Karlsruhe Institute of Technology

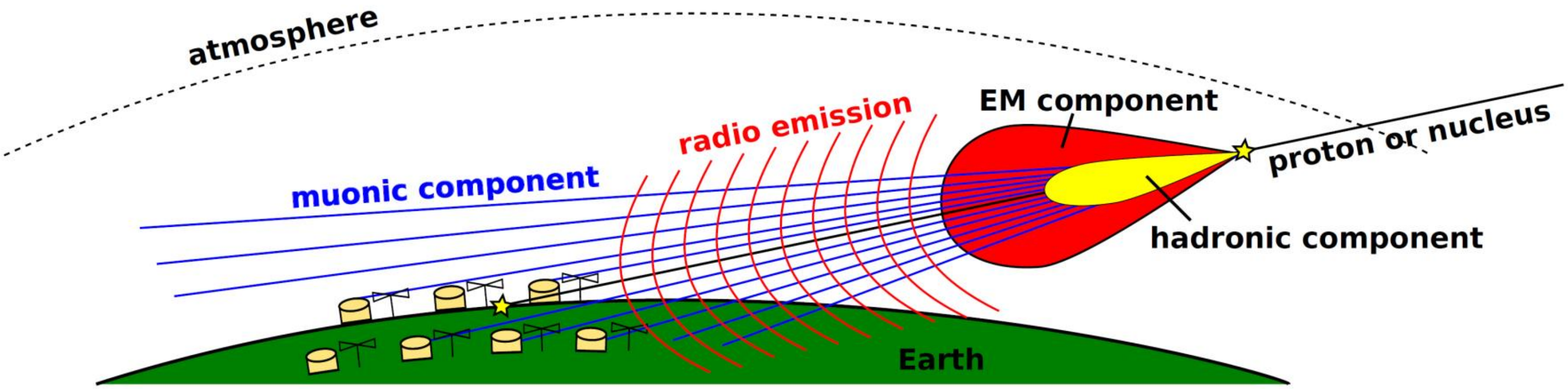
VRIJE UNIVERSITEIT BRUSSEL

PIERRE AUGER OBSERVATORY

Radio detection and its relevance for air shower physics

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

Air-shower radio emission



- EAS emit very short, *coherent*, forward-beamed radio pulses
- Typical detection bands: 30-80 MHz, 50-200 MHz, but up to 1 GHz
- Originally discovered 1965 (after predictions), field revived in early 2000s
- Nowadays very mature technique, both experimentally and theoretically

Simulating radio emission

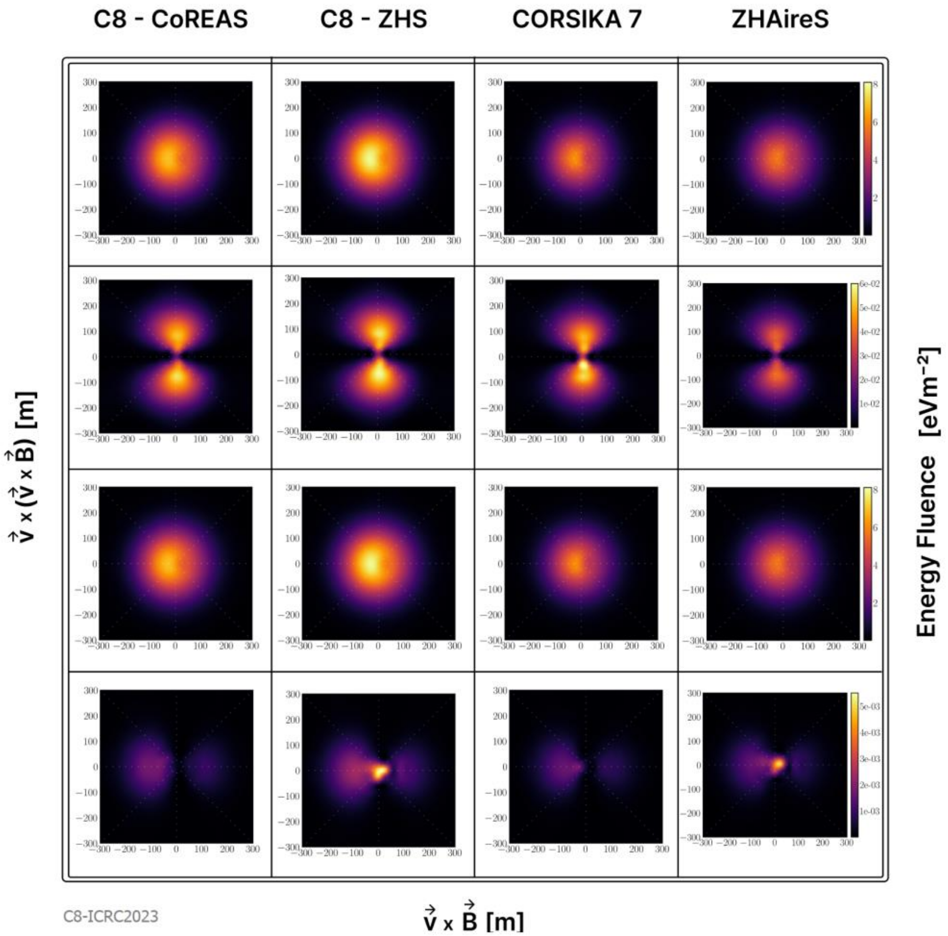
- Within particle MC (C7, C8, AireS) calculate radio emission from each e^- and e^+
- „first-principles“ classical electrodynamics
- Excellent agree-ment with data

modulus

$$\vec{v} \times \left(\vec{v} \times \vec{B}\right)$$

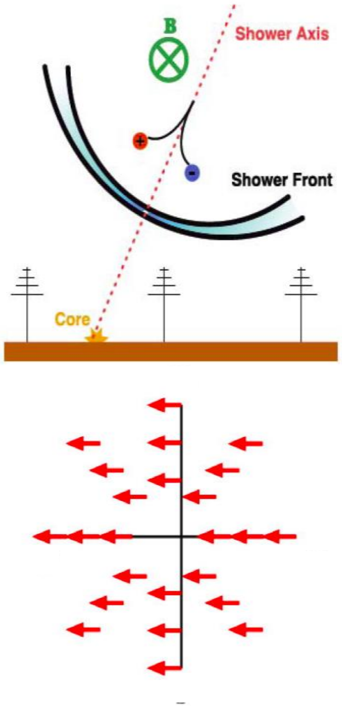
$$\vec{v} \times \vec{B}$$

$$\vec{v}$$



N. Karastathis for C8
PoS(ICRC2023)425

Radio emission physics paradigm



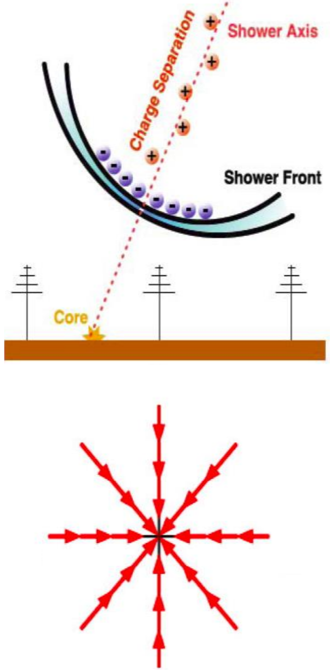
„*v* x *B*“

- primary effect: geomagnetic field induces *time-varying* transverse currents

Kahn & Lerche (1967)

- secondary effect: *time-varying* net charge excess (Askaryan effect)

Askaryan (1962,1965)

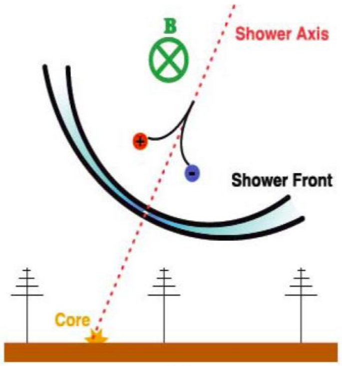


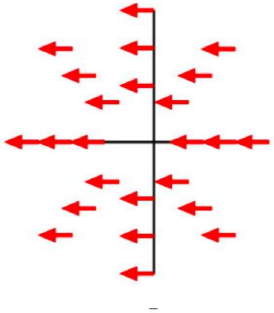
„*radial*“

radio = electromagnetic component

Diagrams by H. Schoorlemmer & K.D. de Vries

Radio emission physics paradigm – refined





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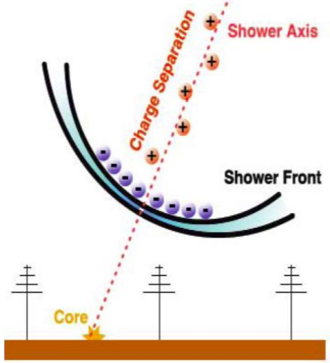
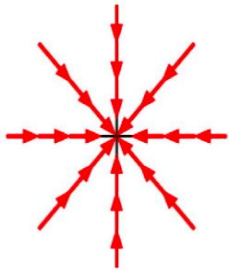




„**radial**“

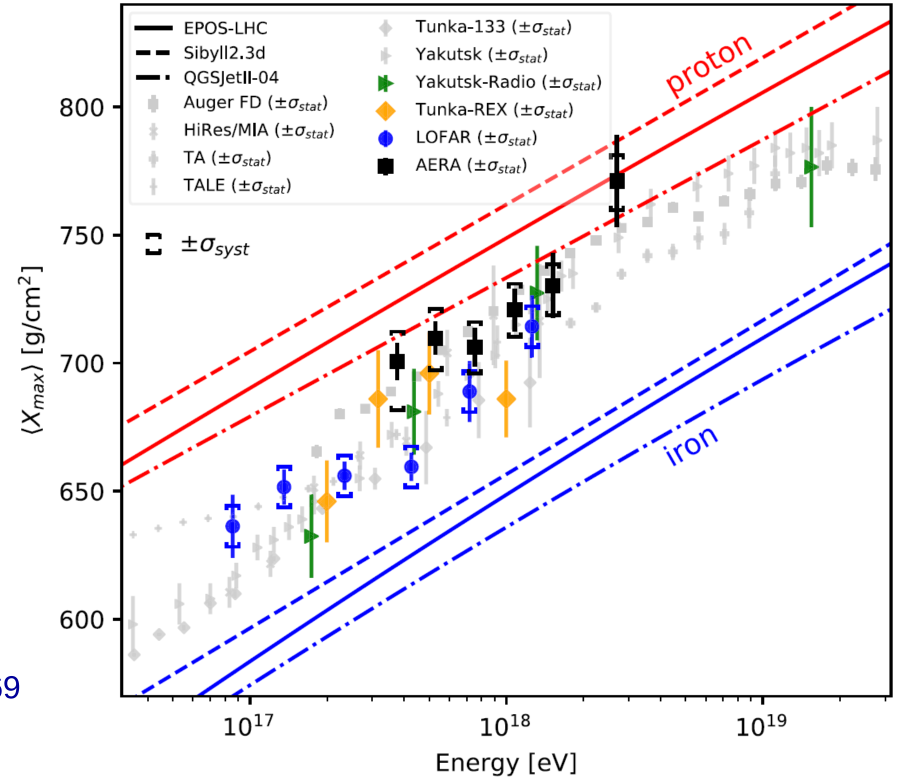
- tertiary effect (high magnetic fields, very inclined air showers): *geosynchrotron radiation* plus *coherence losses*

