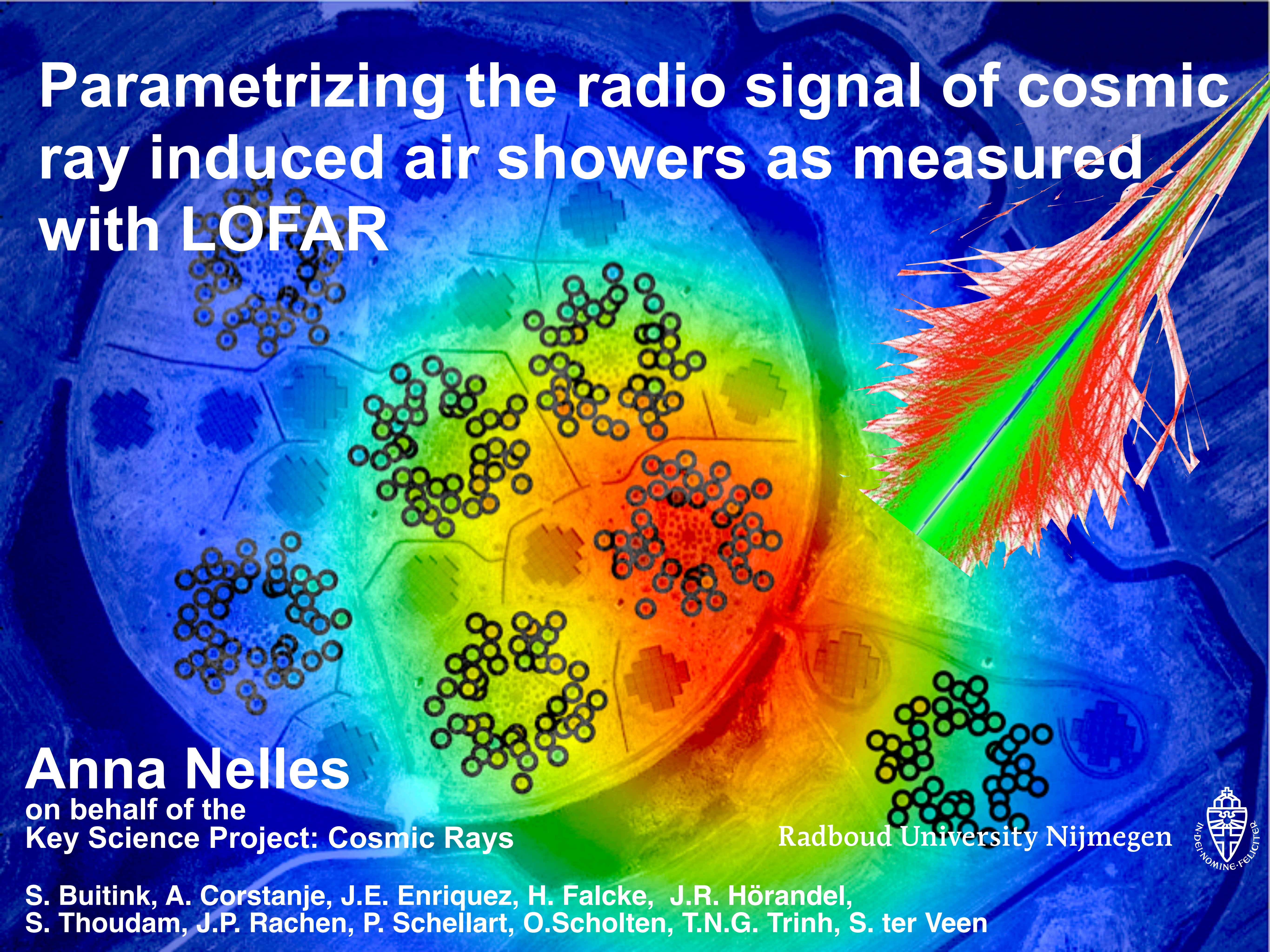


Parametrizing the radio signal of cosmic ray induced air showers as measured with LOFAR

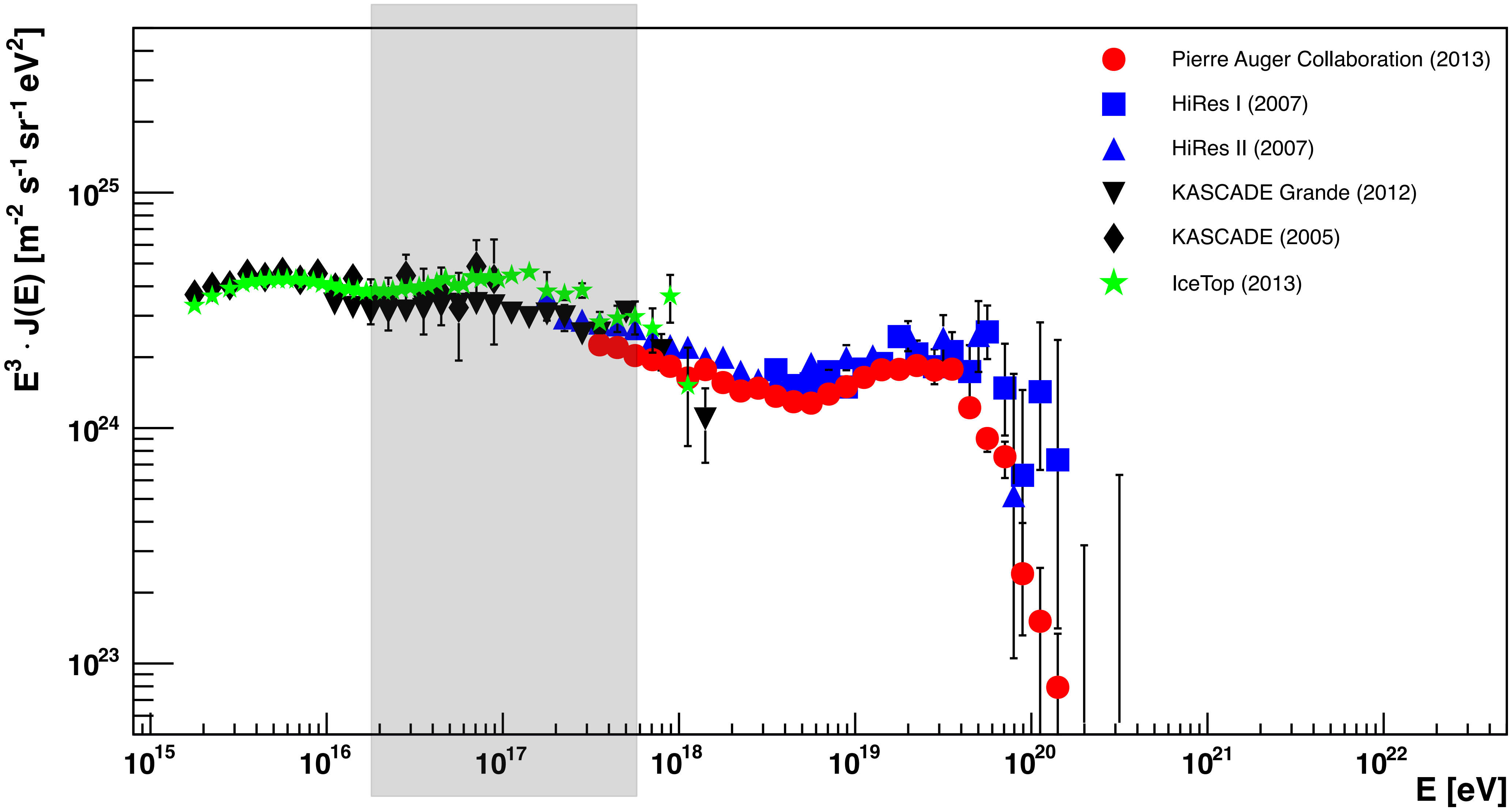
Anna Nelles

on behalf of the
Key Science Project: Cosmic Rays

Radboud University Nijmegen

S. Buitink, A. Corstanje, J.E. Enriquez, H. Falcke, J.R. Hörandel,
S. Thoudam, J.P. Rachen, P. Schellart, O.Scholten, T.N.G. Trinh, S. ter Veen

Why radio detection of cosmic rays?



