Karlsruhe Institute of Technology

VRIJE UNIVERSITEIT BRUSSEL

PIERRE AUGER OBSERVATORY

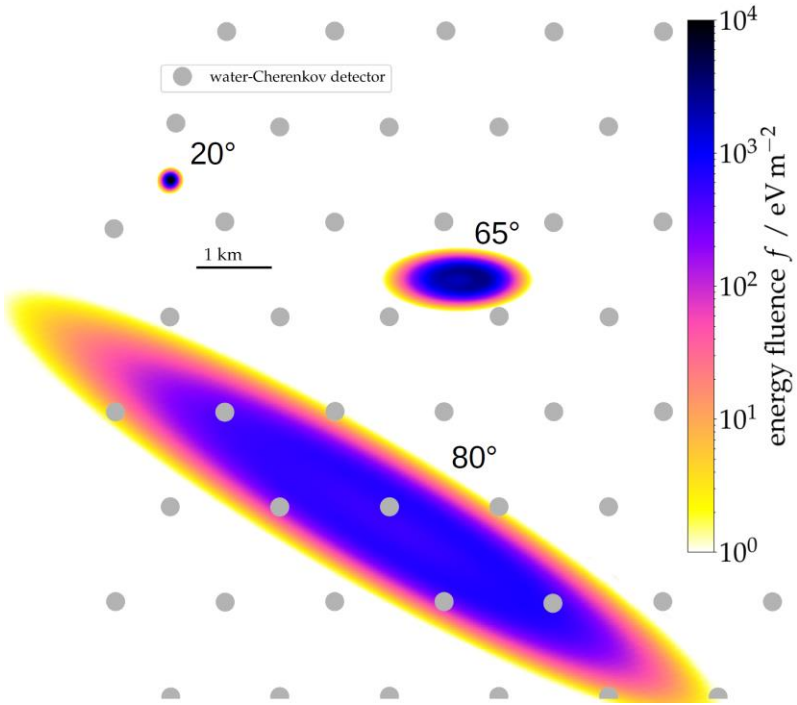
The Radio Detector of the Pierre Auger Observatory – Status and expected performance

Tim Huege (KIT & VUB) for the Pierre Auger Collaboration

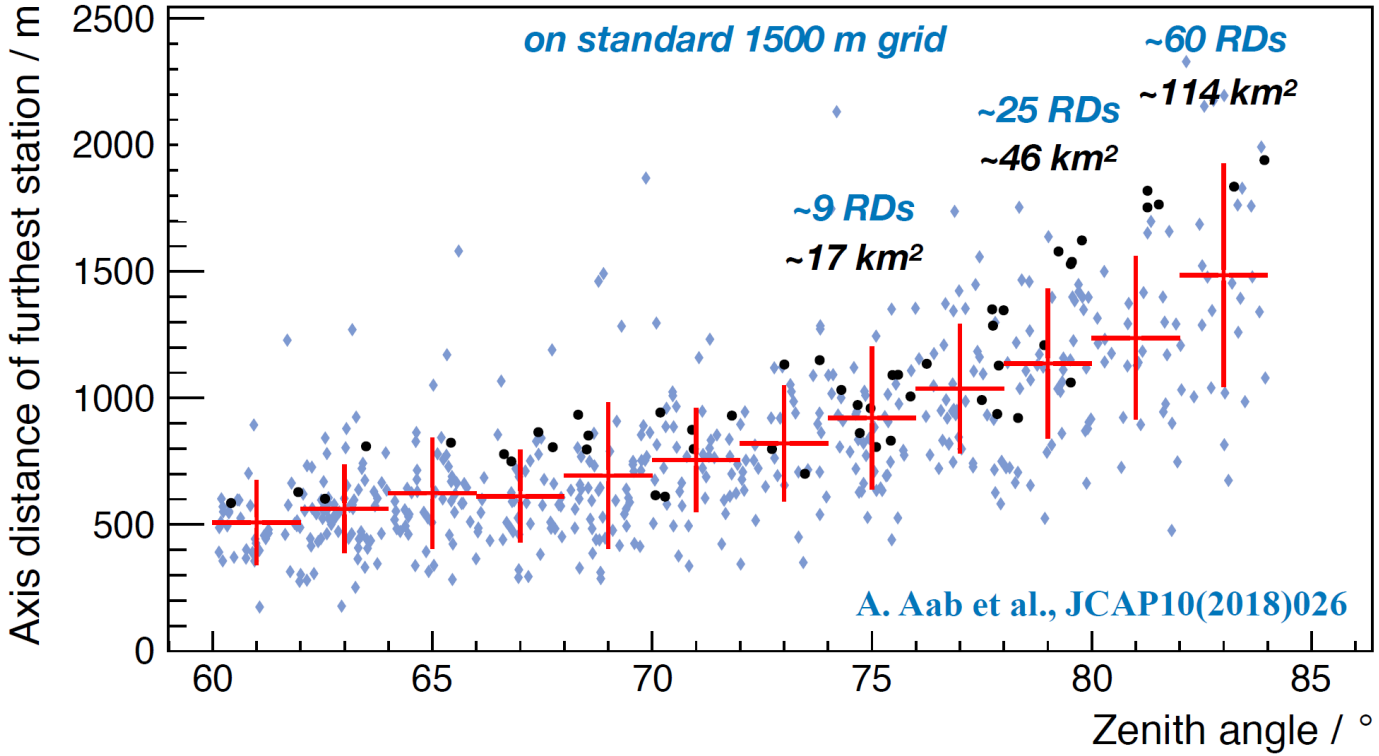
Radio detection of extensive air showers

- Provides calorimetric measurement of electromagnetic energy of air showers
- 100% duty cycle, atmosphere uncritical
- For vertical showers proven to provide Xmax information (see talk B. Pont)
- Zenith Angle ⇔ Spacing ⇔ CR energy
  - Vertical showers need dense arrays, access low energies
  - Inclined showers long predicted to be measurable with sparse arrays, access high energies

