Measurement of extensive air showers with AERA

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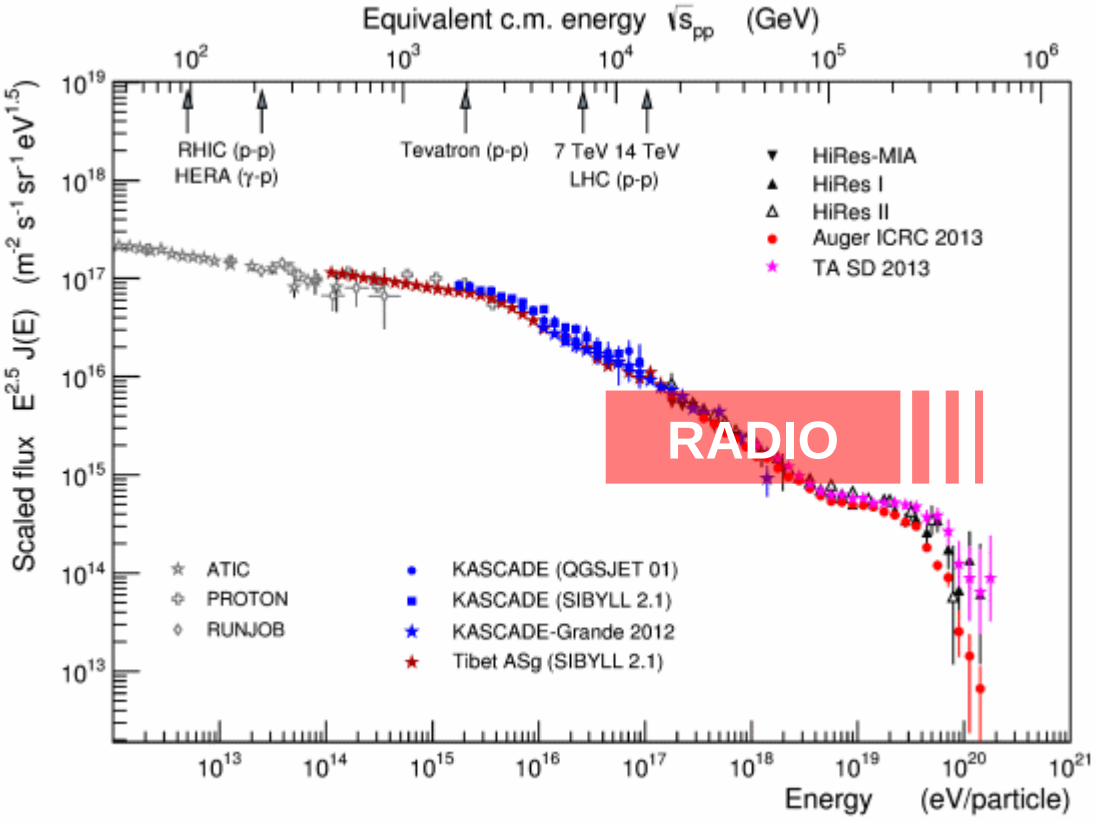
Outline

Cosmic rays
Pierre Auger observatory
AERA
Summary and outlook

Cosmic-ray physics

Energy spectrum of cosmic rays



Plot by R. Engel & T. Huege

Intriguing science questions:
- Origin of cosmic rays
  → **10^{20} eV ?**
- Acceleration mechanism?

Answer requires measurements:
- Direction
- Energy
- Composition

We need large exposure:
→ Large effective area
→ High duty cycles

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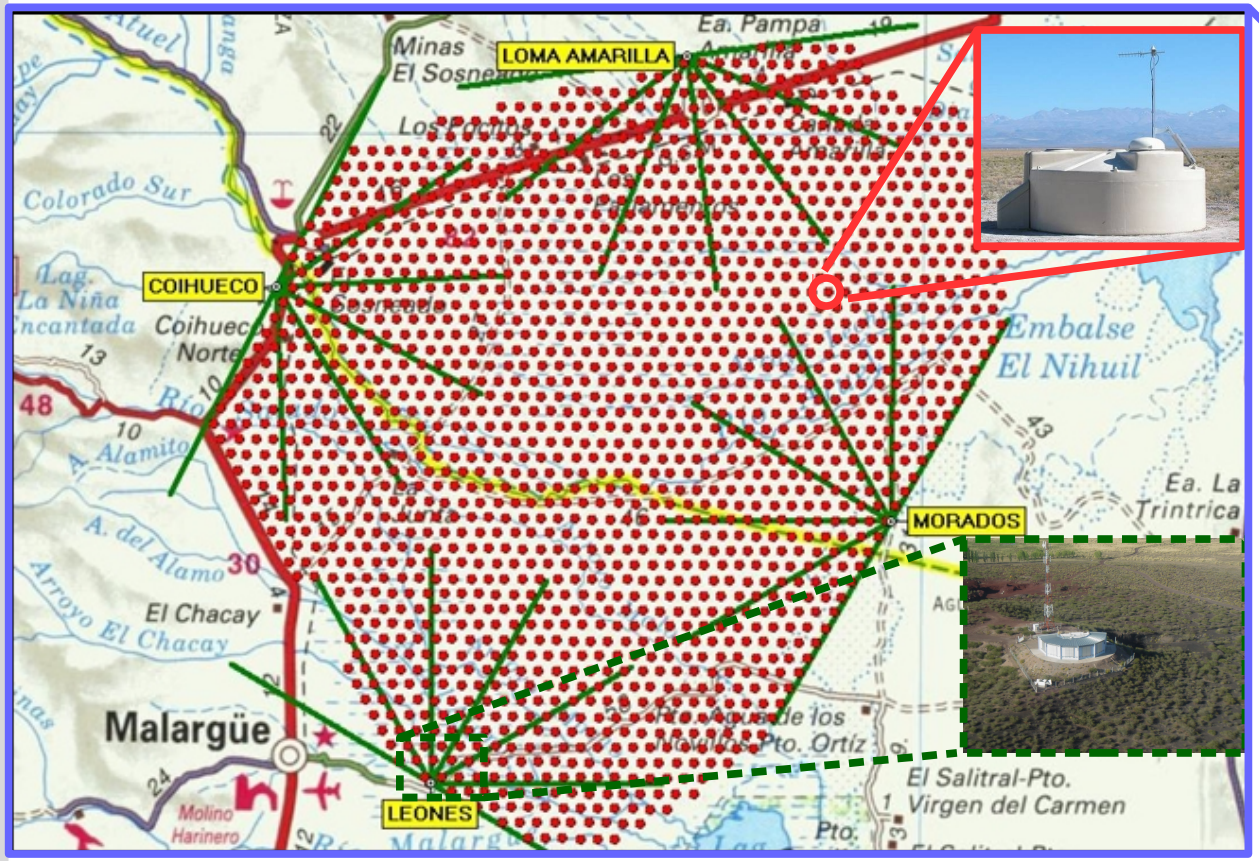
Pierre Auger Observatory

Karlsruhe Institute of Technology

Layout of the Pierre Auger Observatory



Location: Argentina, Mendoza, Malargue

Surface Detectors (SD)
- 1660 Cherenkov tanks
- 100% duty cycle
- High angular resolution

Fluorescence Detector (FD)
- 27 telescopes
- 10-15% duty cycle
- Composition measurement

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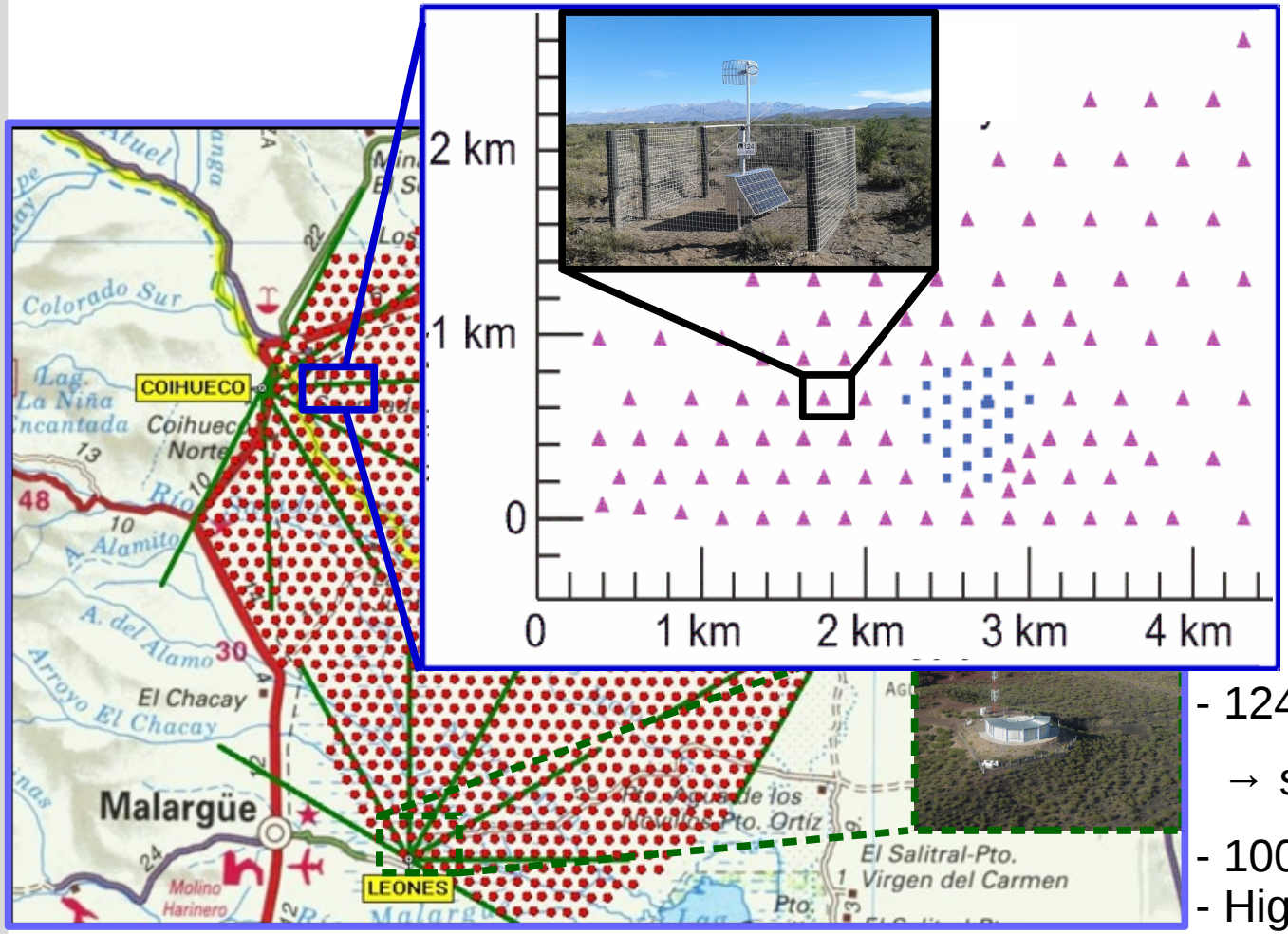
Auger Engineering Radio Array (AERA)



