Karlsruhe Institute of Technology

New LOPES results: Radio Detection of Air Showers

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LOPES history

32 ICRC contributions: 2003: 1 2005: 8 2007: 7 2009: 5 2011: 4 2013: 5 2015: 2

Apr 2003	Feb 2005	Dec 2006	May 2010 - Jan 2013
LOPES 10	**LOPES 30**	**LOPES Dual**	**LOPES 3D**

for main analysis

- Start 2003: **LO**FAR **p**rototype **s**tation
  - Proof-of-principle for digital, interferometric radio detection
- Several configurations to test:
  - antenna types, triggers, polarization, …
- Stop 2013 together with KASCADE
  - Data will become part of KASCADE Cosmic Ray Data Center:
    https://kcdc.ikp.kit.edu/ PoS(ICRC2015)262

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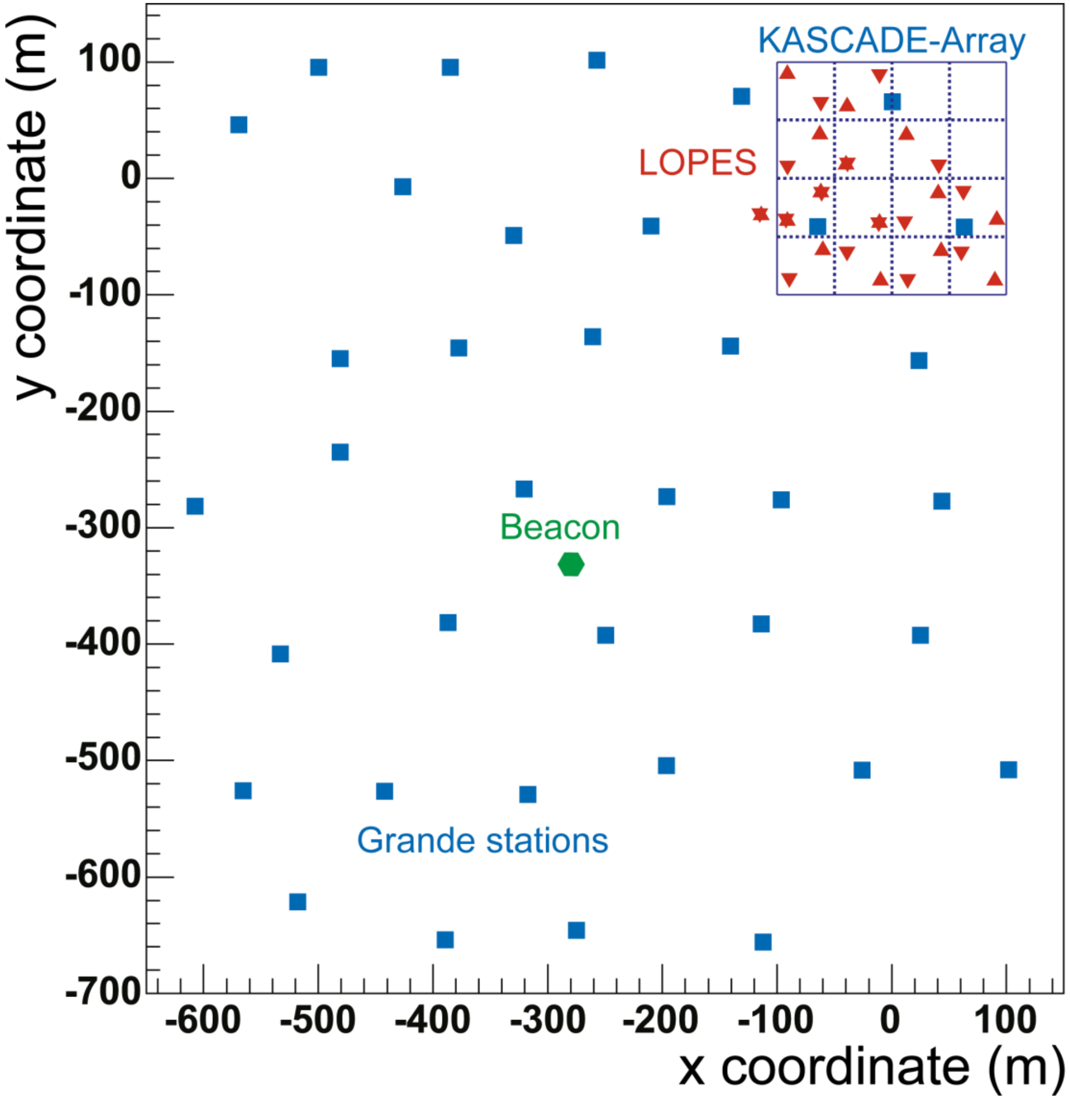
LOPES setup (map of 2009)



- 30 dipole antennas
  - 40 – 80 MHz, **east-west** / north-south
- Trigger by KASCADE

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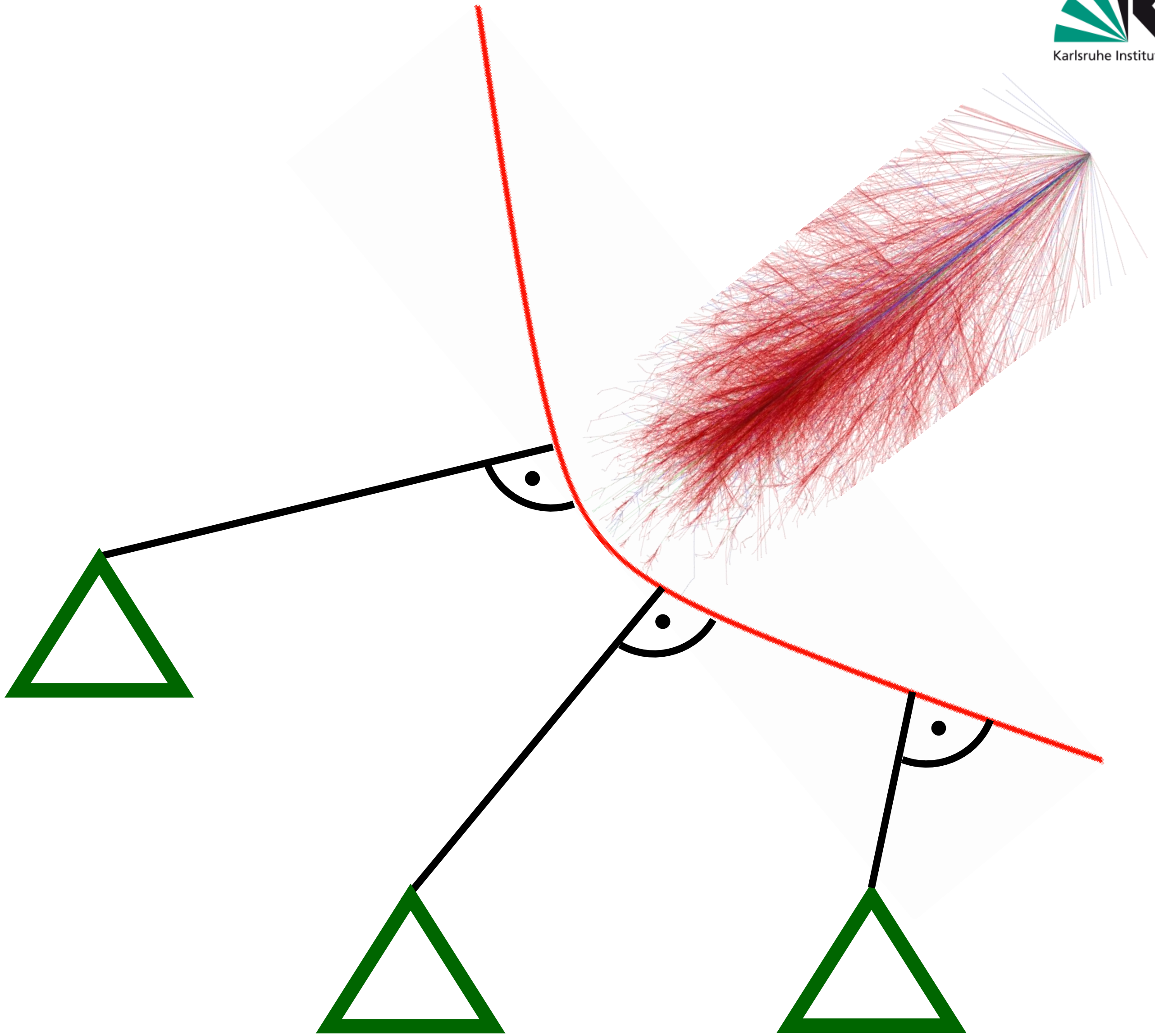
Digital interferometry

- Beamforming
  - Digitally shift all traces in time by *distance to wavefront / c*
  - Hyperbolic wavefront
- Cross-correlation of all traces
  - possible due to 1 ns relative timing accuracy



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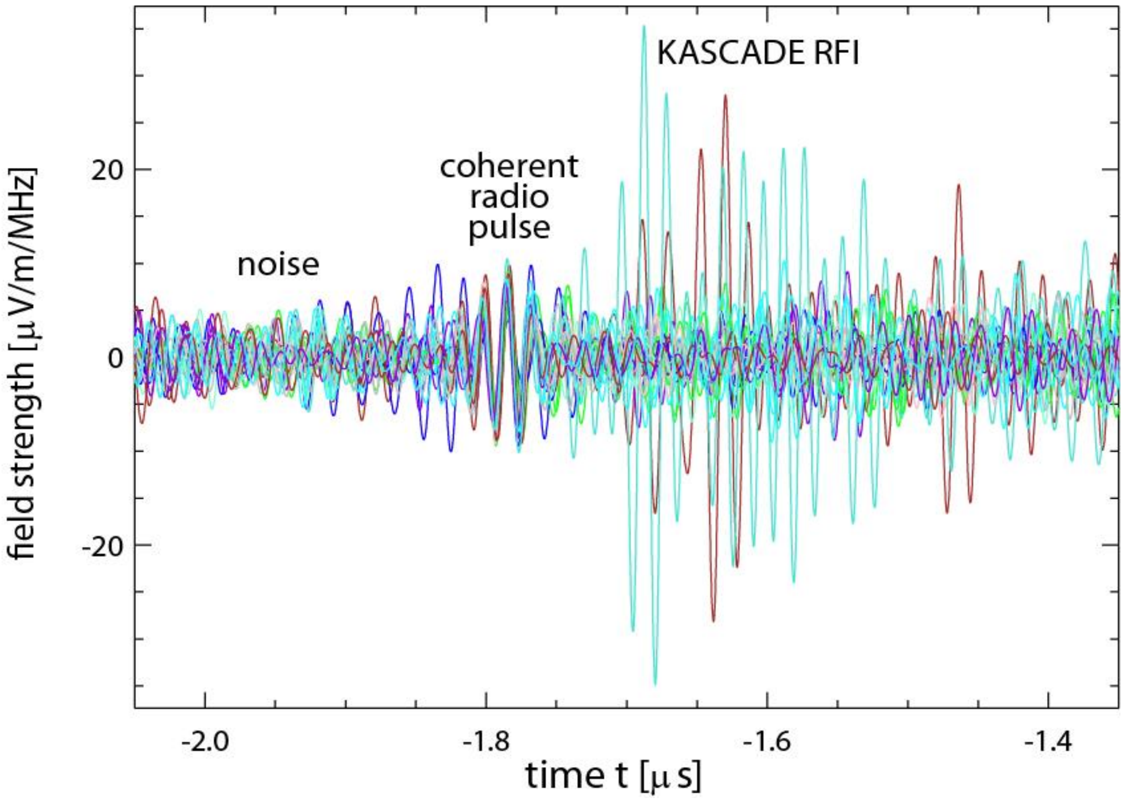
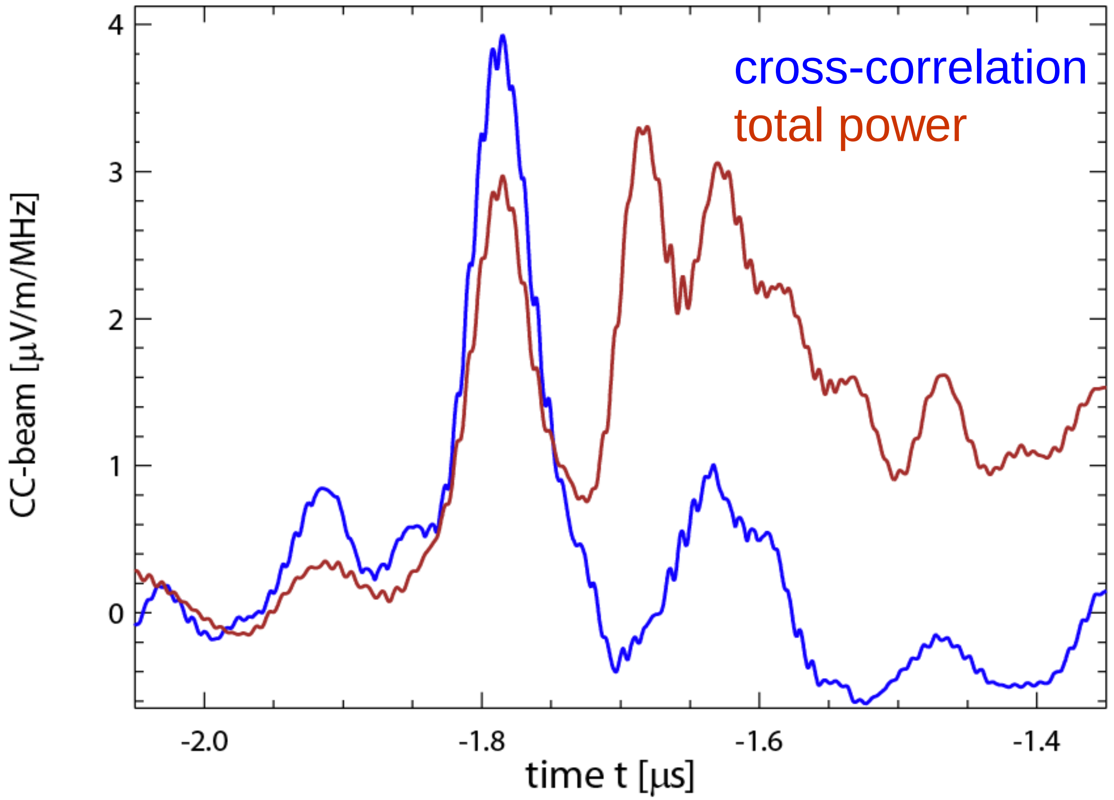
Digital radio interferometry

