DFG NUTRIG anr

Modelling the Radio Emission of Inclined Air Showers in the 50-200 MHz Frequency Band for GRAND

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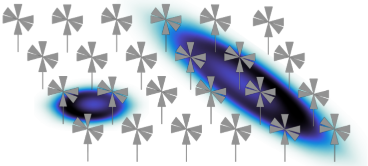
Overview

Signal Model:

- **Radio signal pattern at ground level** for all possible geometries



Reconstruction:

- Integrate over **geomagnetic fluence LDF** to calculate **electromagnetic shower energy**

Goal:

- **Precise event reconstruction** for GRAND sites in China and Argentina
- **Generalise** model for different **sites, frequencies, magnetic fields**, etc.

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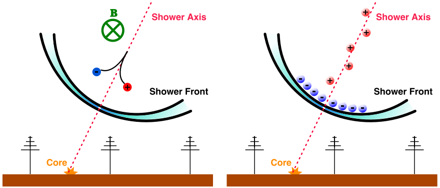
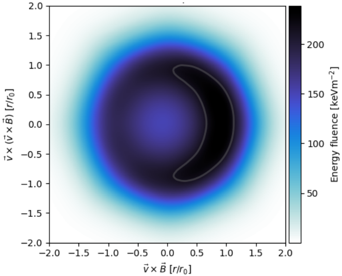
Radio Emission: Important Features

- **Geomagnetic emission**
  Dominant component in air
- **Charge excess emission**
  Subtract for reconstruction
- Superposition leads to **asymmetric radio footprint**

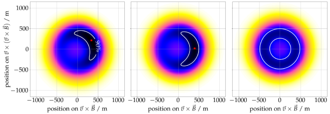


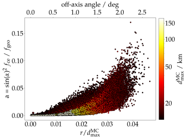


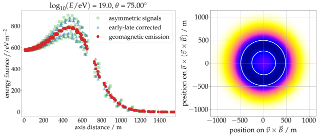
Original Model for 30-80 MHz Frequency Band

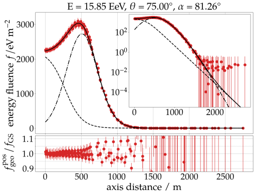
Signal model and event reconstruction for the radio detection of inclined air showers

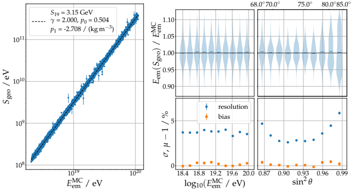
F. Schlüter[a,b,1] and T. Huege[a,c]







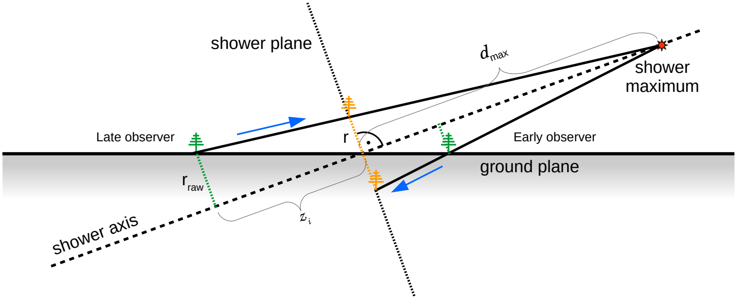




Early-late Correction

- Antennas projected into **shower plane**
- Apply **correction to energy fluence**
- Eliminates **signal differences** from shower geometry

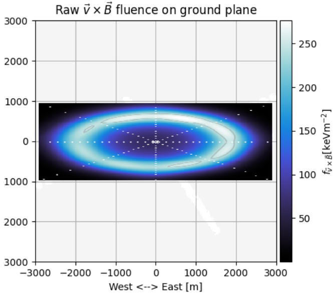
Early-late correction for simulating inclined showers



JCAP01(2023)008

Step-by-Step Symmetrisation

CoREAS air shower simulation in $\underline{50 - 200\,\mathrm{MHz}}$ with zenith angle $\underline{\theta = 75^\circ}$