see T. Huege, A. Haungs, UHECR2014, arXiv:1507.07769

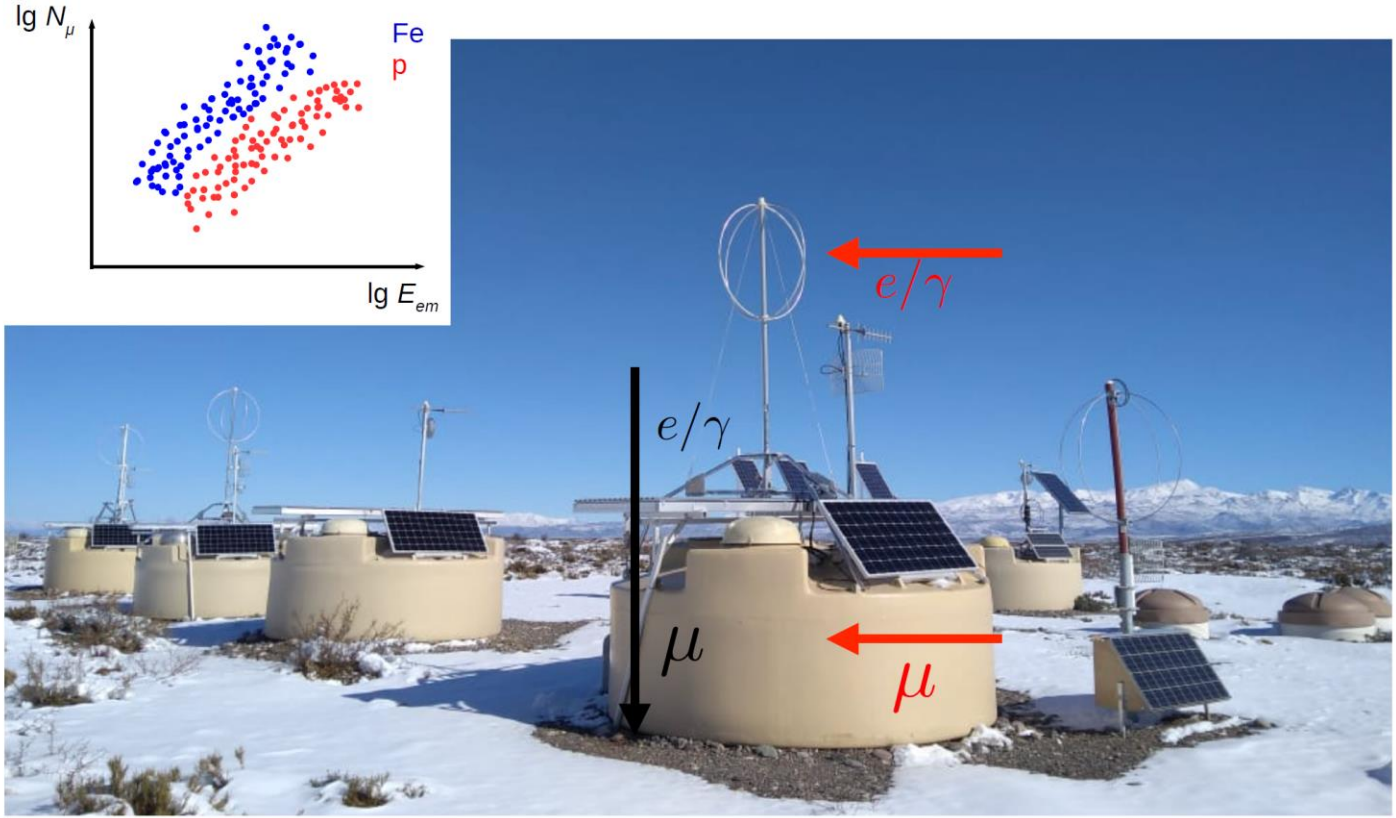


Auger Engineering Radio Array results



- More than 500 inclined air showers detected with ~4 km^2 of AERA
- Inclined air showers indeed measurable with arrays with >1km spacing
- Can measure at highest energies with 1.5 km Auger grid

As part of AugerPrime: Auger Radio Detector

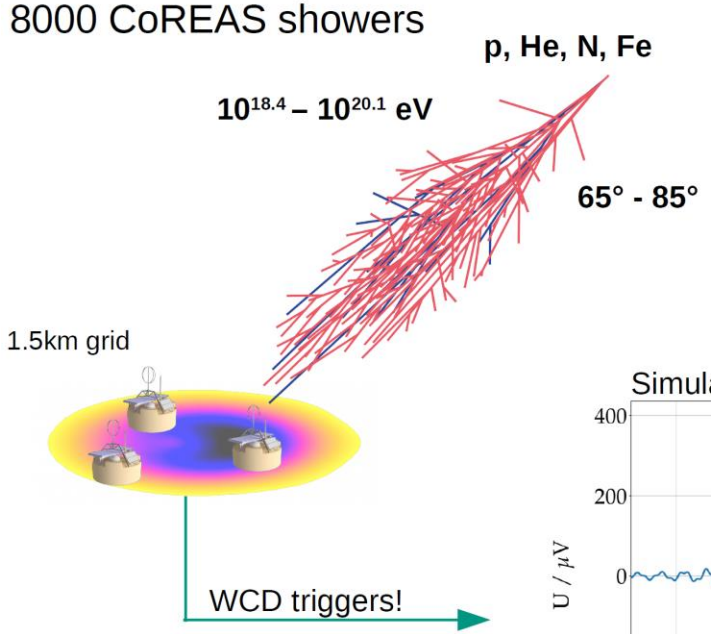


- Mount a dual-polarized radio antenna (30-80 MHz) on each SD station
- 1660 radio antennas over 3000 km^2
- Mass sensitivity for inclined air showers:
  - radio: em
  - WCD: muons
- Beautifully complementary to WCD/SSD

Expected Performance

see PoS(ICRC2021)228

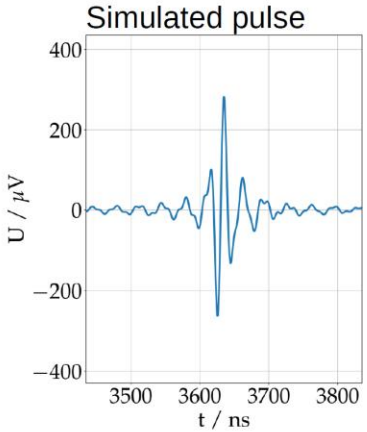
Fully realistic end-to-end simulation study

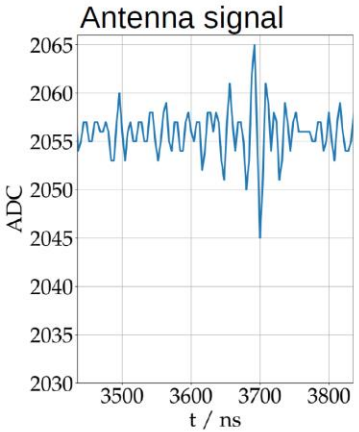


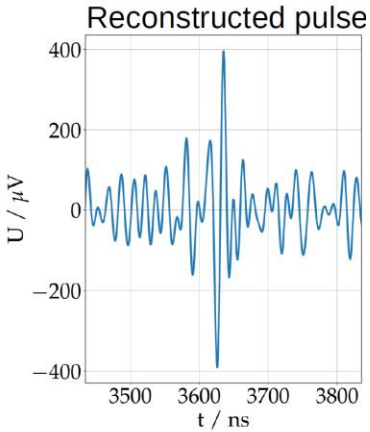
Simulate instrumental response

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

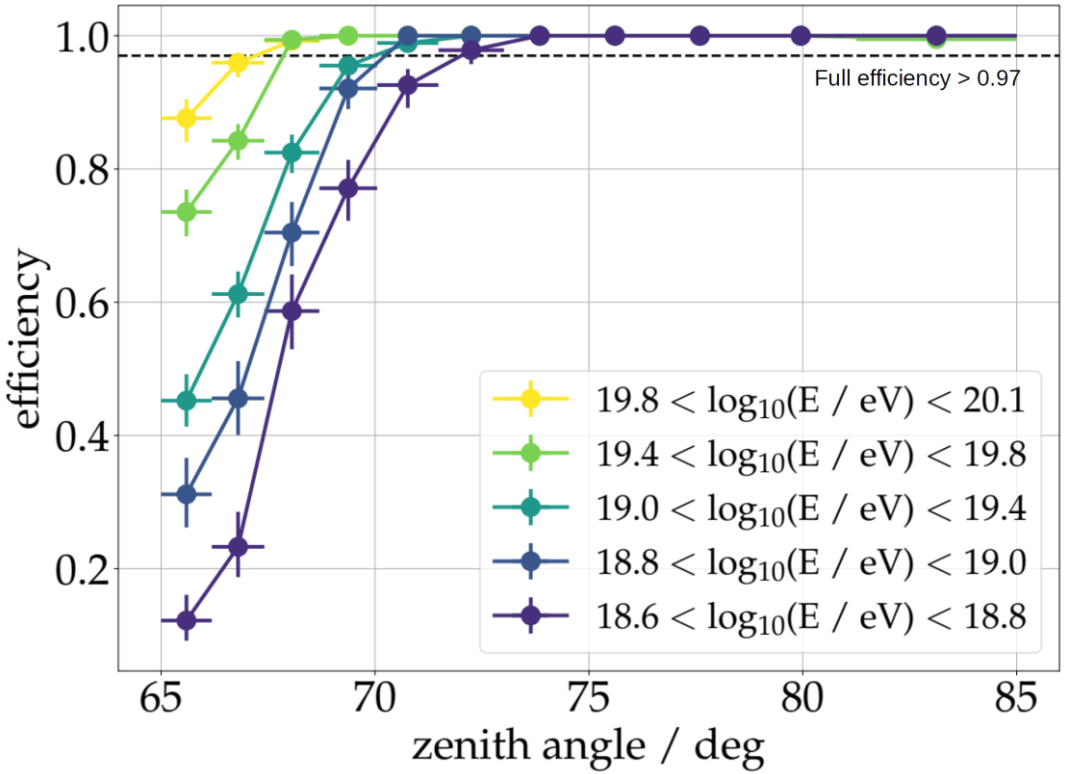
- Including uncertainties (σ_A = 5%)
- Measured noise





