CoREAS simulations of inclined air showers predict refractive displacement of the radio-emission footprint

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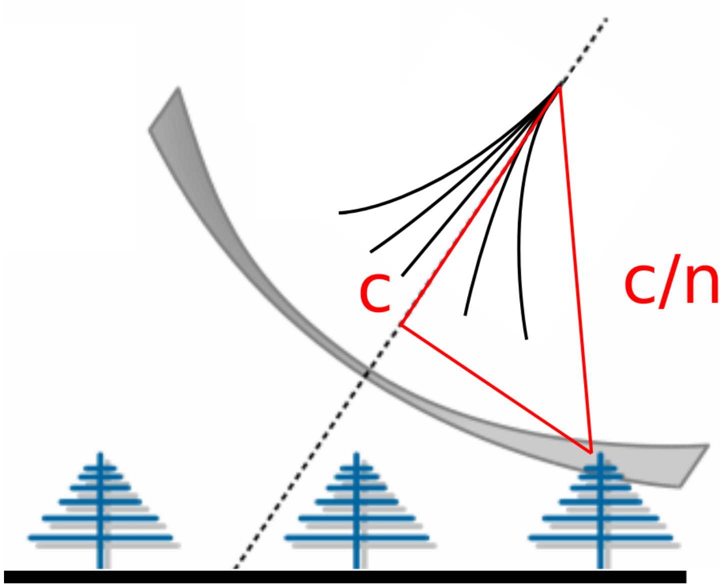
Take home messages:

- Displacement of radio emission up to 1.5 km on ground for θ = 85°
- Results confirmed by model of refraction in the atmosphere
- Full paper with additional information: F. Schlüter et al. EPJ C 80 (2020) 643

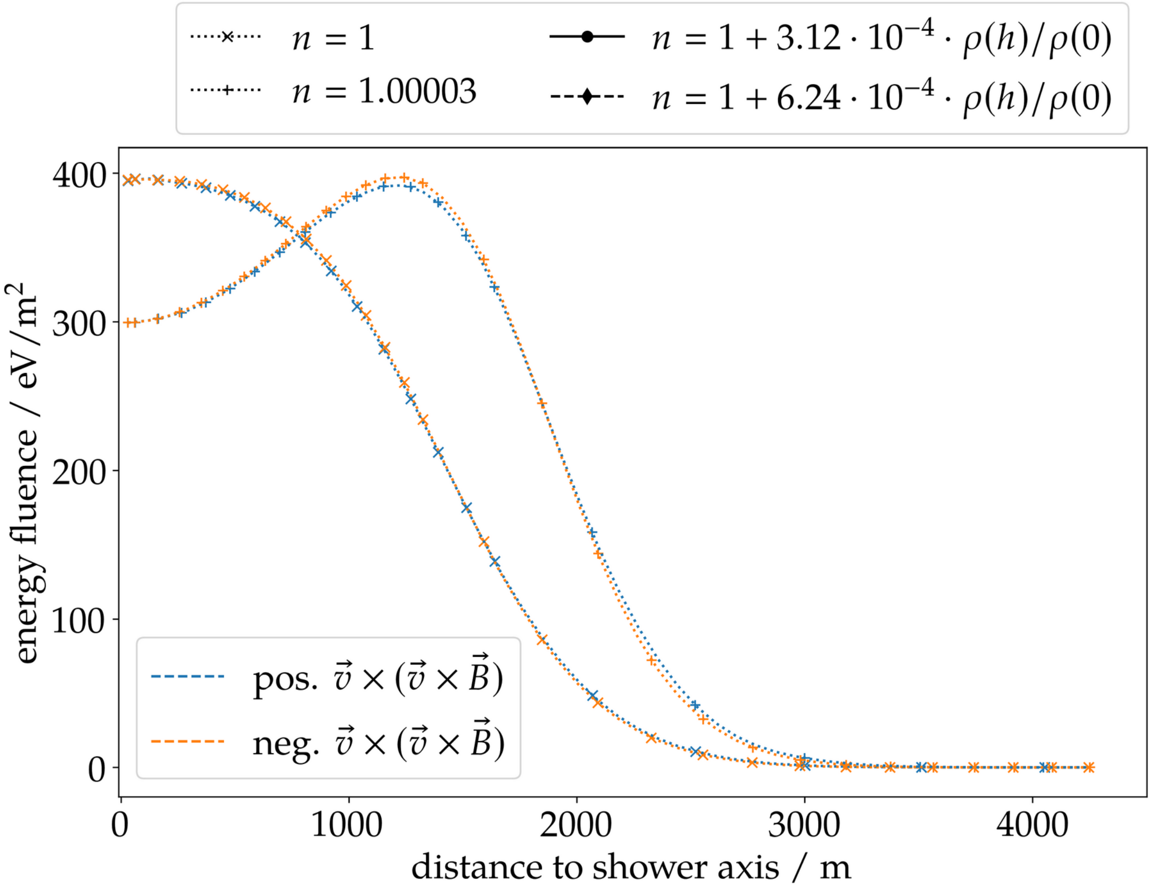
Bundesministerium für Bildung und Forschung

