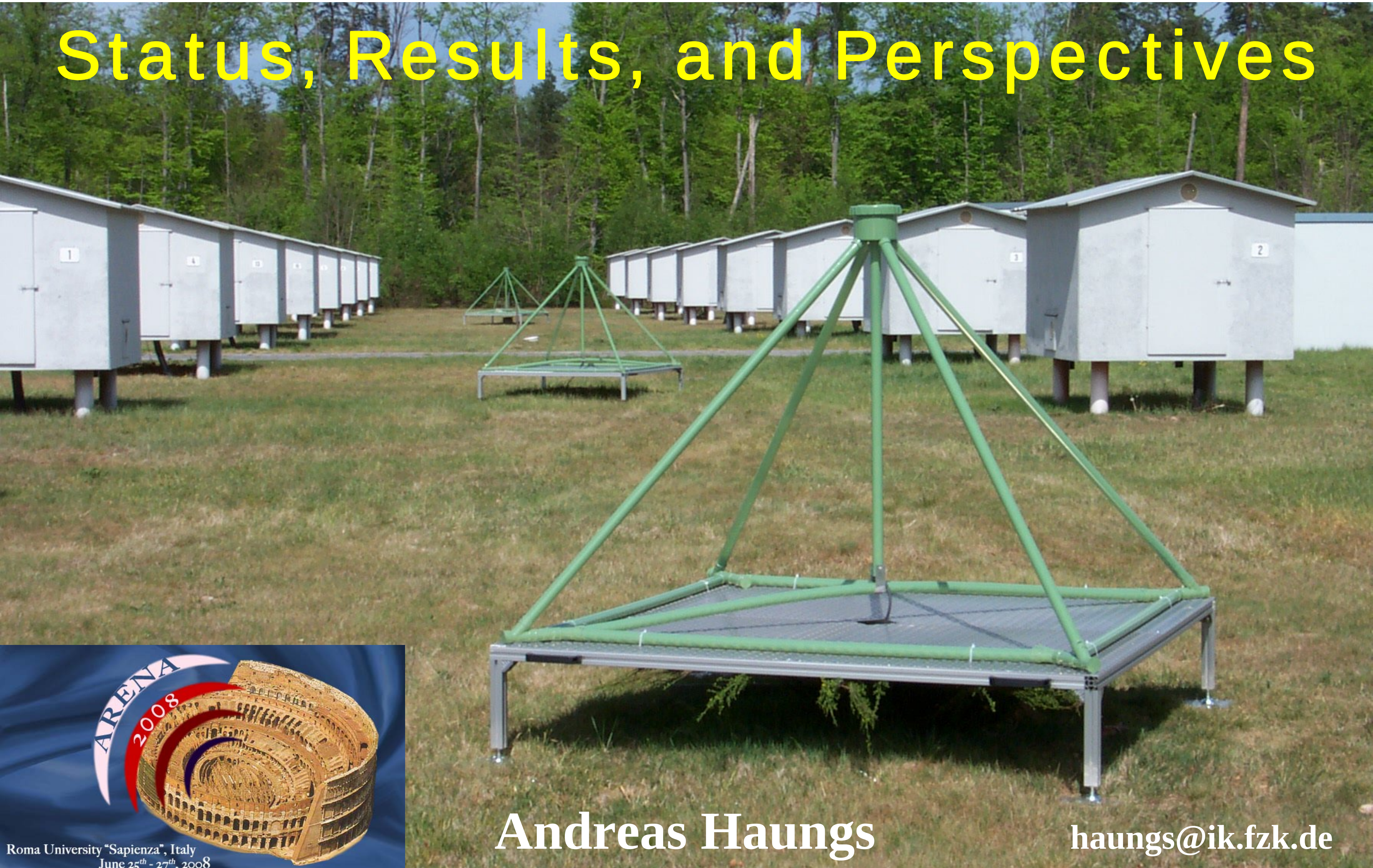
Forschungszentrum Karlsruhe
in der Helmholtzgemeinschaft

LOPES

Karlsruhe Institute of Technology



Status, Results, and Perspectives

ARENA 2008
Roma University "Sapienza", Italy
June 25th - 27th, 2008

Andreas Haungs

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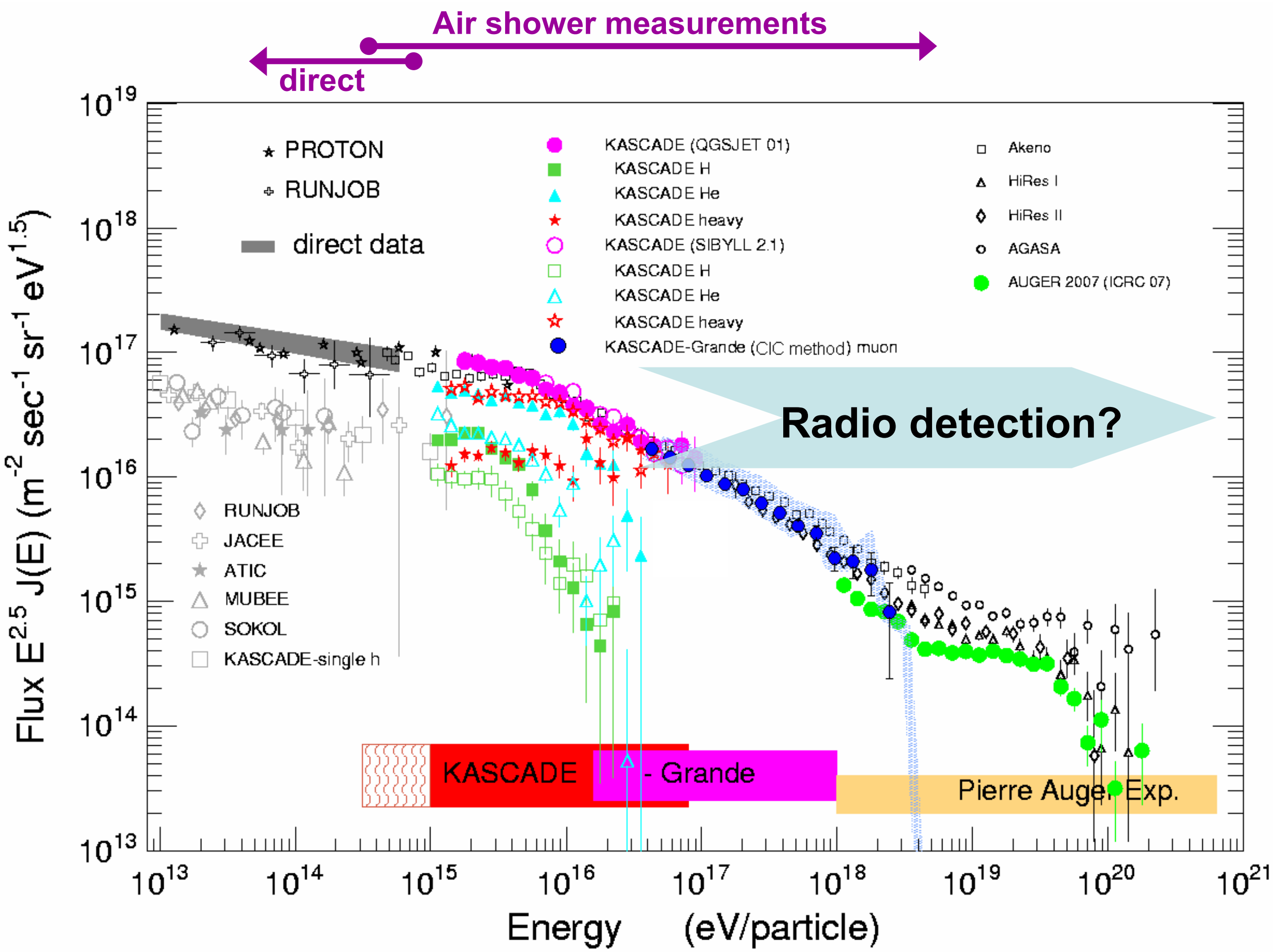
Cosmic Rays



- **The cosmic ray energy spectrum is not fully understood**
- **Above 10^{14}eV primary energy: only air-shower measurements possible**

➔ **More and better experiments needed: new detection techniques ?**

LOPES = LOfar PrototypE Station

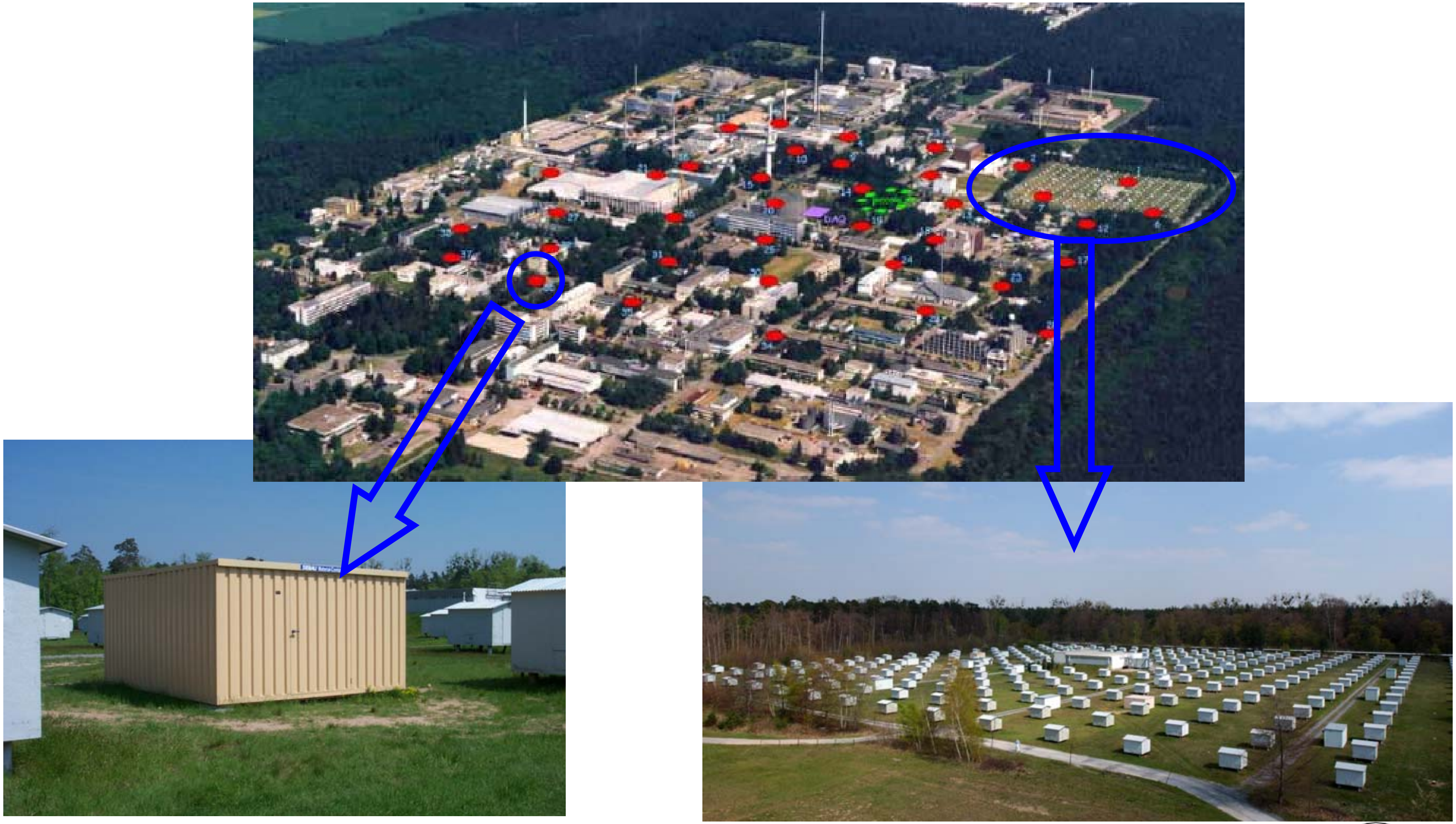
Questions: LOFAR as Cosmic Ray Detector ?
AUGER enhancement with radio measurements?
Needed: Calibration of the radio emission in air showers !

➔ „known“ air showers
➔ well-calibrated air shower experiment

- understanding of the radio signal and all its correlation with EAS parameters
- theory of radio emission and implementation in CORSIKA
- improvement/optimisation hardware (for application in Auger/LOFAR)

KASCADE-Grande
= KArlsruhe Shower Core and Array DEtector + Grande

Measurements of air showers in the energy range E_0 = 100 TeV - 1 EeV

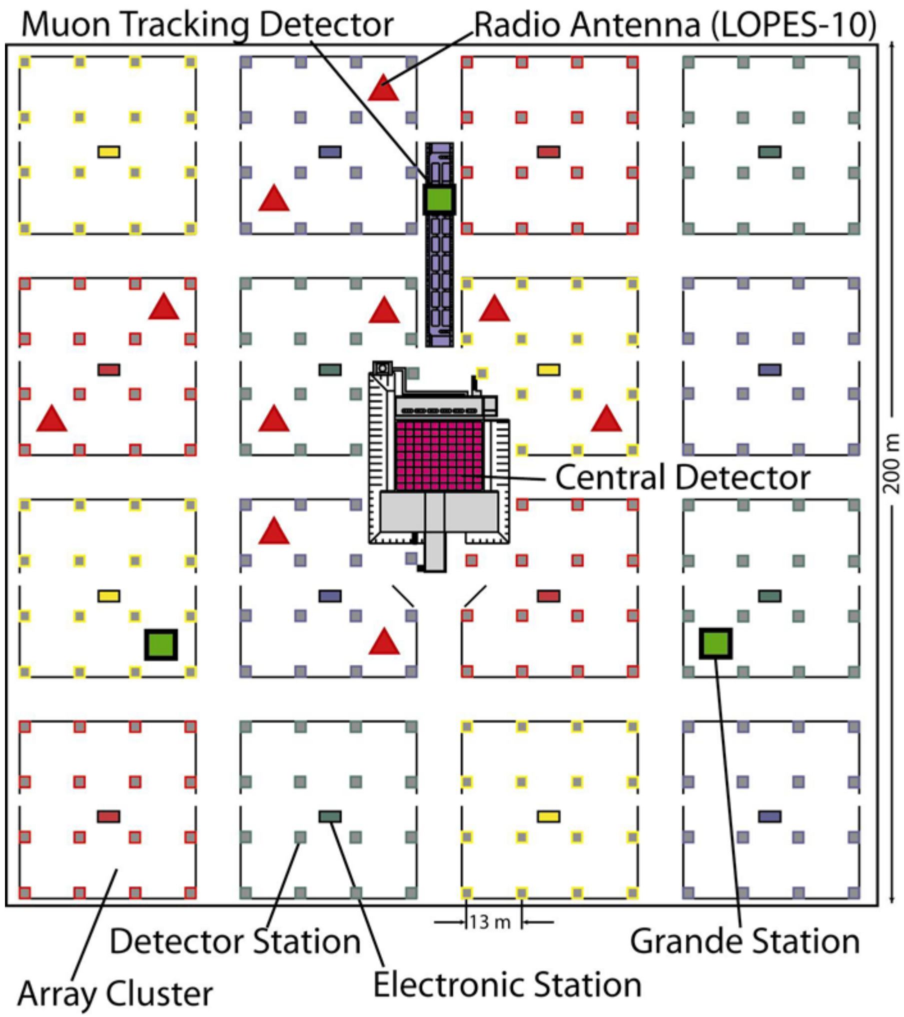


First step: 10 antennas at KASCADE

2004:

- **10 antennas at KASCADE array**
- **frequency band 40-80 MHz**
- **east-west oriented**
- **trigger: >10/16 cluster of KASCADE ($E_0 > 10^{16}$ eV, correlated EAS information)**

➔ „proof-of-principle“

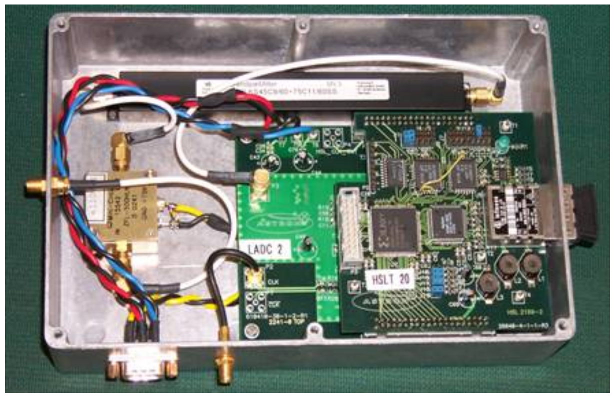


Hardware of LOPES

LOPES-Antenna

- short dipole
- beamwidth 80°-120° (parallel/ perpendicular to dipole)

Receiver Module



- direct sampling with minimal analog parts: amplifier, filter, AD-converter
- sampling with 80MSPS in the 2nd Nyquist domain of the ADC

Memory Buffer

- uses PC133-type memory
- up to 6.1 s per channel
- pre- and post-trigger capability

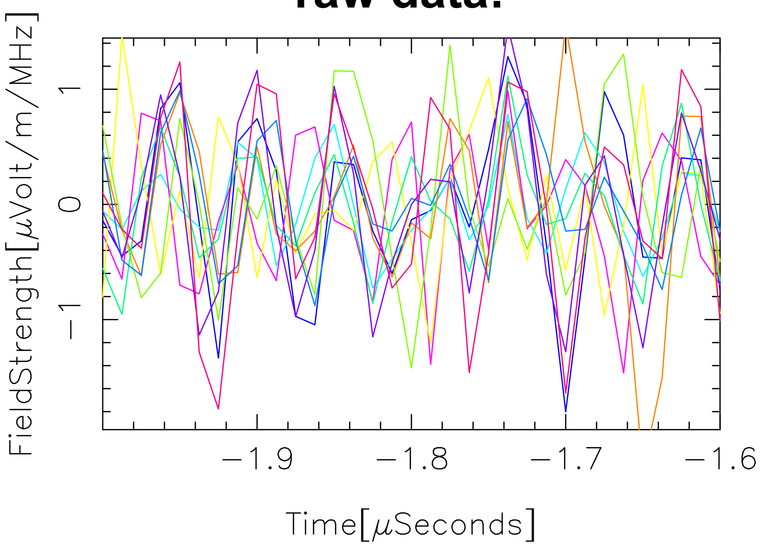
Clock and Trigger Board

- generates and distributes clock and accepts and distributes trigger

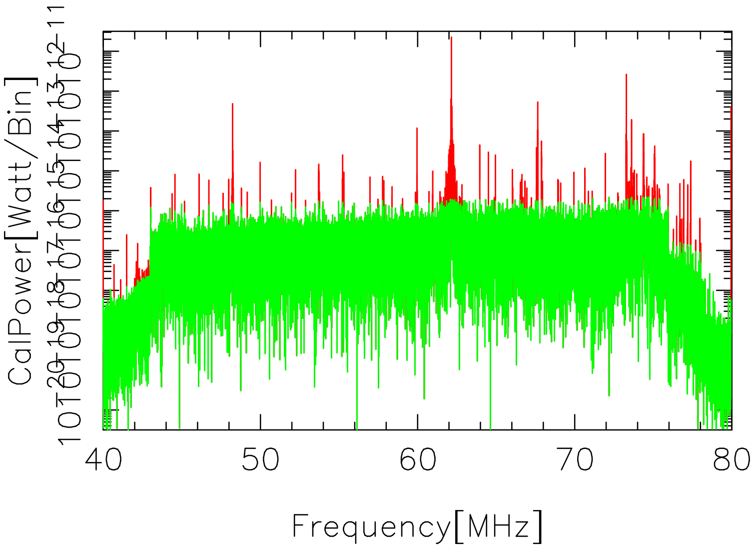
LOPES: data processing

1. **instrumental delay correction from TV or external source**
2. **frequency dependent gain correction**
3. **filtering of narrow band interference**
4. **flagging of bad antennas**

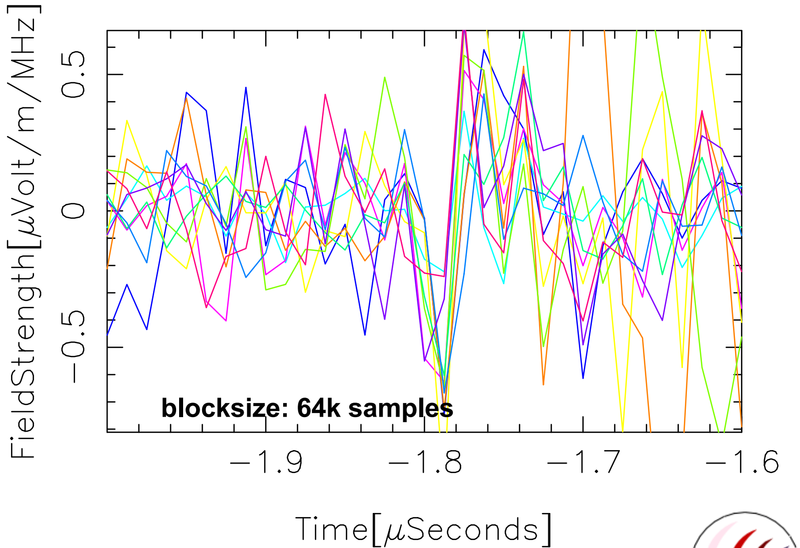
raw data:



power spectrum:



filtered data:



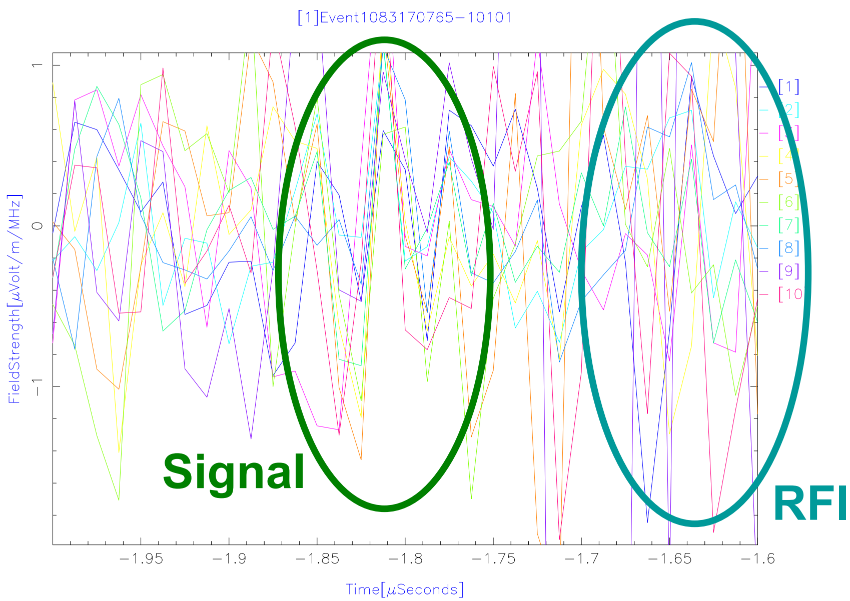
LOPES: data processing

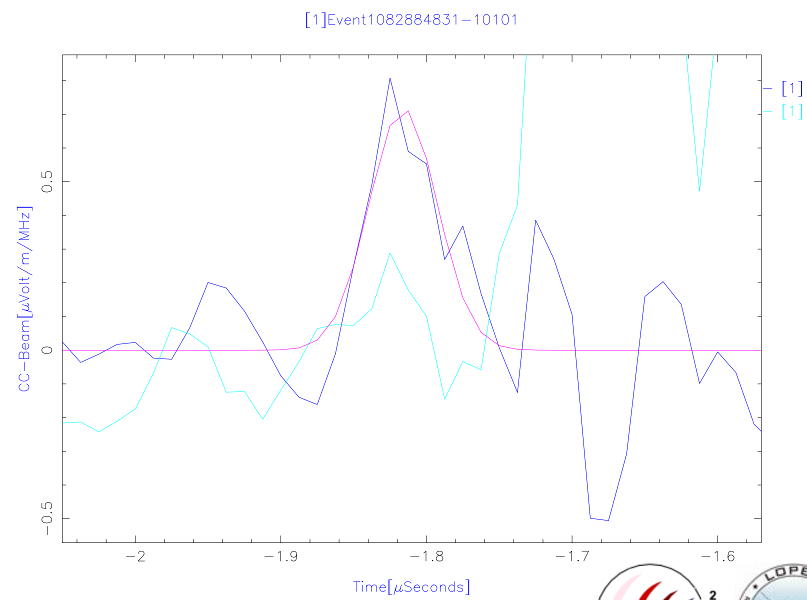
5. beam forming in the direction of the air shower

- quantity: CC-beam pulse height
- Gaussian fit to reconstructed radio pulse
- Field strength: height of Gaussian fit
- First error estimate: uncertainty of fit
- criteria for "good" events:
  - existence of a coherent pulse
  - position in time of pulse
- selection currently done manually
- Cross-check: sky-mapping

$$cc[t] = \pm\sqrt{\left|\frac{1}{N_{Pairs}}\sum_{i=1}^{N-1}\sum_{j>i}^{N} s_i[t]s_j[t]\right|}$$

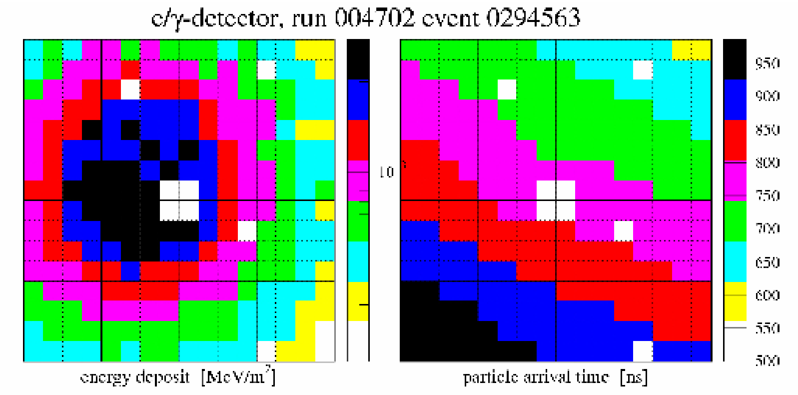
(degree of correlation
➔ extract coherent pulse):



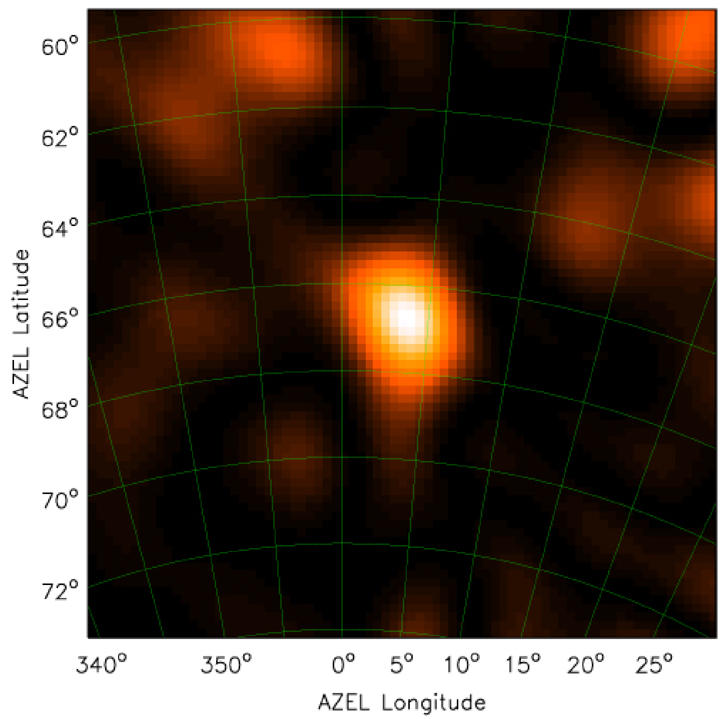


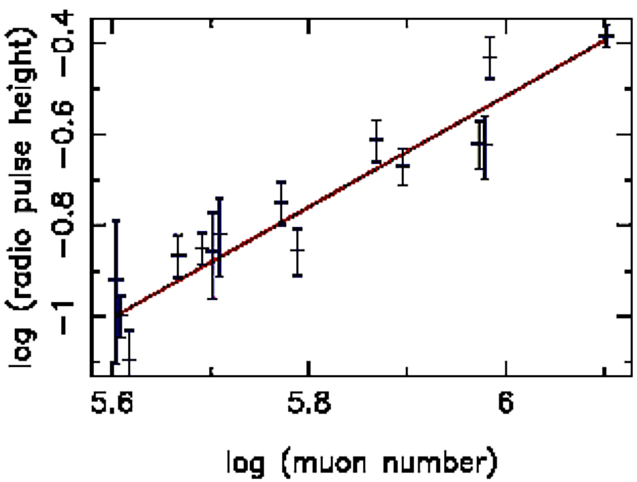
LOPES 10 : Proof of principle

data analyses:
- **EAS analyses KASCADE**
- **radio signal analyses (cc-beam)**
- **sky mapping**



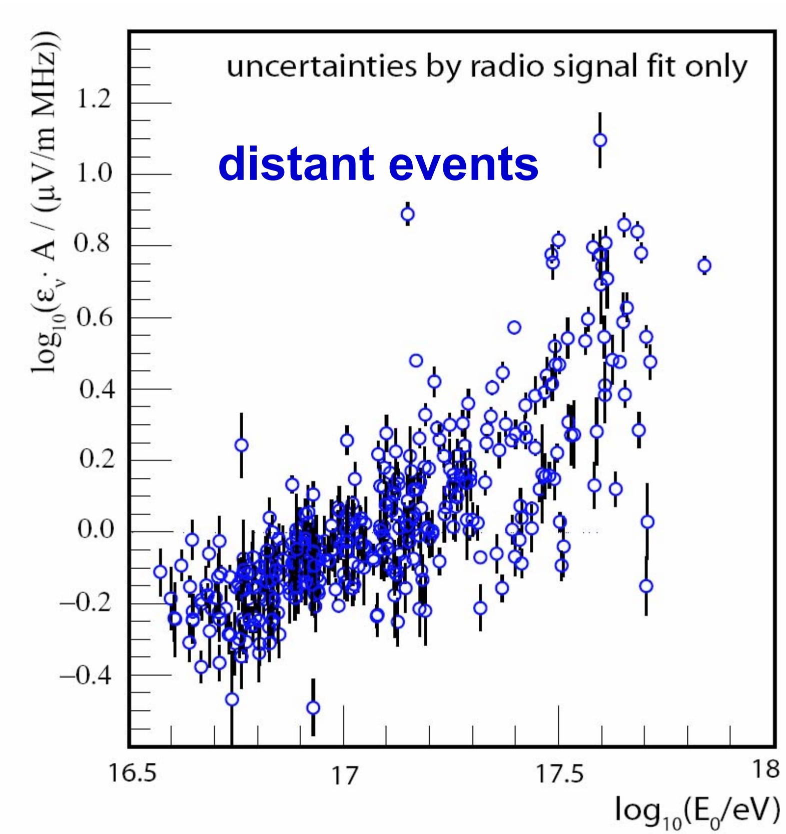
- **energy ≈ 10^{17} eV**
- **EAS core inside antennas**
- **Θ = 25.5°, Φ = 42.5°**
- **signal is coherent**

