Radio Detection of Cosmic Rays with LOPES

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Particle Astronomy at High Energies

main problem: low intensity ϕ (> 10^{20} eV) = 1/(km^2 · century)

photons?

$\gamma\gamma \rightarrow e^+e^-$ on infrared, optical, blackbody photons $\lambda \approx$ 10 kpc

protons?

$\gamma p \rightarrow \Delta^+ \rightarrow n + \pi^+$ $(p + \pi^0)$ $\lambda \approx$ 10 Mpc

only the „local universe“ is visible

way out: neutrinos

Radio emission

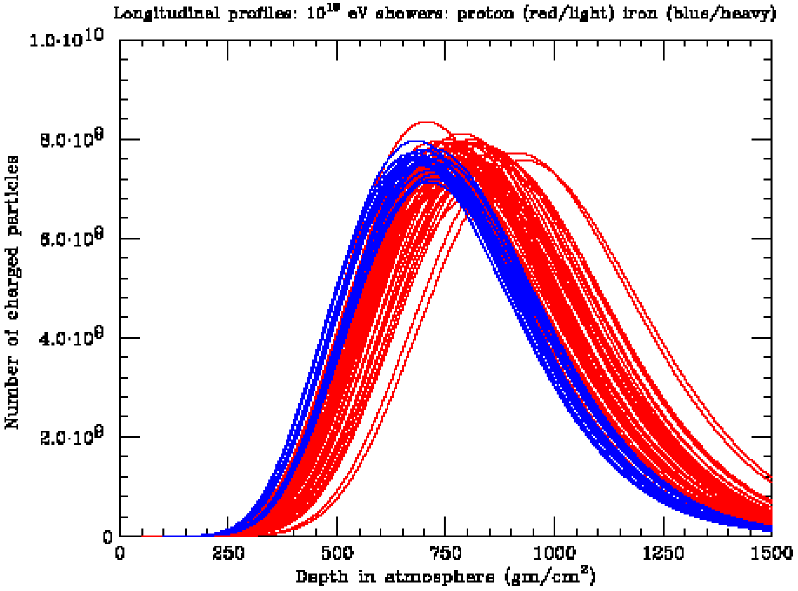
- geo-synchrotron process in the atmosphere (dominant in air)
- Askaryan-effect: coherent radio Cherenkov emission (dominant in ice)
- charge separation in the Earth‘s magnetic field: dipole radiation
- molecular field bremsstrahlung

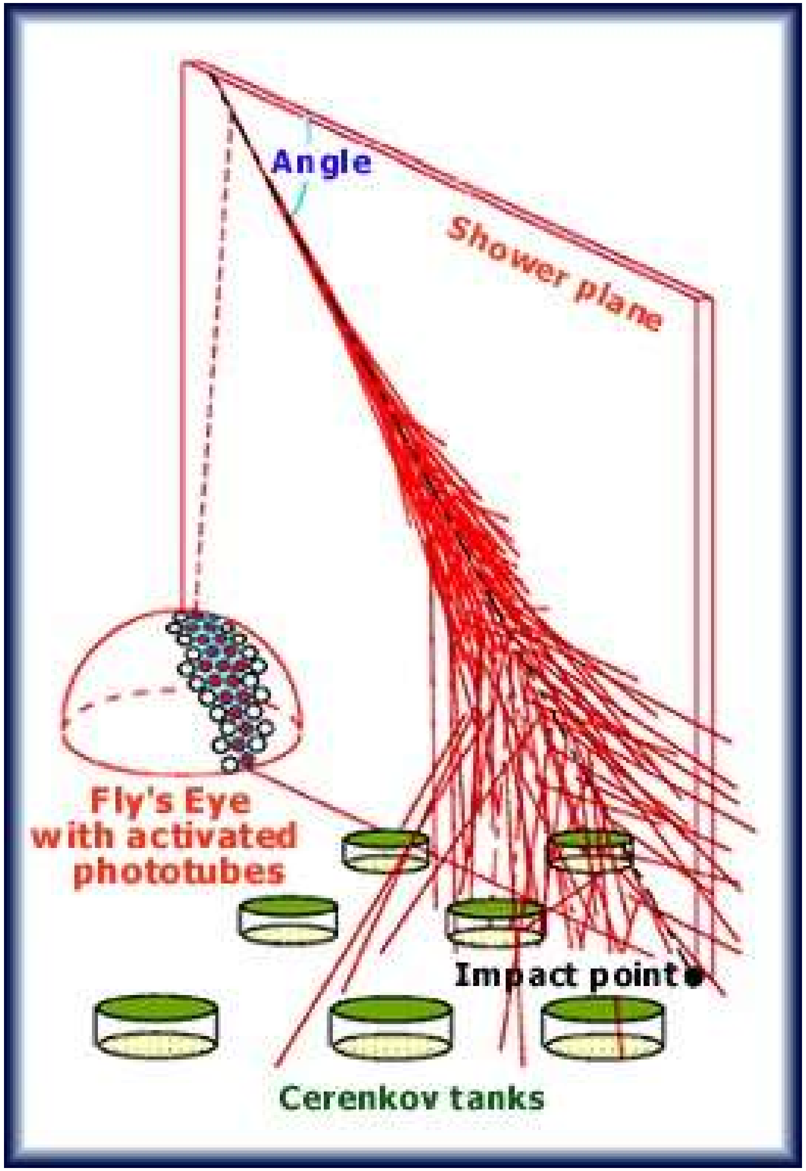
- optimisation of antennas ?

Detection of energetic cosmic rays (> 10^{15} eV)

- no direct measurements possible because of low intensity
- classical sampling technique using standard particle detectors
    - ⇒ expensive
    - ⇒ only information from the end of the cascade
- air fluorescence à la Fly's Eye
    - ⇒ requires clear moonless nights
    - ⇒ 10 % duty time only
- air Cherenkov imaging telescopes
    - ⇒ clear, moonless nights, low duty time

⇒ detection of geosynchrotron emission in the radio band !




Angle
Shower plane
Fly's Eye with activated phototubes
Impact point
Cerenkov tanks

Advantages of Radio Emission from Extensive Air Showers

- simple, robust, cheap detectors
- 24 hours/day operation (- thunderstorms)
- low attenuation
- integration over the whole air shower
- wide field of view

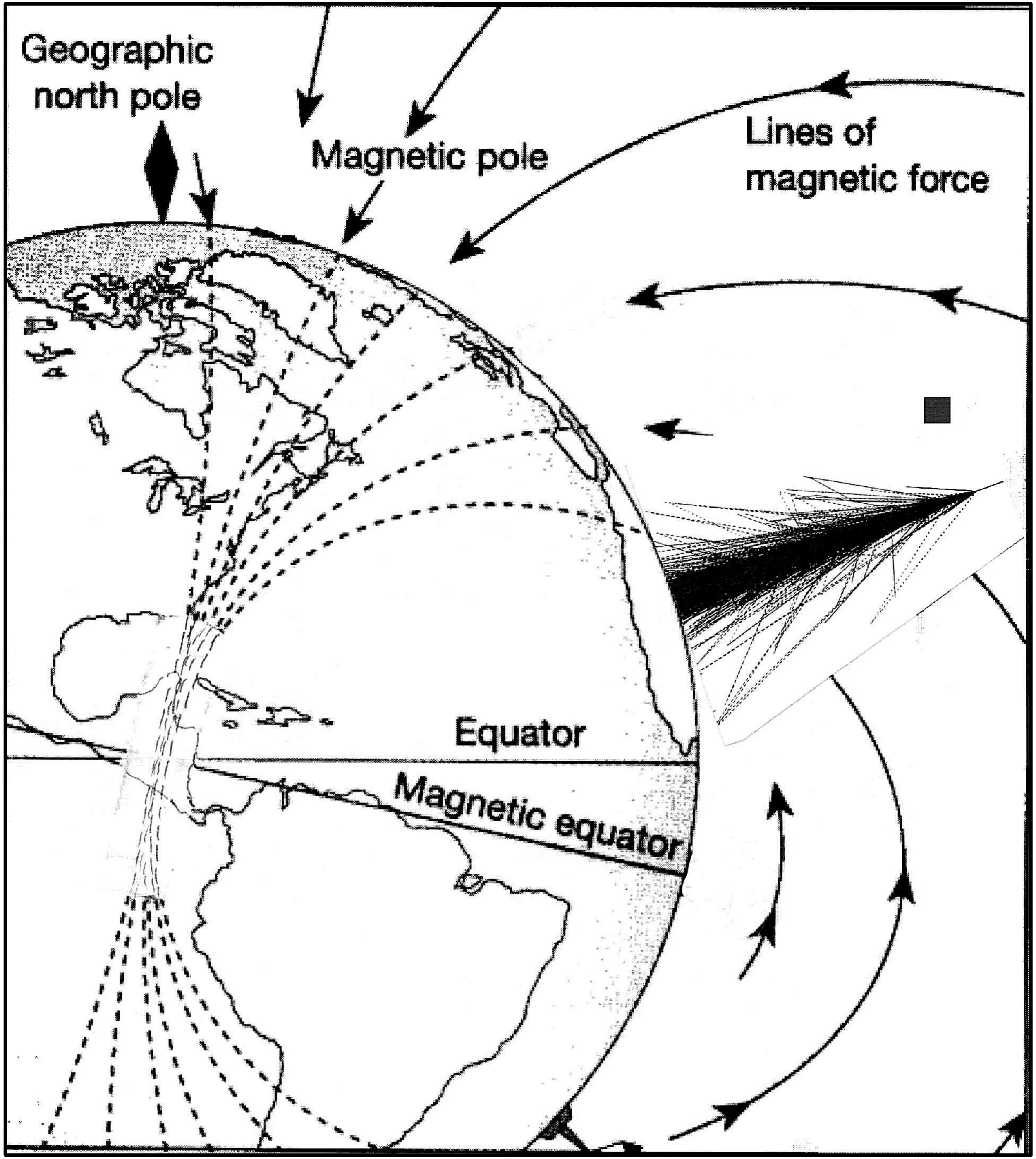
Potential Problems

- radio frequency interference

  ⇒ digital filtering techniques

- only practical at high energies ($\geq 10^{16}$ eV)


