Radio:

- composition-systematics in simulations
- prospects for multi-hybrid measurements

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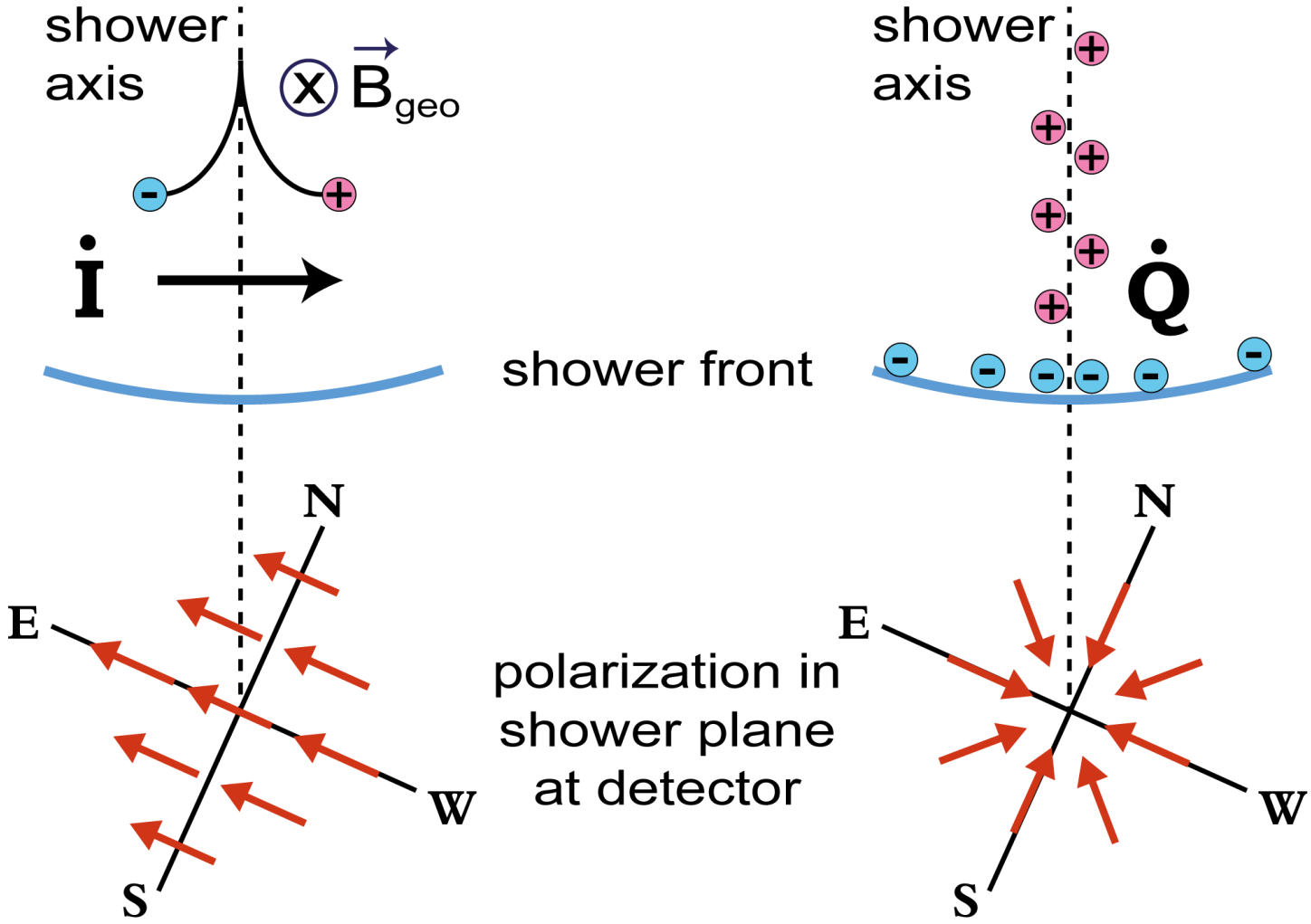
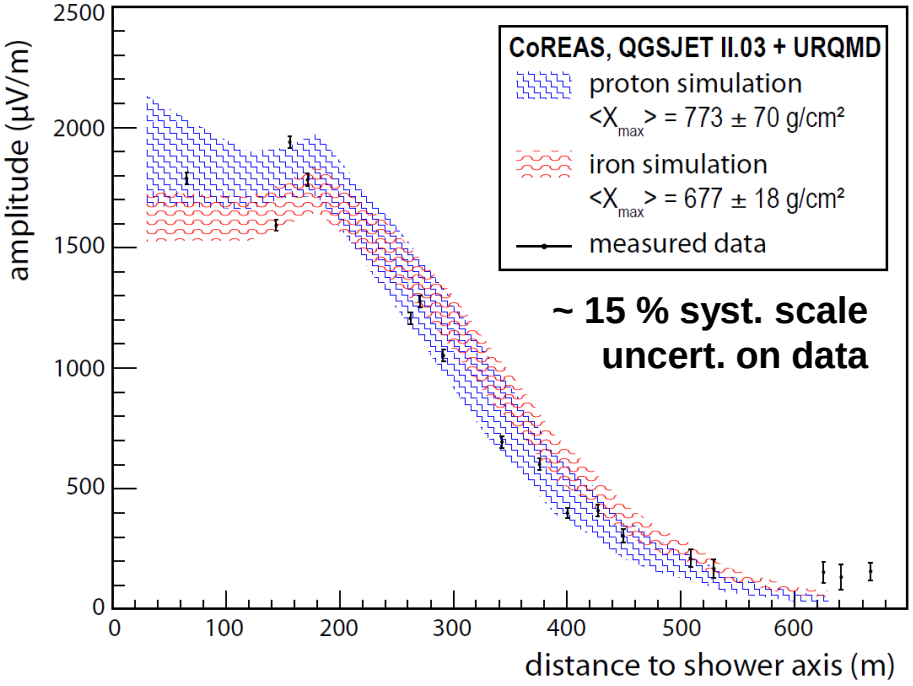
Emission mechanisms