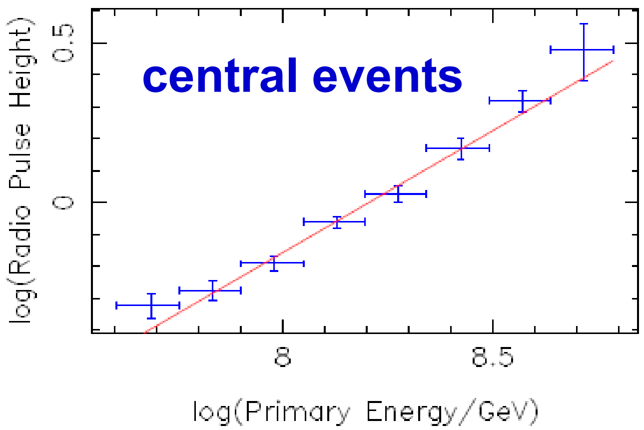




LOPES collaboration, Nature 425 (2005) 313

LOPES 10 Results:
energy dependence of radio signal





Radio signal (electric field) scales with primary energy:

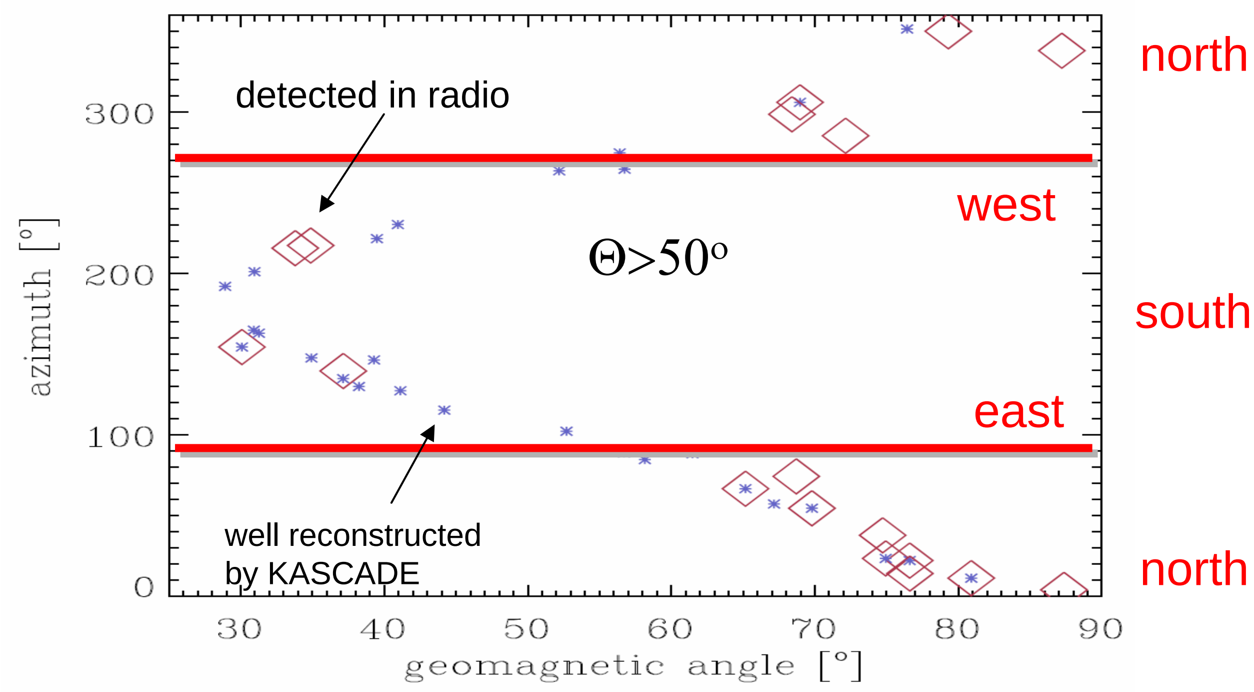
$\varepsilon_\nu \sim E_0^{\sim 1}$

➔ Power of electric field scales approximately quadratically with primary energy !

Apel et al. – LOPES collaboration, Astrop.Phys. 26 (2006) 332

LOPES 10 analysis of inclined showers

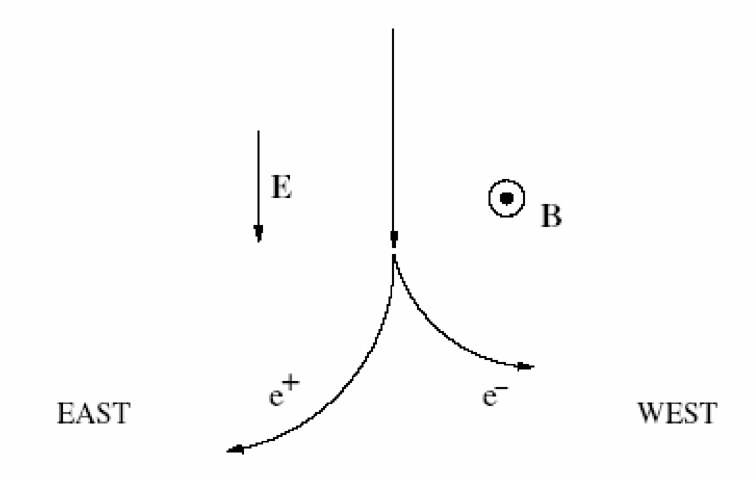
inclined showers ➔ larger lever arm to geomagnetic angle
- reconstruction of shower by particle detectors difficult
- clear radio signals seen

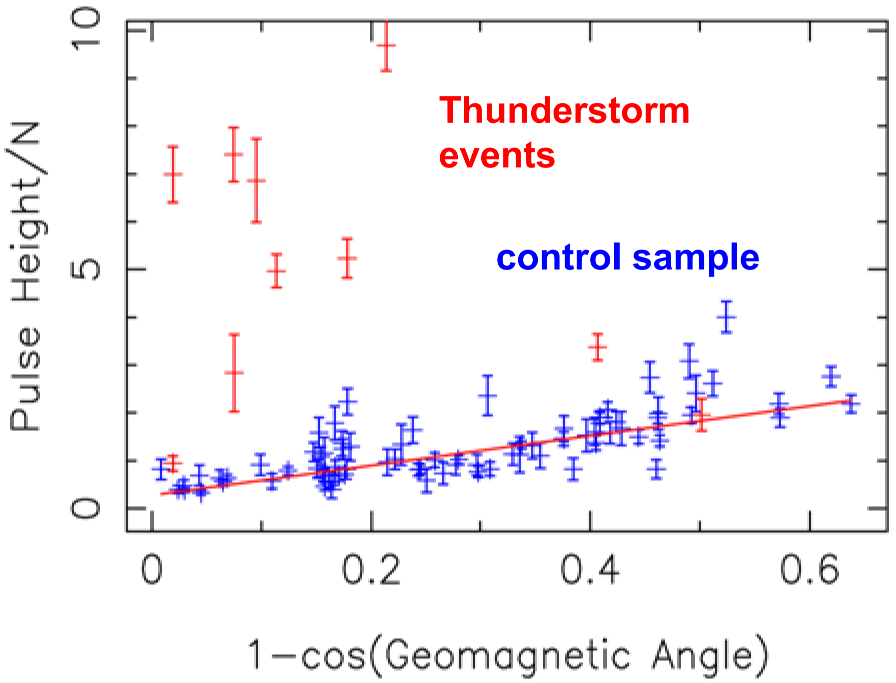


J.Petrovic et al. – LOPES collaboration A&A, 462(2007)389
….more on inclined EAS: A.Saftoiu, ARENA08, next talk!!

LOPES 10 analysis of events during thunderstorms

Downward electric field
➔Asymmetry in trajectories
➔Radio emission

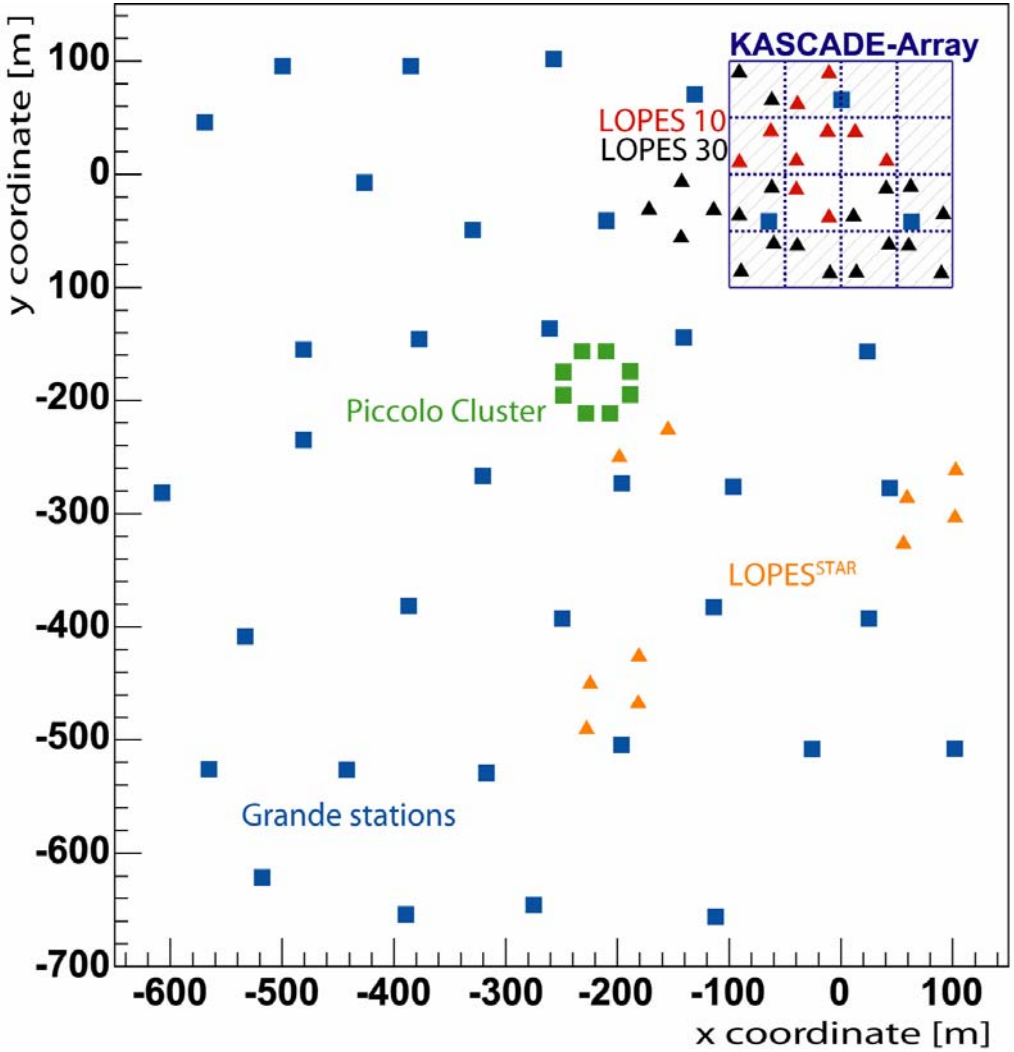




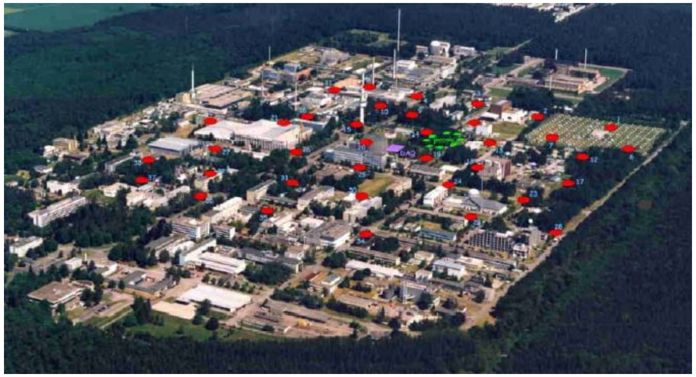
For E>100 V/cm:
E-field force dominates B-field:
Fair weather: E=0,1 V/cm
Thunderstorms: E=1 kV/cm

S.Buitink et al. – LOPES collaboration, A&A 467(2007)385

LOPES Extension

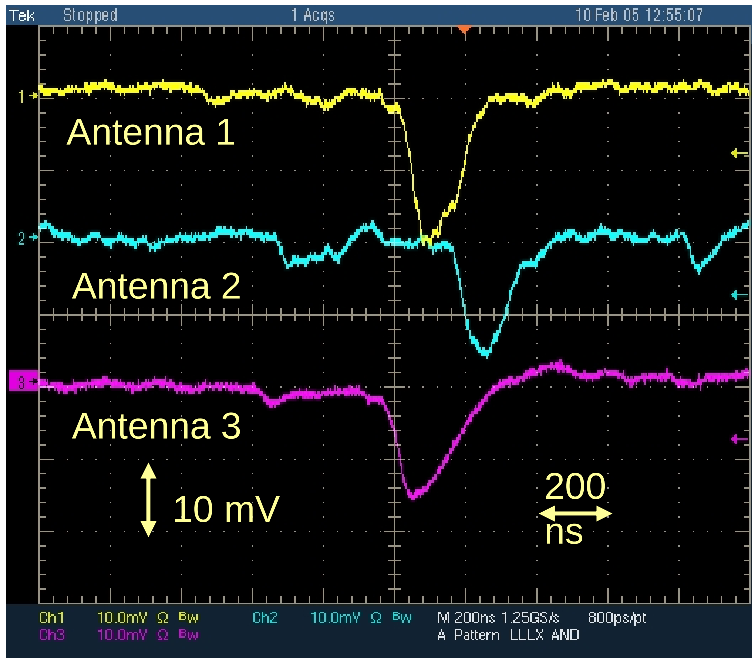


- **LOPES 30: 30 east-west antennas**
- **LOPES^{STAR}: for Auger + selftriggering**
- **Trigger: KASCADE <u>and</u> KASCADE-Grande**
- **Absolute Calibration**
- **Environmental monitoring**



