Karlsruher Institut für Technologie

Friedrich-Alexander-Universität Erlangen-Nürnberg

Erlangen Centre for Astroparticle Physics

Reconstruction of Air Shower induced radio signals with IFT

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PIERRE AUGER OBSERVATORY

LOFAR

Contents

Astroparticle Physics

- Intersection between particle and astrophysics
- Includes cosmic rays, gamma rays, neutrinos, electrons/positrons from astrophysical sources and gravitational waves
- Use particles as messengers from sources in the Universe
- In the past: observation through visible light
- Since 20th century: also through **radio**, microwave, infrared, UV, X-ray and gamma ray

- **Cosmic Ray**: A charged particle arriving from outside of the Earth (typically electrons or nuclei)

Cosmic Rays - Energy Spectrum

- Described by power law

- Left vertical band: Emission from sun dominant
- Central band: presumably of galactic origin
- Right band: extragalactic origin

- High suppression at the highest energies

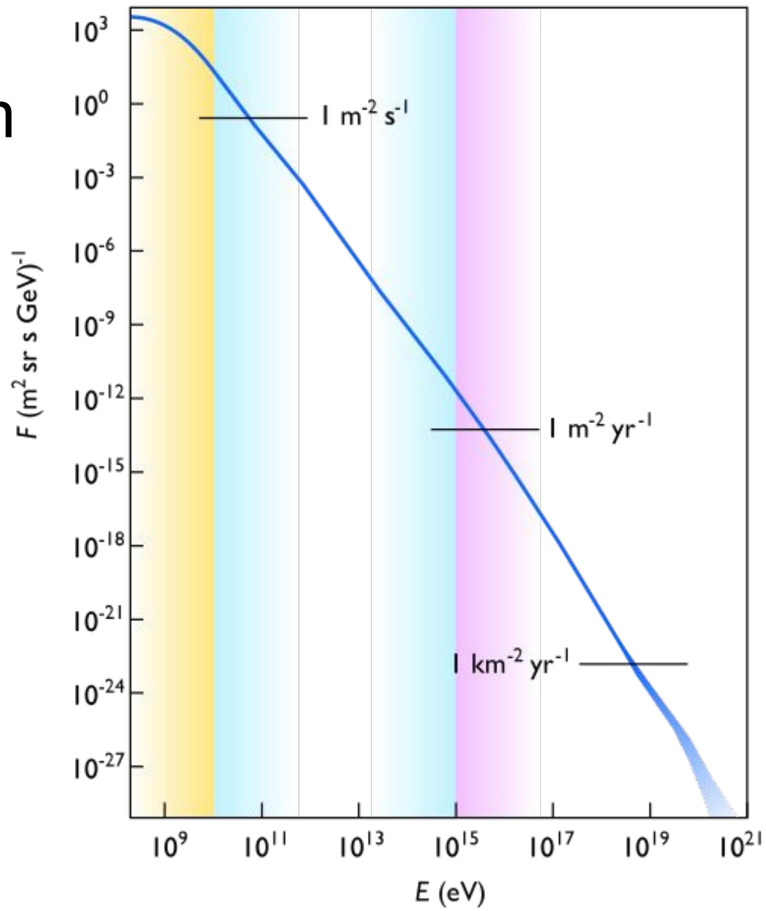


Image: Sven Lafebre

Cosmic Rays - Composition

- Majority of CRs are protons (hydrogen nuclei)
- 10% Helium nuclei
- 1% neutrons or nuclei of heavier elements (e.g. iron), 1% electrons and photons

Cosmic Rays - Air Showers

- Upon interaction with an air molecule, cosmic ray produces an air shower.

- Two effects: Askaryan effect and geomagnetic emission cause radio frequency emission that can be measured with antennas

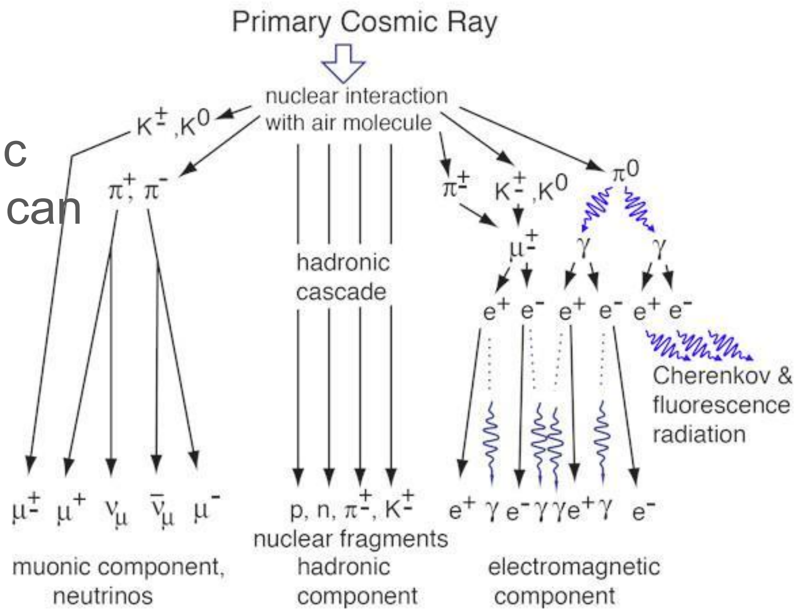
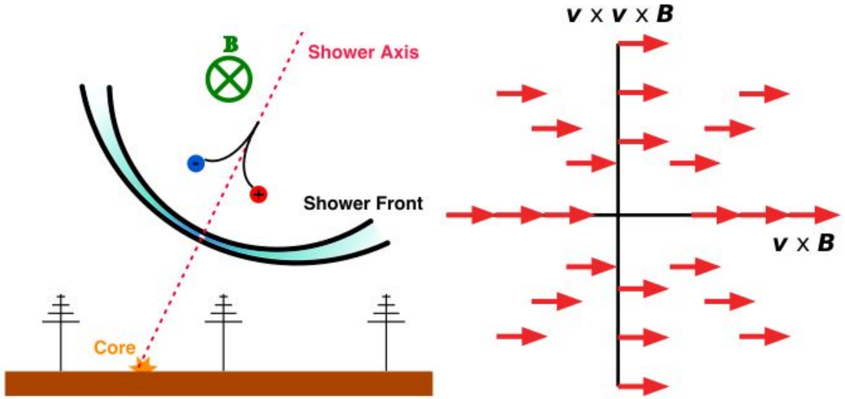