What happens at E > 10^{17} eV?

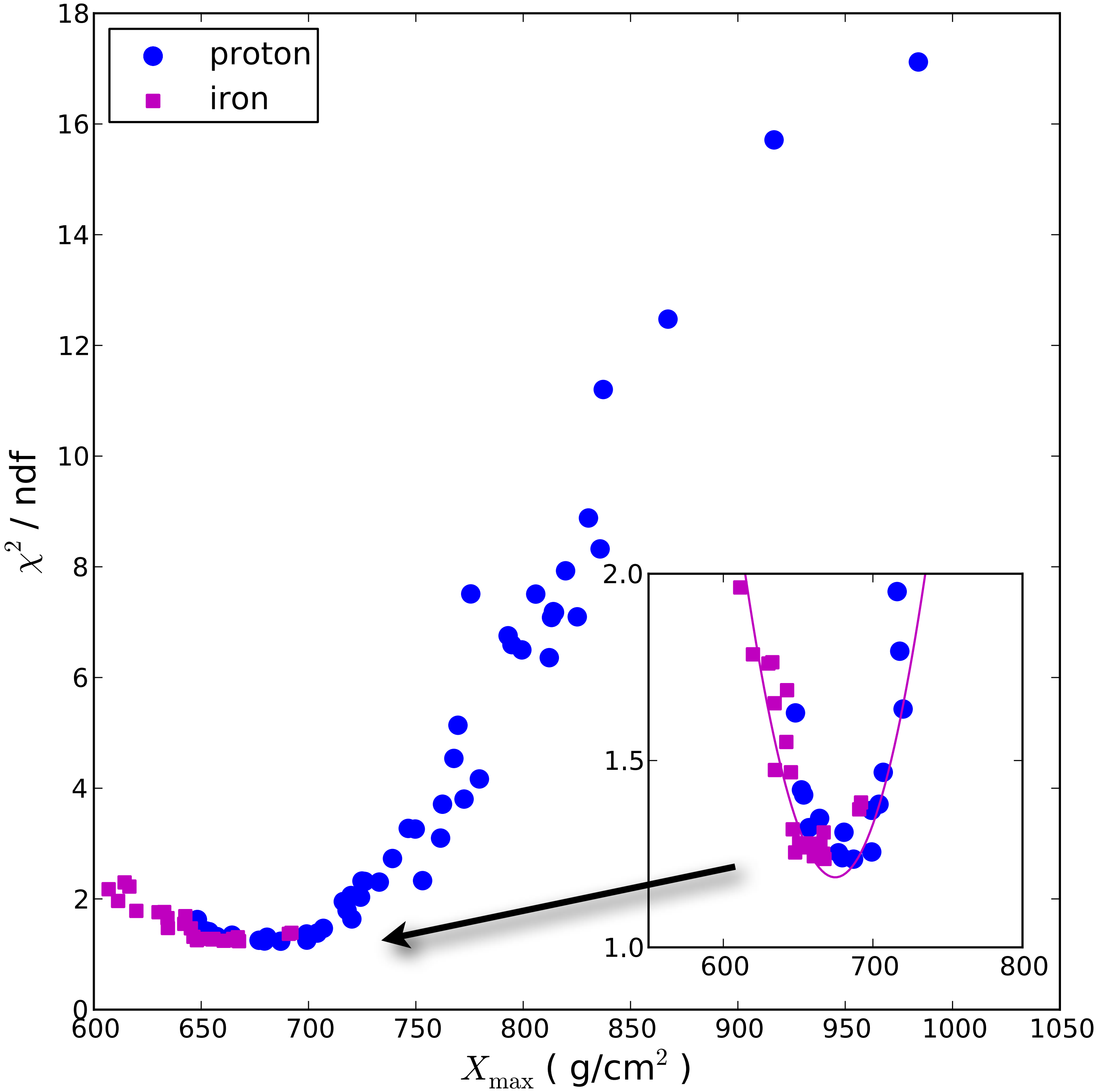
- transition of sources?
- propagation effects?
- accelerators reach limit?

Radio Detection:

- large number of events, i.e. long duty-cycle
- information about **mass of every air shower**