LOPES^{STAR}

- Developing and optimizing antenna design for application in Auger
- Developing self trigger system on FGPA



….more in 30 minutes:
H. Gemmeke – LOPES collaboration, ARENA 08

LOPES 30: amplitude calibration

- **amplification factor V obtained with external commercial calibrated reference source (end-to-end calibration).**

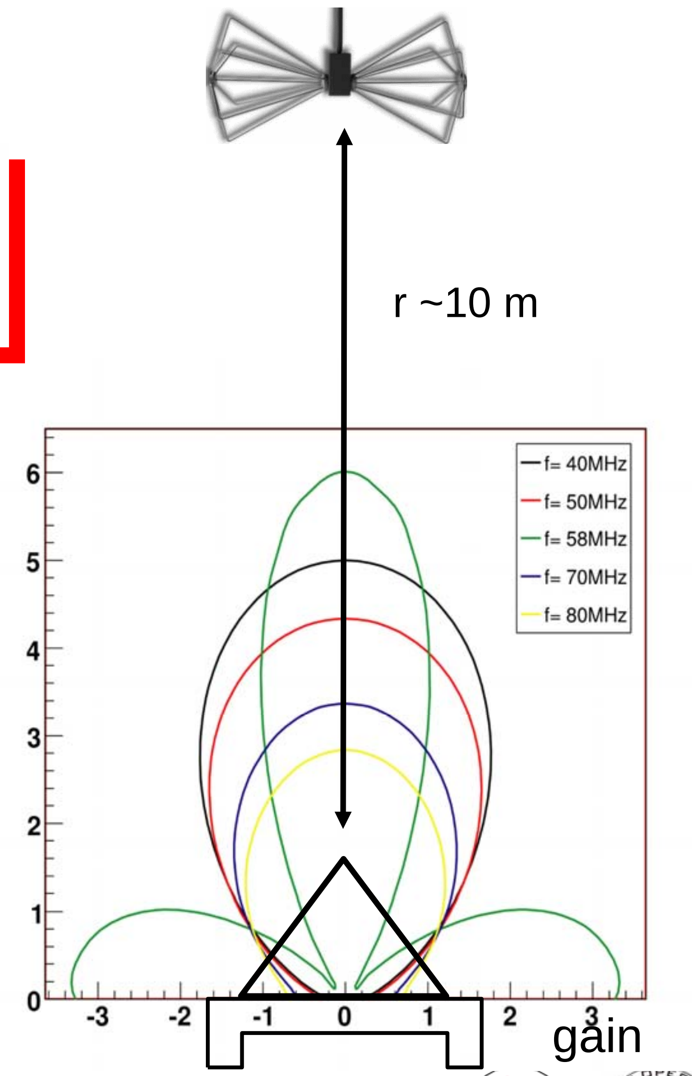
➔ correction factor dependent on

antenna
frequency
weather conditions
angle

LOPES 30: amplitude calibration

- **amplification factor V(ν):**

$$V(\nu) = \frac{P_{\mathrm{M}}(\nu)}{P_{\mathrm{R}}(\nu)} = \left(\frac{4\pi r \nu}{c}\right)^2 \frac{P_{\mathrm{M}}(\nu)}{G_r(\theta,\phi,\nu) G_t P_t(\nu) \cos^2(\beta)}$$

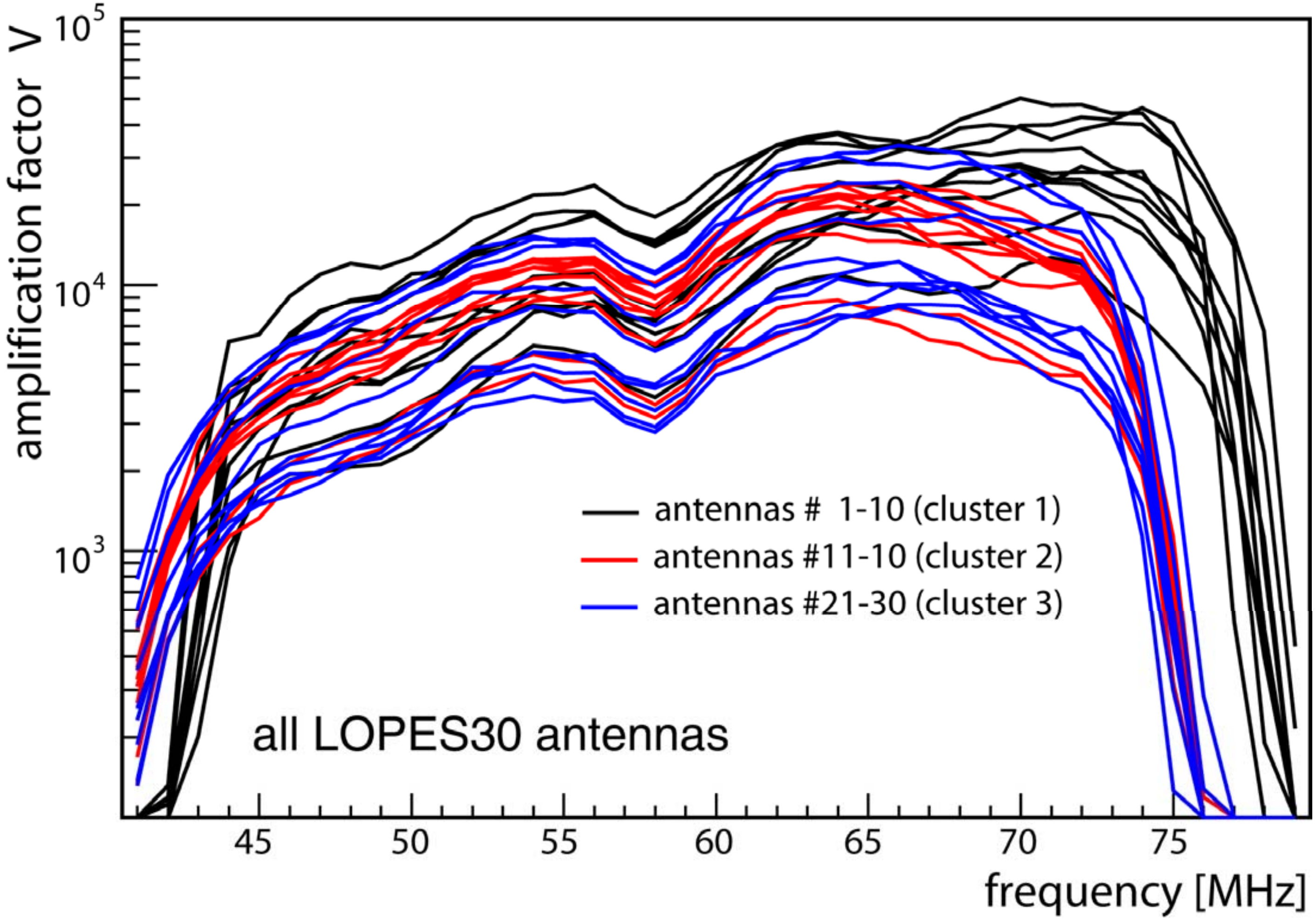


- **P_M measured antenna power**
- **P_R calculated incoming power**
- **ν emitted frequency**
- **r distance**
- **G_r gain of LOPES antenna (calculated)**
- **$G_t P_t$ gain·power of reference source (ε_{ref})**
- **β angle of aligned polarization axis**

S. Nehls et al., NIM A 589 (2008) 350

LOPES 30: absolute Calibration

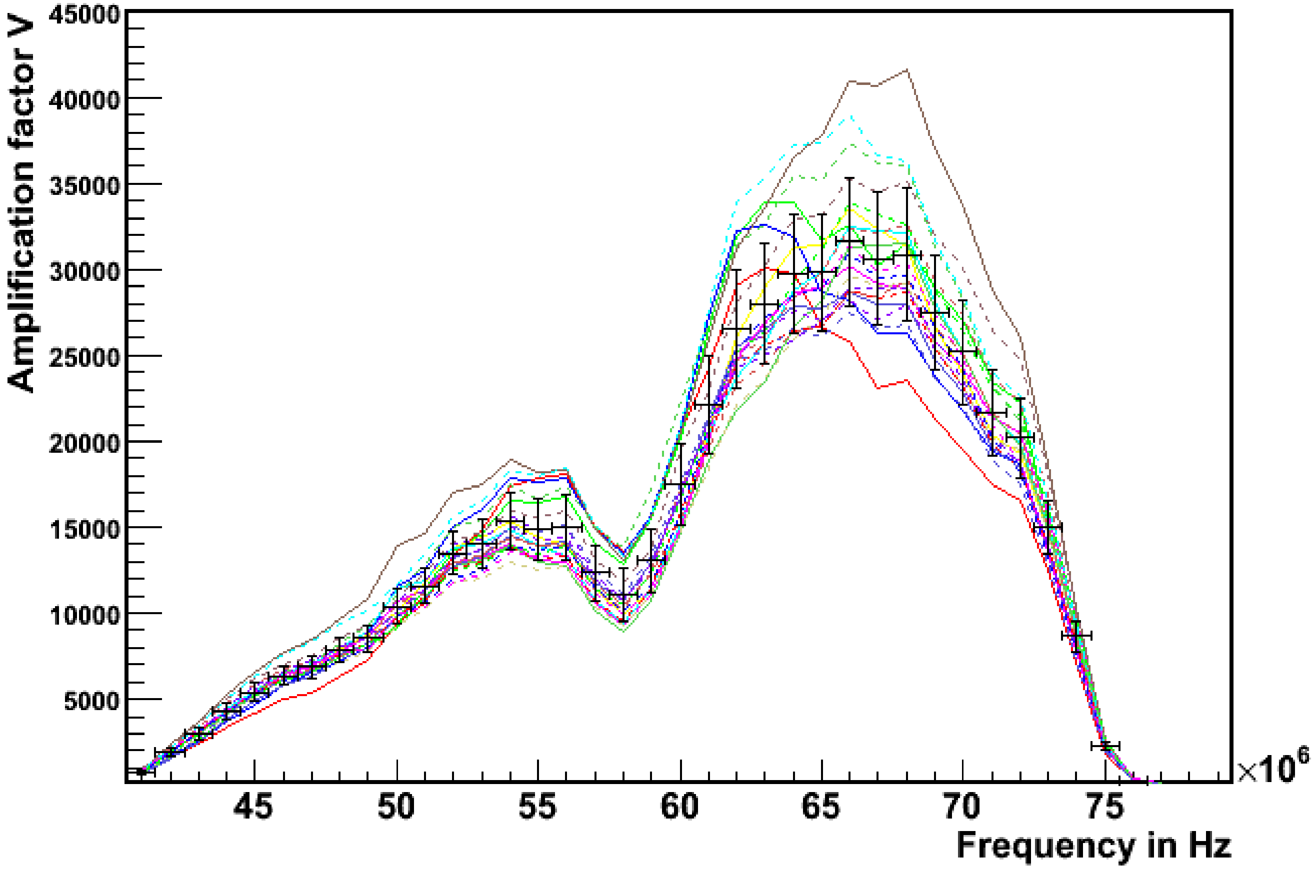
- **amplification factors $V_i(\nu)$ = correction factors at the analysis**



S. Nehls et al., NIM A 589 (2008) 350

LOPES 30: absolute Calibration

- amplification factor for one antenna (2 years)
- uncertainty by environmental conditions ~13%



LOPES 30: absolute Calibration

- statistical uncertainty is small: 1.5%

- systematic uncertainties:
  - distance σ_r: 0.25 m (~ 2.5%)
  - frequency σ_ν: 600 Hz (< 0.5%)
  - reference source: 6% for temperature stability
  - gain simulation G_r: ~15%
  - measured power P_M: ~5%
  - polarization angle β: ~2%
  - environmental effects: ~13%

- 67% for systematic in calibration of reference source

  ← a fixed value for all events and all antennas

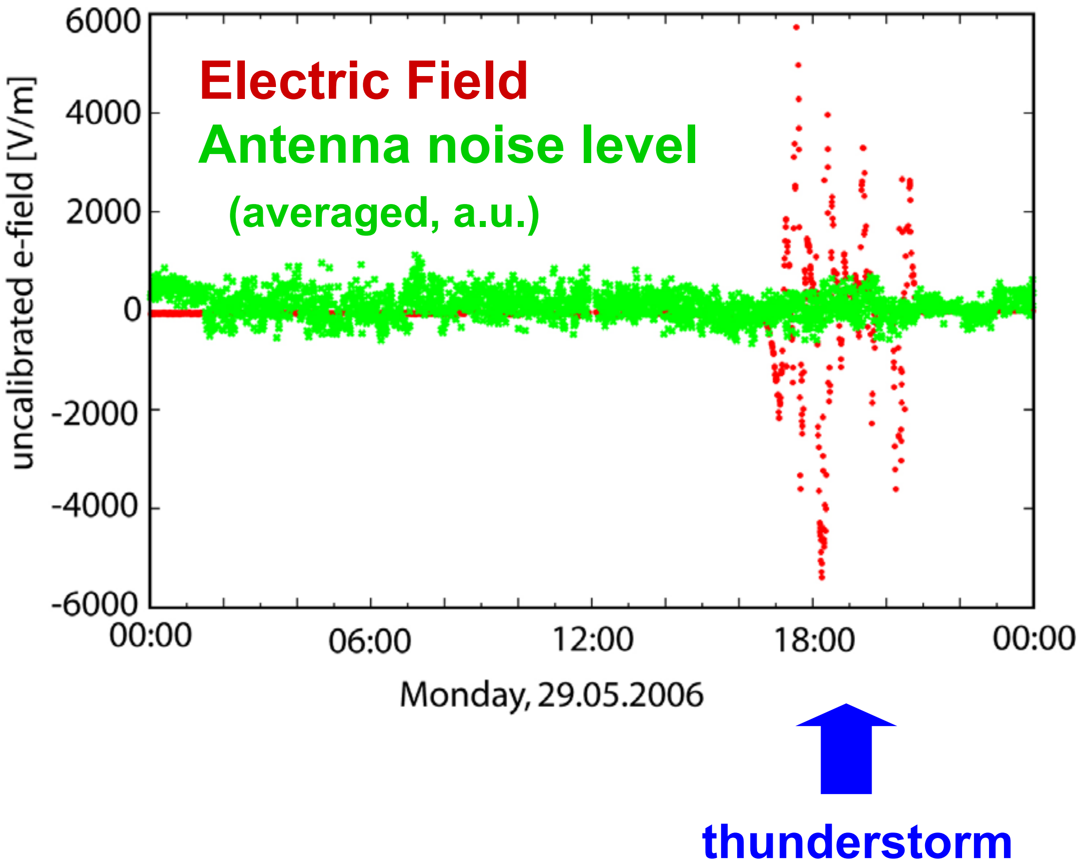
$$(\sigma_V/V)^2 = (0.015)^2 + (0.205)^2 + (0.67)^2 \rightarrow 70\%$$

uncertainty in power

LOPES 30: environmental monitoring

Correlations with signal and noise level of:
- **humidity**
- **temperature**
- **pressure**
- **electric field**
- **lightning detection**
- **rain fall**
- **….**

