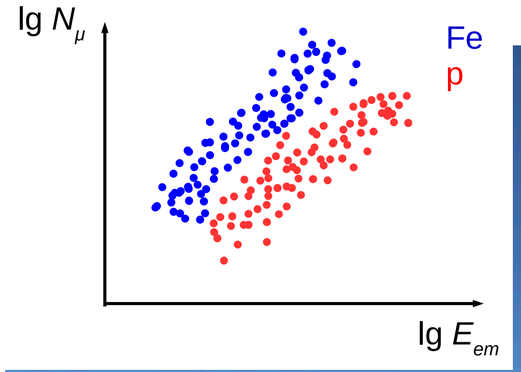
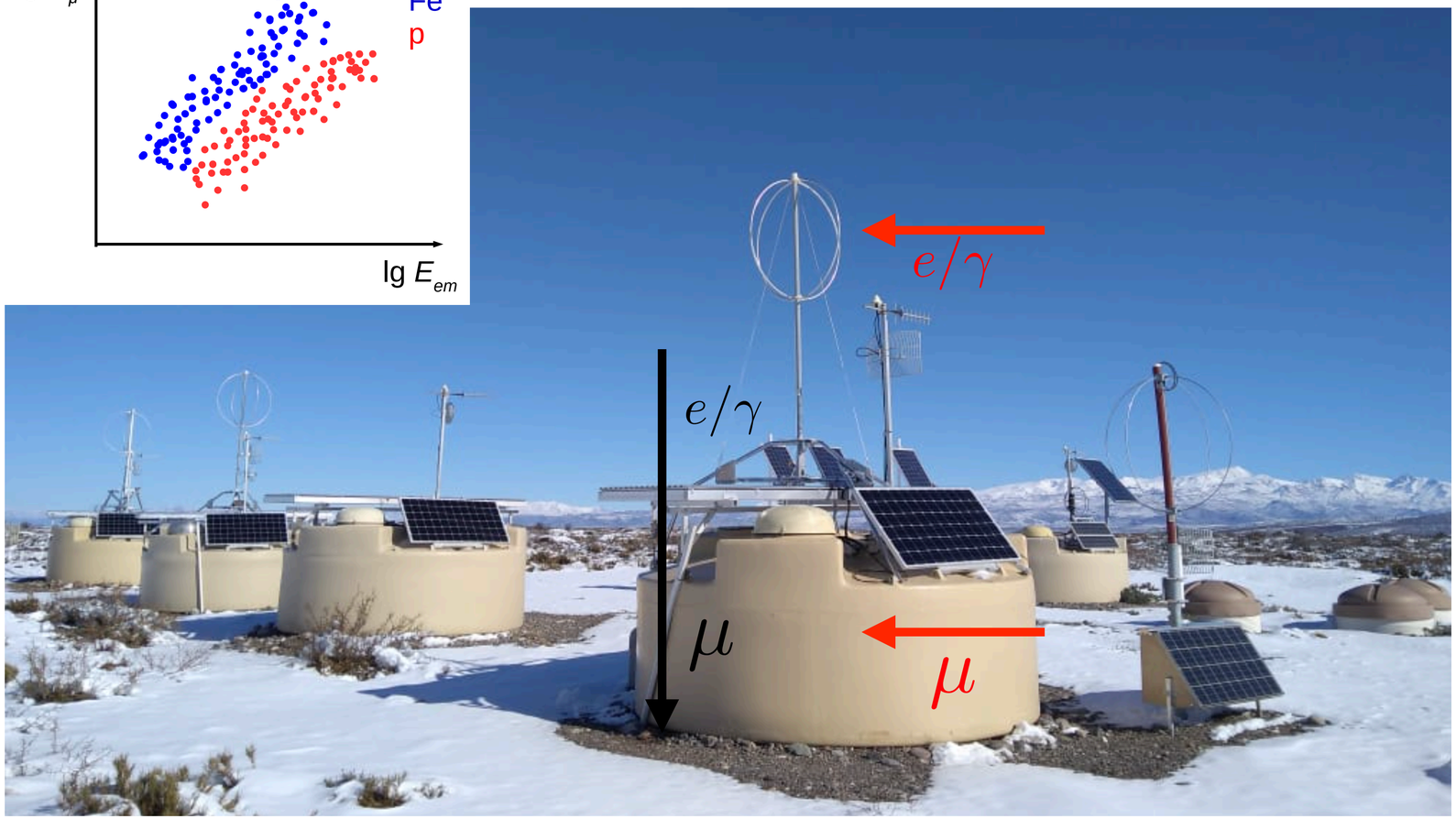
Status and prospects of the Radio Detector of the Pierre Auger Observatory



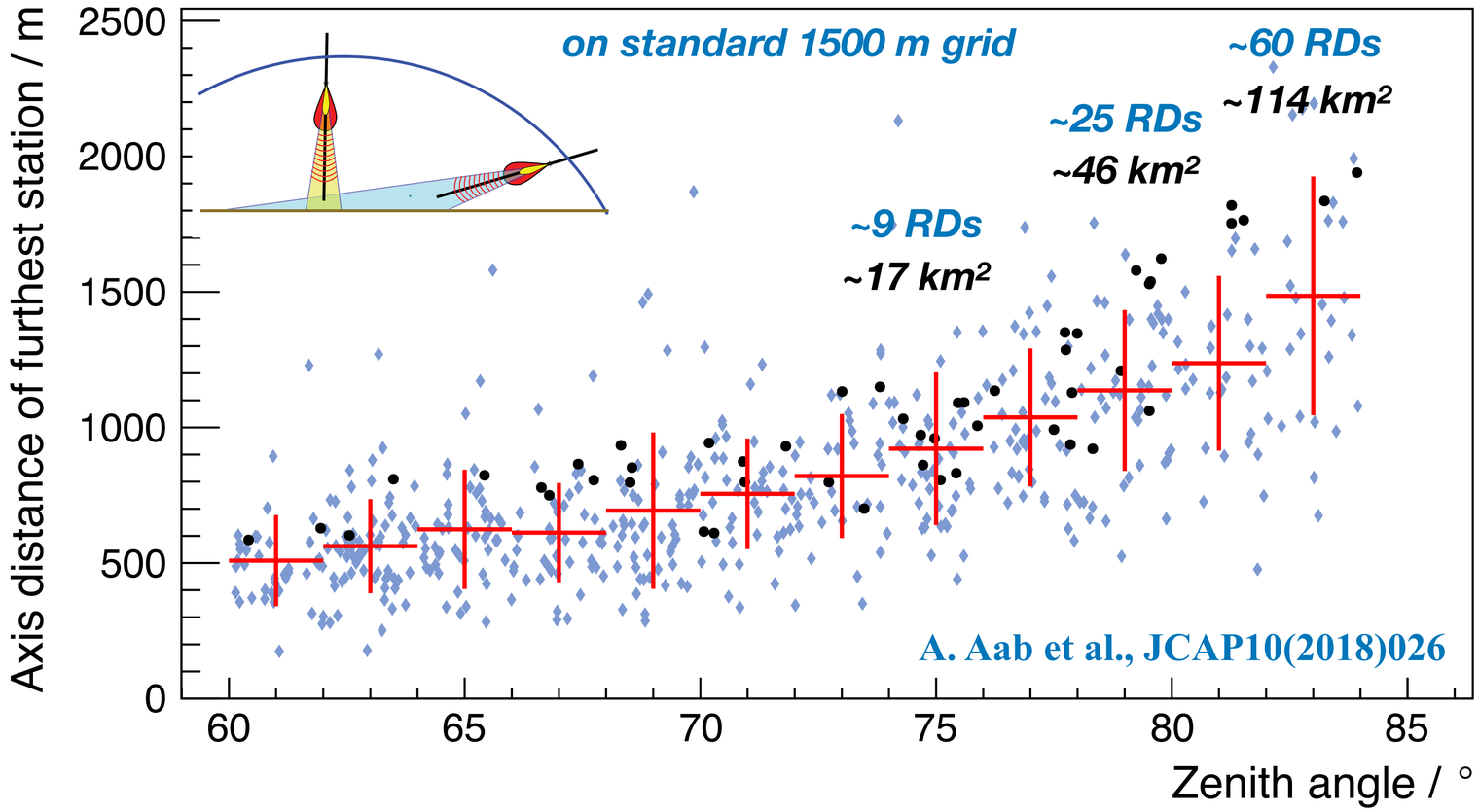


Key science questions

- What are the **sources** and **acceleration** mechanisms of ultra-high-energy cosmic rays (UHECRs)?
- Do we understand **particle** acceleration and **physics** at energies well beyond the LHC (Large Hadron Collider) scale?
- What is the fraction of **protons**, **photons**, and **neutrinos** in cosmic rays at the highest energies?