1
4
3
2

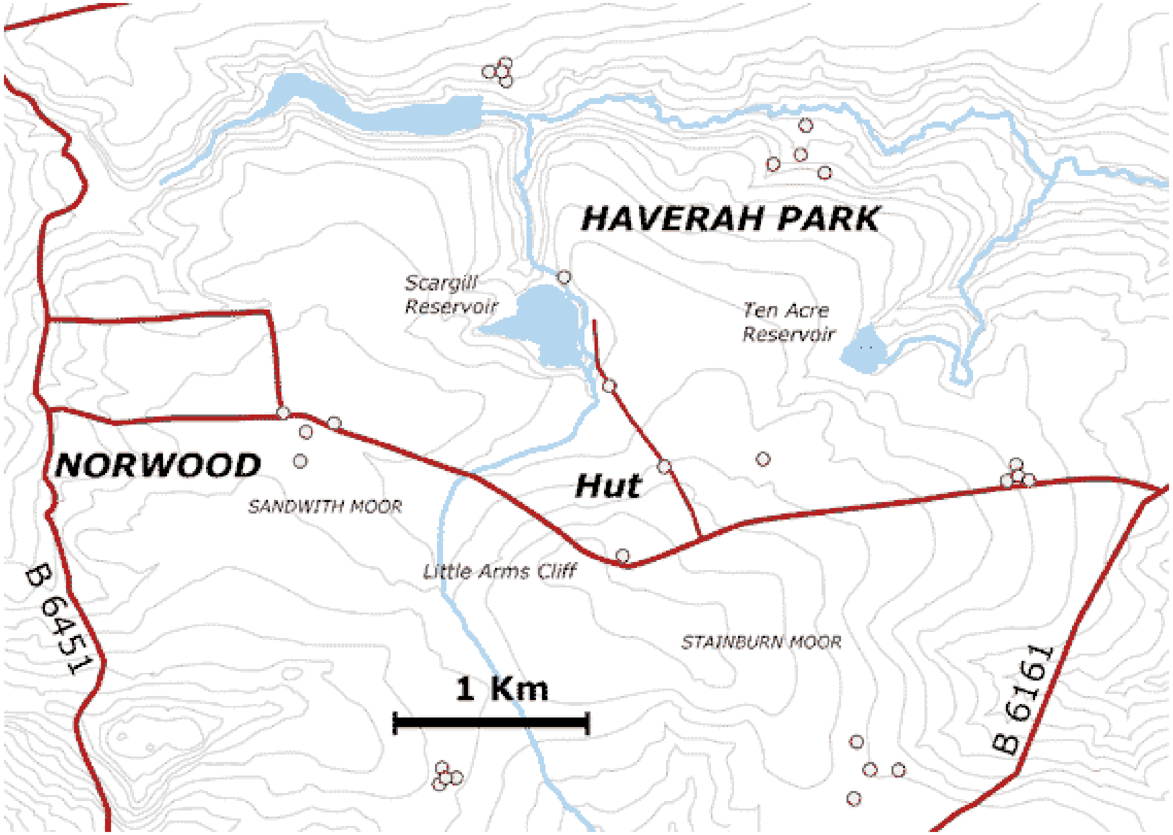

Geographic north pole
Magnetic pole
Lines of magnetic force
Equator
Magnetic equator

History

- discovery of radio emission: Jelley et al. (1965), Jodrell Bank
- theory: Kahn & Lerche (1968) and Colgate (1967)
- many activities in the late 60's and early 70's (Haverah Park)
- problem with radio interference
- poor time resolution (~ 1μ s)
- limited angular acceptance
- low statistics

Now: Monte Carlo code for geosynchrotron emission available (Huege & Falcke 2004/05)

Jelley et al. (1965)

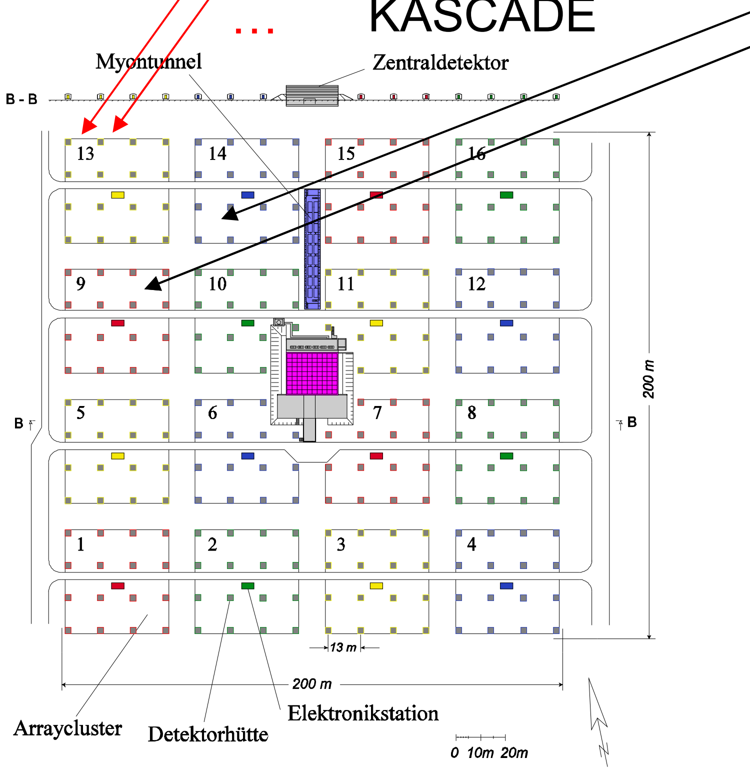

HAVERAH PARK
Scargill Reservoir
Ten Acre Reservoir
NORWOOD
SANDWITH MOOR
Hut
Little Arms Cliff
STAINBURN MOOR
B 6451
B 6161
1 Km

LOPES at KASCADE-Grande

LOPES – LOFAR Prototye Station,
LOFAR – Low Frequency Array)

KASCADE: ~250 electron & muon scintillator detector huts
LOPES30: 30 radio antennas
KASCADE Grande: expansion of KASCADE (red dots)

KASCADE



KASCADE Grande

KASCADE measures

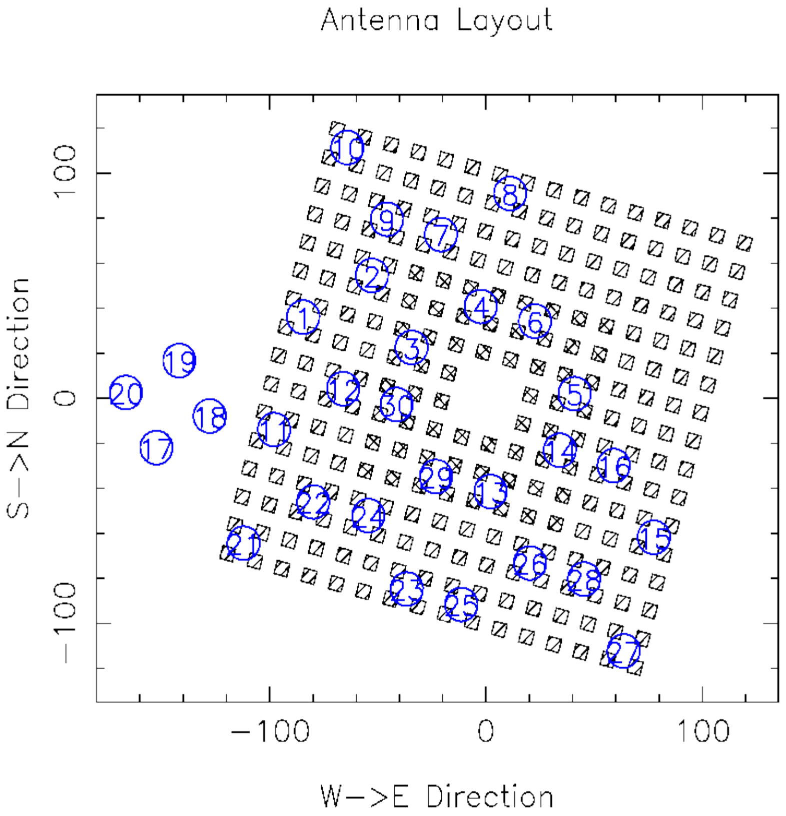
- electron component N_e
- muon component N_μ
- hadron component
- size: 200 x 200 m^2

