On the cosmic-ray energy scale of the LOFAR radio telescope

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Accurately determining the energy of detected cosmic rays is critical for the interpretation of measured data. We discuss:
★ Energy reconstruction at LOFAR ★ Determination of uncertainties ★ Comparing the energy scales of Auger and LORA ★

Energy Reconstruction

Cosmic rays are measured at LOFAR both with a dense array of antennas and with the LOFAR Radboud air shower Array (LORA). Energy reconstructions done using both techniques are consistent.

Radio-based

- LOFAR (Low-Frequency Array) is a radio telescope with a core of 24 stations in the Netherlands which measures radio emission from air showers in the 30-80 MHz range [1]
- Radio-based energy reconstruction uses a minimization procedure based on Monte Carlo simulations (CORSIKA [3] and CoREAS [4]) to determine the best-fit simulation to data with core position and a radio-based energy scale factor as free parameters.

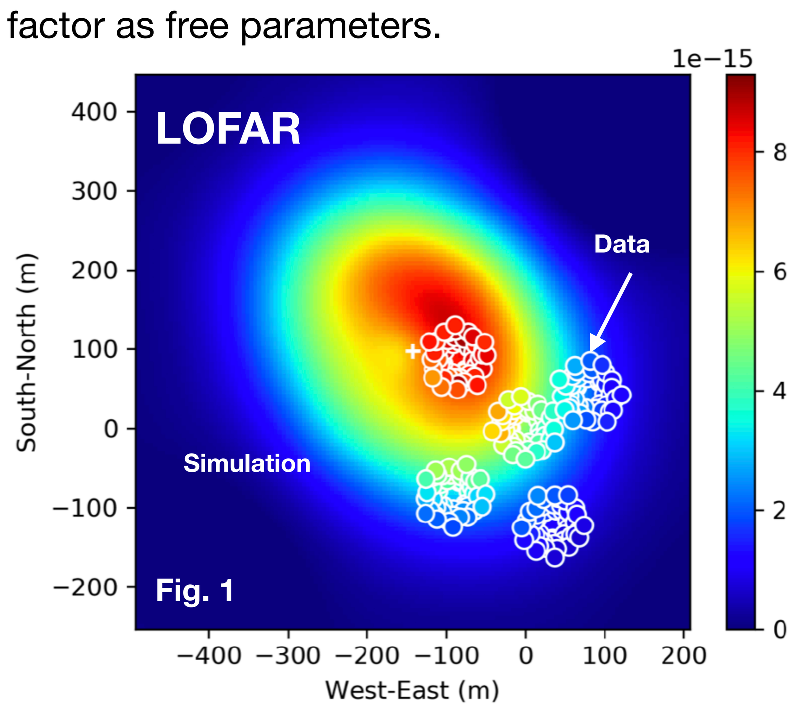
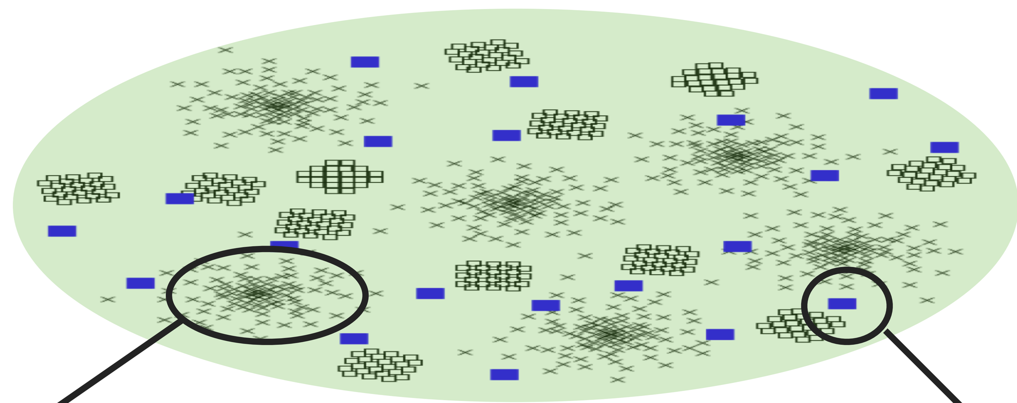
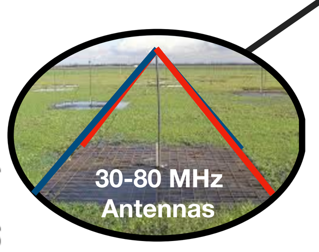


Fig. 1: Example radio event. Simulated radio energy is in the background and measured data is shown at the antenna locations.

