Karlsruher Institut für Technologie

Radio detection of cosmic ray air showers with LOPES

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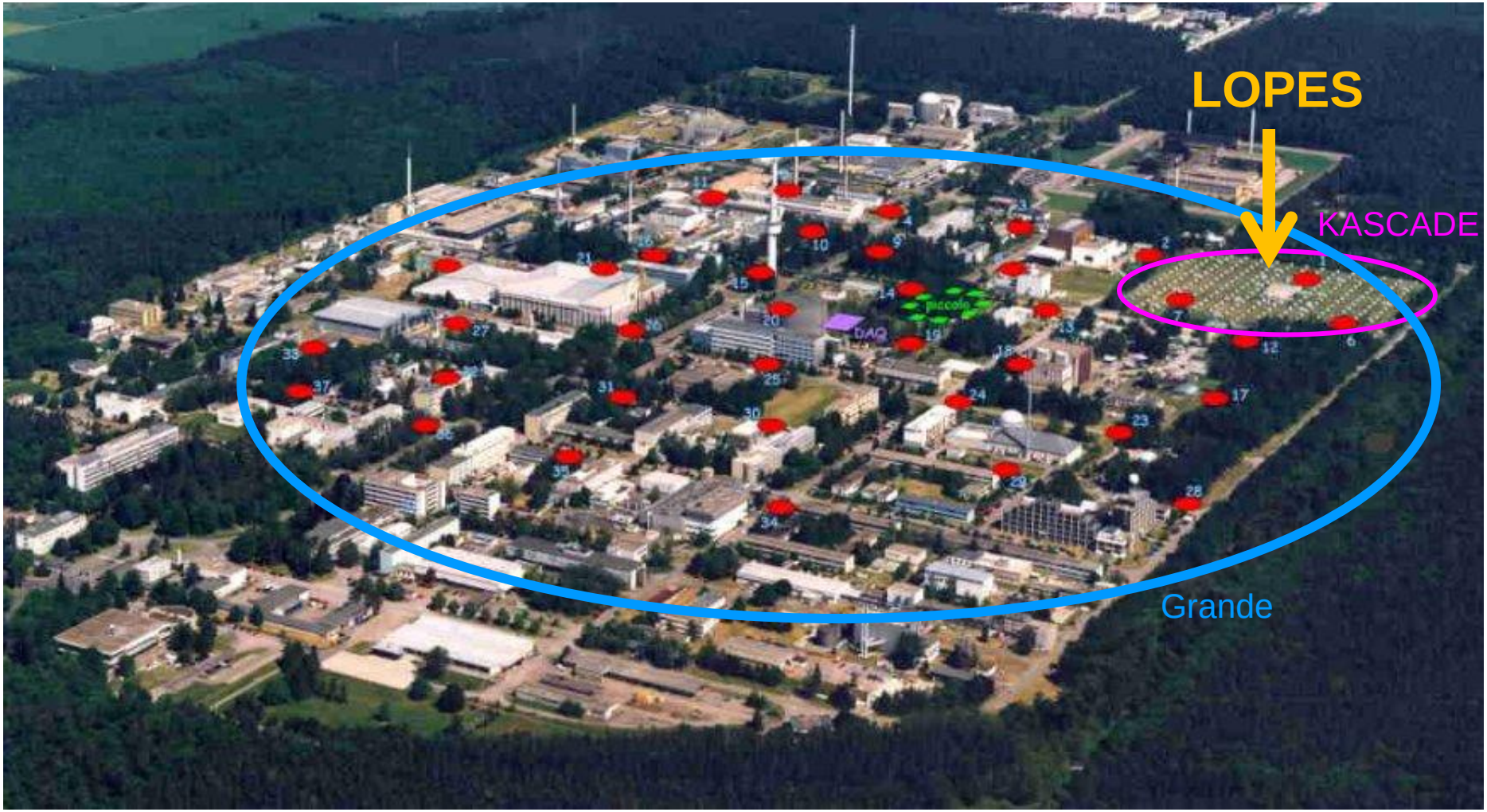
LOPES collaboration

DESY Zeuthen, 24 February 2010

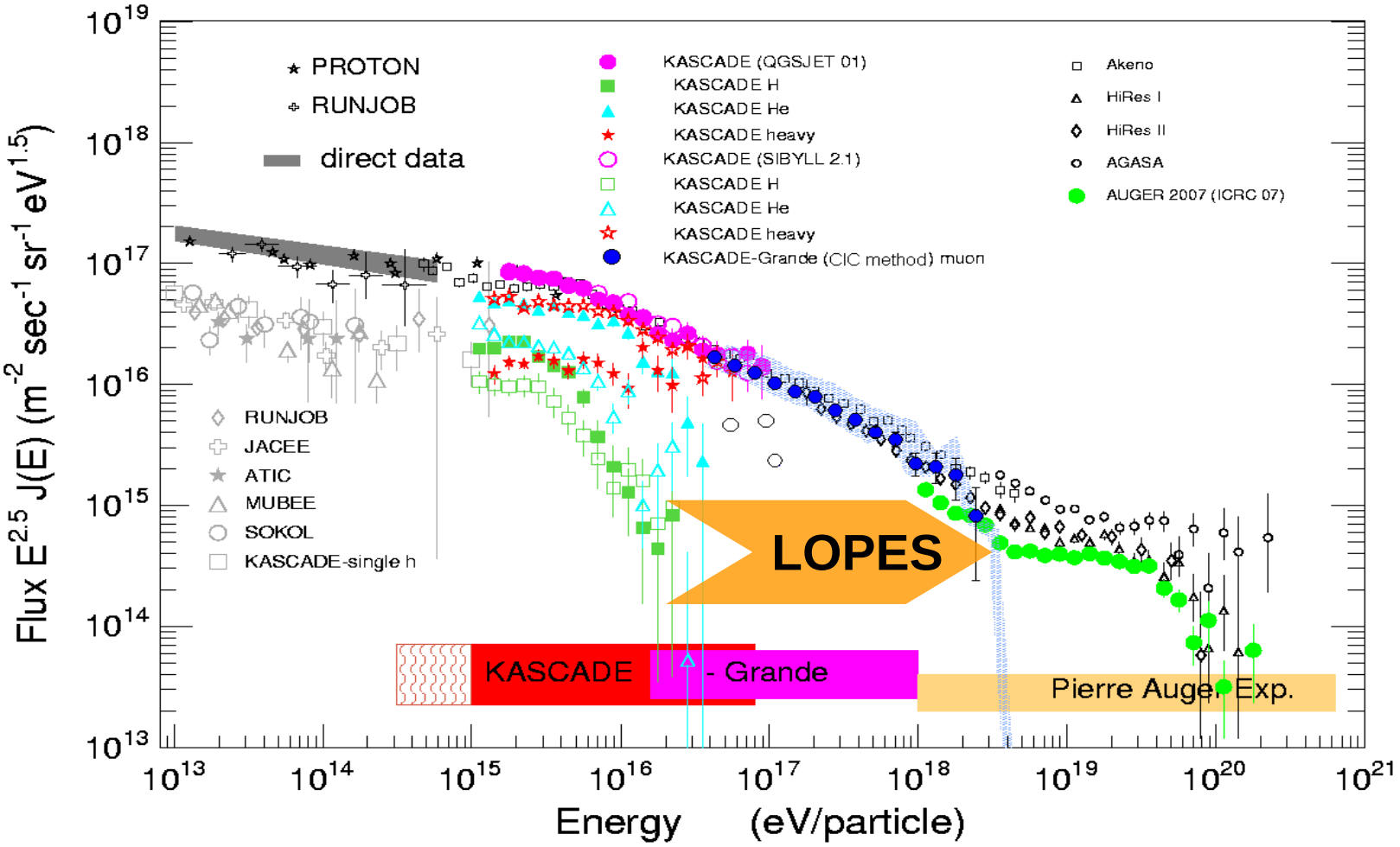
Contents

- Introduction into LOPES
- Data acquisition / processing
- Reconstruction capabilities (direction, energy)
- Results based on
  - Beam-forming
  - Individual antennas (lateral distribution)
- Outlook
  - Future developments and analysis