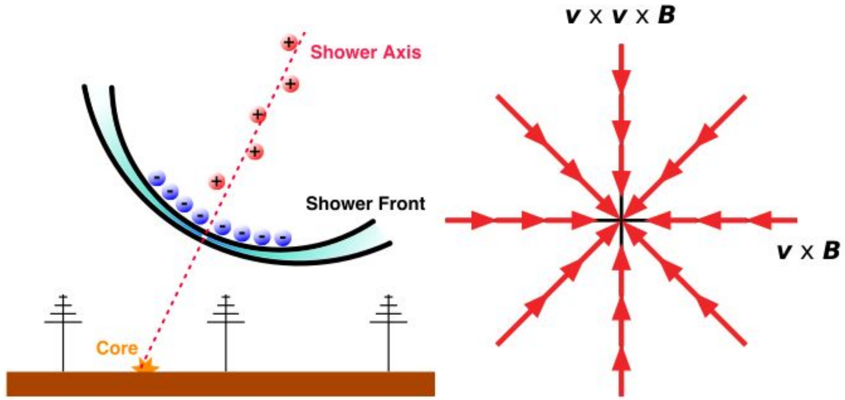
Image: http://hyperphysics.phy-astr.gsu.edu/

Cosmic Rays - Air Showers

https://arxiv.org/abs/1601.07426

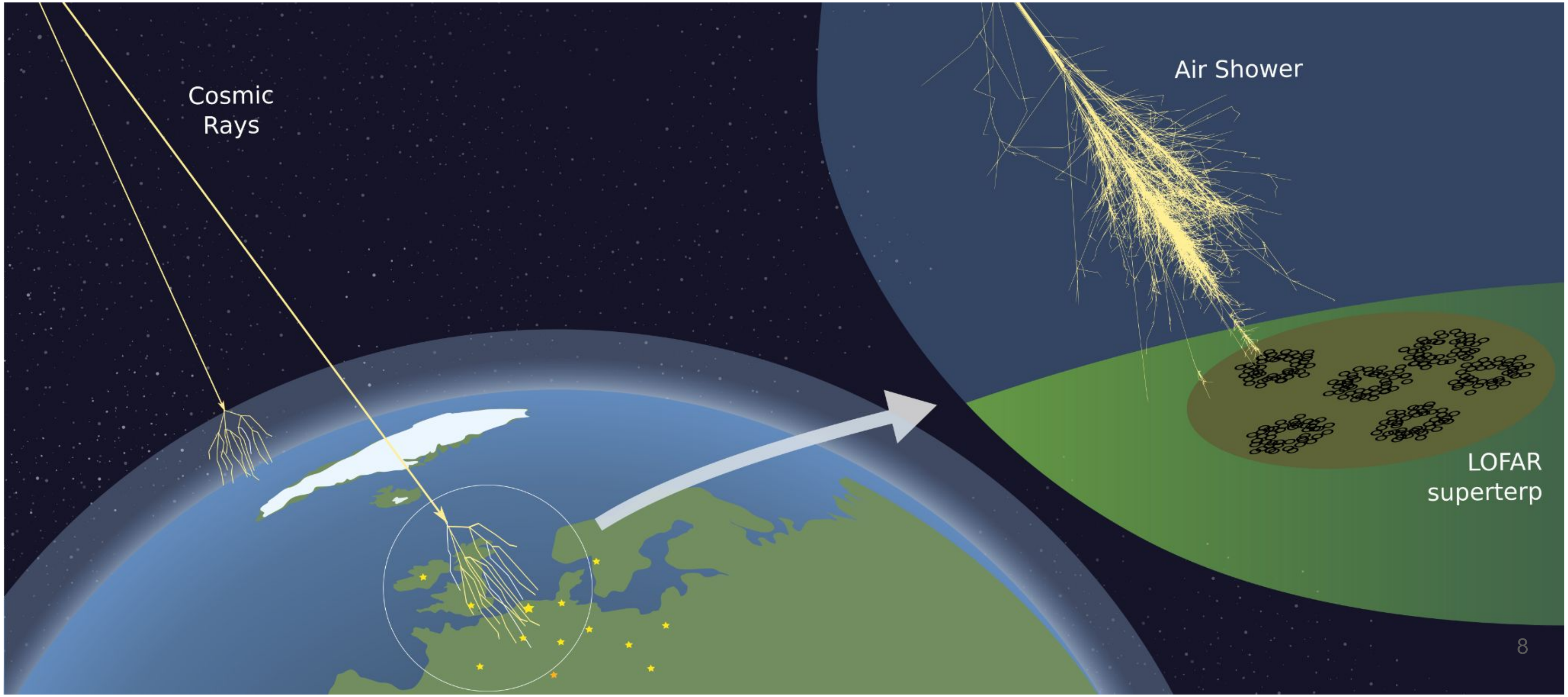


Geomagnetic emission



Askaryan/charge excess effect

Measuring Air Shower induced radio signals with LOFAR



LOFAR

- Low-Frequency Array (LOFAR) is the world's largest radio telescope
- telescope array with stations across Europe
- Core located in the Netherlands

- 52 stations total
- Each station consists of Low Band Antennas (LBA) and High Band Antennas (HBA)

- various key science projects: **Ultra high-energy cosmic rays**

Image: ASTRON

LOFAR

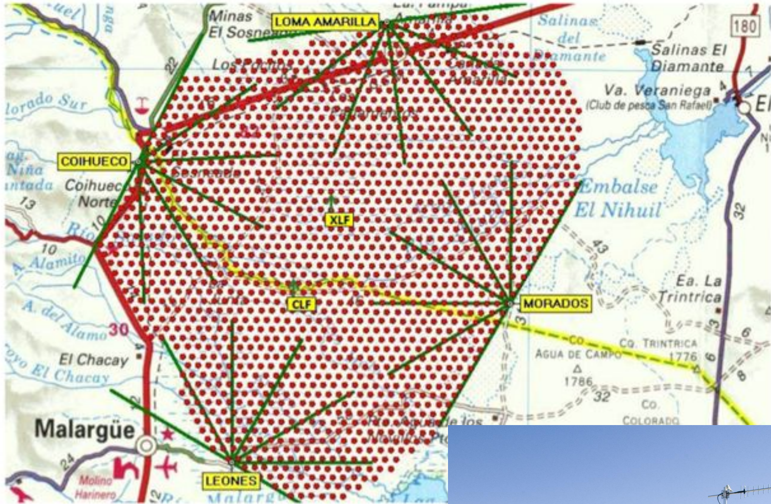
- In superterp, particle detectors (LORA) act as trigger
- LORA also gives first indication for direction reconstruction

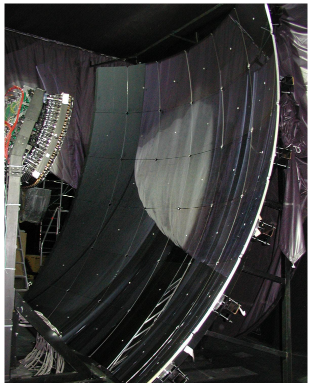
- So far, only LBAs are used for detection (30-80 MHz band)
- In the future, HBAs will be included (110-240 MHz band)

