Expected performance of the AugerPrime Radio Detector

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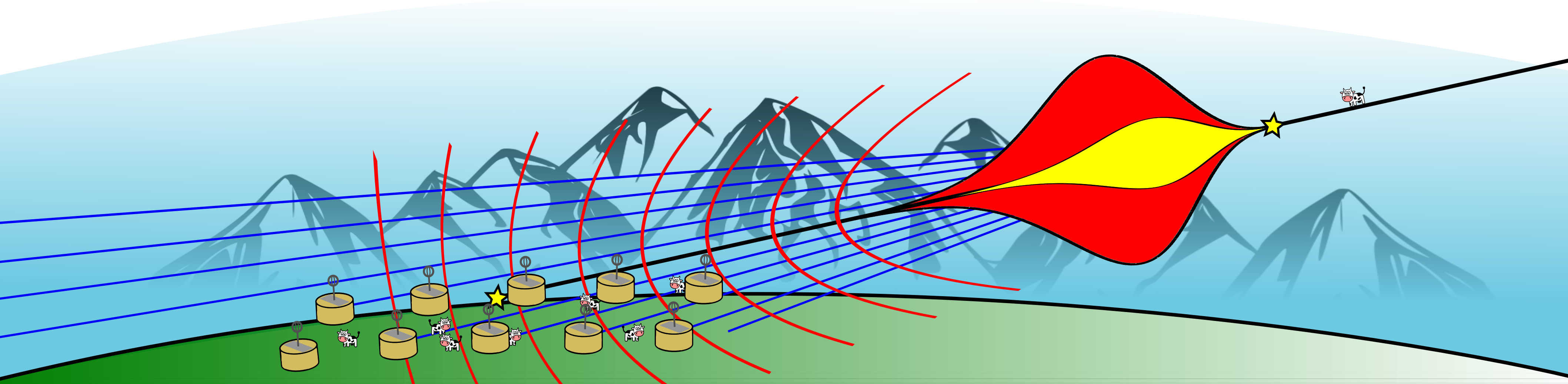
PIERRE AUGER OBSERVATORY

HIRSAP

PoS (ICRC21) 262

ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
15–22 July 2021

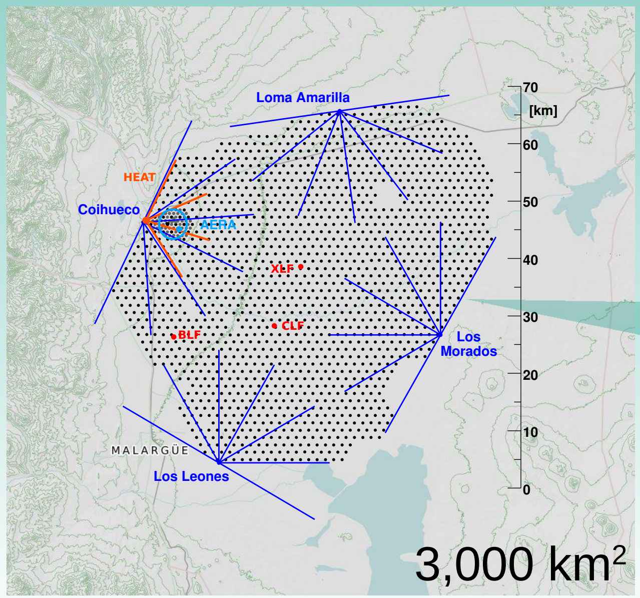
Institute for Astroparticle Physics (IAP)
Instituto de Tecnologías en Detección y Astropartículas (ITeDA)



The AugerPrime Radio Detector

1661 dual-polarized **S**hort **A**periodic **L**oaded **L**oop **A**ntennas (SALLAs)

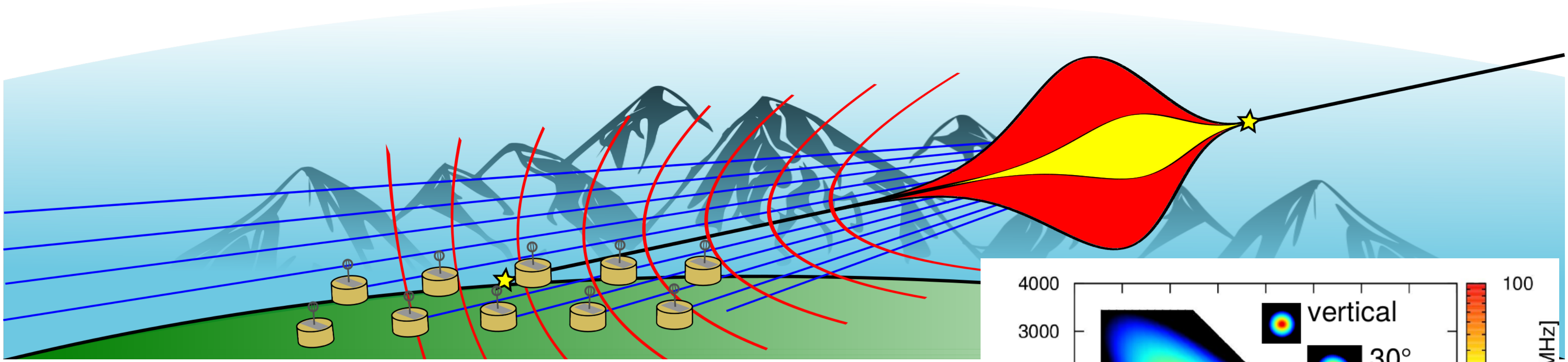
- Triggers from water-Cherenkov detector (WCD)



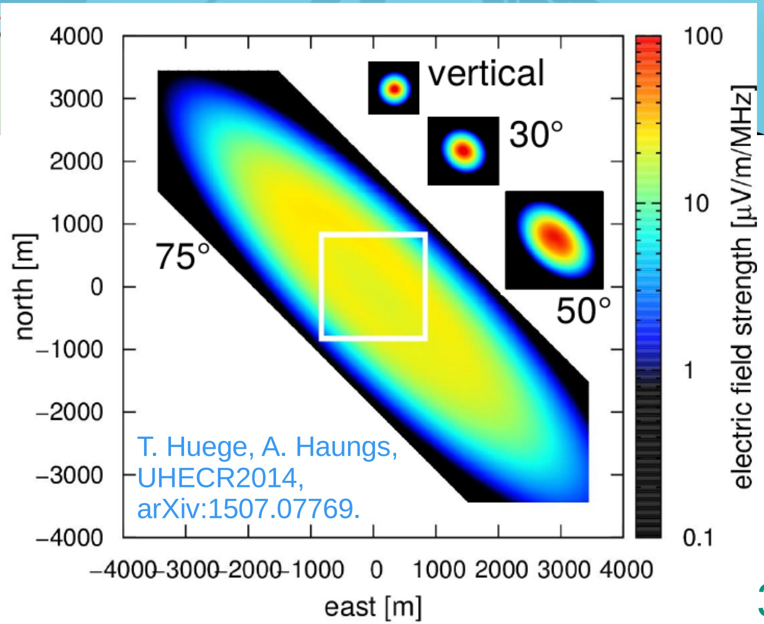
- Prototype stations in field
  → Recording ambient noise

More details: First results from the AugerPrime Radio Detector: PoS (ICRC21) 207

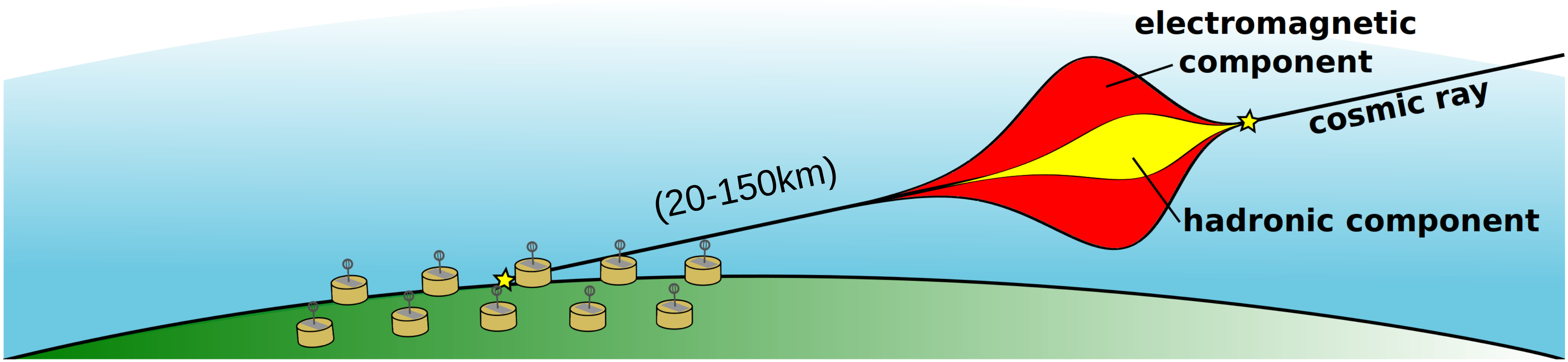
Goal: Extends sky-coverage of mass-sensitive measurements



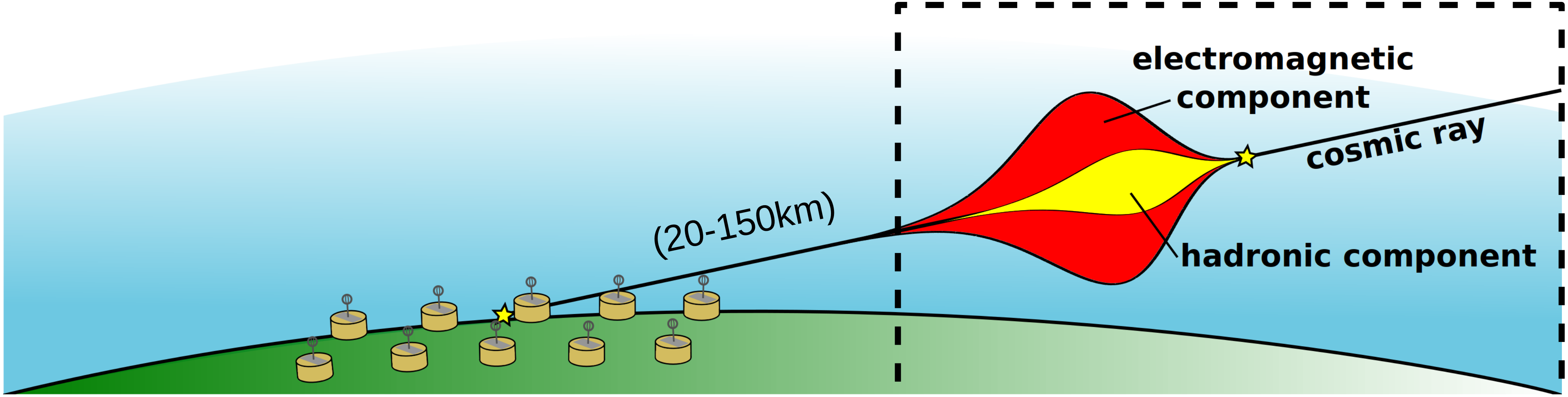
- Radio Detector (RD) combined with Auger particle detector will provide **muon-electron separation** → mass sensitivity
- **Very inclined air showers**: 65° ≲ θ ≲ 85°
- Highest energies: lg(E / eV) ≳ 18.8



