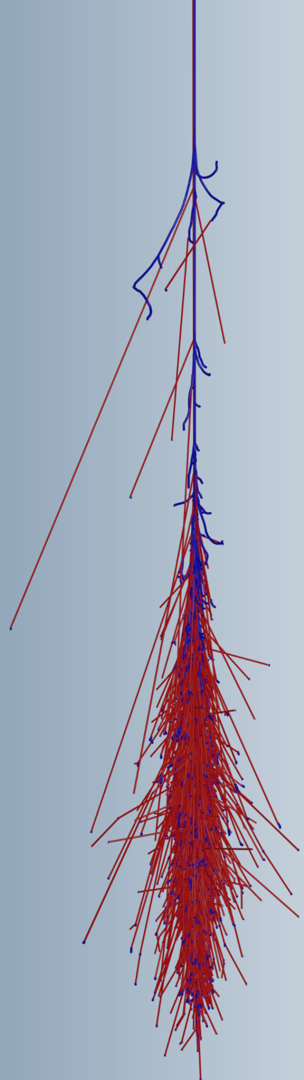
Karlsruher Institut für Technologie

20.06.2024

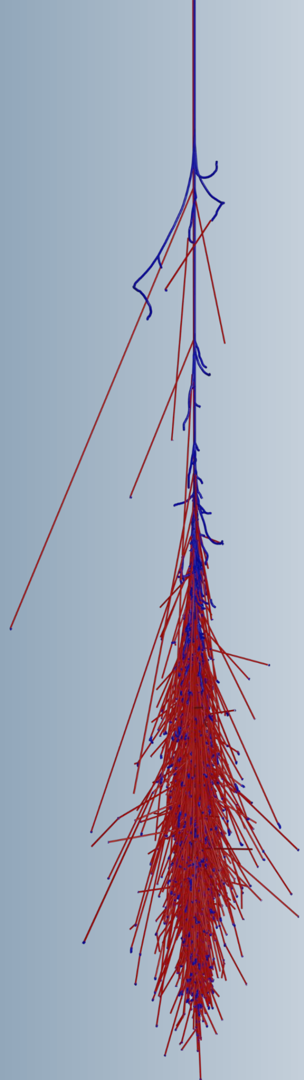
Simulating radio emission from air showers with CORSIKA 8 – Relevance for energy and mass reconstruction

