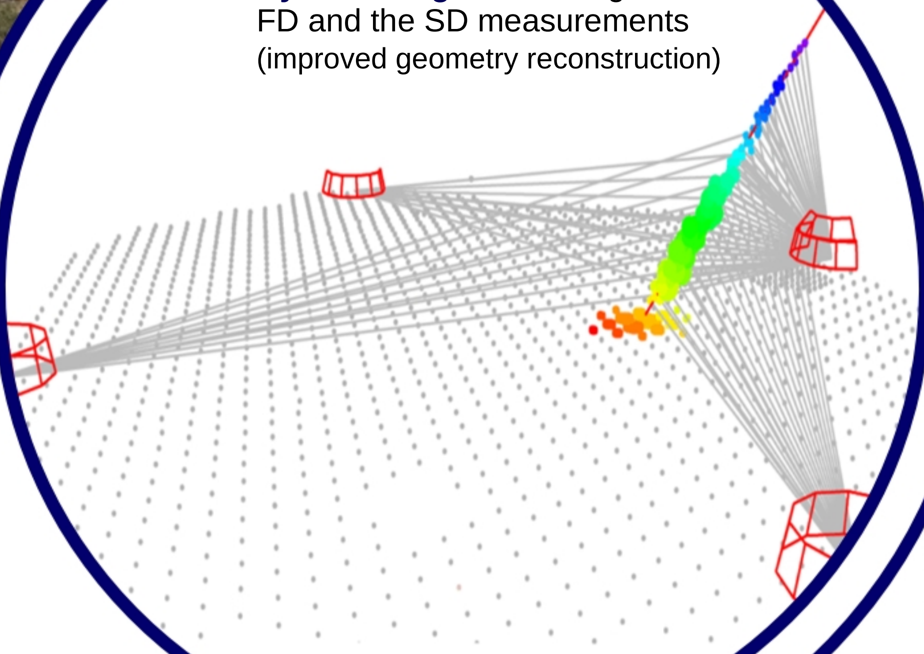
Photons:

Deeper depth at the shower maximum
Lower number of muons

The Pierre Auger Observatory

Surface Detector (SD)

- Ground Array of 1600 Water Chercenkov Detector, separated by 1500 m;
- Covering an area of 3000 m^2
- Sampling the secondary particle that reach the ground
- Duty cycle of 100 %

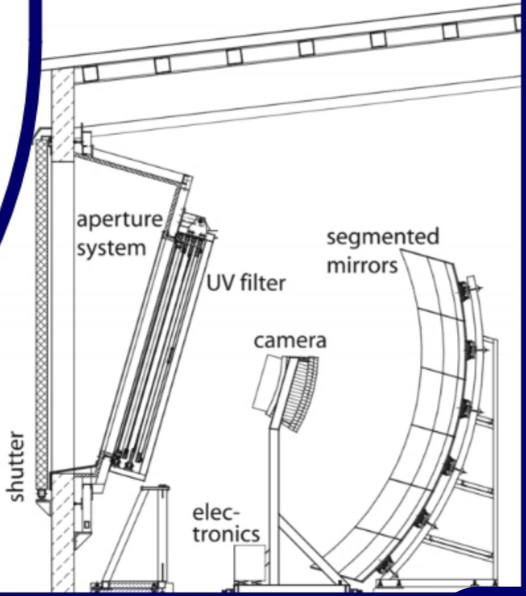


Hybrid design combining the FD and the SD measurements (improved geometry reconstruction)

Mendoza (Argentina) at 1400 m a.s.l.

Fluorescence Detector (FD)

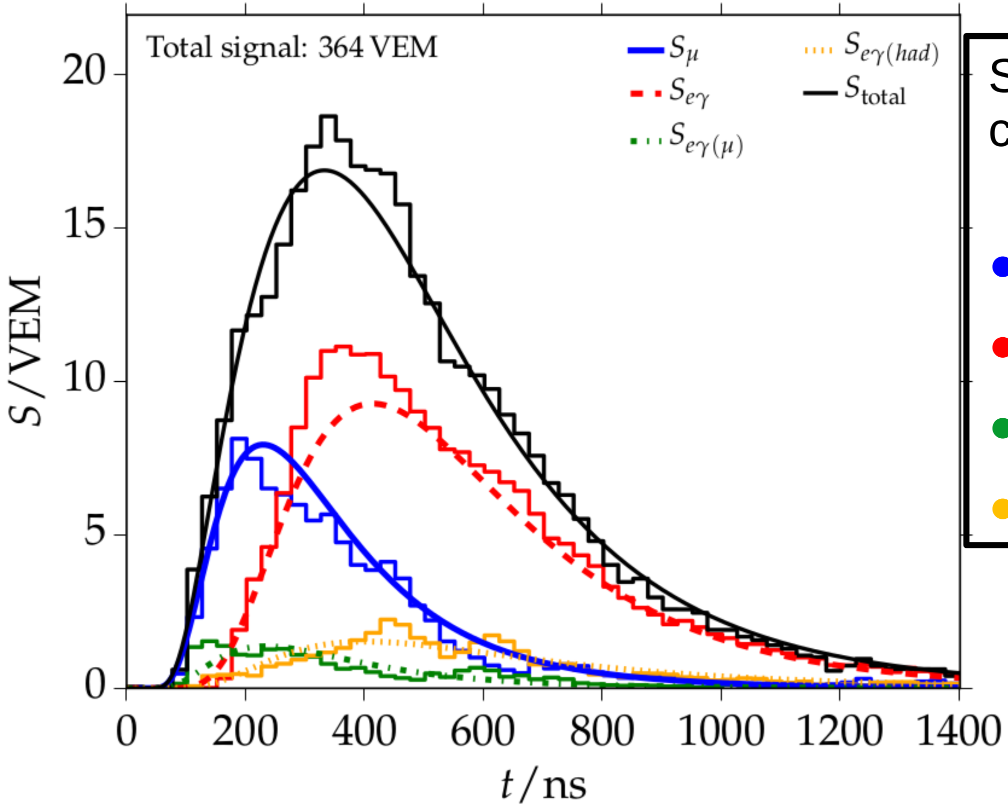
- 24 Telescopes overlook the array from 4 sites
- Measuring light produced by the deexcitation of air nitrogen molecules
- Duty cycle: only moonless nights



Universality-based description of the Auger SD signals

Universality: distributions of the secondary particles depend only on a few parameters: energy and stage of shower evolution and geometry

Model of the SD signal in a station derived from the distribution of the secondary particle at the ground



Signal in stations parametrized as the sum of 4 components:

- muons (S_μ);
- e.m. particles from high energy π^0 ($S_{e\gamma}$);
- e.m. particles from muons ($S_{e\gamma(\mu)}$);
- e.m. particles from low energy hadrons ($S_{e\gamma(had)}$);

Analysis Technique

Matching of predicted signal (S_{pred}) from universality and hybrid event info, with the reconstructed signal (S_{rec}) from data allows to obtain relative number of muons (**F_μ**) even in a single station