Chiche, Zhang, Kotera, TH et al., PoS(ICRC2023)394

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 Auger PRL & PRD (2024)
- 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



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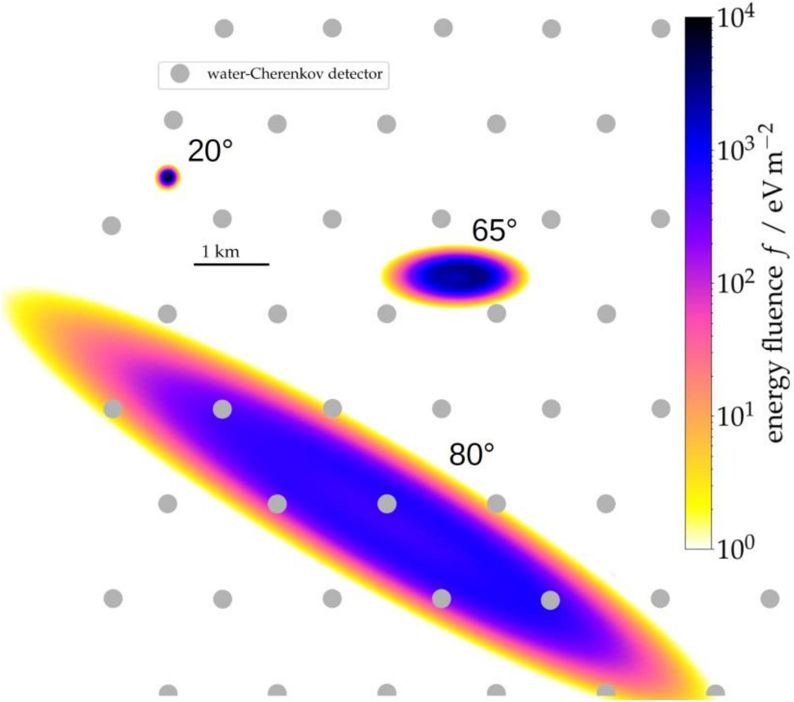
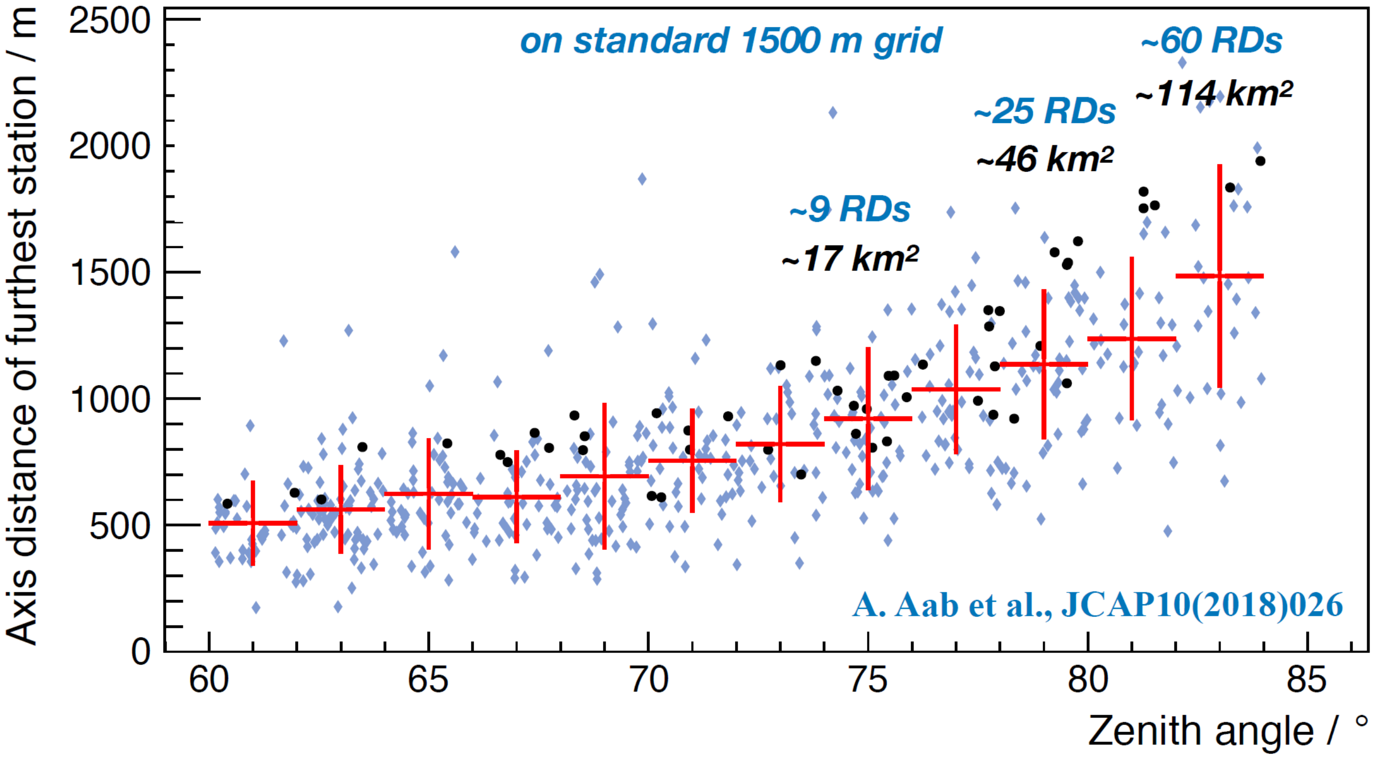
30-80 MHz

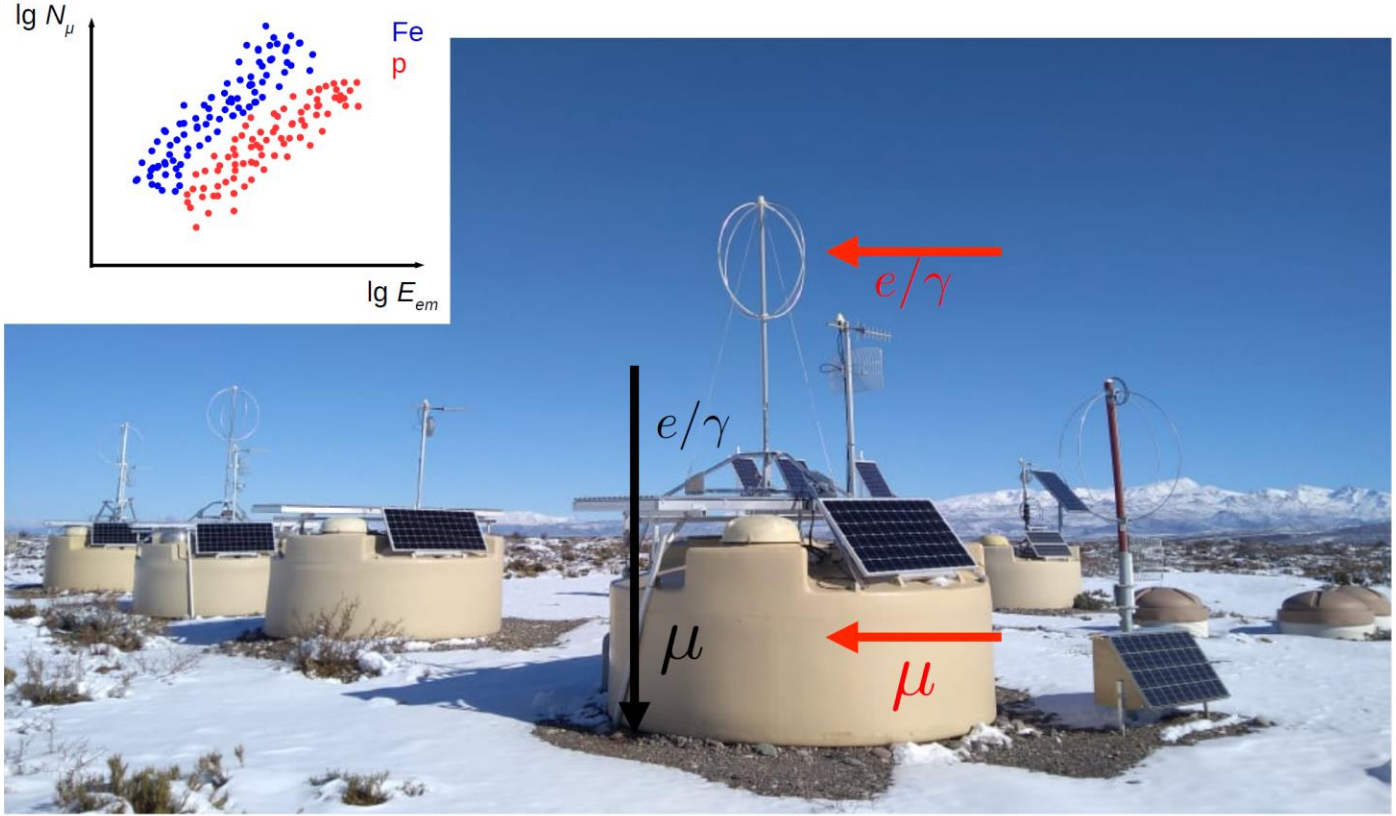


Auger Engineering Radio Array results



- Hundreds of inclined air showers detected with ~6 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

