Cosmic Ray Measurements with LOPES: Status and Recent Results

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http://www.lopes-project.org/

Outline

- LOPES experiment
  - Current status: LOPES 3D
  - Measurement method
- Understanding the radio signal
  - Polarization measurements → see posters (D. Huber, G. Isar)
  - Comparison to simulations → see next talk (M. Ludwig)
  - Shape of radio wavefront
- Reconstruction of air-shower parameters
  - Direction
  - Energy
  - Atmospheric depth of shower maximum, X_{max}

} see talk by N. Palmieri (this session) [Energy, X_{max}]

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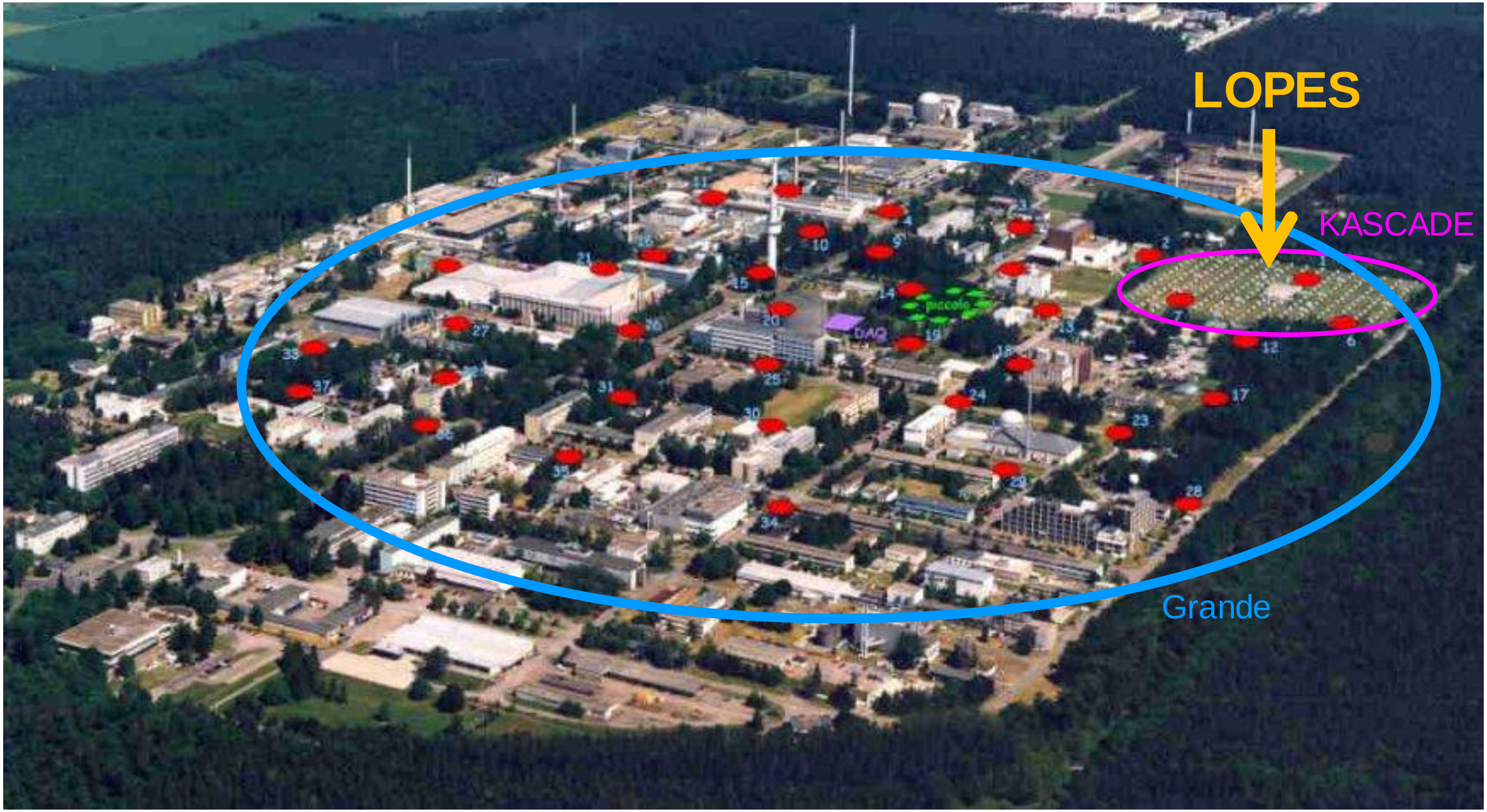
LOPES at KIT, Karlsruhe, Germany

KIT Karlsruhe Institute of Technology



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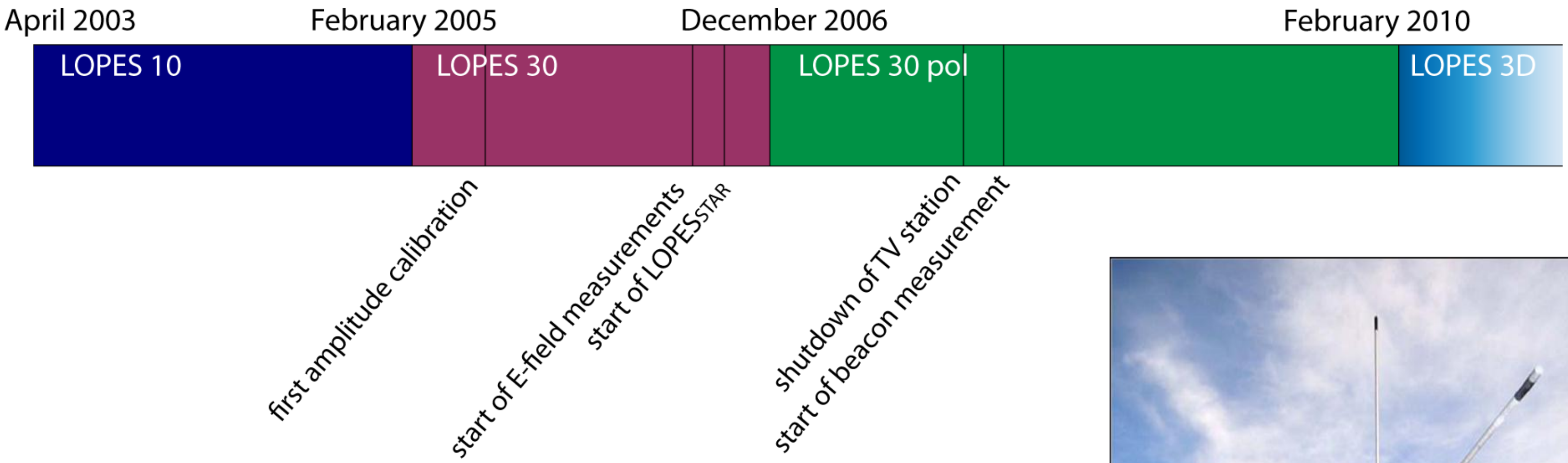
LOPES history



- LOPES started in 2003 as **LO**FAR **p**rototyp**e** **s**tation
  - Proof-of-principle for air-shower detection with digital radio interferometry
- Now LOPES 3D using tripole antennas

  → see poster by D. Huber (LOPES Coll.)
- Data used in this talk from 2005-2009

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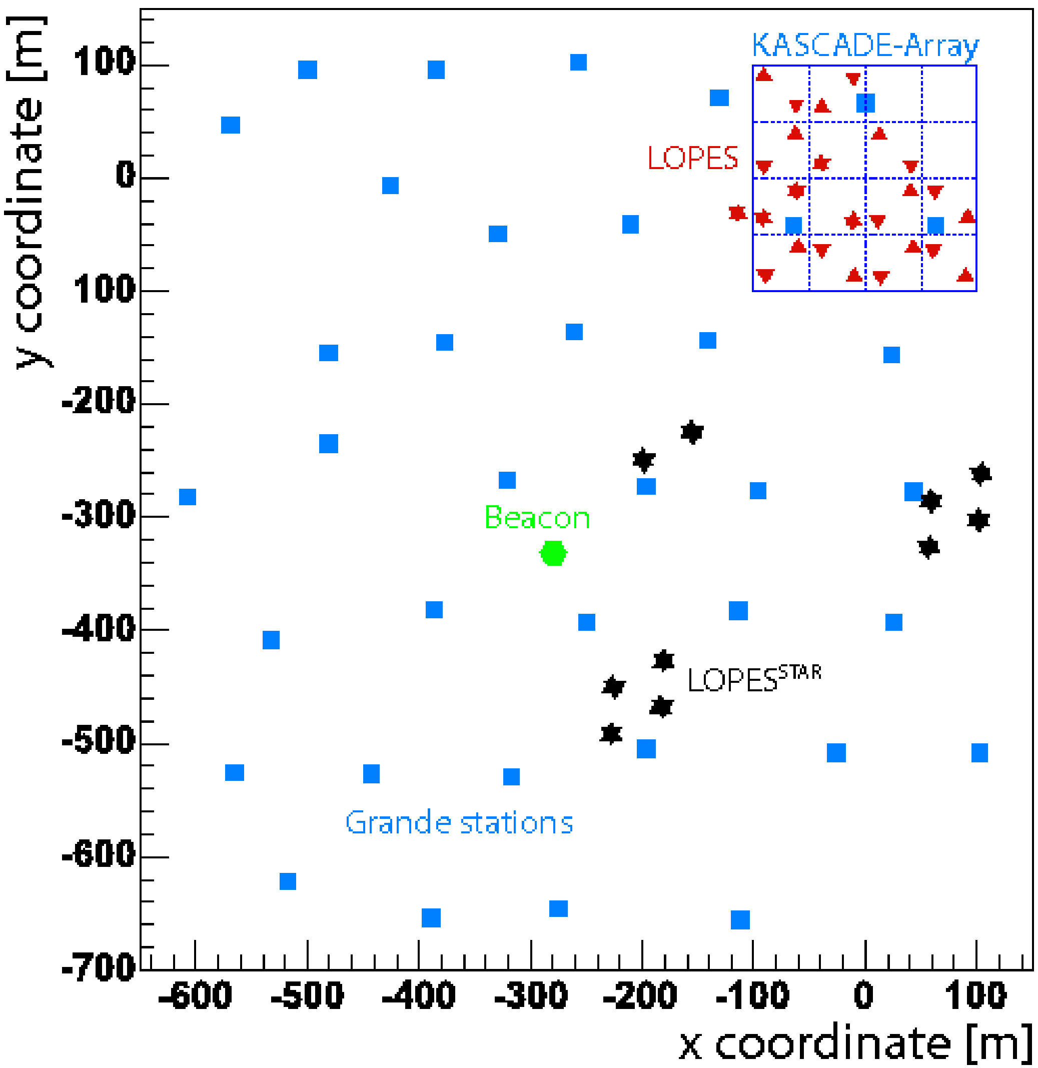
LOPES setup (map of 2009)



