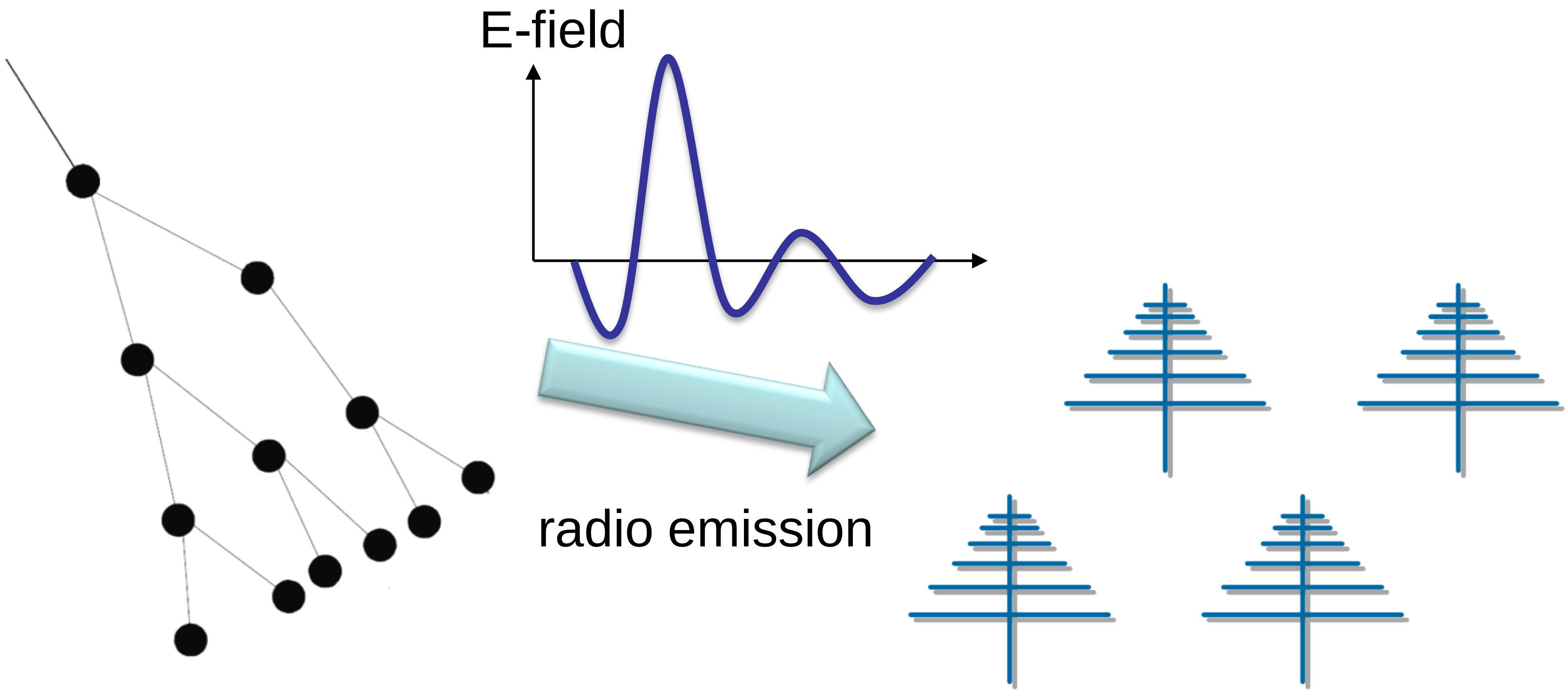
AERA -
The Auger Engineering Radio Array

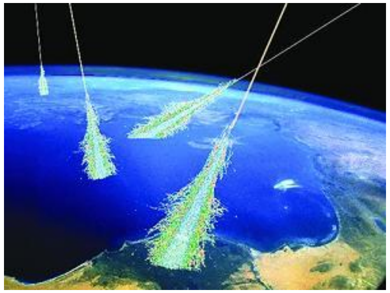


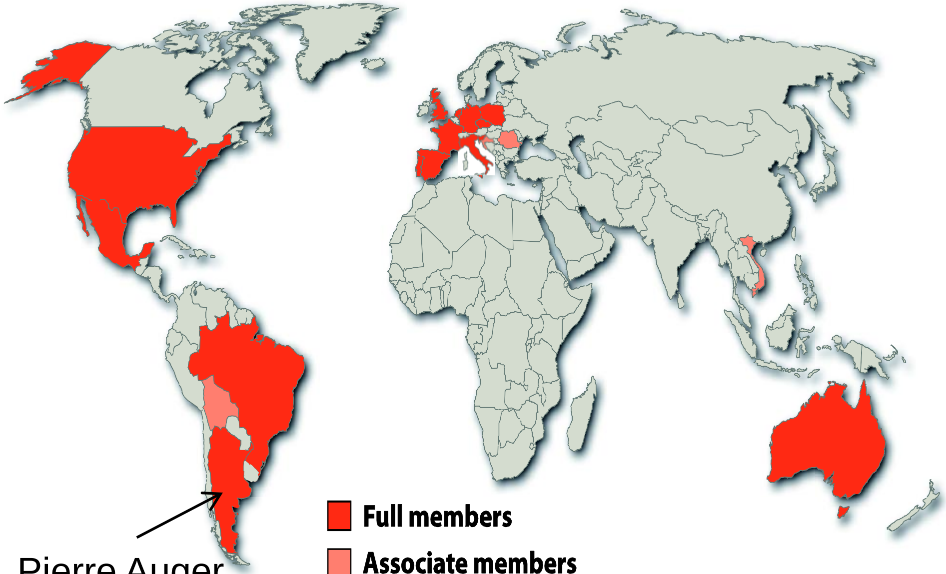
Raphael Krause for the Pierre Auger Collaboration

Vulcano Workshop 2014

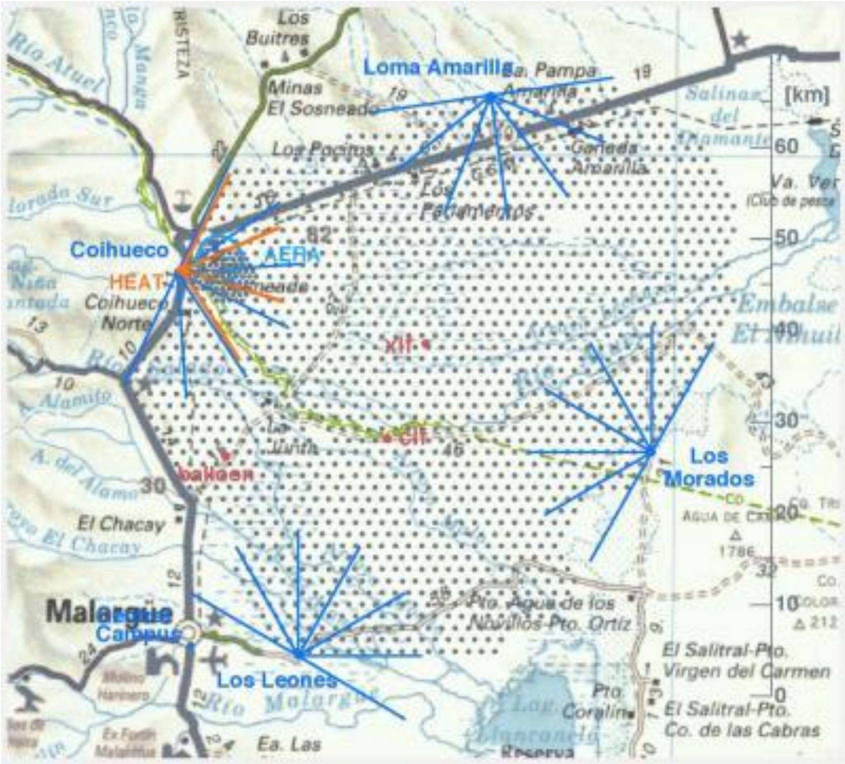
Frontier Objects in Astrophysics and Particle Physics

Pierre Auger Observatory



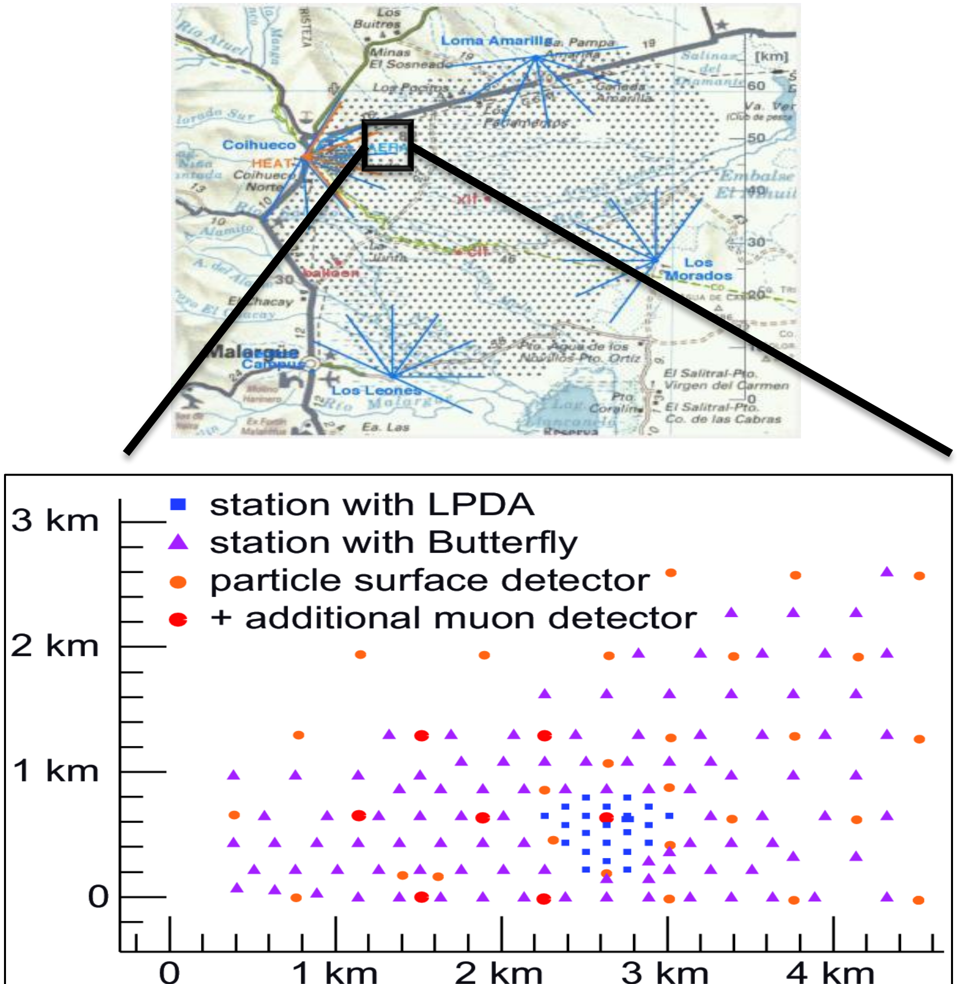


- largest cosmic ray experiment worldwide
- 3000km² area
- observes cosmic rays with energies above 10^{17}eV
- takes data since 2004