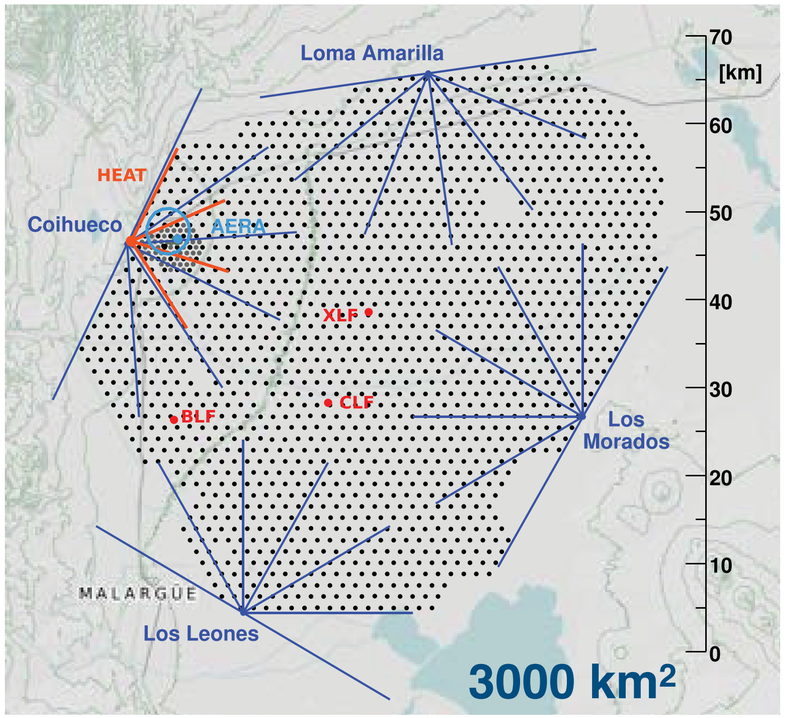
Jörg R. Hörandel for the Pierre Auger Collaboration
http://particle.astro.ru.nl

Horizontal air showers have large footprints in radio emission



this is MEASURED with the *small* 17km² AERA

Pierre Auger Observatory



Surface Detector array:
Water Cherenkov Detector, Surface Scintillator Detector, Radio Detector
1600 stations on 1500 m grid
61 stations on 750 m grid

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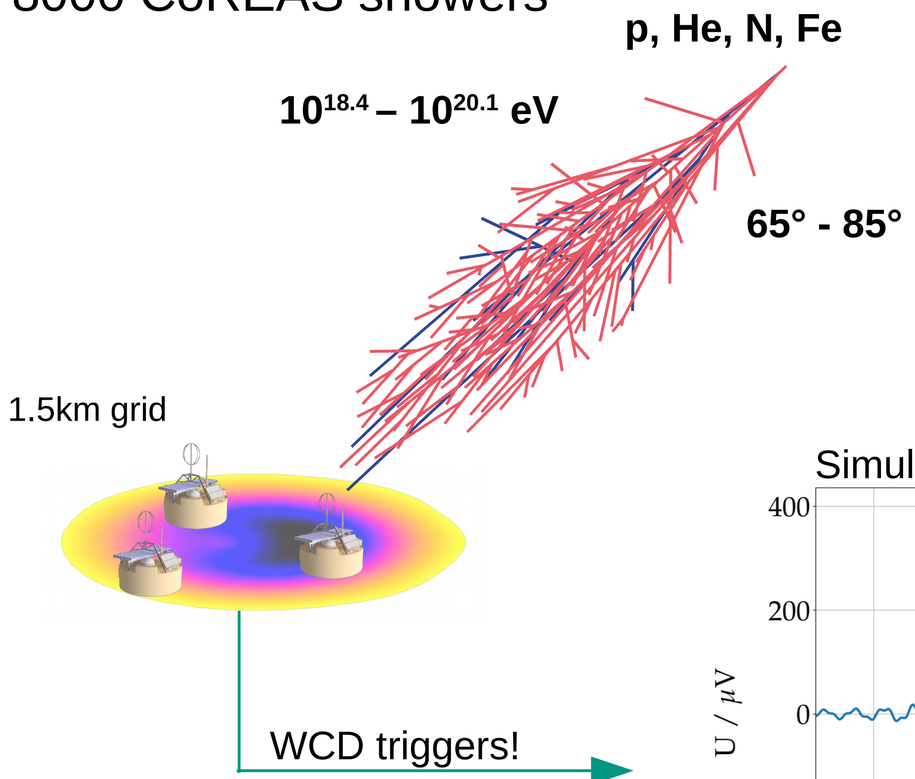
Expected Performance

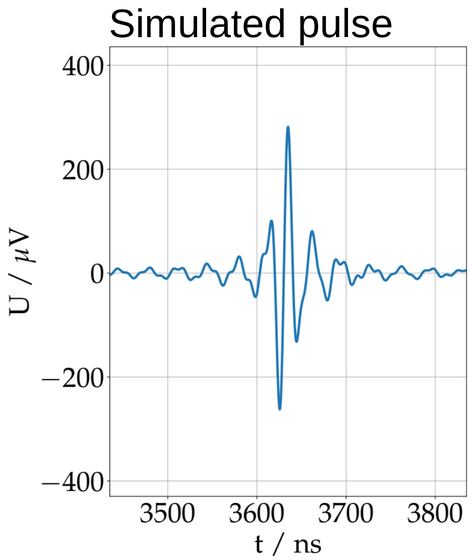
End-to-end simulation

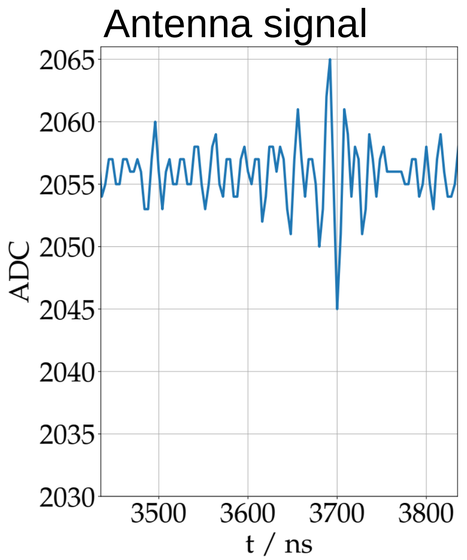
8000 CoREAS showers

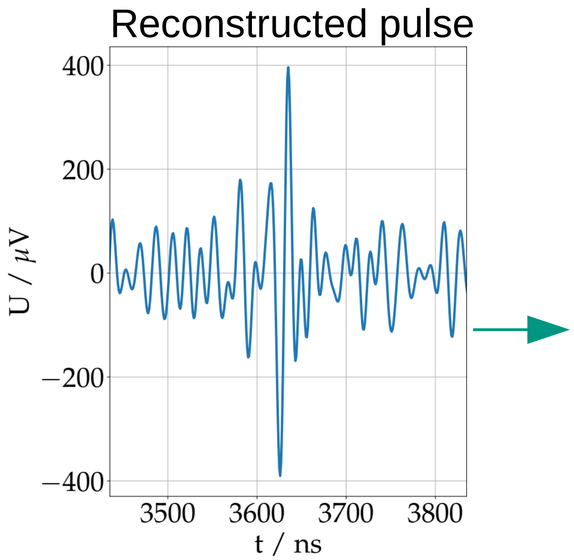


Simulate instrumental response
(directional response, analog gain, digitization, …..)

