Characteristics of Atmosphere-Skimming air showers relevant for high-altitude radio experiments

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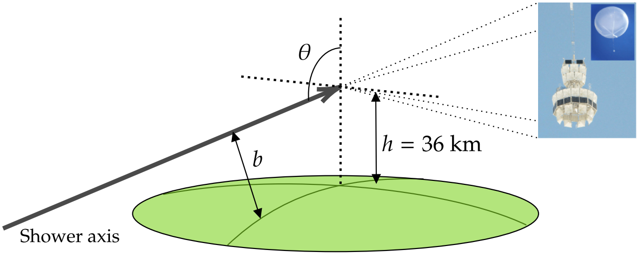
June 12, 2024

Introduction & Motivation

- Air showers developing in the atmosphere without intercepting ground



- Propagation across very low densities under the effect of the geomagnetic field

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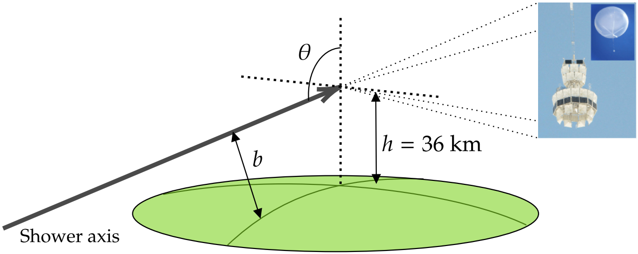

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- 7 atmosphere-skimming events detected in ANITA flights. Recent observations by EUSO-SPB2

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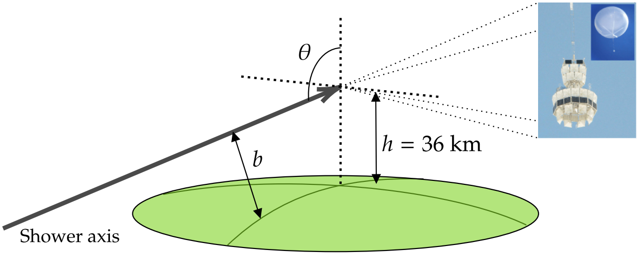
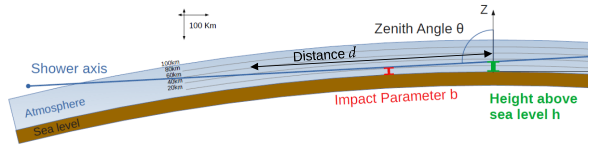
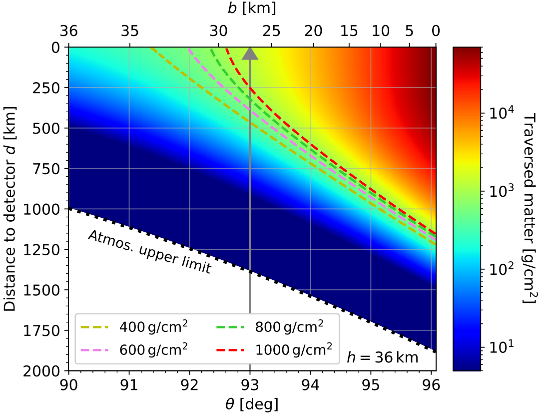


- Propagation across very low densities under the effect of the geomagnetic field
- 7 atmosphere-skimming events detected in ANITA flights. Recent observations by EUSO-SPB2
- *RASPASS*: Version of ZHAireS allowing simulations of any geometry.

Parameter space for shower development

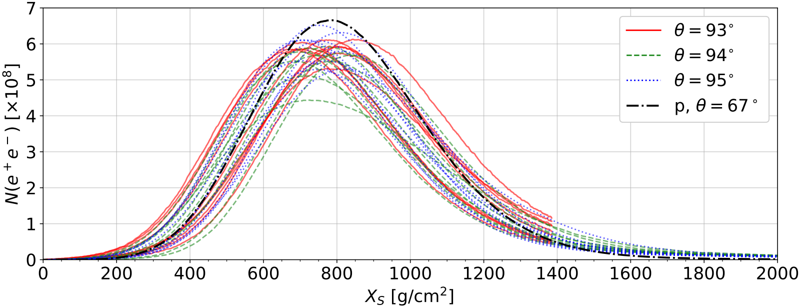




- Balloon-borne detector: $h = 36\,\mathrm{km}$
- Available matter for shower development and impact parameter restrict *detectable* geometries

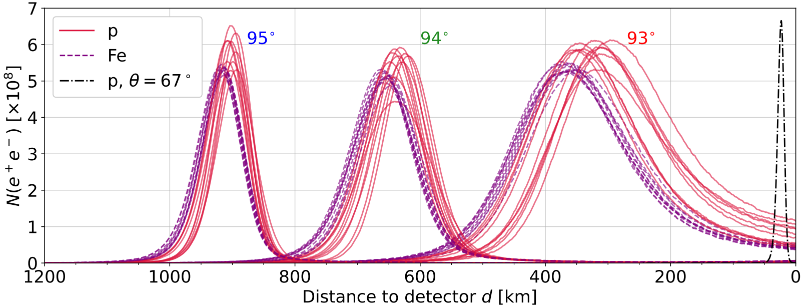
Longitudinal development

- $\langle X_{\mathrm{max}} \rangle$ and $\sigma\left(X_{\mathrm{max}}\right)$ similar to downward-going showers in units of $\mathrm{g/cm^2}$