Inclined air showers with AugerPrime

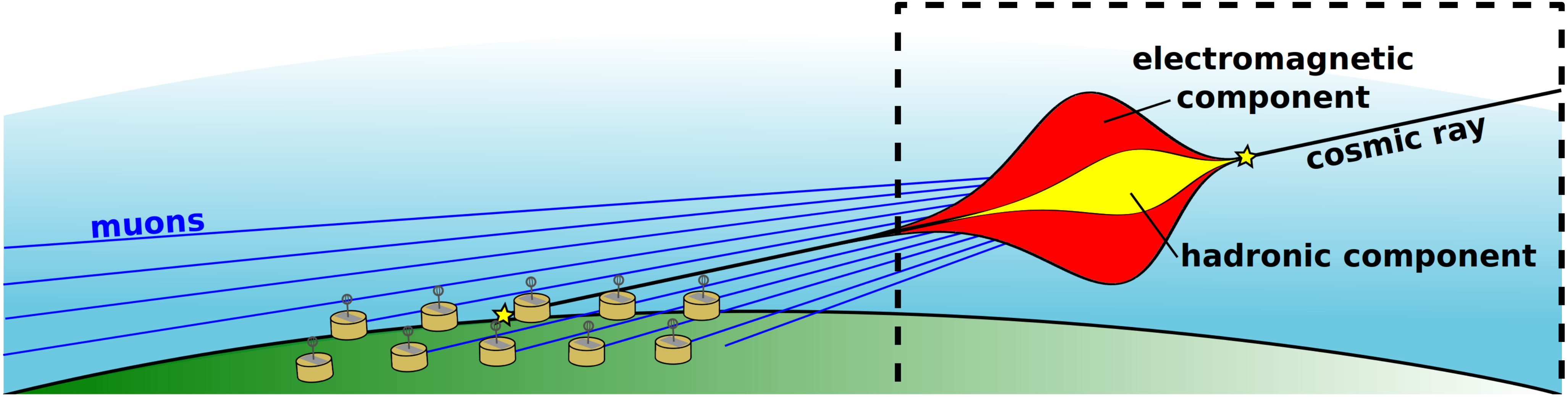


Inclined air showers with AugerPrime



Electromagnetic and hadronic shower particles stopped in atmosphere

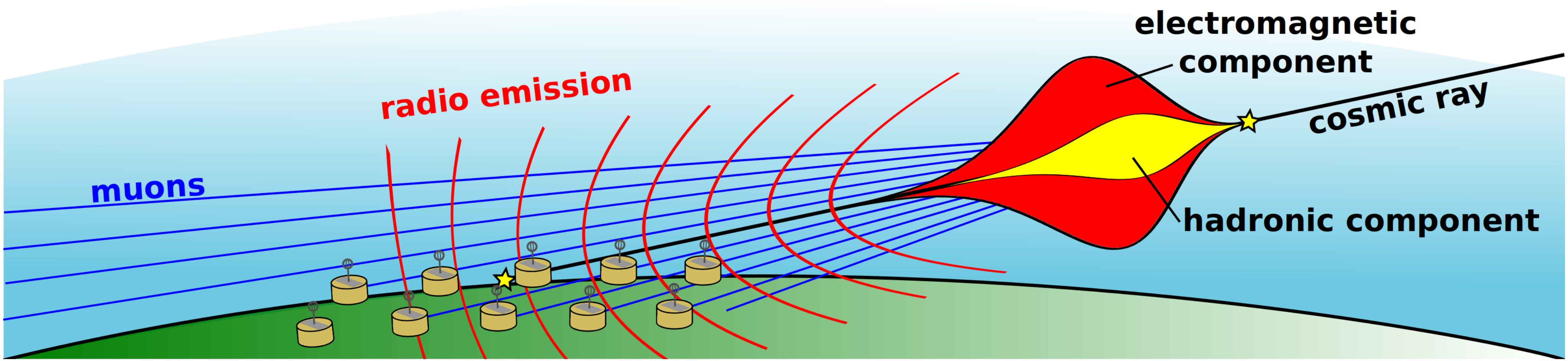
Inclined air showers with AugerPrime



- Muons measured by WCDs

Electromagnetic and hadronic shower particles stopped in atmosphere

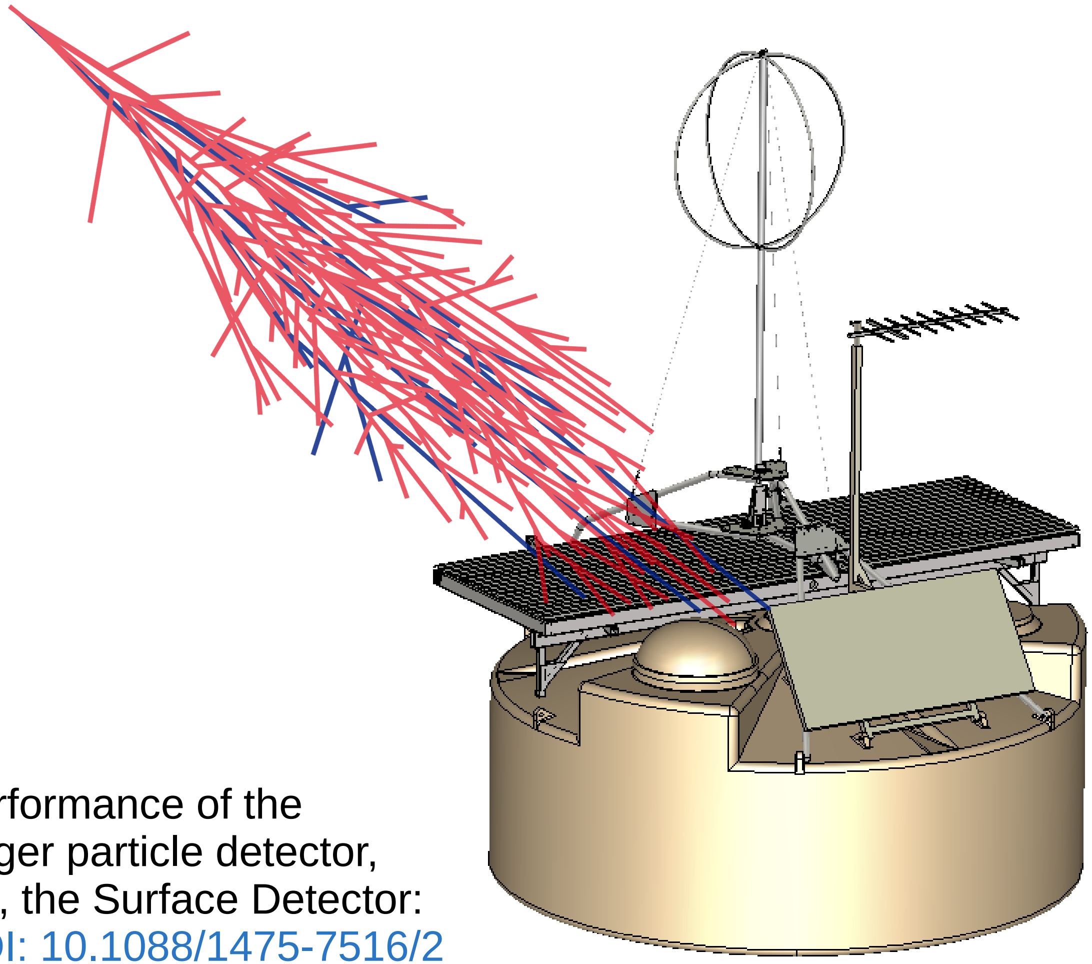
Inclined air showers with AugerPrime



- Muons measured by WCDs
- Radio emission measured by SALLAs

Muon-electron separation due to atmospheric absorption

Expected performance of the AugerPrime Radio Detector



Performance of the
Auger particle detector,
i.e., the Surface Detector:
DOI: 10.1088/1475-7516/2014/08/019

End-to-end simulation study:

Monte-Carlo air shower simulations

↓

Full detector simulation

↓

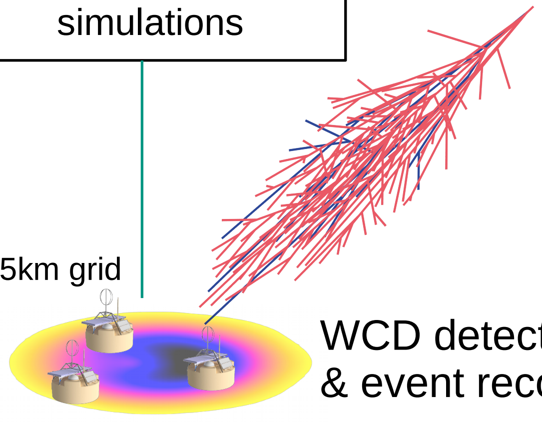
Full & realistic event reconstruction

↓

Physics performance

End-to-end simulation study

CORSIKA/CoREAS simulations



7972 showers
p, He, N, Fe
isotropic arrival direction
θ = 65 - 85°
lgE from 18.4 to 20.1
QGSJETII-04 / URQMD

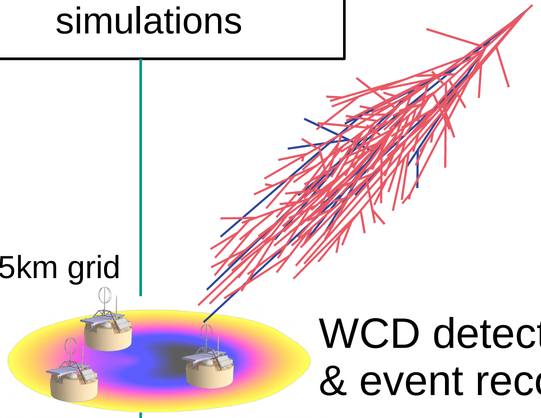
1.5km grid

WCD detector simulation
& event reconstruction

End-to-end simulation study

CORSIKA/CoREAS simulations

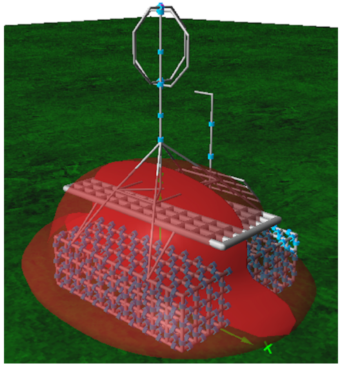
1.5km grid



WCD detector simulation & event reconstruction

Select only stations with triggered WCD

Radio Detector simulation



Mimic antenna-to-antenna variation:

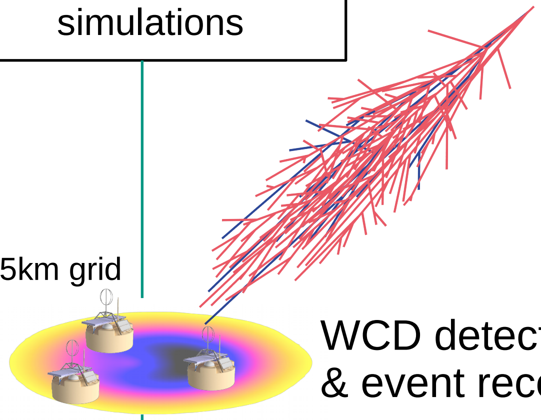
- Amplitude σ_A=5%*
- Time σ_t=6ns

*Motivated from AERA F. Canfora, PhD Thesis

End-to-end simulation study

CORSIKA/CoREAS simulations

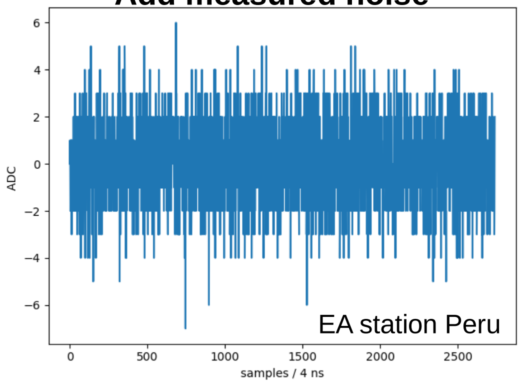
1.5km grid

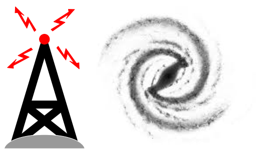


WCD detector simulation & event reconstruction

Select only stations with triggered WCD

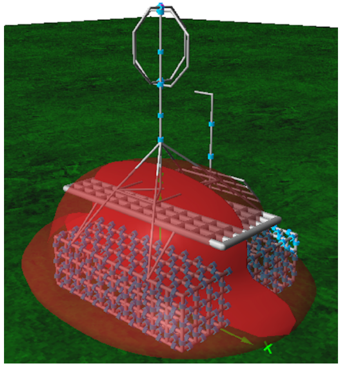
Add measured noise





Galactic emission,
Human-made noise,
Internal noise.