- located near Malargüe, Argentina
- baseline detector:
  - 1660 surface detectors (SD)
    - duty cycle ~100%
  - 27 fluorescence detectors (FD)
    - duty cycle ~14%

AERA
Auger Engineering Radio Array

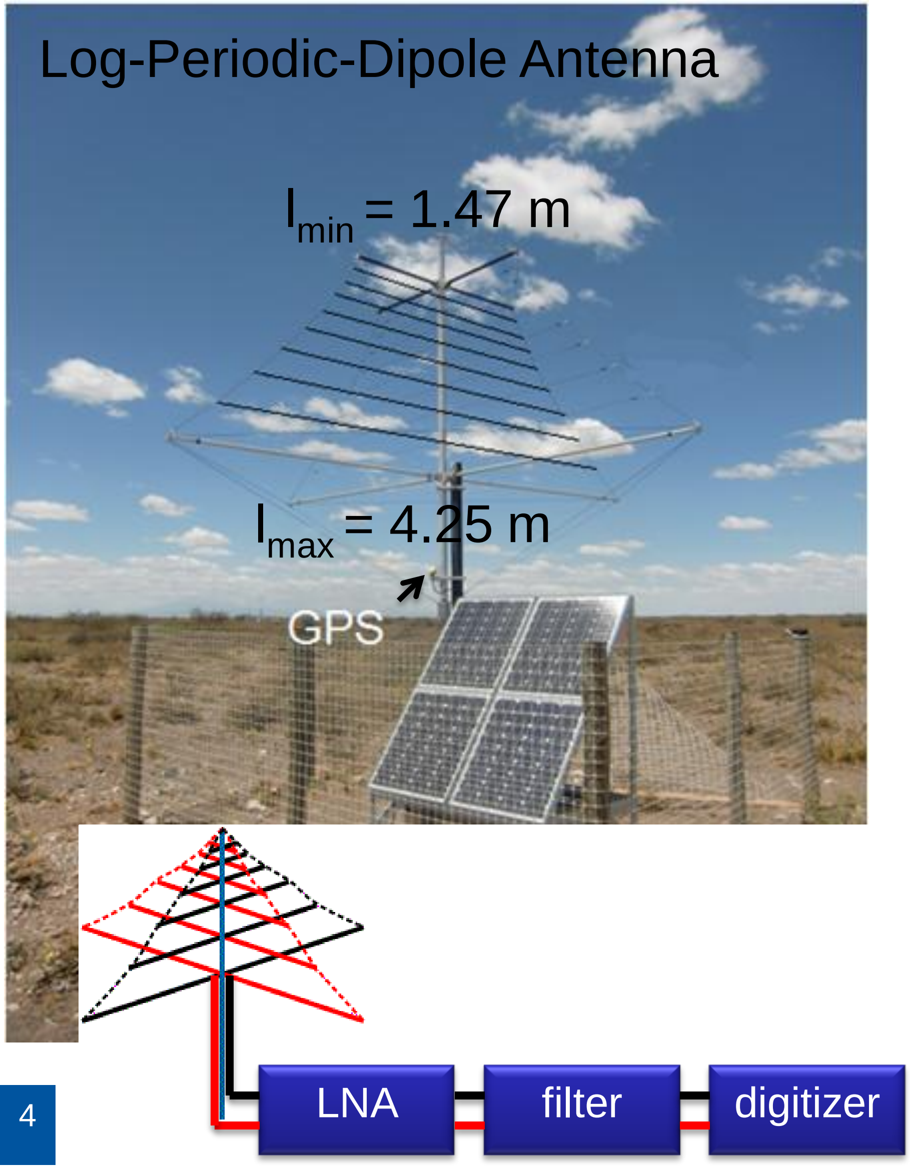


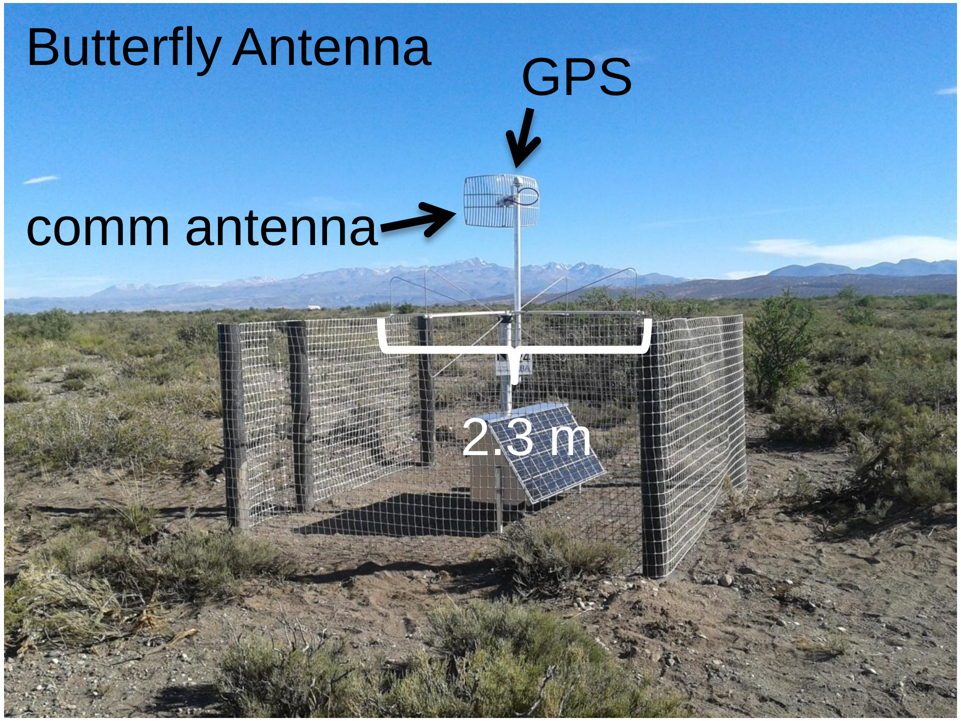
- determine cosmic ray properties:
  - arrival direction
  - energy
  - chemical composition
- duty cycle ~100%
- 124 radio stations
- grid spacing: 150m, 250m, 375m
- covering area 6km²
- energy range:

$$E > 10^{17} eV$$

- data taking since 2011
- overlap with other Auger detector

AERA Radio Stations





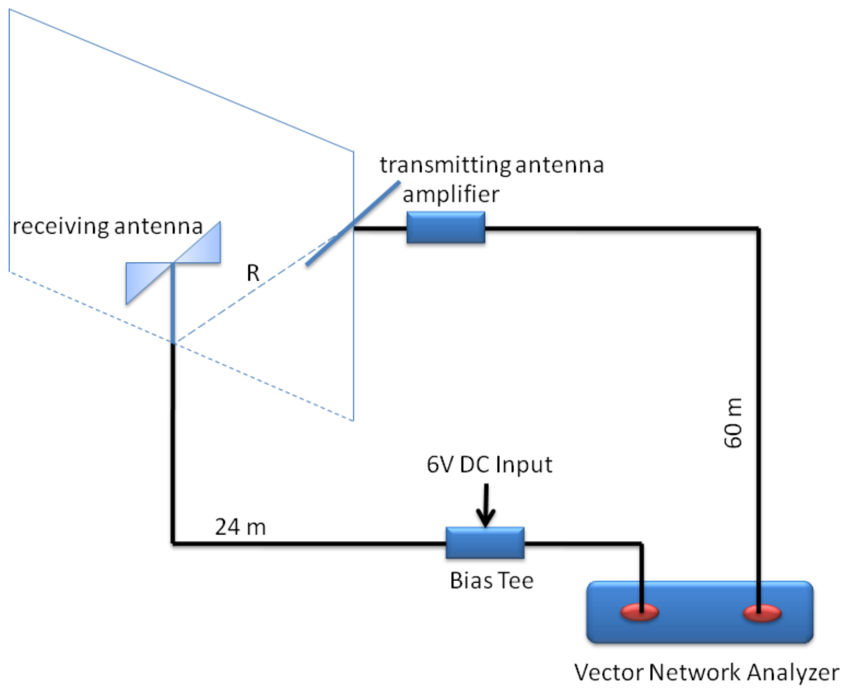
- different antenna types
- NS and EW polarized antenna
- antenna alignment:
  to magnetic north with precision < 1deg
- bandwidth: 30 - 80 MHz
- digitizer sampling rate: 200MHz

