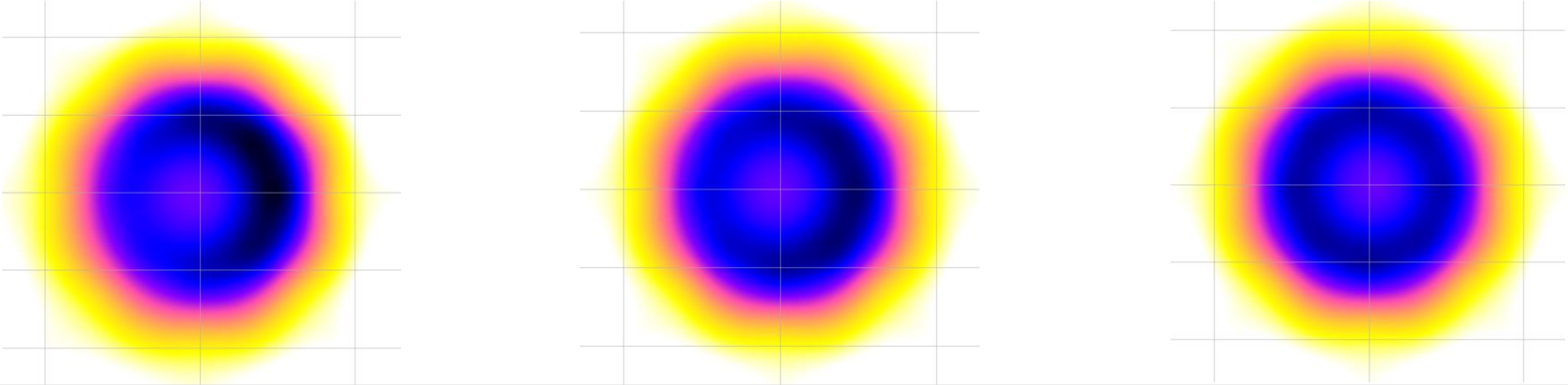
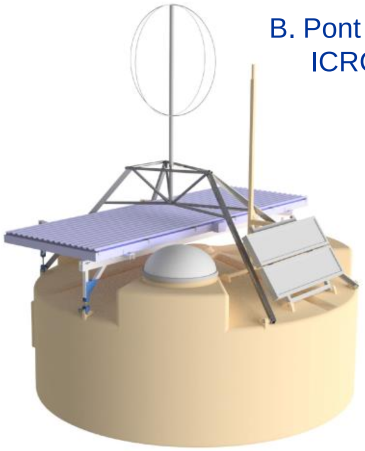
PoS(ICRC2021)209

Reconstructing inclined extensive air showers from radio measurements

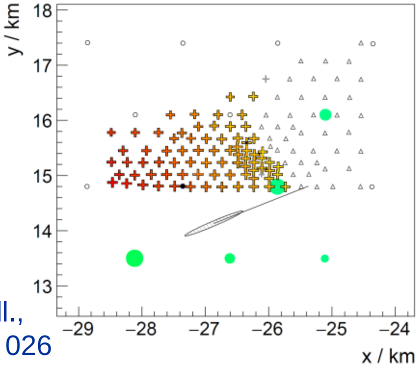
Tim Huege (KIT & VUB), Felix Schlüter (KIT & UNSAM)



Inclined showers are of high interest



B. Pont for Auger,
ICRC 2019



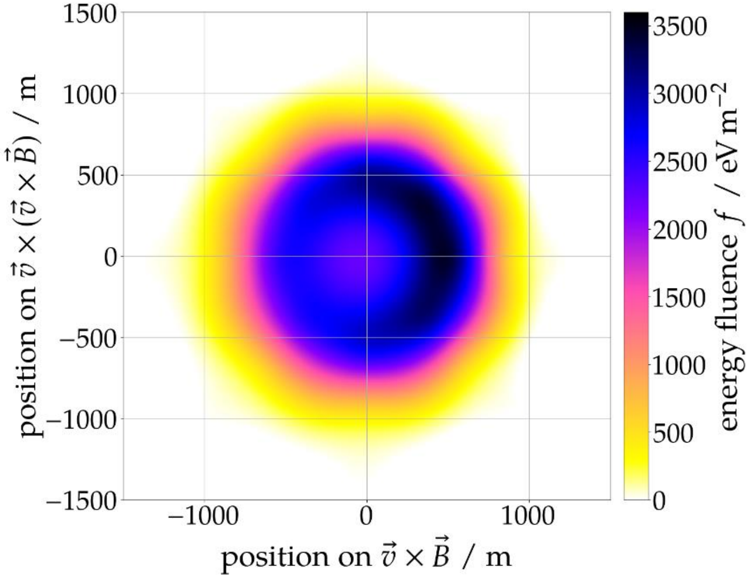
Pierre Auger Coll.,
JCAP 1810 (2018) 026