Radio emission footprint

- Superposition of geomagnetic and charge-excess emission caused by individual polarization patterns
- Cherenkov-like compression of radio signal
  - Radio emission arrives simultaneously → increased signal on a ring around shower axis
  - Later: use Cherenkov ring to fit radio core
- Asymmetric radio footprint, bean-like shape of the signal distribution
- Additional early-late effect for inclined air showers, understood and taken into account (EPJ Web of Conferences 216, 03009 (2019))



From an apparent asymmetry…



- Air shower with 85° zenith angle simulated with 4 different refractivity profiles in the atmosphere
- Expected symmetry on pos. and neg. $\vec{v}\times(\vec{v}\times\vec{B})$ axis for constant values of refractive index
- Apparent asymmetry for a changing refractive index, effect increases when doubling refractivity of the atmosphre

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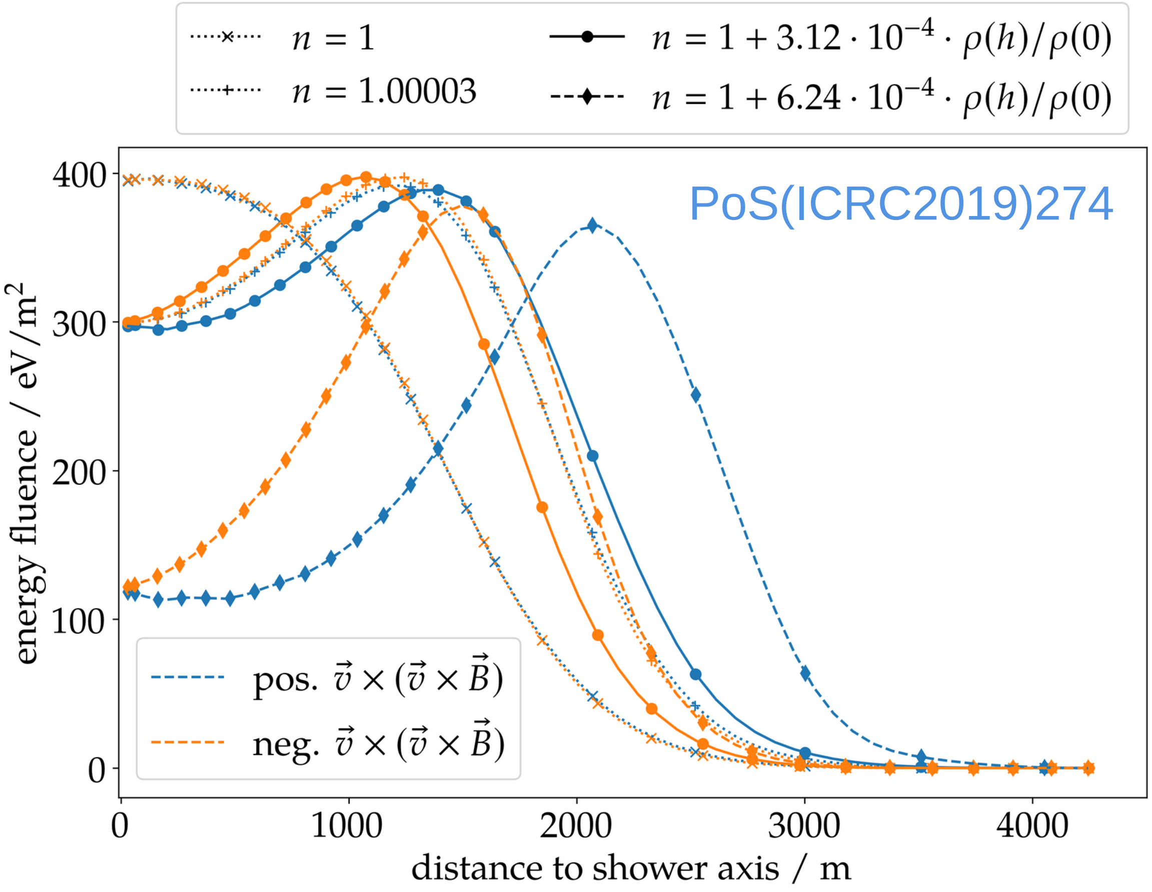

