# Cosmic-ray detection with and novel reconstruction algorithms for the ARIANNA experiment

**Anna Nelles for the ARIANNA Collaboration**

International Cosmic Ray Conference, Madison, Wisconsin, 2019

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

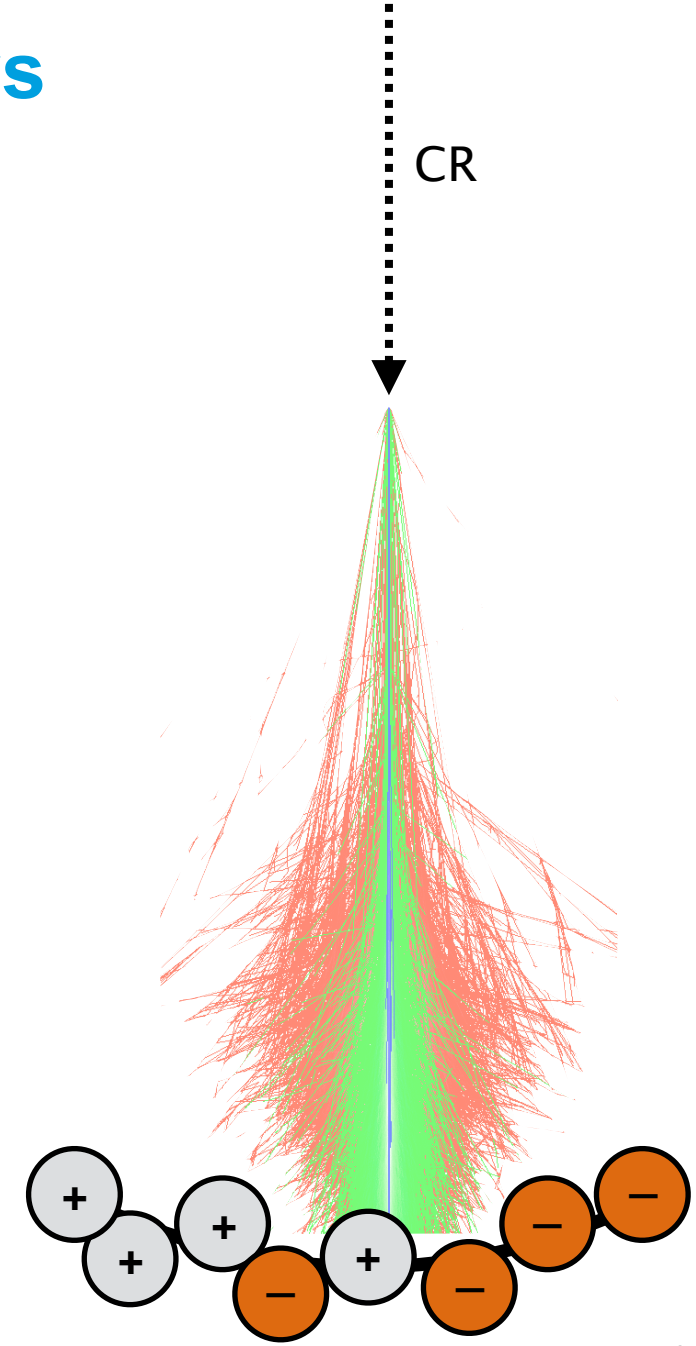
DESY.

# Radio Detection Cosmic Rays

## In a (very small) nutshell

**Cosmic ray creates air shower:**

- Radio emission stems from electro-magnetic component of shower
- Main emission for air showers: **Geomagnetic effect**
- Electrons and positrons are separated due to interaction with Earth's magnetic field
- Macroscopically (i.e. at long wavelengths) this looks like a moving charge/dipole
- Total charge increases and decreases with shower development
- A moving charge creates emission, it is coherent (i.e. strong) at radio wavelengths