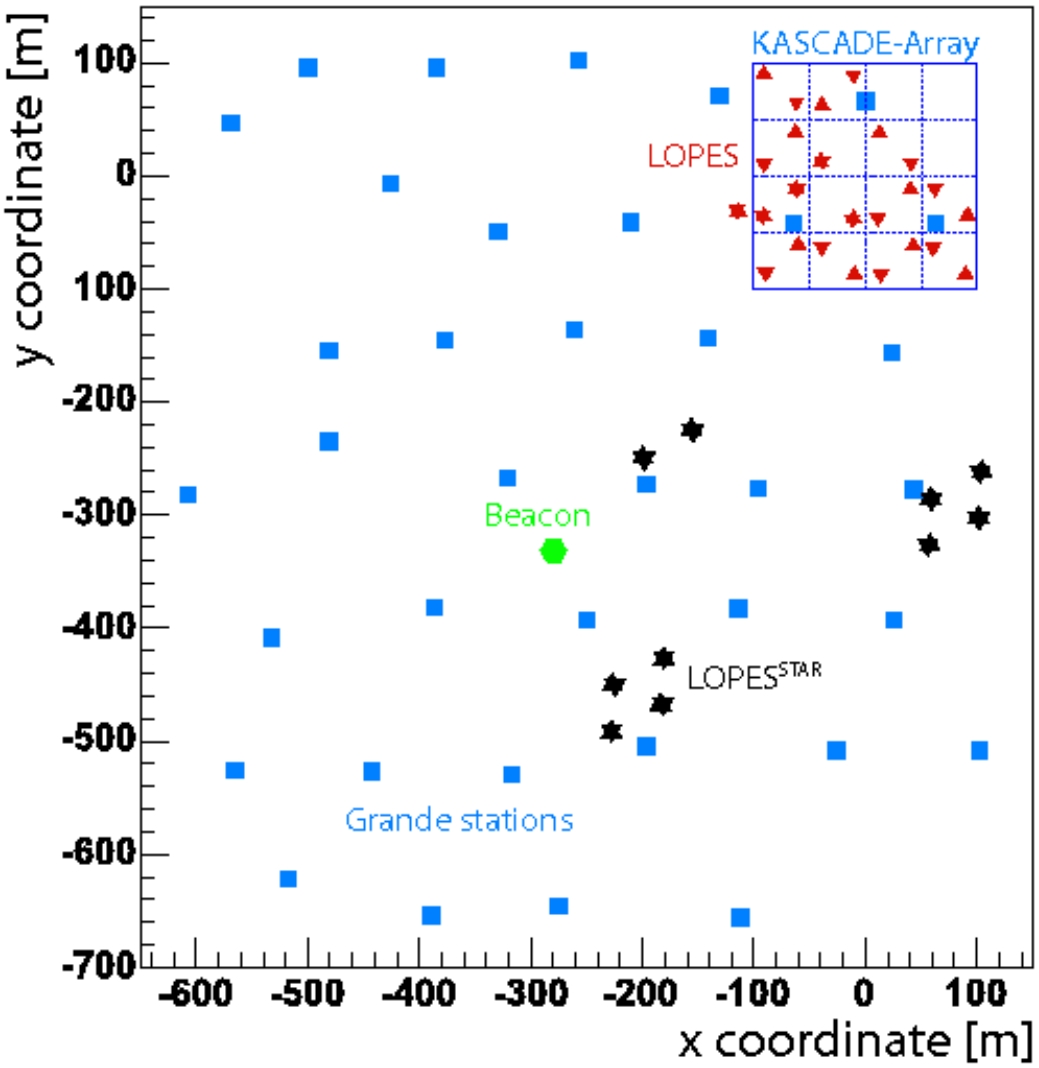
LOPES at KIT Campus North



Energy spectrum



LOPES: Layout until 2009



- 30 dipole antennas within KASCADE
- Lateral extension about 200 m
- Polarization
  - 15 east-west
  - 15 north-south
- 10 Auger prototype antennas
- Now (2010): Tripole antennas

Data Acquisition

- Trigger: KASCADE-Grande
- Frequency Range: 40 – 80 MHz
- Digital 80 MHz ADC
- Trace length ~ 800 µs
  - good frequency resolution
- Digital data treatment
  - noise suppression
  - amplitude calibration
  - time calibration
  - up-sampling

