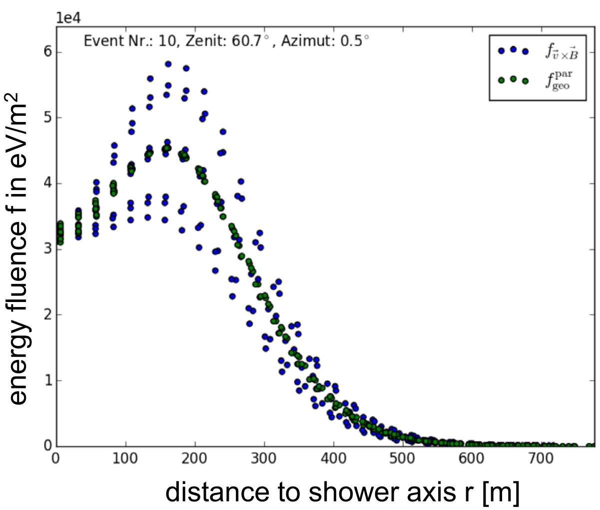
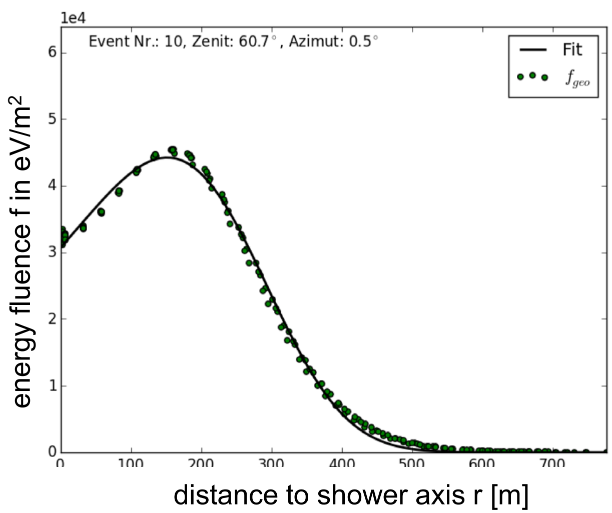
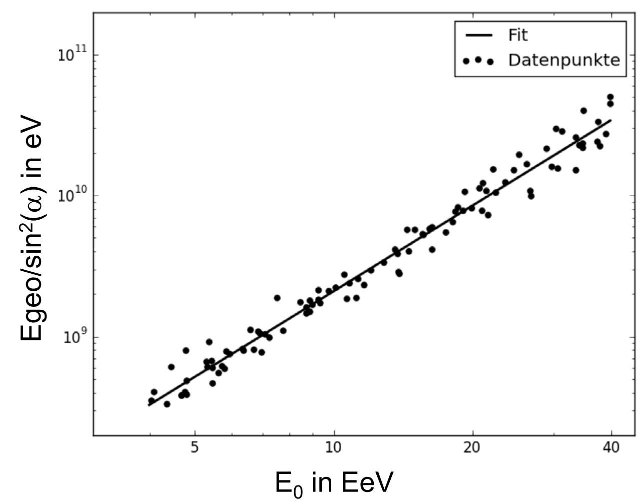
A rotationally symmetric radio LDF for horizontal air showers

T. Huege, L.Brenk





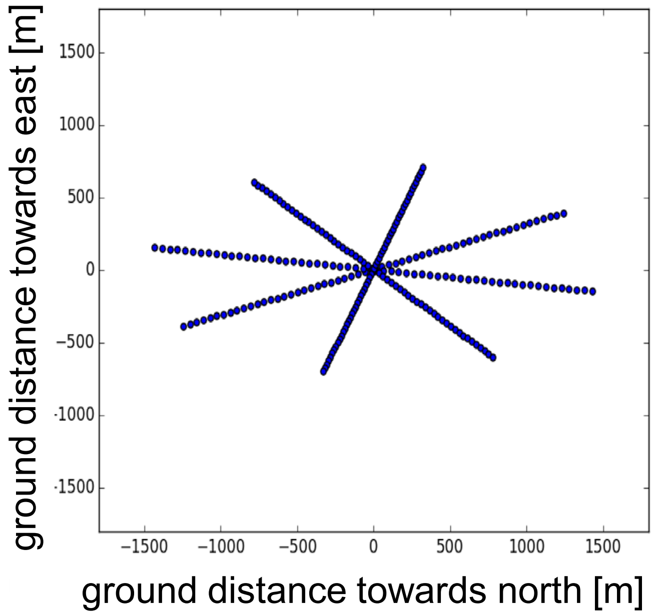


Executive summary

- the radio signal distribution is asymmetric in the shower plane (interference of geomagnetic and charge-excess emission)
- additional asymmetries due to early-late effects complicate the problem for inclined air showers with zenith angles >60°, so far no solution
- here, we correct for all asymmetries and fit the signal distribution with a rotationally symmetric lateral distribution function