Antenna Calibration

voltage = antenna characteristic * electric field

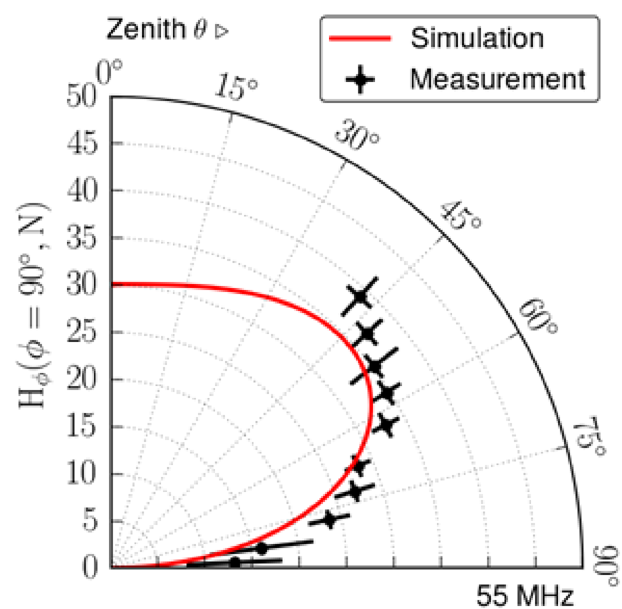
$$U = \vec{H} \cdot \vec{E}$$

H: relation of voltage amplitude to incoming E-field

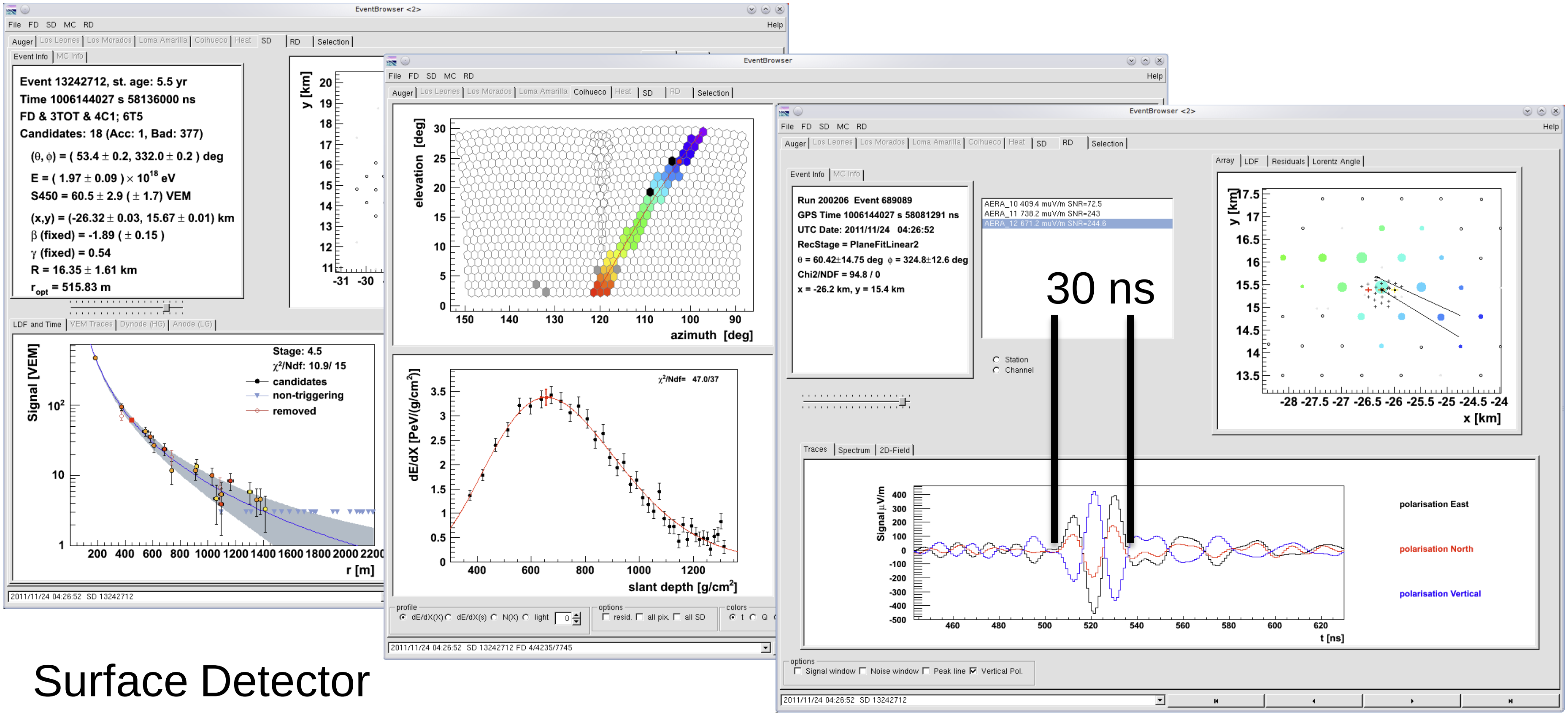


- measurement in far field region
  R > 2 λ (> 25 m)
- measurement and simulation are in fair agreement

butterfly antenna



Superhybrid Events



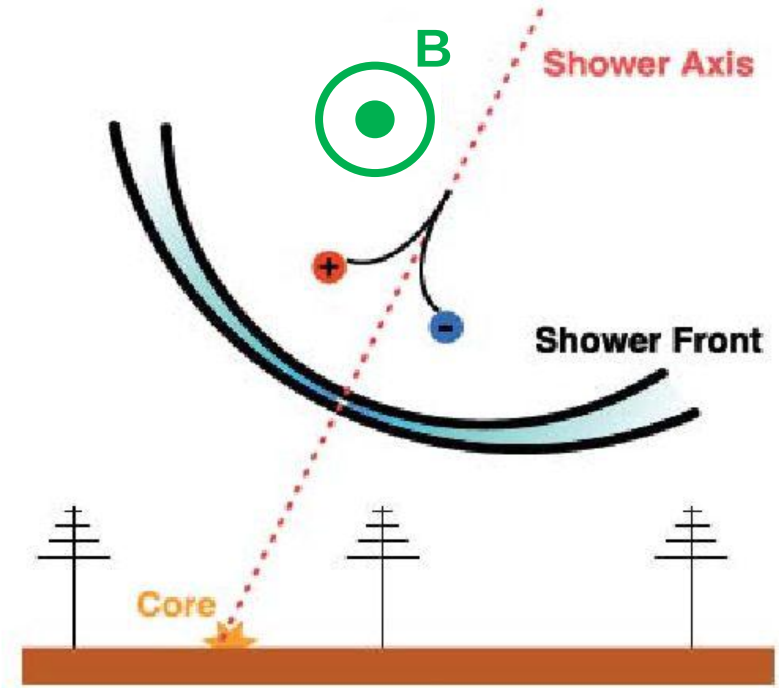
Surface Detector

Fluorescence Detector

Radio Detector

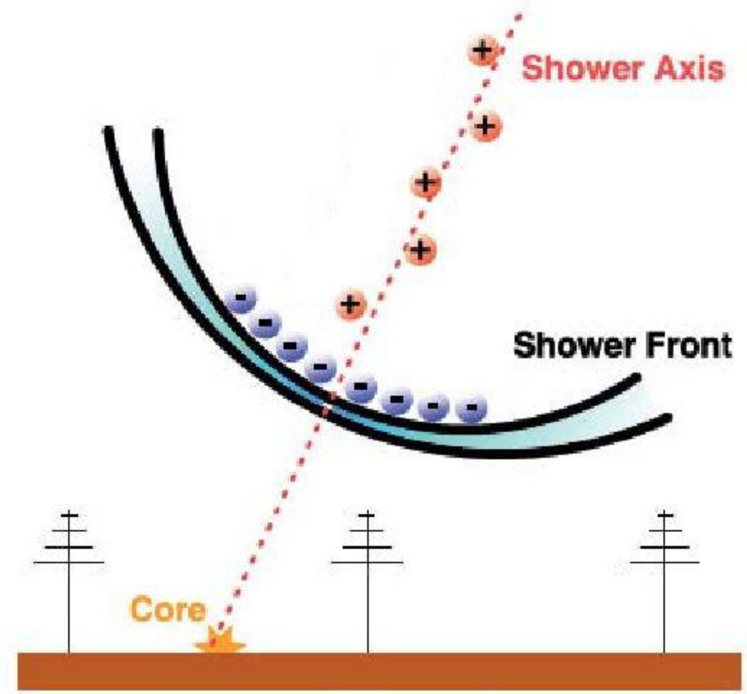
Radio Emission in Extensive Air Showers

geomagnetic emission



- charged particles are deflected in the Earth‘s magnetic field
  - ➢ charge separation
  - ➢ Lorentz force → polarization ~ $\vec{v} \times \vec{B}$
  - ➢ dipole perpendicular to shower axis

charge excess emission

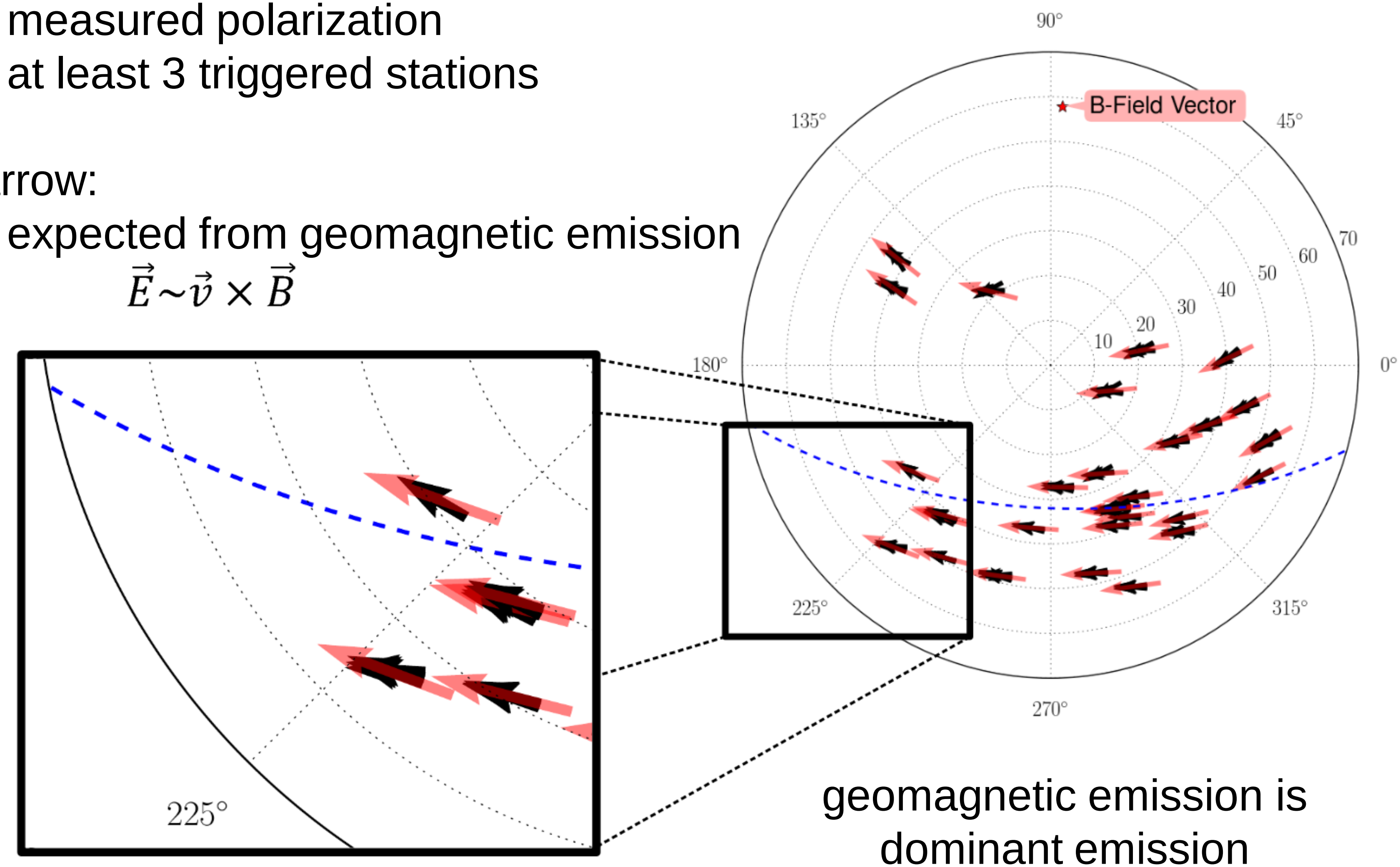


- electrons of air molecules are knocked out
  - ➢ positive charged air molecules remain
  - ➢ charge separation
- positrons partly annihilate in the atmosphere
  - ➢ charge excess
- dipole along the shower axis
  - ➢ radial polarized signal

