Measurement of radio emission induced by Ultra-high energy cosmic rays at energies above 1 EeV with the Pierre Auger Observatory

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The Auger Engineering Radio Array

- World's largest radio detector for cosmic rays
- More than 150 autonomous radio stations on 17 km²
- Taking data since 2011
- Coincident measurements with SD and FD
- Two different antenna types
  - Log-periodic dipole antenna (LPDA)
  - Butterfly antenna
- Two polarizations
- Sensitive in the range of 30 – 80 MHz
Independent Determination of Cosmic-Ray Energy Scale

Measurement

Theoretical calculation

2-dim LDF model

EM shower energy

atmosphere transparent to radio waves

first principles classical electrodynamics

antenna and detector response

antenna and detector response

coincident measurement with other detectors

radiation energy per unit area

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Measuring cosmic ray energy with Radio

- Cosmic rays energies determined by radio
- Quadratic dependency of radio emission on cosmic ray energy
- Resolution of 14% for high-quality data set

3-4 signal stations: \( \sigma = 20\% \)

>5 signal stations: \( \sigma = 14\% \)
Horizontal air showers

- Extensive air showers with zenith angle $\theta > 60^\circ$

- Radio (and muons) reach ground
- EM and hadronic components die out earlier in atmosphere
- Inclined showers have larger footprint on ground
- Increase available phase space for detection of extensive air showers
  - Shower core can be further away
  - More stations triggered
Calibration of antennas

- Calibration campaign with an octocopter for both station types has been performed
- LPDA response pattern already extensively studied (see last years talks)
- For Butterfly: new response pattern established
- Vector effective length $\vec{H}$ relates incoming electric field and measured Voltage

\[ U(f, \theta, \phi) = \vec{H}(f, \theta, \phi) \cdot \vec{E}(f, \theta, \phi) \]
Butterfly Vector Effective Length

- Measurements from North, East, South, West, with 5 MHz spacing, full zenith range
- Use simulations for intermediate ranges in frequency and azimuth
- Precise description up to zenith angles of $80^\circ$ with uncertainties on the order of $15\%$

Corrected Response Pattern, EW horizontal at 55 MHz
Lateral distribution fit is challenging.
Simulations of charge excess emission

- For study of projection effects: simulations without magnetic field and air density set to 1
  - All radio emission produced by charge excess
- Incoming shower at 80° Zenith angle, directly from south, $E = 1$ EeV
- Equal spacing of antennas in shower plane
Simulation results

- Repeated simulation 200 times with proton, 200 with iron primary
- Left-right asymmetries from shower-to-shower fluctuations
  - In mean, asymmetries vanish
- Large absolute spread between simulations
- Strong Xmax correlation of absolute energy fluence
Simulation Iron

- Smaller spread for iron primaries
- As expected: Shower-to-shower fluctuations smaller for heavy primaries
Ratio of peaks

- Take ratio of right peak and left peak
- 1 in mean, but large scatter
- No Xmax dependance

Mean ratio of peaks: 1.02 ± 0.11
Independent Determination of Cosmic-Ray Energy Scale

**Measurement**
- Antenna and detector response
- 2-dim LDF model
- Coincident measurement with other detectors

**Theoretical calculation**
- First principles classical electrodynamics
- EM shower energy
- Atmosphere transparent to radio waves

Work in progress
Summary and Outlook

- Extensive air showers induced by Ultra-High Energy Cosmic Rays hot topic in current research
  - Usable for energy calibration of whole Pierre Auger Observatory
- AERA well suited for study of these showers
- Well understood detector
  - Calibration campaign performed
  - Response pattern of antennas well described
- Need reconstruction of horizontal air showers
  - Asymmetries in charge excess emission found
  - Have to adapt reconstruction fit for horizontal showers
- In future: Energy calibration up to highest energies possible
## Uncertainties Calibration

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Uncertainties Calibration

Systematic uncertainty horizontal

Statistical uncertainty horizontal
Comparison old/new pattern

![Comparison old/new pattern](image-url)