A parameterization of the radio signal as measured on the ground

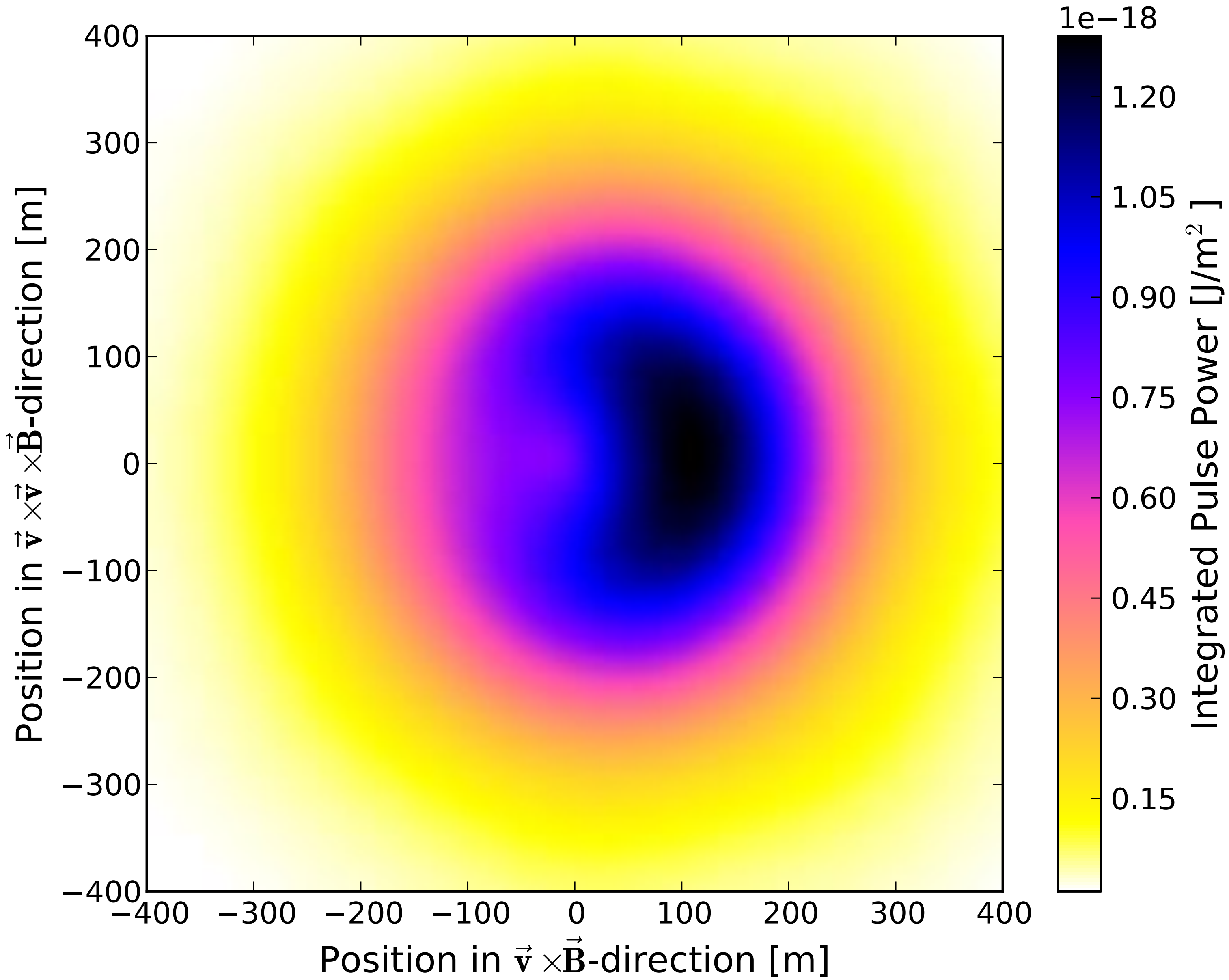
or

"A radio LDF"

Anna Nelles

Radboud University Nijmegen

and the LOFAR Key Science Project Cosmic Rays



CORSIKA + CoREAS simulation of air shower

zenith angle: 45 degrees, azimuth angle: 13 degrees
energy: 2×10^{18} eV

Idea: Model the “bean shape”

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

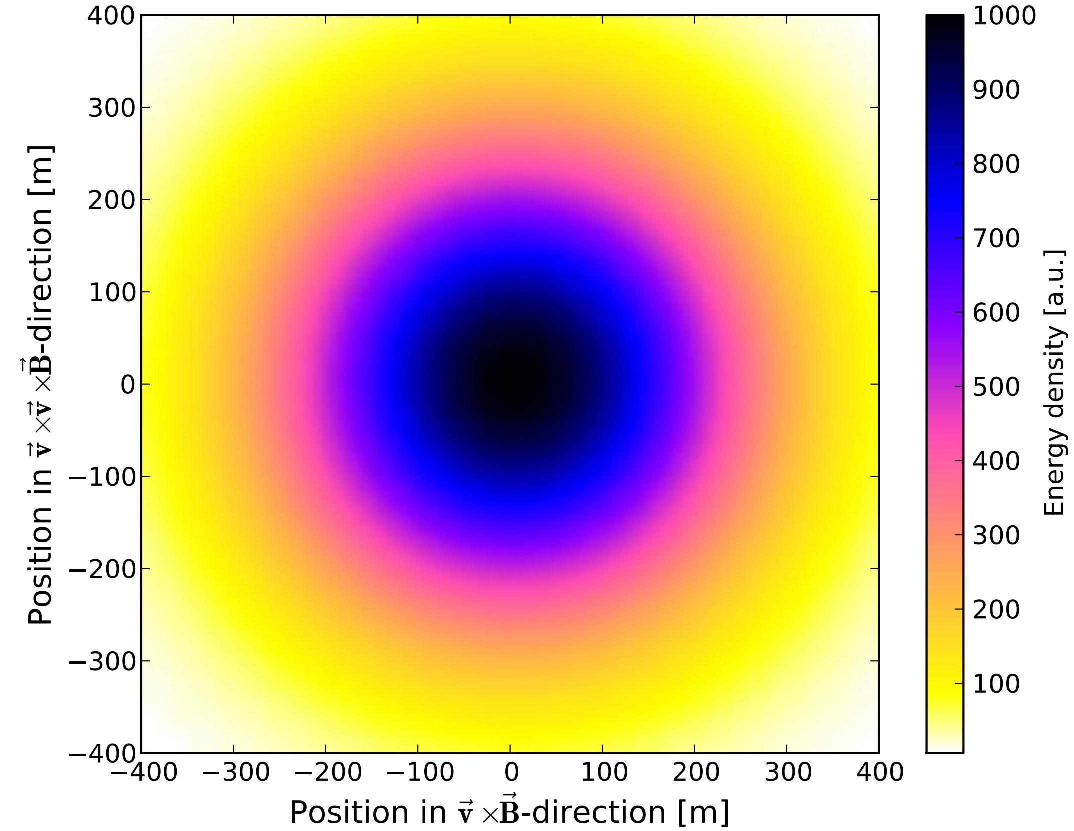
v : shower axis
B: magnetic field vector

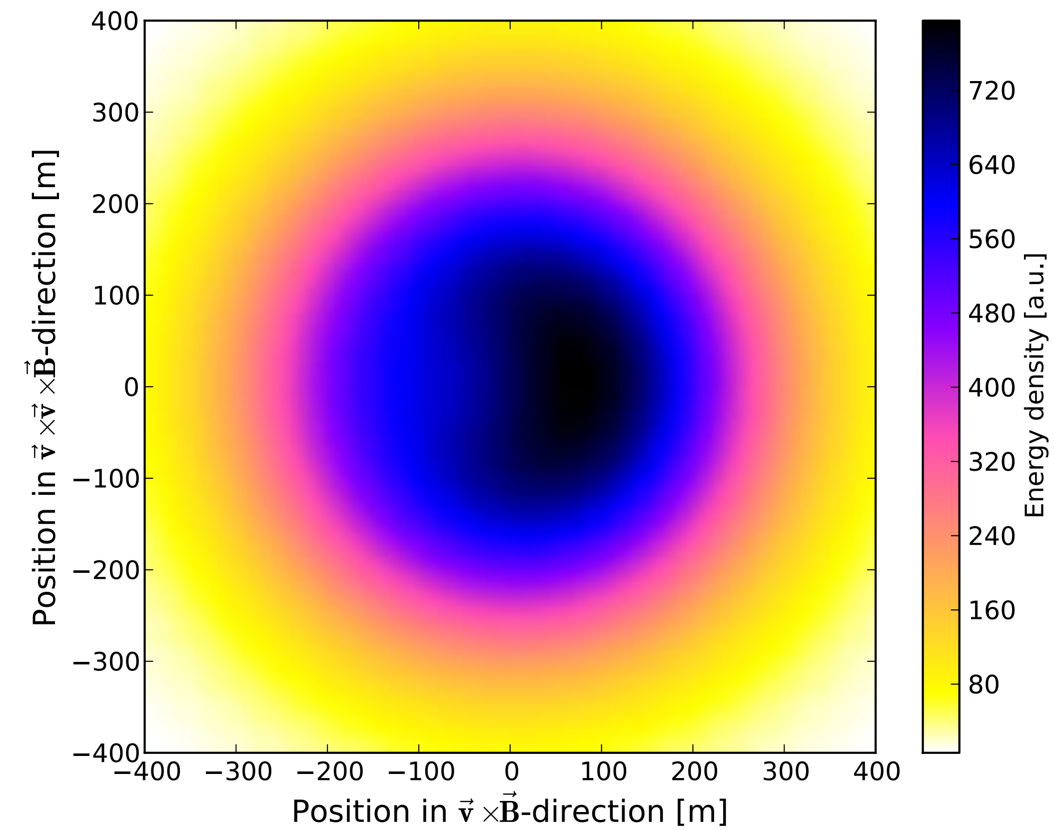
Basic distribution: two-dimensional Gaussian

