Simulating the radio emission from air showers with CORSIKA 8

Nikolaos Karastathis
PhD student @ Institute for Astroparticle Physics

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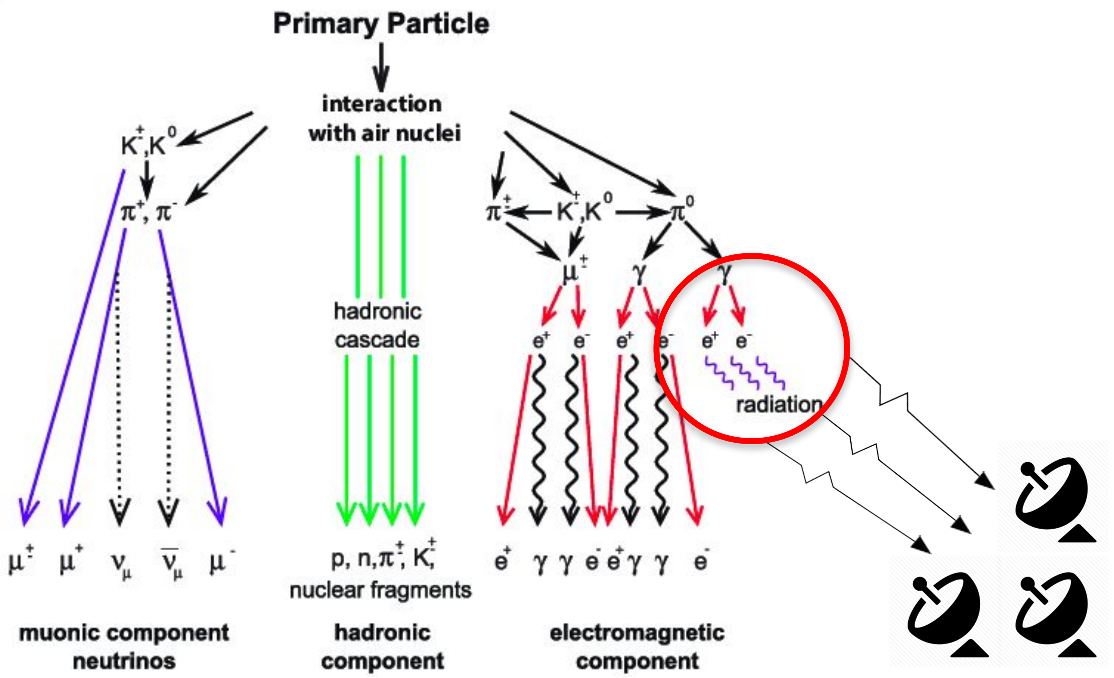
Outline

- The radio emission in Extensive Air Showers (EAS)
- The radio module in CORSIKA 8
- Comparison of a similar shower simulated with different software
- An application on how these simulations are used in the LOFAR experiment
- Pulse shape simulation study

Extensive Air Showers



Cosmic **R**ay **Si**mulatios for **KA**SCADE

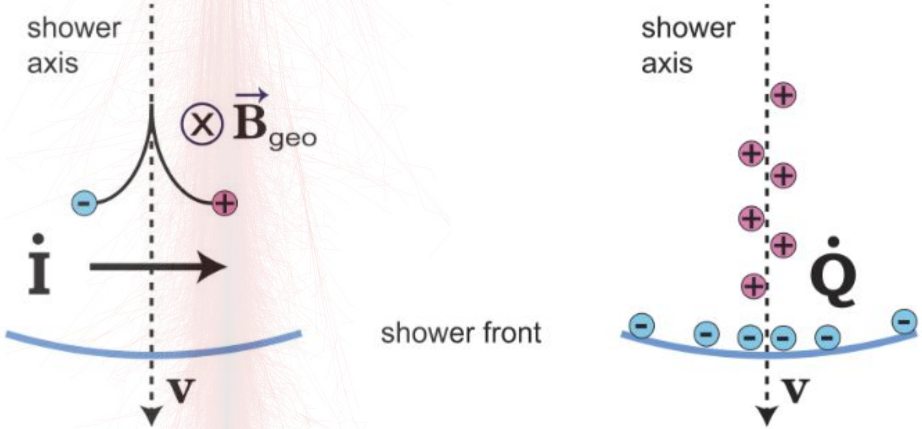
→ **CORSIKA** ←

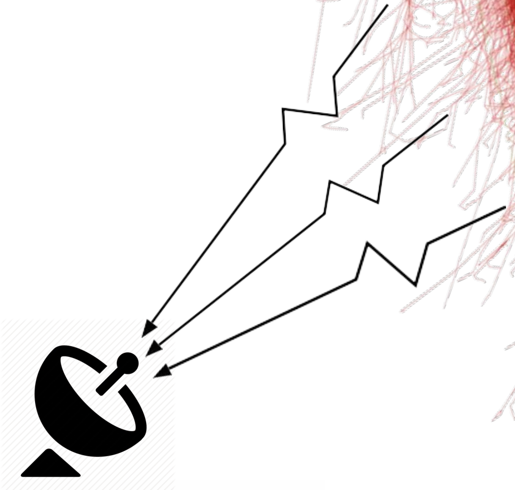
- Monte Carlo program that simulates the interactions and evolution of EAS in the atmosphere
- Has been around for over 30 years
- Has become the universal standard in astroparticle physics
- **CORSIKA 7** is the well established version that people use, **but** with its limitations
- **CORSIKA 8** is the next generation, highly modular and flexible, written in modern C++

Radio emission

Two main mechanisms that contribute to the radio emission

- Geomagnetic (due to Earth's magnetic field – dominant)
- Charge excess (more electrons on the shower front with respect to positrons – subdominant)





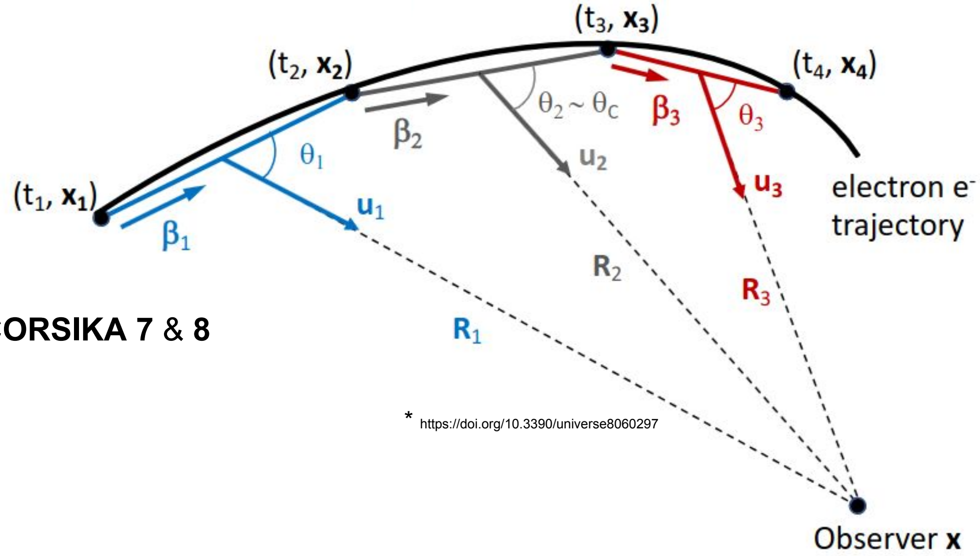
Microscopic modelling

- Endpoints formalism

$$\vec{E}_{\pm}(\vec{x},t) = \pm \frac{1}{\Delta t}\frac{q}{c}\left(\frac{\hat{r}_{1/2}\times(\hat{r}_{1/2}\times\vec{\beta}^*)}{(1-n\vec{\beta}^*\cdot\hat{r}_{1/2})R_{1/2}}\right)$$