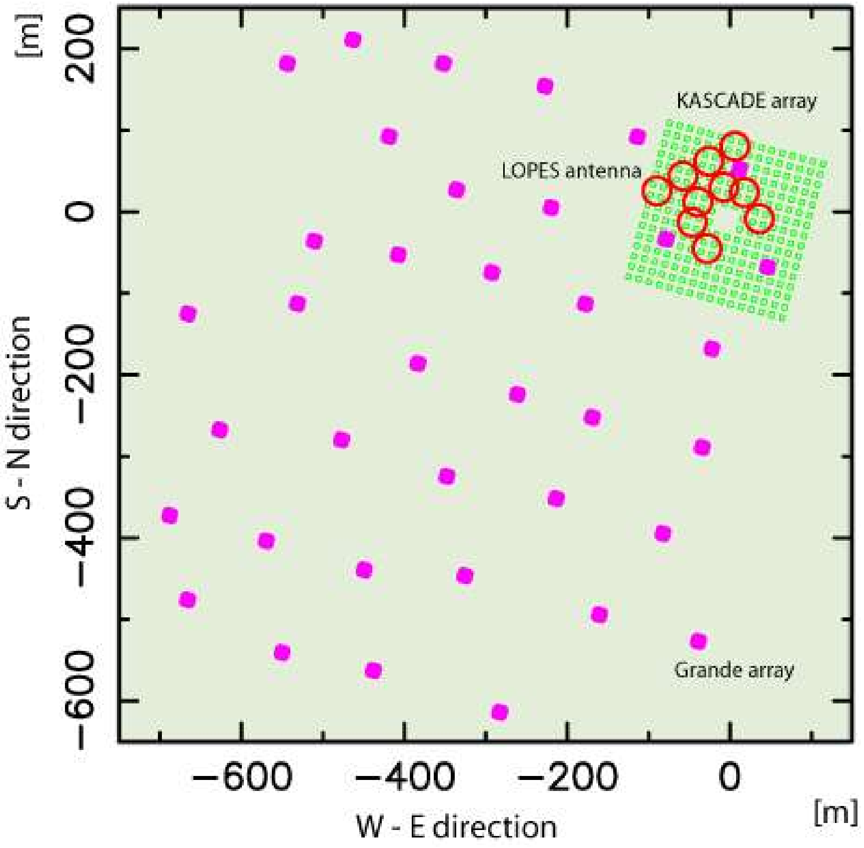
KASCADE Grande

+ 37 detector stations distributed over 800 x 800 m^2
each station with 10 m^2 scintillation counter.

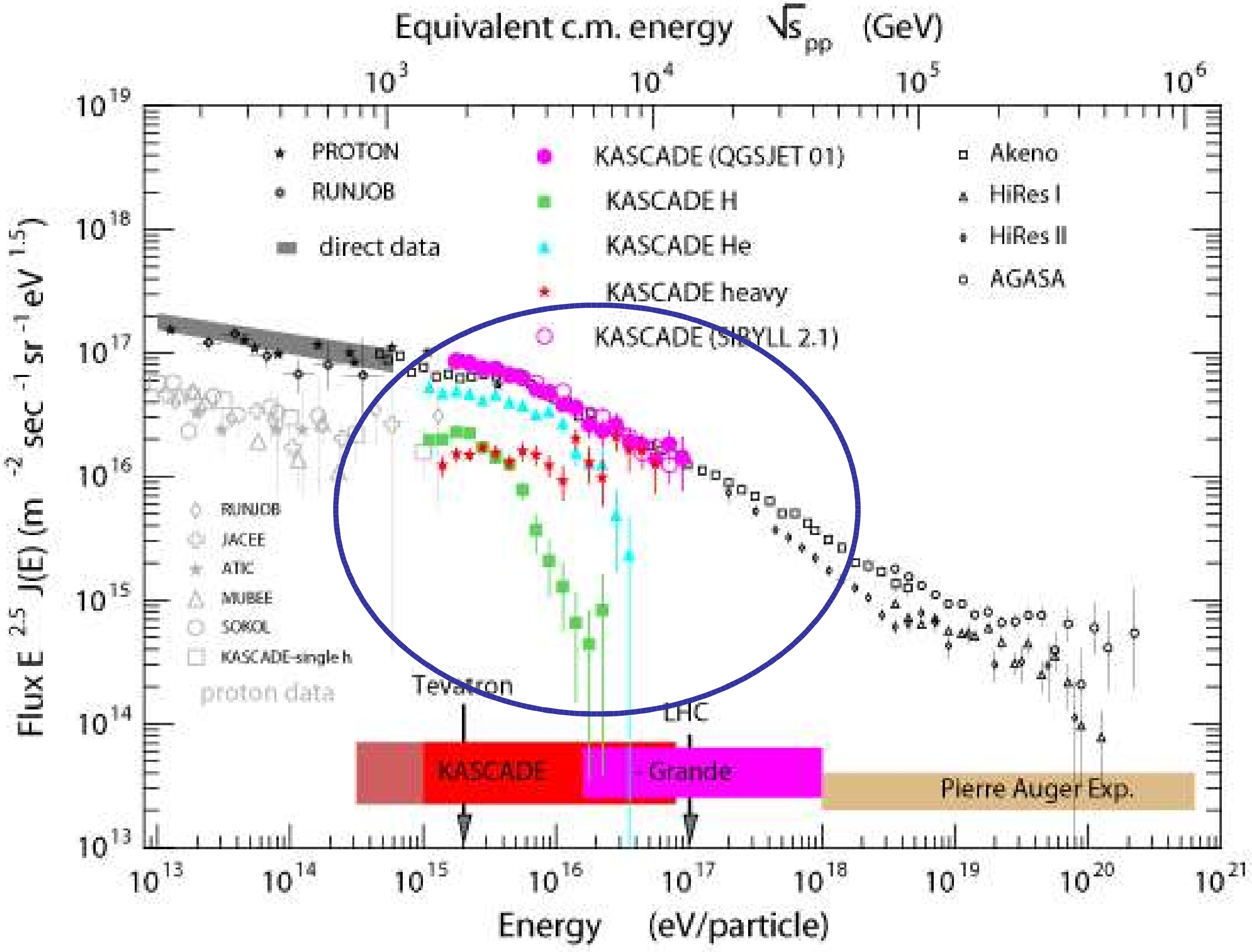
LOPES: current status

- 30 antenna prototype at KASCADE
  (all 30 antennas running)
- triggered by large event (KASCADE) trigger
  (10 out of 16 array clusters)
- offline correlation of KASCADE & LOPES
  (not integrated yet into the KASCADE DAQ)
- KASCADE can provide starting points for LOPES air shower reconstruction
  - core position of the air shower
  - direction of the air shower
  - size of the air shower




KASCADE array
LOPES antenna
Grande array
S - N direction
[m]
200
0
−200
−400
−600
−600
−400
−200
0
[m]
W - E direction

Cosmic Rays around the Knee:



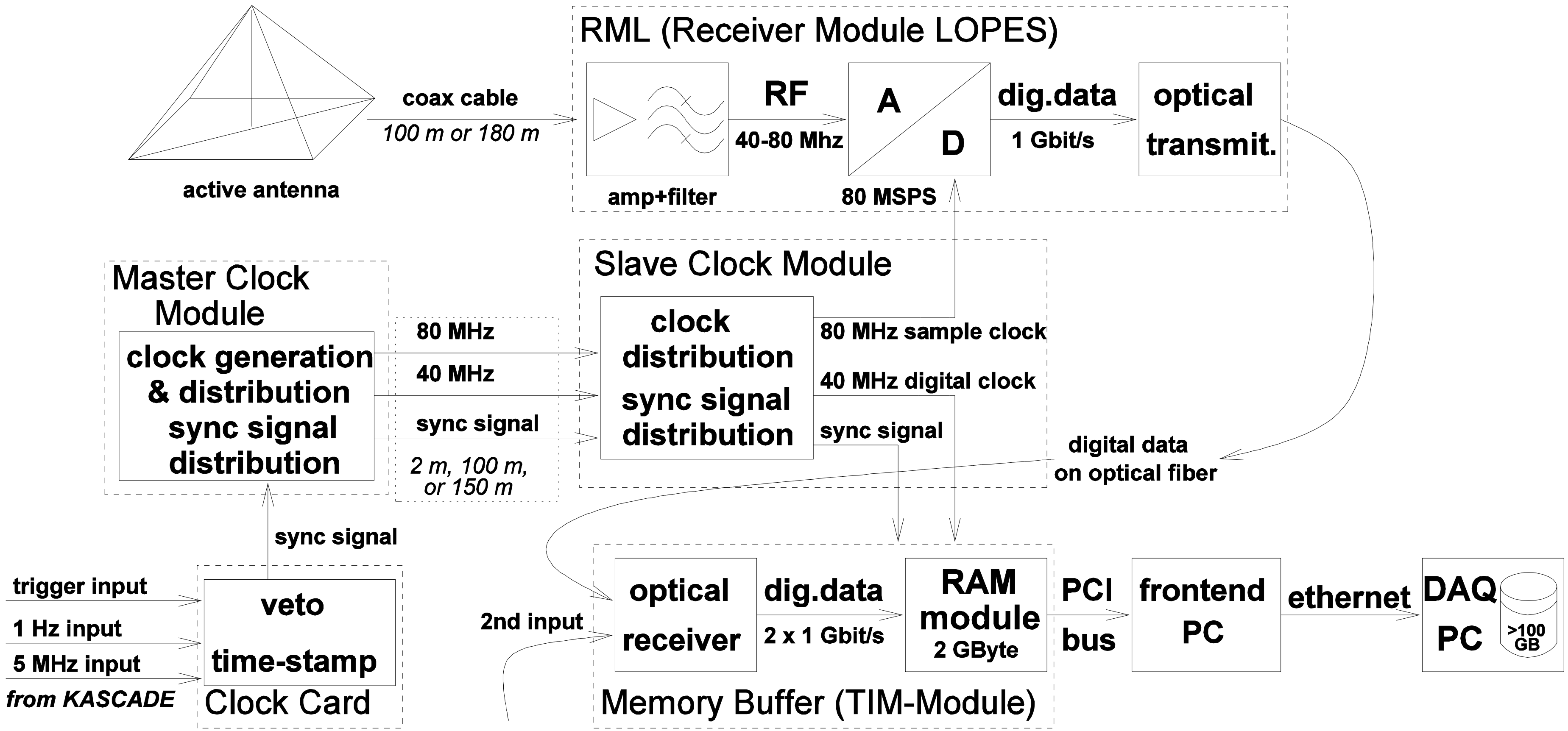
energy ?
mass ?
arrival directions ?
interaction mechanism ?

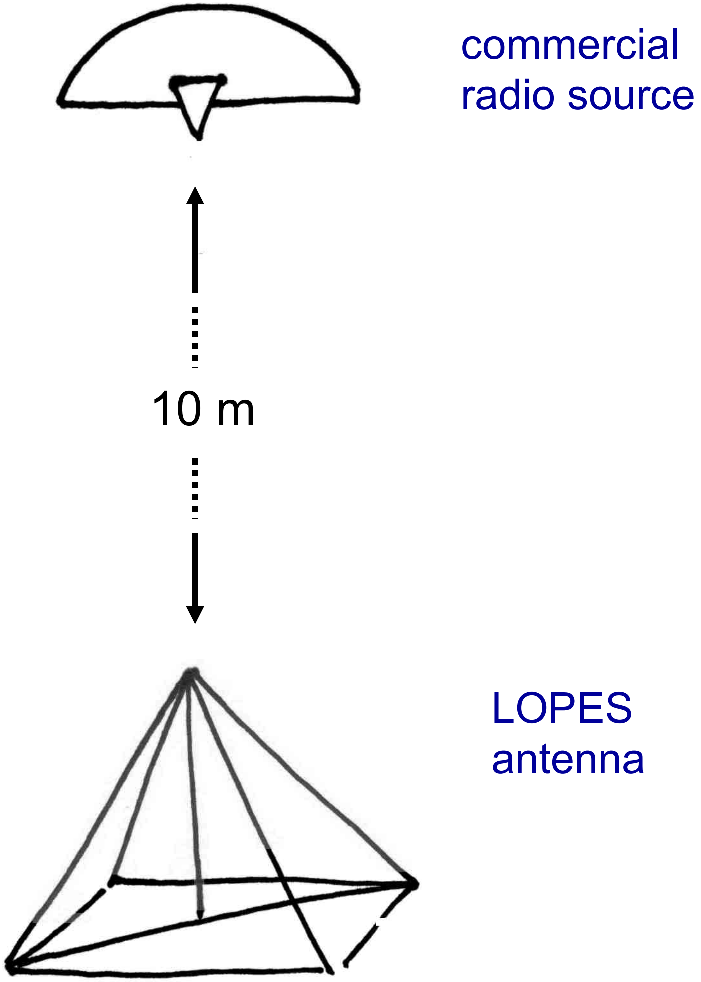
large number of observables

multi-detector system

direct measurements ← → **EAS measurements**

Hardware of LOPES





commercial radio source
VSQ 1000
(www.schaffner.com)

e.g. at ~ 55 MHz
~ $E \approx 80\ \mu V/(m \cdot MHz)$

variation of the frequency
in 1 MHz
5 MHz
10 MHz steps
sine wave signal

$\Rightarrow$ calibration factor for each individual antenna

Data Processing

steps of the data processing:

1. instrumental delay correction from phase information
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. optimizing radius of curvature
8. quantification of peak parameters

Status of LOPES

- data available since January 2004
  triggered by KASCADE
- $> 10^6$ events archived
- offline correlation of KASCADE & LOPES events
- KASCADE provides starting point for LOPES air shower reconstruction
  - core position
  - direction of the shower axis
  - size (and energy) of the air shower
- expected radio yield (electric field)

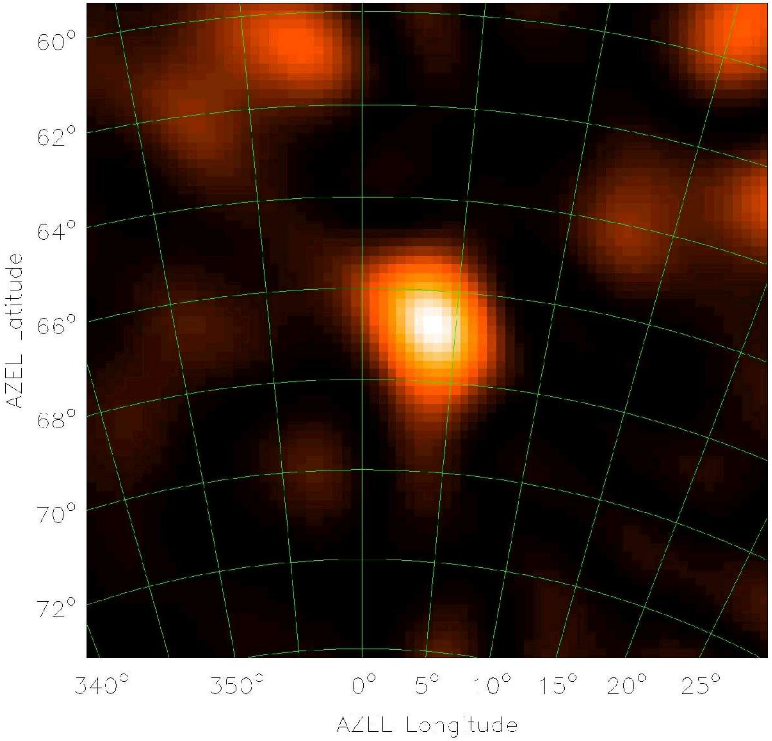
$$\varepsilon_\nu = 20 \left(\frac{E_p}{10^{17}\,\mathrm{GeV}} \right) \sin\alpha \;\cos\theta \;\exp\left\{ \frac{-R}{R_0(\nu,\theta)} \right\} \left[\frac{\mu V}{m\,\mathrm{MHz}} \right]$$

