Karlsruhe Institute of Technology

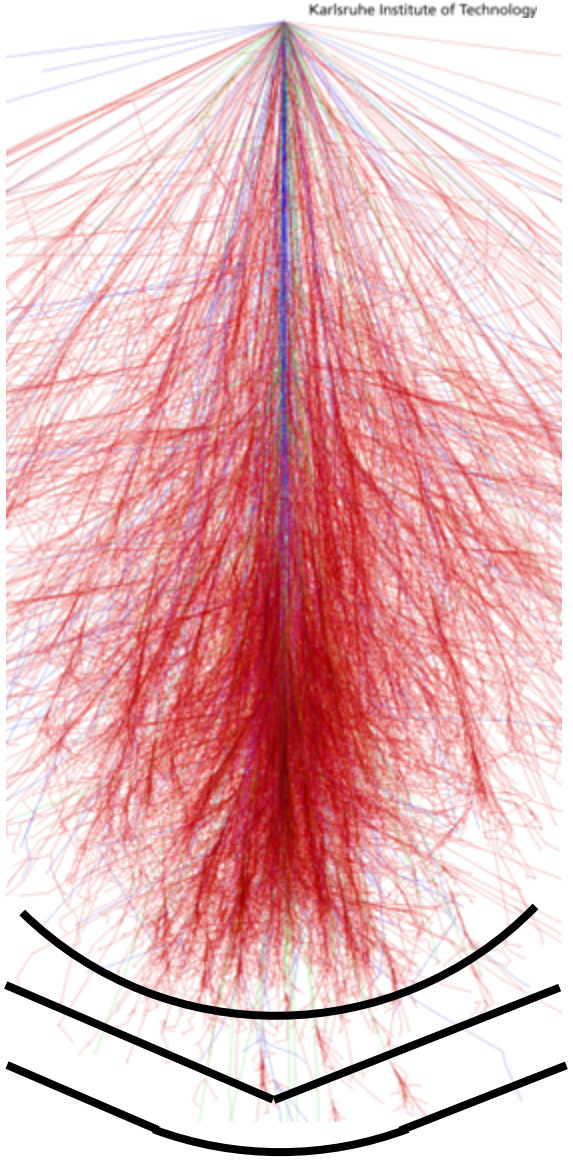
Radio Wavefront of Air Showers

Frank G. Schröder for the LOPES Collaboration

Karlsruhe Institute of Technology (KIT), Institut für Kernphysik, Karlsruhe, Germany

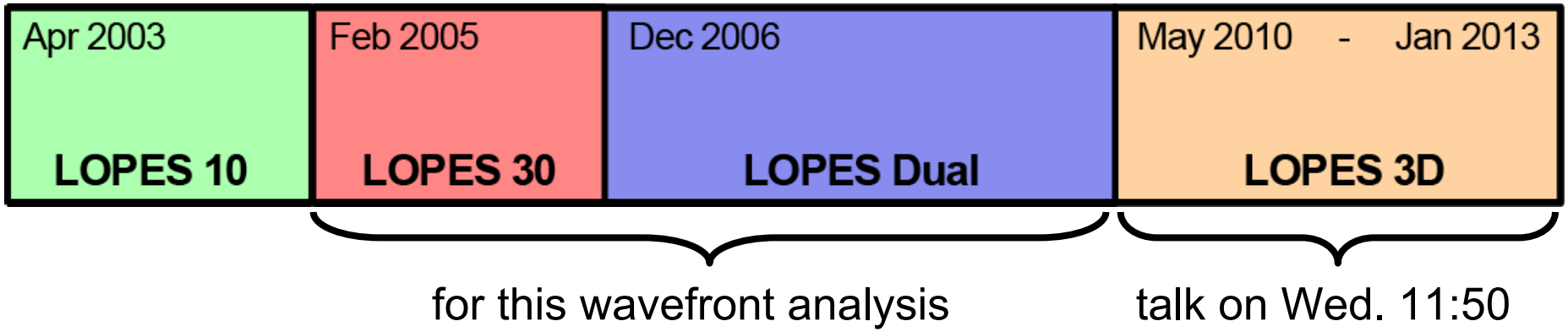
Shape of radio wavefront

- Radio emission generated **during** shower development
  - Radio wavefront ≠ particle front
- Shape of radio wavefront?
  - Sphere → static point source → no!
  - Cone (approximately for d > 50 m)
  - **Hyperbola**
- Correlation with shower parameters
  - Sensitivity to shower maximum



frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

LOPES history



- LOPES = radio extension of KASCADE particle array
  - trigger and air-shower reconstruction for comparison
- LOPES started in 2003 as **LO**FAR **p**rototyp**e** **s**tation
  - stopped in 2013, but analysis still continues
- Data will be made available publicly
  - KASCACE Cosmic Ray Data Center (KCDC): https://kcdc.ikp.kit.edu/

frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

KASCADE
before LOPES

↓

successful
common history

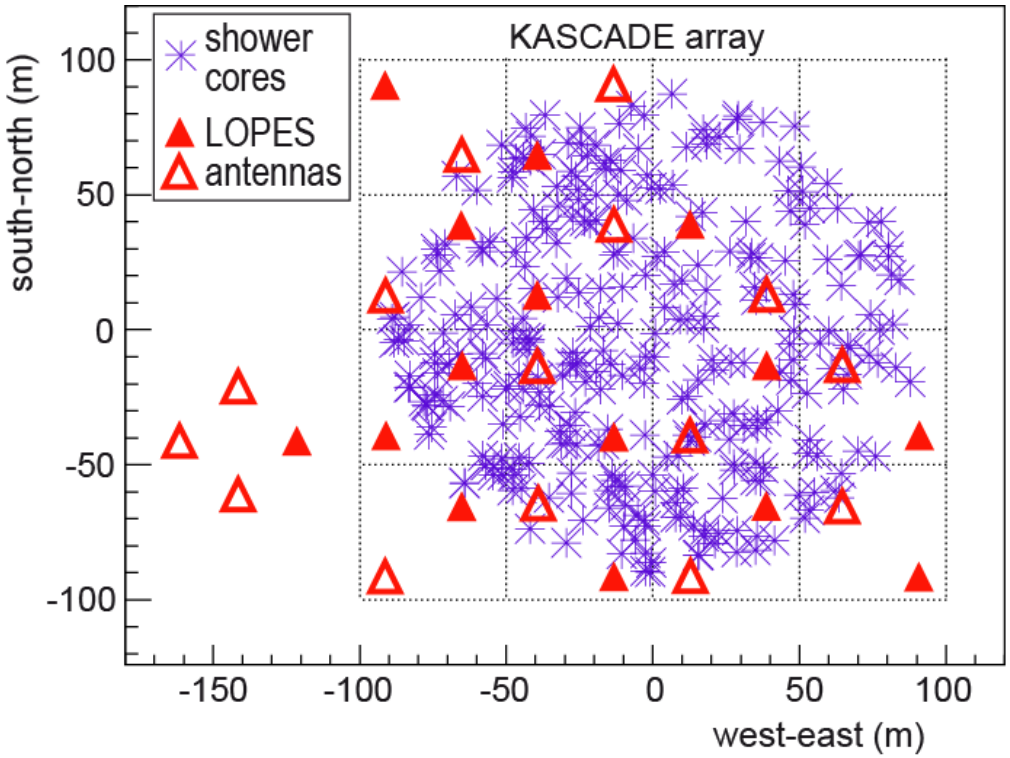
↓

KASCADE
after LOPES

frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

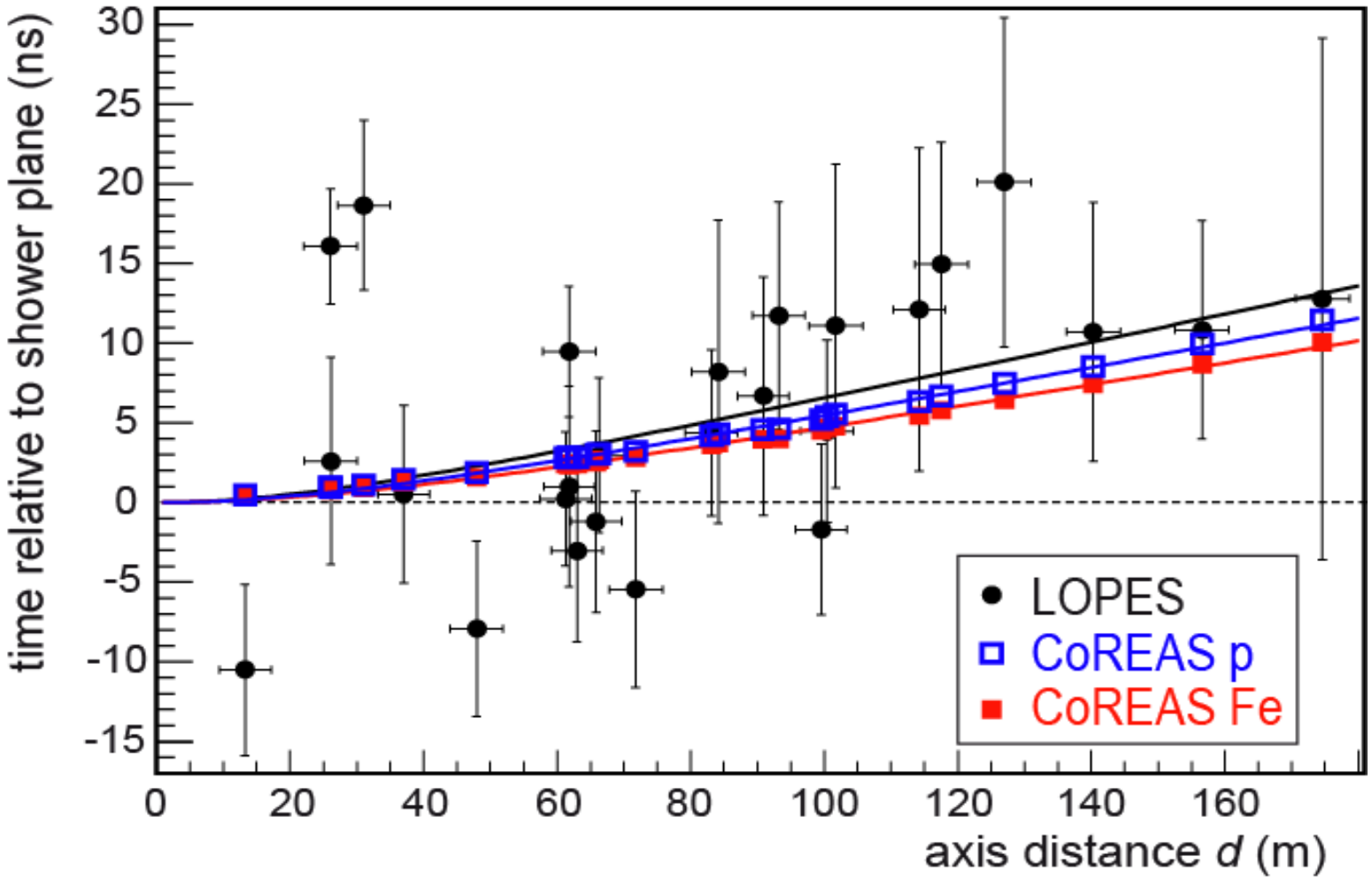
Setup for Wavefront Analysis

- East-west aligned dipole antennas: 43-74 MHz
- 316 measured LOPES events: $E > 10^{17}$ eV, $\theta < 45°$
- 1 proton + 1 iron CoREAS simulation for each event



frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

Example event: LOPES and CoREAS



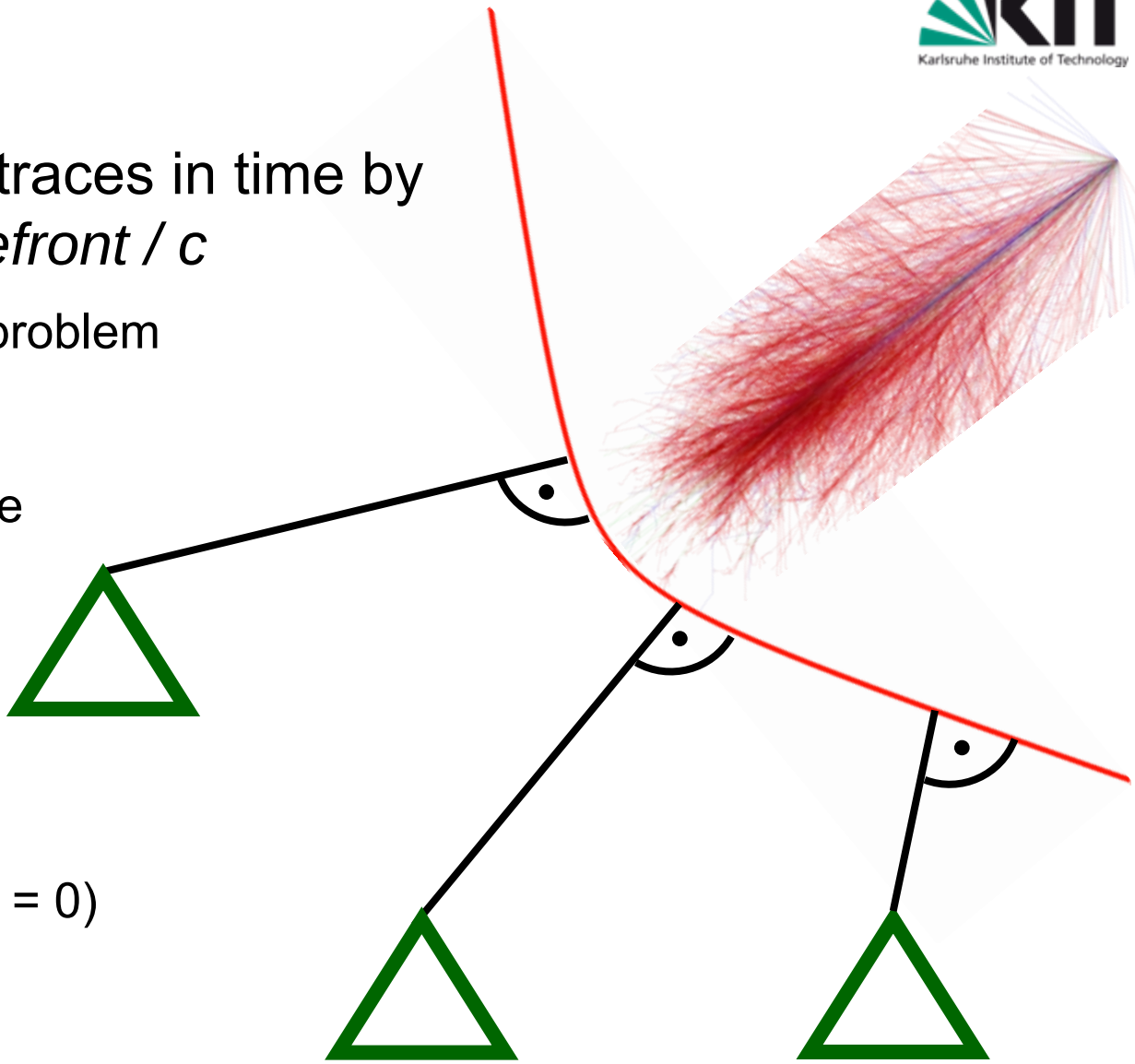
shower plane

Large measurement uncertainties → Use different method for measurements!

frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

Beamforming

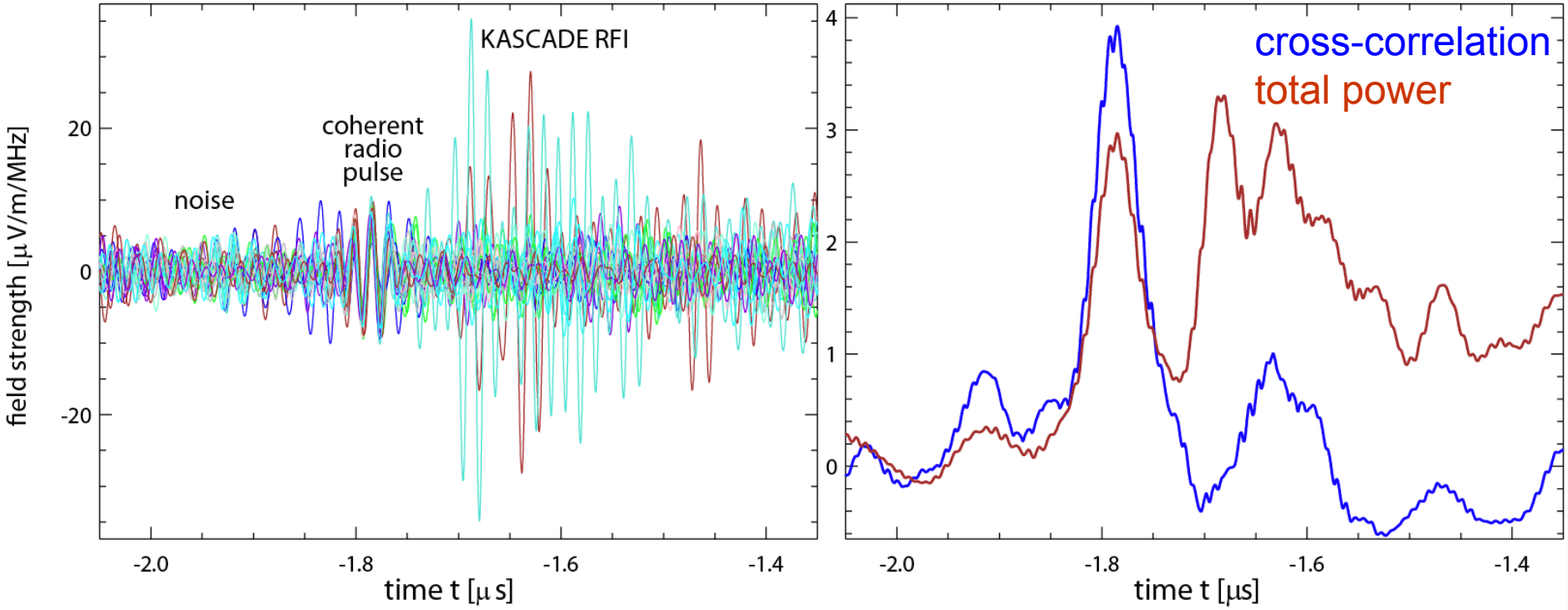
- Digitally shift all traces in time by *distance to wavefront / c*
  - 3-dimensional problem
- depends on
  - wavefront shape
  - shower axis
  - relative time (1 ns precise)
- but not on
  - absolute time (t = 0)



frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

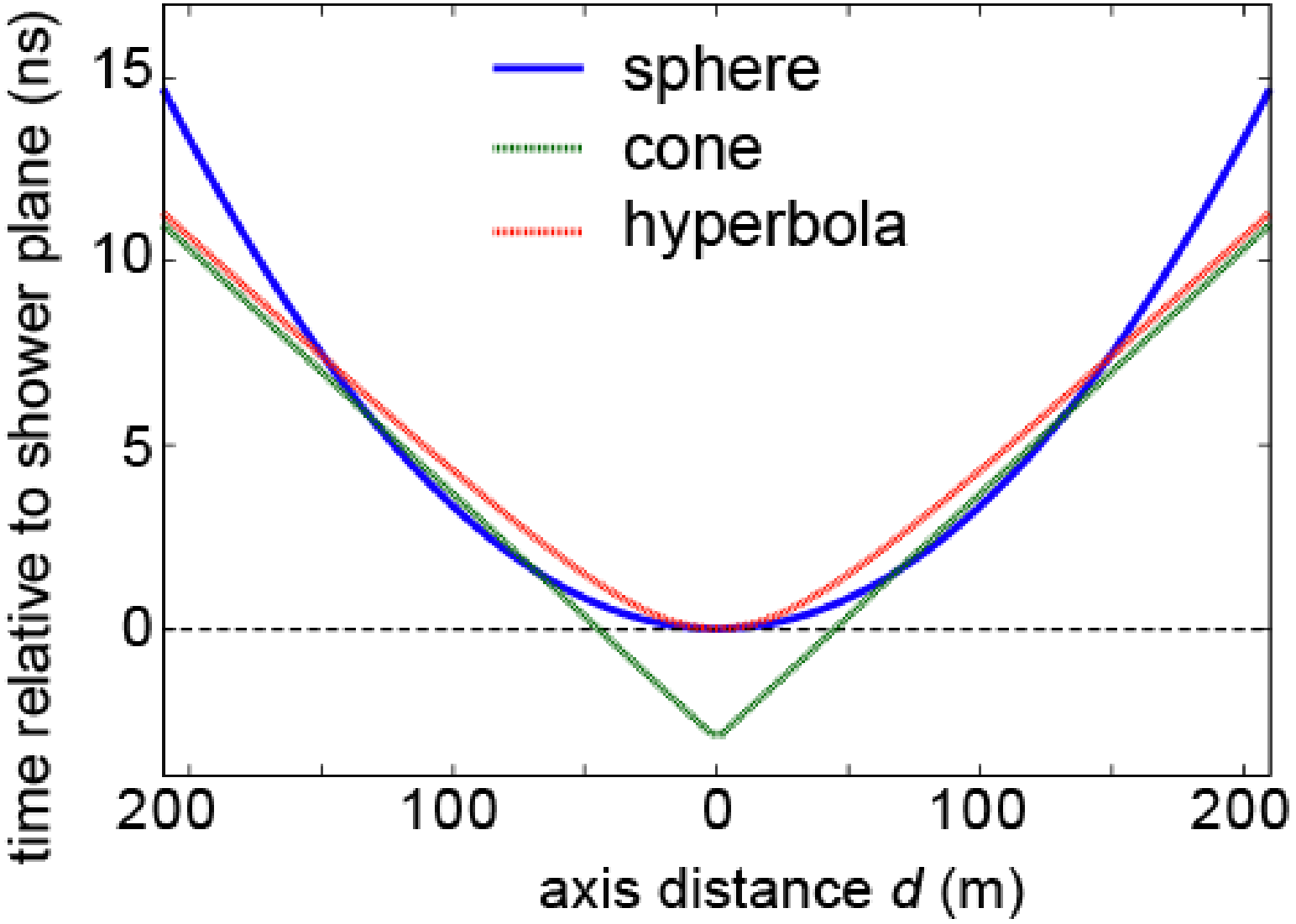
Digital radio interferometry

- After beamformig, cross-correlation for pulse identification
  - only air shower radio pulse is correlated in all antennas



frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

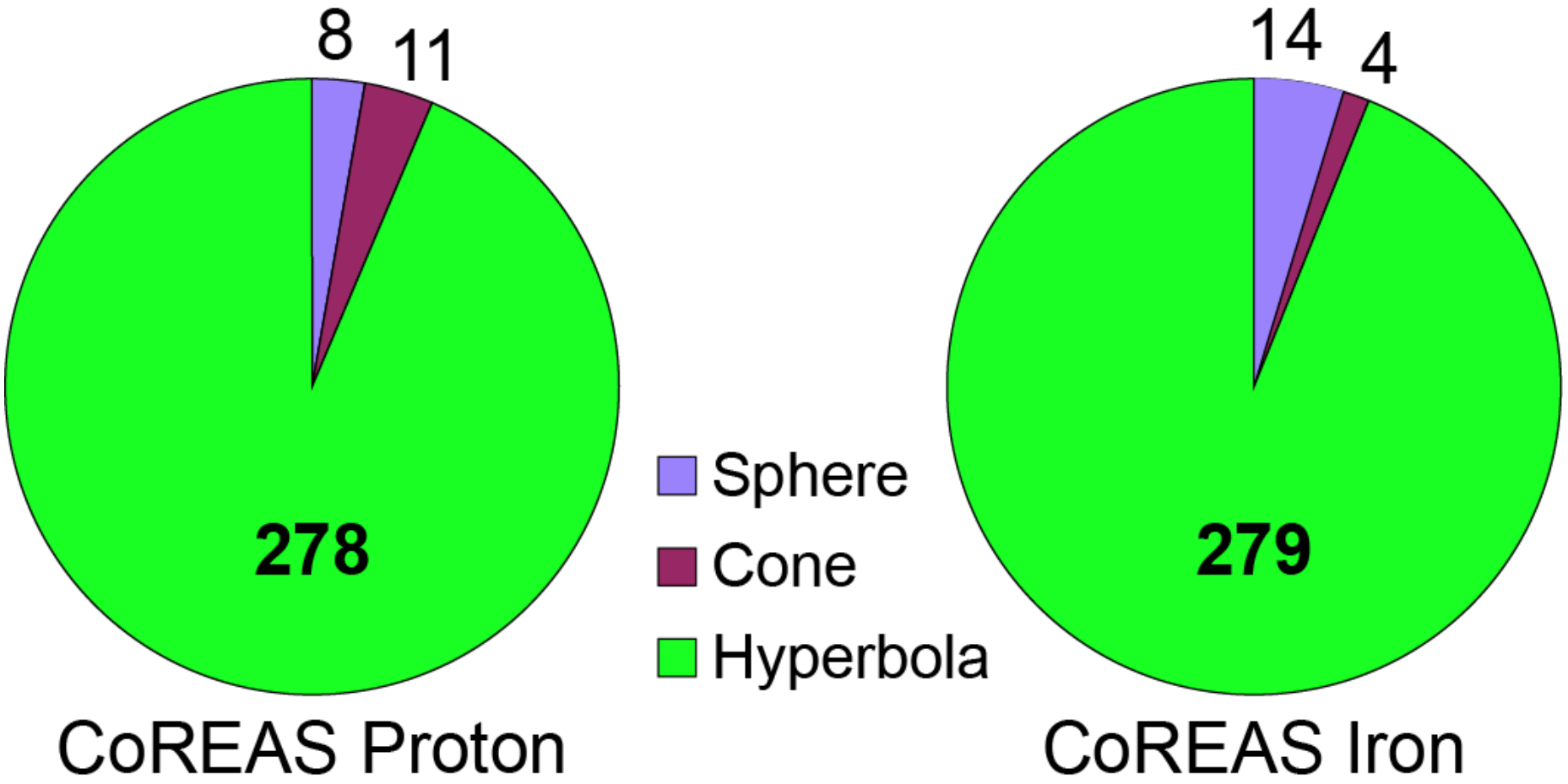
Comparison of wavefront shapes



frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

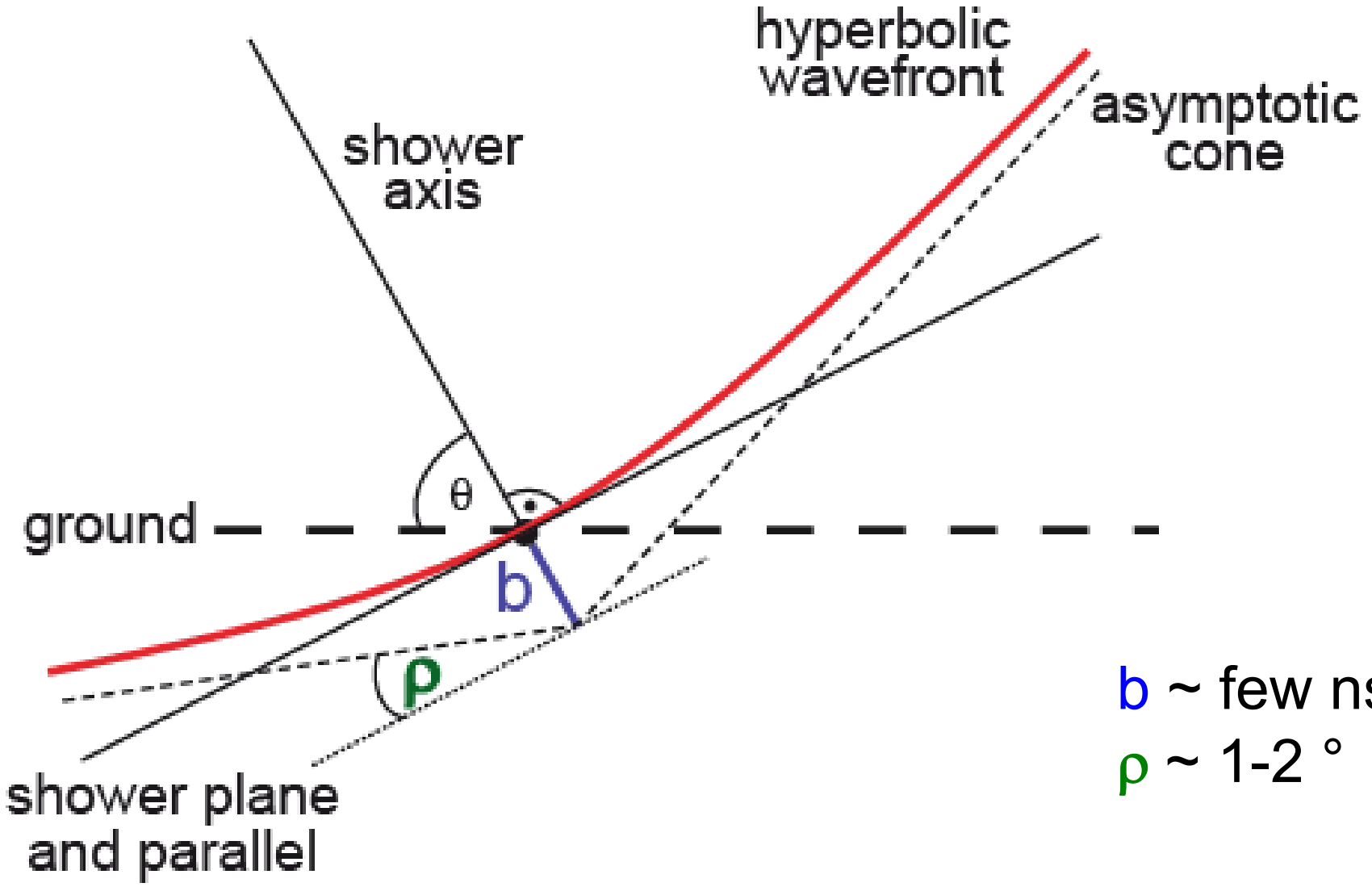
Clear evidence for hyperbola with sims

- Number of events with smallest χ^2 for certain wavefront fit



frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

Parameterization of hyperbola