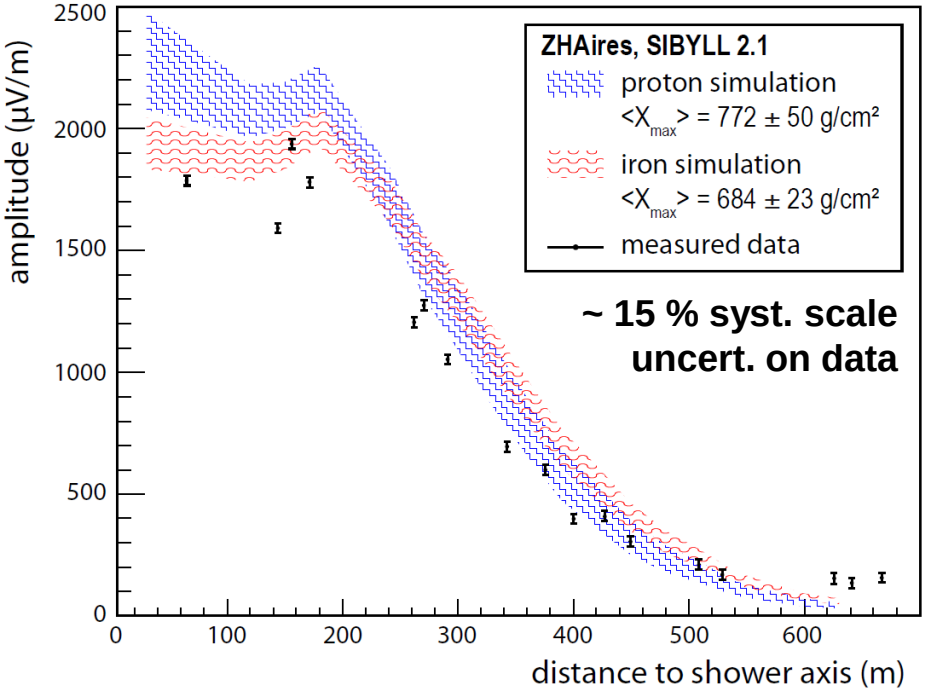


geomagnetic effect ~ 90%

Askaryan effect ~ 10%

CoREAS vs. ZHAires





- Why is there a difference of 10 – 20 % ?
  - CORSIKA vs. Aires
  - hadronic interaction model
  - ZHS vs. end-point formalism

} everything negligible?

Pierre Auger Collaboration, ICRC2013, id #899

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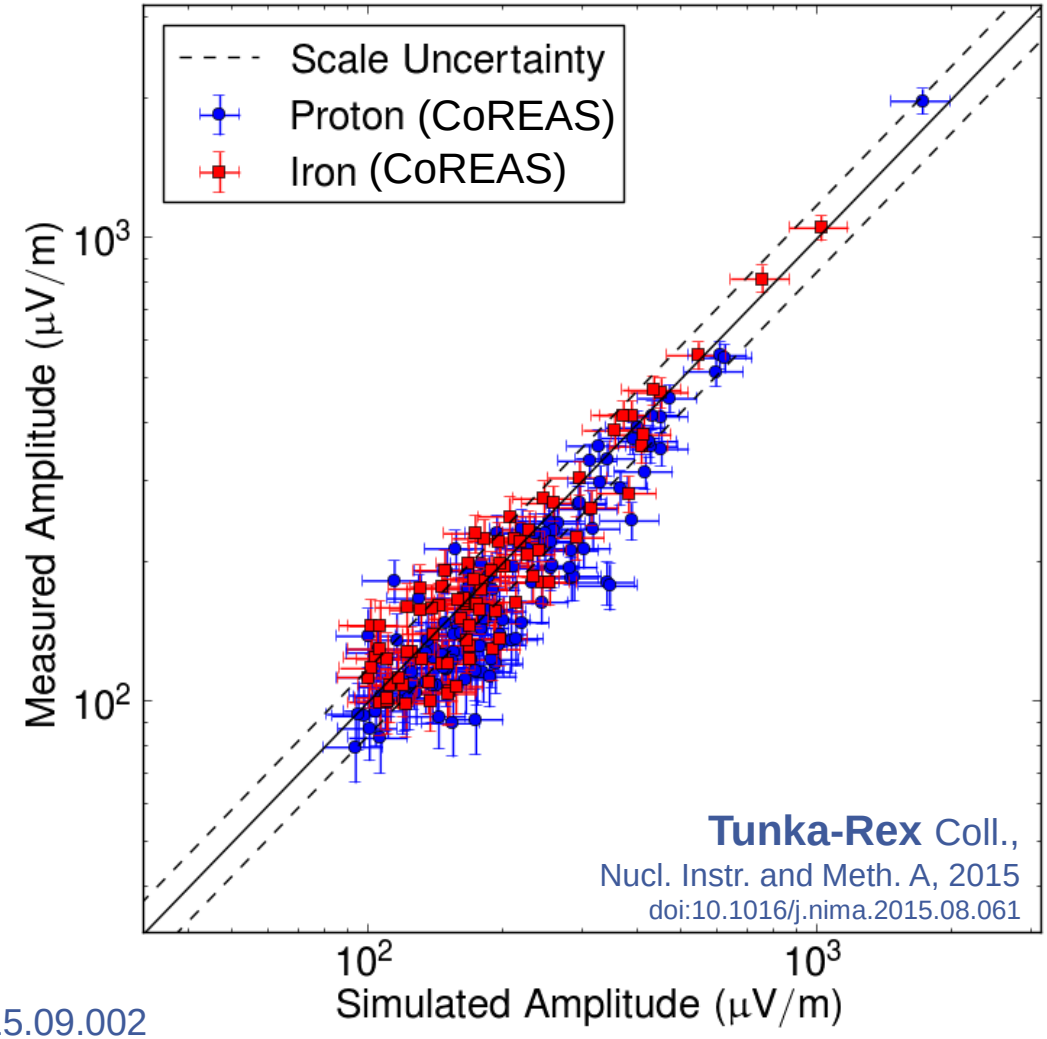
CoREAS vs. Tunka-Rex

- CORSIKA simulations with energy and X_{max} of Tunka-133 measurement
- 20% scale uncertainty on radio amplitude
- Data/MC
  - 0.84 for proton
  - 0.96 for iron
- Difference due to „invisible energy“ in the muonic component?