Direct comparison to simulations

S. Buitink et al., Phys. Rev. D, 2014



"Brute force search" to obtain

- Energy of primary
- Shower maximum X_{max} = proxy for mass of particle

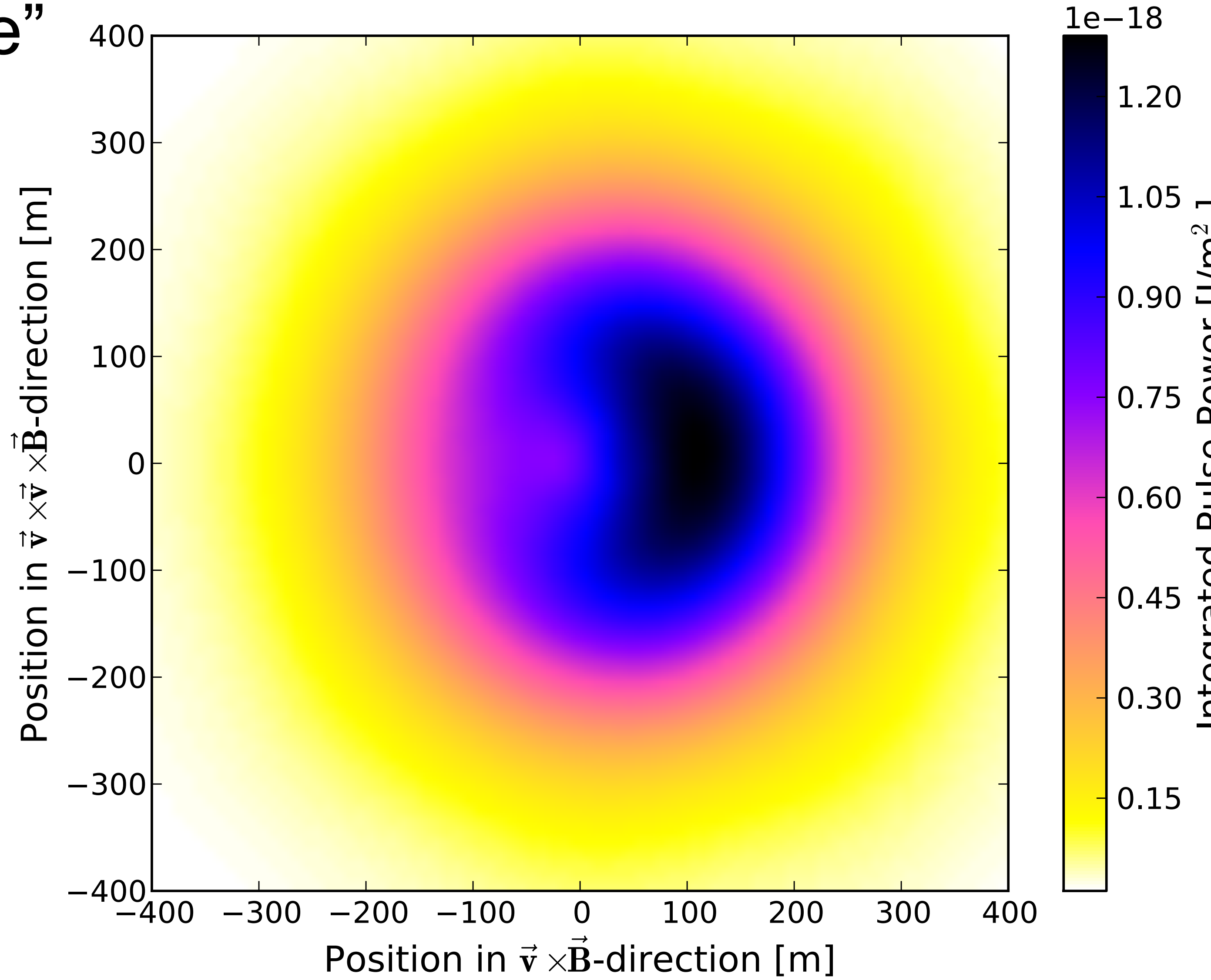
Computationally expensive

- per measured shower, about 120 simulations
- about 120 CPU weeks on single core of cluster in Nijmegen

Idea: All showers have same shape

All simulations show "bean shape" in shower plane, when rotated in **v** x **B** direction

v : shower axis
B: magnetic field vector



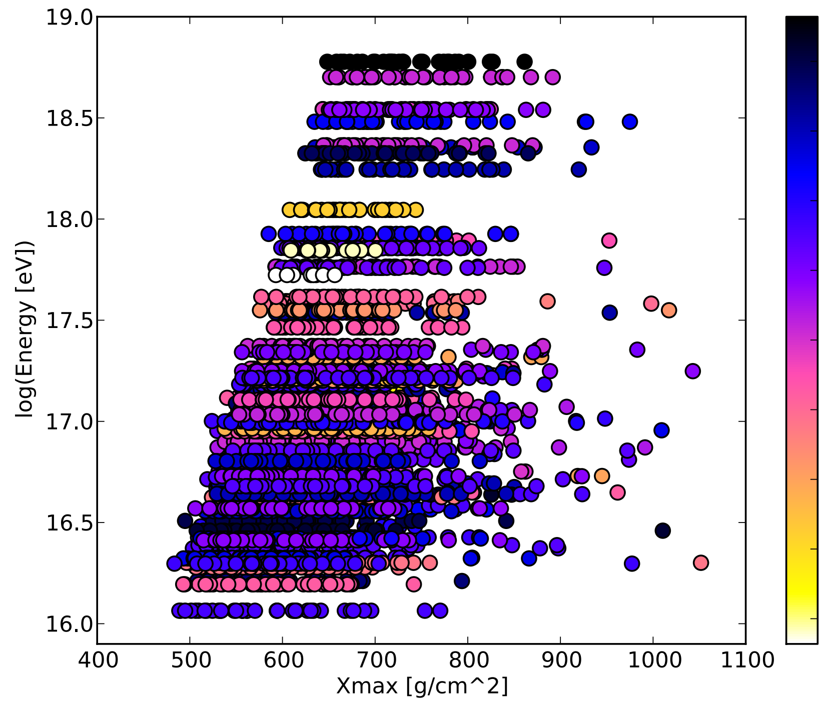
General shape:
One Big Gaussian with a second smaller one subtracted

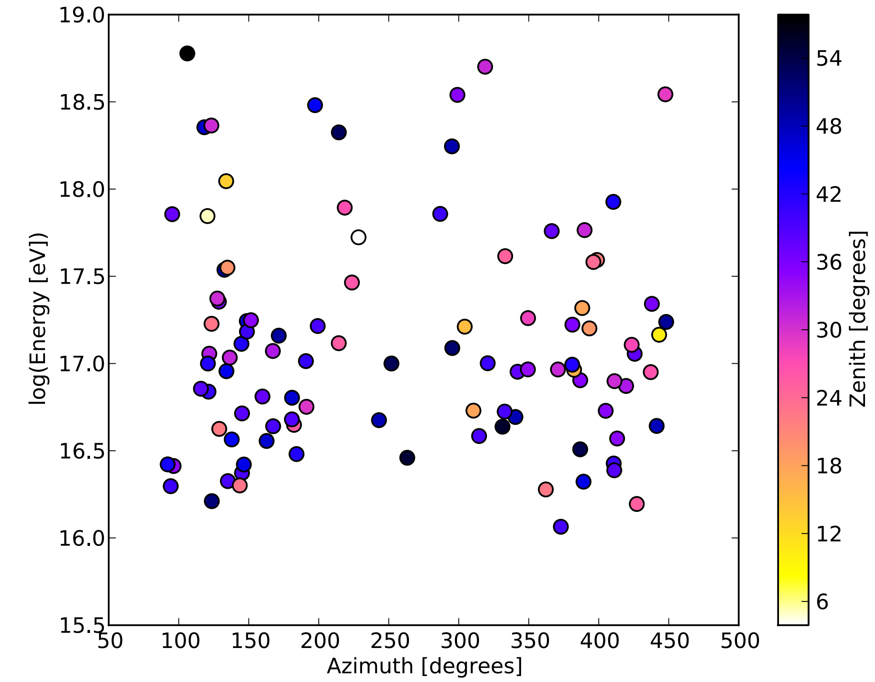
$$P(x', y') = A_+ \cdot \exp\left(\frac{-[(x' - X_+)^2 + (y' - Y_+)^2]}{\sigma_+^2}\right) - A_- \cdot \exp\left(\frac{-[(x' - X_-)^2 + (y' - Y_-)^2]}{\sigma_-^2}\right)$$

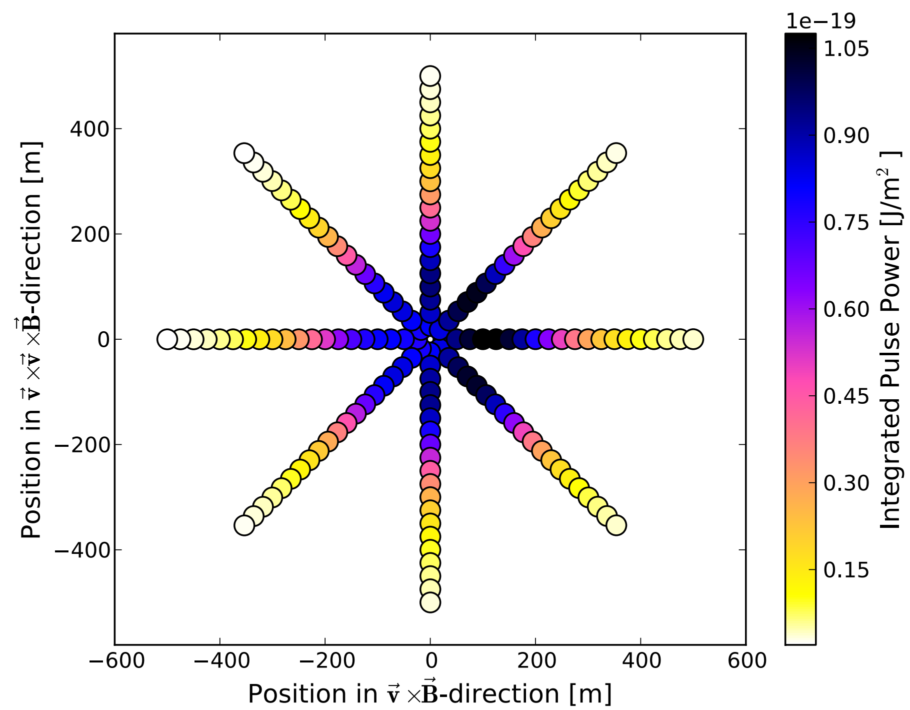
A. Nelles et al., Astropart. Phys.,60, p.13-24