Electric Field Polarization

- black arrow:
  - measured polarization
  - at least 3 triggered stations
- red arrow:
  - expected from geomagnetic emission

$$\vec{E} \sim \vec{v} \times \vec{B}$$



geomagnetic emission is dominant emission process

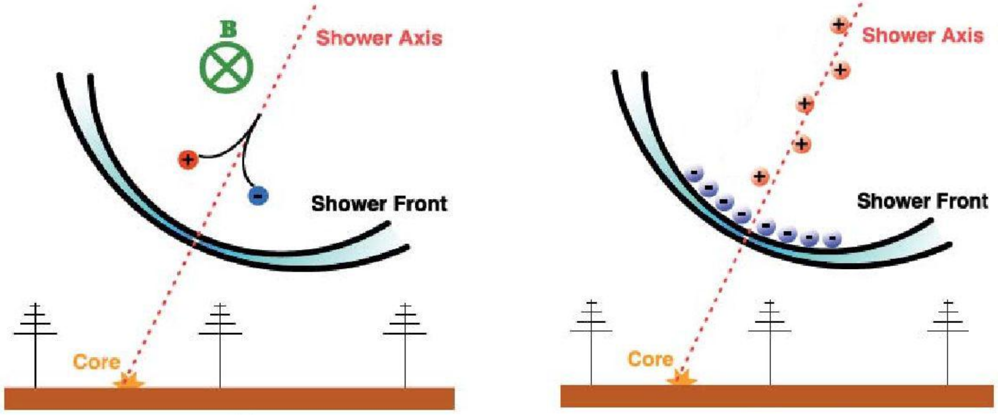
Second Order Emission Process

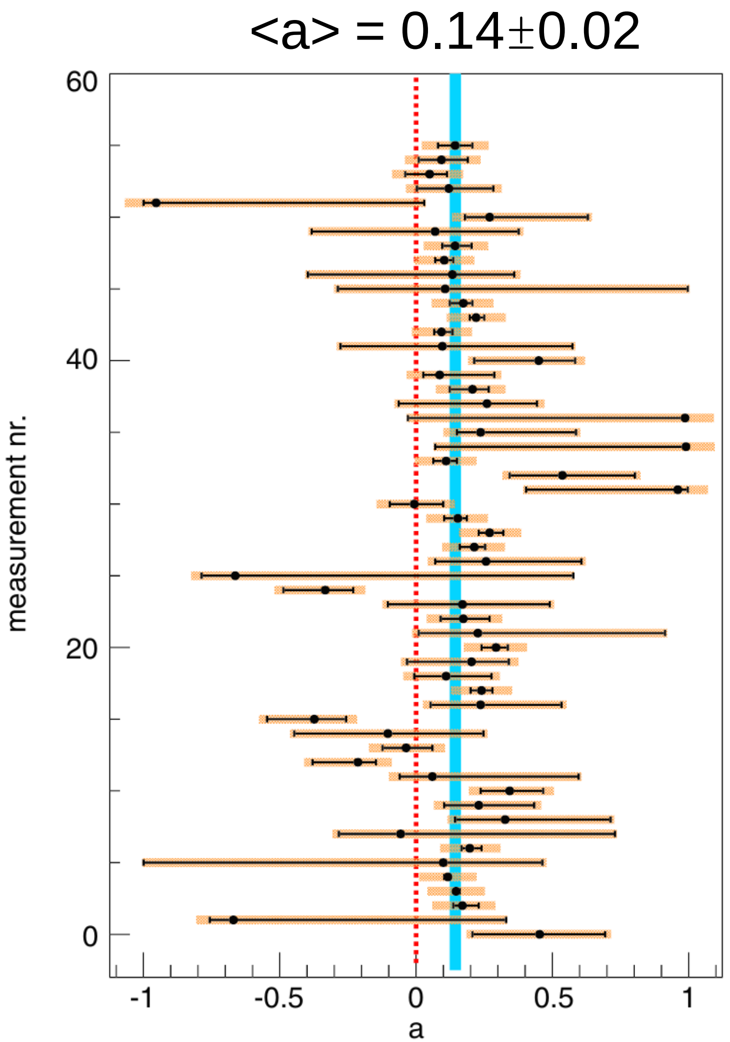
- pure geomagnetic radiation can not fully describe our data
- radial component, caused by a charge excess, is present