* arXiv:1007.4146v3

CoREAS algorithm used in **CORSIKA 7 & 8**



* https://doi.org/10.3390/universe8060297

- ZHS

$$\vec{E}\,(t,\theta) = -\frac{e\,\mu_r}{4\pi\epsilon_0}\vec{v_\perp}\frac{\delta\left(t-\frac{nR}{c}-(1-n\beta\cos\theta)t_1\right)-\delta\left(t-\frac{nR}{c}-(1-n\beta\cos\theta)t_2\right)}{(1-n\beta\cos\theta)}$$

* arXiv:1002.3873v1

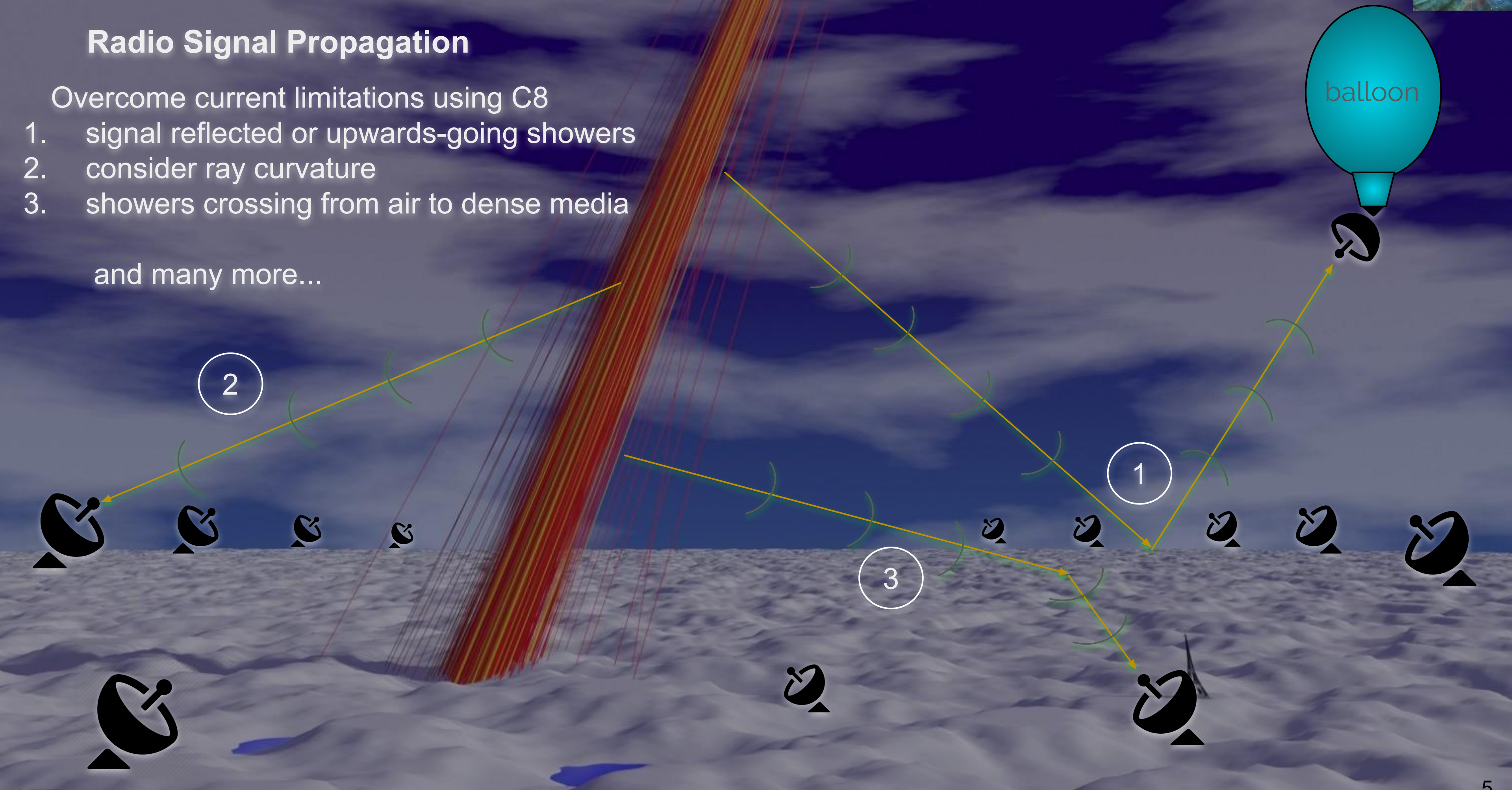
ZHS algorithm used in **ZHAireS** & **CORSIKA 8**

Radio Signal Propagation

Overcome current limitations using C8

1. signal reflected or upwards-going showers
2. consider ray curvature
3. showers crossing from air to dense media