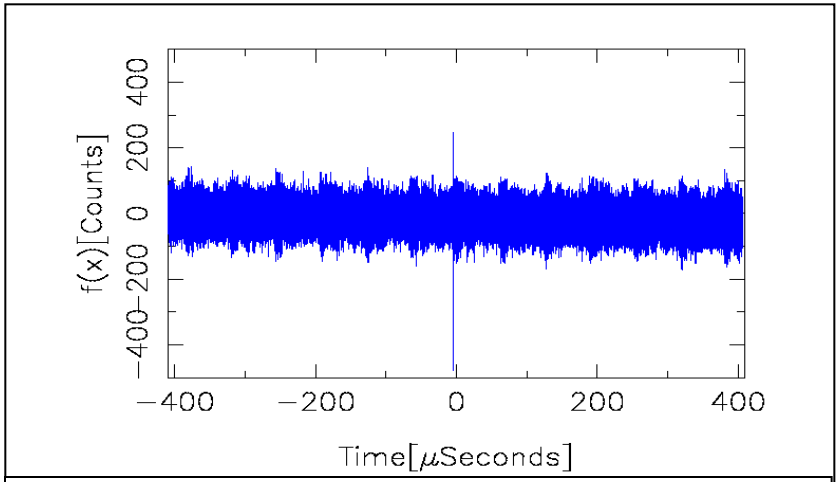
LOPES antenna

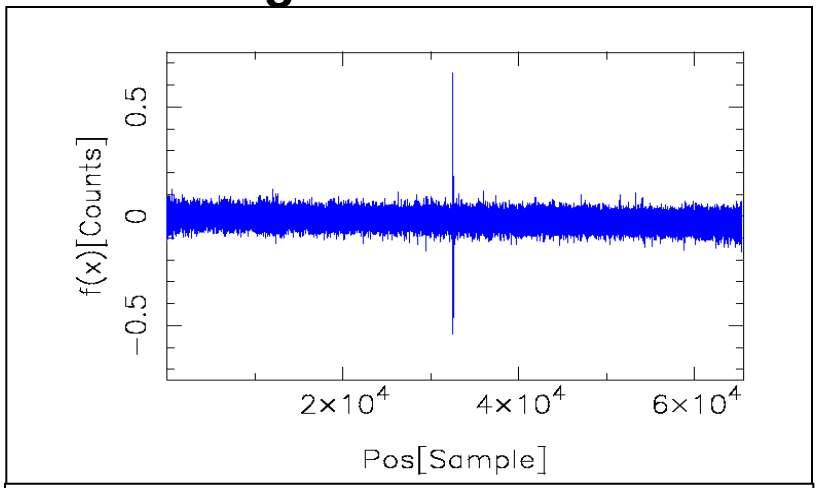
Noise (RFI) Suppression

raw data

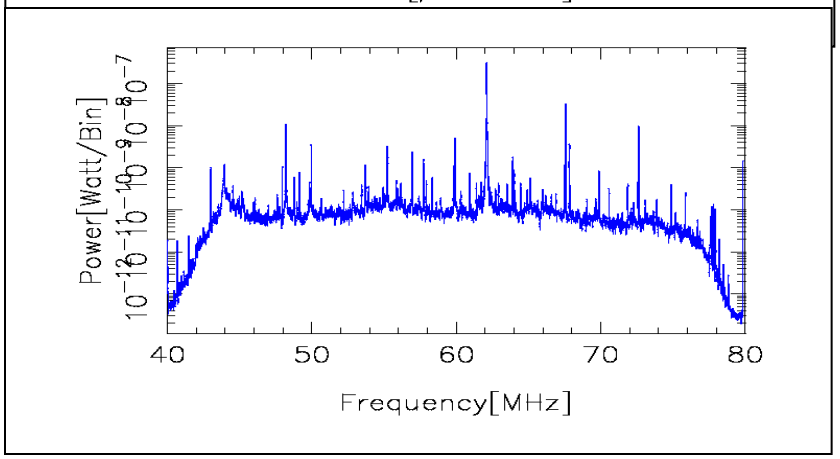
digital filtered data

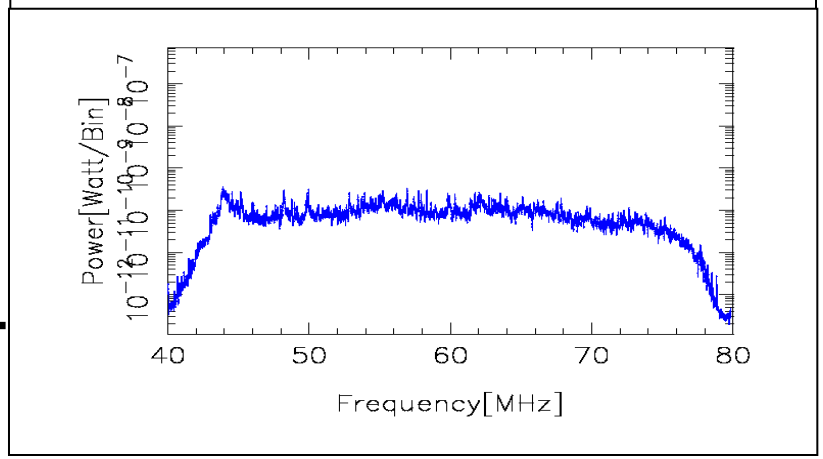
time series





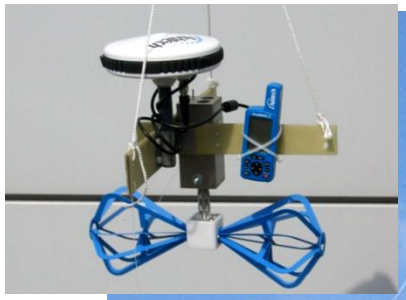
frequency spectrum

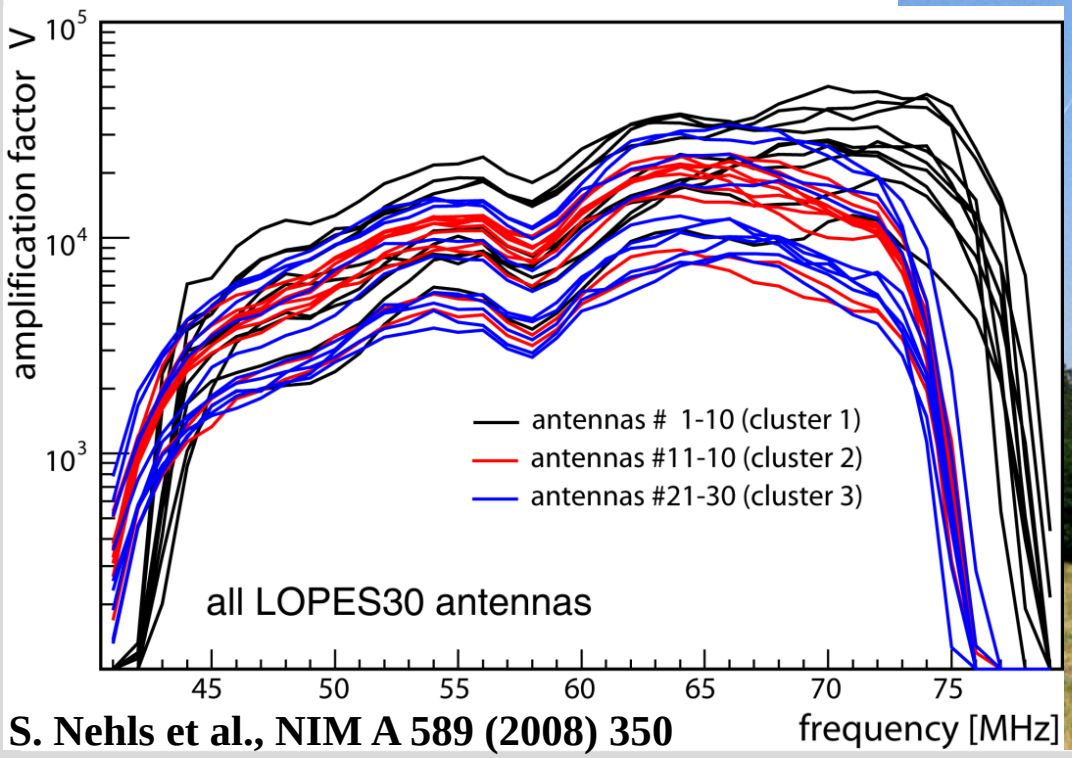




Amplitude Calibration

- Accuracy (power):
  - 20 % syst. error
  - 67 % reference

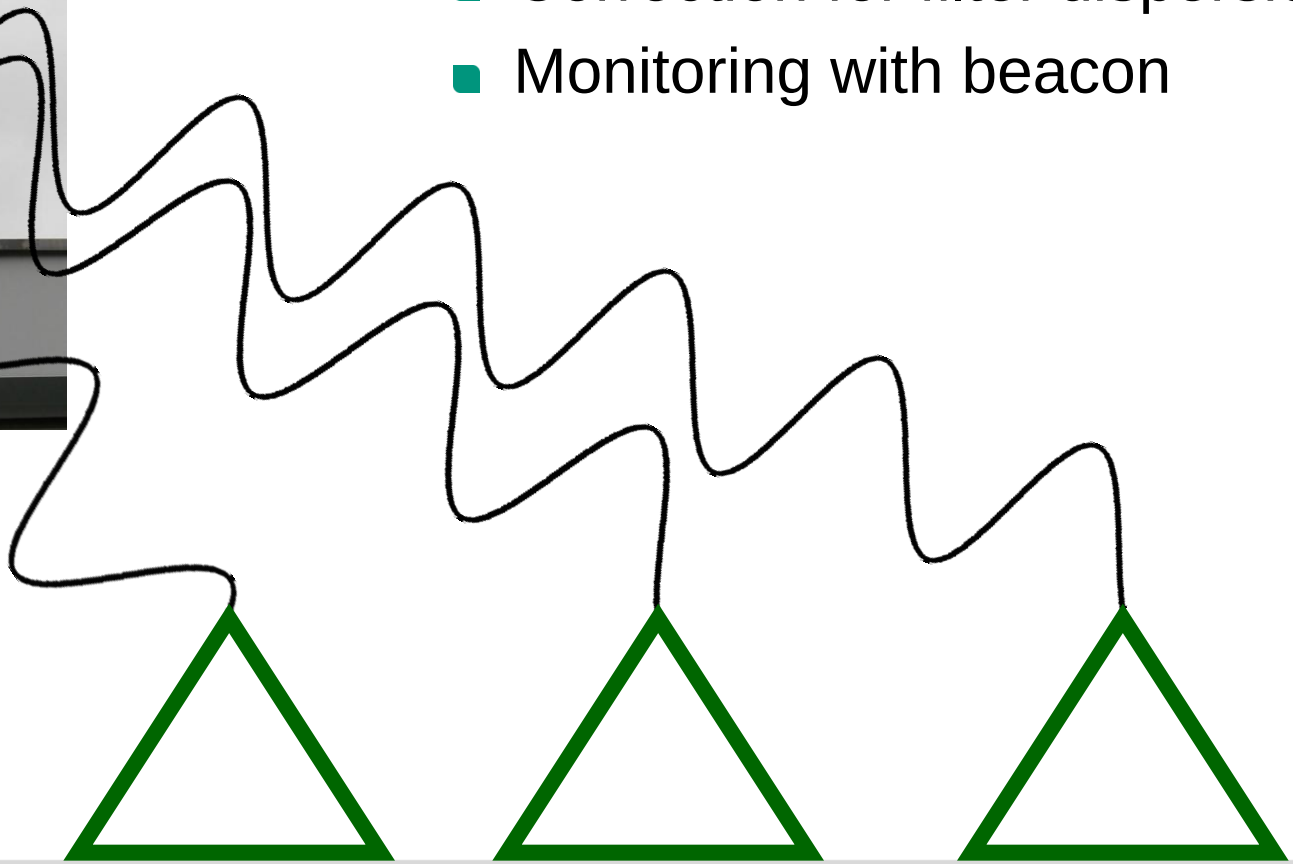




S. Nehls et al., NIM A 589 (2008) 350

Time calibration

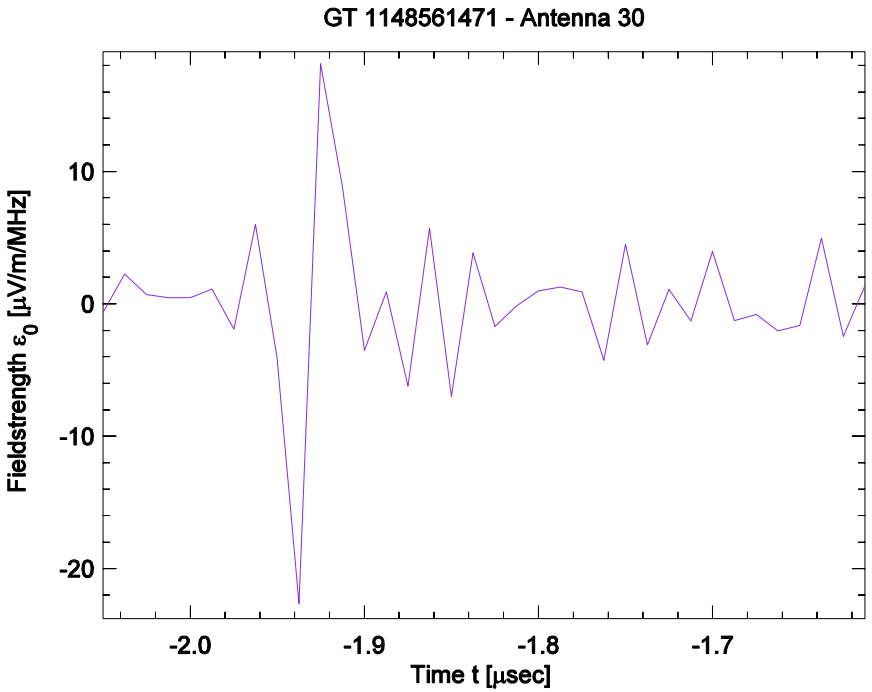
- 3 steps to reach about 1 ns
  - Delay measurements
  - Correction for filter dispersion
  - Monitoring with beacon

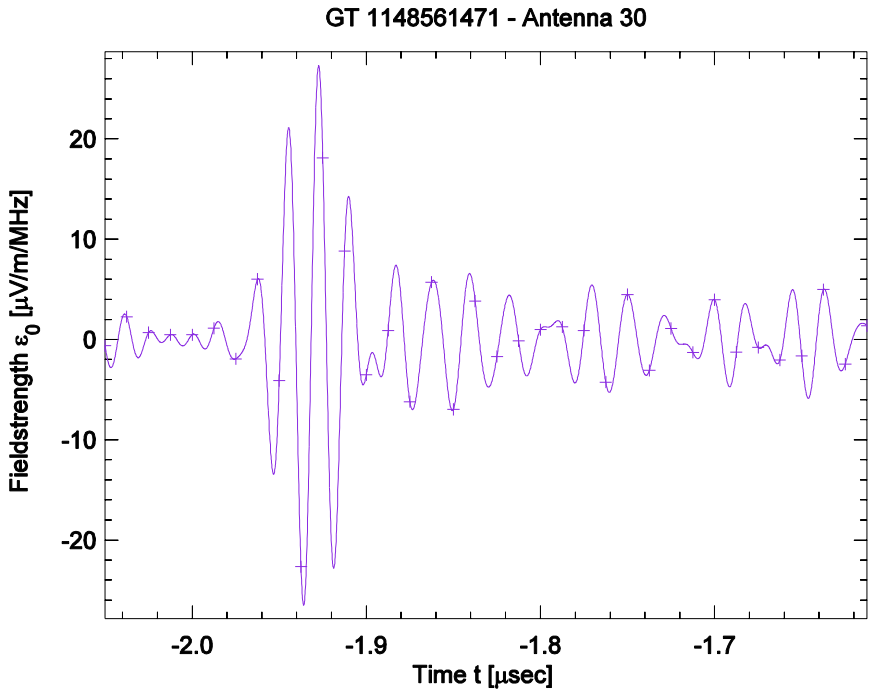


DOI: 10.1016/j.nima.2010.01.072

Up-Sampling

- Correct interpolation between ADC samples
- Zero padding method (in frequency domain)
- Improved sampling: 12.5 ns → up to ~ 0.1 ns