- 124 radio stations

  → self and external triggers

- 100% duty cycle
- High angular resolution
- High energy resolution
- Composition measurement

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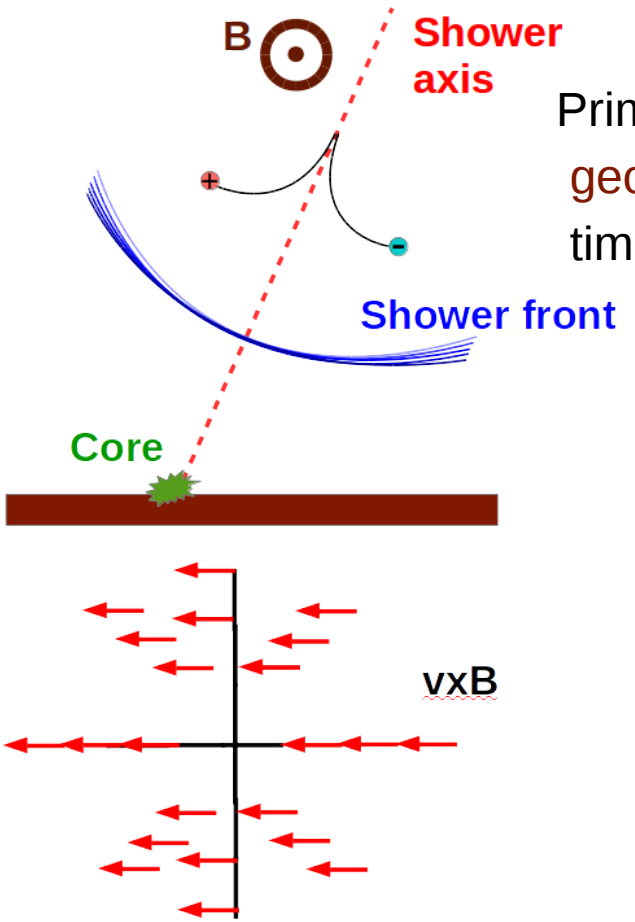
Radio emission mechanism

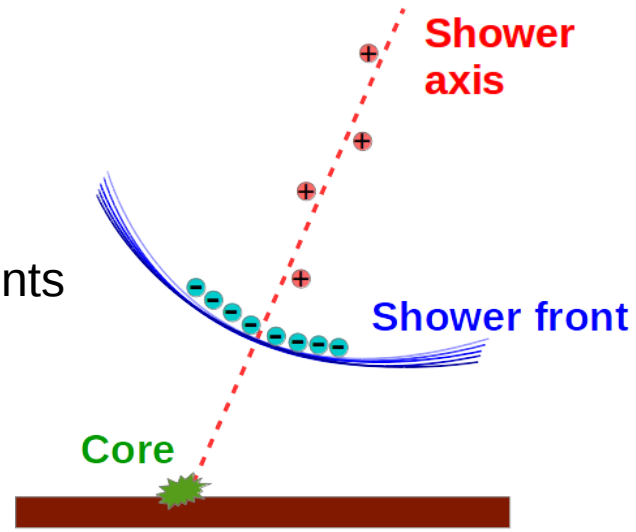
Geomagnetic effect

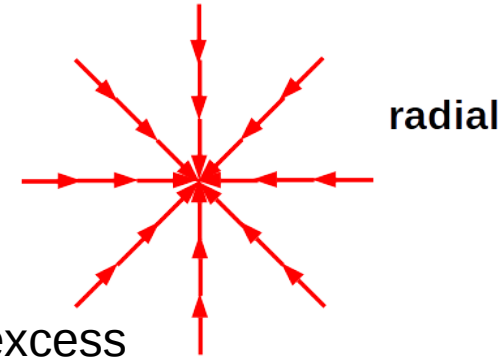


Primary effect:

geomagnetic field induces time-varying transverse currents

Askaryan effect





Secondary effect:

time-varying net charge excess

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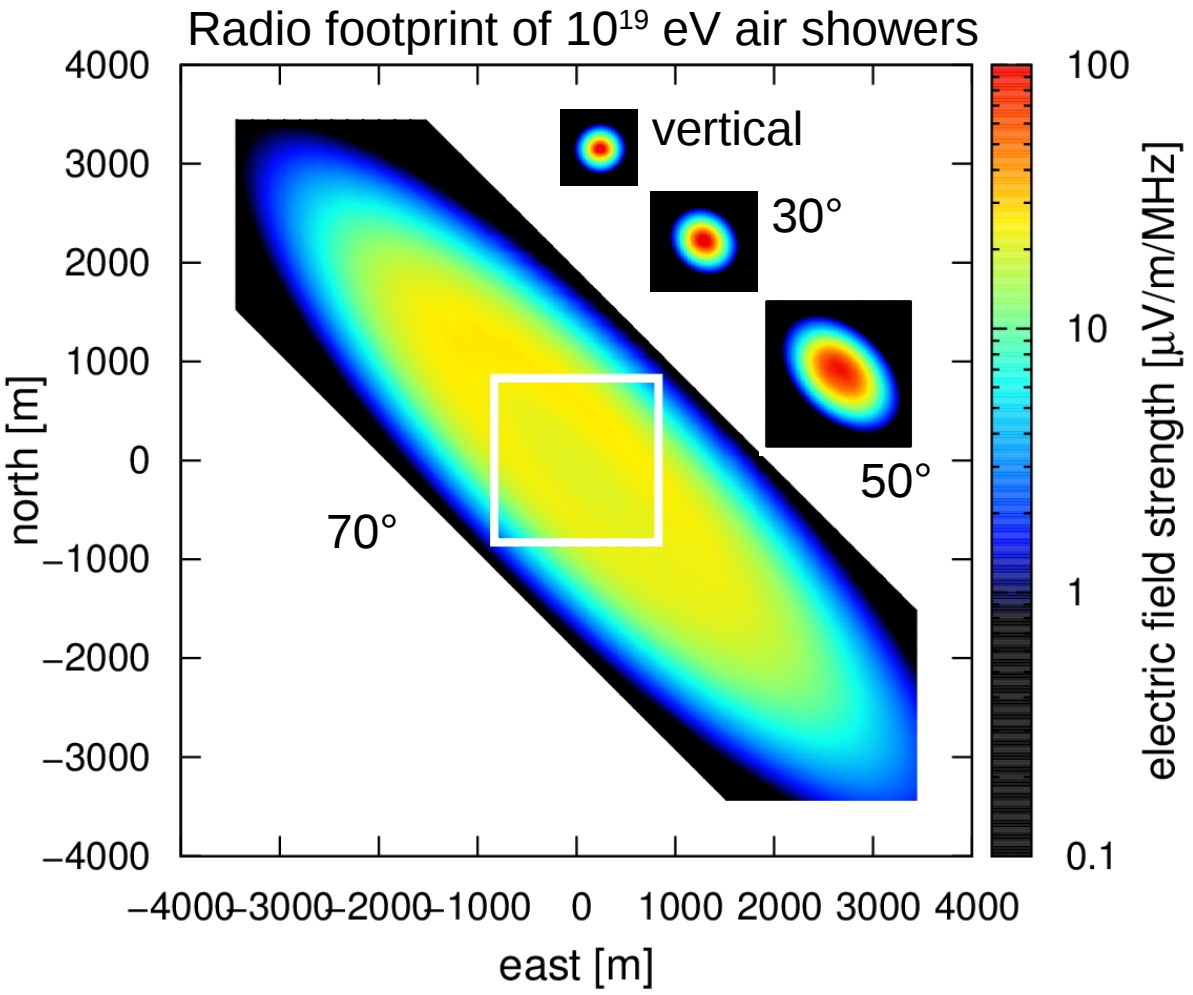
Radio detection of inclined air showers



- Inclined air-showers have *huge* radio footprints
- Antennas on 750/1500 m grid can measure such showers coincidently

  → cost efficient

Radio detection techniques provides unique measurement of inclined showers

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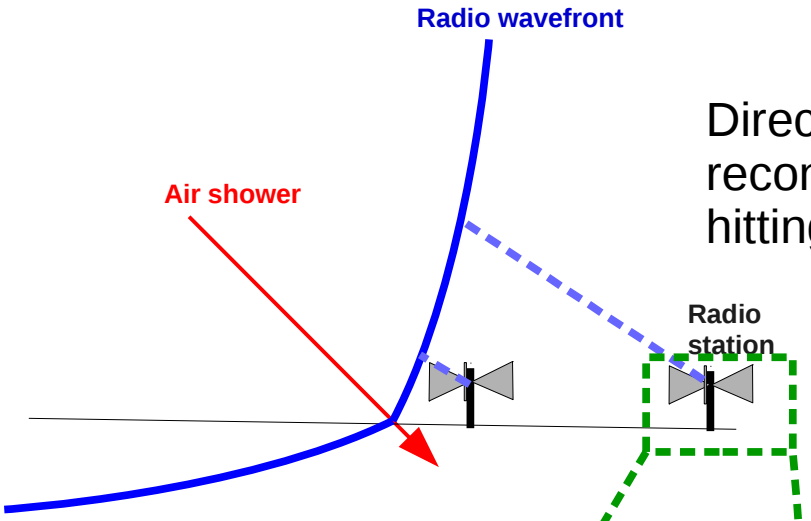
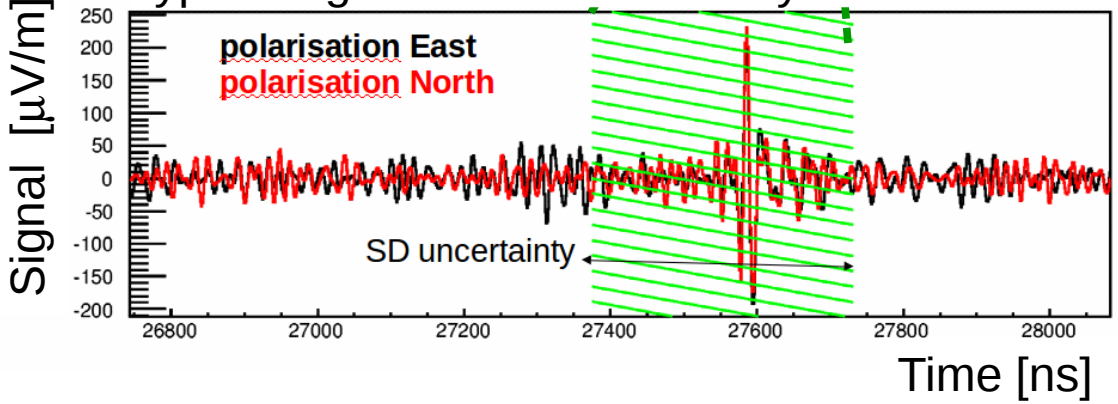
Radio detection principle