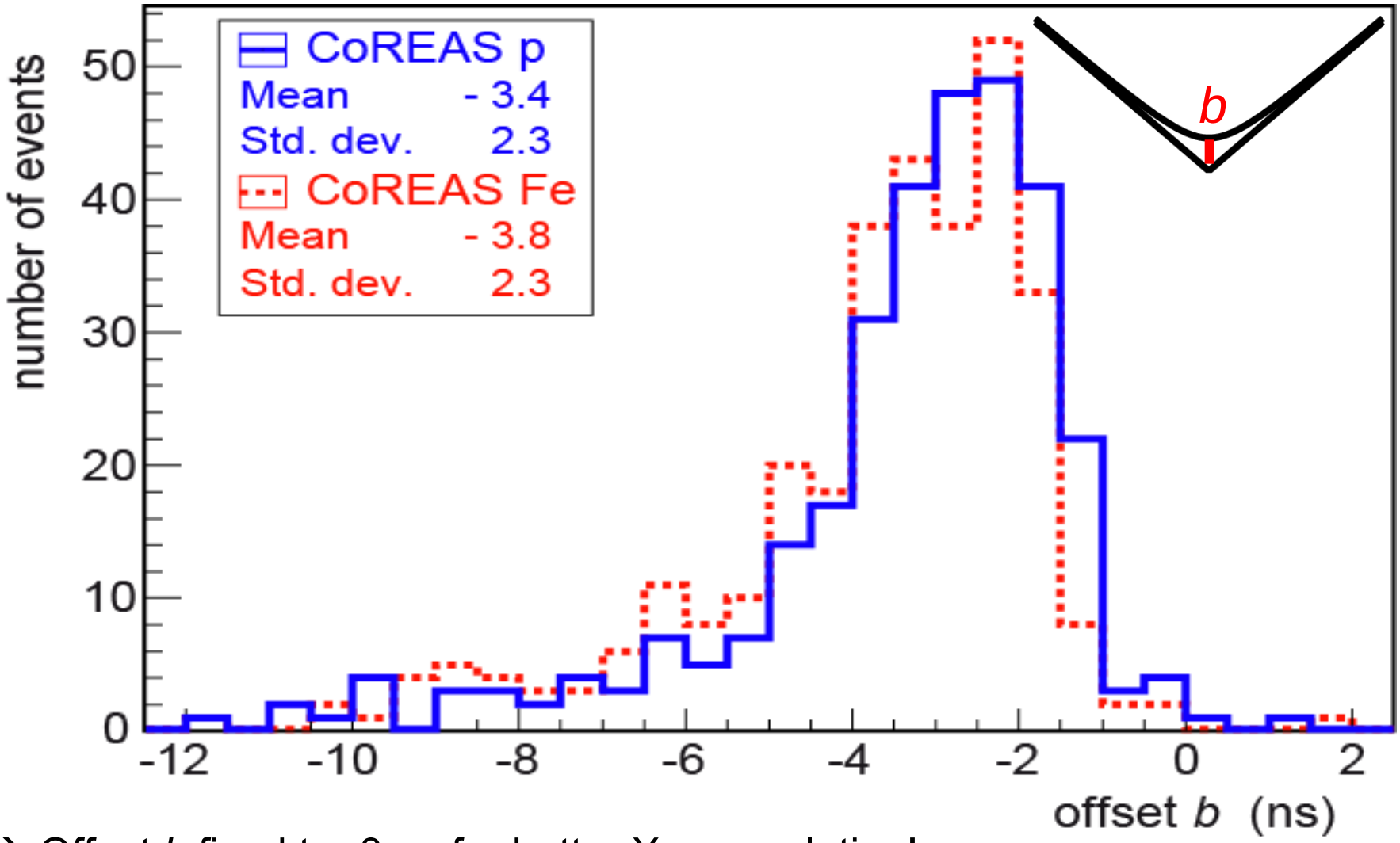


b ~ few ns

ρ ~ 1-2 °

frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

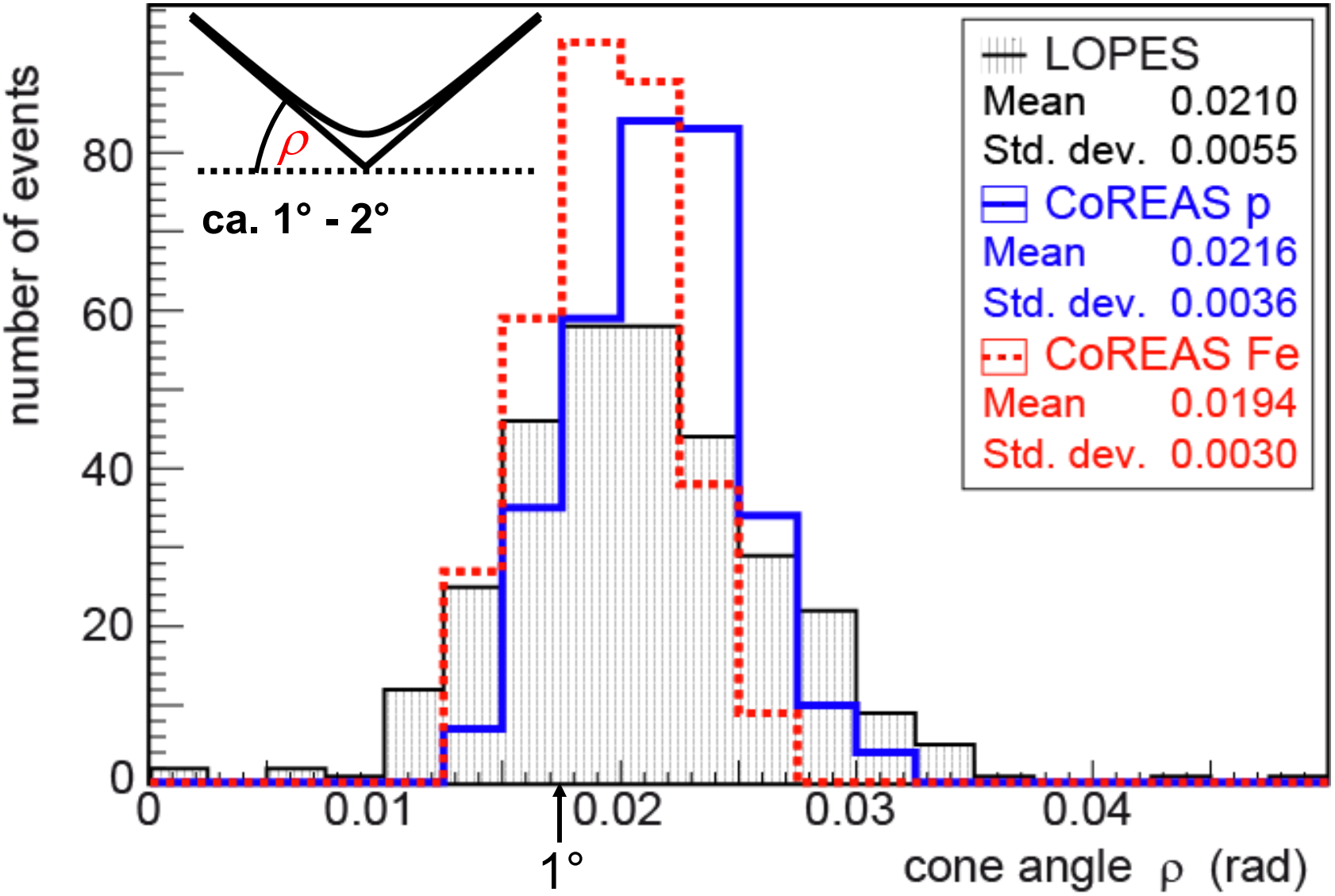
Offset parameter b



→ Offset *b* fixed to -3 ns for better X_{max} resolution!

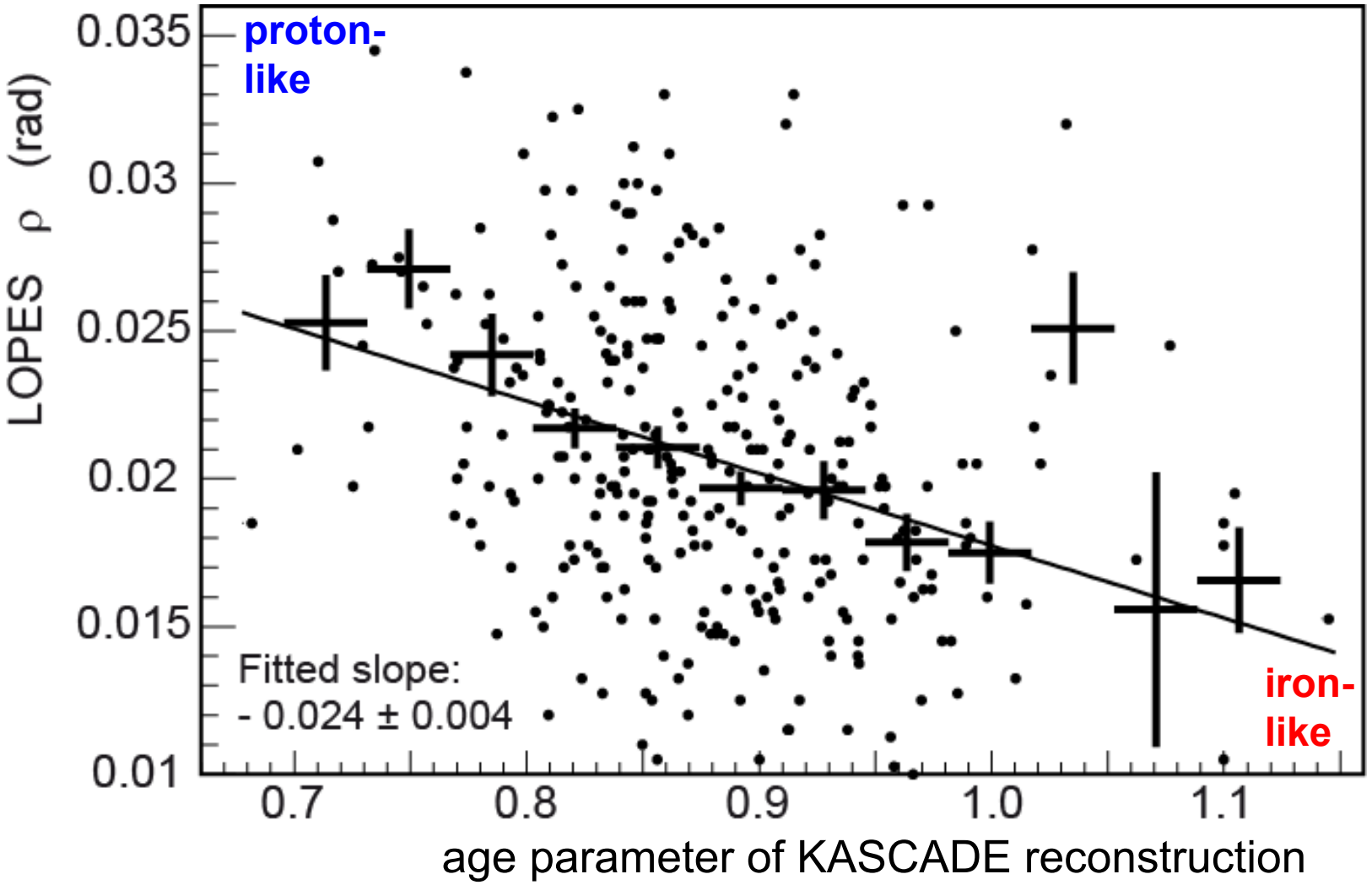
frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

Cone angle ρ



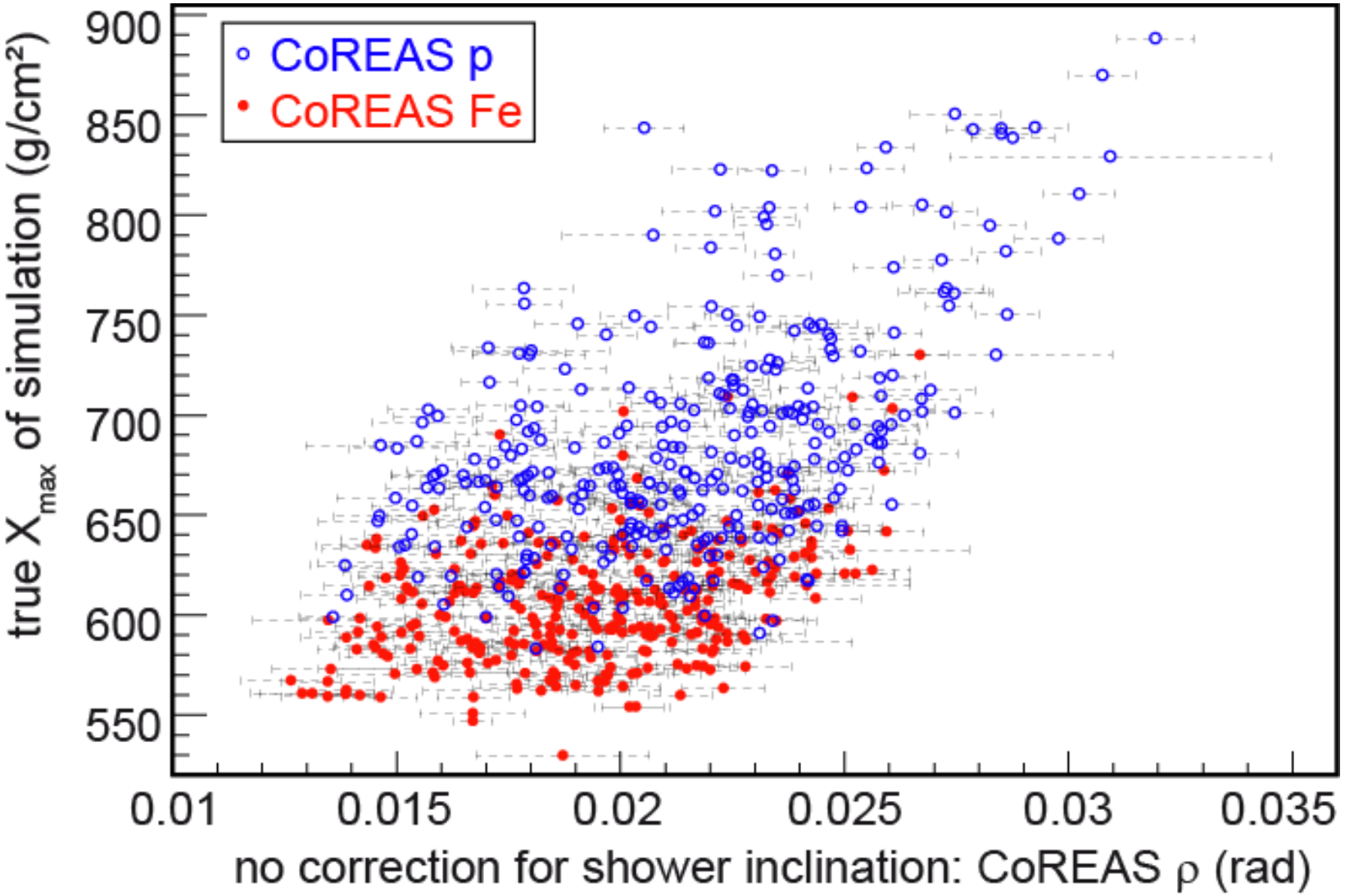
frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