- After beamformig, cross-correlation for pulse identification
  - only air shower radio pulse is correlated in all antennas
- Analyses based on two independent measurements: arrival times + amplitude





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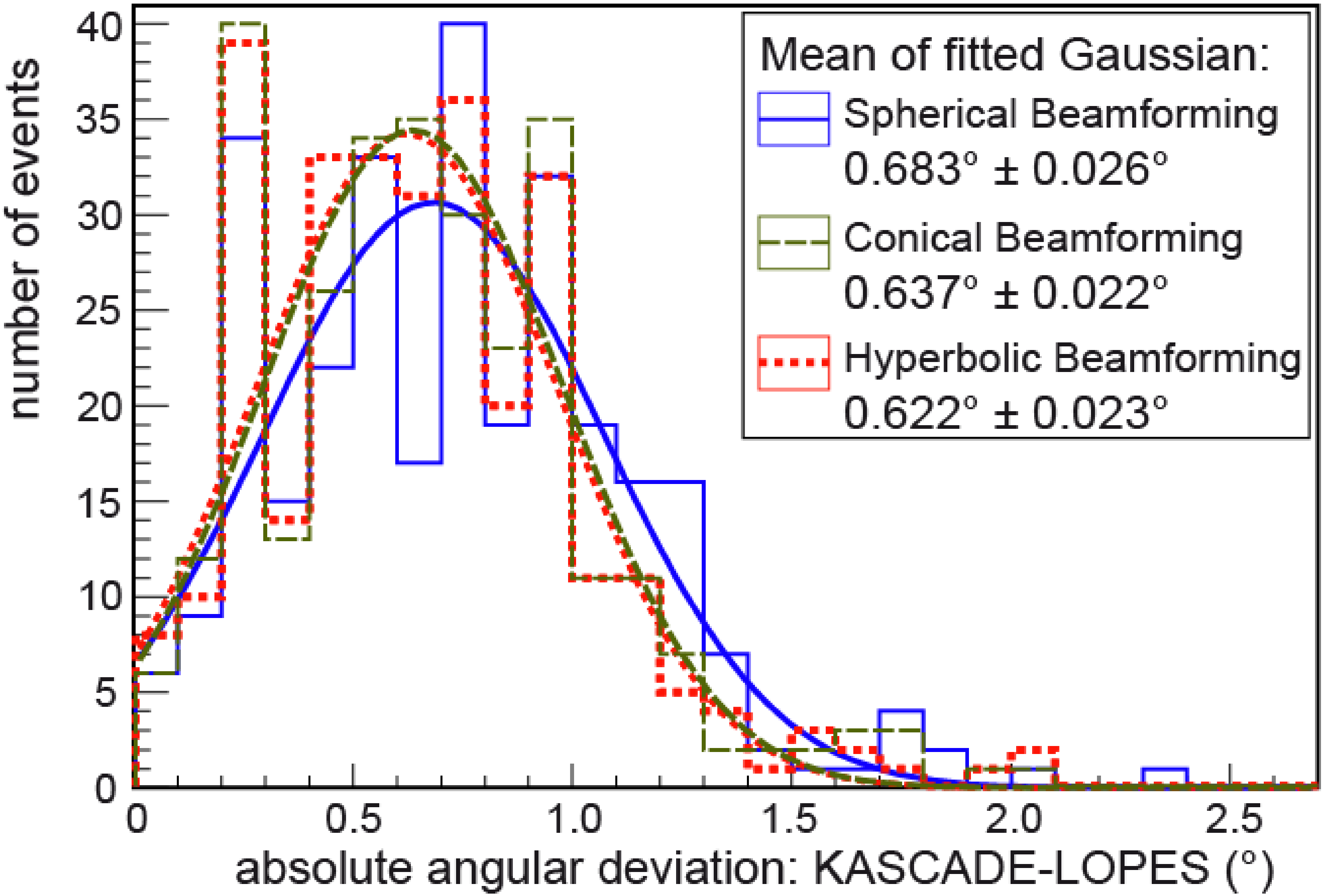
Direction using different wavefronts



JCAP 09 (2014) 025

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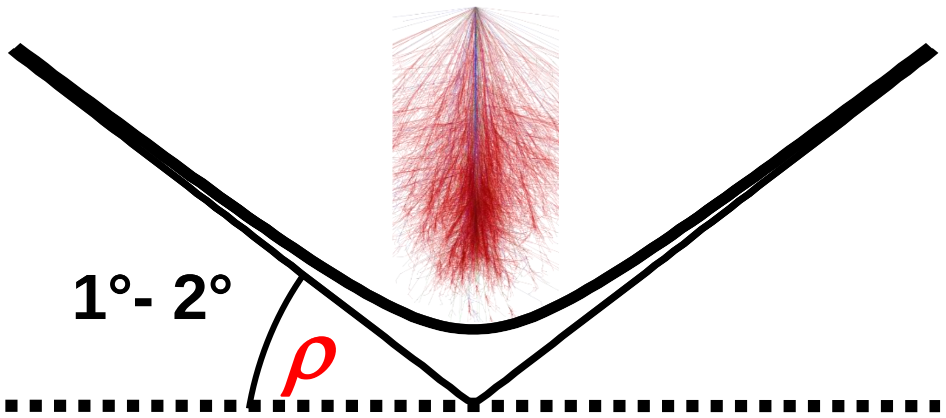
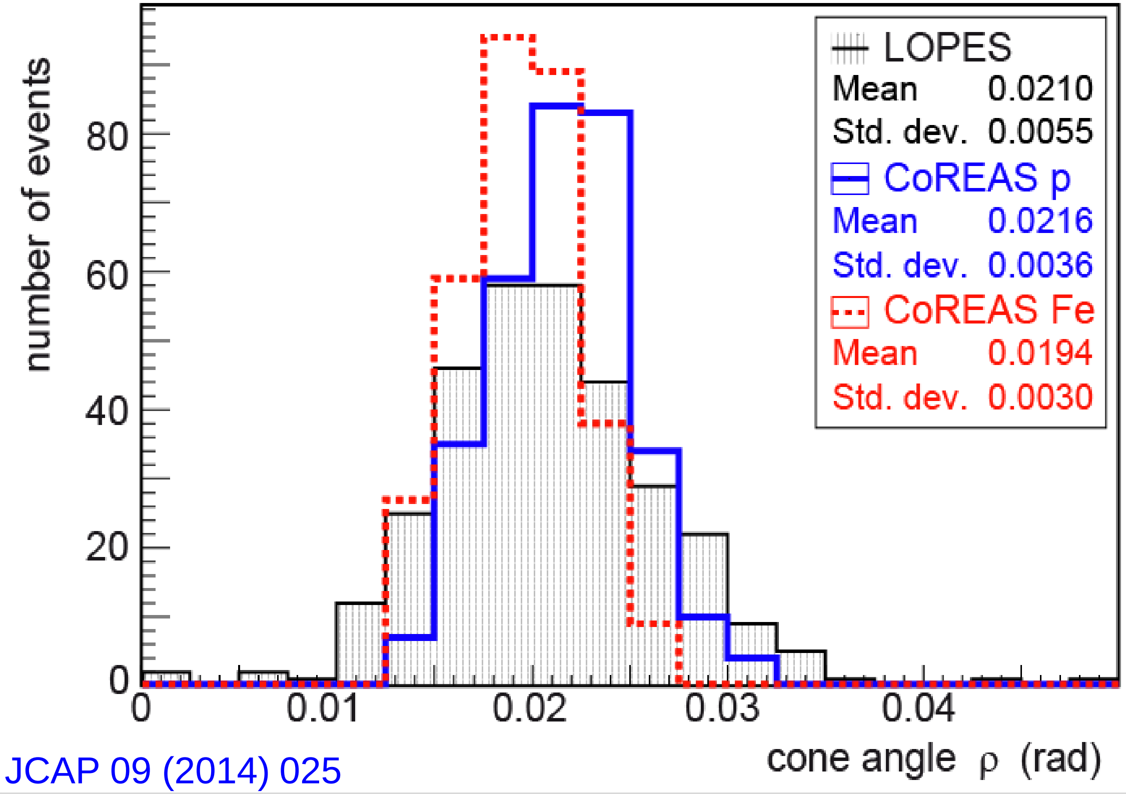
X_{max} via hyperbolic wavefront

- Cone angle ρ ~ distance to X_{max}
- Warning: ρ sensitive to details
  - → see proceeding PoS(ICRC2015)317