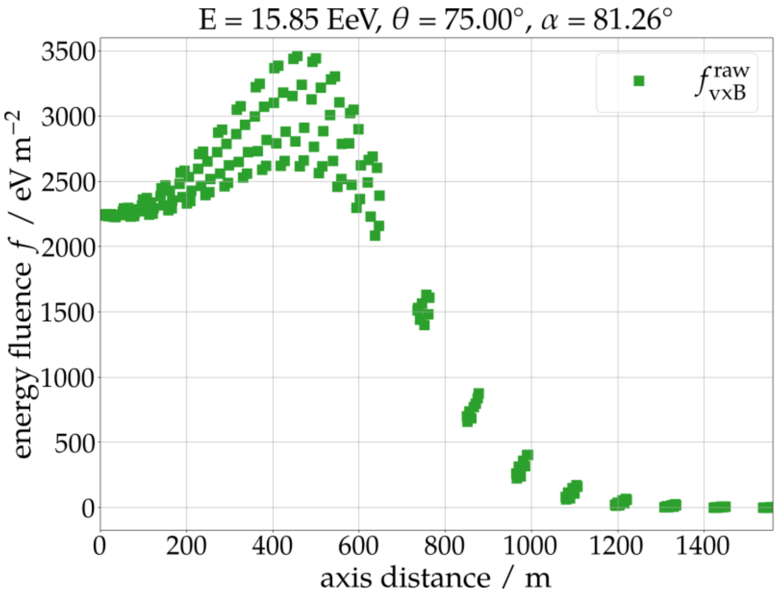
- inclined EAS have been long-predicted to possess large radio-emission footprints
- inclined EAS have been measured by AERA
- the Pierre Auger Collaboration is building the AugerPrime Radio Detector, 1660 antennas on 3,000 km^2, for showers with $\theta > 65°$
- the GRAND collaboration plans up to 200,000 antennas on 200,000 km^2
- we need reliable reconstruction algorithms

Basis of this study

- CORSIKA/CoREAS v7.7 with QGSJETII-04 and UrQMD
- simulations filtered to the 30-80 MHz band
- energies from $10^{18.4}$ to $10^{20.2}$ eV
- zenith angles from 65° to 85°, excluding showers with $\alpha < 20°$
- optimized thinning at 5e-6 (derivation) and 1e-6 (performance check)
- atmospheres and magnetic field as at Pierre Auger Observatory

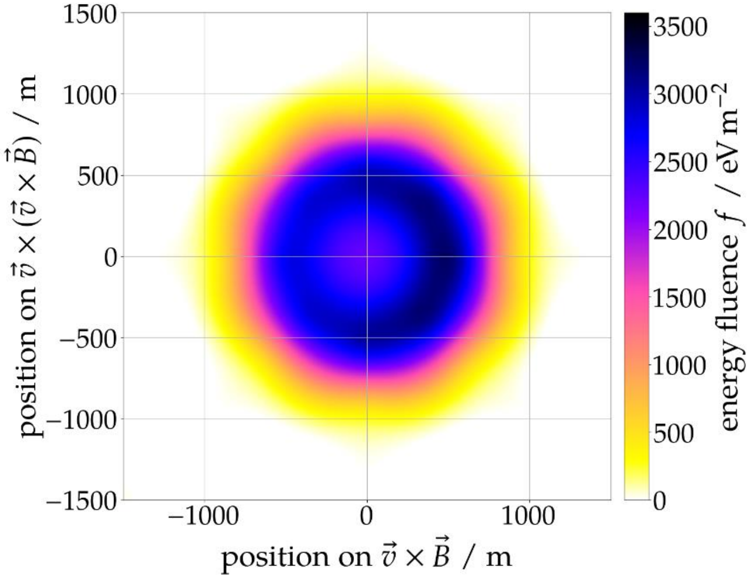
1: Convert to shower axis & apply core fit

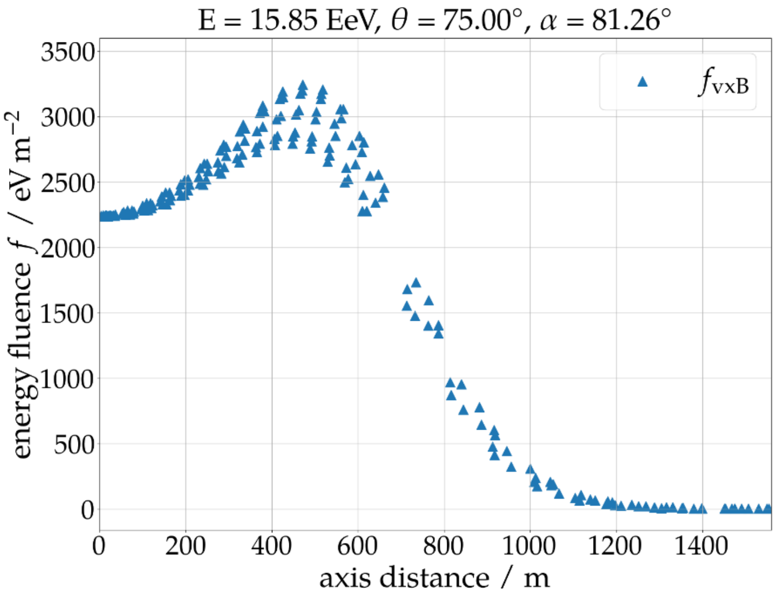




- allow for core shift due to atmospheric refraction (see arXiv:2005.06775)
- significant asymmetries remain in shower plane