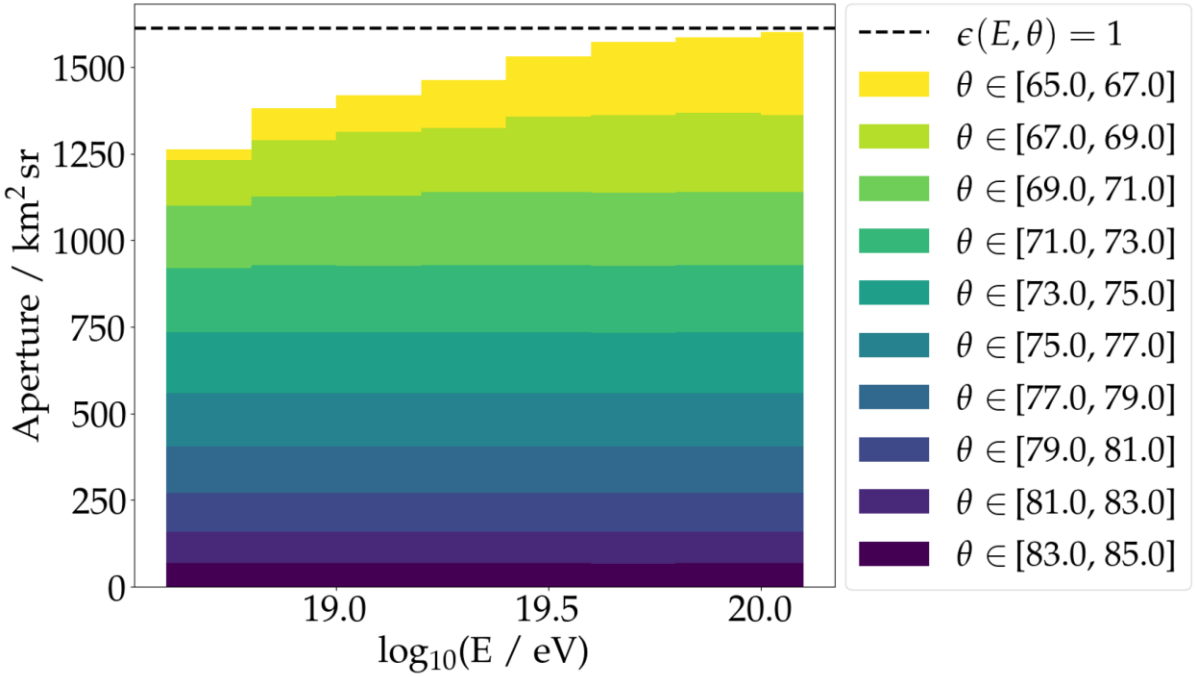


Detection efficiency



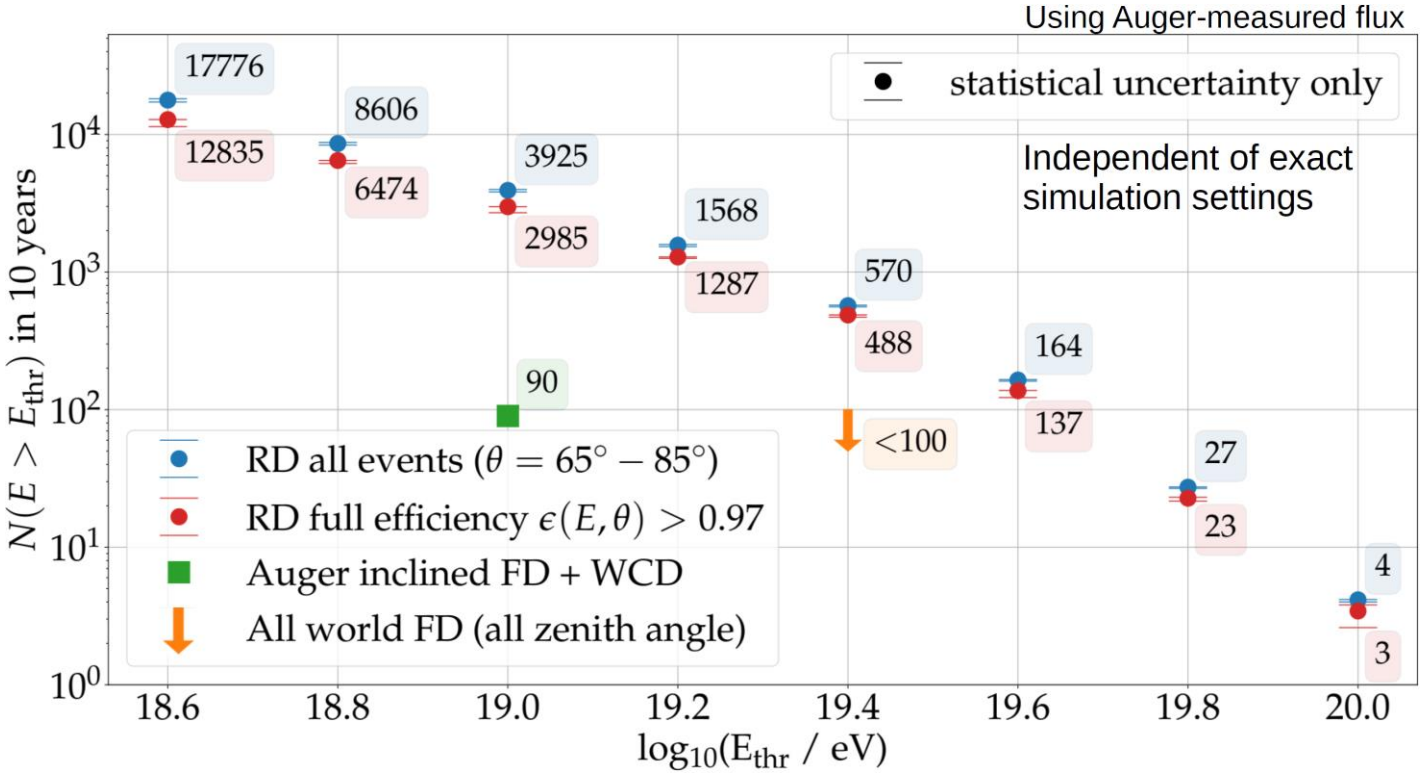
- Requires measurable signal in at least three radio antennas
- 100% efficiency for θ>70° and E>$10^{18.8}$ eV