Radio Detector simulation



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End-to-end simulation study

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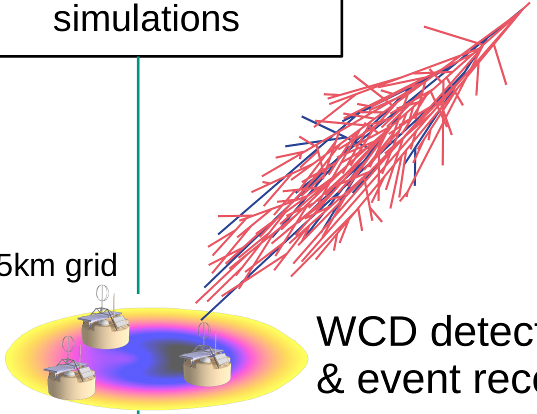
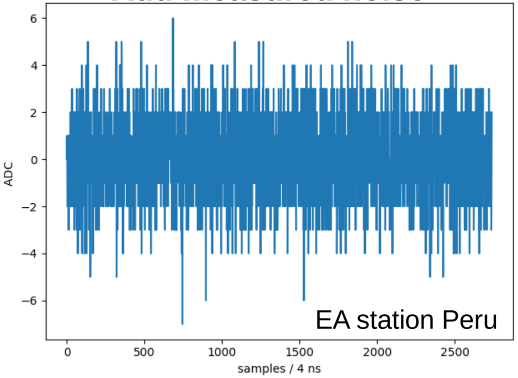


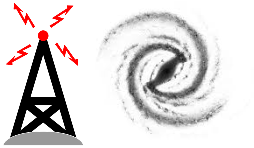
1.5km grid

WCD detector simulation & event reconstruction

Select only stations with triggered WCD

Add measured noise





Galactic emission,
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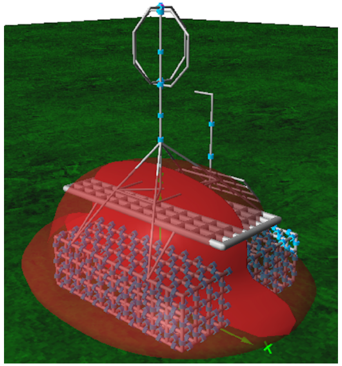
Radio Detector simulation

Station signal reconstruction



Mimic antenna-to-antenna variation:

- Amplitude σ_A=5%*
- Time σ_t=6ns

Calibrated signals:

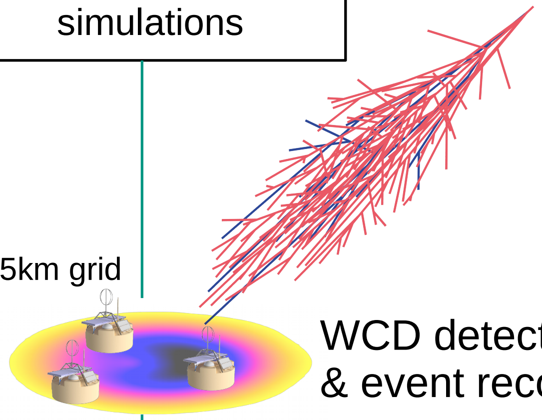
- signal-to-noise ratio SNR
- energy fluence f / eVm^{-2} in 30 – 80 MHz

*σ_A=5% motivated from AERA F. Canfora, PhD Thesis

End-to-end simulation study

CORSIKA/CoREAS simulations

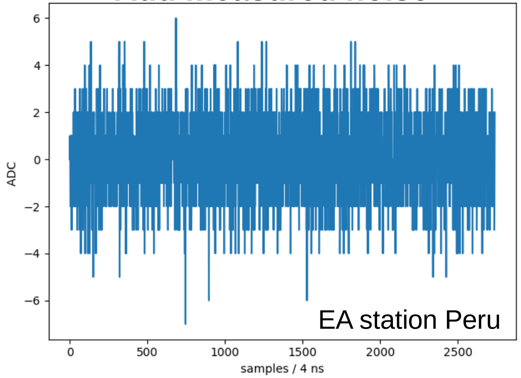
1.5km grid

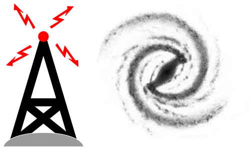


WCD detector simulation & event reconstruction

Select only stations with triggered WCD

Add measured noise



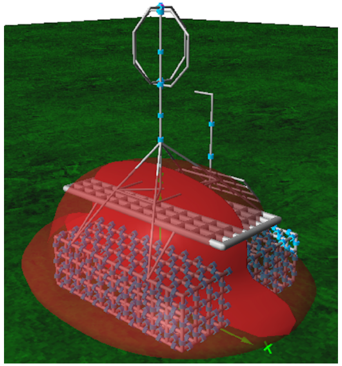


Galactic emission,
Human-made noise,
Internal noise.

Radio Detector simulation

Station signal reconstruction

Detection efficiency / aperture



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Calibrated signals:

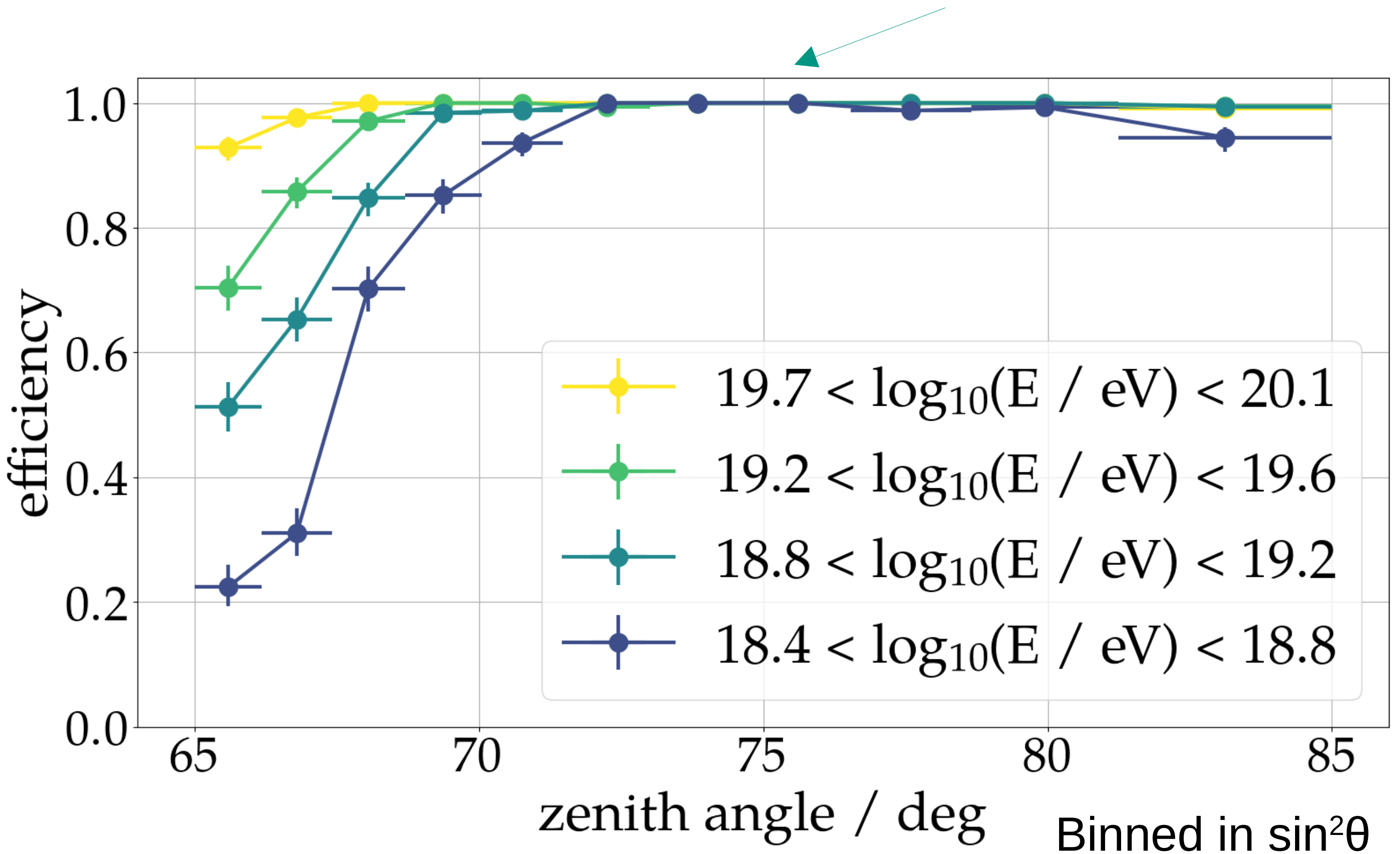
- signal-to-noise ratio SNR
- energy fluence f / eVm^{-2} in 30 – 80 MHz

*σ_A=5% motivated from AERA F. Canfora, PhD Thesis

Detection efficiency

- Min. 3 antennas with signal
- Strong dependence on zenith angle
  - Increasing footprint size
- Weak dependence on energy
- Nearly fully efficient for θ ≳ 70° at higher energies

