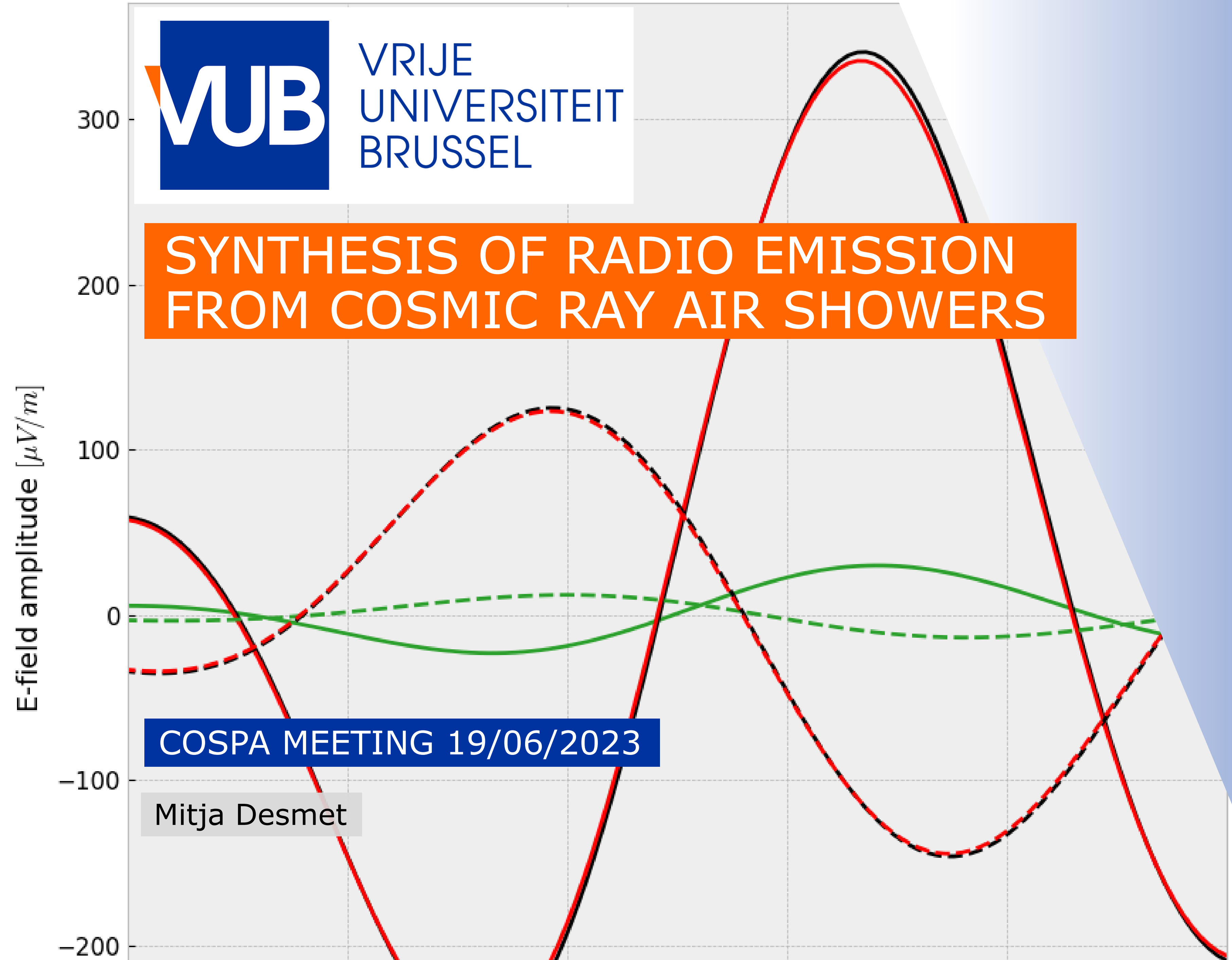
SYNTHESIS OF RADIO EMISSION FROM COSMIC RAY AIR SHOWERS

COSPA MEETING 19/06/2023

Mitja Desmet



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STATE-OF-THE-ART SIMULATION CODES LIMIT OUR ANALYSES

INTRODUCTION

When detecting extensive air showers (EAS) using their radio emission,
we use Monte-Carlo based simulation codes to

- Characterising and evaluating our detector performance.
  - We will want to simulate many more antennas for future arrays (GRAND, SKA, Auger Radio Detector).

- Perform analyses on our data (for example reconstructing X_{max}).
  - We want to extract more information from radio data, like for example the width and asymmetry of the particle number distributions (often referred to as the L and R parameters).

WE NEED A FASTER WAY OF SIMULATING THE RADIO EMISSION FROM EAS

INTRODUCTION

1 CORSIKA/CoREAS shower with

- Proton primary
- Primary energy of 10^{18} eV
- 6 simulated antennas

took **8 days** to complete.

TEMPLATE SYNTHESIS USES SEMI-ANALYTICAL RELATIONS TO CHARACTERISE THE RADIO EMISSION FROM EAS

THE METHOD

- In template synthesis, we characterise the radio signal in an antenna using a parametrized function.

- By relating the parameters of this function to the air showers properties (primary energy, geometry, longitudinal profile), we find relations which can be used to "morph" the emission from one EAS to one with different properties.

- These relations are extracted from a set of Monte-Carlo simulations, thus benefitting from their precision.

The goal: have a method which only needs one Monte-Carlo simulation as input to synthesise the radio emission from hundreds of other ones for a fraction of the computational cost.