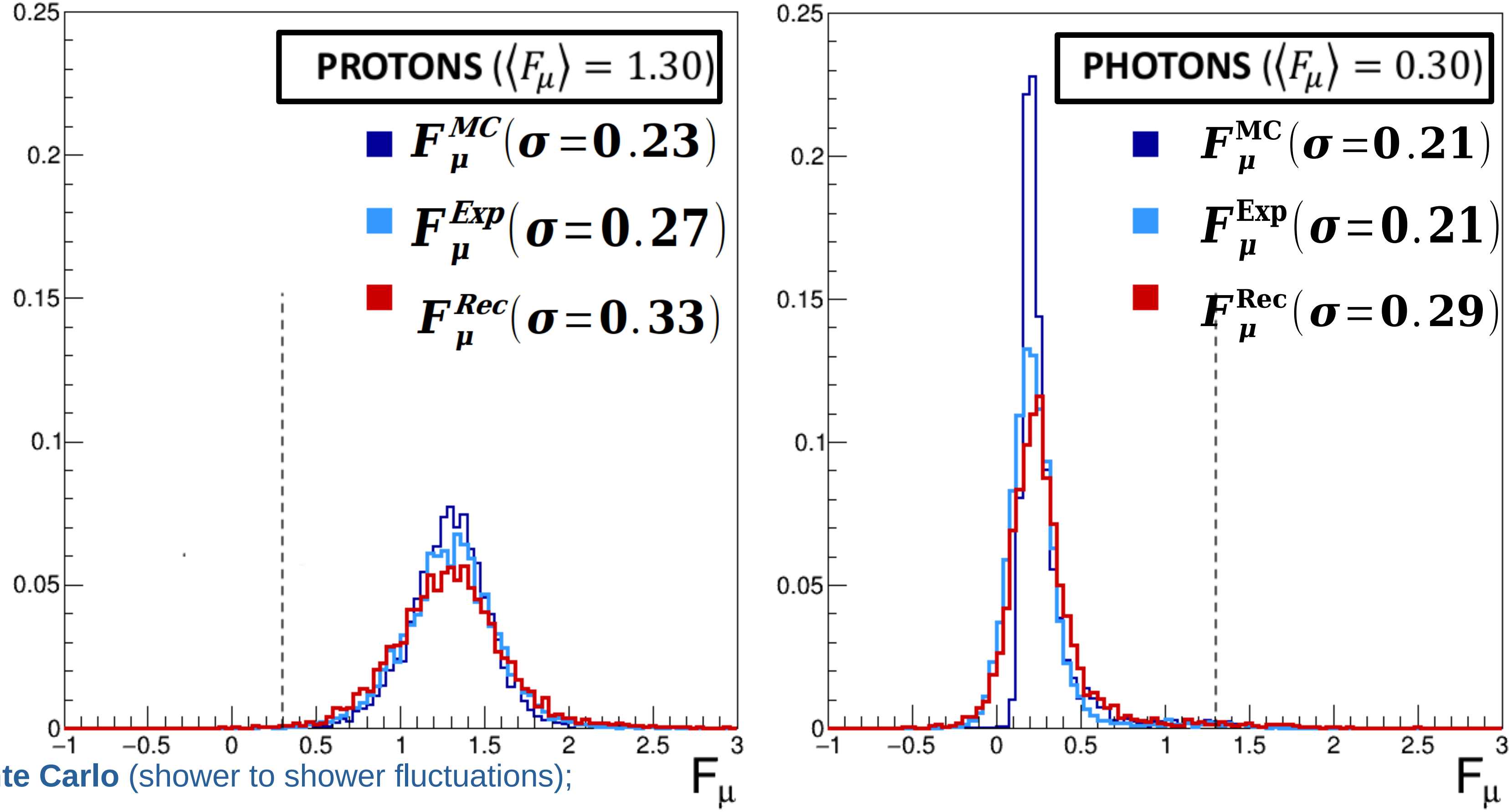
Relative contributions, β_i, depend on a **mass-dependent parameter, F_μ, related to the muonic content.**

Parameters obtained for each event from the hybrid reconstruction

$$S_{\mathrm{pred}} = \sum_{i = \mu,\, e\gamma,\, e\gamma(\mu),\, e\gamma(\mathrm{had})} \beta_i(F_\mu)\, S_i^{\mathrm{comp}}(E, X_{\mathrm{max}}, \theta, \phi, r_{\mathrm{core}})$$

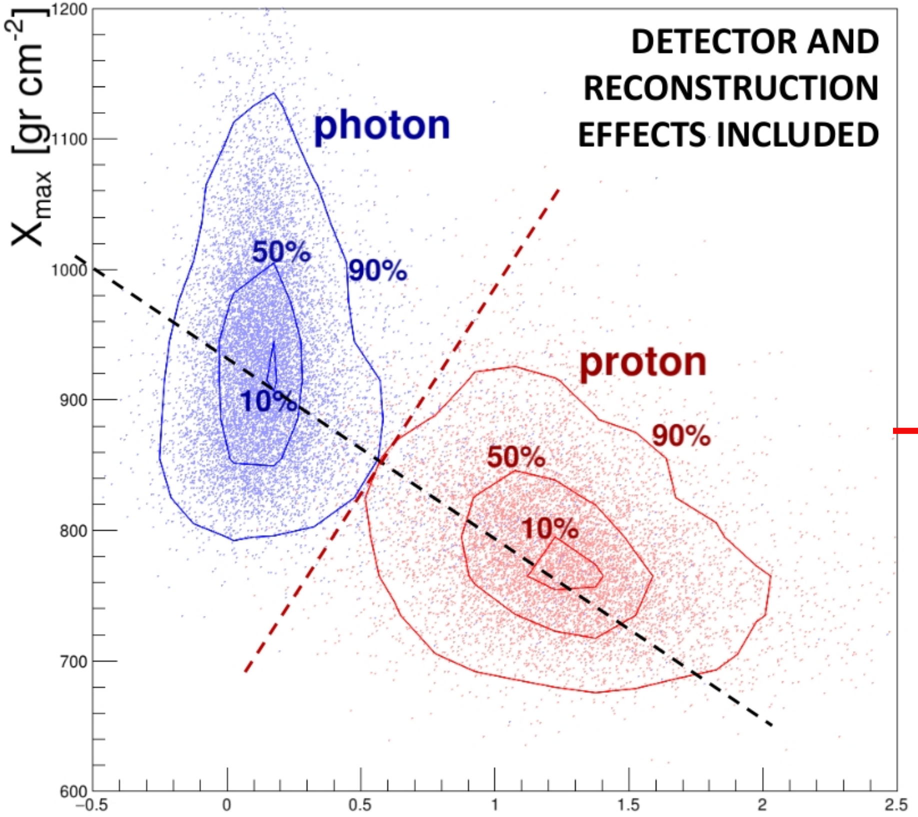
F_μ extrapolated from the **signal of a single station** by requiring $S_{\mathrm{rec}} = S_{\mathrm{pred}}$.