IAP - High-Energy group Seminar

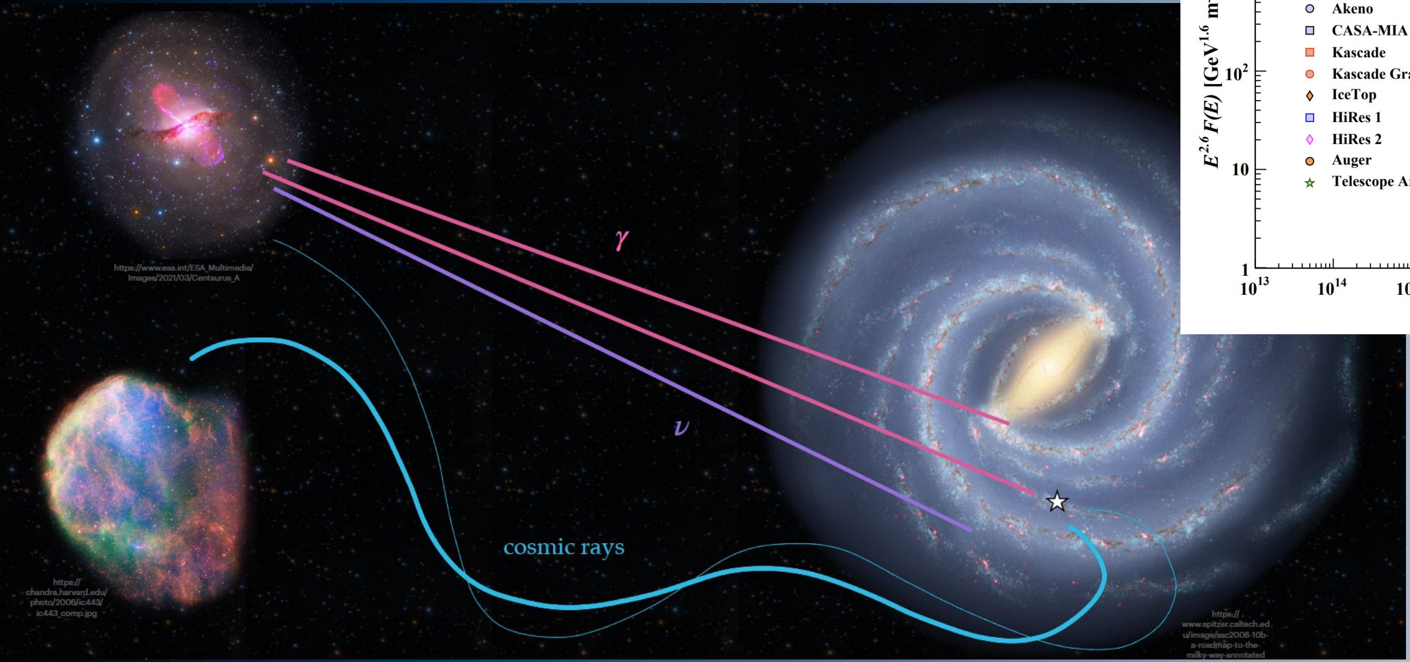
Nikolaos Karastathis

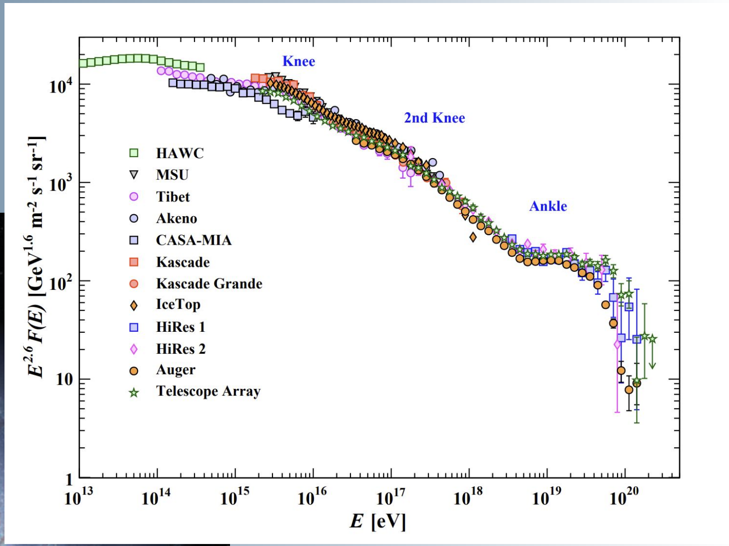


Introduction

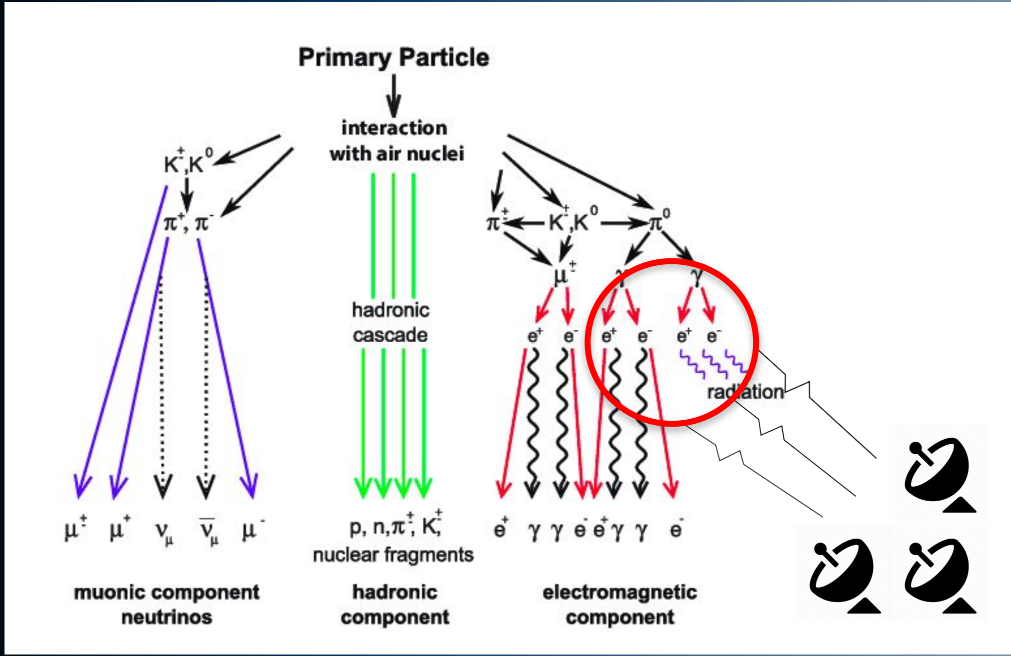


Cosmic Rays from different sources arrive at Earth carrying valuable information

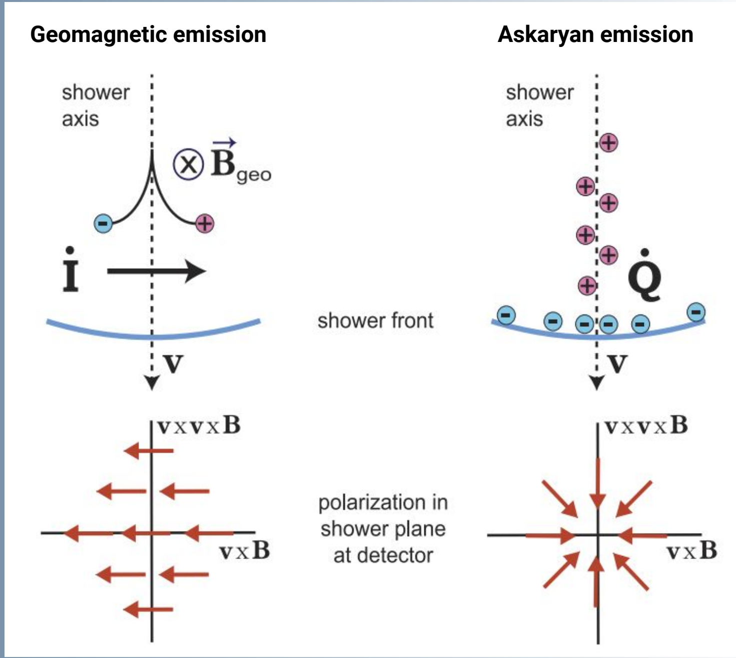




https://doi.org/10.1093/ptep/ptaa104



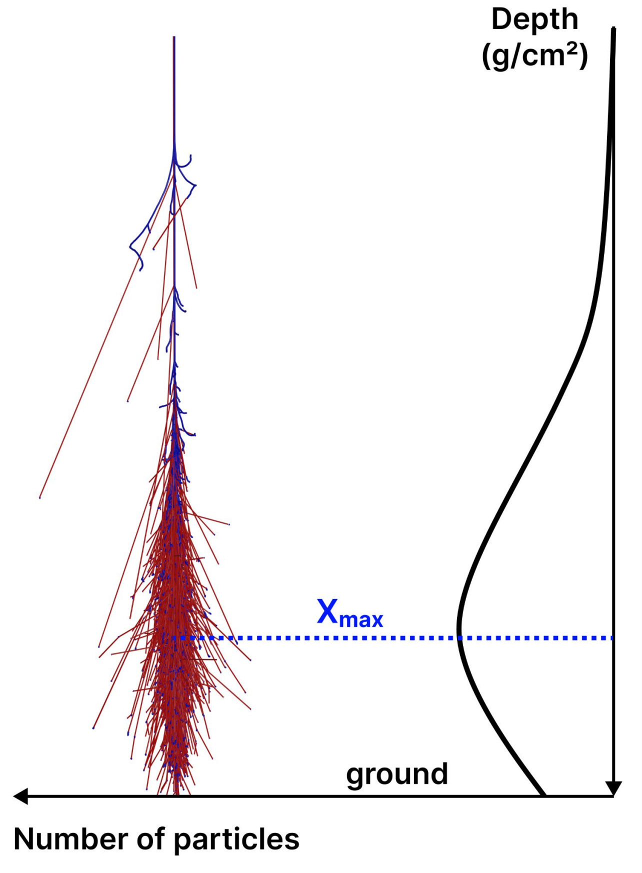
Macroscopic Description



arXiv:1607.08781

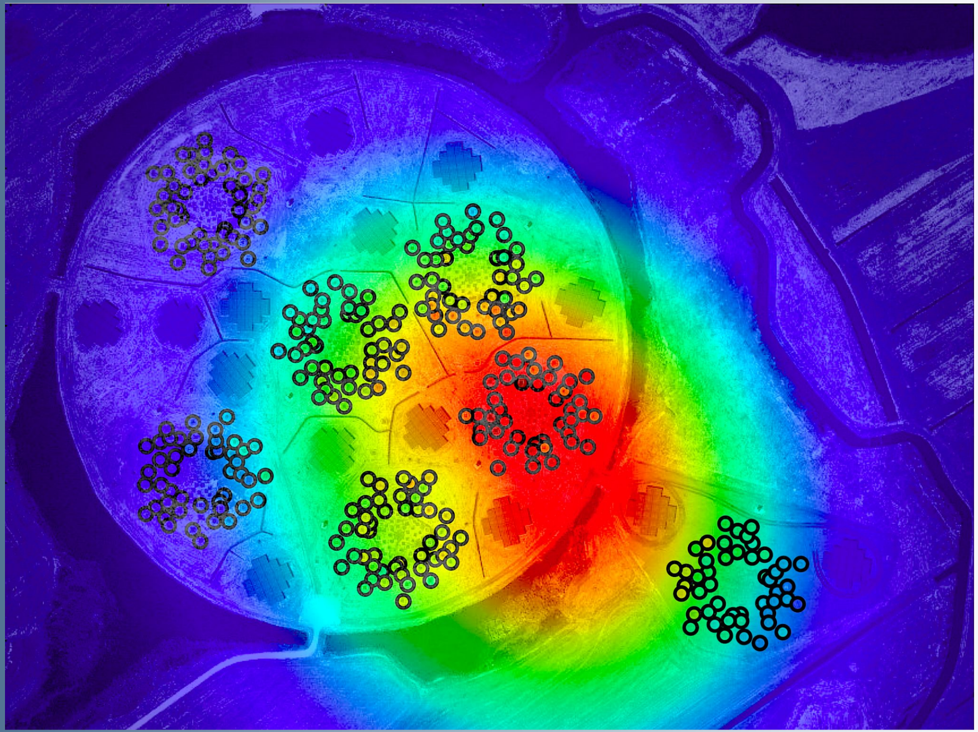
Longitudinal development of an Extensive Air Shower

- Shower maximum (X_{max}) – the slant depth at which the particle number is maximal
- Primary mass dependence on X_{max} – e.g. proton showers are expected to penetrate deeper in the atmosphere compared to iron showers



Fluence footprint of an Air Shower over LOFAR

- Antennas measure the radio waves emitted from the air shower
- Radio detection technique is used by many observatories and is planned to be used in future experiments
- Energy deposited to the ground in the form of radio waves is referred as “fluence” – creates a footprint
- X_{max} is associated with the fluence footprint

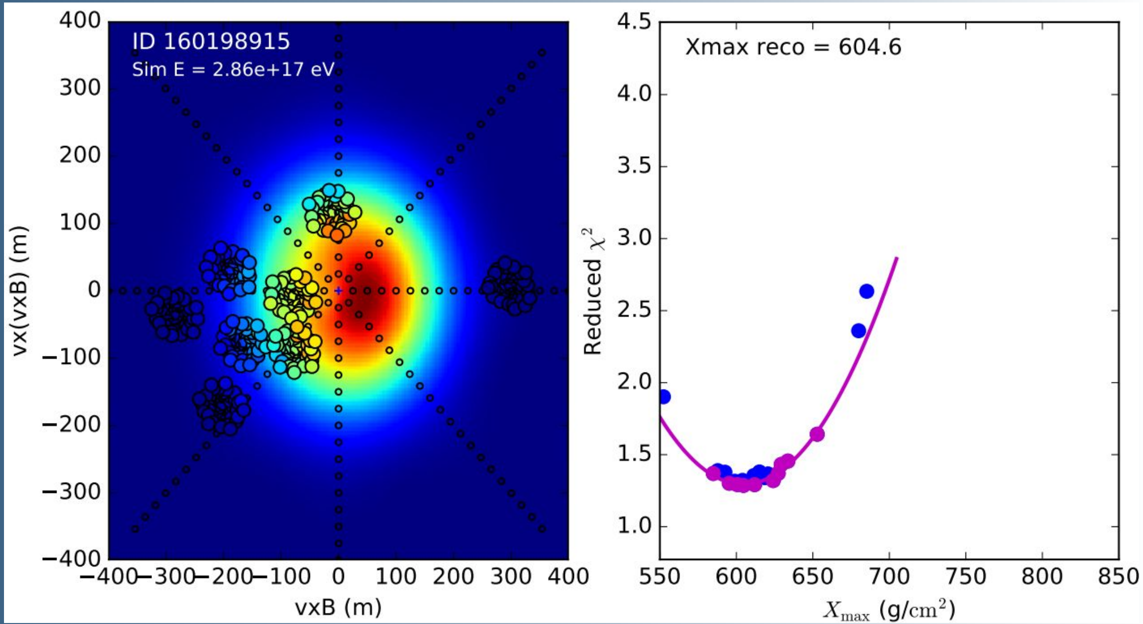


astron.nl

Simulations are crucial for reconstruction of EAS properties

arXiv:2103.12549

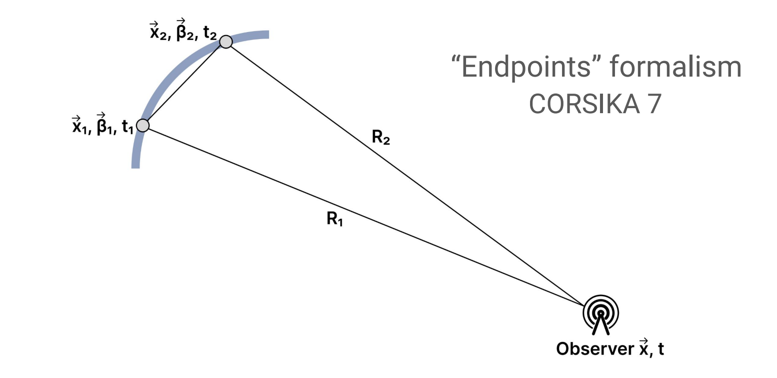
- Match measured fluence footprint to the "best" simulation through the χ^2 minimization procedure – only signal strength is used
- Reconstruct **Xmax** through **fluence footprint** – associate with primary **mass**
- Reconstruct **primary energy** through **radiation energy** – quadratic dependence
- Simulations need to be **rock solid!**

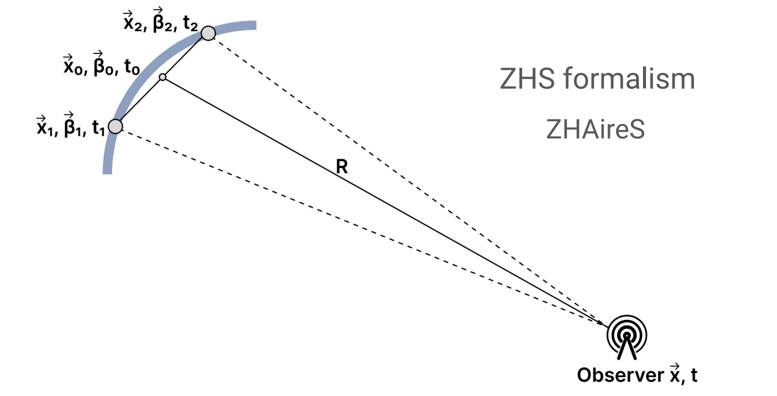


$$\chi^2_{radio} = \sum_{antennas} \left(\frac{P_{ant} - f_r^2 P_{sim}(x_{ant} - x_0, y_{ant} - y_0)}{\sigma_{ant}} \right)^2$$

Microscopic modelling of the radio emission

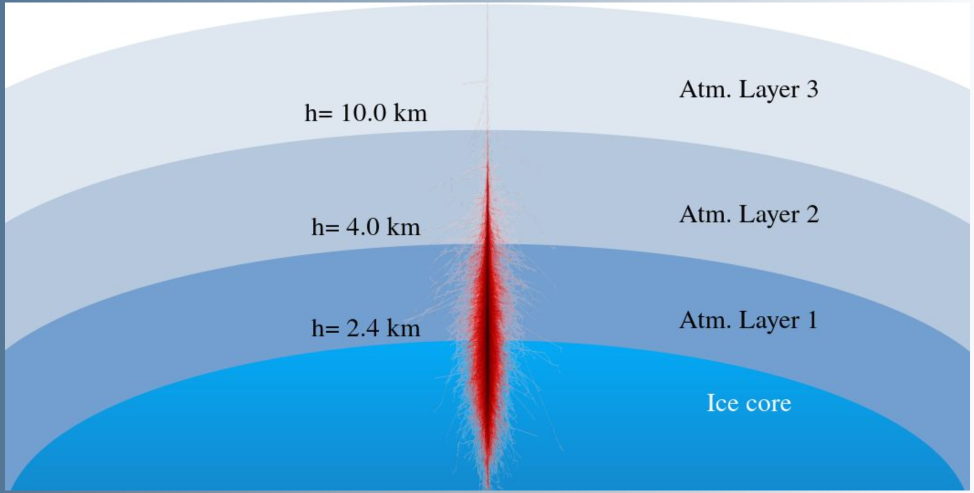
- Used in Monte Carlo simulations
- Both treat individual particle tracks and calculate the resulting electric field summing up the contributions of all tracks
- Both derived from first principles, but under different assumptions
- Inherently different algorithms – Have never been directly compared for the case of air showers
- **Level of agreement is a strong indicator of our understanding of the radio emission**