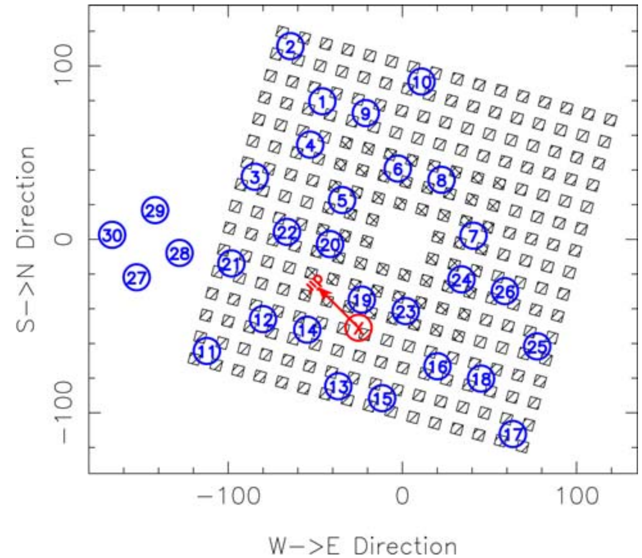
Electric Field Mill:



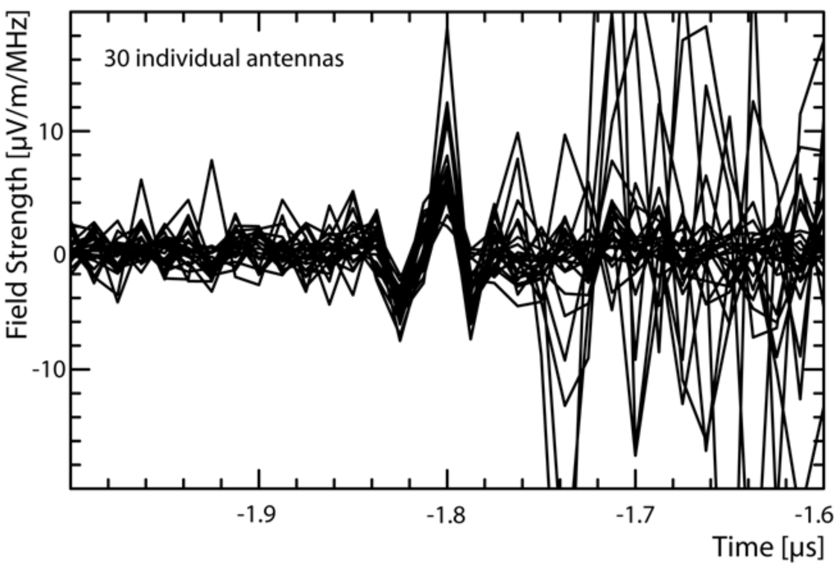
Isar, Nehls et al. – LOPES collaboration, ARENA 2006

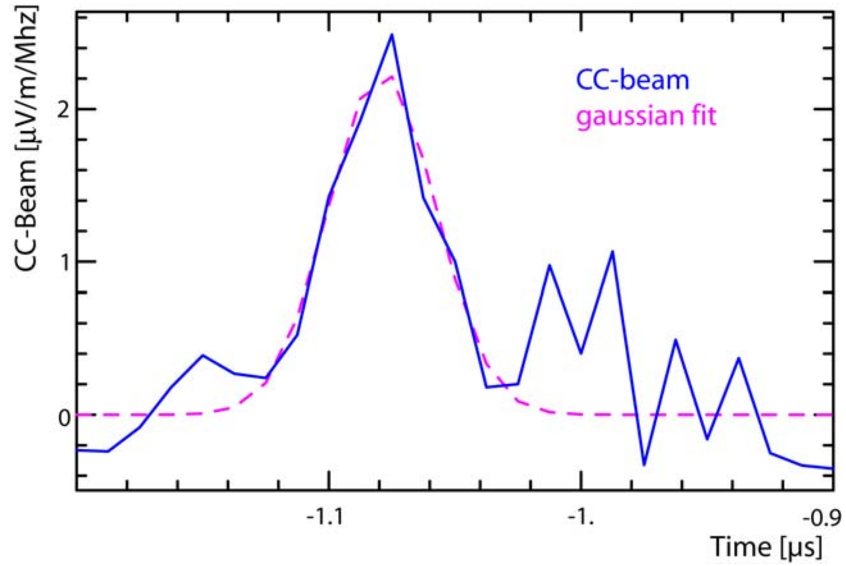
LOPES 30 event example

- **radio reconstruction inclusive calibration factors of antennas**

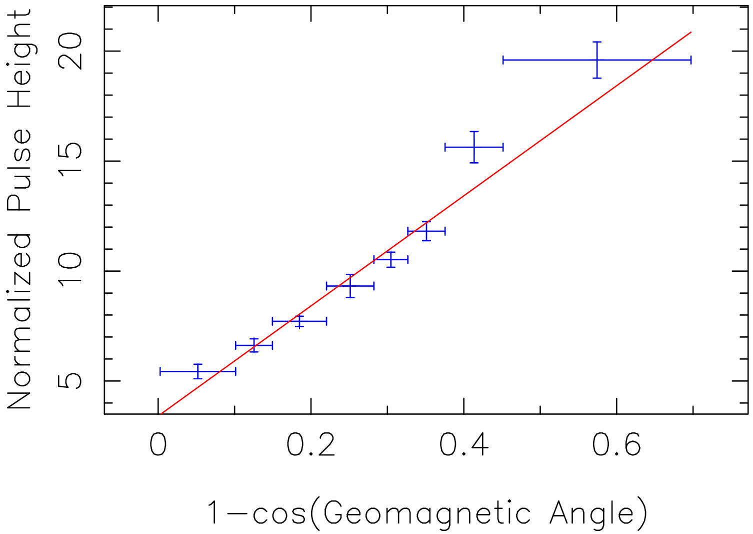


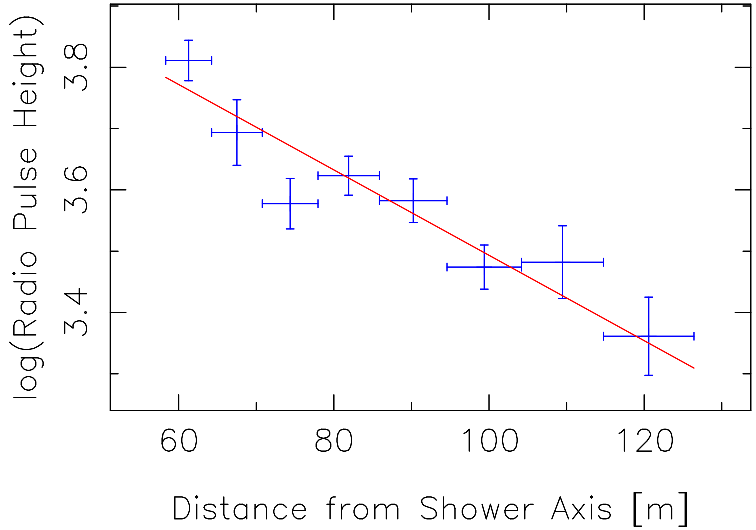
Event:
Φ = 15° θ = 306°
core = in KASCADE
$lg(N_e) \sim 7.4$
$lg(N_\mu) \sim 6.0$
$E_0 \sim 1.6 \cdot 10^{17}$ eV

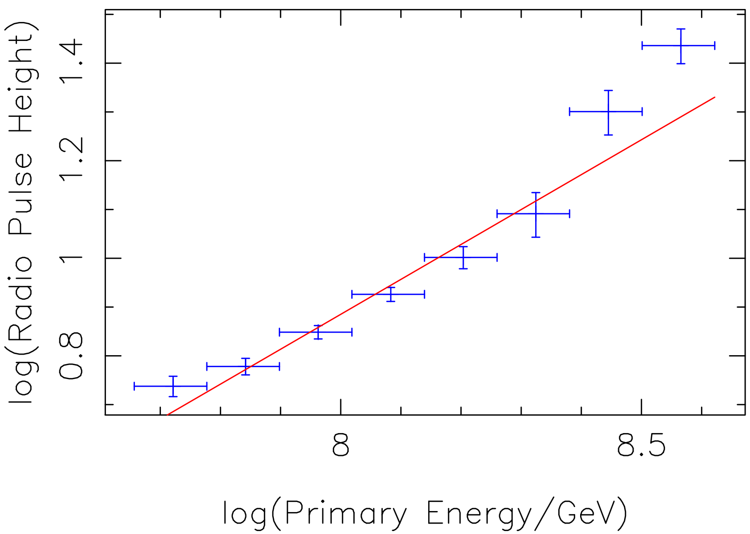




LOPES 30 results (parameterization):







$$\varepsilon_{est\text{-}EW} = A \bullet (1 + B - \cos\alpha) \bullet \cos\theta \bullet \exp(-R/R_0) \bullet (E/\ 10^{17}\mathrm{eV})^{\gamma}$$

[μV / m MHz]

$A = 10.9 \pm 1.1$

$B = 1.16 \pm 0.02$

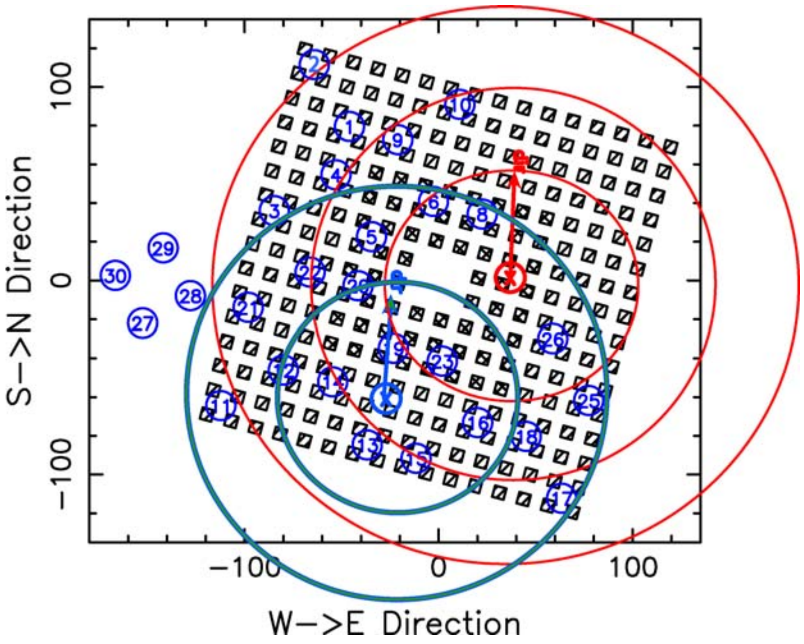
$R_o = 202 \pm 64$ m

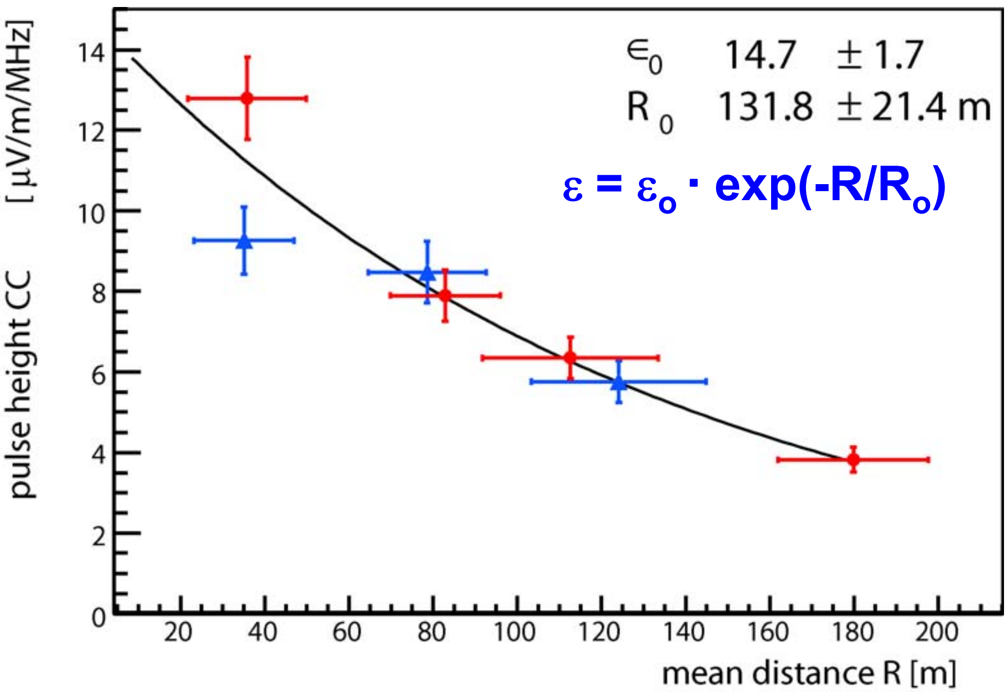
$\gamma = 0.94 \pm 0.03$

A.Horneffer, LOPES coll, ICRC 2007

LOPES 30: lateral behaviour

- **30 antennas: several time beam forming possible**





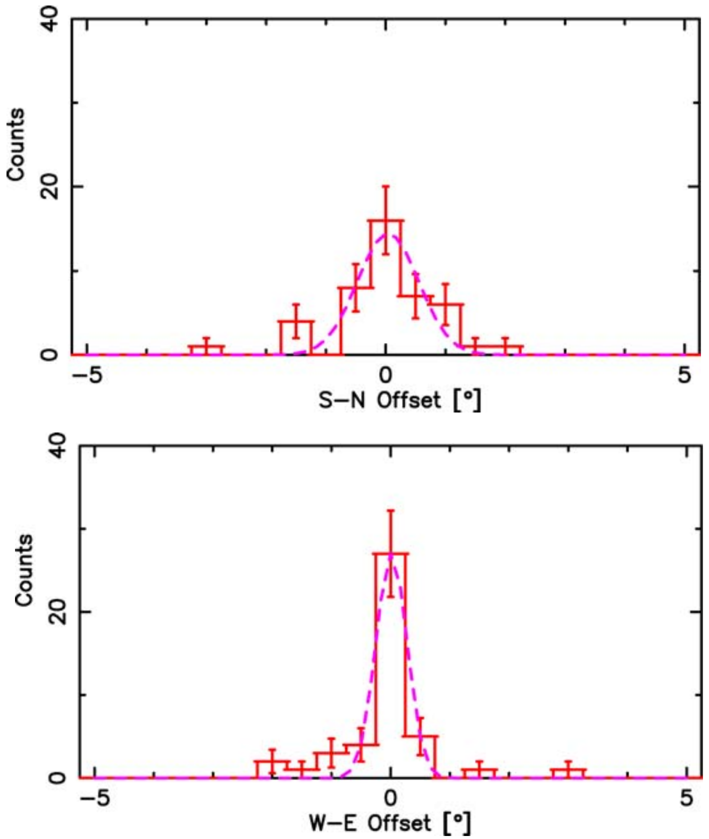
$\log N_e$ = 7.26 $\log N_\mu$= 5.95
E_0 = 2.6 10^{17} eV,
ϕ= 2.3°, θ= 24.0°
CC = 6.8 ± 0.6 µV/m/MHz