Image: T. Krieg

Pierre Auger Observatory

- 3000 km² in Argentina
- ~1600 detector stations
  - Water-Cherenkov Detector
  - Scintillation Detector
  - Radio Detector
- 4 Sites of Fluorescence Telescopes





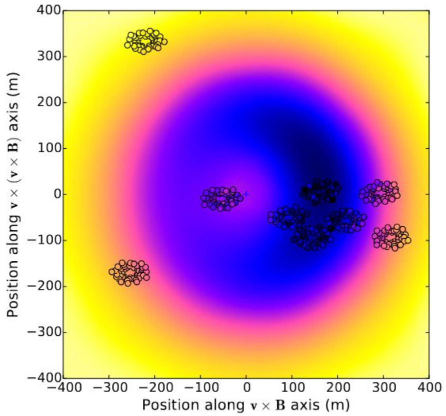
Pierre Auger Observatory - Radio

- **A**uger **E**ngineering **R**adio **A**rray
  - 150 Stations (LPDAs and Butterfly antennas)
- Full radio detector
  - AugerPrime upgrade
  - On all 1600 stations
  - SALLAs
  - 30-80 MHz

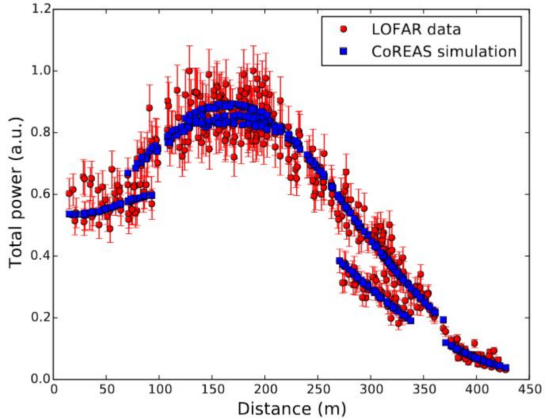
Reconstruction so far - Xmax

- Data is fit to air shower simulations from CoREAS by minimising the χ^2:

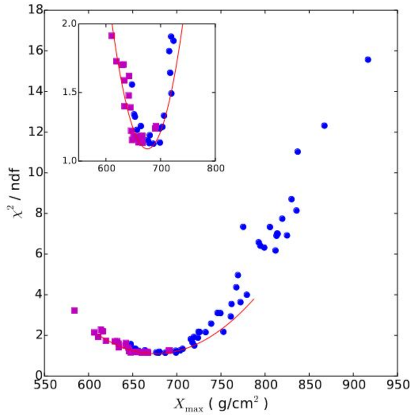
$$\chi^2 = \sum_{\text{antennas}} \left(\frac{P_{\text{ant}} - f_r^2 P_{\text{sim}}(x_{\text{ant}} - x_0, y_{\text{ant}} - y_0)}{\sigma_{\text{ant}}} \right)^2 + \sum_{\substack{\text{particle}\\ \text{detectors}}} \left(\frac{d_{\text{det}} - f_p d_{\text{sim}}(x_{\text{det}} - x_0, y_{\text{det}} - y_0)}{\sigma_{\text{det}}} \right)^2 \quad (1)$$