- 30 dipole antennas
  - **15 east-west**
  - 15 north-south
- Triggered by KASCADE and KASCADE-Grande
- LOPES^{STAR}
  - self-triggering
  - → stopped at LOPES, but further studied at AERA
- Reference beacon
  - for time calibration

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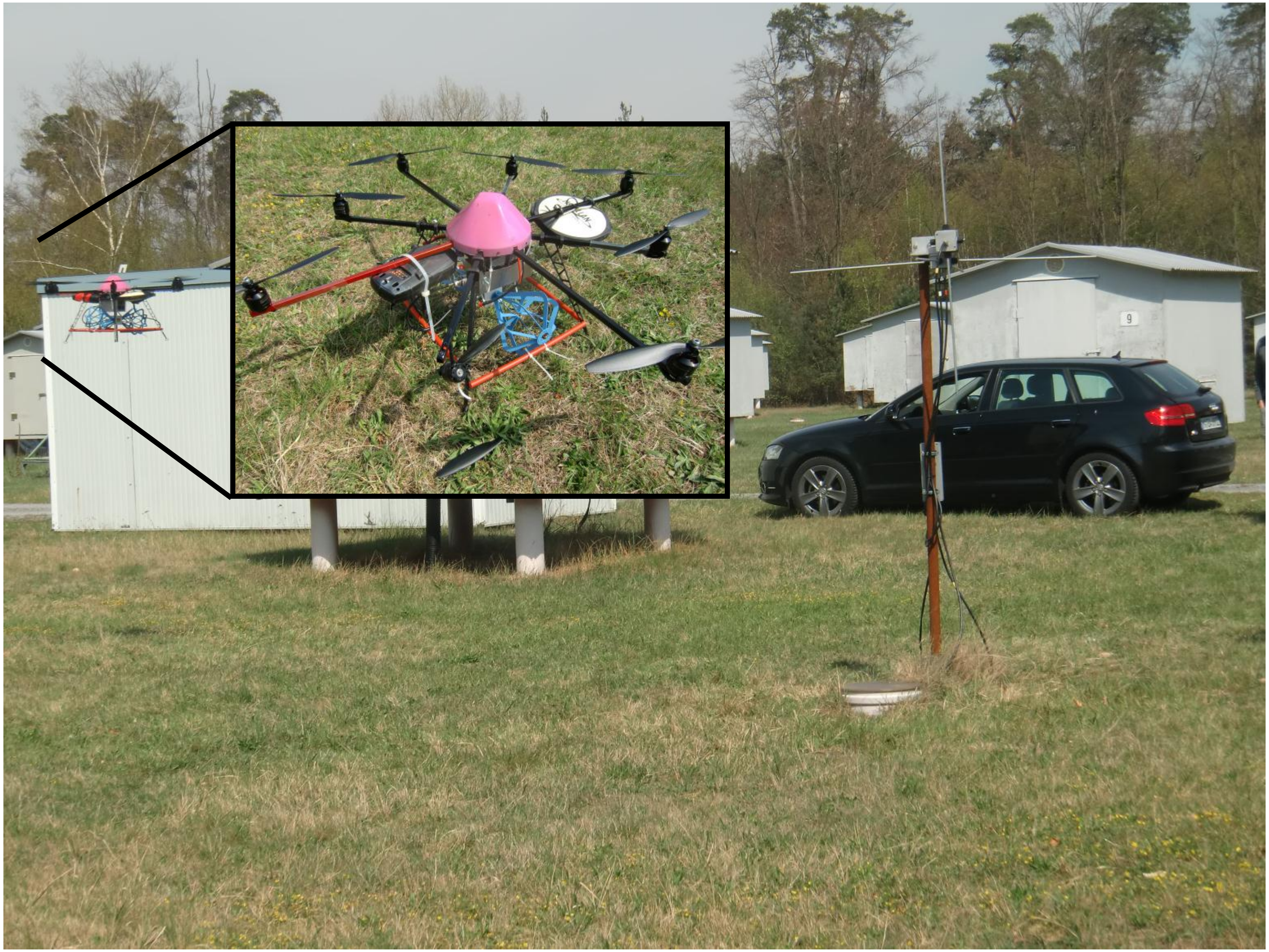
Octocopter calibration tests



in cooperation with the **Pierre Auger Collaboration**

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LOPES technical data

- Frequency range
  - 40-80 MHz
  - 80 MHz ADC sampling (2nd Nyquist domain)
- Trace length: 0.8 ms
  - Radio pulse: ~ 0.1 µs
  - →Frequency resolution for noise reduction
- Digital interferometer
  - relative position accuracy of 5 cm (differential GPS)
  - relative timing accuracy of ~ 1ns

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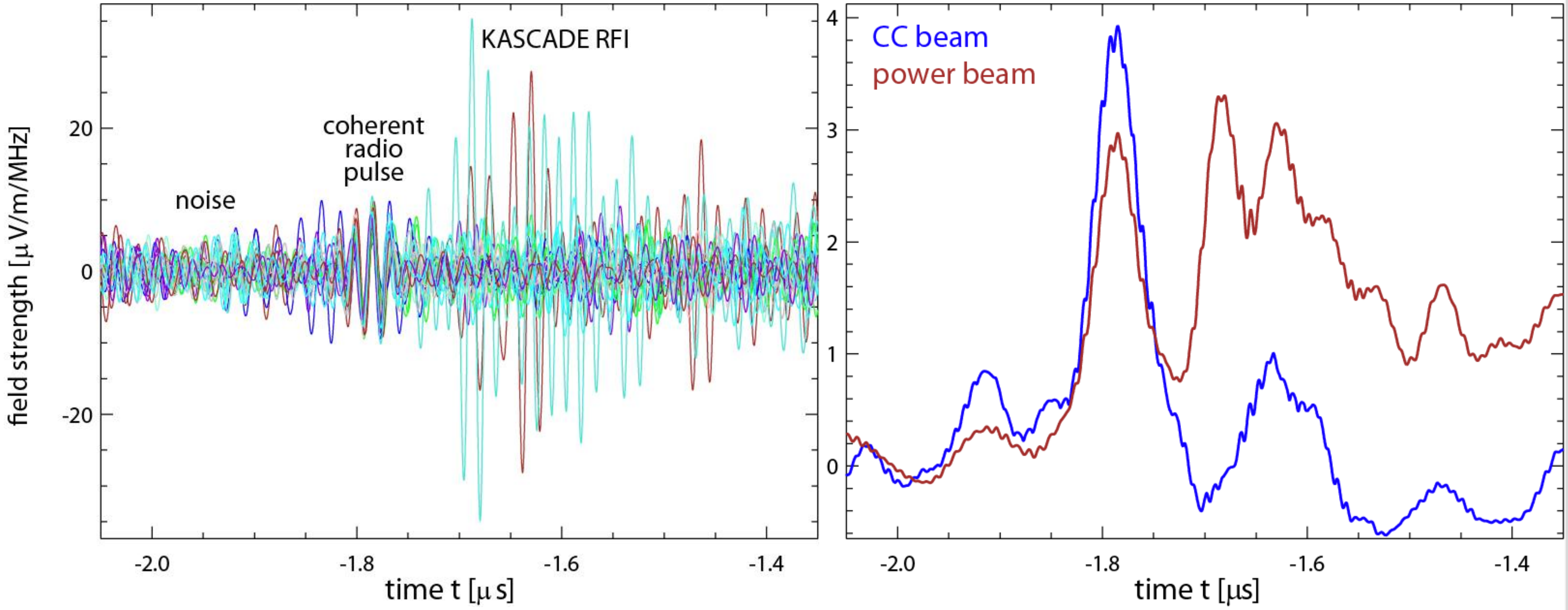
Digital radio interferometry

- Cross-correlation beamforming for pulse identification
  - Shift all traces in time according to arrival direction
  - Only air shower radio pulse correlated in all antennas