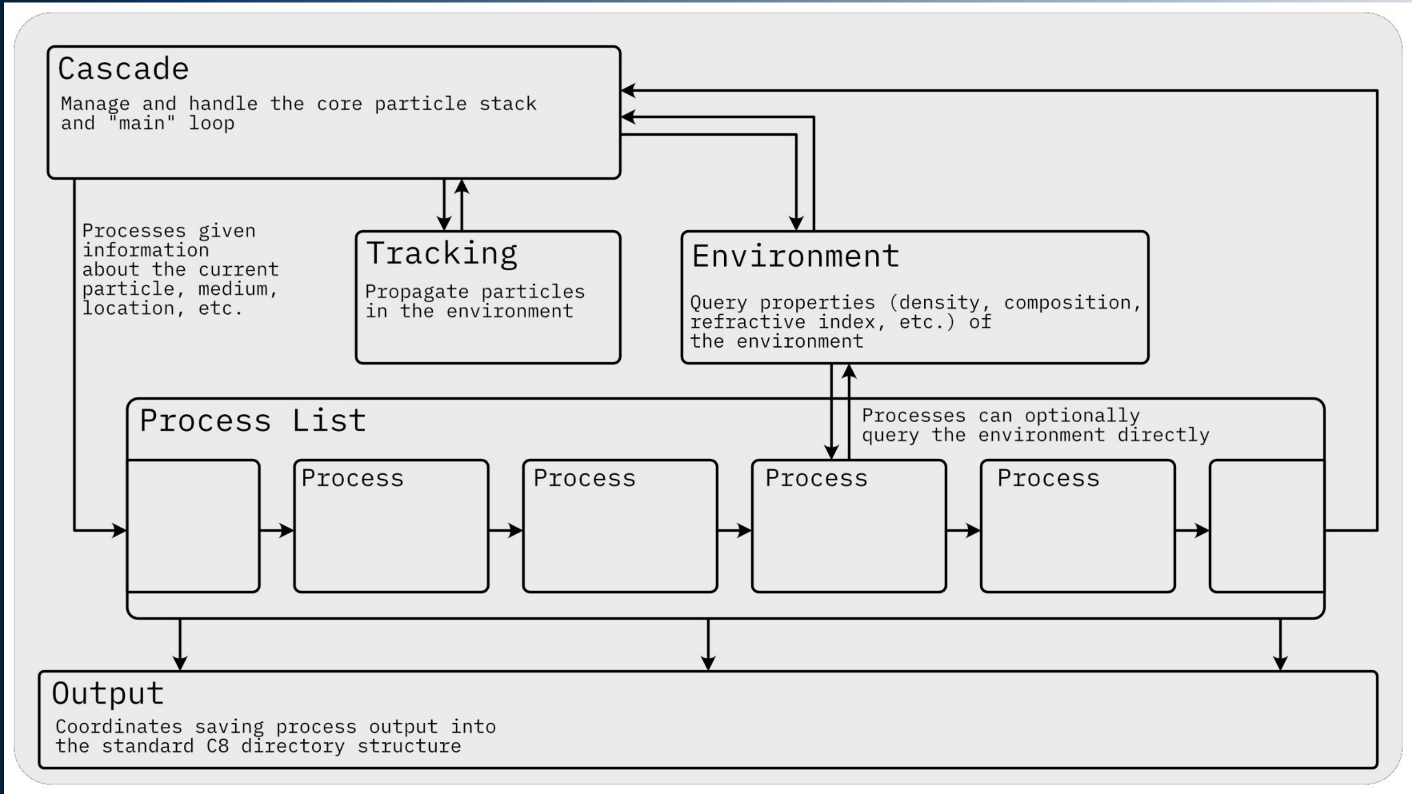
New simulation tools to accommodate growing experimental needs

- Existing software like CORSIKA 7 limit simulation capabilities
- Monolithic FORTRAN structure makes it hard to maintain and update in CORSIKA 7
- CORSIKA 8 based on modularity and flexibility – next generation simulations
- **One of the goals of this work is to create a radio module as an integral part of CORSIKA 8**



arXiv:2309.05897

CORSIKA 8 architecture



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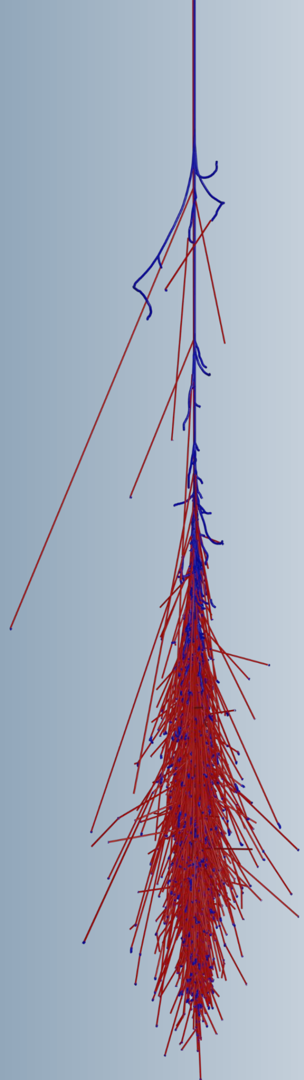
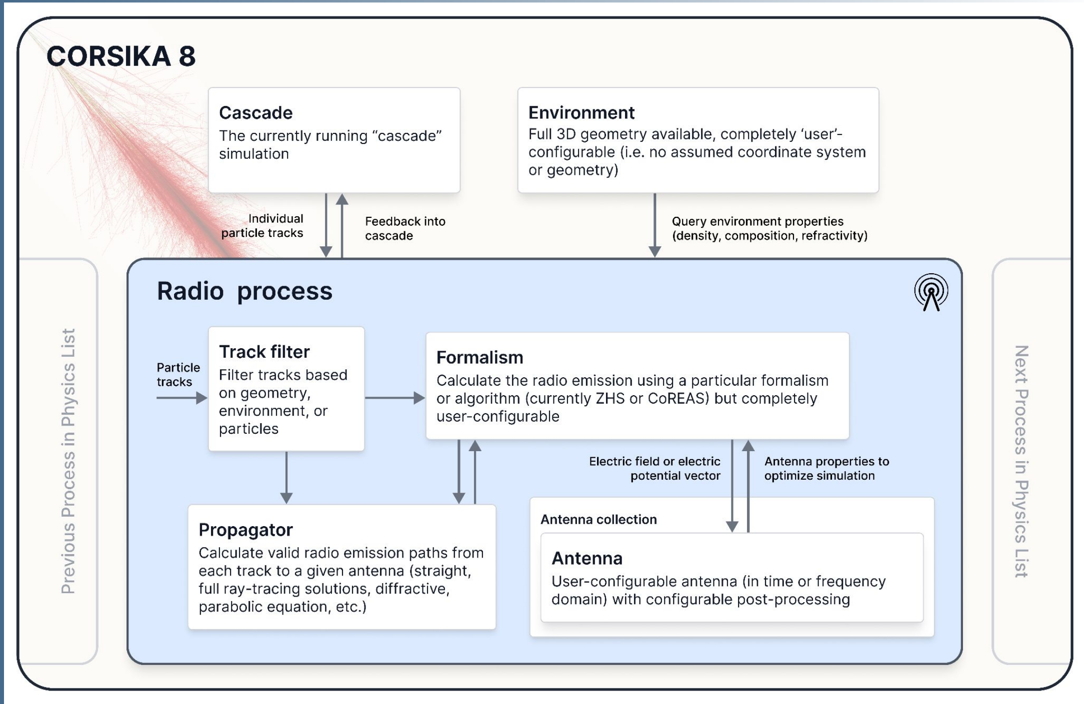
The development of a new radio module in CORSIKA 8



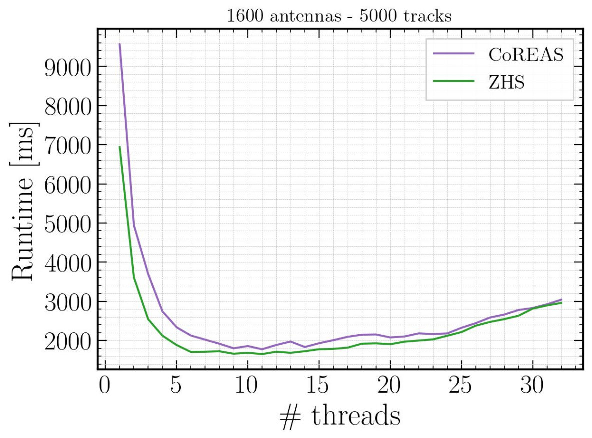
Radio module architecture

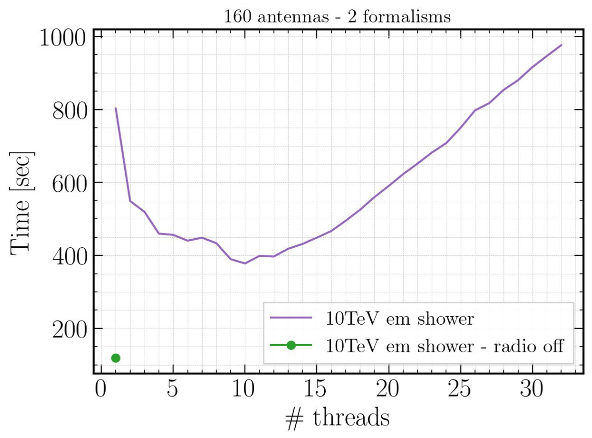
- Modularity, flexibility, upgradeability
- Direct formalism comparisons – **previously not possible**
- New propagators can be easily implemented to accommodate specific experimental needs
- Multithreading capabilities
- Baseline interface that allows inclusion of complex scenarios



Multithreading capabilities

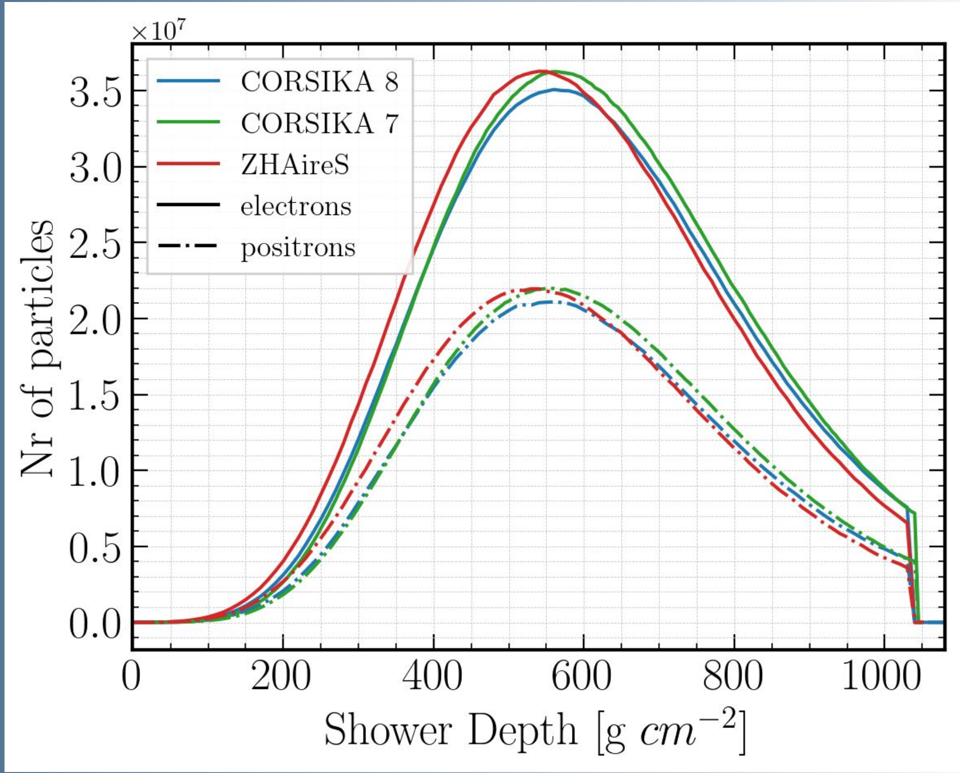
- Parallelization of the radio calculation over antennas
- Proof of principle that the code is **modern** and **thread safe** in order to take advantage of parallelization techniques
- Significant boost in performance – smaller runtimes





Quantitative comparisons for similar showers

- Cherry picked a CORSIKA 8 100 PeV iron induced vertical shower comparison with CORSIKA 7 and ZHAireS for similar showers
- The radio module in CORSIKA 8 is able to fully simulate the radio emission from realistic air showers