Simulated radio map



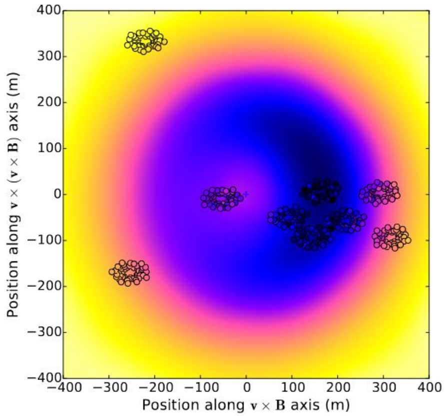
One-dimensional distribution functions



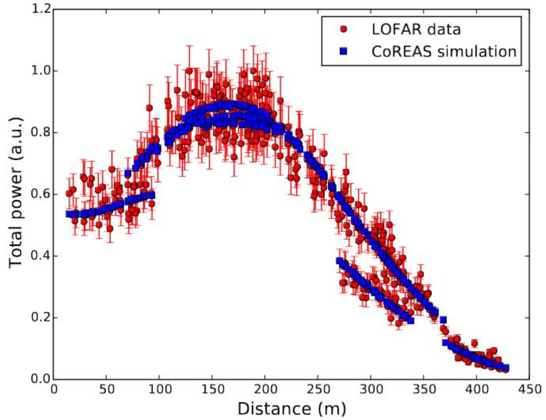
Reduced χ^2 as function of Xmax

S. Buitink et al. (2014)

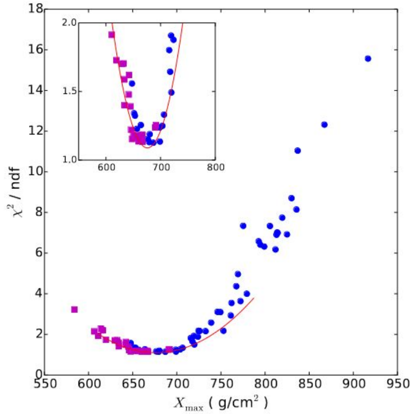
Reconstruction so far - Xmax



Simulated radio map



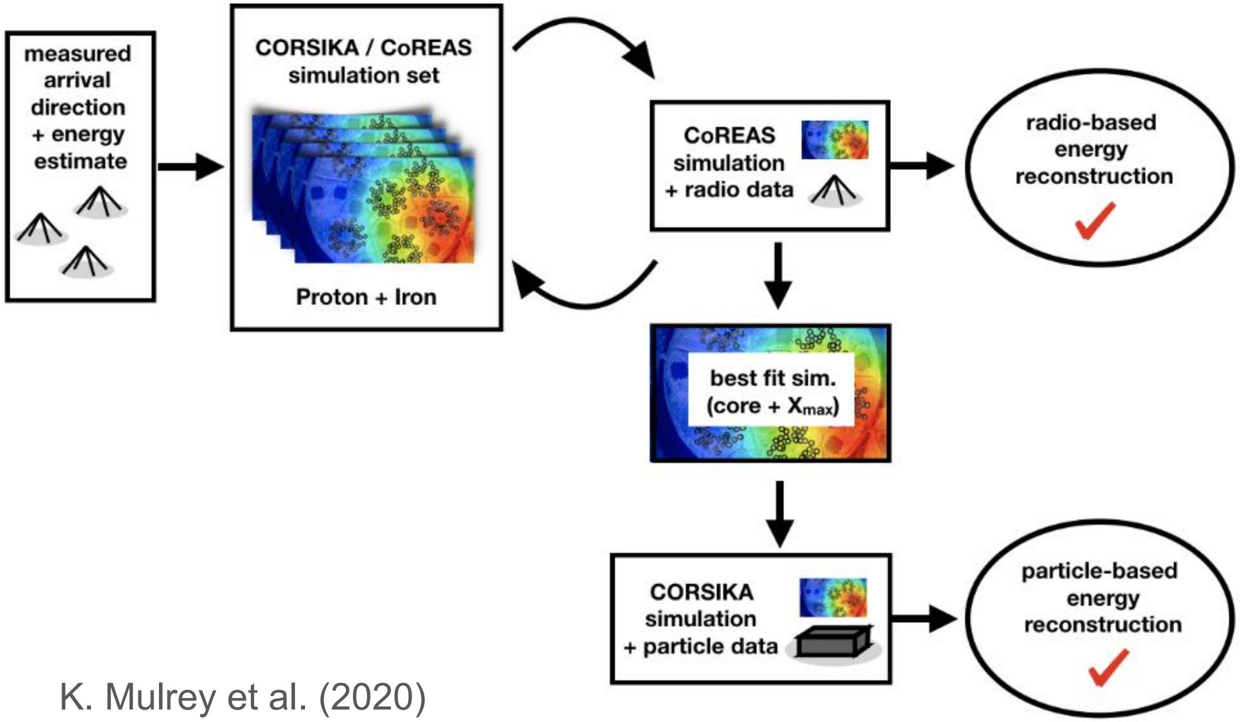
One-dimensional distribution functions



Reduced χ² as function of Xmax

- Uncertainties on Xmax 17 g/cm²
- Con: CoREAS simulations needed, which are very slow

Reconstruction so far - Energy



K. Mulrey et al. (2020)

Radio-based reconstruction is done first, resulting in a best-fit simulation. This is then used in the particle-based reconstruction.

Reconstruction so far - Energy

Radio based	Particle based
compare ε_{sim} at each LOFAR antenna position to the detected ε	uses the best fit CORSIKA simulation as determined by the radio χ^2 fit. With best simulation known, fit particle χ^2

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

$$E_{\text{radio}} = f_r \times E_{\text{sim}}.$$

$$\chi^2_{\text{particle}} = \sum_{\substack{\text{particle}\\ \text{detectors}}} \left(\frac{d_{\text{det}} - f_p d_{\text{sim}}}{\sigma_{\text{det}}} \right)^2$$

$$E_{\text{particle}} = f_p \times E_{\text{sim}} = \frac{f_p}{f_r} \times E_{\text{radio}}.$$

Reconstruction so far - Energy

Radio based

Uncertainty	Value
Event-by-event	
angular dependence of antenna model	5%
temperature dependence	negligible
reconstruction uncertainty	typically 9%
composition uncertainty	10 %
Total event-by-event	11% $\bigoplus$ reconstruction uncertainty
Absolute scale	
antenna calibration and system response	13%
hadronic interaction models	3%
radio simulation method	2.6%
Total absolute scale	13.6%

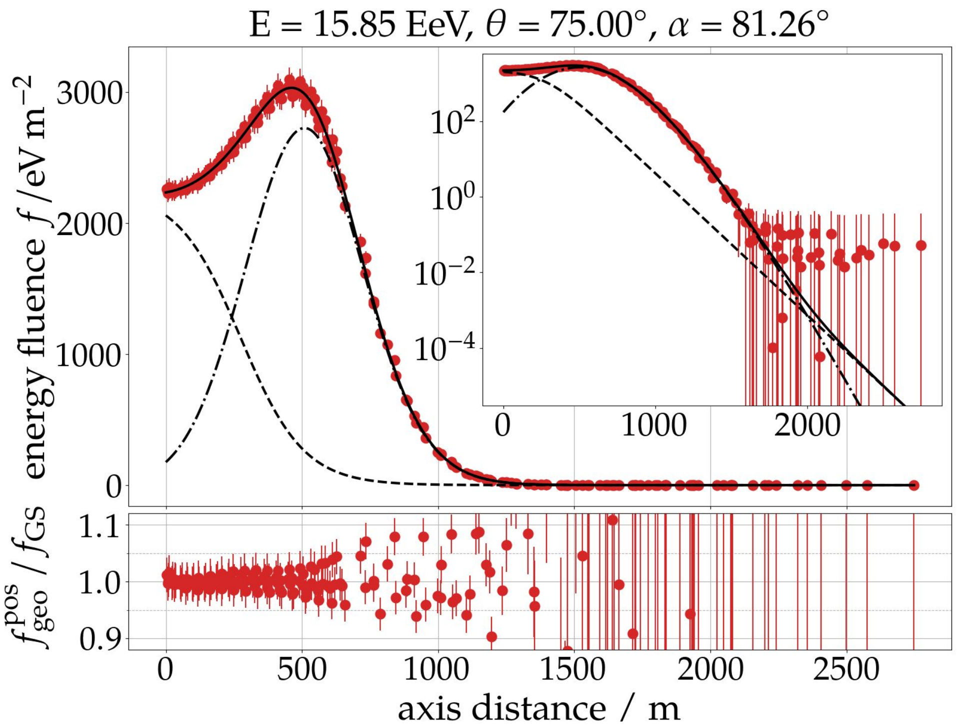
Particle based

Uncertainty	Value
Event-by-event	
scintillator response variation	2.5%
reconstruction uncertainty	10 – 50%
composition uncertainty	2 – 30%
Total event-by-event	2.5% $\bigoplus$ reconstruction uncertainty $\bigoplus$ composition uncertainty
Absolute scale	
scintillator calibration	3%
hadronic interaction models	7%
Total absolute scale	7.6%

Reconstruction so far - HAS LDF fit

- Dissertation of Felix Schlüter

- Lateral distribution parameterised in d_{max} and E_{EM}



Felix Schlüter, Dissertation, 2022

Radio pulse reconstruction with IFT - Previous work

- C. Welling, P. Frank, T. Enßlin, A. Nelles (2021)

$$\mathcal{E}(f) = E(f) \cdot \exp\big(i \cdot \varphi(f)\big)$$

- The E-Field spectrum is defined by its amplitude and phase
  - The E-Field spectrum follows a log-normal distribution
  - Correlation-structure of E-Field is isotropic and homogeneous
  - Linear phase