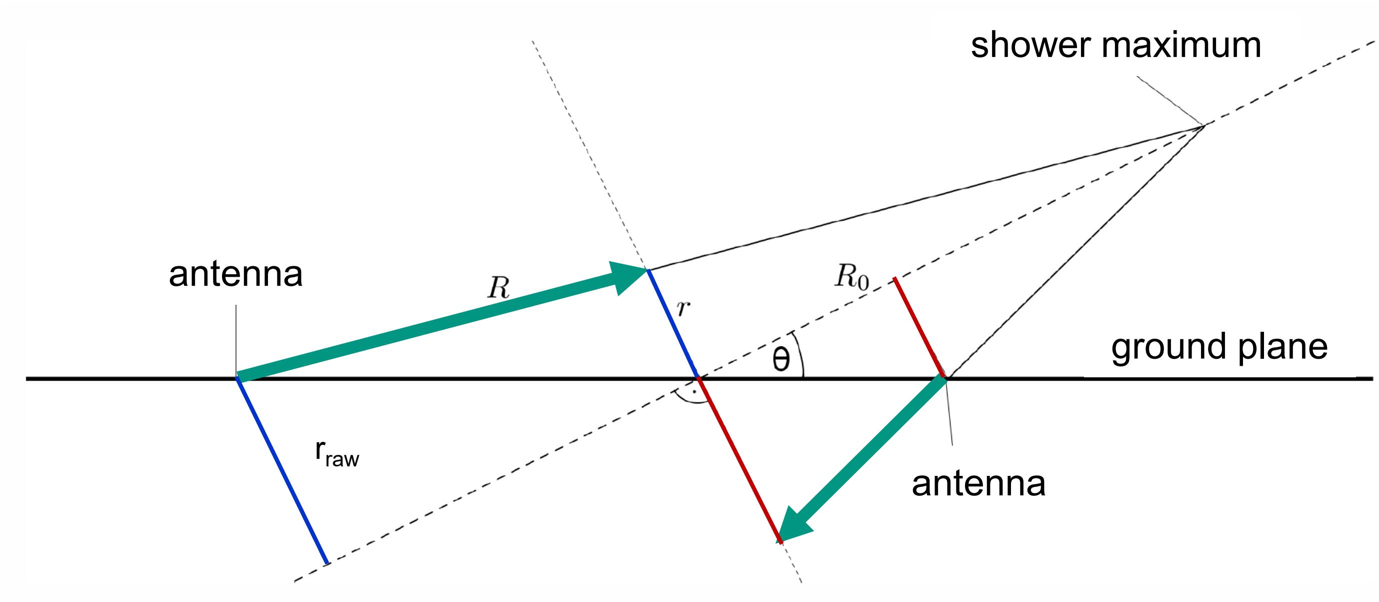
Simulation basis of the model

- 100 proton simulations with CoREAS, providing energy fluences f [eV/m^2] of v$_x$B and v$_x$v$_x$B components (thanks Ch. Glaser!)
- antennas in the ground plane according to star-shape in shower plane
- zenith angles from 60° to 80°, azimuth angle random
- energies from 4 EeV to 40 EeV
- magnetic field, refractive index and observation level as for AERA