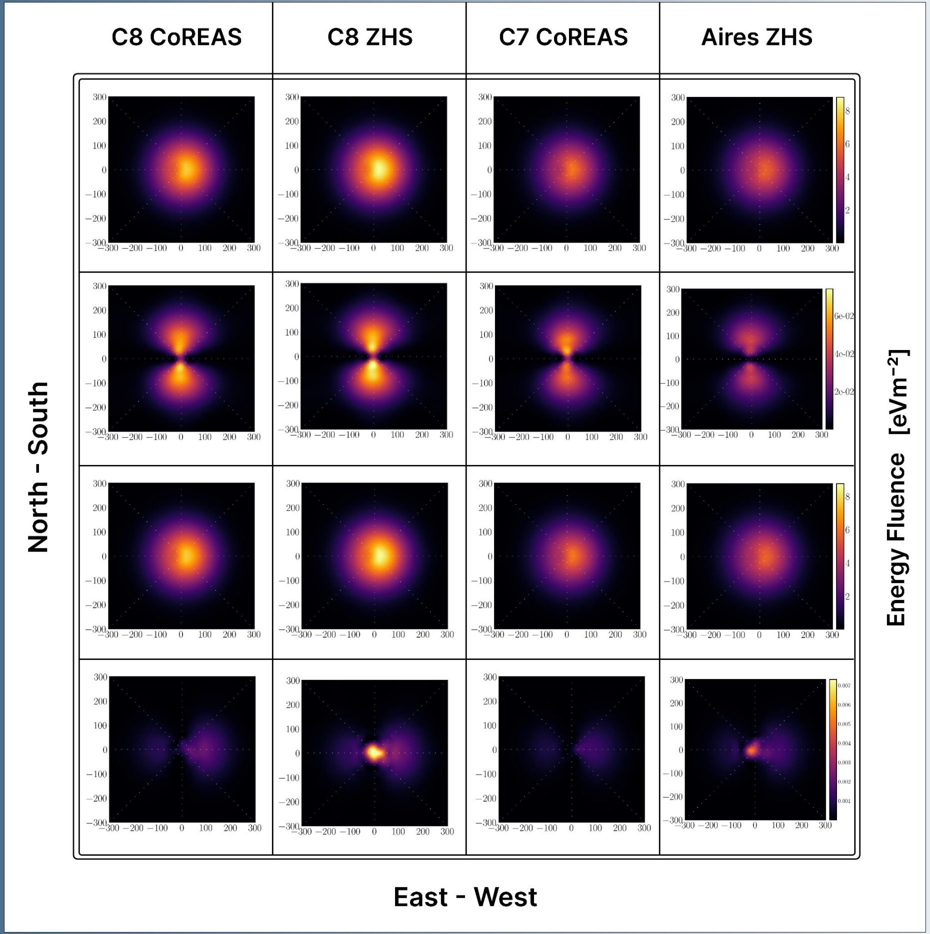
Quantitative comparisons for fluence footprints

All polarizations →

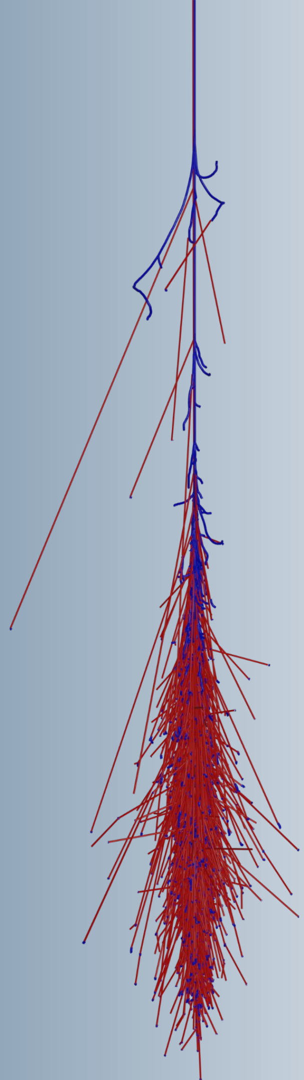
North – South →

East – West →

Vertical →

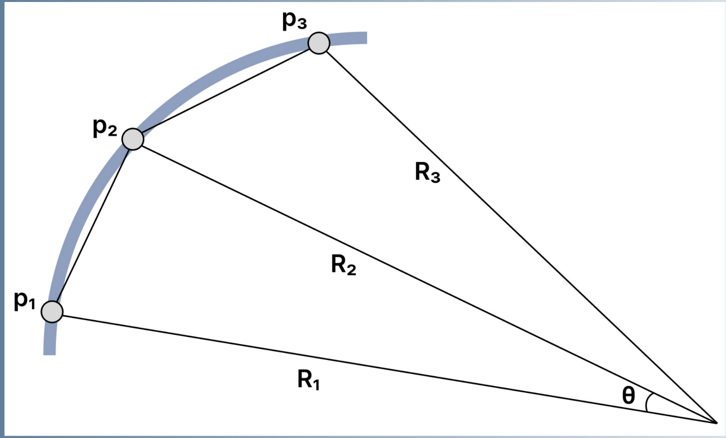


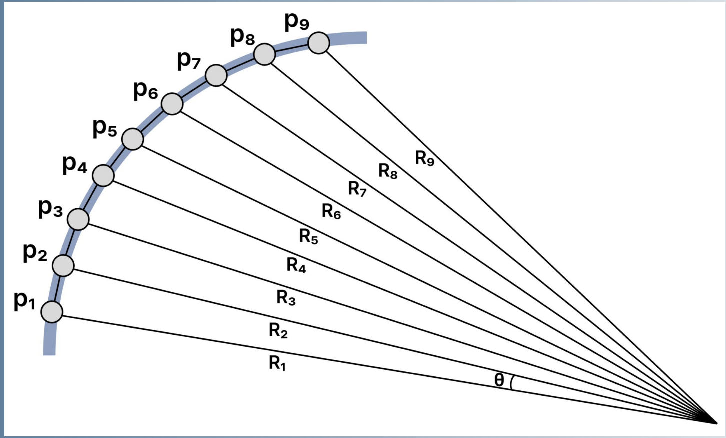
What explains the intensity difference?



Effect of track length on radio simulations

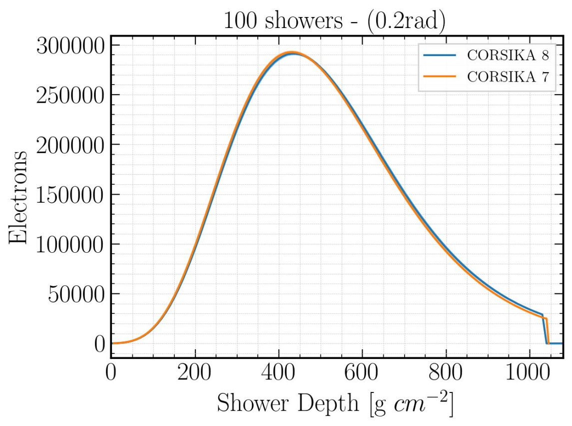
- How is the **fluence footprint** and hence **mass estimation** affected?
- How is the **radiation energy** and hence primary **energy estimation** affected?
- Approximating a trajectory with smaller, finer tracks is “closer to reality” – but computationally expensive
- Track length indirectly adjusted by deflection angle θ (maxRad)

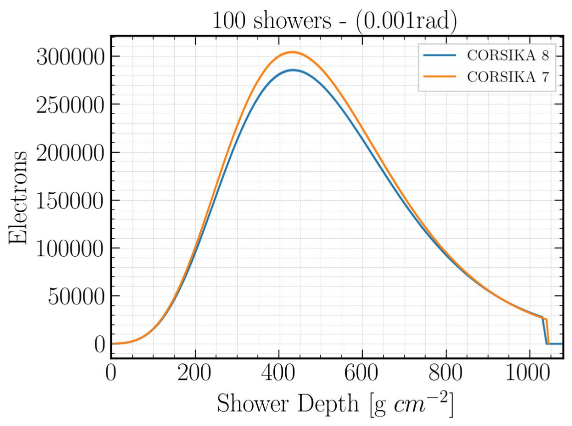




Effect of track length on longitudinal profiles

- 100 showers per maxRad value and simulation software
- Does the track length affect the agreement between CORSIKA 7 and CORSIKA 8?
- Better agreement in terms of particle number for 0.2 rad





Different track lengths affect radiation energy

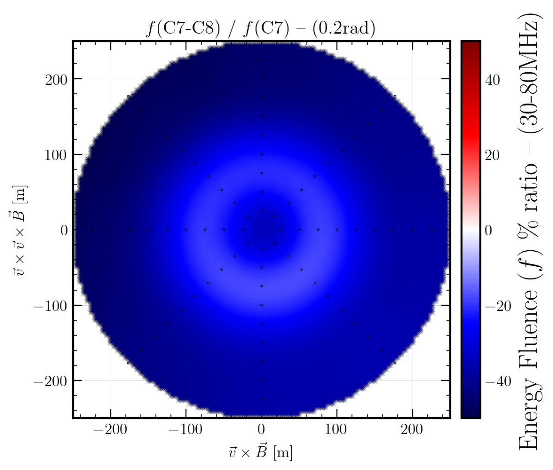
- 30–80MHz frequently used in current experiments and 50–350MHz for SKA
- For 0.2 rad the differences are large – More radiation energy is simulated with CORSIKA 8
- For 0.001 rad the differences become much smaller – More radiation energy is simulated with CORSIKA 7
- In 30–80MHz band for very small tracks (0.001 rad) both software agree within ~10% (5% in energy scale)

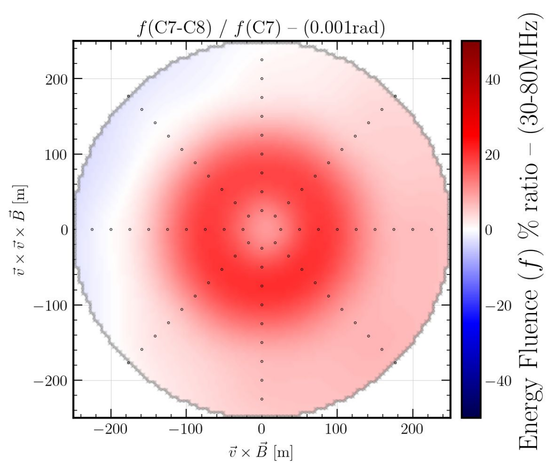
CORSIKA 8 vs CORSIKA 7 – mean difference in terms of % (0.2rad)		
Radiation Energy	30 MHz to 80 MHz	50 MHz to 350 MHz
Total Radiation Energy	-31.9%	-53.6%
Geomagnetic Contribution	-31.8%	-53.5%
Charge Excess	-46.1%	-31.2%

CORSIKA 8 vs CORSIKA 7 – mean difference in terms of % (0.001rad)		
Radiation Energy	30 MHz to 80 MHz	50 MHz to 350 MHz
Total Radiation Energy	10.2%	0.2%
Geomagnetic Contribution	10.1%	-0.2%
Charge Excess	4.6%	7.8%