Predicted aperture



- Lower zenith angles make large contribution, but need high energy for full efficiency
- Higher zenith angles fully efficient, but make smaller contribution
  - contained events

Expected event statistics in 10 years

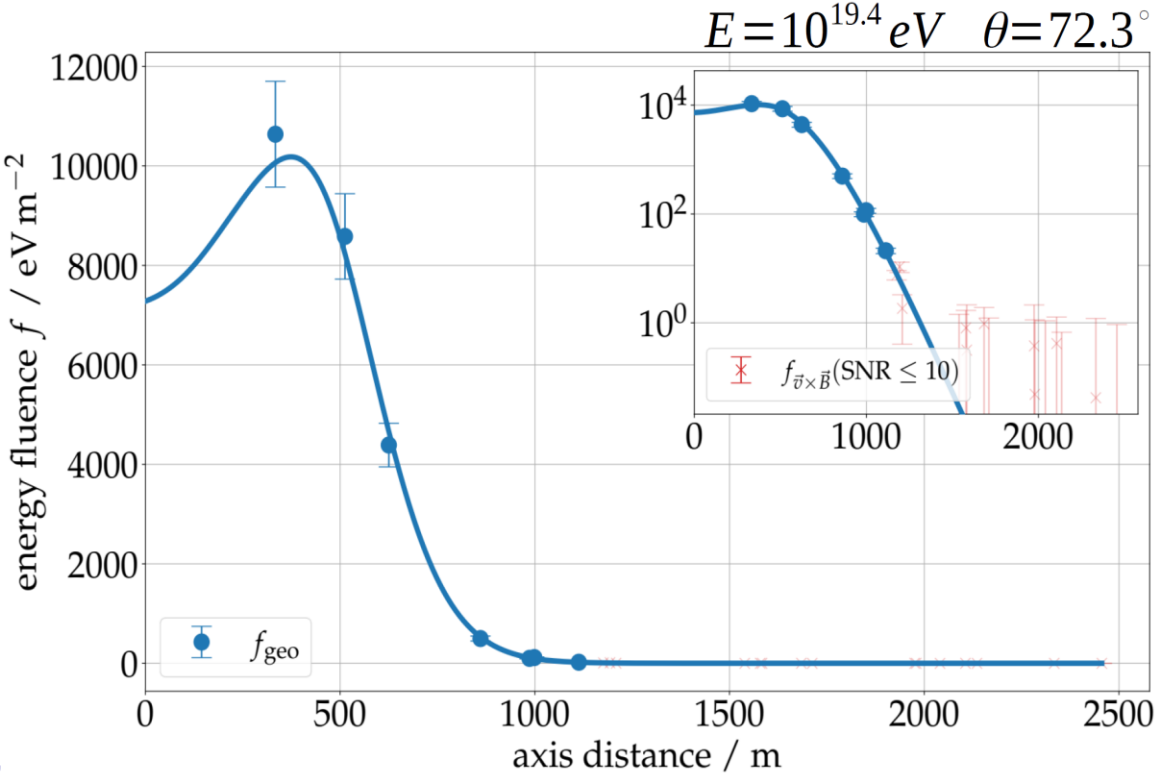


- Integral spectrum from folding flux with aperture
- Expect ~4000 events beyond 10^{19} eV

Event reconstruction

Newly developed LDF model*

- 2 parameter + core coordinates
- Derive start values from WCD
  (use radio rec. arrival direction)
- Integral yields energy estimator



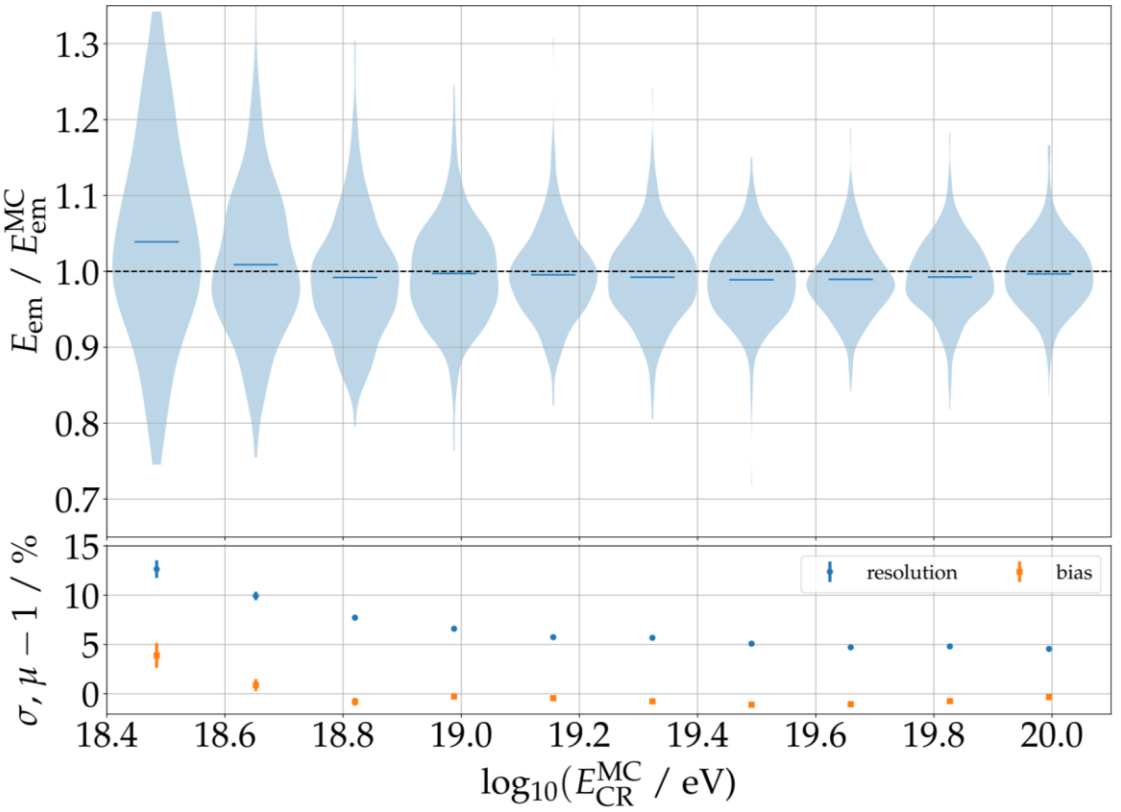
* Signal model and event reconstruction for the radio detection of inclined air showers, F. Schlüter, T. Huege, JCAP submitted, arXiv:2203.04364

Predicted energy resolution of Auger RD

Showers with at least 5 signal stations and θ > 68°

quality cuts: ~95% efficiency

Resolution improves with energy



Predicted energy resolution of Auger Radio Det.

