image credit: Steven Saffi, Pierre Auger Collaboration

Directional Search for Ultra-High-Energy Photons Using the Surface Detector of the Pierre Auger Observatory

Astroparticle School 2024 (7 Oct – 15 Oct)

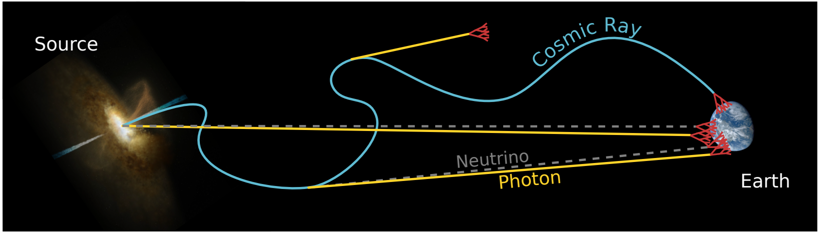
Tim Fehler, Marcus Niechciol, Markus Risse
Center for Particle Physics Siegen, Universität Siegen, Germany

13 Oct 2024

Directional Search for Ultra-High-Energy Photons Using the Surface Detector of the Pierre Auger Observatory

CONTENT

UHE photons as messengers of the Universe

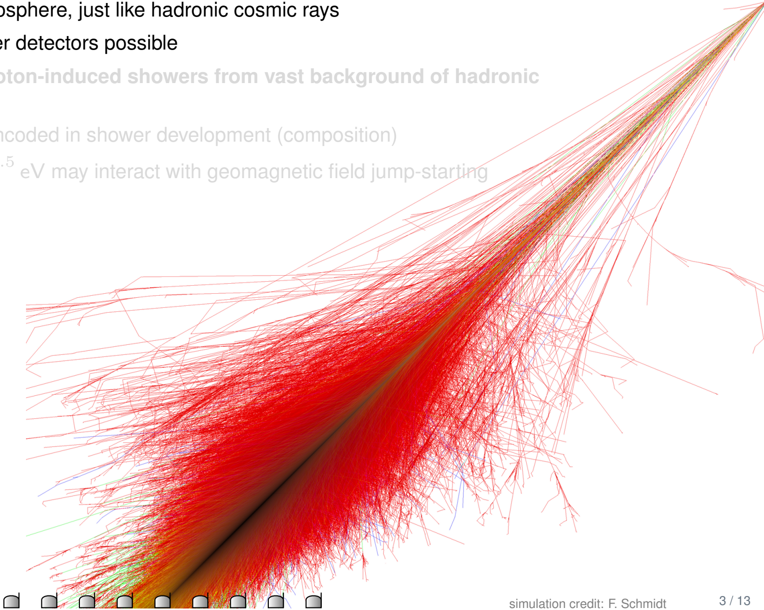


- Open question in astrophysics: **Origin** and **nature** of ultra-high-energy (UHE, $E \gtrsim 10^{17}$ eV) cosmic rays?
  - **Problem:** Magnetic deflection
- UHE photons (and neutrinos) produced in interactions of cosmic radiation
  - Near sources (dense regions): Neutral particles point right back at their sources!
  - Background fields: CMB $\rightarrow$ GZK effect, ...? Photon flux sensitive to cosmic-ray composition
- Other possiblities: Interaction of extragalactic cosmic rays with matter in our galaxy, BSM processes (SHDM), ...
- Photons themselves can interact with background fields: **Effective UHE photon horizon** at the order of $10\,\mathrm{Mpc}$ (10^{18} eV)

M. Risse and P. Homola, Mod. Phys. Lett. A **22**, 749–766 (2007)

Detecting UHE photons

- Photons initiate air showers in the atmosphere, just like hadronic cosmic rays
- Detection with ground-based air-shower detectors possible
- Central challenge: **Distinguishing photon-induced showers from vast background of hadronic showers**
- Information about primary particle is encoded in shower development (composition)
- **Problem:** UHE photons above $\sim 10^{19.5}$ eV may interact with geomagnetic field jump-starting shower development (**pre-showering**)



simulation credit: F. Schmidt

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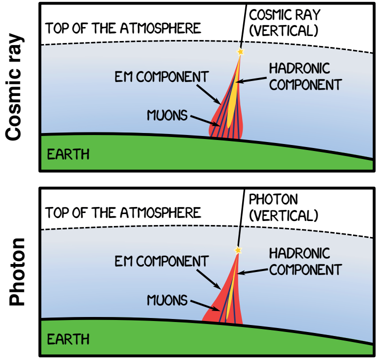

