

# Measurements of Horizontal Air Showers with the Auger Engineering Radio Array

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**Abstract.** The Pierre Auger Observatory is the largest observatory for the detection of cosmic rays. With the Auger Engineering Radio Array (AERA) we measure the emitted radio signal of extensive air showers and reconstruct properties of the primary cosmic rays. For horizontal air showers (zenith angles larger than  $60^\circ$ ) the signal is distributed over a large area of more than several  $\text{km}^2$ . Therefore, detection of air showers using a sparse radio antenna array, compatible with the 1500 m distance between the 1600 surface detector stations, is possible. The radio technique is sensitive to the electromagnetic component of air showers. Combining radio detection with particle information from the surface detector of the Observatory, which at large zenith angles mostly detects muons, allows to study the cosmic ray composition for horizontal air showers.

## 1 Radio Detection of Horizontal Air Showers with AERA

With AERA [1] we observed radio emissions of 561 horizontal air showers with zenith angles  $\theta$  between  $60^\circ$  and  $84^\circ$  in the time period between 26 June 2013 and 28 February 2015 [2]. The distribution of the  $\sin^2 \theta$ , as reconstructed by the surface detector (SD) of the Pierre Auger Observatory [3], increases towards higher zenith angles, cf. Fig 1. This indicates an increase in the detection efficiency for the coincident observation of air showers with the surface detector and AERA. We define a high quality set of 50 events based on the SD reconstruction with a bias-free energy estimation better than 25 % above  $10^{18.5}$  eV [4], reaching up to  $10^{19.5}$  eV.

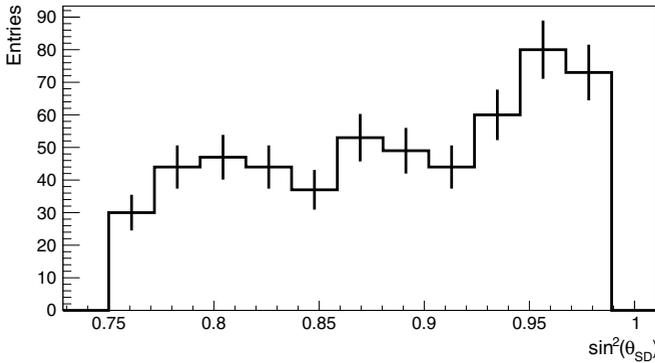
For each of these events we perform a full Monte-Carlo Simulation with CoREAS [5] using protons as primary particle. Comparing the predicted and measured pulse amplitudes for antennas with significant signal in data and simulation we find that simulations underpredict the measured amplitudes by only 2 %, which is well inside the systematic uncertainty.

The illuminated area on the ground increases for horizontal air showers as the distance to the source of the radio emission is large ( $\sim 10$  km to 100 km). For the largest footprints we see signals well above noise at axis distances in the showerplane up to 2300 m. Fig. 2 shows a clear increase of the farthest axis distance at which a signal was measured with increasing zenith angle. This is in agreement with the increased detection efficiency indicated by the  $\sin^2 \theta$  distribution. We also observed a weak correlation with the cosmic ray energy.

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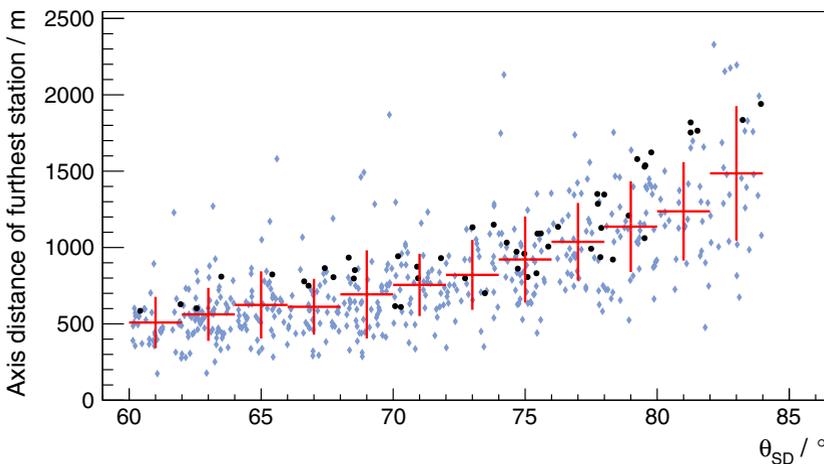