E_p – primary energy

θ – Zenith angle of the shower axis

α – angle relative to the geomagnetic field

R_0 – distance parameter

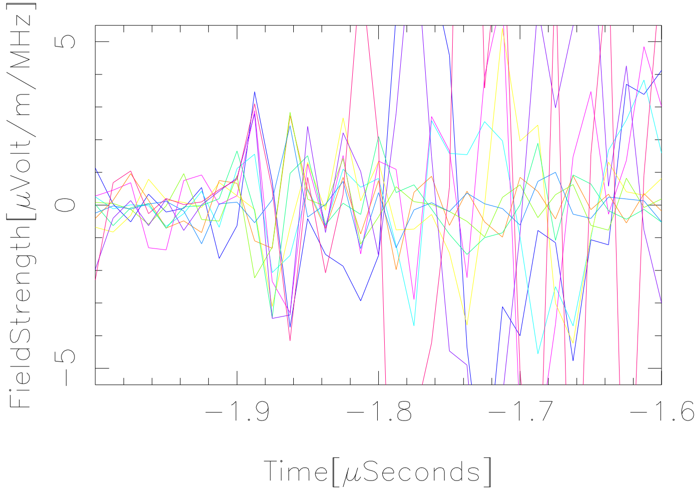


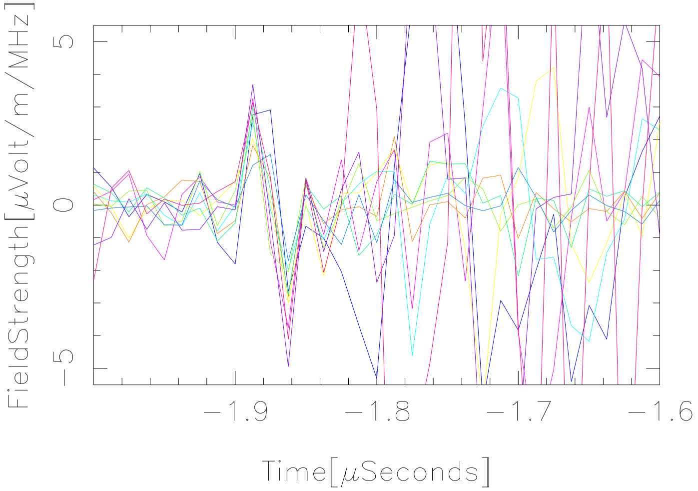
- typical amplitudes for
  40 – 80 MHz
  $R \sim R_0$
  $E_p = 10^{17}$ eV
  $\theta = 50°$
  $\alpha = 50°$

$\varepsilon_\nu \sim 4\,\mu\,V / m\,MHz \approx 150\,\mu\,V / m$

primary energy $E \sim \varepsilon^2_\nu$ (radio power ~ electric field²)

Radius of curvature

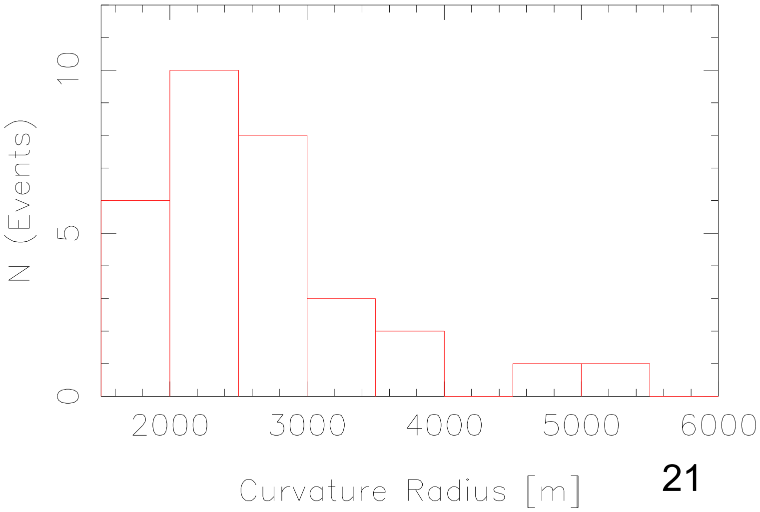

Plane Wave


Sphere

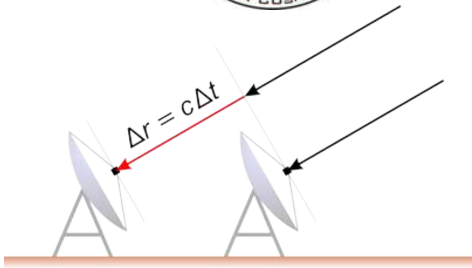
plane wave doesn't fit the data

sphere with finite radius of curvature is better

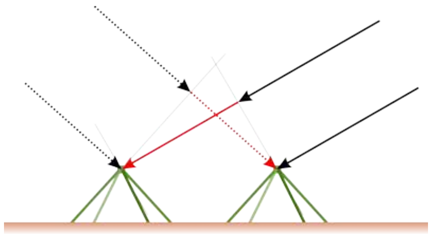
makes radio data sensitive to position of shower center

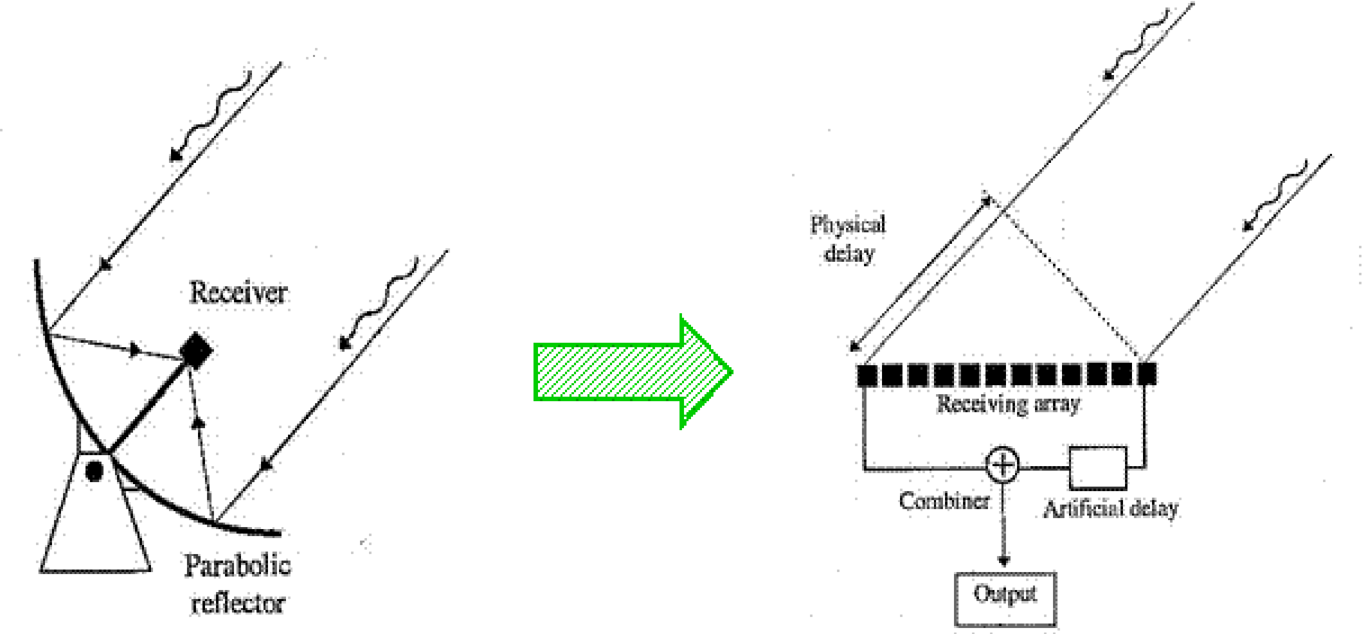


How does the beam forming work ?



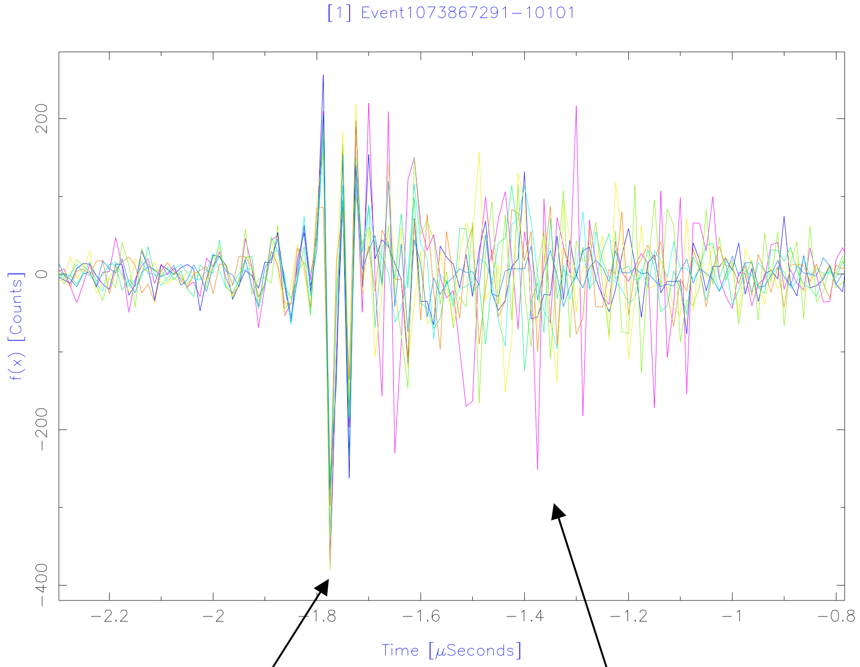
- A parabola antenna looks only at one point in the sky
- A radio antenna array looks in all directions at once!
  - for a special direction the signals are phased by adjustable delays.
  - offline, many different directions can be tested.