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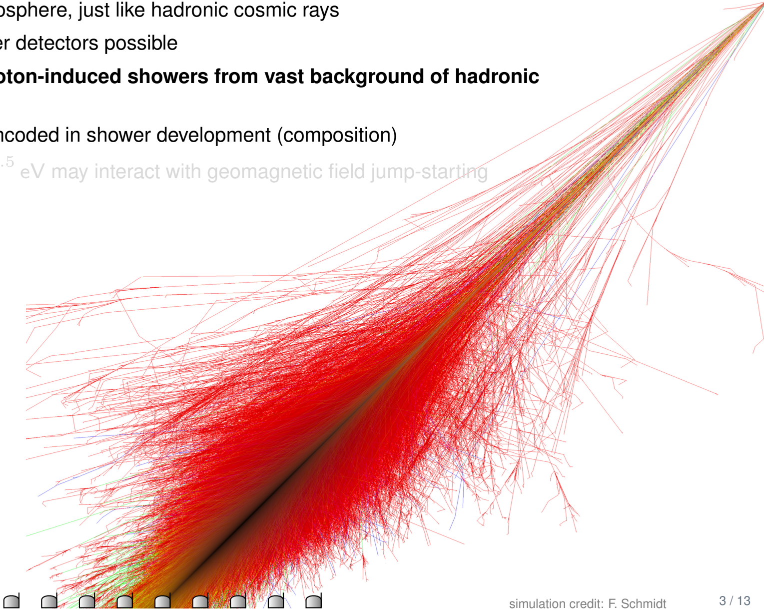

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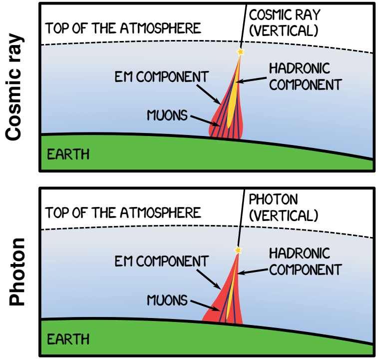

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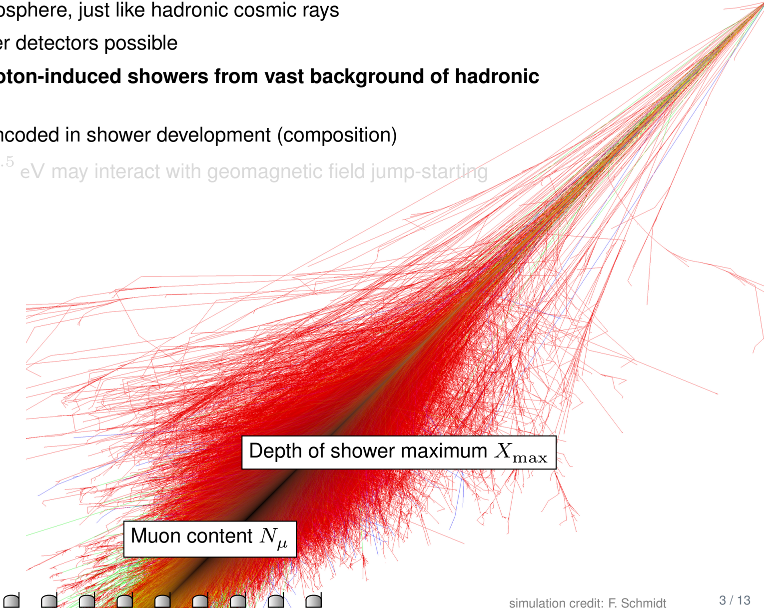