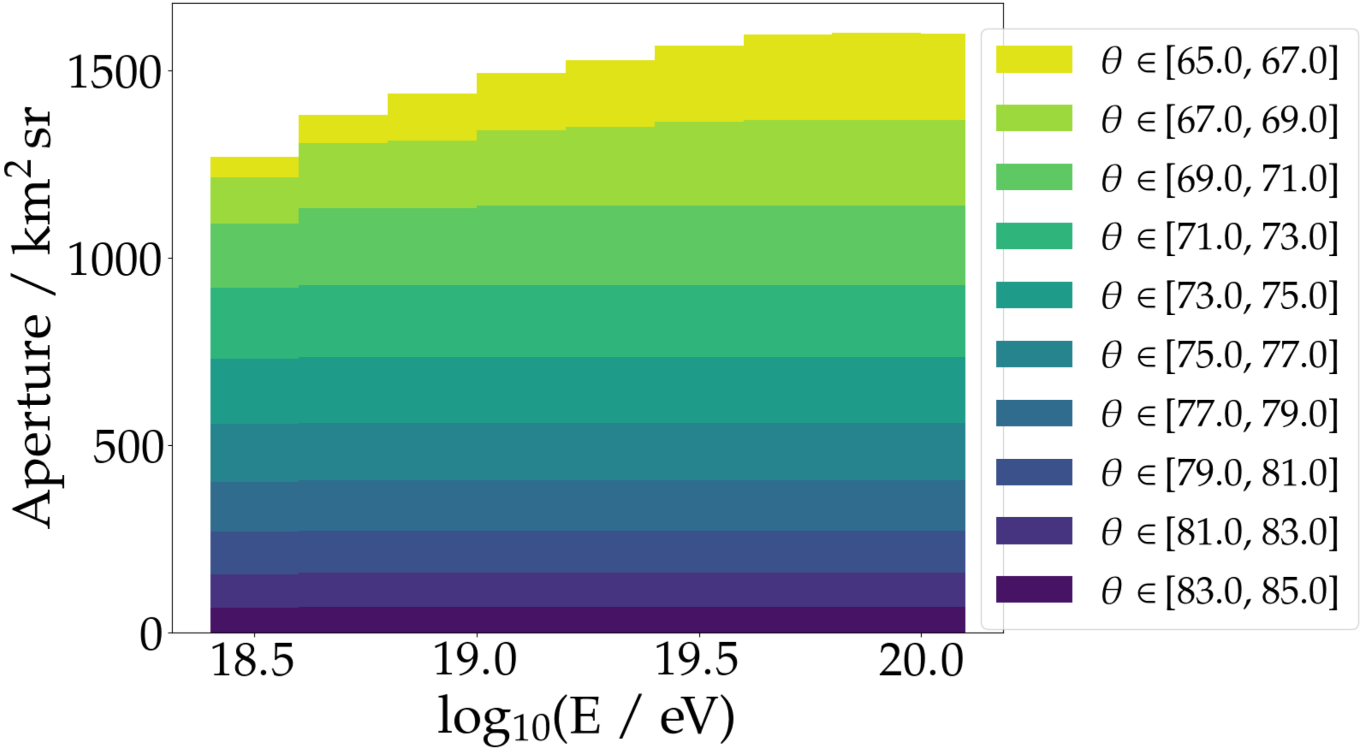
Normalized to WCD-reconstructed showers



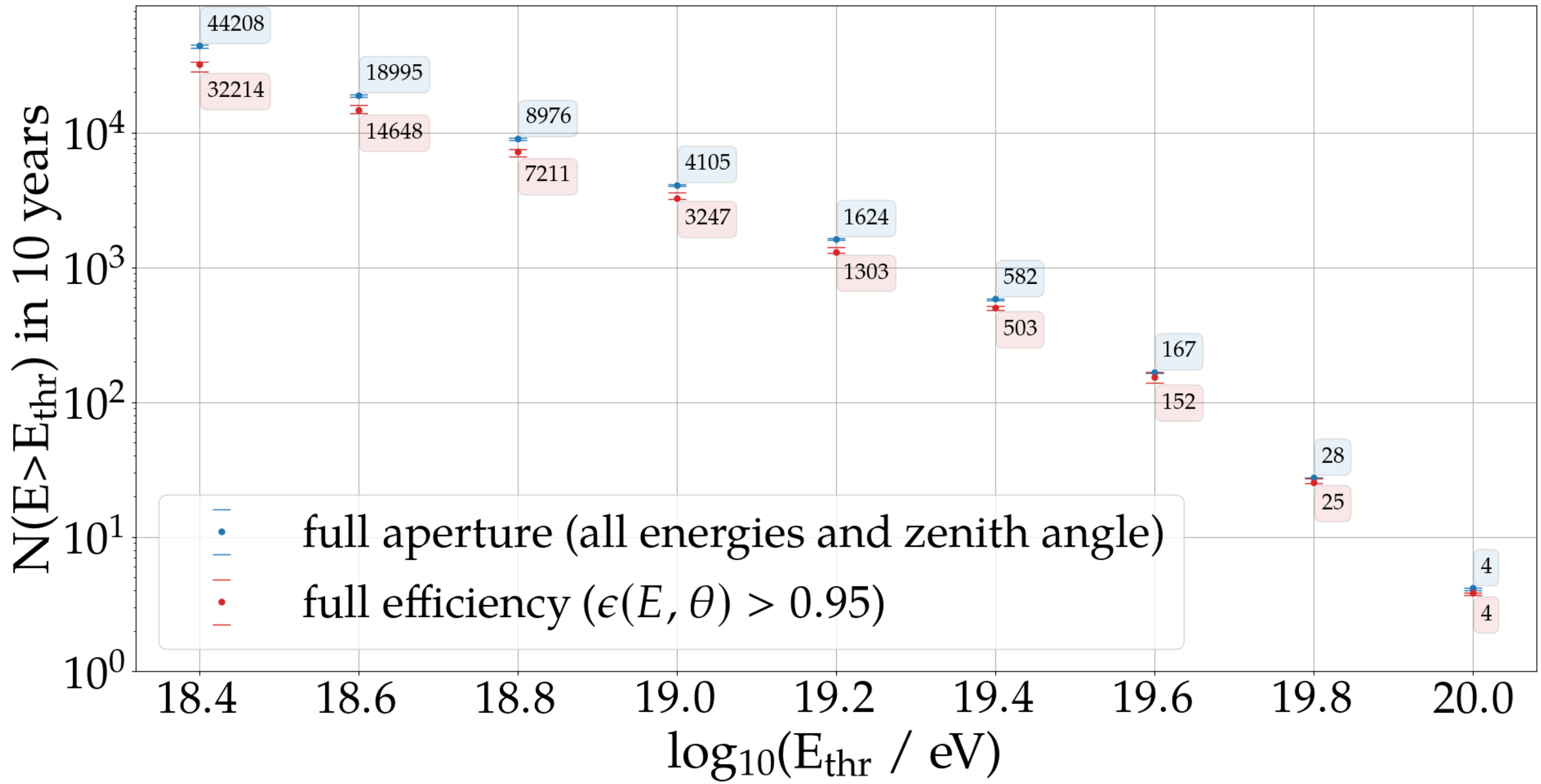
Binned in $\sin^2\theta$

Aperture for a 3000 km² array

- For ”contained events” aperture decreases with zenith angle
  - array projection (in shower frame) shrinks
- Constant aperture → full efficiency
- Good agreement with previous study
  B. Pont, Auger POS(ICRC2019)395



10-year event statistics



Estimated with Auger-measured flux:

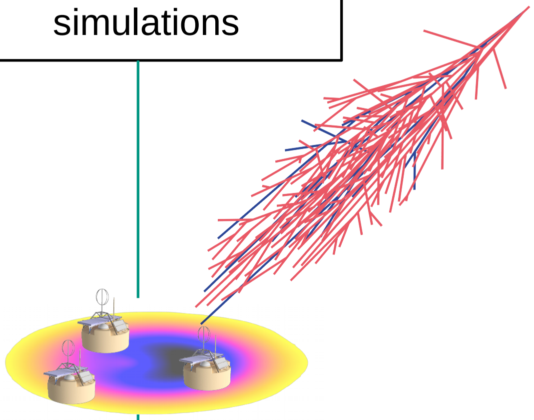
Auger, PRD 102 (2020) 062005

Aperture estimated in bins of $\sin^2\theta$

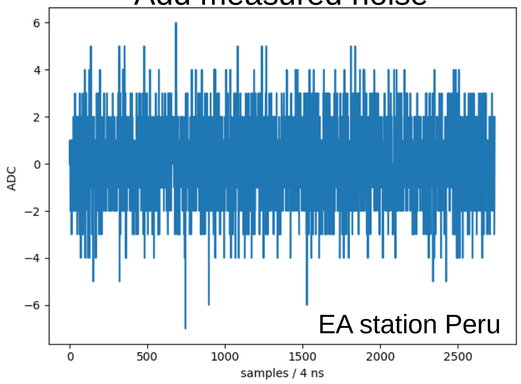
→ N(E > 10 EeV) ~ 4100 N(E > 32 EeV) ~ 330

End-to-end simulation study

CORSIKA/CoREAS simulations



Add measured noise

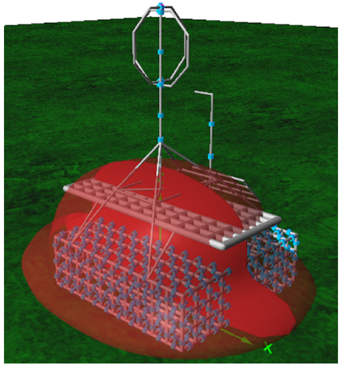


Nearly full efficient θ ≥ 70°
N(10y, lgE>19) = 4100

Detection efficiency / aperture

Radio Detector simulation

Station signal reconstruction



Mimic antenna-to-antenna variation:

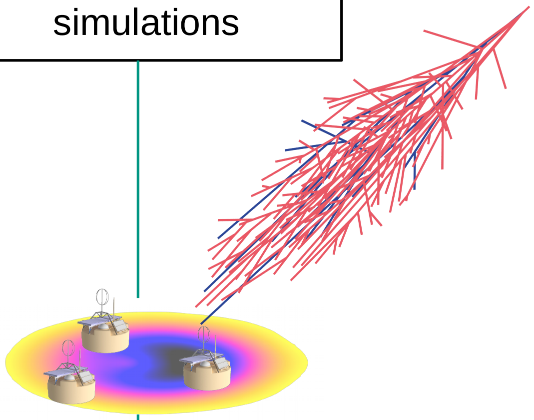
- Amplitude σ_A=5%
- Time σ_t=6ns

Calibrated signals:

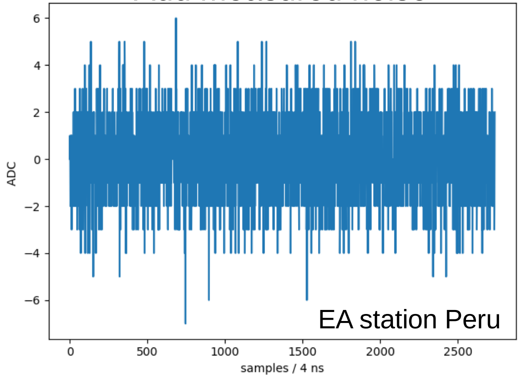
- signal-to-noise ratio SNR
- energy fluence f / eVm^{-2} in 30 – 80 MHz

End-to-end simulation study

CORSIKA/CoREAS simulations



Add measured noise



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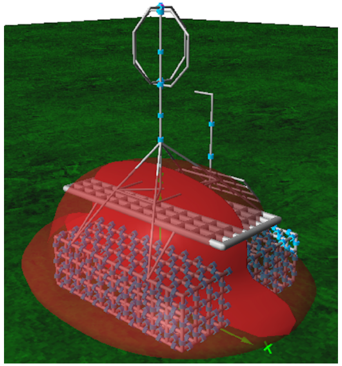