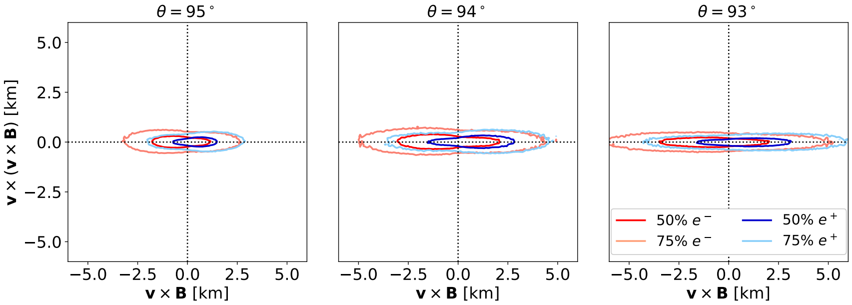
Longitudinal development

- $\langle X_{\mathrm{max}} \rangle$ and $\sigma\left(X_{\mathrm{max}}\right)$ similar to downward-going showers in units of $\mathrm{g/cm^2}$
- Showers stretching distances of hundreds of km, increasing for cascades developing higher in the atmosphere
- Fluctuations in X_{max} reach the order of tens km



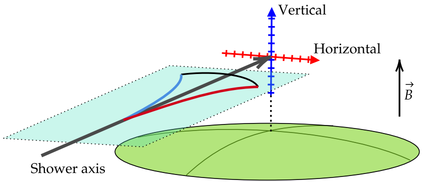
Lateral development at $X_{\max}$

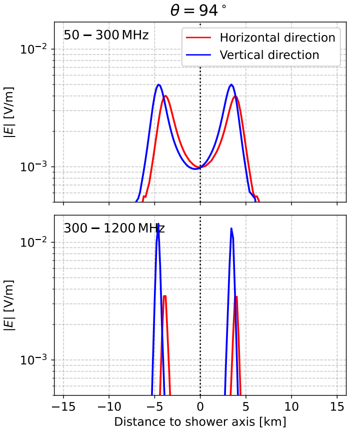
- Showers develop across huge distances under the geomagnetic field
- *Flattening* of the shower front in the $\mathbf{v} \times \mathbf{B}$ direction
- Effect enhanced as cascades propagate in lower densities (smaller θ)



Lateral distribution of the signal

- Geometry and dimensions of cascades affect their radio emission
- Radio LDF displaced downwards: *Refractive asymmetry*
- Enhanced for inclined showers. Independent of frequency





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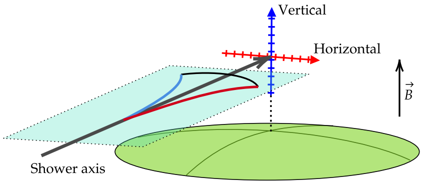
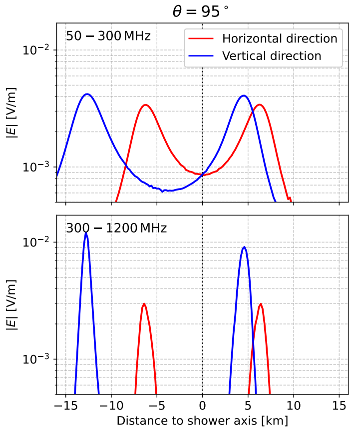
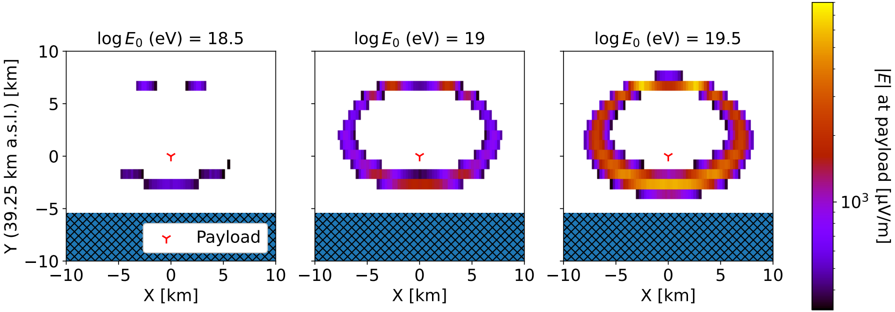




Effects on aperture of balloon-borne experiments

- Asymmetries in the radio emission impact the effective area of high-altitude detectors
- Example: Showers producing signals above trigger threshold of ANITA, assuming elevation angle of event 9734523 of ANITA IV ($\theta = 95.64^\circ$)