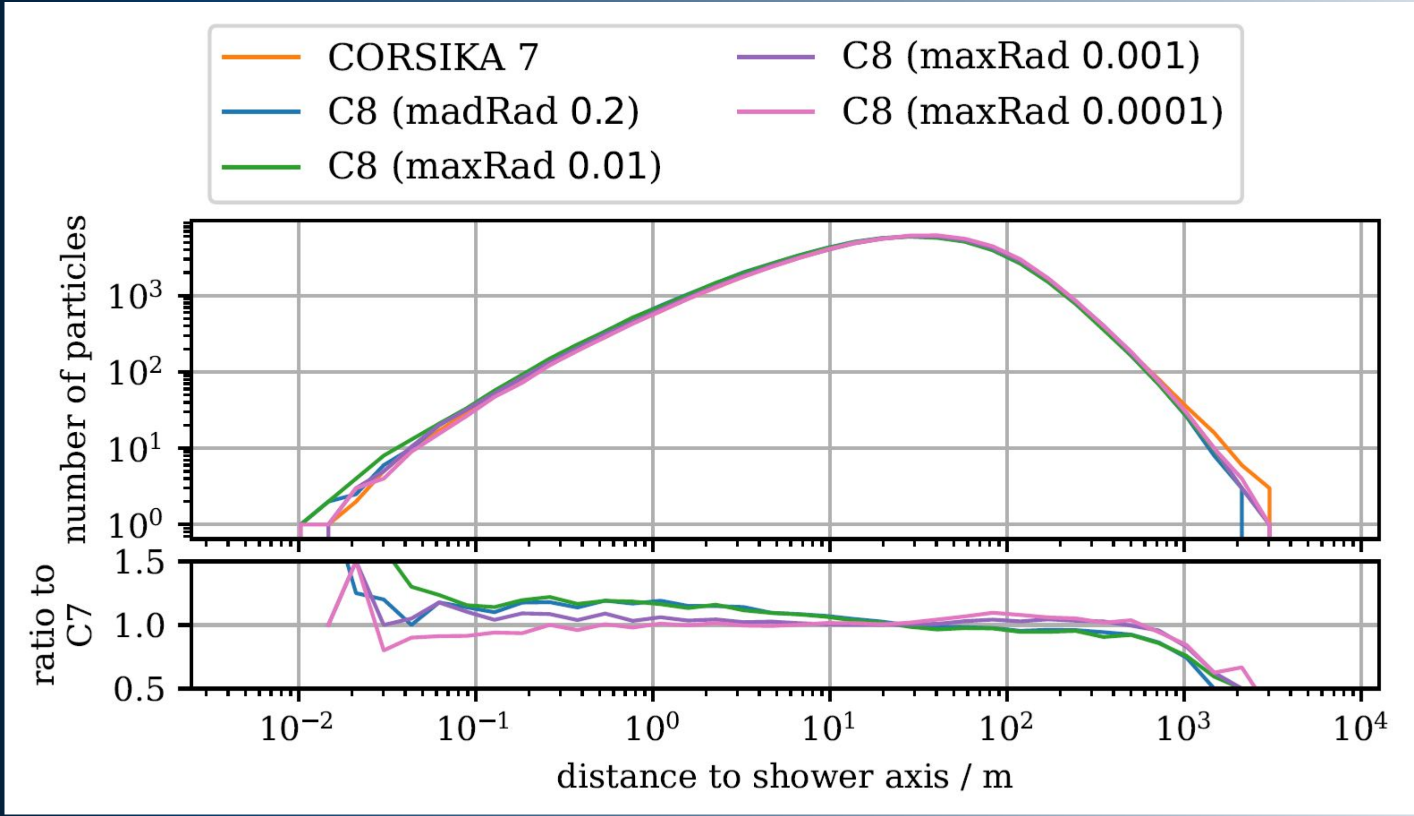
Different track lengths affect fluence footprint

- For smaller tracks (0.001 rad) the differences are smaller but still considerable
- Differences in the tracking algorithms used by CORSIKA 8 and CORSIKA 7
- CORSIKA 8 showers have a narrower lateral distribution compared to CORSIKA 7 – they "spread" less, potentially stronger coherence effects

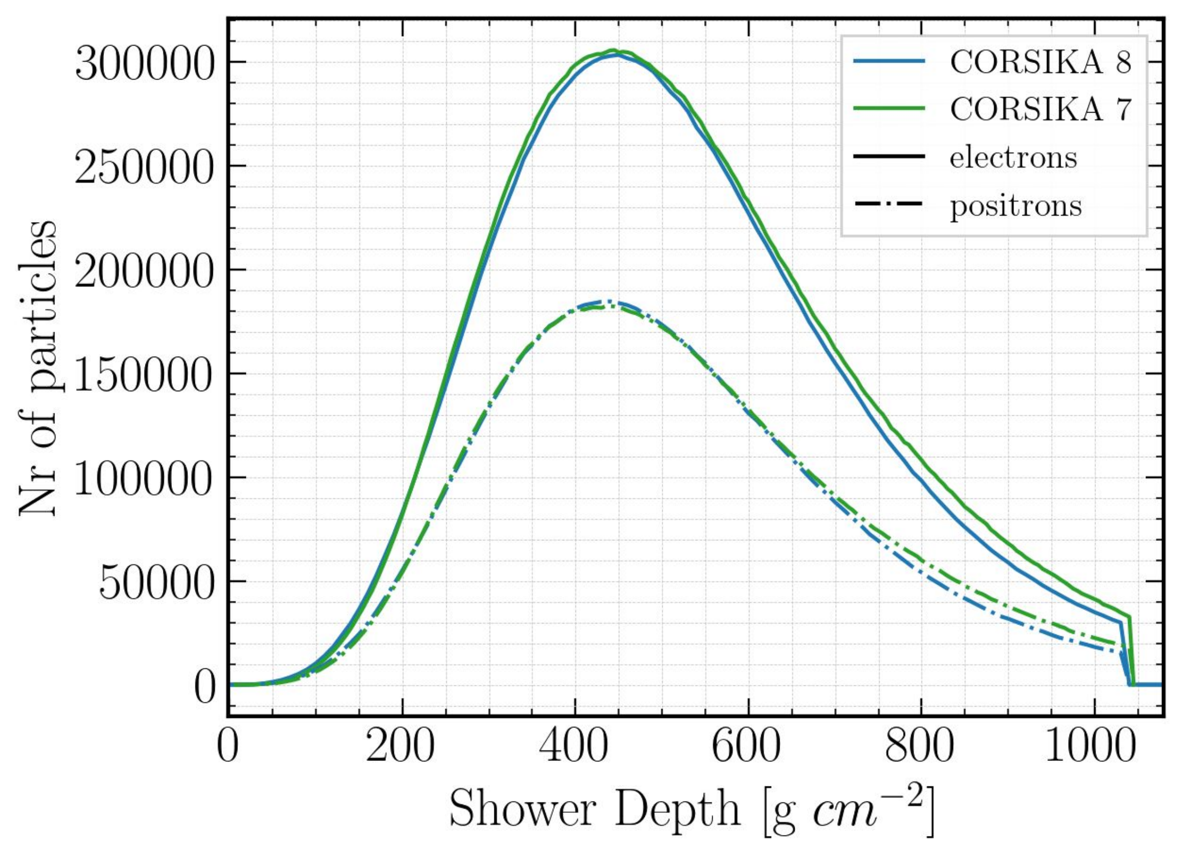




Different track lengths affects the lateral profile



CORSIKA 8 vs CORSIKA 7 for the 0.001 rad case



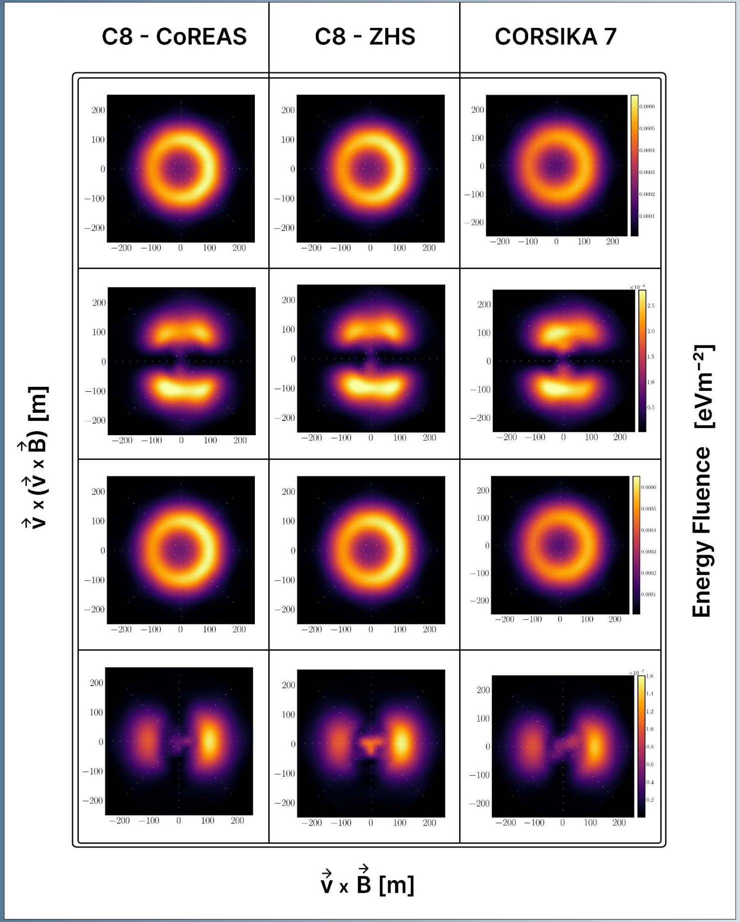
Quantitative comparisons for fluence footprints for the 0.001 rad case