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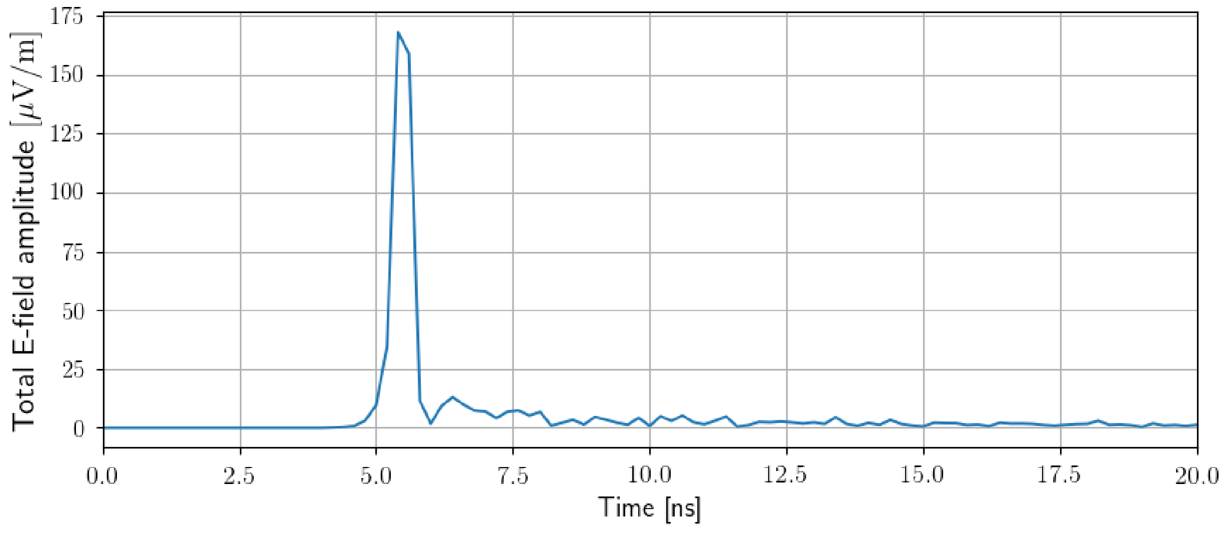
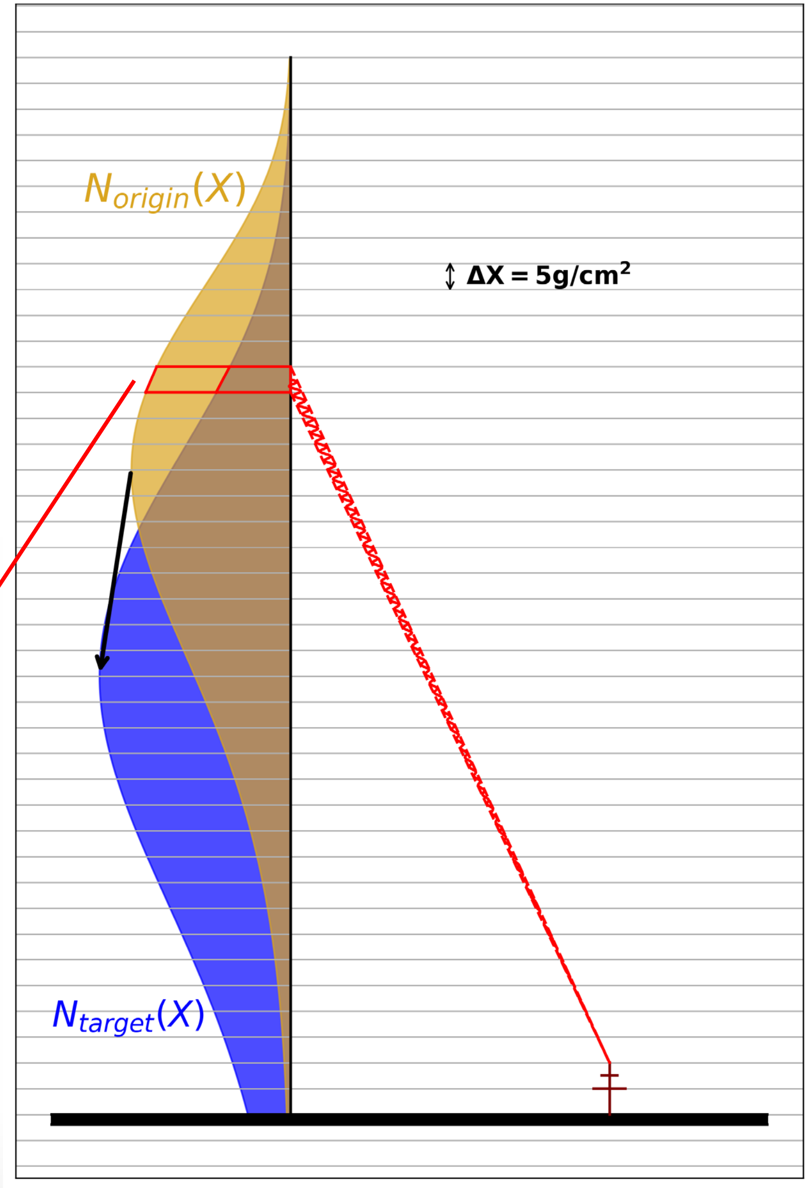
TEMPLATE SYNTHESIS CONSIDERS SLICES OF THE ATMOSPHERE AS POINT SOURCES

THE METHOD

Instead of parametrizing the total emission, we look at the emission coming from atmospheric slices with constant atmospheric depth.

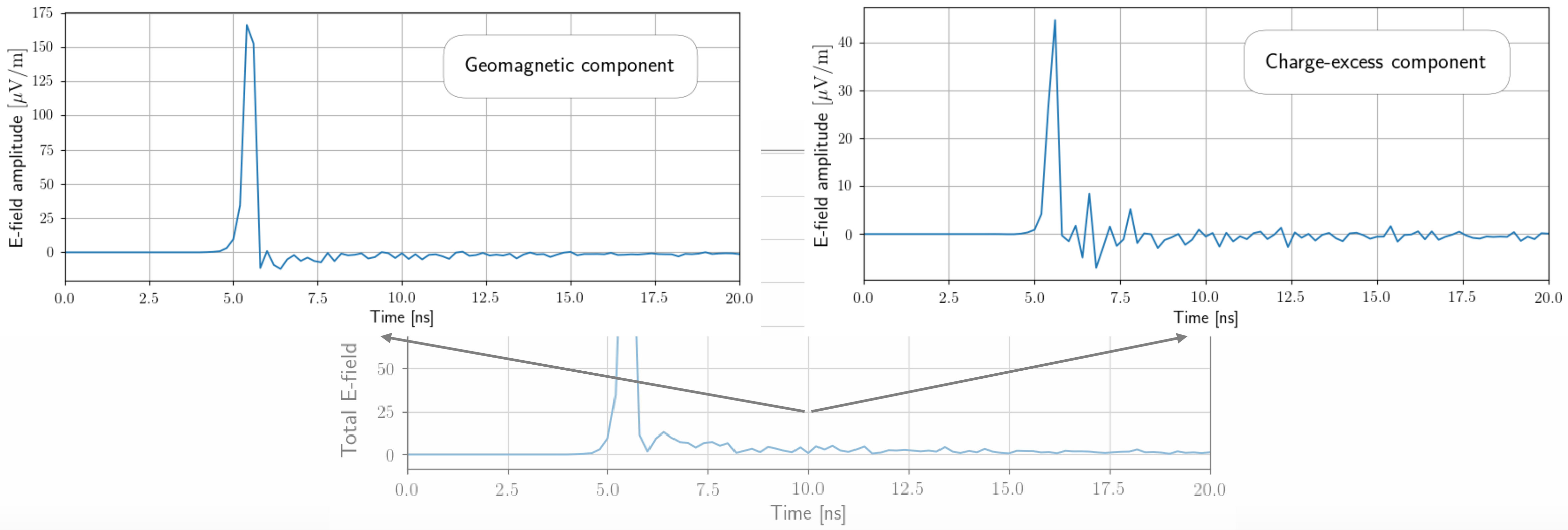
- The emission from a slice depends on the number of particles in it, N_{slice}, as well as the age of the shower in that slice.