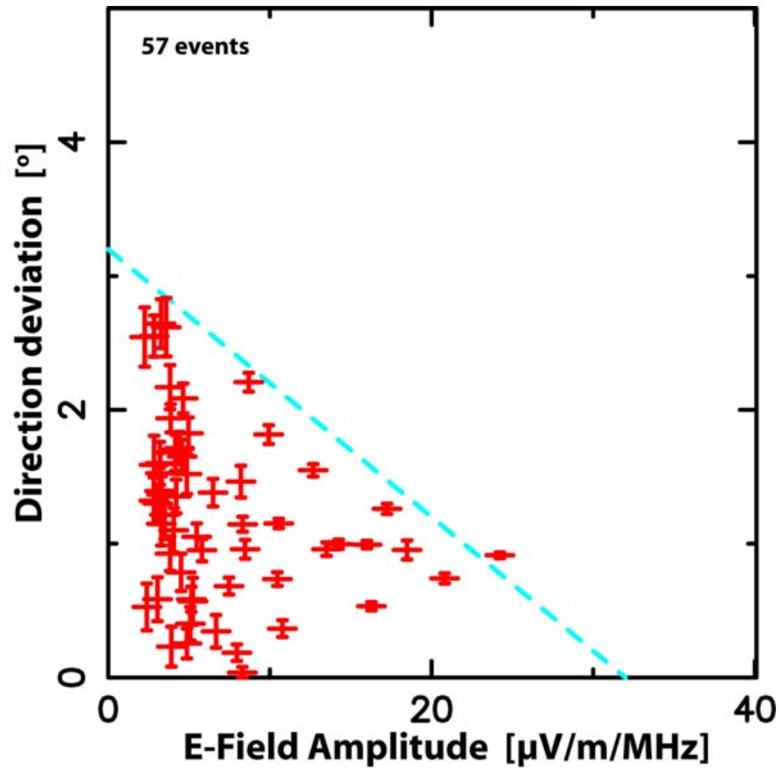
$\log N_e$ = 7.27 $\log N_\mu$= 5.91
E_0 = 2.4 10^{17} eV,
ϕ=4.9°, θ= 23.8°
CC = 6.5 ± 0.8 µV/m/MHz

Nehls et al. – LOPES collaboration, 30th ICRC, Mexico, 2007

LOPES 30: direction resolution

- **KASCADE vs. LOPES direction:**
  deviation = (1.3±0.8)° ➔ resolution better 1°
- **better with increasing field strength**
- **remark: CC-beam fit assumes spherical wave front (direction depend on it)**



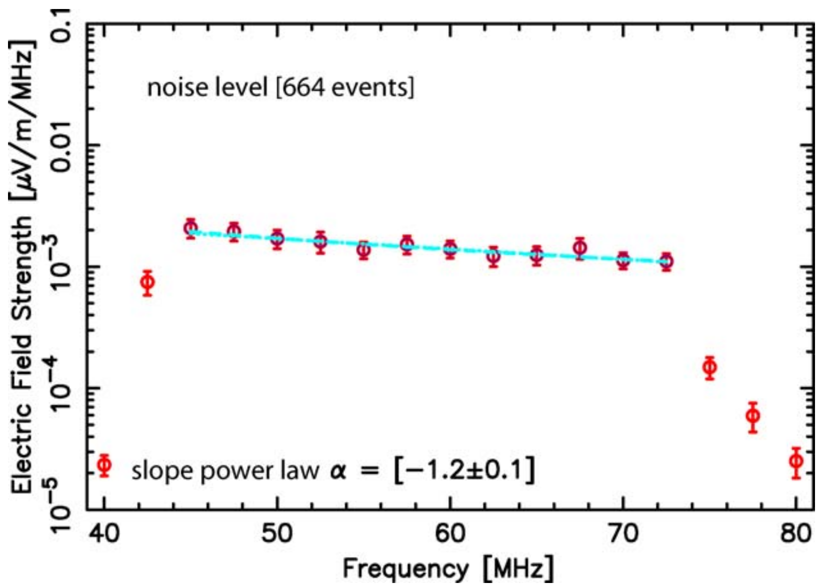


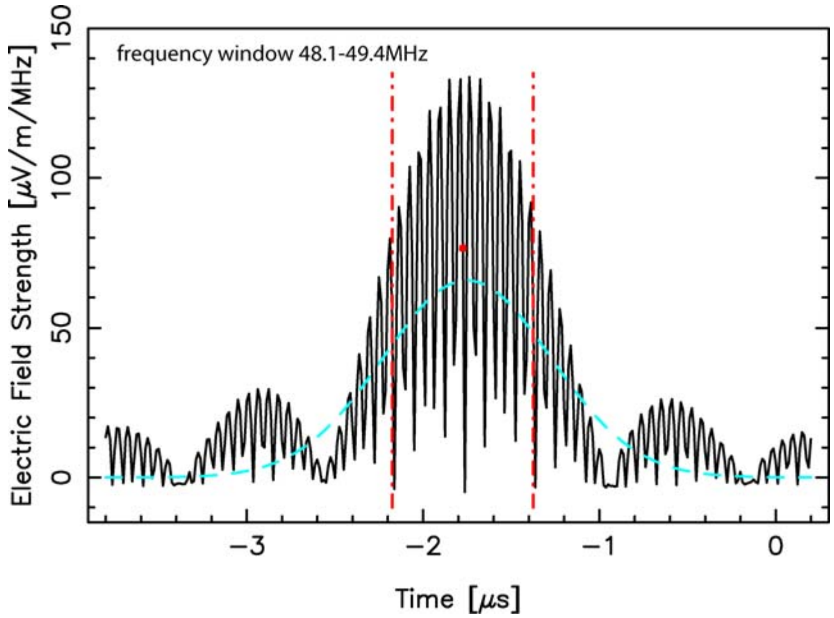
A. Nigl et al. – LOPES collaboration, A&A 2008 submitted

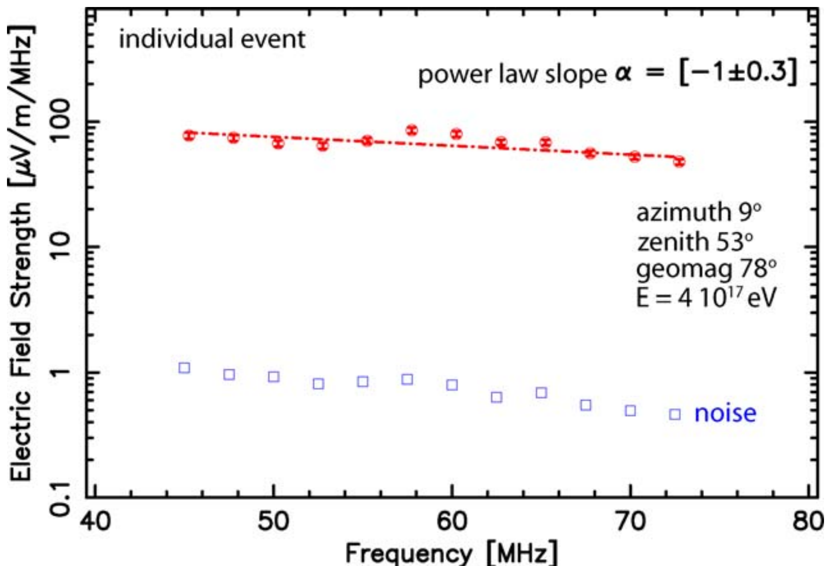
LOPES 30: frequency spectrum

Determination of frequency spectra:

- **methods: sub-band filtering and Fourier transformation of beam-formed data**
- **noise correction**

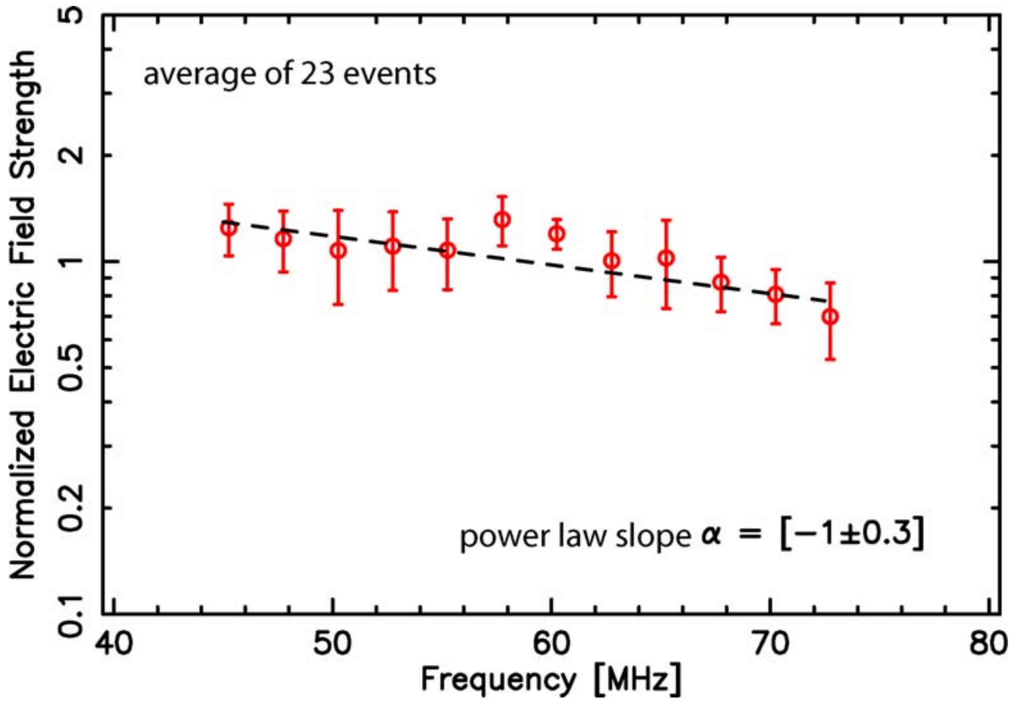






A. Nigl et al. – LOPES collaboration, A&A 2008 submitted

LOPES 30: frequency spectrum



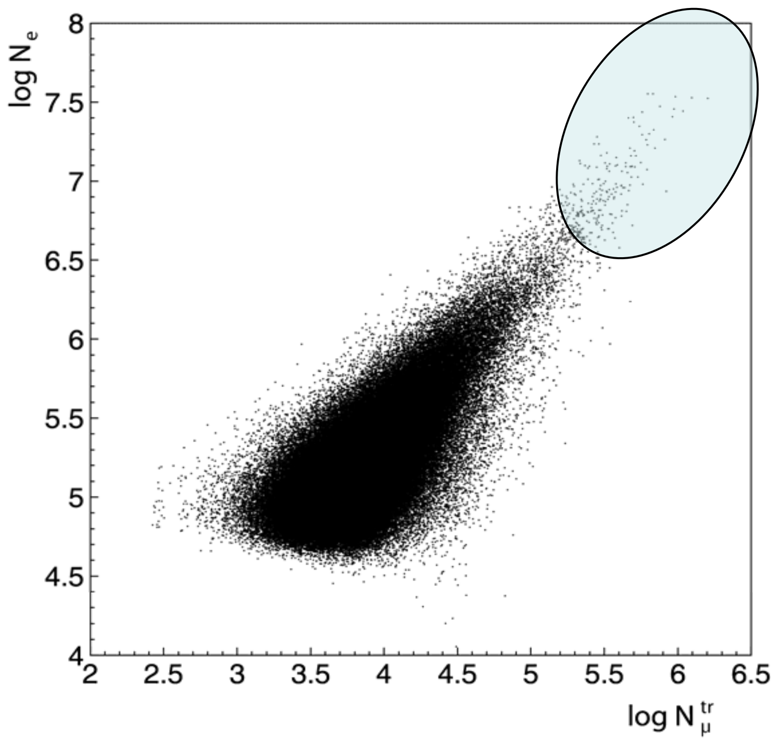
- **frequency spectrum falls off to higher frequencies**
- **fit possible by power law or exponential function – negative slope**
- **no dependence on shower parameters (direction, energy, distance)**

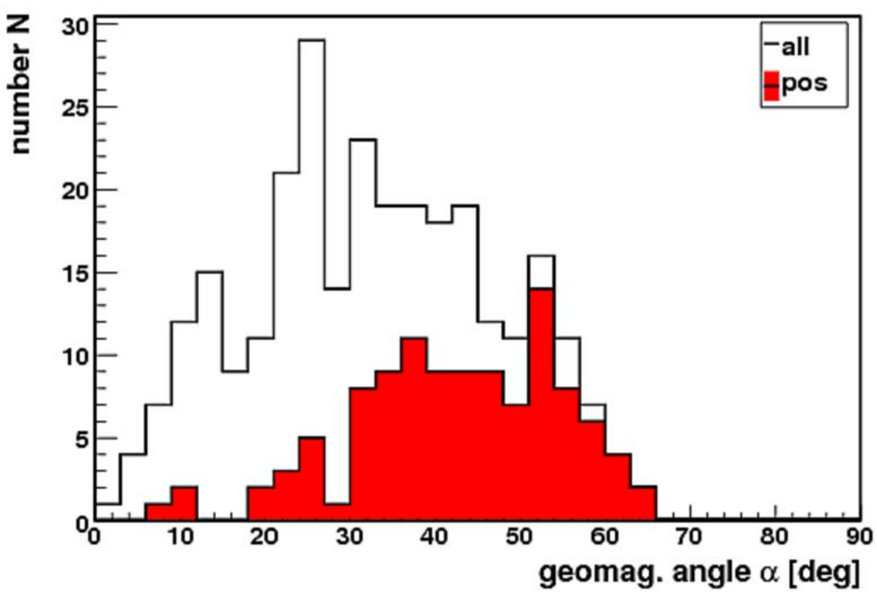
A. Nigl et al. – LOPES collaboration, A&A 2008 submitted

LOPES 30: lateral distribution

Determination of the lateral distribution of the radio emission:

- **on an event-by-event basis**
- **selection: high energy, good CC-beam, S/N>1 for each individual antenna**
  ➔110 events
- **needed: up-sampling technique**