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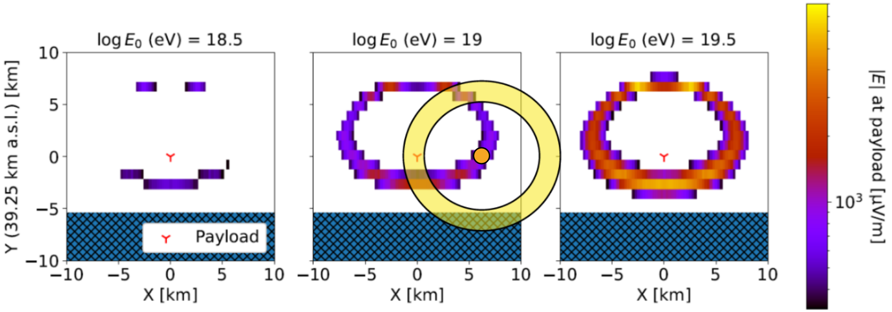

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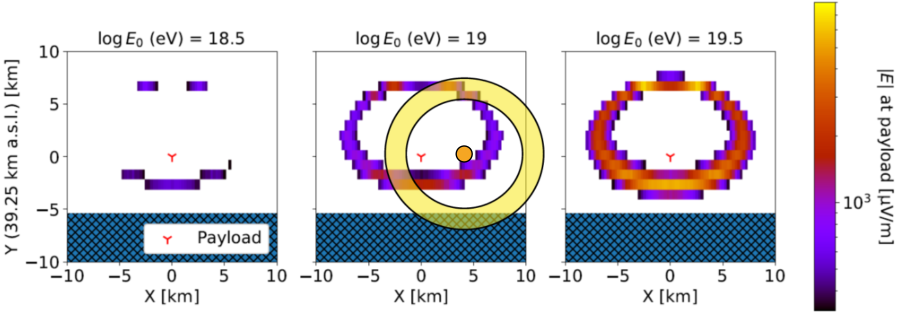

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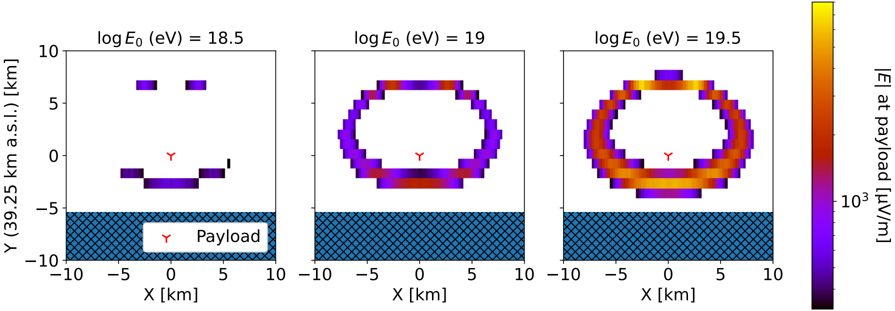
- Asymmetric effective area around the detector due to refractive effects



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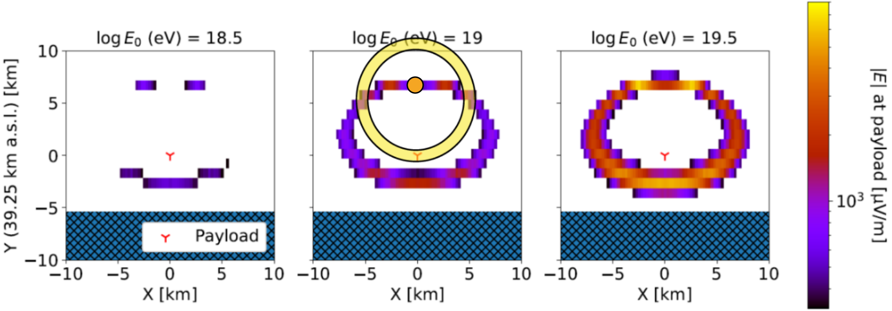

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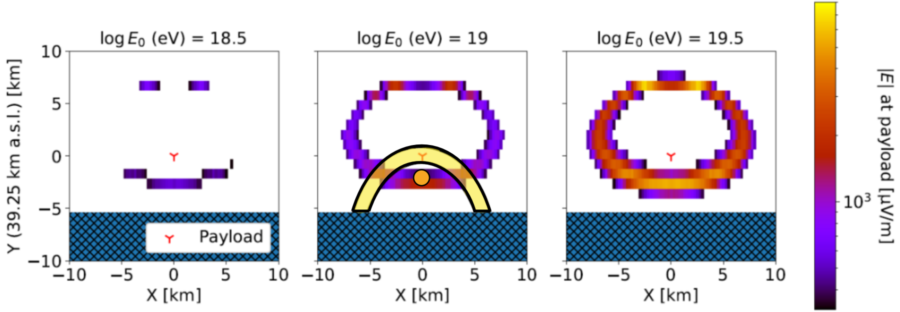
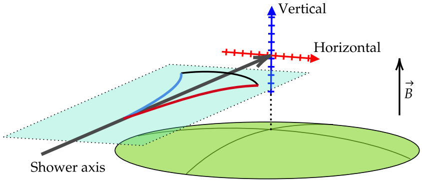
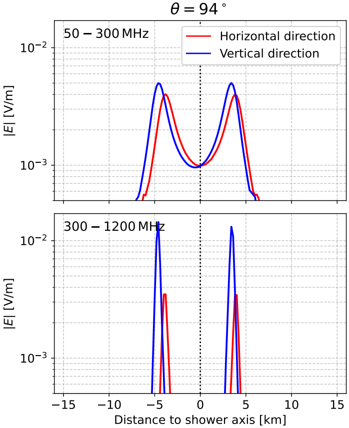


