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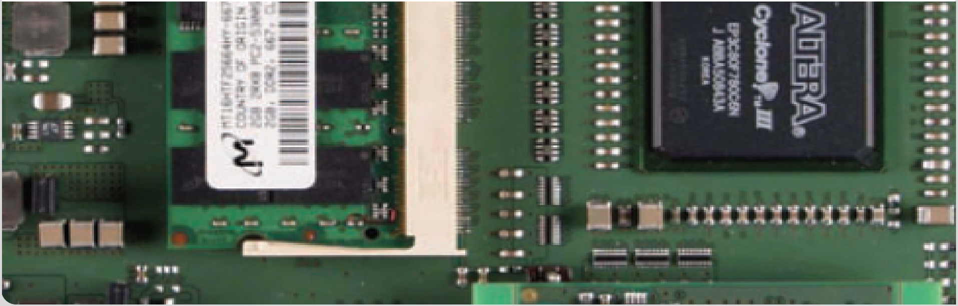
Cosmic ray physics with the Auger Engineering Radio Array (AERA)

Benedikt Zimmermann | 06.07.2016
for the Pierre Auger Collaboration

IPE - INSTITUT FÜR PROZESSDATENVERARBEITUNG UND ELEKTRONIK



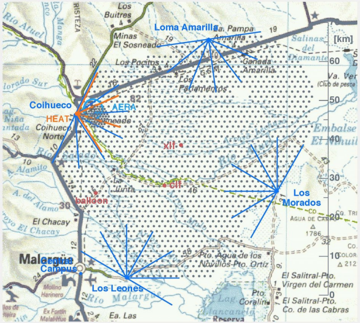
The Pierre Auger Observatory

Characteristic numbers:

- $3000\ km^2$ area.
- Flux at energies $\geq 10^{19}$eV only $0.01/a/km^2$.

Parts:

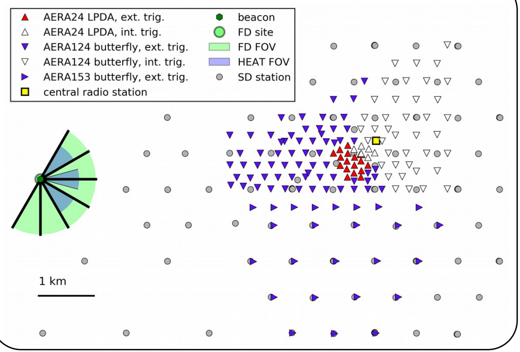
- 1600 water Cerenkov detectors (SD) with 1500 m spacing.
- 750 m spacing in Infill area.
- 4 fluorescence sites (FD).
- 153 radio stations (RD).
- other enhancements (AMIGA, ...).

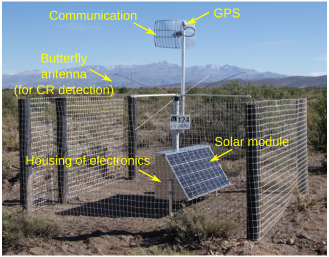


AERA - Auger Engineering Radio Array

- World's largest radio experiment for CR-physics.
- Profiting from 3 other nearby CR-detectors: ($\rightarrow$ high quality data, ext. trigger, ...).
- 100% duty cycle.
- Energy threshold $\sim 10^{17}$ eV.

Since 2015: 153 radio-detectors on an area of 17 square kilometers





AERA - Aims

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Investigating the prospects of radio-detectors as a standalone alternative to conventional air-shower detectors (SD, FD).

- Calibration of the radio emission from the air showers, including sub-dominant emission mechanisms, by using super-hybrid air shower measurements;
- Demonstration of the physics capabilities of the radio technique, e.g. energy, angular, and primary mass resolution; and
- Measurement of the cosmic ray composition in the ankle region, from 0.3 to 5 EeV, with the goal of elucidating the transition from Galactic to extra-Galactic cosmic rays.

Auger collab., Proceedings, 32nd International Cosmic Ray Conference (ICRC 2011)

Auger collab., Nucl. Instrum. Meth. A 617 (2010) 484

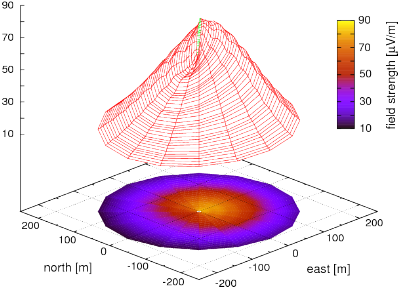
The radio emission mechanism

Strong change of nr of particles around the shower maximum leads to:

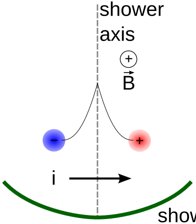
- Time varying transversal current (geomagnetic effect) (90%).
- Time varying charge excess (Askarayan effect) (10%).