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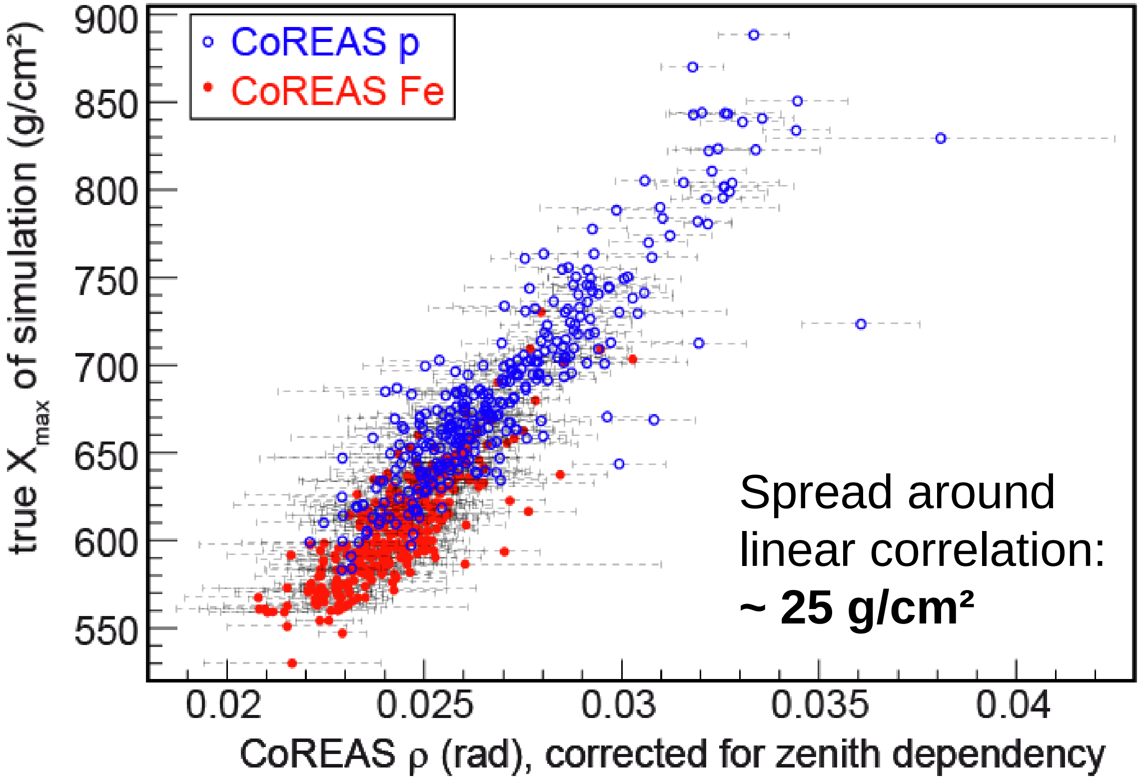
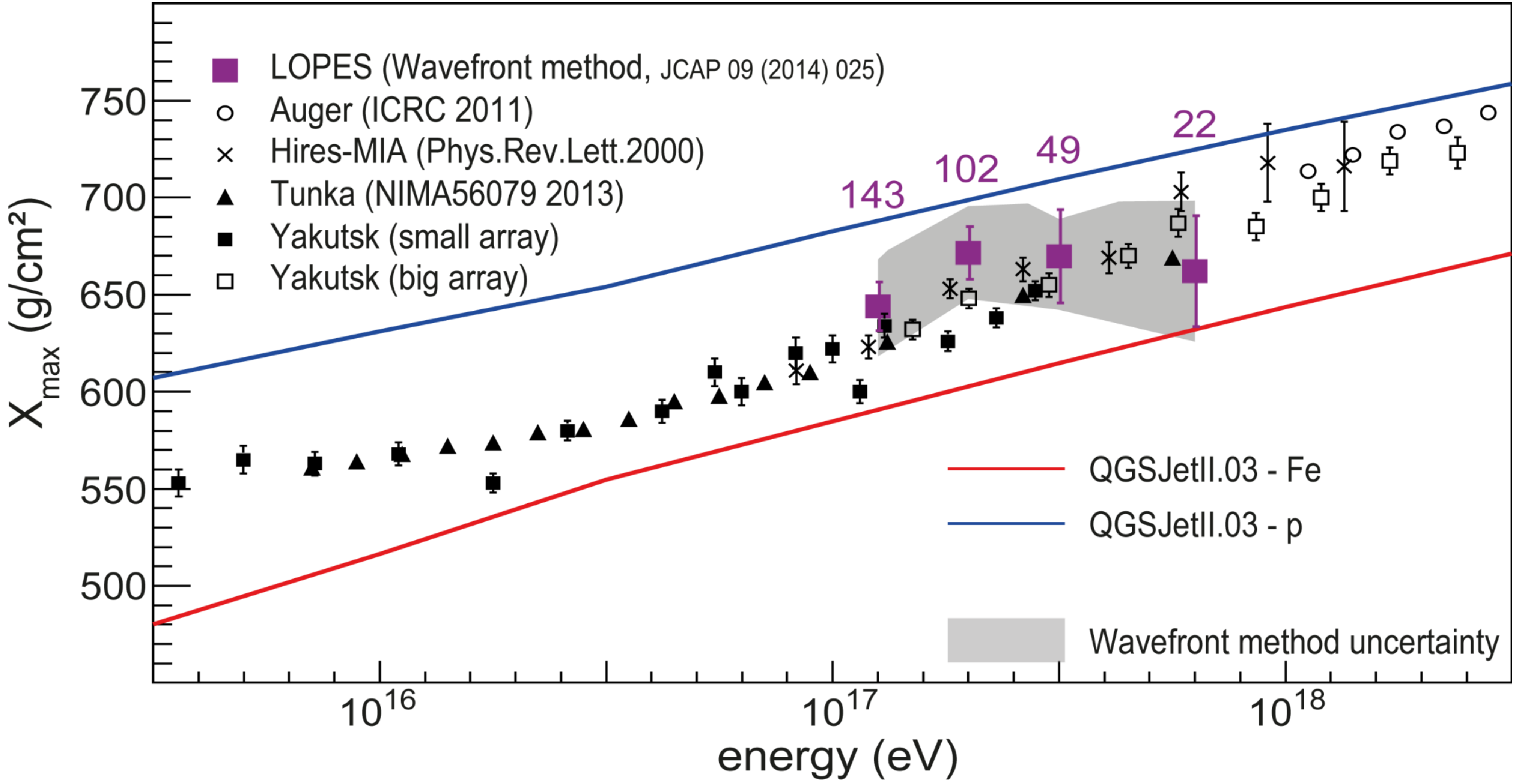


Interpretation of X_{max} measurements



Average uncertainty on individual LOPES events: ~ 140 g/cm²

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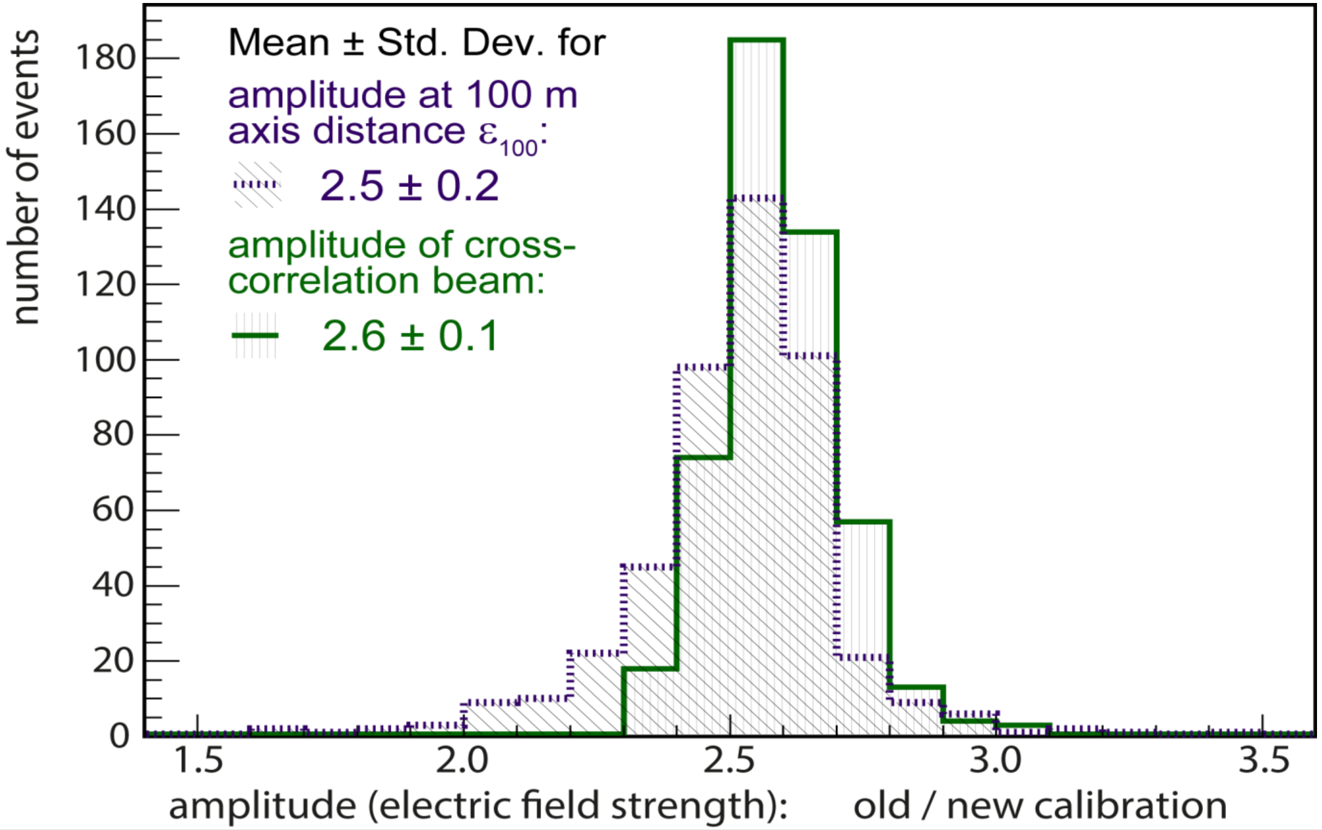
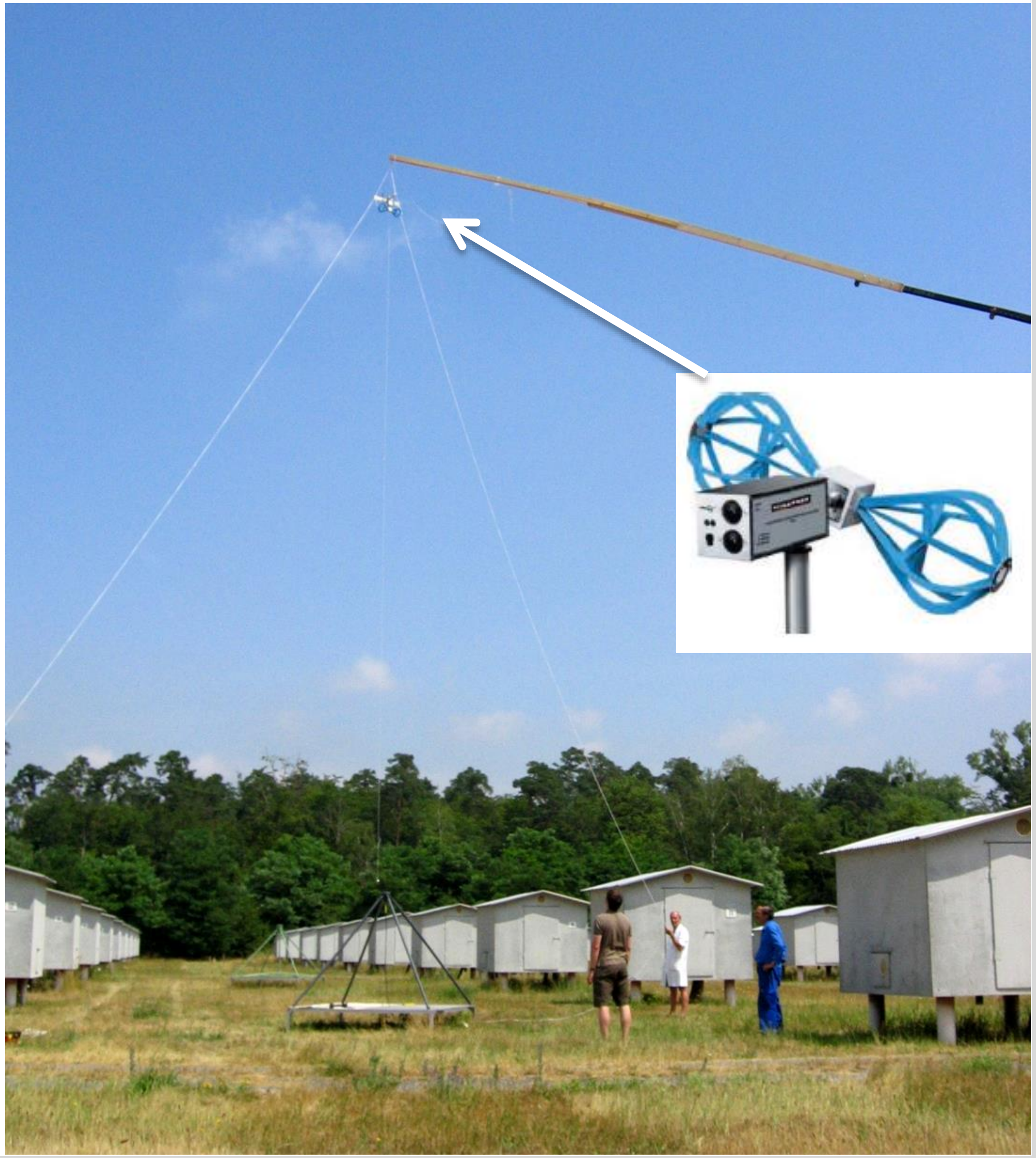
Improved amplitude calibration