LOPES Coll., doi:10.1016/j.astropartphys.2015.09.002
Data/MC: 0.98 for proton, 1.09 for iron

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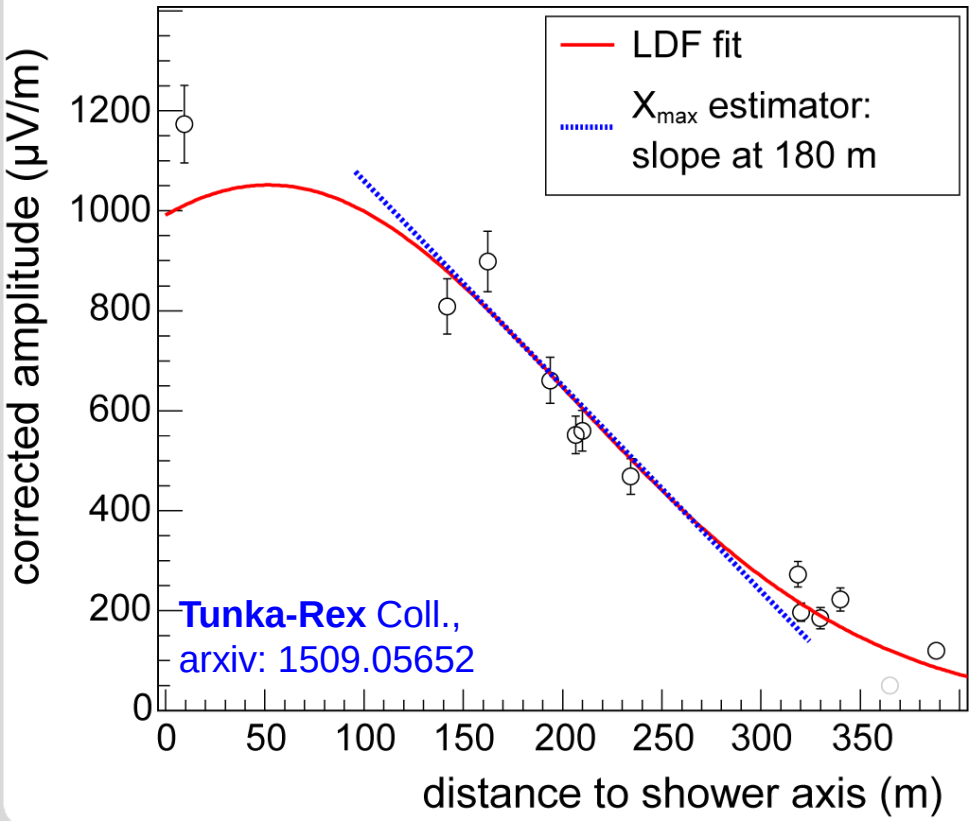
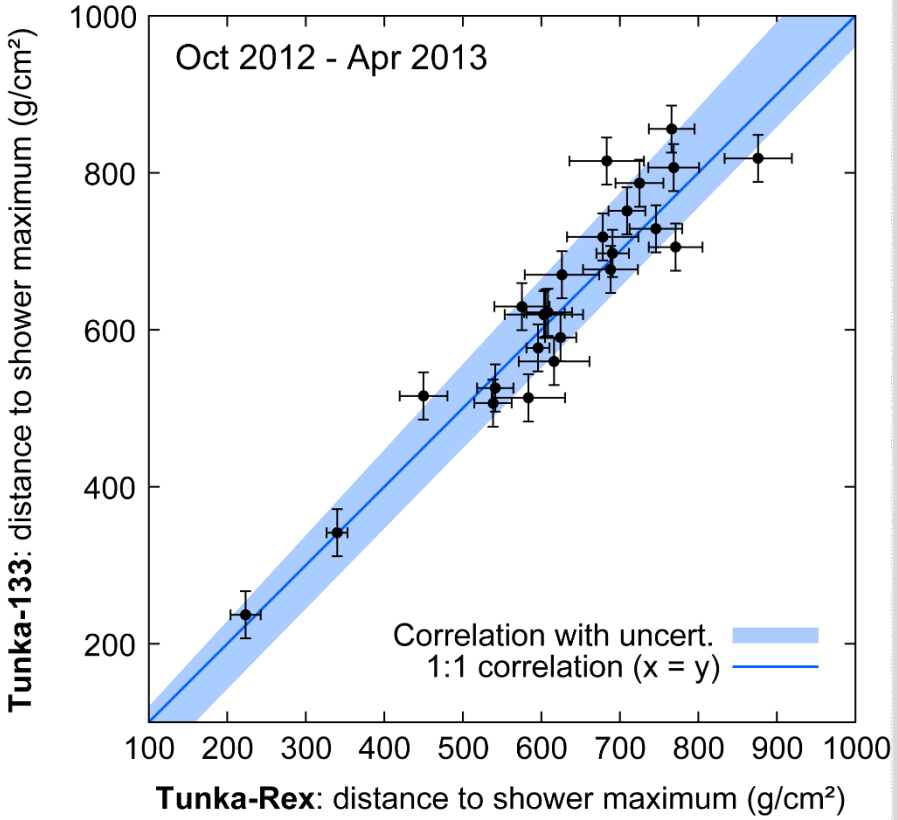
Shower maximum: proof by Tunka-Rex

- Sparse (200 m distance) and economic radio array
- Correlation of radio and air-Cherenkov measurements
  - Tunka-Rex accuracy with ~ 5-10 antennas: 40 g/cm²