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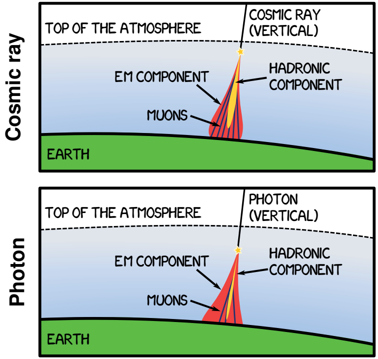

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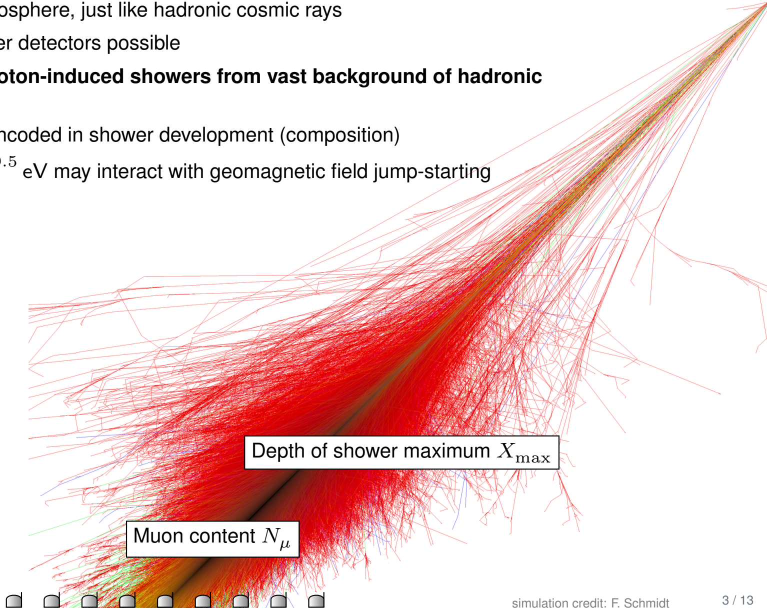

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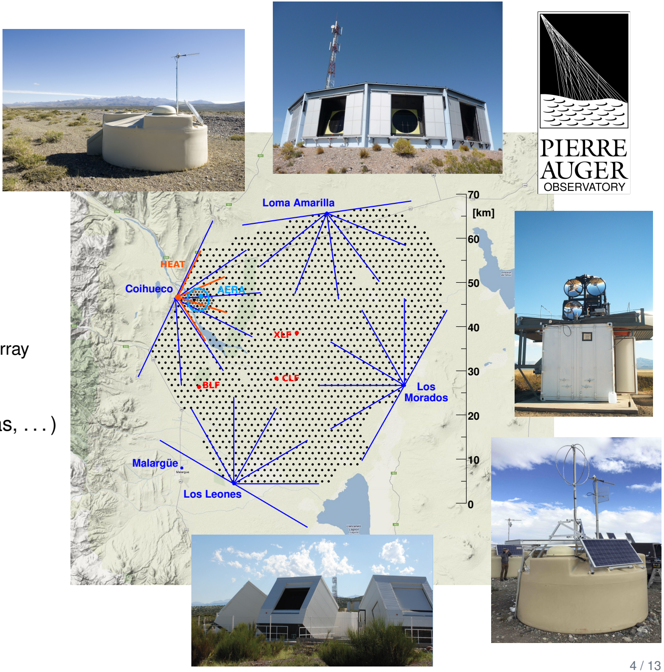
Pierre Auger Observatory