Measured correlation with shower age



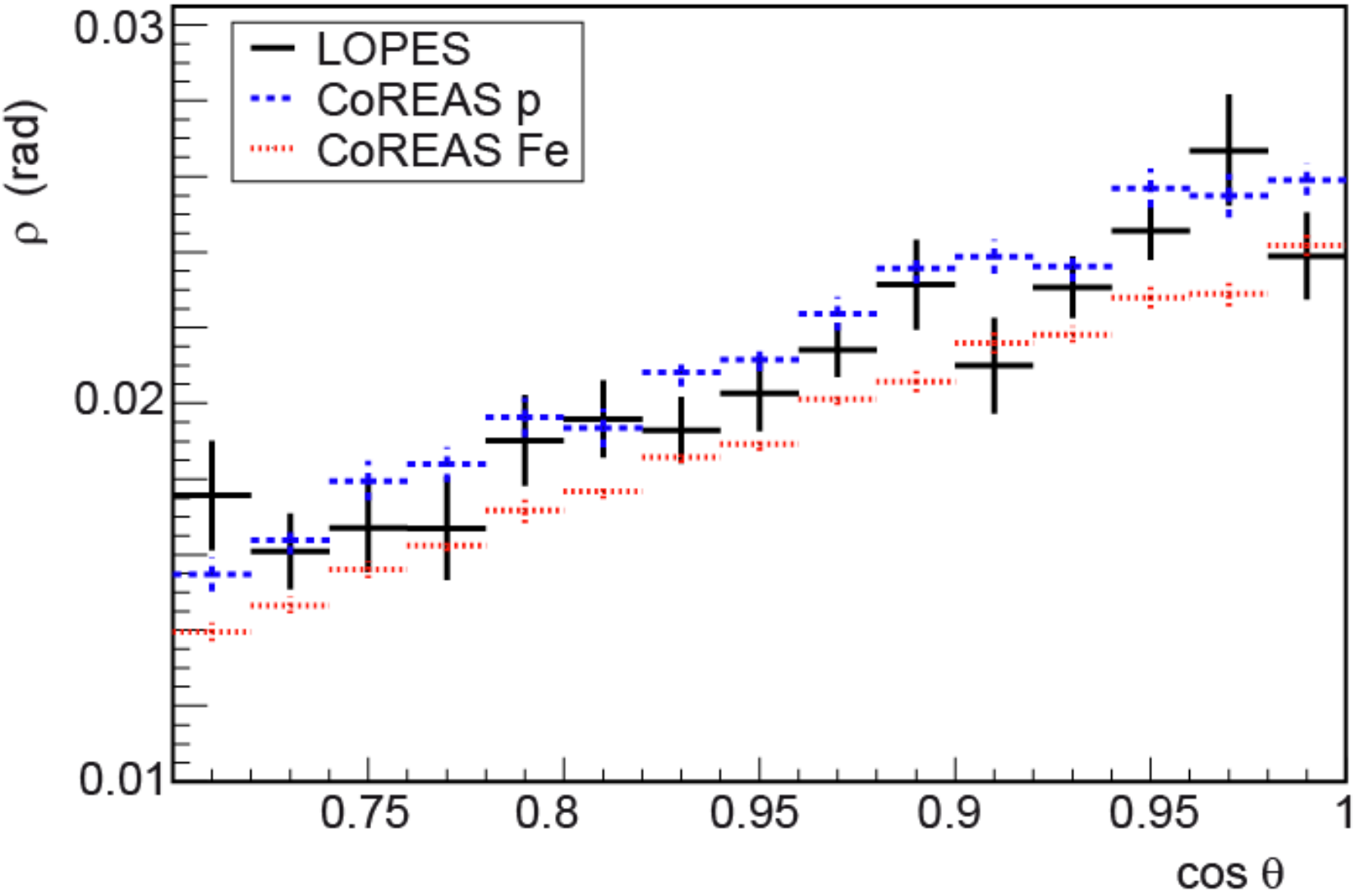
frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

Correlation with X_{max} in simulations



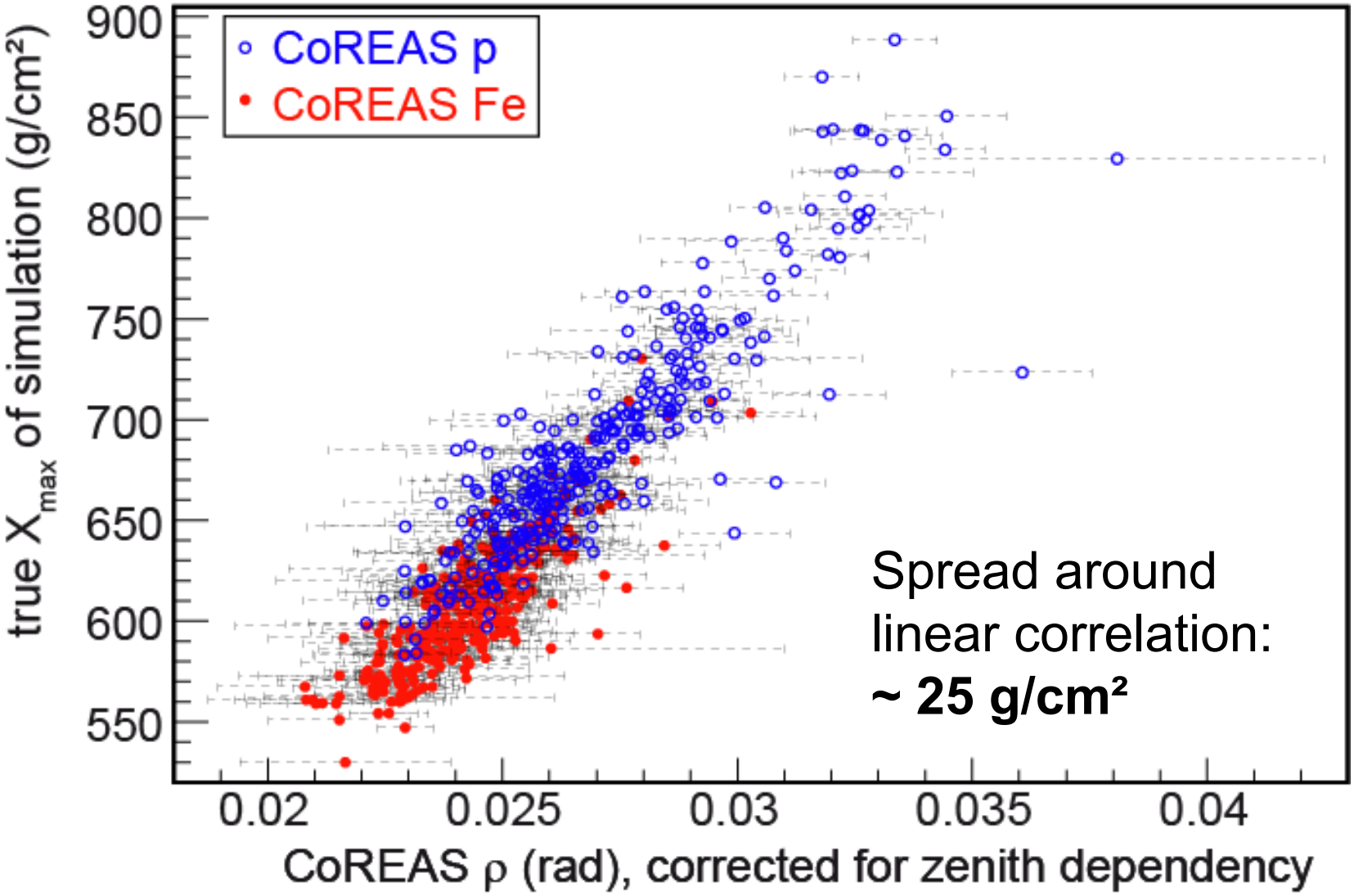
frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