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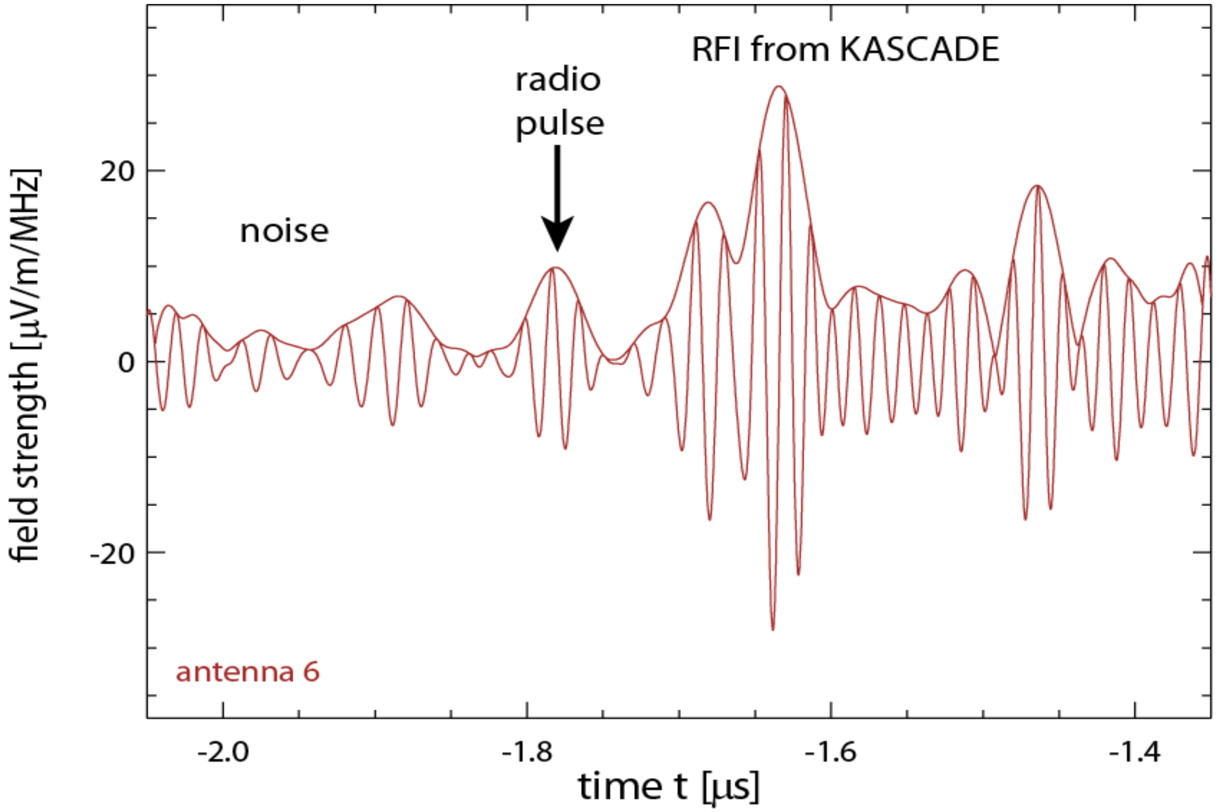
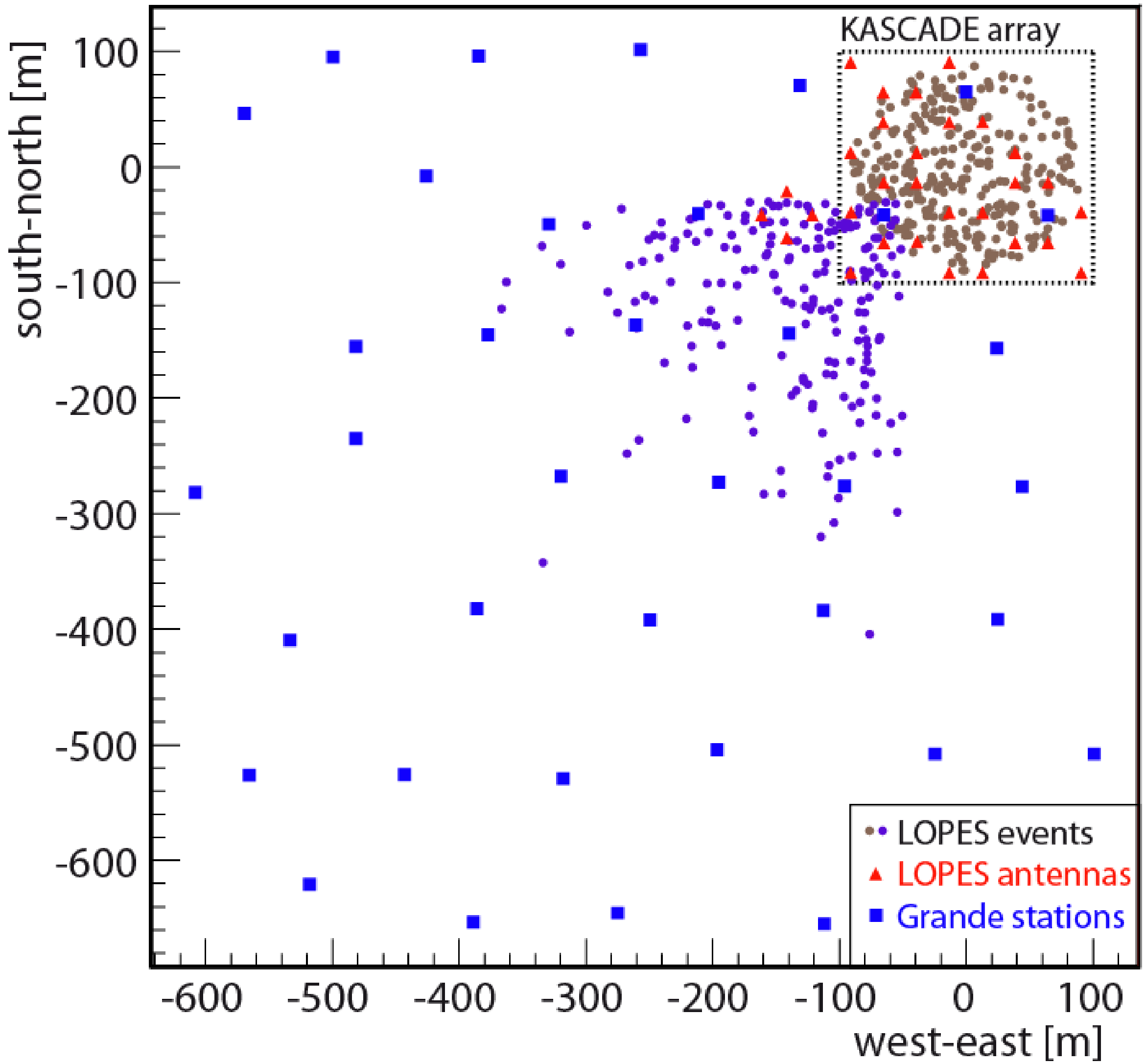
Typical LOPES event in individual antenna

- Radio pulse identified with CC beamforming
- Amplitude and time measurement in individual antennas



Typical event selection



- LOPES events used for analysis:
  - clear CC beam radio signal
  - $E_{K\text{-}G} > 10^{17}$ eV
- about 500 events
  - ~ 300 in KASCADE
  - ~ 200 Grande
  - Further quality cuts (e.g. LDF fit quality) typically reject about 25 % of events

→~ 400 events usable

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Arrival direction

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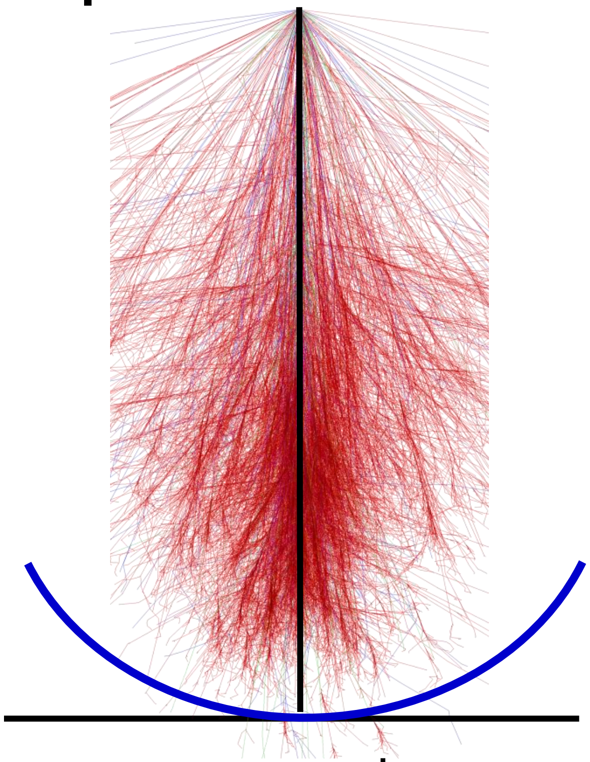
Wavefront assumption for beamforming

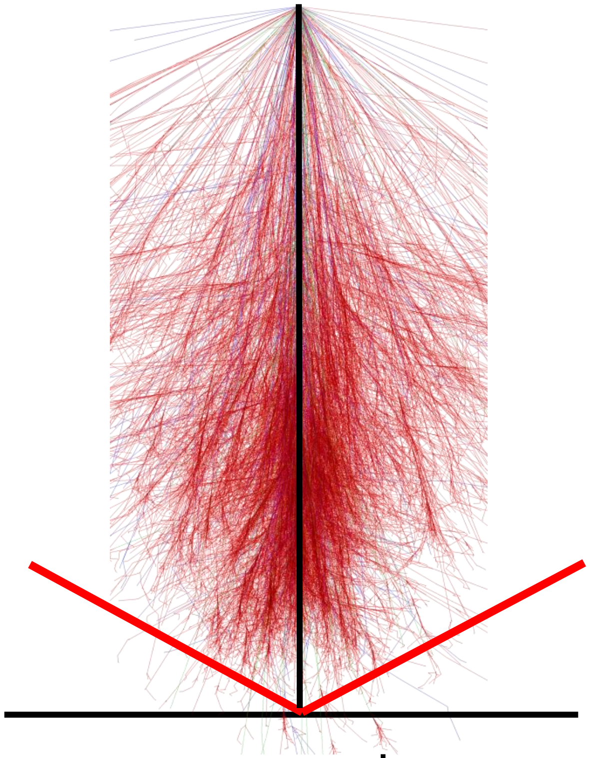
- Beamforming with spherical or conical wavefront
- ‘Real’ wavefront seems to be better approximated by cone

spherical wavefront



ground

conical wavefront



ground

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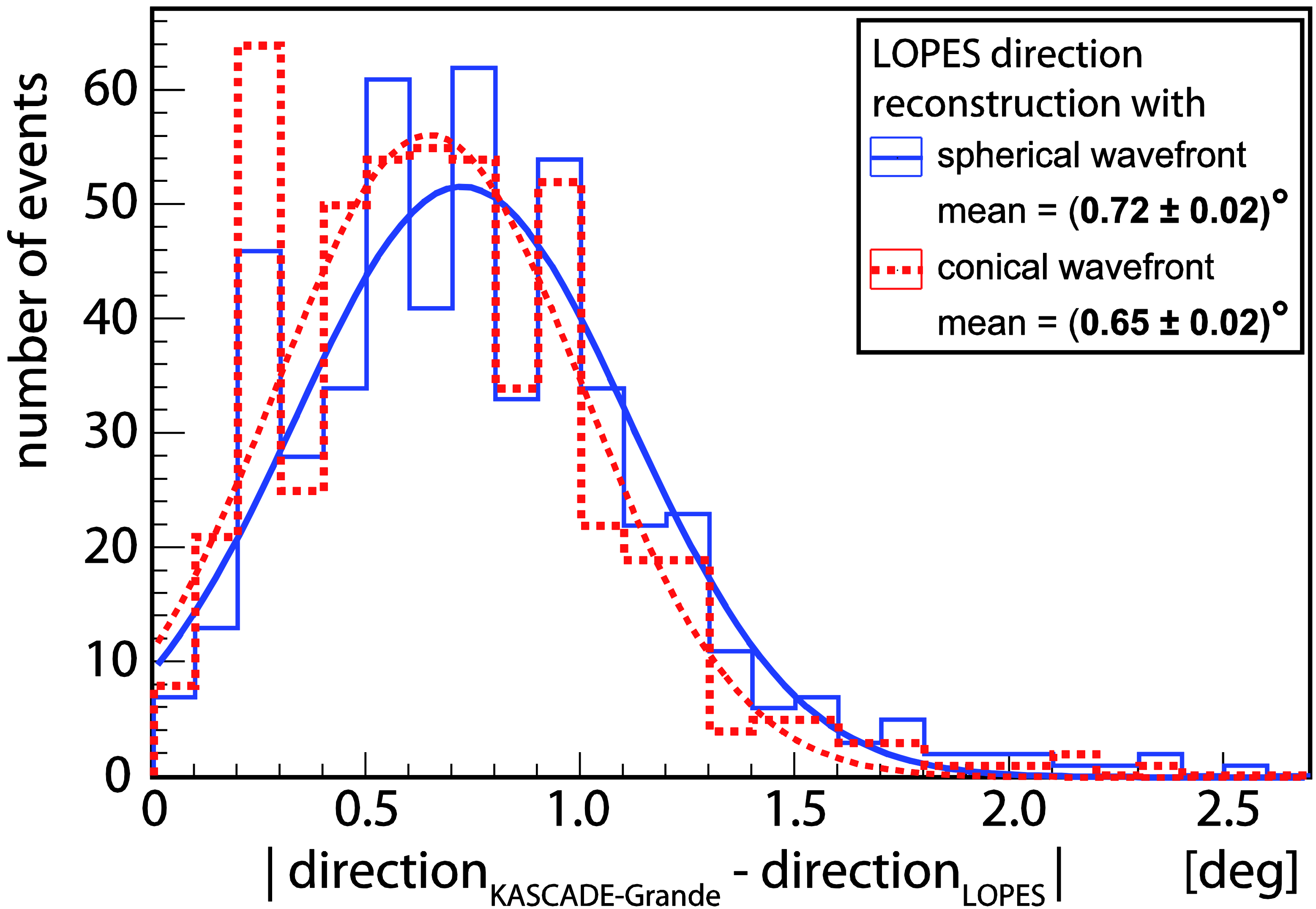
Direction reconstruction