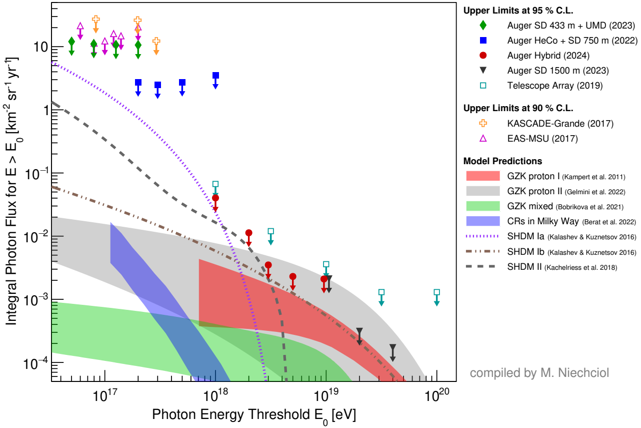
- Largest **cosmic-ray observatory** in the world
- Located near Malargüe, Argentina
- Energy range: 10^{17} eV to $> 10^{20}$ eV
- **Hybrid detector**
- **Surface detector array (SD)**
  - 1660 water-Cherenkov detectors over $3000\,\mathrm{km}^2$
  - Footprint of shower
- **Fluorescence detector (FD)**
  - 27 telescopes distributed over 4 sites overlooking SD array
  - Longitudinal shower development
  - $\sim 15\%$ duty cycle
- Auxiliary detector systems (infill arrays, radio antennas, . . .)
- Atmospheric monitoring (LIDAR, laser facilities, . . .)
- Currently: **AugerPrime upgrade**
  - Primary mass estimate on shower-by-shower basis



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

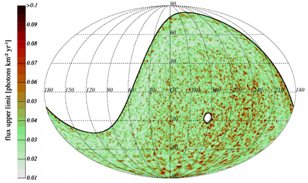
Current status of (published) UHE photon searches

- **No UHE photon unambiguously identified so far**
- Limits on diffuse integral flux of photons



SD 433 m + UMD — N. González, Pierre Auger Coll. PoS(ICRC2023) **444**, 238 (2023)
HeCo + SD 750 m — Pierre Auger Coll., ApJ **933**, 125 (2022)
Hybrid — Pierre Auger Coll., (2024), arXiv:2406.07439 [astro-ph.HE], acc. by PRD
SD — Pierre Auger Coll., JCAP **2023**, 021 (2023)
see also overview: Pierre Auger Coll., Universe **8**, 579 (2022)

- Directional efforts (blind and targeted) using **hybrid** data:
  - Pierre Auger Coll., ApJ **789**, 160 (2014)



  - Pierre Auger Coll., ApJL **837**, L25 (2017)

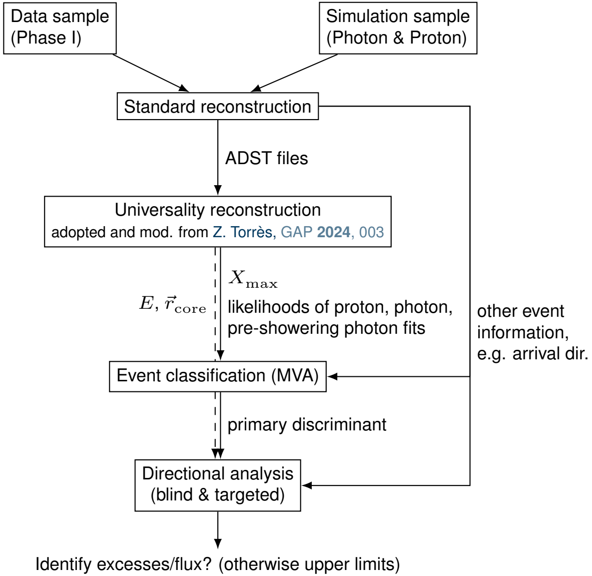
Class	N	$\mathscr{P}$	$\mathscr{P}_w$	p	p^*	$f_{UL}^{0.95}$ [km^{-2} yr^{-1}]
msec PSRs	67	0.14	0.57	0.010	0.476	0.043
γ-ray PSRs	75	0.98	0.97	0.007	0.431	0.045
LMXB	87	0.74	0.13	0.014	0.718	0.046
HMXB	48	0.84	0.33	0.040	0.856	0.036
H.E.S.S. PWN	17	0.90	0.92	0.104	0.845	0.038
H.E.S.S. other	16	0.52	0.12	0.042	0.493	0.040
H.E.S.S. UNID	20	0.45	0.79	0.014	0.251	0.045
Microquasars	13	0.48	0.29	0.037	0.391	0.045
Magnetars	16	0.89	0.30	0.115	0.858	0.031
Gal. Center	1	0.59	0.59	0.471	0.471	0.024
LMC	3	0.62	0.52	0.463	0.845	0.030
Cen A	1	0.31	0.31	0.221	0.221	0.031

- Multimessenger efforts (GW follow-up)
  Pierre Auger Coll., ApJ **952**, 91 (2023)

Directional Search for Ultra-High-Energy Photons Using the Surface Detector of the Pierre Auger Observatory

CONTENT

Design of the analysis



NB: This is very much WIP!