Direction of **air shower** is reconstructed from **radio wavefront** hitting 2D array of **radio stations**

Typical signal trace recorded by radio stations



Event selection:

Radio events externally triggered by Surface Detector (SD)

→ all stations are read-out

→ non-negligible false-positive radio pulses

Pulse selection:

- Search for radio pulses causality connected to SD reconstructed shower

Radio events are reconstructed with high signal-selection purity

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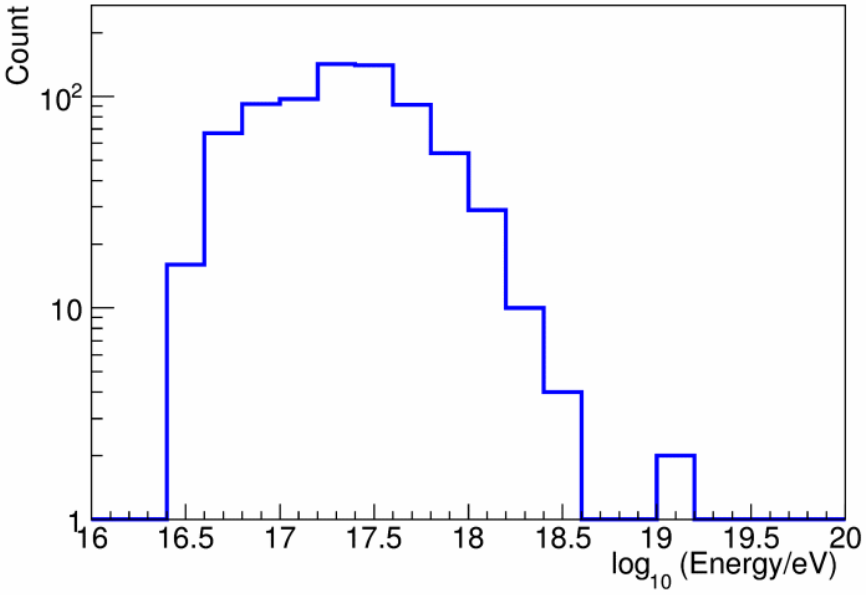
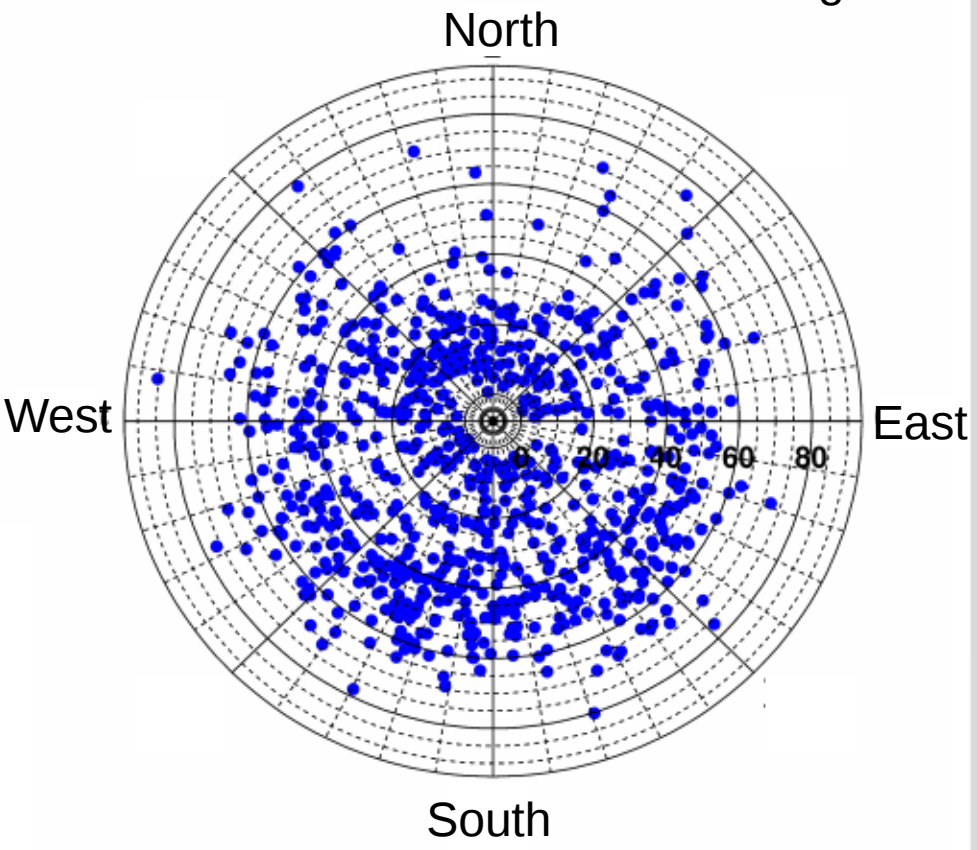
Direction and energy

Energy distribution of the coincidence events



Distribution of azimuth and zenith angles



Dataset: May – December 2013
SD-AERA coincident rate =
10 events / day
North-South asymmetry
→ **Geomagnetic effect**

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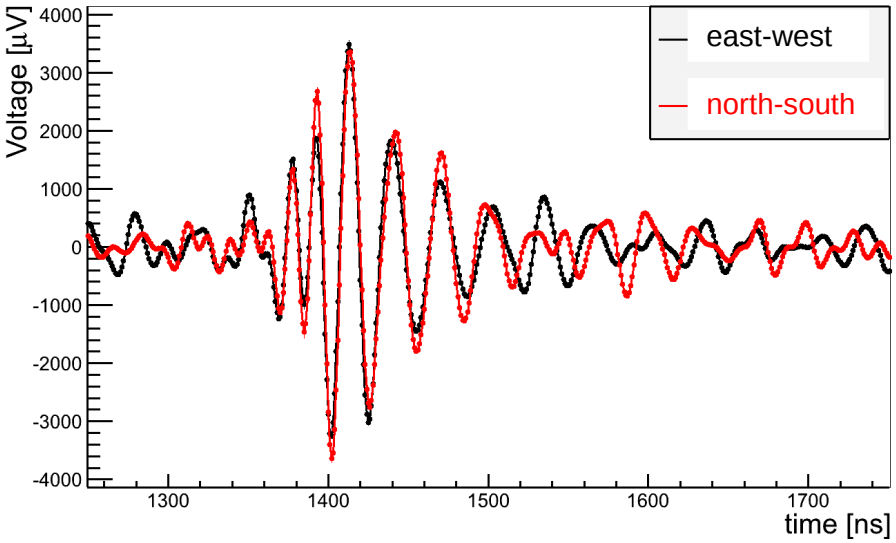
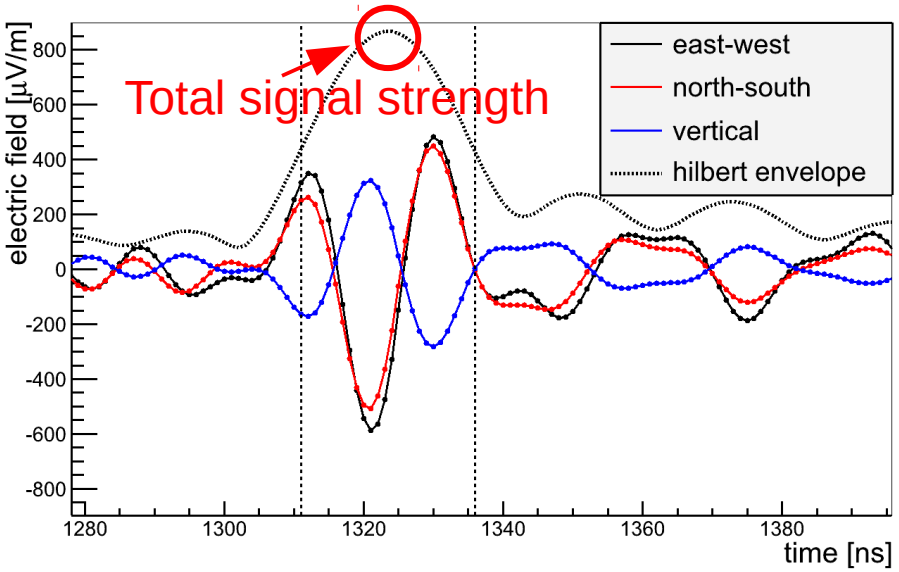
Energy reconstruction