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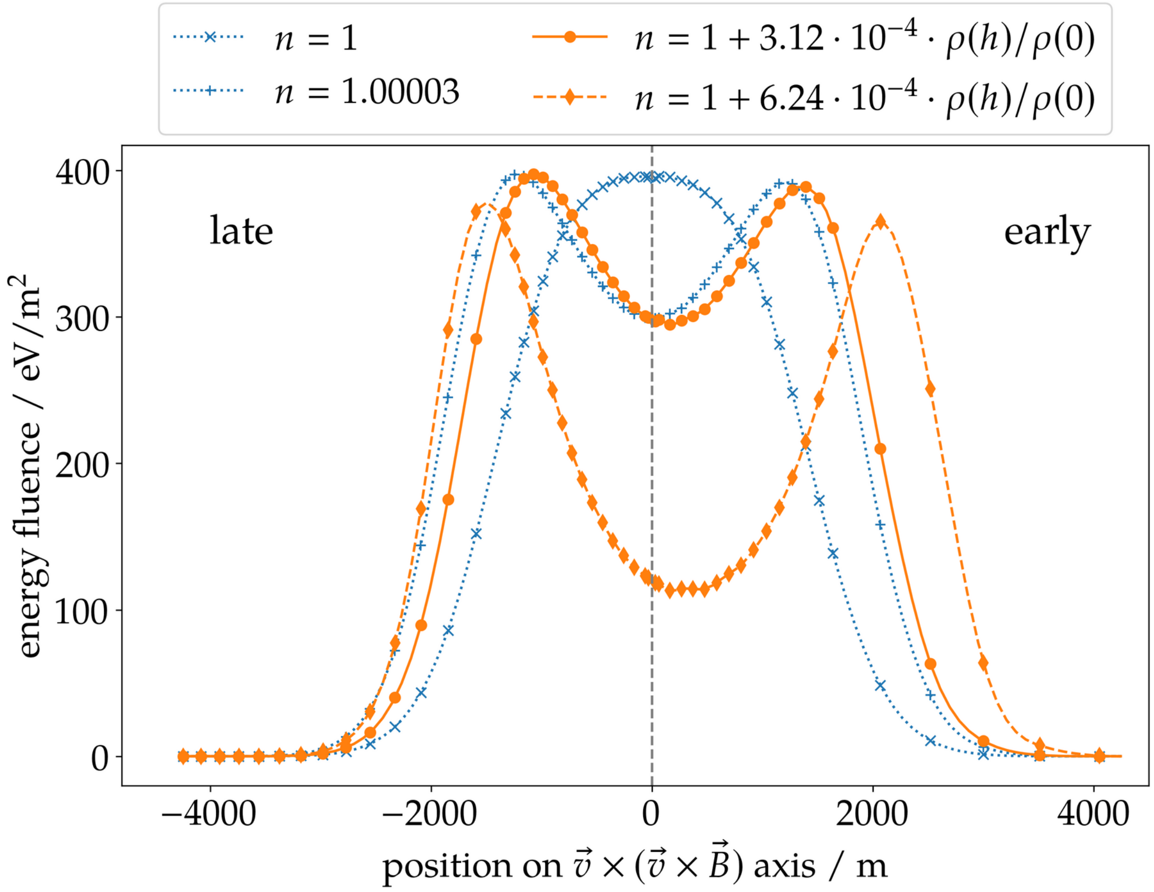
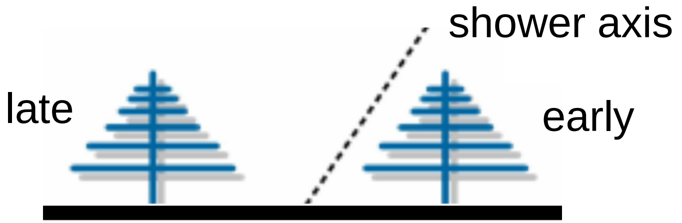
… to a displacement



- Air shower with 85° zenith angle simulated with 4 different refractivity profiles in the atmosphere
- Lateral signal distribution is symmetric, but symmetry axis not the MC axis
- Displacement into pos. $\vec{v}\times(\vec{v}\times\vec{B})$ direction („early direction“)
- Displacement of the radio-emission footprint due to refraction in the atmosphere



Fitting the Cherenkov ring

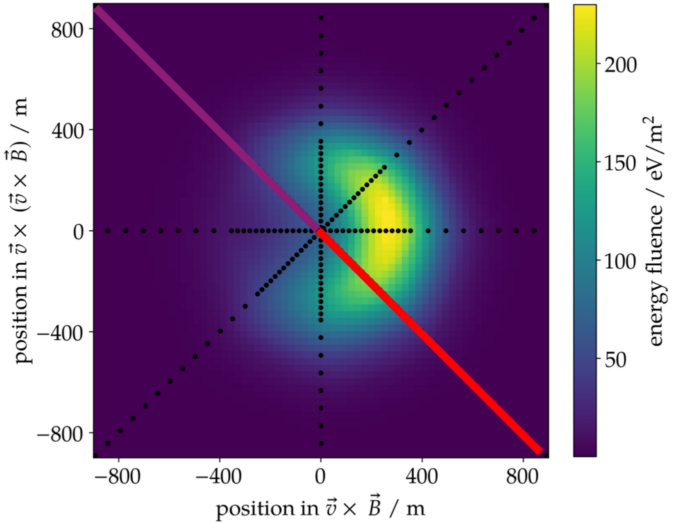
- Simulate observers on a star-shaped grid
- Interference can remove Cherenkov ring for small geomagnetic angles
  → use only geomagnetic fluence
- Radio core = center of the Cherenkov ring