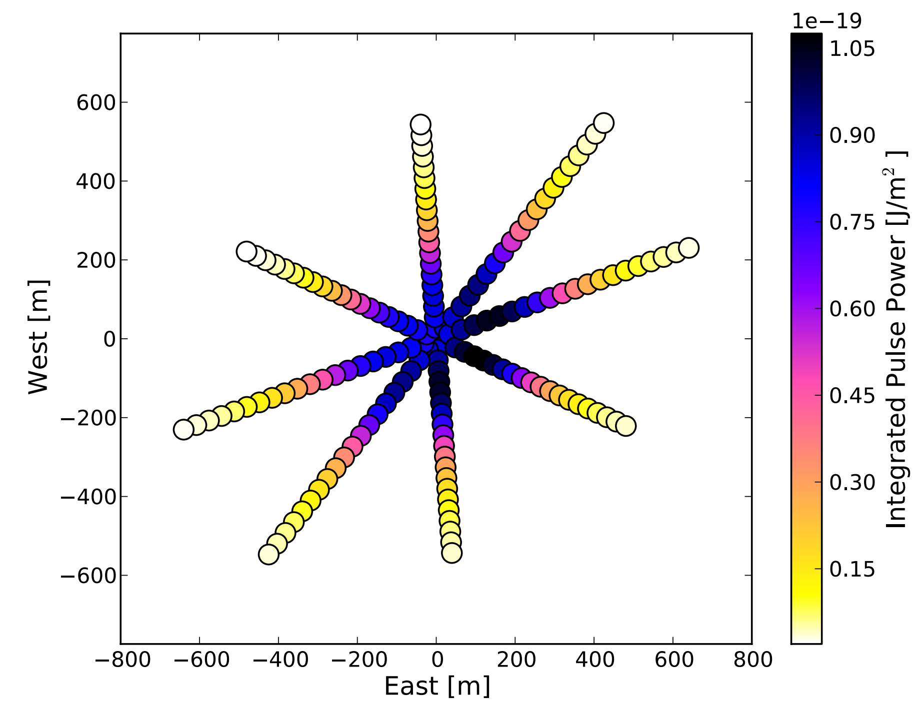
Extensive air shower simulation study

- about 1250 proton and 750 iron air showers
- CORSIKA 7.400 FLUKA 2011.2b QGSJETII.04 95 CoREAS
- LOFAR specific height and magnetic field
- Antennas on star-shaped pattern in shower plane, allows good interpolation of signals









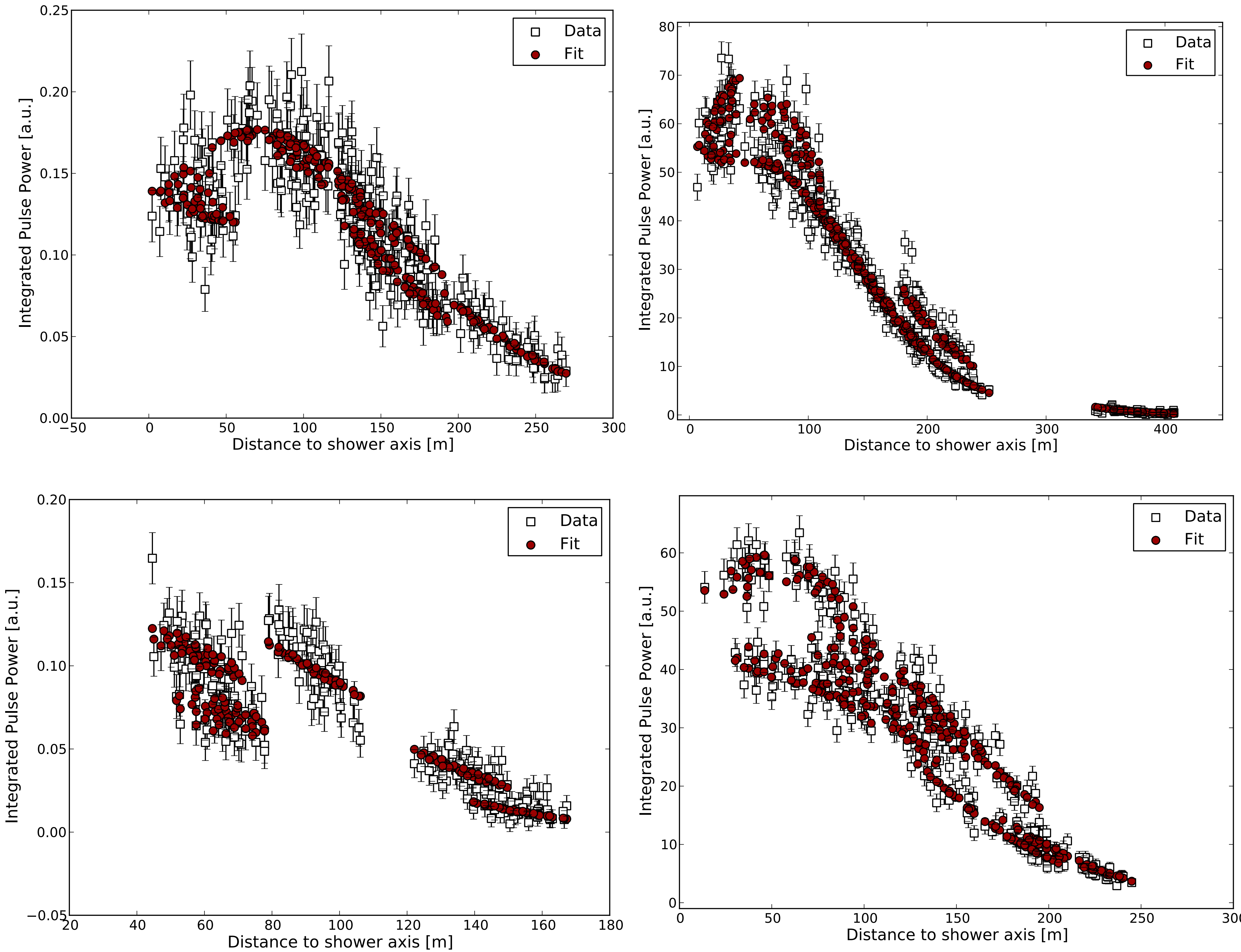
A. Nelles et al., Astropart. Phys.,60, p.13-24