simulated antenna positions on the ground for one particular air shower

Tackling early-late asymmetries

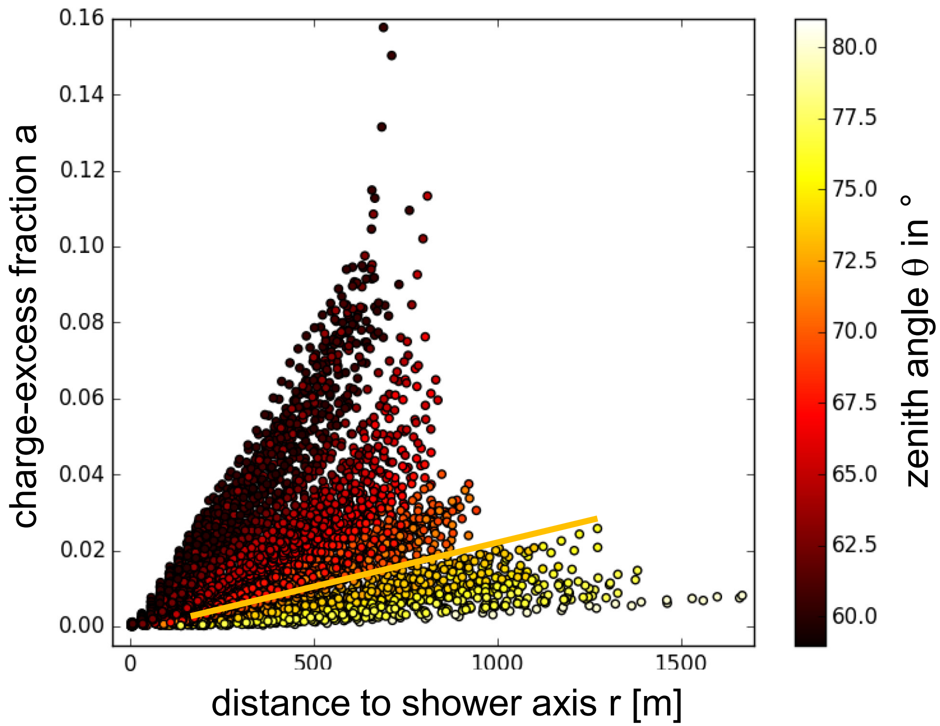


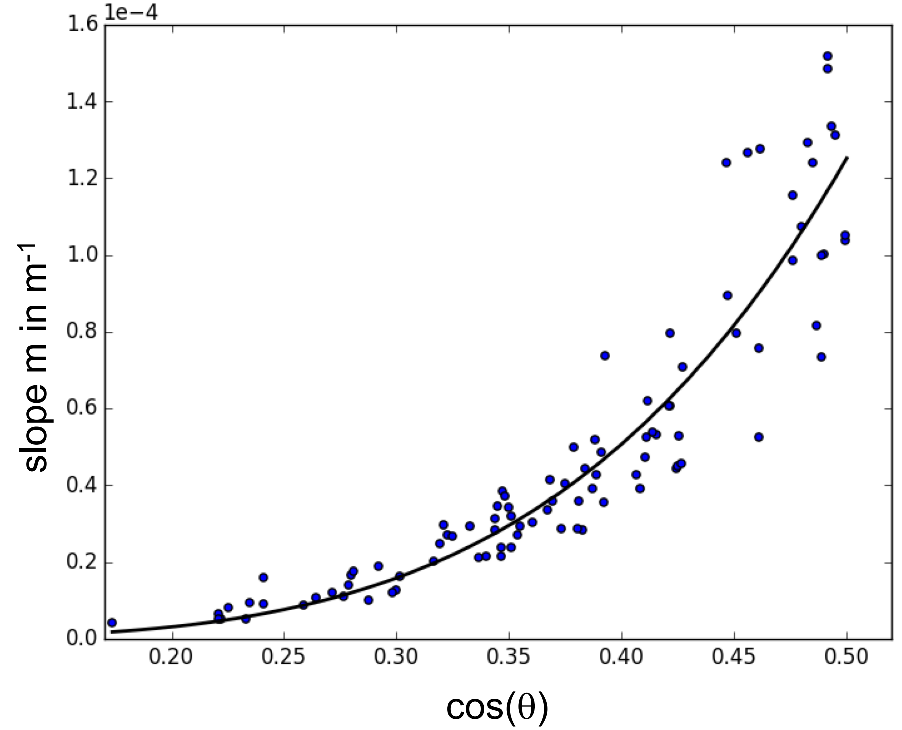
- assume radio source is a point at (known) shower maximum
- project radio antenna positions into shower plane at the core along the line between the antenna and the shower maximum
  - changes source distance and thus received energy fluence $f \sim 1/R^2$ [eV/m^2]
  - changes lateral distance of antenna for the LDF

Parametrize charge excess fraction from sims

- study $a(r) = \sin^2(\alpha) \cdot \frac{f_{ce}(r)}{f_{geo}(r)}$ as function of zenith angle