2: Apply geometrical early-late correction

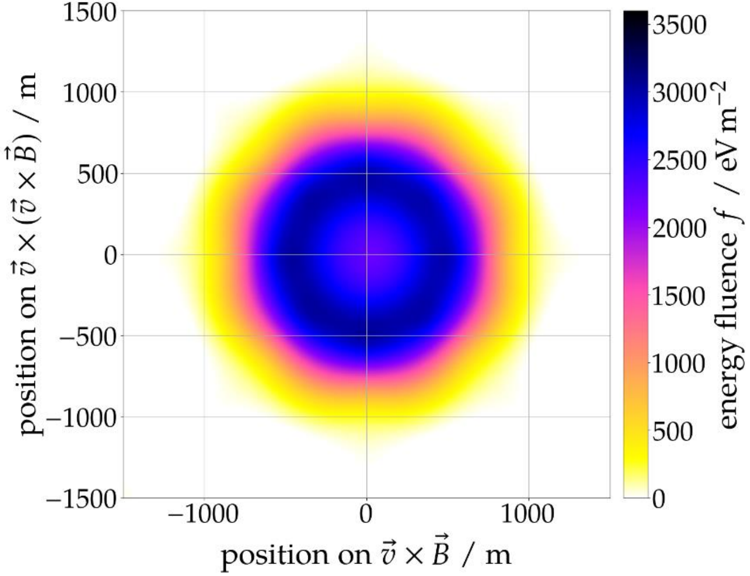


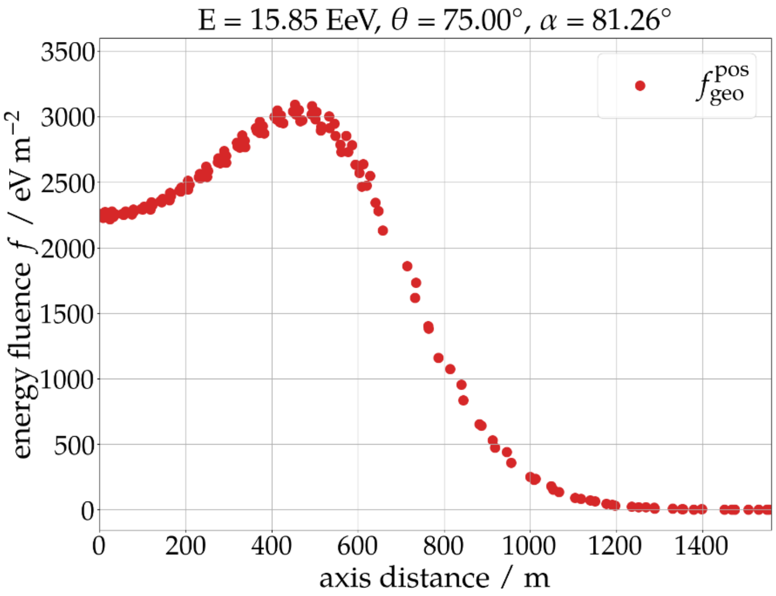


- geometrical early-late correction improves symmetry (arXiv:1908.07840)
- corrects axis distance and energy fluence for a given source distance

3: Calculate pure geomagnetic emission

Karlsruhe Institute of Technology

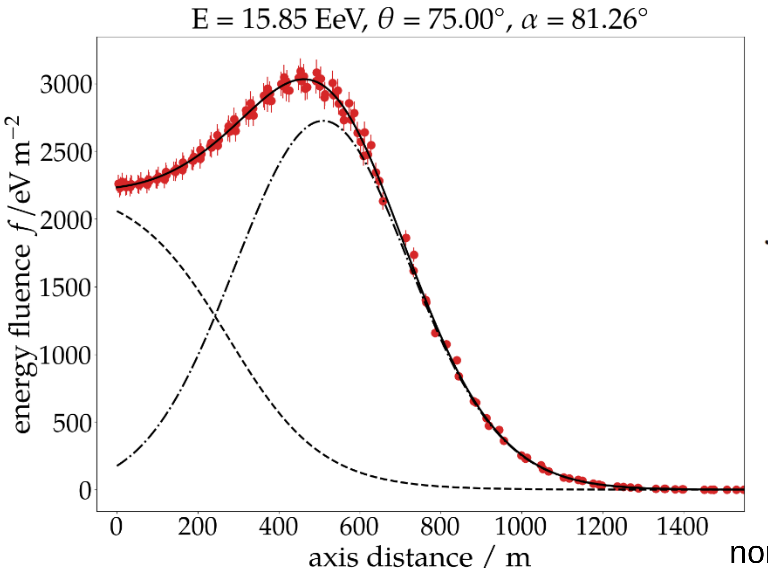




- deduct charge-excess via known polarisation properties
- pure geomagnetic emission component is rotationally symmetric