- Including uncertainties (σ_A = 5%)
- Measured noise

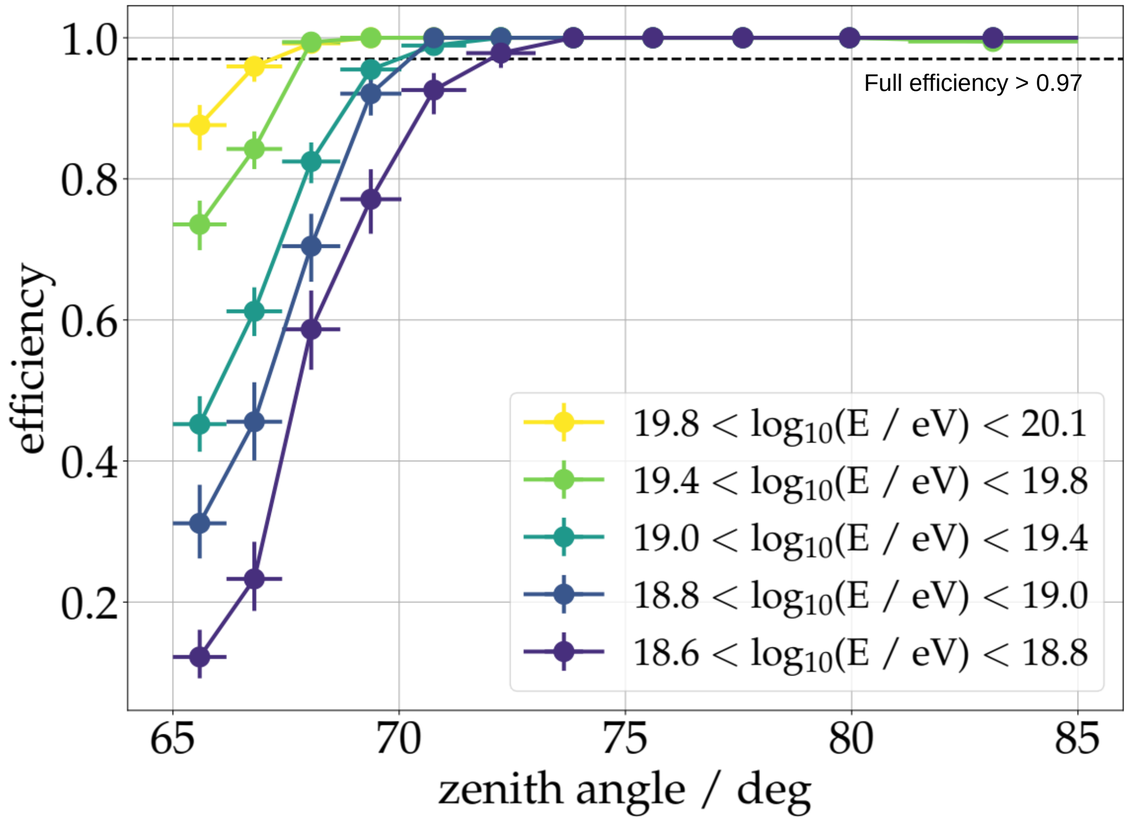






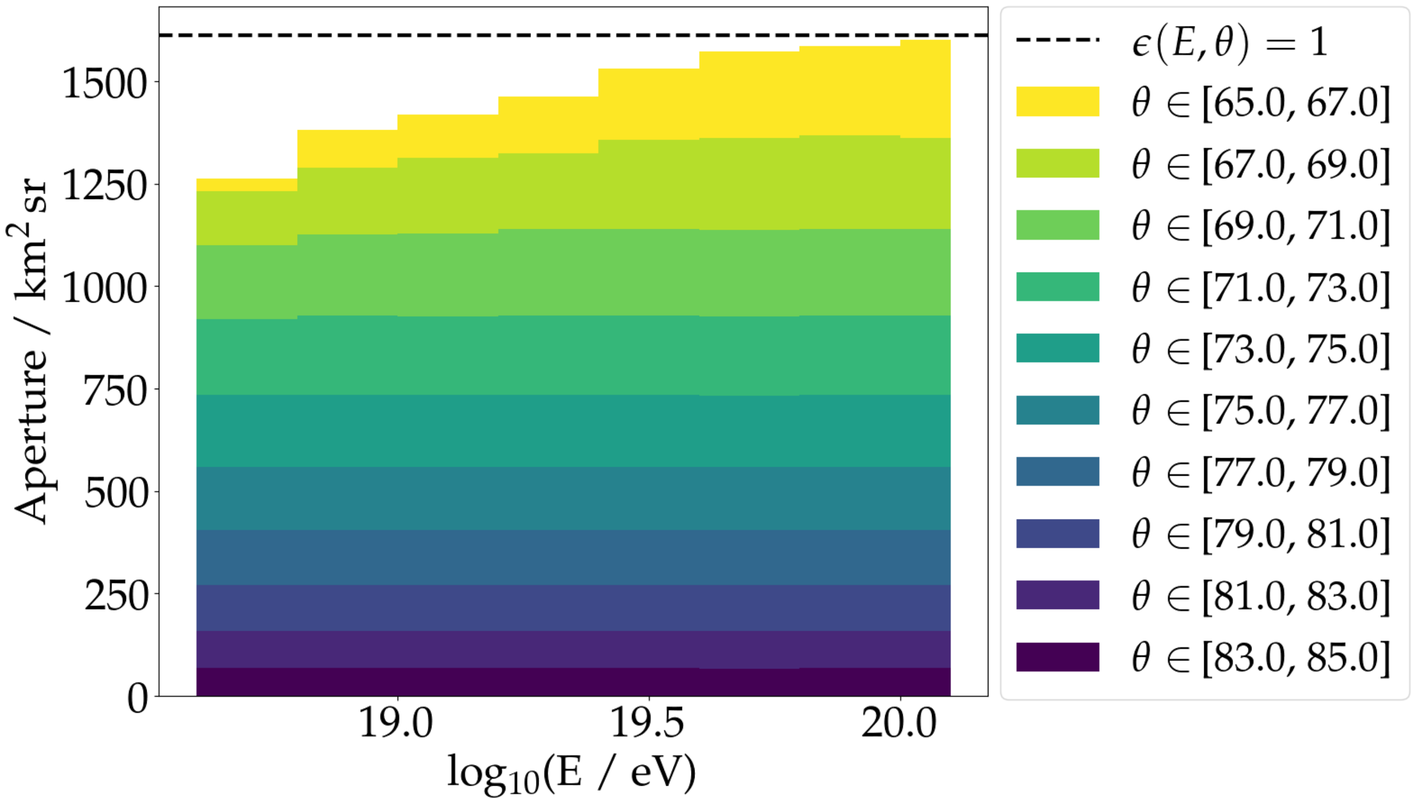
see Felix Schlüter, ARENA 2022

Detection Efficiency



Detection condition: >= 3 stations w signals

Aperture for 3000 km² array



~25% of aperture with vertical air showers (0°-60°)