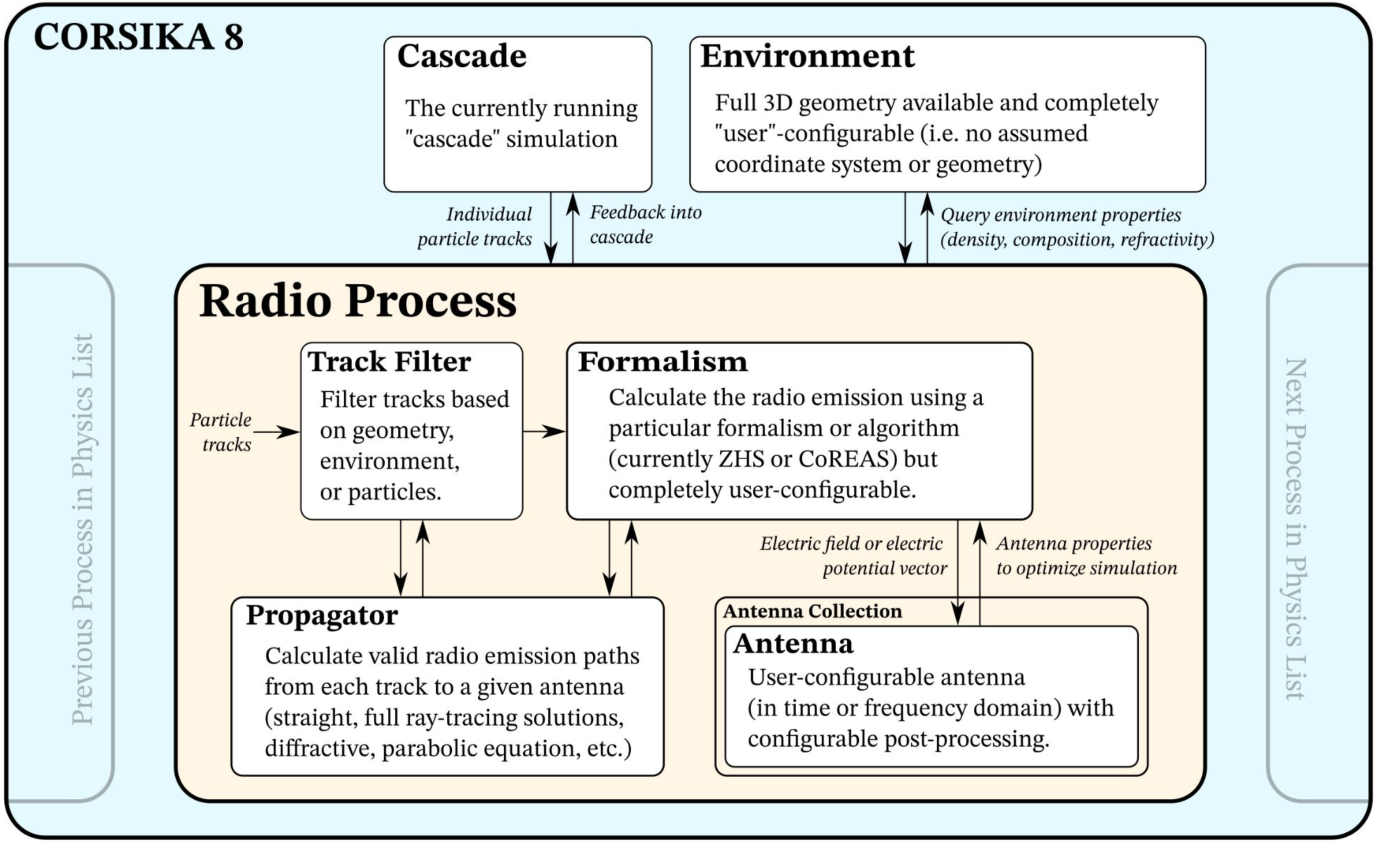
and many more...



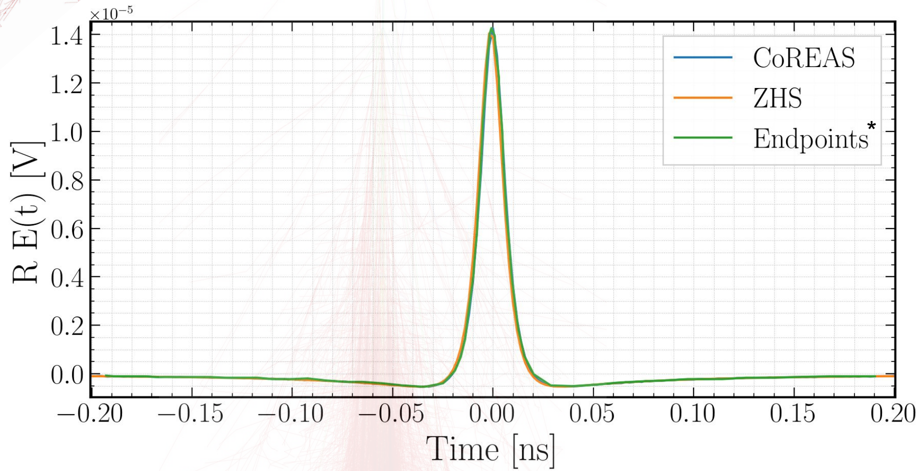
Radio module architecture

User-configurable parameters

- Filter
- Formalism
- Propagator
- Antenna



Electron in a uniform magnetic field

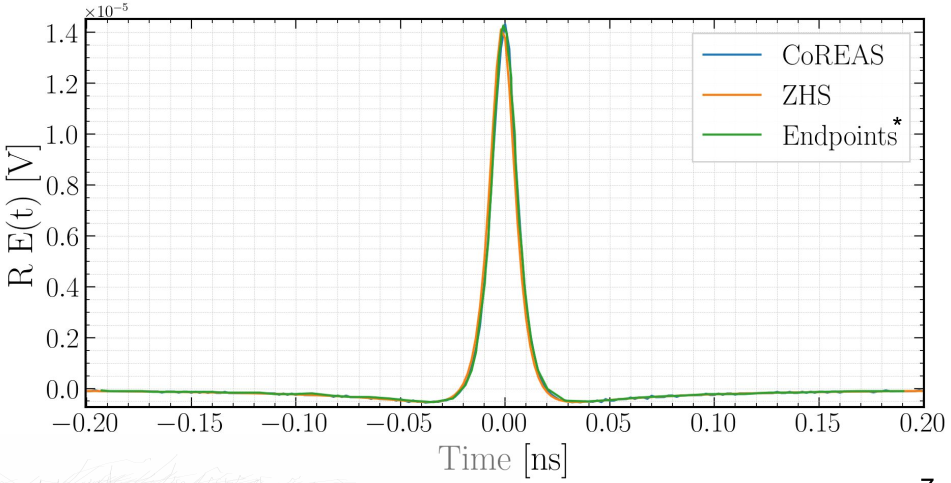


→ Manual tracking algorithm

100.000 points on a circle (L = 100m) connected by straight track segments. The relativistic electron of fixed energy, is allowed to travel on these tracks.

→ CORSIKA 8 tracking algorithm

Used C8's LeapFrog magnetic field tracking algorithm. Created a suitable environment with the corresponding values for magnetic field and gyrofrequency of the relativistic electron.



* C.W. James, H. Falcke, T. Huege and M. Ludwig, doi: 10.1103/PhysRevE.84.056602

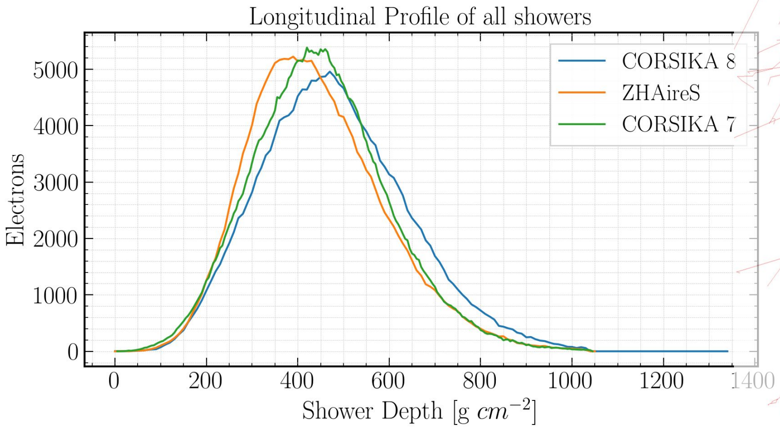
Simulation of an extensive air shower

- 10 TeV electron-induced vertical shower
- US Standard atmosphere – uniform refractive index (n=1.000327)
- Horizontal geomagnetic field B = 50 μT aligned in the x direction
- $X_{\max} \approx 430\, g\, cm^{-2}$
- Star-shaped grid of antennas – 20 concentric rings (25m - 500m)