4: Fit a radially symmetric LDF

Karlsruhe Institute of Technology



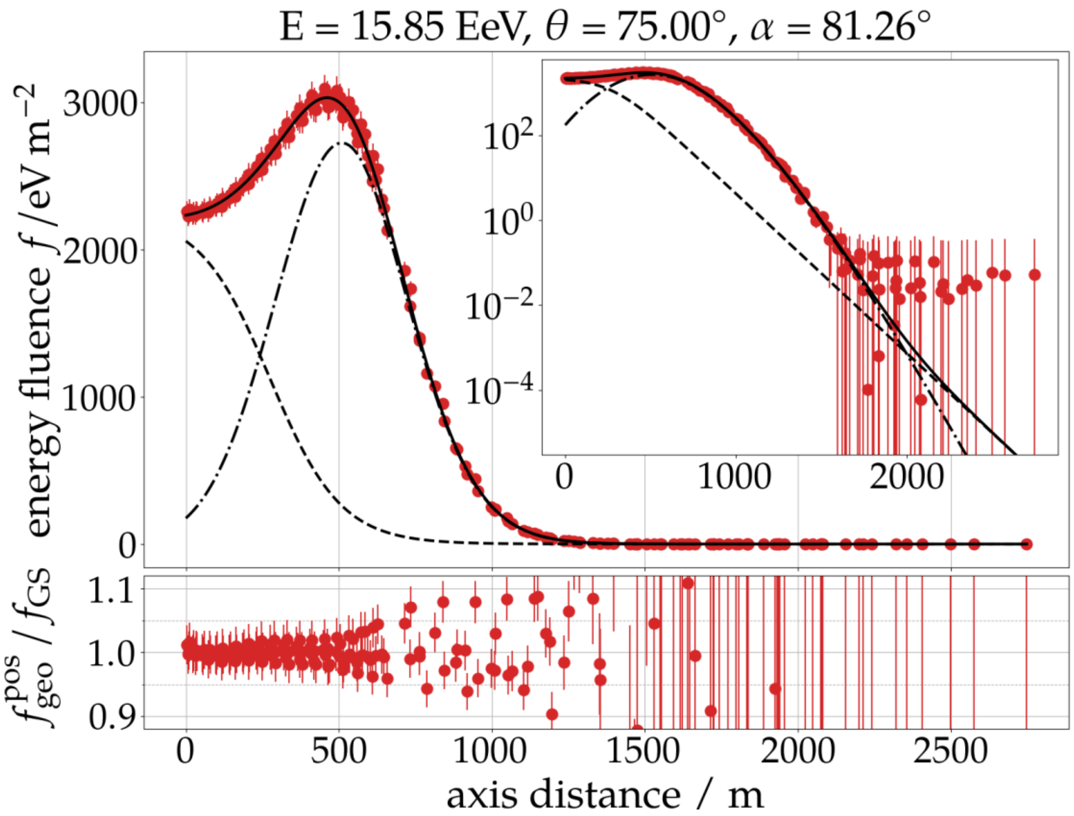
Gaussian | Sigmoid

$$f_{GS}(r) = f_0 \left[\exp\left(- \left(\frac{r - r_0}{\sigma} \right)^{p(r)} \right) + \frac{a_{rel}}{1 + \exp\left(s \cdot \left(\frac{r}{r_0} - r_{02} \right) \right)} \right]$$

- normalization: f_0
- width of Gaussian: σ
- position of Gaussian: r_0
- $p(r)$: ~2, cf. b
- relative amplitude of Sigmoid vs. Gauss: a_{rel}
- shape parameters: s, r_{02}

- function changed from ICRC2019 for a better fit at large distances
- 7 parameters plus 2 core coordinates, too many for practical application

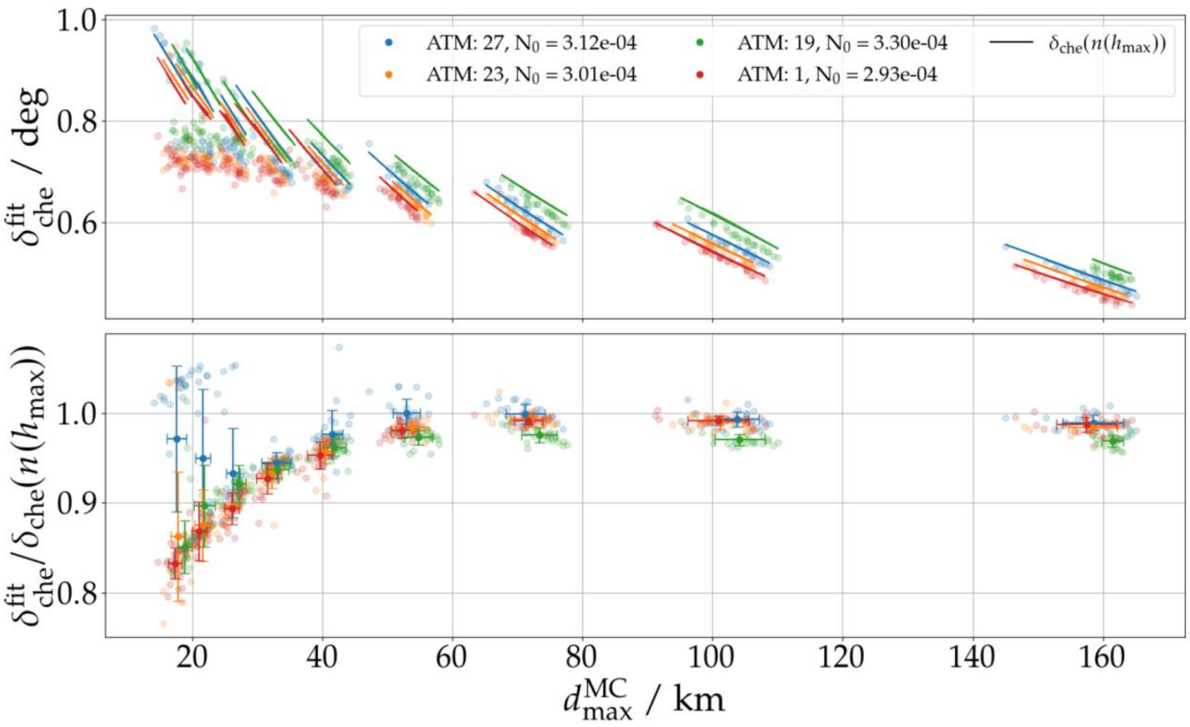
4: Performance of Gauss-Sigmoid fit function