- Re-calibration of existing measurements with new *free-space* reference values
  - same reference used for LOFAR + Tunka-Rex





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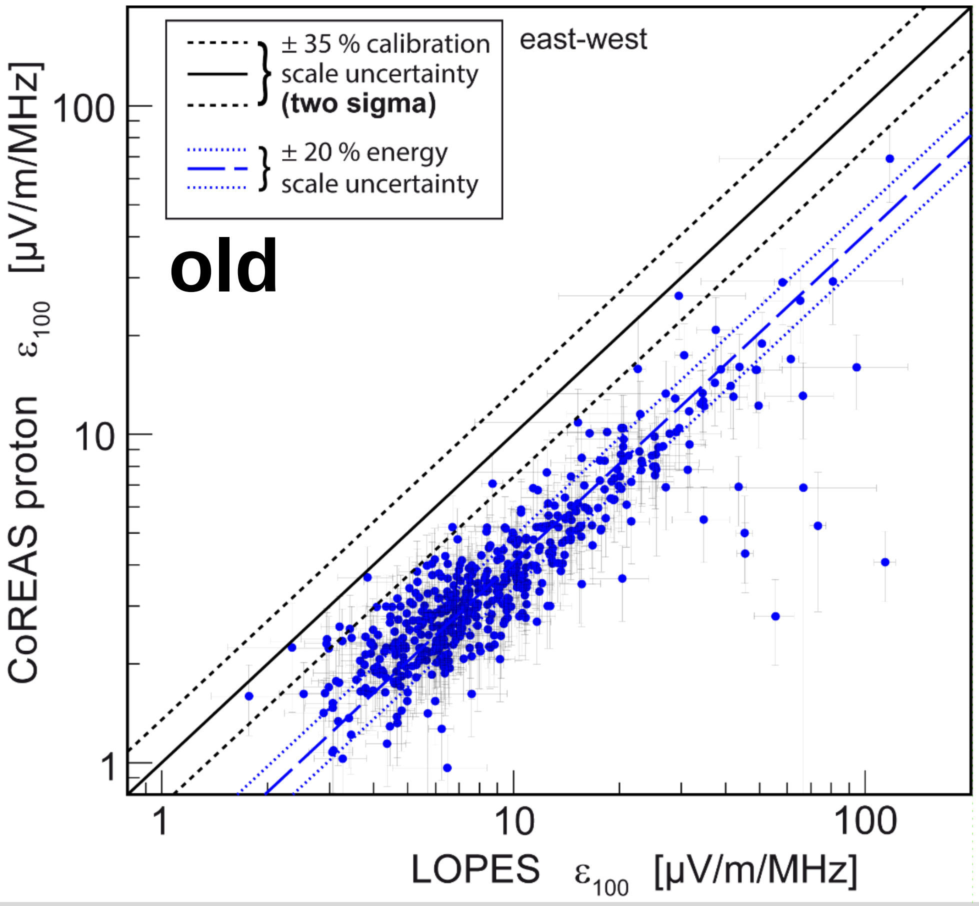
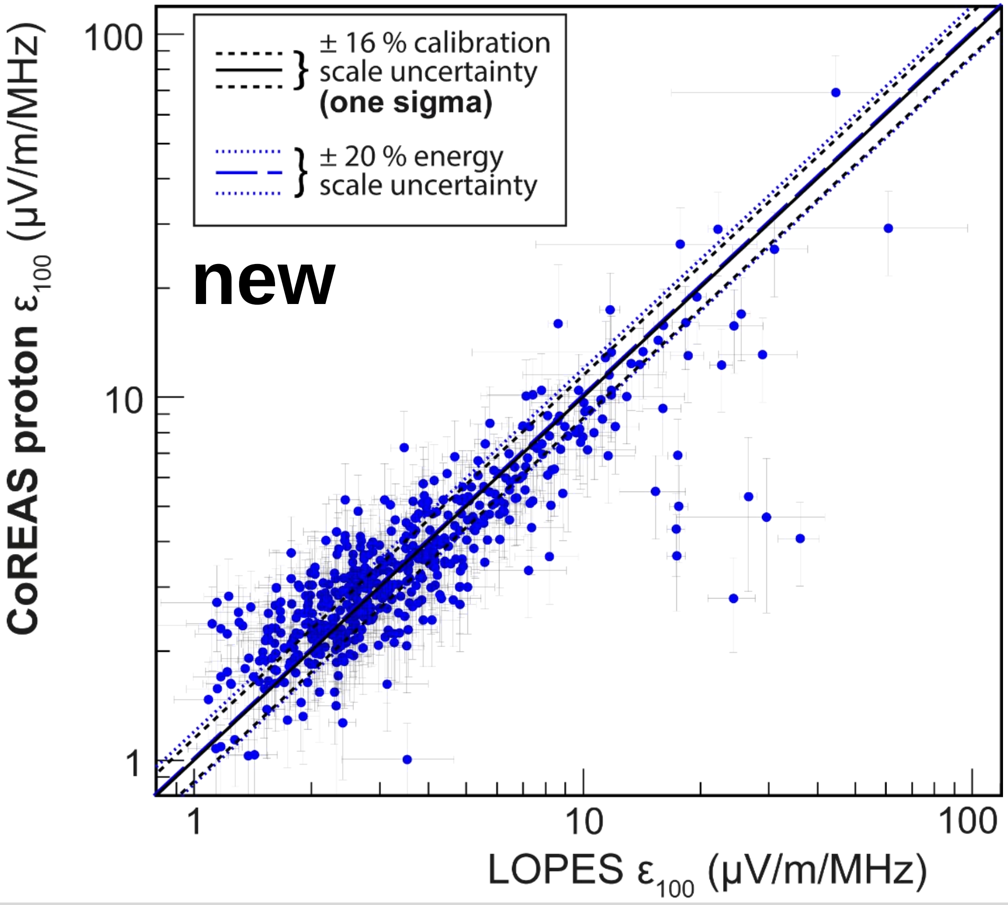
Comparing LOPES with simulations

- Amplitude at 100 m now compatible with CoREAS simulations

  → see poster today for more details: PoS(ICRC2015)311





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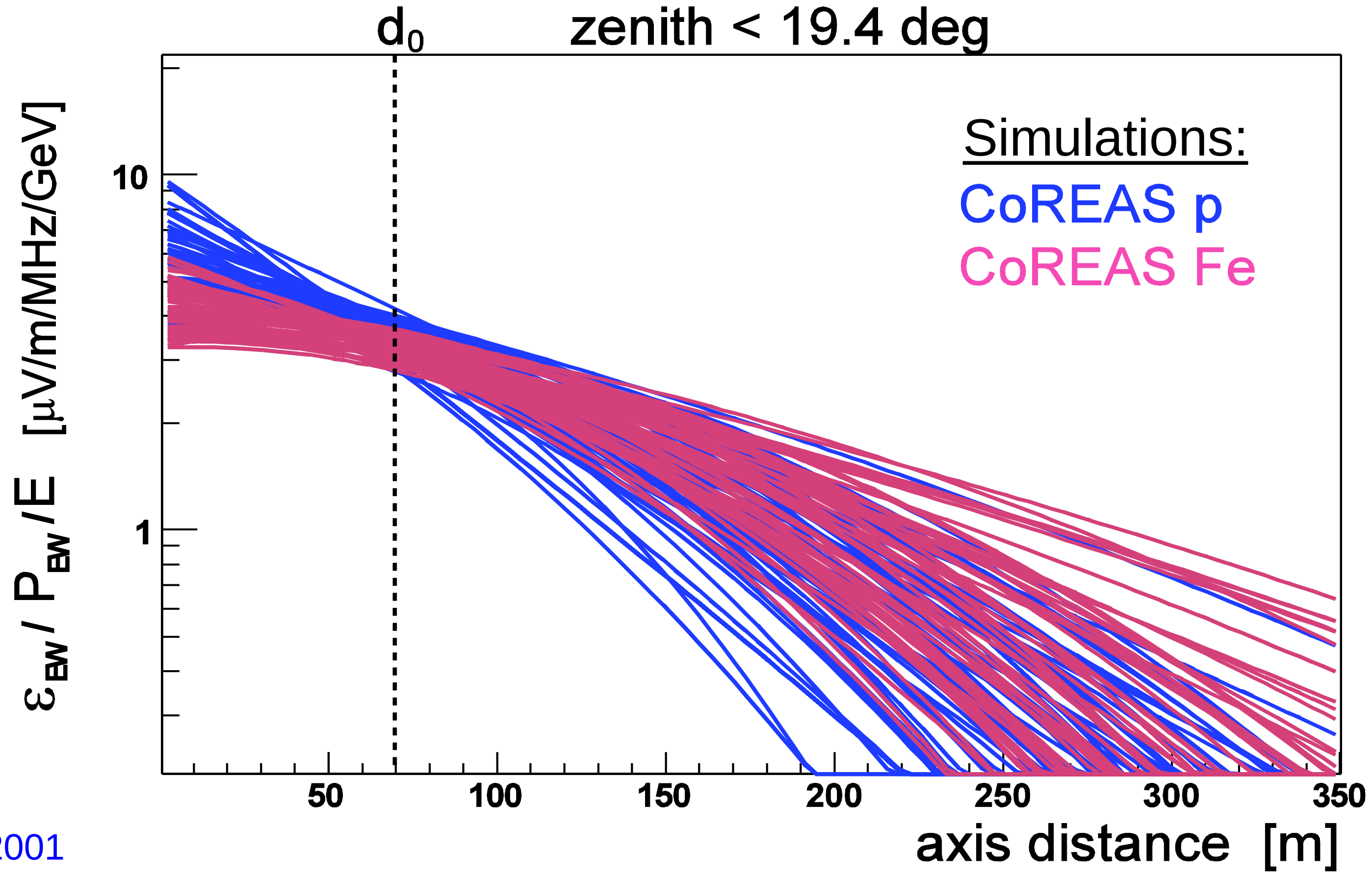
Lateral distribution

- **Amplitude** at specific distance → **Energy**
- **Slope** or ratio between two distances → X_{max}