Both time dependent currents lead to coherent radio emission in MHZ regime.

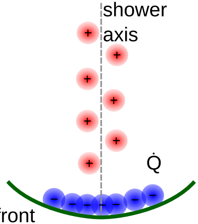
T. Huege, Phys.Rept. 620 (2016) 1-52 (2016-03-15)

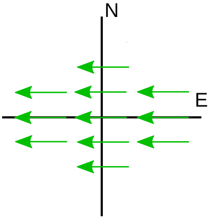


Geomagnetic effect

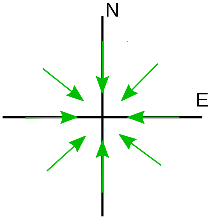


Charge excess





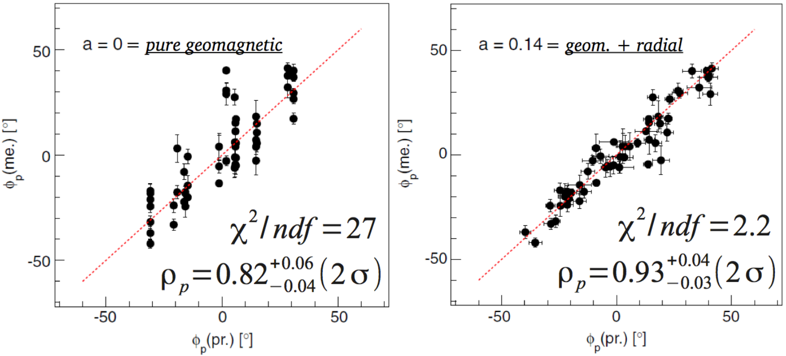
Polarisation parallel to Lorentz force



Radial polarisation

Deep understanding of radio emission

Measurement and simulations agree well with our emission model:

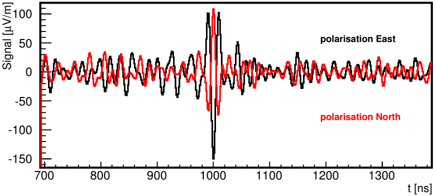


Auger collab., Phys. Rev. D 89, 052002 (2014)

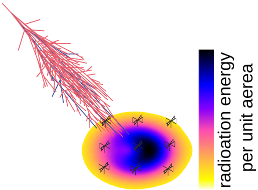
Data is described best with a mean of 14% Askarayan emission.

Our Data

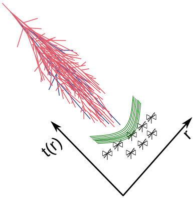
- What information do we have?



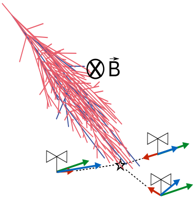
Amplitude	*Time*	*Polarisation*
Peak position of Hilbert envelope	Time integral around peak of Hilbert envelope	



2 dim LDF fit



arrival time fit



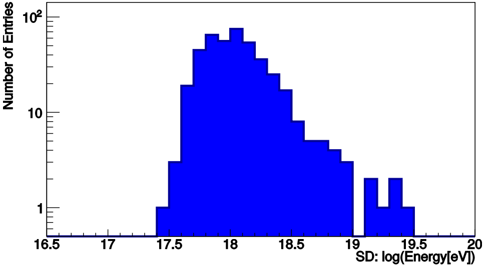
station rejection

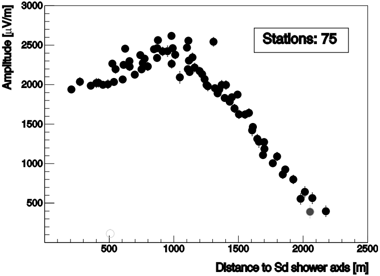
Geometry

The standard up to now:

- Reconstruction up to 55° for zenith.
- Fit of plane wavefront yields good resolution.