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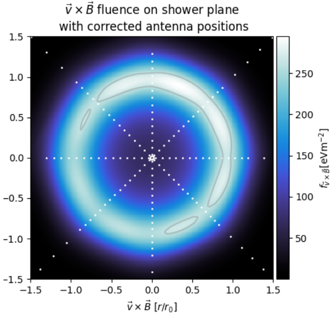

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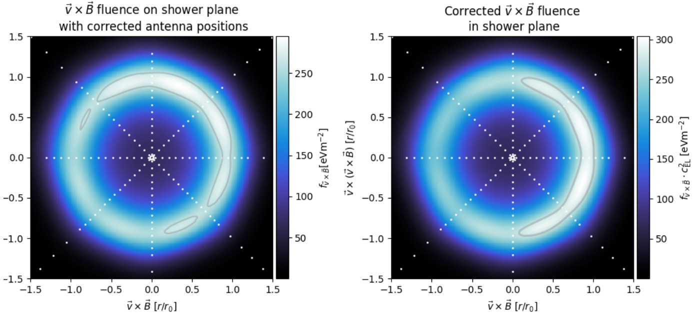

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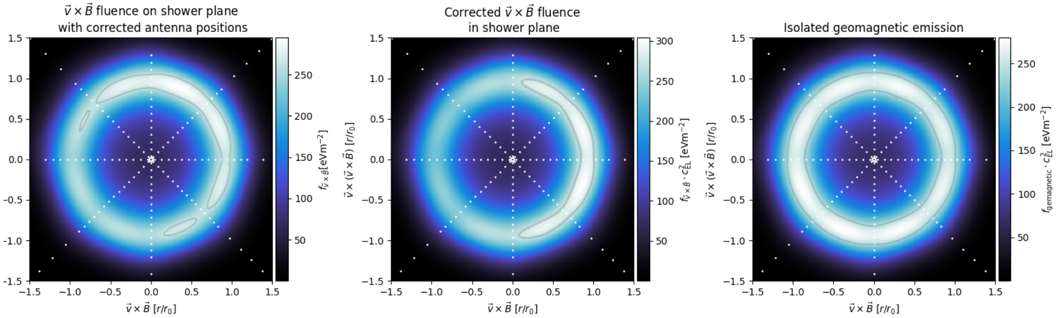
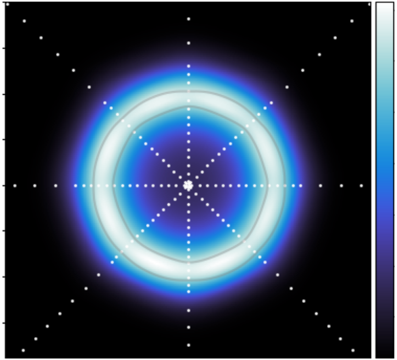
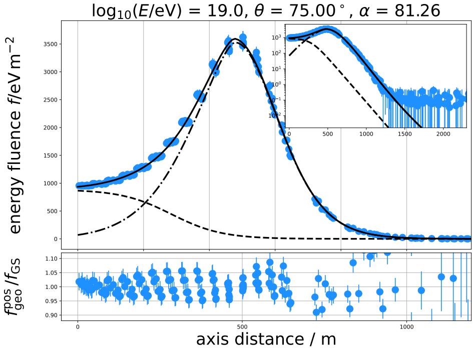


Lateral Distribution Function of Energy Fluence

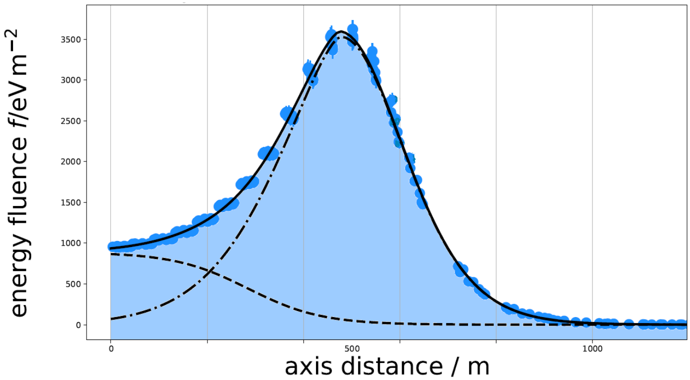
Radially symmetric fluence $\rightarrow$ Lateral fluence distribution