LOFAR Superterp





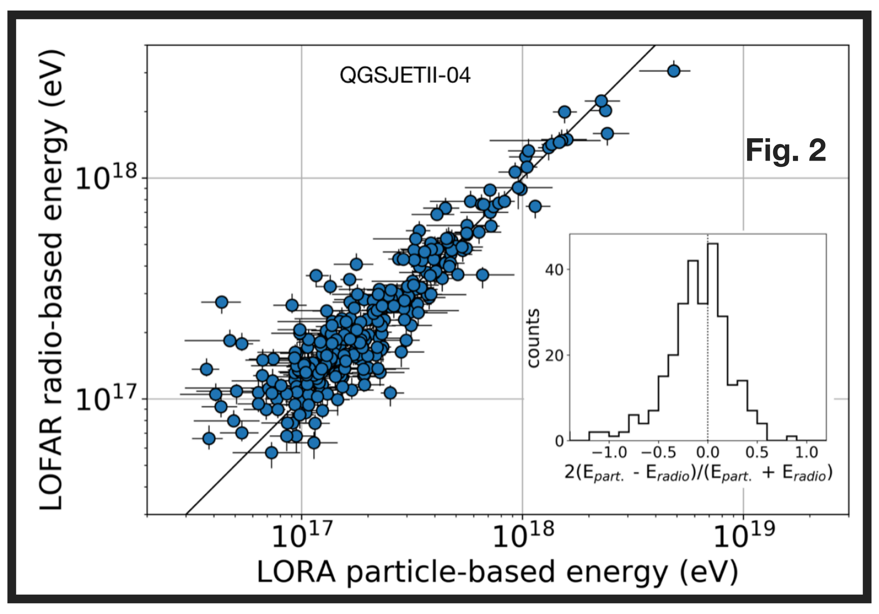
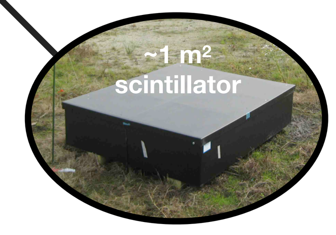


Fig. 2: Comparison of the reconstructed energies using radio and particle techniques, indicating that the two techniques are consistent.



Particle-based

- LORA (LOFAR Radboud Air Shower Array) [2] consists of 20 scintillators on the superterp (the densest area of LOFAR antennas) and provides the cosmic-ray trigger for LOFAR antenna read-out.
- Particle-based energy reconstruction uses a minimization procedure based on Monte Carlo simulations (CORSIKA [3]) to determine the best-fit simulation to data. The core position from the radio-based reconstruction is used and a particle-based energy scale factor is a free parameter.

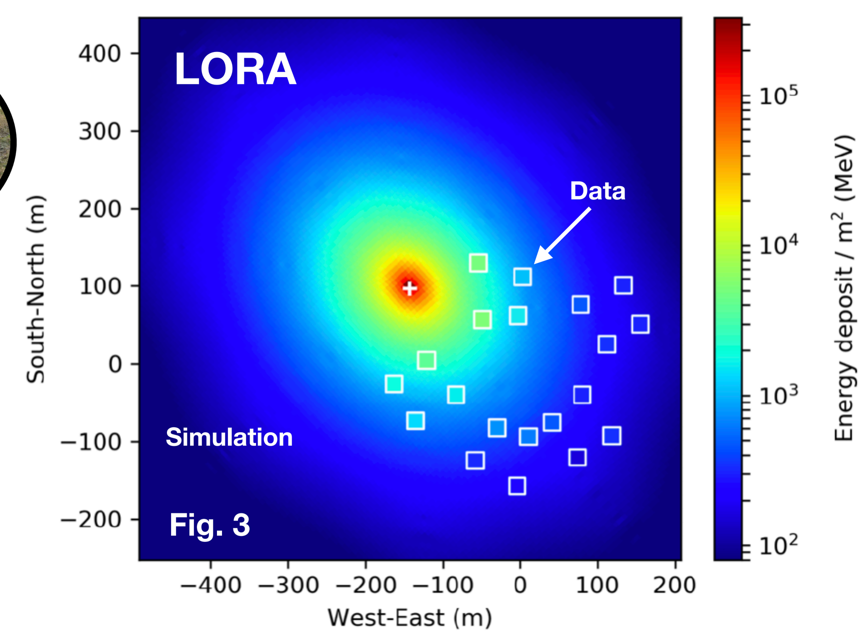


Fig. 3: Example particle event. Simulated energy deposit in a 1 m² scintillator is in the background and measured data is shown at the scintillator locations.