Key aspects:

- Sole dependence on **SD data** (profiting from non-stop exposure)
- Full **phase I** data set (2004 – 2024)
- Modular design/implementation
  - Ease of development and maintainability (debugging, testing, ...)
  - Distributed computing (SiMPLE cluster)
- Overcoming technical limitation of **pre-showering** ($E > 10^{19.5}$ eV)

Details on the next slides ...

Universality reconstruction I

Air-shower universality

Due to the averaging of the innumerable individual particle-level processes, the energy spectrum of secondary particles, as well as their angular and lateral distributions can be described by only the energy of the primary particle and the stage of shower development (shower age).

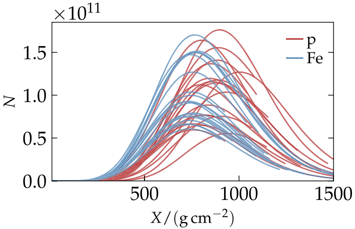
- “All air showers look/behave the same” (non-trivial!)
- **Consequence:** Signal (and risetime) in SD stations can be modeled as

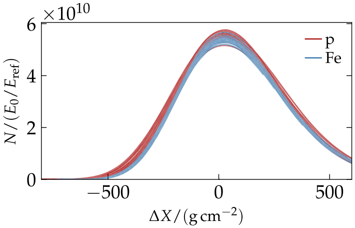
$$f_{\text{univ}}(\underbrace{r, \psi, h,}_{\text{rel. pos. of station}} \underbrace{E, X_{\text{max}}, N_\mu}_{\text{air-shower}})$$

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

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

- **Universality reconstruction:** From signal in SD stations estimate one unknown parameter





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

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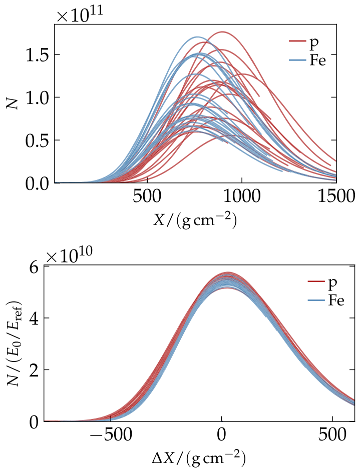

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Universality reconstruction II

Steps :	1	2	3	4
Energy	Reconstructed : **Start** = median of Ehad/EMC (θ,S1000) **Range** = 10%-90% quantiles	Fixed to reconstructed value from step 1	Reconstructed : **Start** = reconstructed value from step 1 **Range** : 2/3 of range in step 1	Fixed to reconstructed value from step 3
Core	Fixed to standard SD reconstruction + corrected for the asymmetry as function of cos²θ	Reconstructed : **Start** = standard SD reconstruction + corrected for the asymmetry **Range** = radius of 200m from start value	Fixed to reconstructed value from step 2	Fixed to reconstructed value from step 2
Xmax	Using **<Xmax>(E)** for photons	Fixed to **<Xmax>(E)** for the reconstructed energy is step 1	Using **<Xmax>(E)** for photons	Reconstructed : **Start** = <Xmax>(E) for the reconstructed energy in step 3 **Range** = no bounds

Z. Torrès, GAP **2024**, 003

- Idea developed by colleagues at Université Grenoble Alpes
- **Four-step likelihood fit** based on recorded signal and risetime in SD stations
  - signal/risetime assumed to follow Gaussian PDF with
    $$\mu = f_{\text{univ}}(E, X_{\max}, N_\mu, \ldots)$$
    and σ estimated from simulations
  - $N_\mu = \langle N_{\mu,\text{sim.}}^{p,\gamma} \rangle$
  - ML fit one parameter at a time
- **Initial parameter values:**
  - Standard reconstruction
  - Customized photon energy scale with look-up tables
  - Use mean $X_{\max}(E)$ determined from simulations
- Slightly **modified procedures** for pre-showering photons and protons