$$E(f) = \exp\big(s(f)\big)$$

$$s(k) = k^{-\alpha} \cdot f(\xi(k))$$

where $P(\xi) = \mathcal{G}(\xi, 1)$

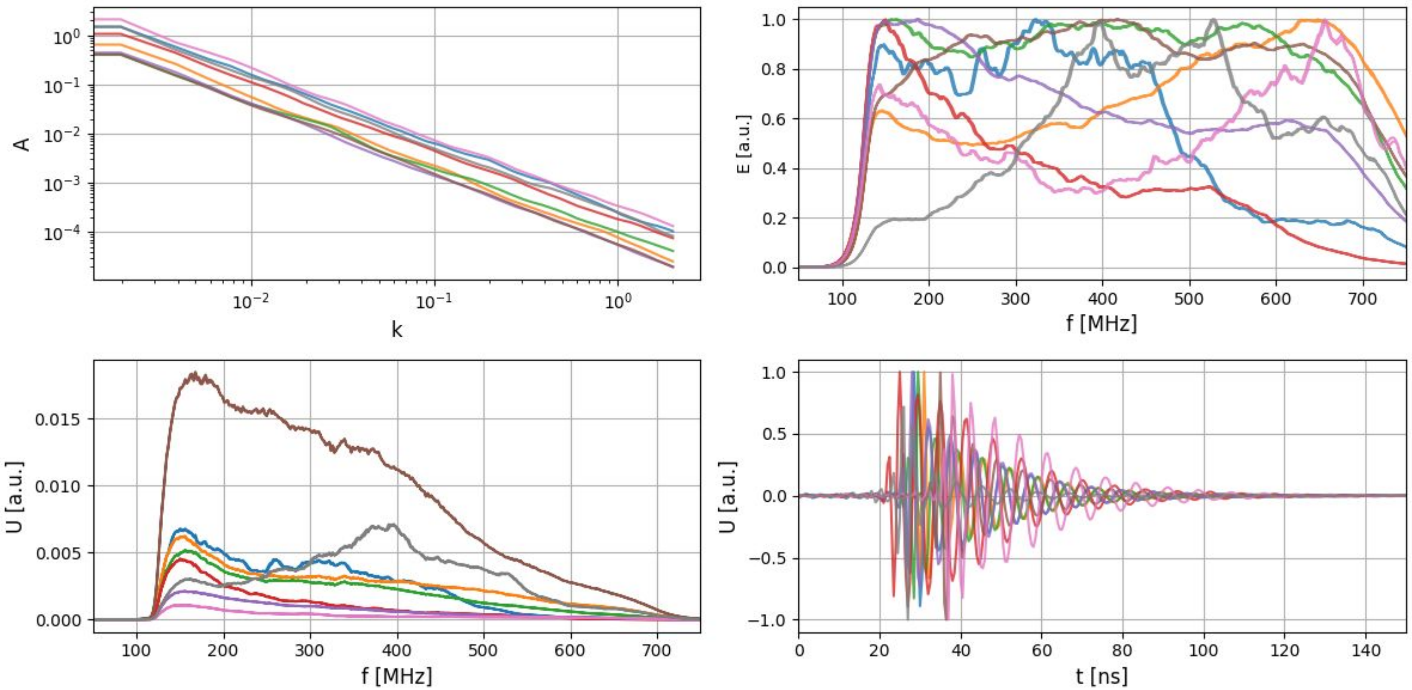
$$\varphi(f) = \phi_0 + mf$$

- Linear polarisation angle ϕ

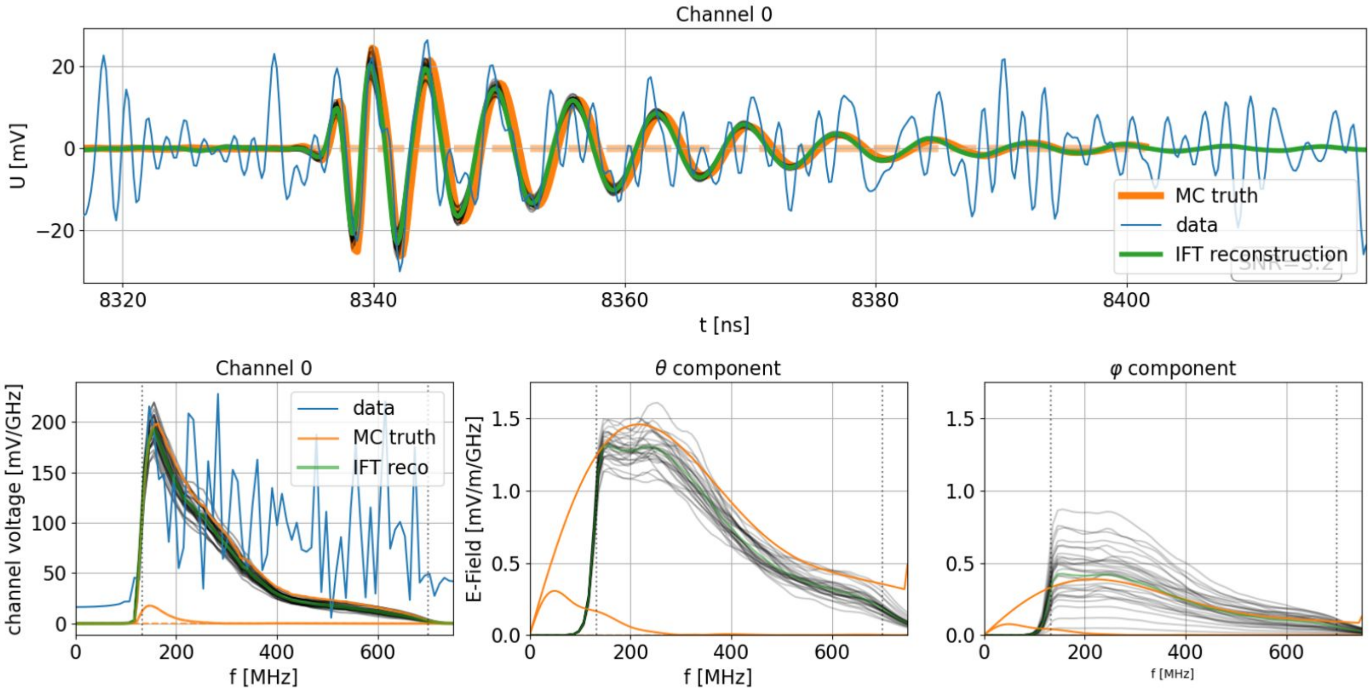
$$\vec{E} = E \cdot (\cos\phi_{pol}\,\hat{\theta} + \sin\phi_{pol}\,\hat{\phi})$$

- Total response: $\mathcal{V}^i(f) = E(f) \cdot \big(\mathcal{H}_\theta^i(f)\cos(\phi_{pol}) + \mathcal{H}_\phi^i \sin(\phi_{pol})\big)$

Radio pulse reconstruction with IFT - Previous work



Radio pulse reconstruction with IFT - Previous work



Aims

1. Reconstruction of the electric field
    - station level
    - detector level
2. Reconstruction of shower parameters
3. Adding high-level data from particle detectors
4. Adding low-level data from particle detectors

Radio pulse reconstruction with IFT

- Problems
  a. “small” bandwidth (30-80 MHz) ⇒ less data
  b. Data depends mostly on response function