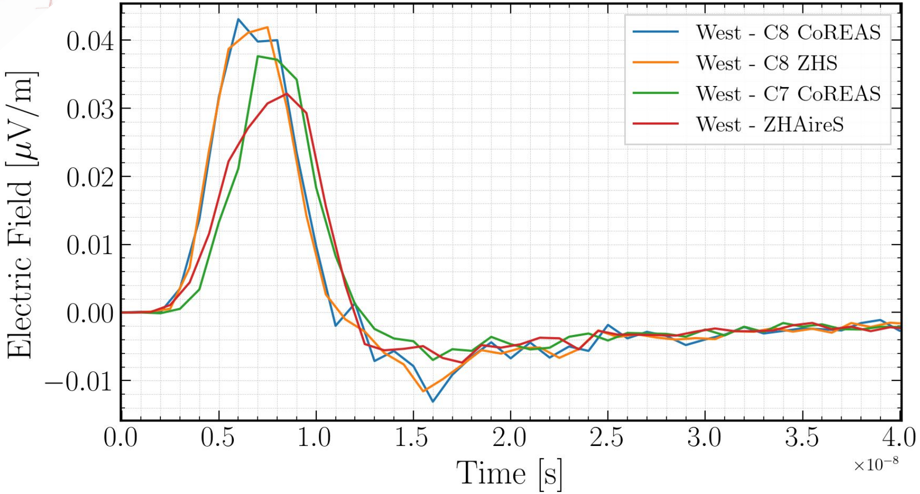
Comparison

- CORSIKA 8 – CoREAS
- CORSIKA 8 – ZHS
- CORSIKA 7 – CoREAS
- ZHAireS

PROPOSAL v. 7.2.1
for C8 simulations



Pulses comparison

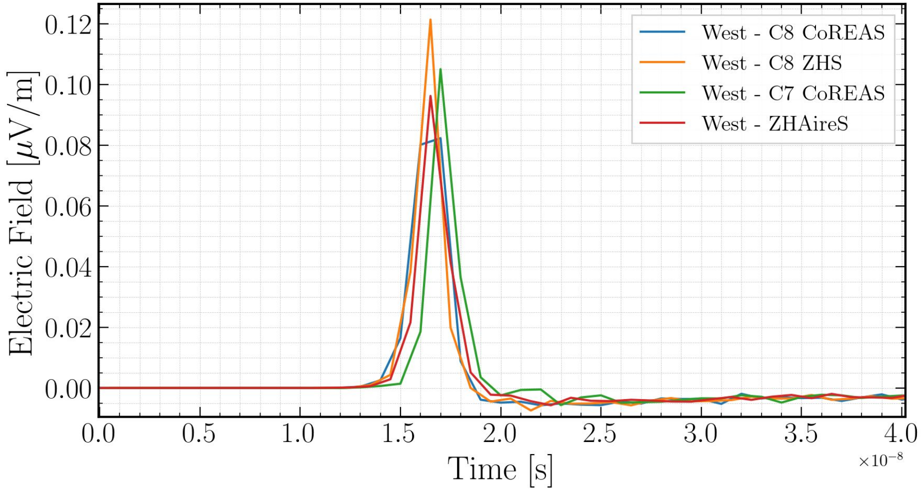


Antenna at 50m from the shower core

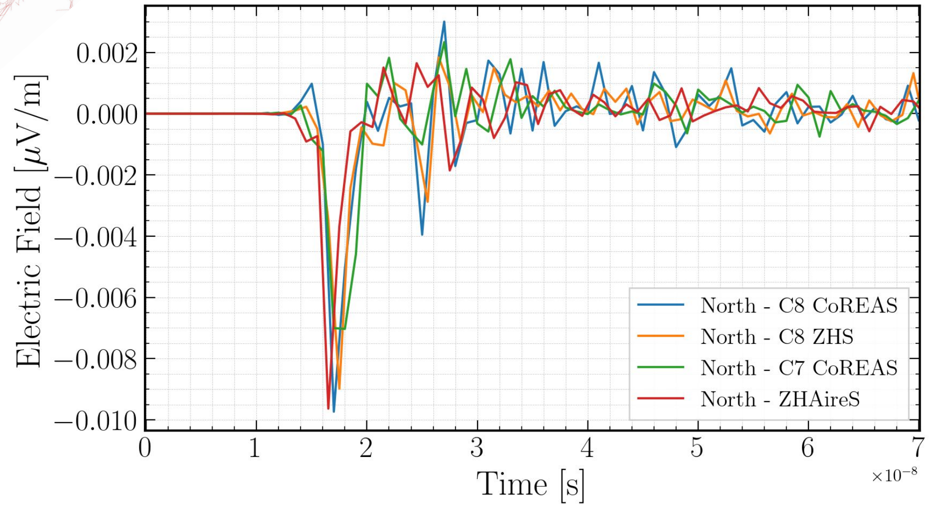
- Very good agreement between C8 (both formalisms) and C7 in pulse amplitude
- ZHAireS seems slightly off

Antenna at 200m from the shower core

- Very good agreement between C7, ZHAireS and C8 CoREAS in pulse amplitude
- C8 ZHS is a bit higher



Pulses comparison

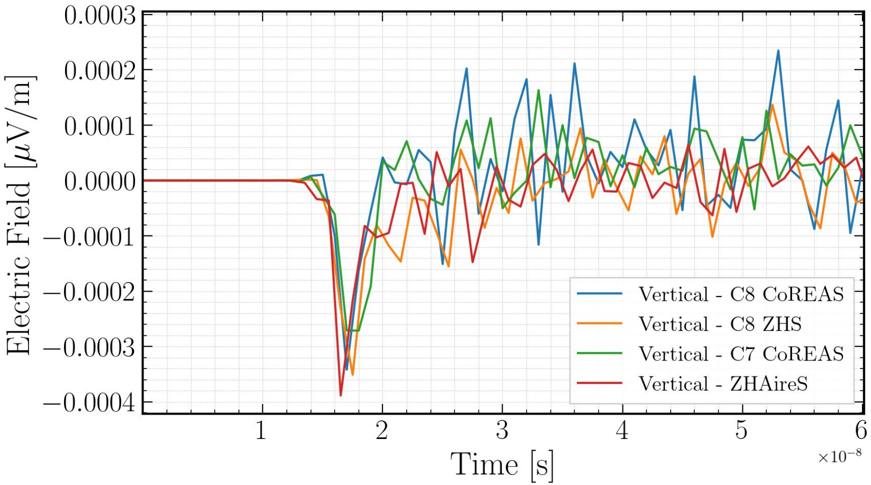


Antenna at 200m from the shower core

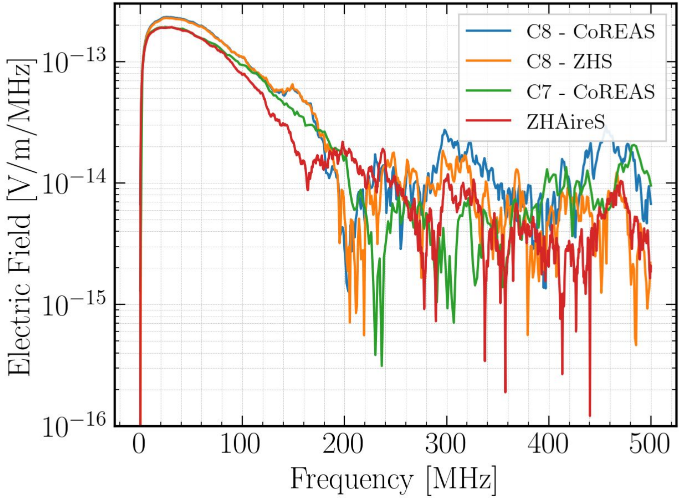
- Very good agreement between ZHAireS and C8 CoREAS & ZHS in pulse amplitude
- C7 seems slightly lower in the peak