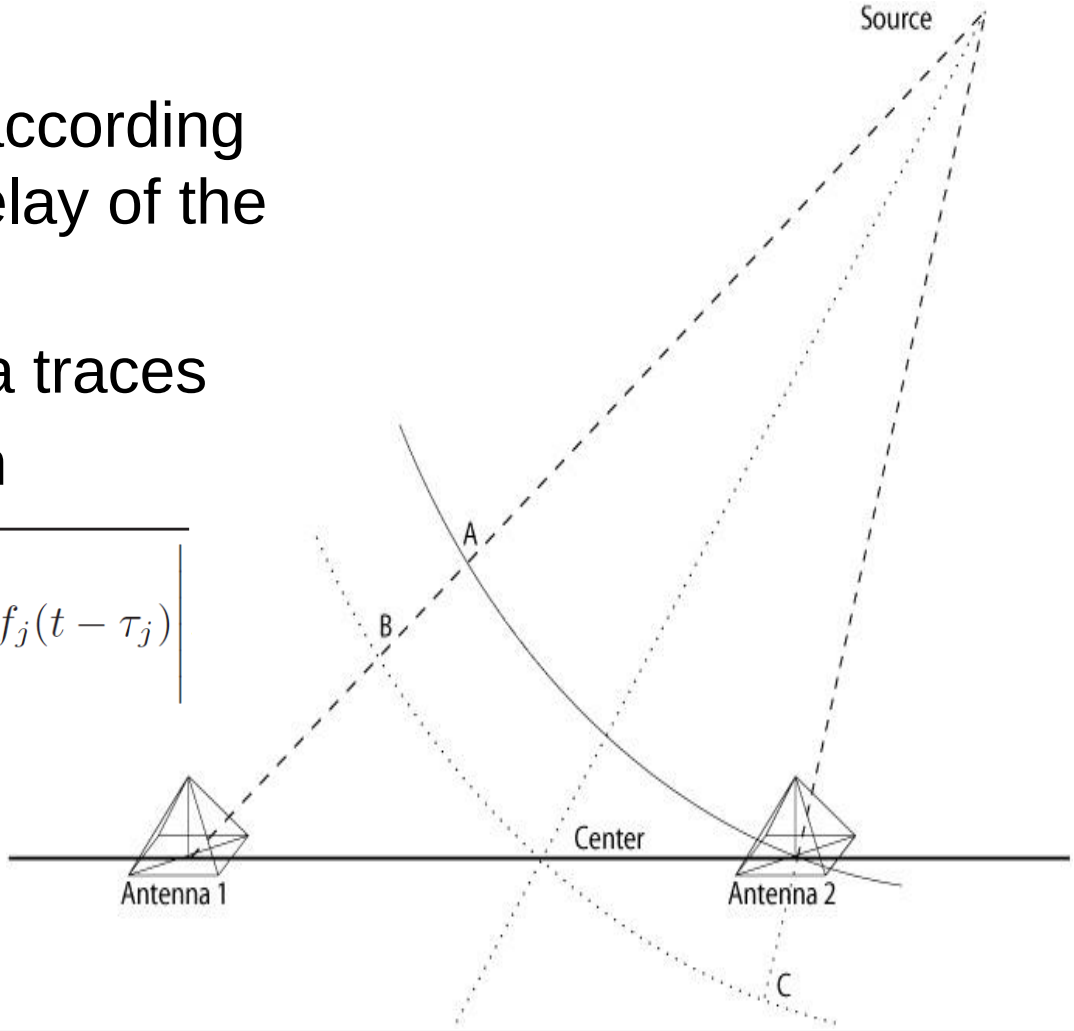




Digital Interferometry

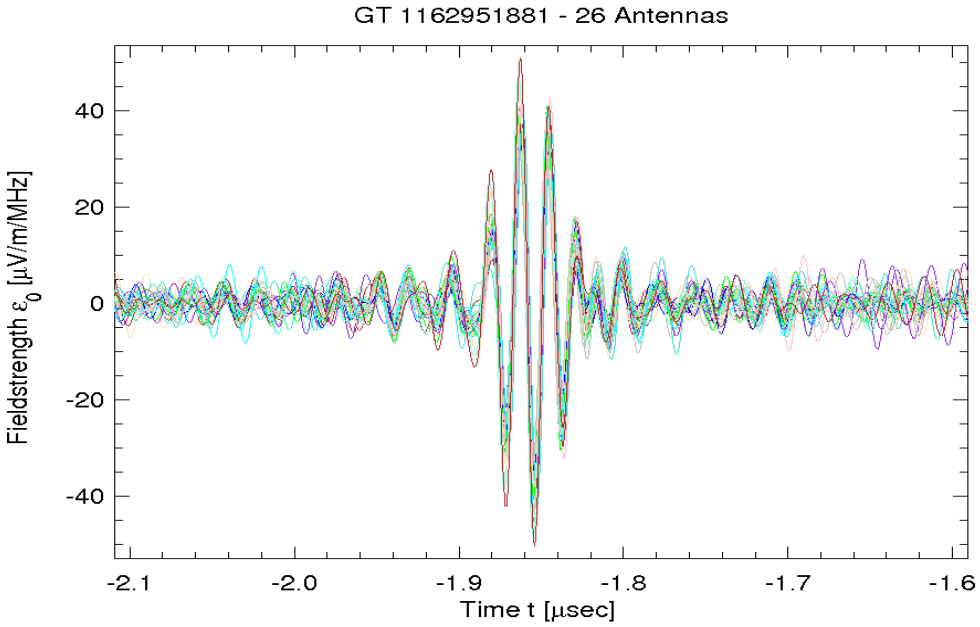
- Beam-forming
  - Shifting time series according to the geometrical delay of the pulse arrival times
  - Sum over all antenna traces
  - e.g. cross-correlation

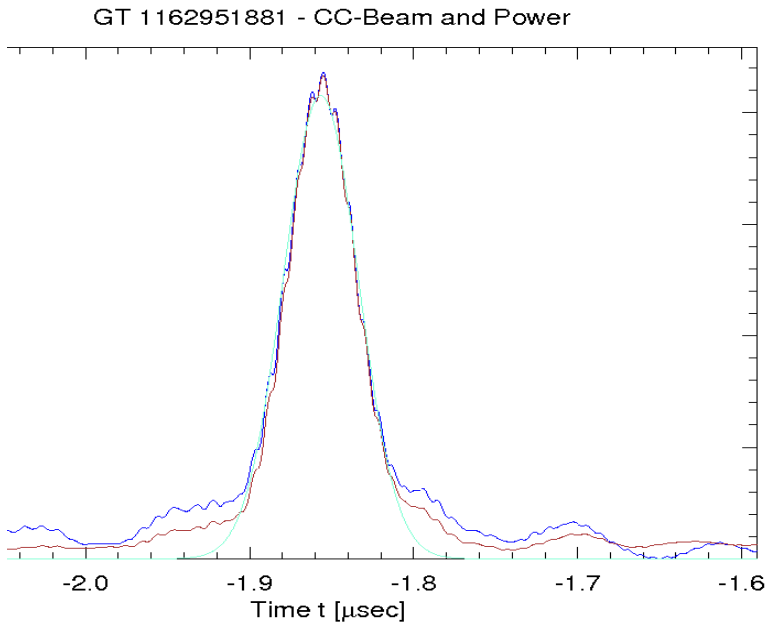
$$S_{cc}(t) = \pm\sqrt{\left|\frac{1}{N_{pairs}}\sum_{i=1}^{N-1}\sum_{j>i}^{N} f_i(t-\tau_i)\, f_j(t-\tau_j)\right|}$$