WE CONSIDER THE GEOMAGNETIC AND CHARGE-EXCESS COMPONENTS SEPARATELY

THE METHOD

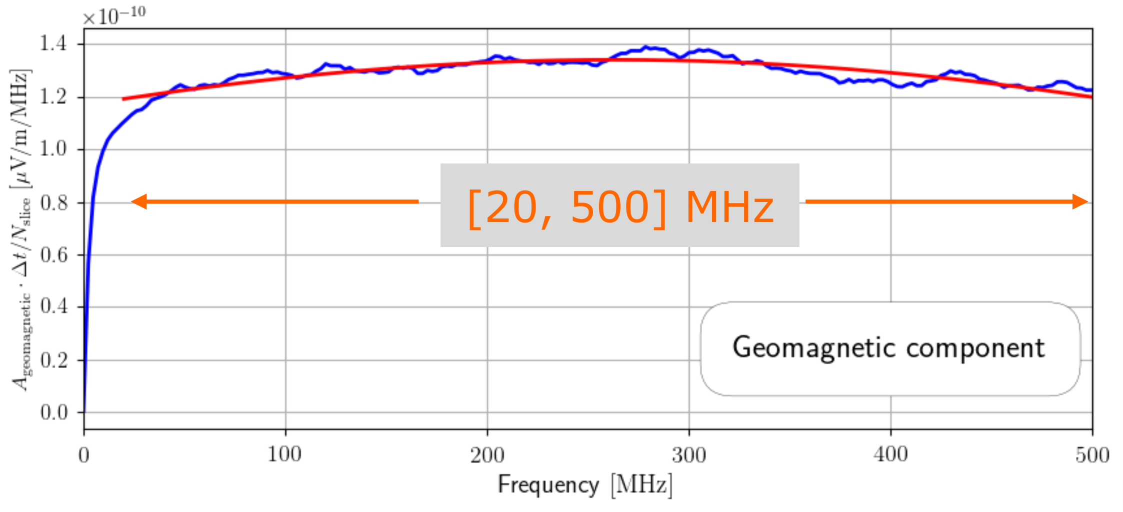


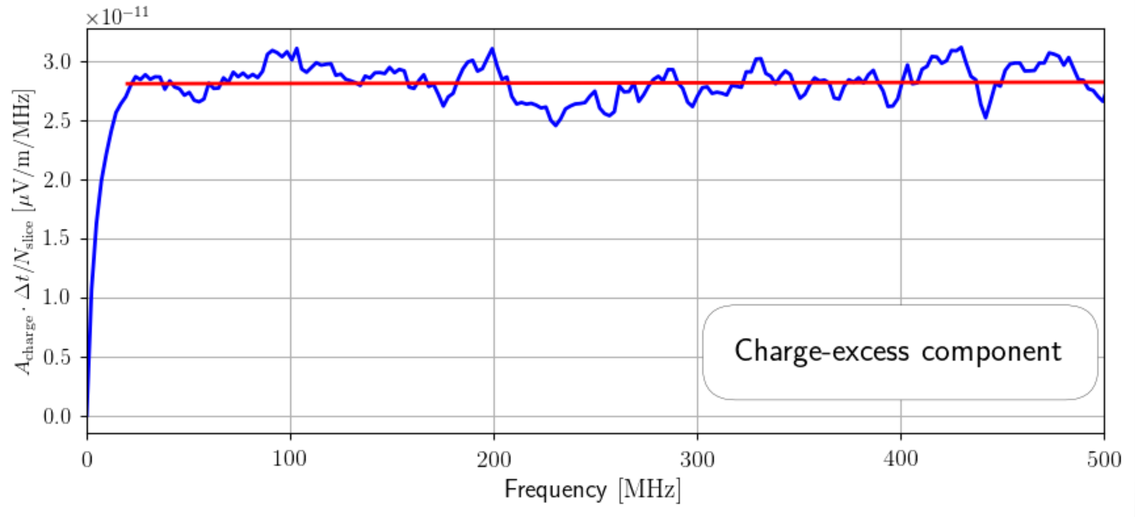
WE PARAMETRIZE THE AMPLITUDE FREQUENCY SPECTRUM OF EACH COMPONENT

THE METHOD

$$A_{geo} = (a \cdot N_{slice}) \cdot \exp(b \cdot (f - f_0) + c \cdot (f - f_0)^2)$$

$$A_{ce} = (a \cdot N_{slice}) \cdot \exp(b \cdot (f - f_0))$$





WE PARAMETRIZE THE AMPLITUDE FREQUENCY SPECTRUM OF EACH COMPONENT

THE METHOD

$$A_{geo} = (a \cdot N_{slice}) \cdot \exp(b \cdot (f - f_0) + c \cdot (f - f_0)^2)$$