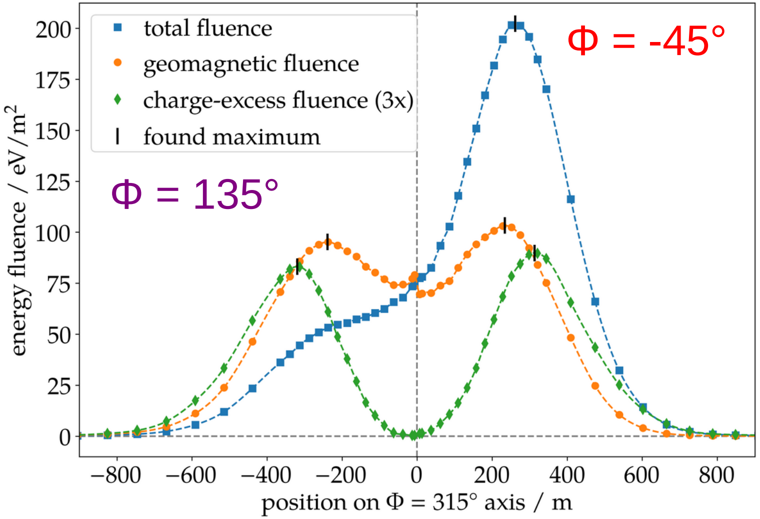
Experts: iterativ extraction of Cherenkov ring

1. Use MC impact point as radio core
2. Calculate geomagnetic energy fluence

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

3. Calculate positition of max fluence on each arm
4. Fit Cherenkov ring and update core position
5. Go to 2. until convergence