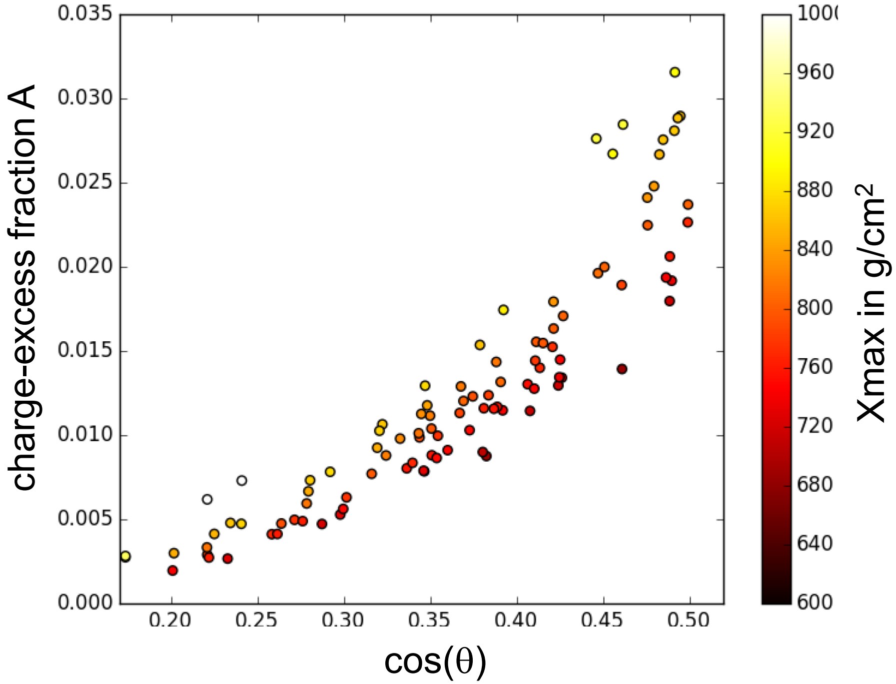
note: this is the square of what is typically used as definition for the c.e. fraction

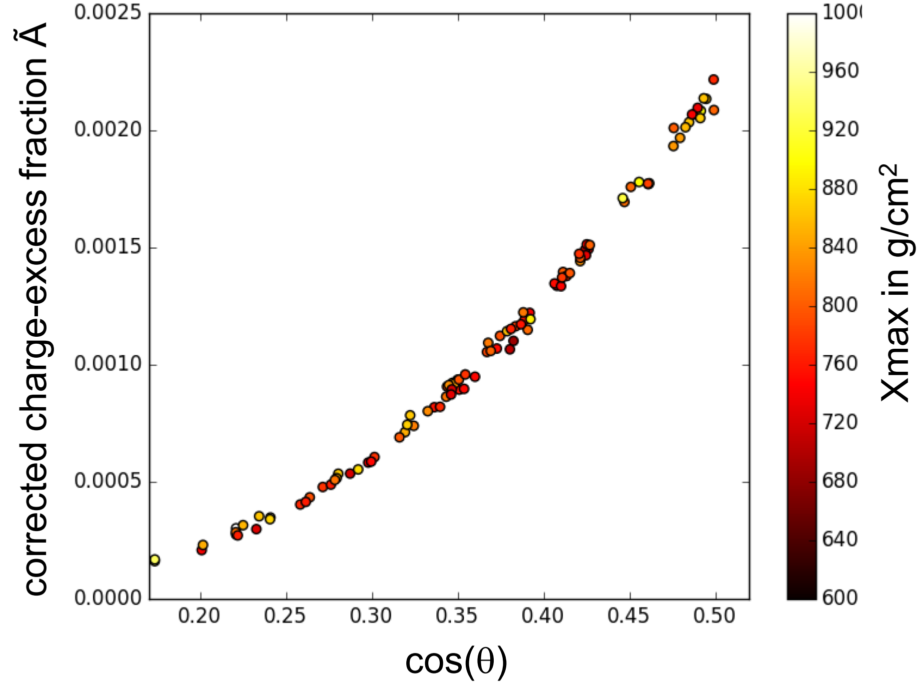




- at a given zenith angle ~linear increase of c.e. fraction with axis distance
- linear slope increases as power-law of cos(θ) – but with scatter

Scatter in c.e. is related to depth of shower max





- applying an exponential correction with Xmax, $\tilde{a} = a \cdot e^{-DX_{\max}}$, effectively removes the scatter
- from Glaser et al. (JCAP 2016, arXiv:1606.01641), correlation of *a* with the atmospheric density at Xmax is known