Lateral distribution of the signal

- Geometry and dimensions of cascades affect their radio emission
- Stronger electric fields outside the $\mathbf{v} \times \mathbf{B}$ plane: *Coherence* asymmetry
- Dependence on shower geometry, orientation w.r.t magnetic field and frequency of observation.





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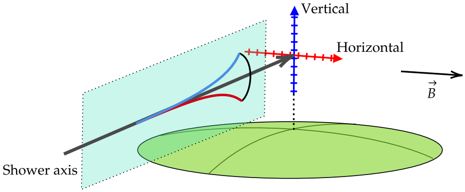

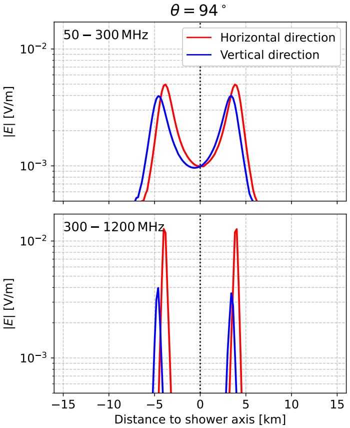

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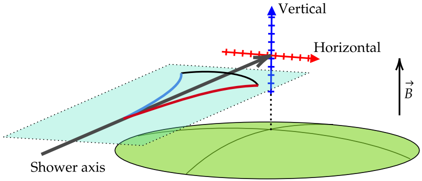

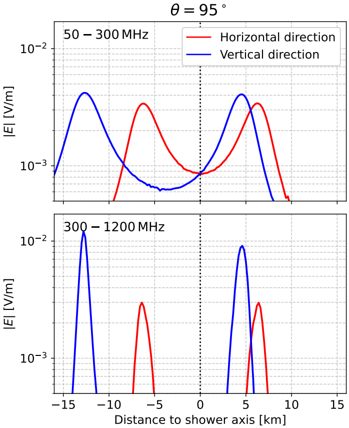

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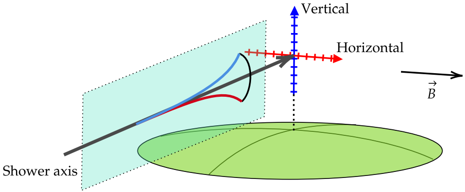

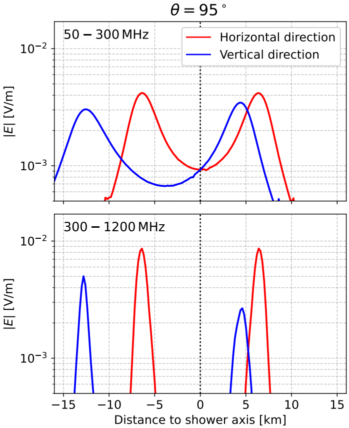

Effects on aperture of balloon-borne experiments

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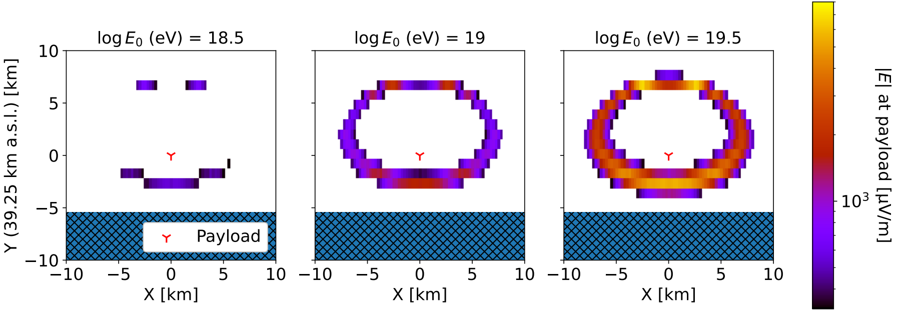
- Coherence asymmetry: Showers leaving the detector outside their *flattening* plane ($\mathbf{v} \times \mathbf{B}$) produce stronger signals (ID 9734523, $\theta = 95.64°$)