Uncertainties

We characterize the event-by-event and systematic uncertainties on radio and particle-based reconstructed energy. Radio-based reconstructed energy has smaller event-by-event uncertainties, and so that technique will be used in future LOFAR analyses.

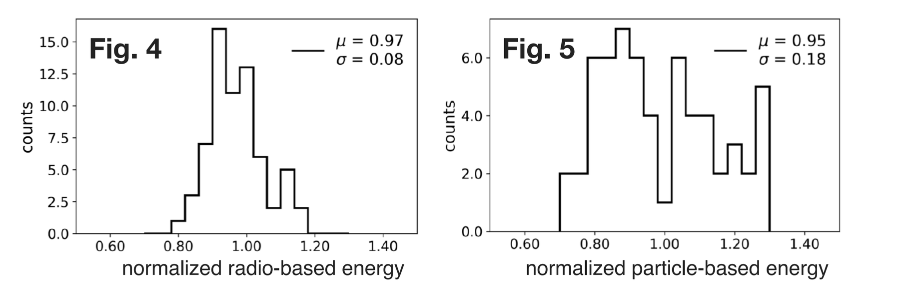
Radio-based energy

Uncertainty	Value
Event-by-event	
angular dependence of antenna model	5%
temperature dependence	negligible
reconstruction uncertainty	typically 9%
composition uncertainty	10 %
Total event-by-event	11% $\oplus$ reconstruction uncertainty
Absolute scale	
antenna calibration and system response	13%
hadronic interaction models	3%
radio simulation method	2.6%
Total absolute scale	13.6%

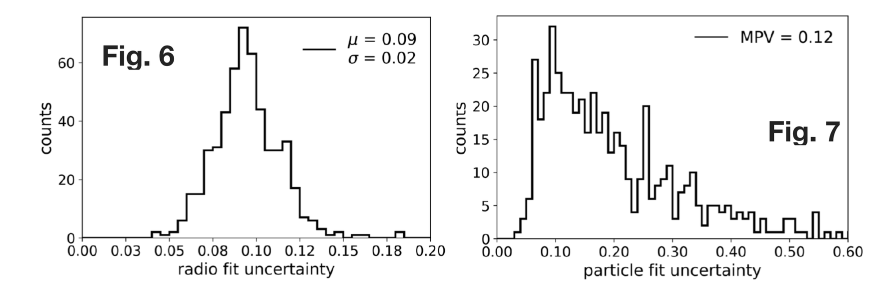
Particle-based energy

Uncertainty	Value
Event-by-event	
scintillator response variation	2.5%
reconstruction uncertainty	10 – 50%
composition uncertainty	2 – 30%
Total event-by-event	2.5% $\oplus$ reconstruction uncertainty $\oplus$ composition uncertainty
Absolute scale	
scintillator calibration	3%
hadronic interaction models	7%
Total absolute scale	7.6%

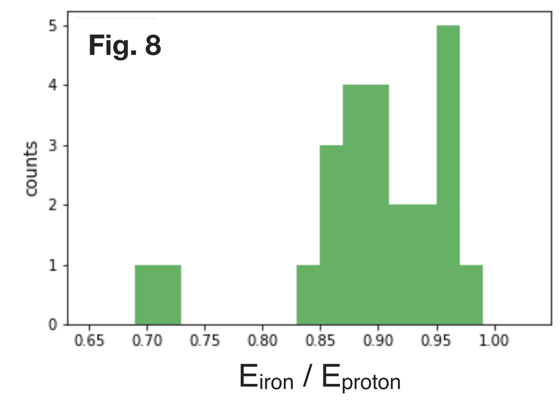
Event-by-event reconstruction uncertainties



- A set of ~40 simulations is produced for each event.
- Energy reconstruction is done using one simulation as "data." This is repeated for each simulation in the set.
- The distributions of reconstructed energies for one event (normalized to 1.0) are shown in **Fig. 4** and **Fig. 5** for radio and particle reconstruction.
- The standard deviations of the distributions are taken to be the radio and particle-based reconstruction uncertainties for this particular event.