Antenna at 200m from the shower core

- Very good agreement between ZHAireS and C8 CoREAS & ZHS in pulse amplitude
- C7 seems slightly lower in the peak



Frequency spectra comparison

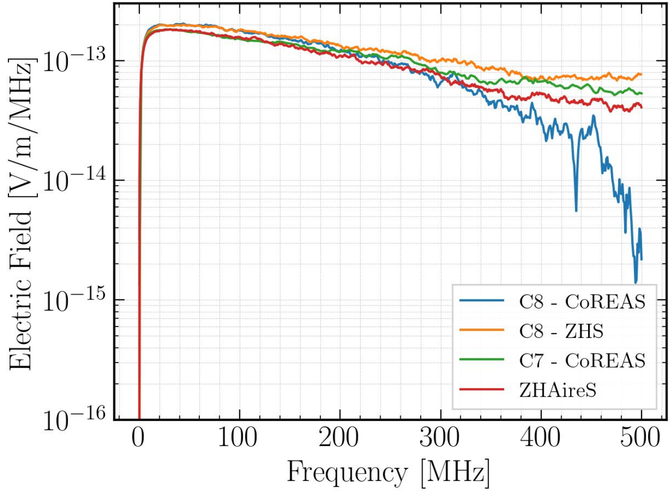


Antenna at 50m from the shower core

- Increase in power below 100 MHz for C8 spectra
- Overall decent agreement

Antenna at 200m from the shower core

- Slight increase in power below 200 MHz for C8 spectra
- C8 CoREAS and C8 ZHS diverge slightly after 250 MHz &C8 CoREAS drops after 400MHz (can be simulation specific artefact)



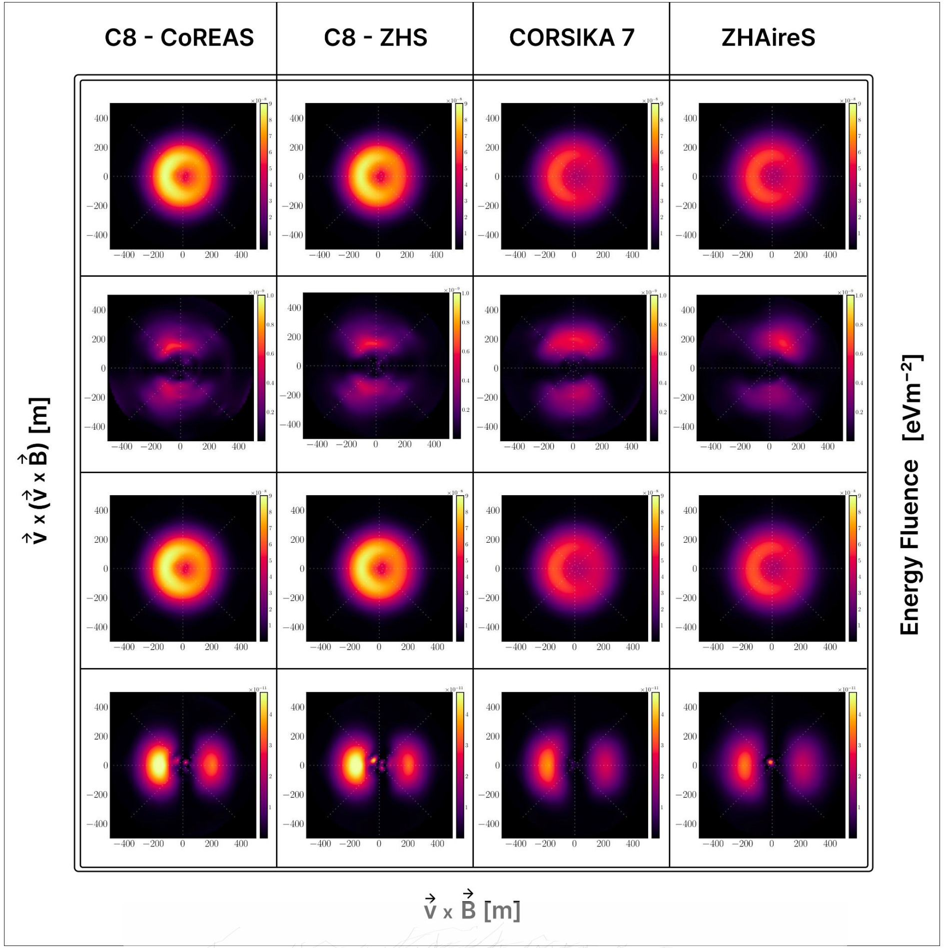
Energy fluence 2D maps (30 - 80 MHz)

All polarizations

$$\vec{v} \times \left(\vec{v} \times \vec{B}\right)$$

$$\vec{v} \times \vec{B}$$

$$\vec{v}$$



CORSIKA 8 status

- Our code is open source and can be found here: https://gitlab.iap.kit.edu/AirShowerPhysics/corsika
- We are currently testing how our software behaves in very high energy showers and looking into in detail to our modules
- We implement “final but important touches”
- We plan for a beta release by ICRC 2023 (July)
- The community still relies and uses CORSIKA 7 because it is well tested and trusted for over 30 years, but the future is CORSIKA 8

But how are all those simulations are used in experiments?

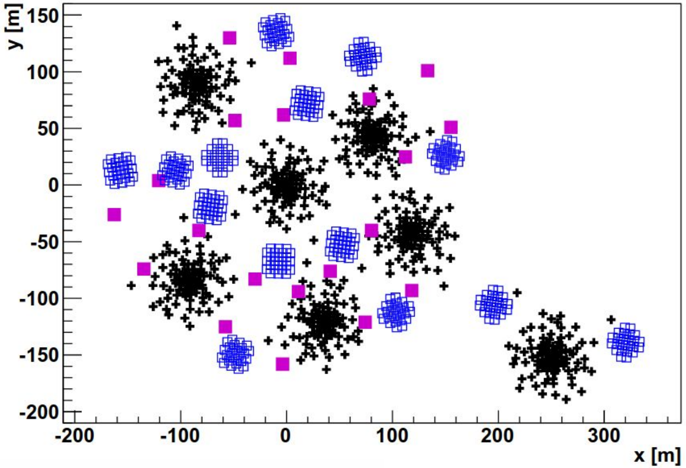
Let’s have a look at the **LOFAR** experiment as an example!