Validation of F_μ reconstruction

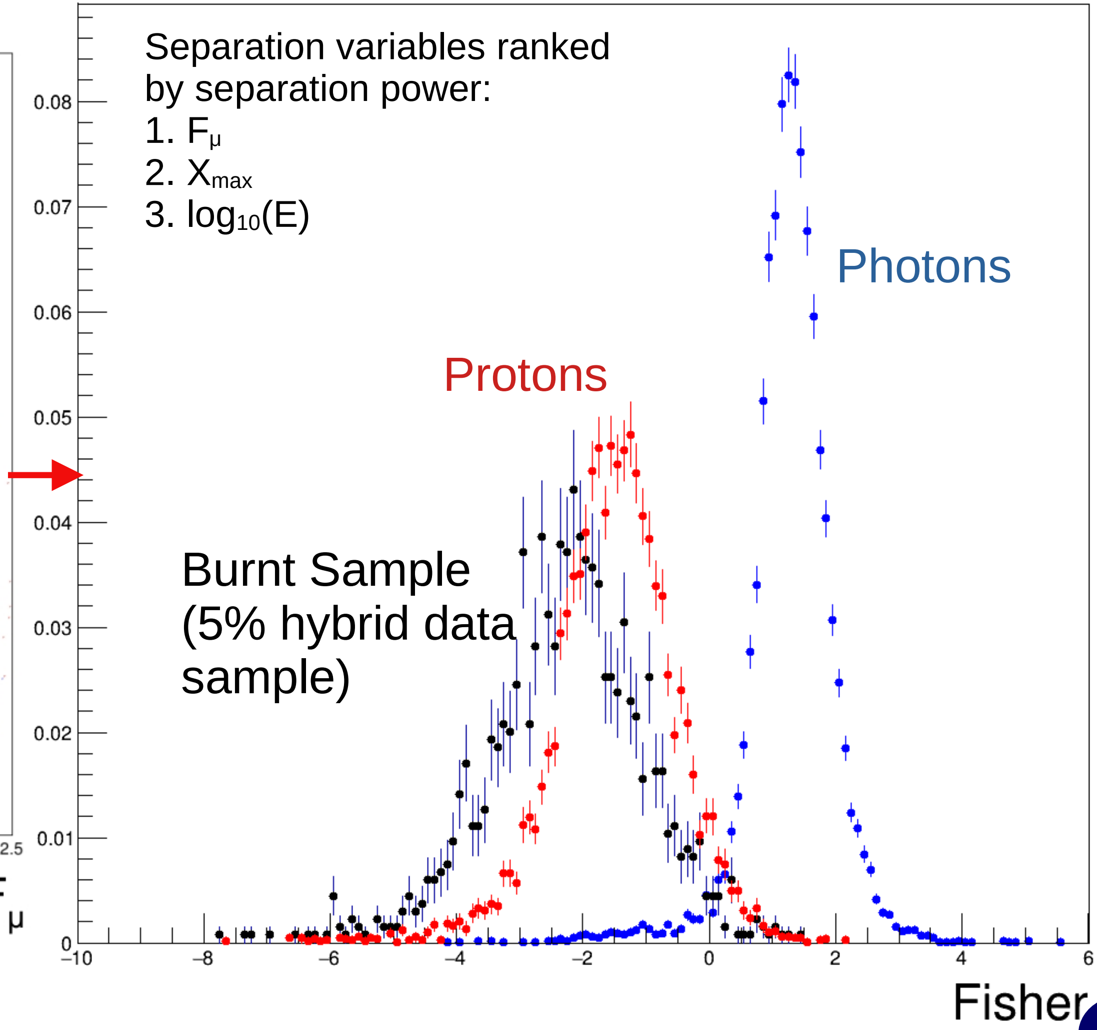


- **True Monte Carlo** (shower to shower fluctuations);
- **Universality method** using **Monte Carlo shower parameters** (shower to shower and signal fluctuations)
- **Universality method** using **hybrid reconstructed parameters** (shower to shower, signal and hybrid reconstruction fluctuations)

Combining X_{max} and F_{μ} in a Fisher Linear Discriminant



Distributions of reconstructed values peaked, with a minimal overlap of the tails.

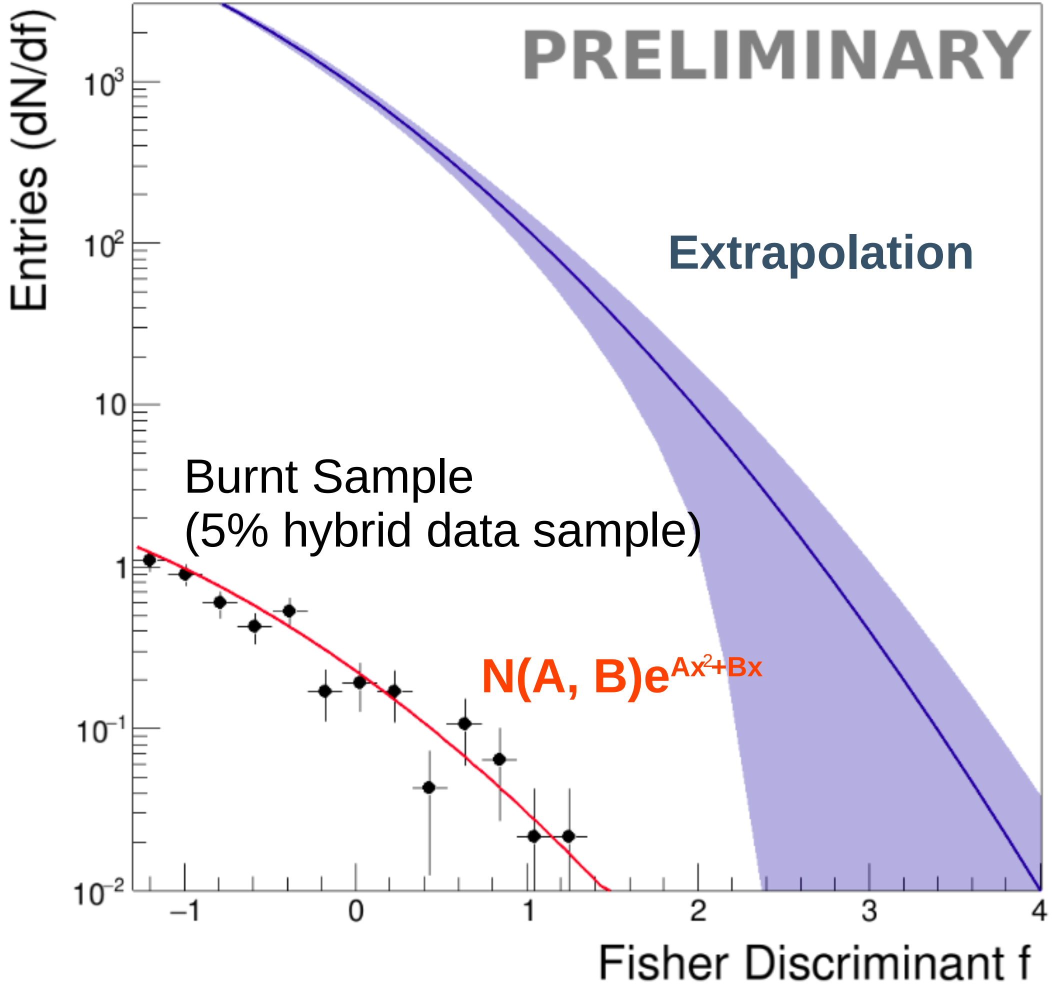


Separation variables ranked by separation power:

1. F_{μ}
2. X_{max}
3. $\log_{10}(E)$

Burnt Sample (5% hybrid data sample)

Modeling the expected background



1. Log-parabolic functional form from proton simulations

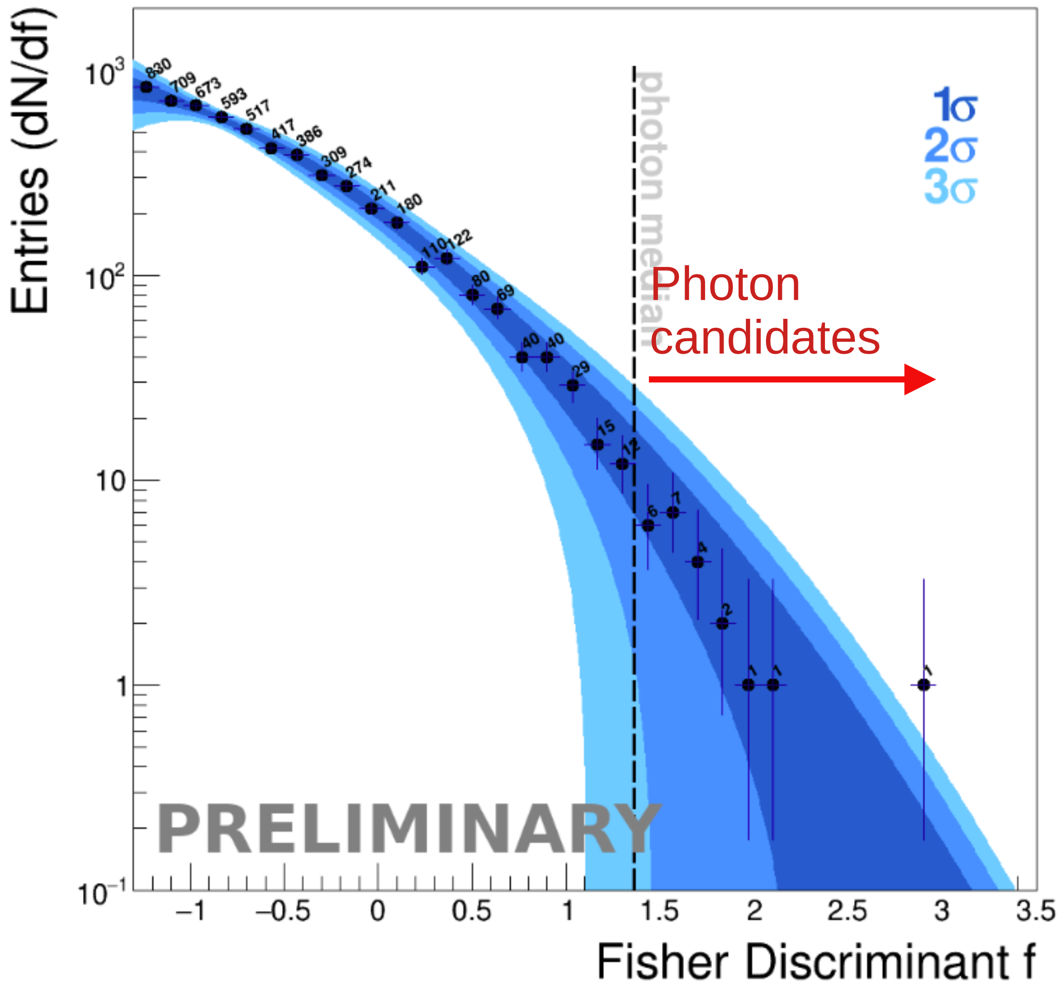
2. Fit to the burnt sample for a **data-driven parametrization of the expected background.**

3. Rescale the **normalization** to the **number of events in the full data sample** (shaded area shows uncertainties).

Median of the photon distribution derived as **photon selection cut** from the study of the background extrapolation.

Photons identified as excess with respect to the expected background

Unblinding of the data



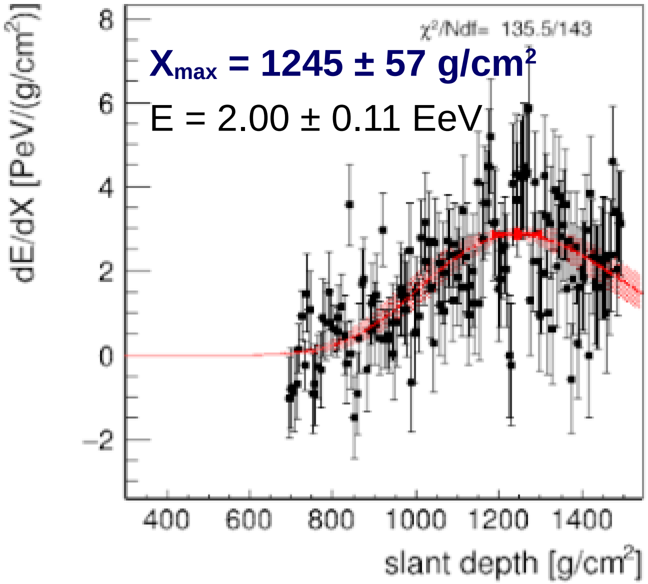
estimated events above median:
$N_{exp}(E > 10^{18.0}\ eV) = 30 \pm 16$

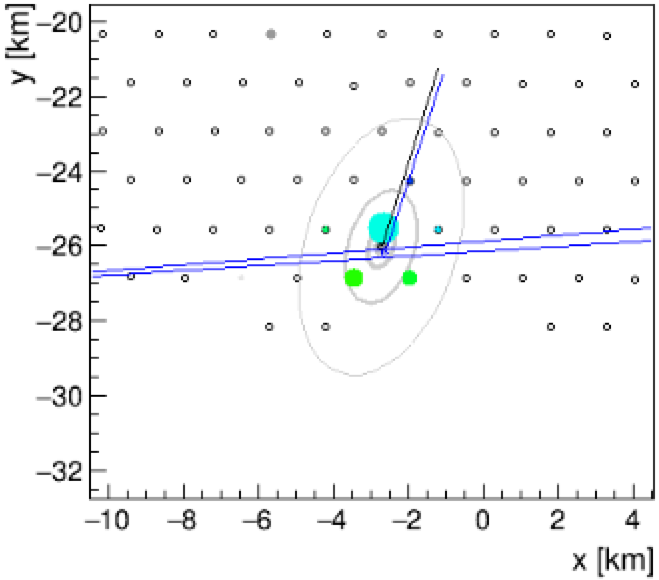
Candidates found:
$N_{obs}(E > 18.0\ eV) = 22$