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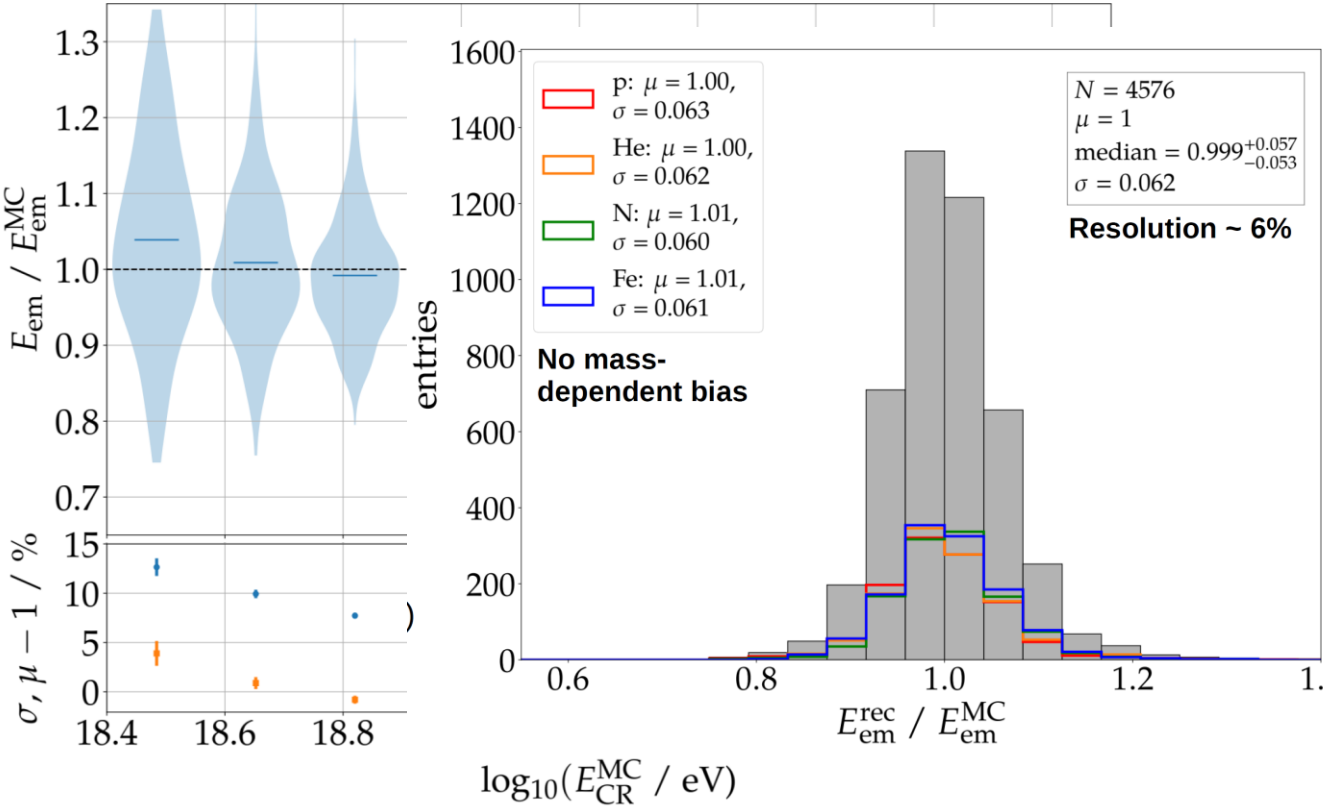


Expected mass composition sensitivity

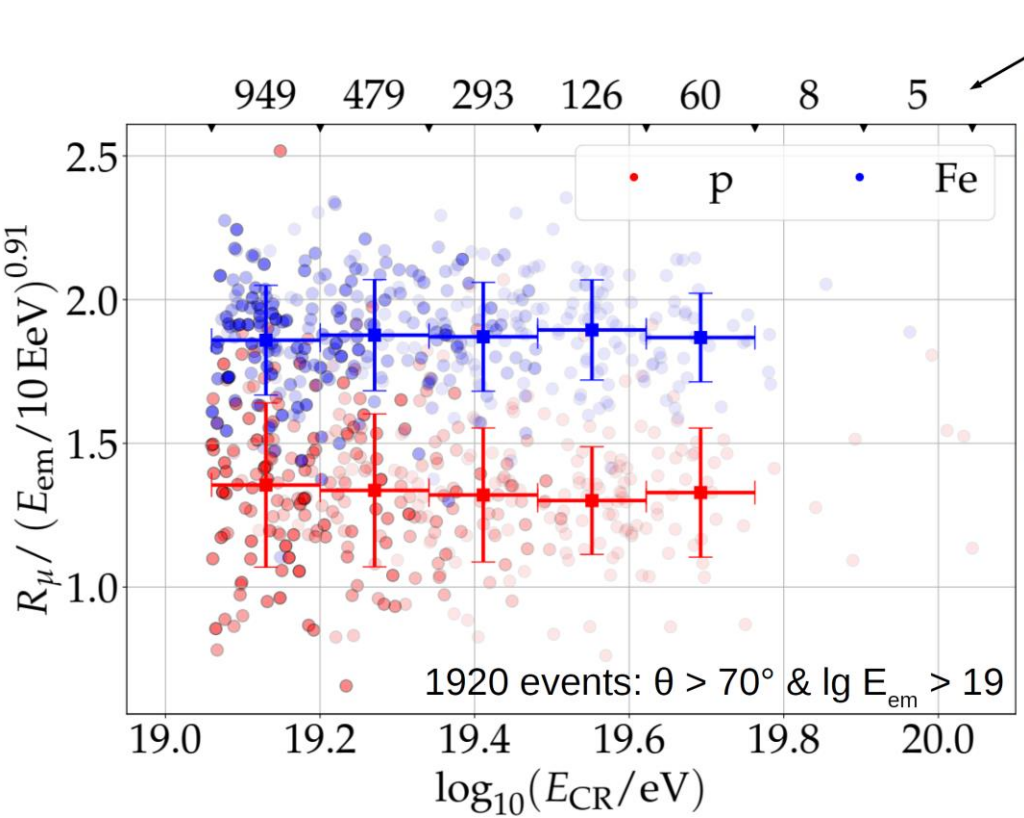


Figure of Merit:

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

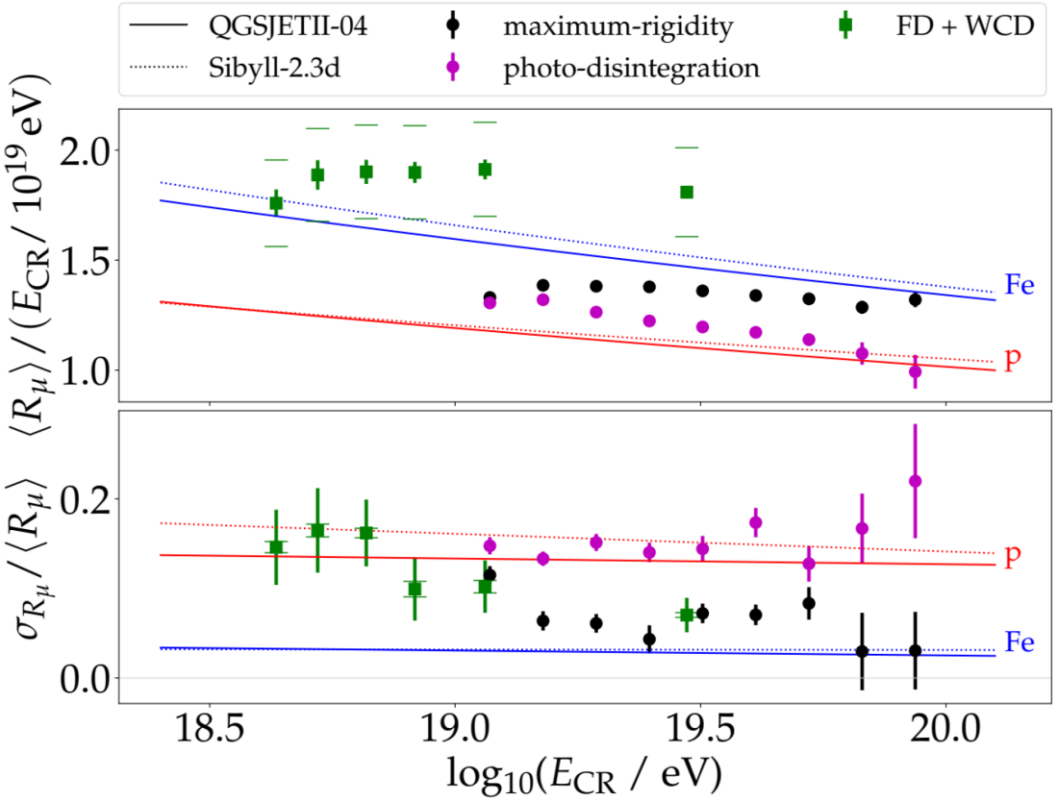
FOM = 1.61 ± 0.04

Equal to X_{max} with perfect resolution!