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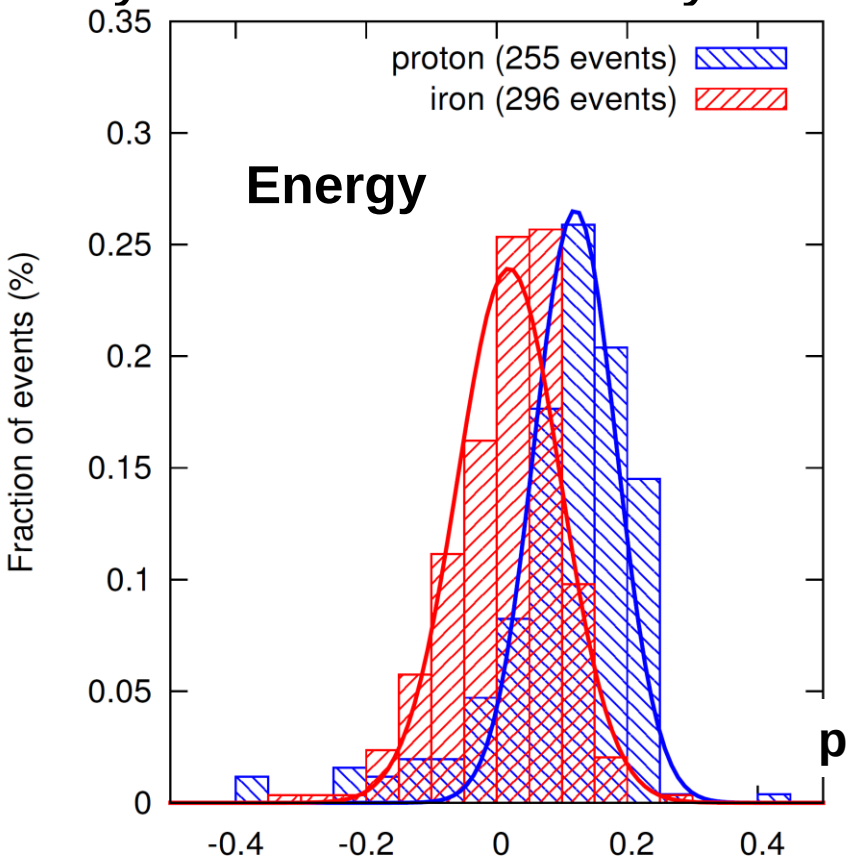
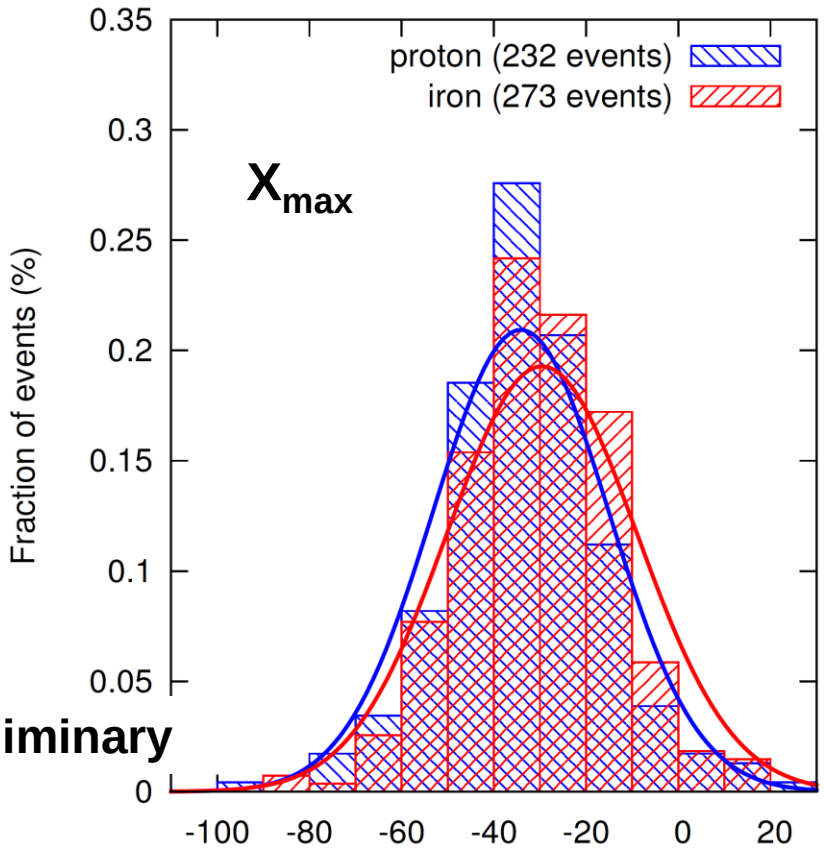
Mass-dependent systematics

- Not only energy, but also X_{max} reconstruction affected
- Systematic uncertainty or additional mass sensitivity?