**Figure 1.** Distributions of the zenith angles of the 561 extensive air showers selected in this analysis as determined with the Auger surface detector. Poissonian errors are shown for each bin.

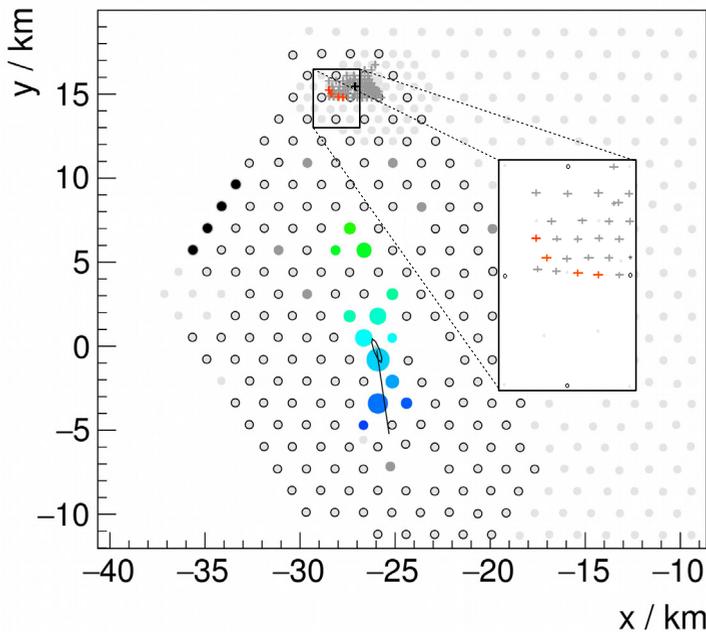
Fig. 3 shows a closer look at one particularly interesting event. The reconstructed shower core is 15 km away from AERA, yet radio emissions are observed. The azimuth angles reconstructed from the arrival times of the radio signals and particle detector reconstruction agree to better than  $0.5^\circ$ . The zenith angle is reconstructed to  $83^\circ$  with the particle detector and  $87^\circ$  with the radio signal. The low multiplicity of radio stations and their alignment along a line perpendicular to the air shower axis might limit the zenith angle resolution for this event. This example event illustrates that the ground area illuminated by radio signals can be significantly larger than the “particle footprint” on the ground.

## 2 Conclusion and Outlook

The radio detection of horizontal air showers shows great potential. Even with a sparse grid of radio antennas detection of horizontal air showers is feasible [6]. We illustrate this by thinning out AERA



**Figure 2.** Farthest axis distance at which a radio signal above noise background has been detected as a function of the air shower zenith angle. Black dots represent the 50 high quality events with an energy reconstruction, blue diamonds denote the remaining 511 events. The red bars show the mean and standard deviation in each  $2^\circ$  bin.



**Figure 3.** Visualisation of the event information. The circles indicate the measurement with the surface detector (size:energy deposit, color:arrival time). Dark-grey circles indicate isolated particle detector stations, being rejected in the reconstruction. The radio stations are shown as crosses, color indicating the arrival time of signal stations.

to only five antennas with a spacing of 1.5 km. We find 44 events fulfilling the same criteria as the originally selected 561 events with only a minor loss in the accuracy of the reconstructed shower direction. For horizontal air showers particle detectors perform a pure measurement of the muonic component whereas radio detectors measure the electromagnetic cascade. Combining both types of information offers significant potential for mass composition measurements [7].

## References

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