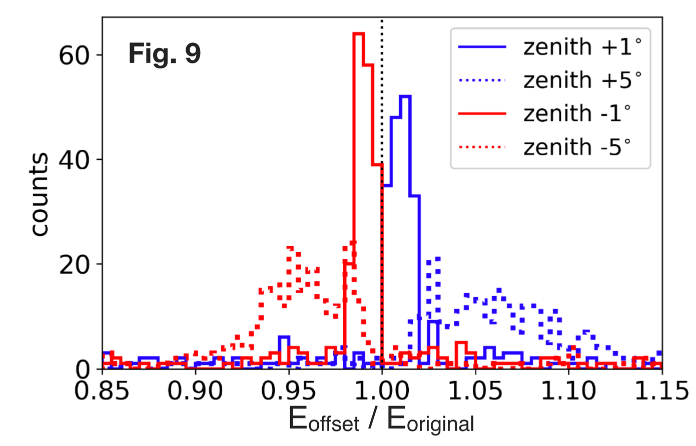


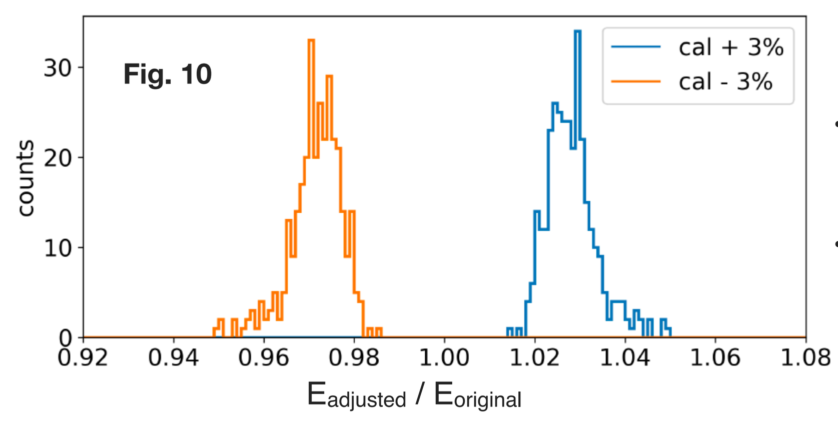
- The distributions of reconstruction uncertainties for all events are shown in **Fig. 6** for radio-based reconstruction and **Fig. 7** for particle-based reconstruction.
- Radio-based reconstruction has smaller and more consistent event-by-event reconstruction uncertainty.



- Event-by-event uncertainty on the particle-based energy due to the unknown primary type is determined by repeating the energy reconstruction using simulations with the same energy, geometry and similar X_{max}, but with different primary types.
- The distribution of ratios between the energy reconstructed with proton and iron primaries event is shown in **Fig. 8**.
- Reconstructed energy assuming an iron primary is typically 10% lower than if a proton primary is assumed.

- Event-by-event uncertainty on radio-based energy due to the angular dependence of the antenna model is determined by offsetting the zenith angle of each event and reconstructing the energy.
- The distribution of ratios between the energy reconstructed with the offset and original reconstruction is shown in **Fig. 9**.