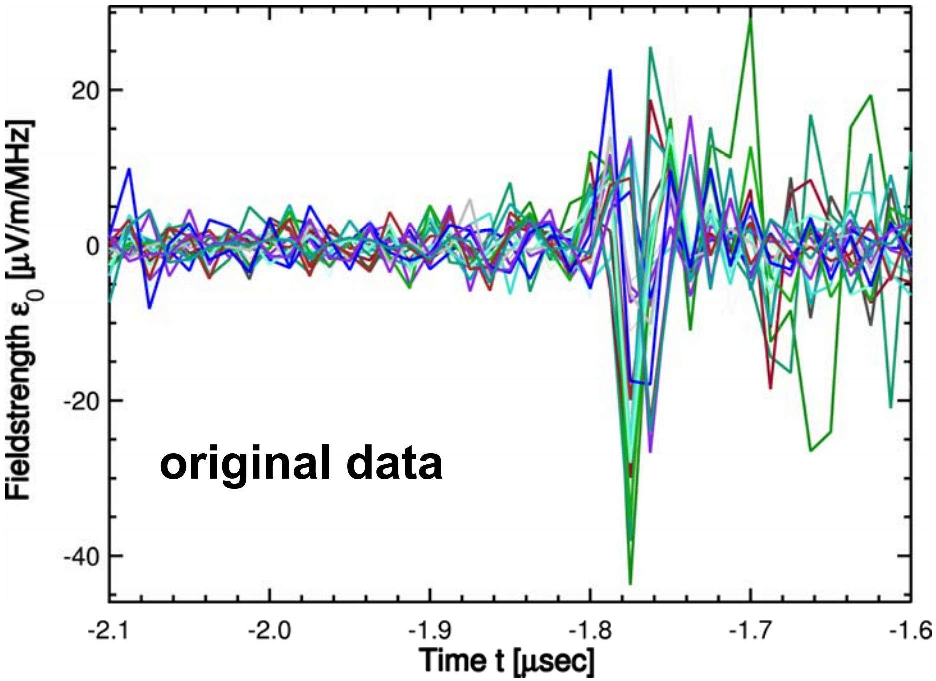


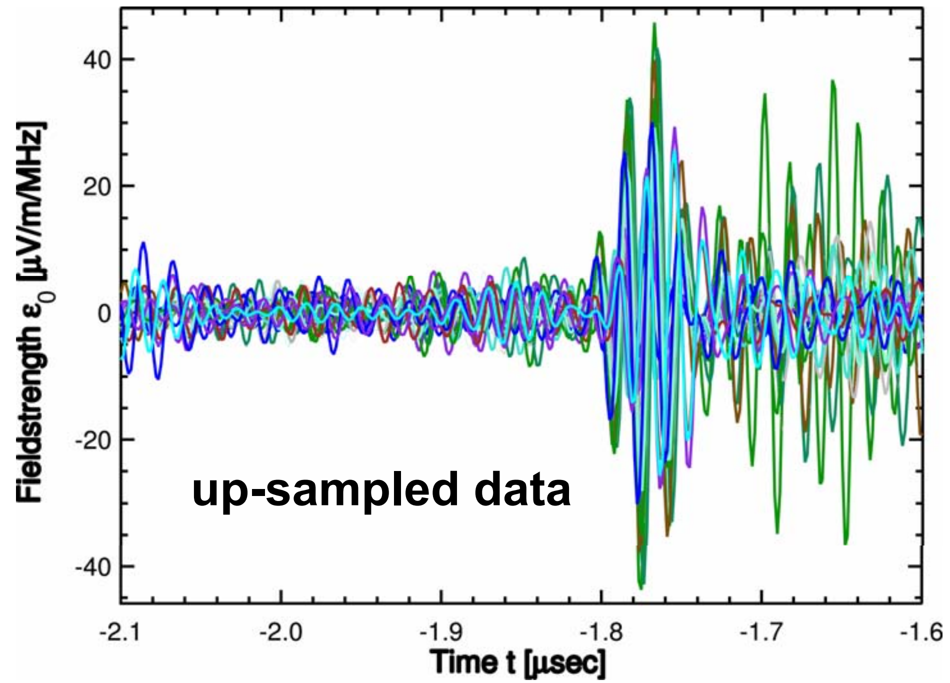


S. Nehls et al. – LOPES collaboration, PhD-thesis 2008 next week!

LOPES 30: up-sampling

- reconstruction of original signal shape from raw data, which are sampled in the 2nd Nyquist domain
- using zero padding in frequency domain
- applying background (noise) correction

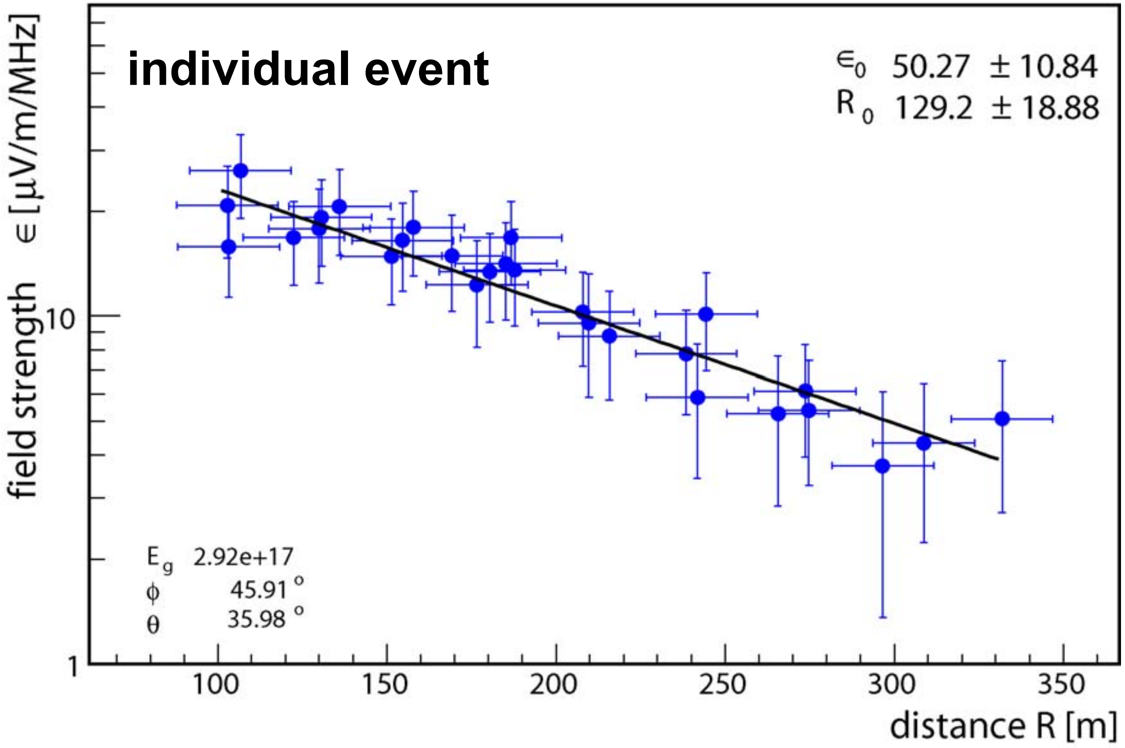




S. Nehls et al. – LOPES collaboration, PhD-thesis 2008 next week!

LOPES 30: lateral distribution

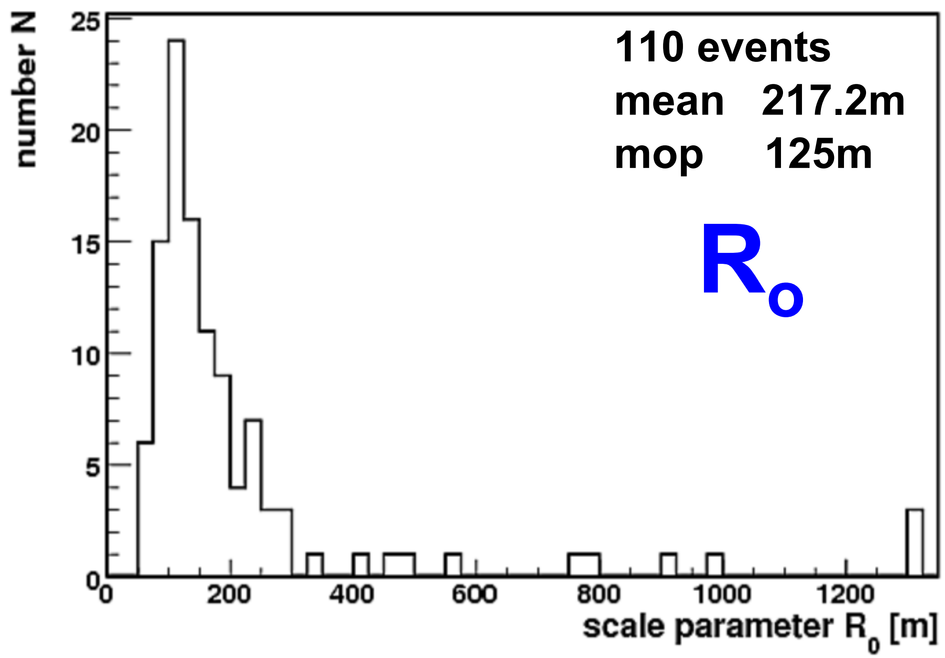
- use of KASCADE-Grande reconstruction of shower core position
  ➔ antenna distance R to shower core
- systematic uncertainty from calibration and noise correction
- fit of exponential function $\varepsilon = \varepsilon_o \cdot \exp(-R/R_o)$
  ➔ scale parameter R_0 and field strength (in core) ε_o

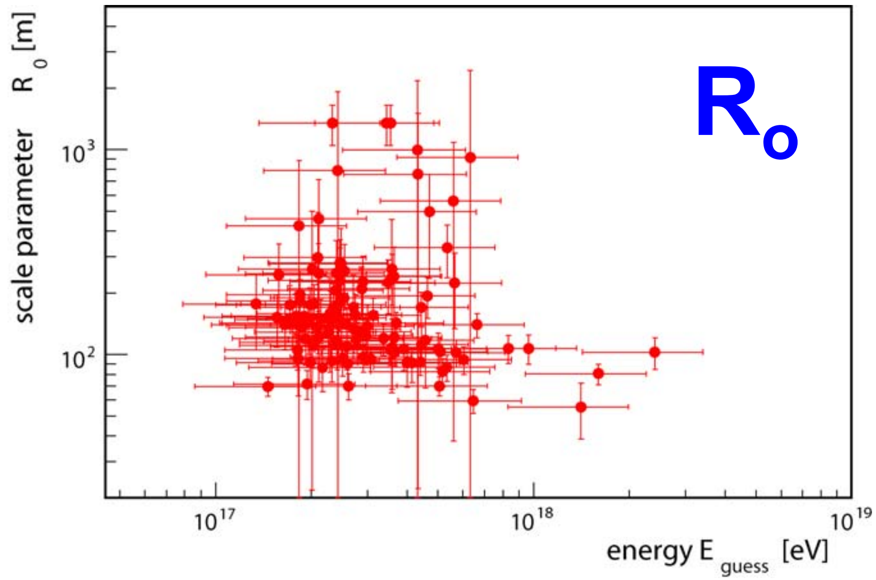


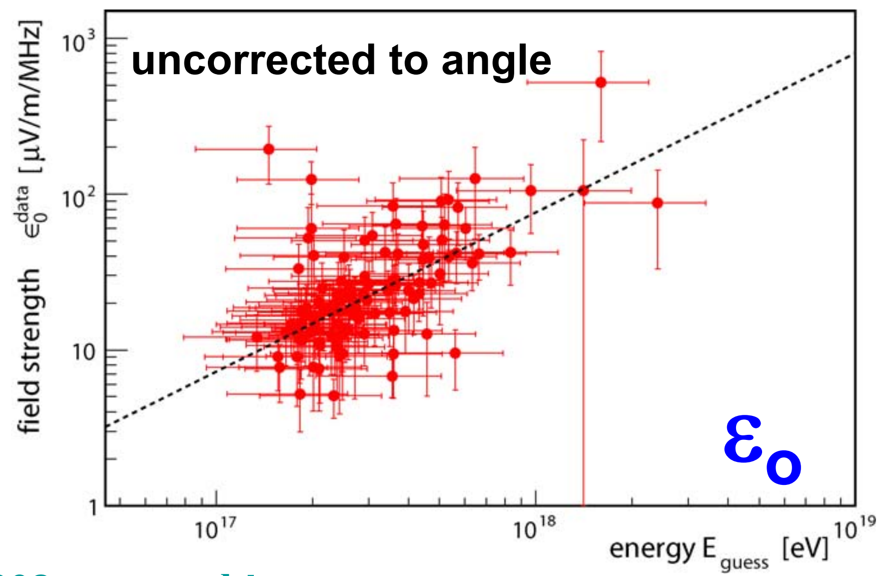
S. Nehls et al. – LOPES collaboration, PhD-thesis 2008 next week!

LOPES 30: lateral distribution

-scale parameter R_0 !
~ 10% of EAS have flat behaviour
mostly at large zenith angles, respectively large angle to geomagnetic field



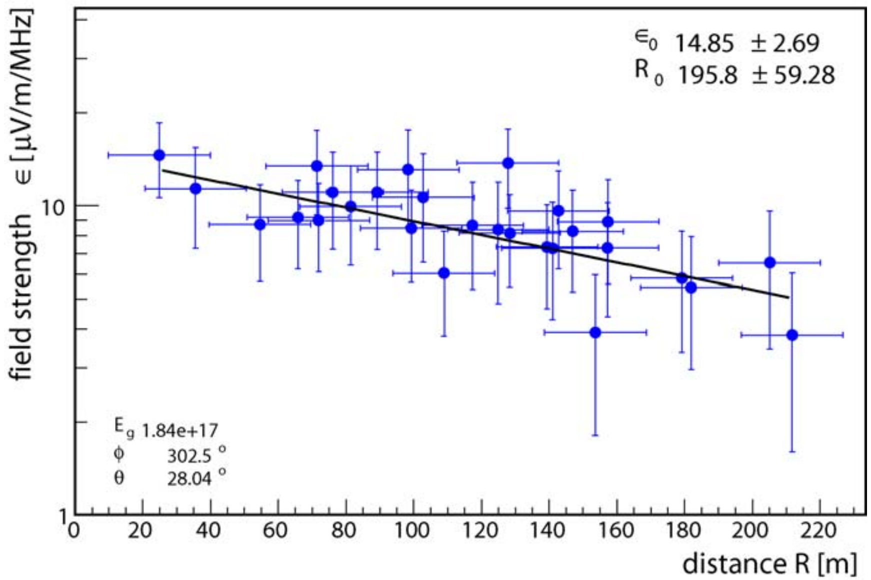


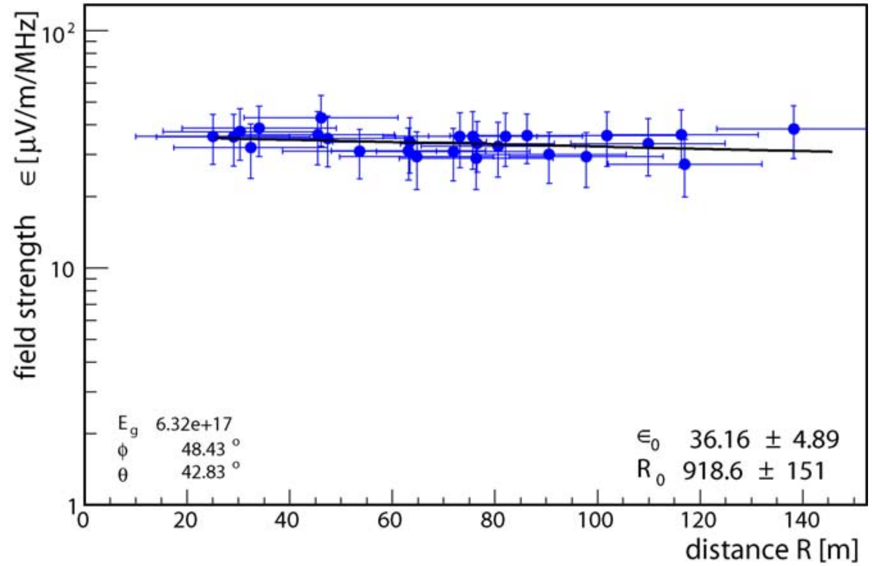


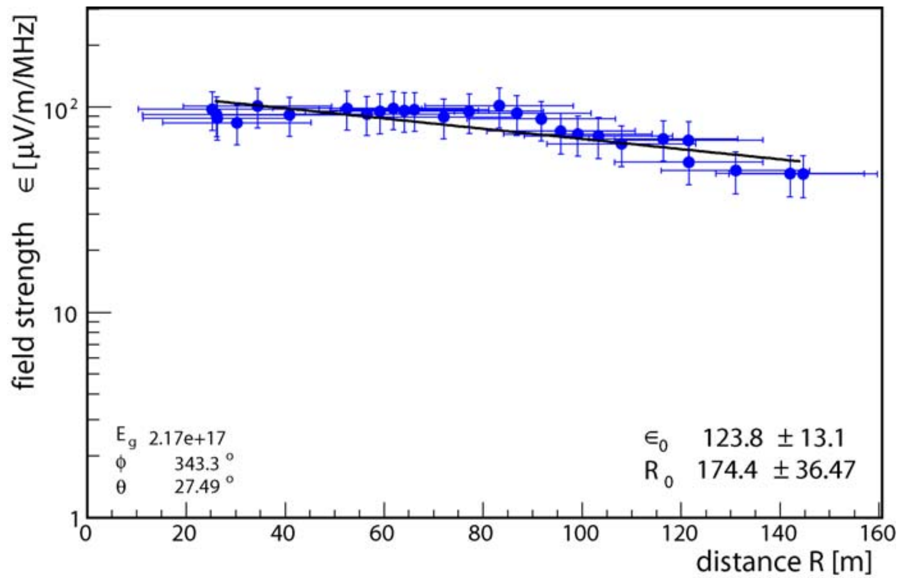
S. Nehls et al. – LOPES collaboration, PhD-thesis 2008 next week!