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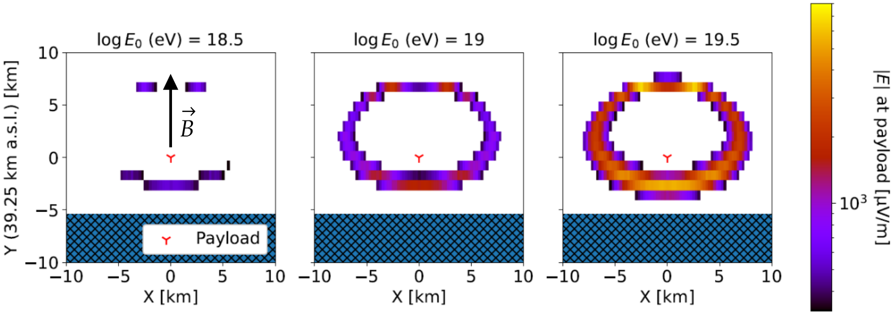
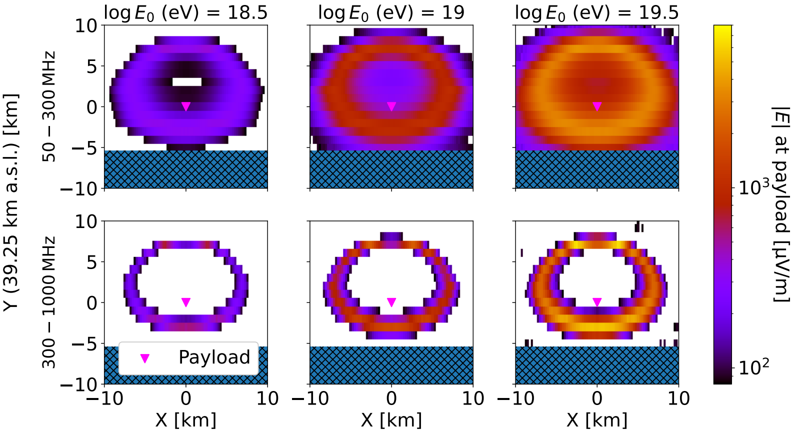


Future detectors

- Lower trigger thresholds will increase the number of observed events
- Instruments working in lower frequency bands will be less affected by coherence asymmetry



Conclusion & Outlook

- Atmosphere-skimming air showers develop across very low densities under the effect of the geomagnetic field.
- Length scales reaching hundreds of km, strongly flattened along the $\mathbf{v} \times \mathbf{B}$ direction
- Two distinct features in the radio emission: refractive and coherence asymmetries
- Complex dependence between shower geometry and detector position

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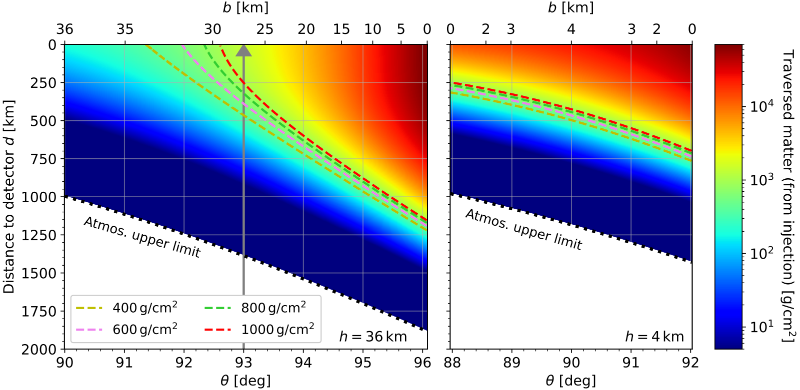
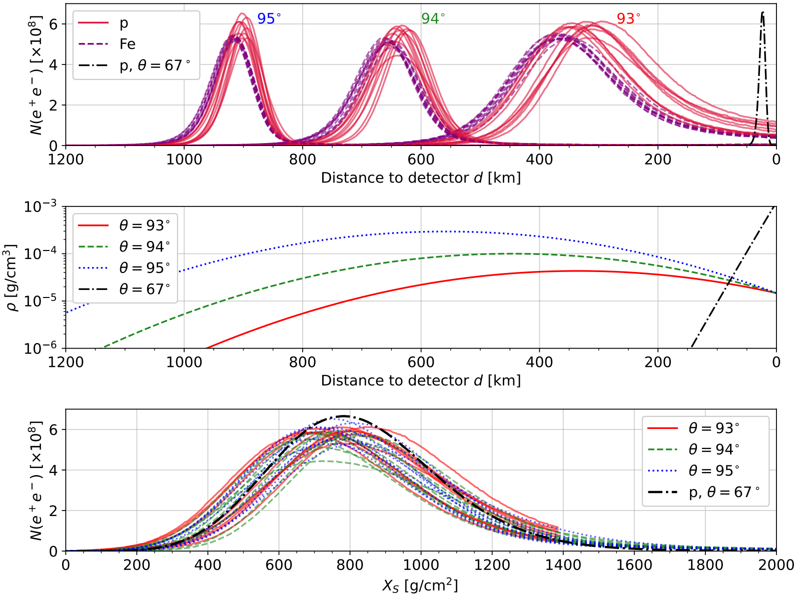
- Two distinct features in the radio emission: refractive and coherence asymmetries
- Complex dependence between shower geometry and detector position
- Detailed simulations will be needed to study how these effects influence the interpretation of collected data
- ZHAireS-RASPASS available upon request

