Forschungszentrum Karlsruhe
in der Helmholtzgemeinschaft

Status and Perspectives of LOPES

ARENA 2006
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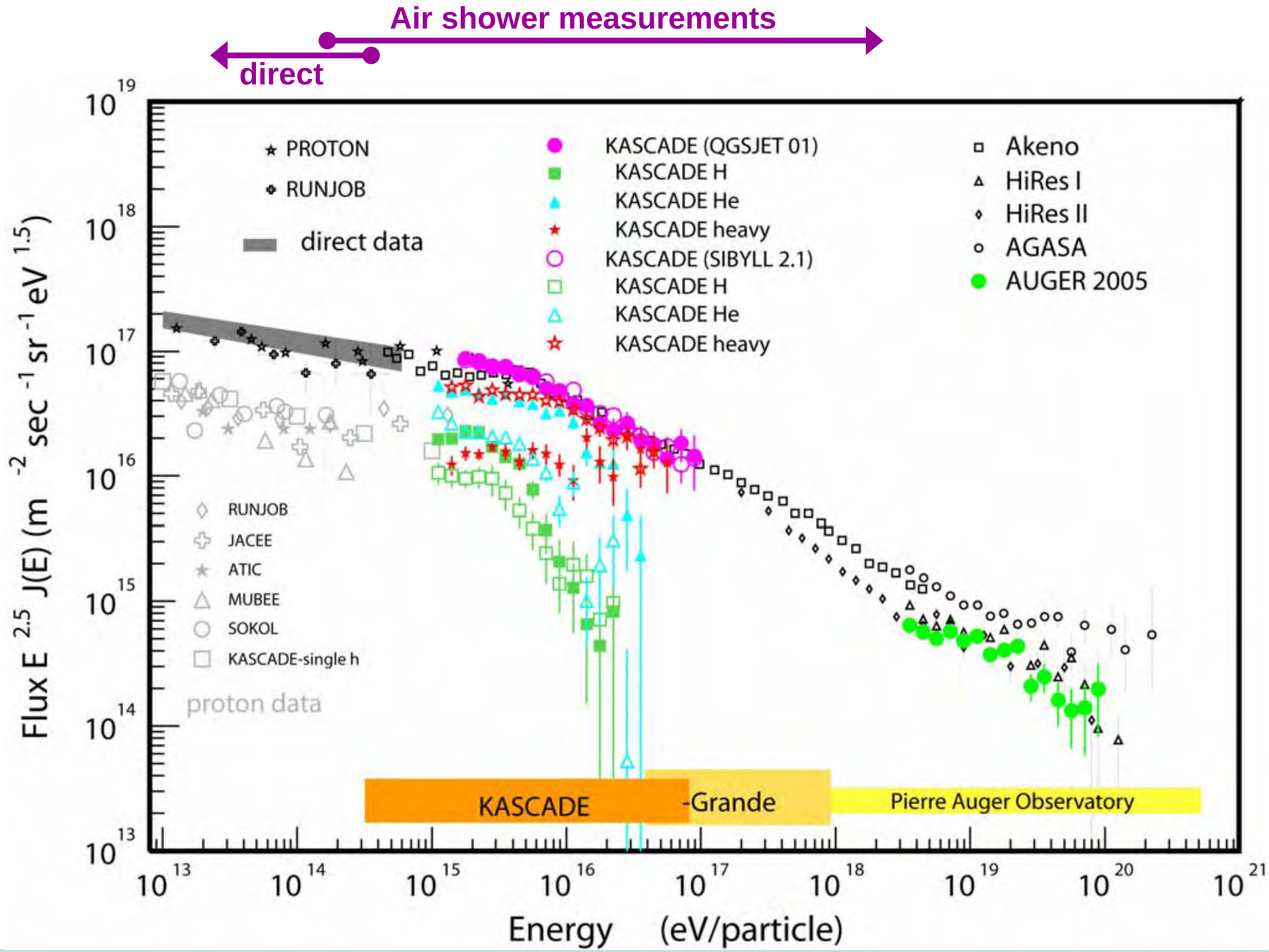
Cosmic Rays

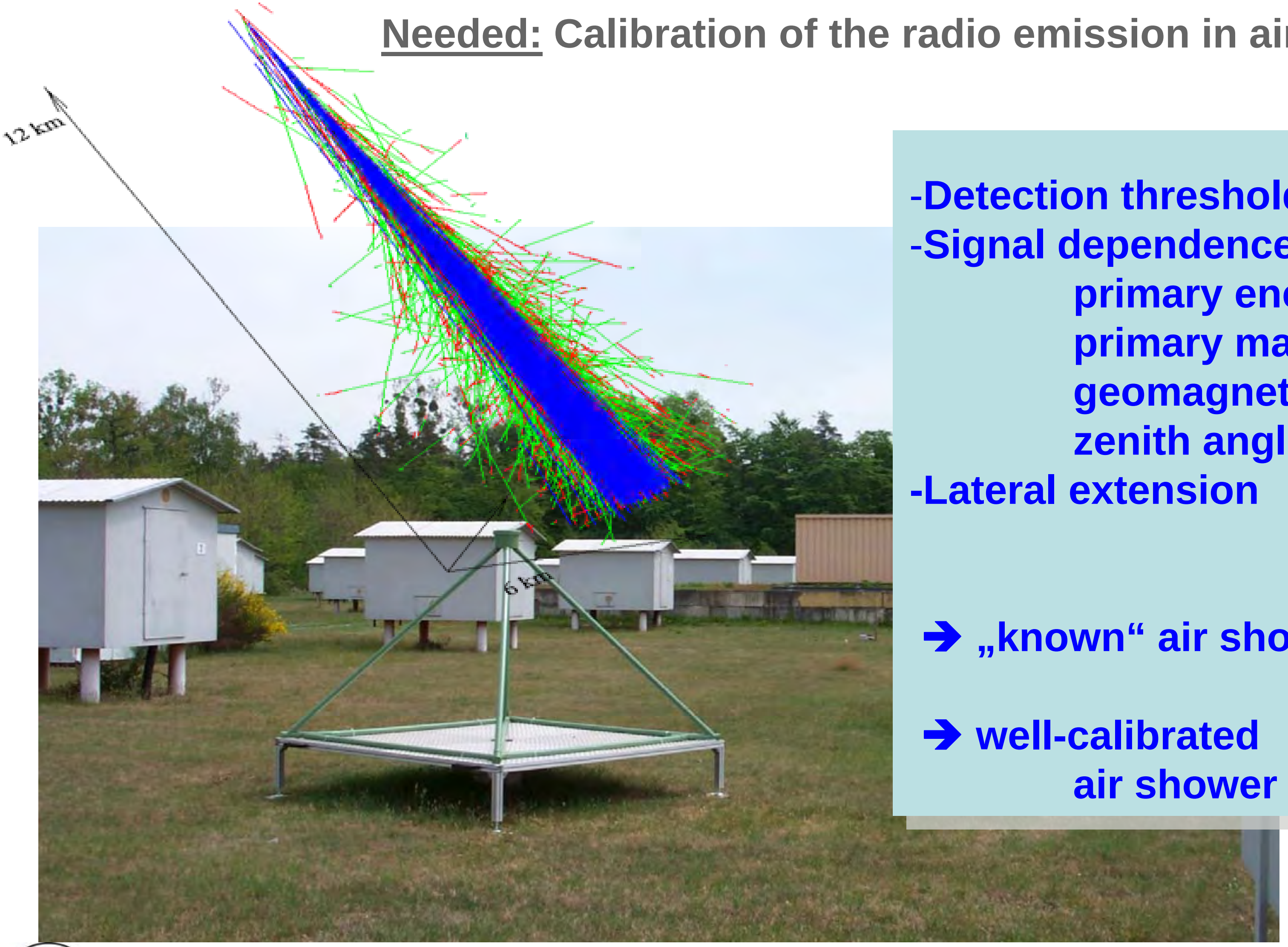


- **The cosmic ray energy spectrum is not fully understood**
- **Above 10^{14}eV primary energy: only air-shower measurements possible**

➔ 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 !



- -Detection threshold
- -Signal dependence on
  - primary energy
  - primary mass
  - geomagnetic angle
  - zenith angle
- -Lateral extension

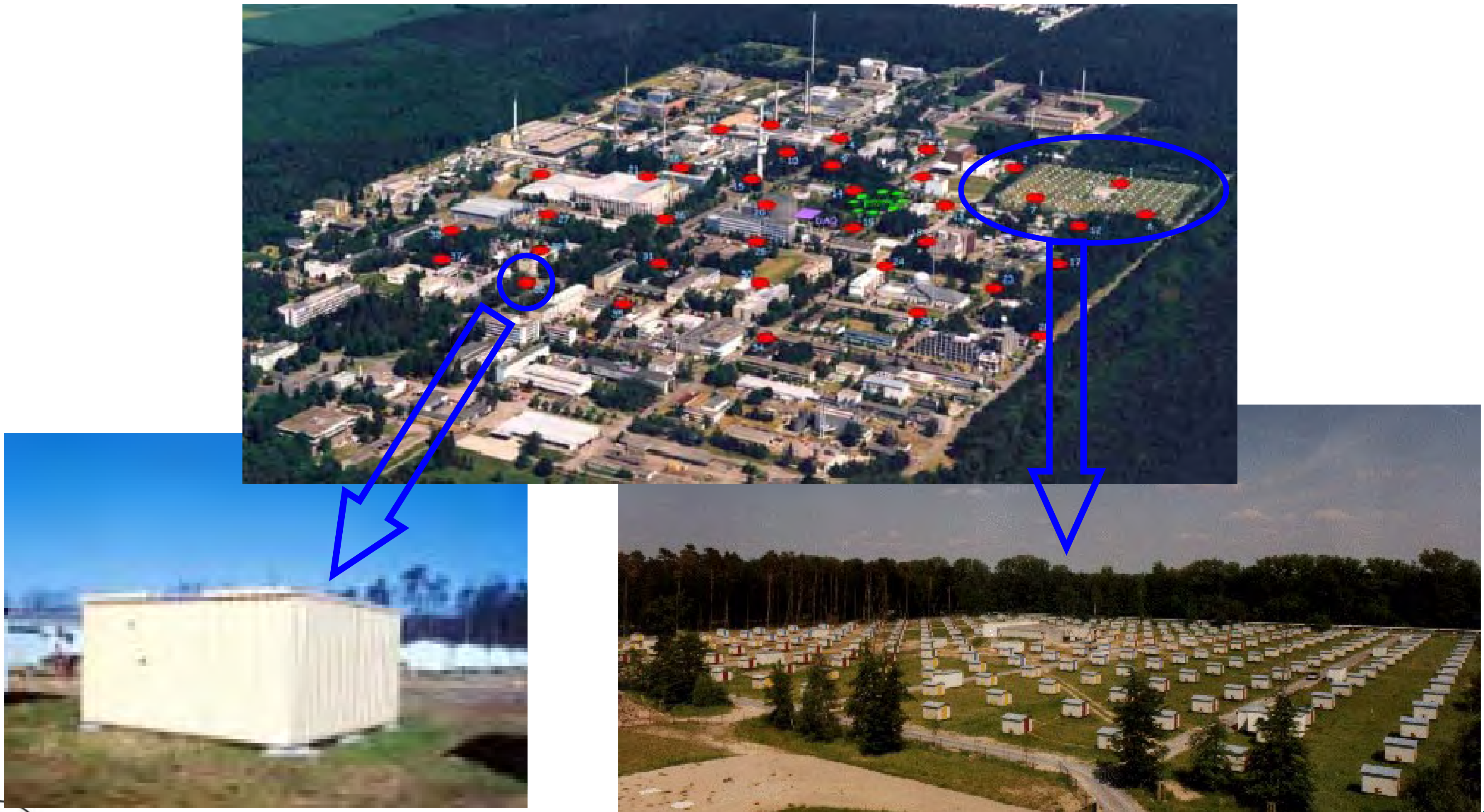
➔ „known“ air showers

➔ well-calibrated air shower experiment

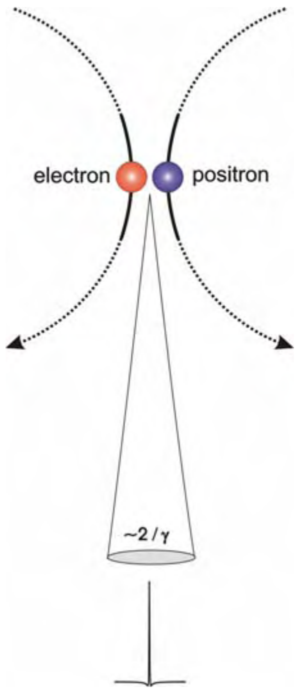
KASCADE-Grande

= KArlsruhe Shower Core and Array DEtector + Grande

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



LOPES :
Radio shower detection



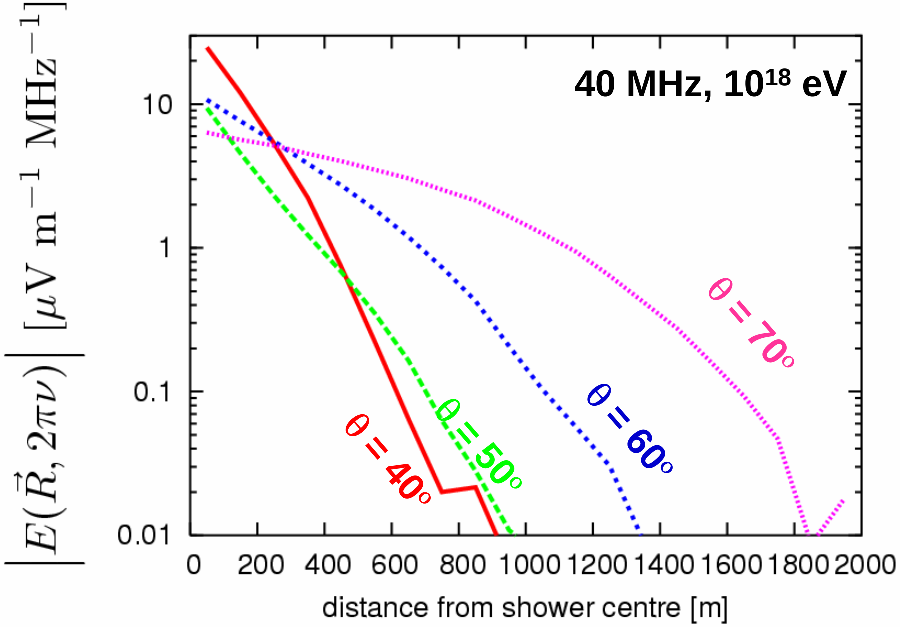
•deflection of
electron-positron pairs
in the Earth‘s magnetic field
➔coherent emission
at low frequencies