From Fluence to Electromagnetic Energy

- Energy fluence = **Energy deposited** in ground plane
- **Fit fluence** with LDF
- Integrate over function = **Geo.radiation energy** E_{geo}



From Fluence to Electromagnetic Energy

- Calculate **corrected radiation energy** S_{geo} with E_{geo}:

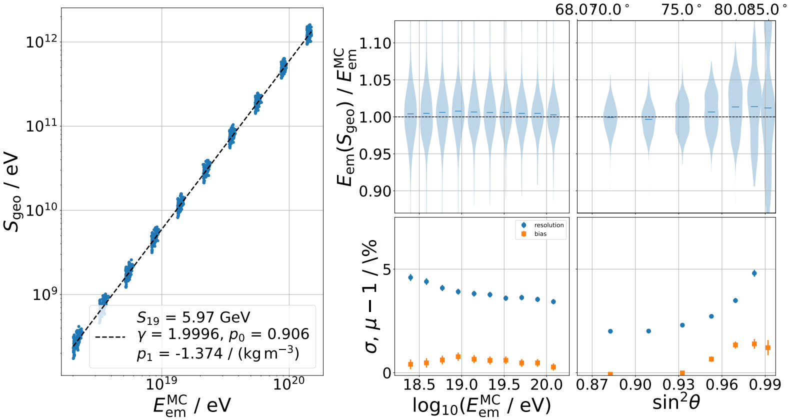
$$S_{geo} = \frac{E_{geo}}{\sin^2(\alpha)} \cdot \frac{1}{(1 - p_0 + p_0 \cdot \exp(p_1 [p_{max} - \bar{p}]))^2}$$

- **Electromagnetic energy** of the shower E_{em} **correlates** with S_{geo}:

$$E_{em} = 10\,\mathrm{EeV} \left(\frac{S_{geo}}{S_{19}} \right)^{1/\gamma}$$

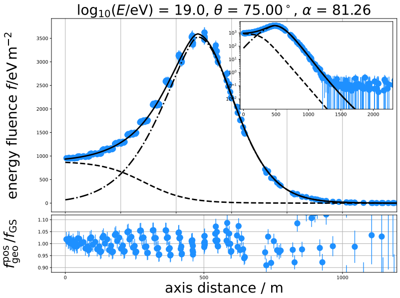
From Fluence to Electromagnetic Energy: Example Result

Comparison of reconstructed S_{geo} and E_{em}^{MC} yields **resolution and bias**



LDF Function and its Parameters

Geomagnetic LDF fit with **normalisation, 6 shape parameters and core position**



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

normalisation (f_0); "Gaussian"; Sigmoid

peak position (r_0); shape of "Gaussian" (σ, $p(r)$); relative amplitude (a_{rel}); Sigmoid shape (s, r_{02})

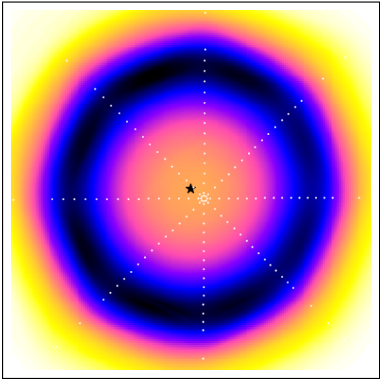
Parameterise LDF shape parameters according to their behaviour with d_{max}

Fit function **slightly modified** from *JCAP01(2023)008*

Modifications to LDF: Shower Core Fit

Refractive Displacement: *(Eur. Phys. J. C 80, 643 (2020))*

- **Radio shower core shifts** from MC core due to refraction
- **Zenith** angle dependent
- **Fixed to projection of shower axis** to preserve azimuth angle



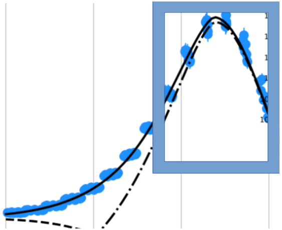
Modifications to LDF: New Parameter

Lateral Distribution Function:

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

Modified left slope of "Gaussian":

$$p(r) = \begin{cases} p_{\text{left}} & \text{for} \quad r < r_0 \\ 2 \cdot \left(\frac{r_0}{r} \right)^{\frac{b}{1000}} & \text{for} \quad r \geq r_0 \end{cases}$$



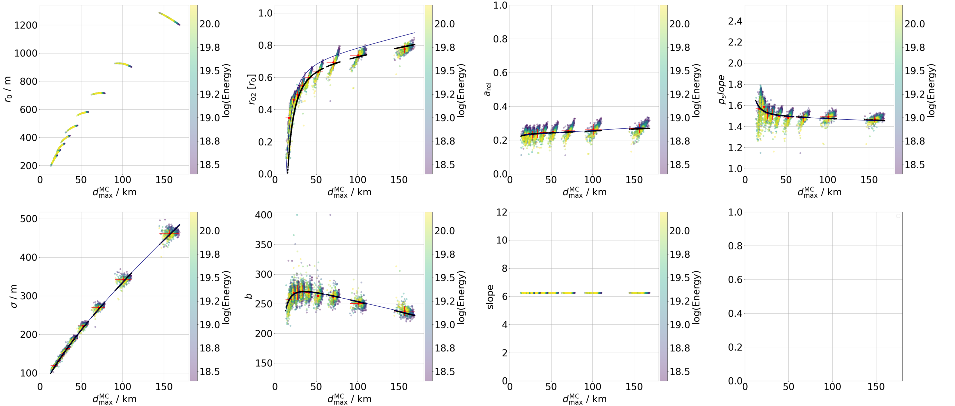
Simulation Libraries

RdStar library:

- Generated with **CoREAS**
- **Starshape** simulations for the Auger site in **Argentina**
- **No noise**
- **4309** simulated air showers; **3 seeds** for each unique geometry
- 50% **proton** + 50% **iron** primaries

Fit Performance: Parameter Behaviour

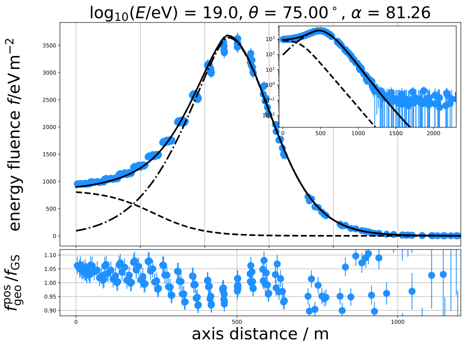
Fit over all simulations in RdStar library with all LDF shape **parameters left free**

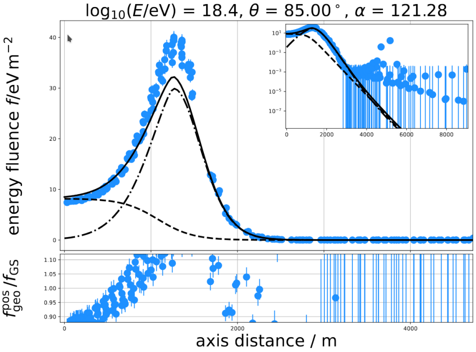


Fit Performance: Success Rate

After fully parametrised fit:

$\sim$ 80% of LDFs show agreement within 10% or better, $\sim$ 20% can deviate significantly





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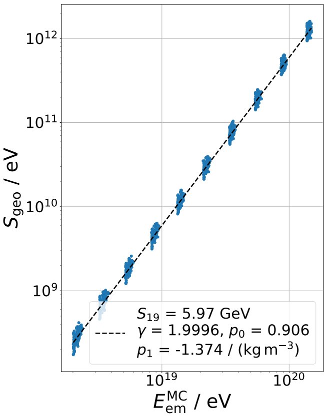
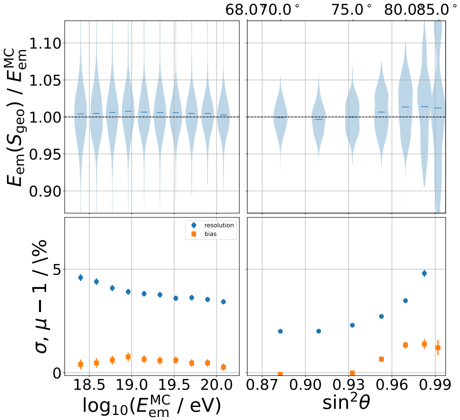
GRAND