Full parametrizatino of charge excess fraction

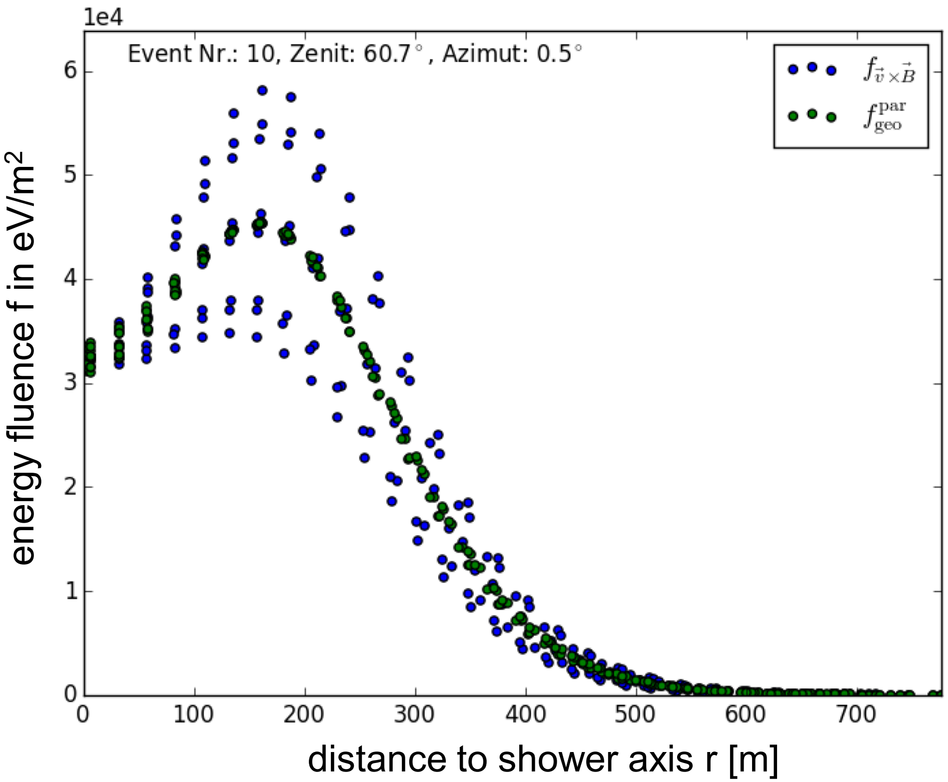
$$a(r,\theta) = A \cdot r \cdot \cos^B(\theta) \cdot e^{Cr + DX_{\max}}$$

- for the 30-80 MHz band
- valid parameters for location of AERA (altitude, magnetic field, representative Malargüe October atmosphere, refractive index)
  - A = 1.260 x 10^{-4} m^{-1}
  - B = 4.118
  - C = 8.189 x 10^{-4} m^{-1}
  - D = 3.017 x 10^{-3} cm^2/g

Symmetrization of LDF (c.e. parametrization)

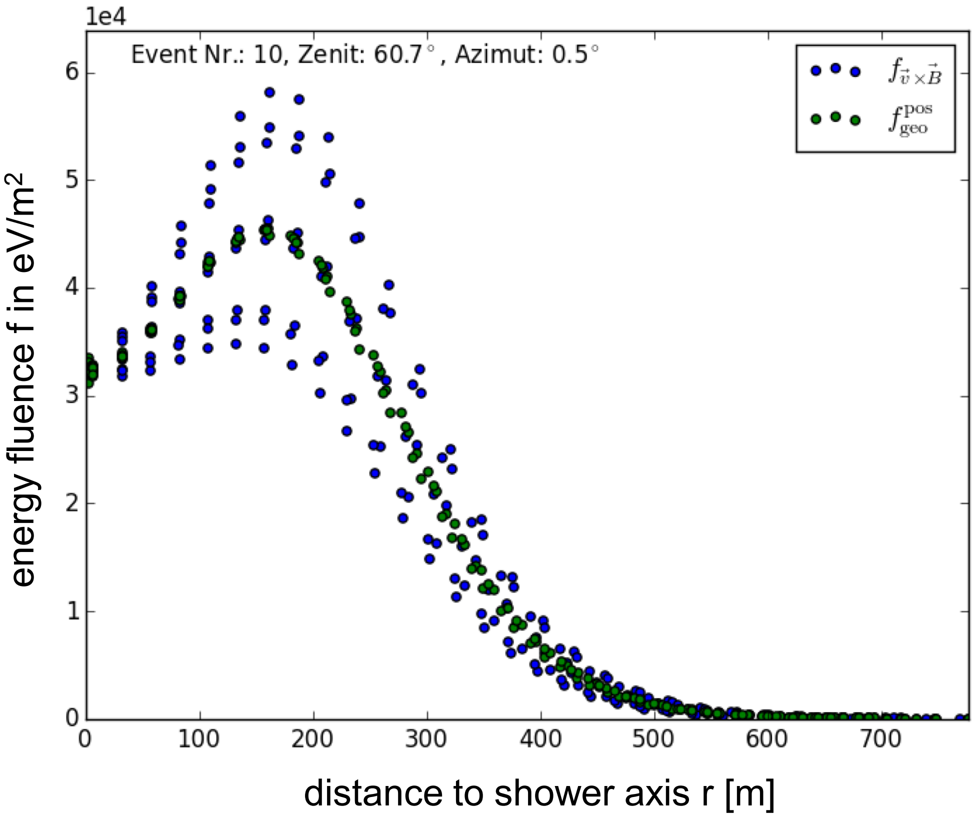
- assuming rotational symmetry of geomagnetic and charge-excess emission, and using the early-late correction, we can now subtract the charge-excess contribution received at a given antenna and determine the pure geomagnetic emission LDF, which is rotationally symmetric