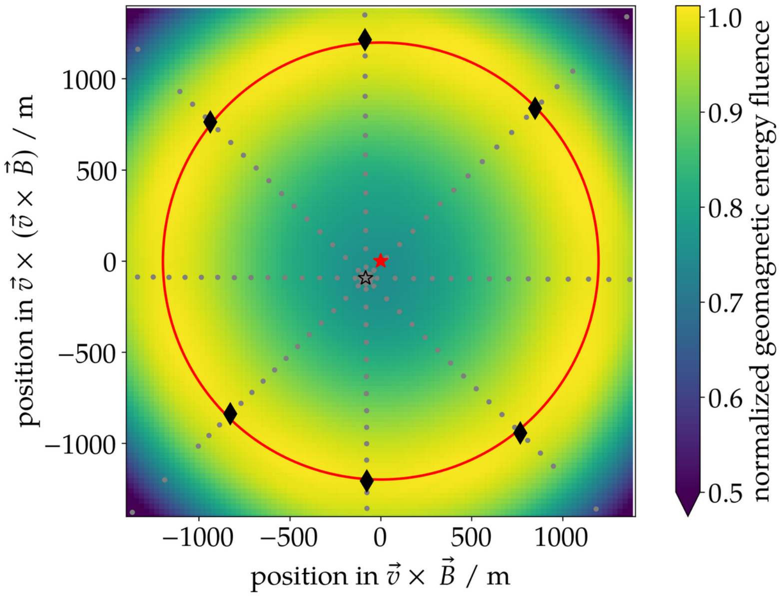


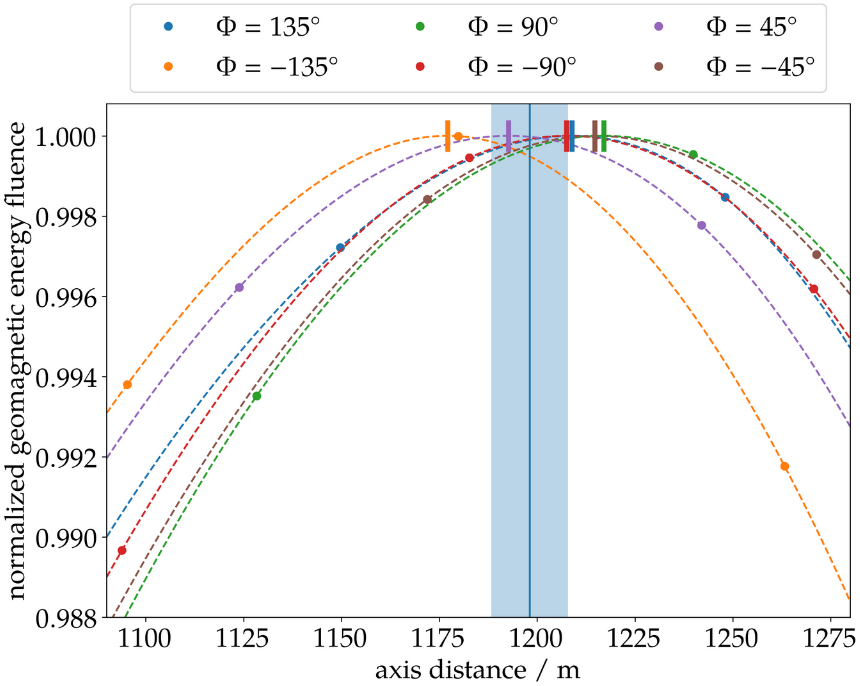


Example fit

- Event with θ = 85° coming from N-W
- 125 ± 21 m displacement in shower plane, 1428 ± 240 m in ground plane

- Simulations match ambient conditions of the Pierre Auger Observatory, e.g. frequency band 30 – 80 MHz (also used by LOFAR/Tunka-Rex)





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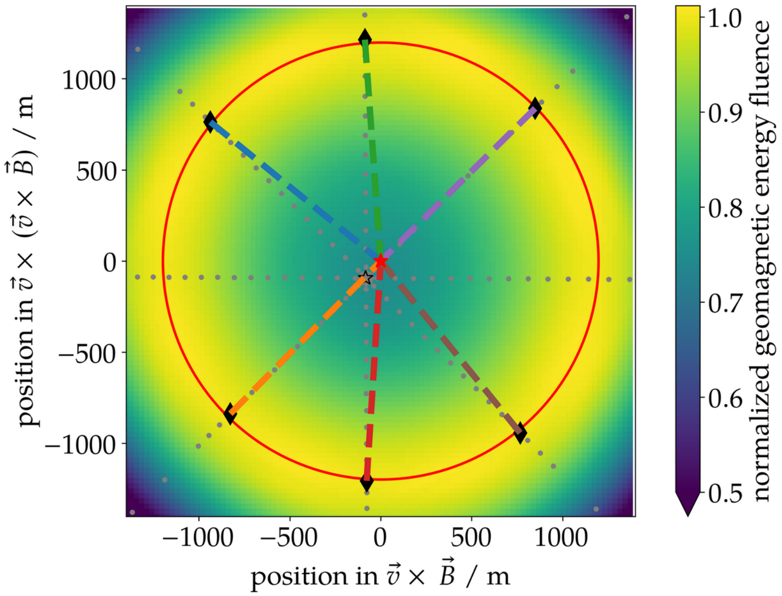
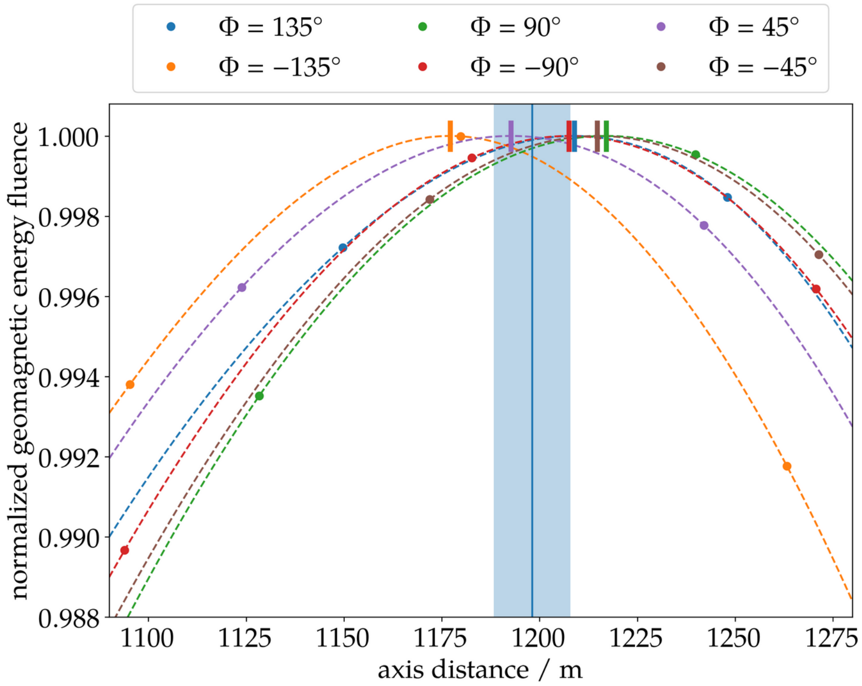
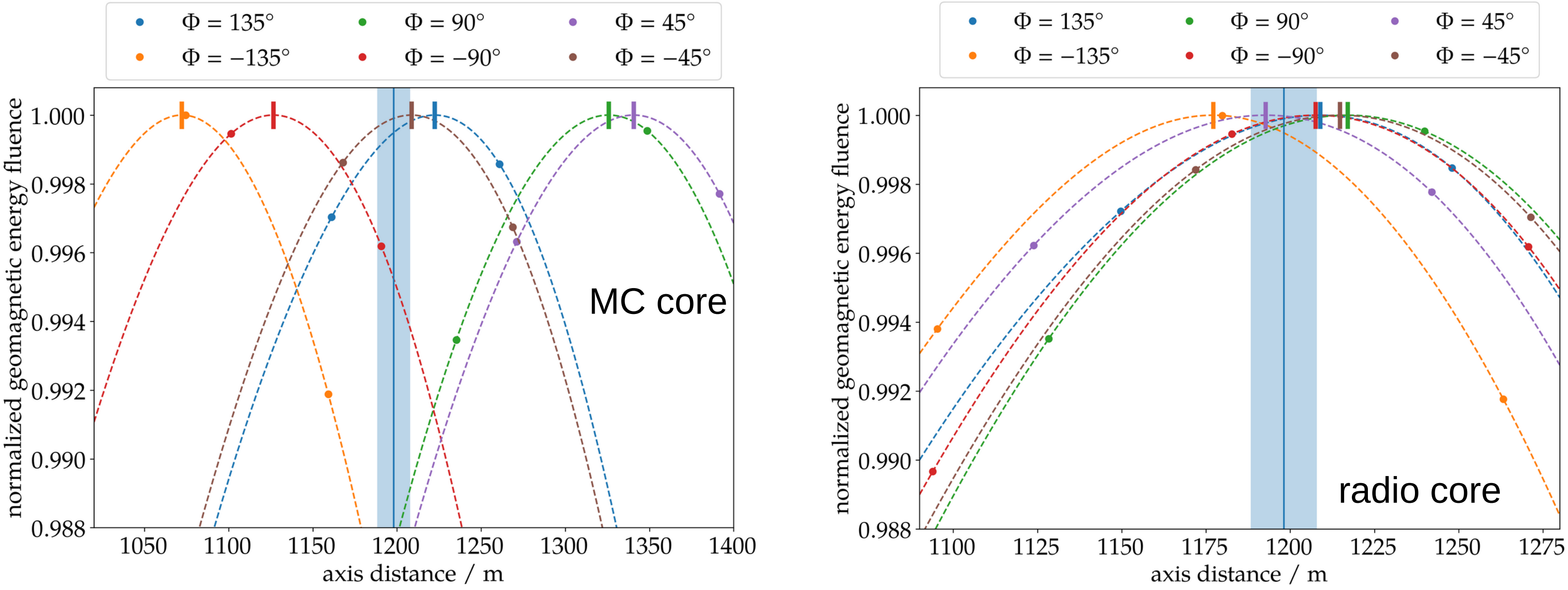