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

Create “bean shape” by subtracting second Gaussian

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

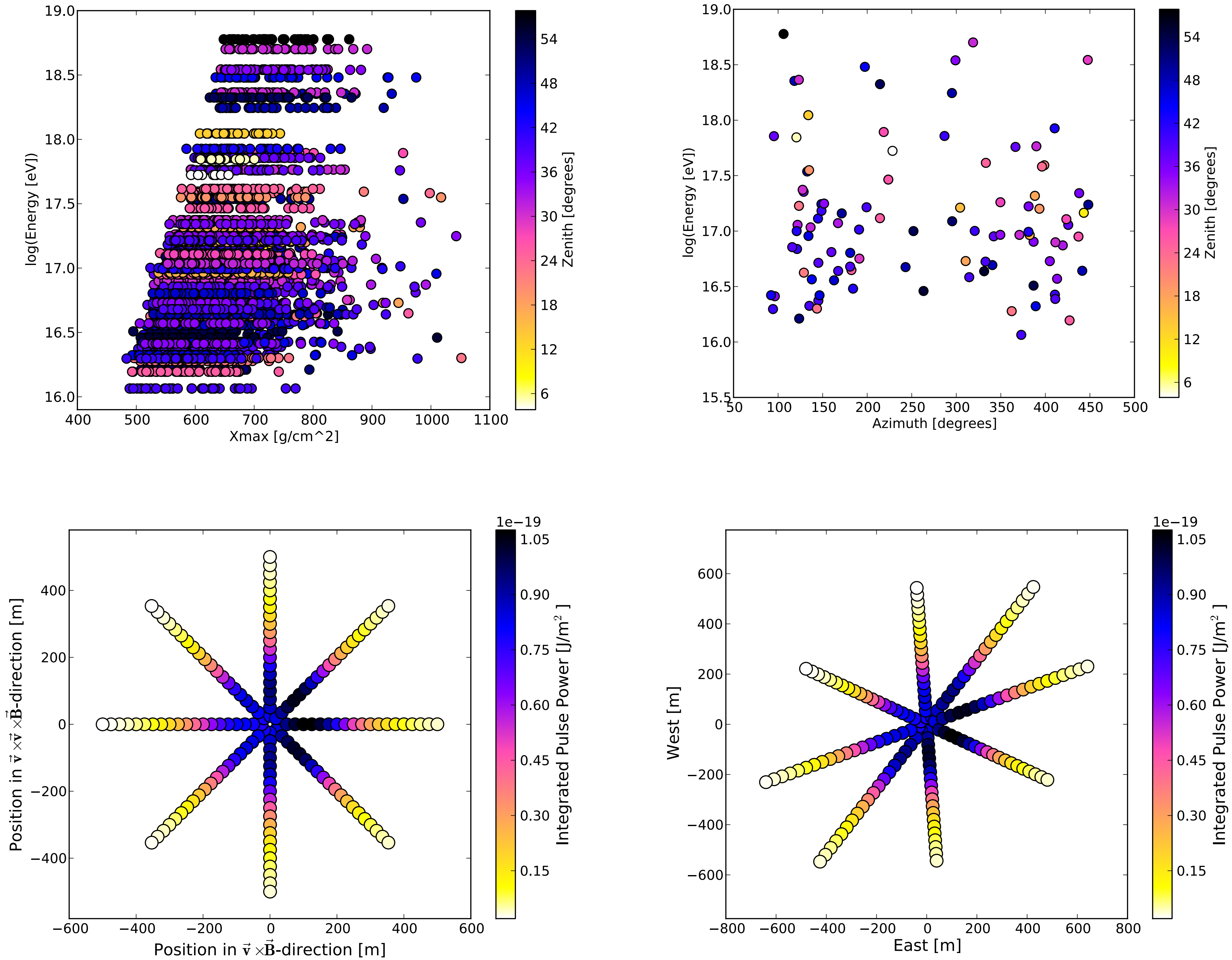




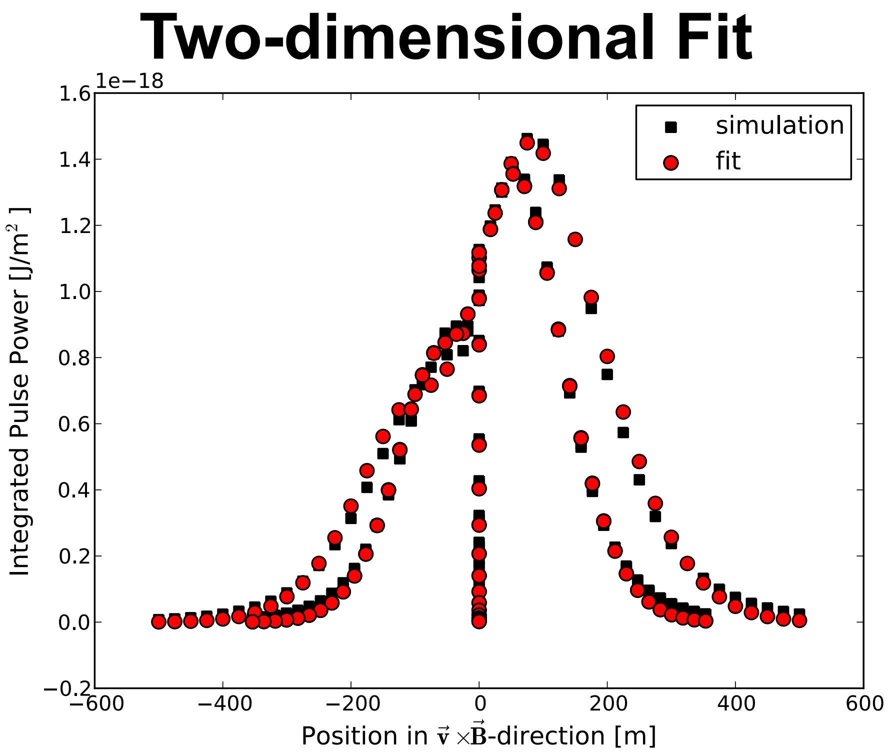
See also: A. Nelles et al., Astropart. Phys., in press

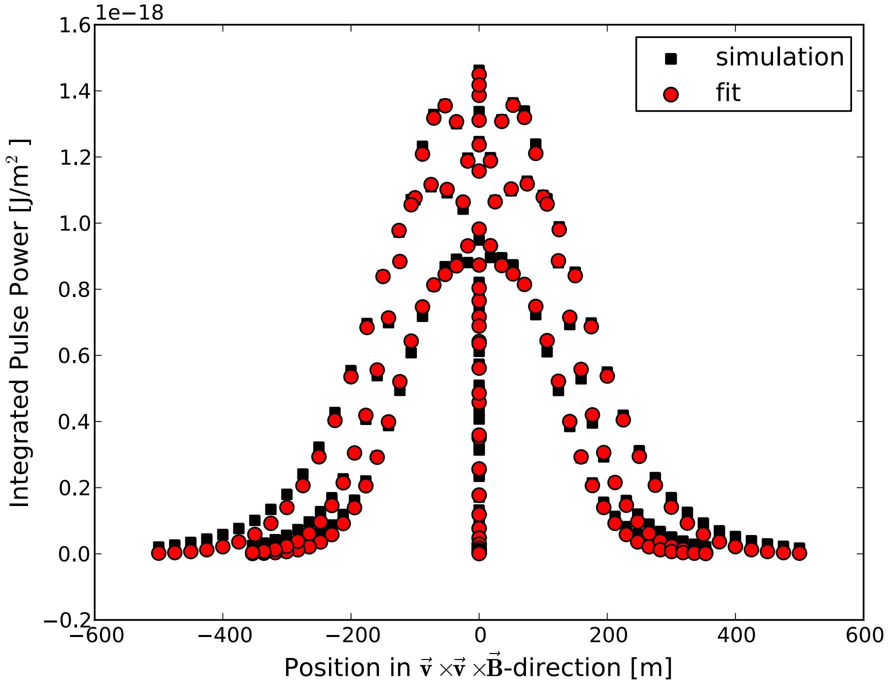
Simulation Set-up

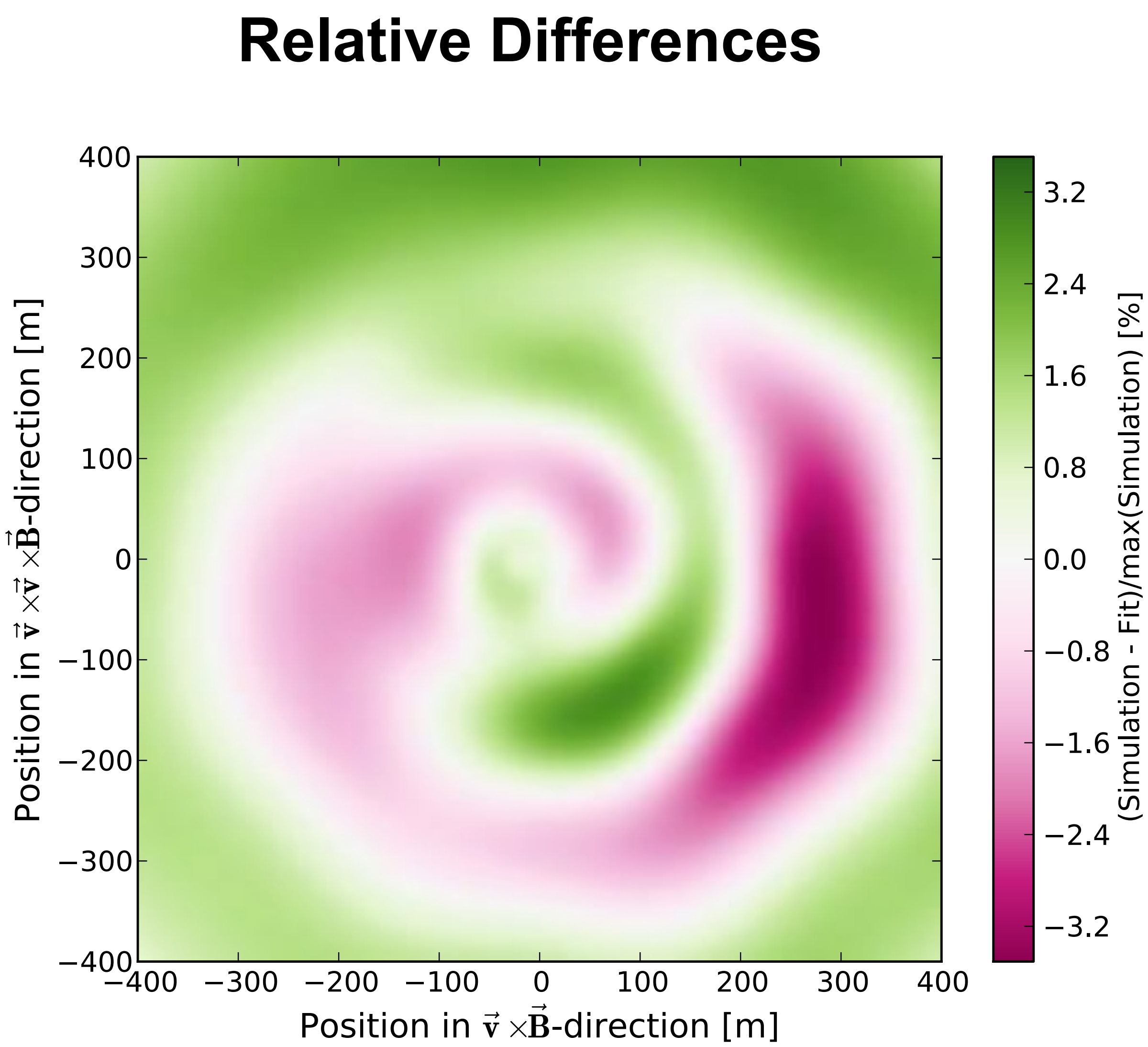
- about 1250 proton and 750 iron air showers
- CORSIKA 7.400 FLUKA 2011.2b QGSJETII.04 95 CoREAS
- LOFAR specific height and magnetic field
- Antennas on star-shaped pattern in shower plane, allows good interpolation of signals
- Mis-aligned star-pattern show same results