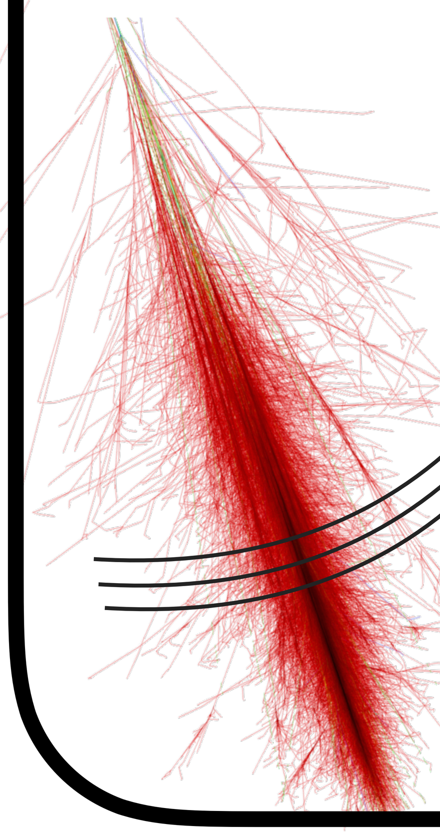




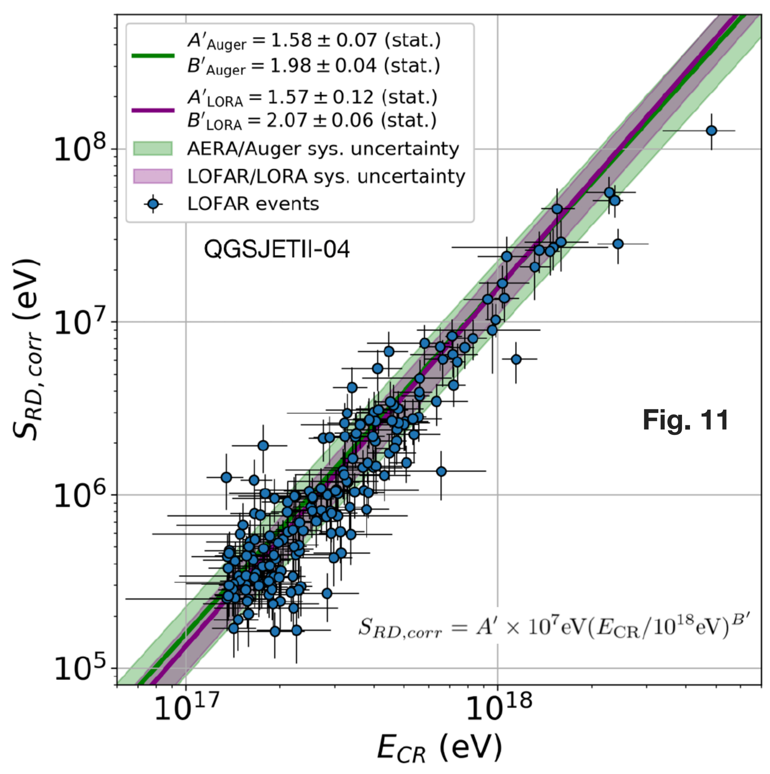
- The systematic uncertainty on the scintillator calibration due to response variation is determined by recalibrating the scintillators at different times.
- The standard deviation of calibration values is 3%. The energy is reconstructed while offsetting the calibration by +/- 3%. This is shown in **Fig. 10**.

Radiation Energy

Radiation energy measurements can be used to compare energy scales of different experiments. We compare the LORA energy scale to the Auger energy scale and find that they agree to within (6 ± 20)% for a radiation energy of 1 MeV.



- ***Radiation energy***: energy emitted by the air shower in the form of radio waves
- "Corrected radiation energy," $S_{RD,corr}$, is a universal quantity when corrected for:
  - local magnetic field strength
  - relative angle between magnetic field and shower development
  - relative charge excess contribution
- Radiation energy scales with energy in electromagnetic components of the air shower



Radiation energy for LOFAR events was found following [5] and compared to LORA cosmic-ray energy, $E_{CR,LORA}$. **Fig. 11**

Radiation energy for AERA [6] events was found and compared to Auger cosmic-ray energy, $E_{CR,Auger}$ [7], **Fig. 11**

At corrected radiation energy: $S_{RD,corr}$=1 MeV:

$E_{CR,Auger}$ → 2.48 ± 0:52 (sys) x 10^{17} eV
$E_{CR,LORA}$ → 2.64 ± 0:42 (sys) x 10^{17} eV

$$E_{CR,LORA}/E_{CR,Auger} = 1.06 \pm 0.20$$

Large uncertainty on the comparison! Eliminate this using the CR energy-scale cross-calibration array (ICRC 1034)

★ Energy scales can be compared between experiments!

[1] P. Schellart et al. A&A , 560(A98), 2013
[2] S. Thoudam et al. Nucl.Instrum.Meth , A767:339–346, 2014
[3] D. Heck et al., Report FZKA, 6019, 1998.
[4] T. Huege et al. AIP Conf. Proc., 1535:128, 2013.
[5] C. Glaser et al. JCAP 09 (2016) 024.
[6] A. Aab et al. PoS (ICRC2015) 615.
[7] A. Aab et al. Phys. Rev. D 93 (2016) 122005.

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