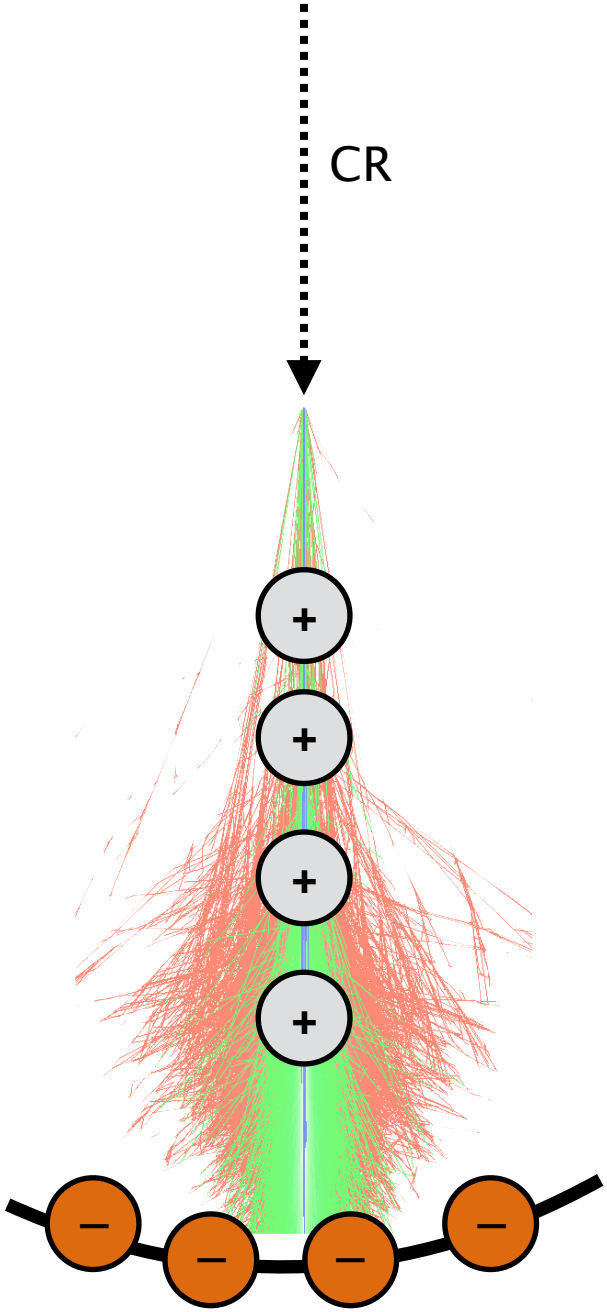
# Radio Detection Cosmic Rays

## In a (very small) nutshell

**Secondary effect in air showers:**

- Shower front becomes increasingly negative (Compton effect on electrons in medium)
- Macroscopically (i.e. at long wavelengths) this looks like a moving charge/dipole
- Total charge increases and decreases with shower development
- A moving charge creates emission, it is coherent (i.e. strong) at radio wavelengths

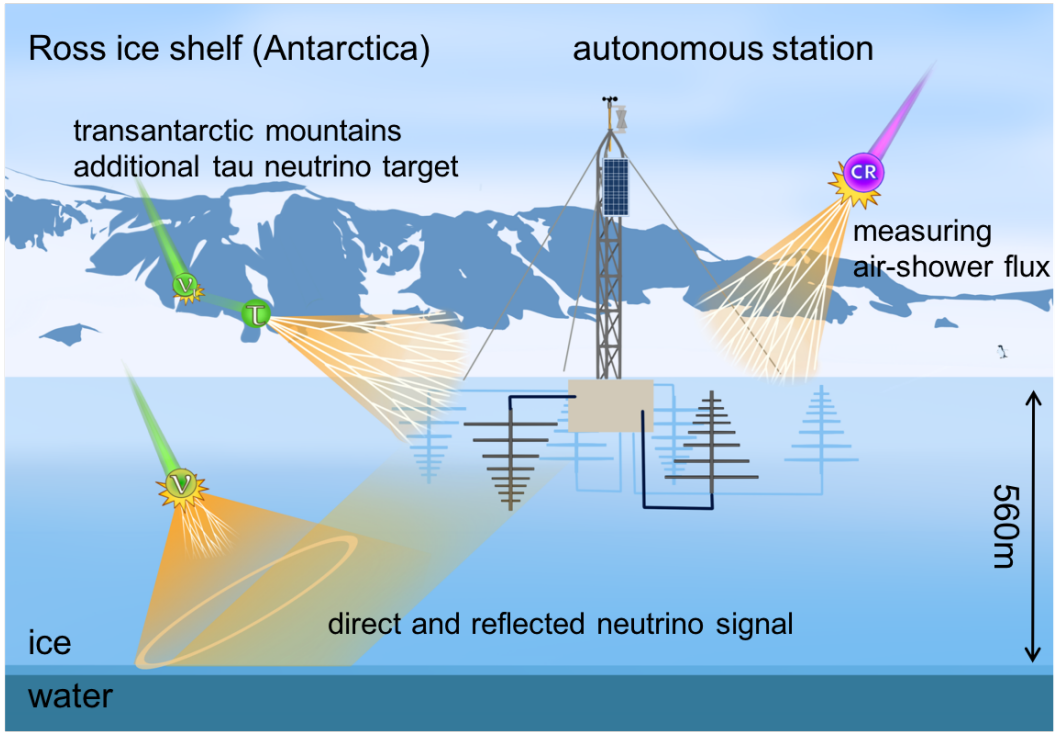
- Both types of emission are subject to coherence criteria: Cherenkov-like effects