- **Yields:** E, $X_{\max}$, log-likelihood ratios for hypotheses (photon/hadron) based on signal/timing-model

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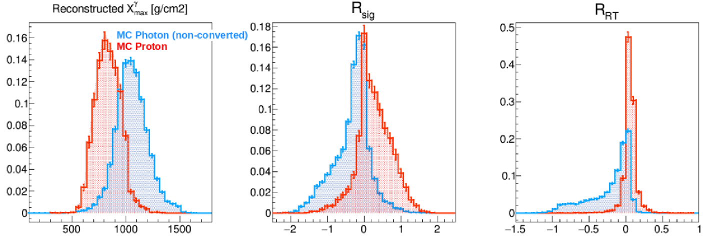
Event classification



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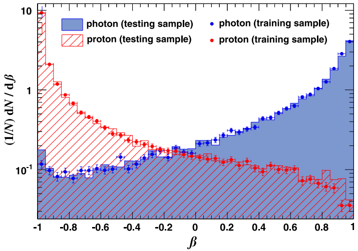
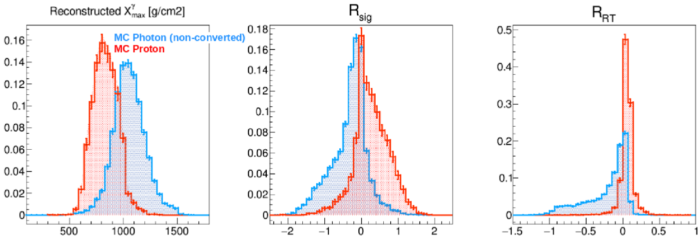


Final MVA discriminant
Pierre Auger Coll., ApJ **789**, 160 (2014)

- First **adoption study** shows results competitive with current SD analysis (Pierre Auger Coll., JCAP **2023**, 021 (2023))
- New! For MVA event classification: Use E, θ, $X_{\max}$ and primary likelihoods, and assign single discriminatory parameter with BDT
  - "photon-likeliness" of event $\rightarrow$ candidate cut
- Clean and modern reimplementation of procedure ✓, confirmation of results with up-to-date simulation set provided by Collaboration, fine-tuning

Event classification



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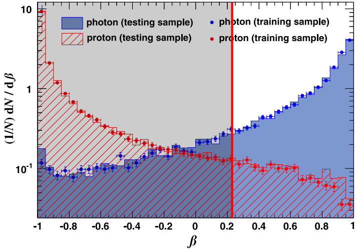

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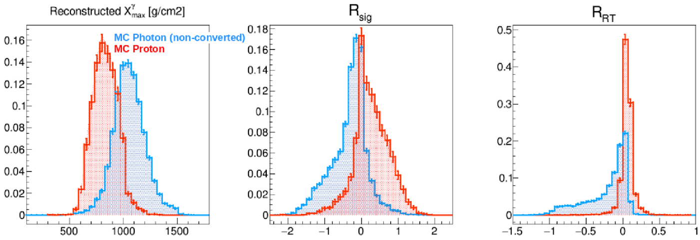

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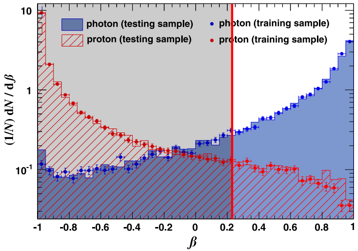

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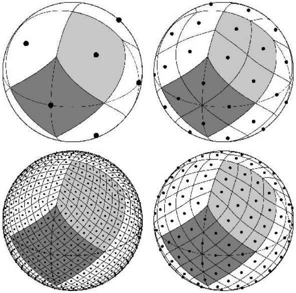
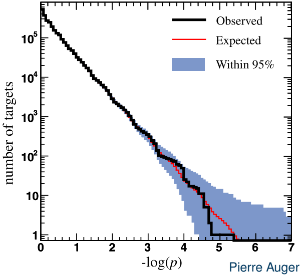
Directional analysis

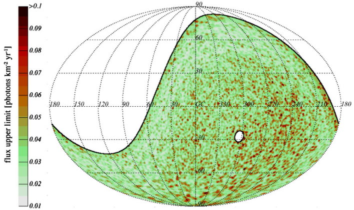
New!