Signal Detection

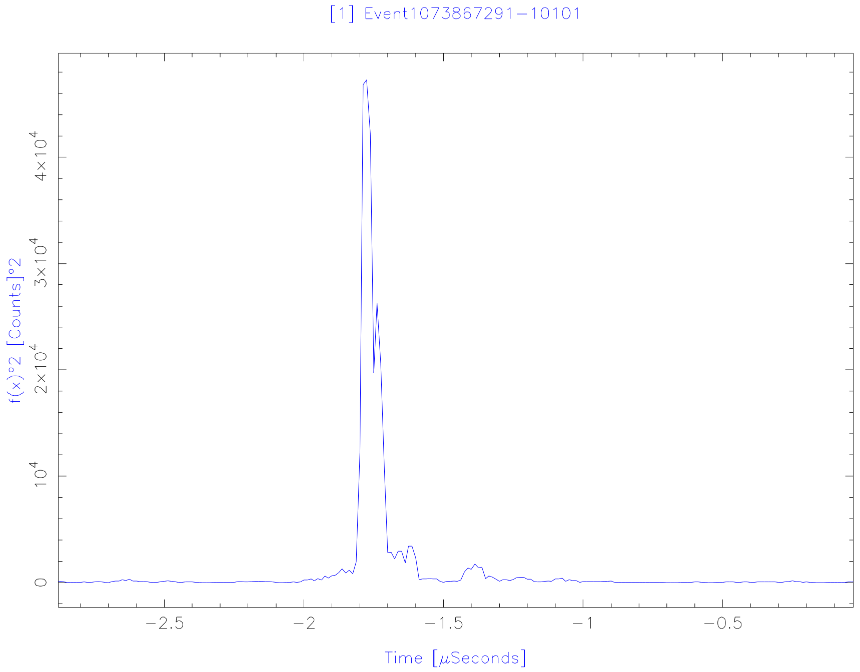
Electric field at each antenna corrected for arrival direction of CR



coherent
(CR)

incoherent
(detectors)

Sum of delay-corrected E-field from all antennas, squared



Event Selection

1. choice

core distance < 91 m
zenith angle < 40°
number of electrons $< 5 \cdot 10^6$
primary energy $\geq 10^{17}$ eV

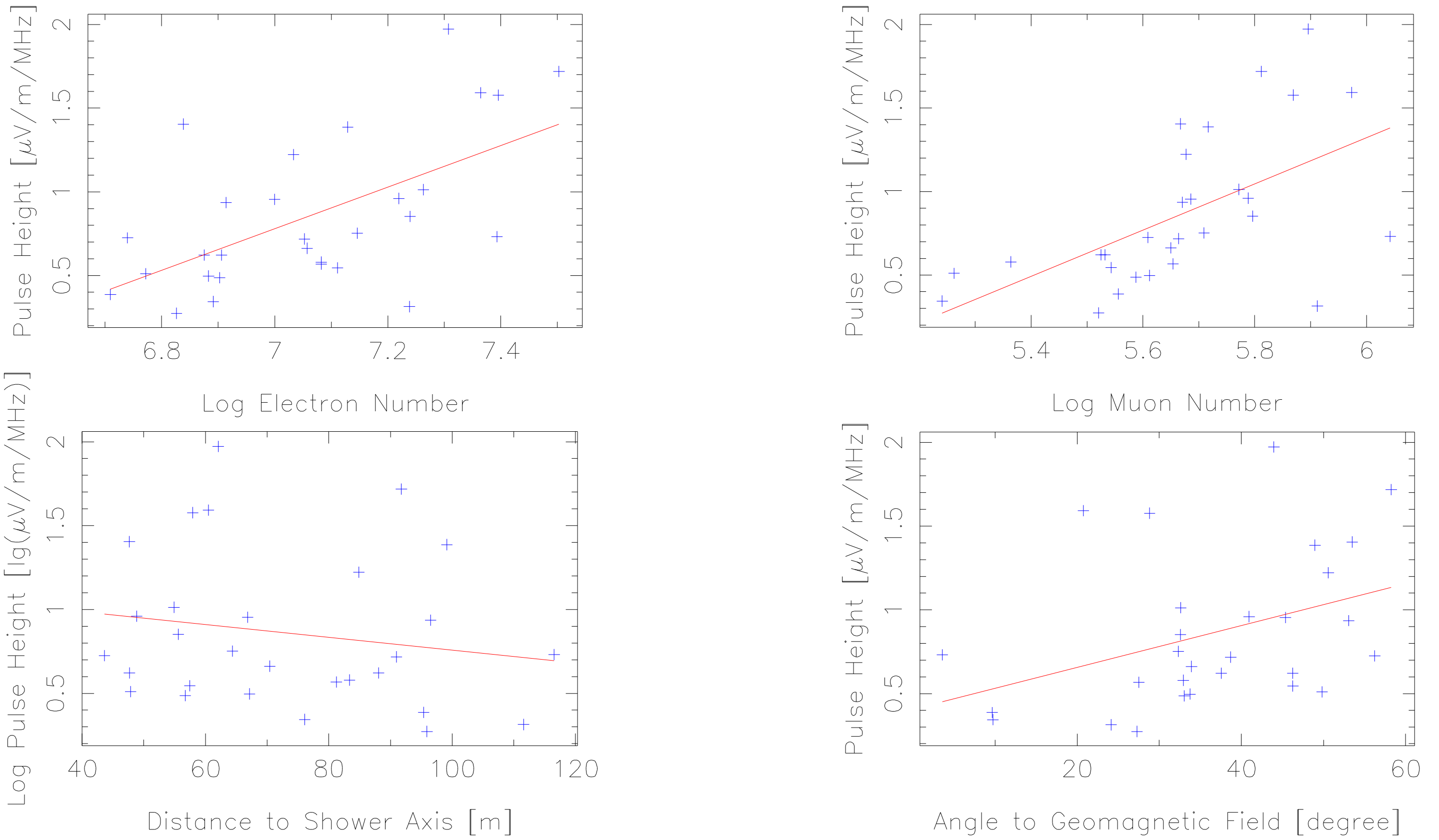
} from KASCADE

⇒ 89 KASCADE events
33 detected by LOPES

⇒ Raw Data show some reasonable features

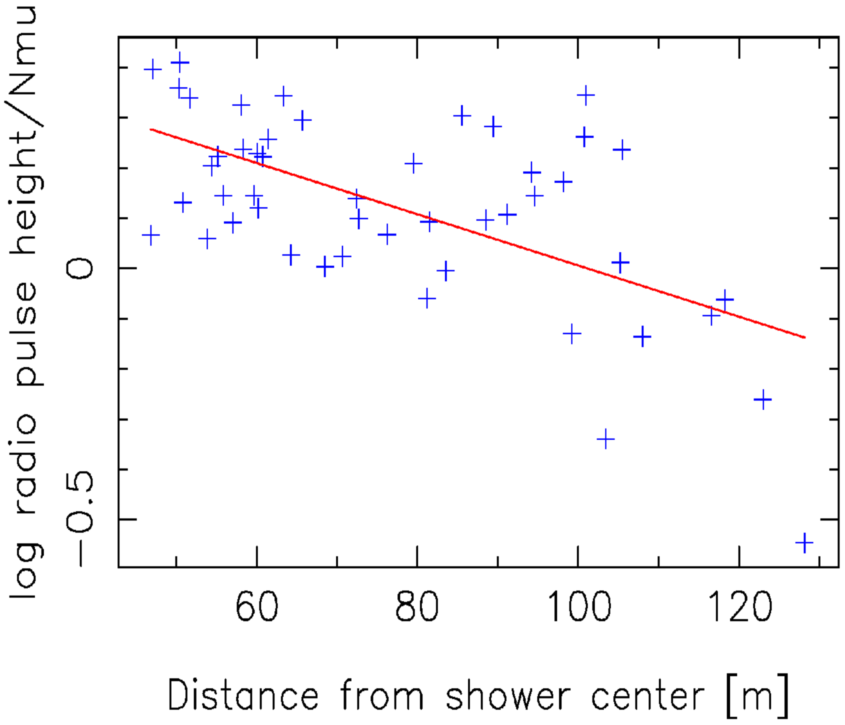
Dependencies: Raw Data

Pulse height should depend simultaneously (!) on a number parameters: number of electrons, number of muons, distance to the shower axis, and angle to the geomagnetic field