Correlation with zenith angle



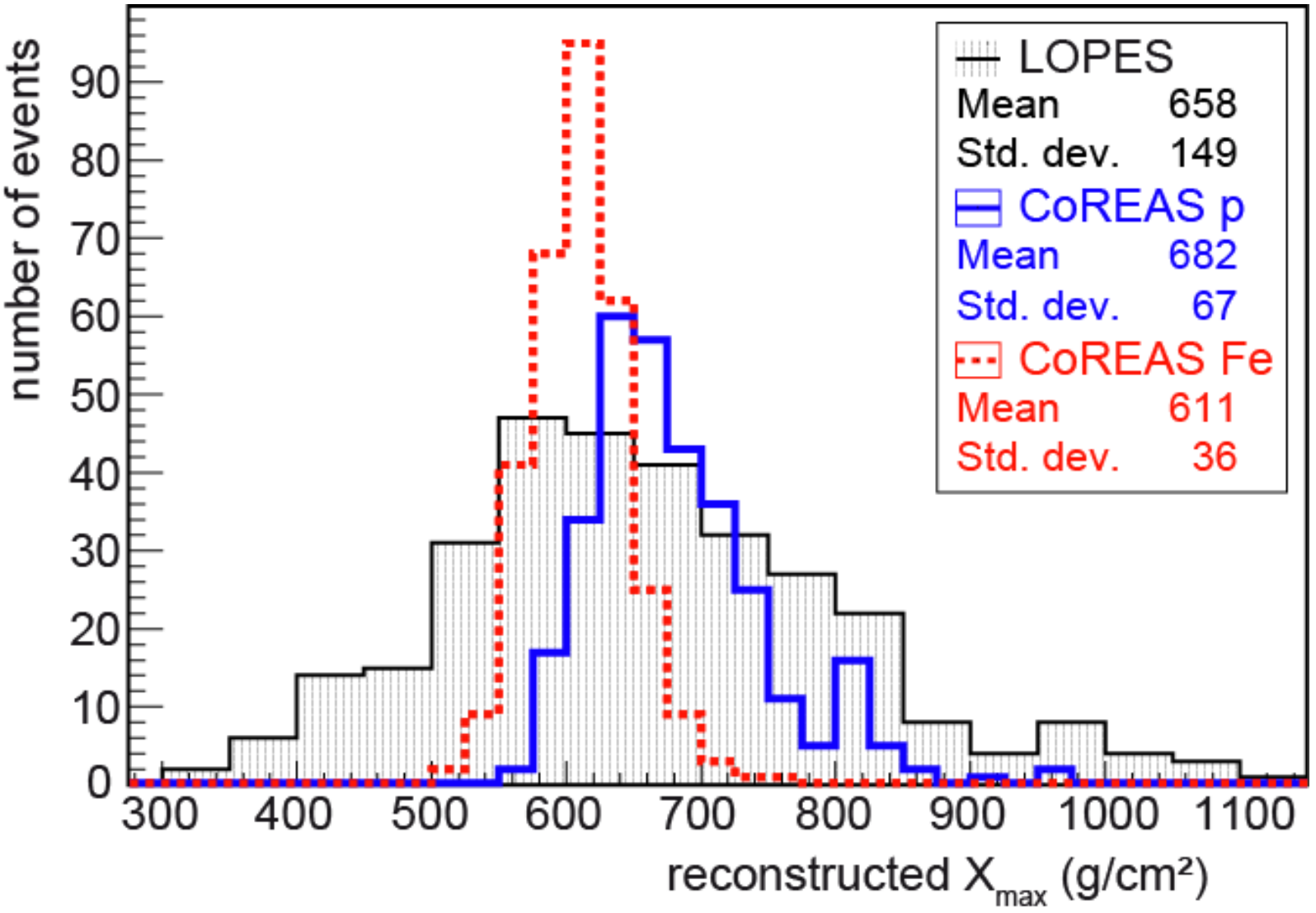
frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

X_{max} correlation after zenith correction



frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

Reconstructed X_{max}



frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

Conclusion

- Shape of radio wavefront
  - **Hyperbola**
  - Cone: good approximation at large distances (d > 50 m)
  - Sphere, i.e., point source at shower maximum: poor approximation
- Practical applicability
  - Reconstruction of shower geometry
  - Discrimination between air showers and disturbances
  - X_{max}: also in combination with independent lateral-slope method

    → Composition of primary cosmic rays

frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

LOPES Collaboration

Institut für experimentelle Kernphysik, KIT, Germany
J.C. Arteaga, B. Fuchs, D. Kang, M. Ludwig, N. Palmieri, V. De Souza, D. Huber, K. Link, M. Melissas

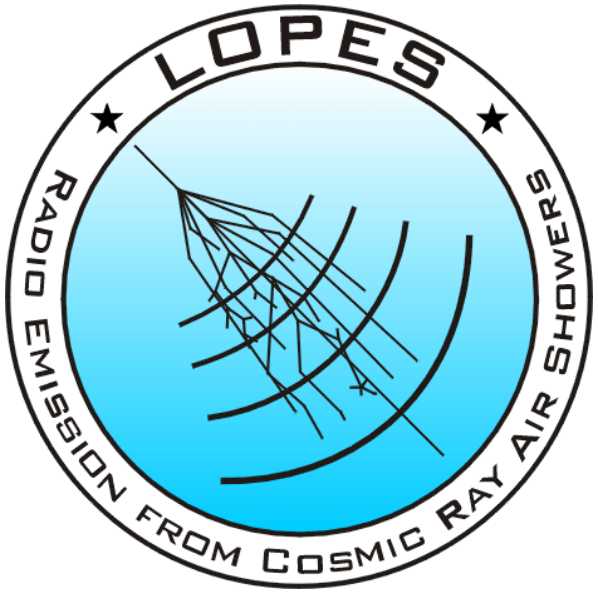
Max-Planck-Institut für Radio-astronomie, Bonn, Germany
P.L. Biermann, J.A. Zensus, A. Horneffer

Osservatorio Astrofisico di Torino, INAF Torino, Italy
E. Cantoni, G.C. Trinchero, C. Morello

National Centre for Nuclear Research, Lodz, Poland
P. Łuczak, J. Zabierowski

Dipartimento di Fisica dell' Università Torino, Italy
M. Bertaina, F. Di Pierro, A. Chiavassa

Dept of Astrophysics, Nijmegen, The Netherlands
L. Bähren, J.R. Hörandel, H. Falcke, J. Kuijpers



National Inst of Physics and Nuclear Engineering Bucharest, Romania
I.M. Brancus, O. Sima, A. Saftoiu, G. Toma

Institut für Kernphysik, KIT, Germany
W.D. Apel, J. Blümer, K. Daumiller, R. Engel, D. Heck, P.G. Isar, J. Oehlschläger, H. Rebel, H. Schieler, A. Weindl, K. Bekk, H. Bozdog, P. Doll, A. Haungs, T. Huege, H.J. Mathes, T. Pierog, M. Roth, F.G. Schröder, J. Wochele

Institut Prozessdatenverarbeitung und Elektronik, KIT, Germany
H. Gemmeke, Ch. Rühle, O. Krömer, A. Schmidt

ASTRON, The Netherlands
H. Butcher, W. van Capellen, G.W. Kant, S. Wijnholds

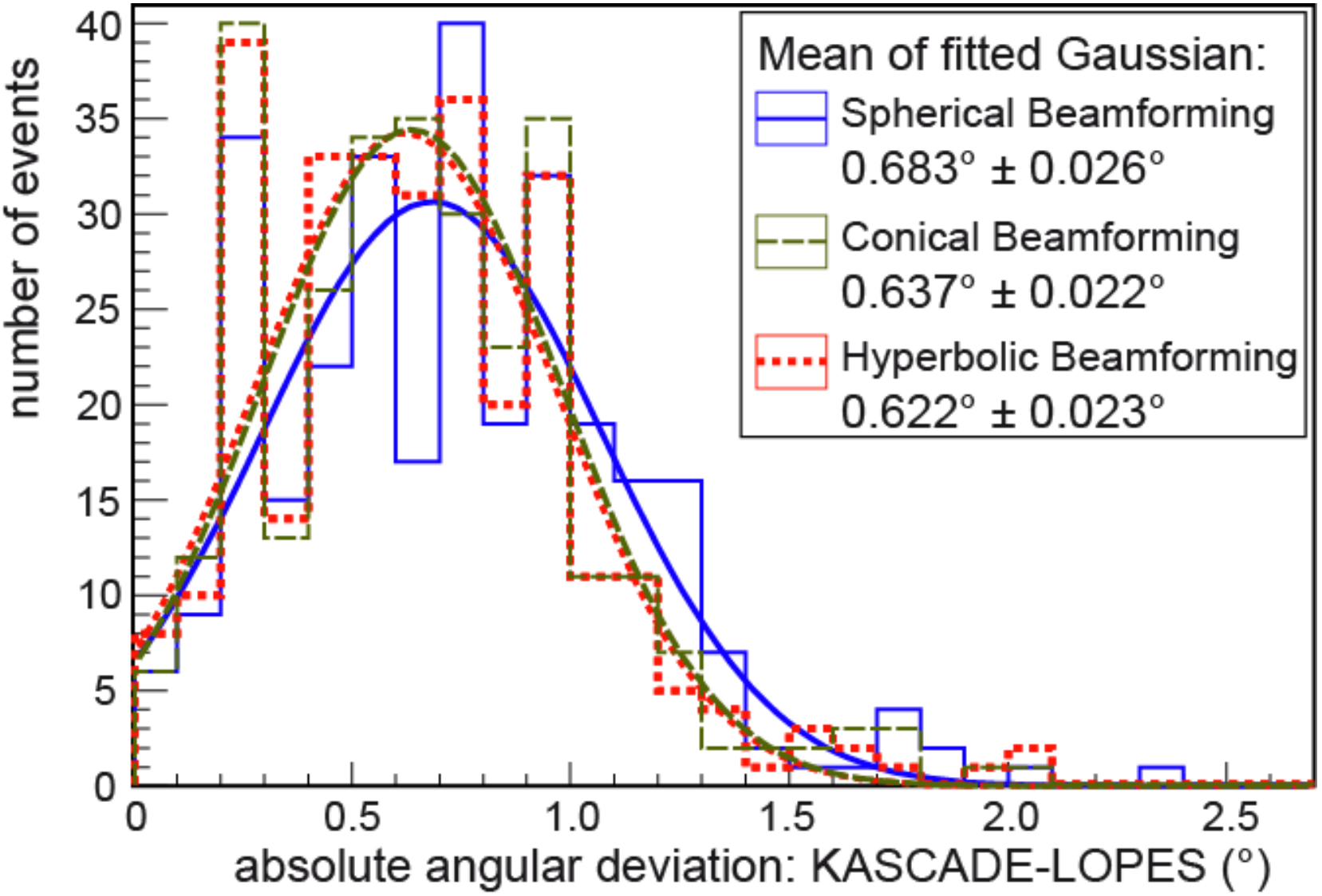
Universität Wuppertal, Germany
D. Fuhrmann, J. Rautenberg, K.H. Kampert