full efficiency $\Theta \geq 70^\circ \quad \lg(E/\mathrm{eV}) > 18.8$

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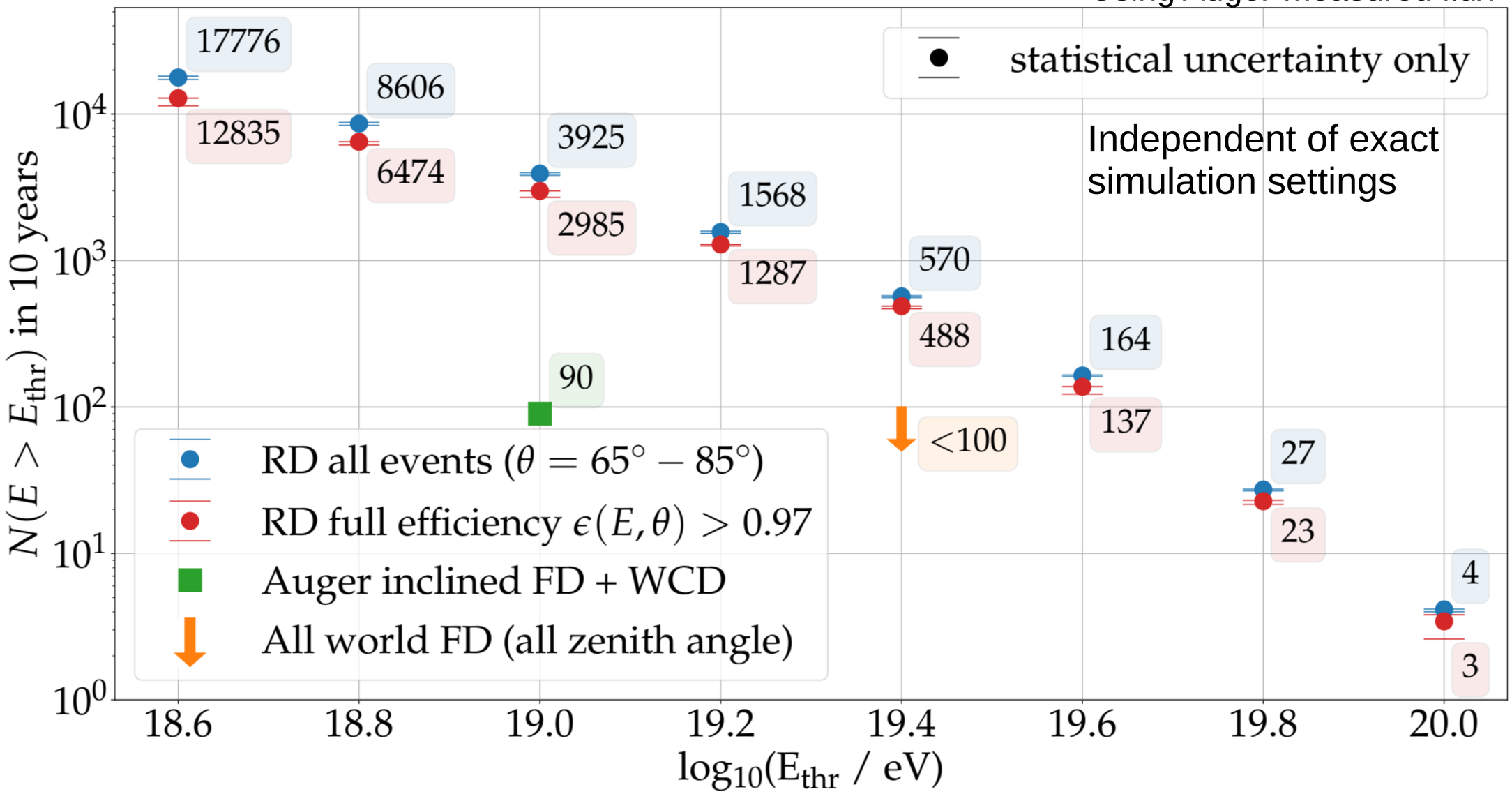
Expected number of cosmic rays after 10 years

Using Auger-measured flux



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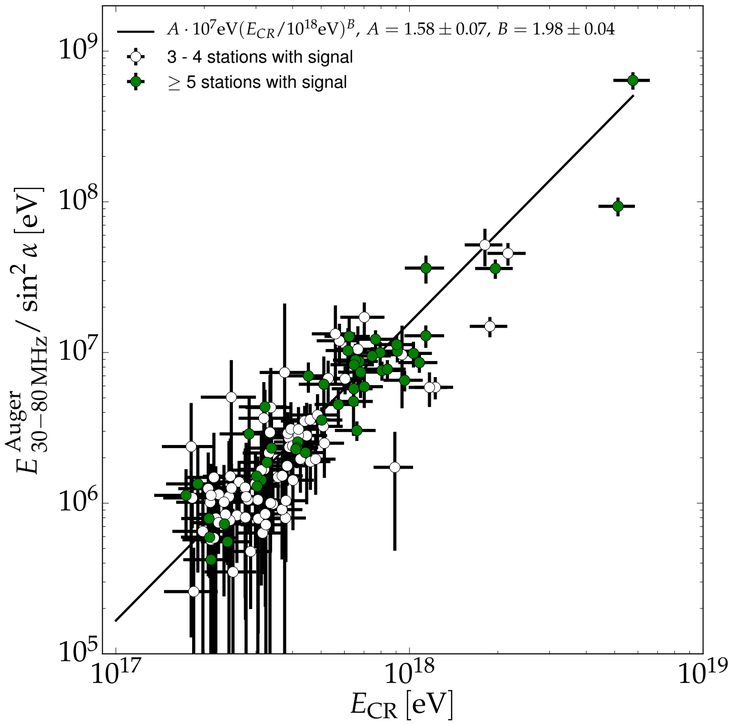
Lateral signal distribution

new model for LDF

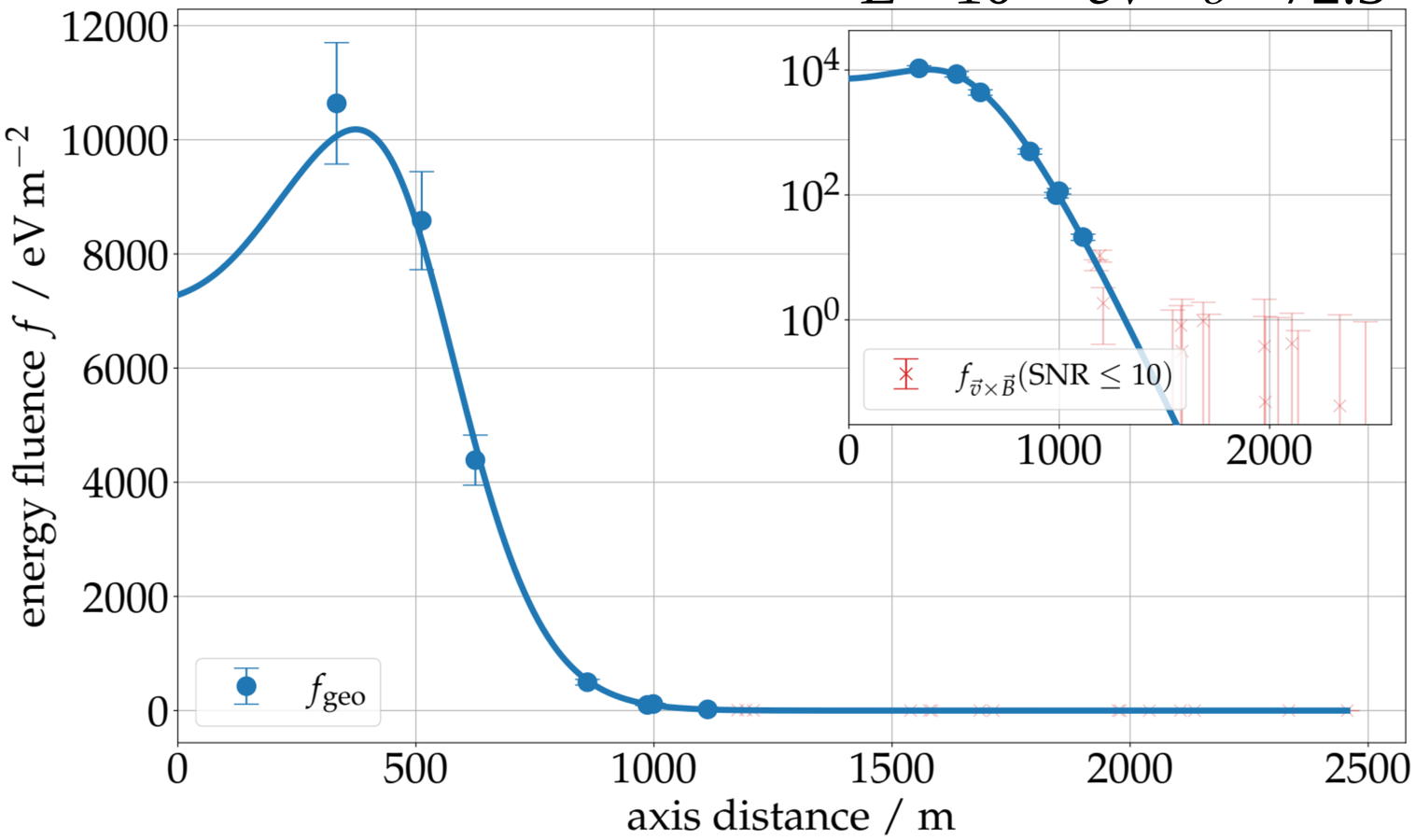
- 2 parameter + core coordinates
- derive start values from WCD (use RD arrival direction)
- integral -> energy estimator