Radio Detector simulation → Station signal reconstruction → Shower reconstruction

Radio Detector simulation

Mimic antenna-to-antenna variation:

- Amplitude σ_A=5%
- Time σ_t=6ns

Station signal reconstruction

Calibrated signals:

- signal-to-noise ratio SNR
- energy fluence f / eVm^{-2} in 30 – 80 MHz

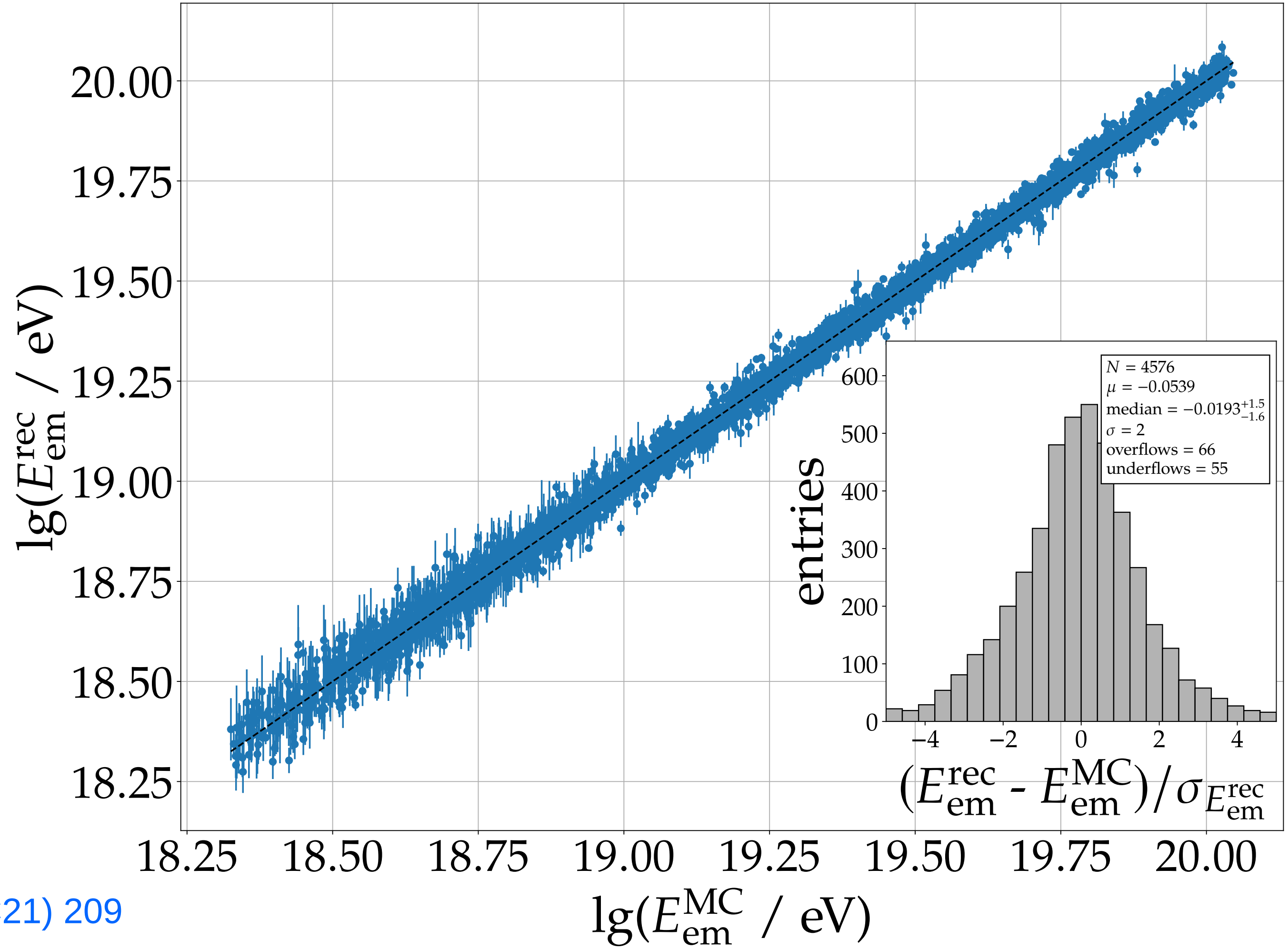
Shower reconstruction

1. Spherical wavefront fit
2. LDF fit

- Input: $\mathbf{x}_{WCD}$, θ_{RD}, E_{WCD}

Shower reconstruction

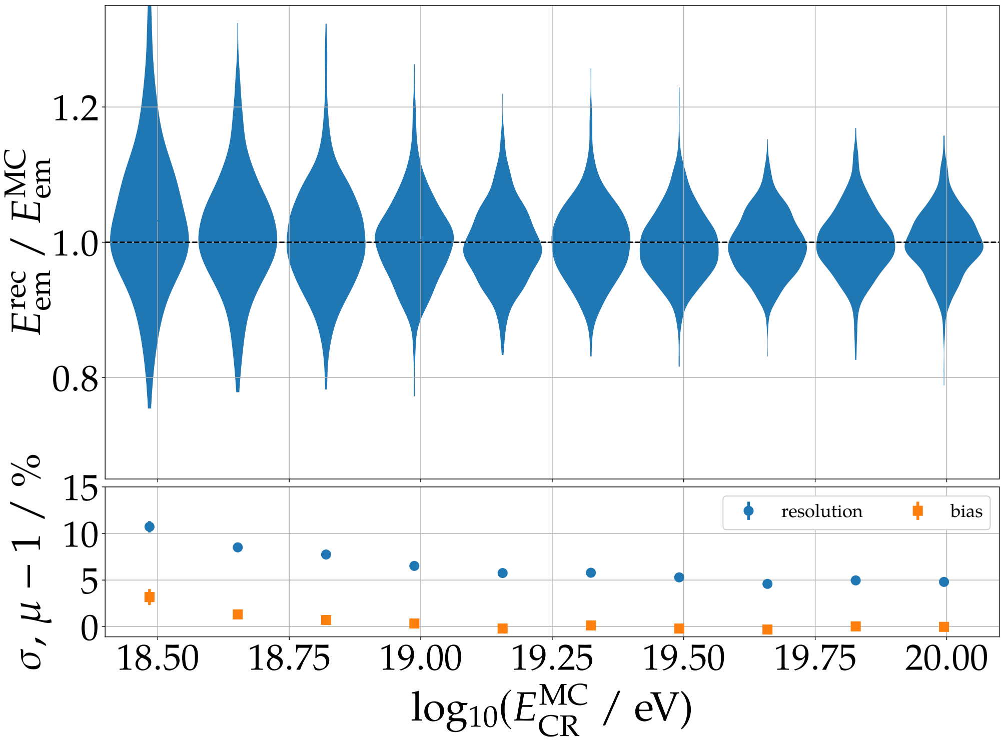
- Fit 4 parameters*
  - Electronmagnetic energy E_{em}
- Selection applied
  - At least 5 signal stations, ...
  - Not equally efficient for all primaries
- Uncertainties underestimated



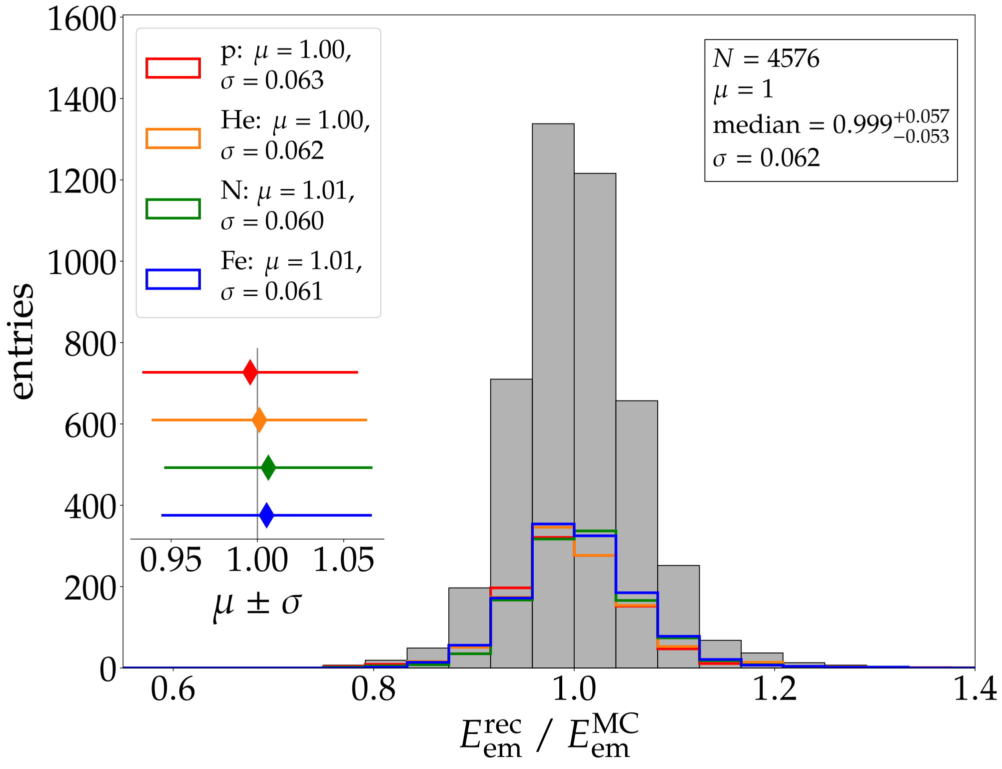
*LDF model T. Huege, FS, PoS (ICRC21) 209

Shower reconstruction

- Resolution < 10% at higher energies
  - Improves with energy expected due to noise

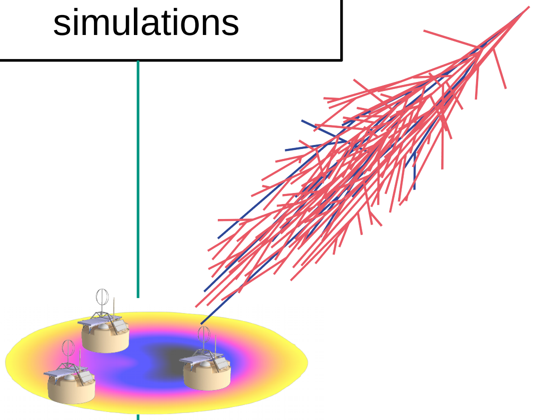


- No significant bias
- No dependency on mass

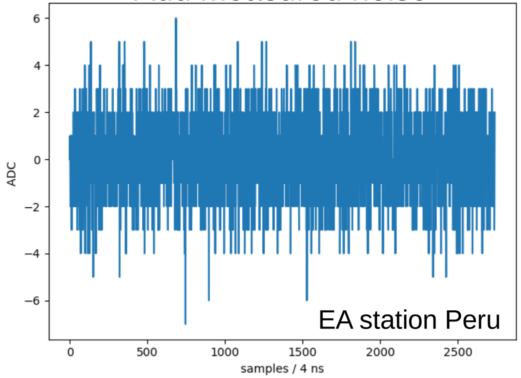


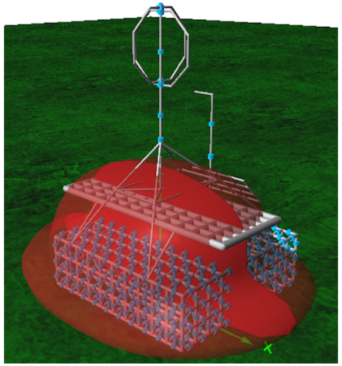
End-to-end simulation study

CORSIKA/CoREAS simulations



Add measured noise





Radio Detector simulation

Mimic antenna-to-antenna variation:

- Amplitude σ_A=5%
- Time σ_t=6ns

Station signal reconstruction

Calibrated signals:

- signal-to-noise ratio SNR
- energy fluence f / eVm^{-2} in 30 – 80 MHz

Detection efficiency / aperture

Nearly full efficient $\theta \geq 70°$
N(10y, lgE>19) = 4100

Shower reconstruction

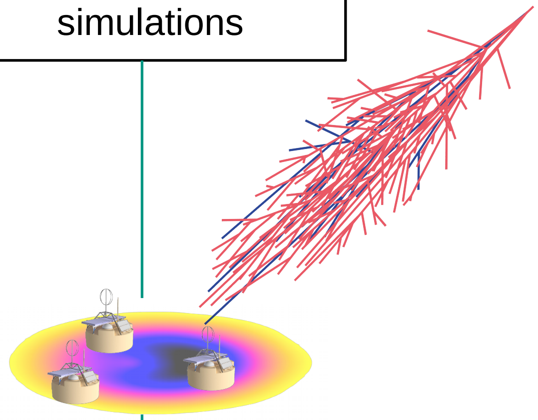
1. Spherical wavefront fit
2. LDF fit

- Input: $\mathbf{x}_{WCD}$, θ_{RD}, E_{WCD}

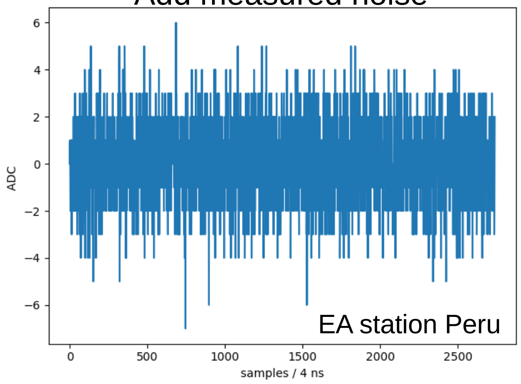
σ_E < 10%
no bias

End-to-end simulation study

CORSIKA/CoREAS simulations



Add measured noise



Nearly full efficient θ ≥ 70°

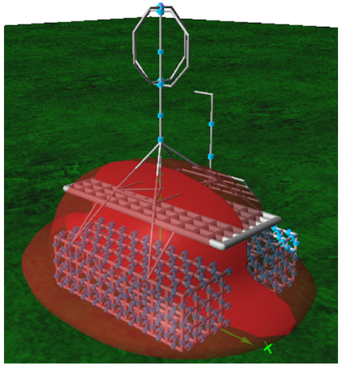
N(10y, lgE>19) = 4100

Mass composition analysis

Detection efficiency / aperture

$\sigma_E < 10\%$

no bias



Radio Detector simulation

Station signal reconstruction

Shower reconstruction

Mimic antenna-to-antenna variation:

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1. Spherical wavefront fit
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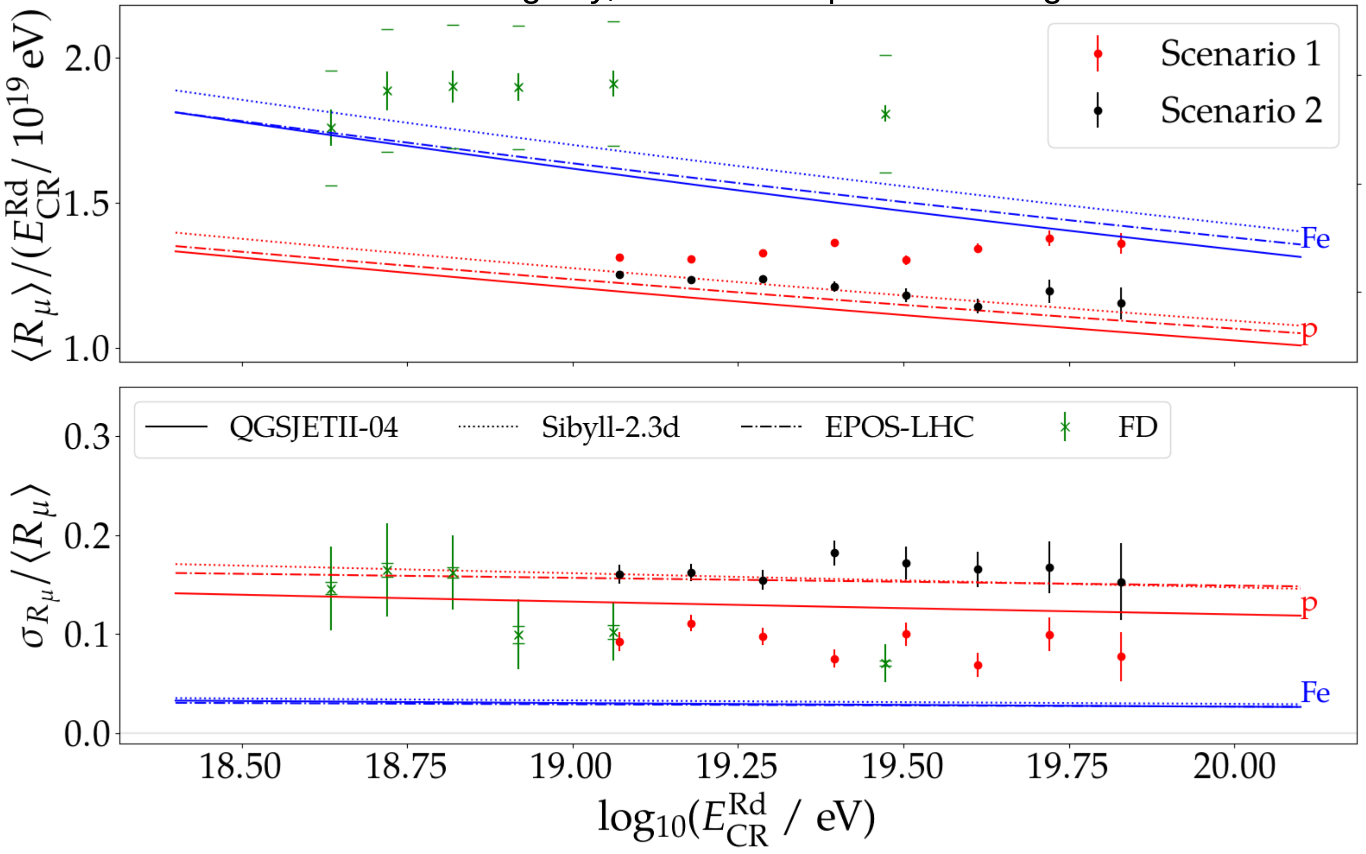
- Input: $\mathbf{x}_{WCD}$, θ_{RD}, E_{WCD}

Relative number of muons

- Mass composition sensitive variables
  - Lighter primaries produce fewer muons
- Exp. exposure and two mass-composition scenarios*
- **Higher statistics (w.r.t. FD)** at highest energies
- Fluctuation less affected by systematic uncertainties → **discrimination potential**

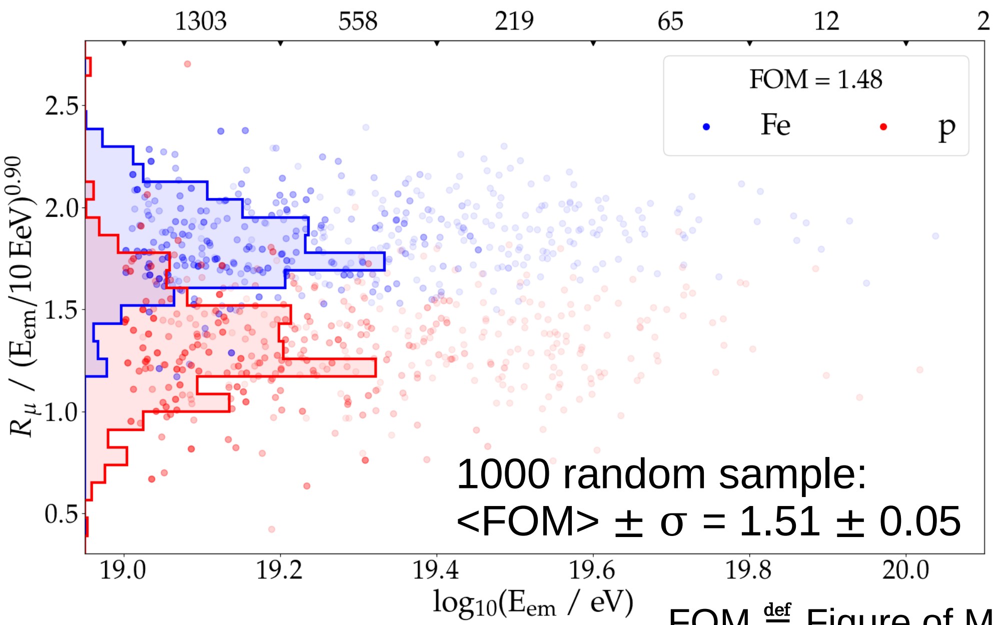
Scenario 1: maximum-rigidity, Scenario 2: photo-disintegration

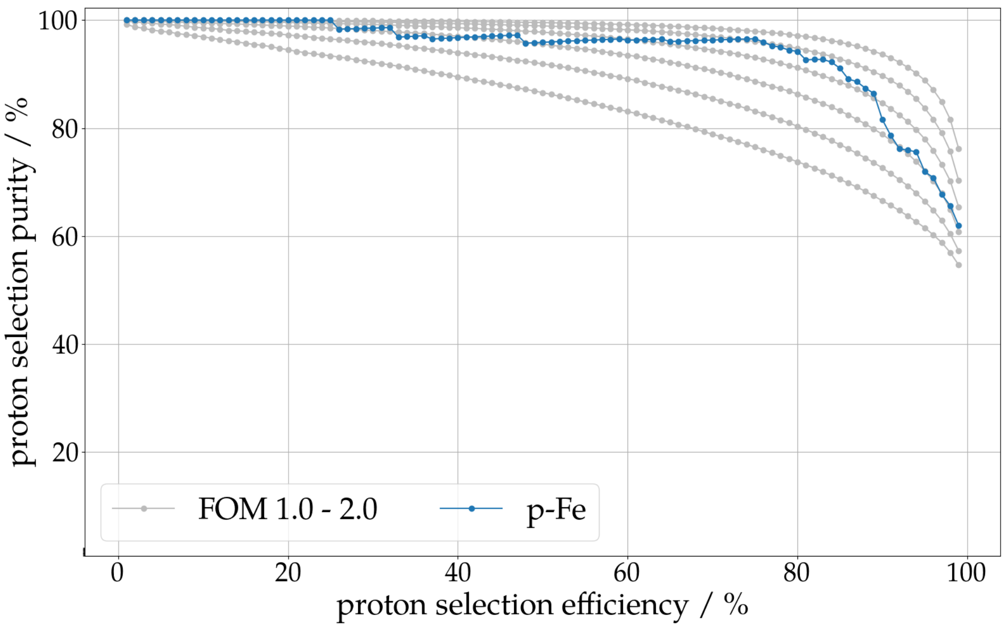


*AugerPrime Design Report arXiv:1604.03637

Event-by-event mass discrimination

- 50-50 p-Fe, with expected energy spectrum (events appear several times)
- Simple, energy-independent discriminator $R_\mu / E^{0.9}_{em}$ (~ Fisher analysis)
  - Good energy resolution critical!
  - FOM of 1.5 ≊ separation with X_{max} and σ_{Xmax} = 15 g/cm^2