- very good fit over the complete distance range
- artifacts from particle thinning visible at largest distances, care taken that fit not biased by these

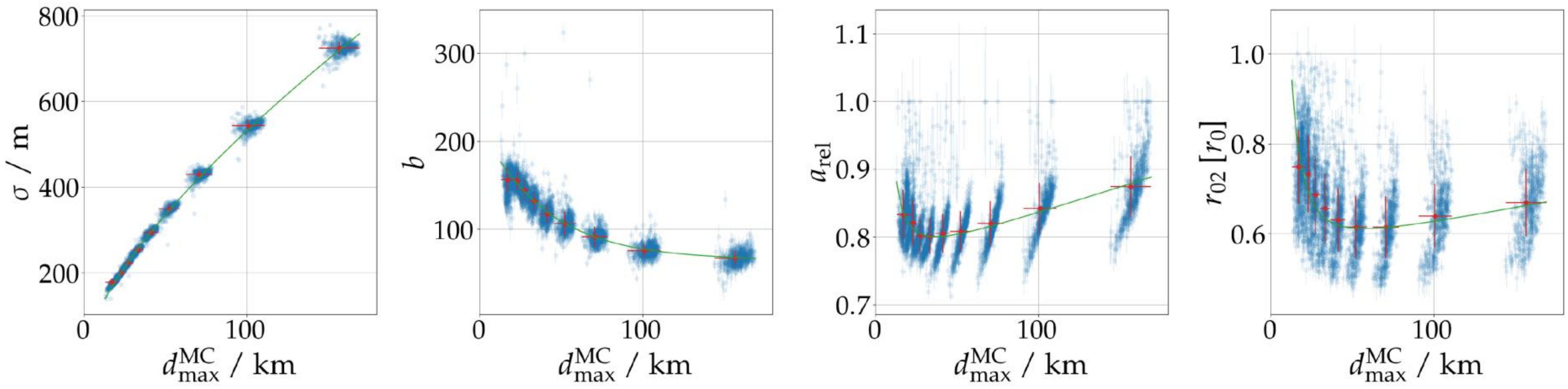
5: Reduce number of parameters

Karlsruhe Institute of Technology



- position of Gauss corresponds to Cherenkov radius calculated from refractive index at Xmax!
- some deviations at lowest zenith angles

5: Recuce number of parameters



- shape parameter s is set to s = 5 (ensures Sigmoid dominant in center)
- other parameters can be parameterized as f(distance to X_{max})
- second-order influence of Xmax value, but decided not to parameterize
- out of 7 fit parameters, 6 successfully fixed or correlated to d_{max}

6: Parameterization of charge-excess fraction

- so far determined from polarisation, but impractical in presence of noise
- therefore parameterize charge-excess fraction

$$a_{ce} = \left[0.348 - \frac{d_{max}}{850.9\,\mathrm{km}}\right] \cdot \frac{r}{d_{max}} \cdot \exp\left[\frac{r}{622.3\,\mathrm{m}}\right] \cdot \left[\left(\frac{\rho_{max}}{0.428\,\mathrm{kg\,m^{-3}}}\right)^{3.32} - 0.0057\right]$$

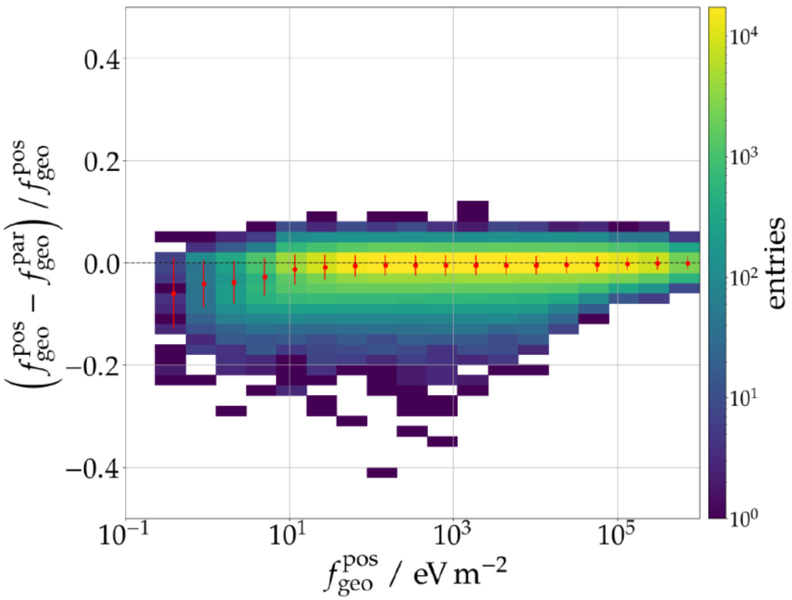
source dist. off-axis angle axis distance atmospheric density correction