Example Event

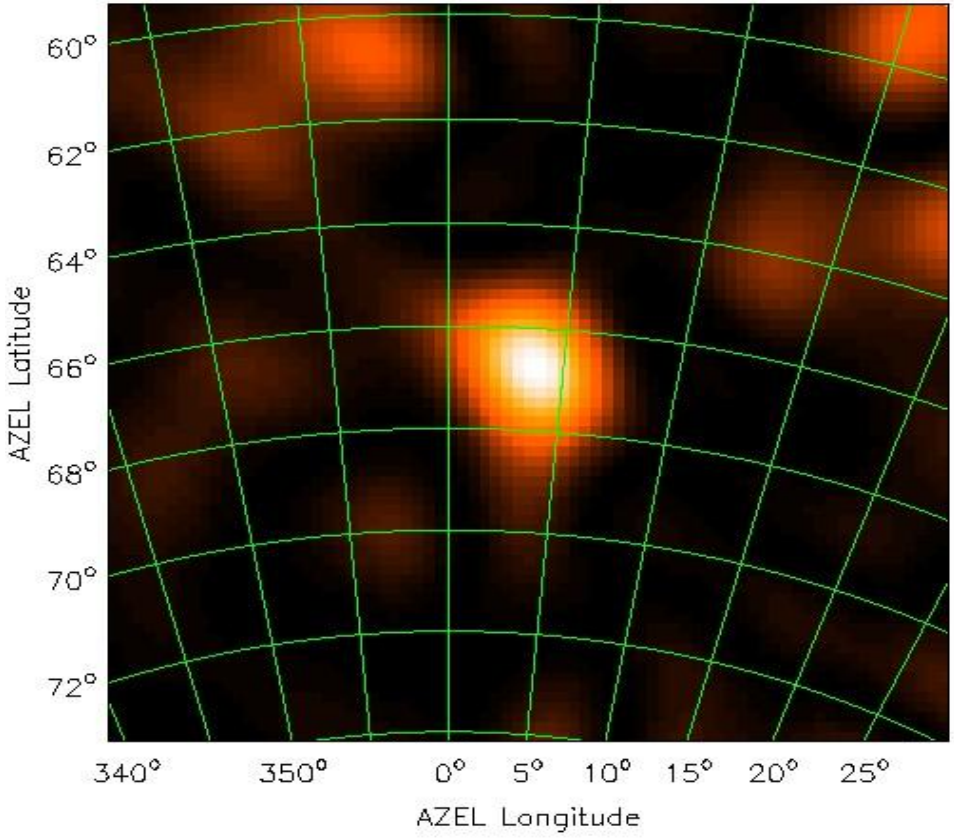
- Coherent traces after beam-forming
- Cross-correlation beam height as measure for radio pulse strength

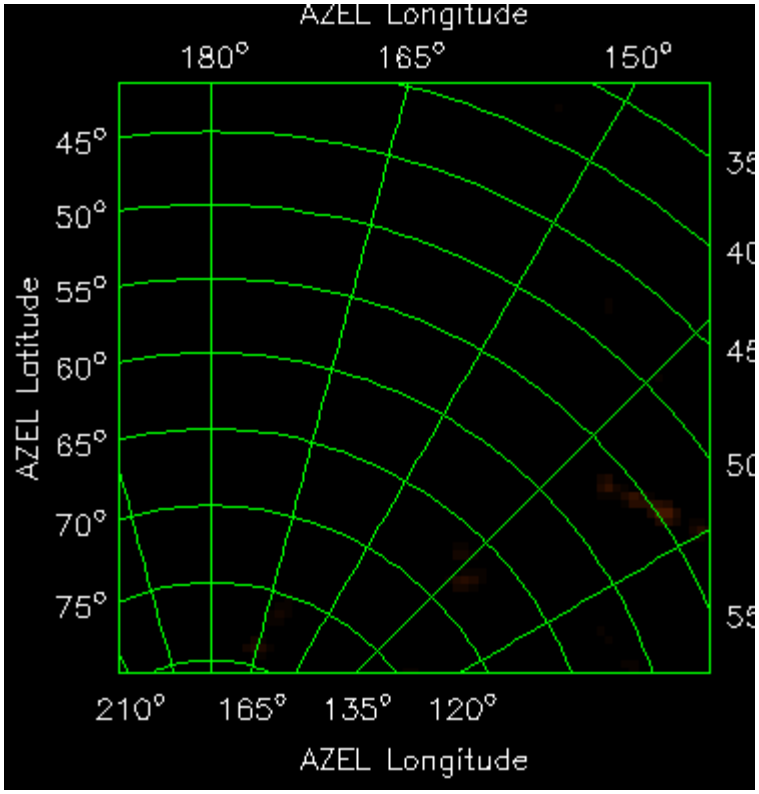




First detection

- Angular resolution ~ 1°

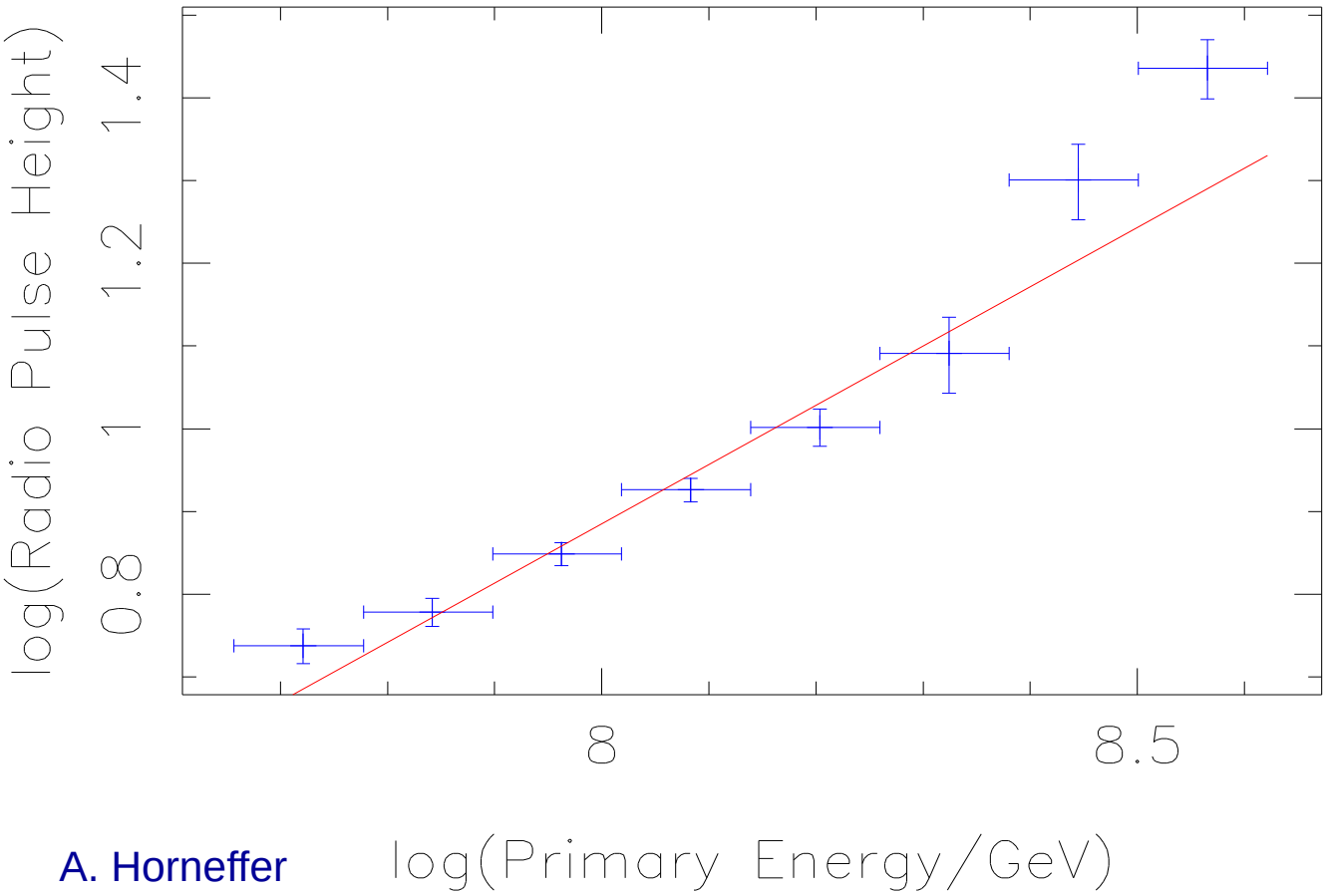




Falcke et al. (LOPES coll.) 2005, Nature

Energy Estimation

- Field strength: energy, geomagnetic angle, distance
  - ~ E^1
  - ~ sin α or
    (1 - cos α)
  - ~ exp(-R/R_0)