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Energy

$$E \propto \frac{\varepsilon_{radio}}{\sin\alpha \cdot \cos\theta \cdot \exp(-d/d_0)}$$

Allan (1971)

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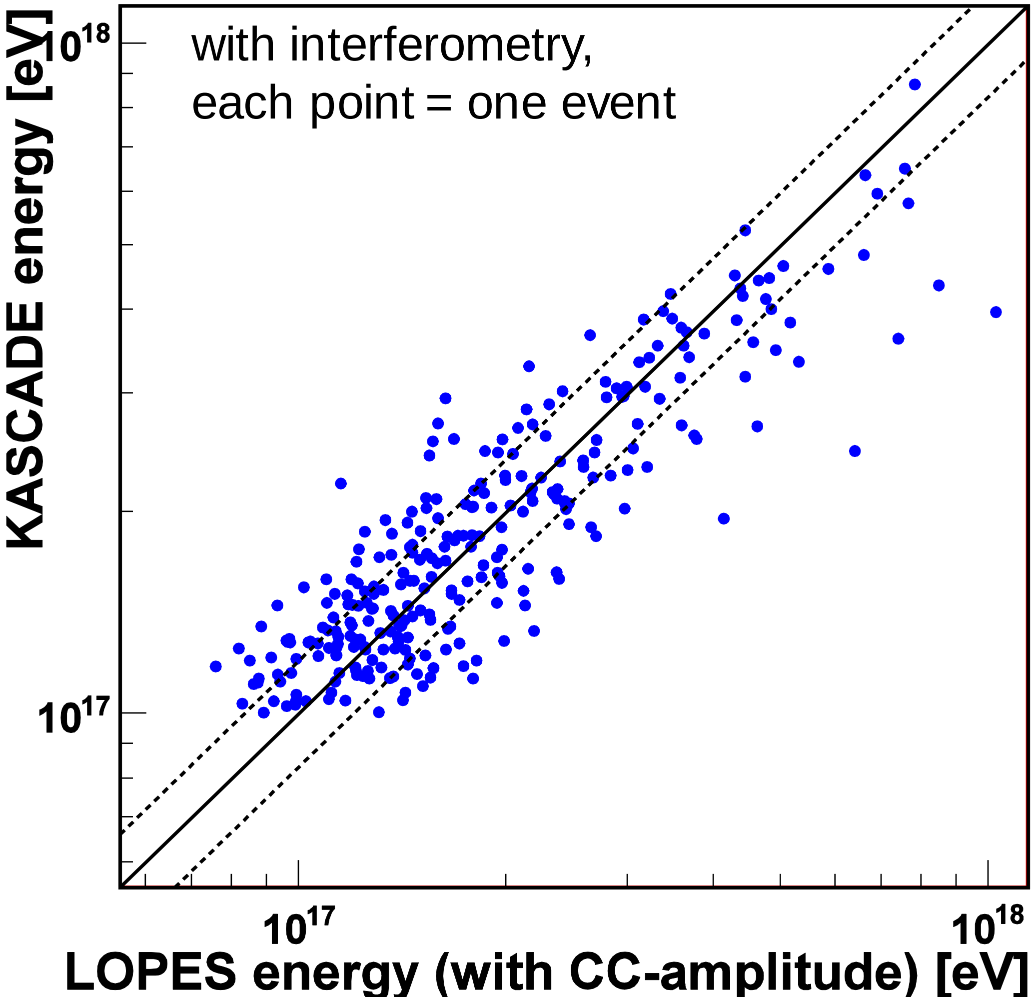
Energy with CC amplitude, KASCADE



- LOPES today:
  - data from 2005-2009
  - improved many details on analysis
- geomagnetic correction
- axis distance correction
- no zenith correction!
  (would increase spread)

$$E = a \cdot \frac{\varepsilon_{CC-beam(east-west)}}{\left|\vec{v} \times \vec{B}\right|_{EW} \cdot \exp(-d/180\mathrm{m})}$$

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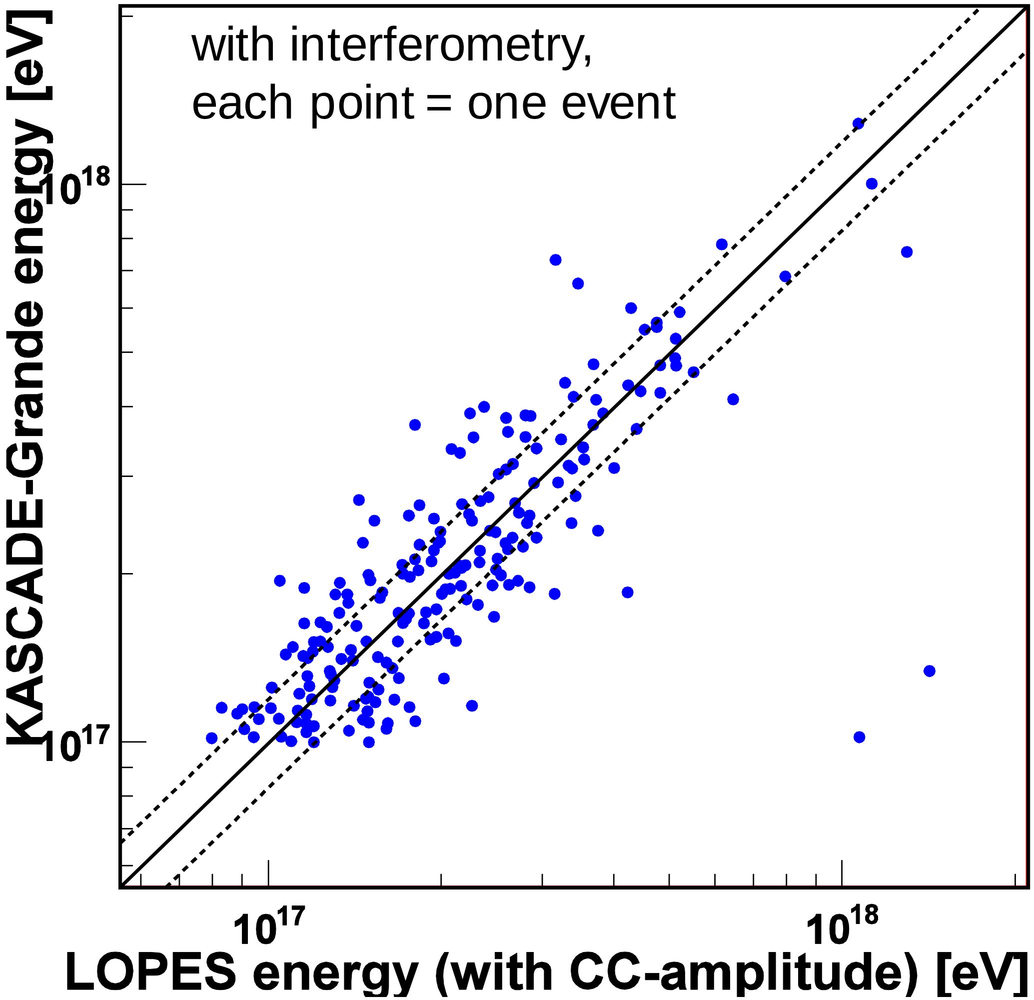
Energy with CC amplitude, Grande



- LOPES today:
  - data from 2005-2009
  - improved many details on analysis
- geomagnetic correction
- axis distance correction
- no zenith correction!
  (would increase spread)

$$E = b \cdot \frac{\varepsilon_{CC-beam(east-west)}}{\left|\vec{v} \times \vec{B}\right|_{EW} \cdot \exp(-d/180\mathrm{m})}$$