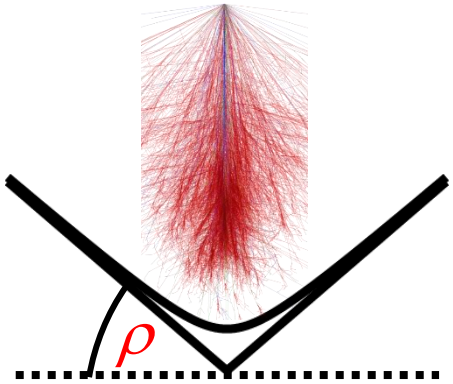


preliminary

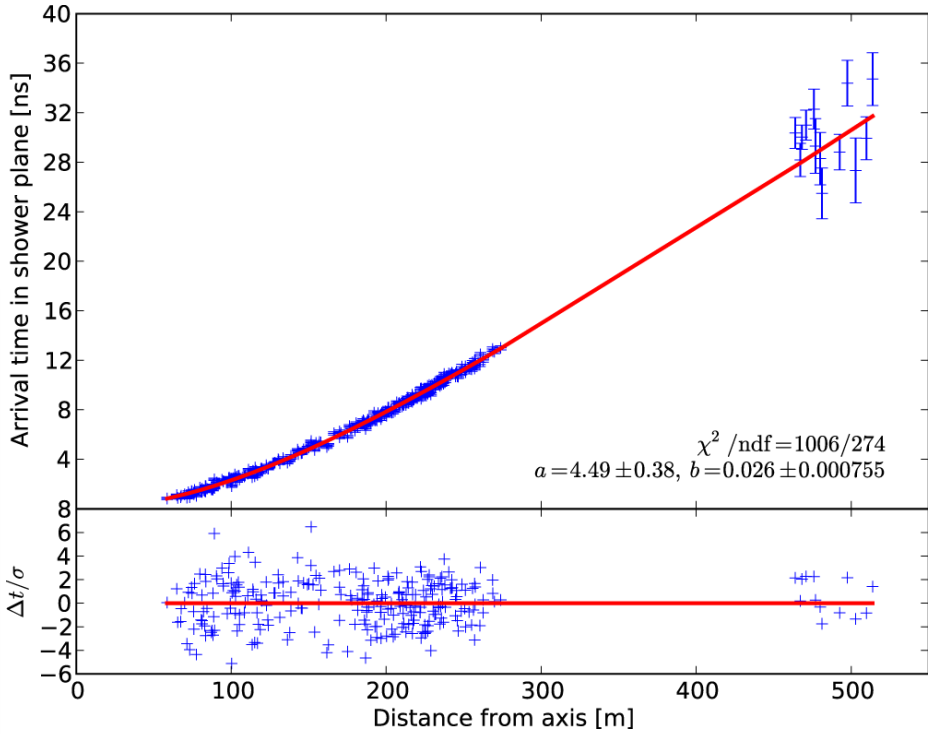
D. Kostunin

Wavefront

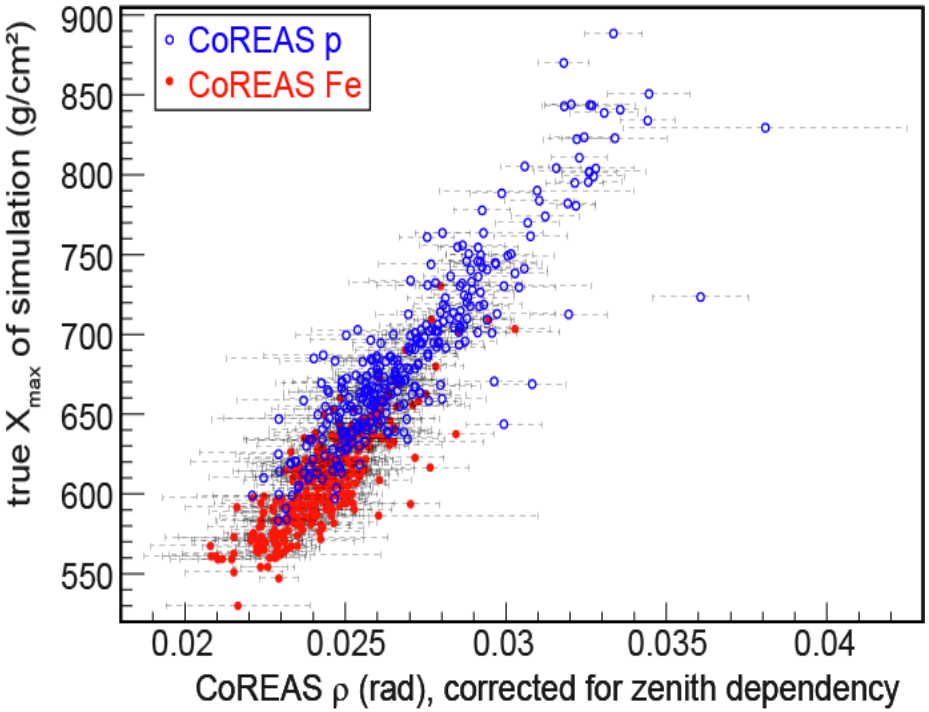
- Simulated X_{max} dependence differs for proton and iron by few percent



ca. 1° - 2°



LOFAR Coll, Astropp. 61 (2015) 22



LOPES Coll., JCAP 09 (2014) 025

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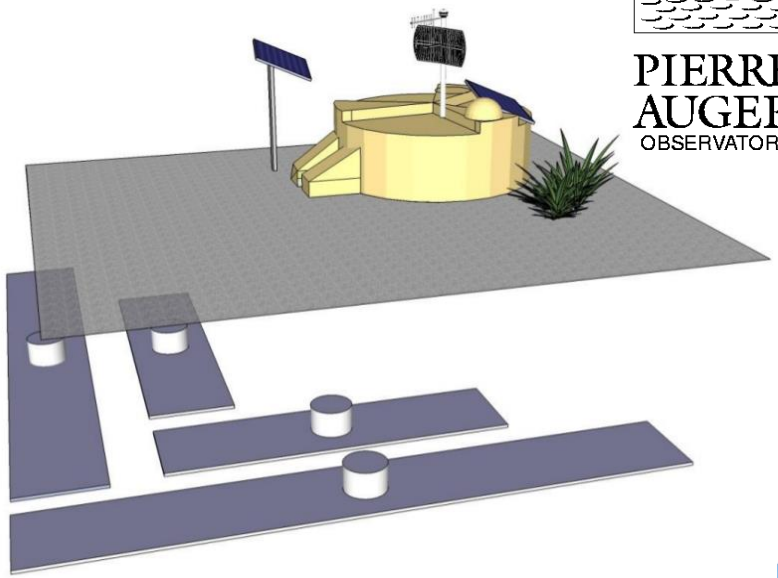
Combining Radio + Muons

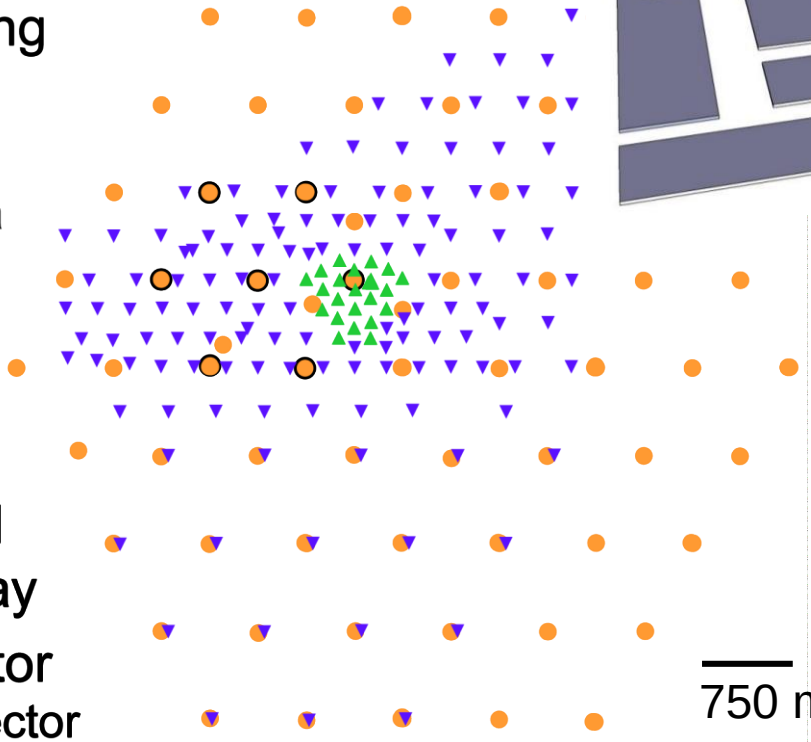
- Pierre Auger enhancements
  - 153 antenna station on 17 km²
  - surface and underground detectors