All polarizations →

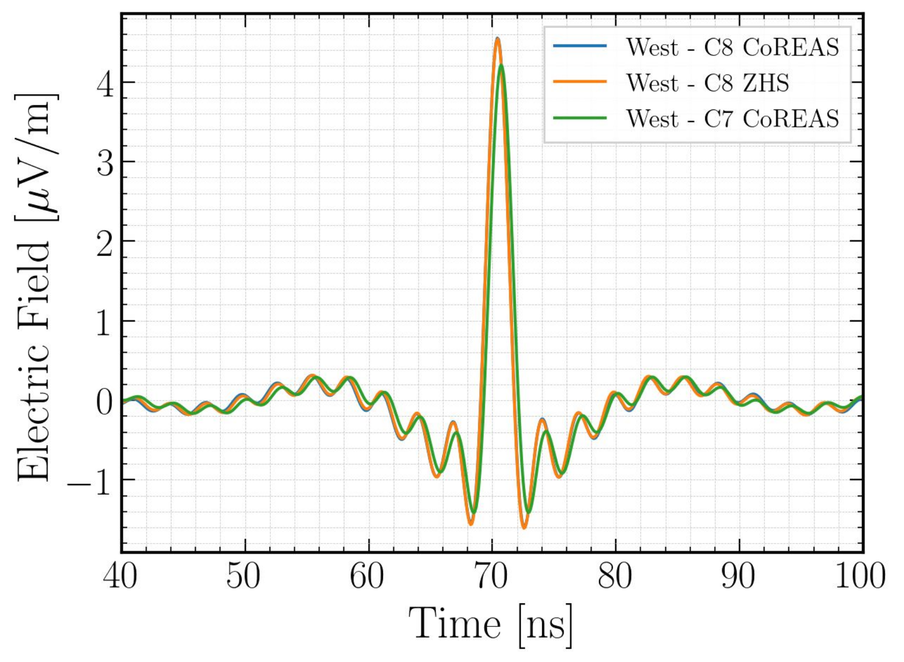
North – South →

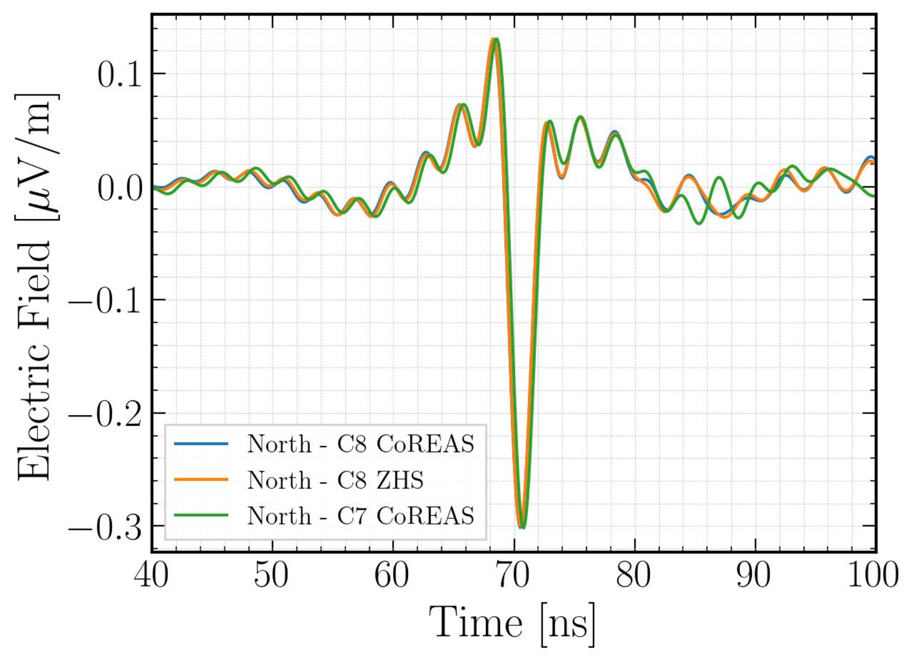
East – West →

Vertical →

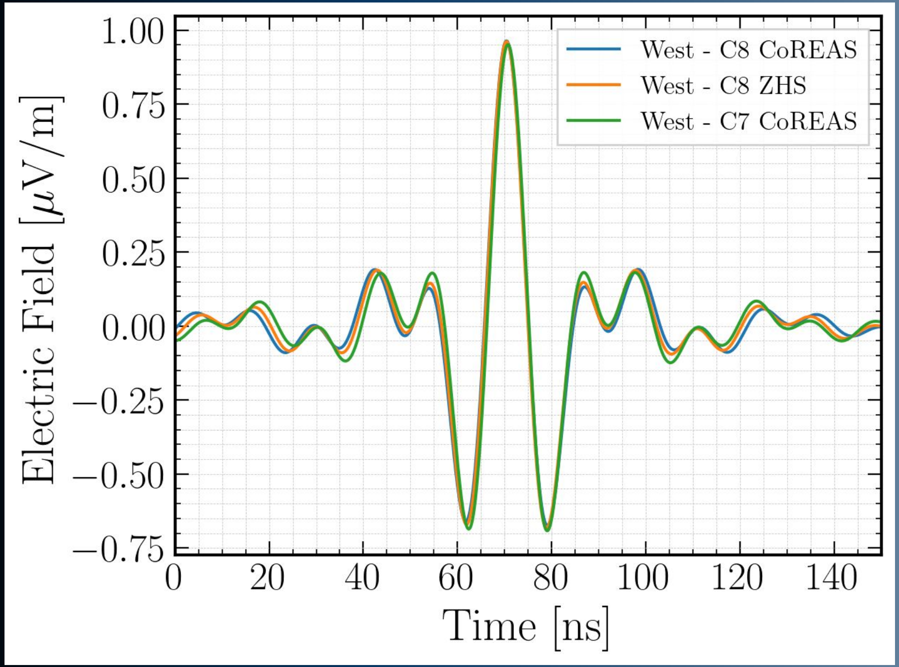


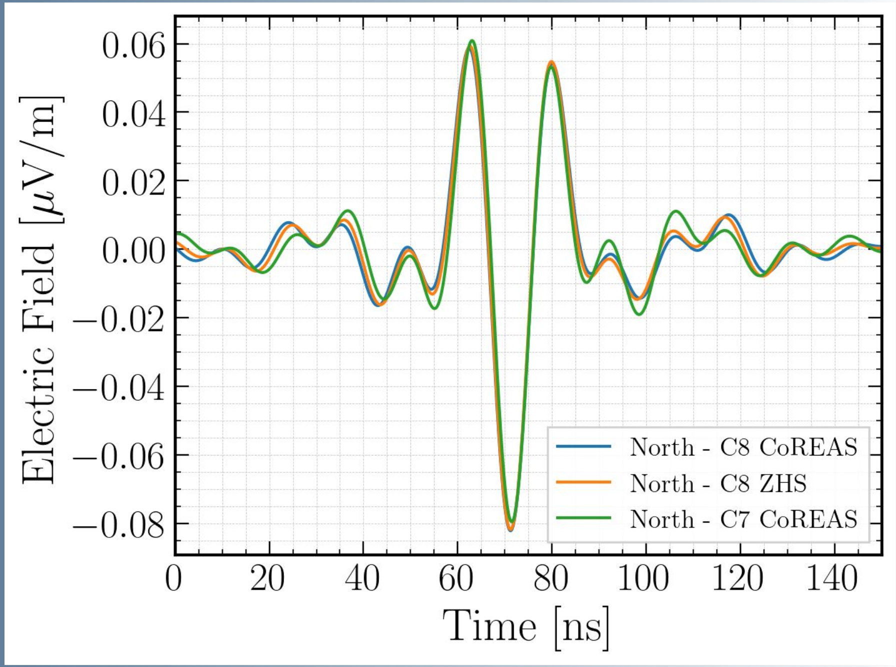
Quantitative comparisons for pulses for the 0.001 rad case – 50-350MHz





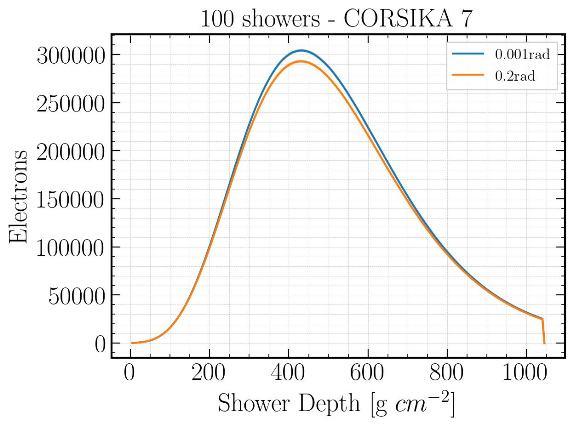
Quantitative comparisons for pulses for the 0.001 rad case – 30-80MHz

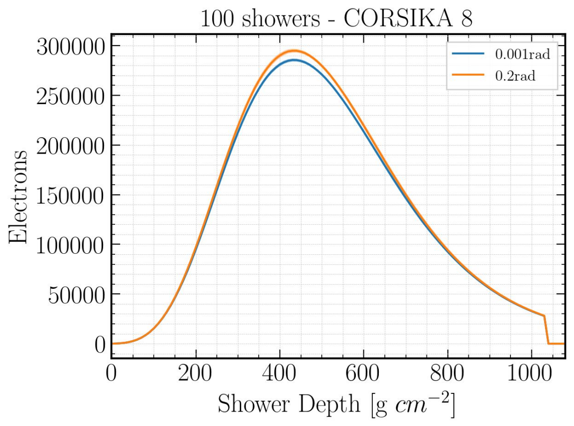




Effect of track length on longitudinal profiles

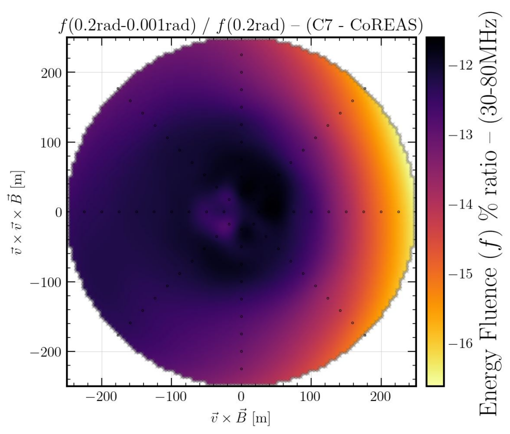
- Does the track length affect the number of particles?
- Separate comparison study for CORSIKA 8 and CORSIKA 7
- CORSIKA 7 simulates more particles for the 0.001 rad
- CORSIKA 8 simulates more particles for the 0.2 rad

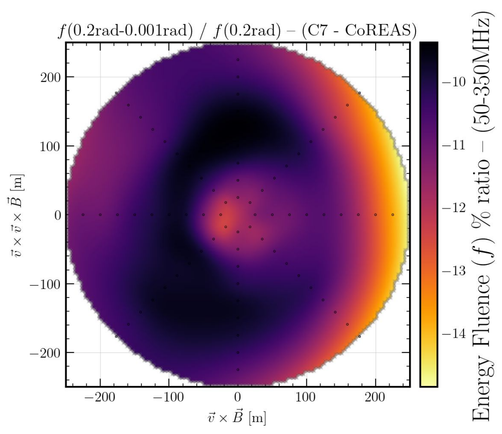




Effect of different track lengths in CORSIKA 7

- Effect of different track lengths in CORSIKA 7 – default value vs very small tracks
- Smaller tracks (0.001 rad) simulate consistently more radiation energy – radiation follows the increased number of particles for 0.001 rad
- The fluence footprint is also affected on a few % level
- For the CORSIKA 8 case the differences are even more pronounced there due to different tracking algorithm

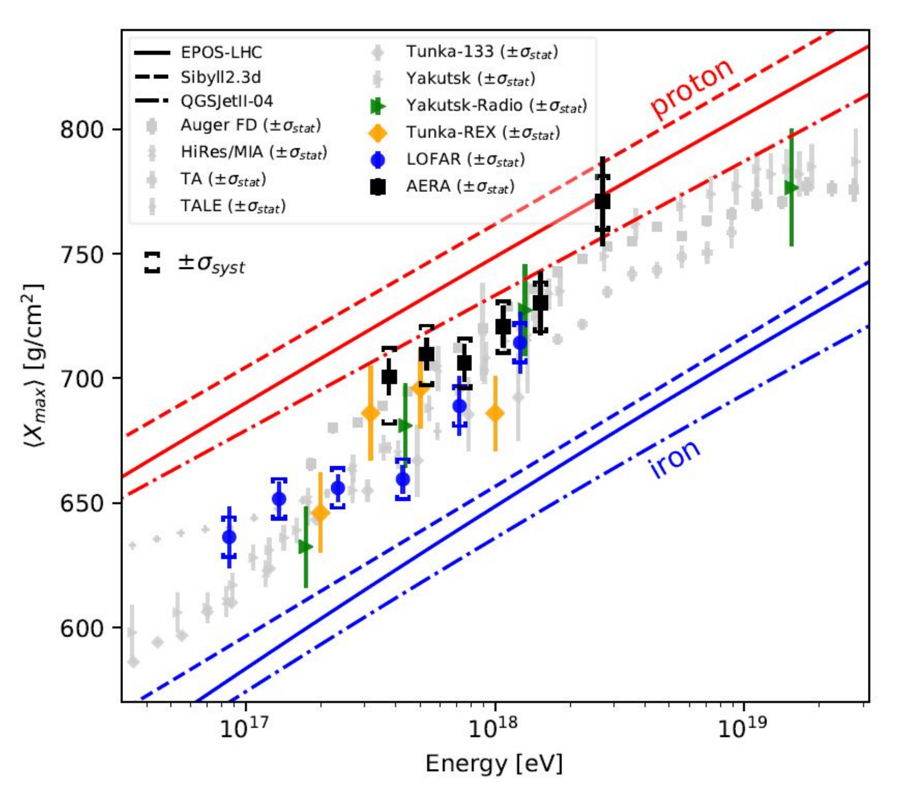




0.2rad vs 0.001rad – mean difference in terms of % (C7 CoREAS)		
Radiation Energy	30 MHz to 80 MHz	50 MHz to 350 MHz
Total Radiation Energy	-12.3%	-10.0%
Geomagnetic Contribution	-12.7%	-10.4%
Charge Excess	-12.9%	-12.4%