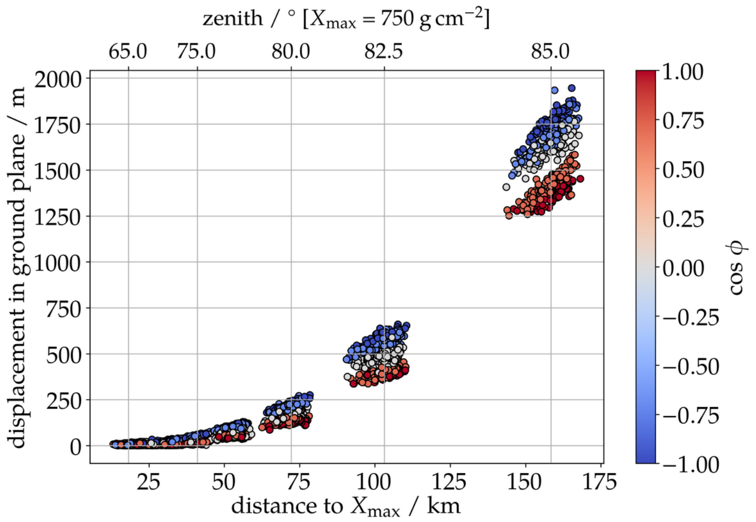
Radio core restores radial symmetry

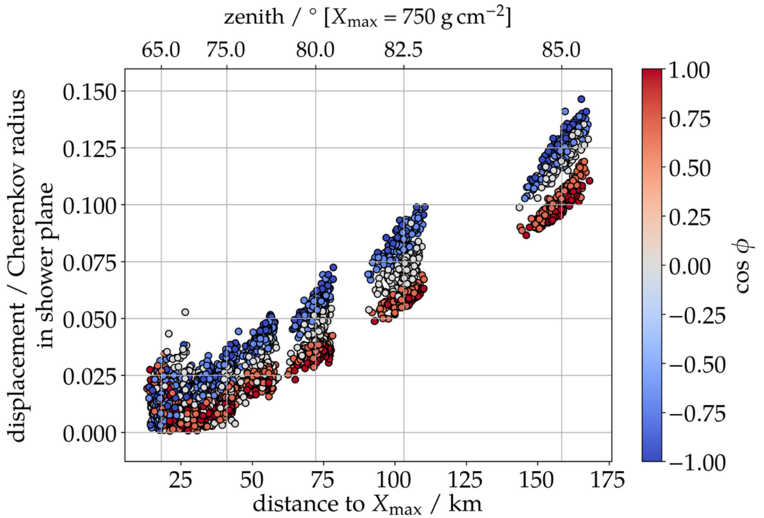
- Maximal difference between the Cherenkov radii of geomagnetic emission on individual arms: 268 m (MC core) → 40 m (radio core)