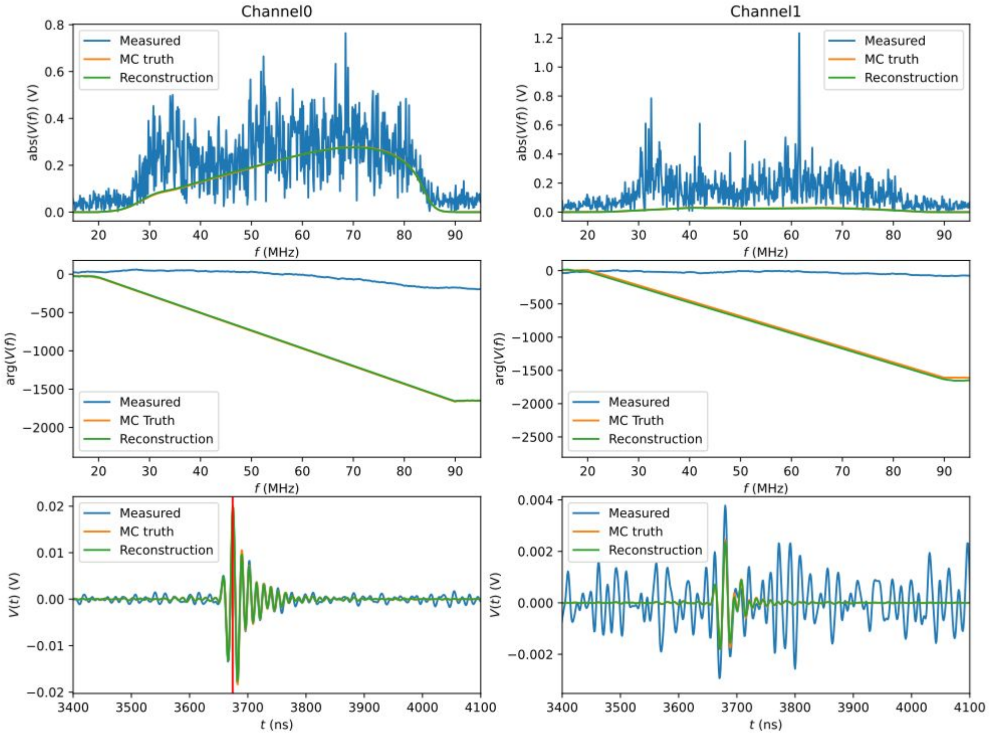
  ⇒ Good fit to data can be realised with a very wrong field

- Solution
  a. Amplitude spectrum → broken power law
  b. Polarisation angle → $v \times B$ direction

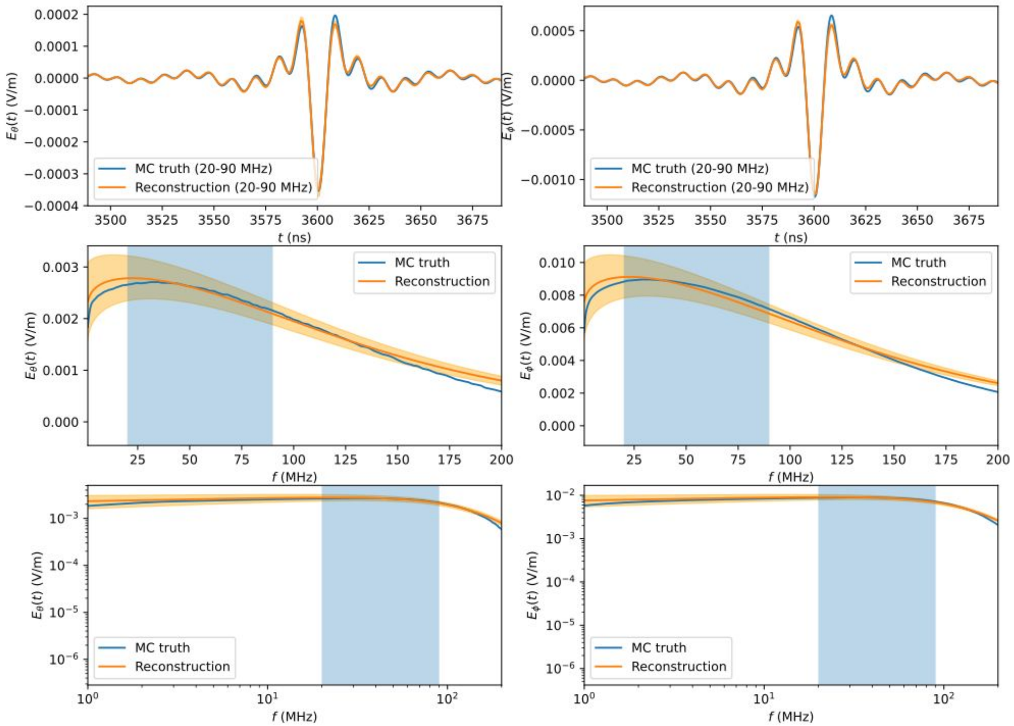
$$E(f) = 10^{\alpha} f_{12}^{\beta_2 - \beta_1} f^{\beta_1} (f^s - f_{12}^s)^{\frac{\beta_1 - \beta_2}{s}}$$