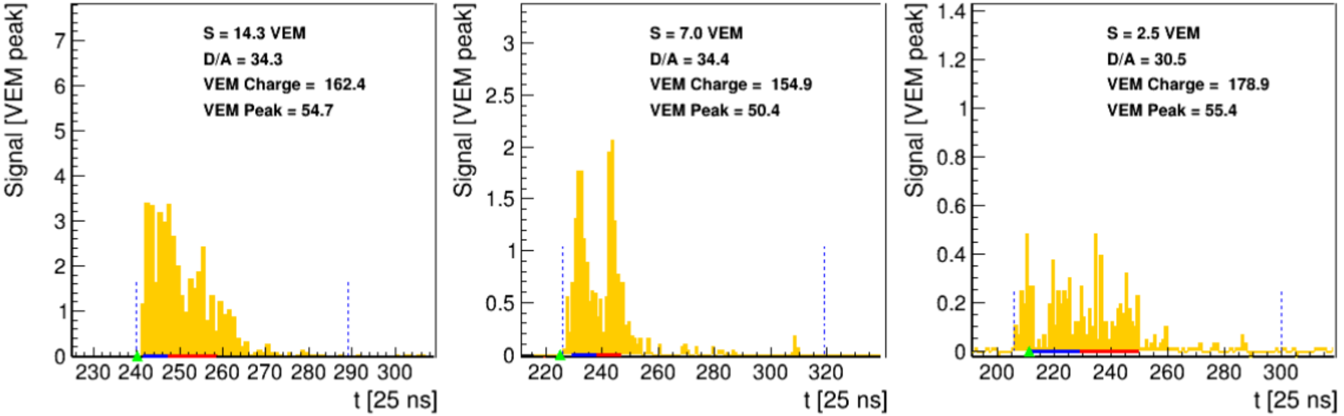
Median of the photon distribution derived as **photon selection cut** from the study of the background extrapolation.

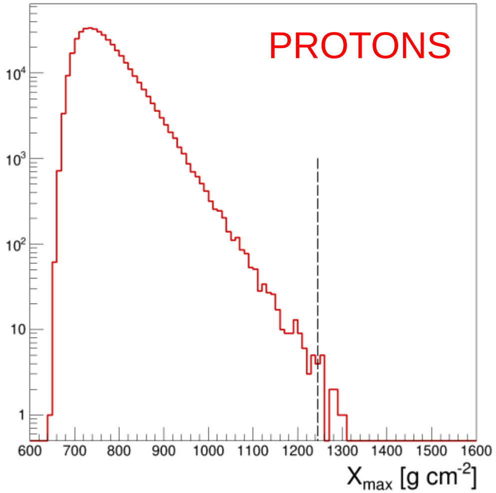
Photons identified as excess with respect to the expected background