- method 1: use the derived parametrization for the c.e. fraction and the measurement in the vxB component (i.e., ignore the vxvxB component)
- method of choice when signal-to-noise ratio of weaker vxvxB component is not sufficient



Symmetrization of LDF (direct measurement)

- method 2: if signal-to-noise ratio in $v \times v \times B$ component is sufficient, need not use c.e. parametrization but can determine it directly from polarization measurement and antenna position relative to core



Fit of symmetrized LDF

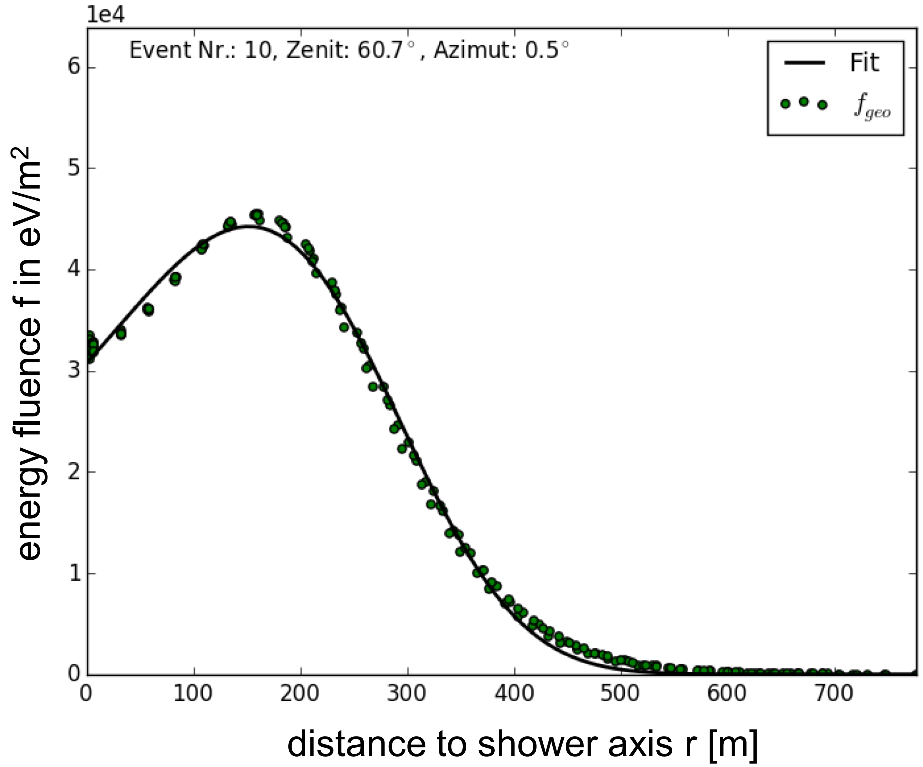
- an exponential of a 3rd-order polynomial works just fine

$$f_{\rm geo}^{\rm fit} = A_4 \cdot e^{-B_4 \cdot r - C_4 \cdot r^2 - D_4 \cdot r^3}$$

Gaussian term added by Tunka-Rex, for Cherenkov bump

simple expo-nential as used by LOPES, CODALEMA

cubic term added here to deal with behavior inside Cherenkov bump



- this is a practical function from the point of fit stability (in log-space)