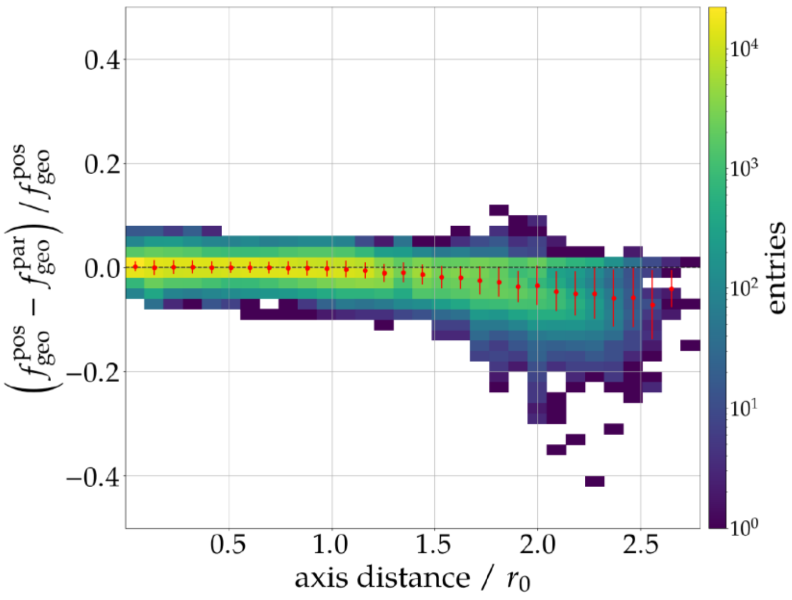
- with this, we can calculate geomagnetic energy fluence at any location by subtraction of charge-excess fluence from ***v*** x ***B*** measurement

$$f_{geo}^{par} = \frac{f_{\mathbf{v}\times\mathbf{B}}}{\left(1 + \frac{\cos(\phi)}{|\sin(\alpha)|} \cdot \sqrt{a(r, d_{max}, \rho_{max})}\right)^2}$$

cf. Glaser et al. JCAP 09 (2016) 024 and Astroparticle Physics 104 (2019) 64-77

6: Performance of charge-excess parametrization





- agreement of charge-excess parameterization with direct calculation agrees on average within 2%

7: Final fit function

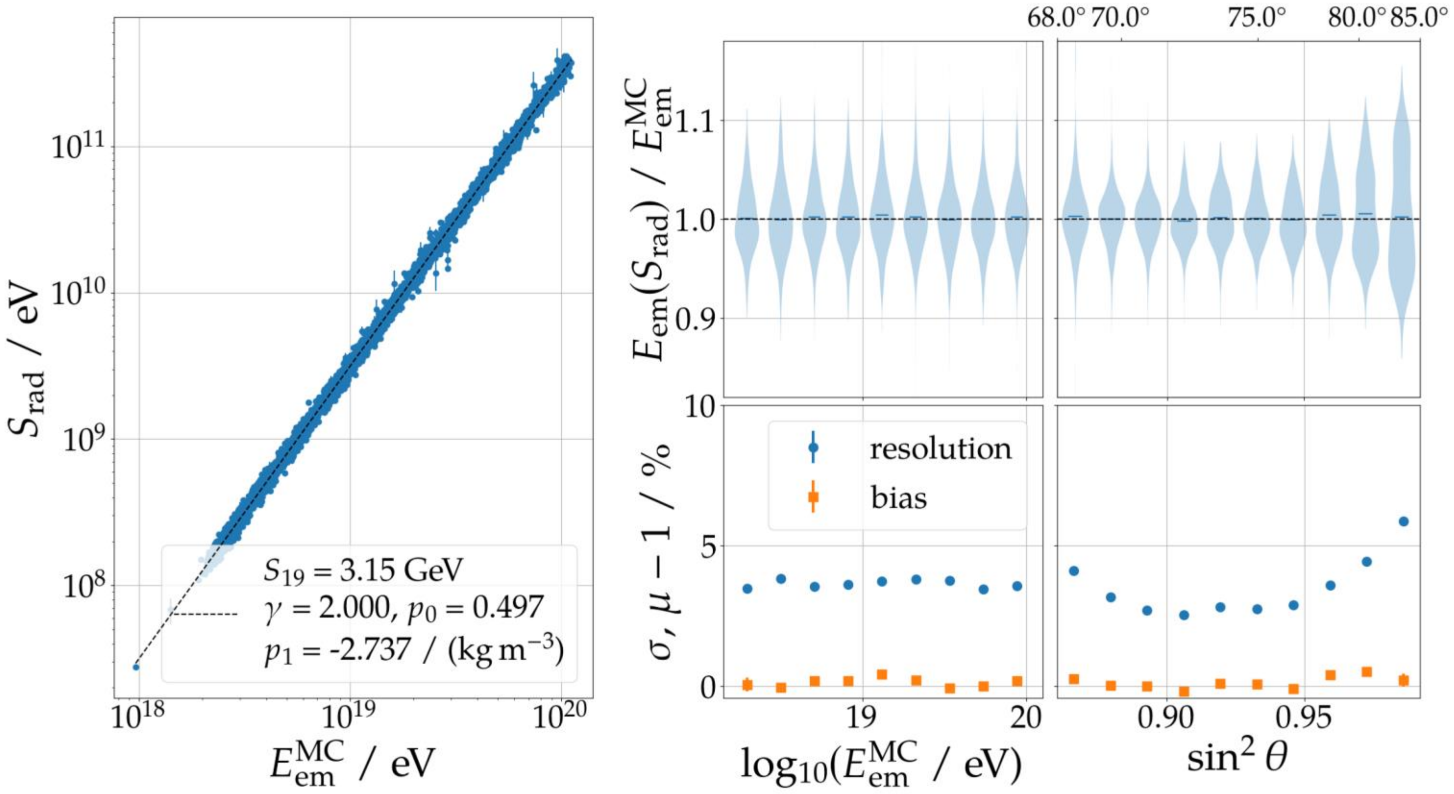
- fit with 4 free parameters: geomagetic radiation energy, d_{max}, core x/y