# ARIANNA

## Antarctic Ross Ice-Shelf ANtenna Neutrino Array

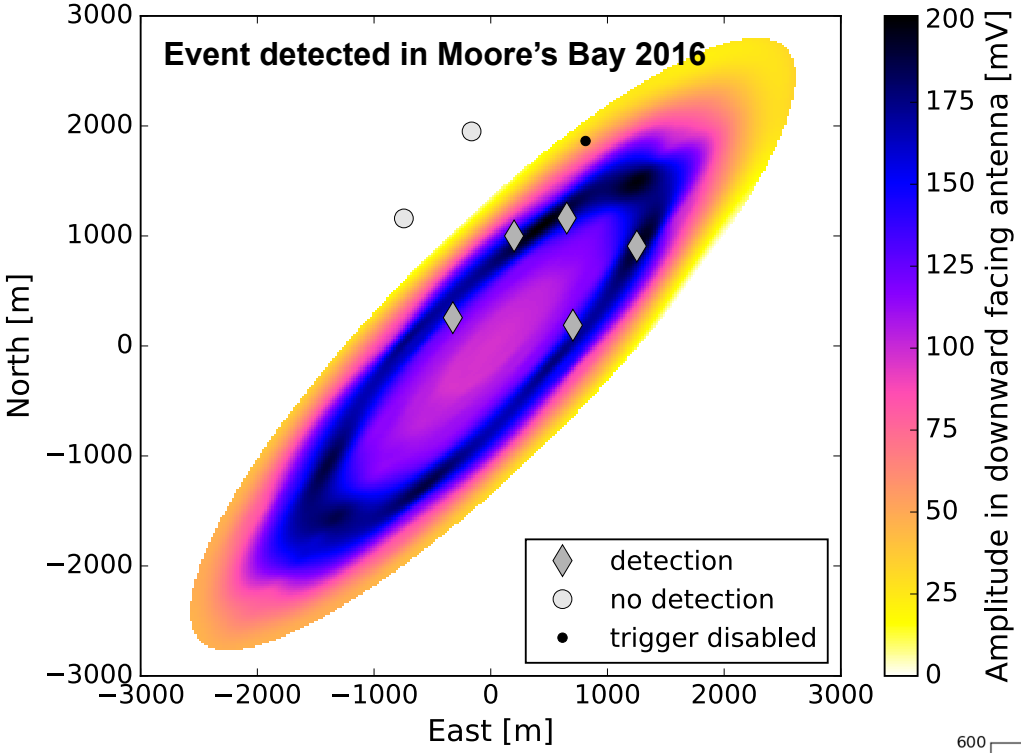
- Has been running in various configurations since 2012
- Stations are deployed close to the surface for maximum flexibility in antenna and station design
- Autonomous, light-weight stations with minimal data transferred via Iridium
- Isolated on Ross Ice-Shelf reduced man-made background
- Air showers unique calibration signal




**See also Talk C. Glaser Monday**

# Cosmic ray searches

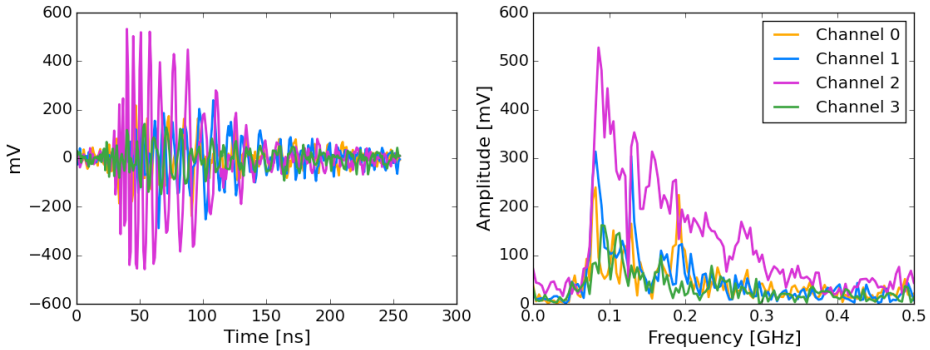
## With ARIANNA




- Cosmic rays are being used as proof-of-principle for detection efficiency and reconstruction methods
- typical "chirp" from LPDA and amplifier make signals very distinct given the broad-band nature of pulse
- very good frequency-resolution
- excellent detector to test energy reconstruction from frequency slope