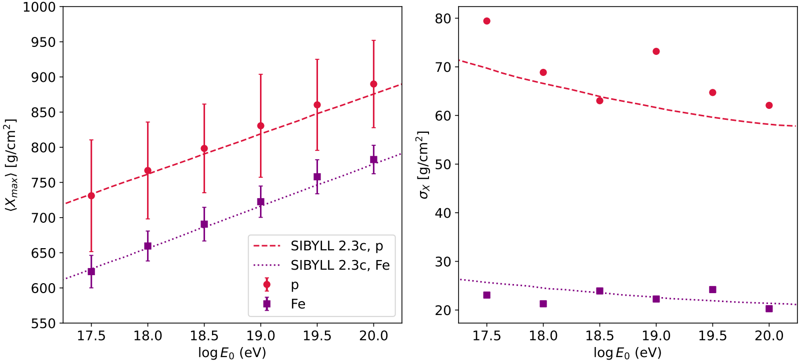
Backup: Phase space



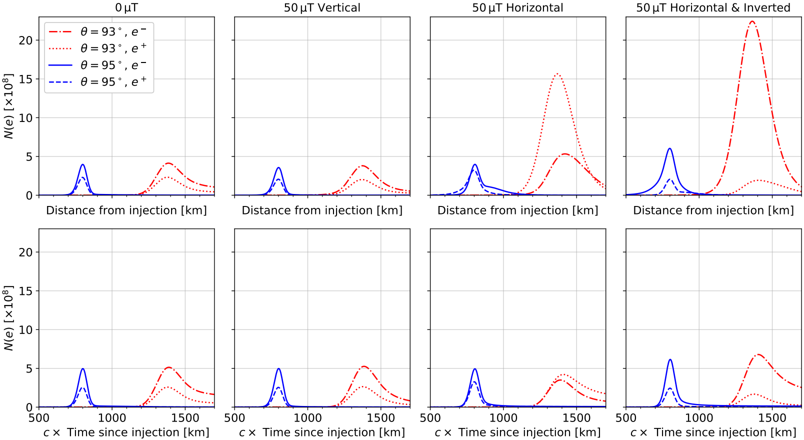
Backup: Longitudinal development



Backup: Elongation Rate



Backup: Longitudinal development & magnetic field effects



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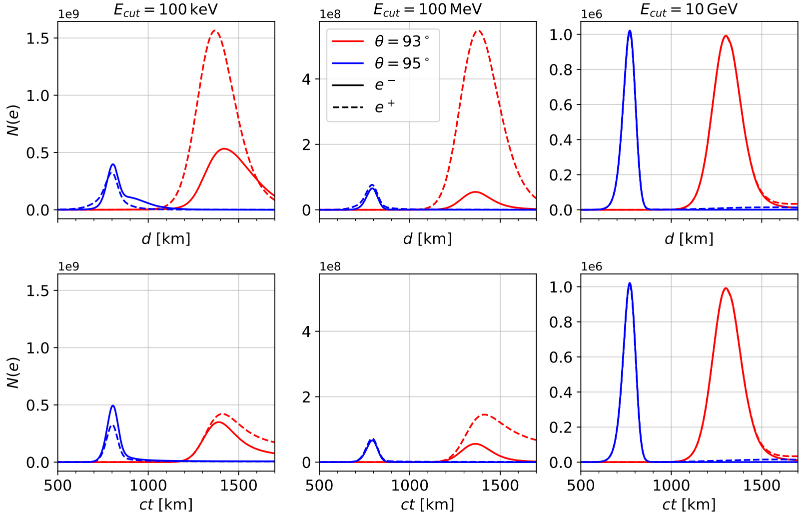
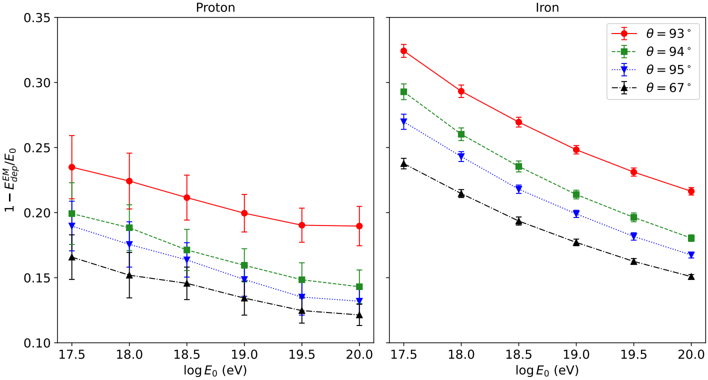