FOM ≝ Figure of Merit

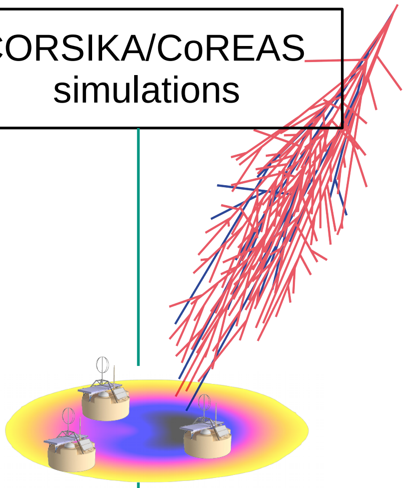
Summary & Conclusion

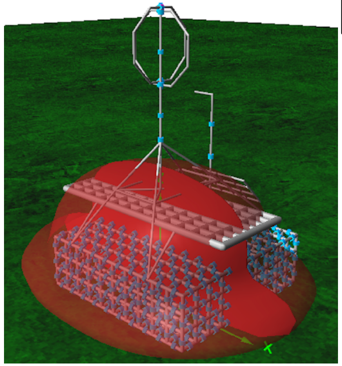
- End-to-end simulation study:
  - Monte-Carlo shower simulations, full detector simulation, measured background, realistic radio-based reconstruction
- Expected performance:
  - Event statistics: N(10y, lgE > 19) = 4105
  - Preliminary energy resolution: $\sigma_E < 10\%$
- Explored potential of hybrid measurements
  - Discriminate between composition scenarios
  - Discrimination between proton and iron / Contain a wealth of mass information

Backup

Expected performance of the AugerPrime Radio Detector

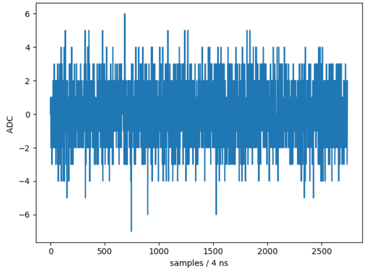
CORSIKA/CoREAS simulations



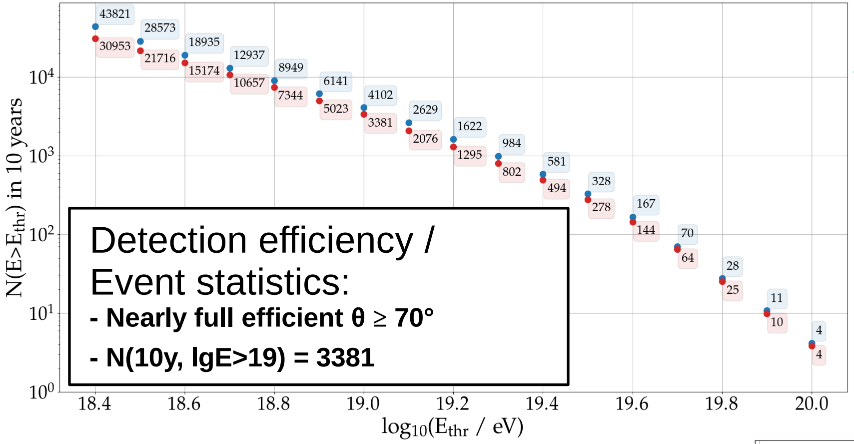


RD Detector simulation

Add measured noise



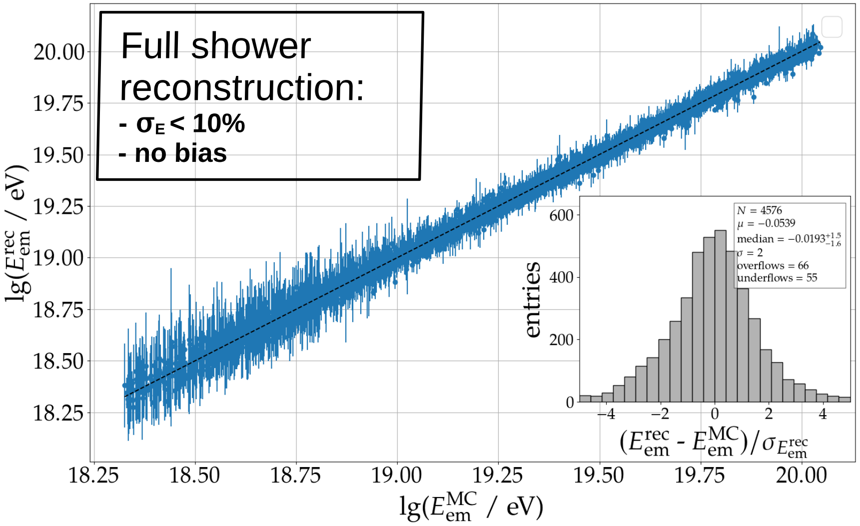
Station signal reconstruction



Detection efficiency / Event statistics:

- Nearly full efficient θ ≥ 70°

- N(10y, lgE>19) = 3381



Full shower reconstruction:

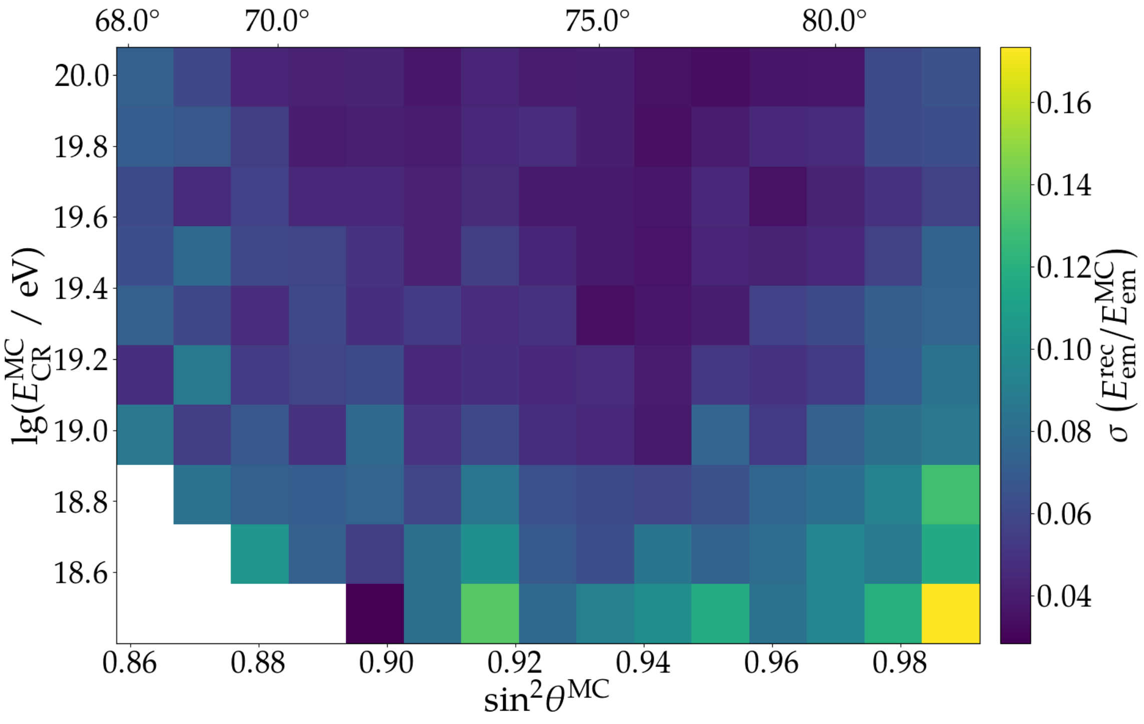
- σ_E < 10%

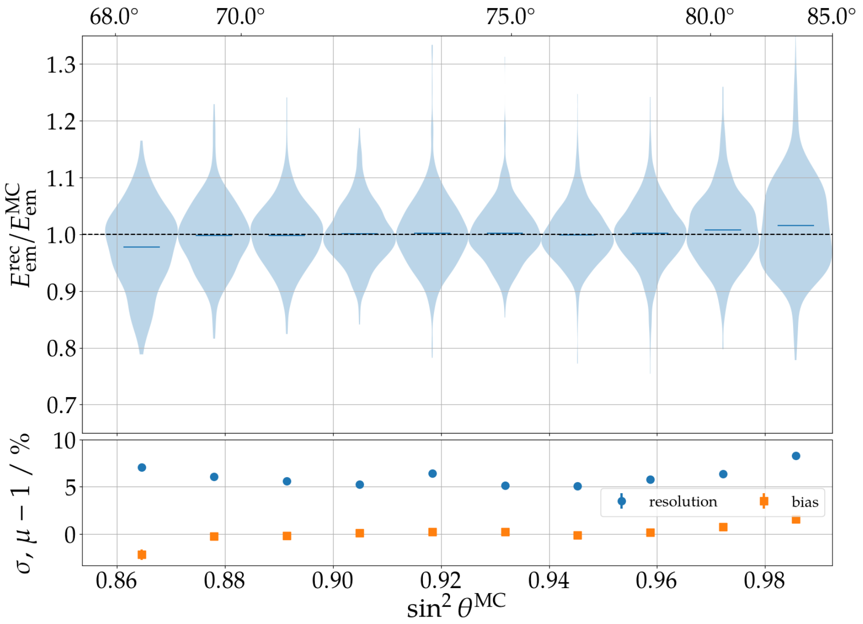
- no bias

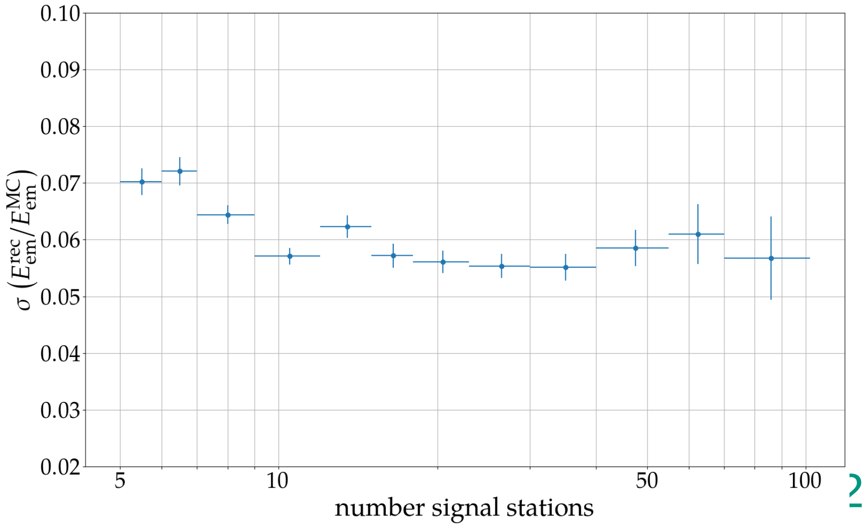
Mass composition analysis

Energy reconstruction

- Θ > 68°, n_{ant} >=5, ...