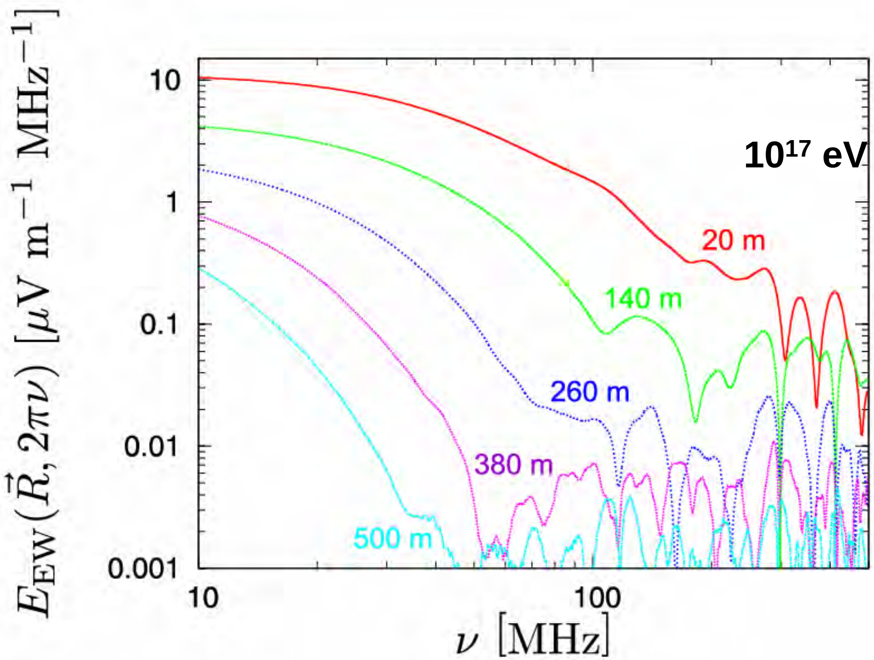
• radio detection
➔ is a calorimetric measure
➔ observe 24 hrs/day

• 30 dipole antennas at KASCADE-Grande
• calibration of radio emission
• theory of radio emission and implementation in CORSIKA
• improvement/optimisation hardware (for application in Auger/LOFAR)

Radio shower detection: Simulations

1. analytical calculation of emission processes
2. Monte Carlo simulations of radio signals
3. implementation in CORSIKA



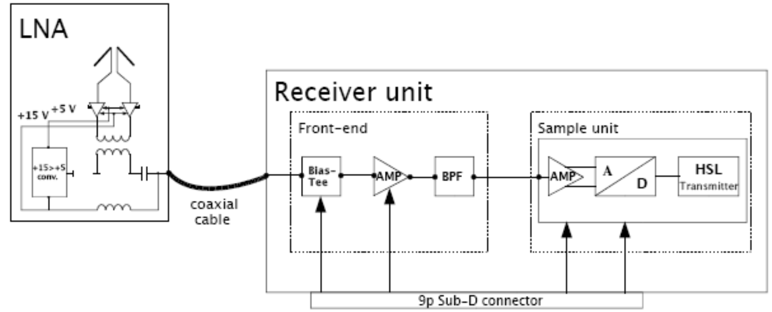


- expectations on
  - ➔ frequency spectrum
  - ➔ lateral distribution
  - ➔ polarization
  - ➔ …

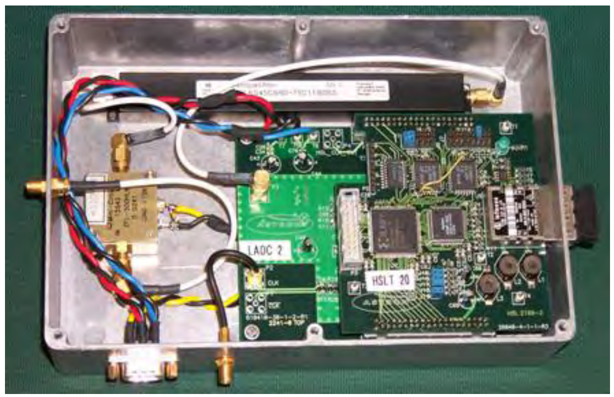
T. Huege & H. Falcke
Astrop. Phys. 24 (2005) 116

Hardware of LOPES:

LOPES-Antenna
Receiver Module
Memory Buffer
Clock and Trigger Board



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

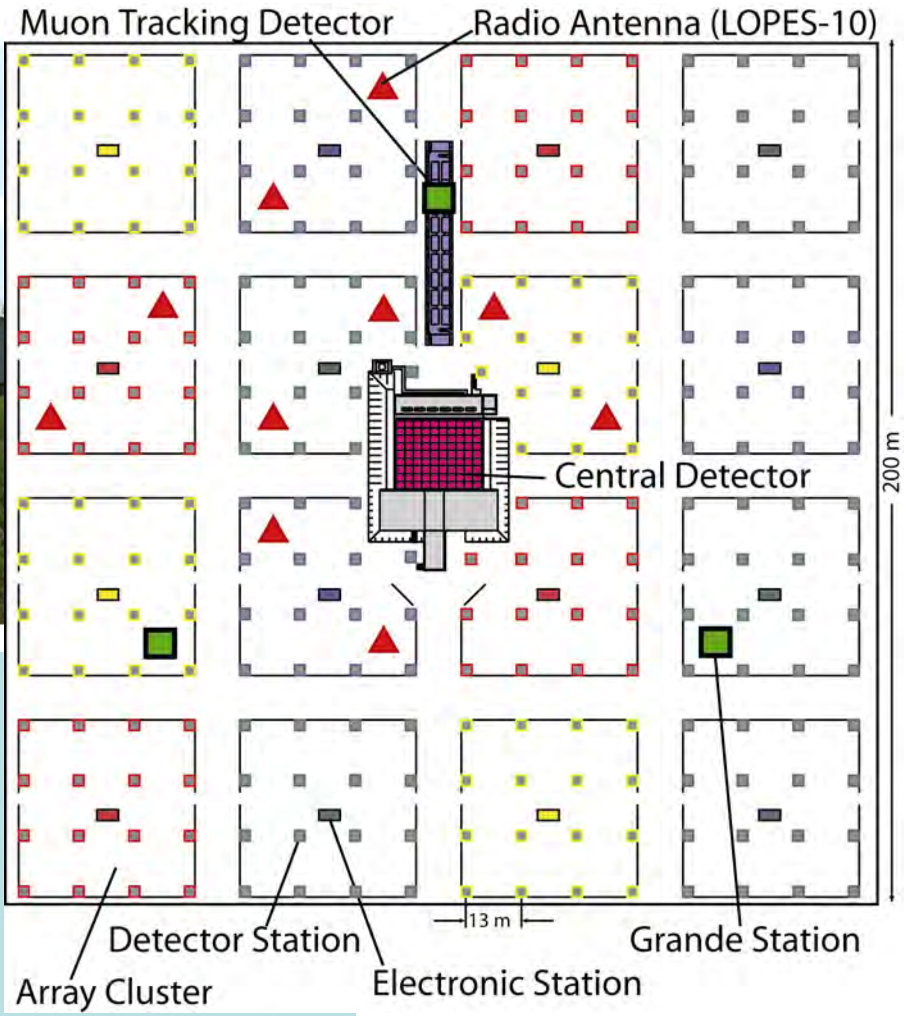


- direct sampling with minimal analog parts: amplifier, filter, AD-converter
- sampling with 80MSPS in the 2nd Nyquist domain of the ADC

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

- generates and distributes clock and accepts and distributes trigger

LOPES : First step: 10 antennas at KASCADE (2004)



- 10 antennas at KASCADE array
- frequency band 40-80 MHz
- trigger: >10/16 cluster of KASCADE
  ($E_0 > 10^{16}$ eV)
- 2004: 7 months runtime
- ~630.000 triggered events
  (and correlated EAS information)

➔ sufficient sample of events for detailed analyses

LOPES 10 :

Calibration of radio emission in air showers:
← check or improvement of Allan's parametrisation of the early measurements
← quantification of dependencies

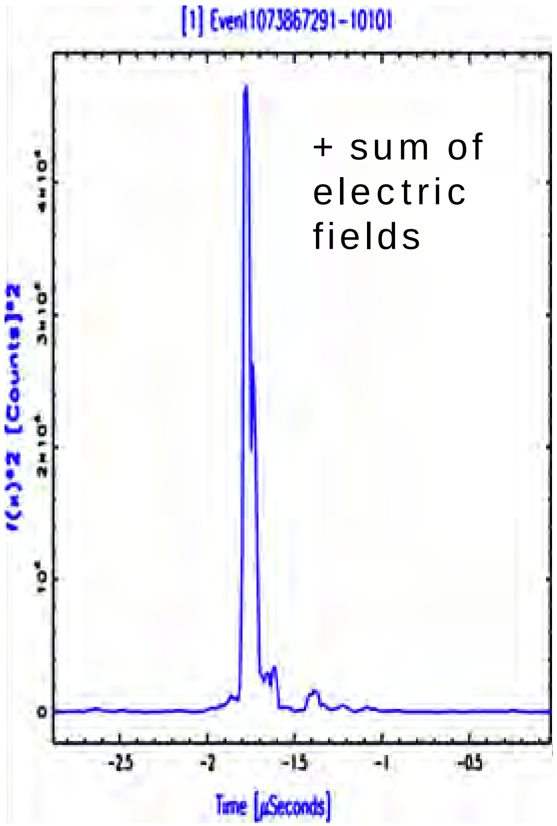
$$\varepsilon_\nu = 20 \cdot (E / 10^{17} \mathrm{eV}) \cdot \sin \alpha \cdot \cos \theta \cdot \exp(- R / R_0(\nu,\theta))$$

[μV / m MHz]

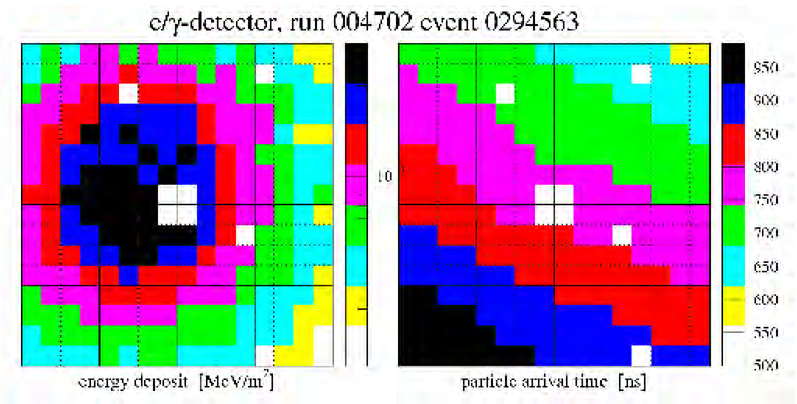
ε_ν	– radio pulse amplitude per unit bandwith
E	– primary energy
α	– angle to geomagnetic field
θ	– zenith angle
R	– distance to shower axis
R_0	– scaling radius (110 m at 55 MHz)

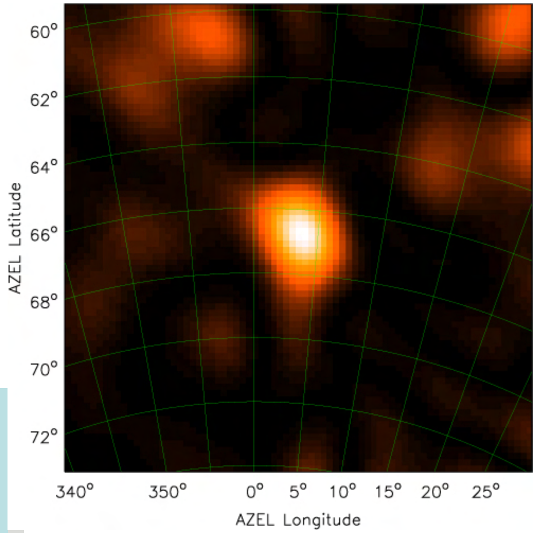
H.R. Allan, review 1971, p.269

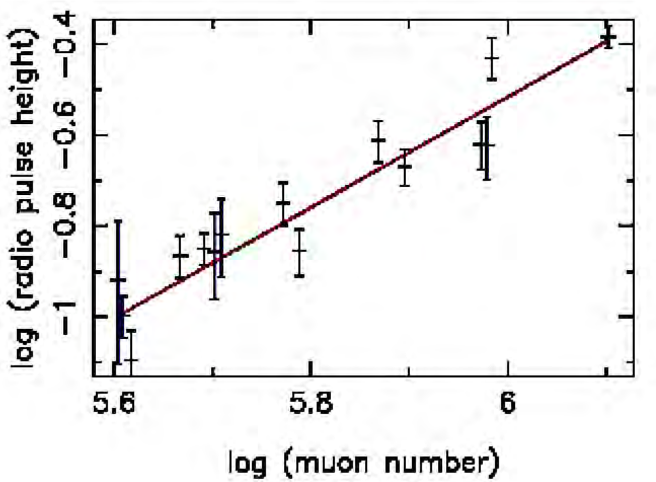
LOPES 10 Analysis : Results
Proof of Principle