Goal for the Upgrade: 1.5

see also proof of principle study with AERA, PoS(ARENA2022)

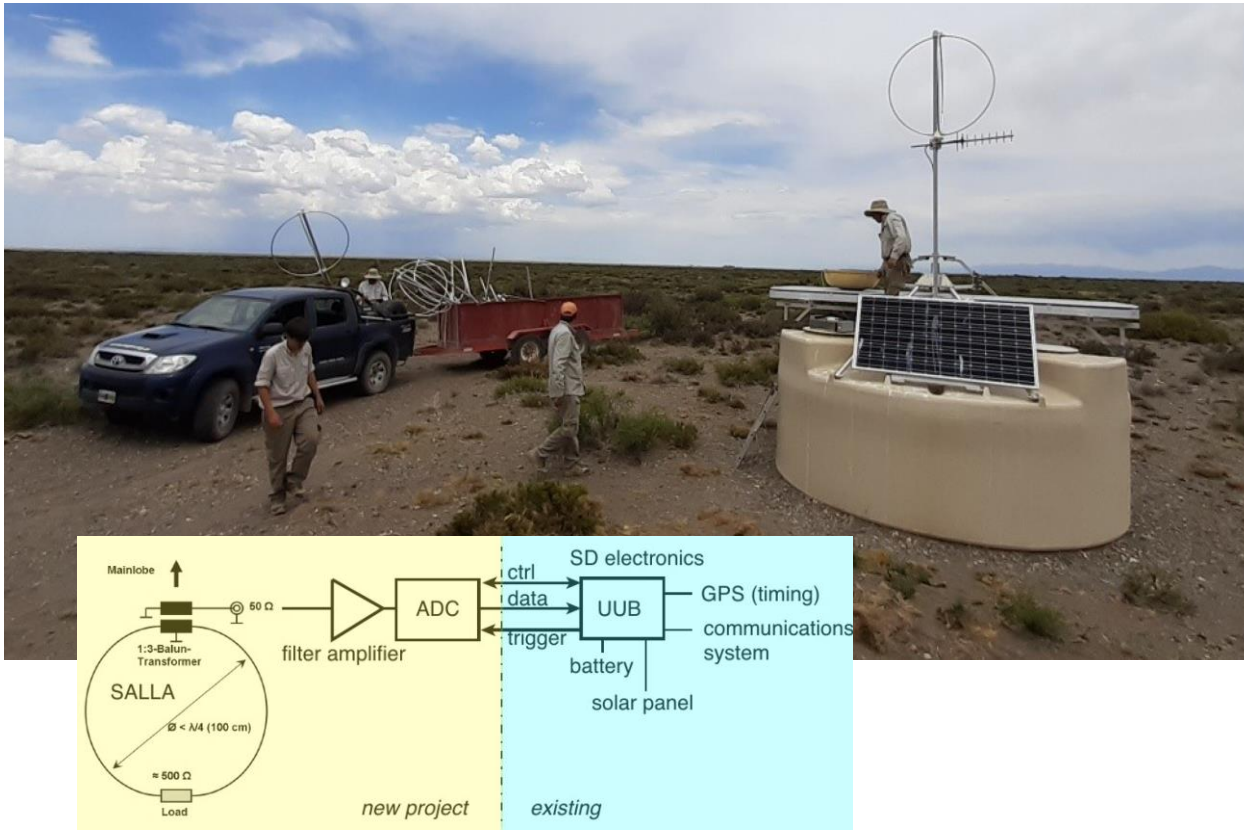
Prediction for number measurements



- Very high-statistics measurements of muon number with WCD+RD at highest energies
- Especially measurement of the variation of the muon number with will be very powerful

Status and Outlook

RD Engineering Array



- 10 prototype stations in the field, 7 measuring in a hexagon since 11/2019
- Mechanical and electronics design finalized and proven to work long-term
- Trigger for now from WCD, but working on hybrid trigger

Galactic background measured ⇒ calibrator

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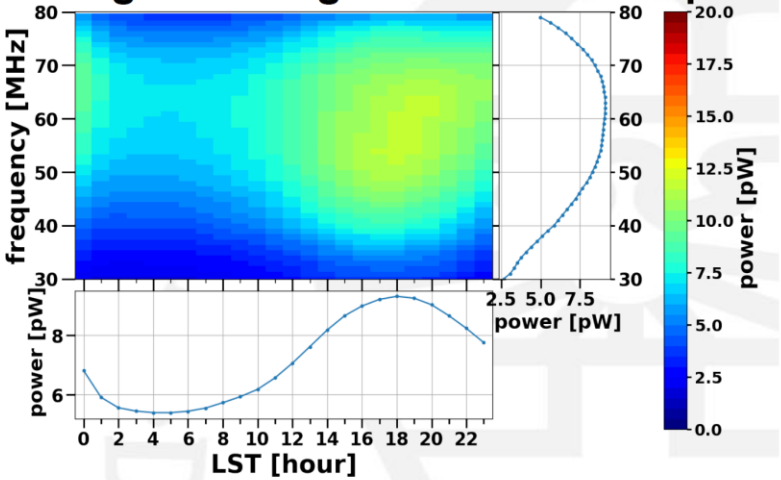
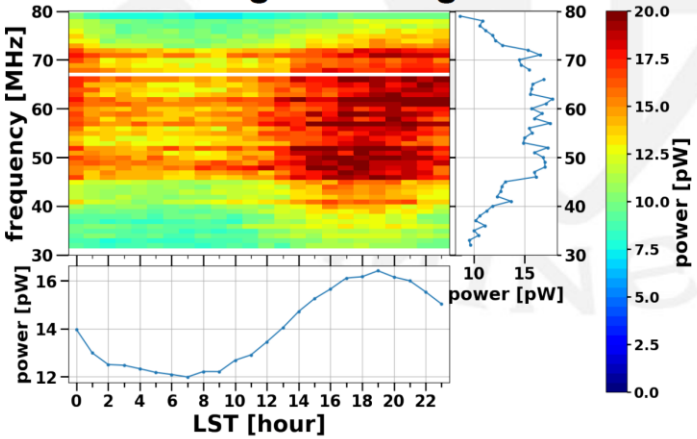
Simulated galactic signal in the EW loop