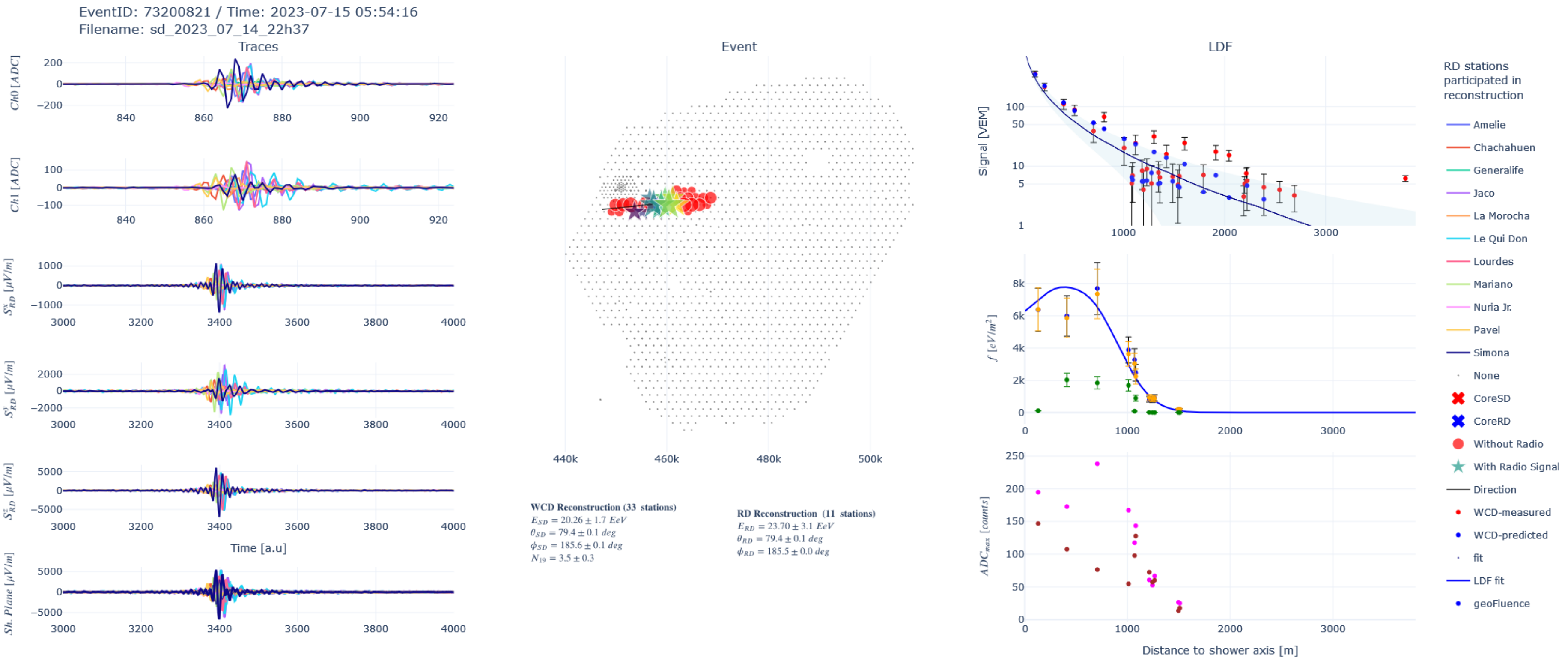


- Mount a dual-polarized radio antenna (30-80 MHz) on each SD station
- 1660 radio antennas over 3000 km^2
- Mass sensitivity for inclined air showers:
  - radio: em
  - WCD: muons
- Beautifully complementary to WCD/SSD

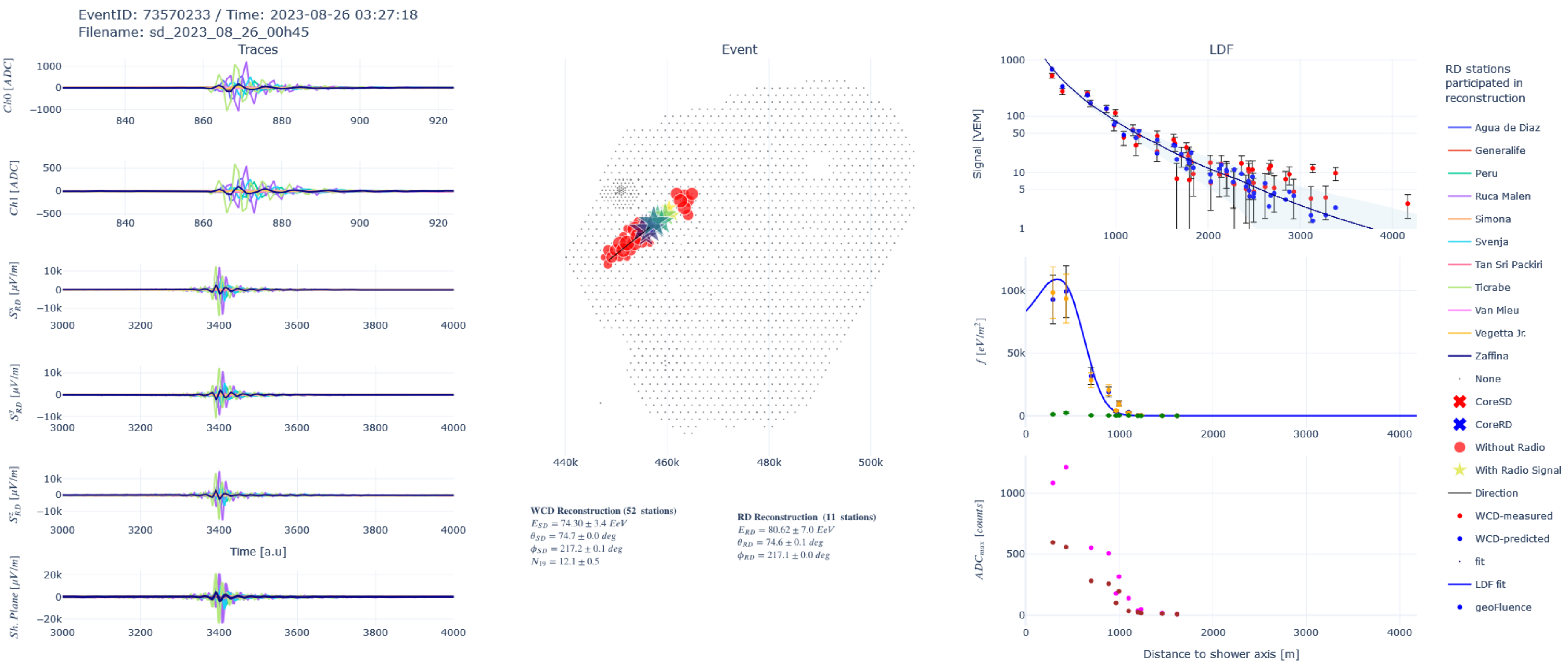
Auger Radio Detector current status

- January 2024: ~800 antennas in the field, ~200 operating
- Mechanical and electronics design mature and proven
- Trigger for now from WCD, but working on hybrid trigger

Auger RD measured air shower (I)

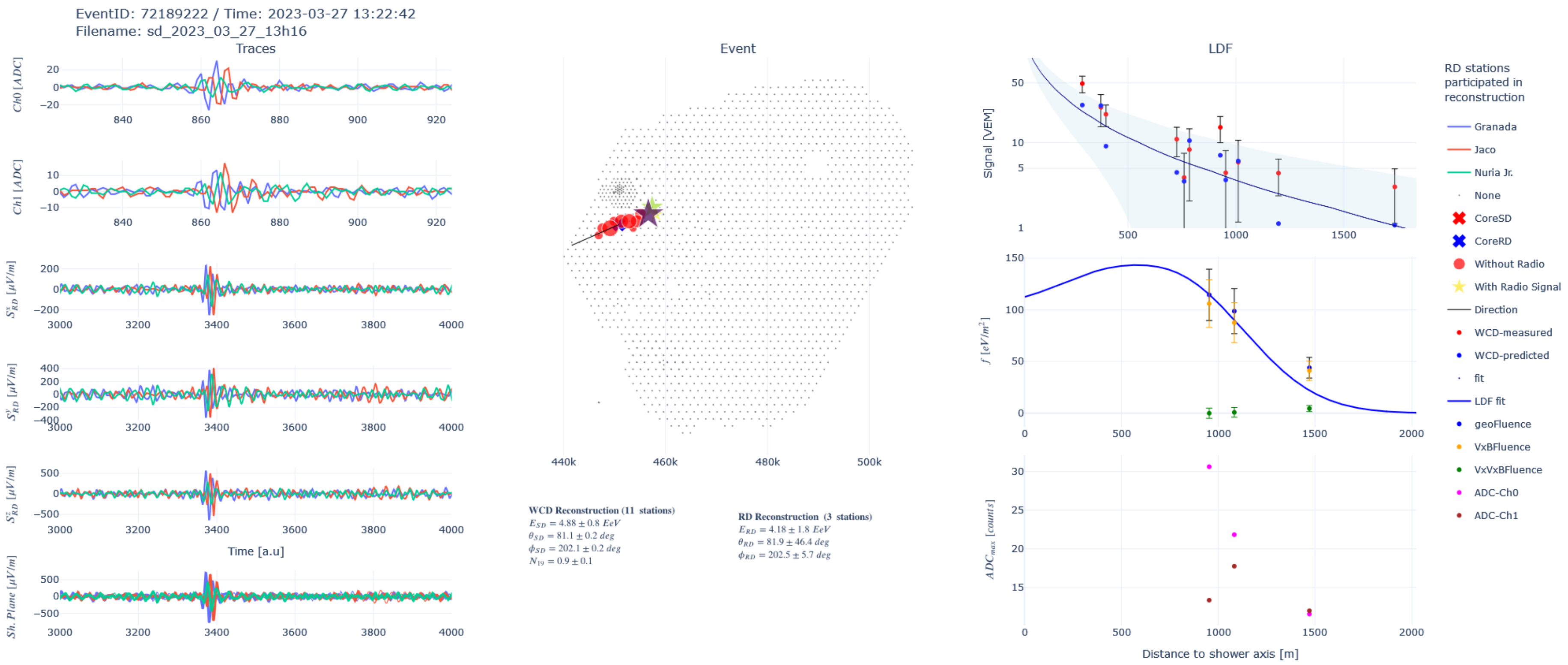


Auger RD measured air shower (II)



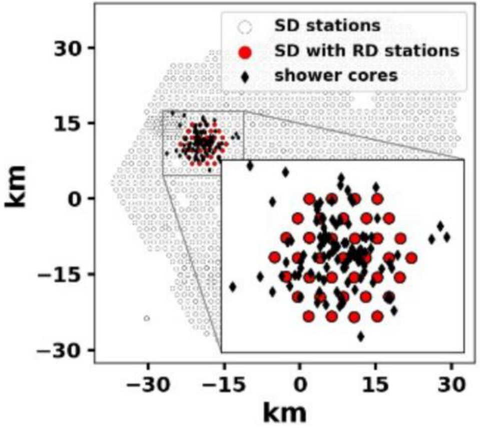
Tim Huege <tim.huege@kit.edu>

Auger RD measured air shower (III)