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







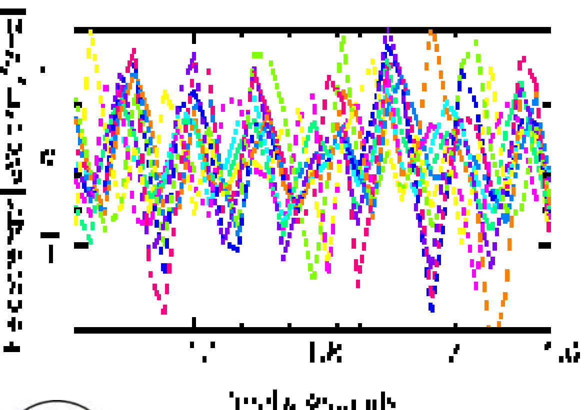
data analyses:
- **EAS analyses KASCADE**
- **radio signal analyses**
- **sky mapping**

LOPES collaboration, Nature 425 (2005) 313

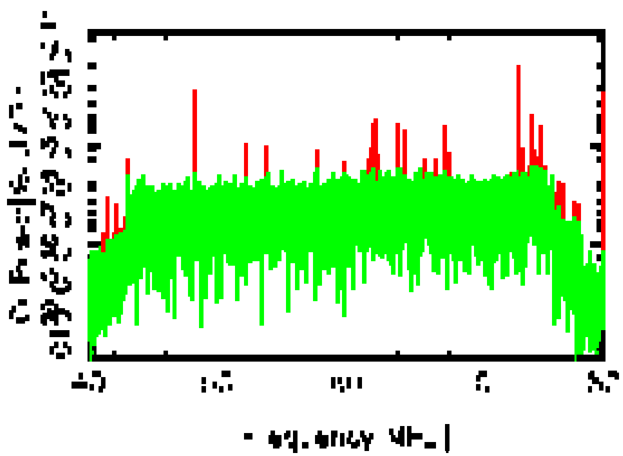
LOPES: Data Processing

1. instrumental delay correction from TV-phases
2. frequency dependent gain correction
3. filtering of narrow band interference
4. flagging of antennas
5. correction of trigger & instrumental delay
6. beam forming in the direction of the air shower
7. quantification of peak parameters

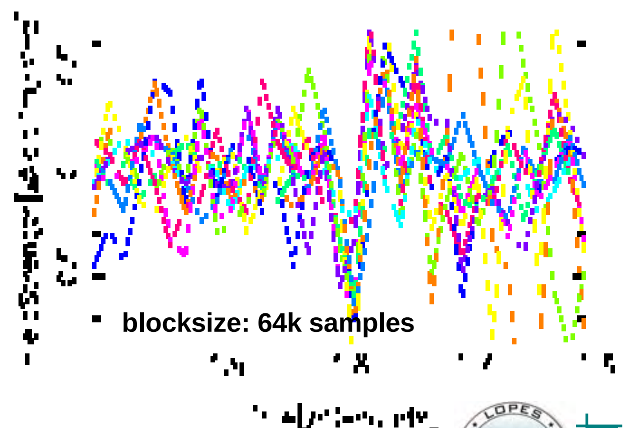
raw data:



power spectrum:

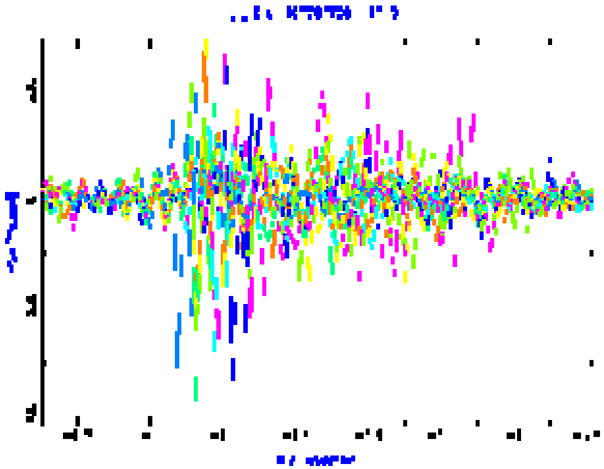


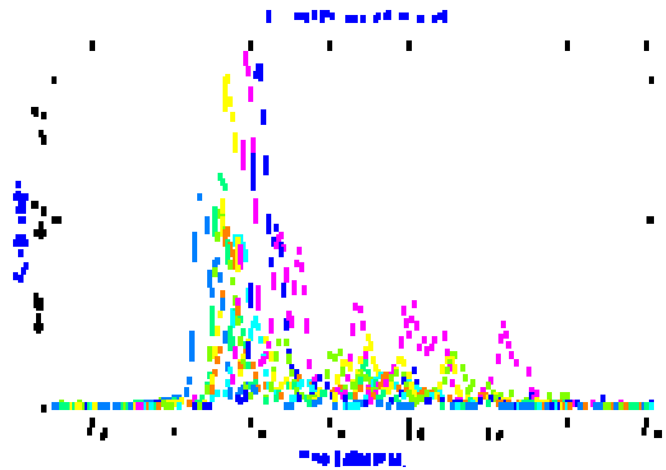
filtered data:



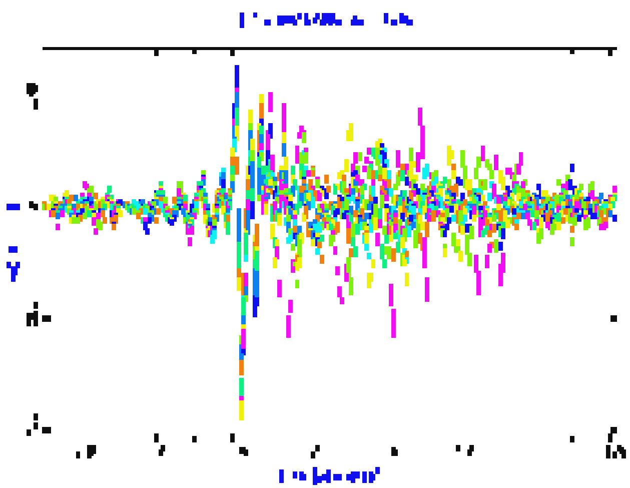
LOPES: Data Processing
Beamforming

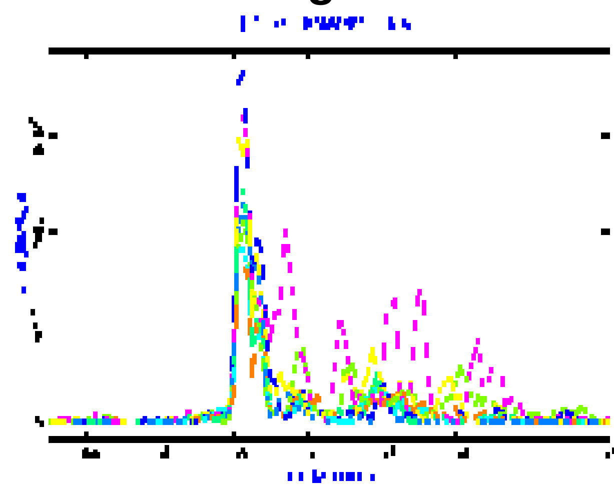
Electric field and power before time shifting:





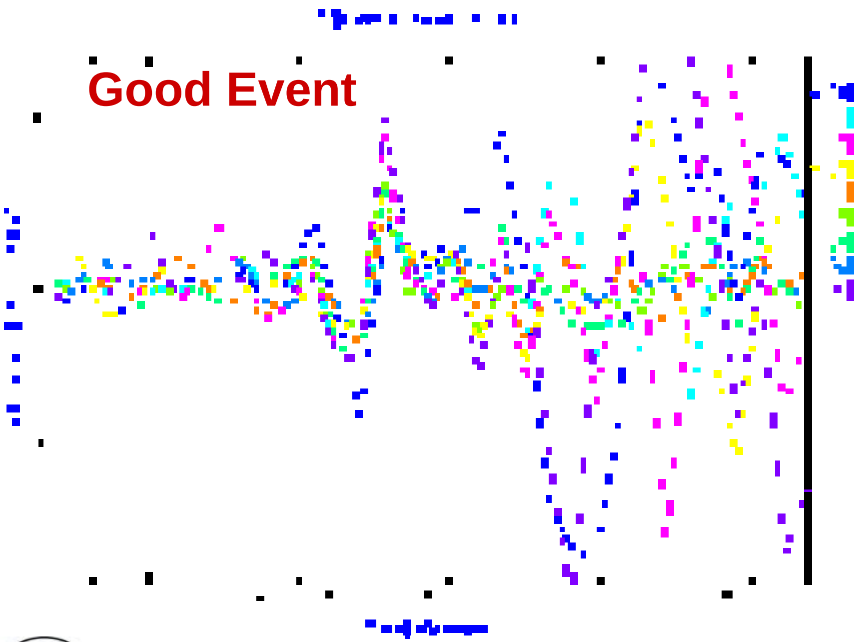
Electric field and power after time shifting:

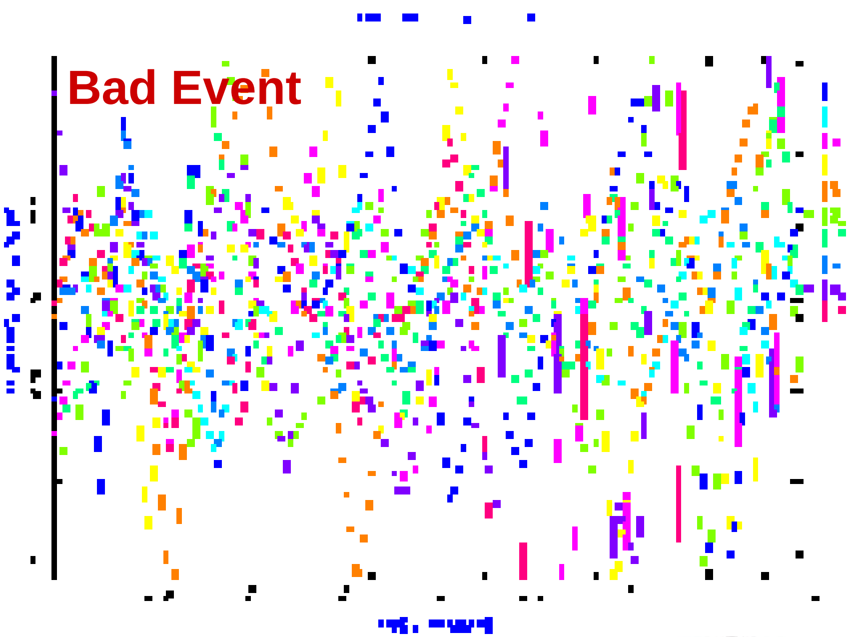




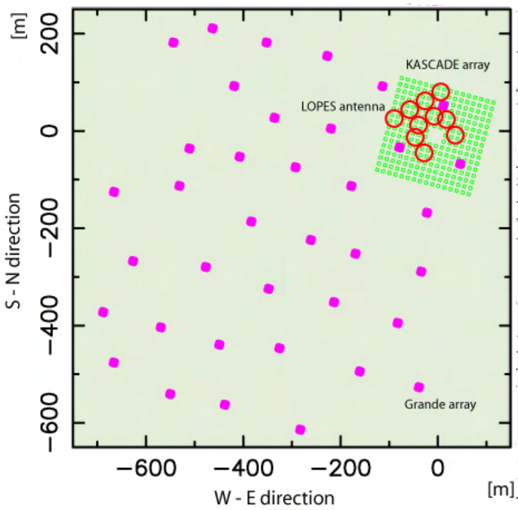
LOPES: Data Processing
Event Discrimination

- criteria for “good” events:
  - existence of a coherent pulse
  - position in time of pulse
  - uniform pulse height in all antennas
- selection currently done manually





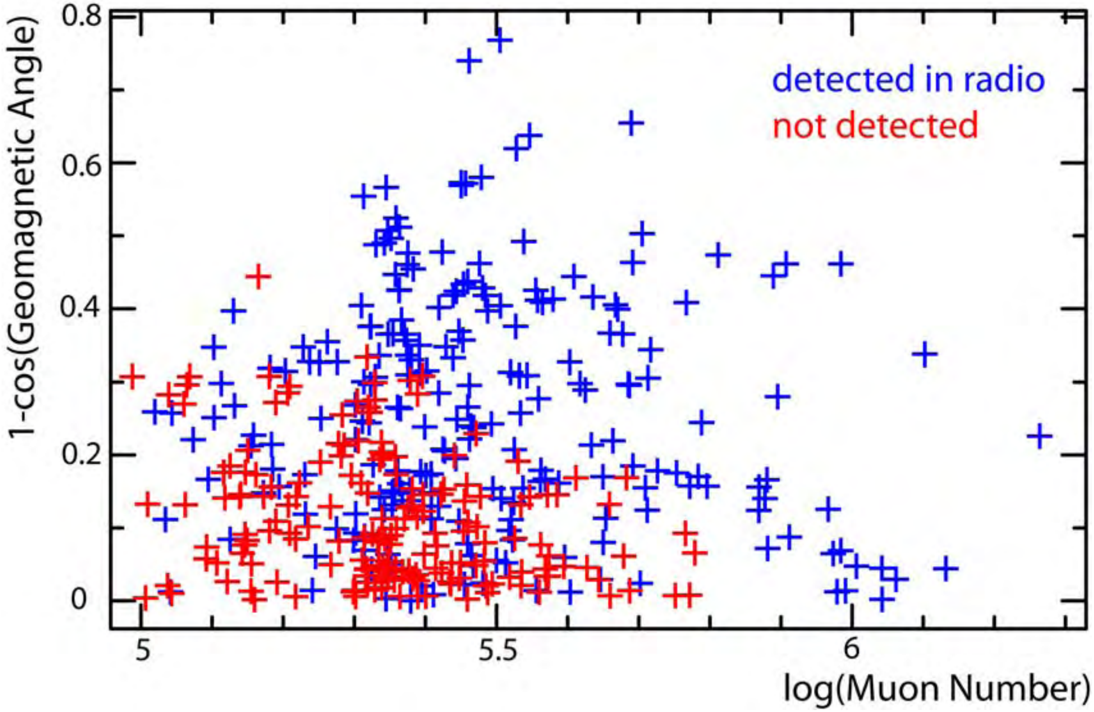
LOPES 10 :
Analysis of central, distant, and inclined events



Showers trigger LOPES with KASCADE:
➔ central event ➔ basic dependencies
But most have also trigger in Grande
➔higher energies ➔larger distances (lateral extension)