Fitting the model



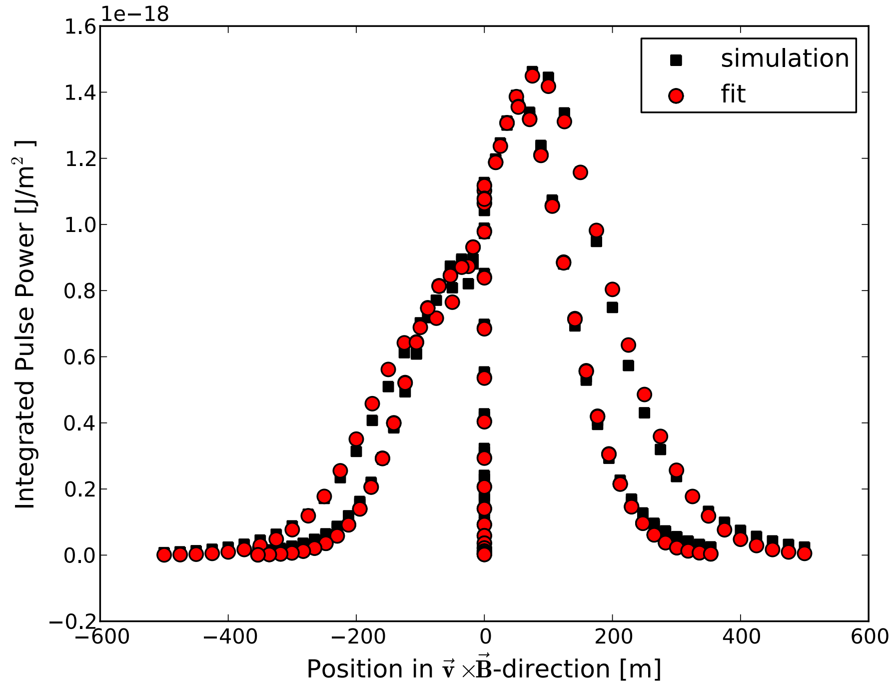


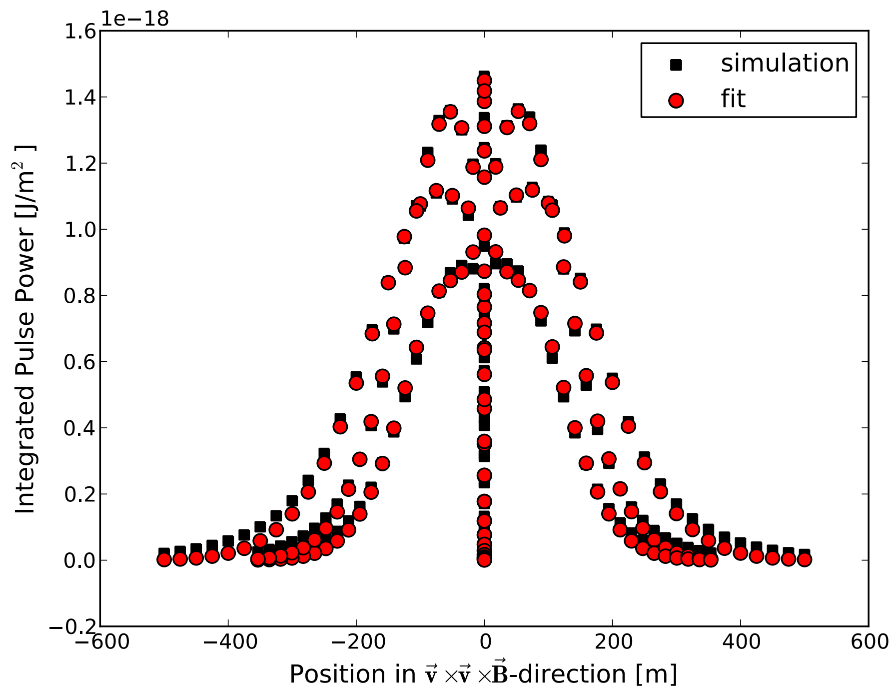


- Deviations less than 10% for most events

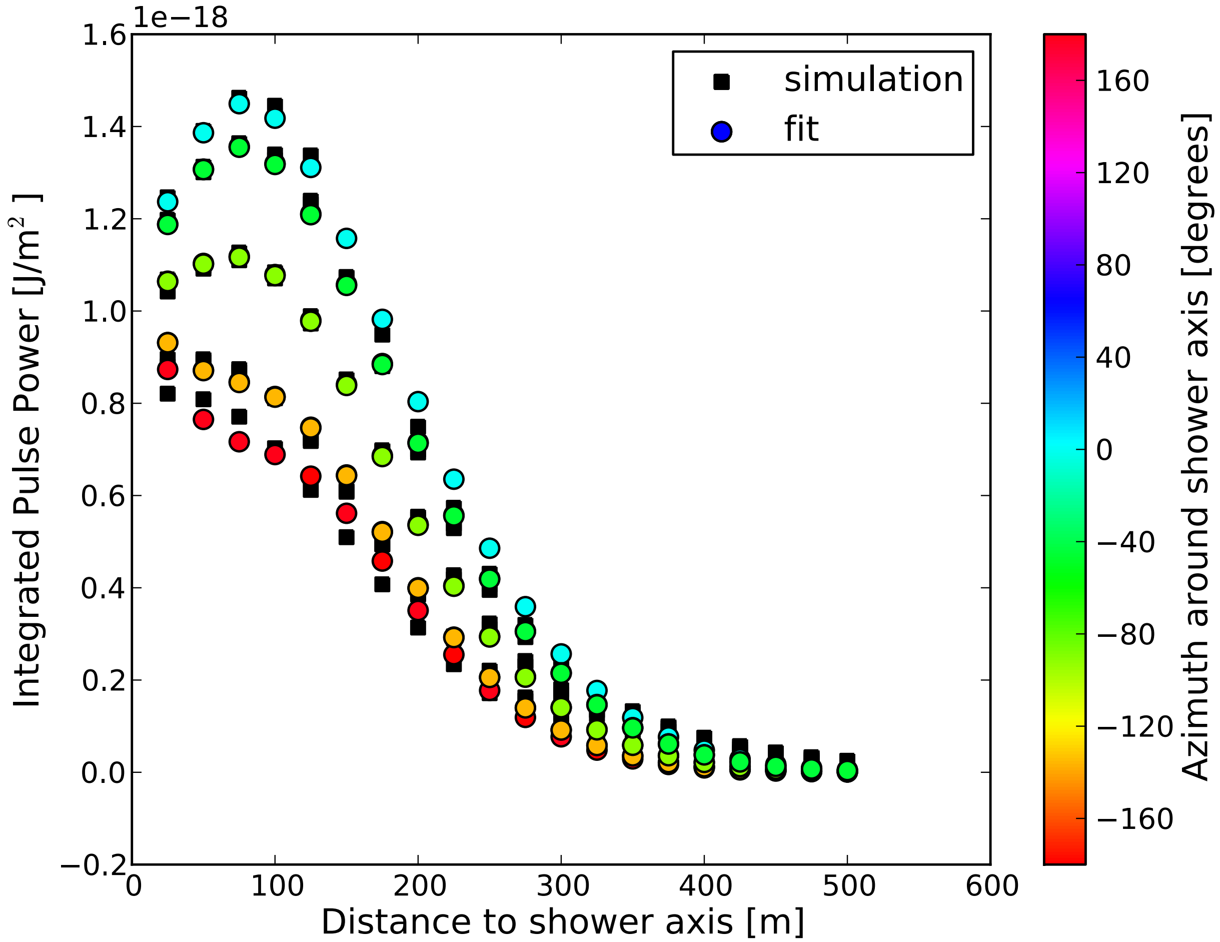
Fitting the model

Two-dimensional Fit



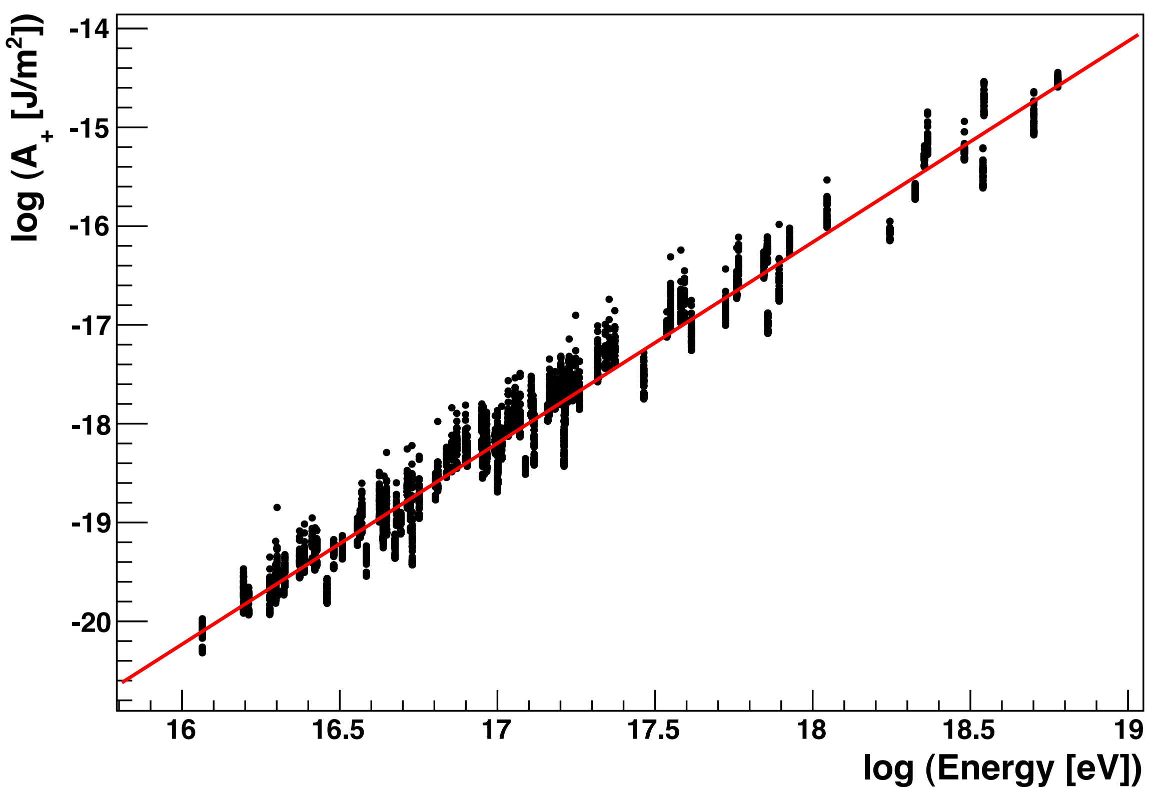


"Classical LDF view"