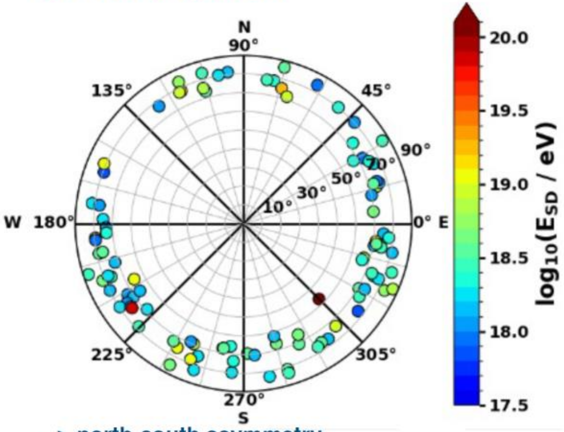


Auger RD first look at data

location of EAS axes

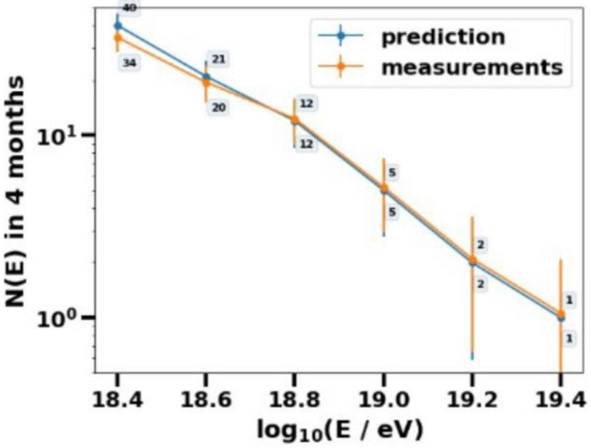


arrival direction

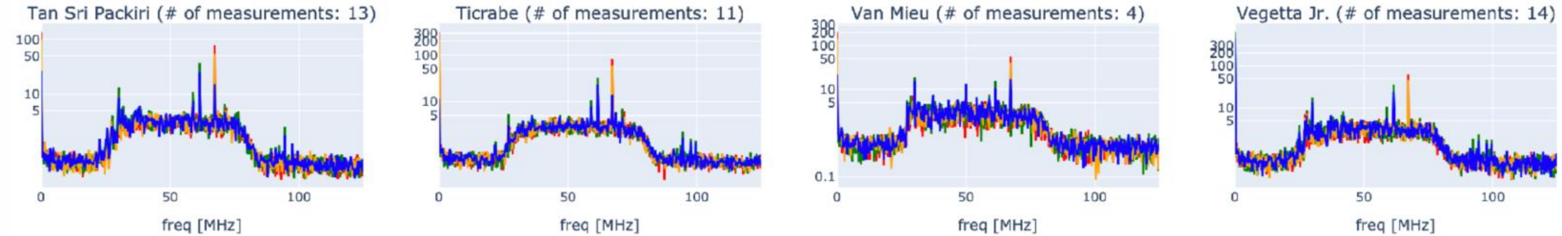


—> north-south asymmetry
—> emission mechanism vxB

of measured cosmic rays



frequency spectra

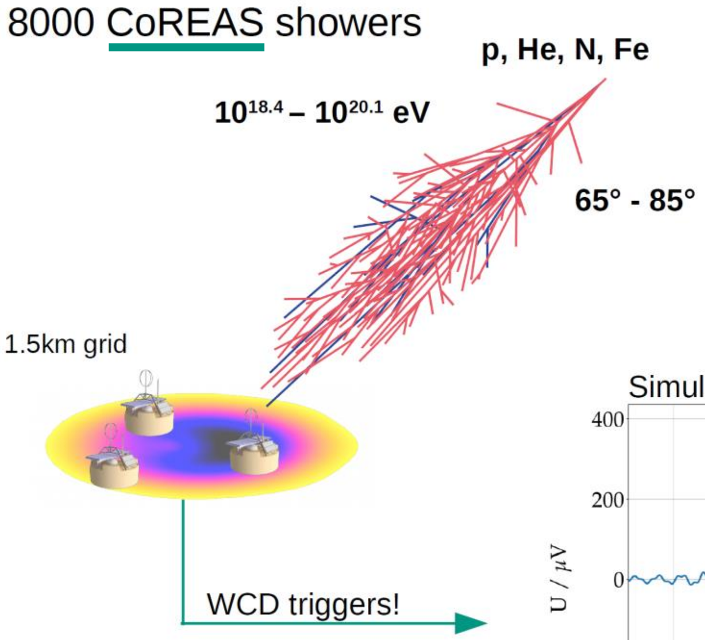


Expected Performance of Auger-RD

see PoS(ICRC2021)228

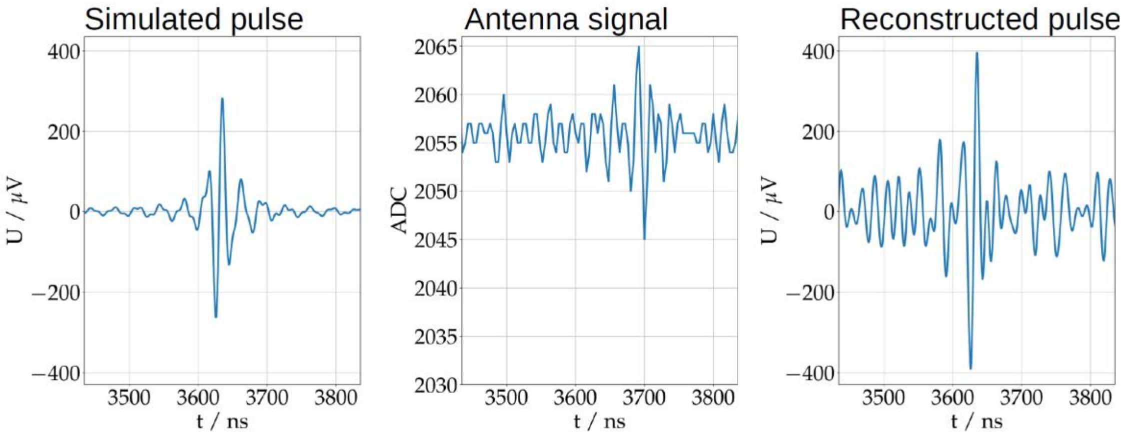
Tim Huege <tim.huege@kit.edu>

Fully realistic end-to-end simulation study



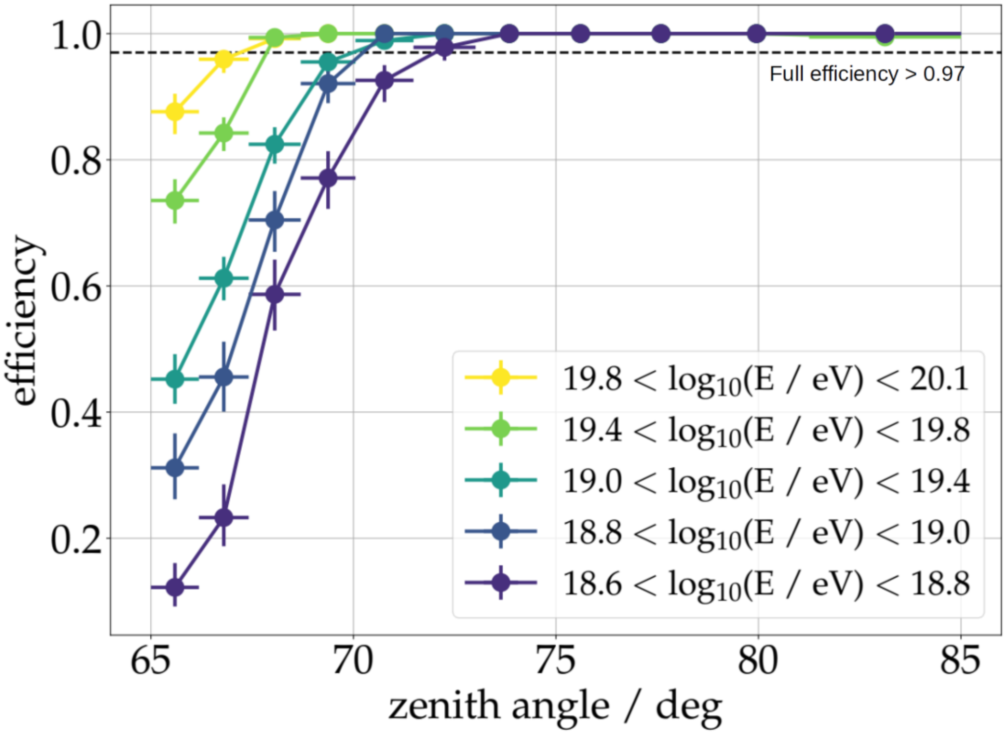
Simulate instrumental response
(directional response, analog gain, digitization, …..)