Measured noise & galactic signal in the EW loop



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

Example extensive air shower measured with RD

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

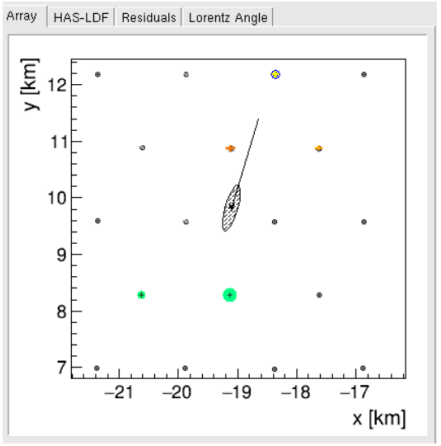
Monitoring
average stations age: 15.7 yr
T = 6.0°C; T (day) = 6.0°C

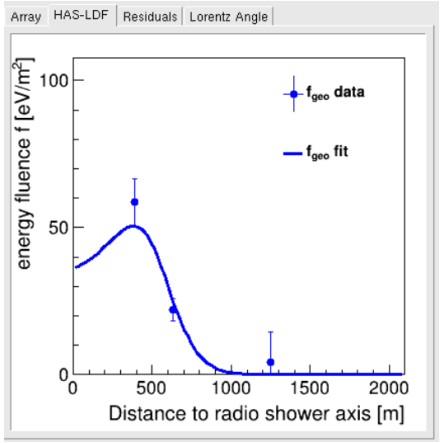
Event Info | MC Info | HAS LDF Info

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

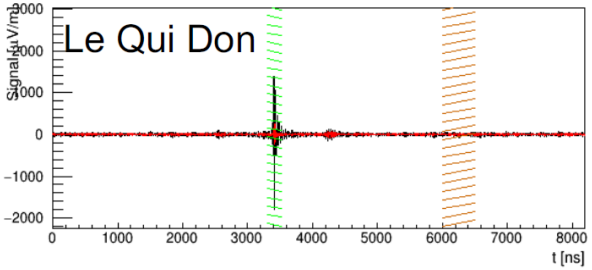
Wavefront: (sphere)
$(\theta, \phi) = (76.49 \pm 3.3, 74.08 \pm 10.49)$ deg
geomagnetic angle $\alpha = 114.1°$
χ^2 / ndf = (< 0.01) / 1
radius = 30 ± 334 km

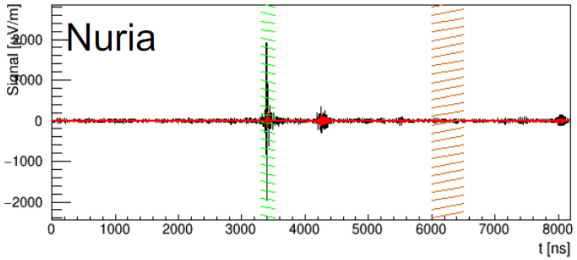
LDF: (HAS)
Emag energy = $(3.96 \pm 0.43) \times 10^{18}$ eV
Core (x, y) = (-19.10, 9.82) km