Typical trace of measured raw voltage



Reconstructed electric field vs time



Reconstructed electric field is used to measure the signal strength

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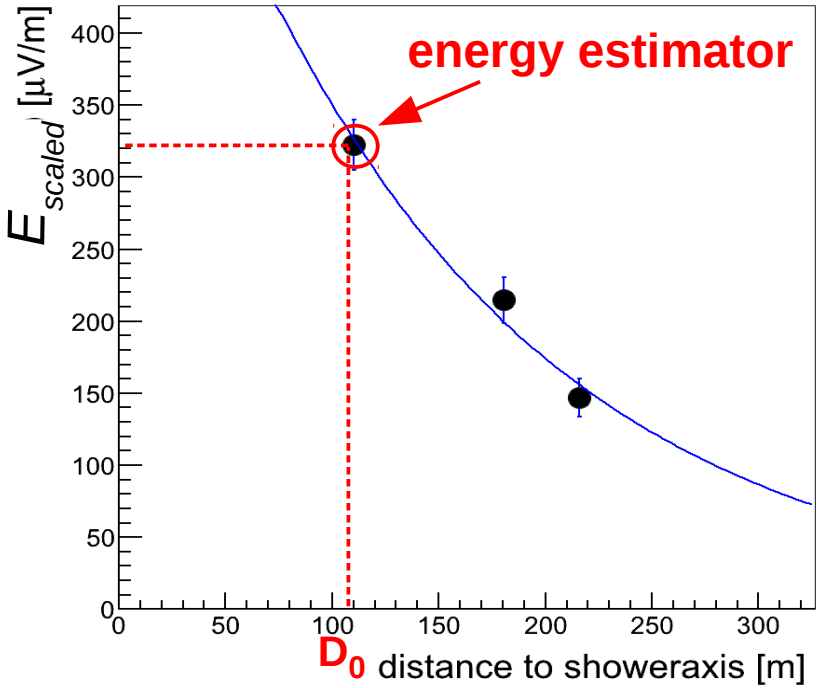
Definition of an energy estimator

Typical reconstructed signal strength
as a function of distance to shower axis

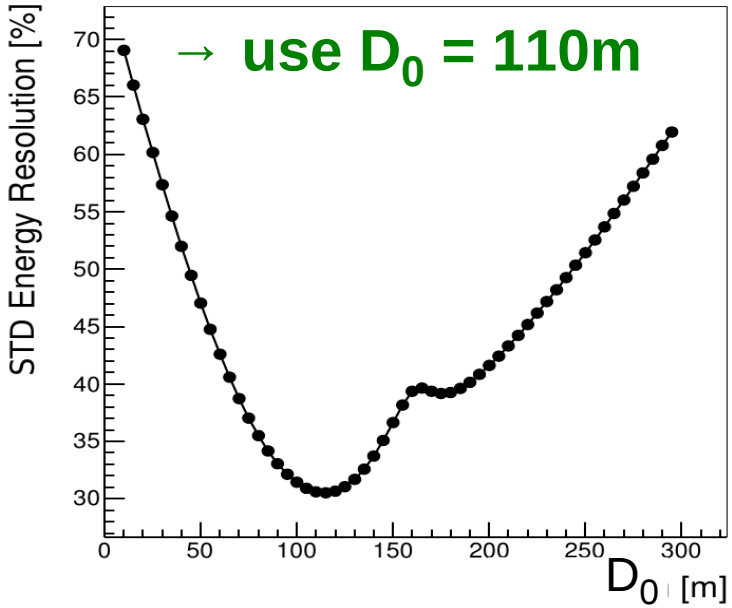


- correct Electric field for geomagnetic effect → E_{scaled}
- use exponential function to interpolate between data points

$$E_{scaled} = A \cdot exp(D/R_0)$$

Energy estimator:
Strength of signal at optimal distance D_0 is correlated to shower energy

energy resolution as a function of D_0



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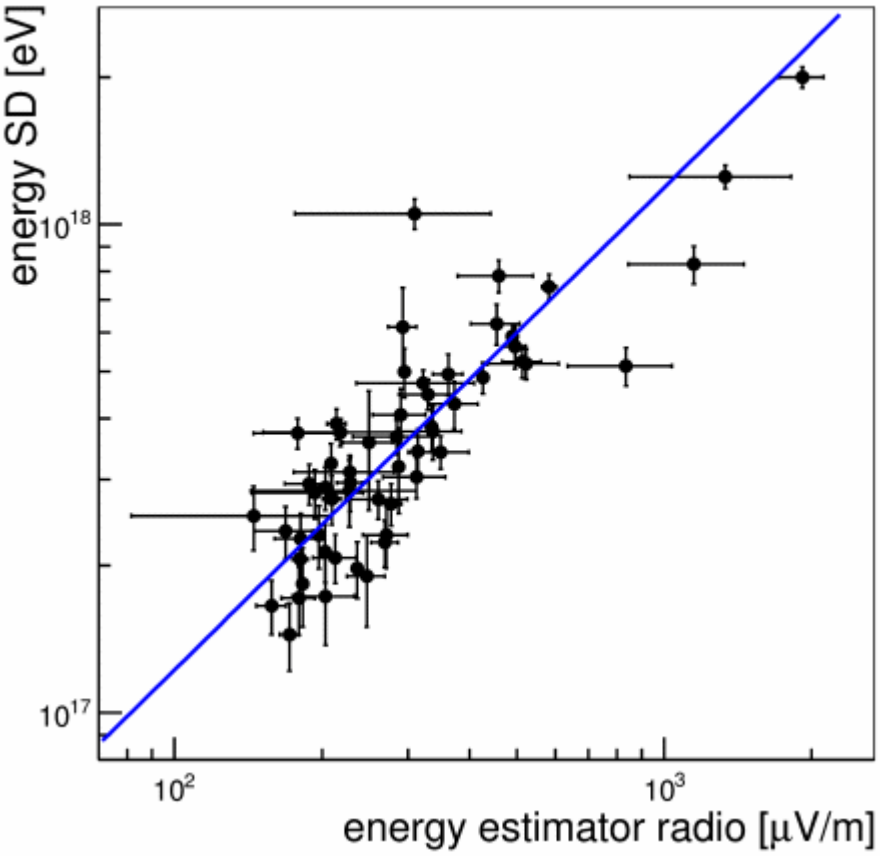
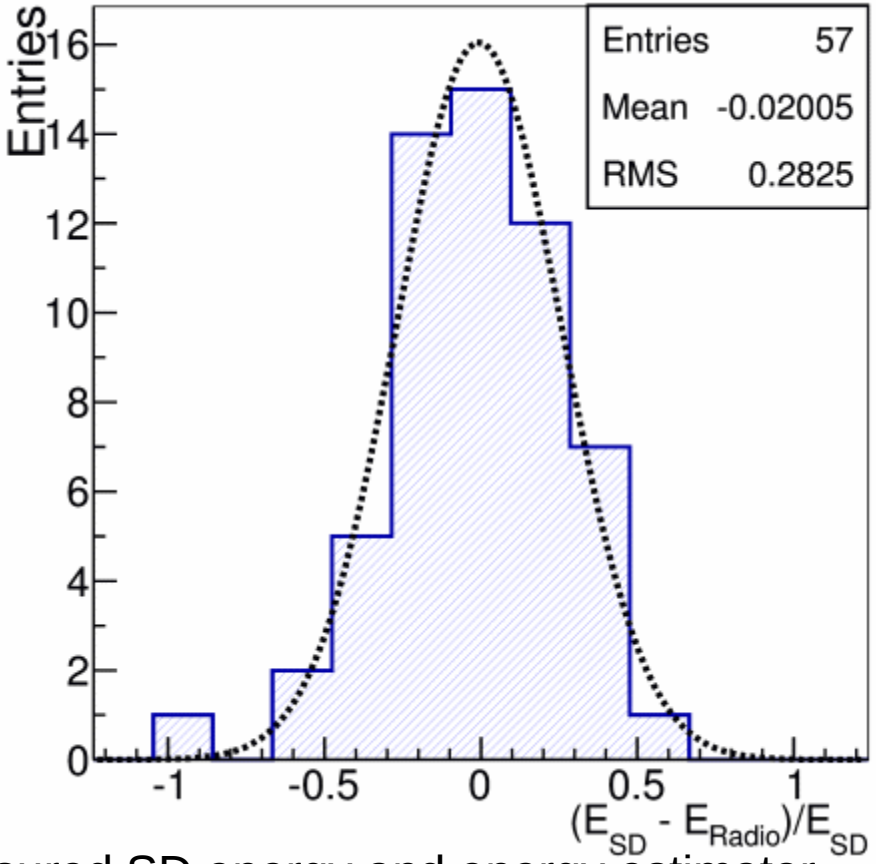
Performance: energy reconstruction

Measured SD energy vs energy estimator



Distribution of error of energy reconstruction



Excellent correlation between measured SD energy and energy estimator

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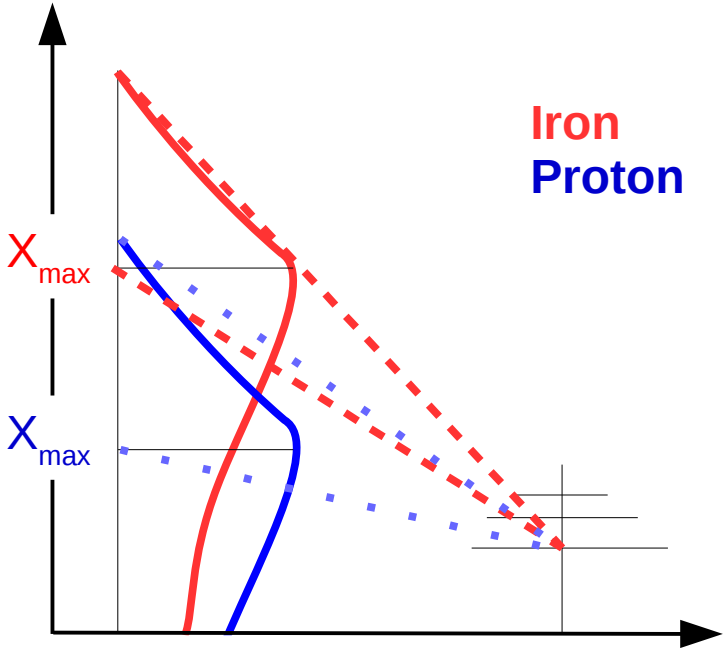
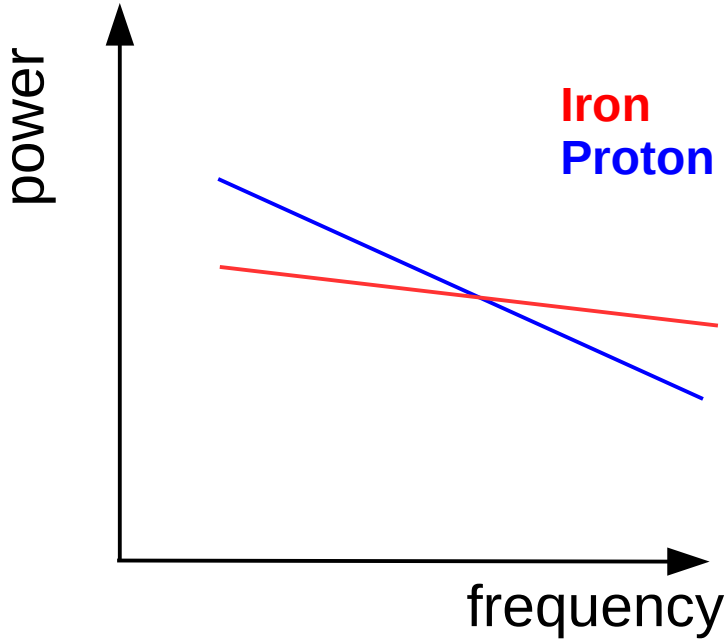
Reconstruction of primary mass