PRD 90 (2014) 062001

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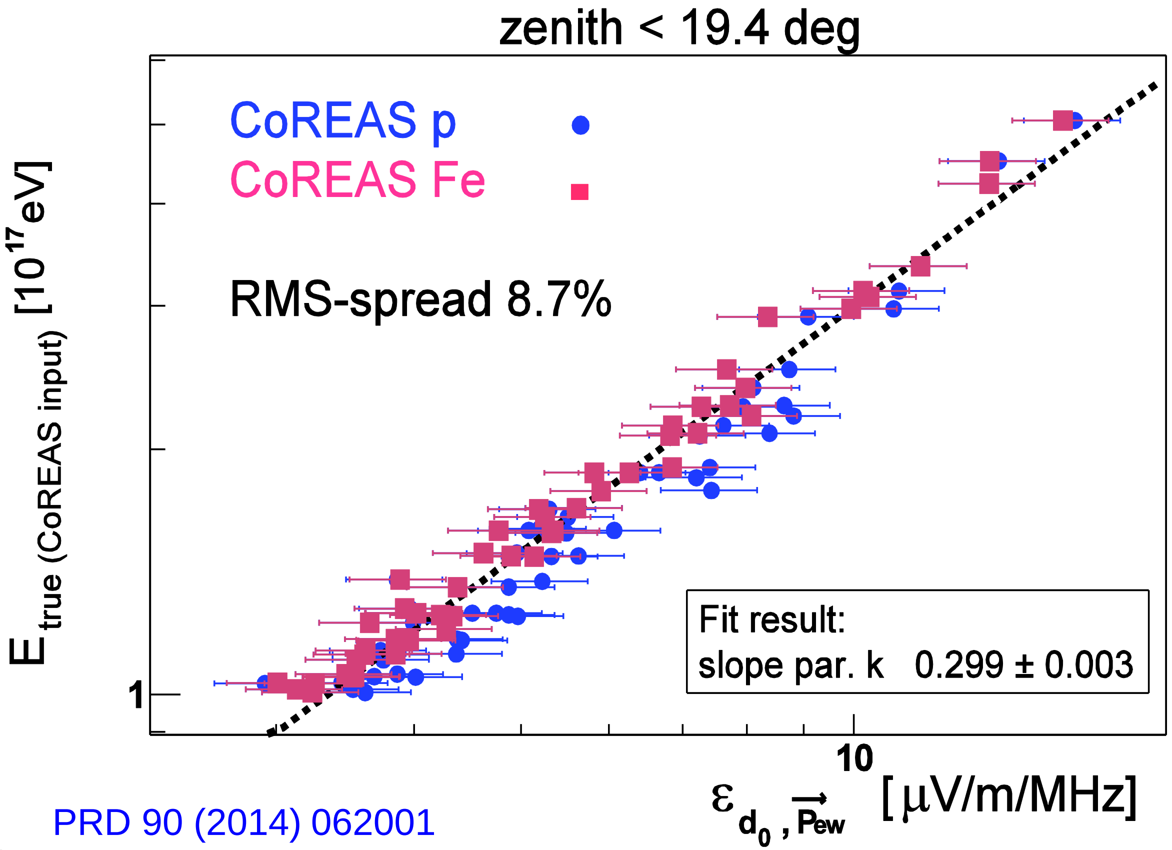
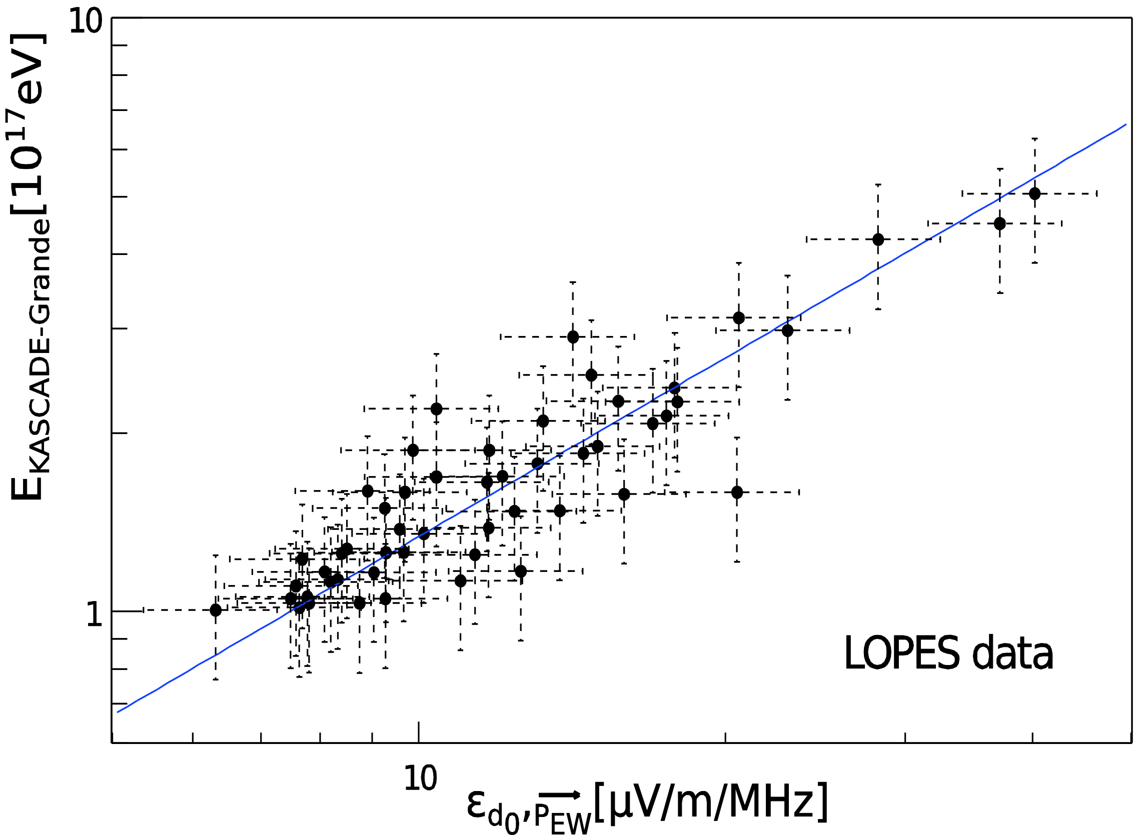
Energy reconstruction

- Theoretical energy precision of 9 % possible
- LOPES (at least) as precise as KASCADE-Grande: ~ 20%
  - but absolute scale by cross-calibration



PRD 90 (2014) 062001



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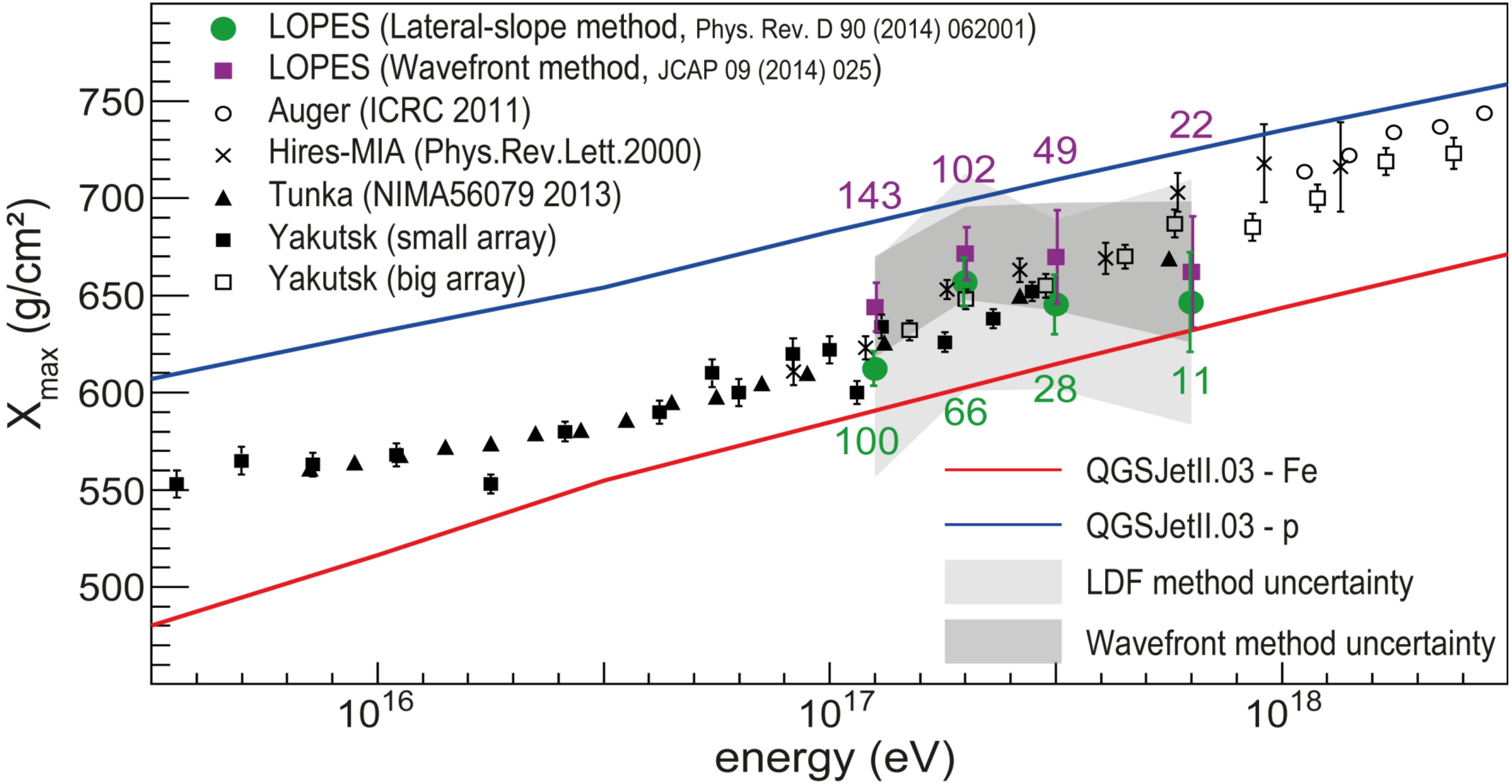
Interpretation of X_{max} measurements



Warning: additional systematic uncertainties due to detector effects not shown.

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15 Journal Papers

Reconstruction of the ***energy and depth of maximum*** *of cosmic-ray air showers from LOPES radio measurements*
Physical Review D 90 (2014) 062001

The ***wavefront*** *of the radio signal emitted by cosmic ray air showers*
JCAP 09 (2014) 025

Comparing LOPES measurements of air-shower radio emission with REAS 3.11 and CoREAS simulations
Astroparticle Physics 50-52 (2013) 76-91

LOPES-3D: An antenna array for full signal detection of air-shower radio emission
Nucl. Instr. and Meth. A 696 (2012) 100-109

Experimental evidence for *the sensitivity of the air-shower radio signal to the* ***longitudinal shower development***
Physical Review D 85 (2012) 071101(R)

Thunderstorm observations *by air-shower radio antenna arrays*
Advances in Space Research 48 (2011) 1295–1303

Lateral distribution *of the radio signal in extensive air showers measured with LOPES*
Astroparticle Physics 32 (2010) 294-303

New method for the ***time calibration*** *of an interferometric radio antenna array*
Nucl. Instr. and Meth. A 615 (2010) 277-284 (short authorlist)

Frequency spectra *of cosmic ray air shower radio emission measured with LOPES*
Astronomy & Astrophysics 488 (2008) 807-817

Direction identification in radio images of cosmic-ray air showers detected with LOPES and KASCADE
Astronomy & Astrophysics 487 (2008) 781-788

Amplitude calibration *of a digital radio antenna array for measuring cosmic ray air showers*
Nucl. Instr. and Meth. A 589 (2008) 350-361 (short authorlist)

Amplified radio emission from cosmic ray air showers in ***thunderstorms***
Astronomy & Astrophysics 467 (2007) 385-394

Radio emission of ***highly inclined cosmic ray*** *air showers measured with LOPES*
Astronomy & Astrophysics 462 (2007) 389-395

Progress in air shower radio measurements: Detection of distant events
Astroparticle Physics 26 (2006) 332-340

Detection and imaging of atmospheric radio flashes from cosmic ray air showers
Nature 435 (2005) 313-316

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Conclusion

- LOPES provided many proof-of-principles
  - Key to success: KASCADE-Grande measurements of same air showers
- New: improved calibration lowered amplitude scale by factor of 2.6 ± 0.2
  - State-of-the-art CoREAS simulations now compatible with LOPES measurements
  - Other results remain qualitatively valid
- Reconstruction of shower parameters with LOPES
  - Competitive for direction: precision < 0.7°
  - Competitive for energy: precision < 20 %
  - Not competitive for X_{max}: precision ~ 90 g/cm²
- Methods now applied at current experiments with lower background