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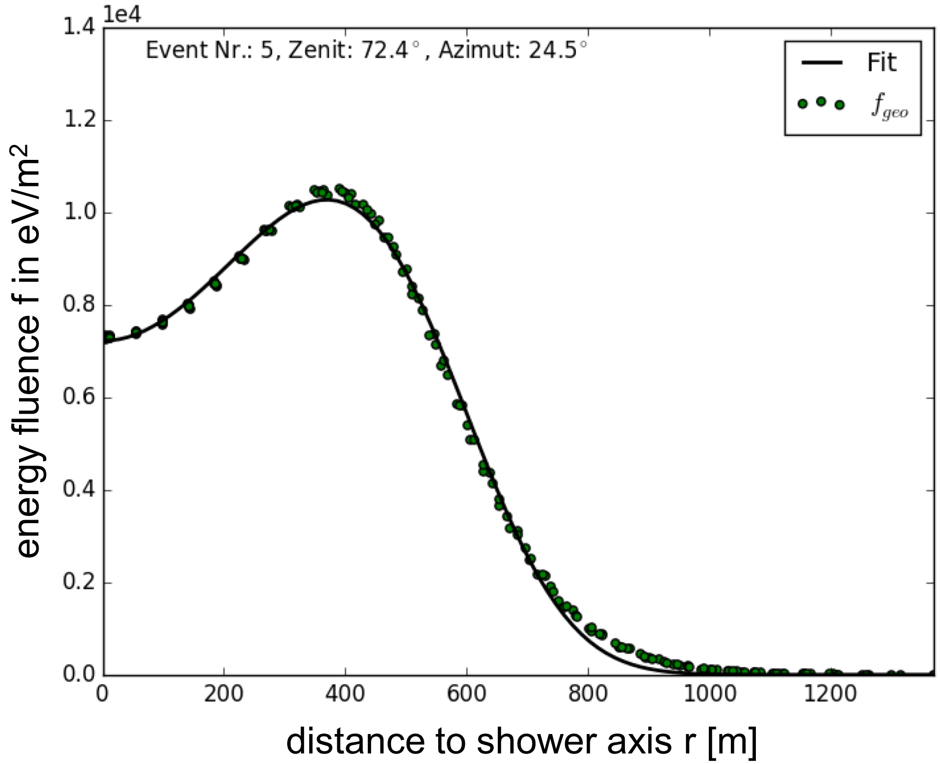

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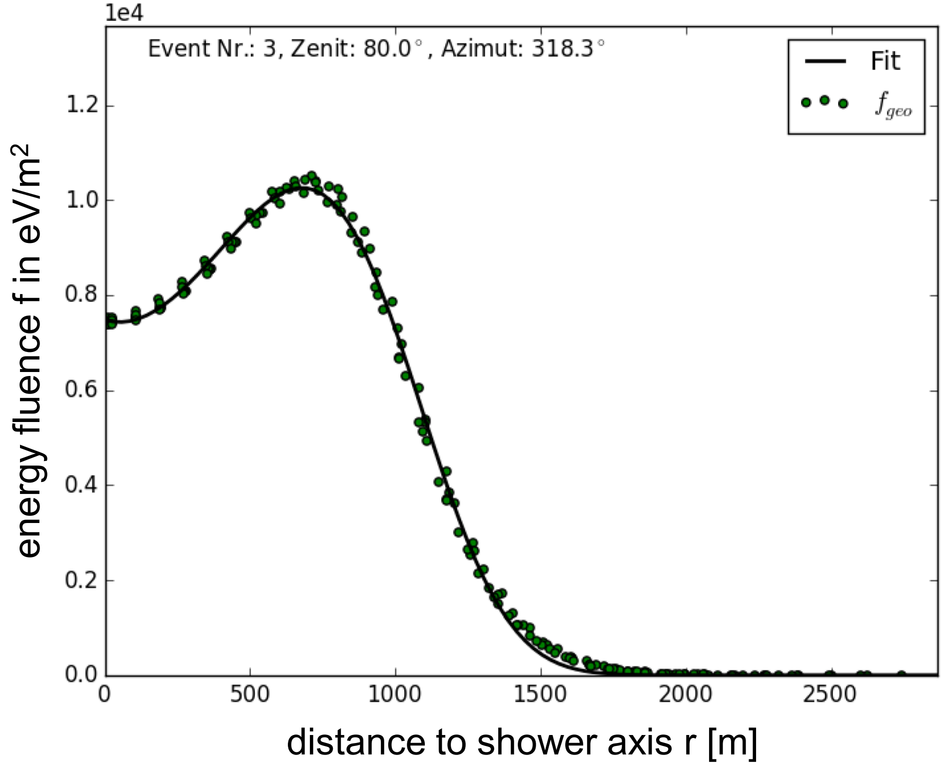