Pulse shape analysis

Schematic view **Iron** and **proton** showers



Power as a function of frequency



radio pulse of heavy nuclei is shorter
→ more power in the high frequencies

spectral slope is sensitive to X_{max}

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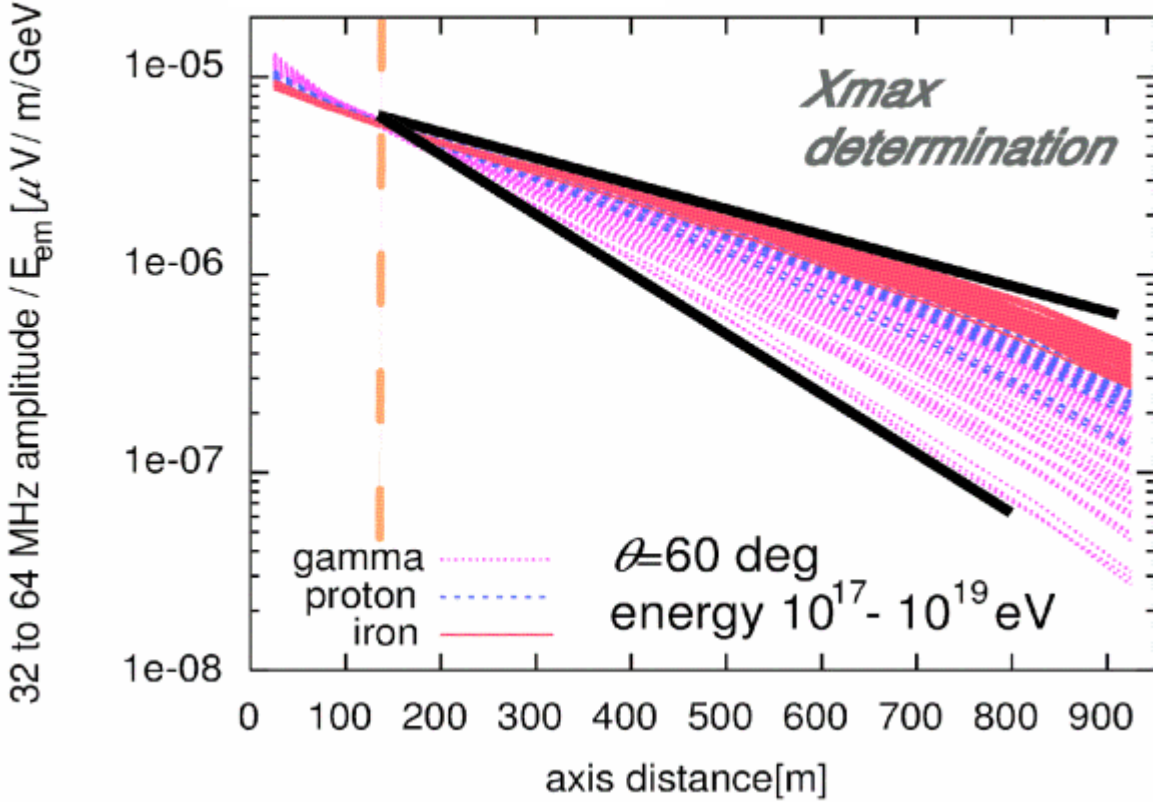
Reconstruction of primary mass

Lateral Distribution Function (LDF) analysis

LDF for Iron, proton and gamma primaries



T. Huege,Ulrich,Engel (2008) Astrop.Ph. 30,96

The slope of LDF relates to Xmax

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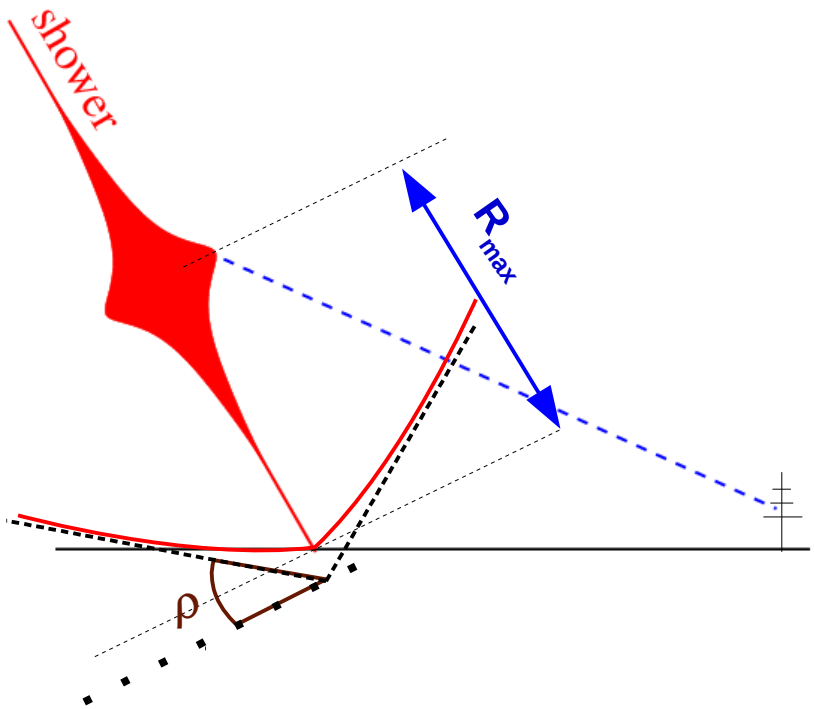
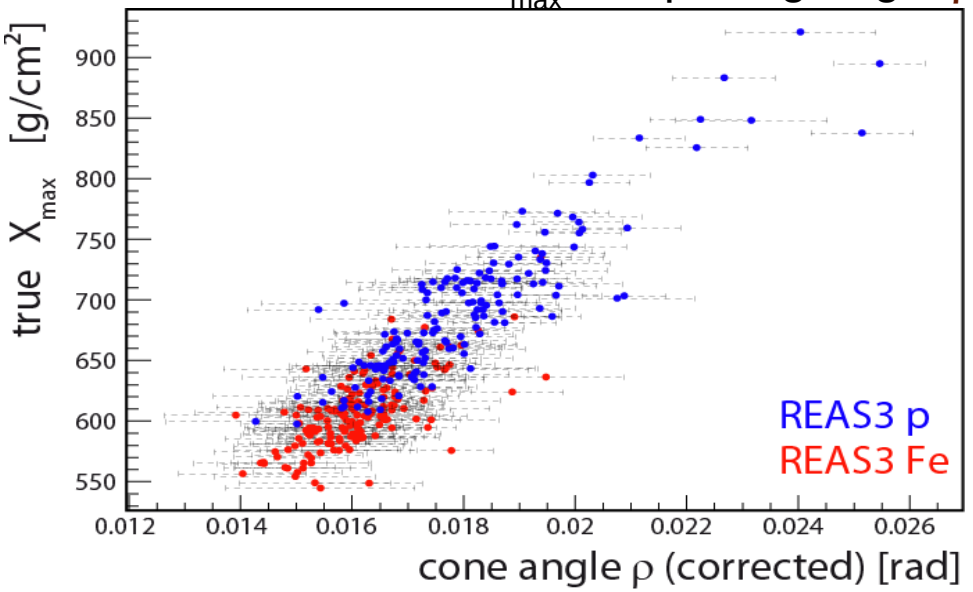
Hyperbolic radio wavefront