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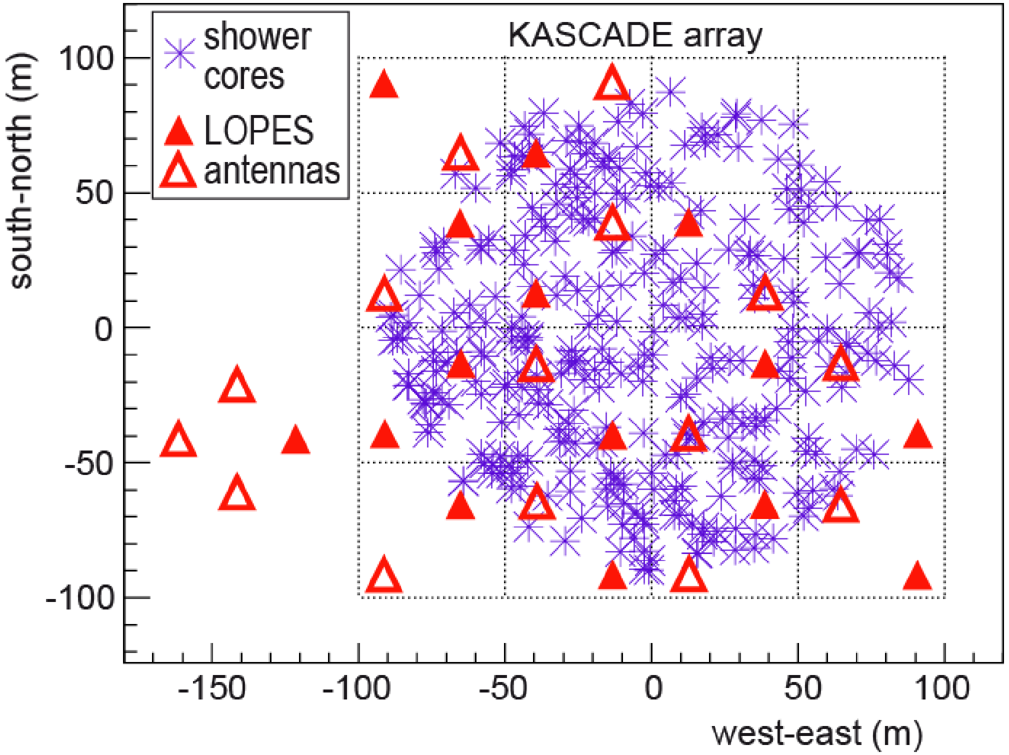
http://www.lopes-project.org/

Typical event selection

- East-west aligned dipole antennas
- 316 measured LOPES events: E > 10^{17} eV, θ < 45°
- 1 proton + 1 iron CoREAS simulation for each event



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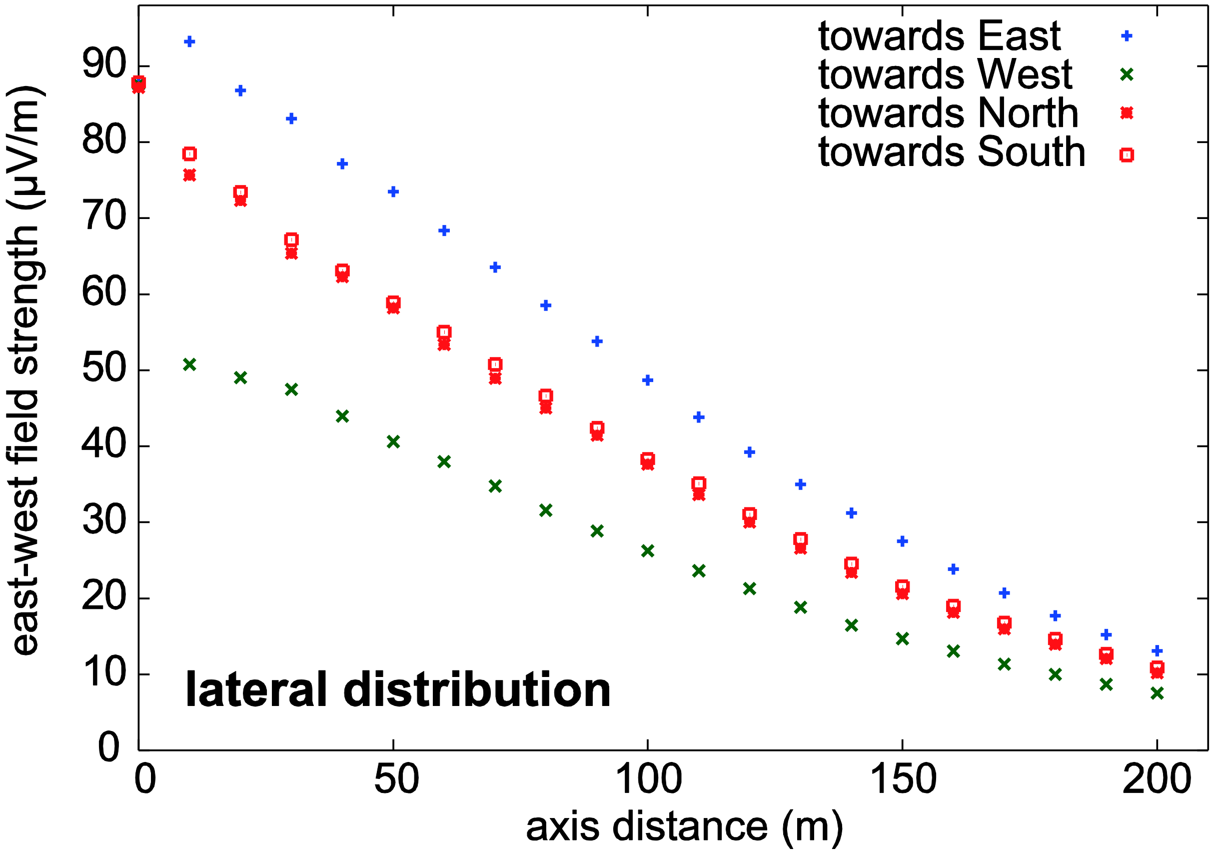
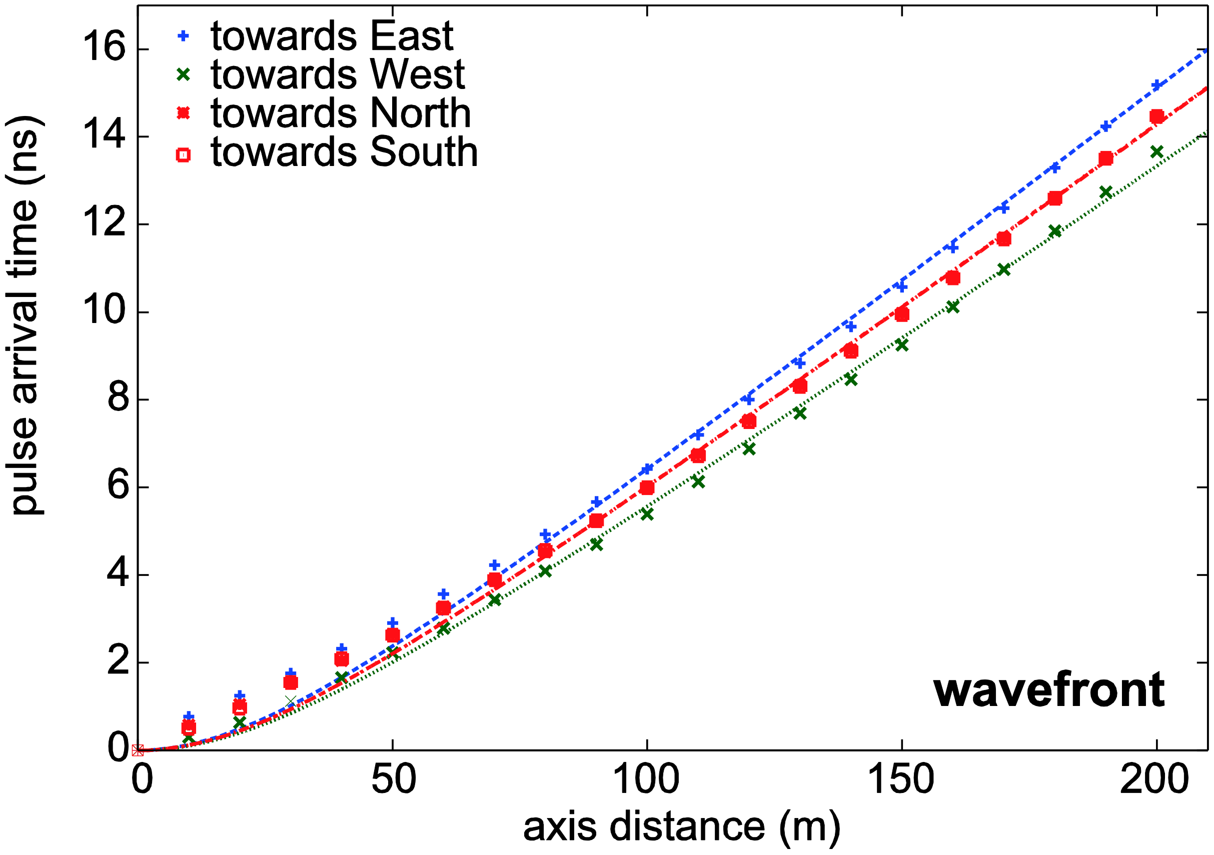
Asymmetry: Wavefront and Lateral Distribution





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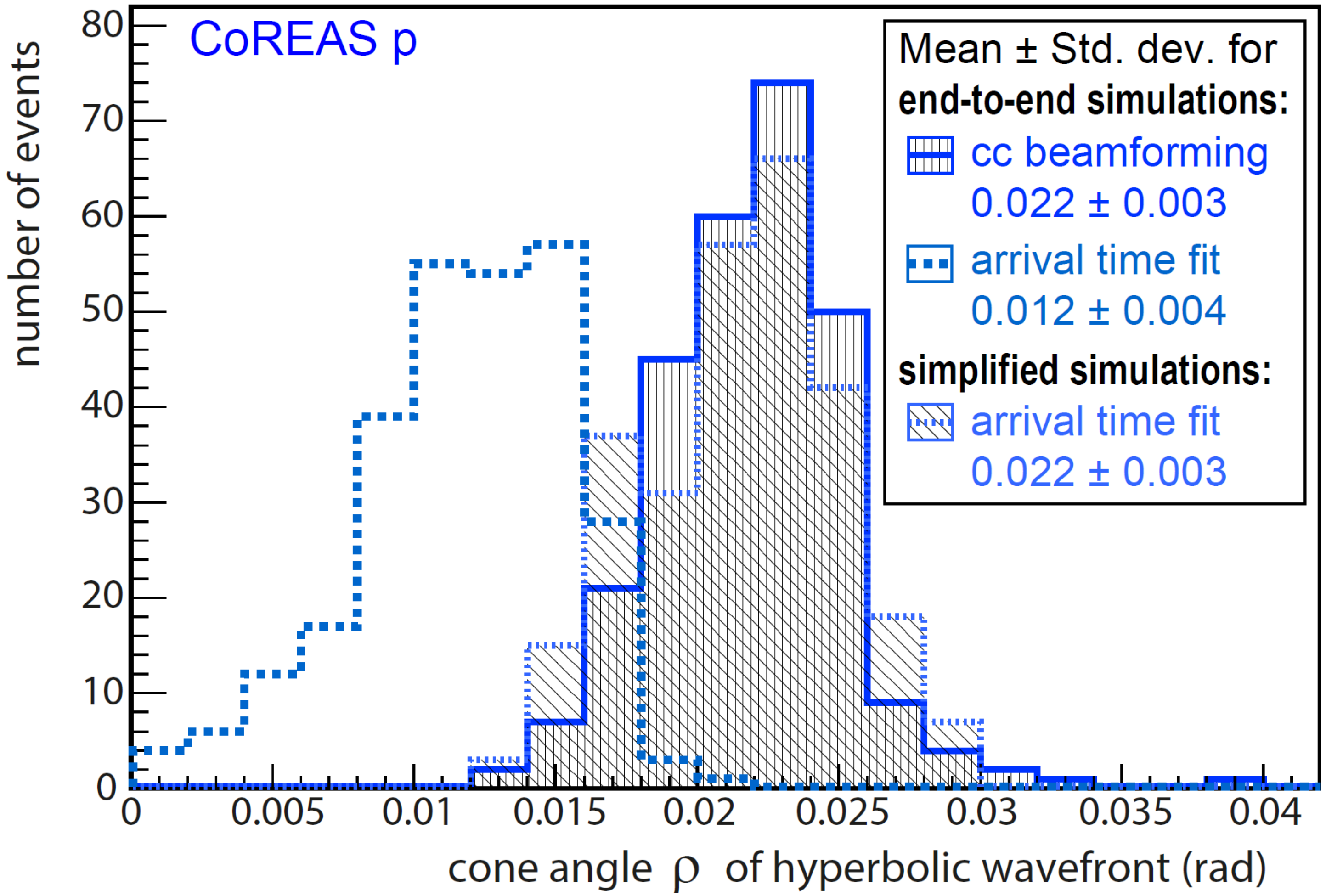
Wavefront cone angle in simulations

