The Energy Content of Extensive Air Showers in the Radio Frequency Range of 30-80 MHz

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Engineering Radio Array of the Pierre Auger Observatory

- World's largest radio detector
- Deployed in different stages (2011: 0.6 km², 2013: 6 km², 2015: 17 km²)

more information
→ J. Schulz, Poster 615
**Auger Engineering Radio Array (AERA)**

- AERA phase 1 detector well understood
  - 24 antennas (out of 153 deployed)
  - 144 m spacing
  - ~2 years of runtime
- Antenna characteristics (LPDA) measured and simulated
- Individual measurement of whole signal chain
  - **Systematic uncertainty 14%**

**Data set**
- Coincidences with surface detector (750 m array)
- Zenith angle < 55°
- Quality cuts
  - Polarization of radio signal (removes noise pulses)
  - No thunderstorm conditions
- 126 events with $E > 10^{17}$ eV

Abreu et al., Jinst 7, 10011 (2012)
From Voltage to Cosmic Ray Energy

- **Voltage** [V]
- **Electric field** [V/m]
- **Radiation energy density** [eV/m²]
- **Radiation energy of air shower** [eV]
- **Cosmic ray energy estimator**

antenna + detector response

time integral of Poynting vector

fit 2D-LDF + spatial integral

geometry correction

$1/\sin^2(\alpha)$ with $\alpha = \mathbf{\hat{z}}(\mathbf{v}, \mathbf{B})$
Radiation Energy of Air Showers

- Interference between emission mechanisms
  - 2D lateral distribution function

- ≥ 5 signal stations or 3-4 signal stations and SD core

geomagnetic charge excess

- Polarized into direction of Lorentz force
- Radially polarized towards shower axis

Energy Calibration

- Likelihood fit of calibration function taking into account detection efficiencies

16 MeV radiation energy for a 1 EeV cosmic ray
Radiation Energy of Air Showers

- Generalization: normalizing to local geomagnetic field

\[ E_{30-80 \text{ MHz}} = 16 \text{ MeV} \left( \sin \alpha \frac{E}{10^{18} \text{ eV}} \frac{B_{\text{Earth}}}{0.24 \text{ G}} \right)^2 \]

- 28% syst. uncertainty
- 16% systematic uncertainty

- Can be used anywhere on Earth

- Cross calibration of cosmic ray observatories

magnetic field intensity
Potential of Independent Determination of Energy Scale

**Experiment**
- measurement of air shower
  - calibrated radio detector
    - energy density at each radio station [eV/m²]
  - LDF

**Theory**
- cosmic ray energy [eV]
  - data-driven method
    - Tueros et al., 33rd ICRC 2013
      - arXiv:1307.5059, p. 11
  - energy in electromagnetic component [eV]
    - first principles

- Radio emission purely described by classical electrodynamics (no free parameters)
- Atmosphere transparent to radio emission
Summary

- Pierre Auger Observatory: well calibrated environment for development of future detector technologies
- Auger Engineering Radio Array
  - Thoroughly calibrated through the entire signal chain
  - Reconstruction of energy density at detector station
- Radiation energy of air showers measured
  - 16 MeV for $E_{\text{CR}} = 1 \text{ EeV}$
- Cosmic ray energy resolution 17%
- Universal prediction of radiation energy
- Potential of determination of energy scale by first principles
Backup
Energy Resolution

energy resolution 22%

energy resolution 17%

number of signal stations ≥5

\[ \frac{2(\text{E}_{\text{SD}} - \text{E}_{\text{RD}})}{(\text{E}_{\text{SD}} + \text{E}_{\text{RD}})} \]
Calculating Energy Density

- Window around maximum of Hilbert envelope
- Energy density in eV/m²
  - Time integral of Poynting vector
  - Noise expectation subtracted
  - \( u = \varepsilon_0 c \left( \Delta t \sum_{t_1}^{t_2} |\bar{E}(t_i)|^2 - \Delta t \frac{t_2 - t_1}{t_4 - t_3} \sum_{t_3}^{t_4} |\bar{E}(t_i)|^2 \right) \)
LDF – Interference between Emission Mechanisms

- **1st order: geomagnetic radiation**
  - Electrons/positrons deflected in Earth magnetic field $\mathbf{B}$
  - Polarized into direction of Lorentz force

- **2nd order: charge excess / Askaryan effect**
  - Time varying net charge excess
  - Radially polarized towards shower axis
Pierre Auger Observatory

- Mendoza, Argentina
- World's largest cosmic ray detector (~3000 km²)
- 27 fluorescence telescopes
- 1660 surface detectors