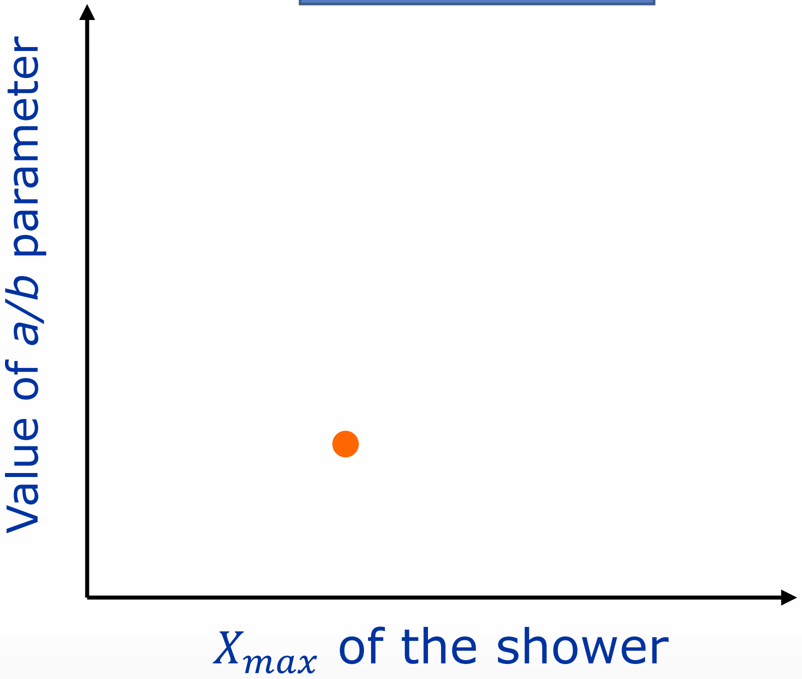
Spectral parameters

THE SPECTRAL PARAMETERS CAN BE RELATED TO THE XMAX OF THE SHOWER

THE METHOD

Geomagnetic

Charge-excess

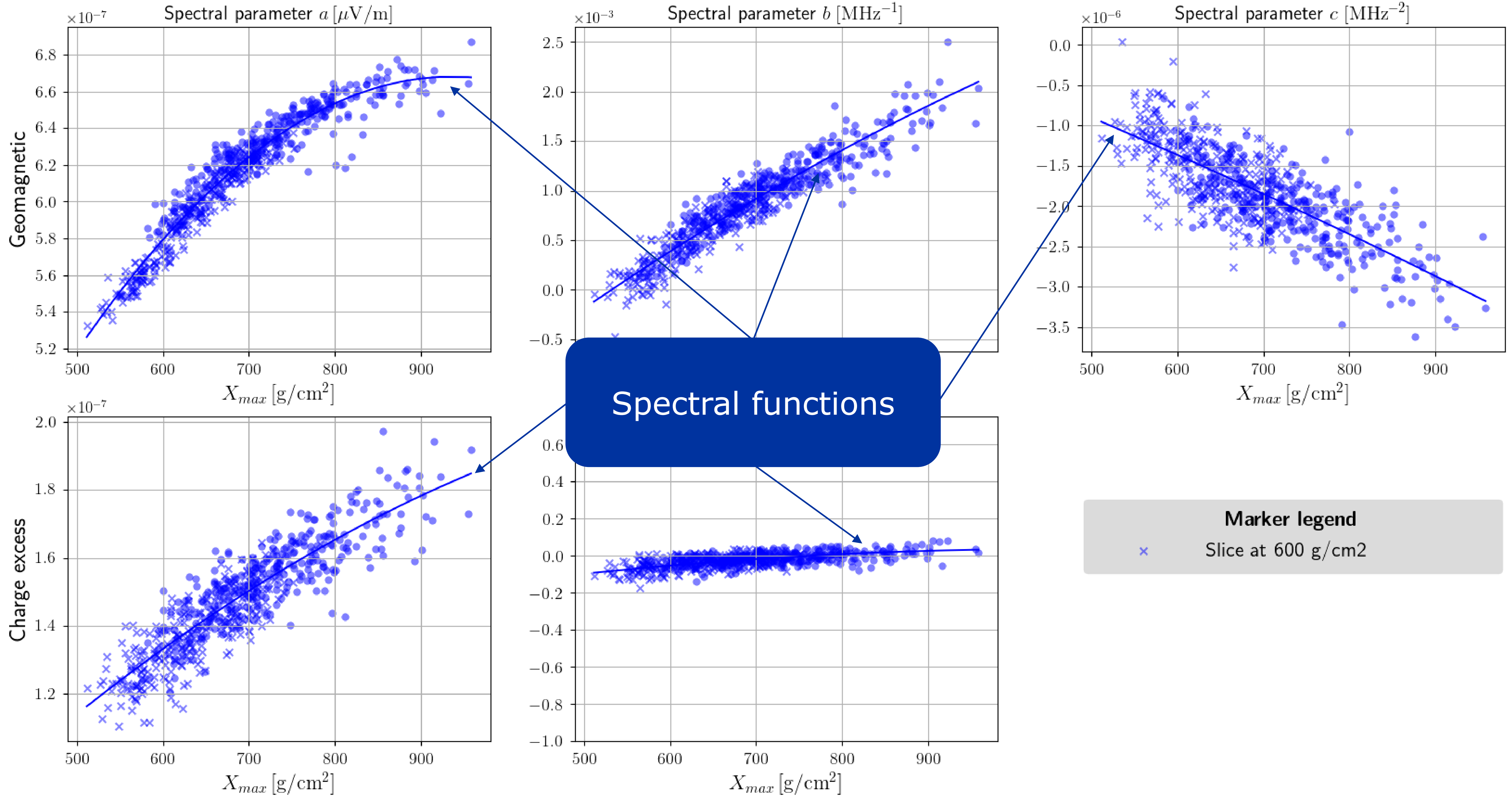


THE SPECTRAL PARAMETERS ARE CORRELATED WITH XMAX

THE METHOD

We repeat this process for 600 showers, simulated with CORSIKA and using CoREAS for the calculation of the radio emission.

- We used QGSJETII-04 and FLUKA as hadronic interaction models.
- All showers had the same, vertical geometry.
- The atmosphere and magnetic field were also kept constant.
- Half of the showers had a proton as primary particle, the other half had an iron nucleus.
- For each primary type, we simulated showers with primary energies of 10^{17}, 10^{18} and 10^{19} eV (100 showers for each energy).


Spectral parameter a [μV/m]
Spectral parameter b [MHz^{-1}]
Spectral parameter c [MHz^{-2}]
$\times 10^{-7}$
$\times 10^{-3}$
$\times 10^{-6}$
Geomagnetic
Charge excess
X_{max} [g/cm^2]
Spectral functions
Marker legend
Slice at 600 g/cm2

THE SPECTRAL FUNCTIONS ENCODE THE PARABOLIC DEPENDENCE OF THE SPECTRAL PARAMETERS ON XMAX

THE METHOD

The previous plot was made for one atmospheric slice and for a single antenna. We can do this for every simulated antenna, going over every of the 207 slices to obtain the complete **spectral functions**

$$a(r_{\text{ant}}, X_{\text{slice}},\ X_{\text{max}}) = p_0^a + p_1^a \cdot\ X_{\text{max}} + p_2^a \cdot\ X_{\text{max}}^2$$

$$b(r_{\text{ant}}, X_{\text{slice}},\ X_{\text{max}}) = p_0^b + p_1^b \cdot\ X_{\text{max}} + p_2^b \cdot\ X_{\text{max}}^2$$

$$c(r_{\text{ant}}, X_{\text{slice}},\ X_{\text{max}}) = p_0^c + p_1^c \cdot\ X_{\text{max}} + p_2^c \cdot\ X_{\text{max}}^2$$

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WE SYNTHESISE STARTING FROM A LONGITUDINAL PROFILE

THE SYNTHESIS

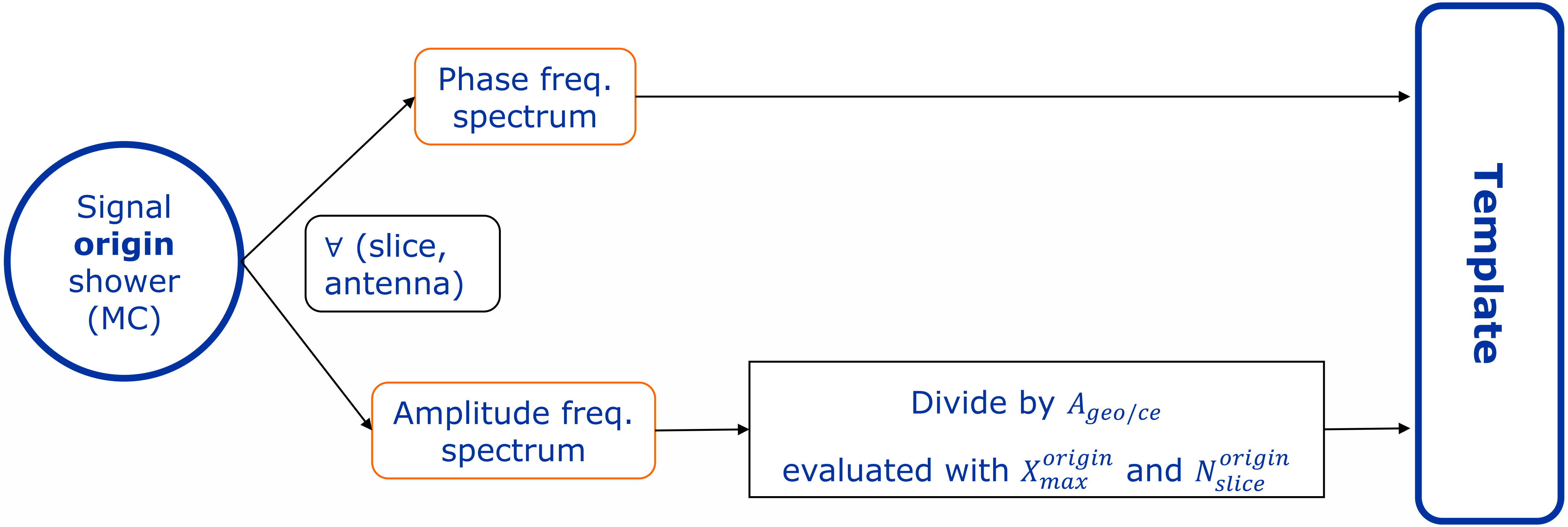
Given a target longitudinal profile, we can use the spectral functions to synthesise the radio emission. To do this, we start from our initial microscopic simulation (the “origin”).