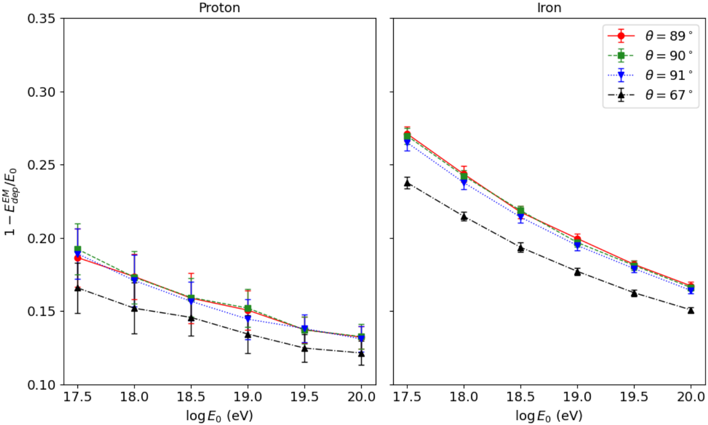
Backup: Invisible energy for radio

- Showers passing at $h = 36\,\mathrm{km}$



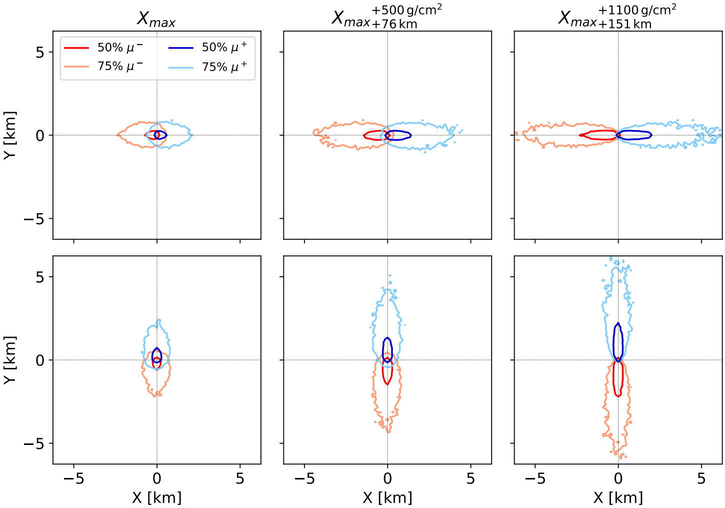
Backup: Invisible energy for radio

- Showers passing at $h = 4\,\mathrm{km}$



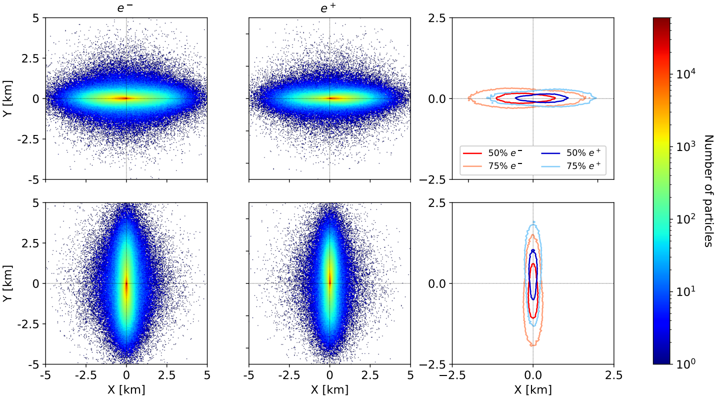
Backup: Muon lateral development

- Proton shower with $\theta = 94°$, $h = 36\,\mathrm{km}$



Backup: Electron lateral development

- Proton shower with $\theta = 94^\circ$, $h = 36\,\mathrm{km}$ at X_{max}



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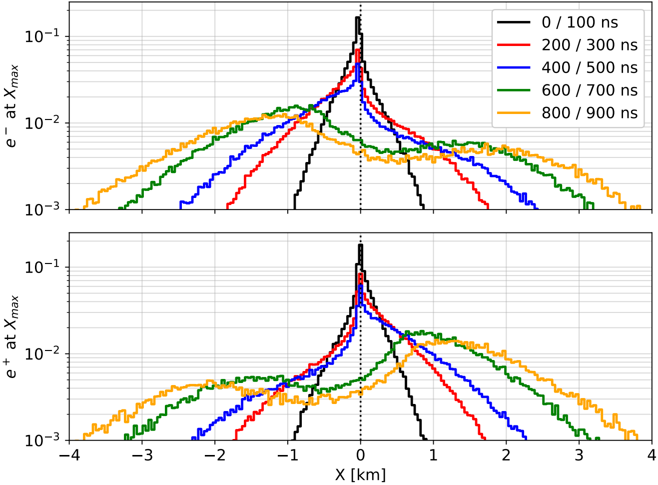
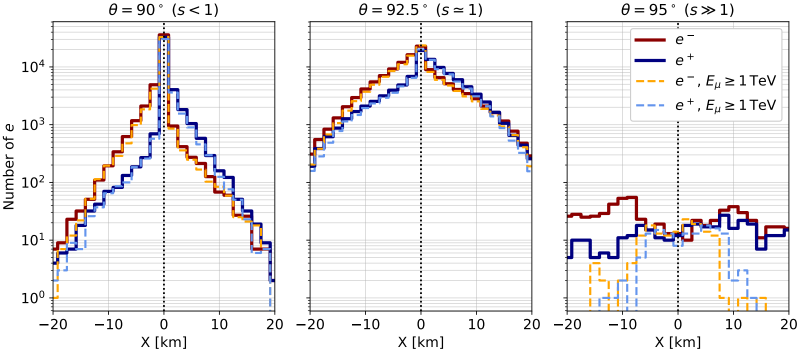
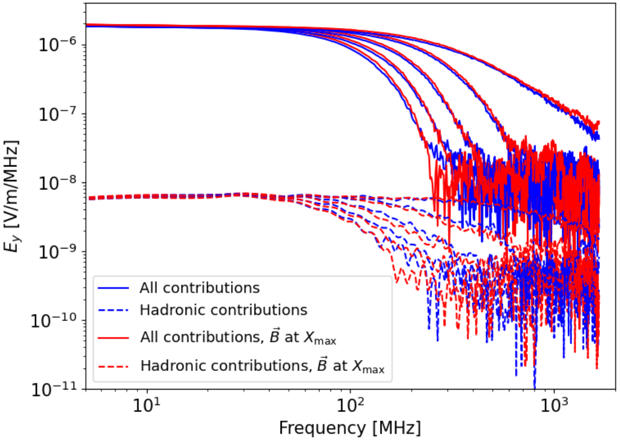