LOPES 10 Analysis : Results
Central events

- **228 out of 412 events considered good**
- **Fraction of "good" to "bad" events increases with increasing muon number and increasing geomagnetic angle**
- **fraction also increases with zenith angle**



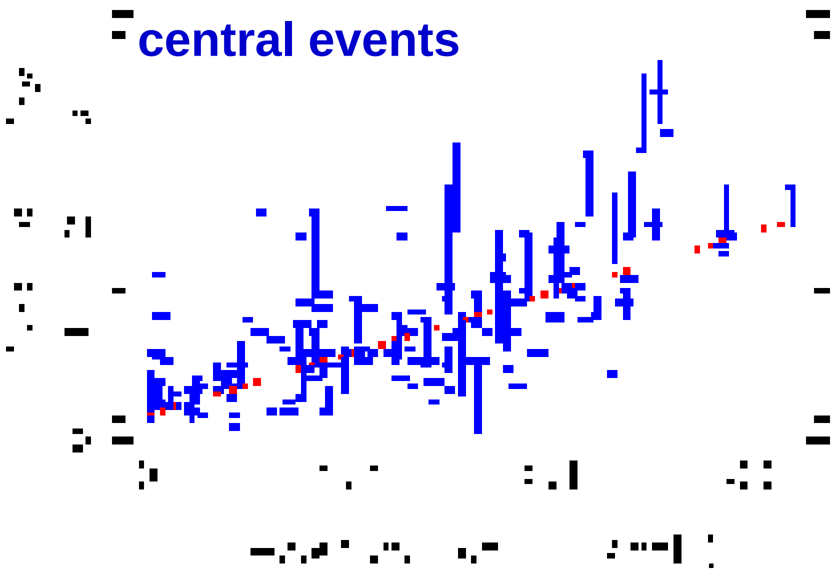
Horneffer et al. – LOPES collaboration, 29th ICRC, Pune, 2005

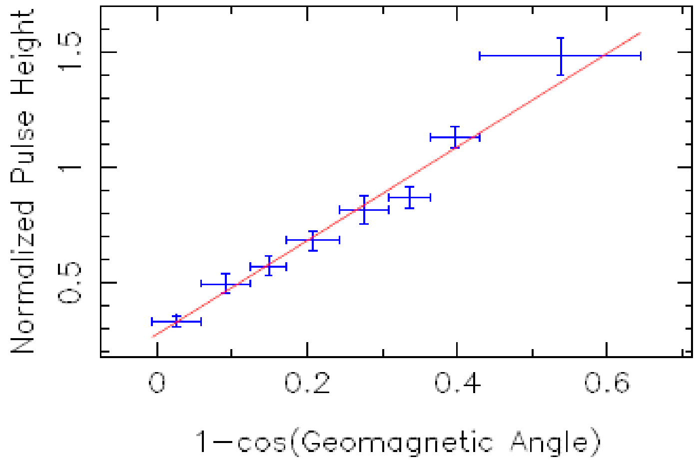
LOPES 10 Analysis : Results
Central Events

Signal dependencies from shower parameters in respect of Allan's idea:

$$\varepsilon_\nu = 20 \cdot (E / 10^{17} eV) \cdot \sin\alpha \cdot \cos\theta \cdot \exp(-R / R_0(\nu,\theta))$$

[μV / m MHz]





Radio signal scales with geomagnetic field:

$\varepsilon_\nu \sim \cos\alpha$

Horneffer et al. – LOPES collaboration, 29th ICRC, Pune, 2005

LOPES 10 Analysis : Results
angle dependencies vs. simulations

Radio signal scales with geomagnetic field:

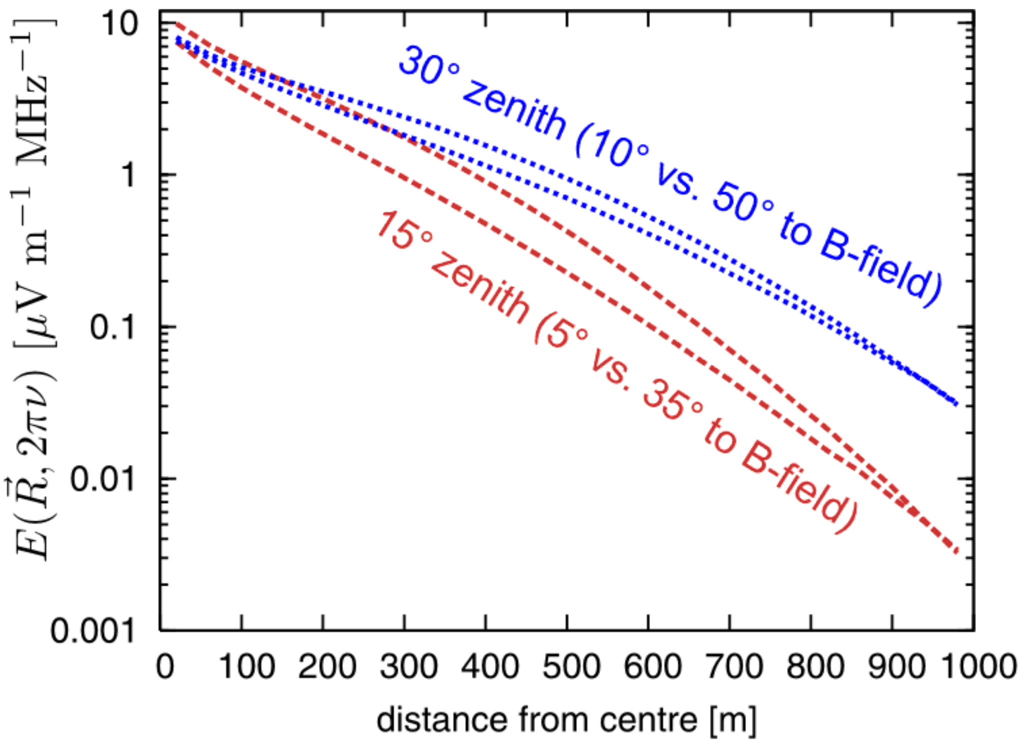
$\varepsilon_\nu \sim \cos \alpha$

Monte Carlo Simulations:

separate dependence expected

- **on geomagnetic (Earth magnetic field)**
- **on zenith (footprint broadening & elongation)**
- **and azimuth (polarization effects)**

➔ leads to rather complex predicted behaviour in angle dependencies



Tim Huege

LOPES 10 Analysis : Distant Events
Interplay of radio and shower particle analysis

Grande Event:

$\Phi = 302.18^o$ $\theta = 41.01^o$

$\alpha = 57.91^o$

$X_c = -142.85$ m $Y_c = 40.27$ m

lg(E/eV) = 17.73   ln(A) = 3.16

curvature = 3250 m

rence

58°

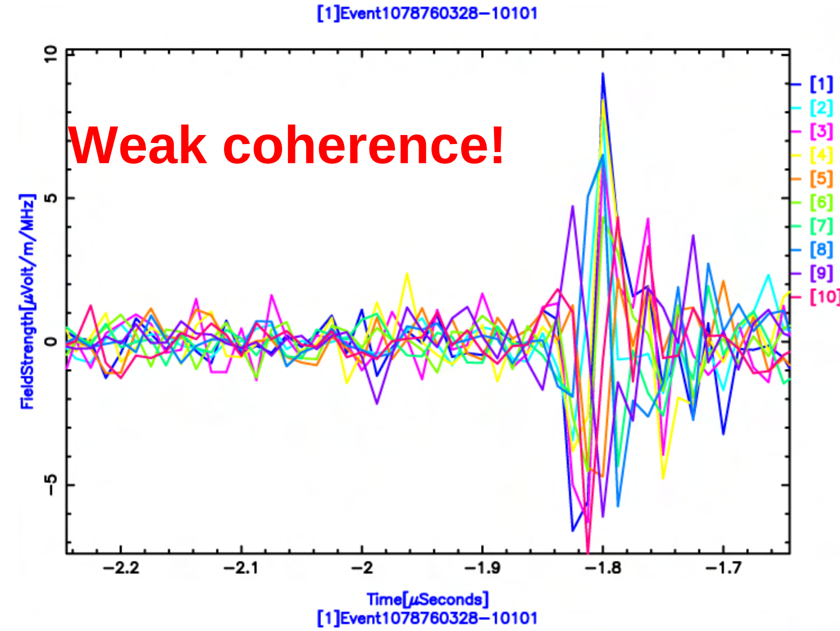
°

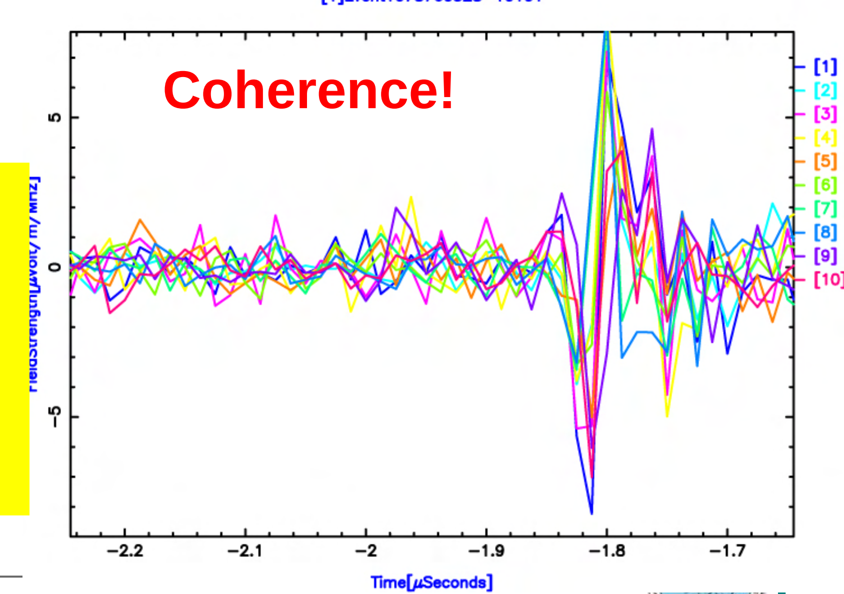
85 m

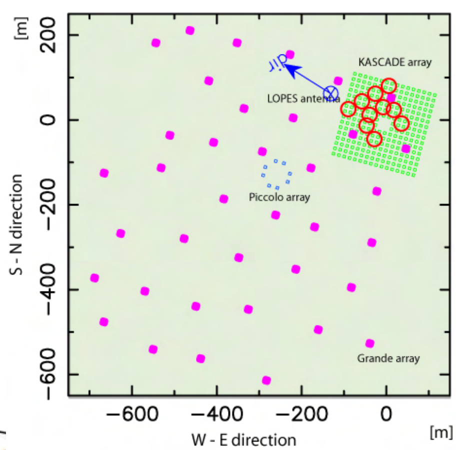
m

ln(A) = 3.16

curvature = 3250 m   = 4250 m







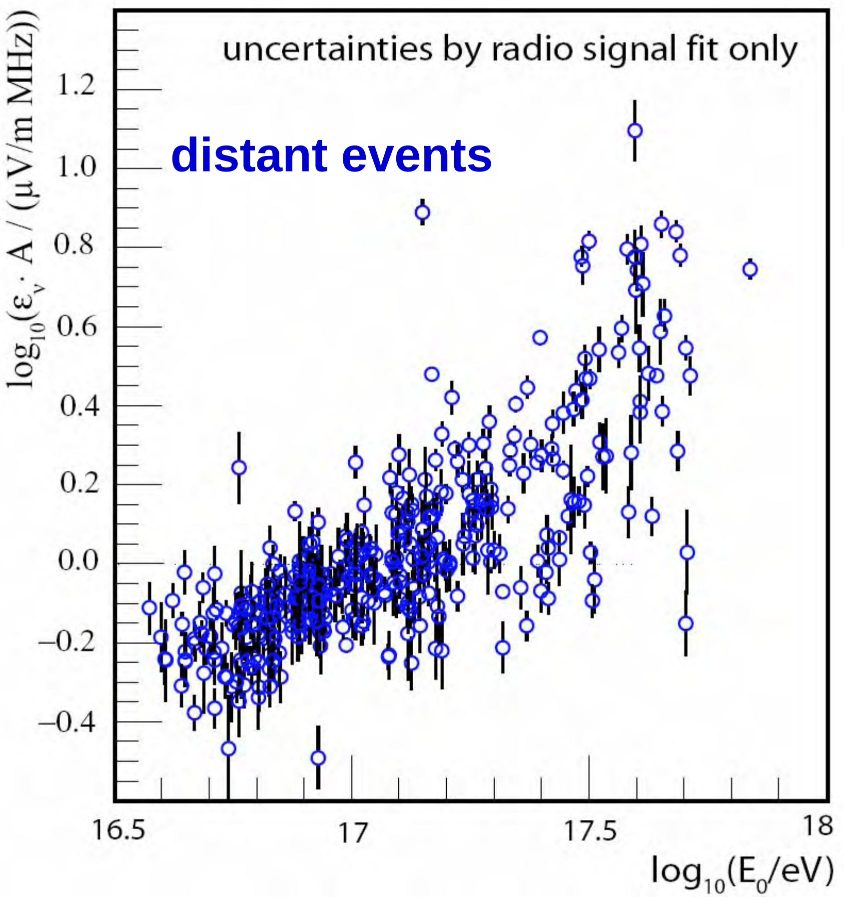
➔Improvement of shower core and arrival direction estimate in Grande by LOPES !

LOPES 10 Analysis : Results
energy dependence of radio signal

Signal dependencies from shower parameters in respect of Allan's idea:

$$\varepsilon_\nu = 20 \cdot (E / 10^{17} eV) \cdot \sin\alpha \cdot \cos\theta \cdot \exp(- R / R_0(\nu,\theta))$$

[μV / m MHz]



Radio signal (electric field) scales with primary energy:
$\varepsilon_\nu \sim E_0$

➔ Power of electric field scales approx. quadratically with primary energy !