PIERRE AUGER OBSERVATORY

Auger Engineering Radio Array

- LPDA antenna
- Butterfly antenna



Auger Muon and Infill Ground Array

- **Surface Detector**
- **with Muon Detector**

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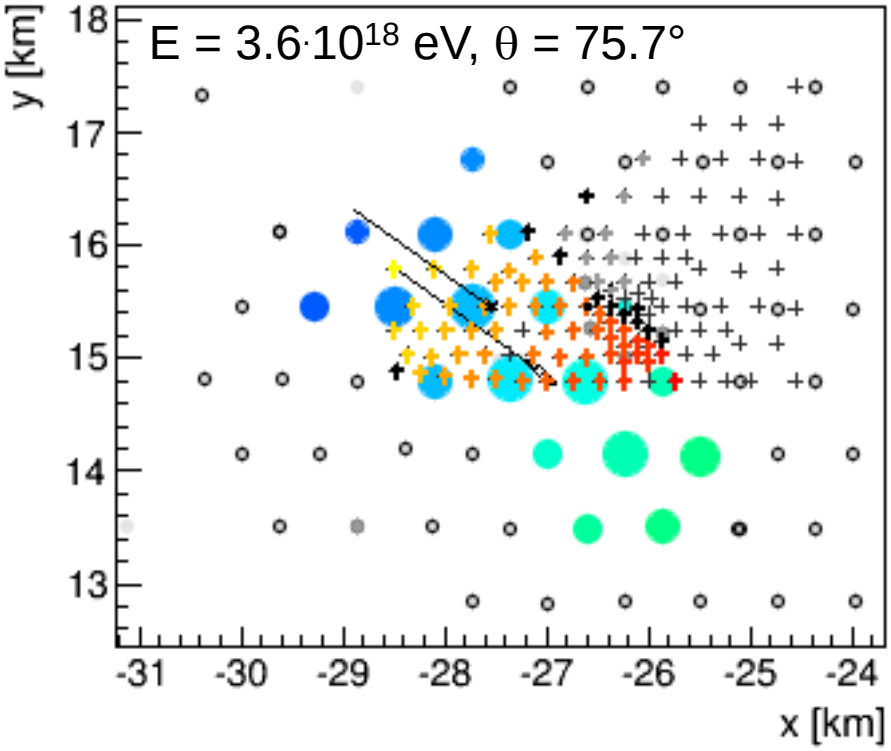
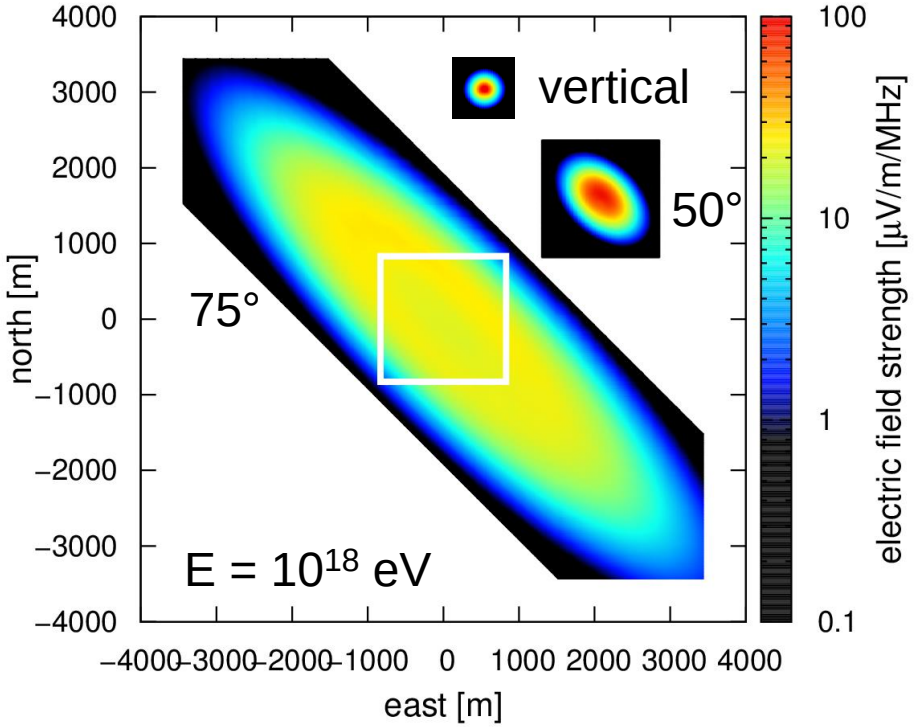
Huge footprint for inclined showers

- Sparse antenna spacing feasible for inclined showers
  - Radio becomes applicable to largest scales for reasonable costs

Auger measurement



CoREAS simulation



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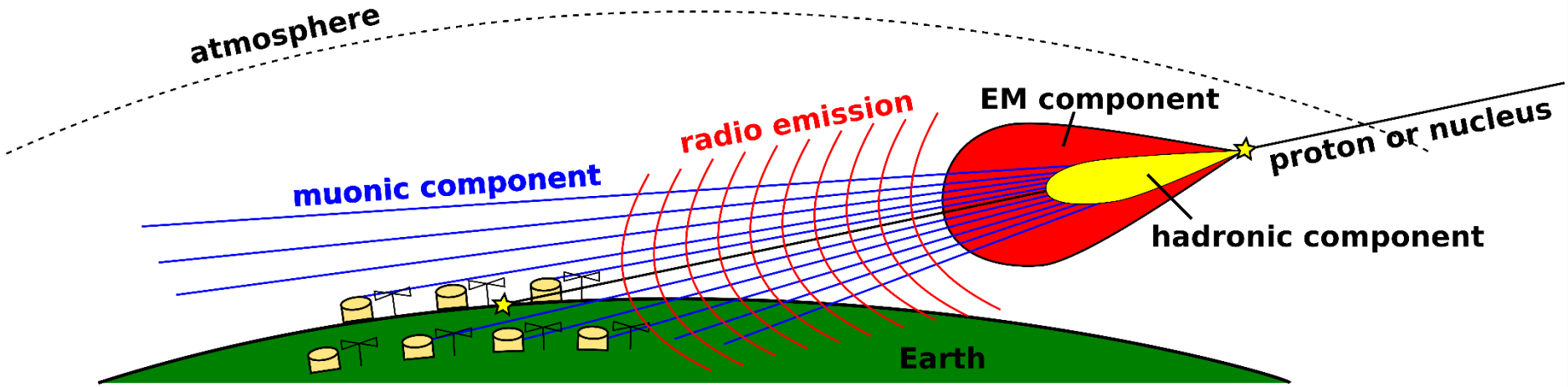
Radio ideal for inclined showers



- Electrons and photons attenuate in atmosphere
- Only muons and radio emission survives (no absorption)
  - Complementary information on shower → primary particle type

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Conclusion

- Simulations consistently agree with measurements
  - radio emission understood to at least 10-20 % accuracy
  - proton vs. iron ~ 10 % influence on amplitude
- Smaller effects of few percent on other observables
  - could be exploited to boost mass reconstruction at ultra precise arrays (~ 10,000 antennas)
- Alternative: Muon measurements + Radio
  - determine fraction of primary energy invisible in radio
  - increase mass sensitivity by complementary information