- We have the X_{max}^{origin} and the X_{max}^{target}.
  - With these we can evaluate the spectral functions for the origin and the target in every slice.
- For every slice, we also have the number of particles in the origin and target profile, N_{slice}^{origin} and N_{slice}^{target} respectively.
  - Together with the evaluated spectral parameters, we can calculate the fitted amplitude spectra in each slice.

$$A = (a \cdot N_{slice}) \cdot \exp(b \cdot (f - f_0) + c \cdot (f - f_0)^2)$$

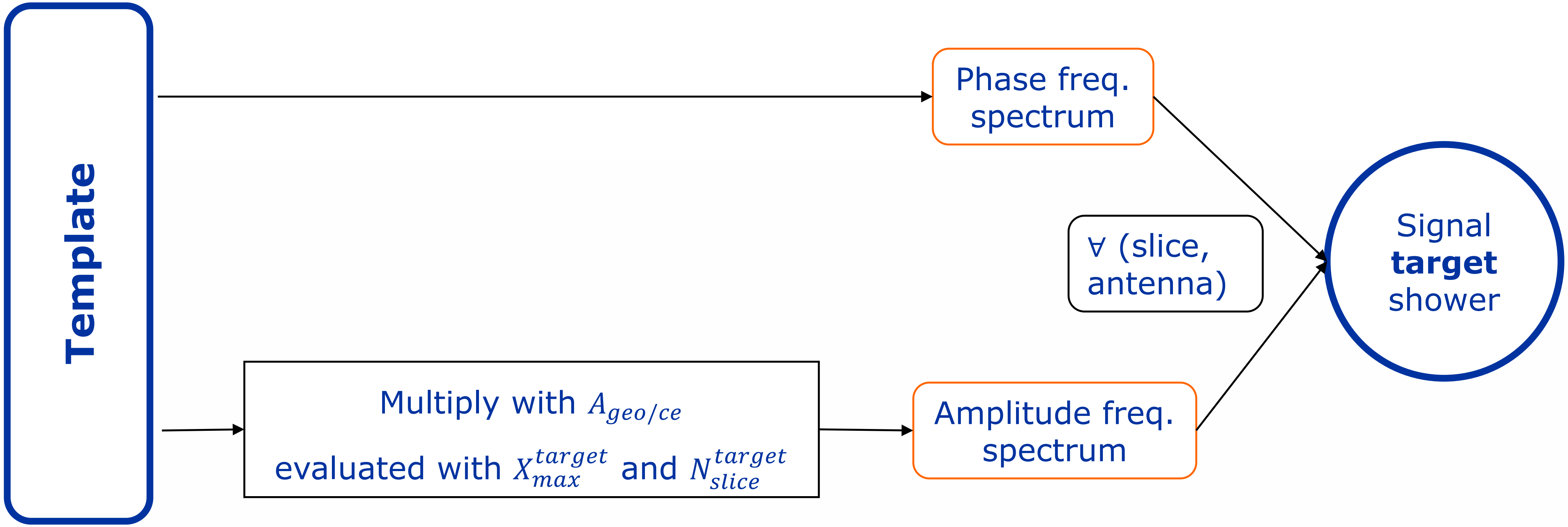
WE PROCESS THE ORIGIN SHOWER INTO A TEMPLATE

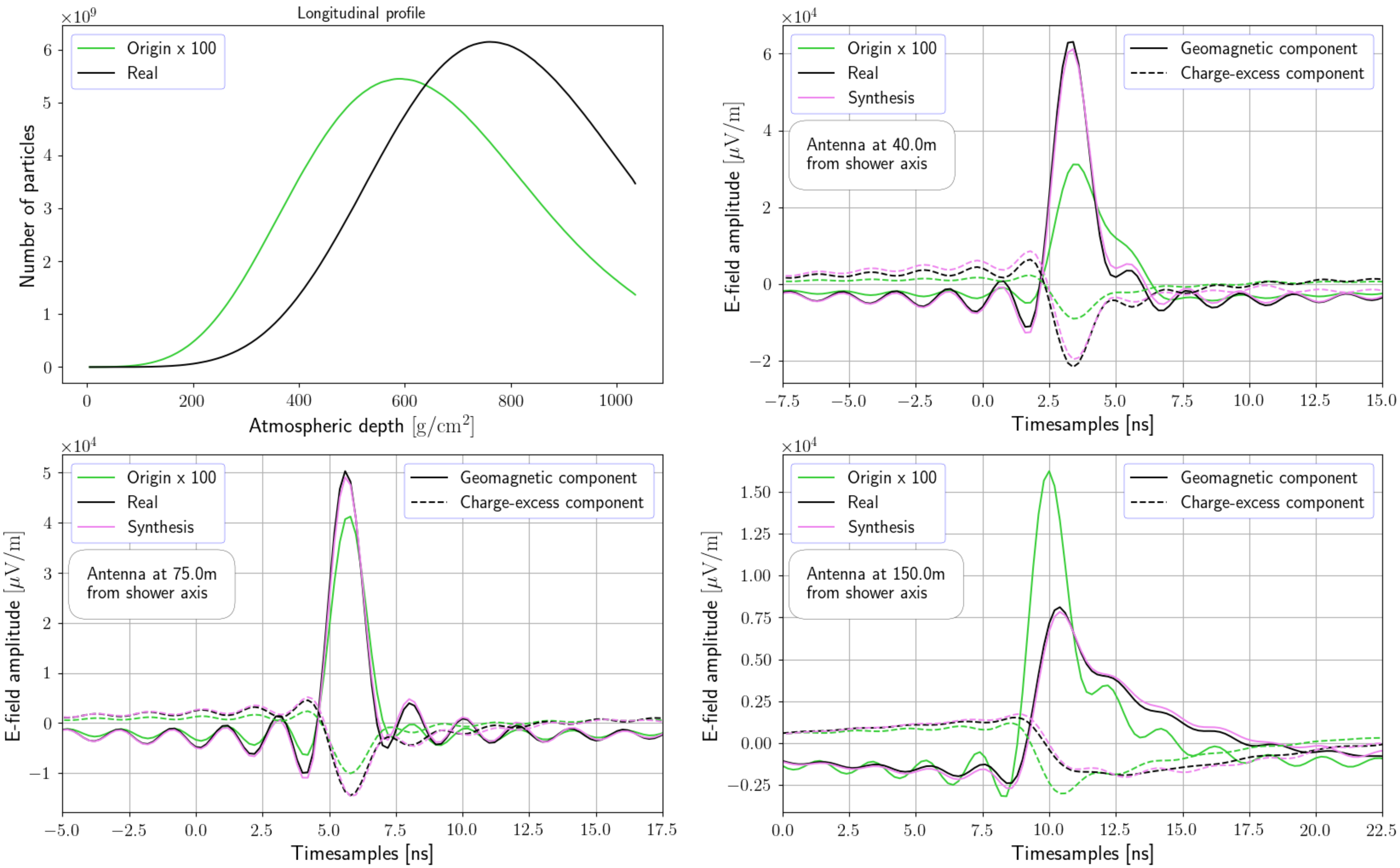
THE SYNTHESIS



FROM THE TEMPLATE WE SYNTHESISE THE SIGNAL

THE SYNTHESIS





Longitudinal profile
×10^9
Origin x 100
Real
Number of particles
Atmospheric depth [g/cm^2]
×10^4
Origin x 100
Real
Synthesis
Geomagnetic component
Charge-excess component
Antenna at 40.0m from shower axis
E-field amplitude [μV/m]
Timesamples [ns]
×10^4
Origin x 100
Real
Synthesis
Geomagnetic component
Charge-excess component
Antenna at 75.0m from shower axis
E-field amplitude [μV/m]
Timesamples [ns]
×10^4
Origin x 100
Real
Synthesis
Geomagnetic component
Charge-excess component
Antenna at 150.0m from shower axis
E-field amplitude [μV/m]
Timesamples [ns]