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

LOPES 10 Analysis : Results
energy dependence of radio signal

Signal dependencies from shower parameters in respect of Allan's idea:

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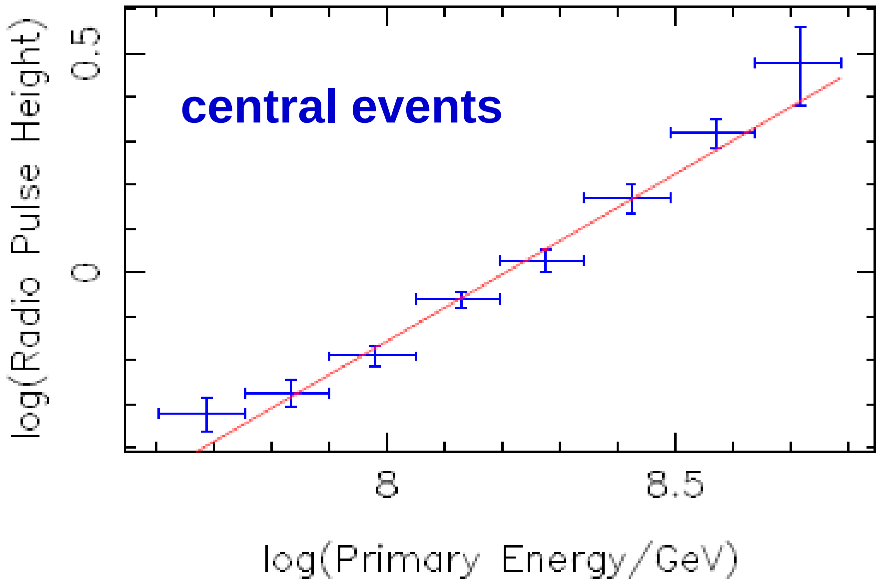
[μV / m MHz]



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➔ Power of electric field scales approx. quadratically with primary energy !

Horneffer et al. – LOPES collaboration, 29th ICRC, Pune, 2005

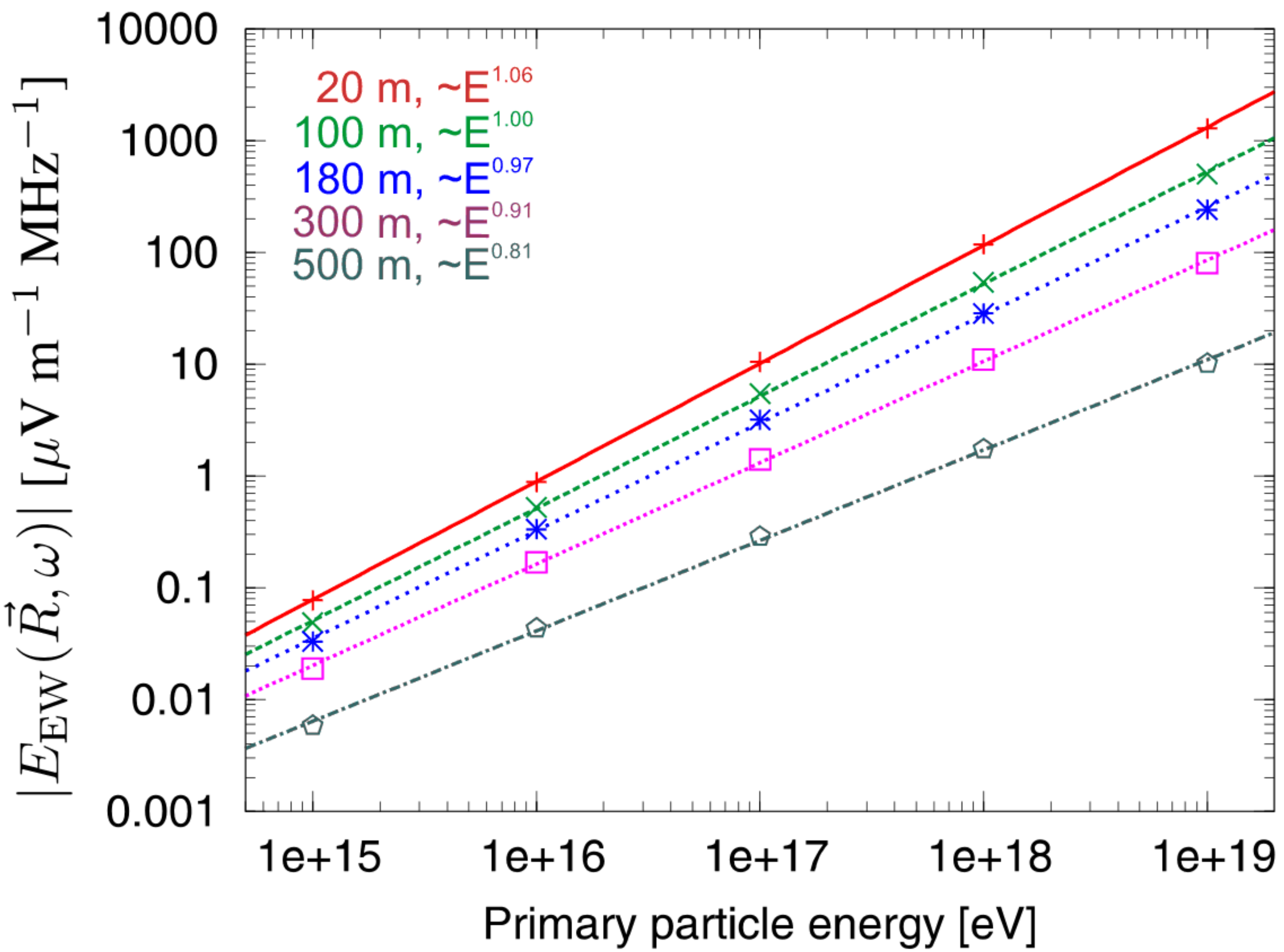
LOPES 10 Analysis : Results
signal dependency vs. simulations

Radio signal (electric field) scales with primary energy:

$\varepsilon_\nu \sim E_0$

Monte Carlo Simulations:

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



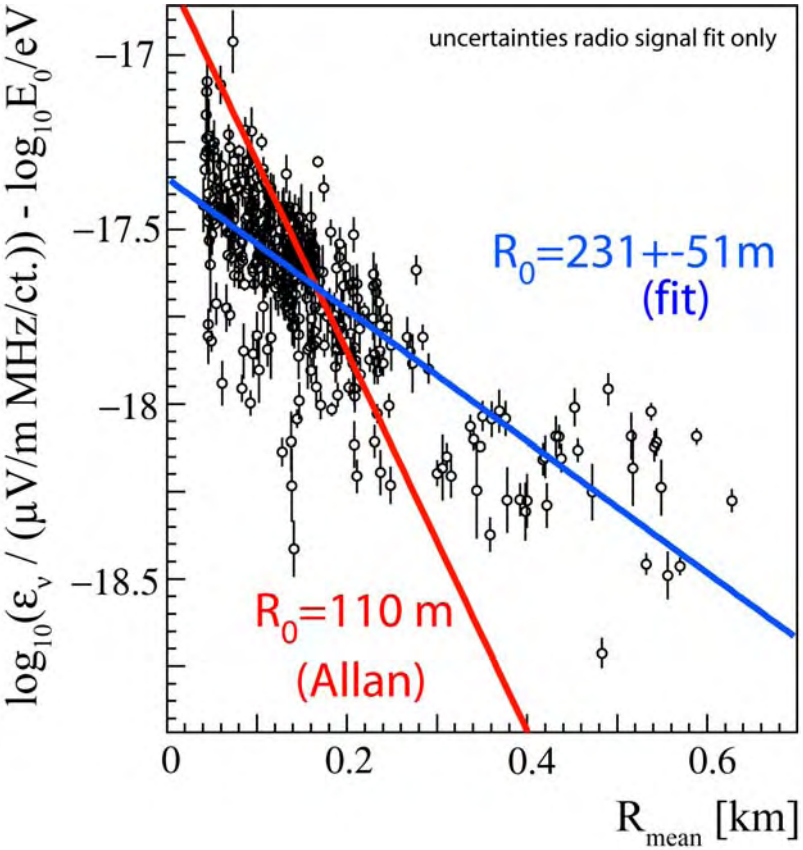
Tim Huege, 29th ICRC, Pune, 2005

LOPES 10 Analysis : Results
lateral profile of radio signal

Signal dependencies from shower parameters in respect of Allan's idea:

$$\varepsilon_\nu = 20 \cdot (E / 10^{17} eV) \cdot \sin \alpha \cdot \cos \theta \cdot \exp(- R / R_0(\nu,\theta))$$

[μV / m MHz]



Radio signal scales with core distance: $\varepsilon_\nu \sim \exp(-R/R_0)$

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

LOPES 10 Analysis : Results
lateral profile vs. simulations

Radio signal scales with core distance:

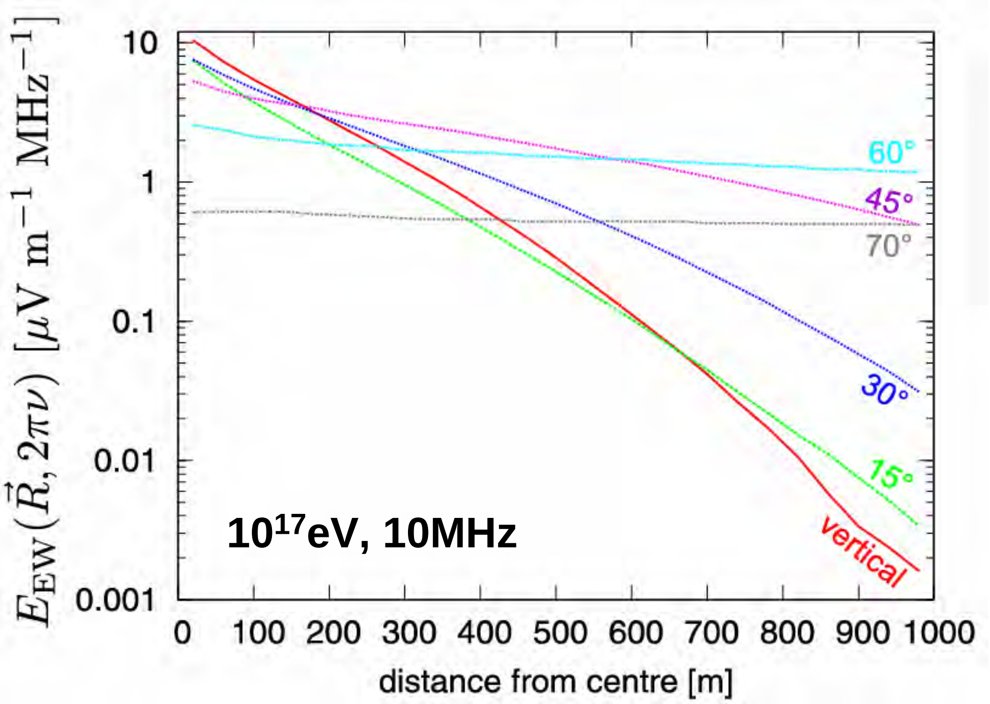
$\varepsilon_\nu \sim \exp(-R/R_0)$

$(R_0 \sim 230m)$

Monte Carlo Simulations:

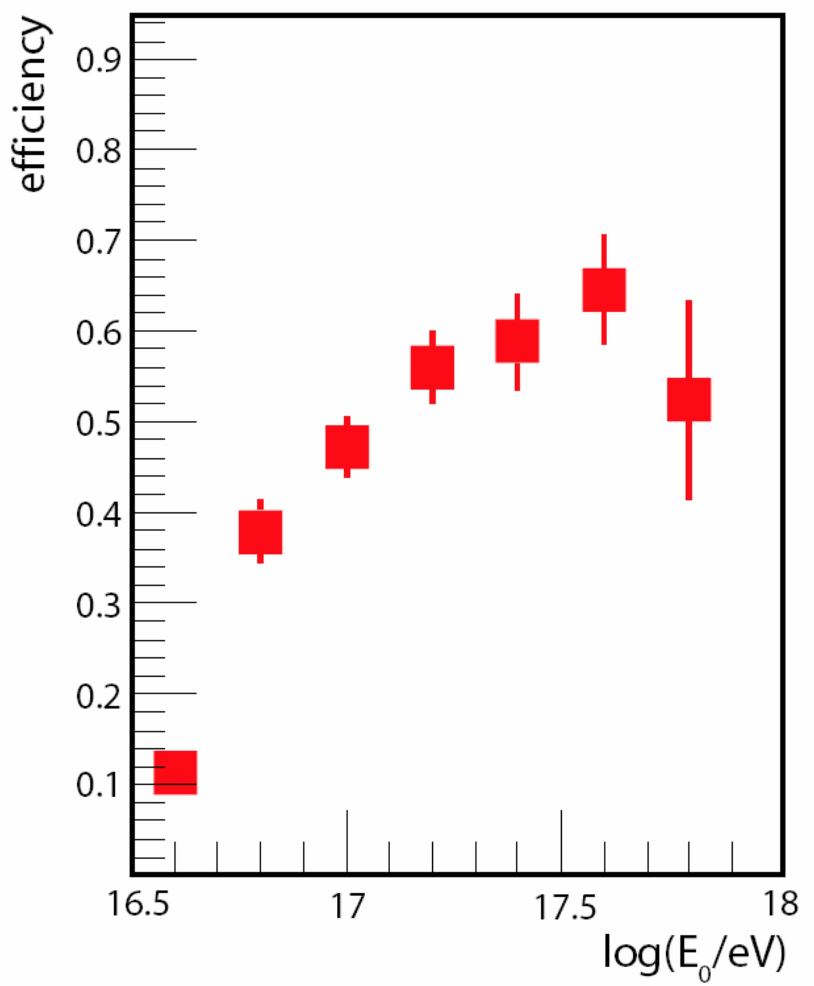
flattening with zenith angle

approx. exponential scaling $R_0 \sim 100$ to 800 m



Tim Huege, 29th ICRC, Pune, 2005

LOPES 10 Analysis : distant events efficiency



detection threshold at
$E_0 \sim 10^{17}$eV

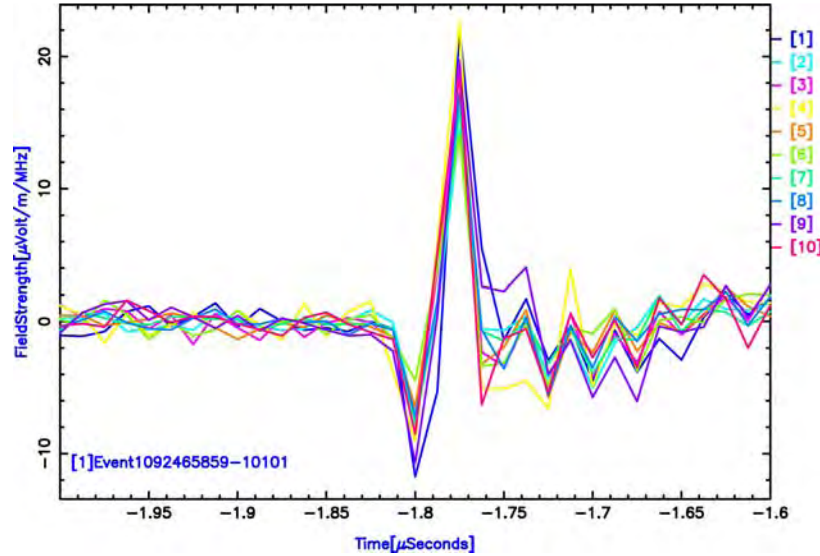
Missing efficiency due to
- polarization
- geomagnetic angle