$$f_{\mathrm{geo}}(r, E_{\mathrm{geo}}, d_{\mathrm{max}}) = E_{\mathrm{geo}} \frac{f_{\mathrm{GS}}(r, d_{\mathrm{max}})}{2\pi \int_0^{5r_0} f_{\mathrm{GS}}(r, d_{\mathrm{max}}) r \, \mathrm{d}r}$$

- then apply geomagnetic angle and atmospheric density correction to get „corrected geomagnetic radiation energy“ S_{geo}
- finally correlate S_{geo} with shower electromagnetic energy

$$S_{\mathrm{geo}} = S_{19} \cdot \left(\frac{E_{\mathrm{em}}}{10\,\mathrm{EeV}} \right)^{\gamma}$$

7: Test performance on 1.5 km grid simulations



- use MC start values - intrinsic resolution
- quadratic scaling
- negligible bias
- resolution <5%

Tim Huege <tim.huege@kit.edu>

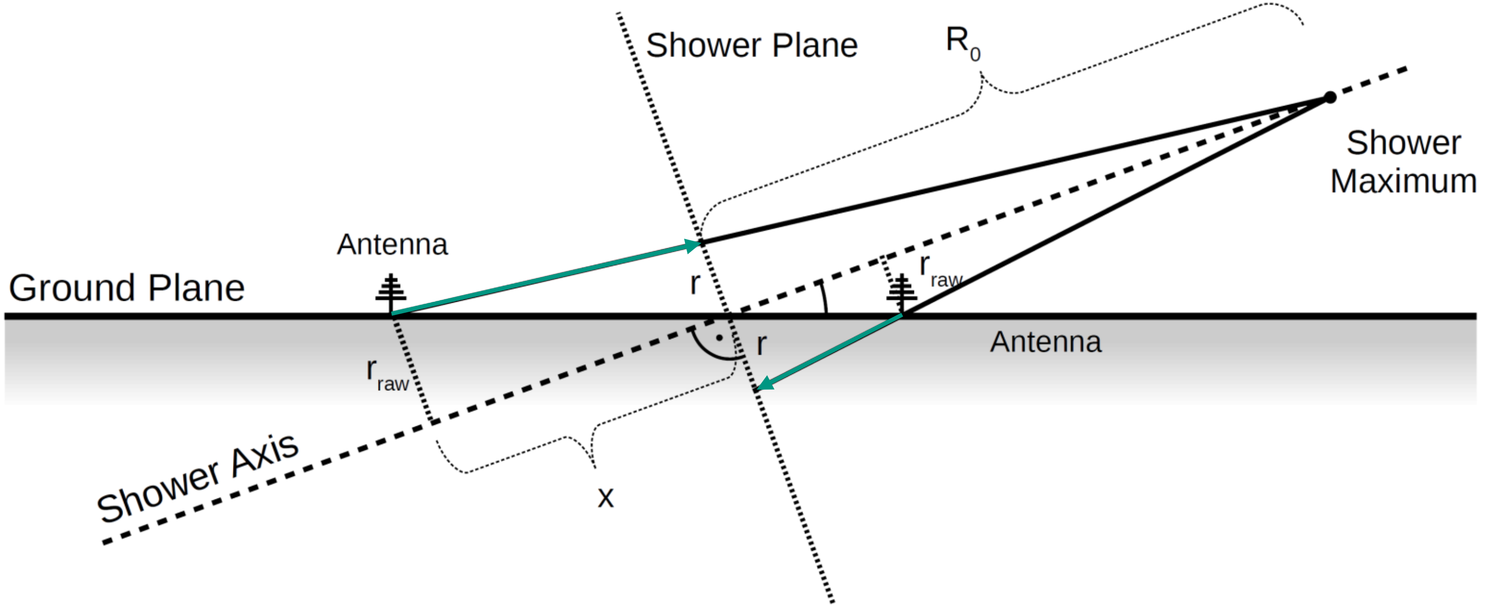
Conclusions

- we have developed a signal model and reconstruction for inclined EAS
- we fit the symmetric geomagnetic emission with a Gauss-sigmoid LDF
- the fit has two free parameters plus two core coordinates
- the intrinsic energy resolution is better than 5% on a 1.5 km grid
- can be used for AugerPrime Radio Detector, likely GRAND