- Smaller for arrival-time fit than for beamforming



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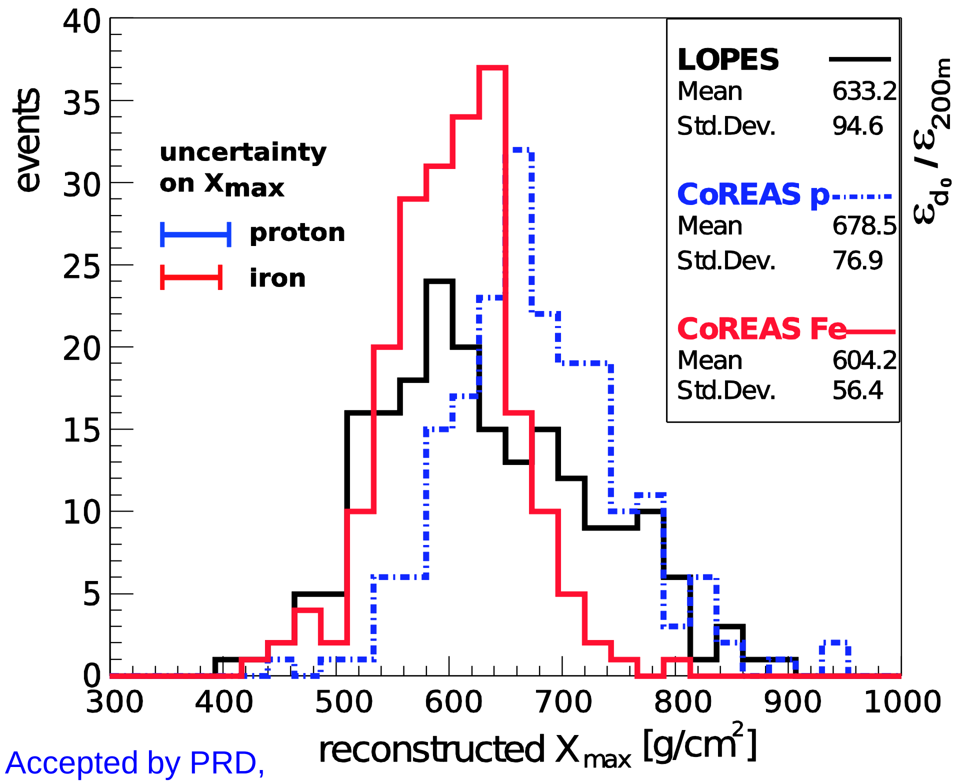
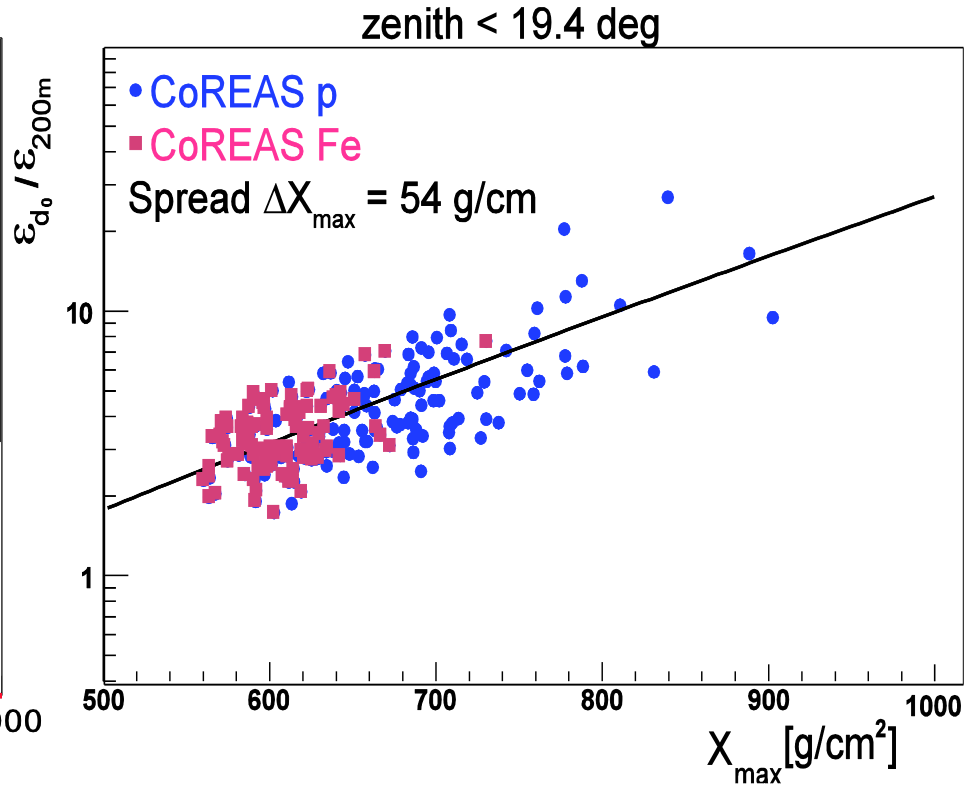
X_{max} reconstruction with LDF

- CoREAS simulations: precision of ~ 50 g/cm² (w/o noise)
- LOPES measurements: precision of ~ 90 g/cm²





Accepted by PRD,
arXiv: 1404.3283

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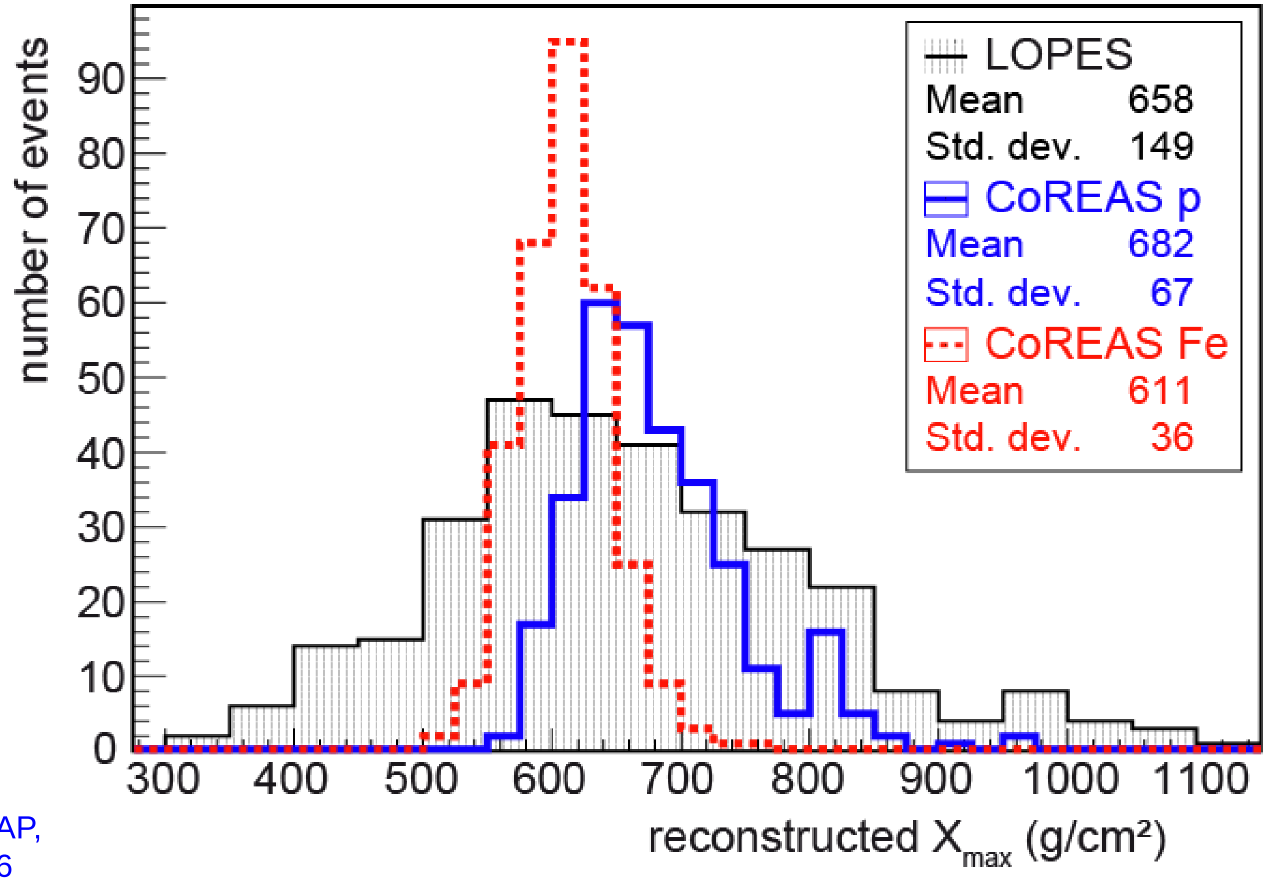
X_{max} reconstruction with wavefront

- CoREAS simulations: precision of ~ 30 g/cm² (w/o noise)
- LOPES measurements: precision of ~ 140 g/cm²



Accepted by JCAP,
arXiv: 1408.2346

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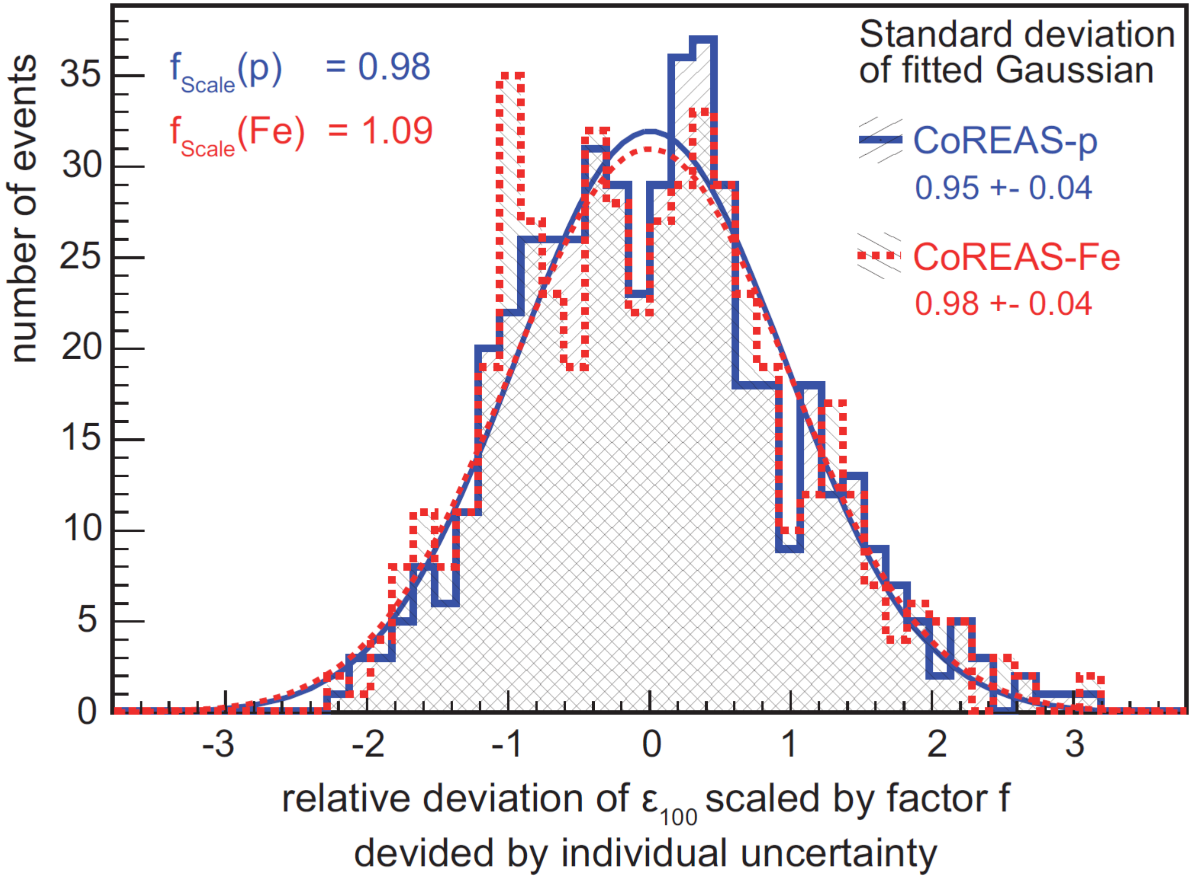
Amplitude comparison