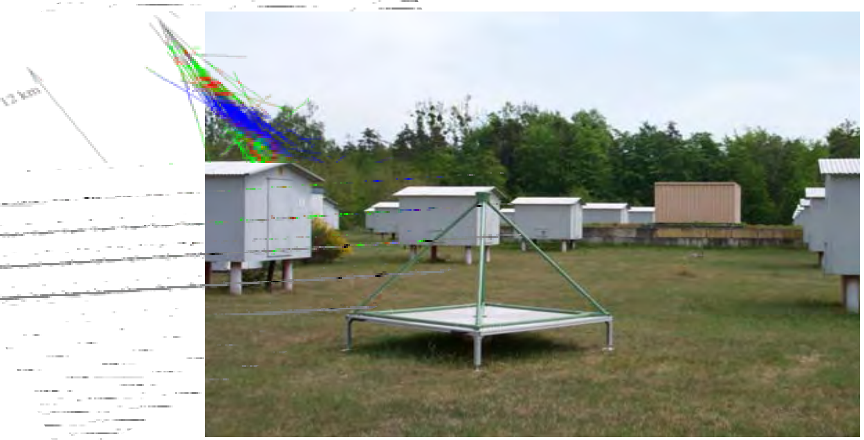
Apel et al. – LOPES collaboration, Astrop.Phys. (2006) submitted

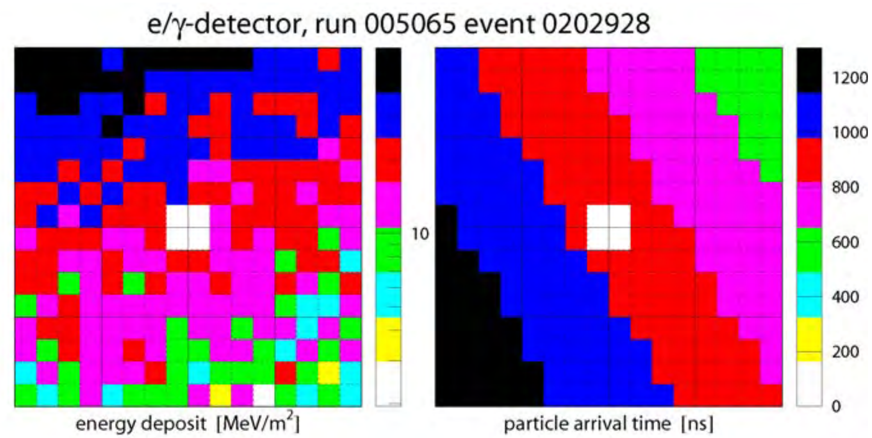
LOPES 10 : Analysis of inclined events

<u>Event:</u>
Φ = 74,4º **θ = 68º**
core = outside
lg(N_e) ~ 6 ? **lg(N_μ) ~ 5.7 ?**
but clear radio signal !!

-reconstruction of shower by particle detectors difficult
-clear radio signals seen







Petrovic et al. – LOPES collaboration, 29th ICRC, Pune, 2005

LOPES 10 Analysis : Results
inclined events vs. simulations

inclined showers ➔ larger lever arm to geomagnetic angle

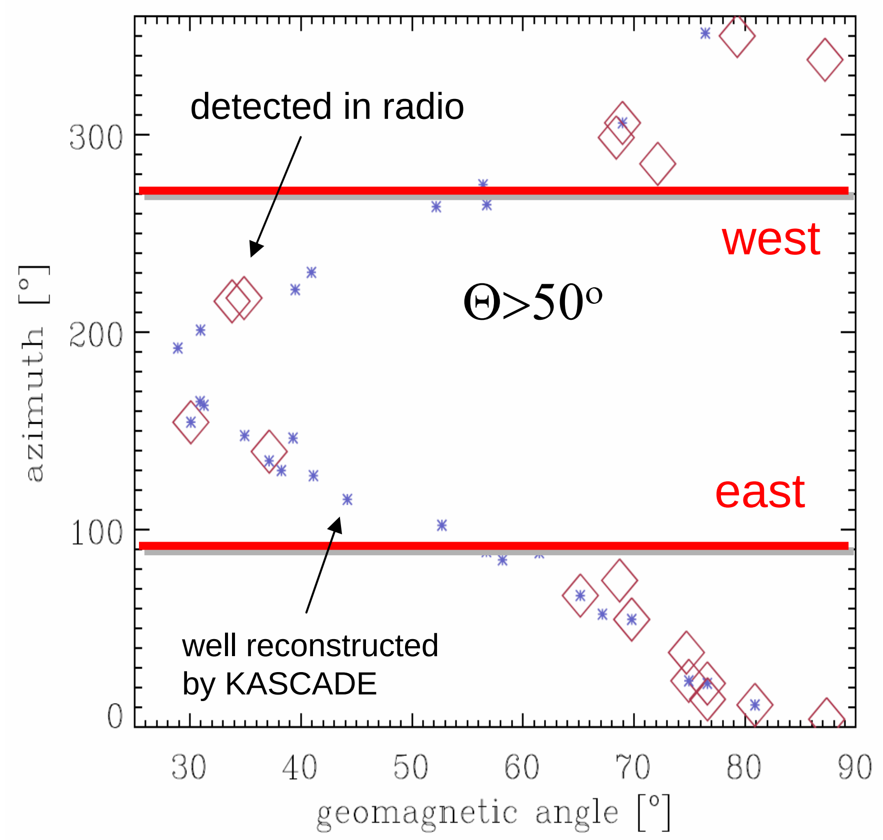
no radio events from east or west?

north-south asymmetry in radio events?

Monte Carlo Simulations:

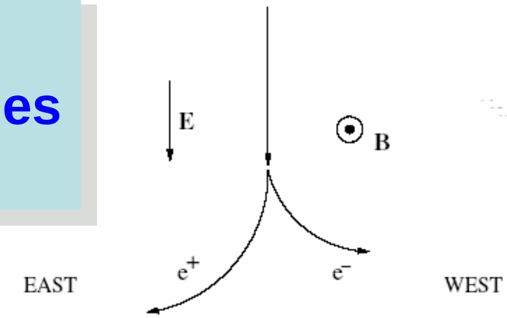
east-west ⇔ north-south asymmetries expected due to polarization, antenna gain and geomagnetic effects

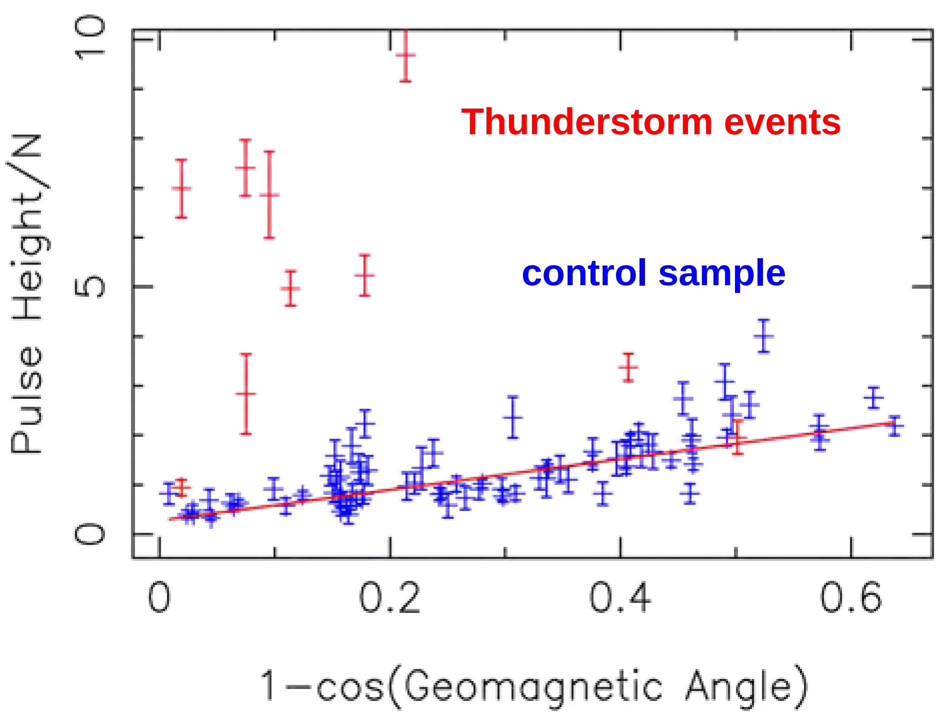
first measurements consistent with simulation
but difficult situation



LOPES 10 : Analysis of events during thunderstorms

Downward electric field
→Asymmetry in trajectories
→Radio emission



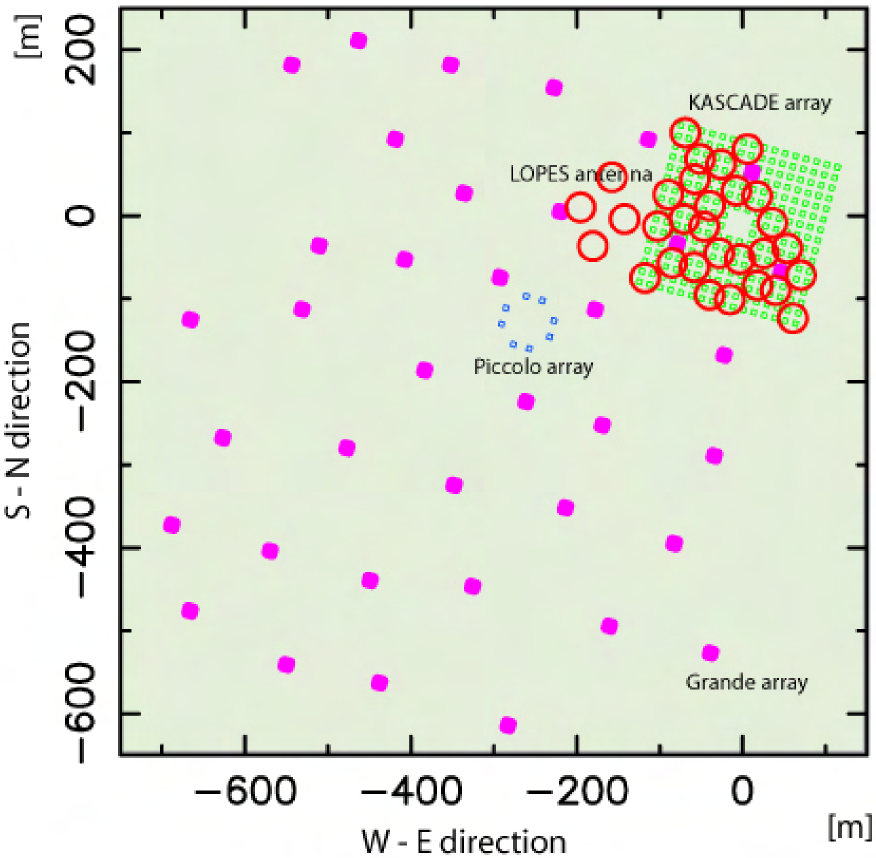


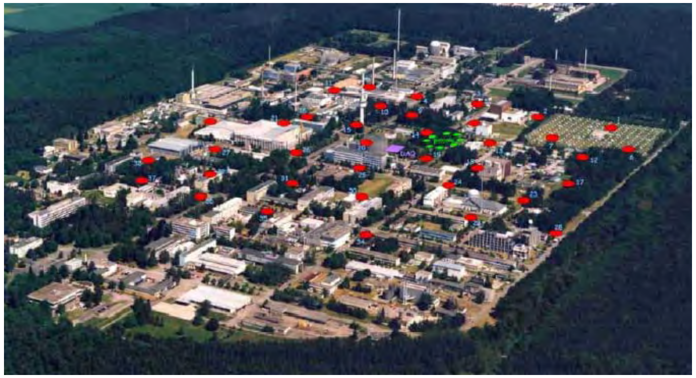
For E>100 V/cm:
E-field force dominates B-field:
Fair weather: E=0,1 V/cm
Thunderstorms: E=1 kV/cm

Buitink et al. – LOPES collaboration, 29th ICRC, Pune, 2005

LOPES 30: Extension: 30 antennas at KASCADE-Grande

- **30 antennas at KASCADE-Grande**
- **Maximum baseline: ~300 m**
- **Trigger: KASCADE <u>and</u> KASCADE-Grande**
- **Absolute Calibration**
- **Environmental monitoring**