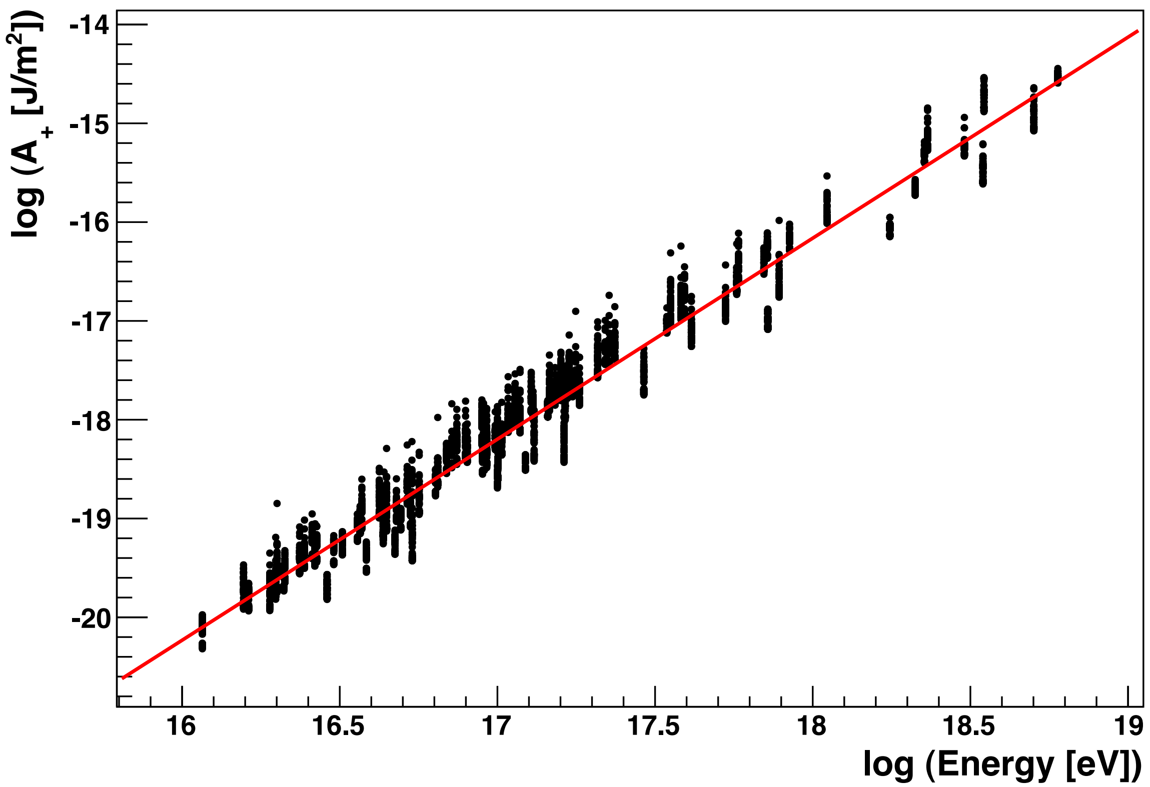
- Fit captures all features of the shape
- Azimuthal asymmetry
- 1-d LDF cannot work without correction

Study of air shower characteristics



- Scaling parameter A_+ is a function of the energy
- Slope in log-log depiction ~ 2.0, i.e. power depends quadratic on energy
- Remaining scatter is a function of angle with magnetic field, sin(alpha) and distance to the shower maximum

Study of air shower characteristics

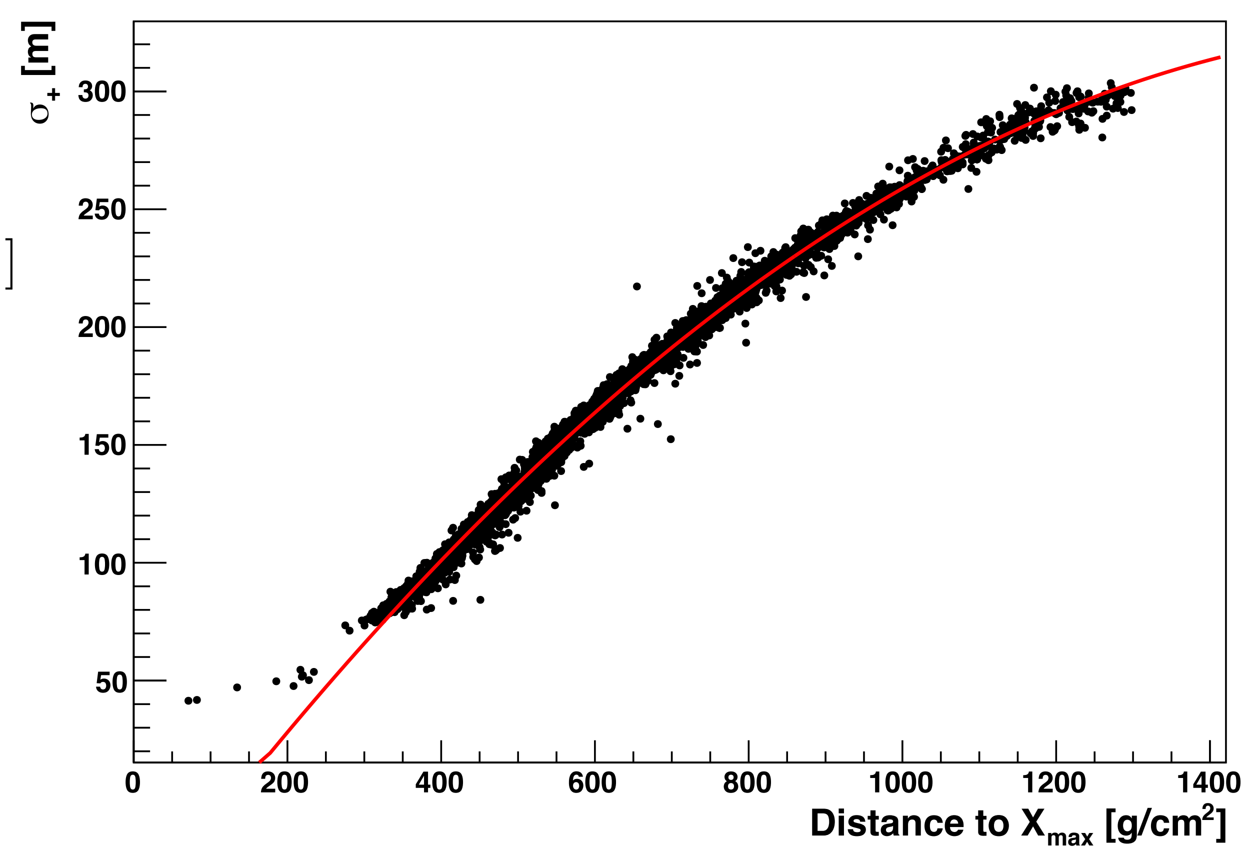


- Scaling parameter A_+ is a function of the energy
- Slope in log-log depiction ~ 2.0, i.e. power depends quadratic on energy
- Remaining scatter is a function of angle with magnetic field, sin(alpha) and distance to the shower maximum

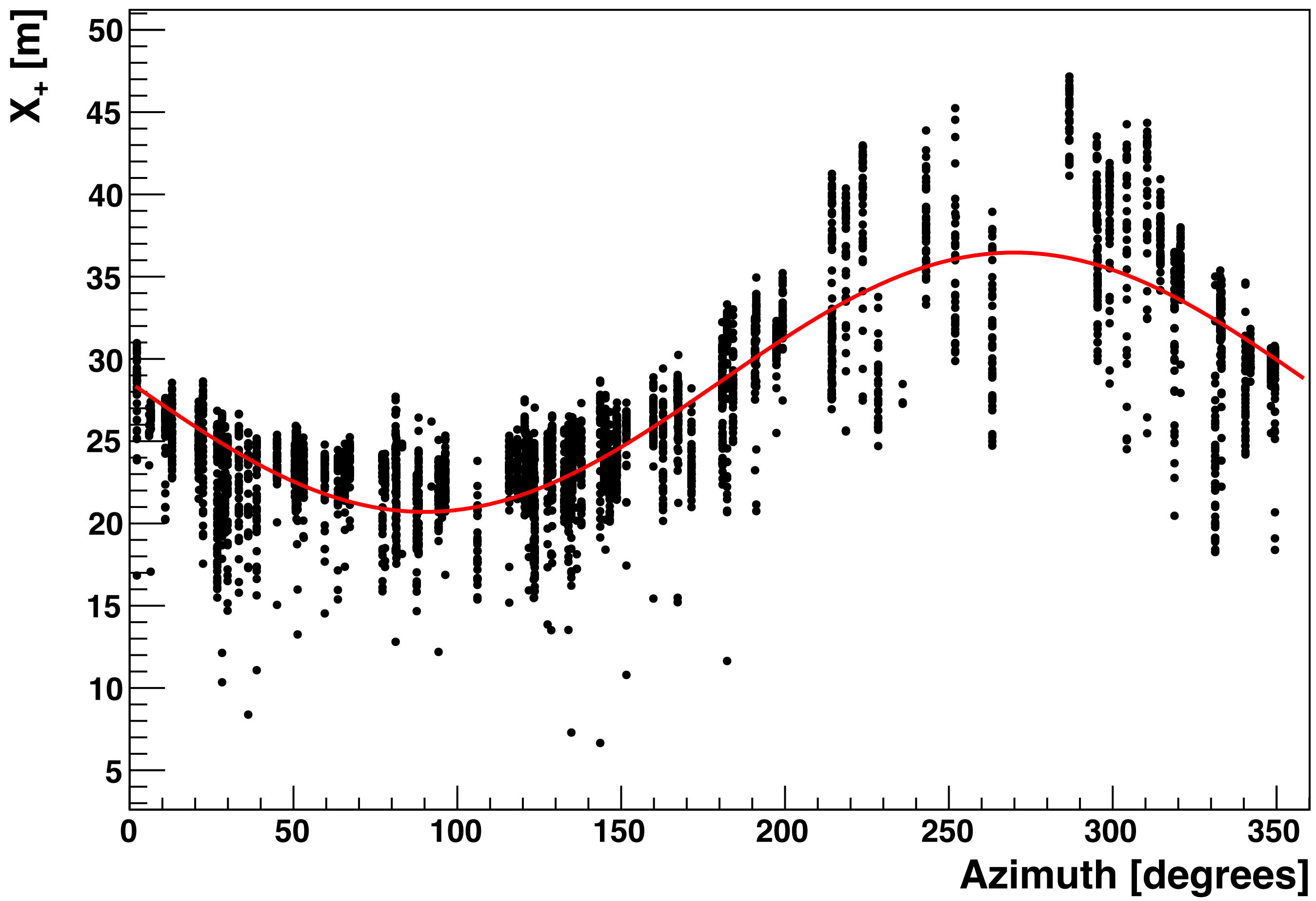
- Width parameter σ_+ is a function of the distance to the shower maximum

$$D(X_{\max})[\mathrm{g/cm^2}] = \mathrm{X_{atm}}[\mathrm{g/cm^2}]/\cos(\theta) - X_{\max}[\mathrm{g/cm^2}]$$

- Sigma- scales similarly
- Remaining scatter is no function of primary air shower parameters