- see it in action in talk by F. Schlüter, PoS(ICRC2021)262

Backup

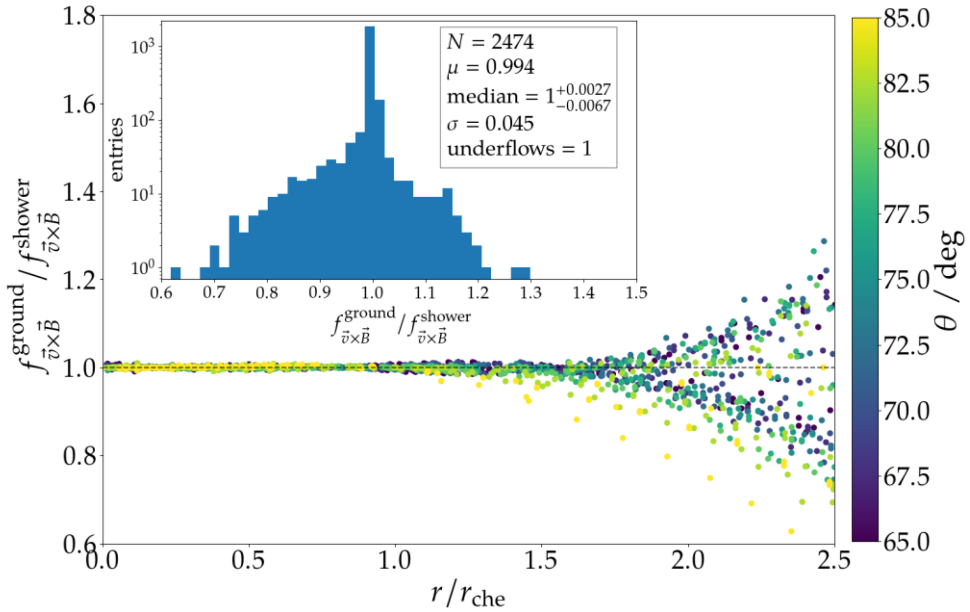
Correcting for early-late asymmetries



- correcting axis distances and energy fluences

$$f = f_{\mathrm{raw}} \cdot \left(\frac{R}{R_0}\right)^2 \qquad r = r_{\mathrm{raw}} \cdot \frac{R_0}{R} \qquad R \equiv R_0 + x$$

Performance of early-late correction



- most significant deviations are at large lateral distances and large zenith angles

Determining charge-excess fraction directly

Karlsruhe Institute of Technology

$$f_{\mathrm{geo}}^{\mathrm{pos}} = \left(\sqrt{f_{\mathbf{v}\times\mathbf{B}}} - \frac{\cos(\phi)}{|\sin(\phi)|} \cdot \sqrt{f_{\mathbf{v}\times\mathbf{v}\times\mathbf{B}}} \right)^2$$

$$f_{\mathrm{ce}}^{\mathrm{pos}} = \frac{1}{\sin^2(\phi)} \cdot f_{\mathbf{v}\times\mathbf{v}\times\mathbf{B}}.$$

- for a given observation position, the charge-excess fraction can be determined directly via the known polarisation characteristics of the geomagnetic and charge-excess contributions, cf. Glaser et al., Astroparticle Physics 104 (2019) 64-77

Parameter correlations

Karlsruhe Institute of Technology

$$r_0 = \tan(\delta_{\text{che}}) \cdot d_{\text{max}}\,, \qquad \delta_{\text{che}} = \cos^{-1}\left(\frac{1}{n(h(d_{\text{max}}))}\right)$$

$$\sigma = \left(0.132 \cdot \left(\frac{d_{\text{max}} - 5\,\text{km}}{\text{m}}\right)^{0.714} + 56.3\right)\,\text{m}$$

$$p(r) = \begin{cases} 2 & r \leq r_0 \\ 2 \cdot (r_0/r)^{b/1000} & r > r_0 \end{cases}\,, \quad b = 154.9 \cdot \exp\left(-\frac{d_{\text{max}}}{40.0\,\text{km}}\right) + 64.9,$$

$$a_{\text{rel}} = 0.757 + \frac{d_{\text{max}}}{1301.4\,\text{km}} + \frac{19.8\,\text{km}^2}{d_{\text{max}}^2},$$

$$r_{02} = 0.552 + \frac{d_{\text{max}}}{1454.2\,\text{km}} + \frac{66.2\,\text{km}^2}{d_{\text{max}}^2}.$$