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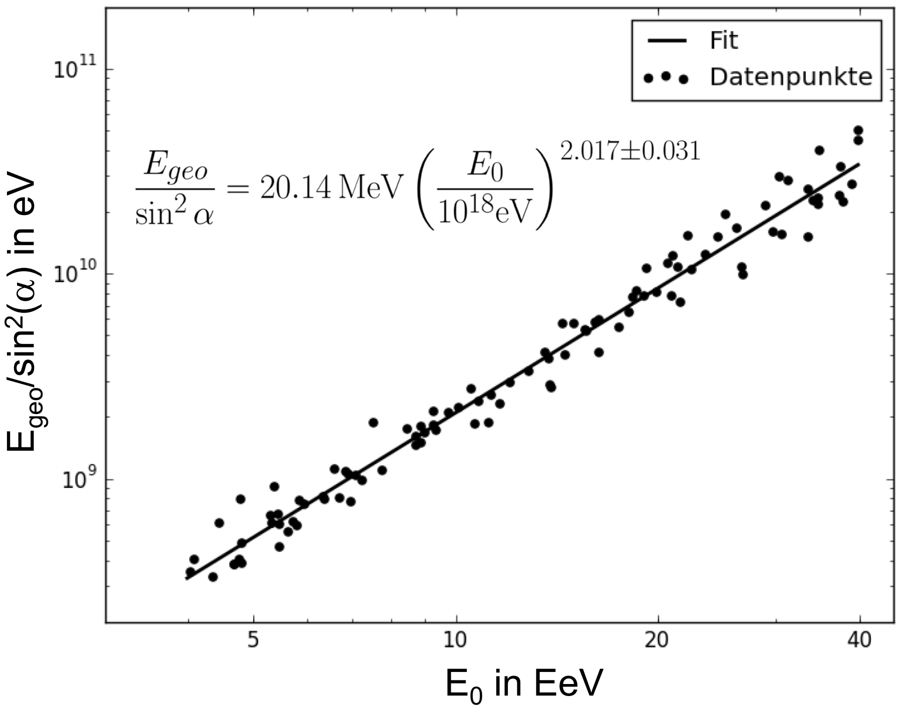
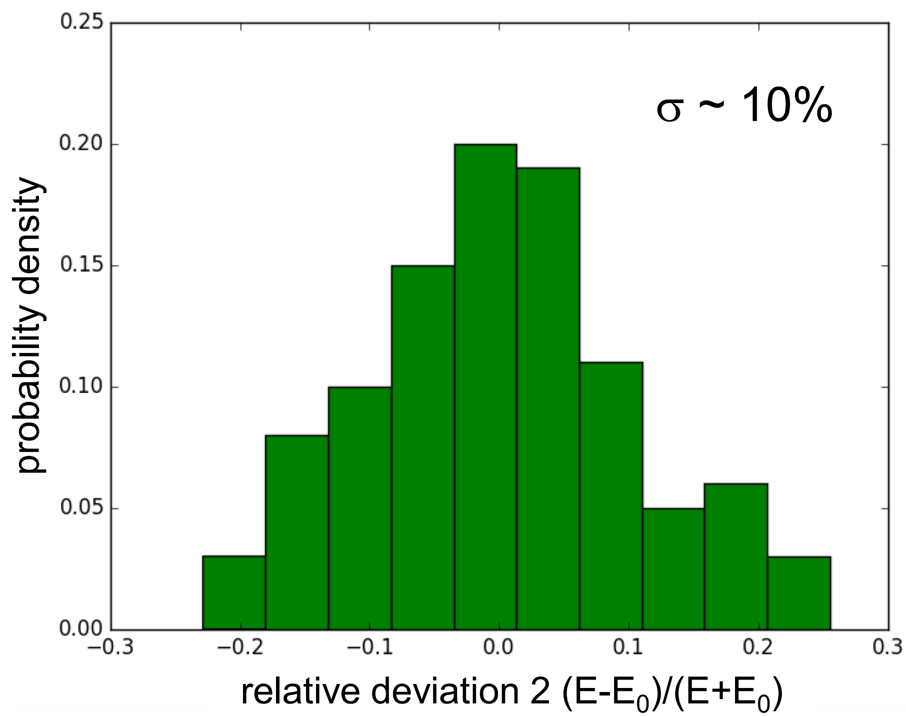
Determine radiation energy via area integral

- area integral of LDF yields radiation energy in geomagnetic component
- find expected quadratic scaling of rad. energy with cosmic ray energy
- the intrinsic scatter of the corresponding energy estimate is ~10%
  - no correction for density at Xmax yet
  - correlation with electromagnetic energy will be better





Conclusion

- we found a way to symmetrize the LDFs of inclined air showers
  - correct for early-late effects
  - assume rotational symmetry of the c.e. and geomagnetic components
  - subtract parametrized or directly measured c.e. component
- we found a practical fit function for the symmetrized LDF
  - exponential of a cubic polynomial
- the radiation energy (and thus cosmic ray energy) can be determined well from an area integral of the symmetrized LDF