$$\vec{E} = \sin(\alpha) \cdot \vec{e}_{GM} + a \cdot \vec{e}_{CE}$$

geomagnetic emission

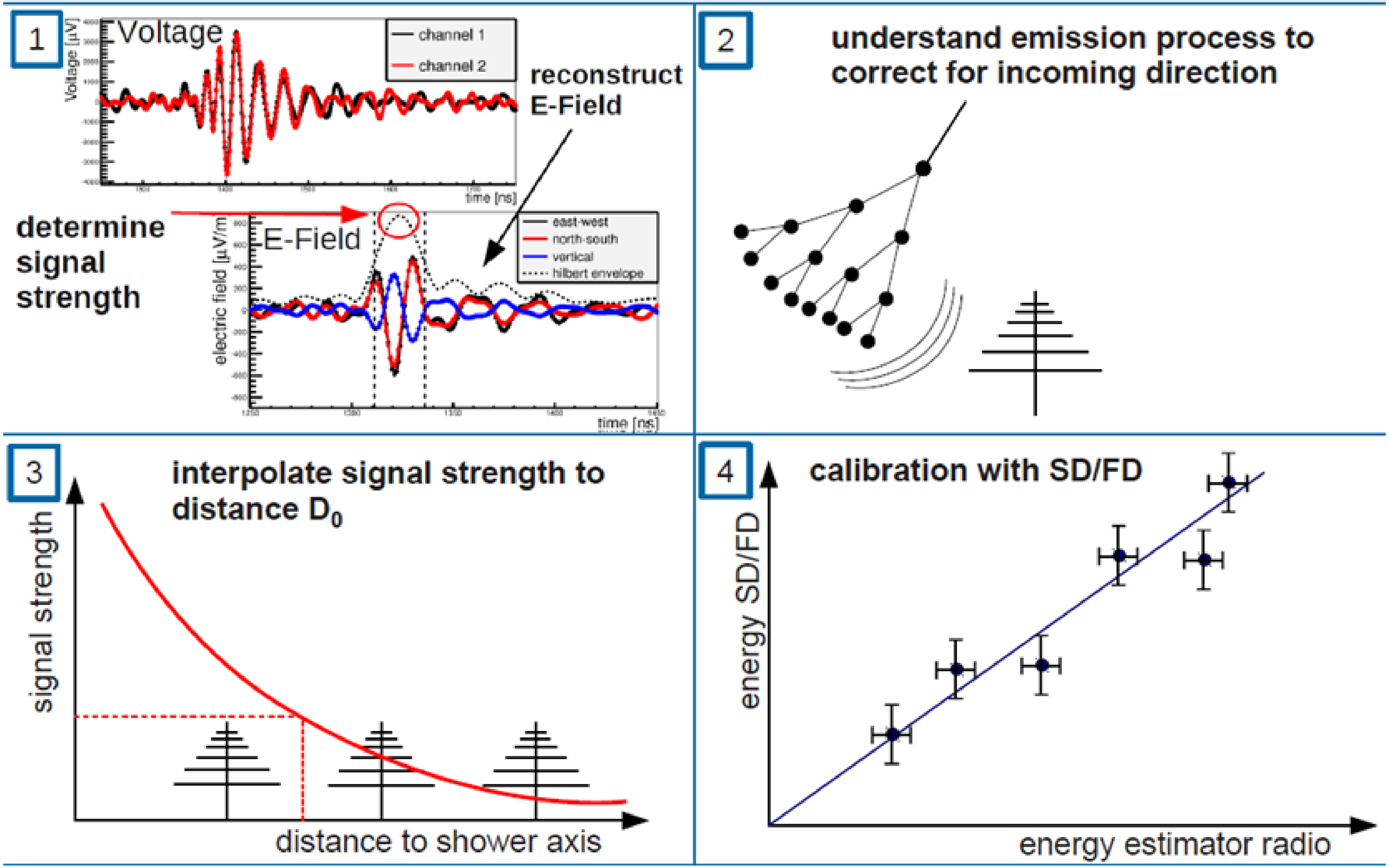
charge effect emission



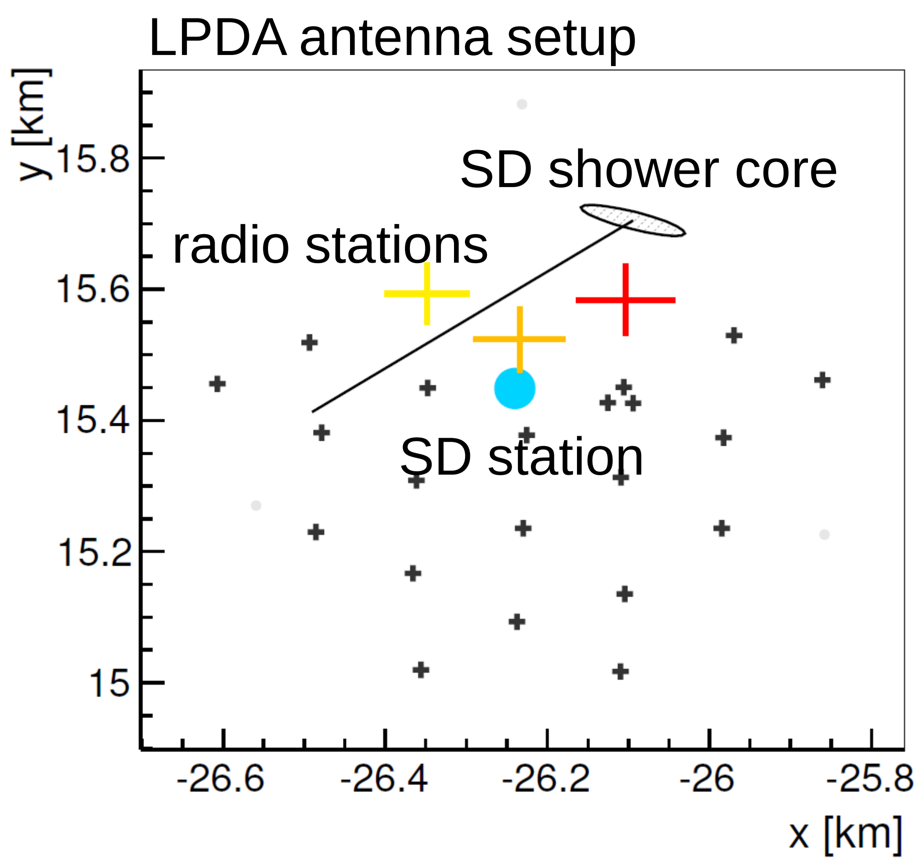


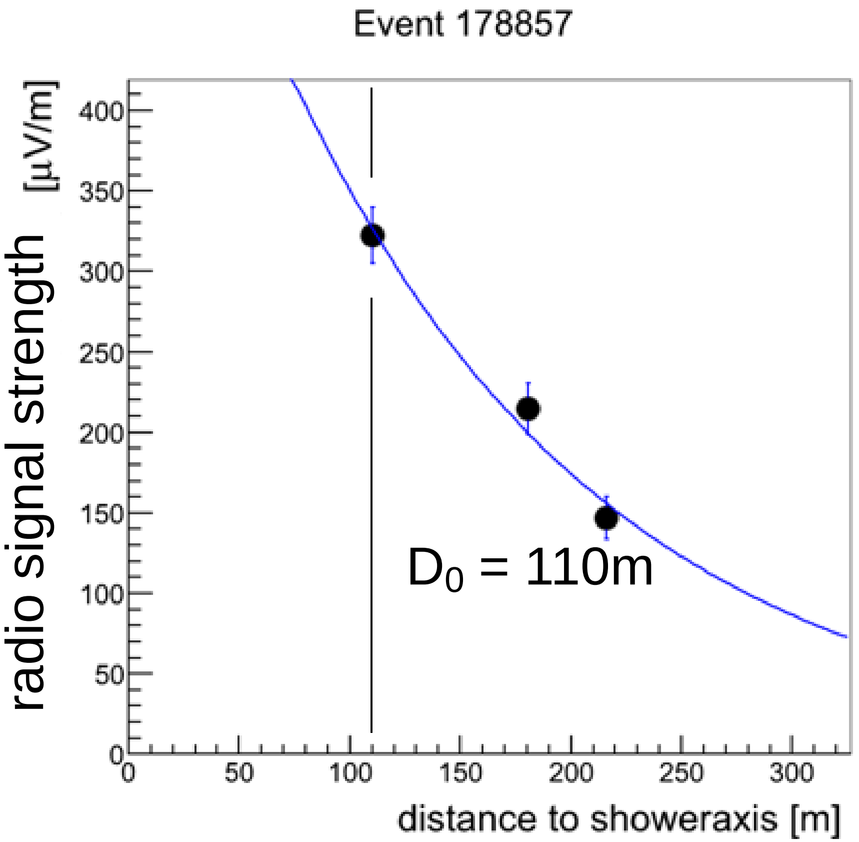
A. Aab et al., Phys. Rev. D 89, 2014

Radio Energy Reconstruction



Example Event

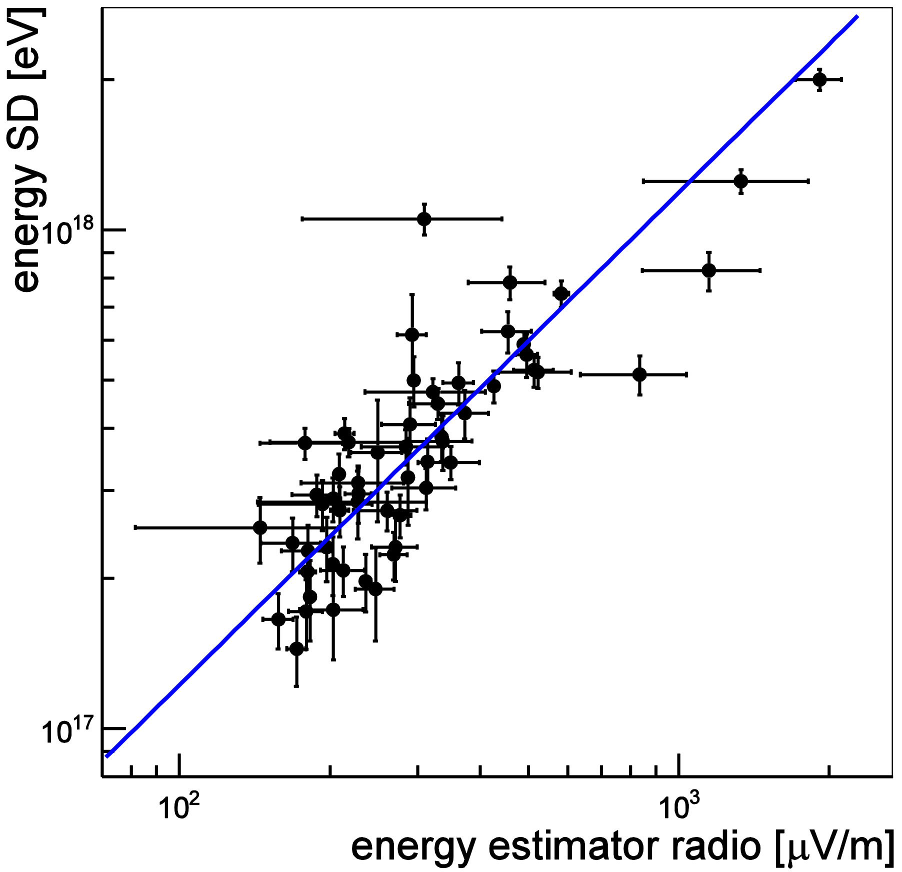


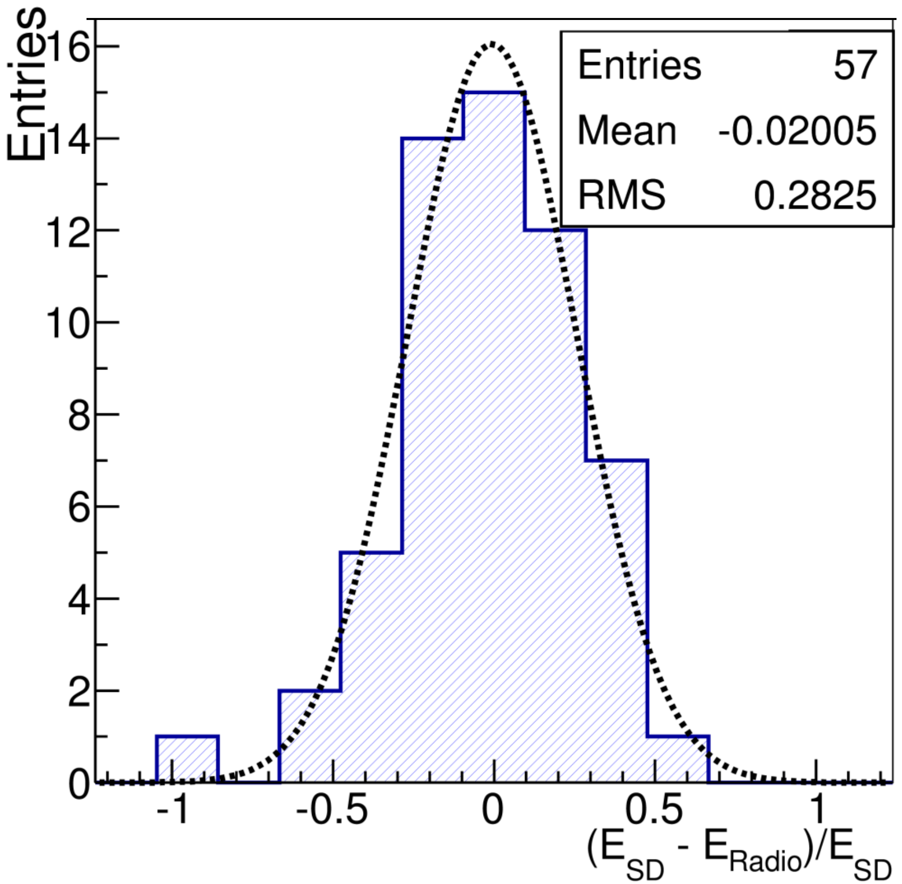


$$|\vec{E}_{cor}| = \varepsilon_{D_0} \cdot \exp\left(-\frac{(D_{axis} - D_0)}{R_0}\right)$$

Radio Energy Estimator

- LPDA antenna setup
- at least three triggered radio stations
- zenith angle smaller than 55°





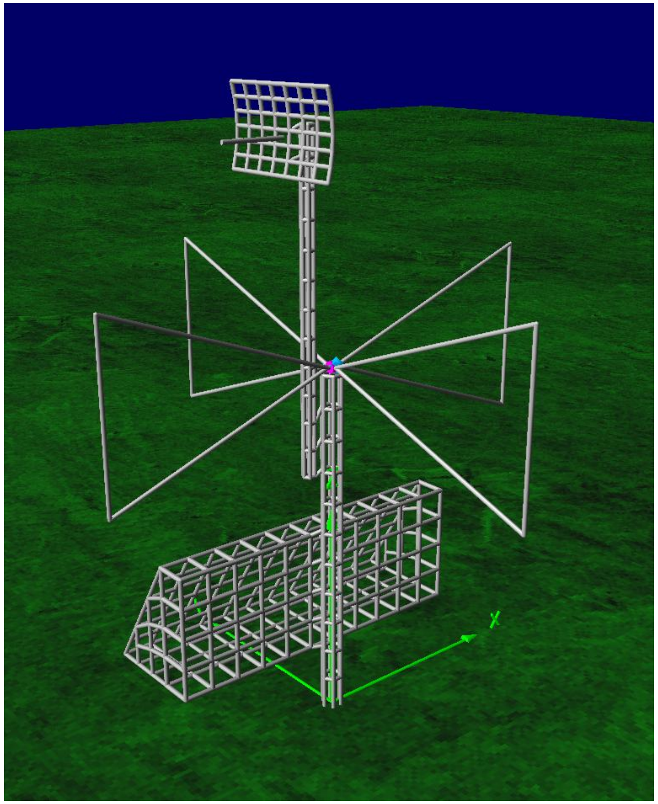
linear dependency:

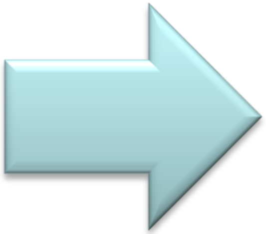
energy ⟷ electric field amplitude

energy resolution about 28%
(including SD resolution)

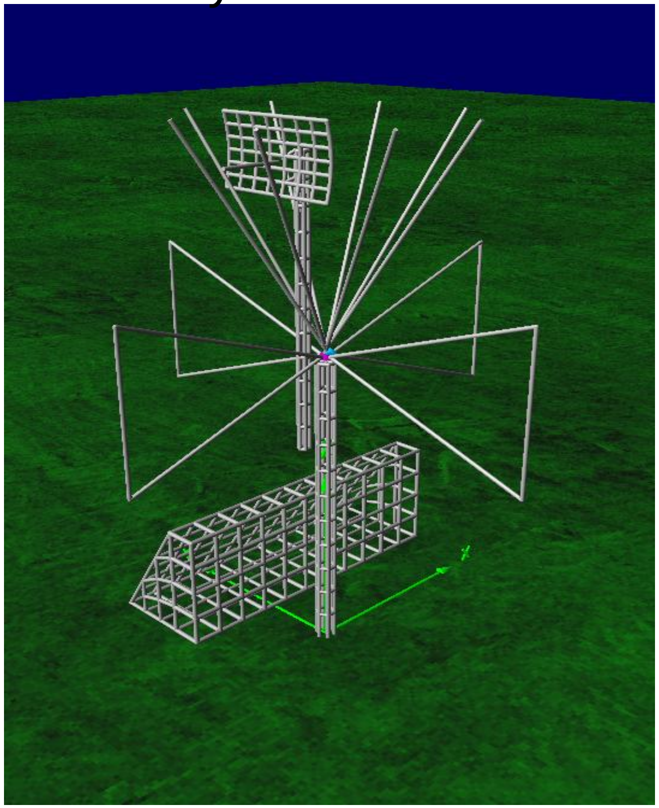
Vertical Polarization: 3D Radio Station

Butterfly Station





Butterfly + Whisk Antenna

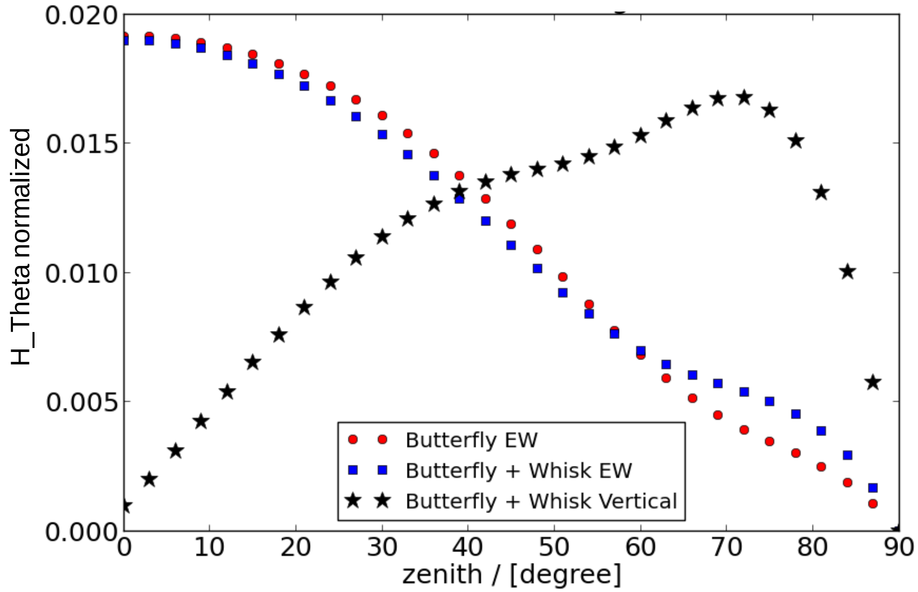


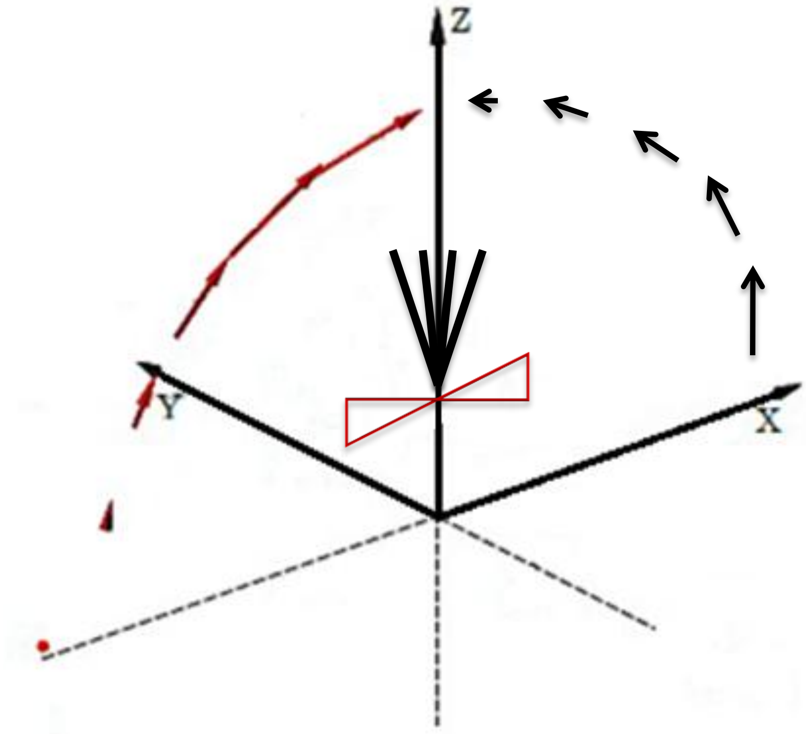
- each radio station measures all three components of the signal
  - ➢ better resolution of the electric field
- measurement of signals coming from the horizon

Frequency Average Simulation: Antenna Characteristics

frequency range: 25-85 MHz
frequency spacing: 1 MHz

signal coming from west





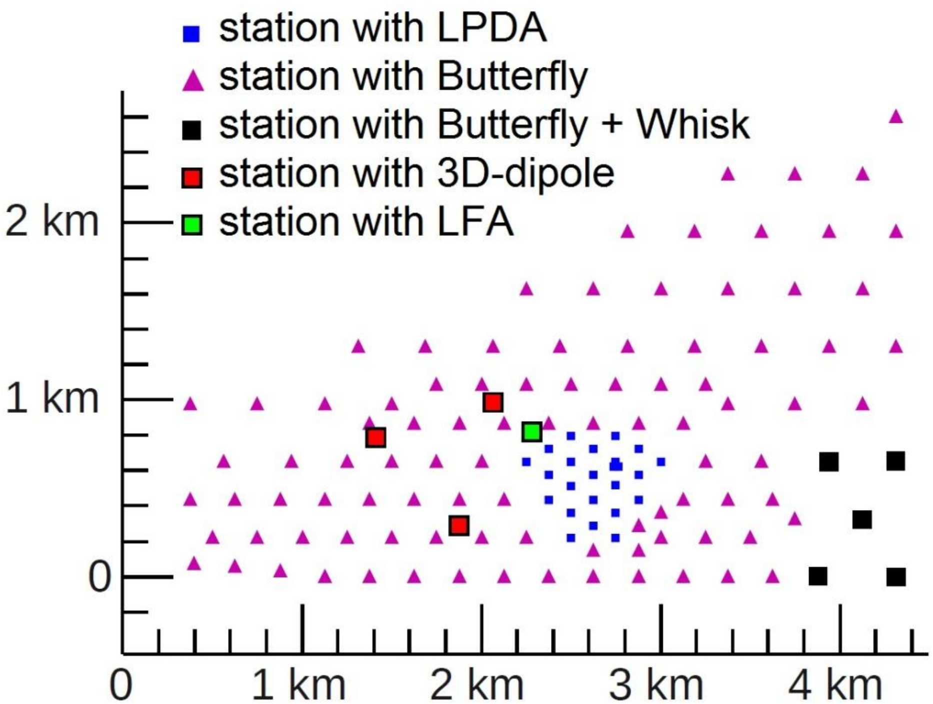
- horizontal antenna most sensitive for theta < 60 degree
- small influence of whisk on butterfly antenna in frequency average
- whisk antenna most sensitive to horizon in θ-component
- antennas complementary cover the full sky

3D Radio Stations

- November 2013

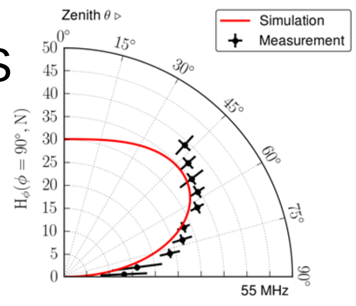
- 5 new butterfly + whisk radio stations
- covering area: ~0.3km²

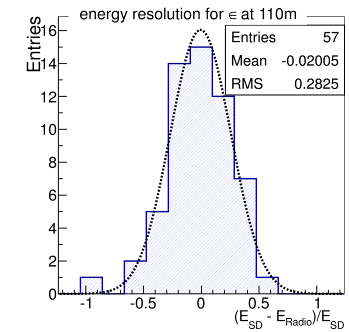
- 3 new 3D-dipole radio stations
- 1 low frequency antenna (1.5 to 6 Mhz)
- covering area: ~0.3km²