Schematic of hyperbolic wavefront



Distribution of true X_{max} vs opening angle ρ



X_{max} proportional to ρ after correction for zenith angle

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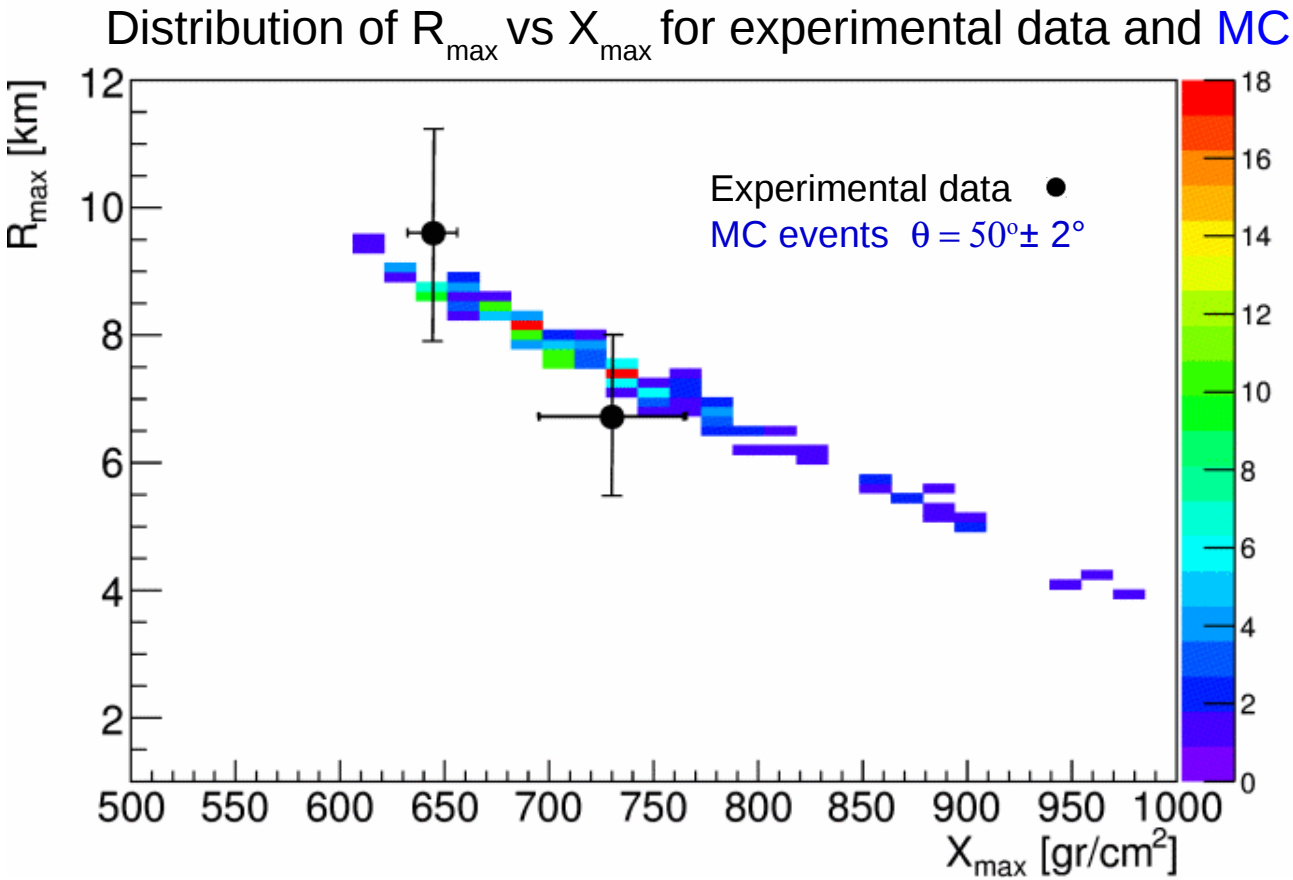
Performance



Agreement between experimental data and MC

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Summary and outlook

- Radio detectors are efficient for **inclined** showers detection
  → for vertical shower detection we need a dense array

- AERA reconstructs shower energy and direction with high efficiency

Outlook

- Mass reconstruction:
  Independent techniques have been developed
  we are working to increase statistics

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Spare slides

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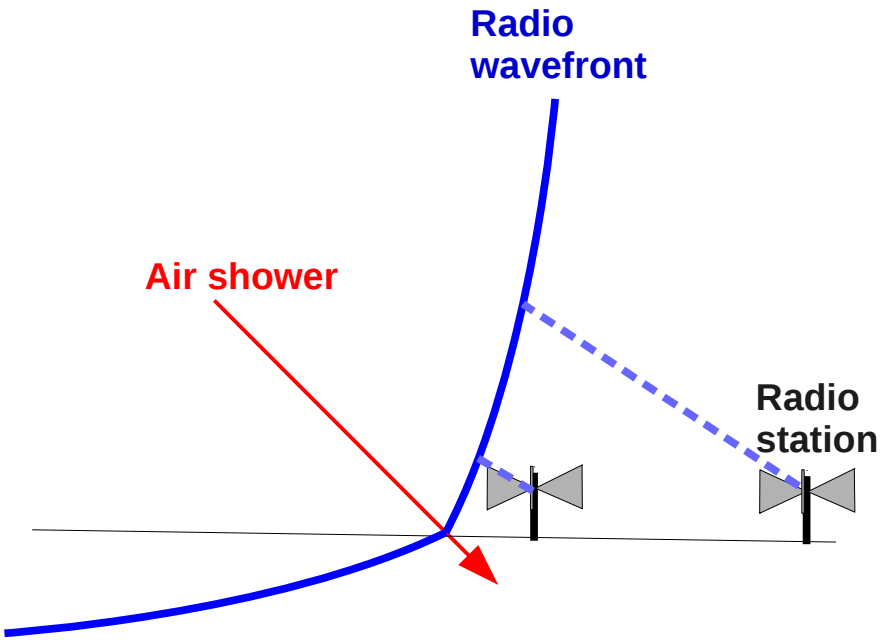
Detection principle



Direction of **air shower** is reconstructed from **radio wavefront** hitting 2D array of **radio stations**

Event selection:
Radio events externally triggered by Surface Detector (SD)
→ all stations are read-out
→ non-negligible false-positive radio pulses (**RFI source**)

We need to efficiently reduce the contamination of false-positive pulses

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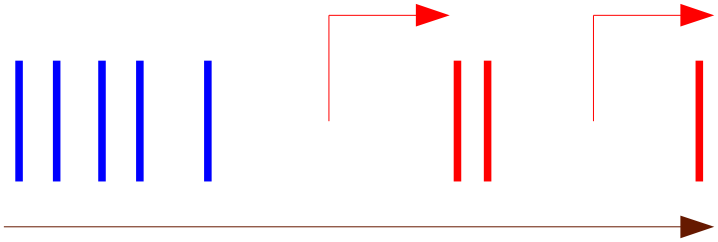
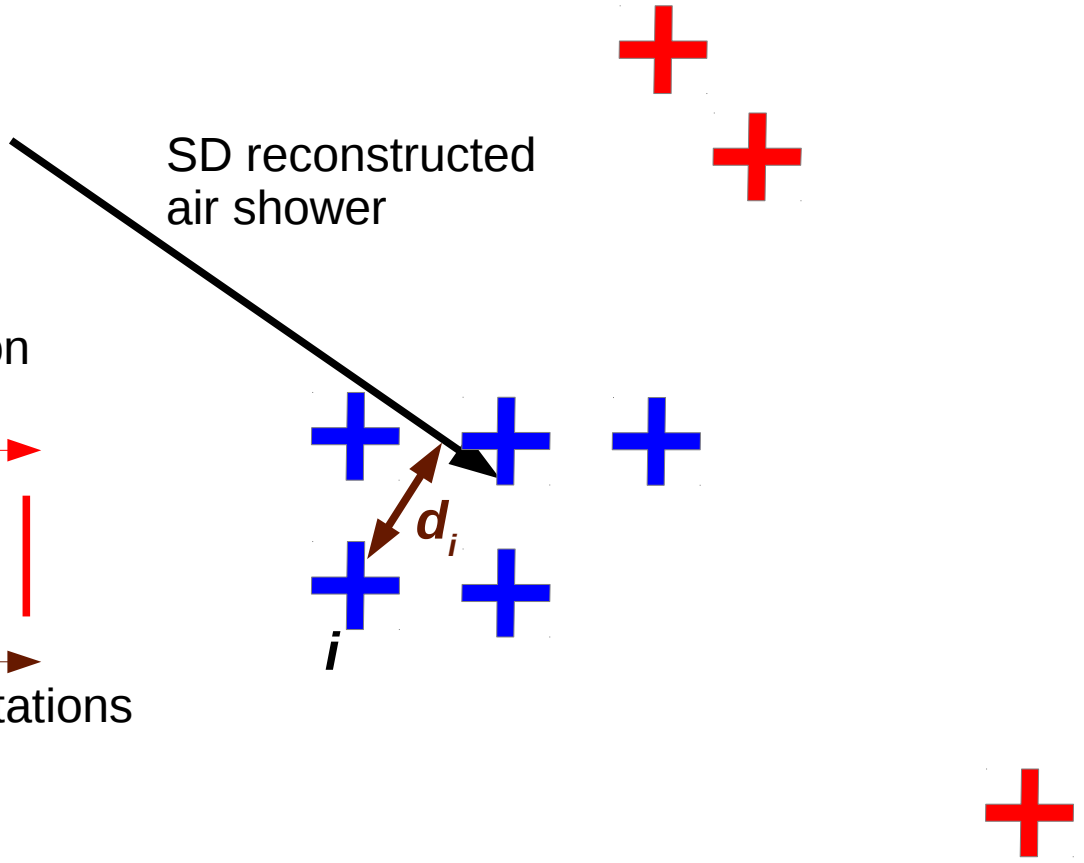
Cluster finder algorithm

Method:
- Sorts stations according to **euclidean distances** between SD axis and station positions
- Rejects **isolated stations** i.e. discontinuity in the distribution