A. Aab et al., PRL 116 (2016) no.24, 241101

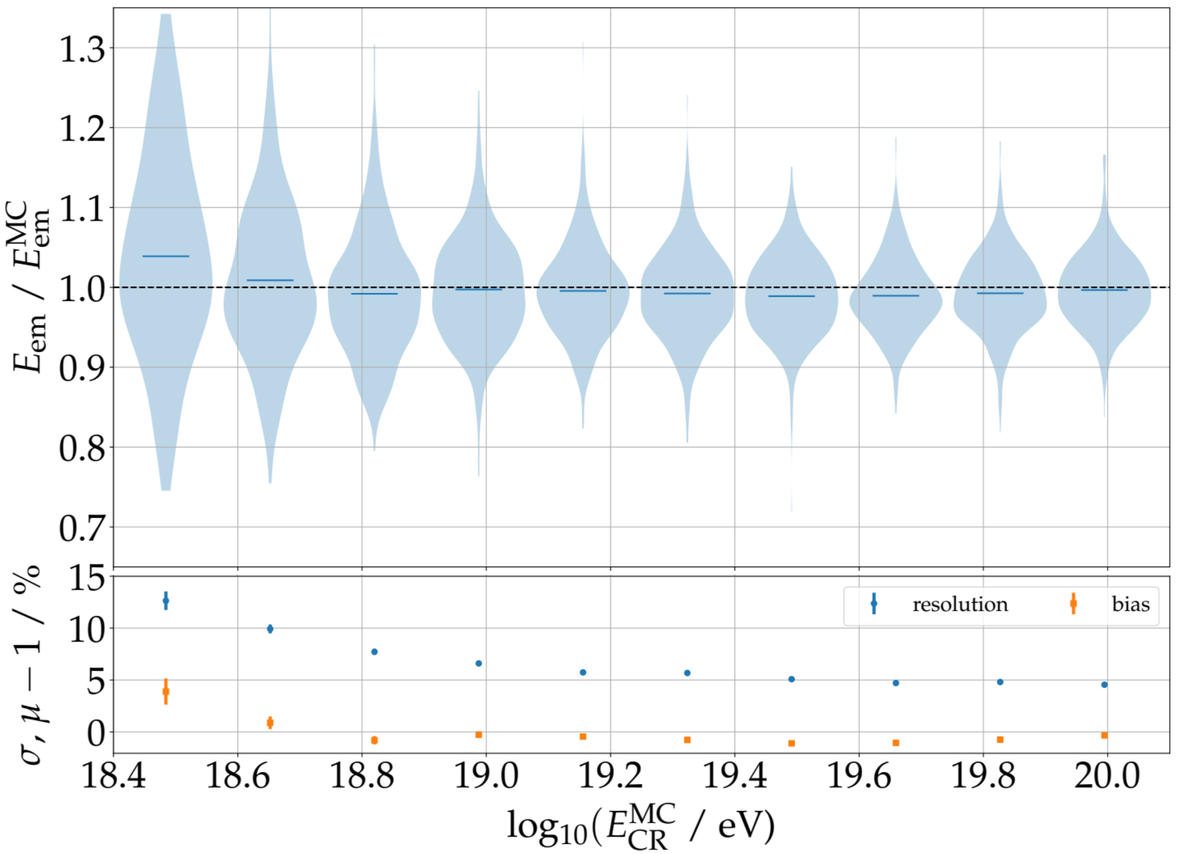
A. Aab et al., PRD 93 (2016) no.12, 122005

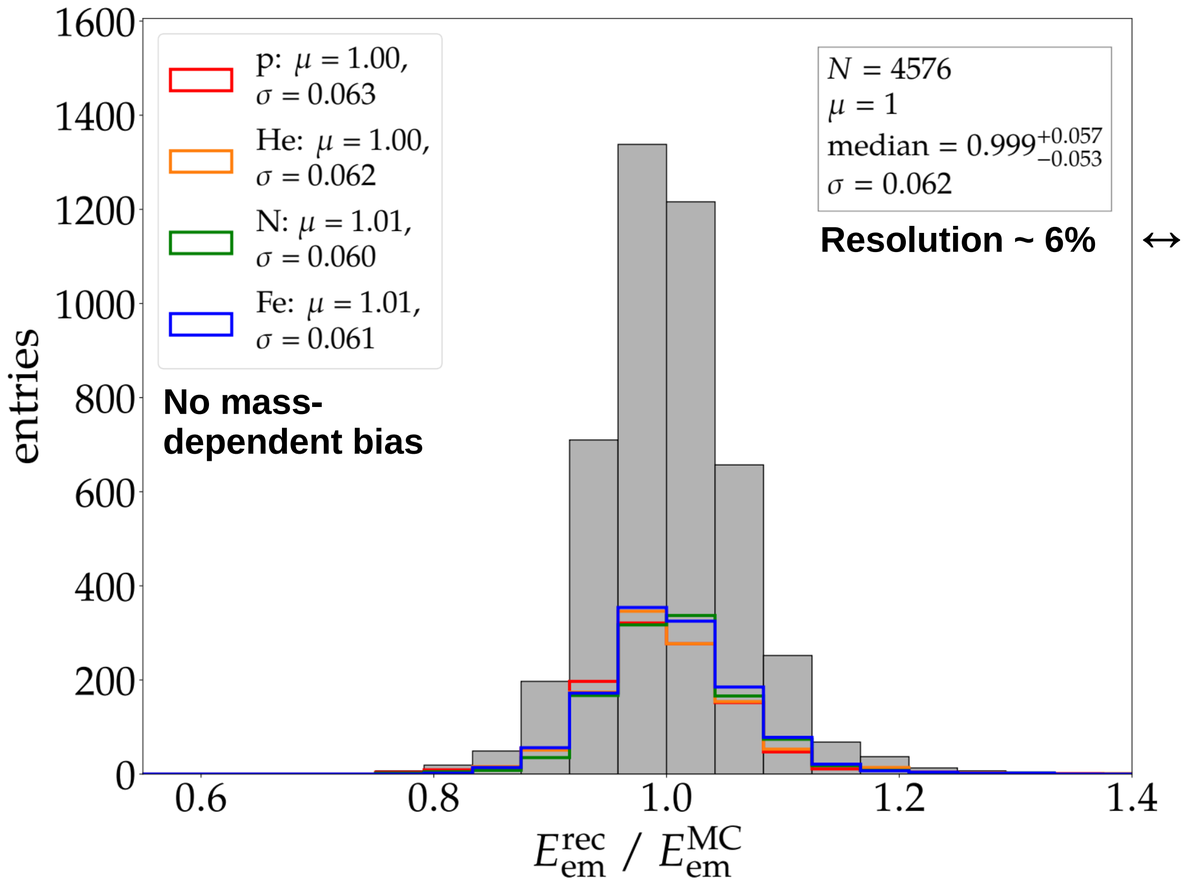
$E = 10^{19.4}\,eV \quad \theta = 72.3^\circ$