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



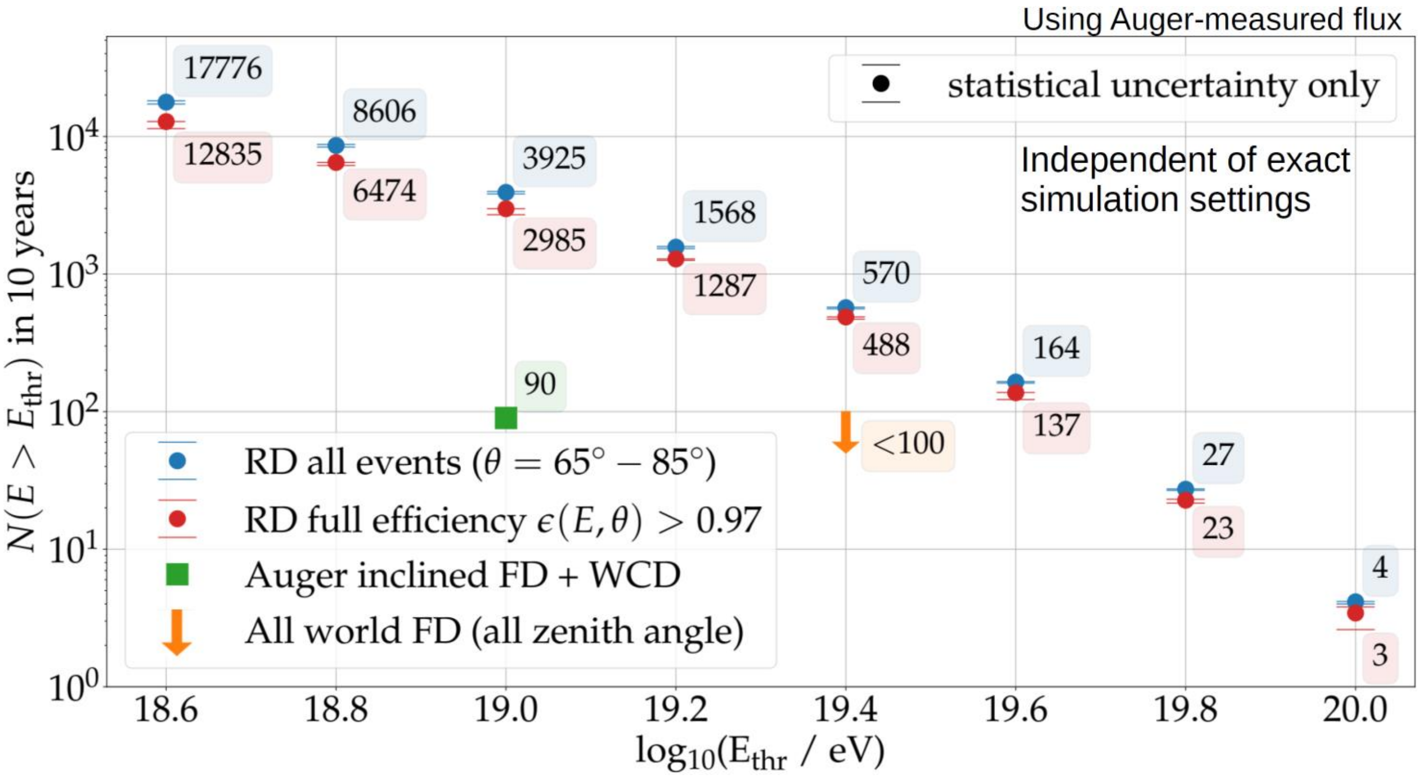
30-80 MHz

Detection efficiency



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

Expected event statistics in 10 years

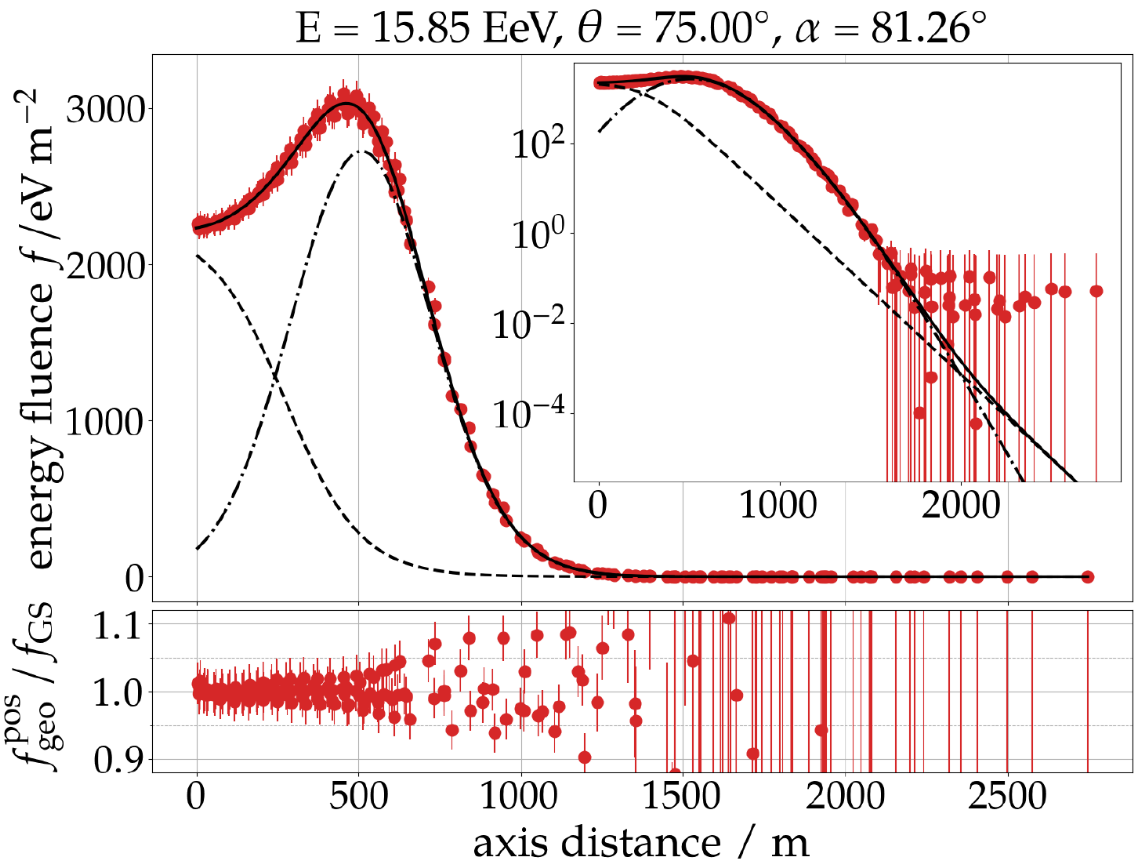


- Integral spectrum from folding flux with aperture
- Expect ~4000 events beyond 10^{19} eV

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

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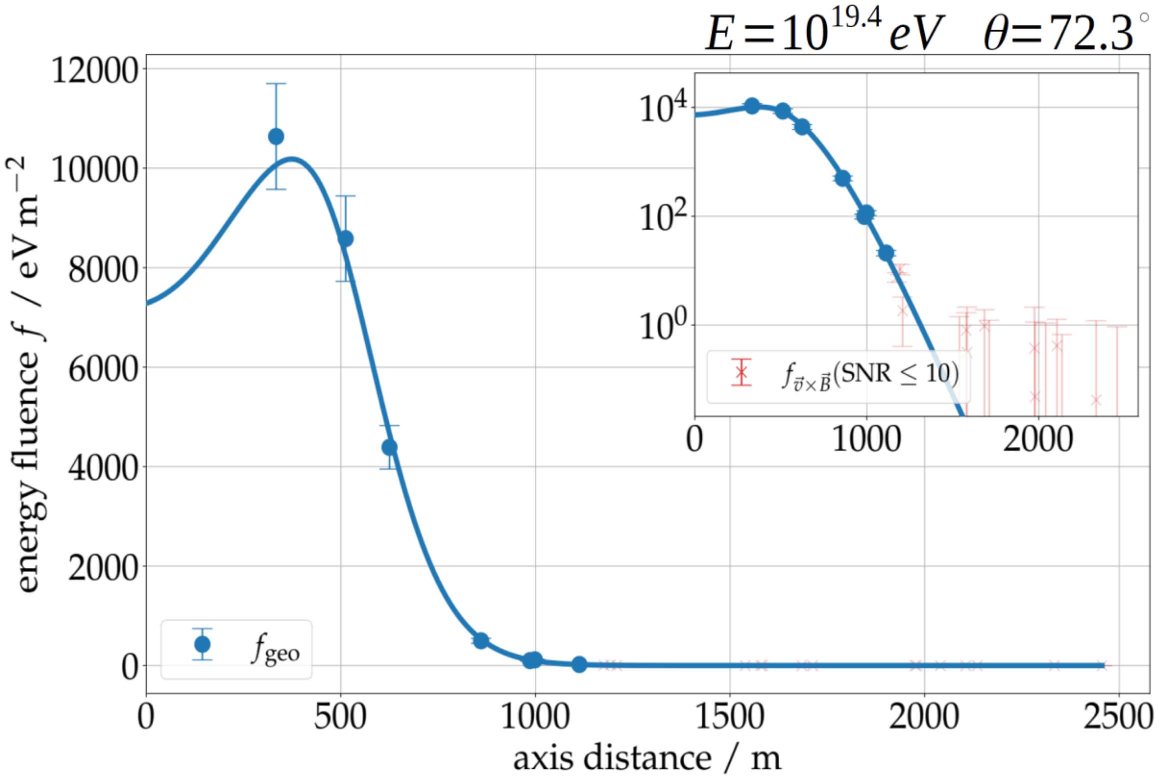


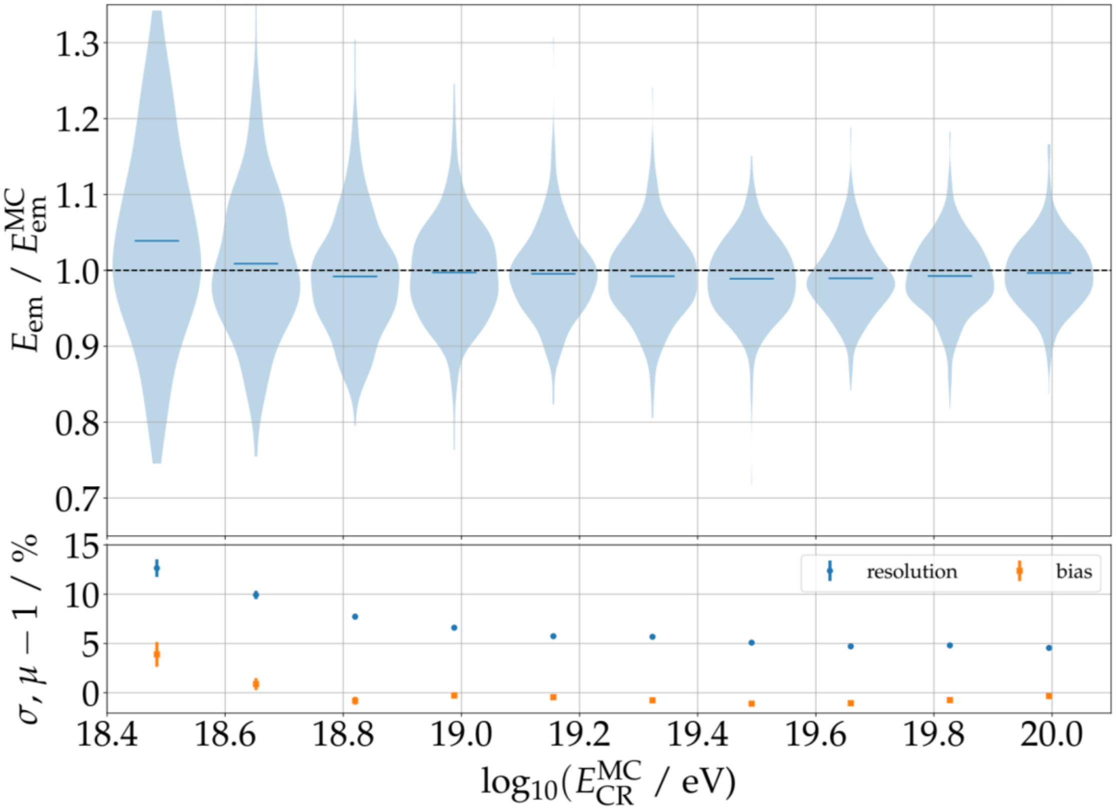
* Signal model and event reconstruction for the radio detection of inclined air showers, F. Schlüter, T. Huege, JCAP

Predicted energy resolution of Auger RD

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

quality cuts: ~95% efficiency

Resolution improves with energy



Tim Huege <tim.huege@kit.edu>

Predicted energy resolution of Auger Radio Det.