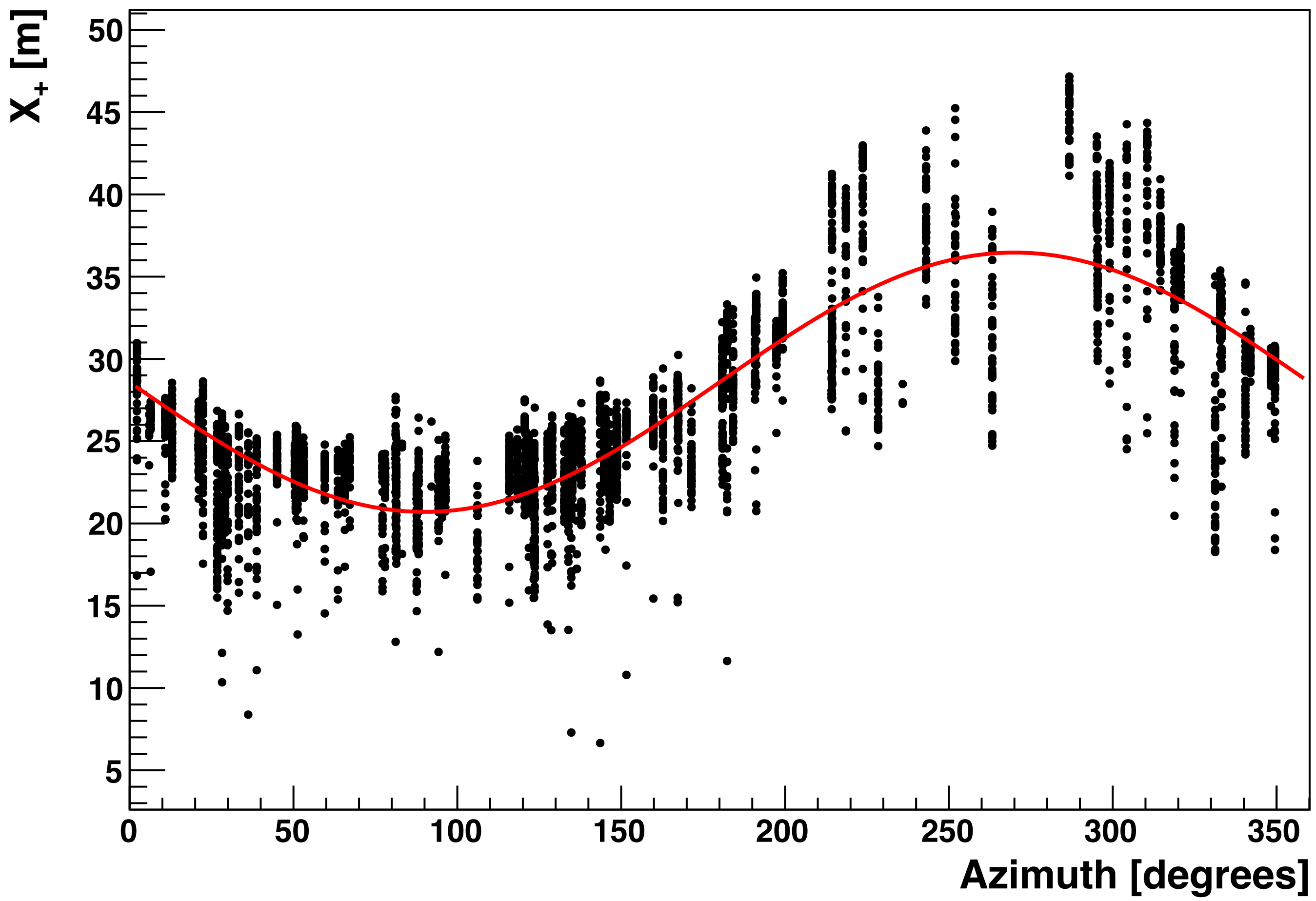


Study of air shower characteristics



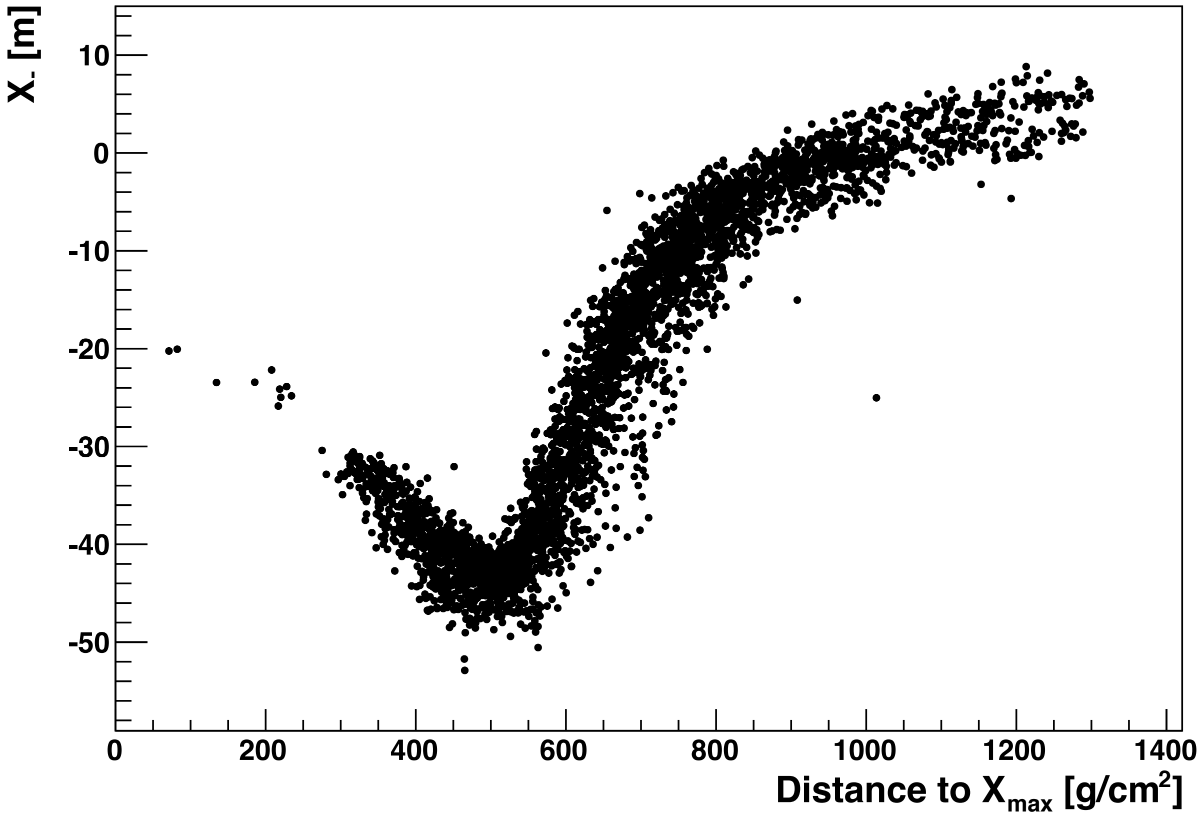
- **Shift parameter X_+** is a function of the azimuth angle of the shower
- Shift represents interplay between emission mechanisms
- Largest shift for azimuth parallel to magnetic field
- Small but not measurable **shift in Y_+** direction

Study of air shower characteristics



- **Shift parameter X₊** is a function of the azimuth angle of the shower
- Shift represents interplay between emission mechanisms
- Largest shift for azimuth parallel to magnetic field
- Small but not measurable **shift in Y₊** direction

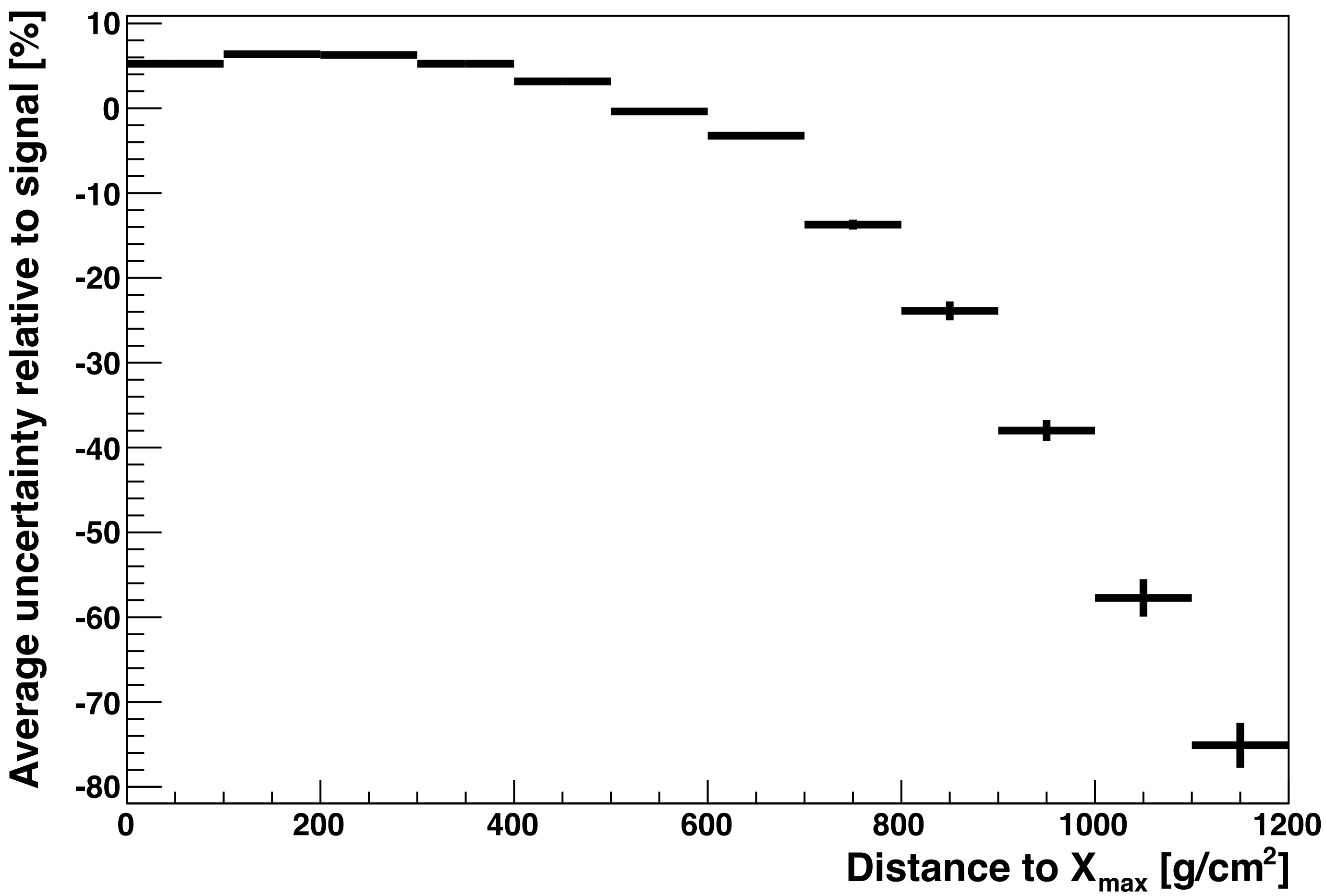
- **Offset of small Gaussian** to shower core (X_-) is function of distance to the shower maximum
- Behavior changes direction and medium distances
- Shift needed for Cherenkov and charge excess, dominance of contribution



Using function as prediction

$$P(x', y') = f_1(E) \cdot \exp\left(\frac{-f_2(\phi, X, Y, x', y')}{f_3(\theta, X_{\rm max})}\right) - C_0 \cdot f_1(E) \cdot \exp\left(\frac{-f_4(\theta, X_{\rm max}, X, Y, x', y')}{f_5(\theta, X_{\rm max})}\right)$$

- Use functions of physical air shower parameters instead of fit parameters
- Very fast and simple prediction for studies of efficiencies, detection thresholds etc.