$b/a \approx 77\ \%$

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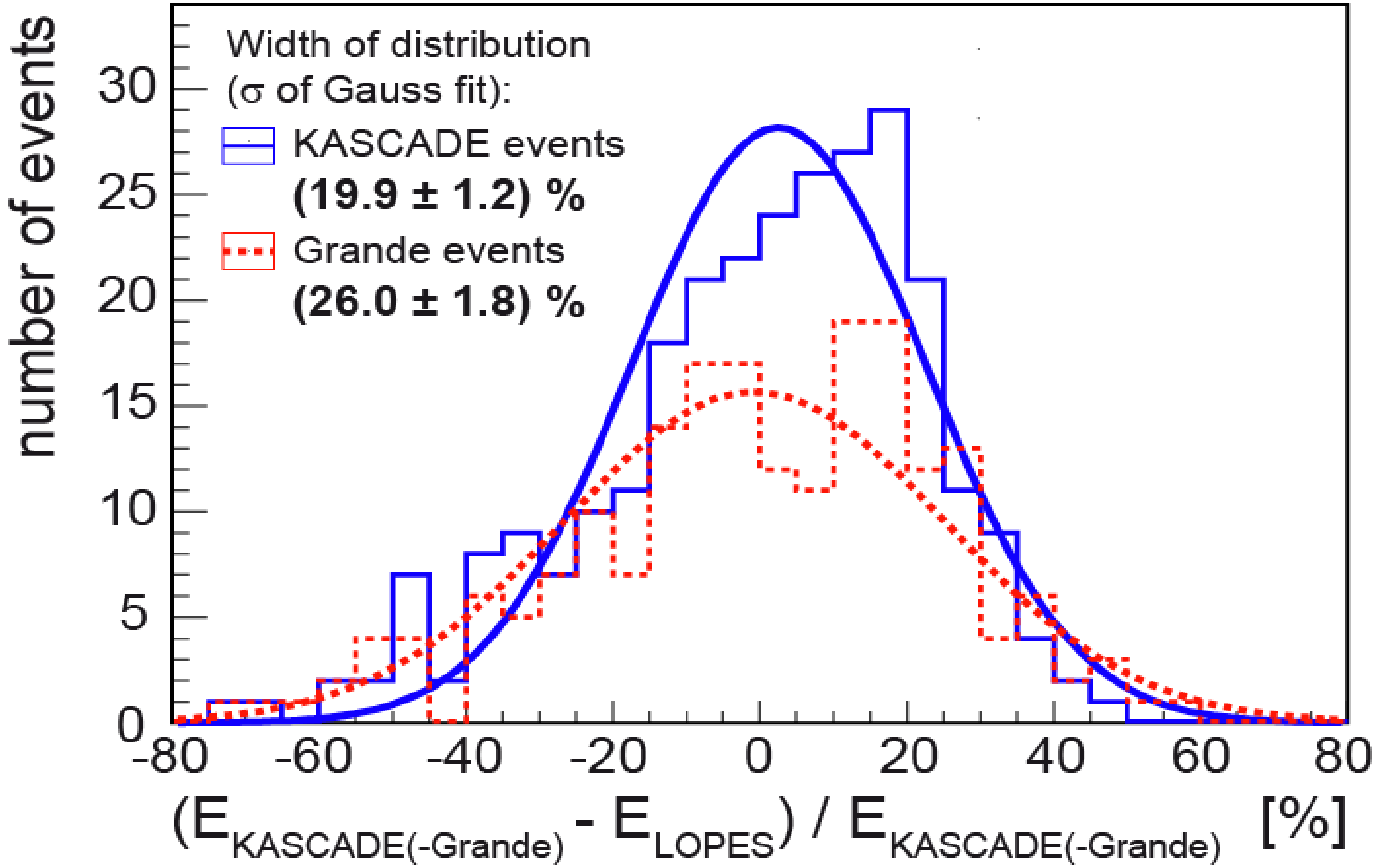
LOPES energy precision (CC beam)



→LOPES precision comparable to KASCADE-Grande (20 %), but additional systematic and scale uncertainties unknown

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Shower maximum

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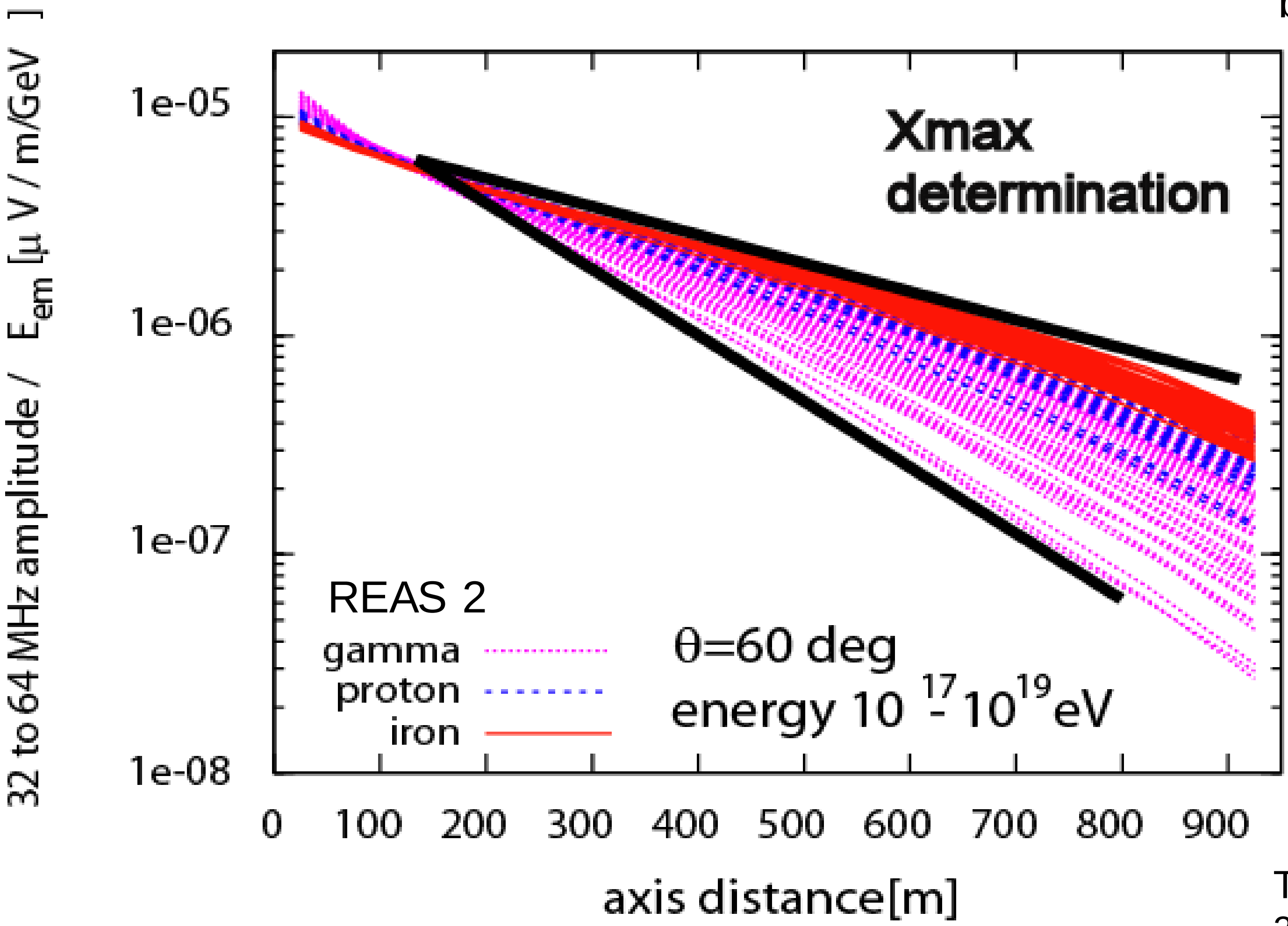
Theoretical prediction

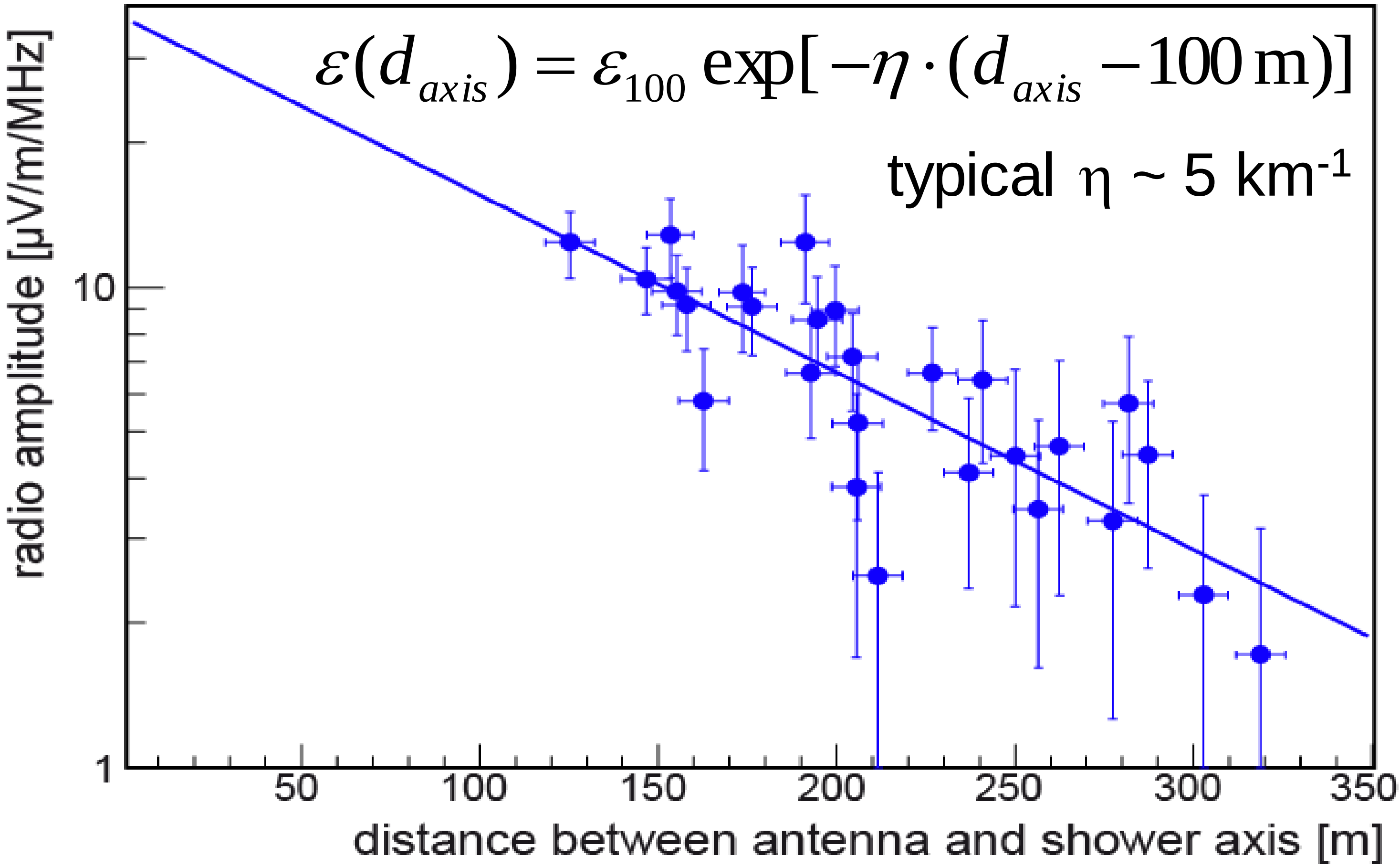
→ see also talk by N. Palmieri



T. Huege, et. al., 2008, Astropp. 30, 96

Lateral distribution, example event

- ‘Real’ lateral distribution complicated, but exponential LDF sufficient as approximation for most LOPES events