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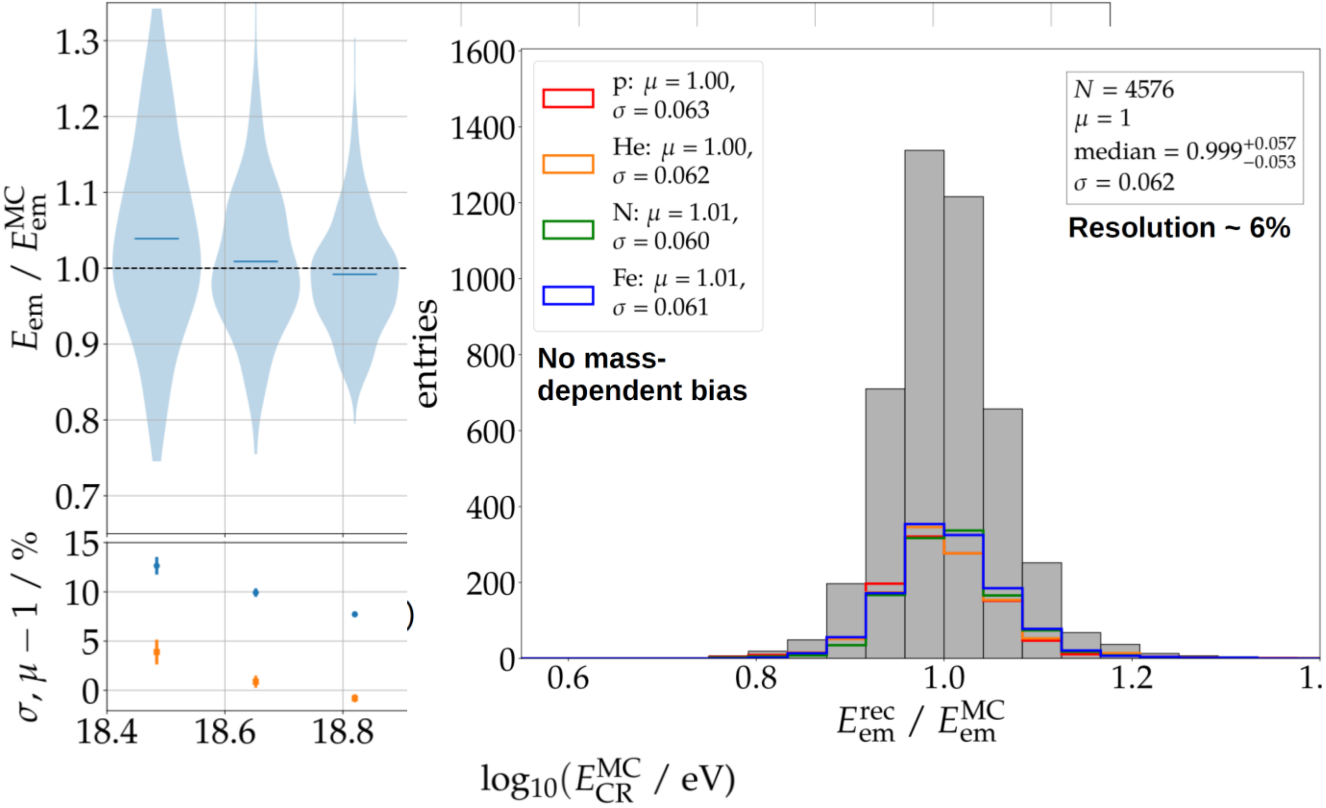


Mass composition sensitivity

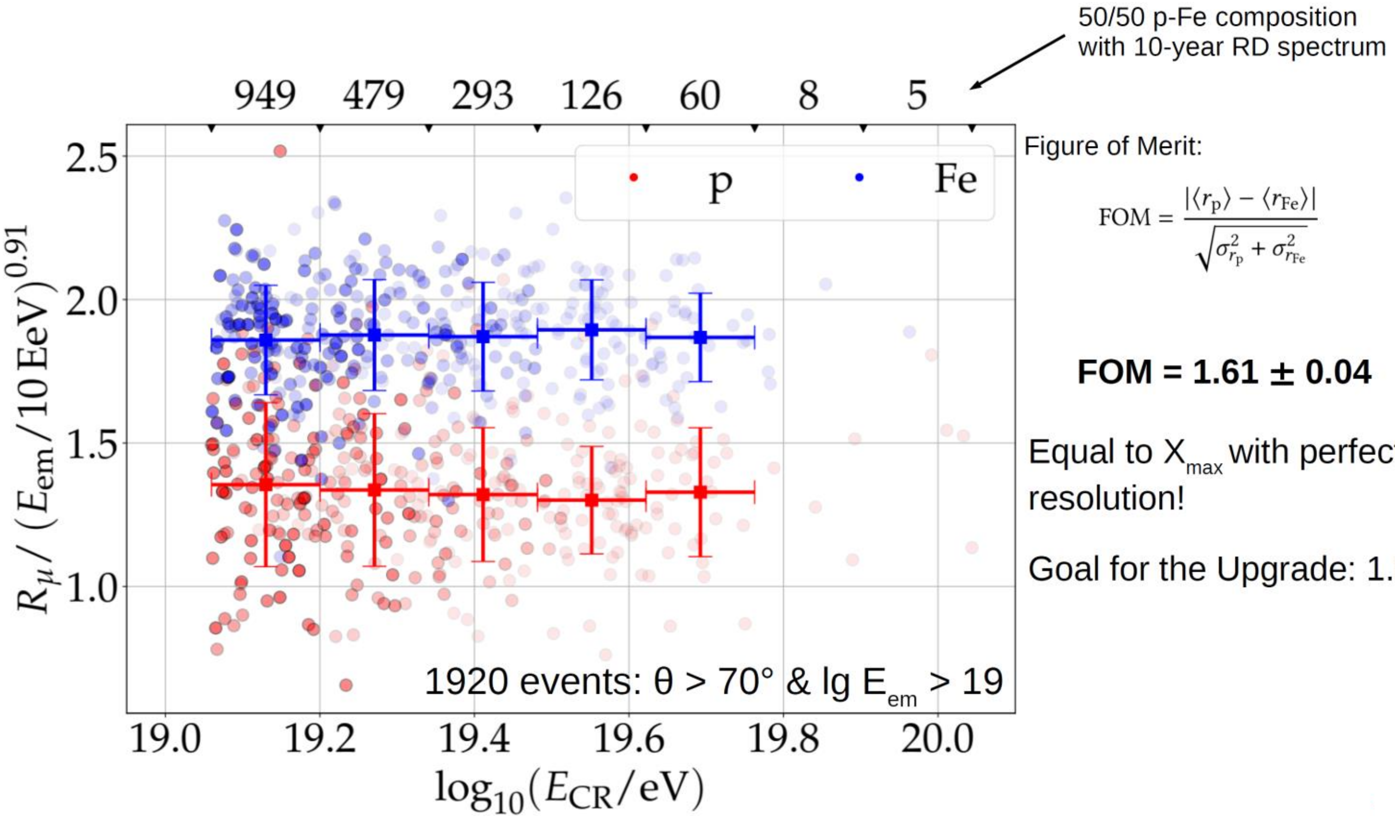


Figure of Merit:

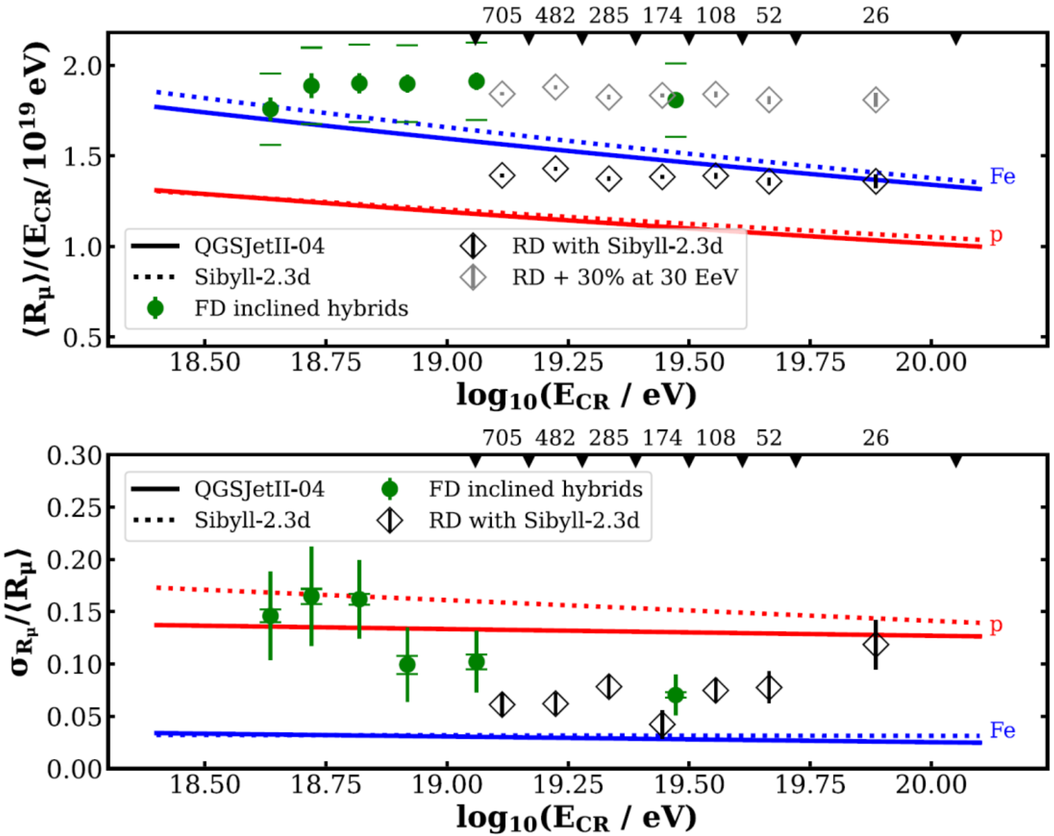
$$\mathrm{FOM} = \frac{|\langle r_p \rangle - \langle r_{Fe} \rangle|}{\sqrt{\sigma_{r_p}^2 + \sigma_{r_{Fe}}^2}}$$

FOM = 1.61 ± 0.04

Equal to X_{max} with perfect resolution!