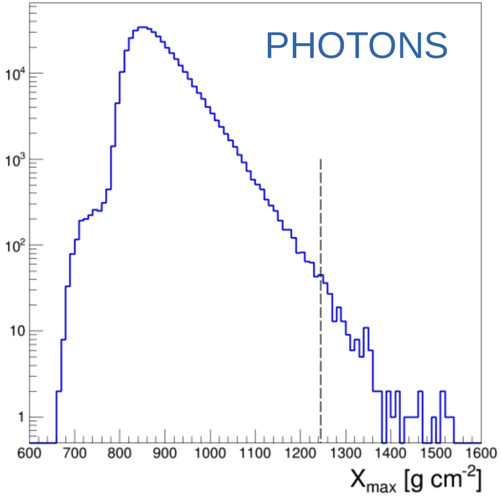
The most peculiar event





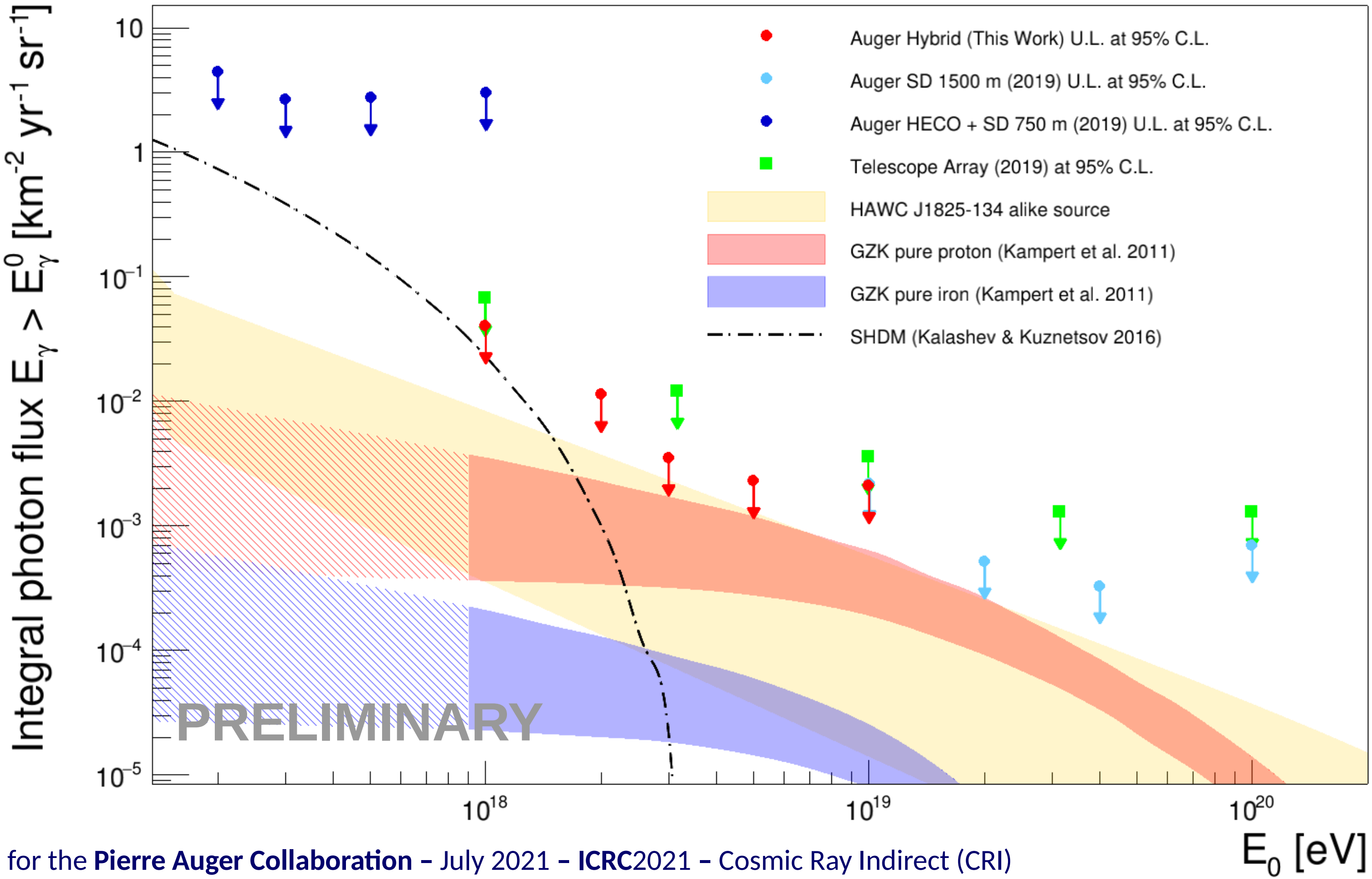






Claim for a photon observation **not possible** from a statistical point of view.

Upper Limits to the UHE photon flux



Conclusions

- **New hybrid analysis technique above 1 EeV**
  Energy, **X_{max}** and geometry from the hybrid reconstruction
  F_μ derived from SD signals exploiting Universality

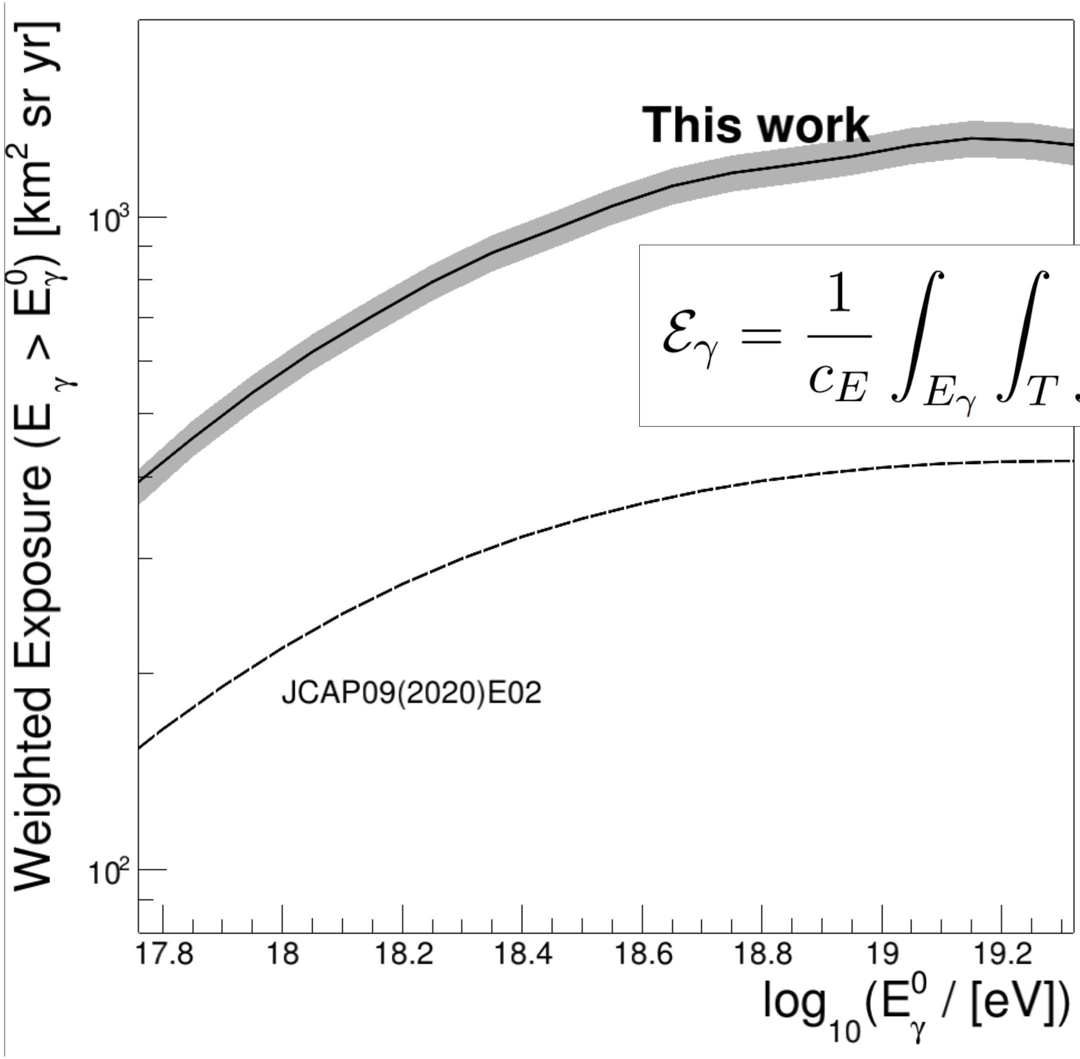
- **Hybrid data 01/01/05–31/12/17:**
  22 photon candidates between above 1 EeV
  30 ± 16 expected from the background

- **strictest limits on the UHE photon flux above $E > 10^{18}$ eV**

- **start constraining the most optimistic models of cosmogenic photon production by protons**

- **Mass and lifetime of SHDM particles constrained**

Upper limits calculation: hybrid photon exposure



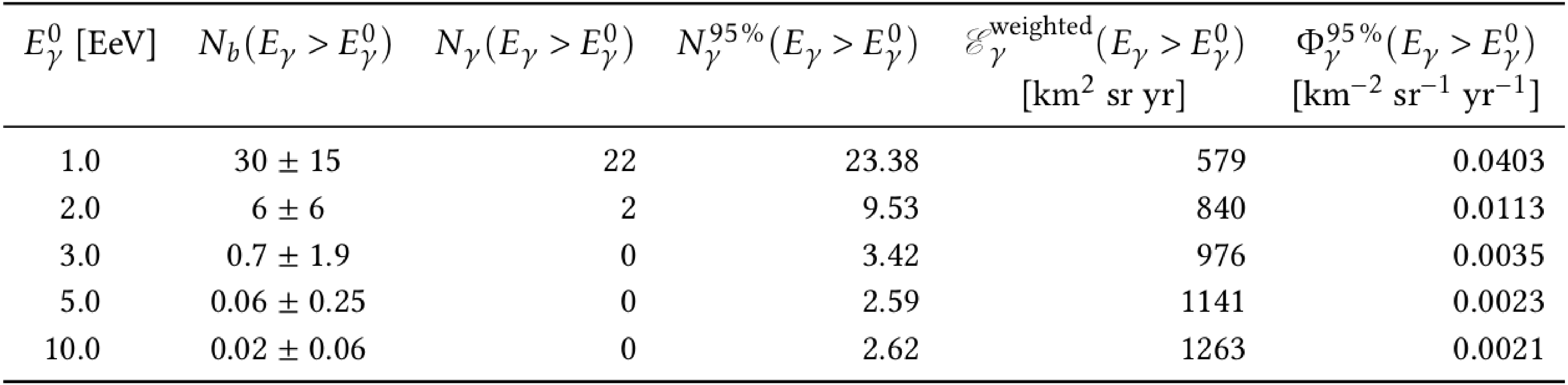
$\Gamma = 2$

$$\mathcal{E}_\gamma = \frac{1}{c_E} \int_{E_\gamma} \int_T \int_S \int_\Omega E_\gamma^{-\Gamma} \epsilon(E_\gamma, t, \theta, \phi, x, y)\, dS\, dt\, dE d\Omega$$

Exposure of the detector operating in hybrid mode:

- detectors actual status;
- detectors time evolution;
- atmospheric conditions.