Known LOFAR vs AERA Xmax results mismatch

- Different track lengths affect the radiation energy **and** the fluence footprint – As a result, Xmax and energy reconstruction are affected
- Worth redoing the Xmax reconstruction analysis for selected events of both LOFAR and AERA measurements using simulations with small track length
- Redo analysis with CORSIKA 8 radio – 2 formalisms available – Validate CORSIKA 7 and CORSIKA 8



arXiv:2310.19963

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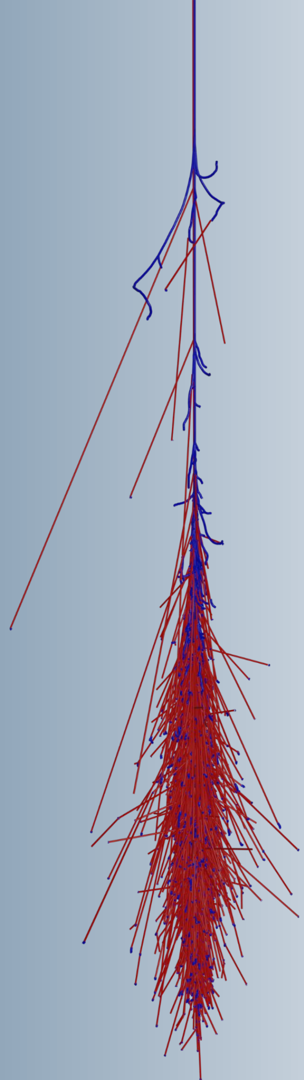
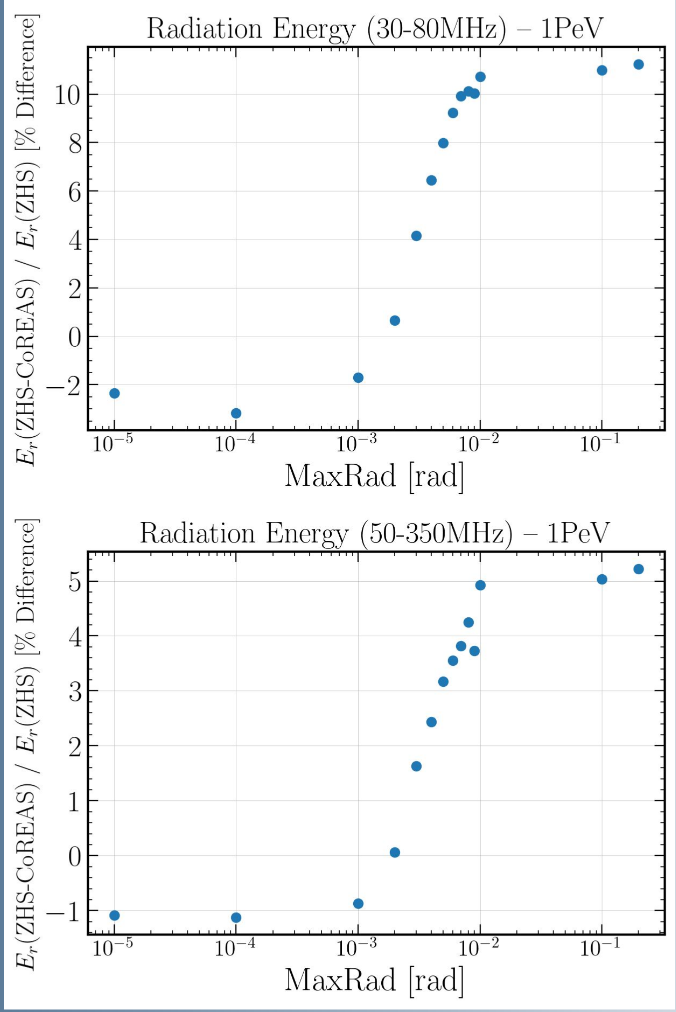
Direct comparison of “Endpoints” vs ZHS



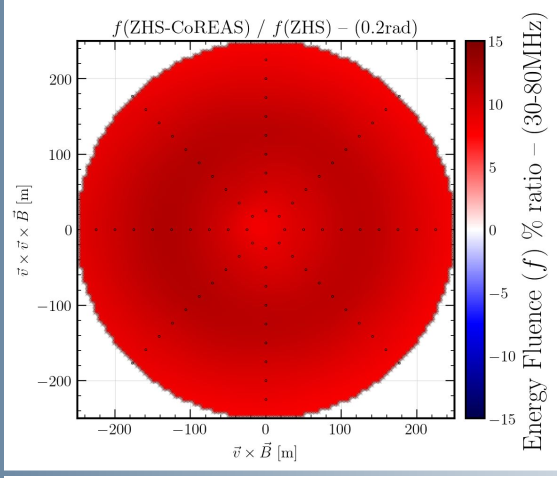
“Endpoints” vs ZHS is affected by track length

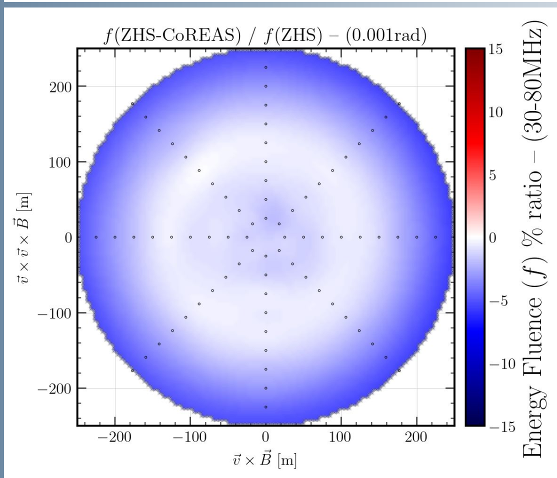
- Agreement on **radiation energy** depends on track length
- For very small tracks, both algorithms practically converge – strong indication that radio calculations are well understood
- Level of agreement independent of primary particle energy or type



“Endpoints” vs ZHS fluence footprint comparison

- Better agreement for small track lengths
- Deviations are larger in areas where the signal is weaker
- This is not the case for larger tracks in the 30–80MHz band though
- A good agreement between the 2 formalisms solidifies the idea that the radio emission calculations in air showers is well understood





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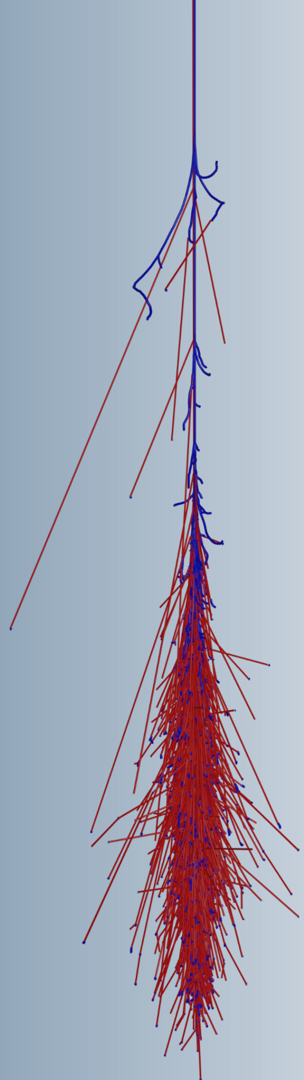
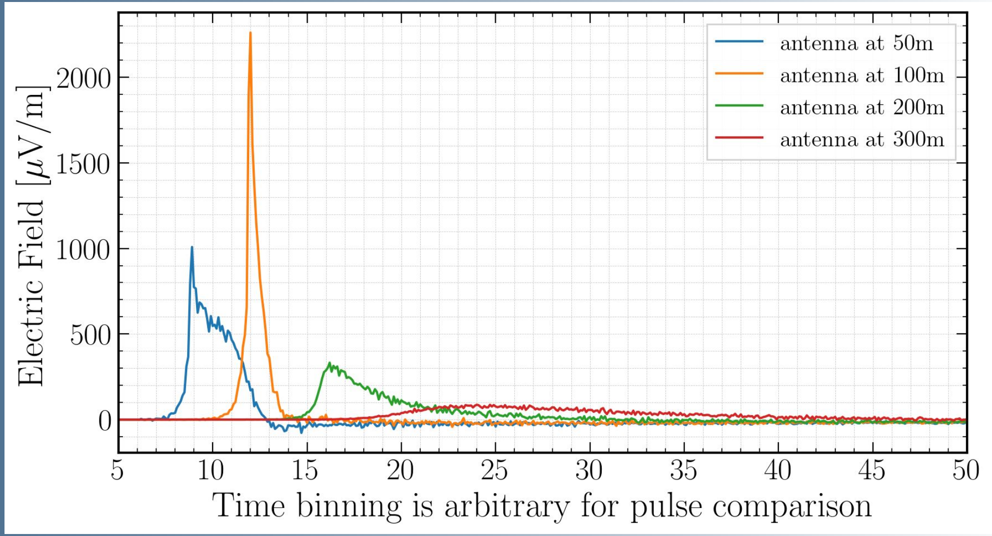
A new X_{max} reconstruction scheme



There is information hidden the pulse shape

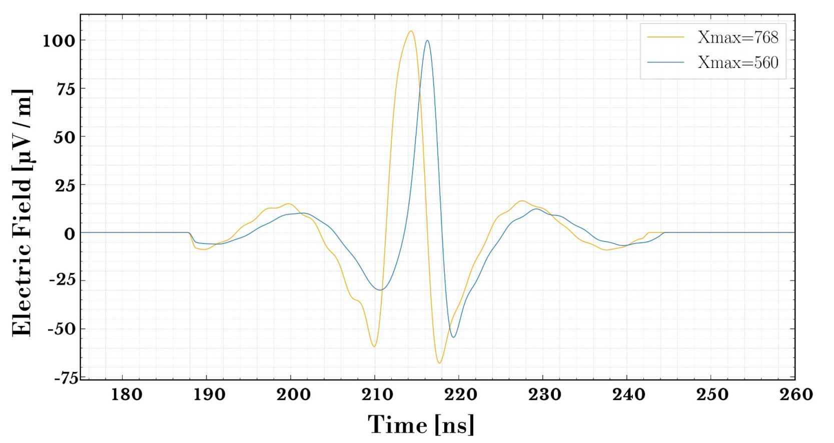
- Standard $\mathcal{X}^2$ minimization procedure **discards** pulse shape information
- Information is hidden in the pulse shape though, that can be used to reconstruct Xmax
- **Pulse shape changes with distance from the shower core**



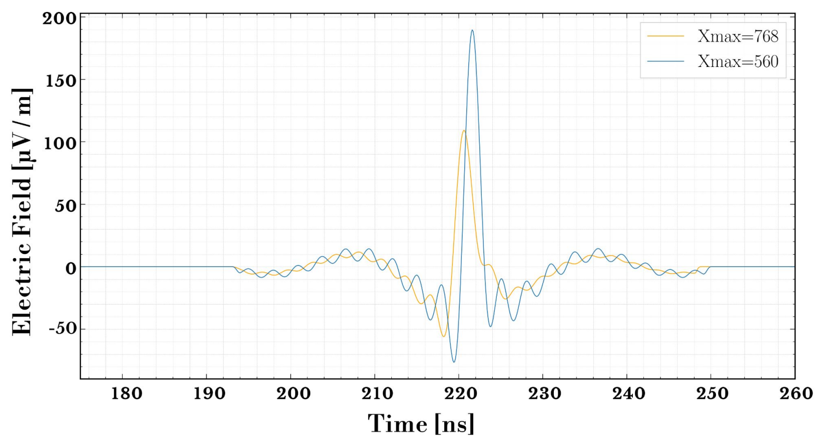
Pulse shape changes with Xmax

- Showers with same characteristics but different Xmax have different pulse shapes
- Different Xmax will produce different footprint on the ground