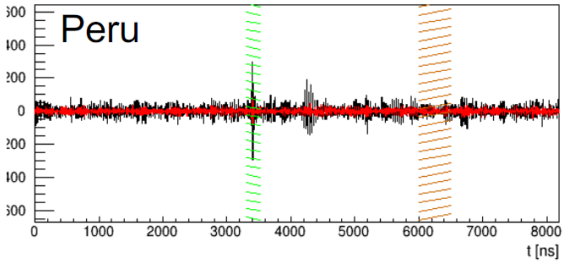




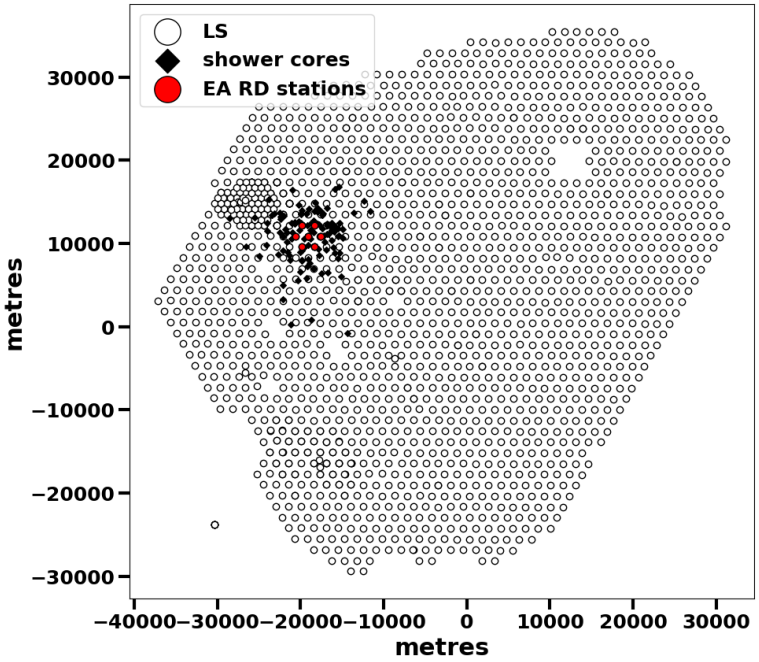
- Clear pulsesin very clean traces

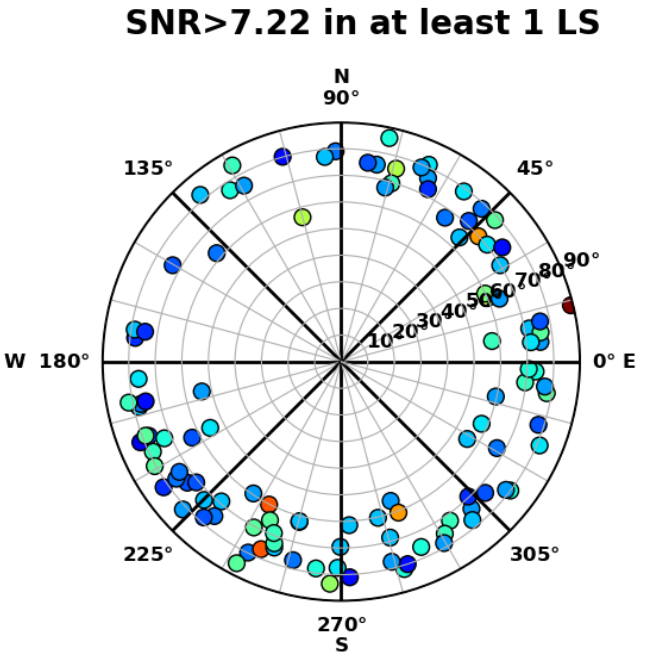


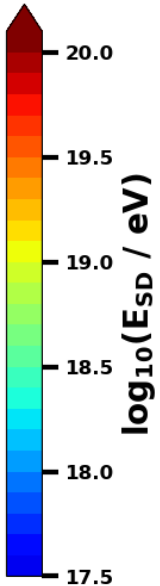




Analysis of ~1 year of RD EA data



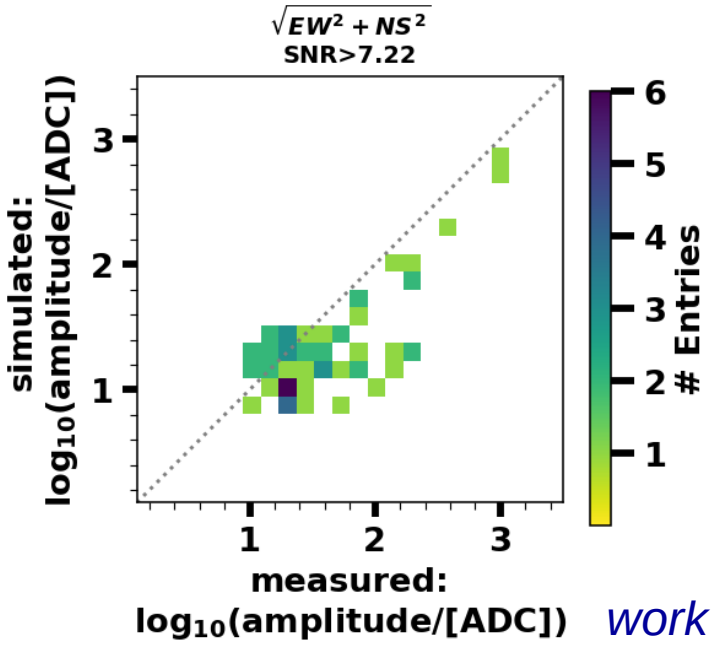




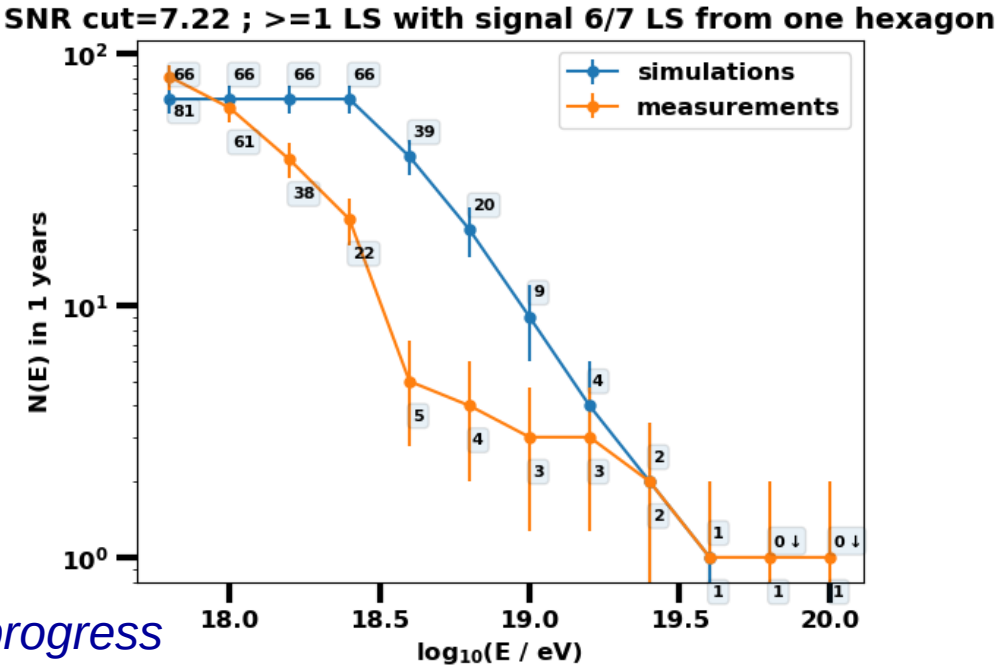
- 114 events, 158 traces with detectable radio signal
- Typical north-south asymmetry (angle to geomagnetic field)

work in progress

Comparison with CoREAS simulations

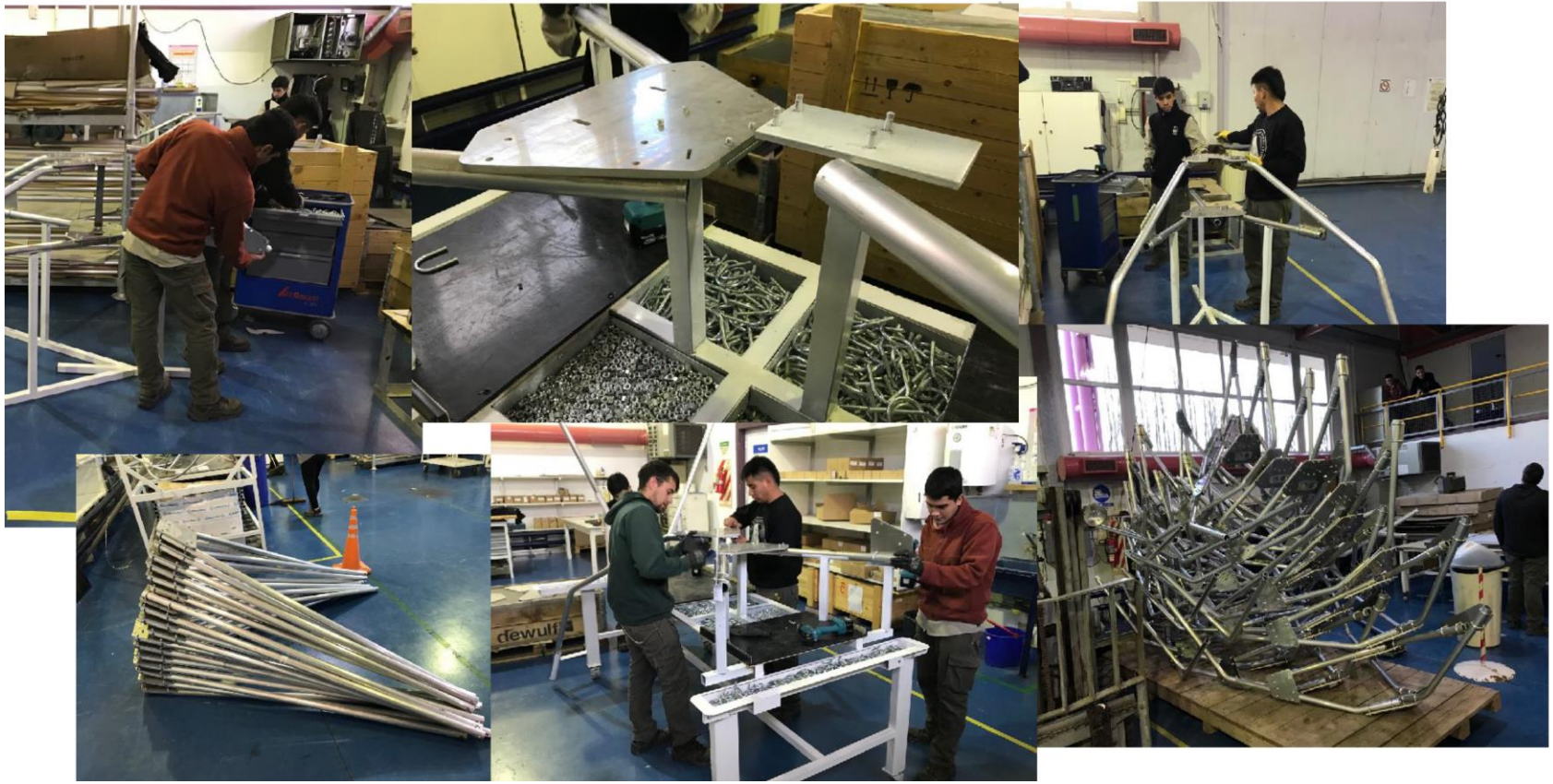


work in progress



- Observed signal strengths and event rates in reasonable agreement with simulations (low statistics, selection effects may matter)

Mass production ongoing, full deployment in 2023



Summary

- We are equipping the whole of Auger with 1660 radio antennas
- This will allow mass-sensitive measurements of inclined air showers
- Expected performance from end-to-end simulation study
  - ~4000 events measurable beyond 10^{19} eV in 10 years
  - Expect electromagnetic energy resolution of ~6%
  - Very good mass composition sensitivity/muon number measurements
- Design proven, mass production ongoing, deployment complete in 2023