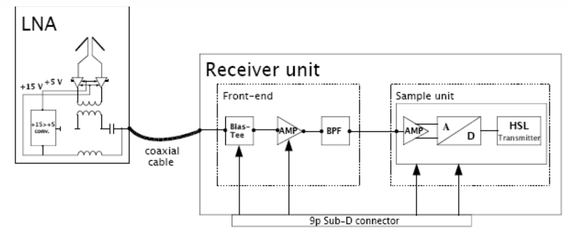
LOPES 30: absolute calibration

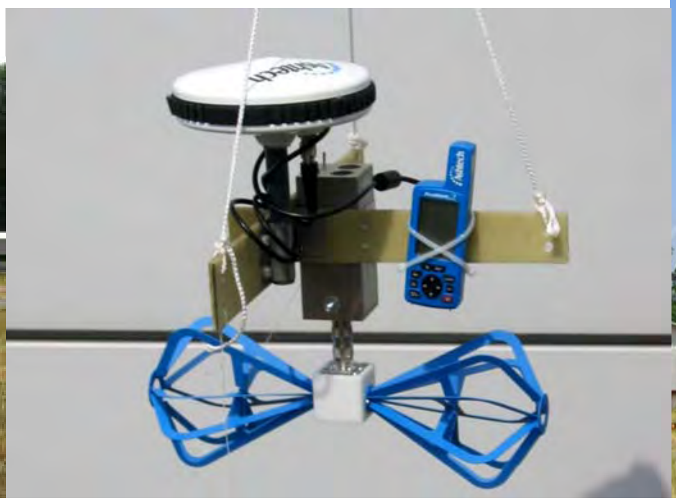
- **amplification factor V per antenna obtained with external commercial calibrated reference antenna**

➔ **correction factor dependent on**
  - **antenna**
  - **frequency**
  - **weather conditions**
  - **angle**

measured power $P_{DAQ}(\nu)$ of each antenna compared with received power $P_{rec}(\nu)$ from reference radio source

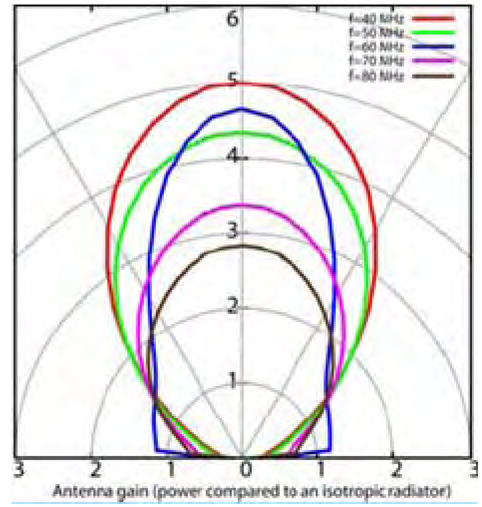
$$V(\nu) = \frac{P_{DAQ}(\nu)}{P_{rec}(\nu)} = \frac{P_{DAQ}(\nu)}{\frac{E^2(\nu)}{Z_0} \cdot r^2 G(\nu) \cdot \frac{1}{4\pi} \left(\frac{c}{\nu d} \right)^2}$$

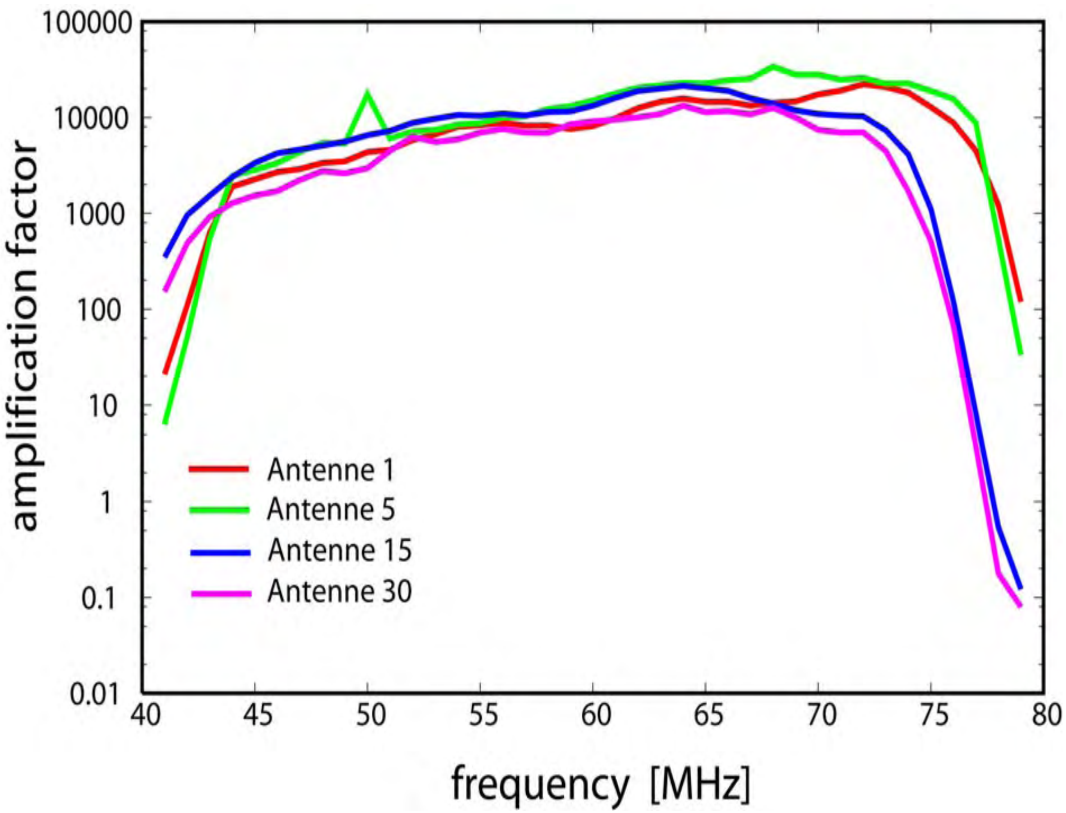


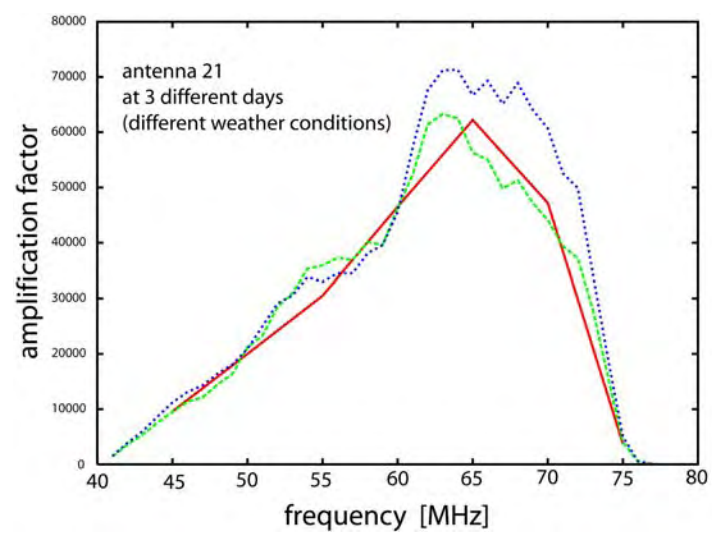


LOPES 30: absolute Calibration

- **antenna gain by simulations**
- **amplification factor from measurements**



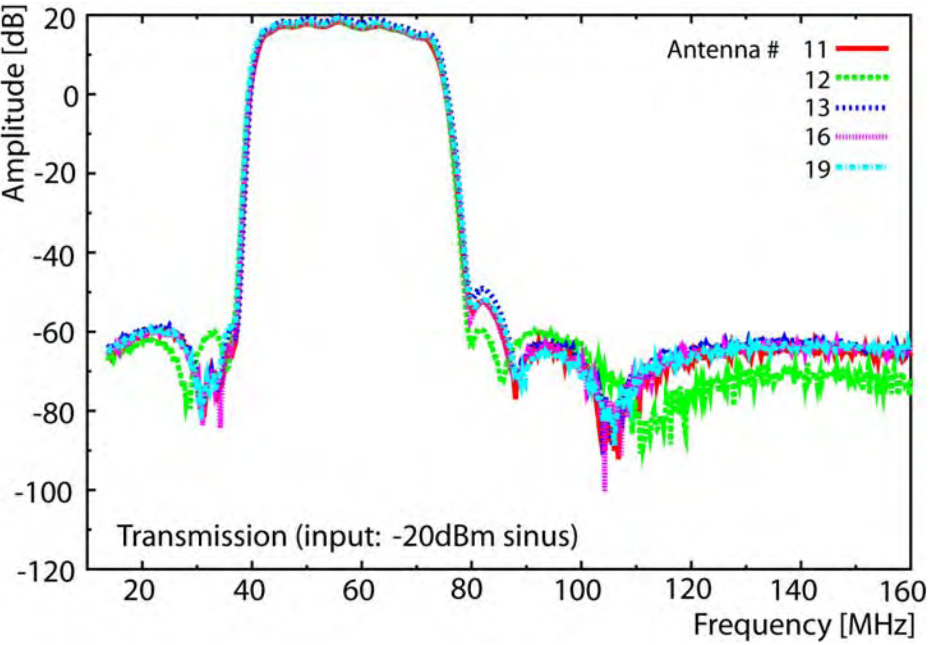


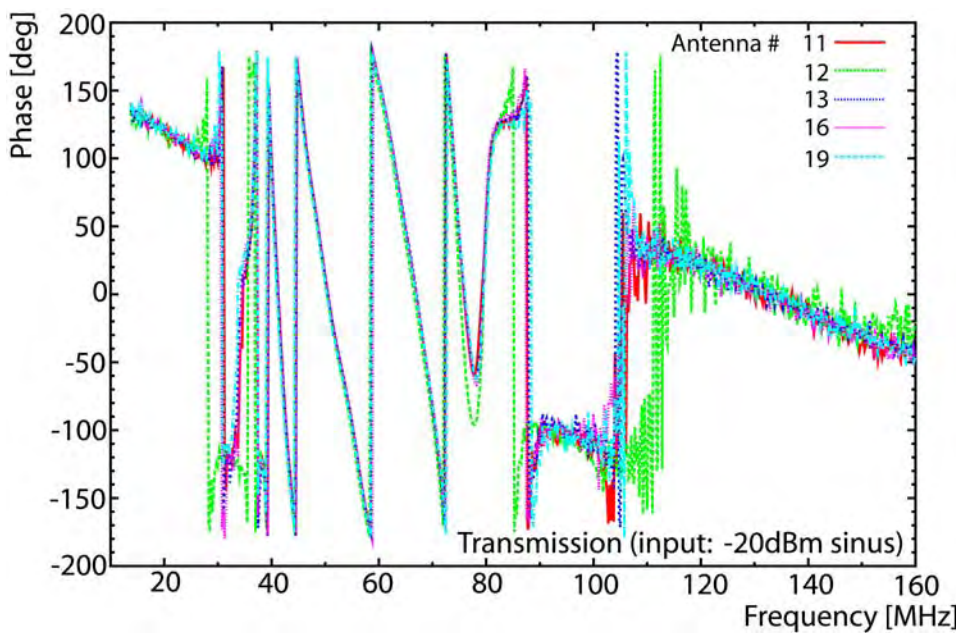


Nehls et al. – LOPES collaboration, 29th ICRC, Pune, 2005

LOPES 30: absolute Calibration

- crosscheck: Lab measurements
- systematic analysis of all LOPES-electronic components
- amplitude and phase measurements to determine system response
- LNA, coaxial cable, Front-end, Sample unit



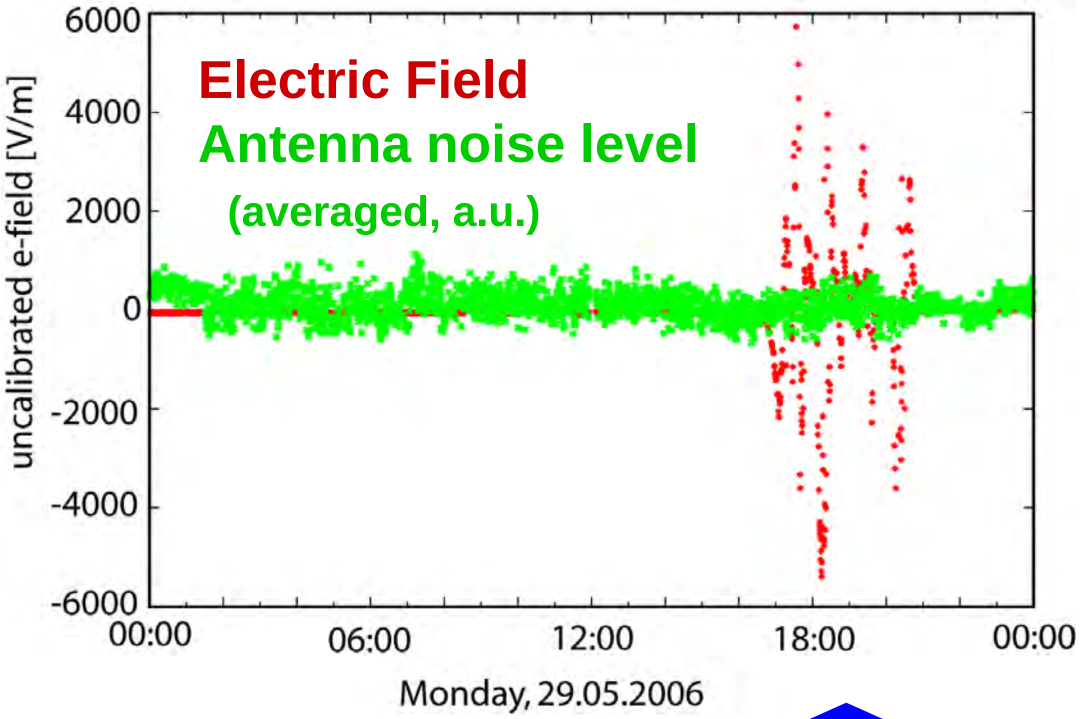


Nehls et al. – LOPES collaboration, 29th ICRC, Pune, 2005

LOPES 30: environmental monitoring

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

Electric Field Mill:



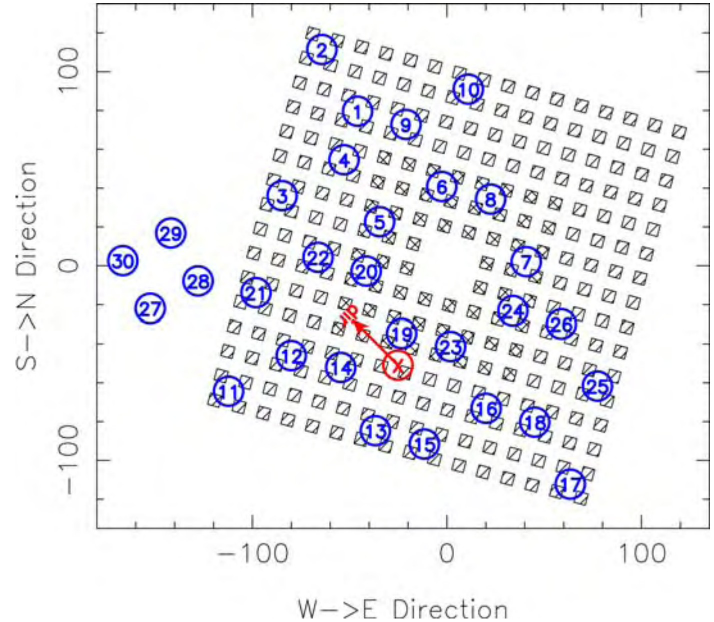
thunderstorm

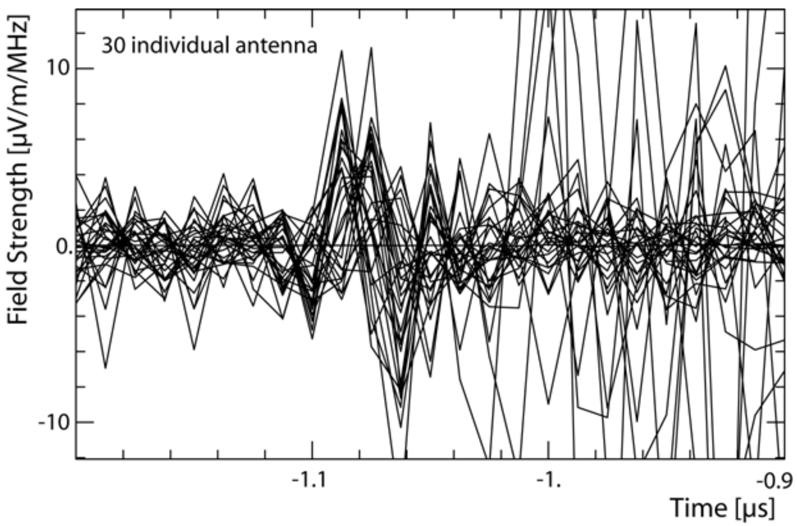
Isar, Nehls et al. – LOPES collaboration, ARENA 2006 poster

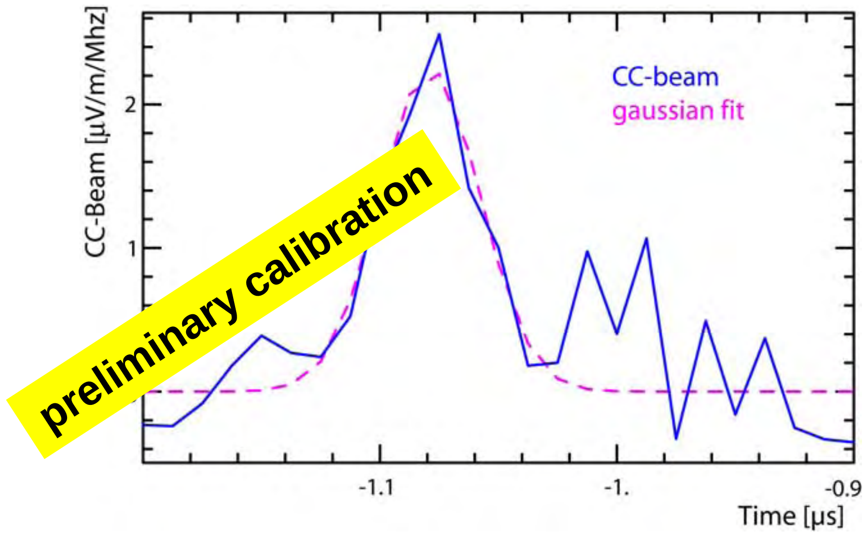
LOPES 30: first events

Event:
Φ = 15° θ = 306°
core = in KASCADE
lg(N_e) ~ 7.4 lg(N_μ) ~ 6.0
E_0 ~ 1.6·10^{17} eV

- **several beam formings possible**
- **radio reconstruction inclusive calibration factors of antennas**



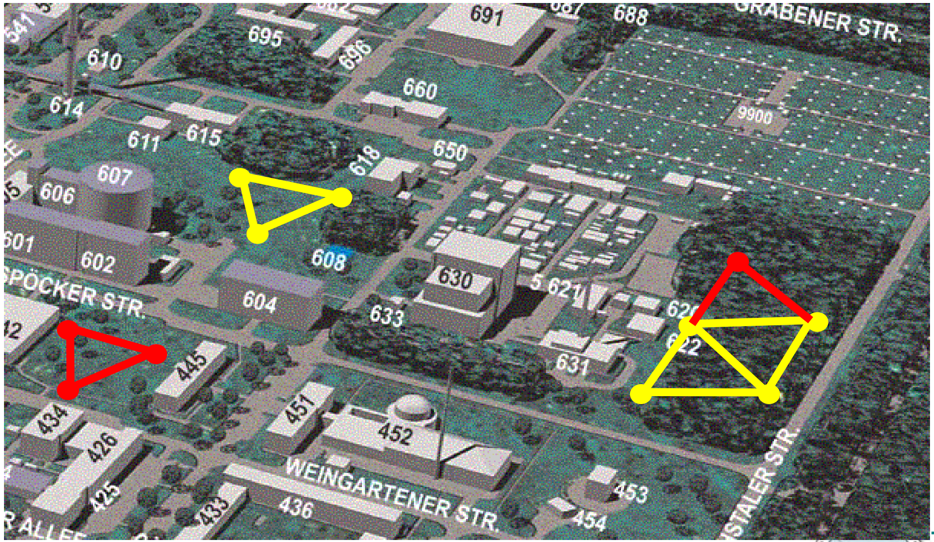




Isar, Nehls et al. – LOPES collaboration, ARENA 2006 poster

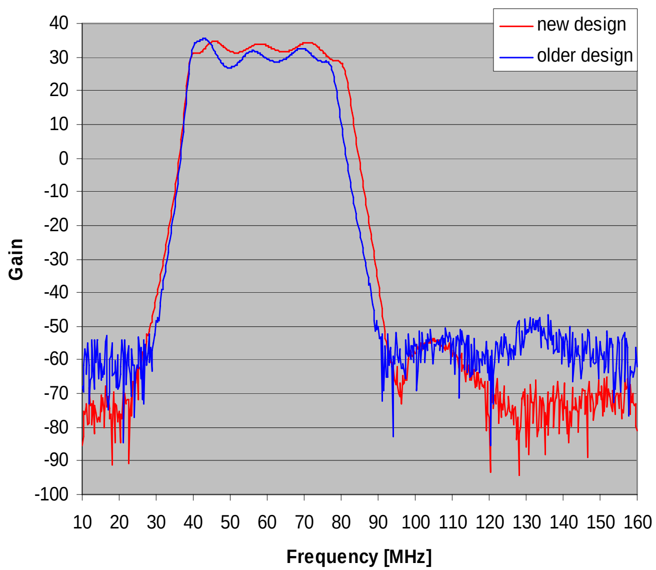
LOPES^{STAR}: large scale application?

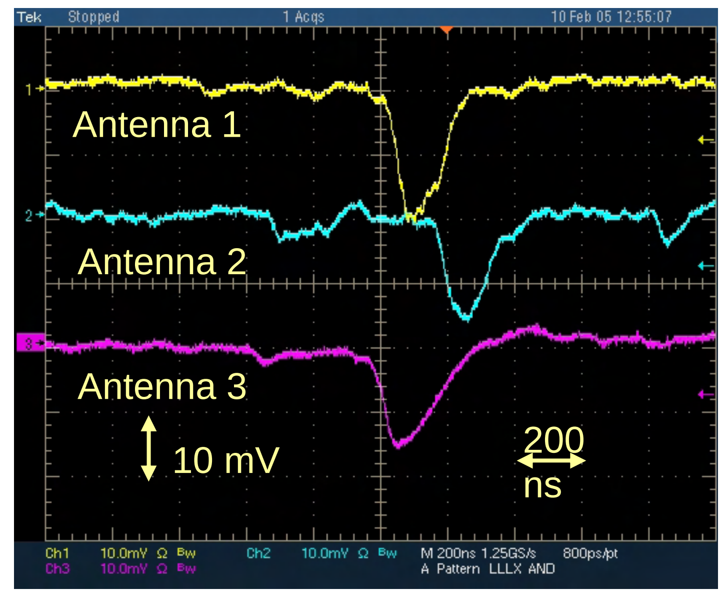
- **radio technique has great potential for large scale application:**
  - **LOFAR will measure CRs**
  - **R&D for use in the Pierre Auger Observatory has started**
- **LOPES continues to contribute experience and physics results**
- **application in Auger needs a different detector concept:**
  - **LOPES develops LOPES^{STAR}**
  - **self-triggered by radio signals only**
  - **low power consumption**
  - **decentralized array organization**



LOPES^{STAR}

- -crossed logarithmic-periodic dipole antenna (crossed LPDA)
- -dual channel low noise, low power amplifier (0,022 W/Channel)
- -RF mainboard with BIAS-T, 32nd order RF- bandpass filter, limiter, amplifier, envelope rectifier
- ADC and circular buffer (80 Mhz sampling rate)
- basic (self)trigger setup by enveloping

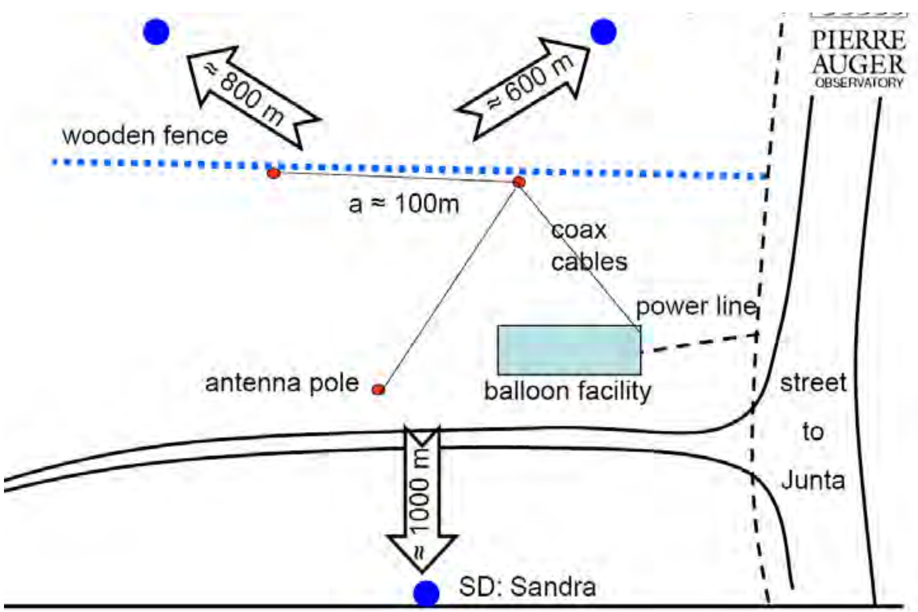


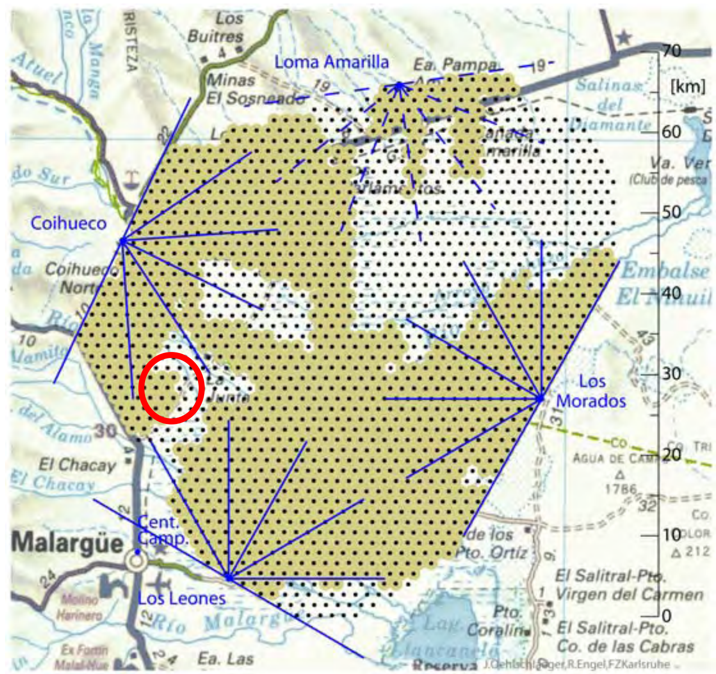


Krömer et al. – LOPES collaboration, SPIE 2005

LOPES^{STAR}: test station at Auger Observatory

- **close to Balloon Launching Station**
- **flexible setup**
- **define hardware and measure background**
- **test trigger system**
- **test hardware**
- **installation in 2006**
- **ask for additional tank**





LOPES: next steps

LOPES 10

- continuation data analysis

LOPES 30

- continuation absolute calibration LOPES 30
- monitoring environmental conditions
- continuation data taking LOPES 30
- analysis of LOPES 30 data
- polarisation measurements
- comparison with simulations

Simulations

- inclusion in CORSIKA

LOPES^{STAR}

- data taking in Karlsruhe
- tests and improvements in hard- and software
- test setup in Argentina

Summary : LOPES

- Successful cooperation of Radioastronomy and Astroparticle Physics groups
- LOPES 10:
  - ➔ Large Sample of radio detected showers
  - ➔ Detailed analyses of central events, distant events, inclined showers, thunderstorm events

➔ Proof of Principle

- LOPES 30
  - ➔ absolute calibrated, higher energies, longer maximum baseline
  - ➔ direct comparison of simulations with measurements

➔ 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 (with all the dependencies on cosmic ray parameters)**

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