- Mean deviation smaller than 16% LOPES scale uncertainty
- Scatter roughly as expected for Gaussian uncertainties



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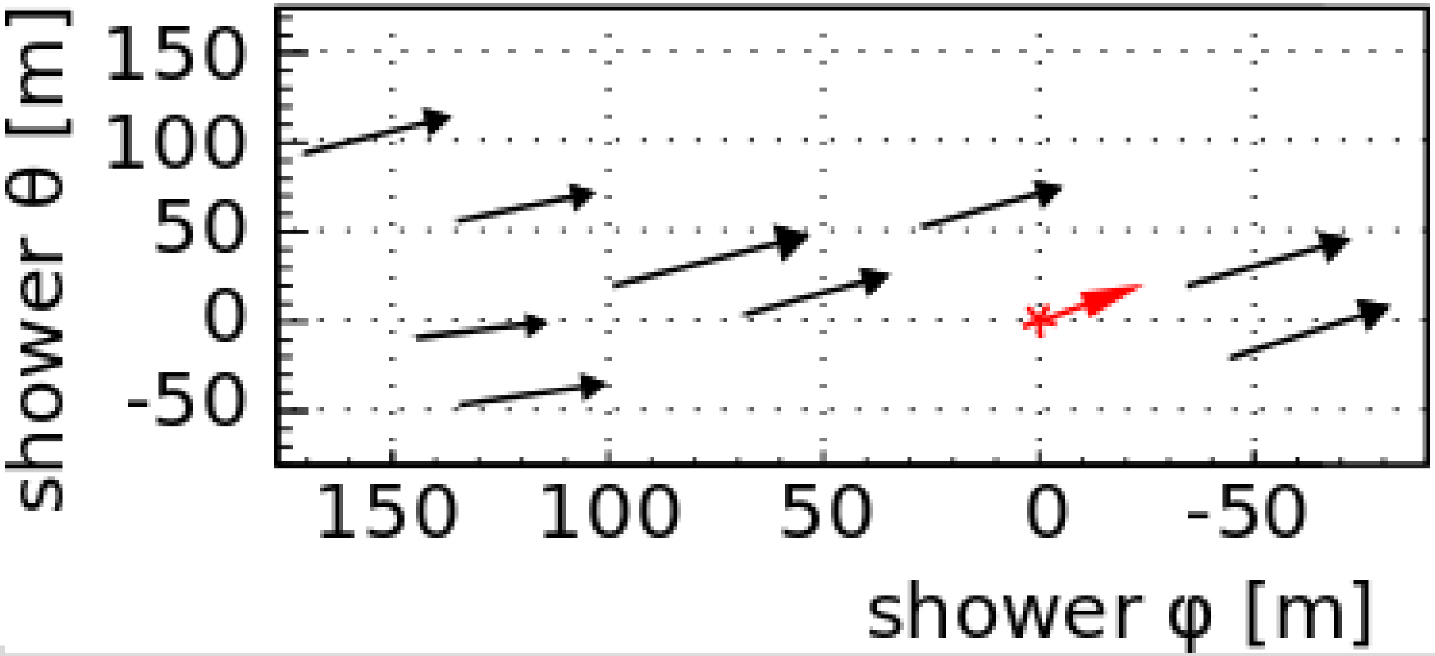
LOPES-3D results (with latest setup)

- Results support dominant geomagnetic emission process
- Precise measurements hampered by high background
  - Very high background in vertical component

One of the few nice LOPES-3D events



Measured
E-field vector

Geomagnetic
prediction

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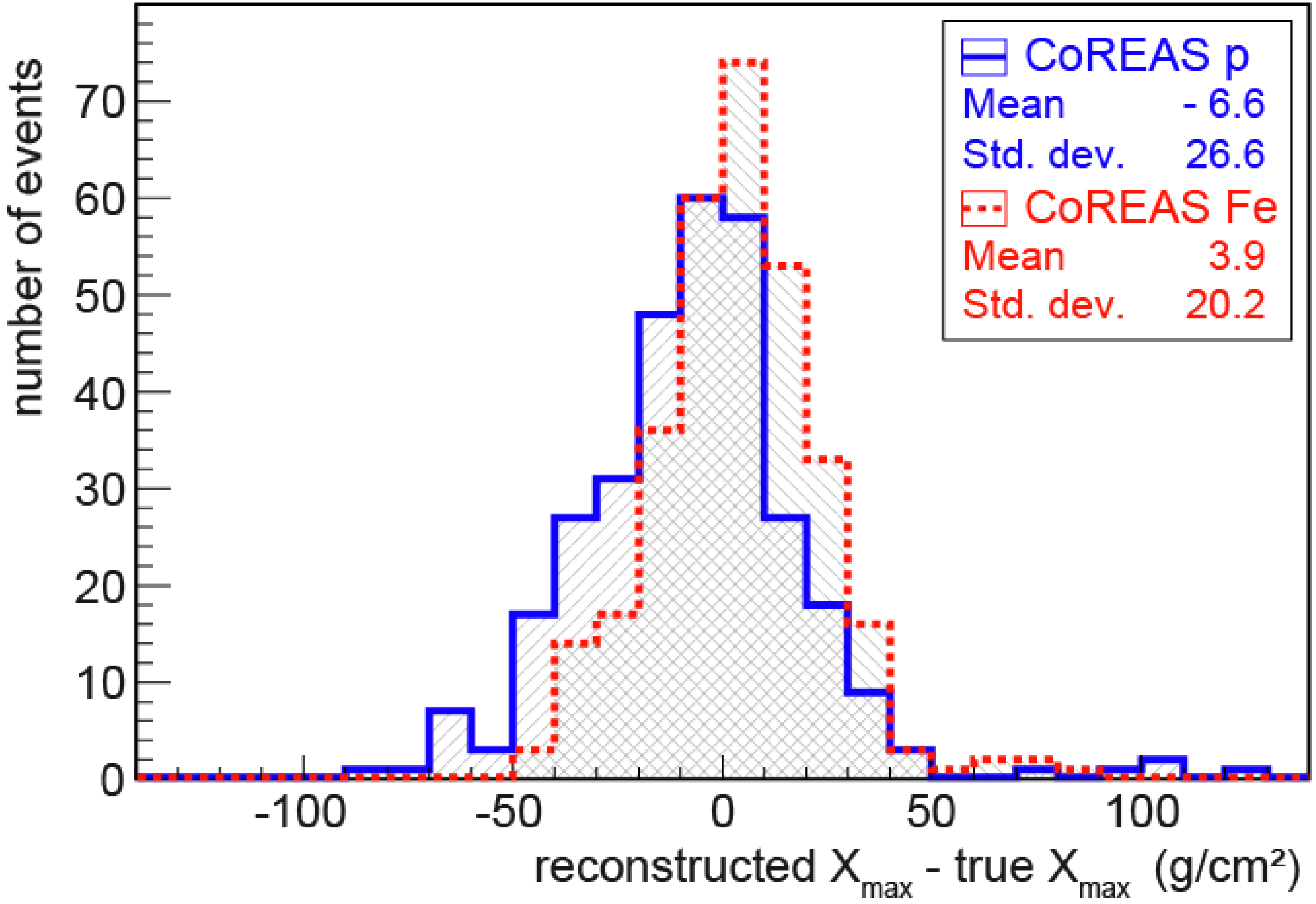
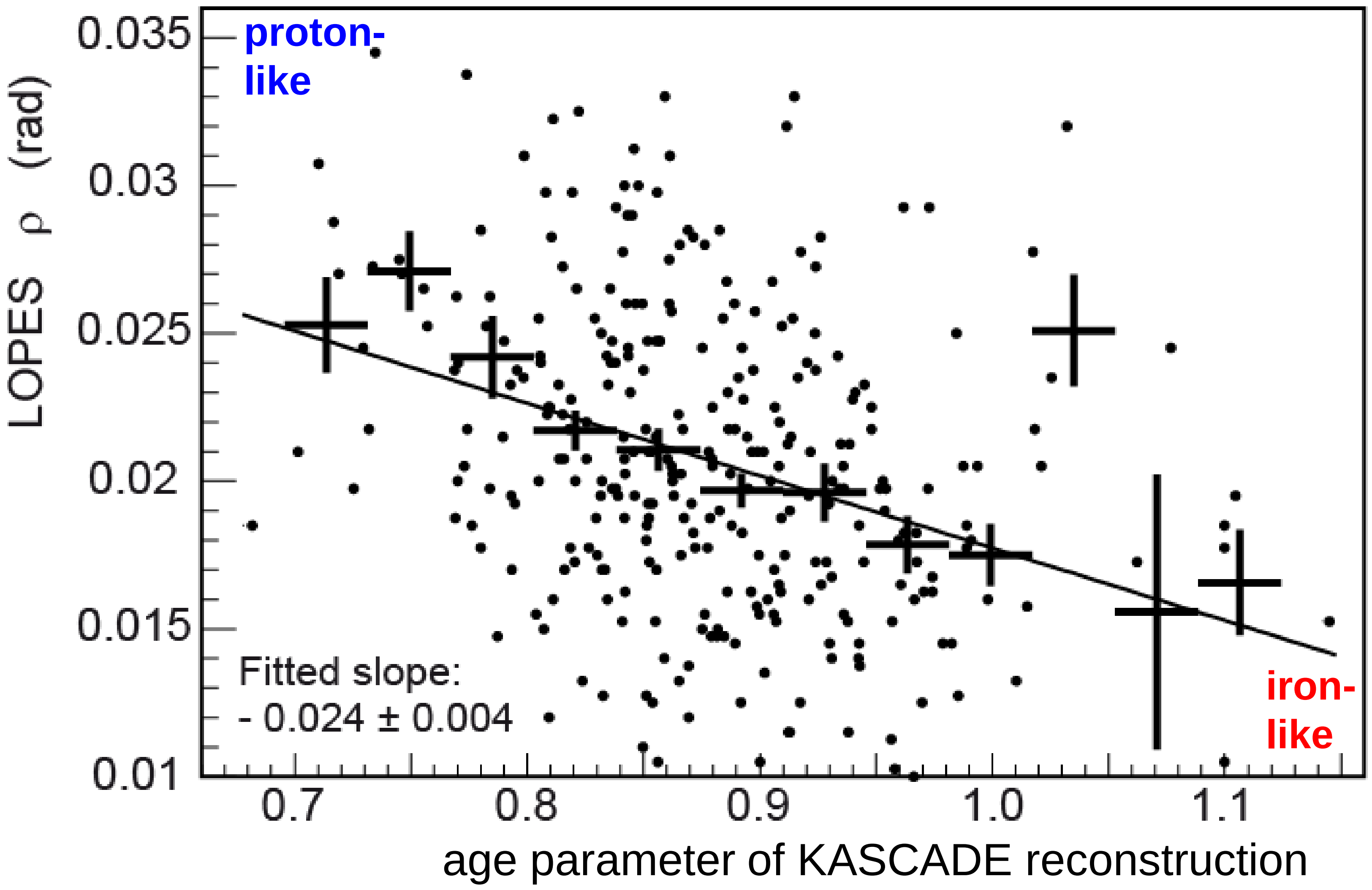
Wavefront: true vs. reconstructed X_{max}



Measured correlation with shower age



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