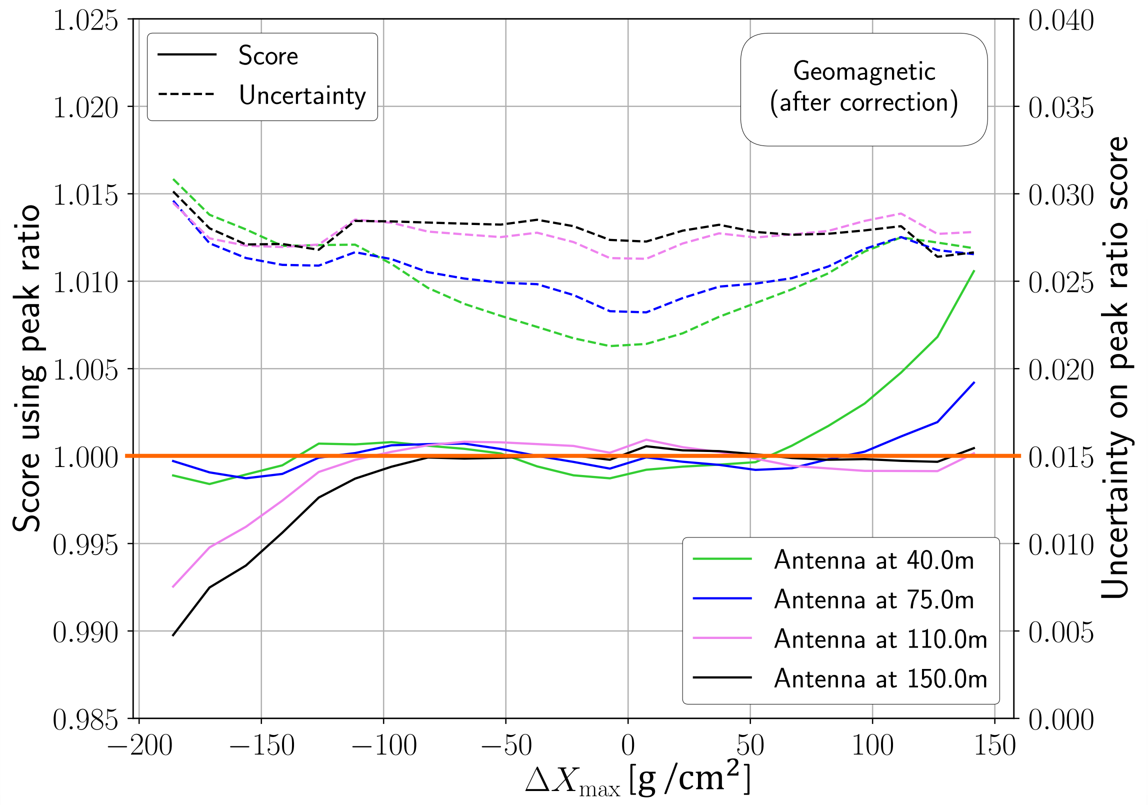
WE EVALUATE THE PERFORMANCE OF TEMPLATE SYNTHESIS OVER OUR SIMULATION SET

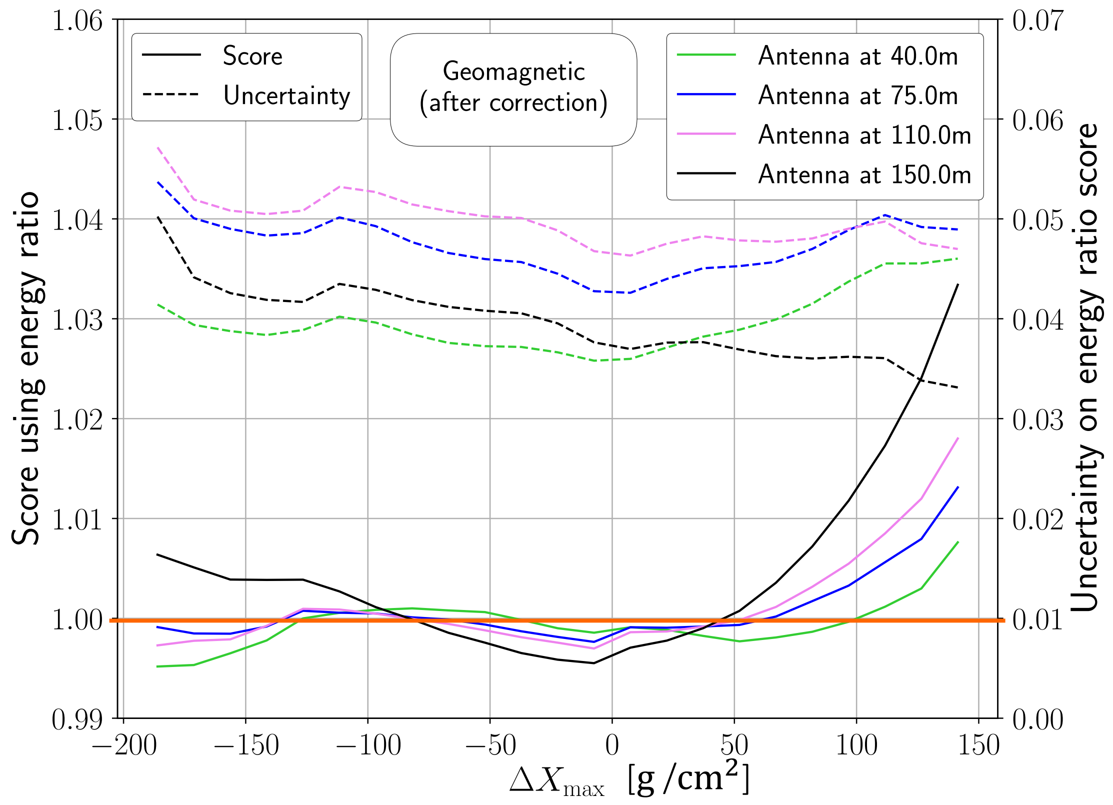
THE TEST

- To gauge the capability of template synthesis to accurately synthesise the radio emission, we subsequently use every shower from our simulation as the origin shower.
- We then synthesise the emission for every other shower in the set (using the longitudinal profile from CORSIKA).
- Using two different metrics, we score the synthesised signal.
  a) Comparing the peaks of the synthesised and CoREAS signals.
  b) Comparing the energy fluence of the synthesised and CoREAS signals.

THE SHIFT IN XMAX DETERMINES THE SYNTHESIS QUALITY

THE TEST





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WE HAVE A PROOF-OF-PRINCIPLE FOR VERTICAL AIR SHOWERS

CONCLUSION

- The method performs well for vertical air showers.
  - We are preparing a publication on these results (*Template synthesis approach for radio emission from extensive air showers*; M. Desmet, S. Buitink, T. Huege, D. Butler, R. Engel, O. Scholten).
- Recent results indicate we can play the same game for other geometries and achieve good synthesis quality.

Next steps:

- Understand the scaling of the spectral functions with geometry.
  - For this, we will probably need to reinterpret the spectral functions as being dependent on (some proxy of) shower age instead of purely X_{max}.