Summary

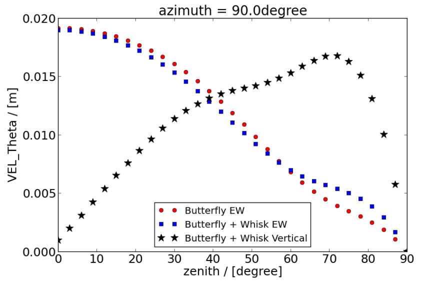
- Pierre Auger Observatory:
  - ➢ well calibrated environment for development of future detector technologies
- Auger Engineering Radio Array
  - ➢ one of the largest experiment to measure radio emission of EAS
  - ➢ several approaches to calibrate antennas
  - ➢ radio emission in Extensive Air Showers:
    - ➢ geomagnetic emission (dominant)
    - ➢ charge excess emission (measured to 14% on average)
  - ➢ energy of primary particles is reconstructed at 28% accuracy





Outlook

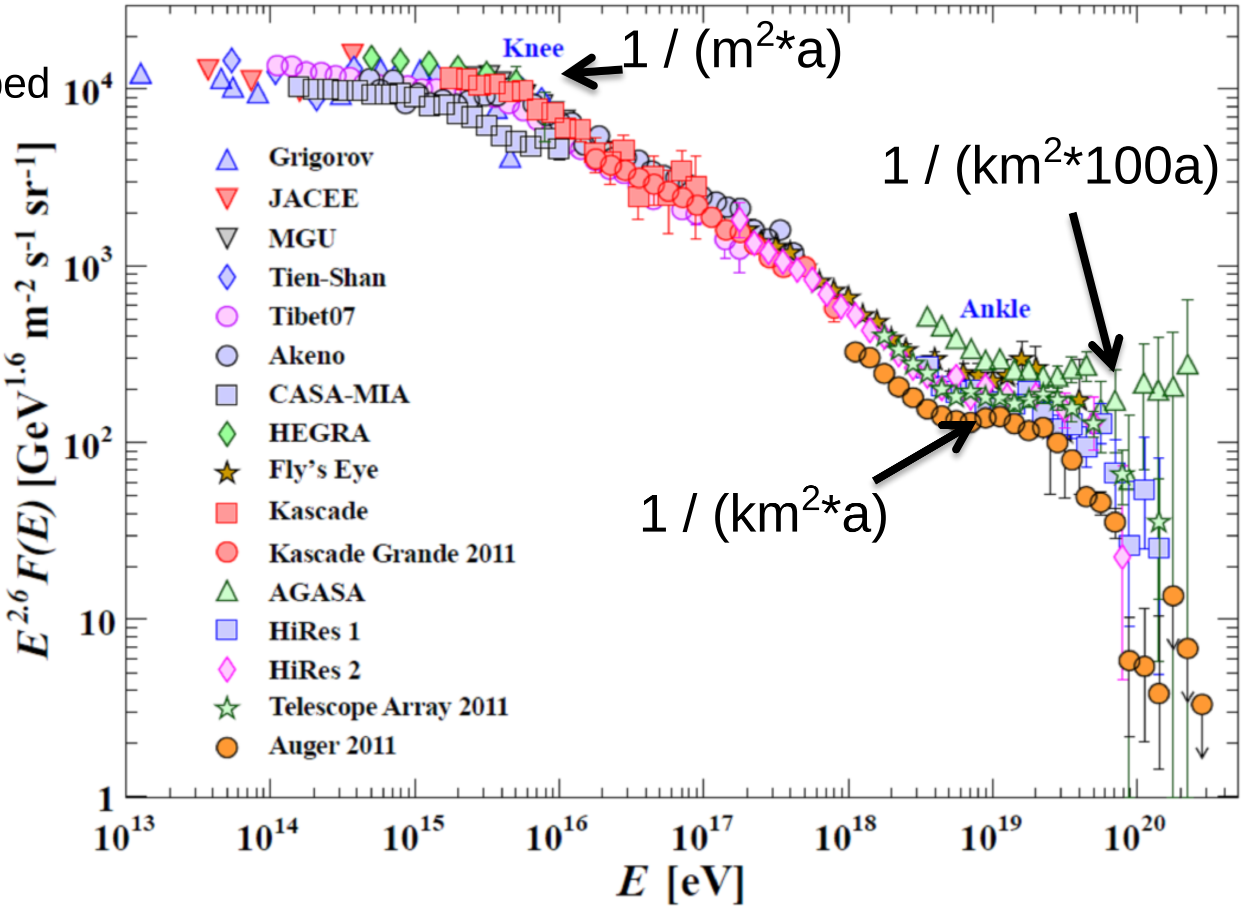
- data analysis of 6km² array and of the 3D radio stations
- in progress: reconstruction of shower maximum to get information about the chemical composition of UHECRs



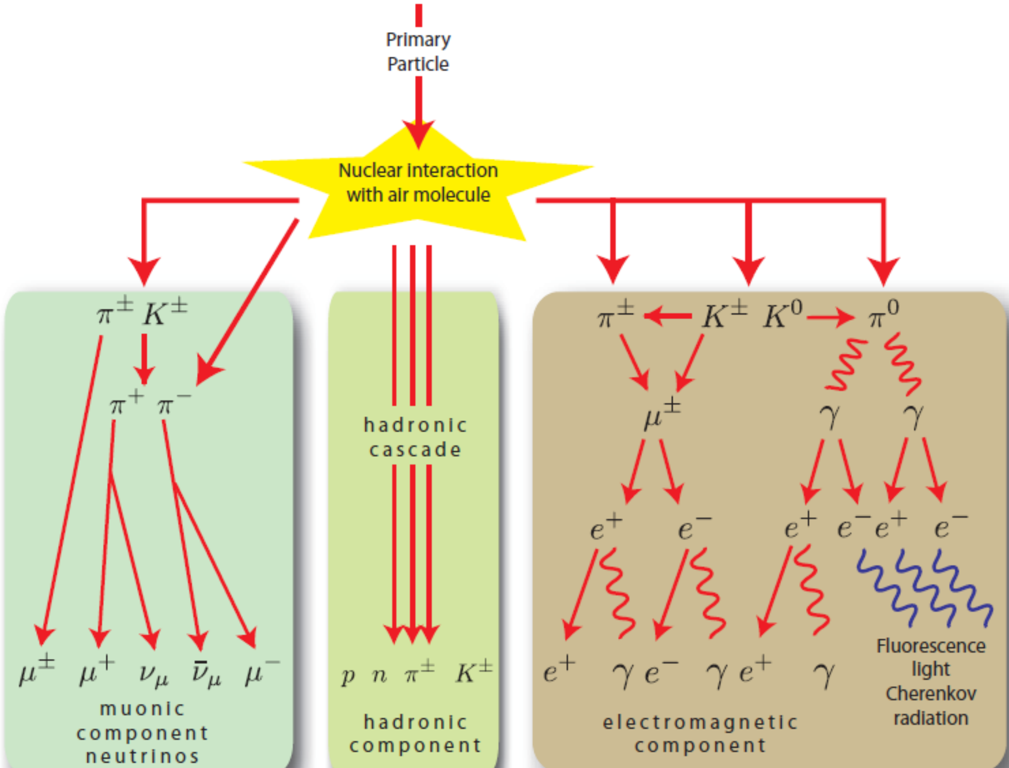
Backup

Cosmic Ray Energy Spectrum

- spectrum can be partly described by a power law: $F \sim E^{-\gamma}$
- UHECR events are very rare
- no direct measurement of UHECRs
- large ground-based experiments are needed
- measurement of secondary particles produced in extensive air showers

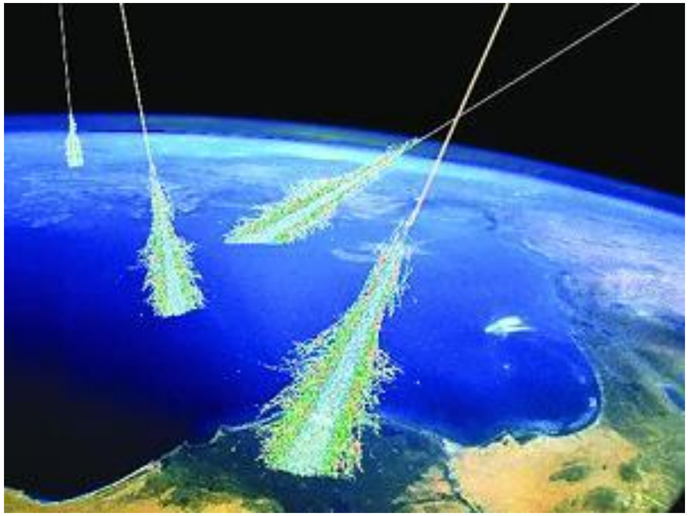


Extensive Air Showers



- interaction between UHECRs and air molecules
- Extensive Air Showers (EAS): muonic, hadronic and el.mag. component

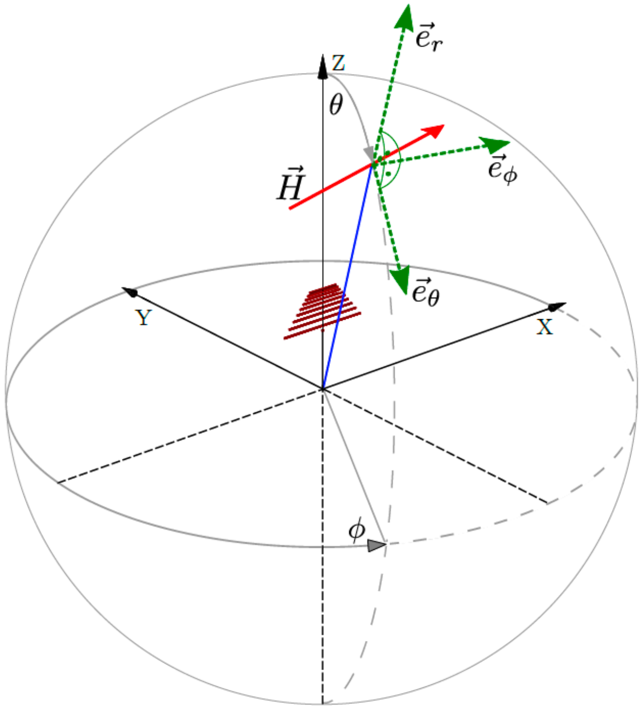
atmosphere corresponds to a large calorimeter