Upper limits calculation: results

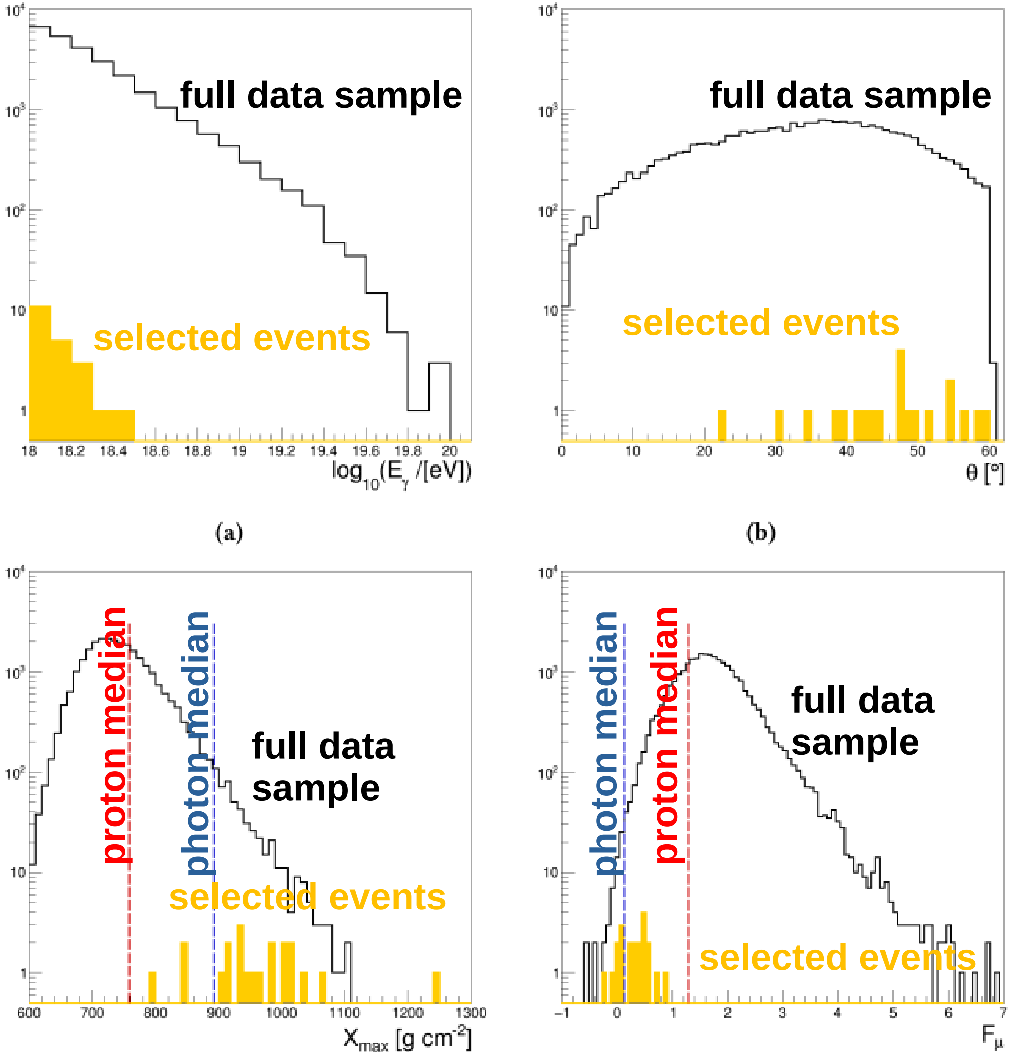


E_γ^0 [EeV]	$N_b(E_\gamma > E_\gamma^0)$	$N_\gamma(E_\gamma > E_\gamma^0)$	$N_\gamma^{95\%}(E_\gamma > E_\gamma^0)$	$\mathcal{E}_\gamma^{\text{weighted}}(E_\gamma > E_\gamma^0)$ [km^2 sr yr]	$\Phi_\gamma^{95\%}(E_\gamma > E_\gamma^0)$ [km^{-2} sr^{-1} yr^{-1}]
1.0	30 ± 15	22	23.38	579	0.0403
2.0	6 ± 6	2	9.53	840	0.0113
3.0	0.7 ± 1.9	0	3.42	976	0.0035
5.0	0.06 ± 0.25	0	2.59	1141	0.0023
10.0	0.02 ± 0.06	0	2.62	1263	0.0021

Systematic uncertainties on the upper limits:
- reconstructed hybrid parameters (energy, X_{max})
- unknown photon spectral index
- hadronic model (not accounted yet)

E^0_γ [EeV]	1	2	3	5	10
E (± 14%)	~25%	~10%	-	-	-
X_{max} (± 10 g/cm^2)	~15%	-	-	-	-
Γ = 1.5	~15%	~15%	-	-	-
Γ = 2.5	~20%	~20%	-	-	-