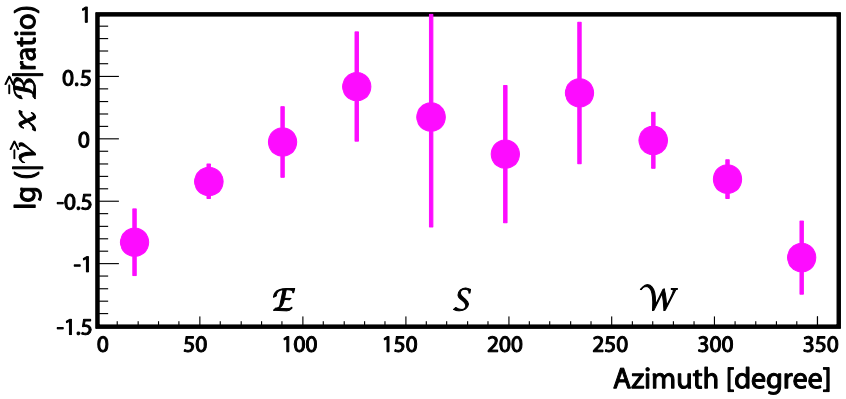


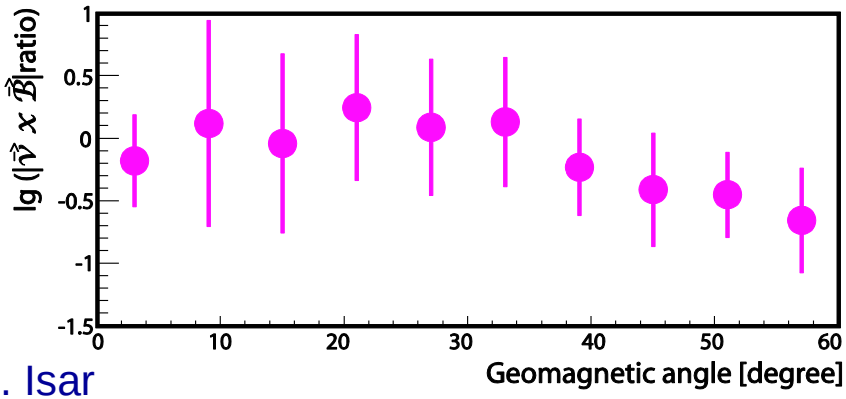
A. Horneffer

Polarization vs. Azimuth

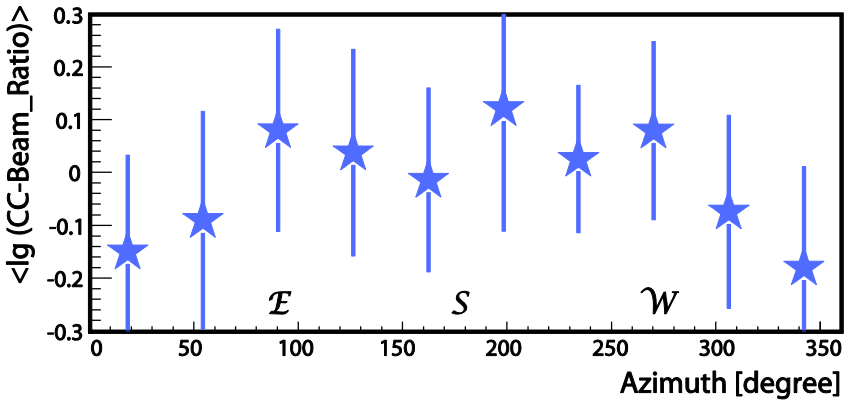
- Simple, geo-magnetical, analytical **E** ~ **v** x **B** model

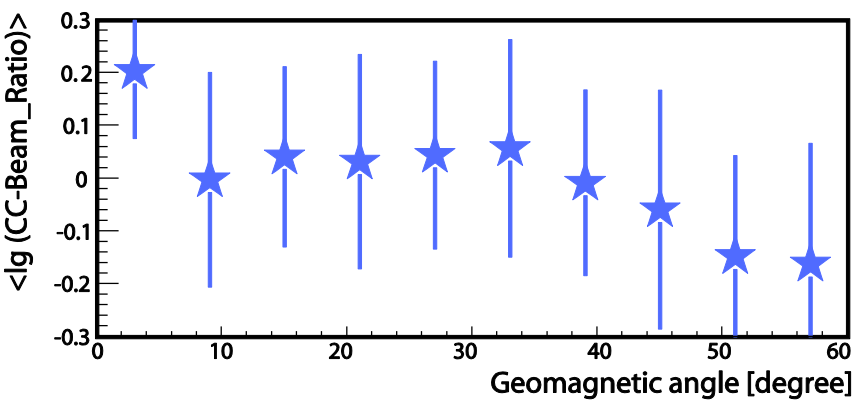
model prediction





LOPES data





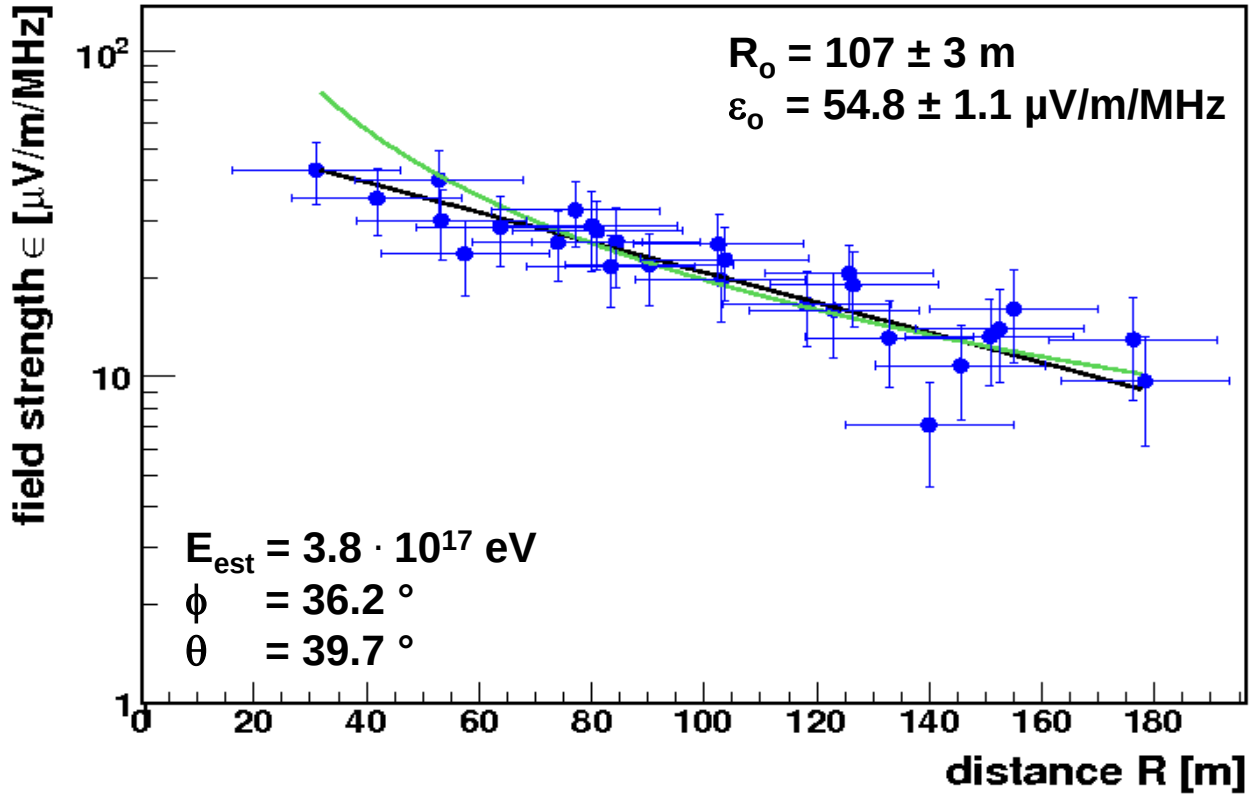
G. Isar

Lateral distribution

- Pulse height in each antenna as function of distance to shower axis
- Selection
  - 110 events from Steffen Nehls' thesis and paper about lateral distribution: Astrop. Ph., 2010, 32, 294
  - LOPES 30, east-west polarization only
  - KASCADE-Grande: high muon or electron number
  - High SNR in cross-correlation beam and each antenna
- Pulse height = maximum amplitude in each antenna close to time of cross correlation beam

Lateral distribution - example

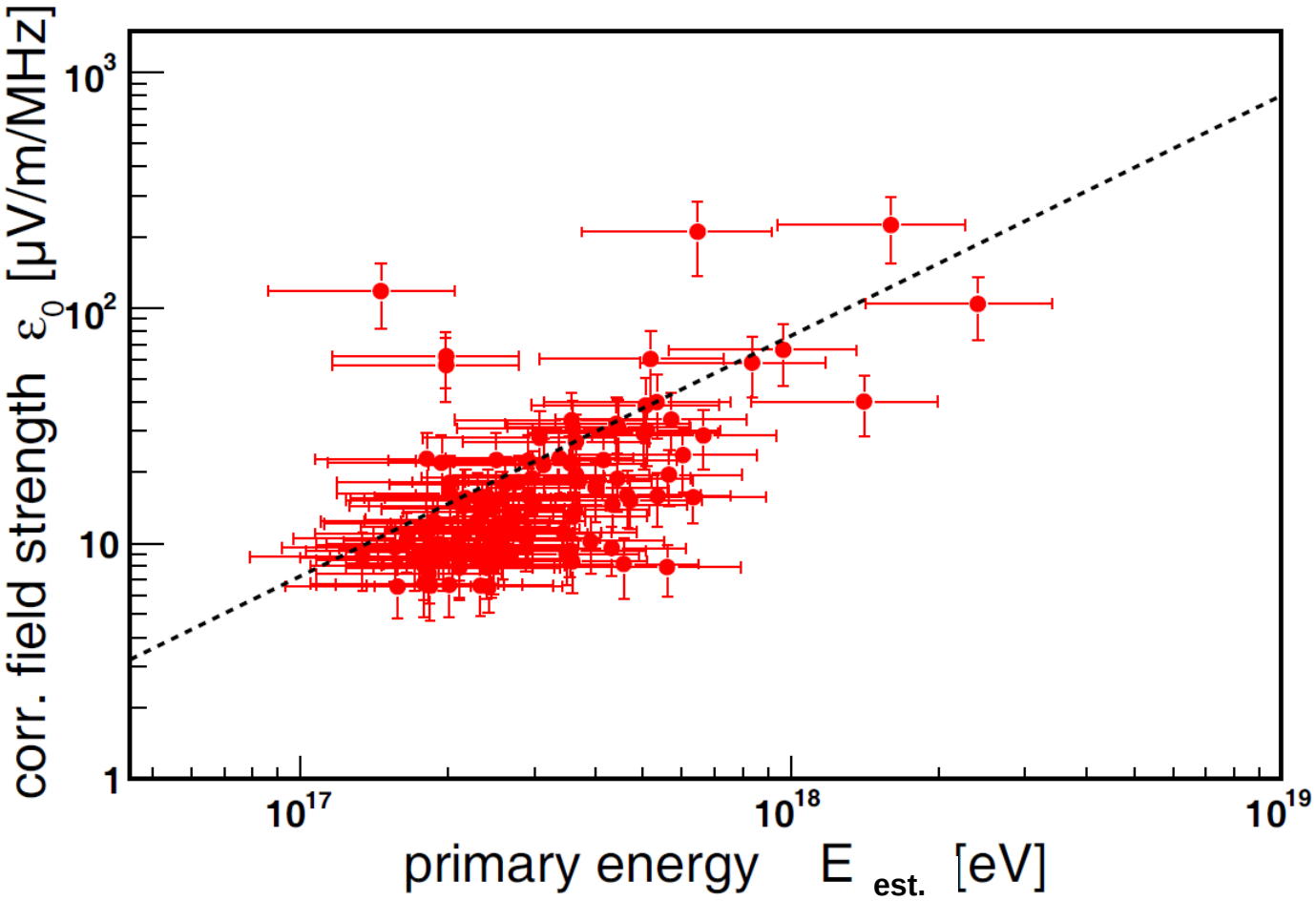
- Fit of exponential function: $\varepsilon = \varepsilon_0 \cdot \exp(-R/R_0)$
- Power law overestimates field strength close to core