LOPES 30: lateral distribution

-some more examples
(remember: all measurements with east-west oriented antennas only)





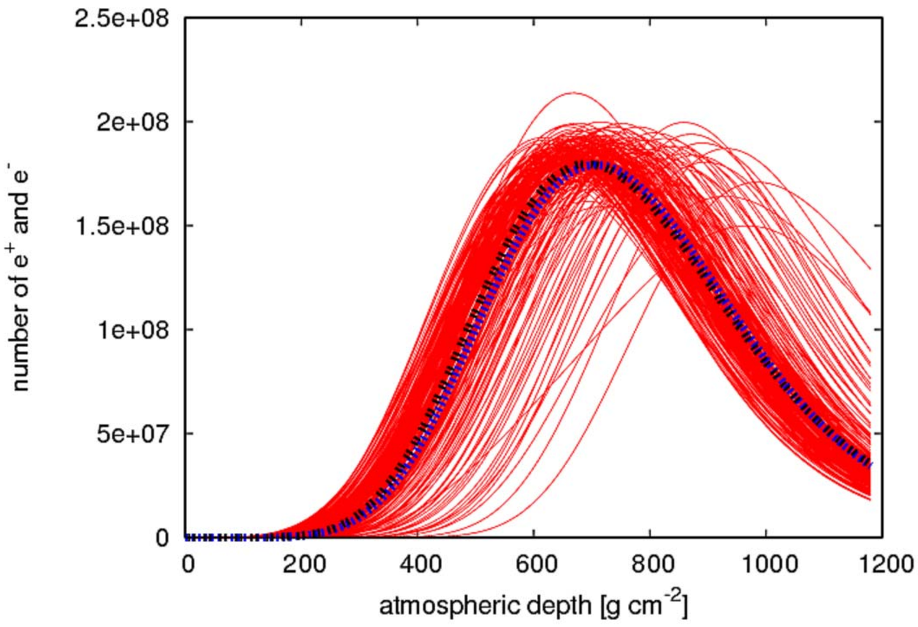


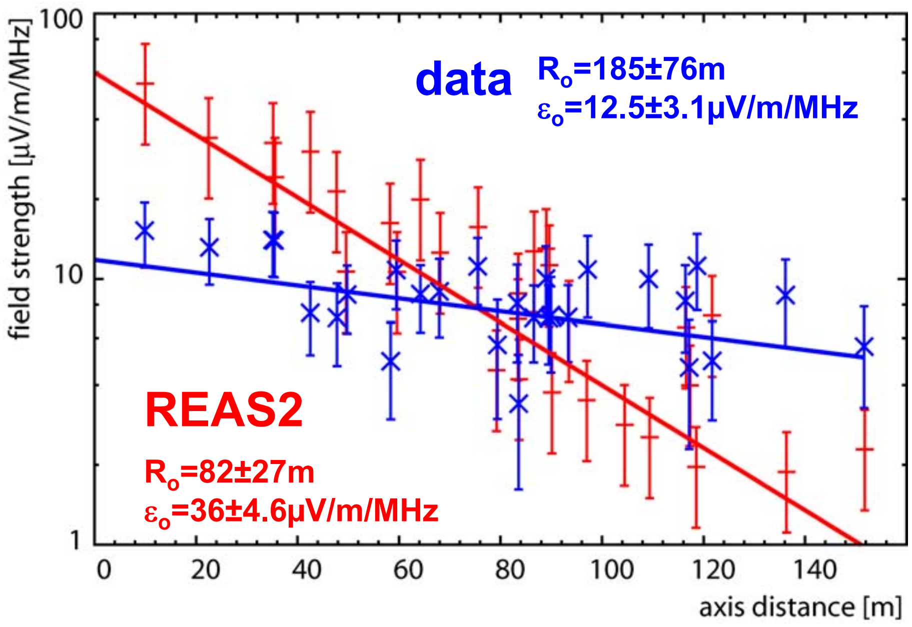
S. Nehls et al. – LOPES collaboration, PhD-thesis 2008 next week!

lateral distributions vs. simulations

- **REAS2: CORSIKA based Monte Carlo simulations of radio emission**
- **performed for individual shower by using KASCADE parameters**
- **250 CONEX shower ➔ for one „typical“ full REAS2 simulation**

➔Expected field strength per antenna position of LOPES30





ev# 1143070602 x_c = -44.3m y_c= -22m E_0 = 2.3 10^{17} eV ϕ=19.3° θ= 5.9°

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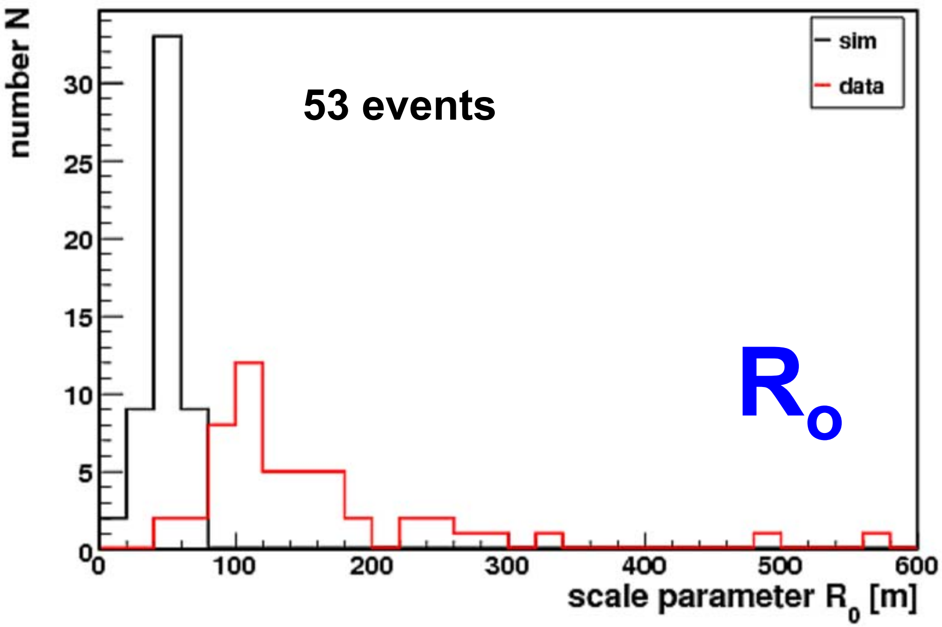
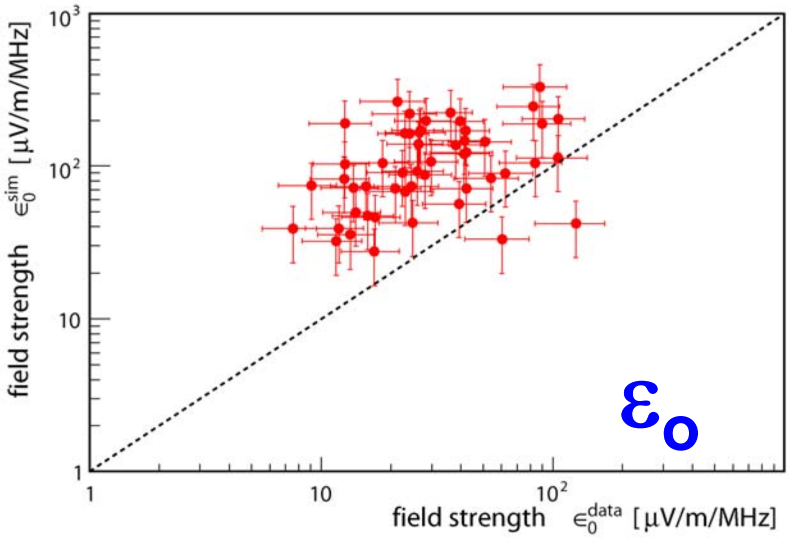
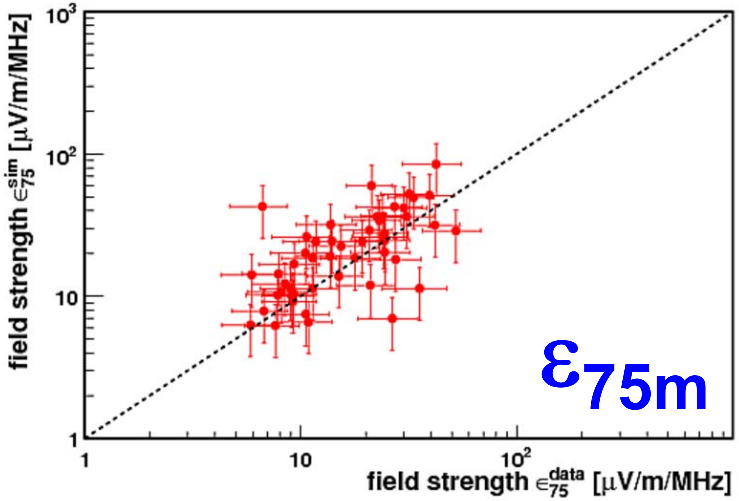
lateral distributions vs. simulations

- simulations predict systematically smaller scale parameters
- no flat distributions obtained







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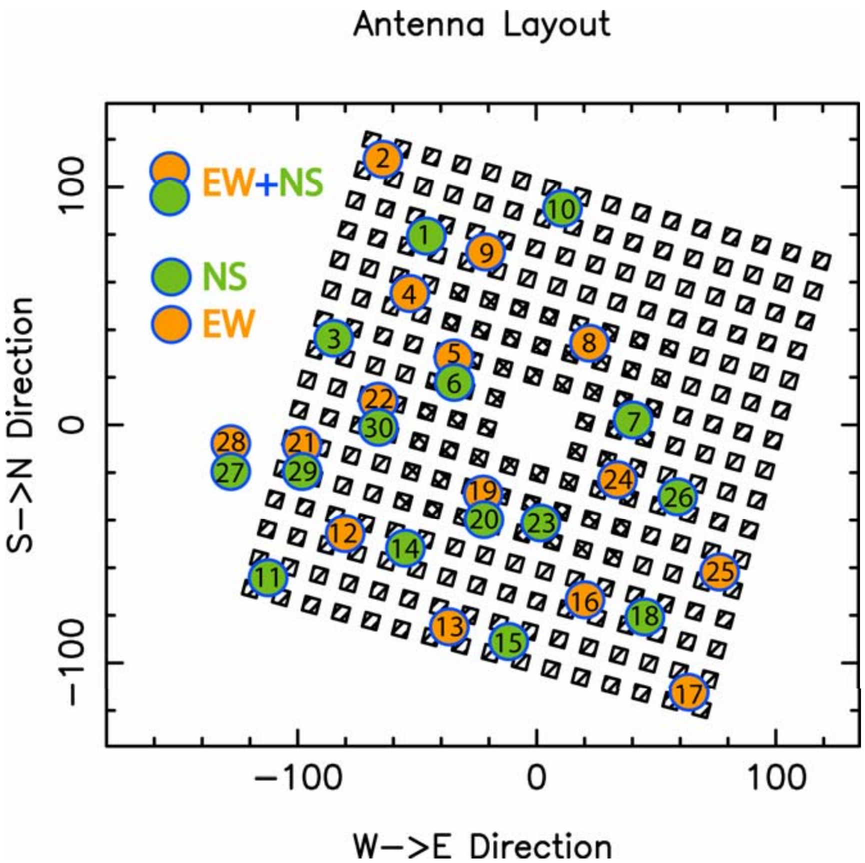
LOPES 30: polarization measurements

December 2006: re-configuration to perform measurements for E-W and N-S polarization of radio emission



G. Isar, ARENA 2008, this afternoon!

G. Isar et al. – LOPES collaboration, 30th ICRC, Mexico, 2007

Summary of (some) LOPES results

<u>**main goal of LOPES:**</u>

understanding of the radio emission and all its correlation with EAS parameters!

- **Radio signal (electric field) scales with primary energy:** $\varepsilon \sim E_0^{\gamma}$ ($\gamma \sim 1$)

Simulations: E-field scales approx. linearly with E_0 ➔ proof of coherence

- **Radio signal scales with geomagnetic field:** $\varepsilon \sim \cos \alpha$?

Simulations: separate dependence expected: on geomagnetic (Earth magnetic field); on zenith (footprint broadening & elongation); on azimuth (polarization effects)

- **Radio signal scales with core distance:** $\varepsilon \sim \exp(-R/R_0)$ (R_0~100-200m)

Simulations: approx. exponential scaling R_0 ~ 20 to 100 m, ε_{75m} okay!!

- **Frequency spectrum is a decreasing power law (or exp)** $\varepsilon \sim \nu^{\delta}$ ($\delta \sim -1$)

Simulations: spectrum decreasing exponential (for 40-80MHz also power law possible)

- **Radio signal is polarized and polarization vector azimuth dependent**

Simulations: Radio signal is polarized and polarization vector azimuth dependent

Conclusions LOPES

• Successful cooperation of Radio Astronomy and Astroparticle Physics groups

• LOPES 10:

➔ large sample of radio detected showers

➔ detailed analyses: results are in agreement with simulation

➔Proof of Principle

• LOPES 30

➔ absolute calibrated, higher energies, longer maximum baseline, polarization

➔ direct comparison of simulations with measurements on event-by-event basis

➔Precision measurements for energies up to 10^{18}eV

• LOPES^{STAR}

➔ autonomous system, self-trigger system, test facility for Auger application

➔Optimization for large scale application

➔LOPES will `calibrate´ the radio signal in EAS of 10^{16}-10^{18}eV (all the correlations with cosmic ray parameters)

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