Reduction of parametrization

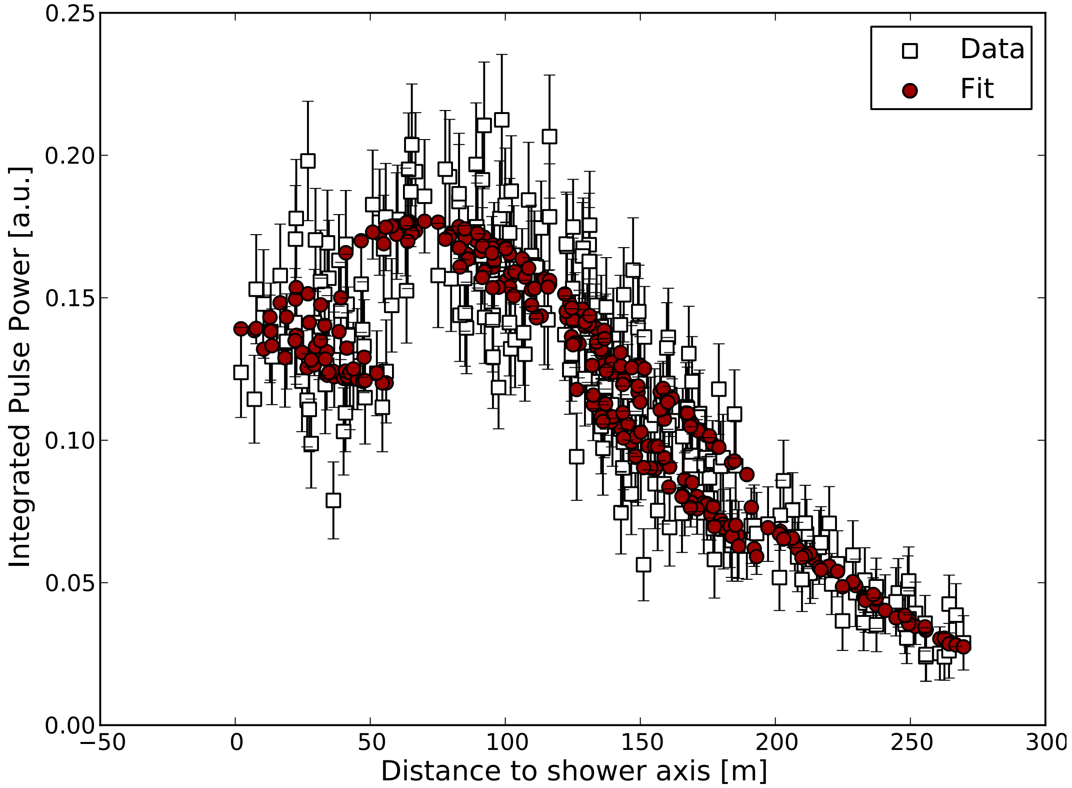
$$P(x',y') = A_+ \cdot \exp\left(\frac{-[(x'-X_c)^2+(y'-Y_c)^2]}{\sigma_+^2}\right) - C_0 \cdot A_+ \cdot \exp\left(\frac{-[(x'-(X_c-C_3))^2+(y'-Y_c)^2]}{\left(e^{C_1+C_2\cdot\sigma_+}\right)^2}\right)$$

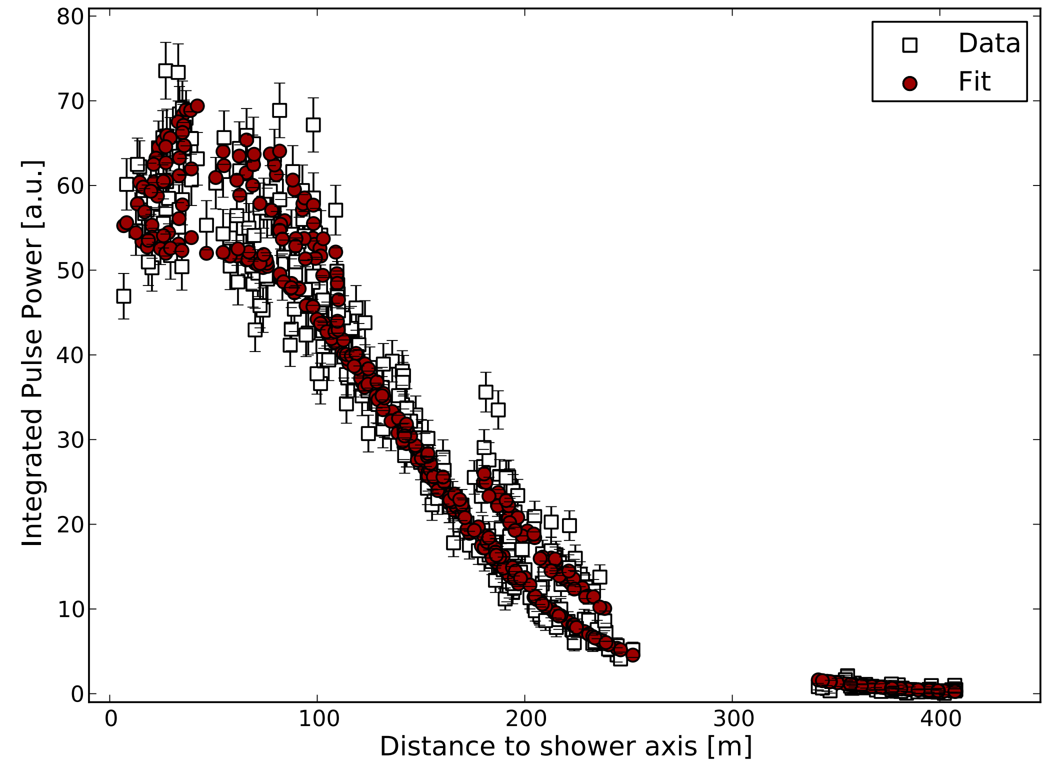
- Reduction in several ways possible, exploiting correlations between parameters

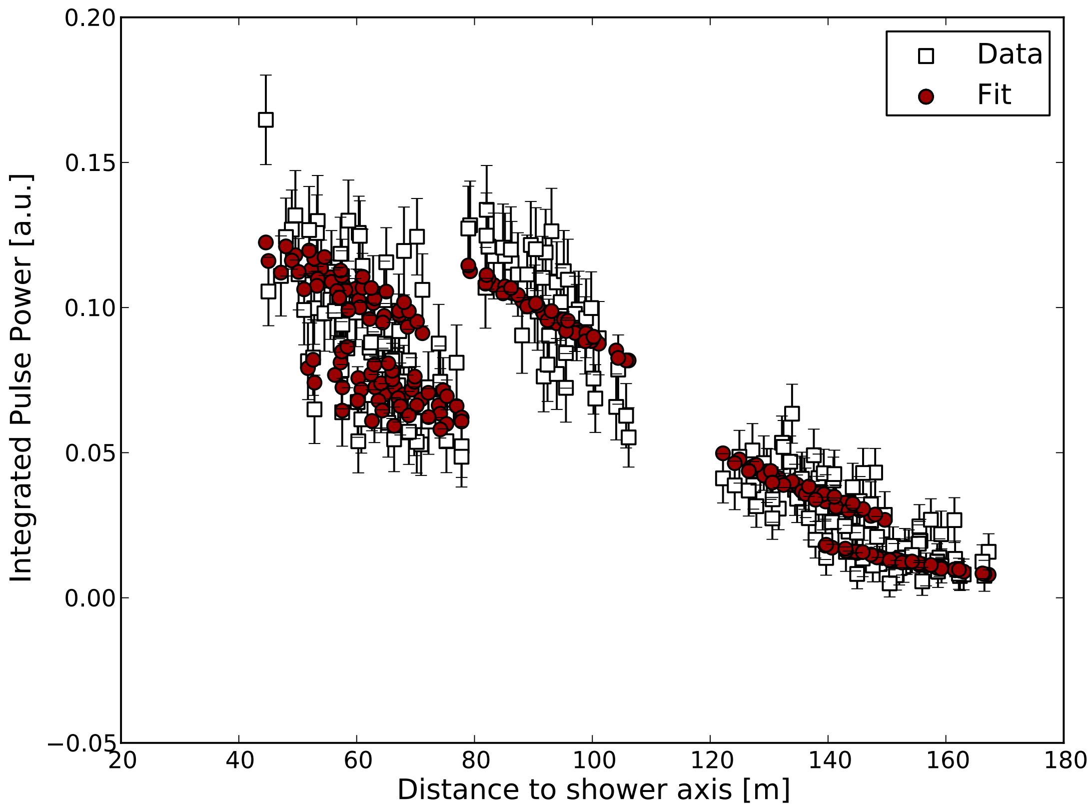
- Maximum reduction: 4 free parameters A_+, Sigma_+, X_c and Y_c
  - C_0, C_1 and C_2 constant
  - C_3 binned for zenith angle

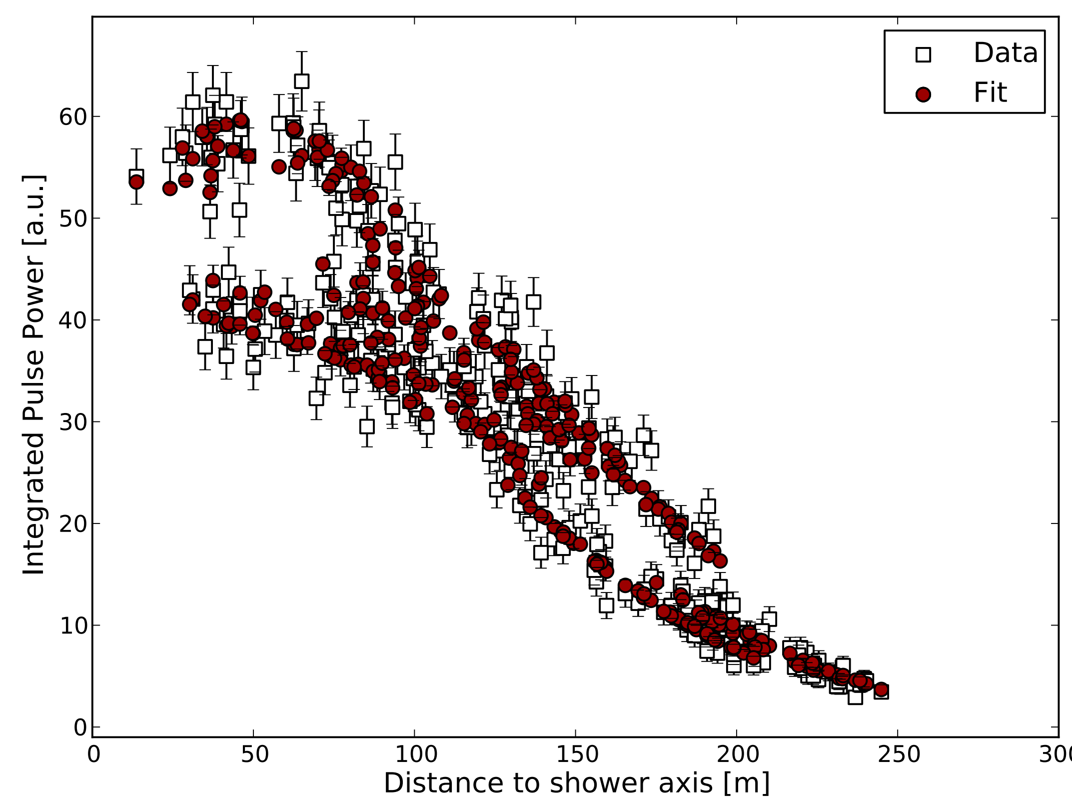
- At LOFAR:
  - C_3 free parameter as sufficient number of antennas
  - C_0 can vary in restricted range