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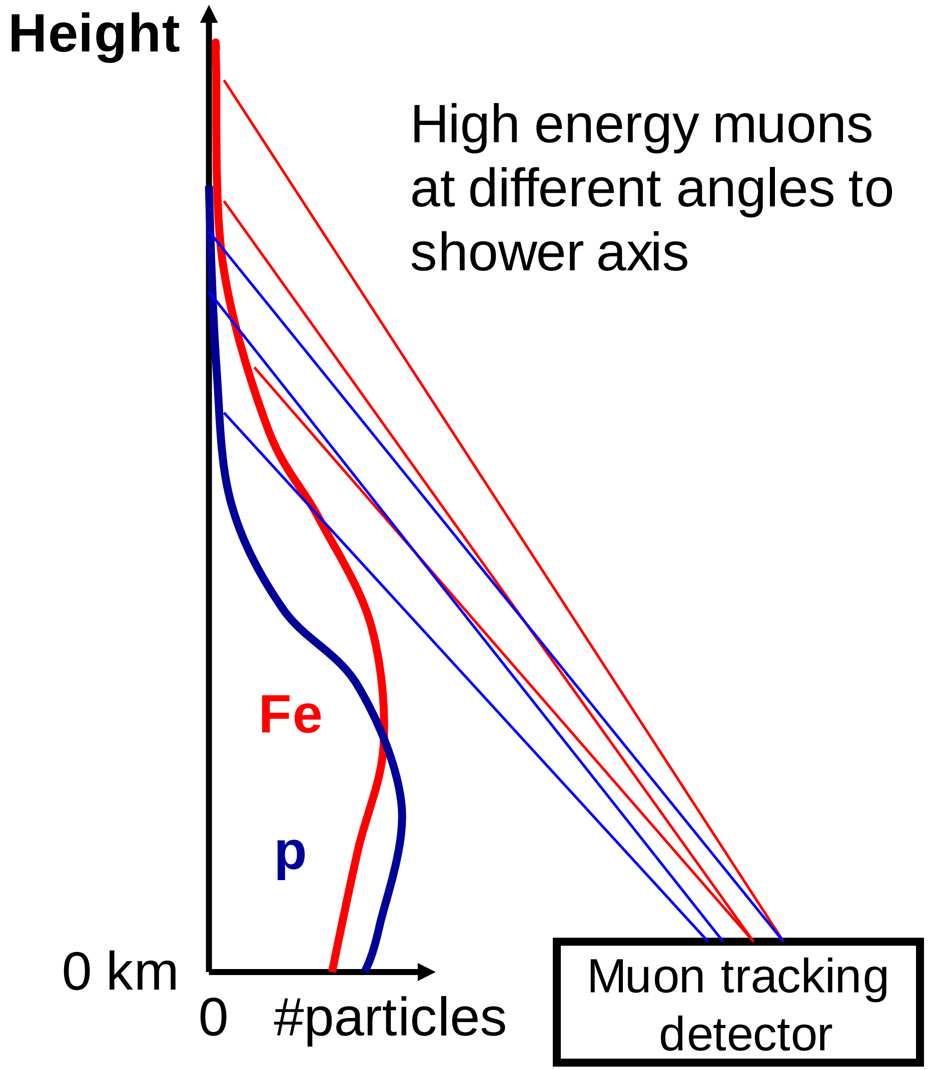
Mean myon pseudo rapidities



High energy muons at different angles to shower axis

small angles = large mean pseudorapidity

large angles = small mean pseudorapidity

Mean muon pseudorapidity
=
measure for logitudinal shower development (after geometry corrections)

KASCADE-Grande Coll., Astropp. 34 (2011) 476

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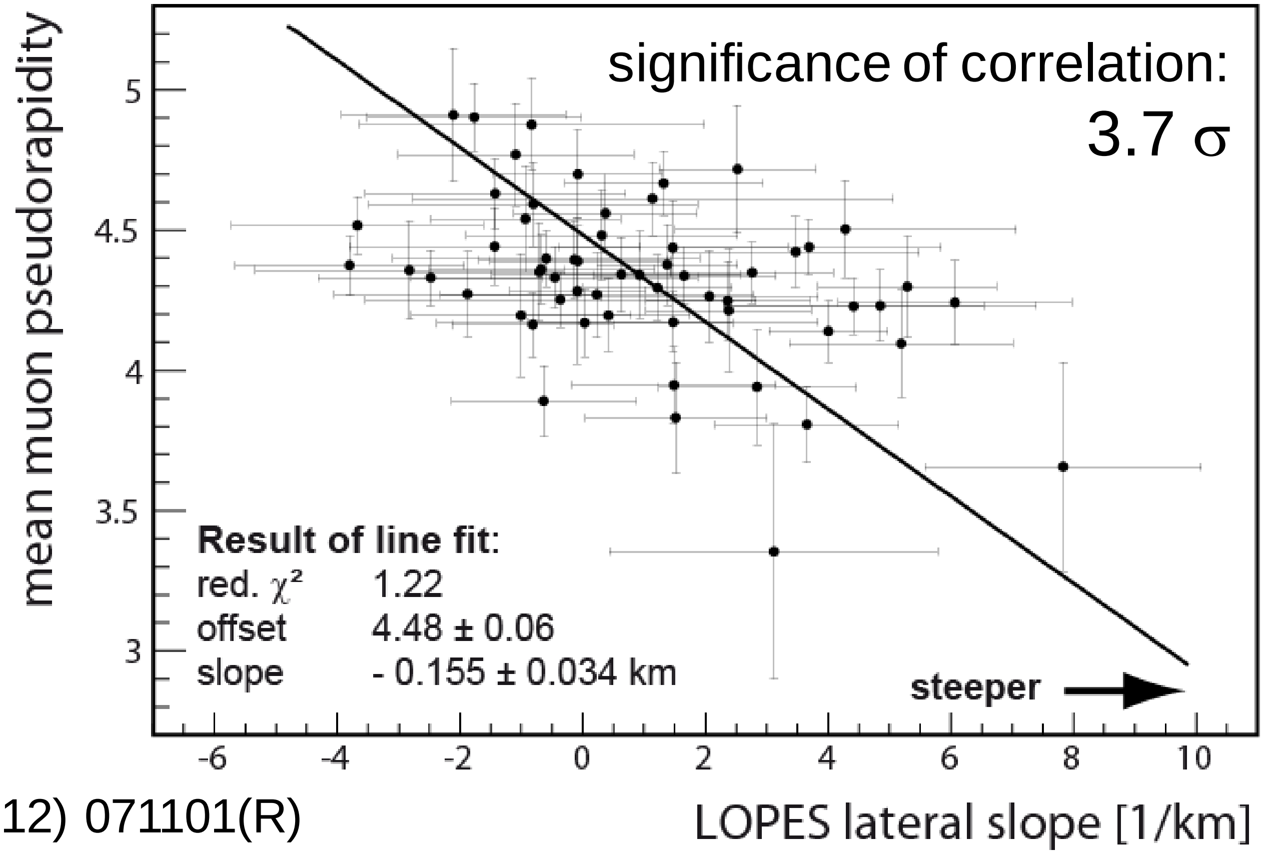
Significant correlation observed

- First experimental proof that radio is sensitive to longitudinal shower development (direct sensitivity to geometrical distance)
- Sensitivity to geometrical distance implies X_{max} sensitivity

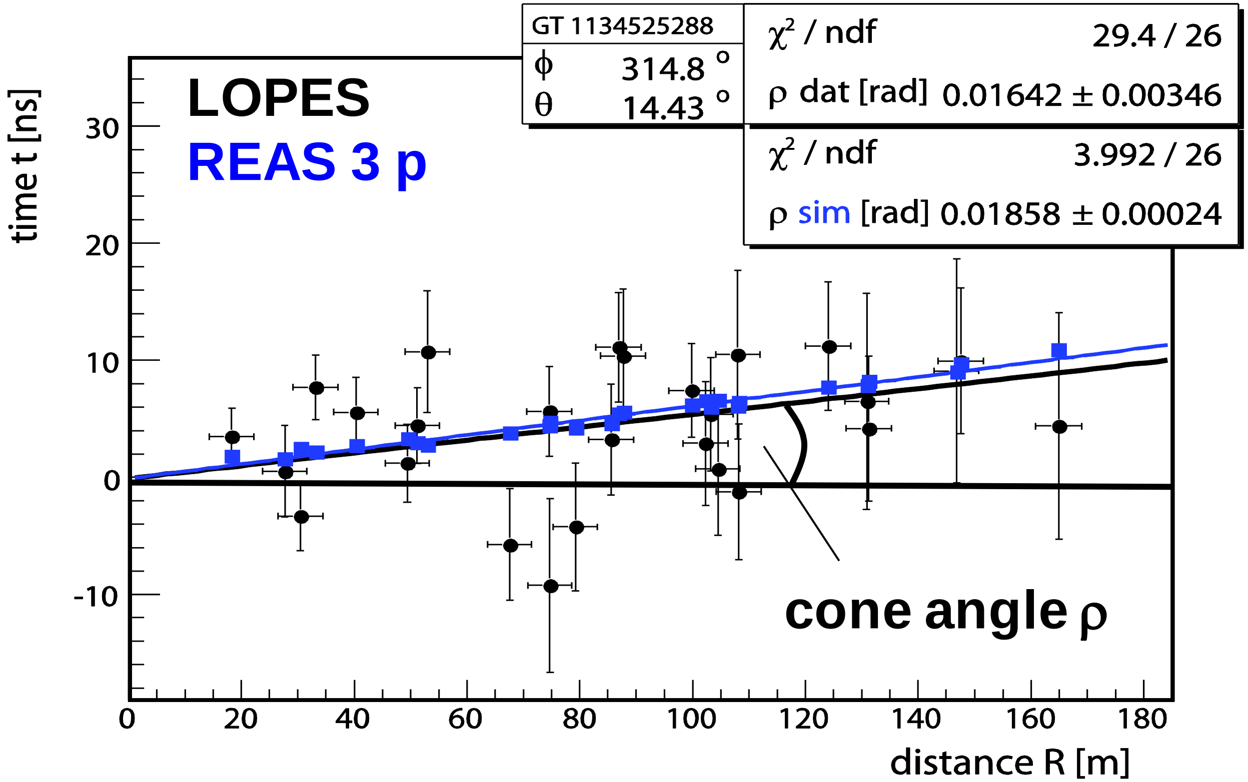


59 events:
after corr. for axis distance + zenith angle

PRD 85 (2012) 071101(R)

X_{max} via conical radio wavefront fit

- Shower geometry by KASCADE-Grande
- LOPES pulse arrival times relative to plane wave
- **Cone angle** from fit