Core displacement

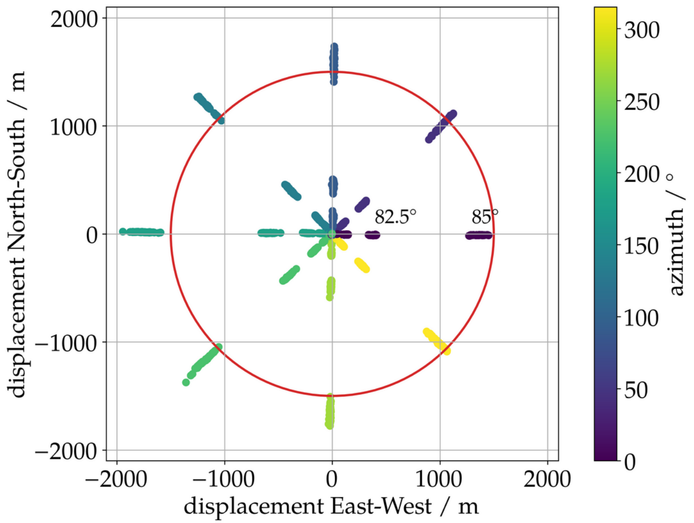
- Analysis of 4185 events:
  - $\log_{10}(E/eV)$ = 18.4, 18.6, … , 20.2
  - Zenith angles = 65°, 67.7°, … , 85°
  - Azimuth angles = East, South-East, South, ….
- Relevant quantity geometric distance to X_{max}, combination θ (1st order) and X_{max} (2nd order)
- Displacement of more than 1.5 km ground, corresponds to ~15 % of the Cherenkov radius in the shower plane
- East-West asymmetry, stronger displacement for showers coming from West (cos ϕ = -1) than East (cos ϕ = 1)

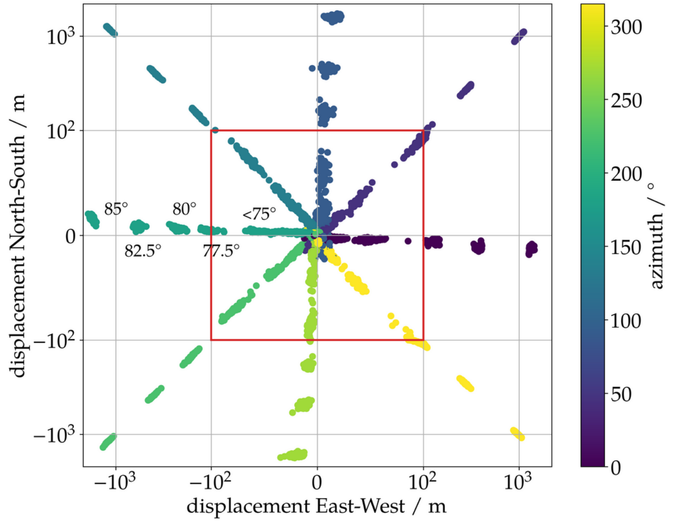




Directional core displacement

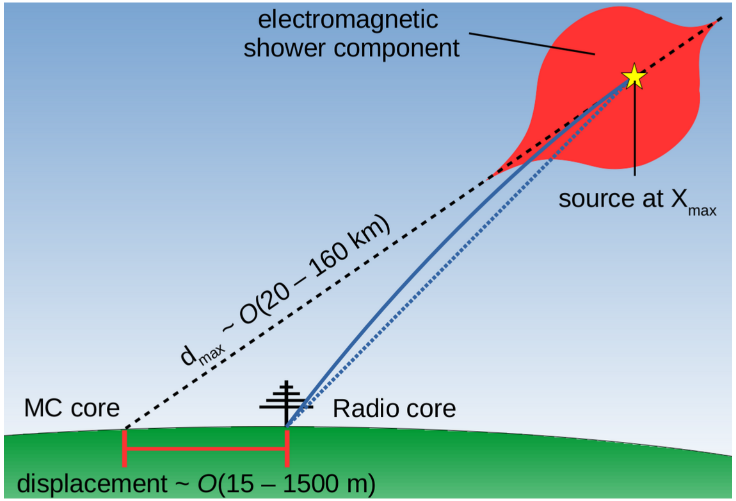
- Displacement always into the incoming direction of the air shower
  - Top plot: linear scale, circle denotes constant displacement of 1500 m
  - Bottom plot: lineare scale inside red square, logarithmic outside of square
- East-West asymmetry and rotation of the pattern need further investigation