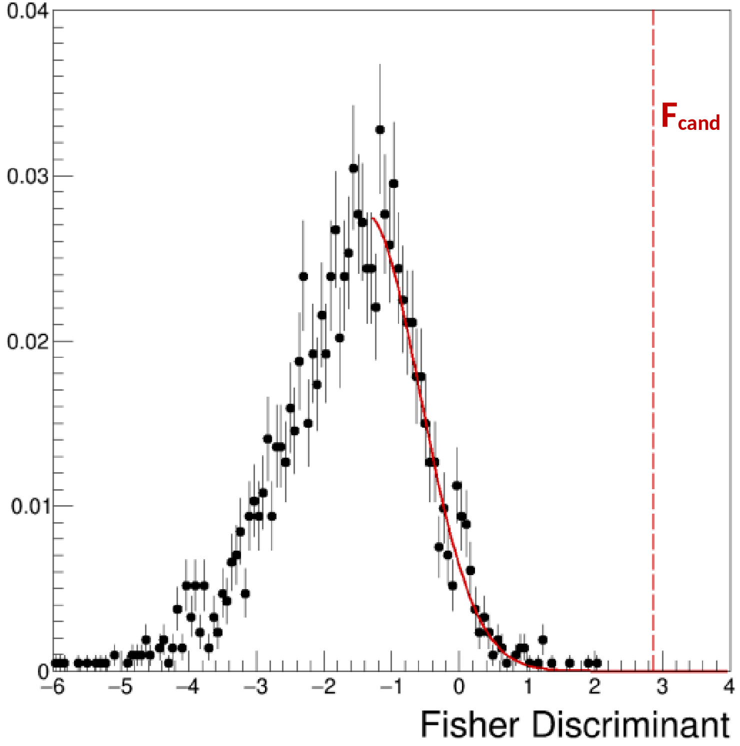
Characterization of the candidates

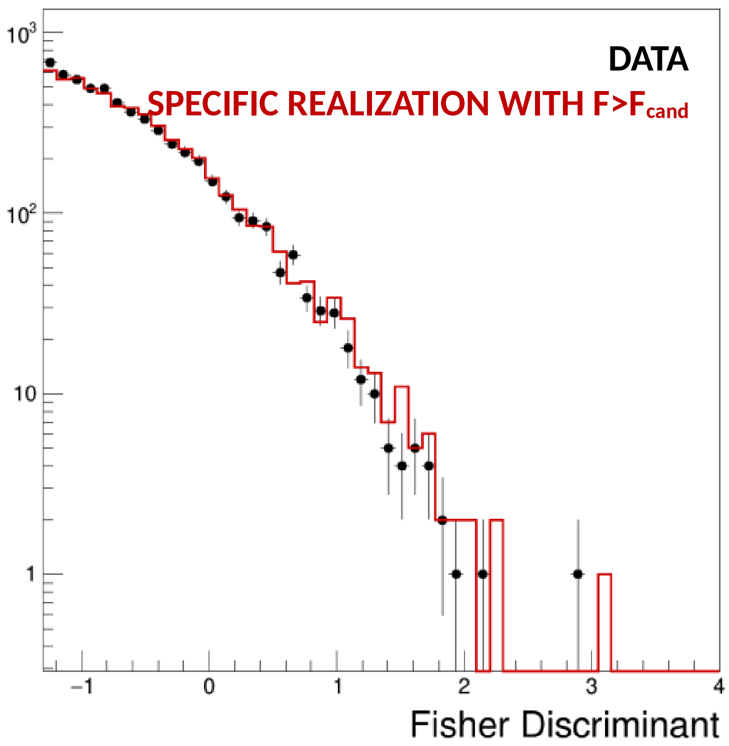


(a)

(b)

Significance and “look-elsewhere” effect





Local significance quantified simulating 2000 proton events with same energy and geometry of the candidate.

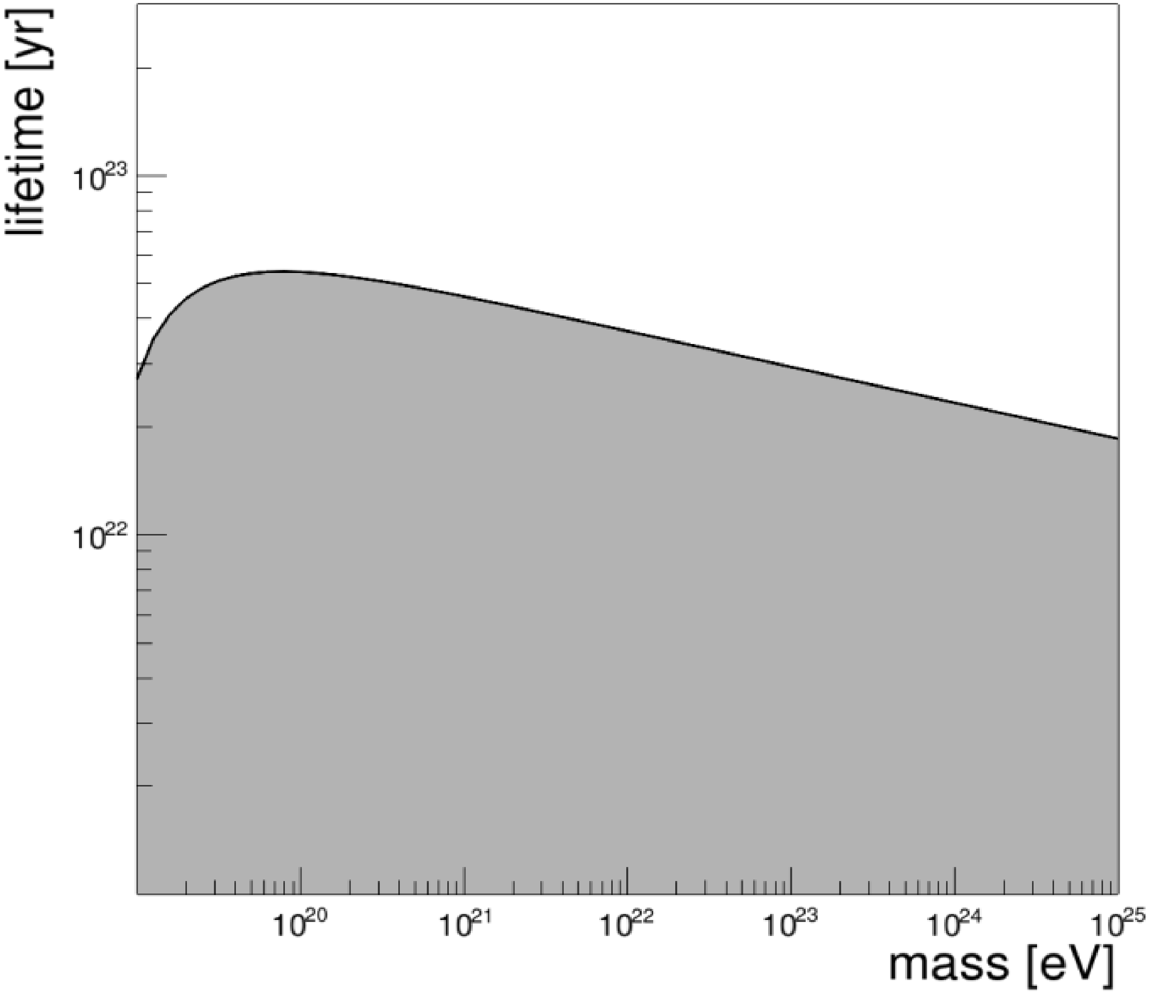
Local significance above 3.5σ

Global p-value accounts for the look-elsewhere effect

Generated 100000 realizations of the data samples according to the extrapolated background.

Global p-value found: ~25%

Physics implications



From the absence of photons constraints, on the mass M_X and lifetime τ_X can be inferred.

The strongest constrain over the whole mass range is $\tau_X > 3 \times 10^{22}$ yr at $M_X \approx 10^{20}$ eV.