Goal for the Upgrade: 1.5

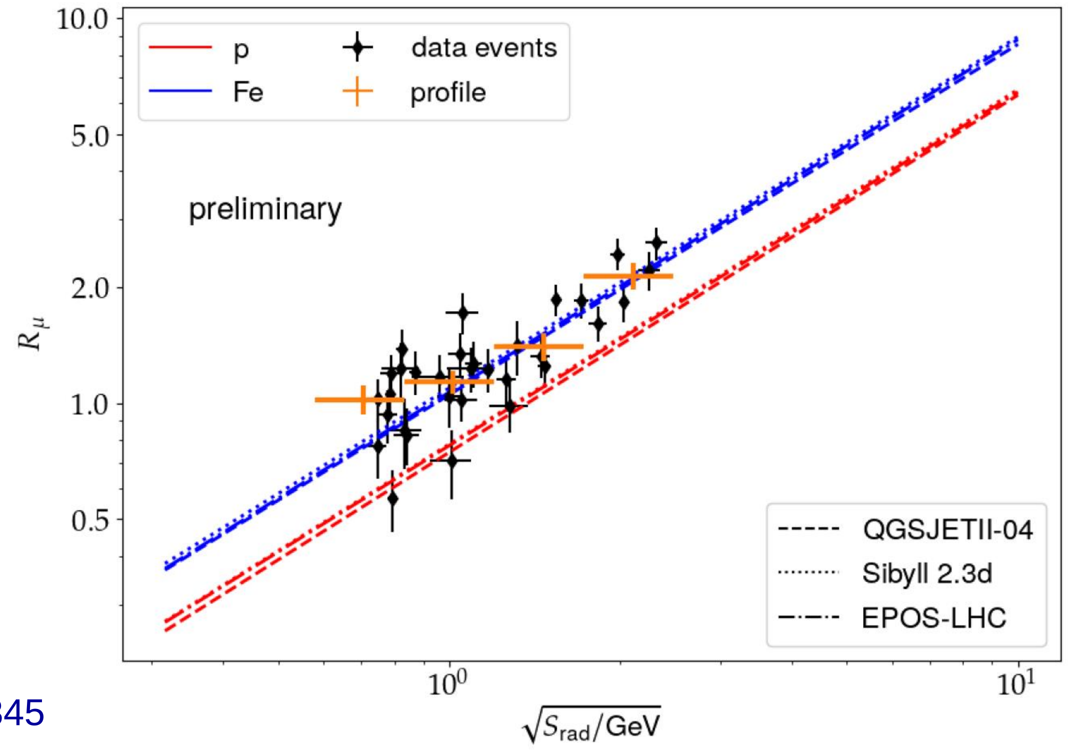
Muon number measurements



- 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

At lower energies: Auger Engineering Radio Array

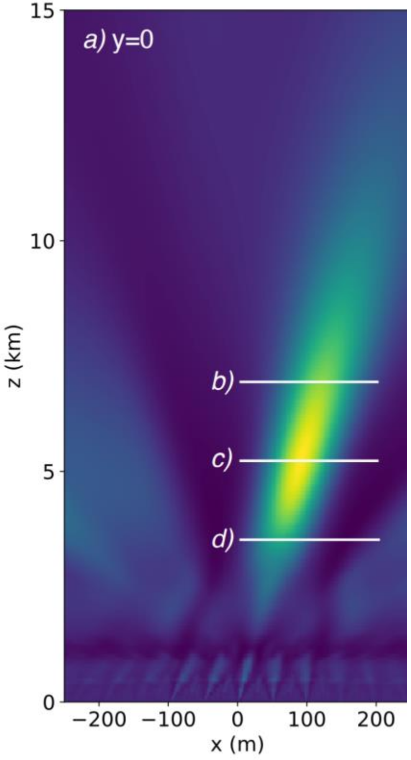
- Similar approach with vertical air showers combining AERA and 750 m SD infill data (10^{17} to few 10^{18} eV)
- Proof of principle with 1500 m SD data
- Less clean because of EM contamination in particle measurement



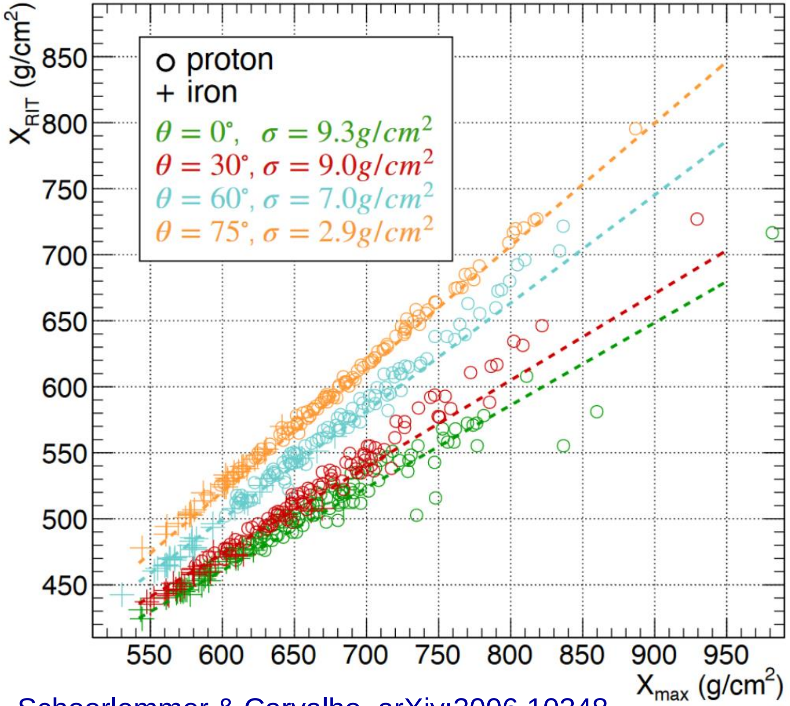
Pierre Auger Coll., PoS(ICRC2023)345

Radio-interferometric reconstruction

Interferometric map



Xmax determination

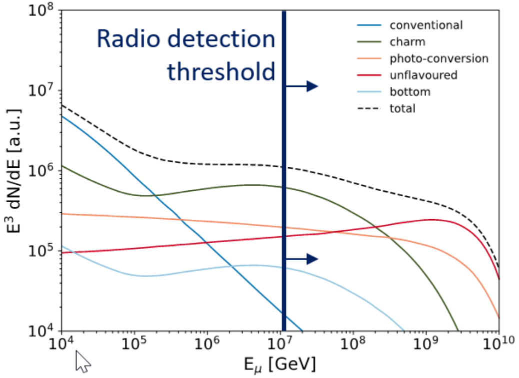


Schoorlemmer & Carvalho, arXiv:2006.10348
Schlüter & Huege, arXiv:2102.13577

- Radio pulses contain phase information
- LOPES successfully used interferometry
- Recent simulation studies and first AERA data show Xmax sensitivity
  - We would have N_e, N_μ and Xmax
- Requires 1 ns detector synching

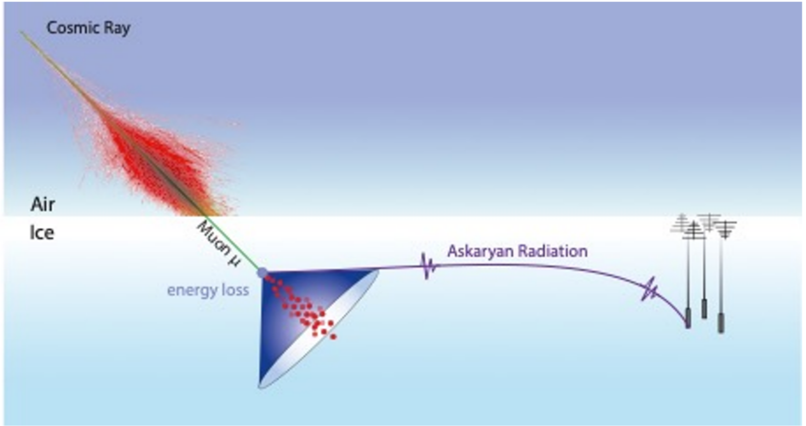
Atmospheric muons at PeV energies in radio neutrino detectors

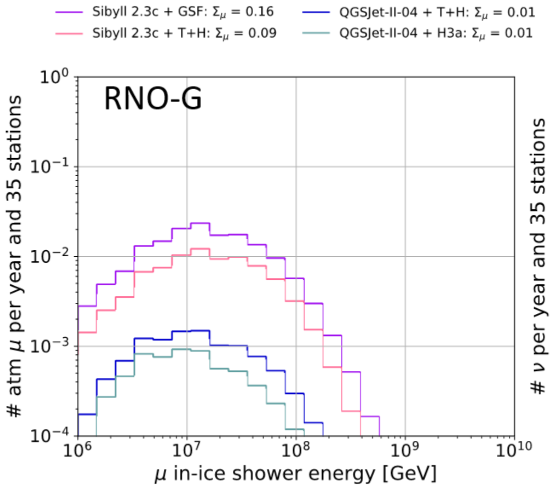
Pyras et al. JCAP10(2023)043

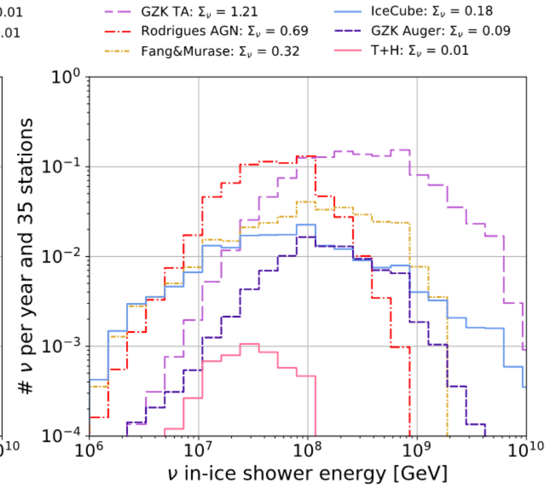


Identify muon by measuring in-ice particle cascade and parent air shower
→ likely detectable with the radio array of IceCube-Gen2

Important background to radio detection of neutrinos, but 2 orders of magnitude uncertainty
→ Need better predictions







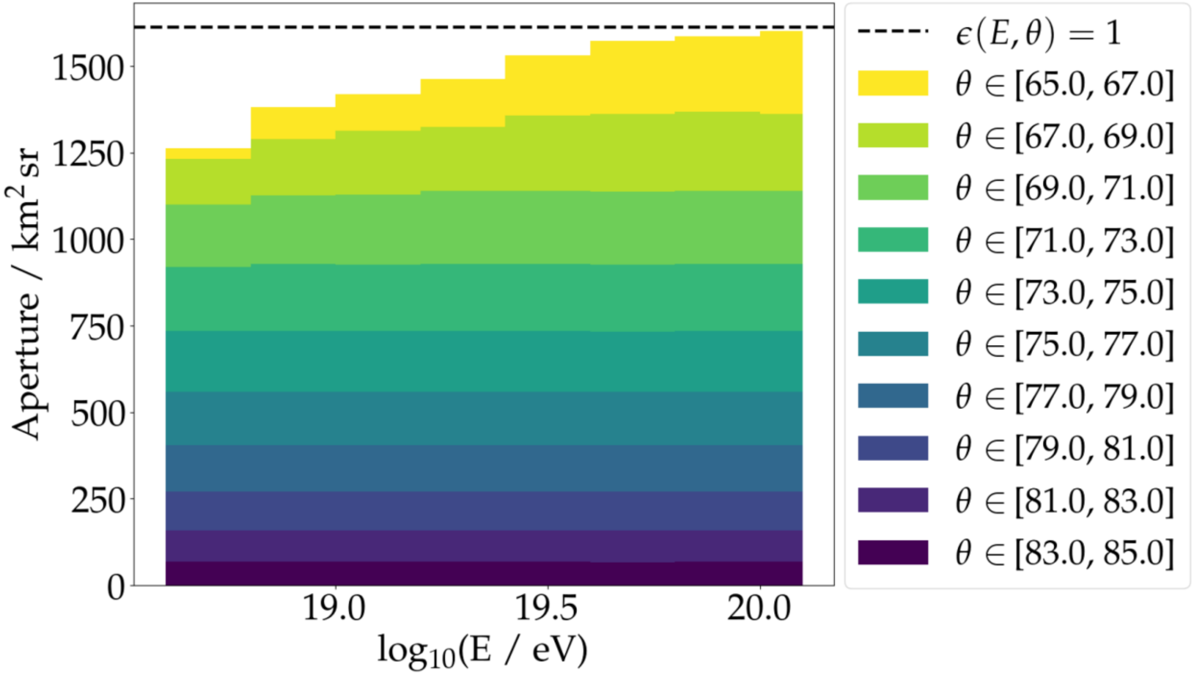
Summary

- Radio delivers very clean measurement of EM component of EAS
- For vertical showers (lower energies), delivers also Xmax
- We are equipping Auger with 1660 radio antennas (30-80 MHz)
  - This will allow high-statistics, high-quality measurements of the muon number and its fluctuations in the highest-energy air showers
  - Design proven, mass production ongoing, deployment complete in 2024
  - Potential also to combine 750 m infill RD data with underground muon detector data and further exploit AERA data (10^{17} to few 10^{18} eV)
- With interferometry, we could even measure EM component, muons and Xmax at the same time at very high energies – stay tuned!