see Felix Schlüter, ARENA 2022

Shower reconstruction





↔ FD: 7%

showers with >= 5 signal stations and $\Theta \geq 68^\circ$

quality cuts: ~95% efficiency

resolution increases to 9% with 10% amplitude uncertainty

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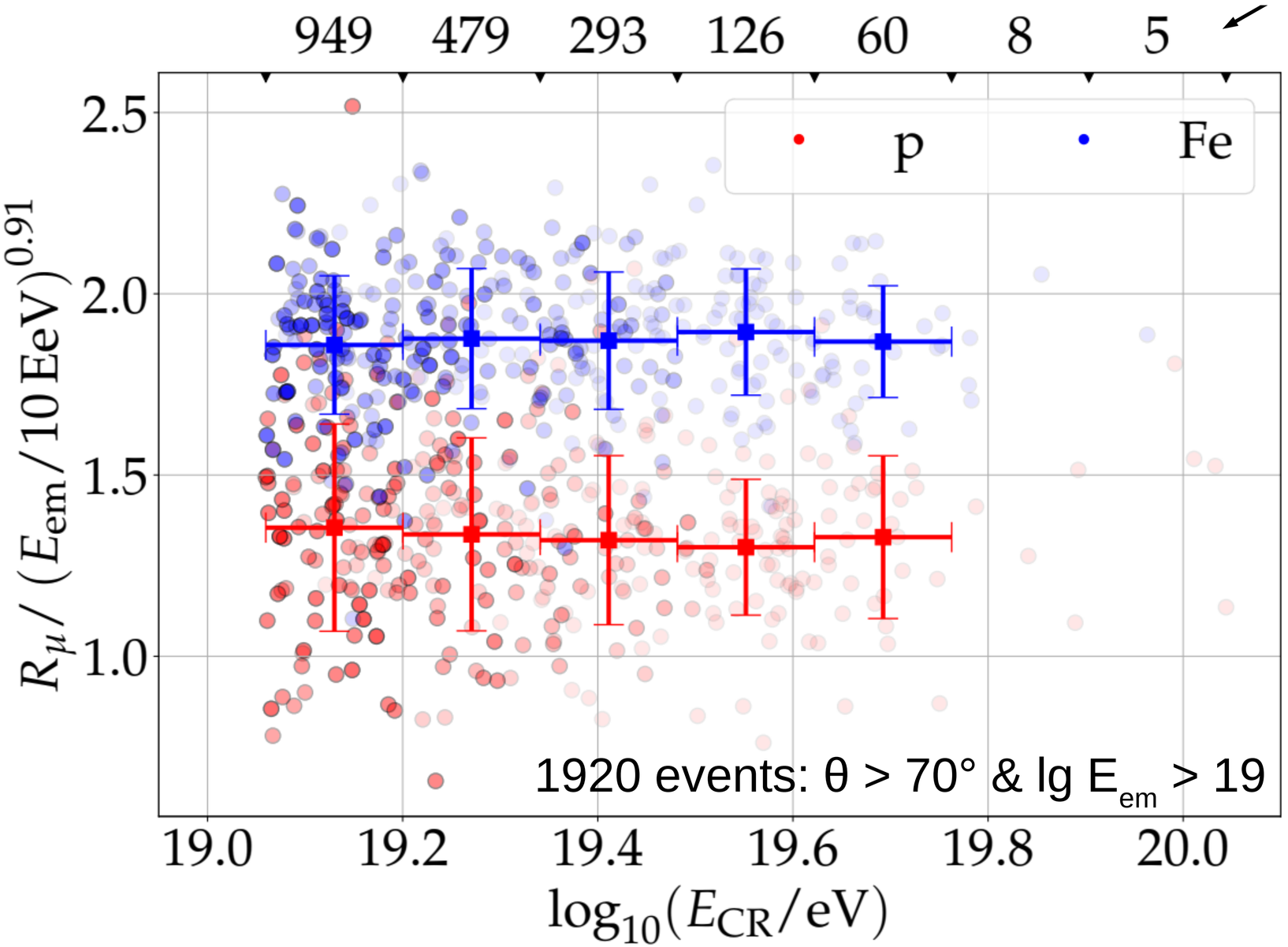
Particle type for each cosmic ray



50/50 p-Fe composition with 10 yr RD measurements

figure of Merit:

$$\mathrm{FOM} = \frac{|\langle r_p \rangle - \langle r_{Fe} \rangle|}{\sqrt{\sigma^2_{r_p} + \sigma^2_{r_{Fe}}}}$$

FOM = 1.61 ± 0.04

equal to X_{max} with perfect resolution

goal for the upgrade: 1.5

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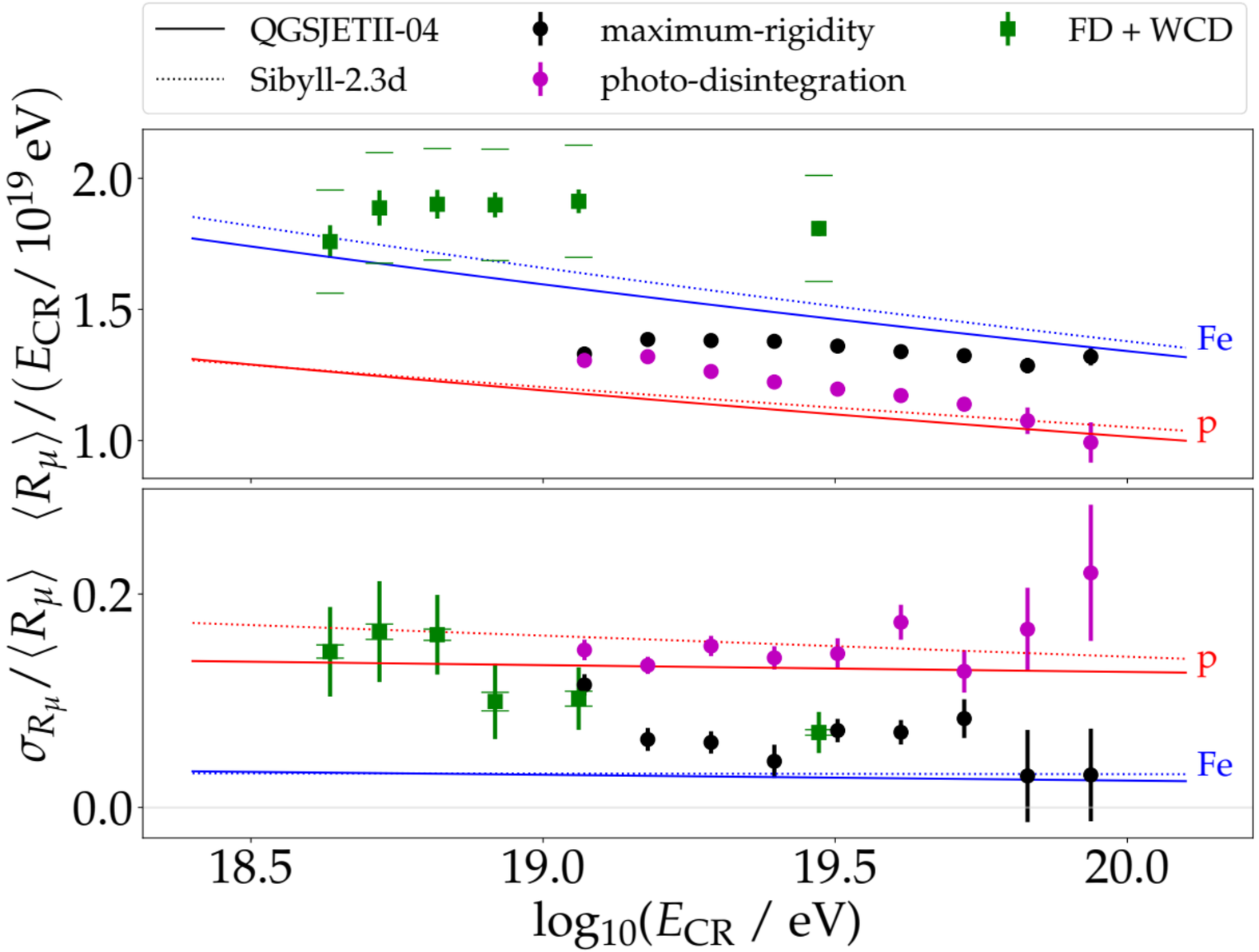
Particle physics in air showers