25m from the shower core



200m from the shower core

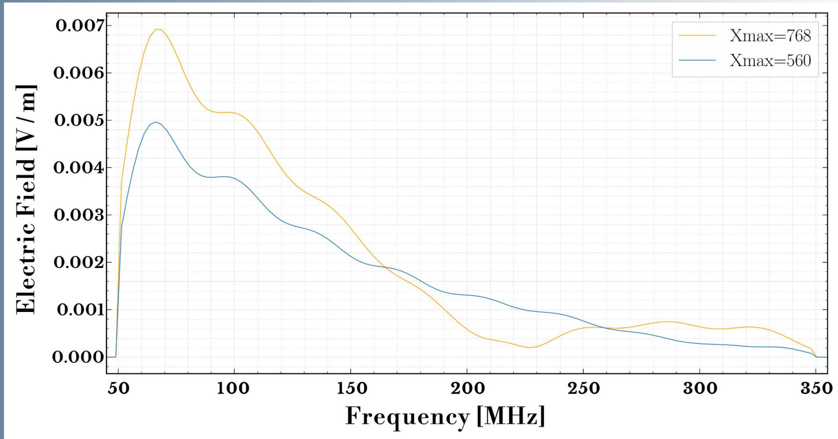


Nikolaos Karastathis

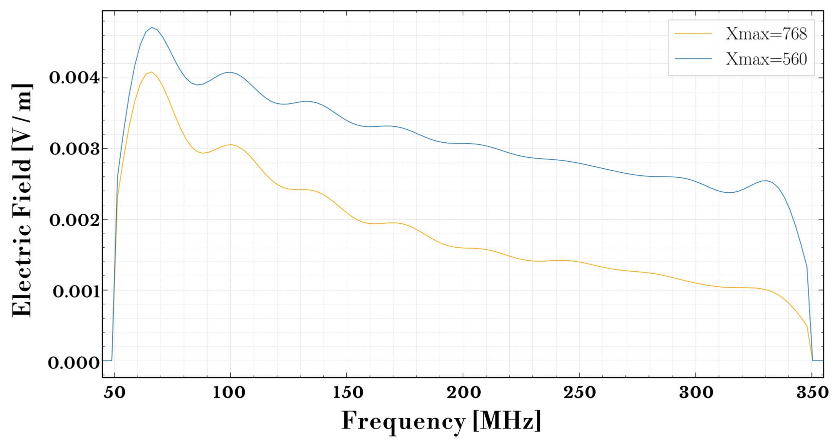
Pulse shape information on the frequency domain

- In the frequency domain the pulse shape information translates as the **slope of the frequency spectra**

25m from the shower core



200m from the shower core

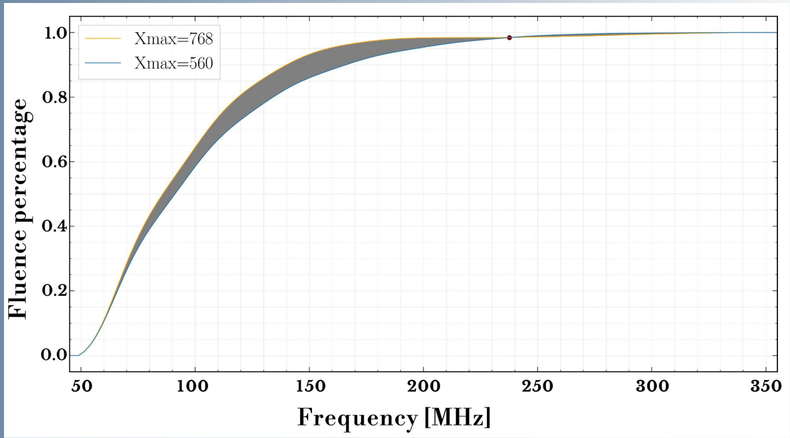


Introducing the "fluence percentage"

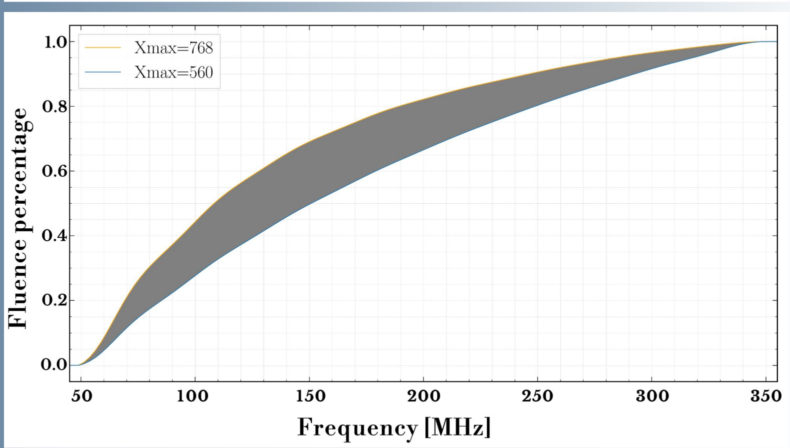
- The fluence percentage is the rate at which energy is being deposited to the antenna
- It is normalized over the total fluence – hence amplitude information is taken out
- The "difference in area" (grey) can be used as a metric for X_{max} reconstruction

$$f_j = \frac{\sum_{i=1}^{j}\left(A_i^2(v) - cor_i^2(v)\right)}{\sum_{i=1}^{N}\left(A_i^2(v) - cor_i^2(v)\right)}$$

25m from the shower core

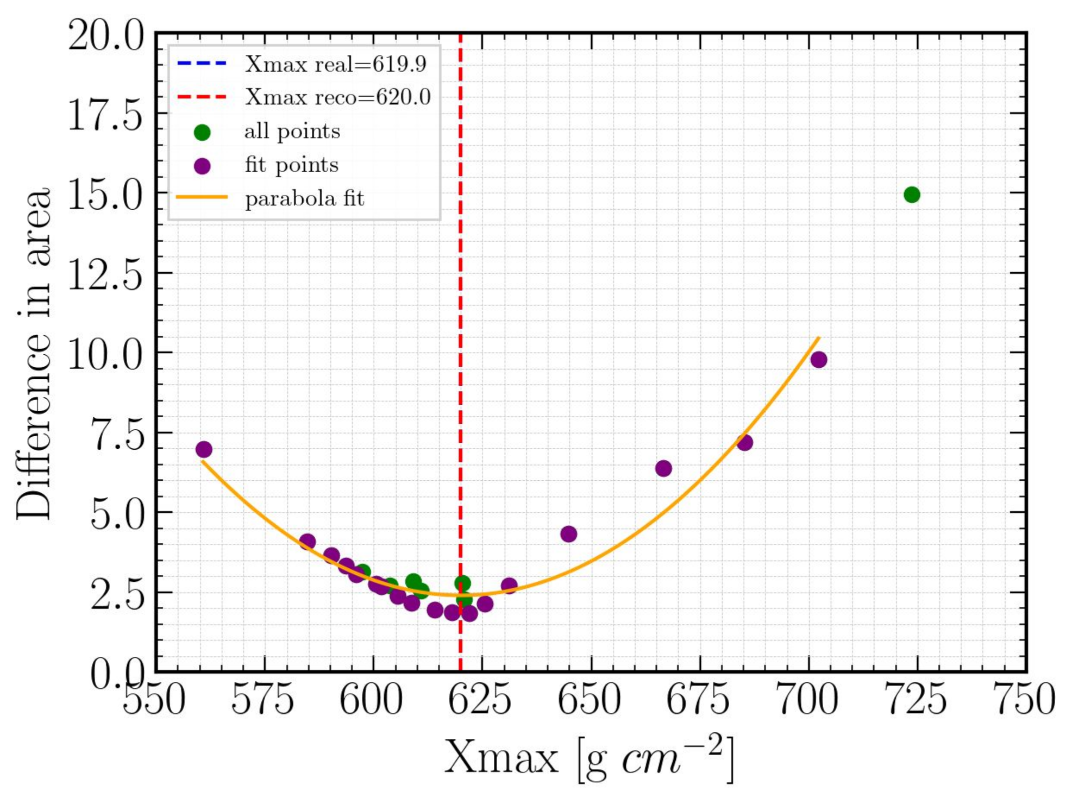


200m from the shower core



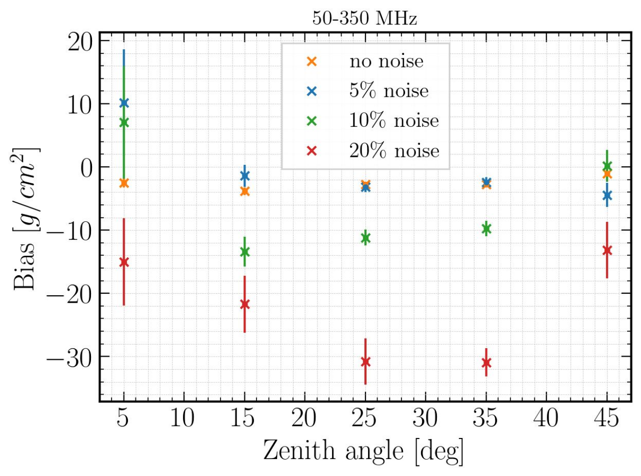
Parabola fitting to reconstruct X_{max}

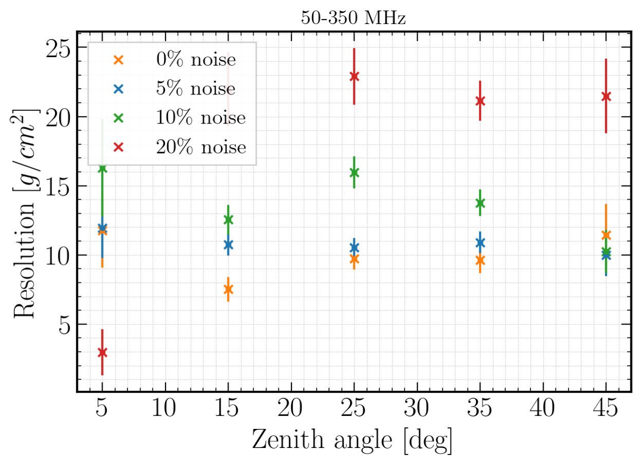
- Each point represents a simulation
- The “difference in area” of each simulation is the average of all antennas and all polarizations
- The smallest the “difference in area” the closer to the X_{max} we are looking for
- Need a cluster of simulations around the Xmax we are looking for



Benchmarking the reconstruction scheme

- Benchmarking the method with 4500 simulations
- Addition of generated noise in different levels
- Simulations are organized in bins with respect to zenith angle





Benchmarking results for 2 frequency bands

- 50–350MHz is aimed for SKA
- 30–80MHz cannot be realistically used for LOFAR as LOFAR antennas are highly resonant around 60 MHz
- Noise seems to throw off the method's resolution
- Successful de-noising of pulses makes this method tempting to use
- Could be used as a second order reconstruction to standard $\mathcal{X}^2$ minimization procedure

Benchmark results (50 MHz to 350 MHz)		
Noise level	Bias ($g\,cm^{-2}$)	Resolution ($g\,cm^{-2}$)
No noise	-2.7	9.7
5% noise	-2.2	10.7
10% noise	-9.0	14.2
20% noise	-27.6	21.1

Benchmark results (30 MHz to 80 MHz)		
Noise level	Bias ($g\,cm^{-2}$)	Resolution ($g\,cm^{-2}$)
No noise	-4.5	11.1
5% noise	-4.9	14.1
10% noise	-5.9	18.8
20% noise	-8.9	22.6

Contributions of my PhD

1. A radio module in CORSIKA 8 is now available that acts as a baseline for current and future radio experiments
2. 2 different radio formalisms were compared and found to agree
3. Radio module acts as a powerful diagnostics tool – CORSIKA 7 and CORSIKA 8 were found to agree within 10% in radiation energy (5% energy scale)
4. Simulation details like track length **do affect**:
    - the simulated radiation energy and hence cosmic ray energy reconstruction
    - the simulated fluence footprint and hence primary mass reconstruction
5. An X_{max} reconstruction scheme that utilizes the pulse shape