Universität Siegen, Germany
C. Grupen

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

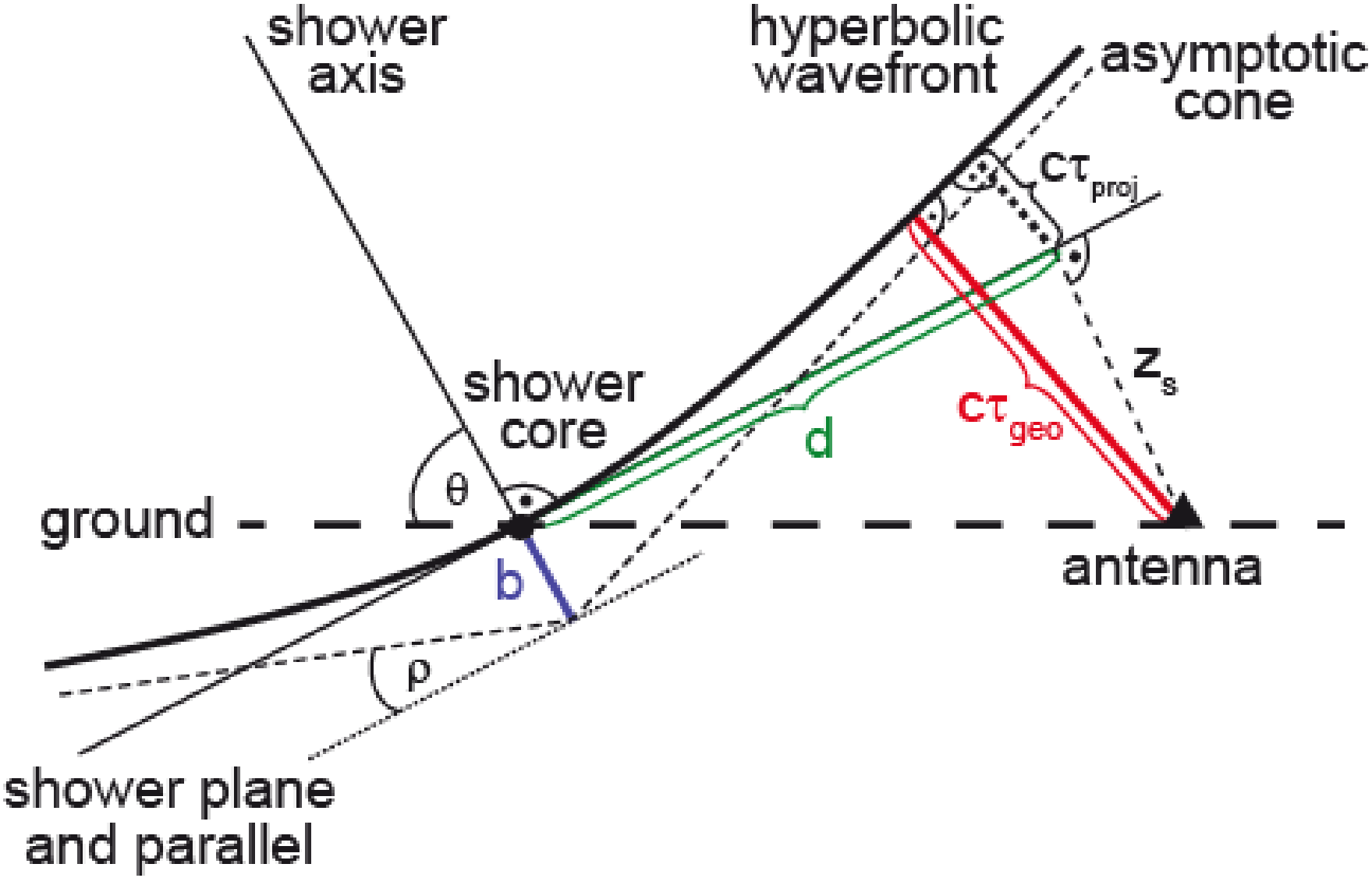
frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

Experimental indications for hyperbola



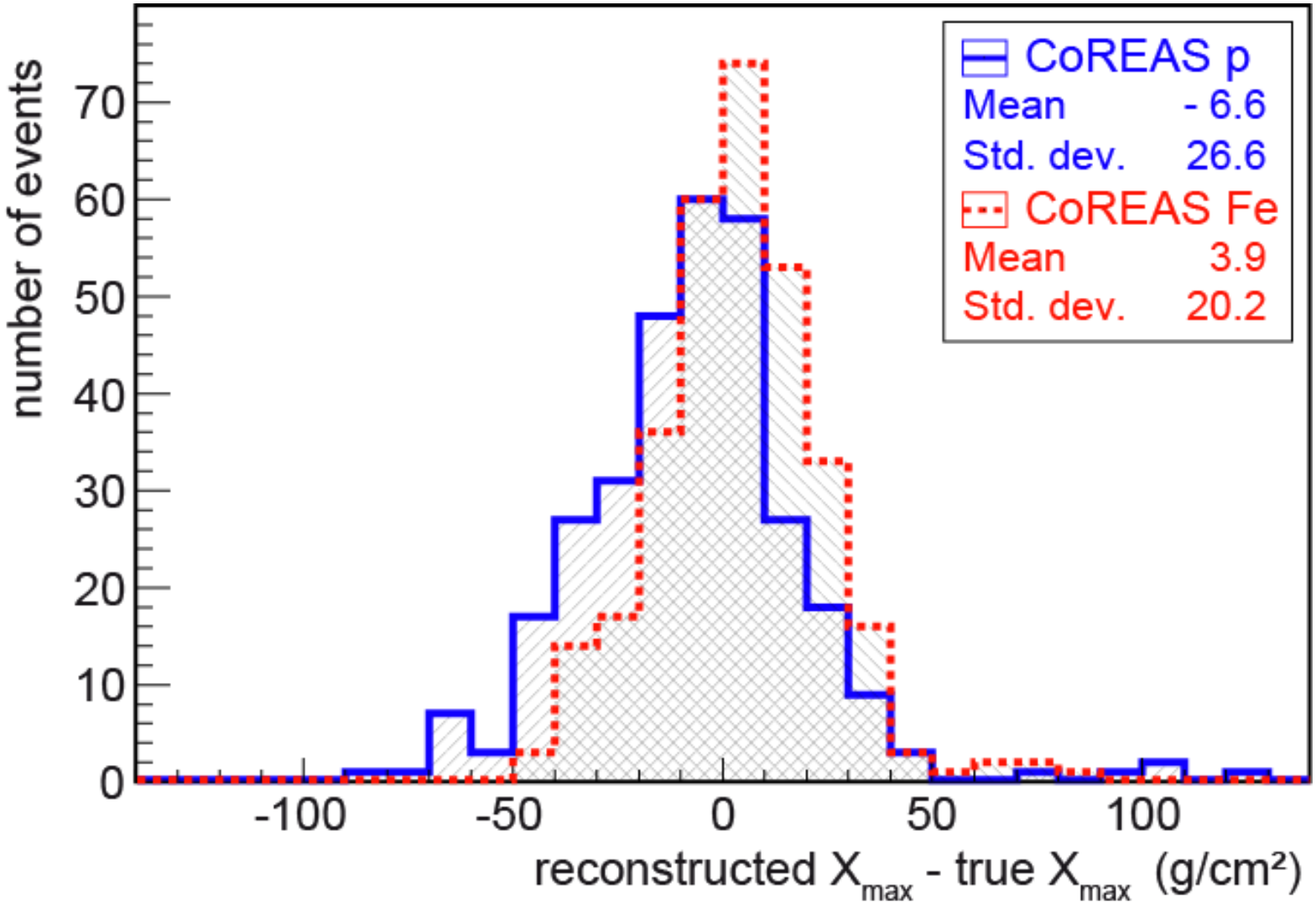
frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

Hyperbolic wavefront



frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

Simulation: true vs. reconstructed X_{max}



frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North

LOPES technical data

- Frequency range
  - 40-80 MHz
  - 80 MHz ADC sampling (2^{nd} 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

frank.schroeder@kit.edu
Institut für Kernphysik, KIT Campus North