Muons in inclined air showers

—> investigation of muon deficit

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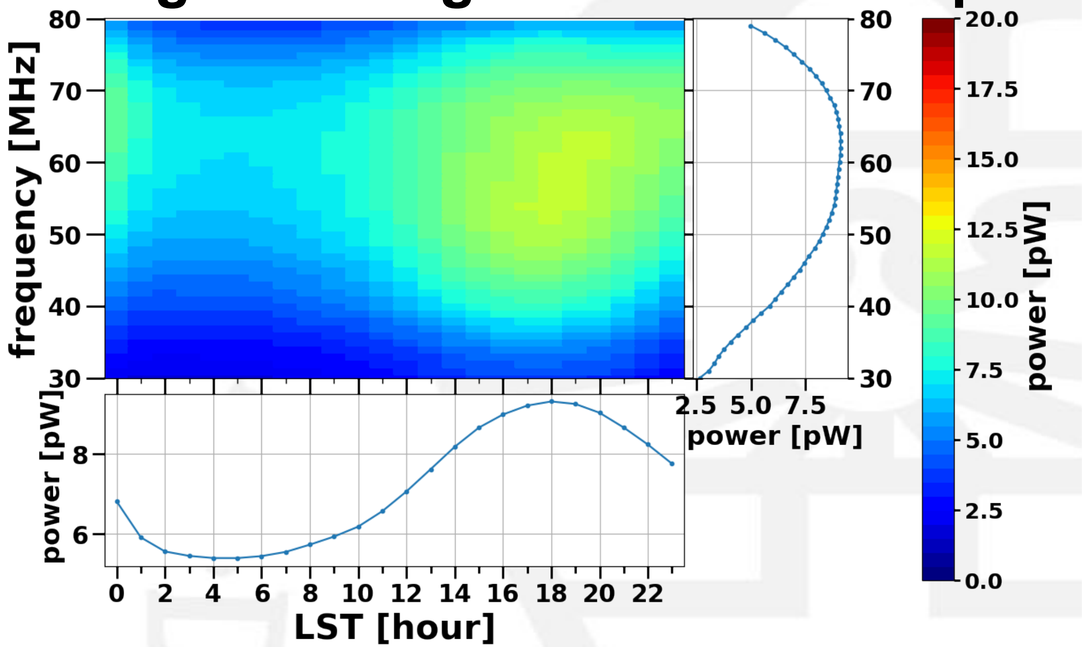
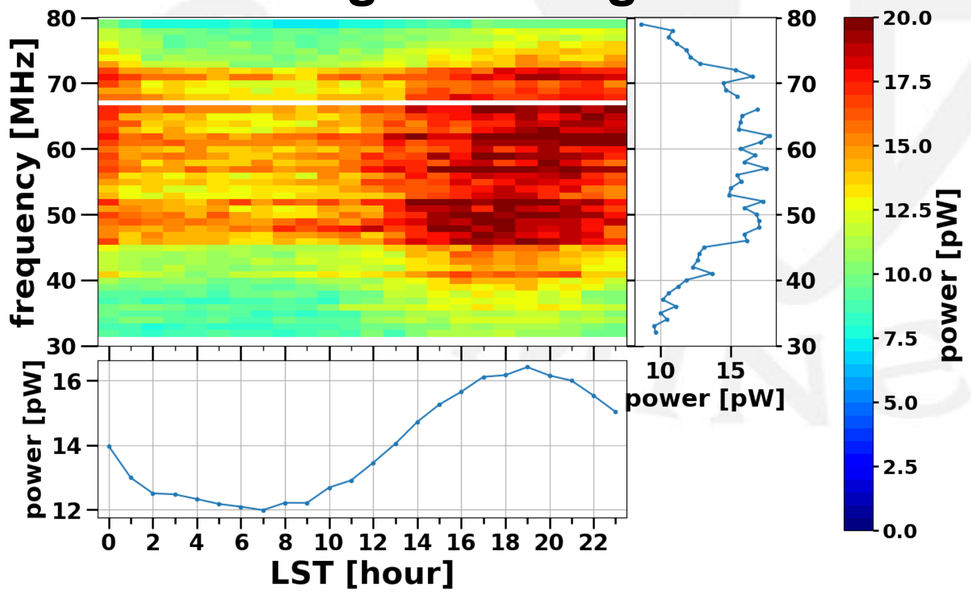
Calibration with Galactic signal

siderial modulation of Galactic signal

Simulated galactic signal in the EW loop



Measured noise & galactic signal in the EW loop



- **EW calibration constant: 1.03 ± 9.6% ± 2%**
- **NS calibration constant: 0.96 ± 9.7% ± 2%**
- **<u>Uncertainty caused by the Antenna model: max 1.5%</u>**
- **For more details see this proceeding: https://pos.sissa.it/395/**

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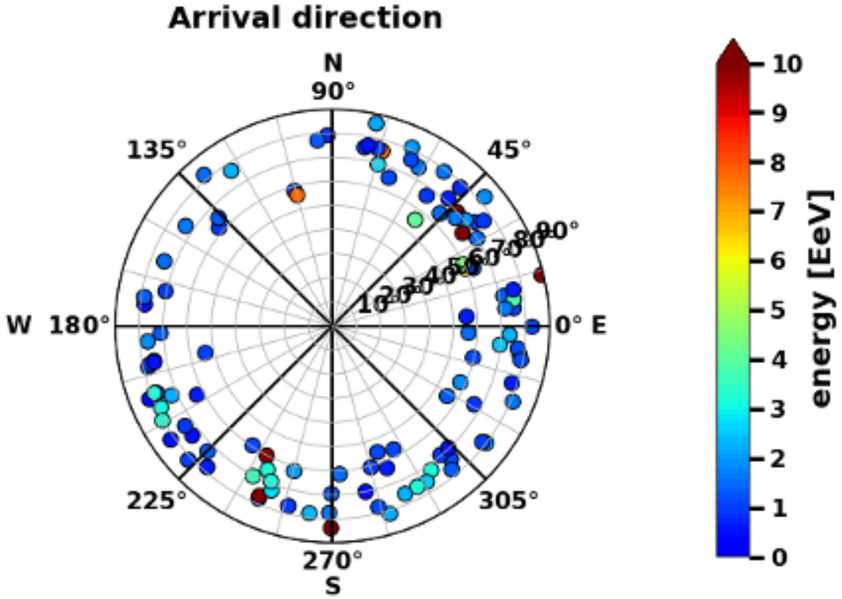
see Tomas Fodran, ARENA 2022

Air showers measured with engineering array

Nice 3-fold event above lg(18.4/eV)



Event 67742721 :-)
Time (UTC): 2022/4/19 18:14:47
Time (GPS): 1334427305 s 414520000 ns
Trigger: 4C1; 6T5 T5Has
Stations: 18 (Acc: 3, Bad: 41)