Backup: Distribution of particles at the detector

- Proton showers with $h = 36\,\mathrm{km}$ intercepted at different ages

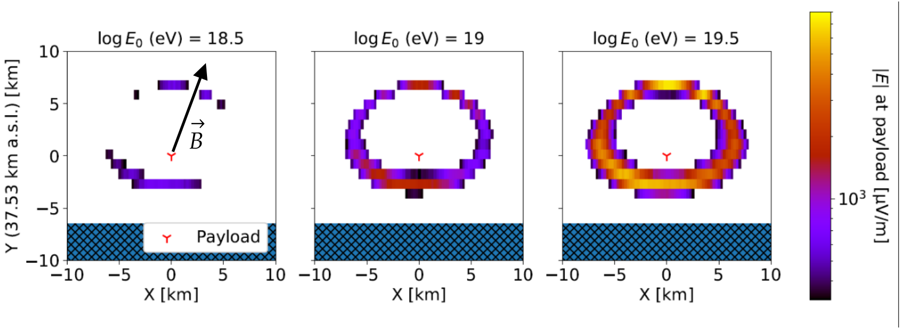


Backup: Hadronic contribution & Constant $\vec{B}$ approx.



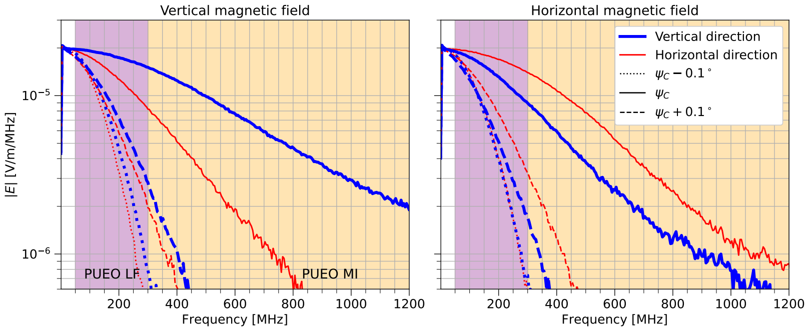
Backup: Aperture of balloon-borne experiments

- Asymmetries in the radio emission impact the effective area of high-altitude detectors
- Coherence asymmetry: Showers leaving the detector outside their *flattening* plane ($\mathbf{v} \times \mathbf{B}$) produce stronger signals (ID 51293223, $\theta = 95.38^{\circ}$)



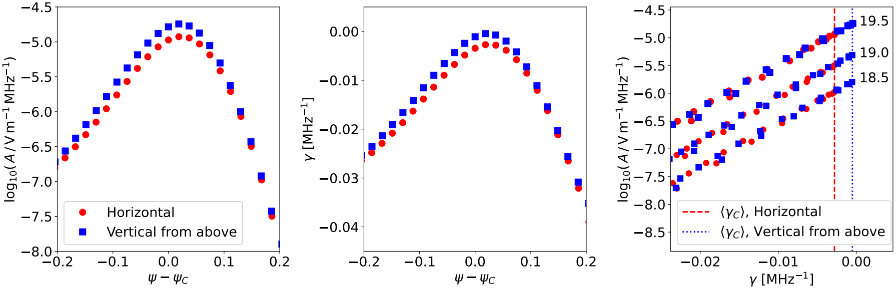
Simulated spectra

- Reduction of high frequency content at positions inside the *flattening* plane of the shower
- Different spectral slope at equivalent off-axis positions.
- Most important differences appear close to the Cherenkov angle
- Possible effects on analysis methods based on spectral shape.



Backup: Impact of asymmetries on spectral slopes

- Exponential fits to the spectrum in the $100 - 250\,\mathrm{MHz}$ band for a proton shower with $\theta = 94^\circ$ and $h = 36\,\mathrm{km}$



Backup: Effective area of ANITA IV

- Assuming elevation angles for the two events detected by ANITA IV
- Multiplied by the cosmic ray flux as measured by Auger