The LOFAR setup

- LOFAR is a digital radio telescope whose antennas operate in the frequency range of 10 – 240 MHz
- Its antennas are spread over several European countries. In the Netherlands there are 24 stations concentrated on ~12 km^2 and its dense core (Superterp) is an area of ~0.1 km^2 with ~600 low-band (10 – 90 MHz) and ~300 high-band (110 – 240 MHz)
- Each station consists of a combination of low-band (LBA - black) and high-band (HBA - blue) antennas
- Distributed in the same area is an independent particle detector array LORA (measures energies 10^16 eV - 10^18 eV - purple) which acts as an external trigger to LOFAR and is also used to establish an absolute energy scale

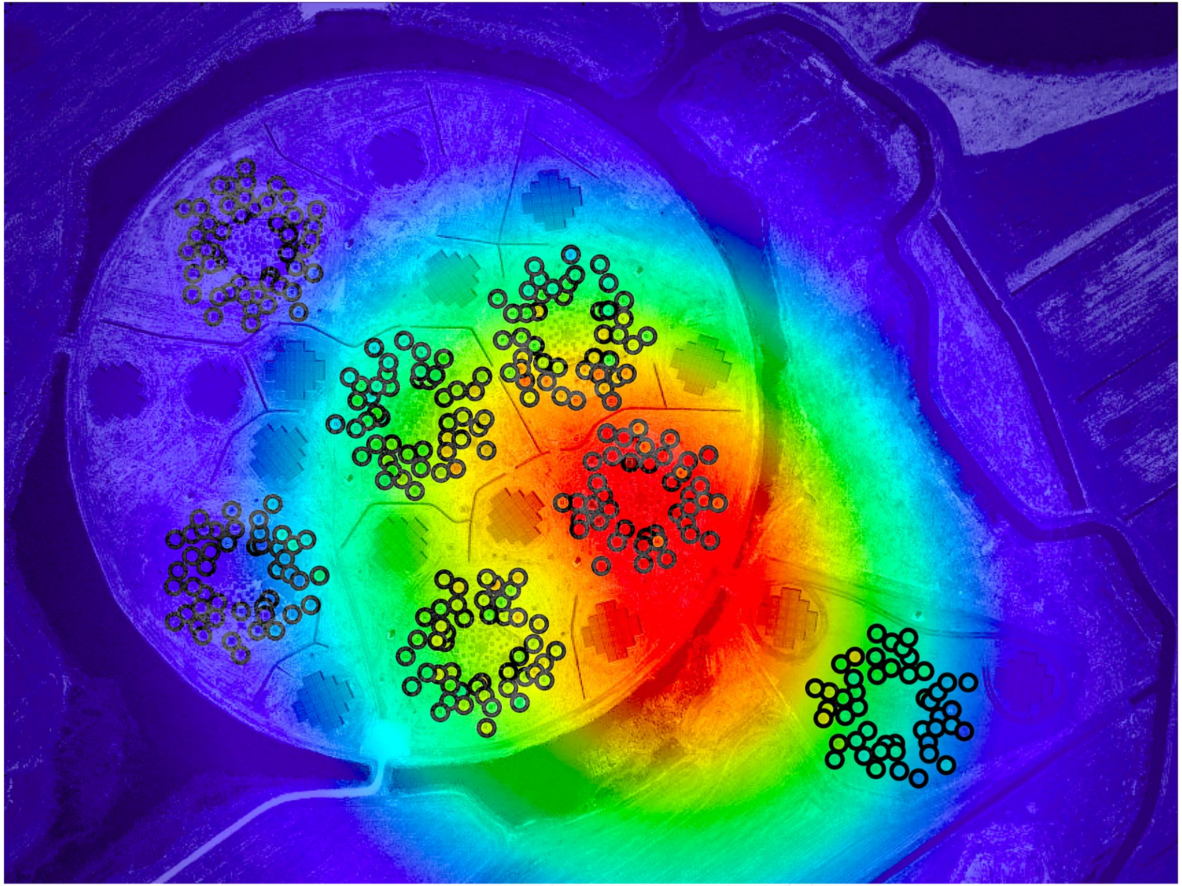
Superterp

6 stations of Superterp



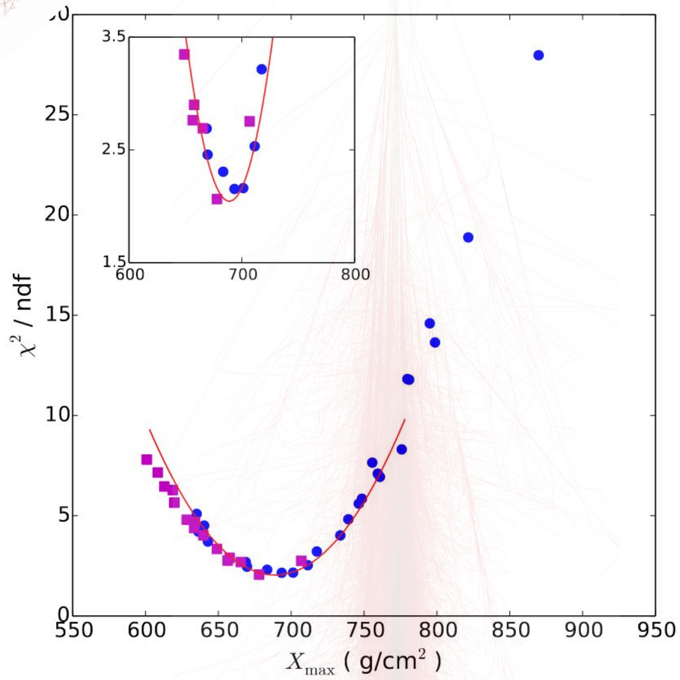
*PoS (ICRC2015) 033

Fluence maps using simulations and data



© image taken from astron.nl

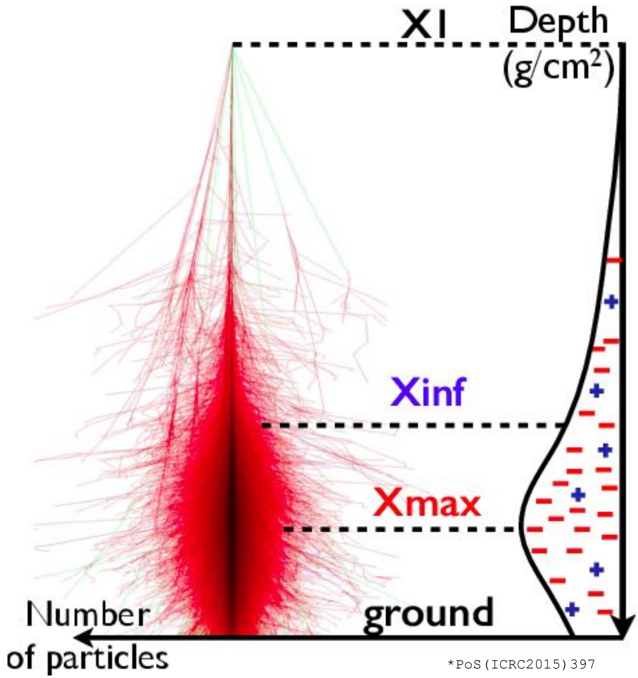
$\mathcal{X}_{max}$ reconstruction



* arXiv:1408.7001 [astro-ph.IM]