Test on Data



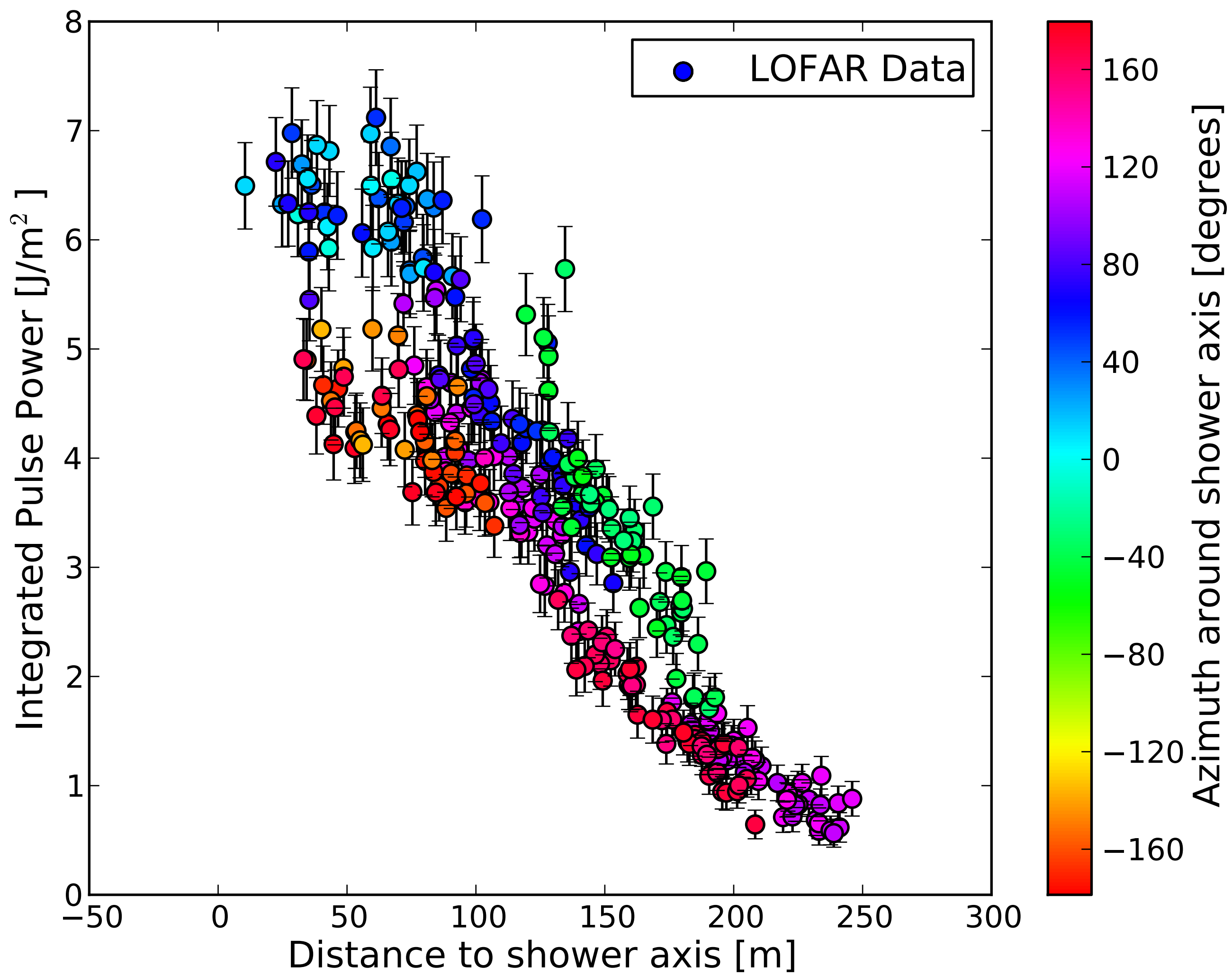


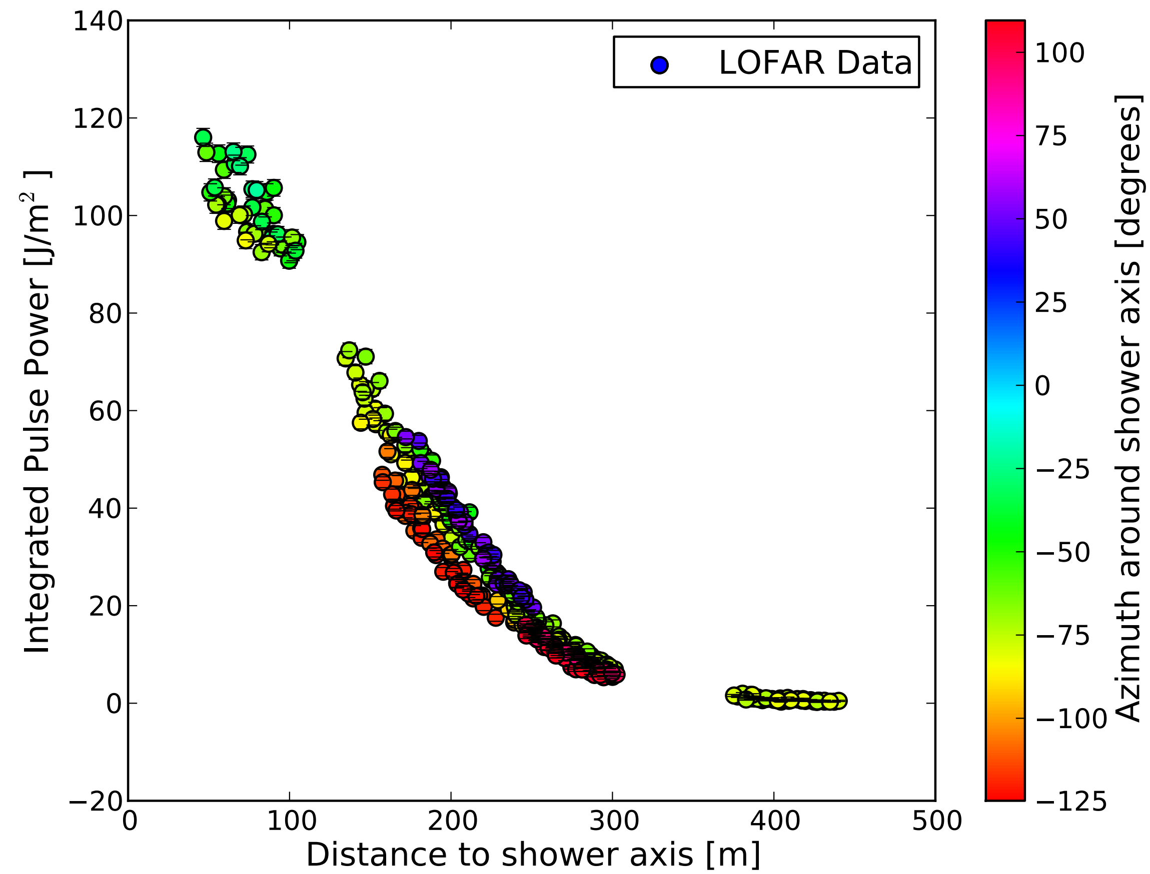


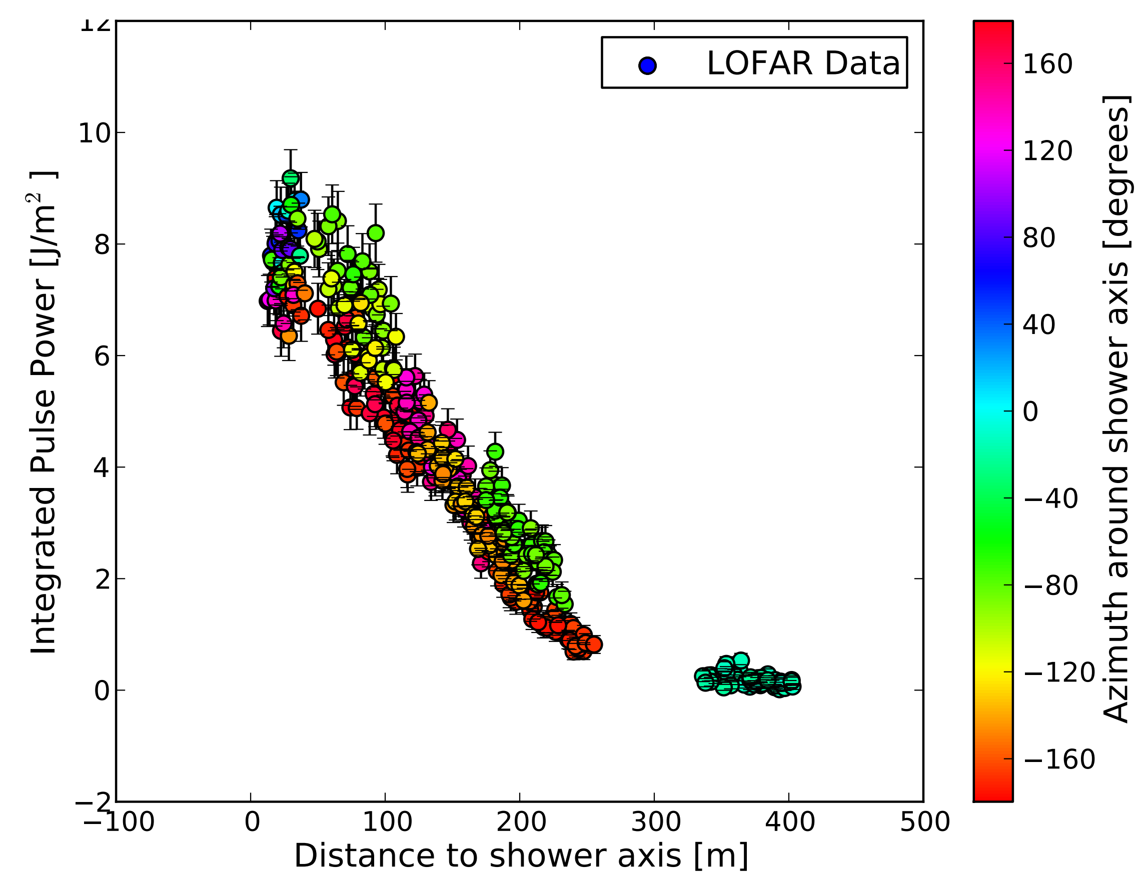


- **All data** from LOFAR can be fitted with this function
- If sufficient “structure” is measured
- Chi^2/ndof distribution centered around 1, only some exceptions ...