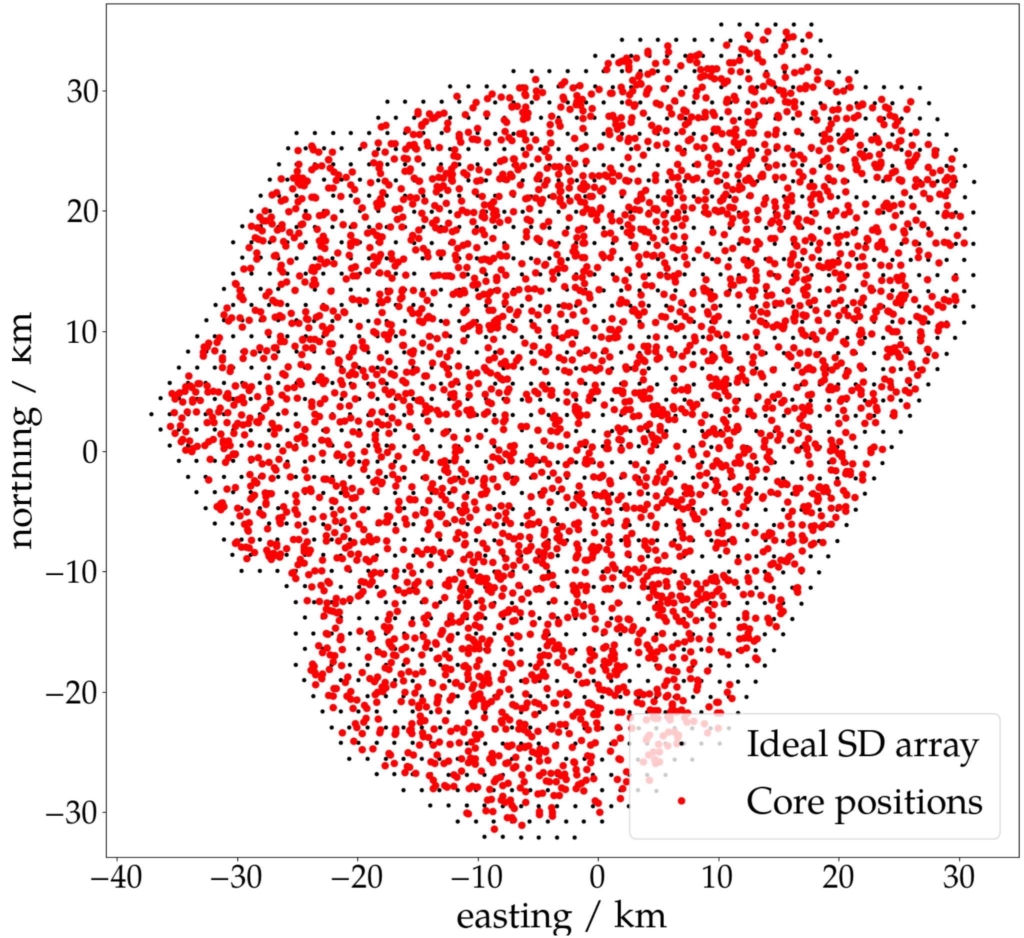
Selection for good RD energy reconstruction

- Selection bias for different primaries

	p / 1996	Fe / 1979	All / 3975
Has SD rec. LDF	1911 (95.7%)	1954 (98.7%)	3865 (97.2%)
min. RD signal stations: 5	1305 (68.3%)	1396 (71.4%)	2701 (69.9%)
Has RD spherical fit	1288 (98.7%)	1388 (99.4%)	2676 (99.1%)
$\alpha_{RD} > 20.0°$	1268 (98.4%)	1364 (98.3%)	2632 (98.4%)
$\theta_{RD} \geq 68.0°$	1232 (97.2%)	1310 (96.0%)	2542 (96.6%)
$\sigma_{\theta_{RD}} < 0.3°$	1229 (99.8%)	1309 (99.9%)	2538 (99.8%)
Has RD rec. LDF	1229 (100%)	1309 (100%)	2538 (100%)
RD LDF with core	1229 (100%)	1309 (100%)	2538 (100%)
$n_{stat}(r < 1.5 r_0) > 0$	1201 (97.7%)	1289 (98.5%)	2490 (98.1%)
$\sigma_{S_{rad}} < 60.0\%$	1145 (95.3%)	1266 (98.2%)	2411 (96.8%)
$\sigma_{d_{max}} < 30.0\%$	1141 (99.7%)	1256 (99.2%)	2397 (99.4%)
χ^2 / ndf < 5.0	1113 (97.5%)	1235 (98.3%)	2348 (98.0%)
fitted core at limit[3]	1106 (99.4%)	1233 (99.8%)	2339 (99.6%)
$\measuredangle(\hat{a}_{RD}, \hat{a}_{SD}) < 1.50°$	1098 (99.3%)	1222 (99.1%)	2320 (99.2%)

Simulation library

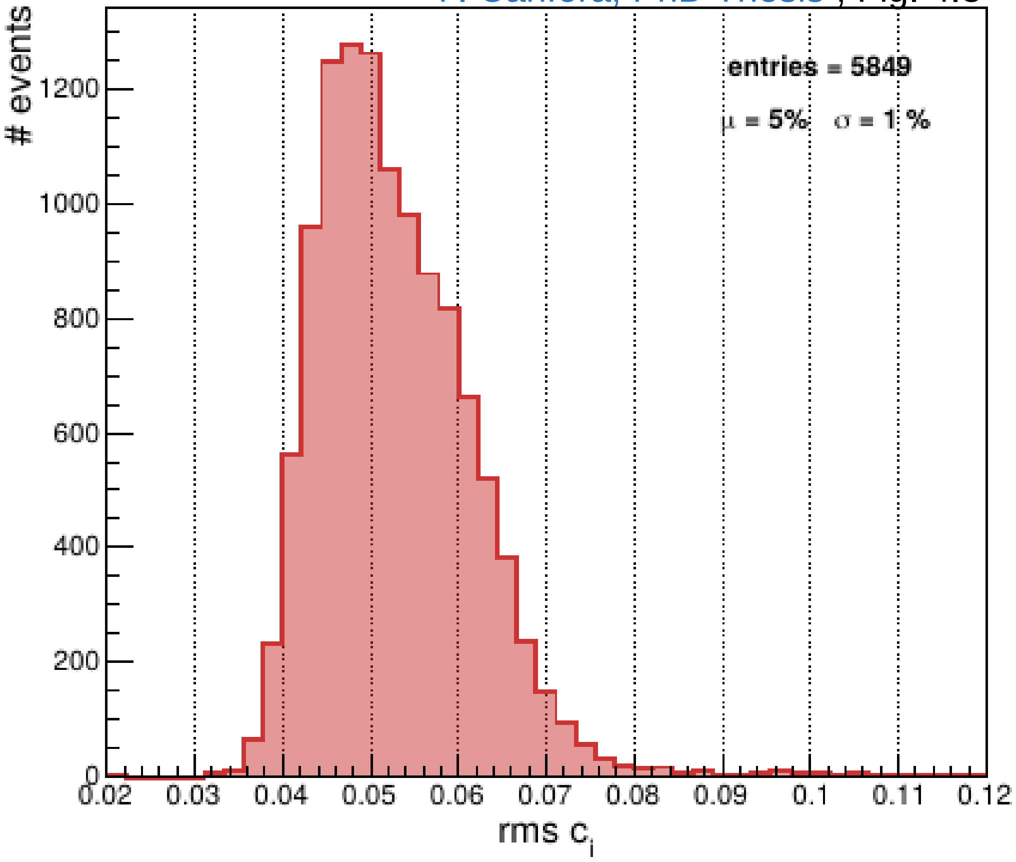
- 7972 p, He, N, Fe showers
  - p ~ sin() ^ 2 from 65 - 85°
  - p_E ~ lgE from 18.4 to 20.1
- Simulated radio signals for stations within r_{max}()
- Malargüe October atmosphere
  - density profile & refractivity
- QGSJETII-04 / URQMD



Antenna-to-antenna variation for AERA Butterfly antennas

- After galactic calibration
- $$c_i = \frac{1}{n} \sum_{j=\nu_1}^{\nu_n} \frac{A(\nu_i)}{\overline{A}_{\nu_i}},$$
    - spread of the amplitudes in single antennas over all antennas for 1 periodic trigger event
- Average over polarization
- Average of RMS is 5%

F. Canfora, PhD Thesis , Fig. 4.8



Reference Scenarios

2.2. *OPEN QUESTIONS AND GOALS OF UPGRADING THE OBSERVATORY* 13

Auger arXiv:1604.03637

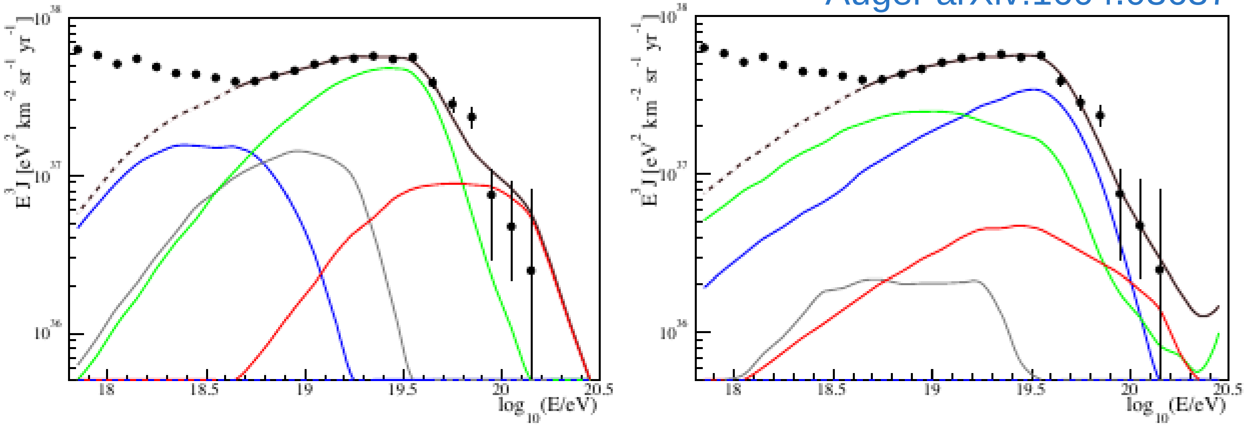


Figure 2.10: Examples of fluxes of different mass groups for describing the Auger spectrum and composition data. Shown are the fluxes of different mass groups that are approximations of one maximum-rigidity scenario (left panel) and one photo-disintegration scenario (right panel). The colors for the different mass groups are protons – blue, helium – gray, nitrogen – green, and iron – red. The model calculations were done with SimProp [30], very similar results are obtained with CRPropa [29].

- Extract primary fractions
- Use 10-years RD exposure

Arrival direction reconstruction

- RD: Spherical fit (point sources, spherical expansion, changing radius)