S. Nehls

Energy estimation

- Primary energy ~ field strength ε_0

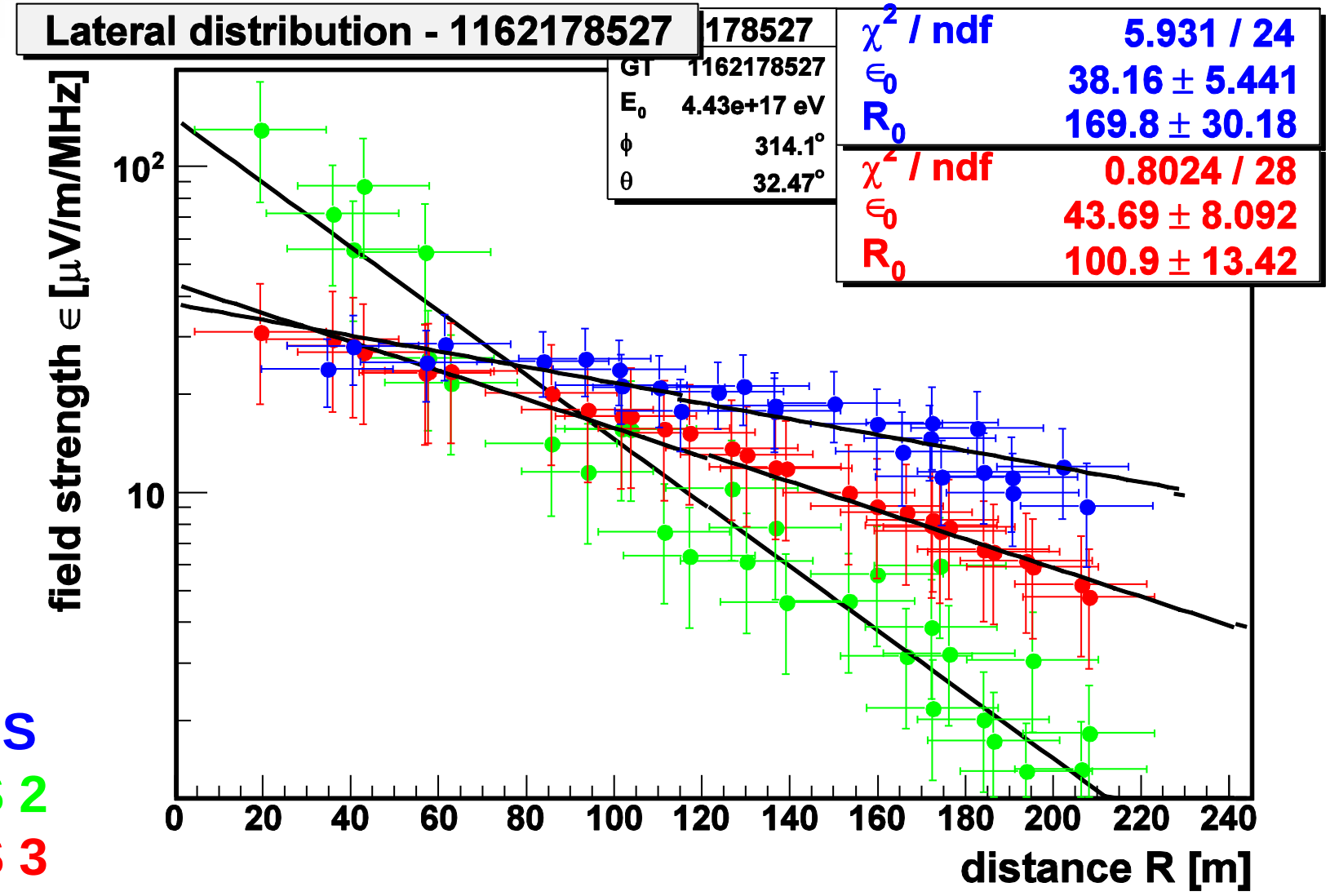


S. Nehls

Comparison to Simulation

- REAS: geo-synchrotron
- Simulated showers:
  - Direction, core + energy from KASCADE-Grande
  - REAS 2: proton showers
  - REAS 3: proton + iron showers
- Simple adaption to detector properties
  - Rectangular filter to LOPES band width
  - Projection of east-west polarization
- Same fitting procedure like for data