Global reconstruction (LDF + axis) (5)
$E = (7.74 \pm 1.10) \times 10^{18}$ eV
$(\theta, \phi) = (75.4 \pm 0.1, 74.1 \pm 0.1)$ deg
$(x,y) = (-19.10 \pm 0.10, 9.82 \pm 0.27)$ km
N19 = 1.4 ± 0.2
radius = 46.75 ± 0.27 km

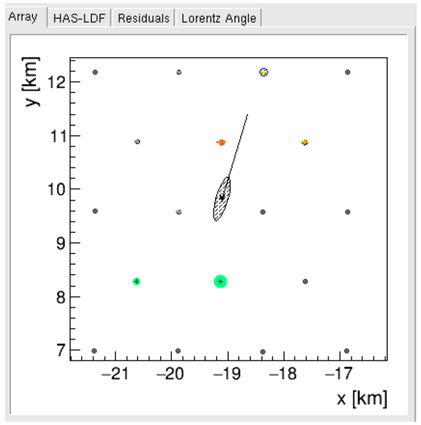
Monitoring
average stations age: 15.7 yr
T = 6.0°C; T (day) = 6.0°C

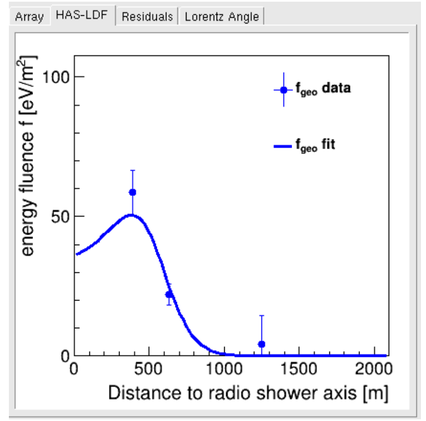
Event Info | MC Info | HAS LDF Info

Run: 0, Event: 67742721
GPS Time 1334427305 s 414520000 ns
UTC Date: 2022/04/19 · 18:14:47
Signal stations: 3 (3 with pulse)

Wavefront: (sphere)
$(\theta, \phi) = (76.49 \pm 3.3, 74.08 \pm 10.49)$ deg
geomagnetic angle $\alpha = 114.1°$
χ^2 / ndf = (< 0.01) / 1
radius = 30 ± 334 km

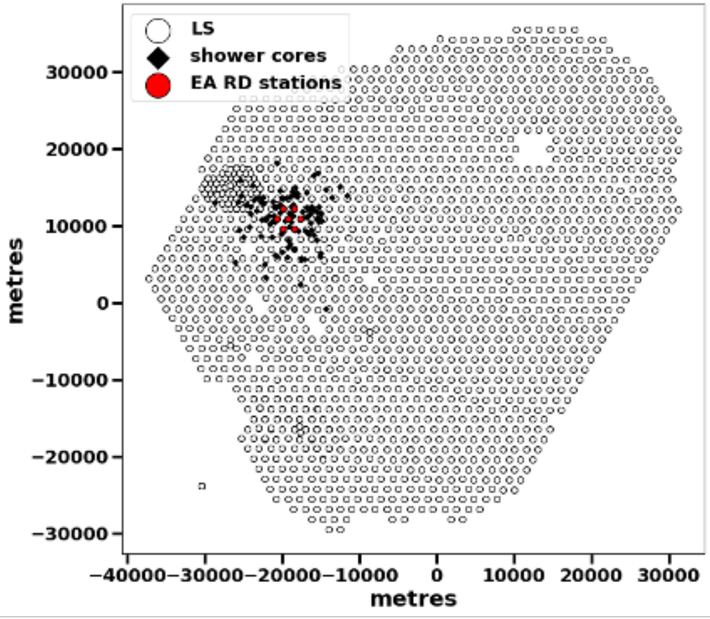
LDF: (HAS)
Emag energy = $(3.96 \pm 0.43) \times 10^{18}$ eV
Core (x, y) = (-19.10, 9.82) km

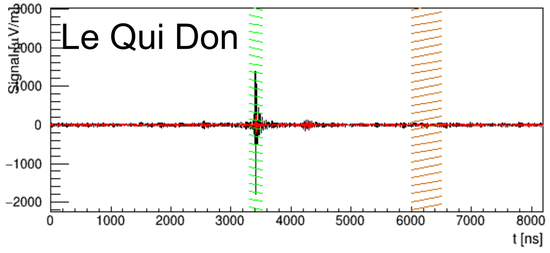


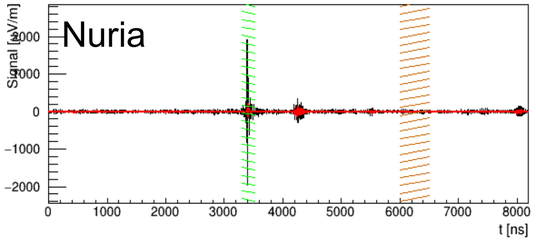


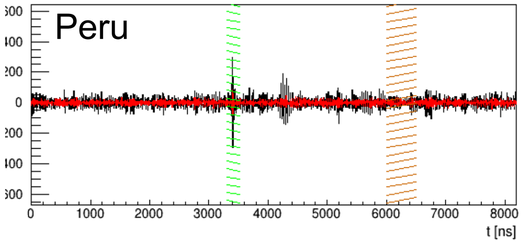
Station List | Options

Le Qui Don: fluence = 2397.0 +/- 272.5 eV/m^2, SNR = 3798.2, d = 583 m
Nuria Jr.: fluence = 2274.0 +/- 258.9 eV/m^2, SNR = 3418.4, d = 375 m
Peru: fluence = 120.8 +/- 19.1 eV/m^2, SNR = 134.6, d = 1196 m
Granada: fluence = -0.5 +/- 7.3 eV/m^2, SNR = 2.2, d = 1749 m
Ruca Malen: fluence = 0.4 +/- 3.2 eV/m^2, SNR = 1.8, d = 677 m
Jaco: fluence = -0.3 +/- 4.3 eV/m^2, SNR = 1.8, d = 1448 m









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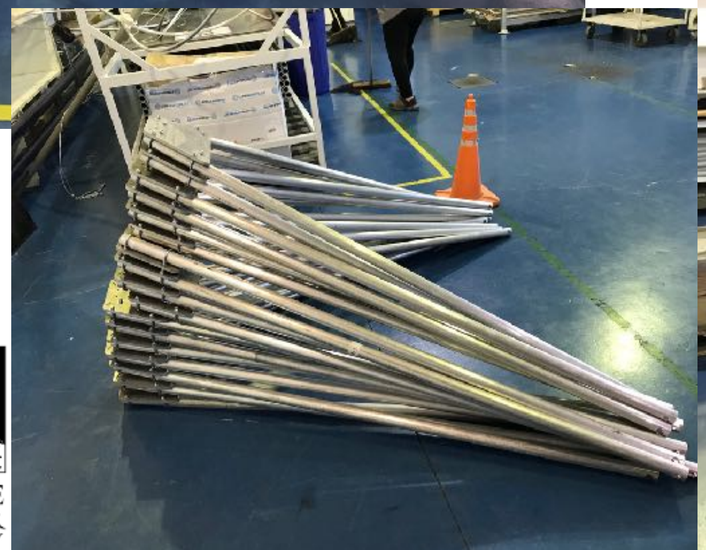
Mass production of RD started at Observatory



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Status and prospects of the Radio Detector of the Pierre Auger Observatory

Radio Detector will enhance the Pierre Auger Observatory with unique features

End-to-end simulation yields excellent performance

Calibration with Galactic emission verified with engineering array

Air showers detected with engineering array match expectations

Expect to complete installation in 2023

Jörg R. Hörandel for the Pierre Auger Collaboration
http://particle.astro.ru.nl