Reduction of parametrization

$$P(x', y') = A_+ \cdot \exp\left(\frac{-[(x' - X_c)^2 + (y' - Y_c)^2]}{\sigma_+^2}\right) - C_0 \cdot A_+ \cdot \exp\left(\frac{-[(x' - (X_c - C_3))^2 + (y' - Y_c)^2]}{(e^{C_1 + C_2 \cdot \sigma_+})^2}\right)$$

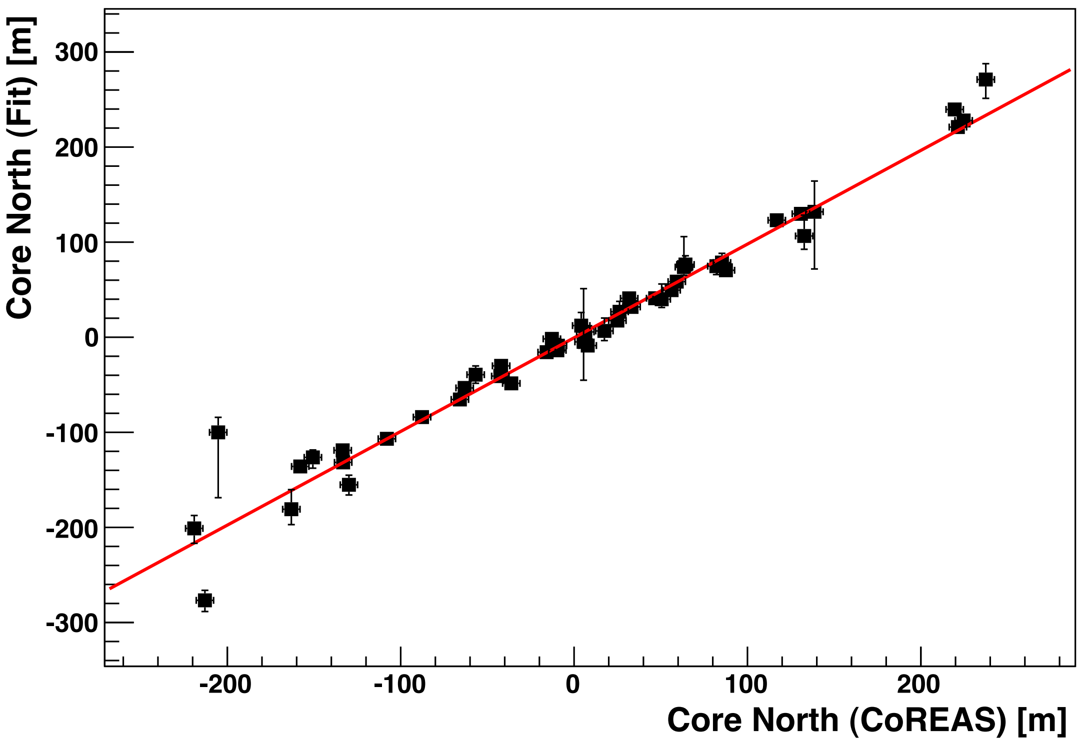
- Reduction in several ways possible, exploiting correlations between parameters
- Maximum reduction: 4 free parameters A_+, $Sigma_+$, X_c and Y_c
  - C_0, C_1 and C_2 constant
  - C_3 binned for zenith angle
- At LOFAR:
  - C_3 free parameter as sufficient number of antennas
  - C_0 can vary in restricted range
  - **Fit of 6 parameters on > 100 antenna signals**