Backup

Tim Huege <tim.huege@kit.edu>

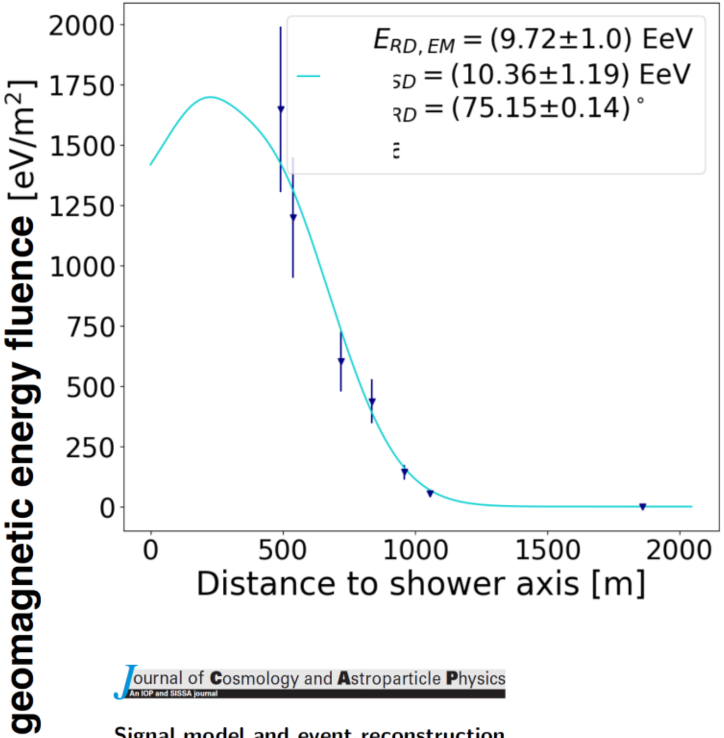
Predicted aperture



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

Tim Huege <tim.huege@kit.edu>

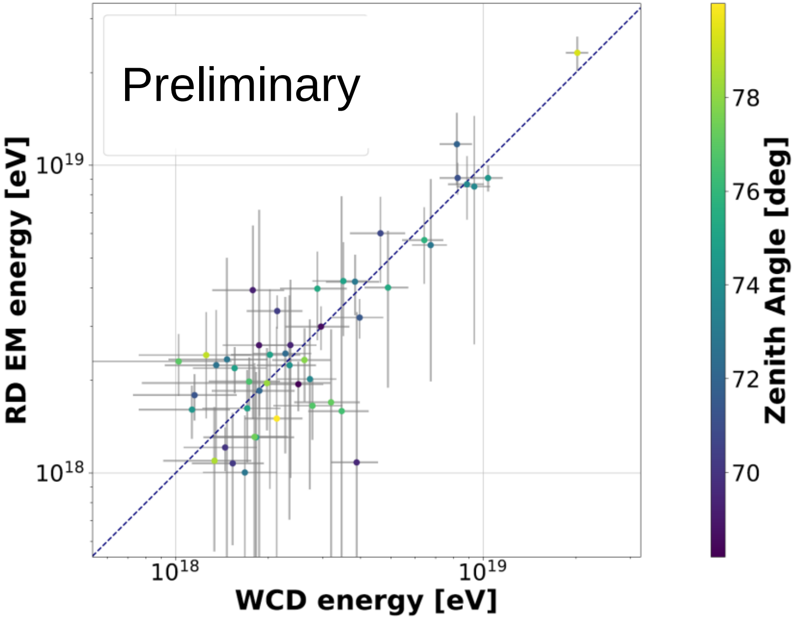
Hybrid measurements RD-WCD



Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Signal model and event reconstruction for the radio detection of inclined air showers

F. Schlüter[a,b,*] and T. Huege[a,c] JCAP01(2023)008

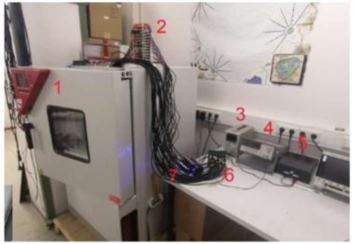


measurement of e/m energy by RD

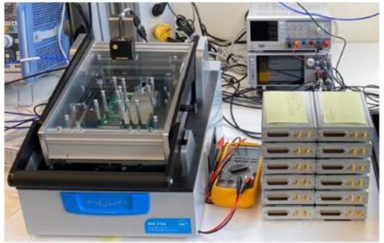
—> full end-to-end verification of complete chain

RD calibration concept

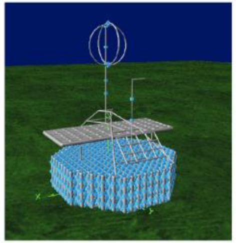
thermal cycling (aging) LNA & digitizer

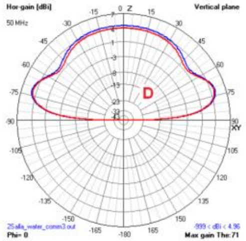


end-to-end calibration in lab LNA & digitizer

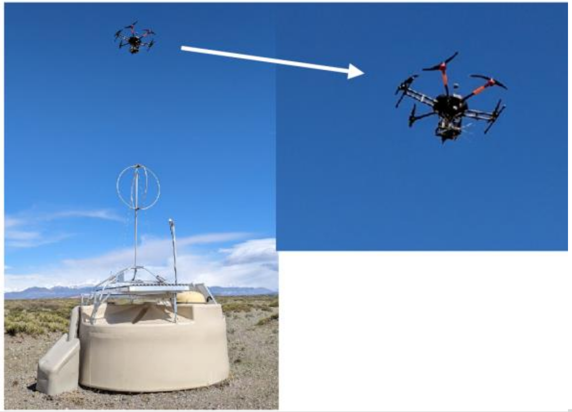


simulation of antenna pattern NEC

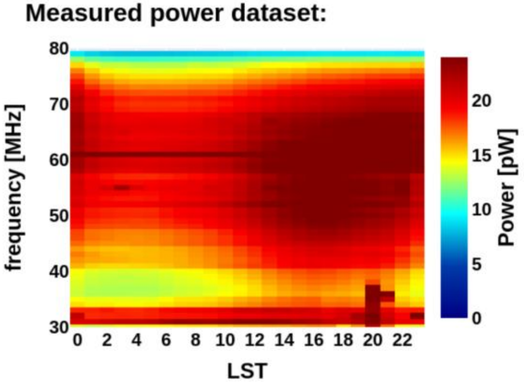




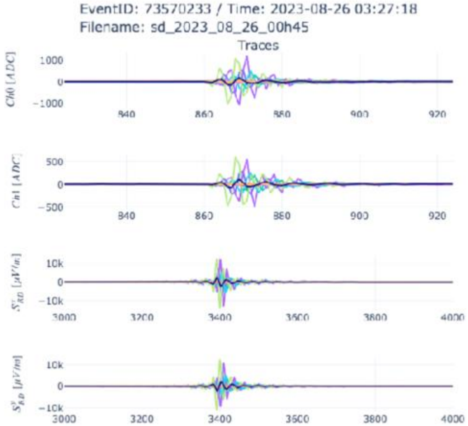
in-situ calibration with reference antenna



Galactic emission

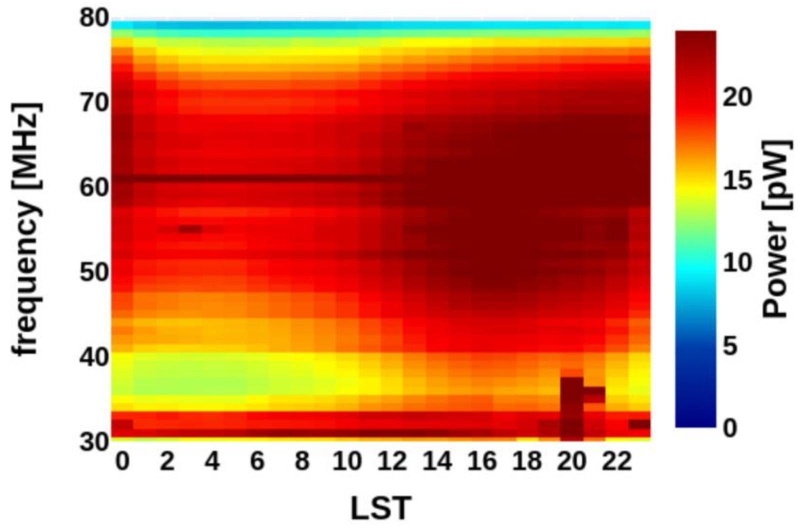


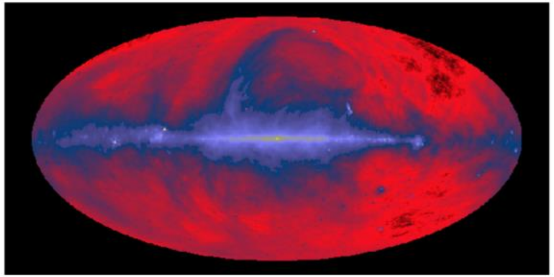
absolutely calibrated signals



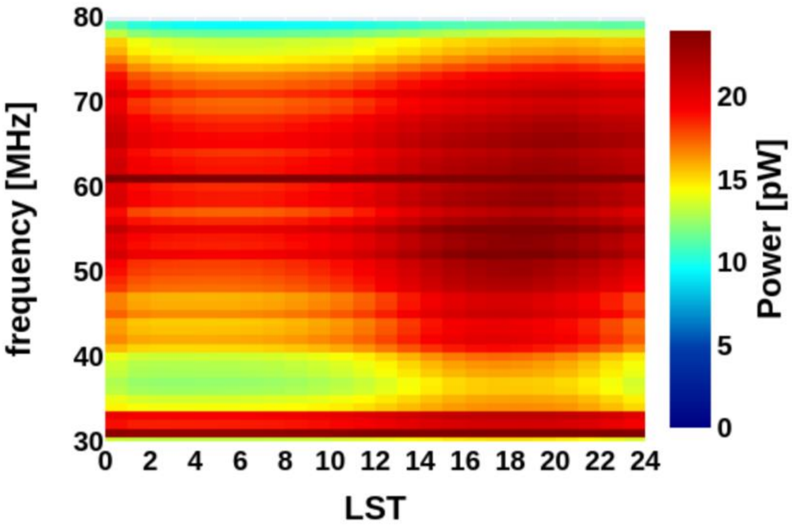
Measurement of Galactic emission

Measured power dataset:





Simulated dataset + fitted noise



—> the „muon peak“ for radio
—> in-situ calibration
(implemented on FPGA)

systematic uncertainty ~10%