Argentina Site: Free LDF Fit

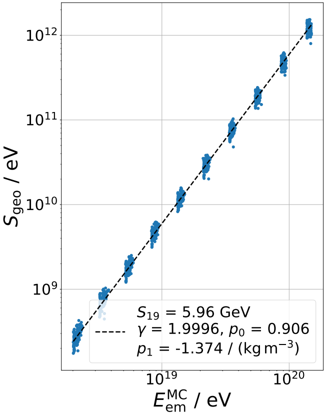
Performance of reconstruction of starshape simulations with completely free LDF fit
$\Rightarrow$ Accurate to $\sim 4\%$

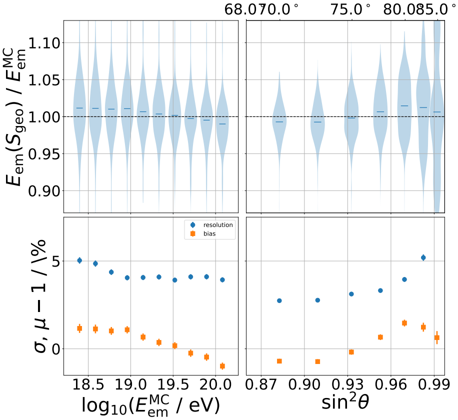




Argentina Site: Parametrised LDF Fit

Performance of reconstruction of starshape simulations with fully parameterised LDF fit
$\Rightarrow$ Accuracy only decreases slightly

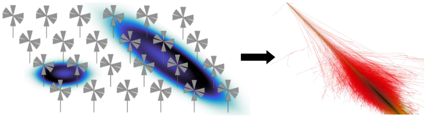




Summary and Outlook

Summary:

- Updated model **performs well** in $50 - 200\,\mathrm{MHz}$ frequency band
- **Working reconstruction** for Argentina site

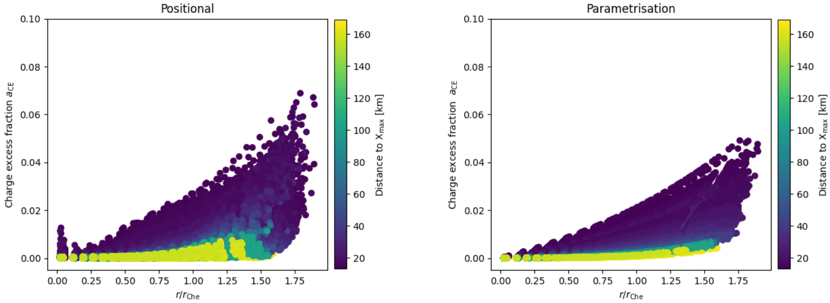


Outlook:

- Optimise model with **starshape simulations for site in China**
- Test performance on **realistic grid with added noise for both sites**

Charge Excess Fraction Fit

Compare **geometrical and parametrical charge excess fraction** at $50 - 200\,\mathrm{MHz}$



$$f_{geo}^{par} = \frac{f_{\vec{v}\times\vec{B}}}{\left(1+\frac{\cos(\theta)}{|\sin(\alpha)|}\cdot\sqrt{a_{ce}}\right)^2}$$

$$a_{ce} = \left[0.348 - \frac{d_{max}}{850\,\mathrm{km}}\right] \cdot \frac{r}{d_{max}} \cdot \exp\left(\frac{r}{622.3\,\mathrm{m}}\right) \cdot \left[\left(\frac{\rho_{max}}{0.428\,\mathrm{kg\,m^{-3}}}\right)^{3.32} - 0.0057\right]$$

Fit of the Density Correction

Fit of the **density correction** used to transform from E_{geo} to S_{geo} (includes p_0, p_1, S_{19} and γ)