THANK YOU

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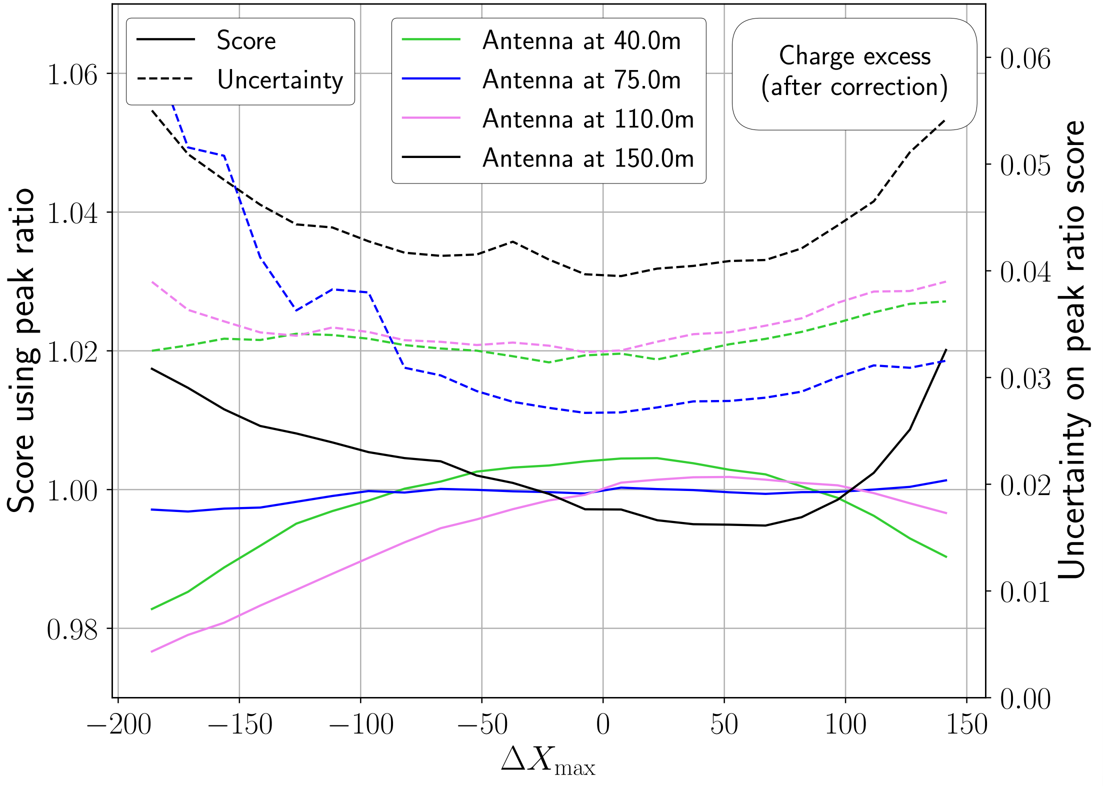
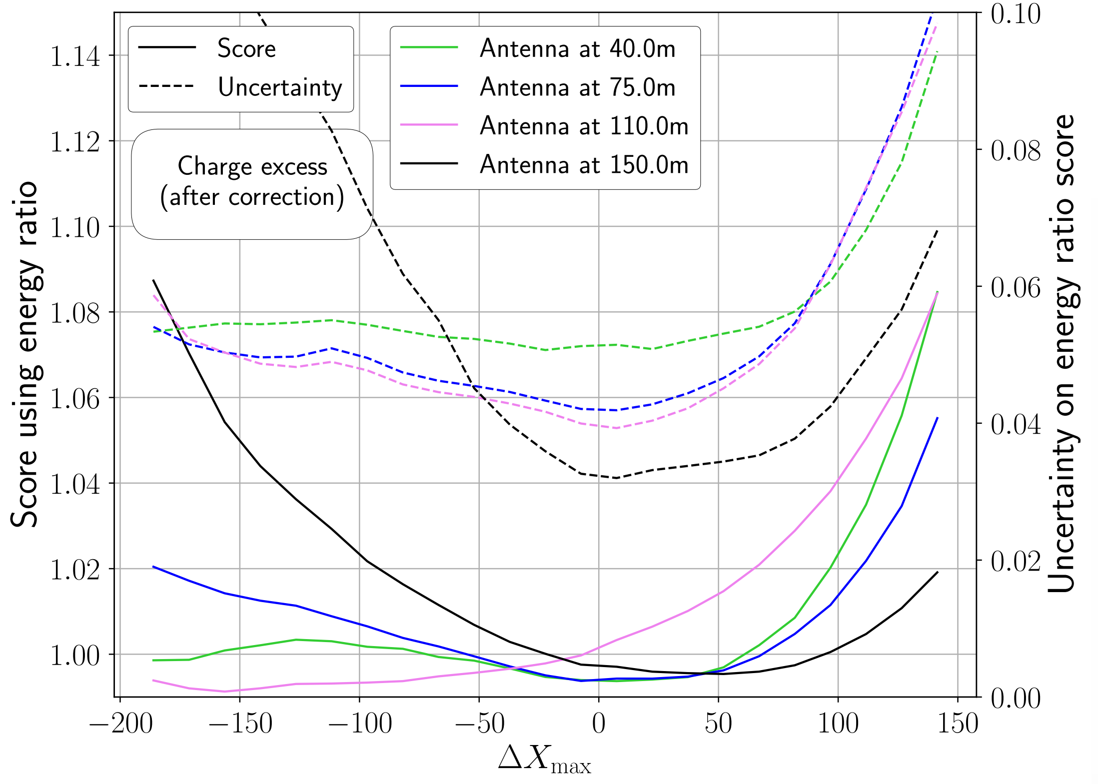
THE SHIFT IN XMAX DETERMINES THE SYNTHESIS QUALITY