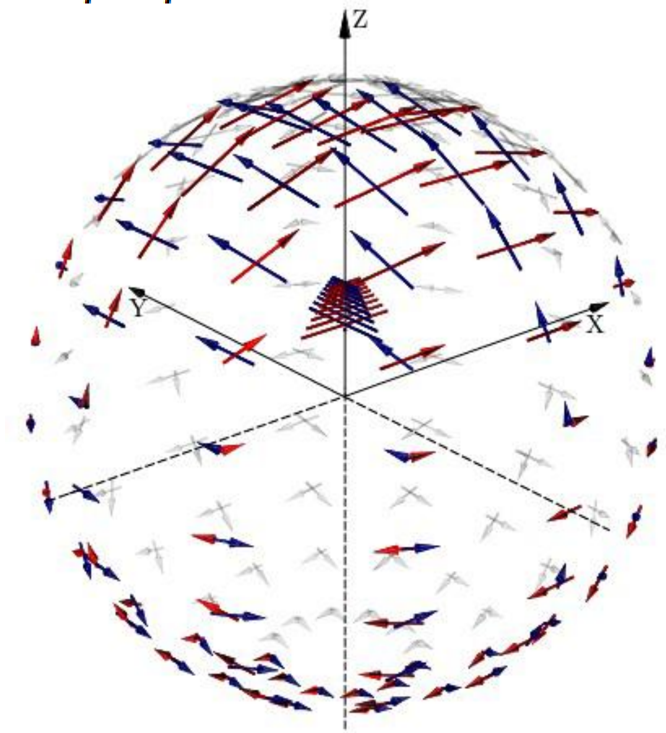


Vector Effective Length (VEL)

$$U(f,\theta,\varphi) = \vec{H}(f,\theta,\varphi) \cdot \vec{E}(f,\theta,\varphi)$$

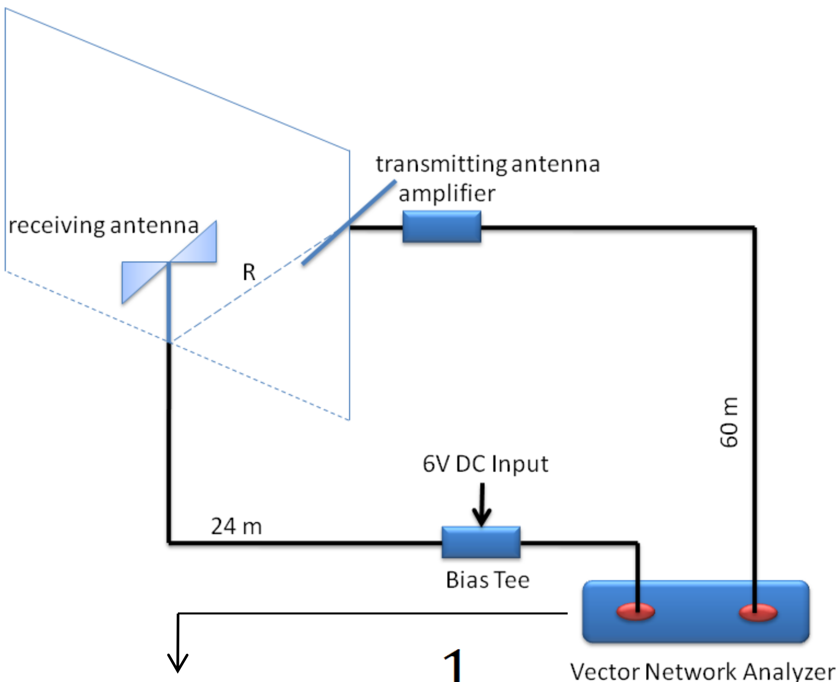
$$\vec{H} = H_\theta \vec{e}_\theta + H_\varphi \vec{e}_\varphi$$





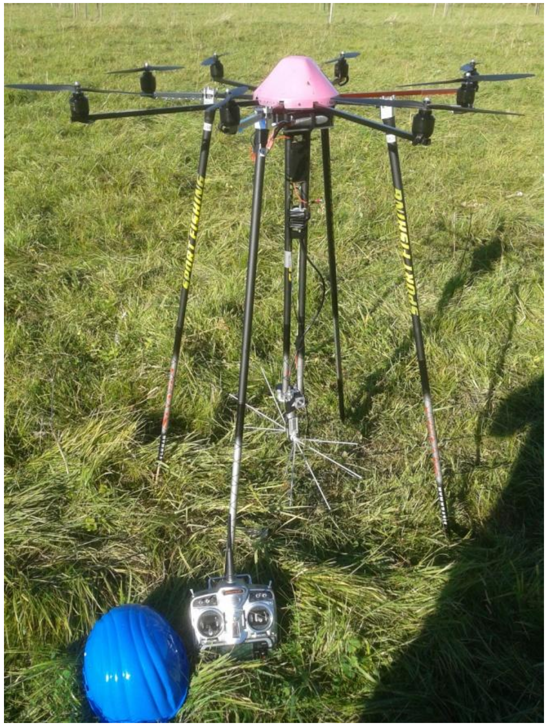
- VEL: relation of voltage amplitude to incoming e-field
- horizontal antenna most sensitive to vertical (zenith) direction

Antenna Calibration

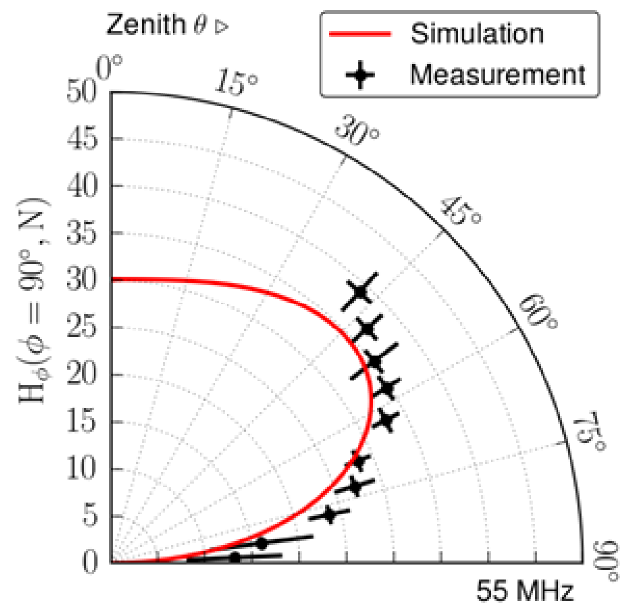


$$\left|H_\varphi\right| = T \cdot R \cdot C \cdot \frac{1}{\sqrt{G_t}}$$

- transmission measurement
- calibrated transmitting antenna
- measurement in far field region
  R > 2 λ (>25m)
- measurement and simulation are in fair agreement

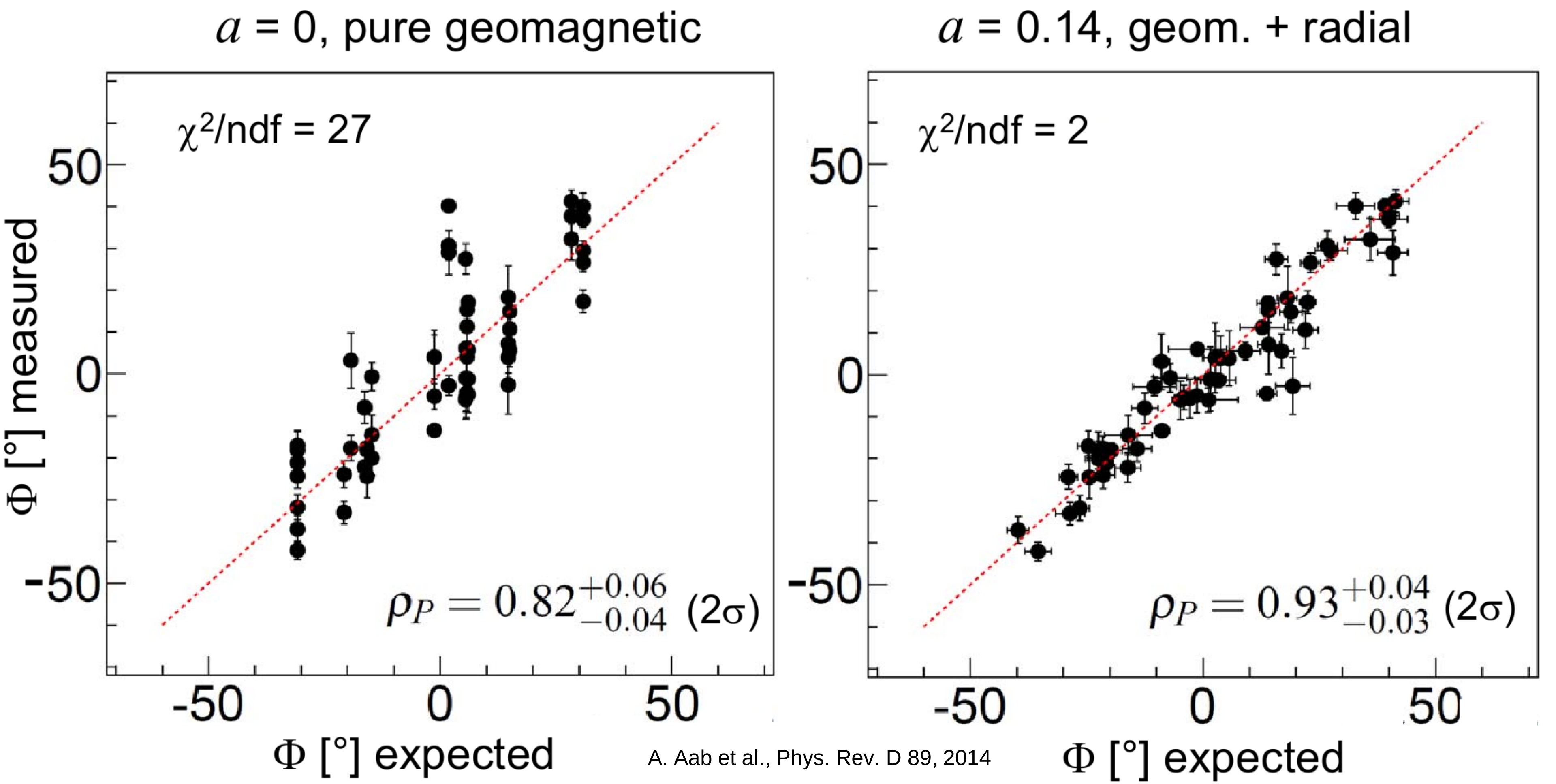


VEL Butterfly:



Second Order Emission Process

- adding a radial component clearly improves agreement



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