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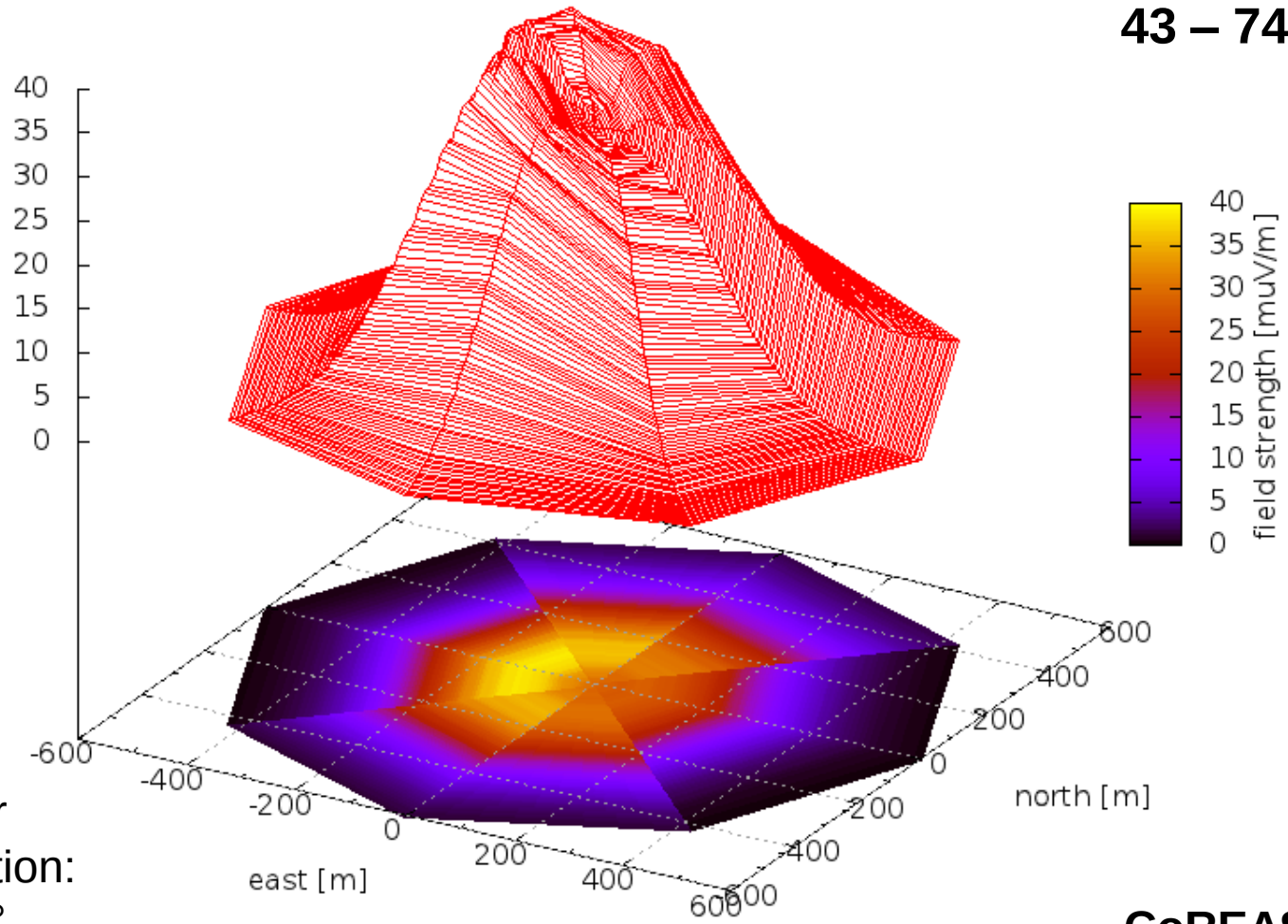
Backup

Asymmetric lateral distribution

43 – 74 MHz



shower inclination:
$\theta = 45°$

CoREAS simulation for LOPES experiment

T. Huege et al., ARENA2012

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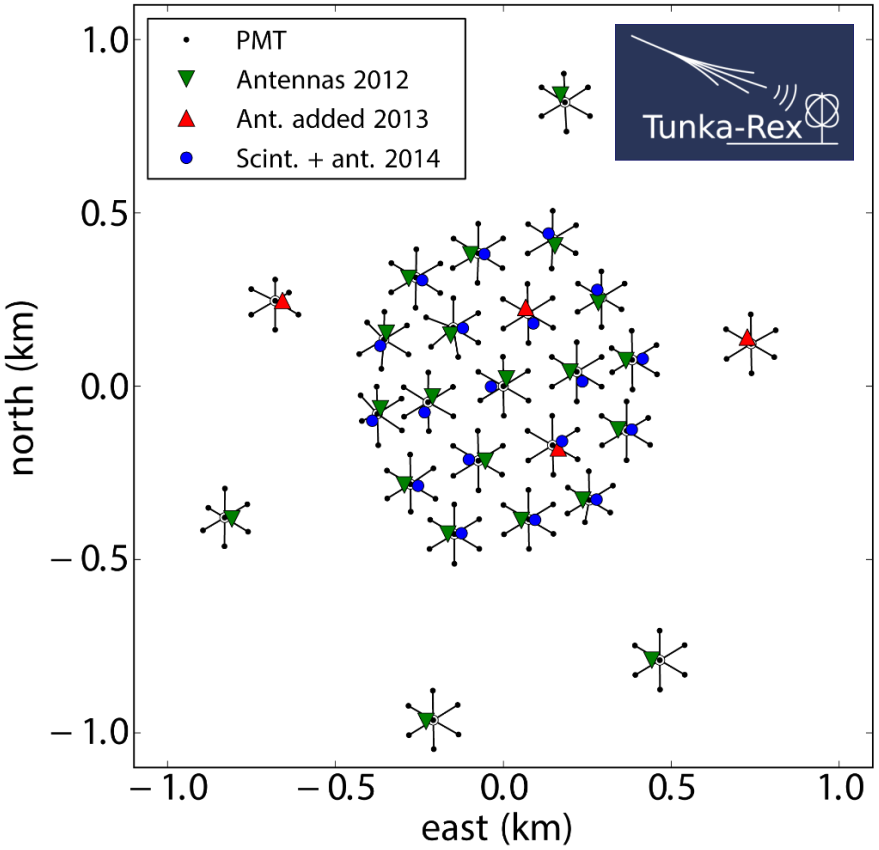
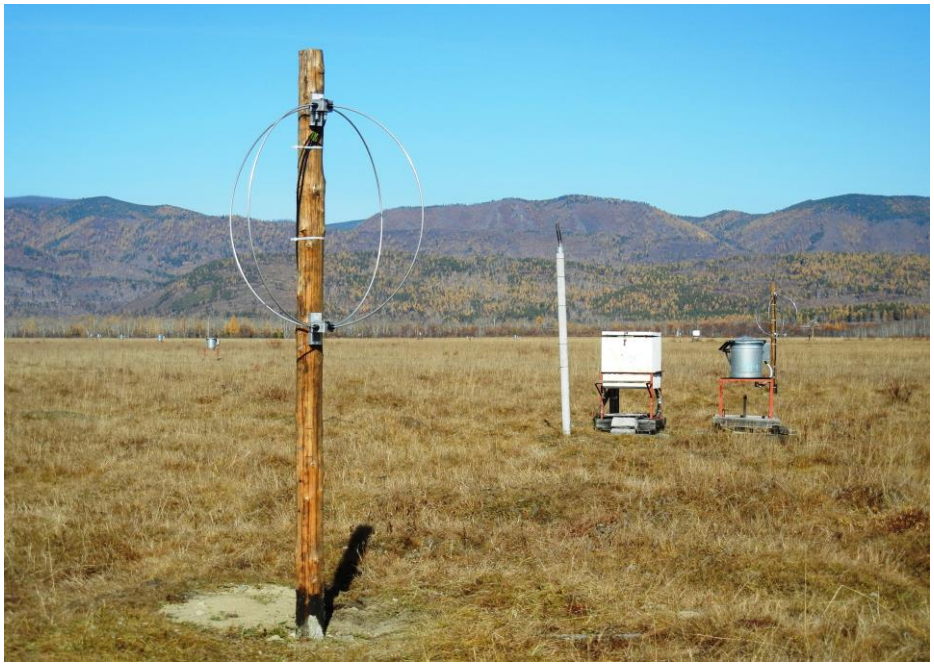
Tunka-Rex in Siberia close to Lake Baikal