Starting to consider horizontal air showers too:





ARENA 2016

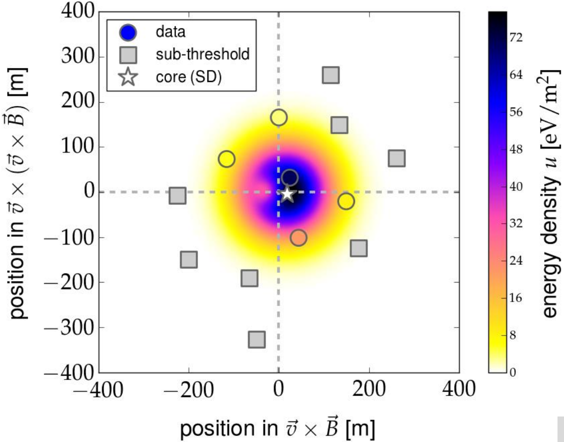
Sensitive to "electronic" part of shower when particle detectors measure only muons. ⇒Combination is sensitive to Xmax.

Energy

Measured radiation energy can be modeled with 2 dim LDF:

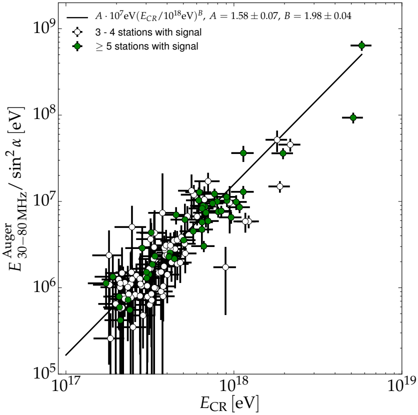
$$LDF(\vec{r}) = \Lambda \left(\exp\left(-\frac{\left(\vec{r} - \vec{r}_{\text{core}} + C_1 \vec{e}_{\vec{v}\times\vec{B}}\right)^2}{\sigma^2} \right) - C_0 \exp\left(-\frac{\left(\vec{r} - \vec{r}_{\text{core}} + C_2 \vec{e}_{\vec{v}\times\vec{B}}\right)^2}{\left(C_3 e^{C_4 \sigma}\right)^2} \right) \right)$$

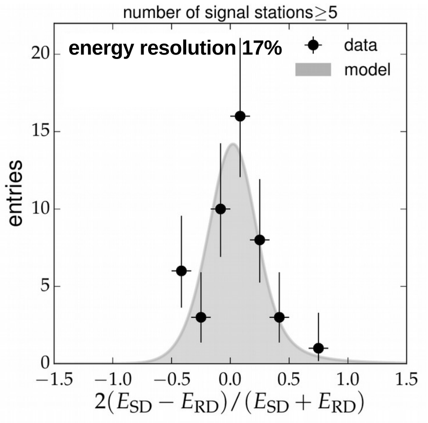
Nelles et al., Astropart. Phys. 60, 13 (2015)



Energy

Radio emission is coherent in [30-80] MHz.
$\Rightarrow E_{\text{rad}}^2 \sim E_{\text{CR}} \sim$ 16 Mev radiation energy for a 1 EeV cosmic ray with $\vec{v} \perp \vec{B}$.

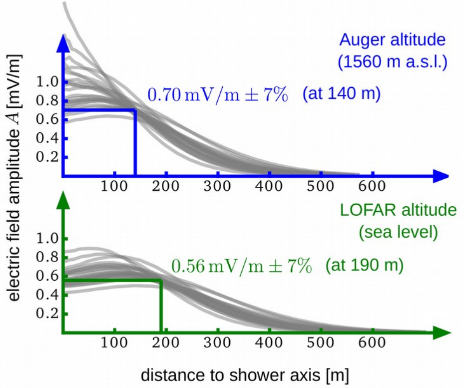




Auger collab., PRL 116, 241101 (2016) Auger collab., PRD 93, 122005 (2016)

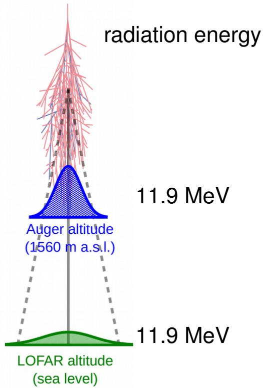
Energy

Methods of CR Energy estimation:



Energy estimation at some optimal distance to shower axis is ambiguous!

Depends on observation level.