- Still undercomplex

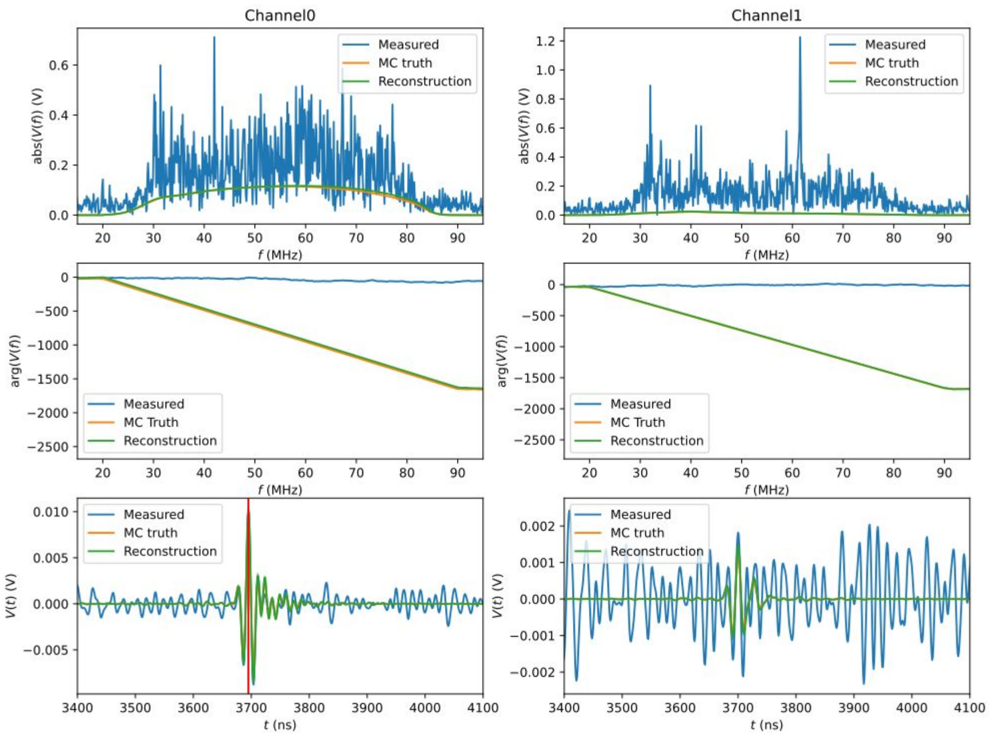
Radio pulse reconstruction with IFT



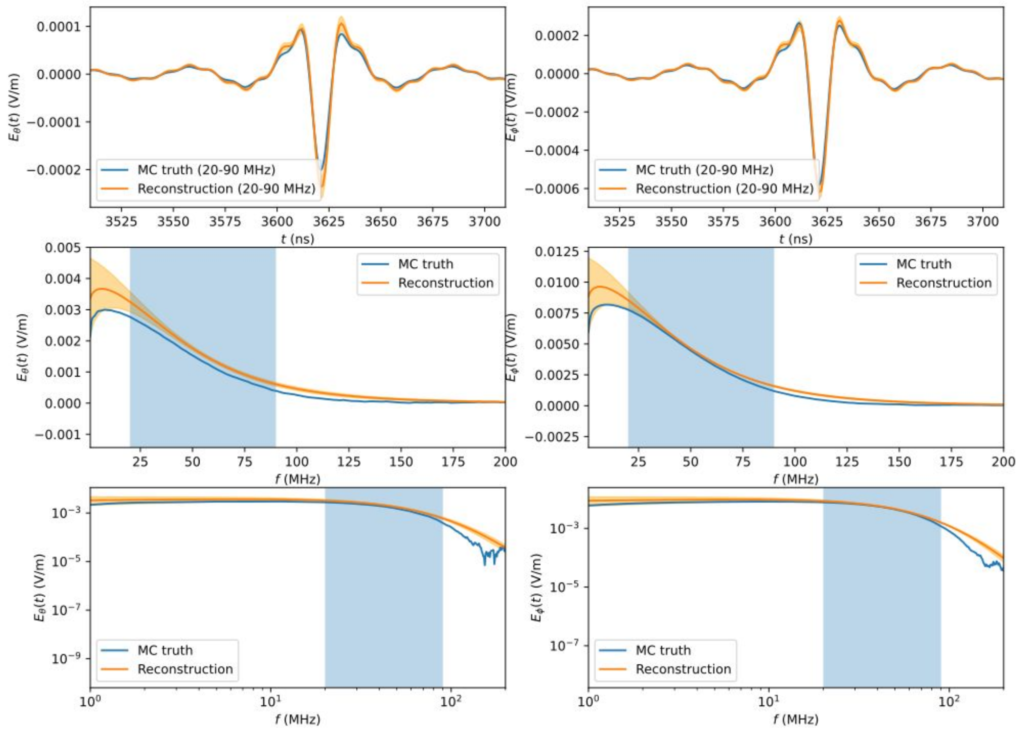
Radio pulse reconstruction with IFT



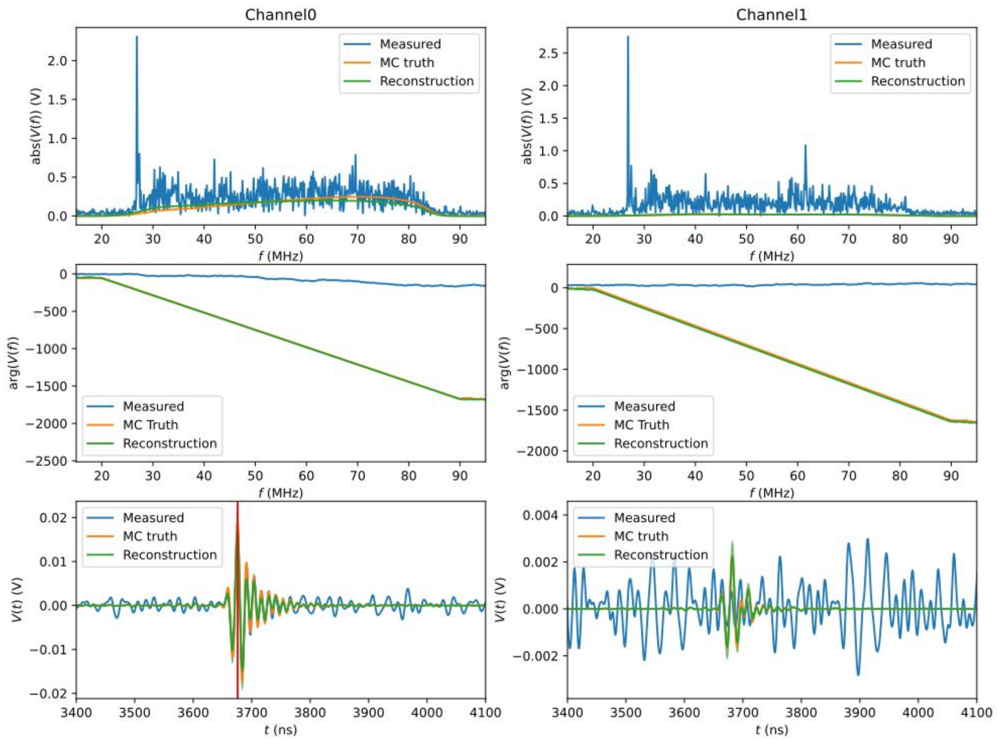
Radio pulse reconstruction with IFT



Radio pulse reconstruction with IFT



Radio pulse reconstruction with IFT



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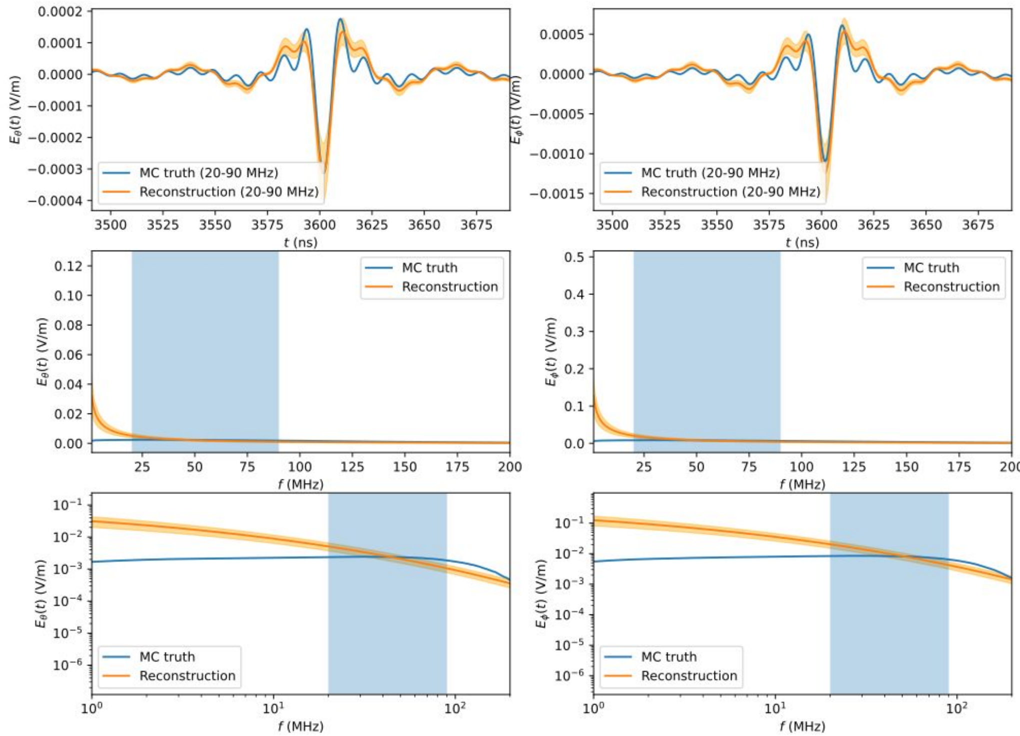
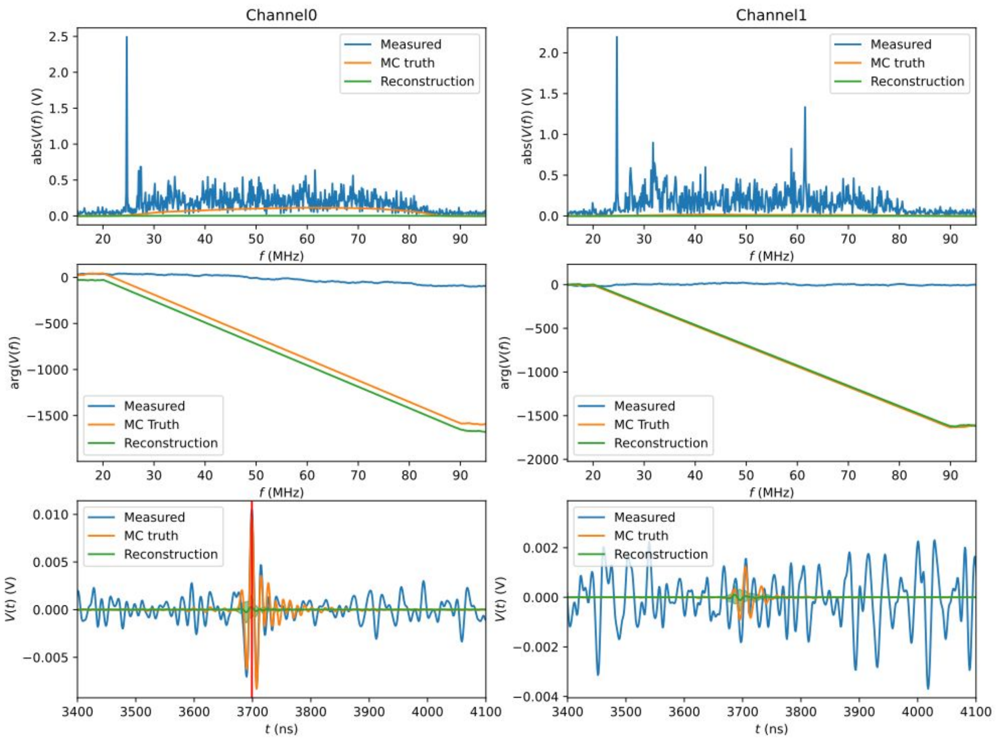