- SALLA antennas, 30 - 80 MHz
- Cross-calibration with co-located air-Cherenkov detector
  - Precision and absolute scale of energy and shower maximum





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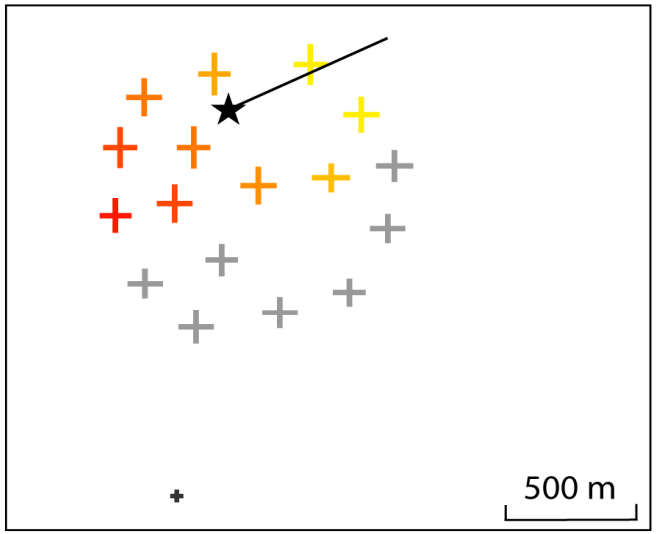
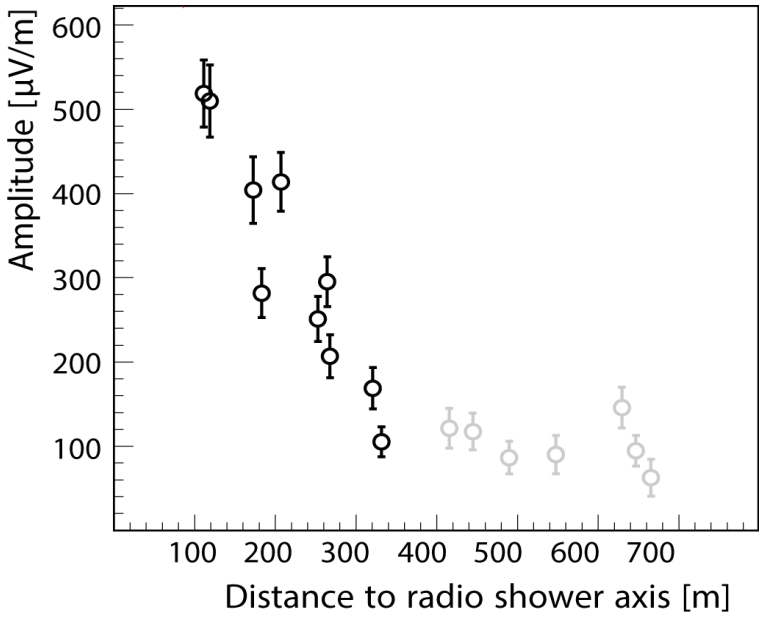
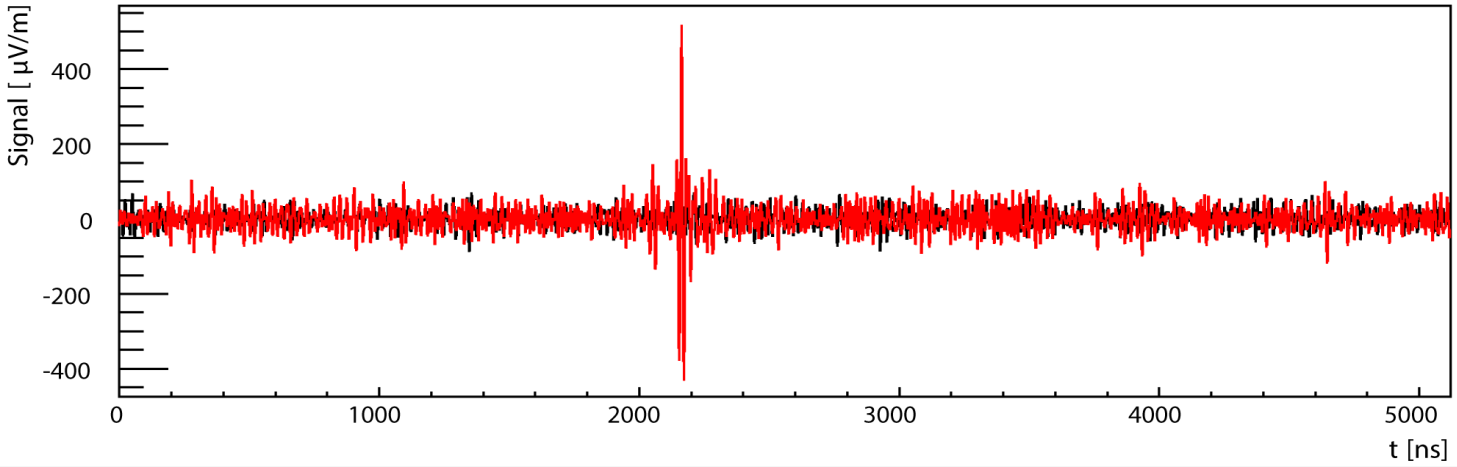
Tunka-Rex example event







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