THE TEST

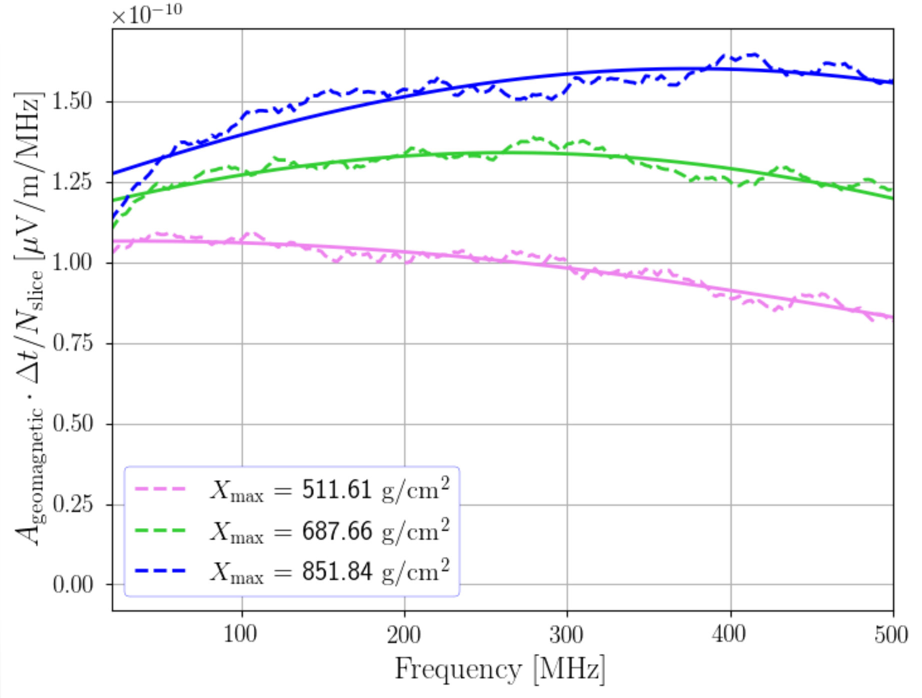


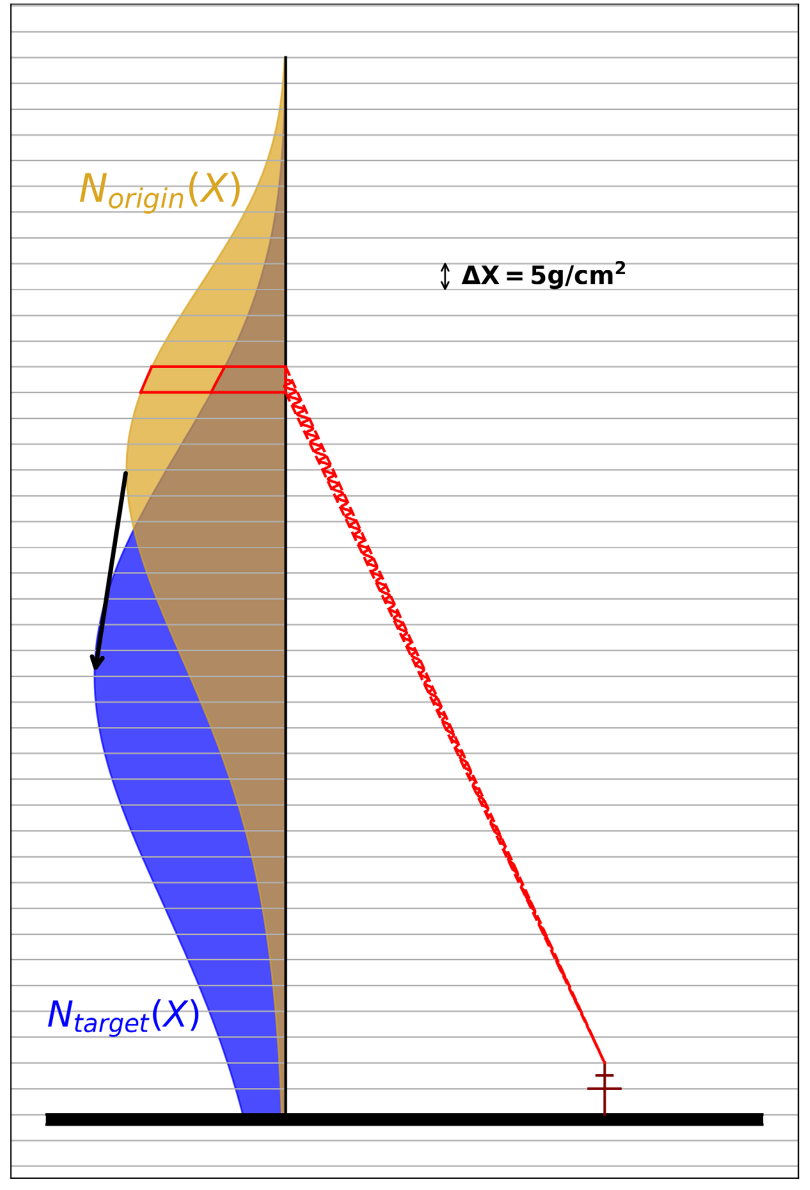


TEMPLATE SYNTHESIS CONSIDERS SLICES OF THE ATMOSPHERE AS POINT SOURCES

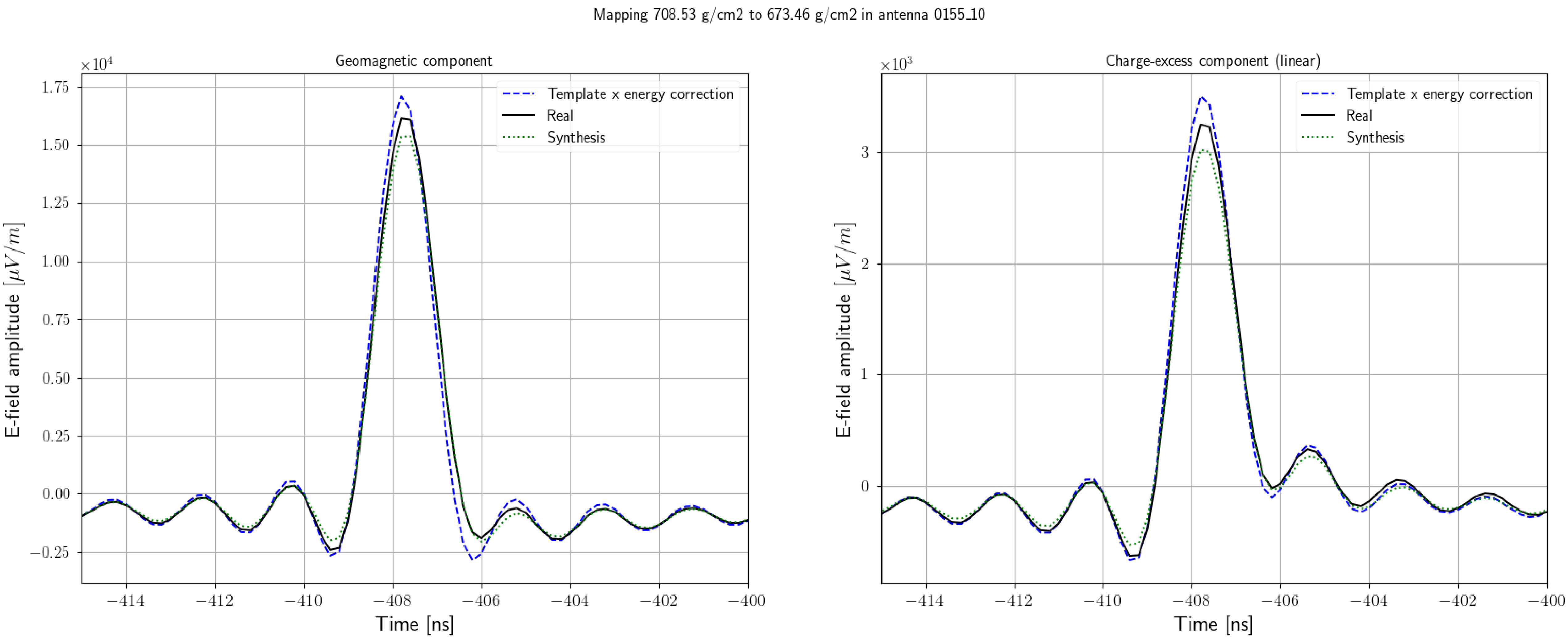
THE METHOD

- The emission from a slice depends on the number of particles in it, N_{slice}, as well as the age of the shower in that slice.





45-DEGREE TEMPLATE SYNTHESIS



TEMPLATE SYNTHESIS USES SEMI-ANALYTICAL RELATIONS TO CHARACTERISE THE RADIO EMISSION FROM EAS

THE METHOD

Radio Morphing	Template Synthesis
Reference shower	Origin shower
Scaling with shower parameters (prim. E, zenith, air density,…)	Scaling with shower parameters (prim. E, particle number, …)
Single point of emission	**Many sources along shower axis**
(3D interpolation)	(Fourier interpolation)