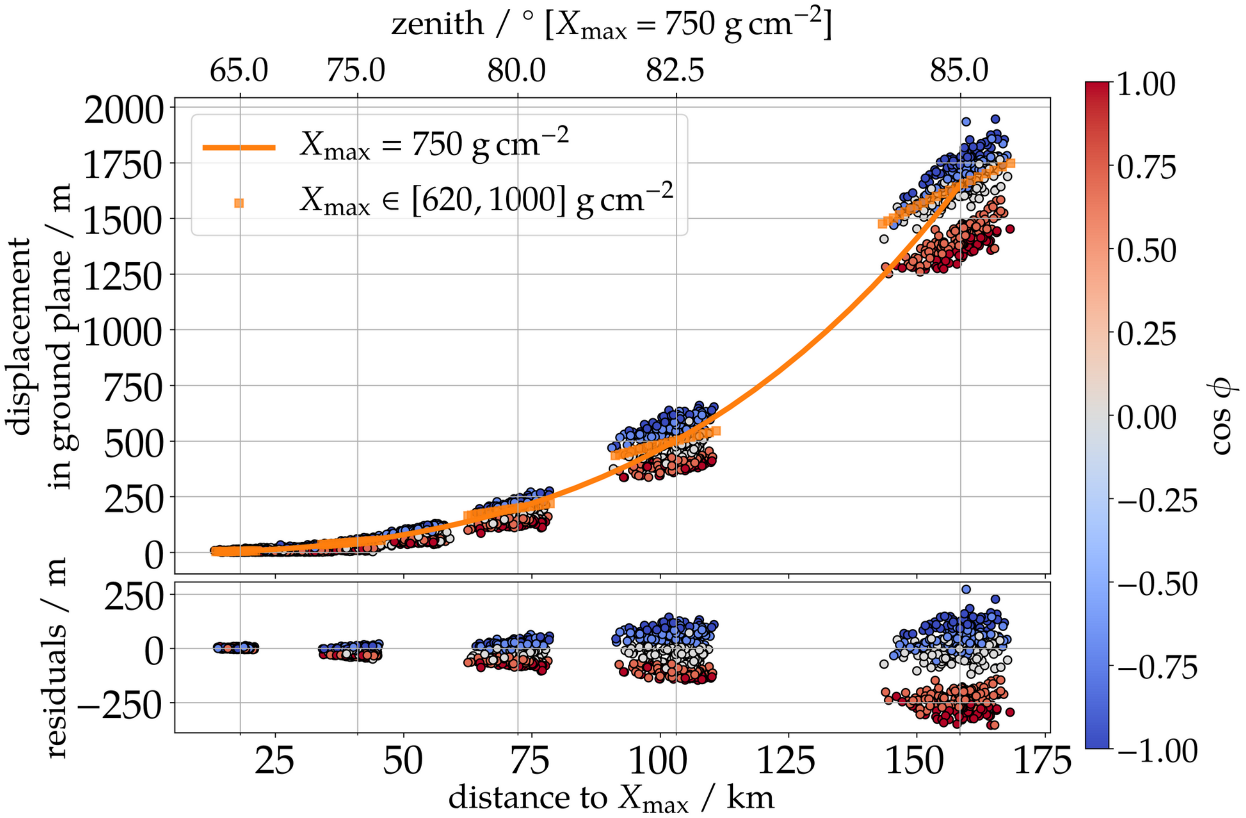




Refraction model

- Reflection of the radio emission following Snell's law for finely layered atmosphere
- Predicts displacement in shower incoming direction





- Reasonable describtion of the magnitude (orange line) and slope (orange squares)
- No strong correlation of residuals with distance to X_{max}

Long paper

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Refractive displacement of the radio-emission footprint of inclined air showers simulated with CoREAS

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- More information in paper: Link
  e.g. similar displacement for 30–80 MHz (e.g. AERA) and 50–200 MHz (e.g. GRAND)

Conclusion

- Radio core is displaced up to 1.5 km with respect to MC core, corresponds to 15% of Cherenkov radius in the shower plane
- Refraction during propagation in an atmosphere with a refractive index gradient
- Detailed understanding of the radio footprint:
  - Superposition of geomagnetic and charge-excess emission
  - Early-late asymmetry (for inclined air showers)
  - Core displacement (for inclined air showers)
- Relevant for development of a radio reconstruction for inclined air showers and interpretation of hybrid detection, i.e. particles and radio
- Further information in F. Schlüter et al. EPJ C 80 (2020) 643