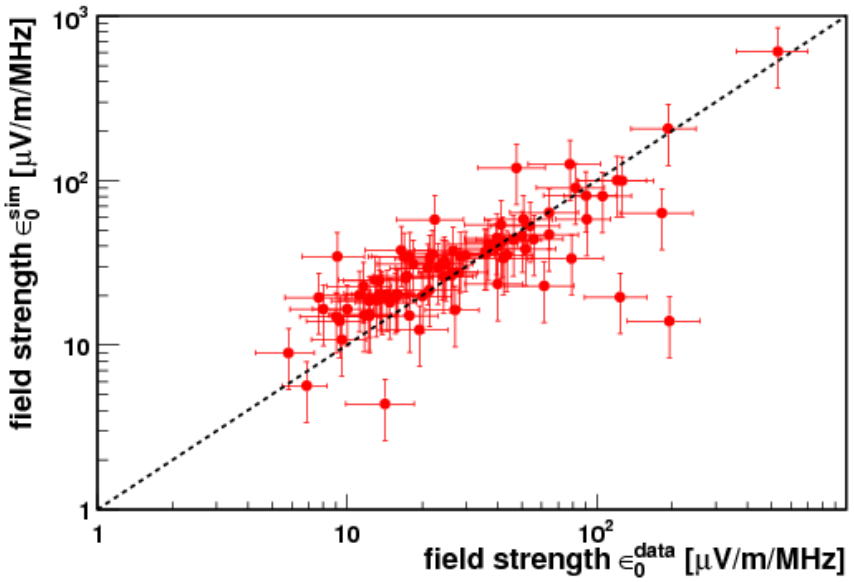
Example event



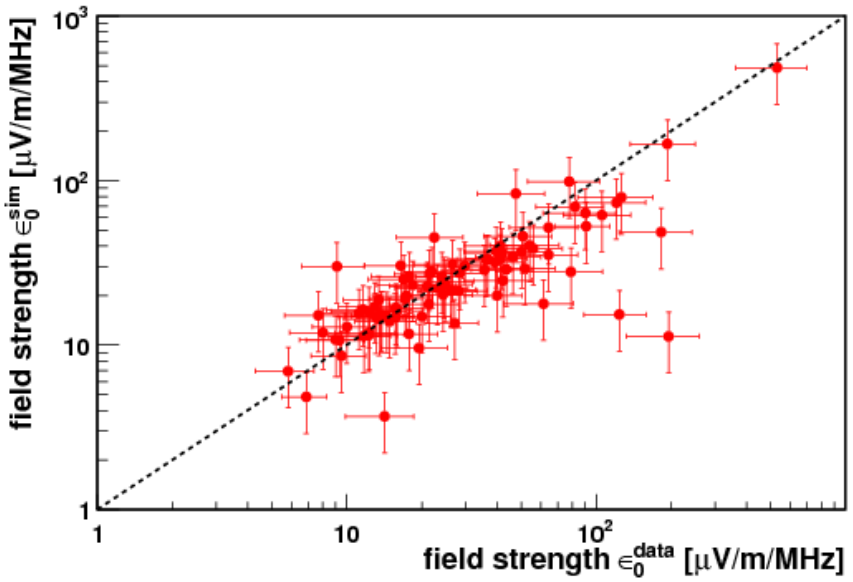
LOPES
REAS 2
REAS 3

Field strength ε_o at 0 m

REAS 3 proton



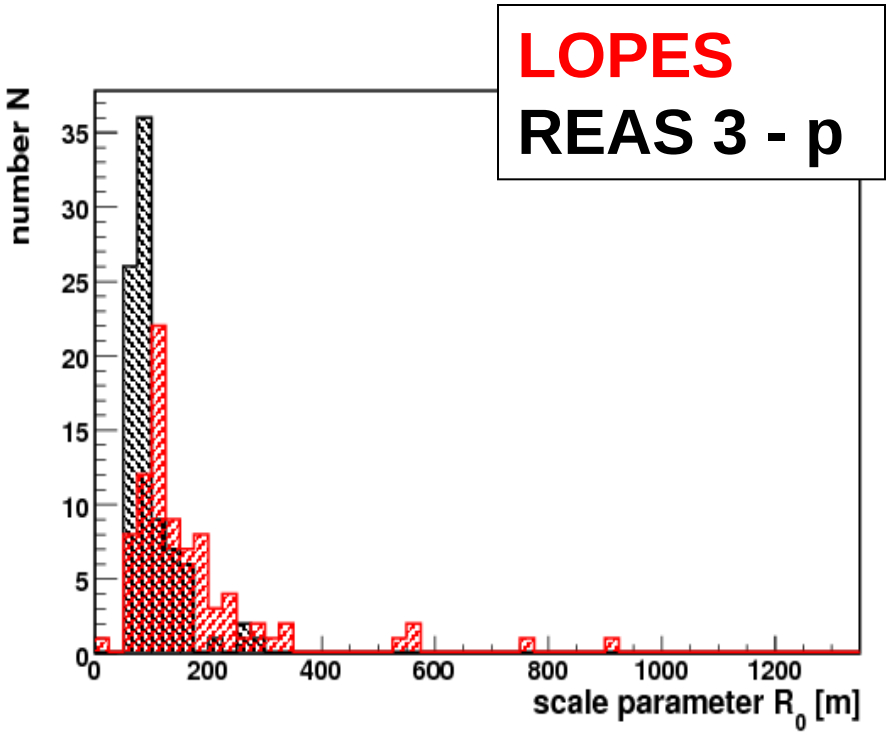
REAS 3 iron

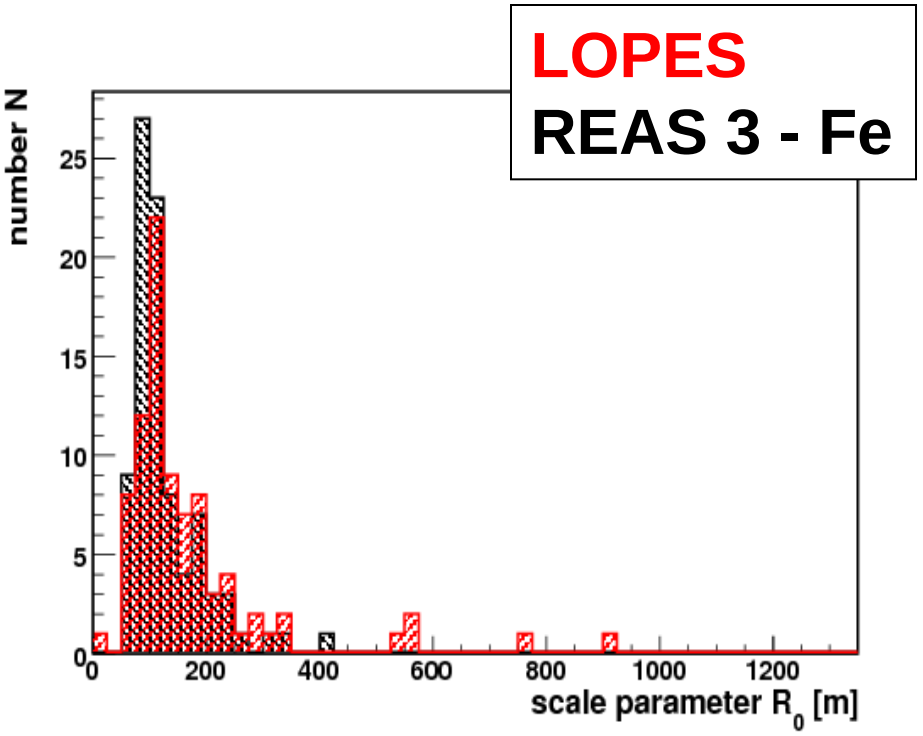


Not for public distribution!

Slope: R_0 histogram

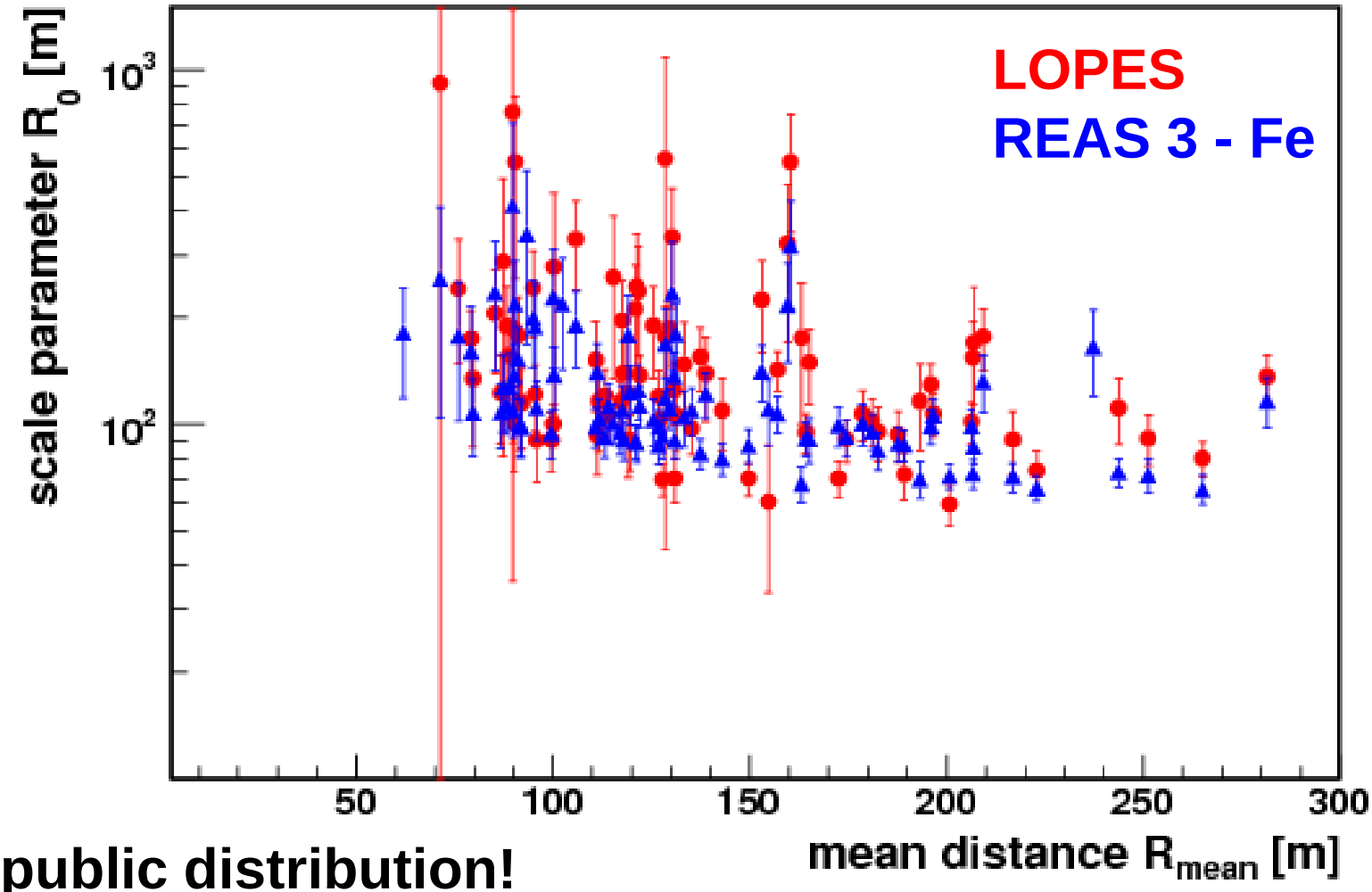
- Preliminary, be careful with any conclusions!





Not for public distribution!

Slope: R_0 versus R_{mean}



Not for public distribution!

Outlook – Lateral Distribution

- Some checks + improvements already done:
  - Calculation of pulse height
  - Dispersion of filters: pulse broadening
  - Frequency band, by using sub-bands

  → Little effects to slope and height
- Checks to do:
  - Influence of noise
  - Fitting conditions (e.g., distance of fitting ε)
  - Taking into account all experimental properties when comparing to simulations

LOPES^{STAR}

- STAR = Self Triggered Array of Radio Detectors
- Developments for the Auger Engineering Radio Array
  - Self trigger
  - Electronics
  - Antennas

Future

- Now: Reconfiguration to 10 tripole antennas
  - 3 dipoles at each position
  - Reconstruction of E-Field vector
- Analysis topics
  - Systematics, Efficiencies
  - Polarization
  - Mass sensitivity
  - Lateral distribution
- Thunderstorms

Summary

- LOPES = digital radio interferometer for cosmic rays
- Requires advanced signal processing + calibration
- Measurement of direction, energy and maybe mass
- Results support geomagnetic emission mechanism
  - Details unknown, but…
  - REAS 3 simulations close to data
- Increasing understanding and capabilities of radio detection of cosmic ray air showers in the last years!