LOPES, ICRC 2011

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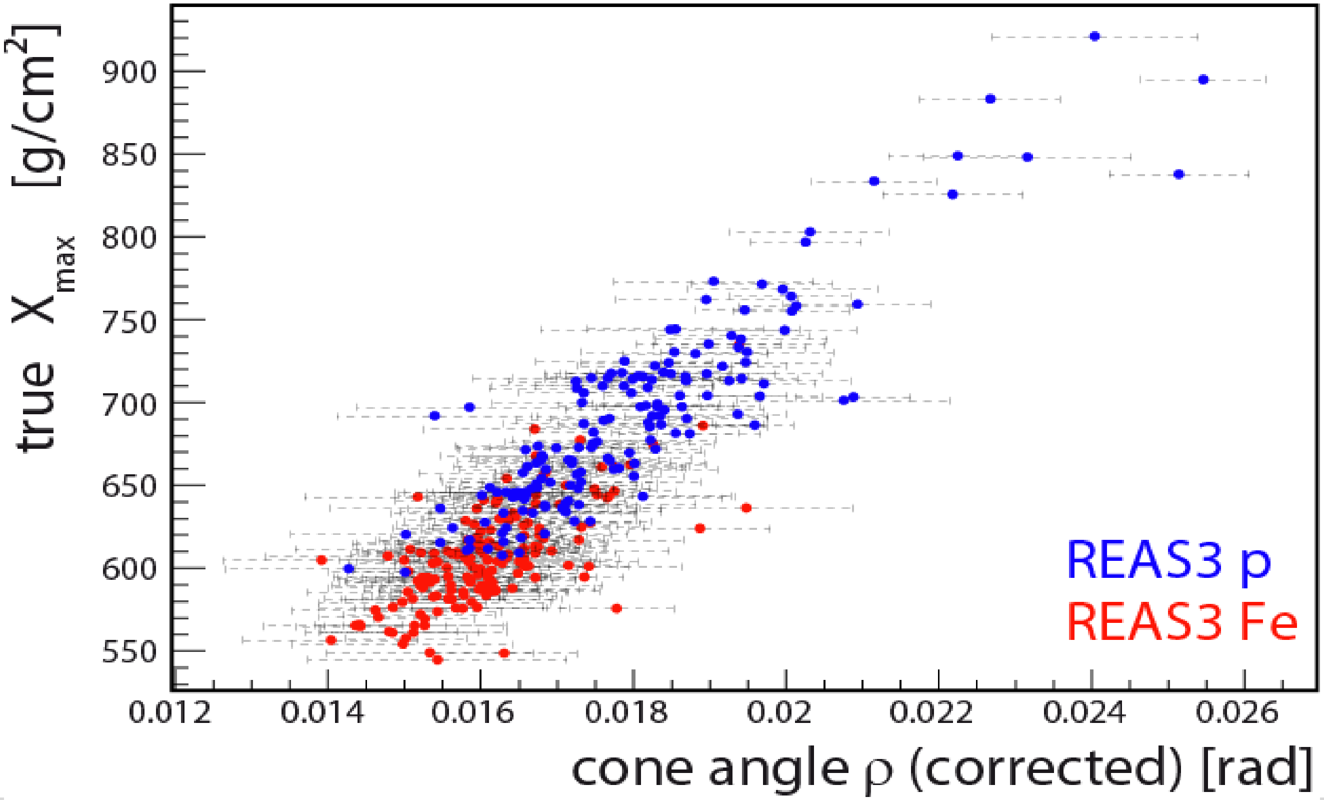
X_{max} reconstruction with cone angle

- X_{max} proportional to ρ after correction for zenith angle
  - precision: ~30 g/cm² for REAS3 simulations without noise
  - precision: ~200 g/cm² for LOPES measurements



LOPES, ICRC 2011

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LOPES reconstruction precision

	Method	LOPES precision
Direction	spherical CC beamforming	≤ 0.72°
	conical CC beamforming	**≤ 0.65°**
	wavefront fit to pulse times	not tested
Energy	**amplitude of CC beam**	**≤ 20 %**
	amp. at charact. axis distance	**≤ 20 %**
	integrated radio signal	not tested
X_{max}	**slope of lateral distribution**	**≤ 90 g/cm²**
	conical wavefront fit	~ 200 g/cm²
	spectral slope	not tested

precision ≤ total accuracy, since there might be additional systematic uncertainties, e.g., scale uncertainties due to calibration and used models

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Conclusion

- LOPES running stable
  - still some technical developments (octocopter calibration)
  - since 2.5 years: tripole configuration collects data
- Understanding of the radio emission
  - measured results are (more or less) theoretically understood
  - radio wavefront is approximately conical
  - radio emission sensitive to shower development (geom. distance)
- Reconstruction of shower parameters
  - improved methods → improved precision
  - high ambient noise level limits precision, at least for X_{max}
  - methods usable for other experiments (software is open-source)

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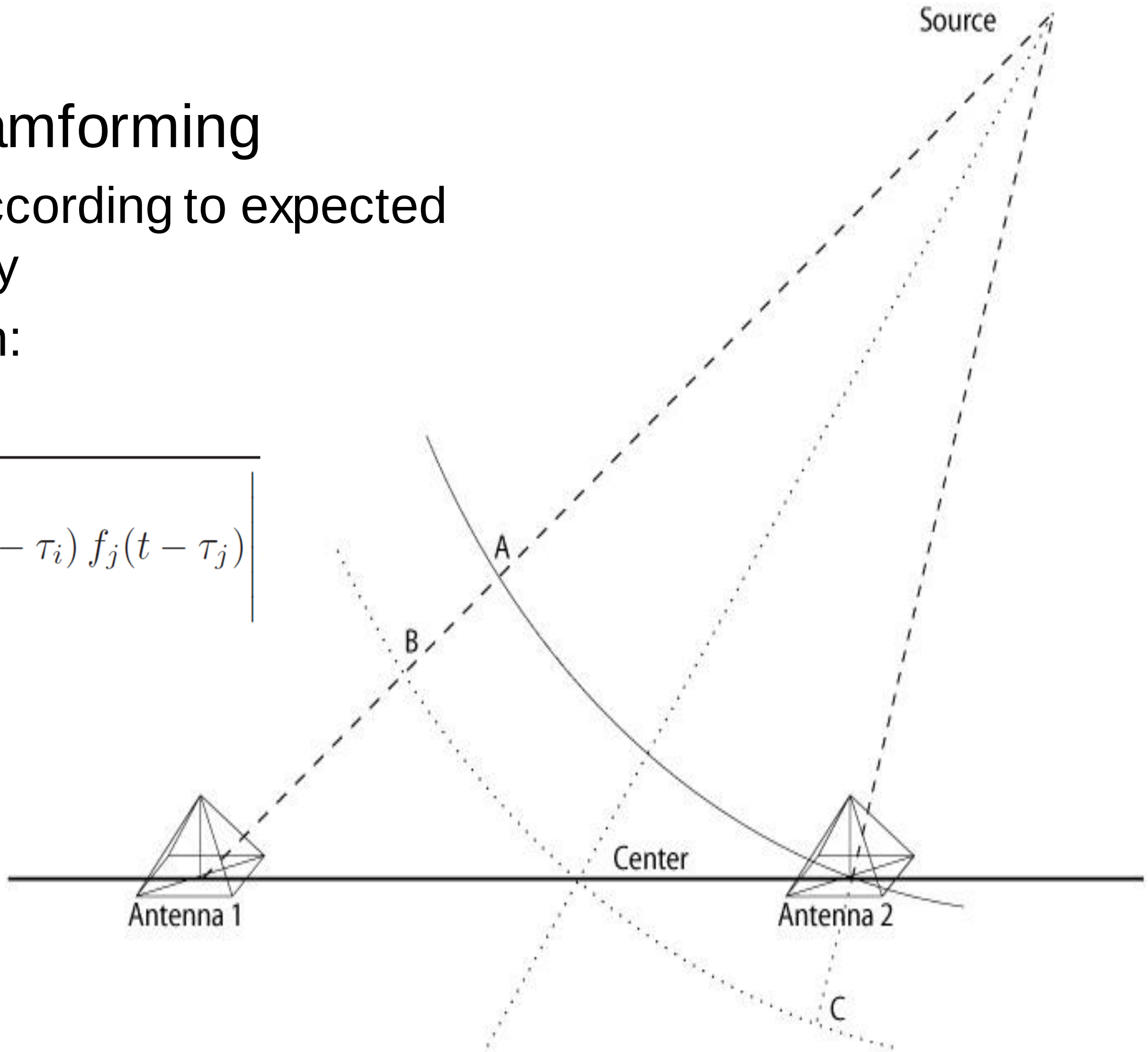
Digital Interferometry

- Interferometric beamforming
  1. Shift radio data according to expected geometrical delay
  2. Cross correlation:

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



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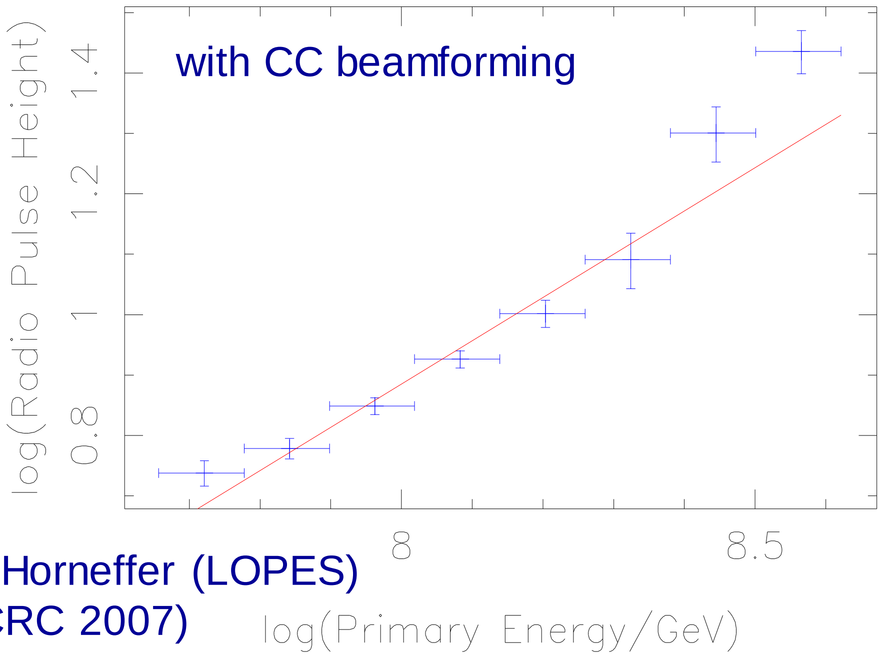
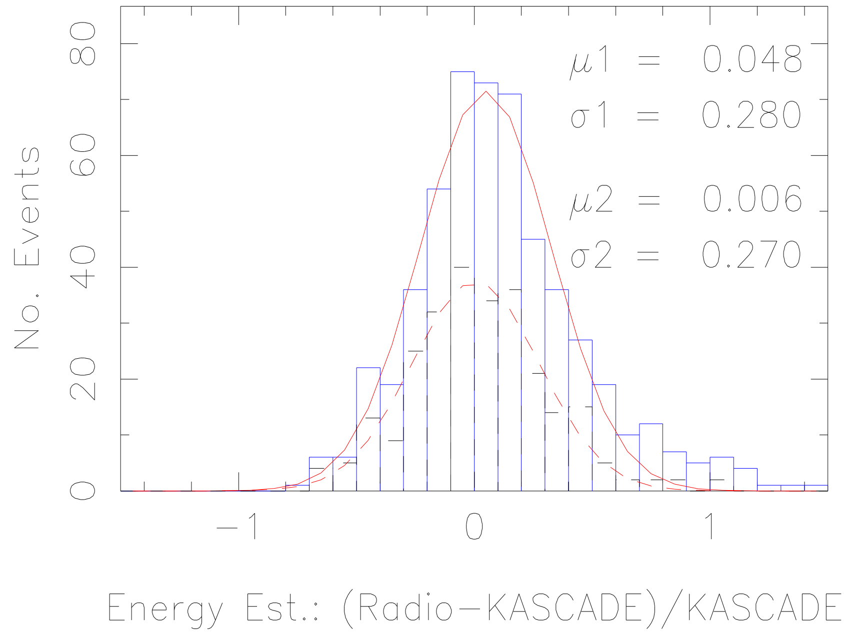
Energy reconstruction, status quo

- Allan formula (1971) $$E \propto \frac{\varepsilon_{radio}}{\sin\alpha \cdot \cos\theta \cdot \exp(-d/d_0)}$$
- LOPES (ICRC 2007) $$E \propto \frac{\varepsilon_{CC-beam(east-west)}}{(1-\cos\alpha) \cdot \cos\theta \cdot \exp(-d/d_0)}$$



A. Horneffer (LOPES) (ICRC 2007)



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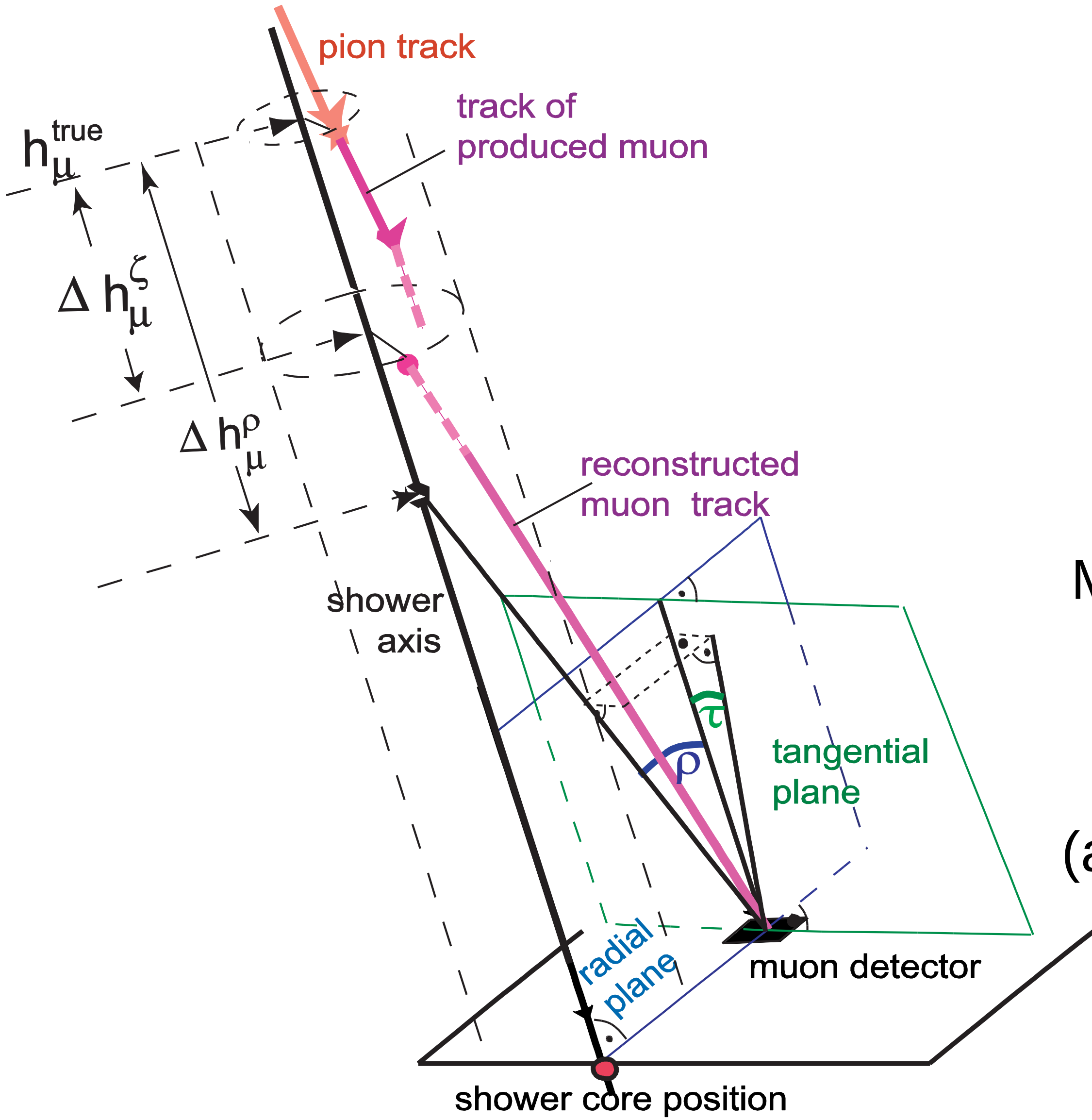
Myon pseudorapidities



$$\text{pseudoRap} = -\ln\left(\frac{1}{2}\sqrt{\tau^2+\rho^2}\right)$$

angle to axis

Mean muon pseudorapidity
=
measure for logitudinal
shower development
(after geometry corrections)

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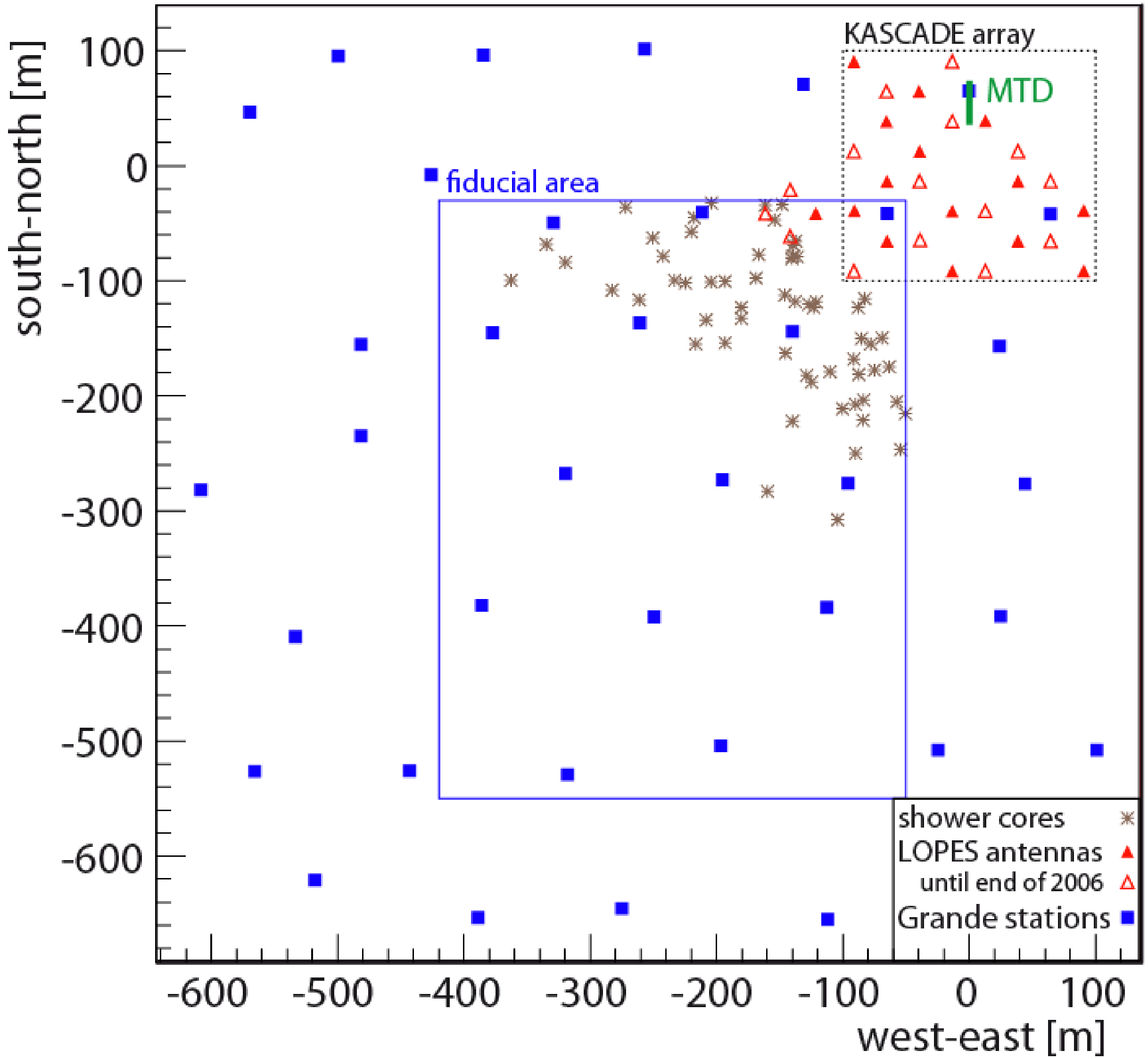
Correlation of LOPES with MTD



59 events

- hybrid measurement: KASCADE-Grande, LOPES and Myon-Tracking-Detector
- axis distance to MTD: 160 m – 320 m
- no thunderstorm
- Exponential fit of radio LDF successful

→ Correlation of radio + muon measurements

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