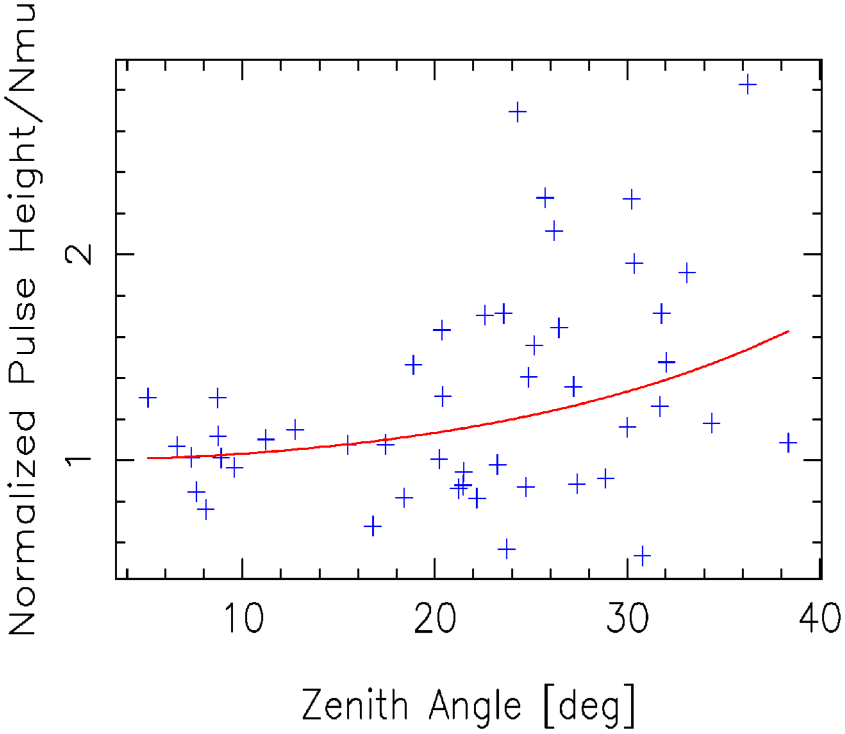


First Statistical Results

lateral distribution

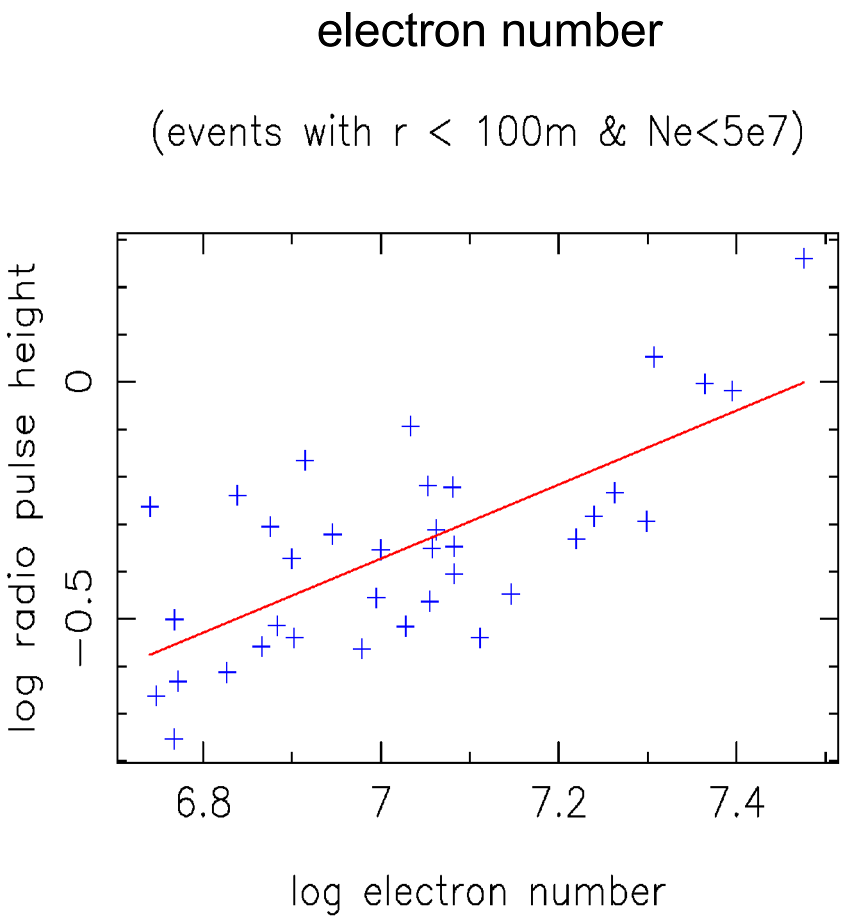


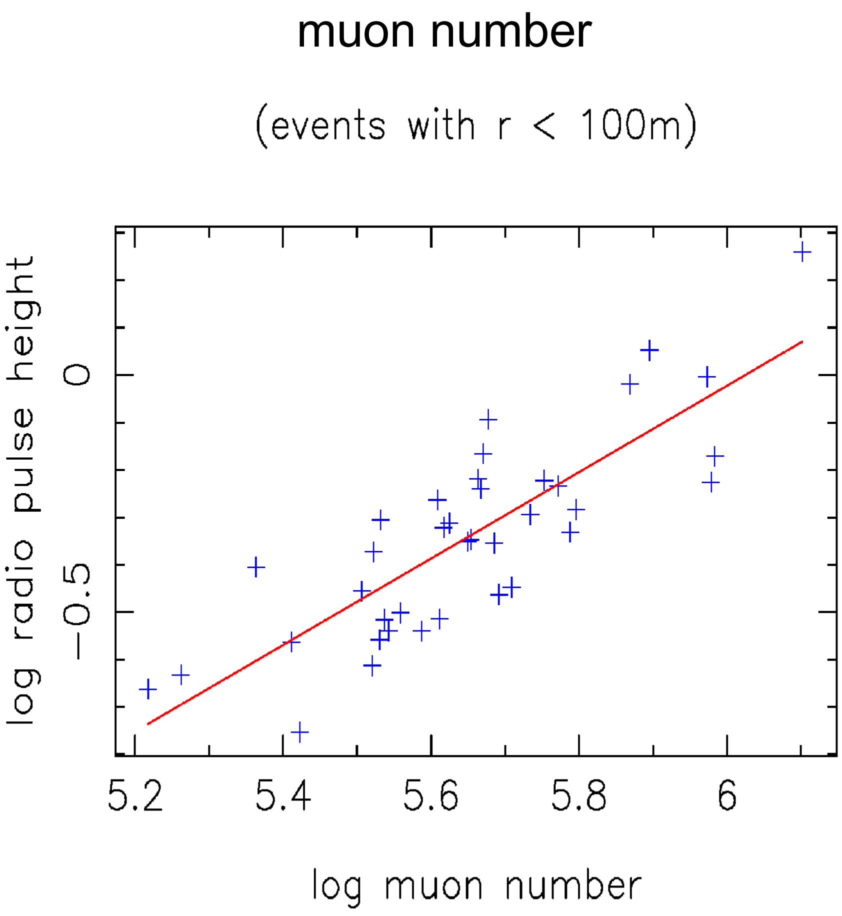
Inclination?



First Statistical Results

(trial correction for inclination and radius)





Radio scales better with muons than with electrons (measured on the ground!)

2. choice of parameters

core distance < 91 m
$N_e > 5 \cdot 10^5$ or $N_\mu > 2 \cdot 10^5$
no cut on zenith angle

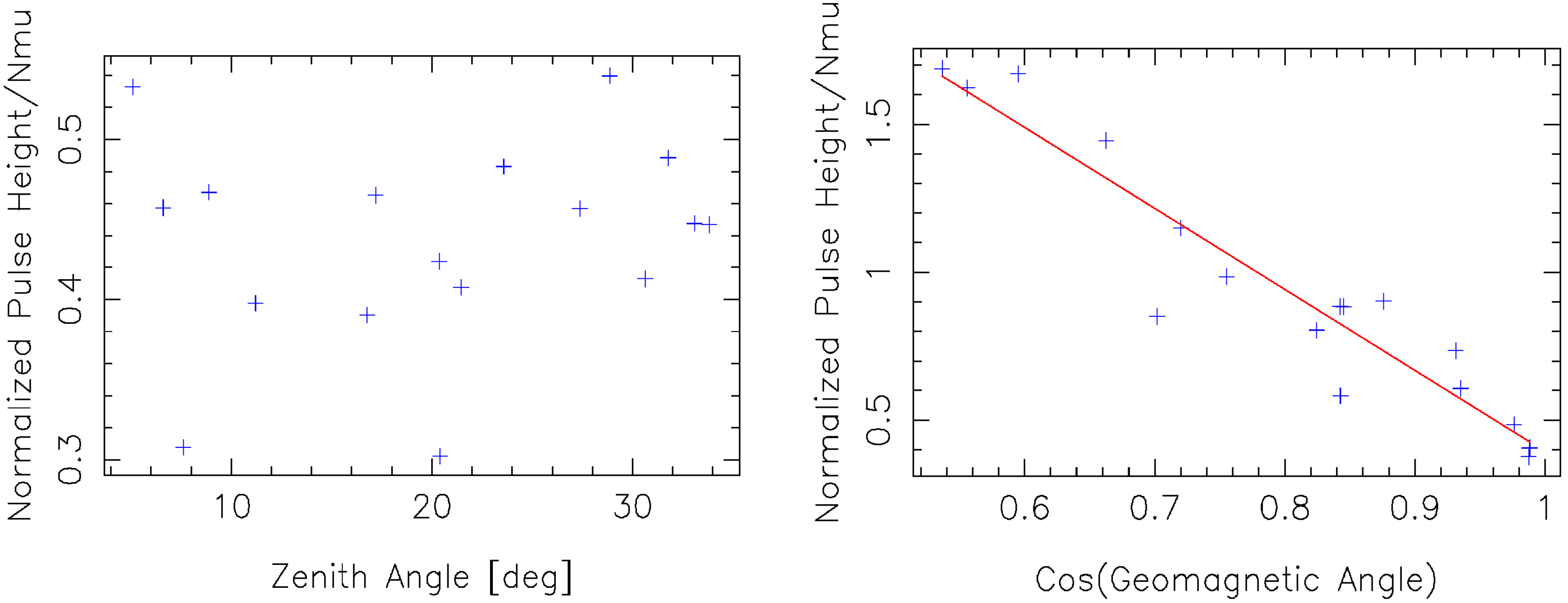
⇒ 247 KASCADE events
134 detected by LOPES

essentially all inclined showers are detected

all events with $N_\mu > 4 \cdot 10^5$ detected

New Selection:
Geomagnetic vs Zenith Angle!