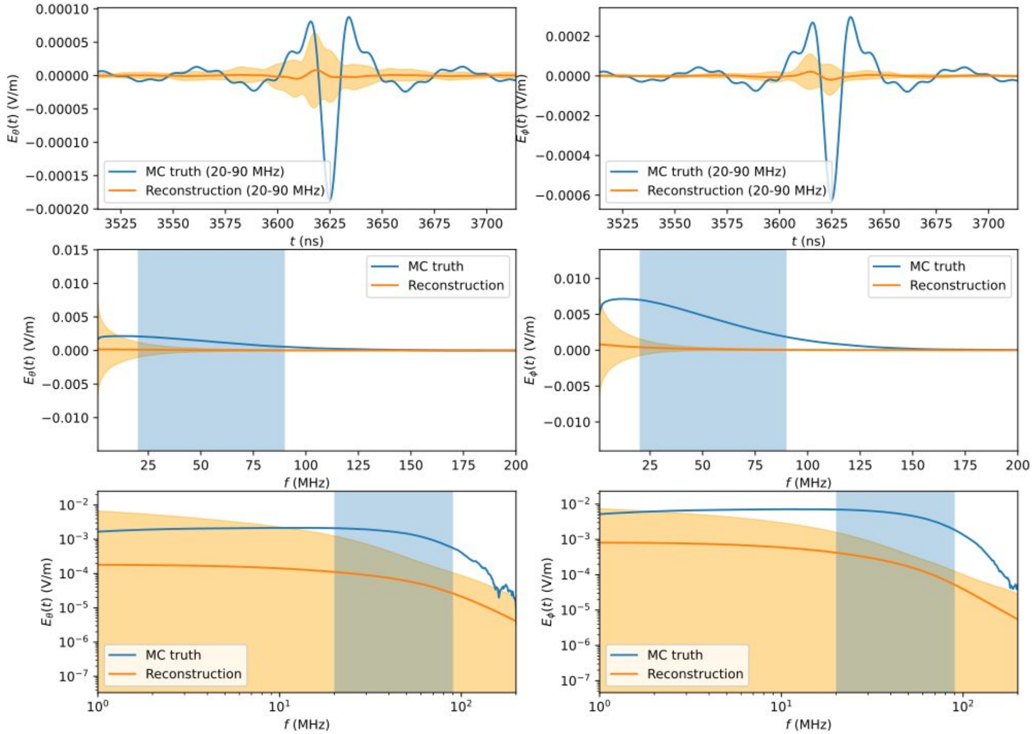


Radio pulse reconstruction with IFT



Radio pulse reconstruction with IFT



What has been done on the LOFAR side?

- NuRadio IFT Electric Field reconstruction code converted from nifty5 to nifty8
- Integration of former Kratos code (LOFAR pipeline) into NuRadioReco -> allows using NuRadio IFT Electric Field reconstruction code
- Antenna model optimisation -> Antenna + amplifier response, almost finished