Distance between SD axis and stations



Algorithm selects **cluster of stations** caused by air shower

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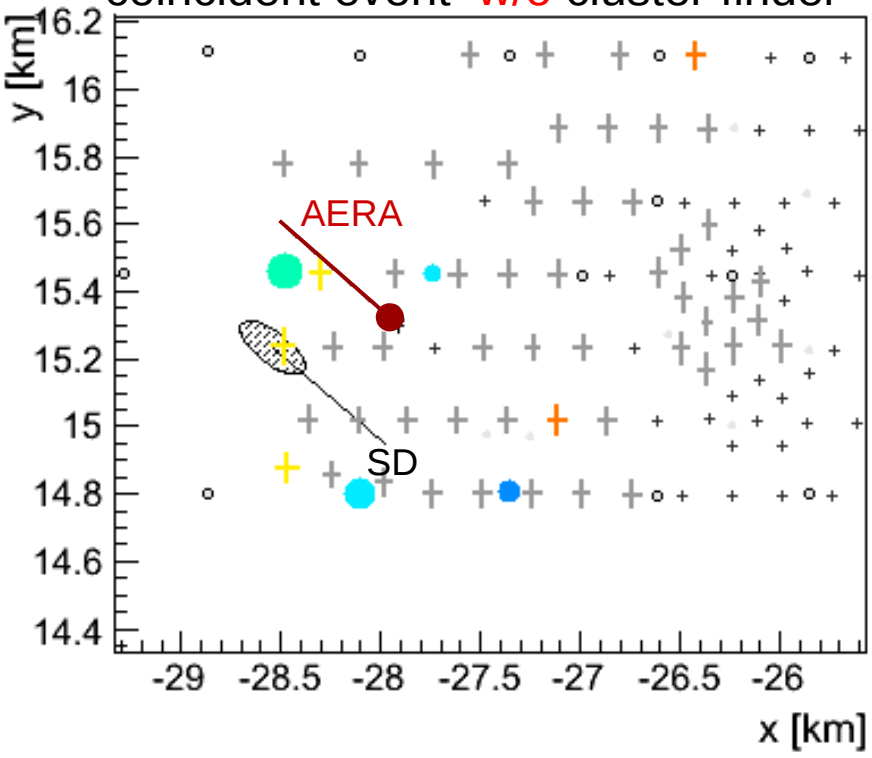
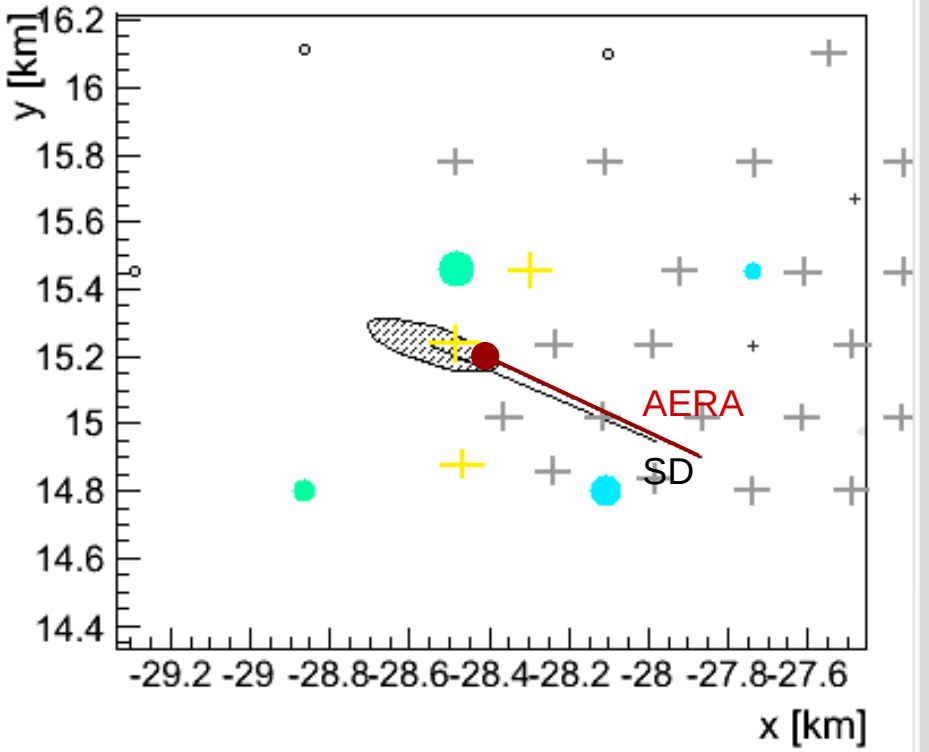
Performance: cluster finder

Reconstruction of SD-AERA coincident event w/o cluster finder



Reconstruction of SD-AERA coincident event w/ cluster finder



Cluster finder recovers more than **23%** of misreconstruted coincident events

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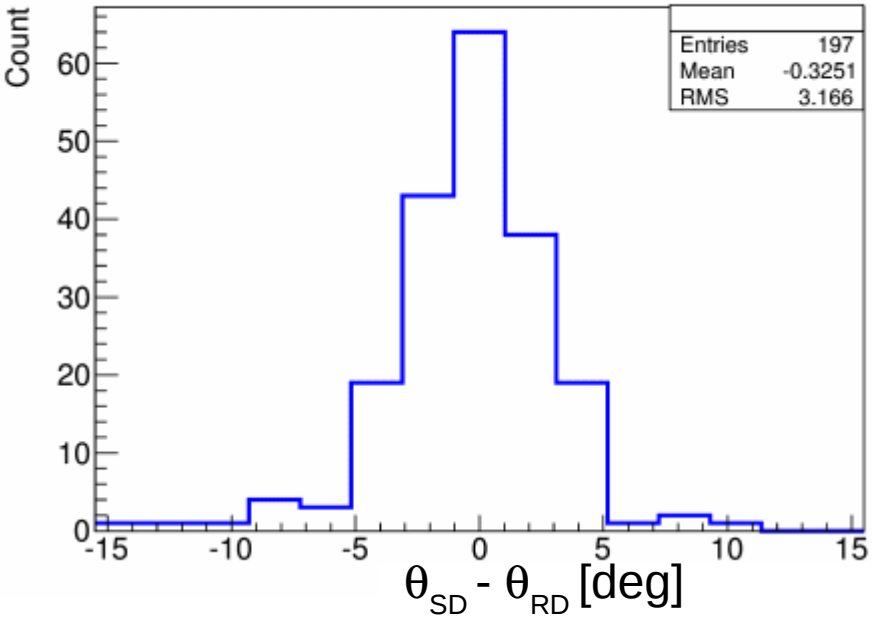
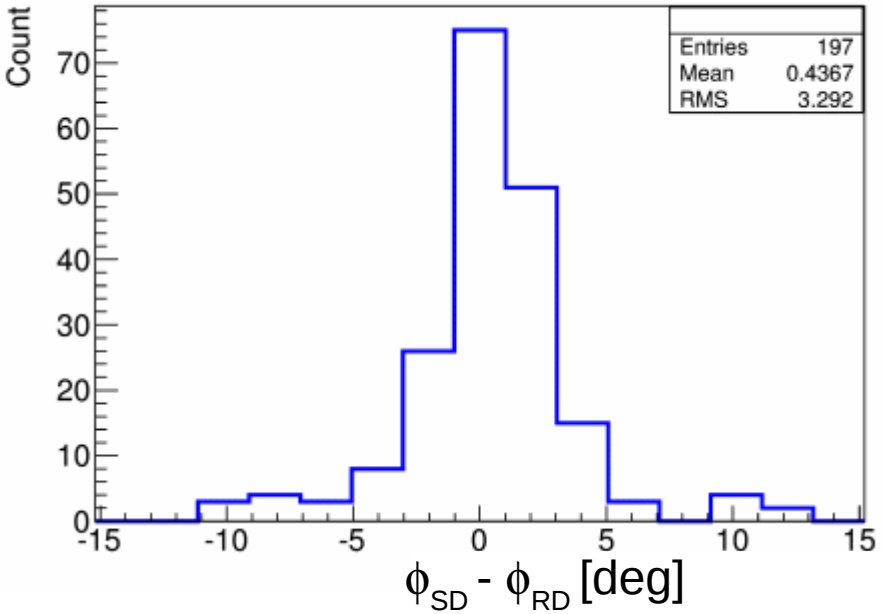
Performance: direction reconstruction

Distribution of error of **zenith** reconstruction



Distribution of error of **azimuth** reconstruction



Agreement between Radio Detector (RD) and SD direction reconstructions

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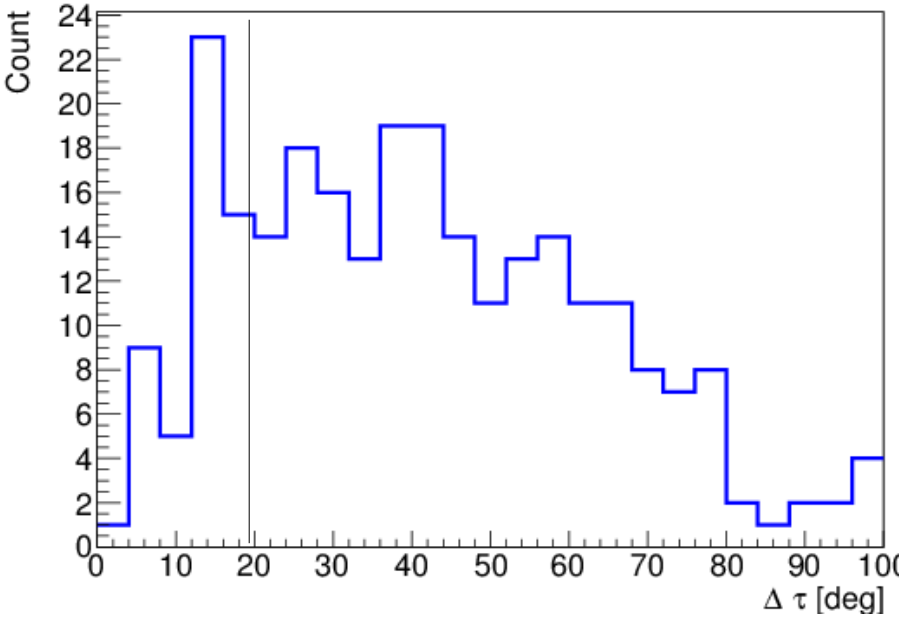
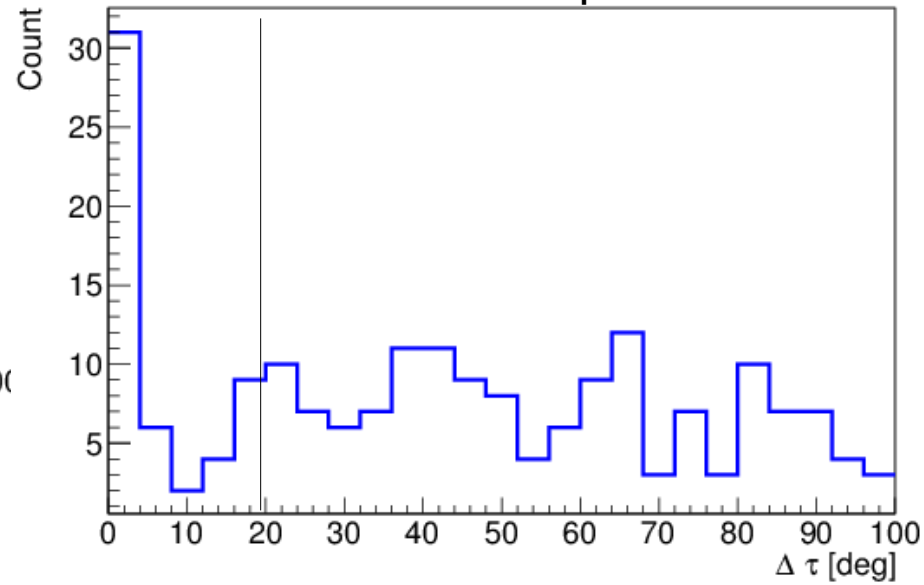
Performance of pulse selection