- Pierre Auger Observatory can cover declinations between -90° and $+20^\circ$ (for $\theta \leq 60^\circ$)
- Regular binning of the sky (target separation $\sim$ angular resolution) or unbinned density method?
- Using “photon-like” subset of data
- Background estimation from data
  - Aiming to avoid technique not suited for celestial south-pole region
- Search for excess $\rightarrow$ p-value
- Up-to-date catalog of promising **source candidate classes** and their positions
- If no excess is found: Calculation of **upper limits**



HEALPix discretation of sphere
K. M. Górski et al., ApJ **622**, 759 (2005)
K. M. Górski and E. Hivon, Astrophys. Source Code Libr., ascl:1107.018 (2011)





Pierre Auger Coll., ApJ **789**, 160 (2014)

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CONTENT

Summary and outlook

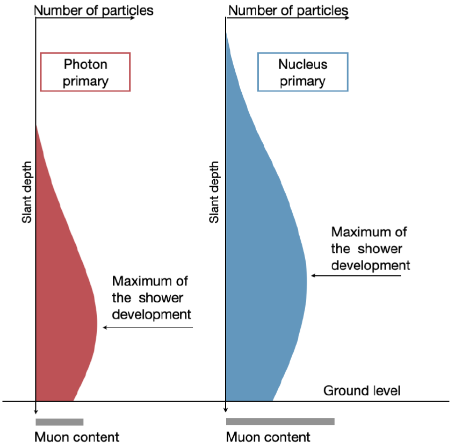
- UHE photons are connected to diverse physical processes and searching for them allows us to probe various scenarios for the origin and nature of UHE cosmic rays.
- Novel directional search for UHE photons exploiting the superb collected exposure of the SD of the Pierre Auger Observatory
- Event reconstruction is complemented by a new universality-based multistage fit and subsequently a dedicated event classification.
- A “photon-like” subset of data will be analyzed for directional excesses in a blind and a targeted manner.
- Further studies: How can the additional components (AugerPrime upgrade) supplement this analysis? Would a real-time application for transients be conceivable?

Thank you for your attention!

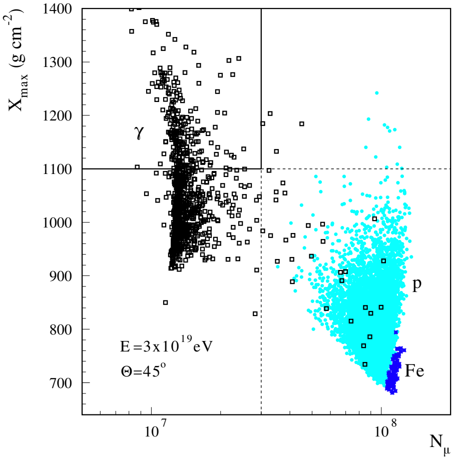
BACK UP

image credit: Pierre Auger Collaboration

How to identify UHE photon primaries



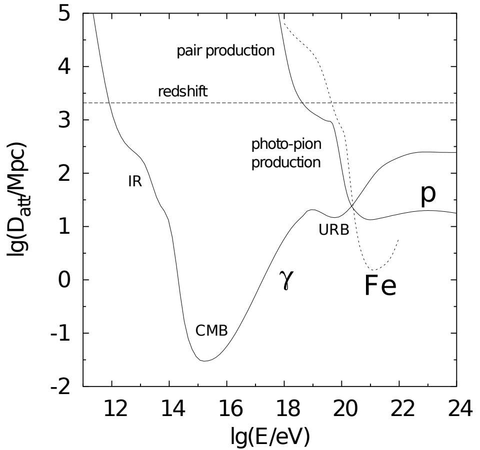
Pierre Auger Coll., Universe **8**, 579 (2022)



M. Risse and P. Homola, Mod. Phys. Lett. A **22**, 749–766 (2007)

Effective UHE photon horizon

Energy loss length of photons in background fields



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