Azimuthal asymmetry in data

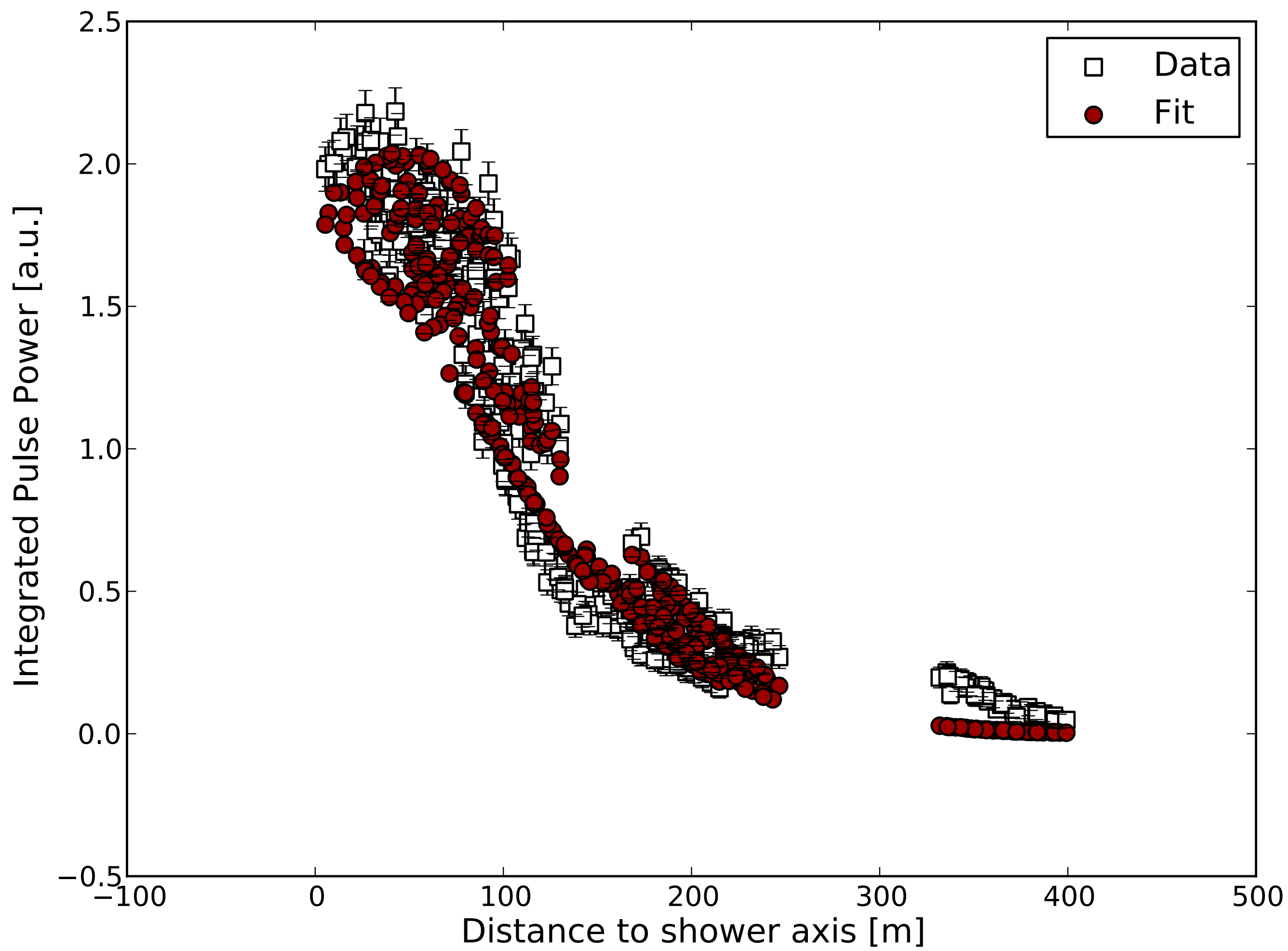


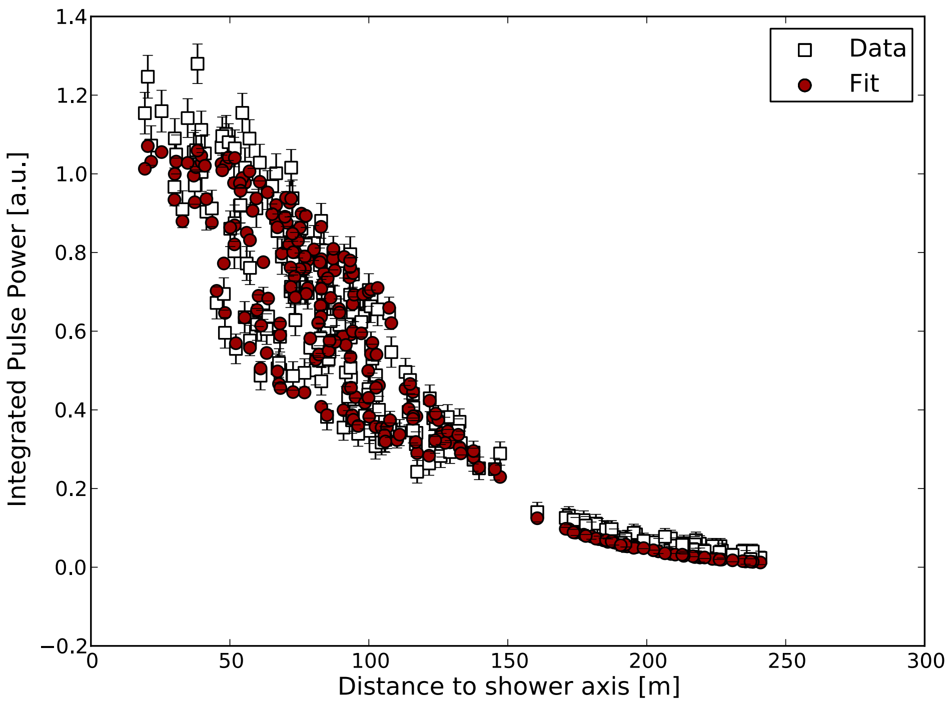




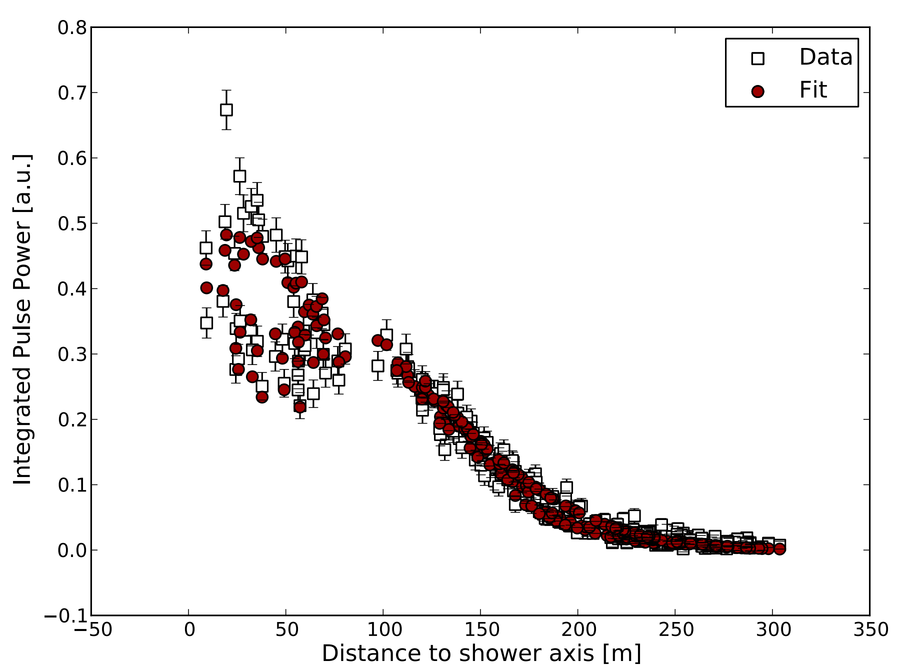
Test on Data

Thunderstorm





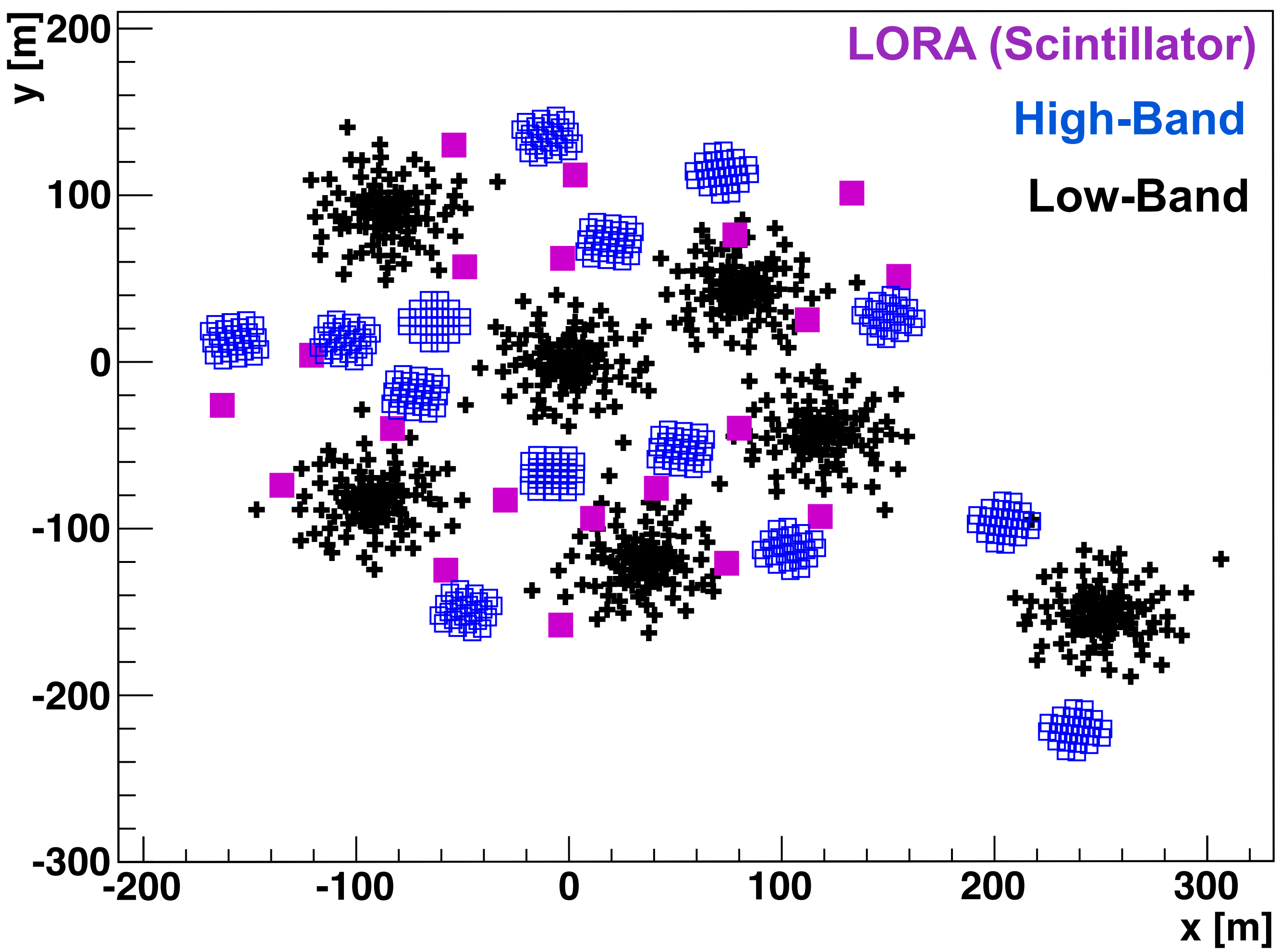
"Vertical events" < 15°



- (Most) events recorded during **strong electric field** cannot be fitted with good quality
- Vertical events show slightly less good fit

Reconstruction of shower parameters

Testing the predictions of the simulations:



- Independent measurement from **particle detectors LORA**:
- instrumented area smaller than LOFAR area
- strong cuts on reconstruction limits sample (cuts on NKG parameters and distance of core position)
- test against full sample contains mis-reconstructions
- (Partly)-Independent reconstruction from **Full Monte Carlo method** (see Talk Stijn Buitink)
- Both methods based on CoREAS
- Both methods use radio only
- Only 50 air showers

Conclusions

- We presented a “Double Gaussian” function with minimal 4 free parameters
- Scaling parameter directly sensitive to energy of air shower
- Width parameter directly sensitive to distance to the shower maximum
- All LOFAR data can be fitted with suggested function
- Correlations of parameters experimentally confirmed
- Next up: cross-check with experiment that has different way of measuring X_{max} as for example AERA at Pierre Auger Observatory