$\Delta\tau$ = angle between SD and AERA reconstructed air shower axes

Distribution of $\Delta\tau$ for the standard method



Distribution of $\Delta\tau$ for the pulse selection



Pulse selection results in a better AERA reconstruction

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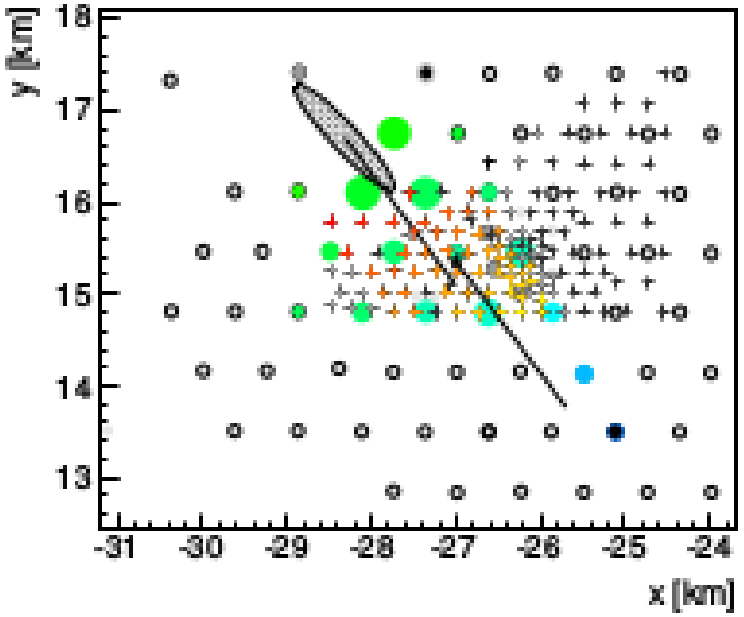
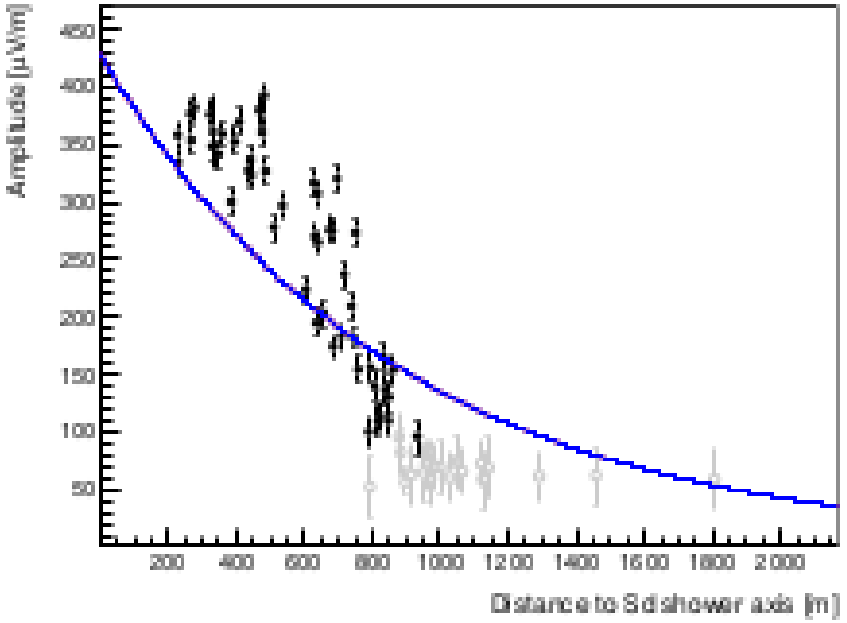
4. Event:

zenith: 75.3 deg, azimuth 309.3 deg, energy $2.5 \cdot 10^{18}$ eV, stations 51





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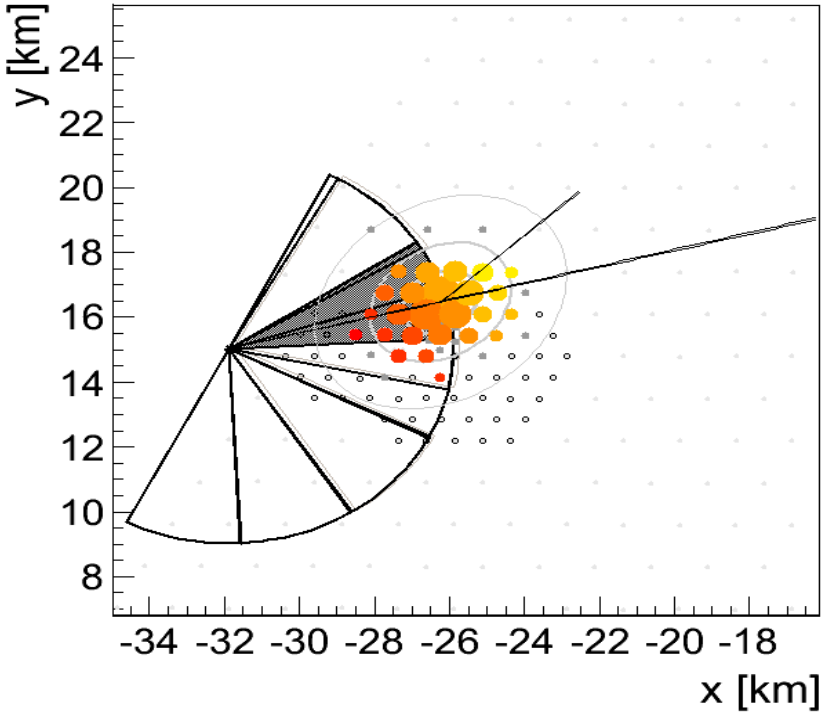
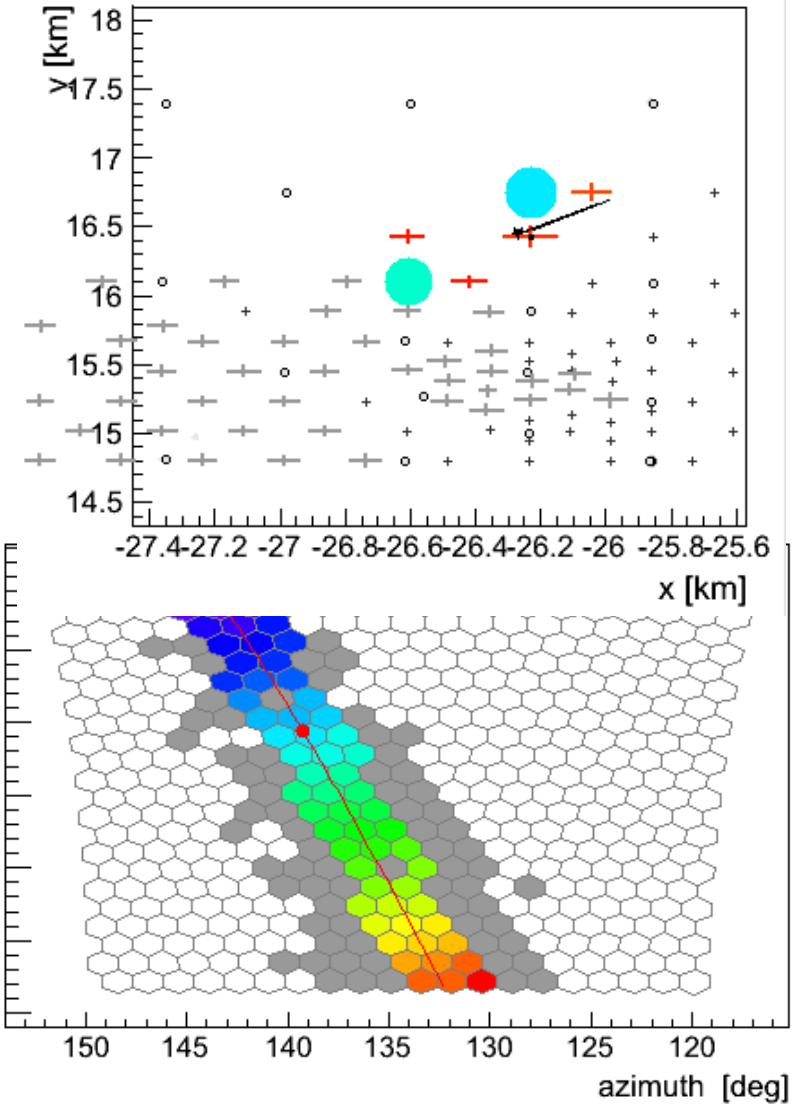
Ultra high energy event





$E = 2 \times 10^{19}$ eV

$\theta = 38^0$

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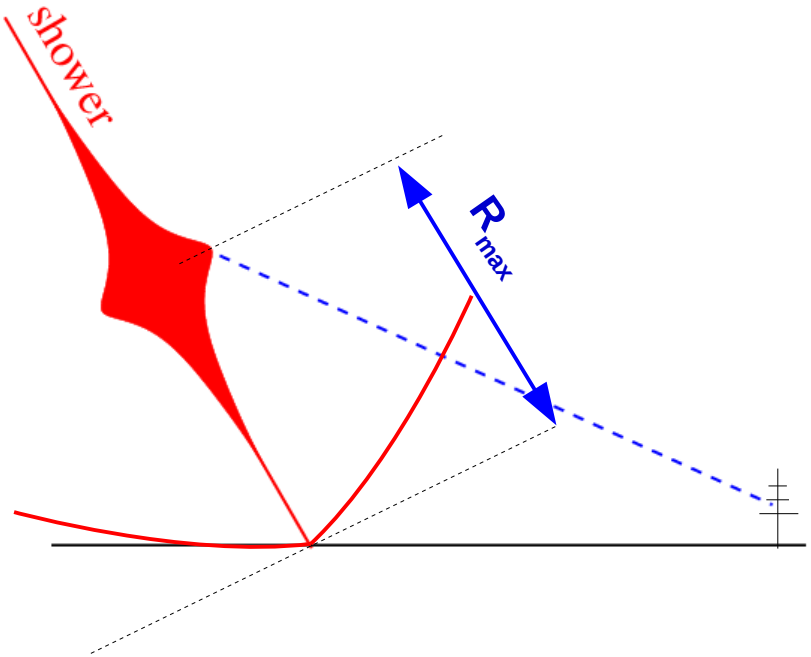
Reconstruction of primary mass

Radio emission originates from a few kilometres in altitude

→ related to distance $\mathbf{R_{max}}$ to shower maximum X_{max}

→ Reconstruct the origin of radio emission



The flattening of the radio **wavefront** relates to the origin

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