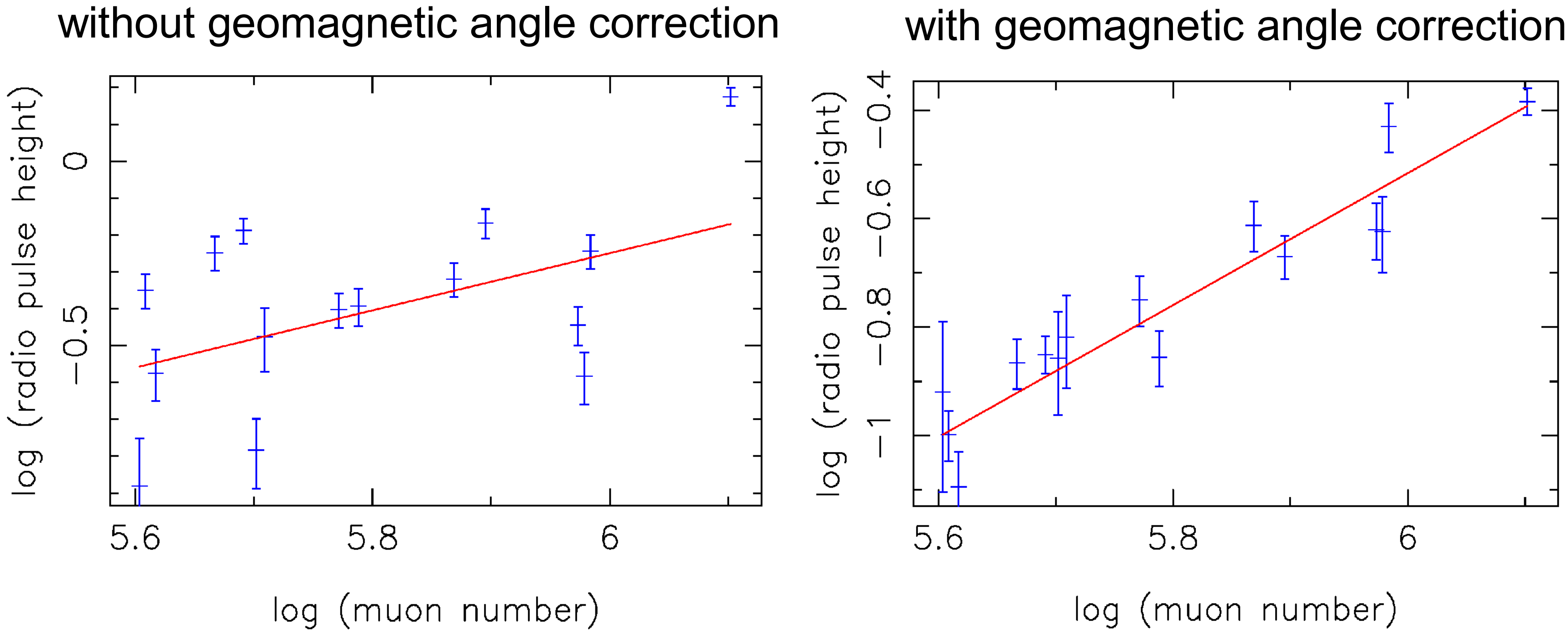
All events with muon number >4×10^5 (to have sure detections)
and R<70 m (to avoid fiddling with radius effects) → 17 events



⇒ Dependence on angle to Earth magnetic field is strongest effect!

New Selection:
Geomagnetic Angle Correction

radio vs. muon number:



without geomagnetic angle correction

with geomagnetic angle correction

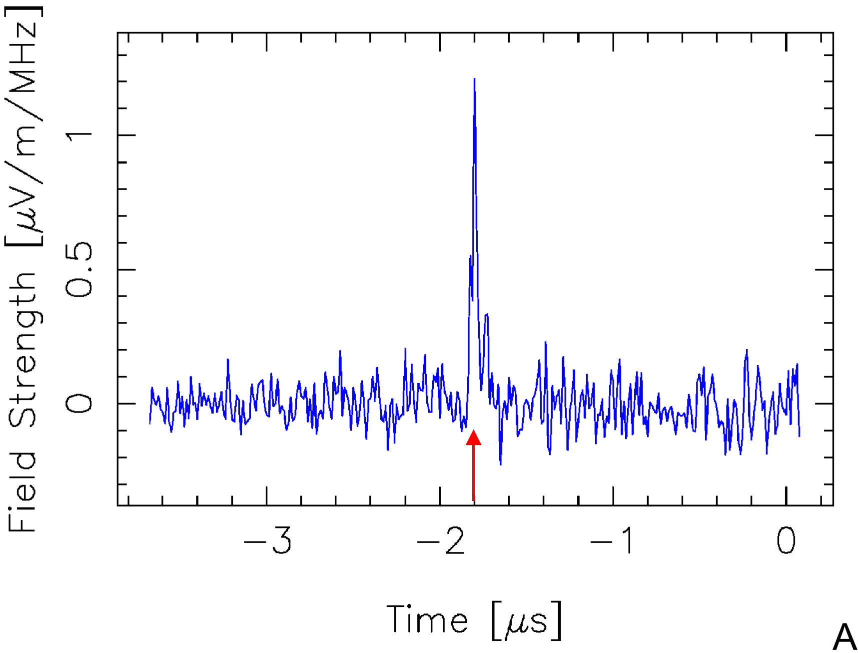
⇒ E-field scales linearly with primary particle engery

⇒ Power (E-field^2) scales quadratically

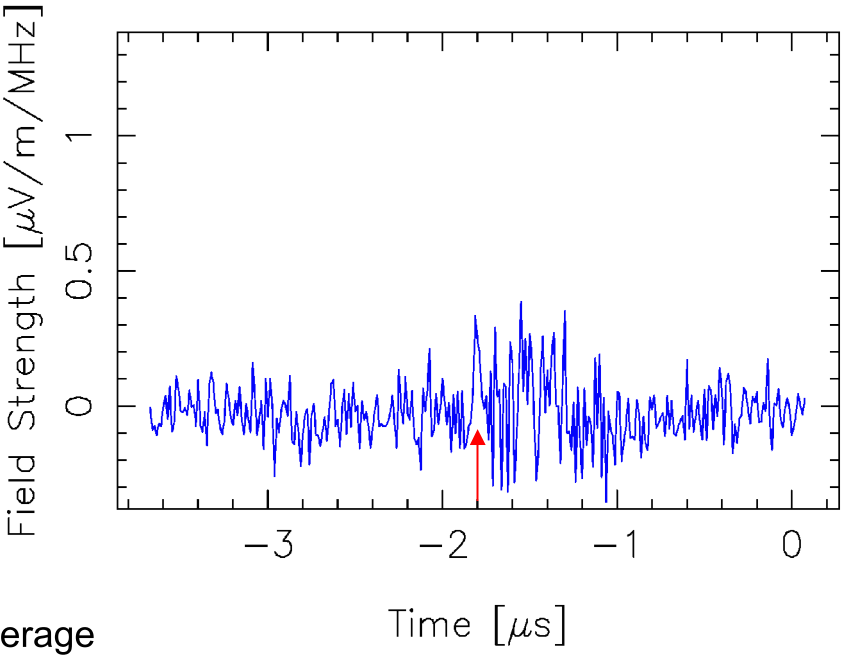
New Selection: Inclined Showers

Sum of all showers with …

… zenith angle >45°
(8 events, 7 detected)



… zenith angle <6°
(8 events, 1 detected)



Average muon number ~3×10^5

Results

angular resolution: better than 1°

width of the radio cone: < 2°

duration of the radio flash: ≤ 45 ns

emission is coherent, origin: geosynchroton effect

radio pulse height correlated with

- geomagnetic angle
- muon number

inclined showers are brighter than vertical ones

Summary

LOPES has verified the geosynchrotron emission of extensive air showers

with digital filtering and beam forming the radio pulses can be measured even in a radio loud environment

Pulse height $\sim$ N_μ , not so well correlated with N_e

Pulse height depends on the angle to the geomagnetic field

core position determination

angle of incidence determination

successful prototype experiment

LOFAR, AUGER-experiment

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LOPES

Radio Emission from Cosmic Ray Air Showers

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