- Simulate ~30 P and Fe showers with realistic atmosphere and known arrival direction
- Calculate reduced $\mathcal{X}^2$ for each simulation
- Parabola fit determines event $\mathcal{X}_{max}$
- Resolution < 20 g/cm2

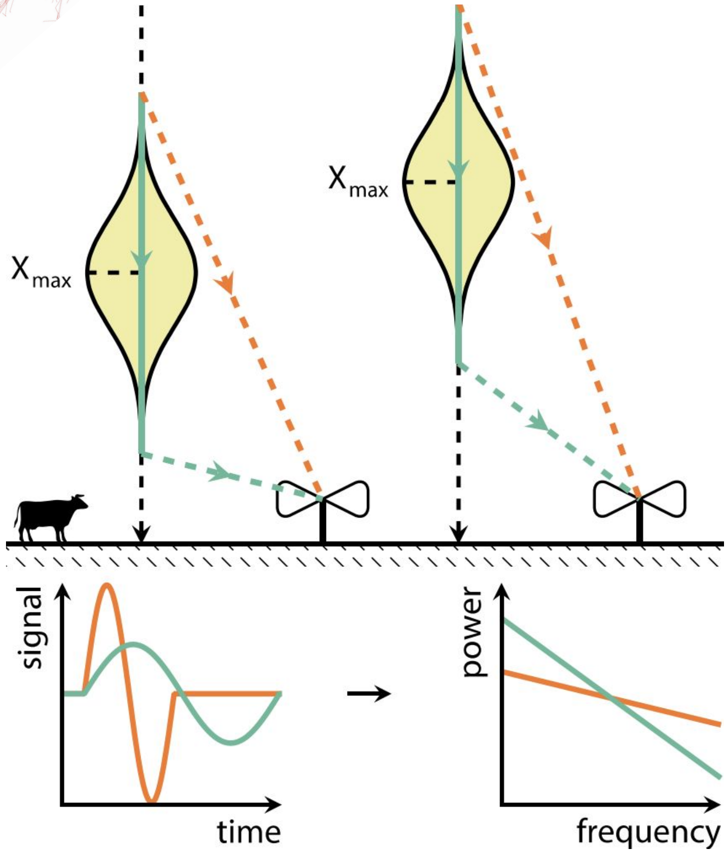
Introduce the pulse shape information in the $\mathcal{X}_{max}$ determination to potentially achieve better resolution

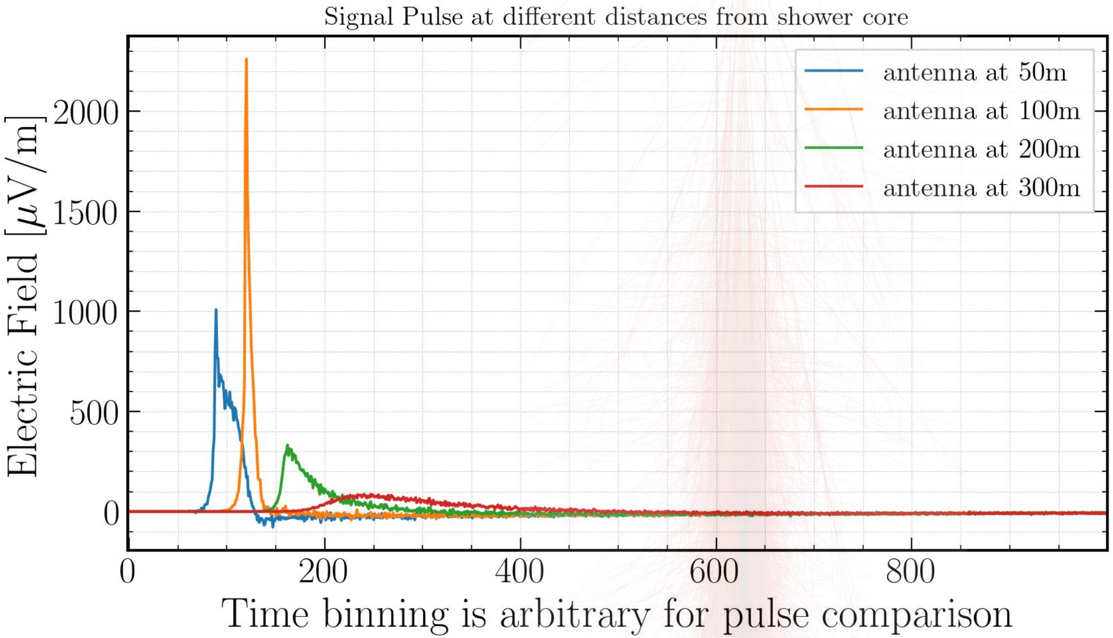


*PoS(ICRC2015)397

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

Pulse shape information





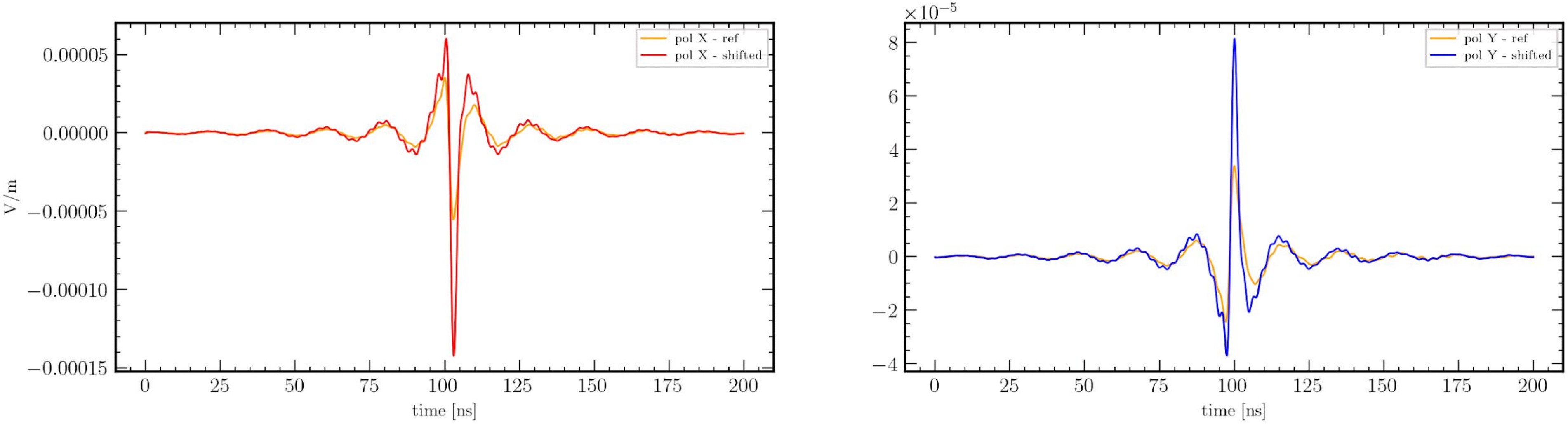
Pulse shape study

- I have looked into some simulated events that have been used in the past for analysis
- The simulations for each event differ only in Xmax
- I have treated one of the simulations of each event as “data” and use it as a reference
- For every antenna in the star shape pattern, I align the pulse with the reference pulse according to the time that corresponds to the maximum value of the correlation factor between the 2 pulses
- I am trying to see if there is sensitivity in the pulse with respect to Xmax and **not** antenna position – which is why antenna position is fixed
- For the correlation factor calculations I use the Pearson correlation coefficient defined like so:

$$r = \frac{\sum (x - m_x)(y - m_y)}{\sqrt{\sum (x - m_x)^2 \sum (y - m_y)^2}}$$

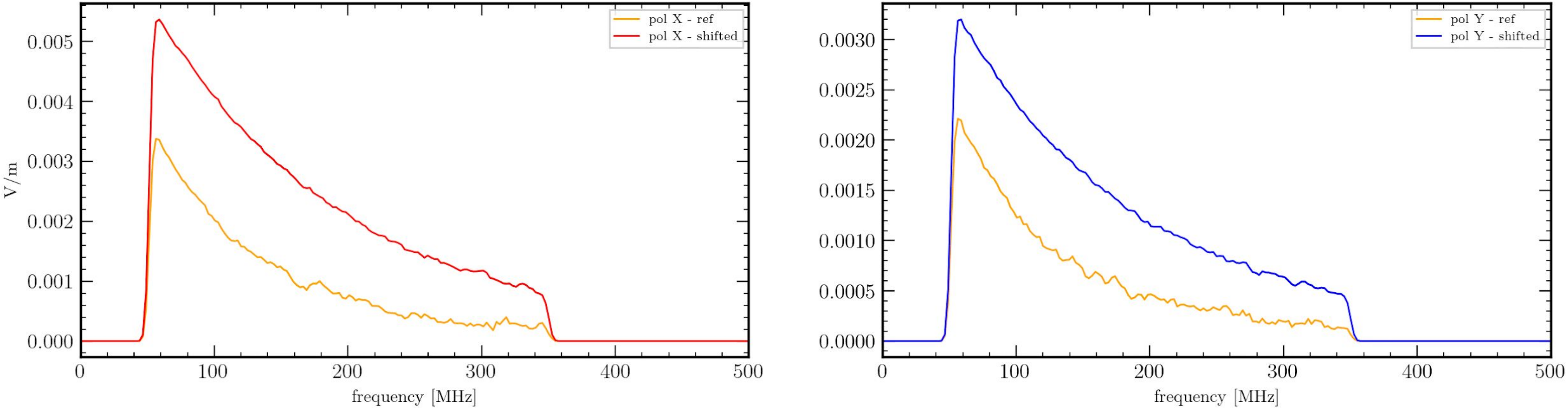
Pulse shape wrt Xmax

Antenna 250m - 135 degrees - Xmax=560.6099194 - CCY = 0.9385779814330923

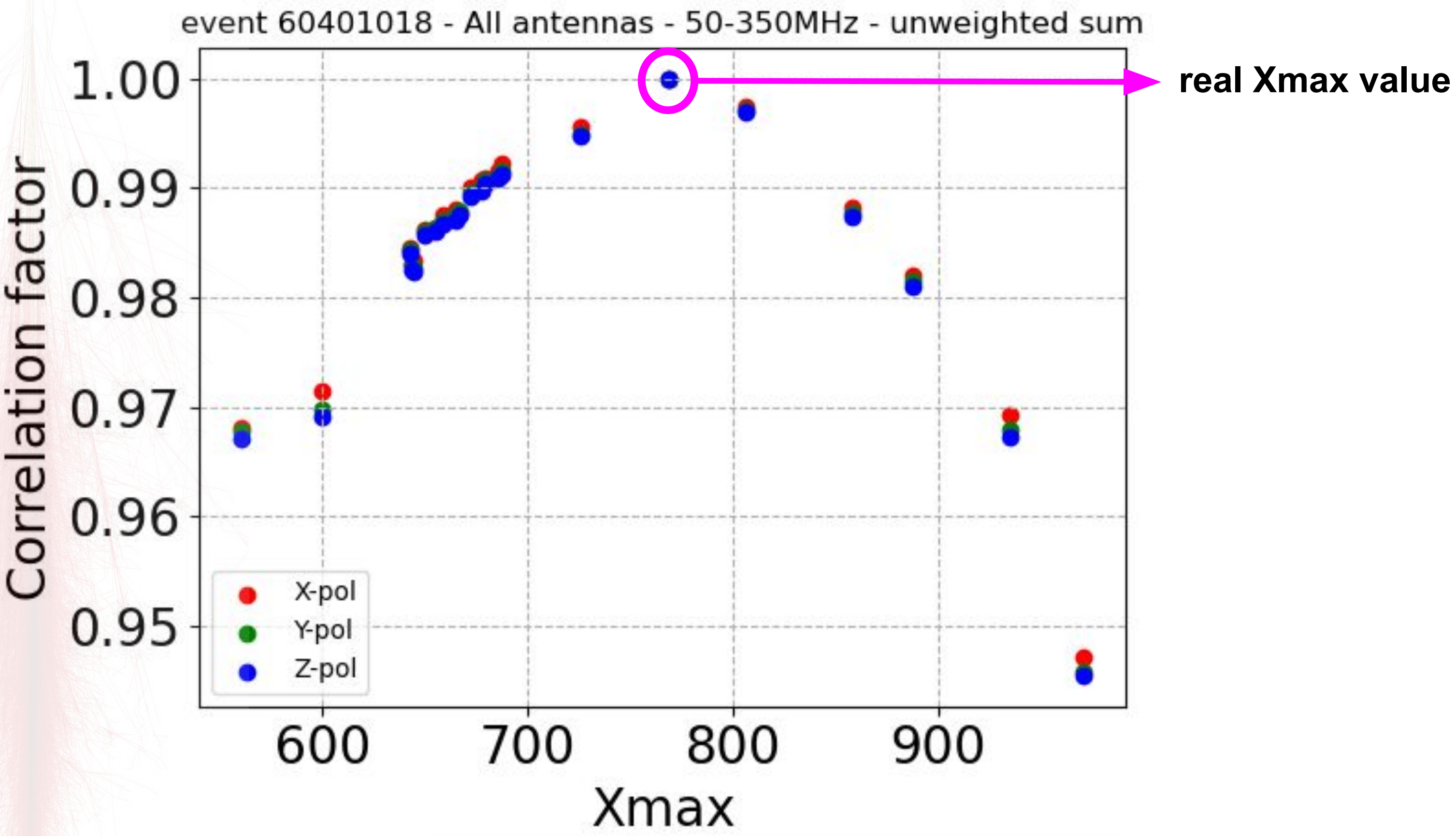


Frequency spectra wrt Xmax

Antenna 250m-135deg || ref-Xmax=768.8947165 vs Xmax=560.6099194



Pulse shape information



Summary

- CORSIKA simulations are crucial to study EAS
- CORSIKA 7 is well established but rests upon old code with limitations
- CORSIKA 8 is the next generation simulation software – to be released soon
- Radio in CORSIKA 8 is in a good shape – able to produce simulations and easily upgradable in order to be “future proof”
- Studying simulations can help us come up with better analysis techniques to potentially increase accuracy as discussed in the pulse shape study example

Thank you!