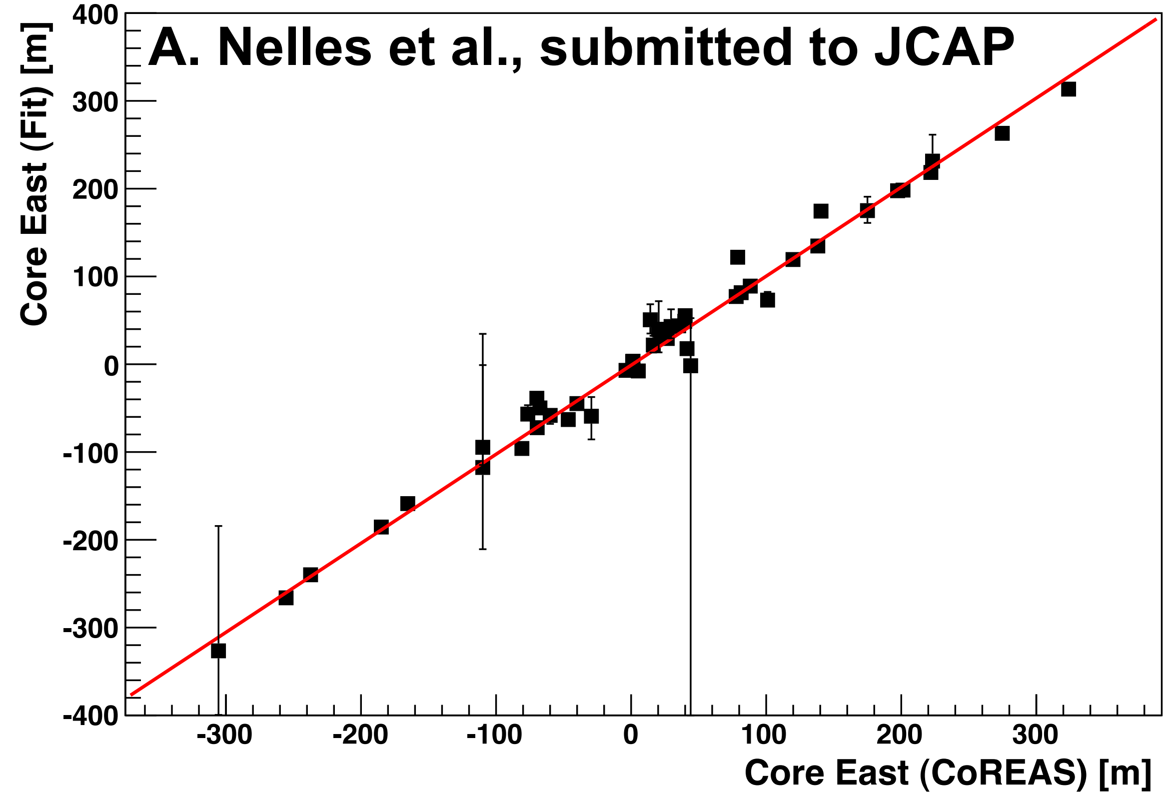
Test on (currently) 405 showers

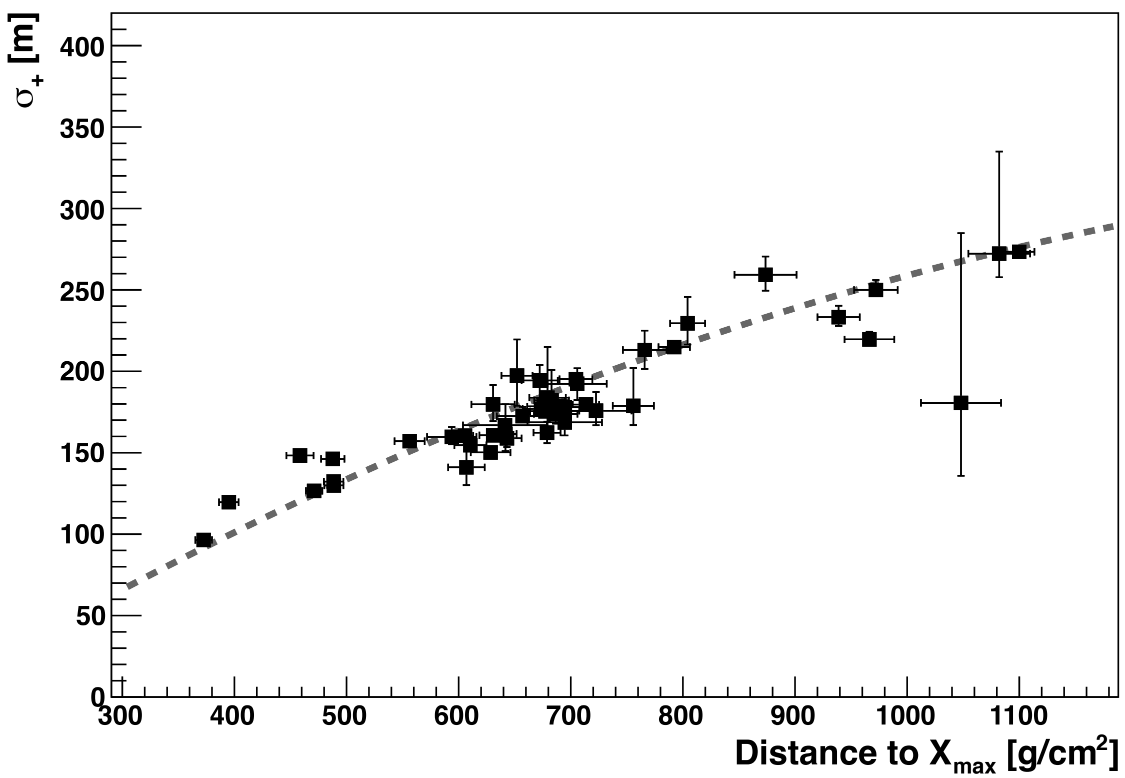


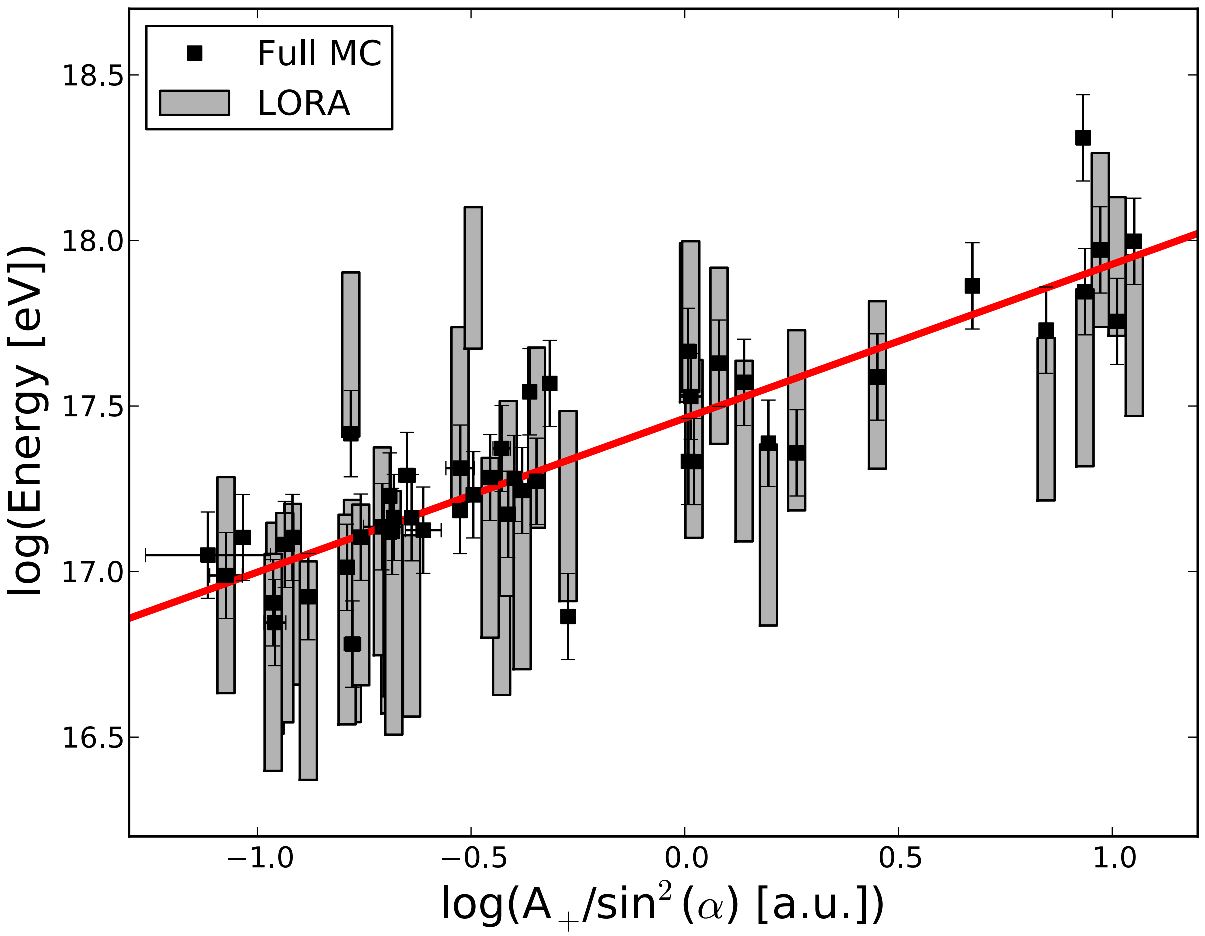
- **All data** from LOFAR can be fitted with this function
- If sufficient "structure" is measured
- Irregular layout not handy for air showers
- Chi^2/ndof distribution centered around 1