Auger collab., PRL 116, 241101 (2016) Auger collab., PRD 93, 122005 (2016)

$\Longrightarrow$ Universal energy scale for other CR experiments:

$$E_{[30:80]\mathrm{MHz}} = 15.8\ \mathrm{MeV} \left(\sin(\alpha) \frac{E}{1\ \mathrm{EeV}} \frac{B}{0.24\ \mathrm{G}} \right)^2$$

Composition sensitivity

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Several methods to determine the primary particle with radio:

1.) Amplitude based:

a) Fitting Xmax sensitive models to data
b) Fitting whole shower simulations to data — $\sim 40\ \mathrm{g/cm^2}$

2.) Time based:

a) Fitting Xmax sensitive time model to data — work in progress

3.) Combination with particle detector information:

a) Radio measures purely the emission from the “electronic” cascade like SD, MD yields the electron / muon ratio.

work in progress

Composition sensitivity:
Example 2d LDF fit:

The width of LDF is sensitive to Xmax:

$$LDF(\vec{r}) = \Lambda \left(\exp\left(-\frac{\left(\vec{r} - \vec{r}_{\text{core}} + C_1 \vec{e}_{\vec{v}\times\vec{B}}\right)^2}{\sigma^2} \right) - C_0 \exp\left(-\frac{\left(\vec{r} - \vec{r}_{\text{core}} + C_2 \vec{e}_{\vec{v}\times\vec{B}}\right)^2}{\left(C_3 e^{C_4 \sigma}\right)^2} \right) \right)$$

AERA vs. FD measurement:

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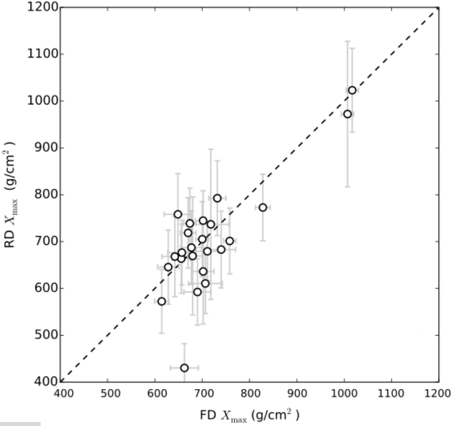

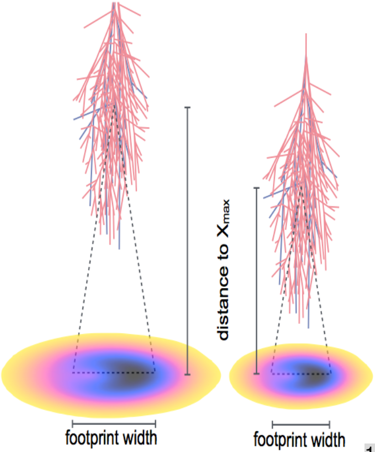

In future: global fit ansatz

Aim: Determining physical observables more precisely using all measured information.

Method: Fitting the needed parameters in one go considering their dependencies.

Beginning with amplitude fit and arrival time fit.

Strongly correlated analysis methods motivate joint fit procedure:

Fit method	Parameter	Observables
t	$X, Y, Z, \theta, \phi, \gamma, t_0$	$\vec{R}, \theta, \phi, X_{max}$
ϵ	$X, Y, Z, \theta, \phi, \sigma_+, A_+$	$\vec{R}, \theta, \phi, X_{max}, E$
$t\&\epsilon$	$X, Y, Z, \theta, \phi, \sigma_+, A_+, \gamma, t_0$	$\vec{R}, \theta, \phi, X_{max}, E$

Use shared parameters to improve the fit precision.

In future: global fit ansatz
Example event

Simulated event characteristics:

Primary: iron

Energy: 0.5 EeV

Direction: Azimuth = -33°, Zenith = 60°

Rmax: 13615 m

Reconstruction results:

Deviation to MC	amplitude	timing	global fit
Core [m]	216	405	54
Direction [°]	-	0.5	0.2
Sigma [m]	264	-	257
Gamma [m·ns]	-	162	203

Conclusion

- The radio emission is well understood.
- Direction reconstruction works with good resolution.
- Energy:
  - The primary energy is partly released as radiation energy in a calorimetric way: 1 EeV $\rightarrow$ 16 MeV in [30-80] MHz
  - The resolution is 17%
  - Radio provides an independent energy scale!
- Composition:
  - Resolution of 40 g/cm^2 with 100% duty cycle.
    Work and improvement in progress!
  - At the moment, we investigate into several methods.

AERA is ready to contribute to astrophysics!

Thanks