Agreement with full simulations

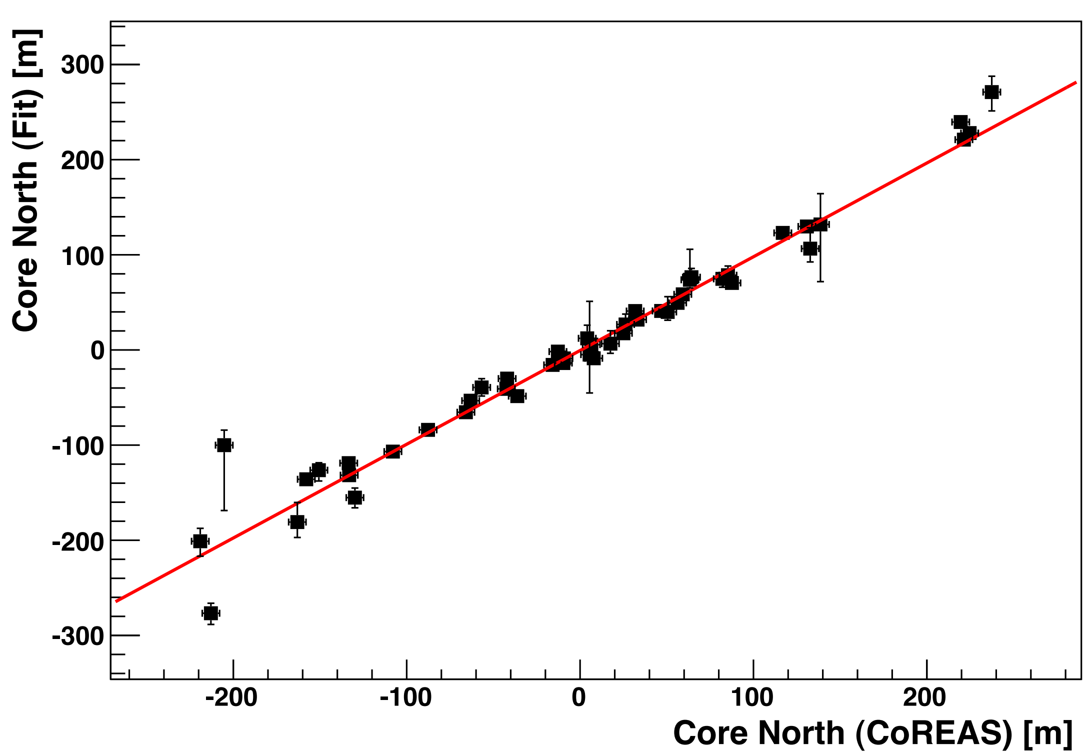


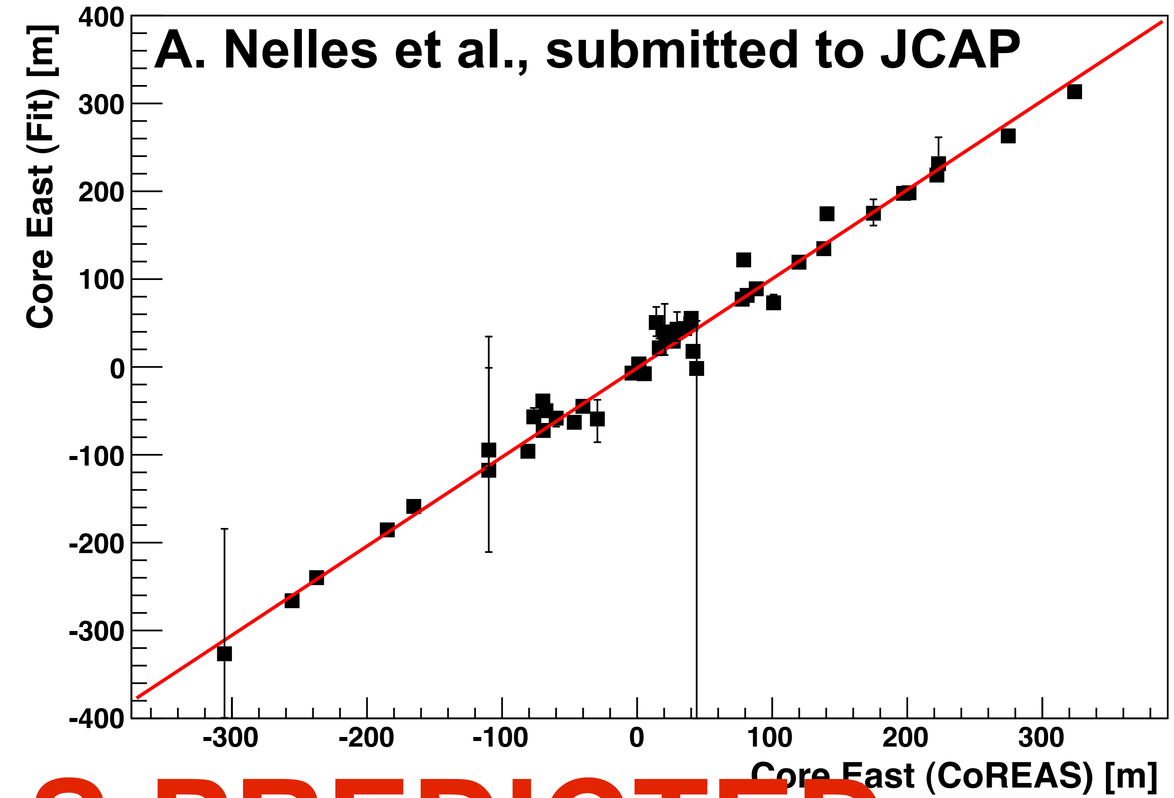




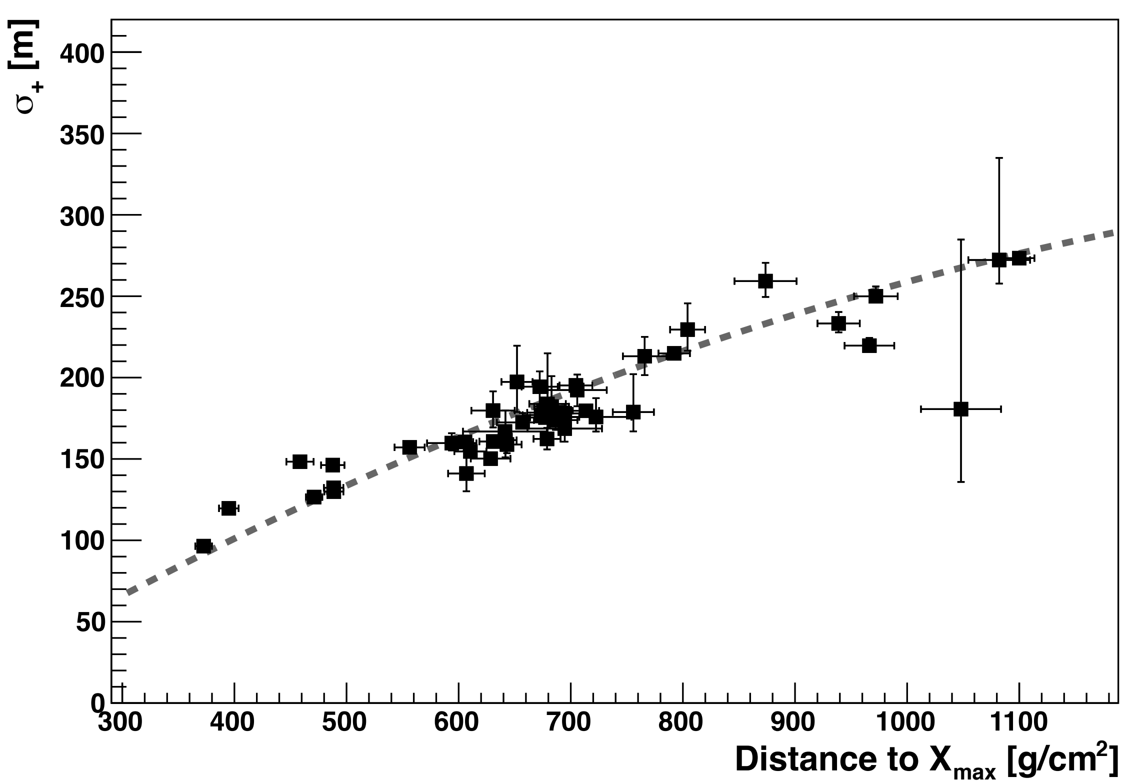


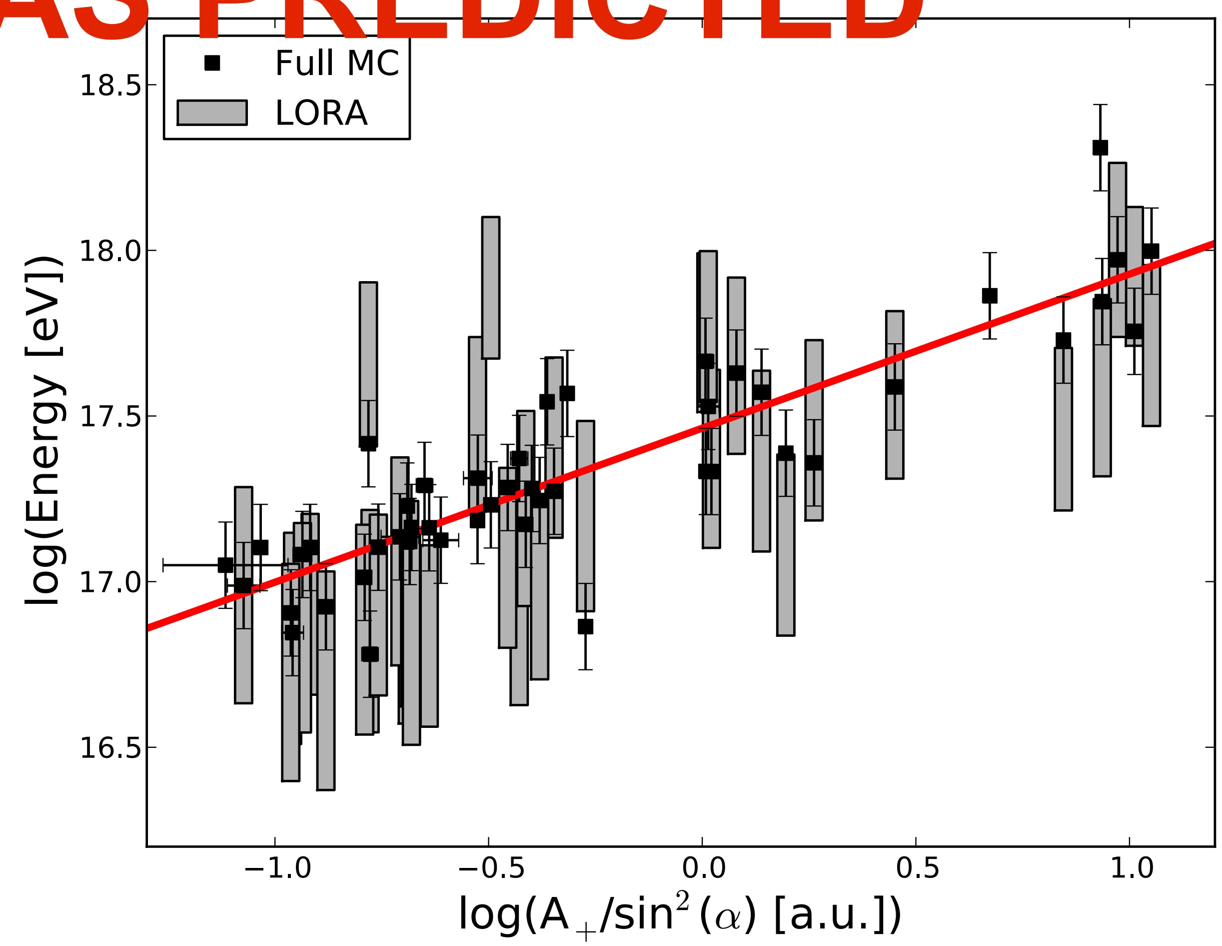
Agreement with full simulations





AGREEMENT AS PREDICTED

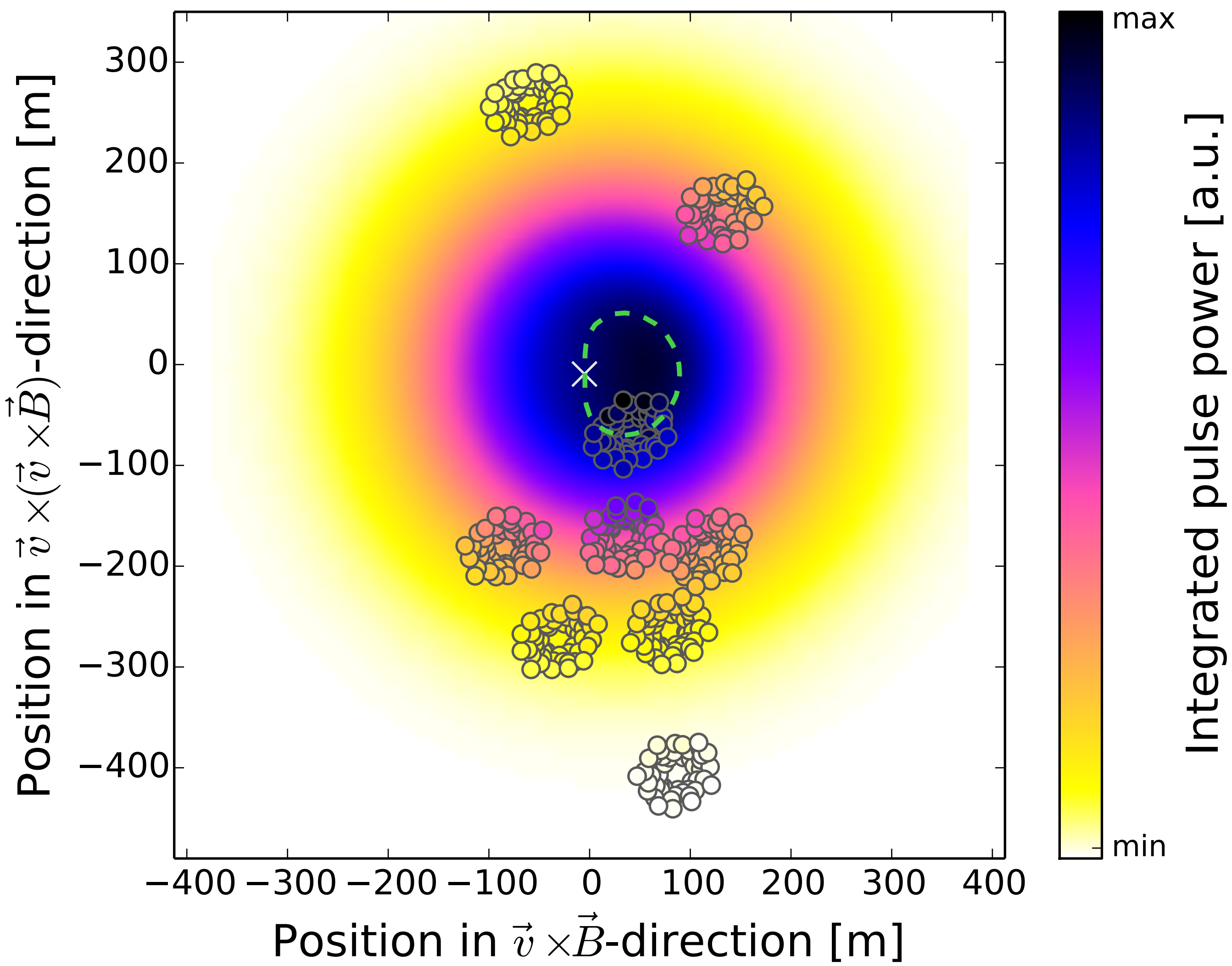




Conclusions

- Cosmic ray studies need **energy** and **mass of particle**
- Brute force simulations:
    - excellent results but expensive
- First working parameterization
    - only 15 instead of 120 simulations needed for same results
    - allows for real-time analysis of data

A. Nelles et al., submitted to JCAP



- So far 7 (+3 to come) publications about methods and emission physics
- Finally: **Physics of cosmic rays** publications to come soon