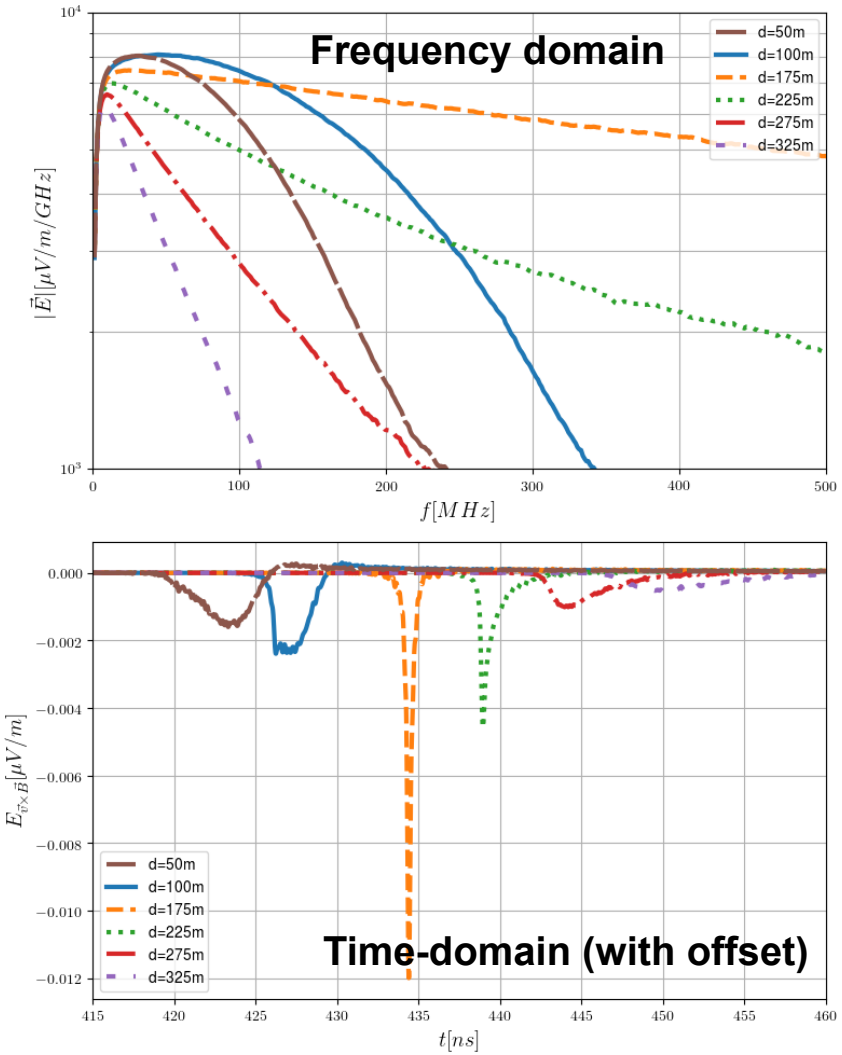
S.W.Barwick, Astro.Part. Phys. 90 (2017) 50-68

- Surface station has unique ability to measure cosmic rays directly and thus veto



# Signal properties

## Radio emission of air showers




### Characteristic signals

- Air shower signals change power (integrated signal) but also frequency content as function of distance to shower axis
- It is known that power scales with energy of shower
- Scaling as function of axis distance more complex, but easier understood in frequency spectrum
- Spectrum (almost) flat at Cherenkov angle, (almost) exponential fall-off outside the cone

# Energy and signal reconstruction

## What quantities are needed?

### Shower energy

- Energy needs to be retrieved from single station in sparse array layout
- Overall scaling of integrated pulse (**fluence** method of Auger, LOFAR et al.)
- Use **spectral slope** to correct for distance to shower axis

### Additional quantities

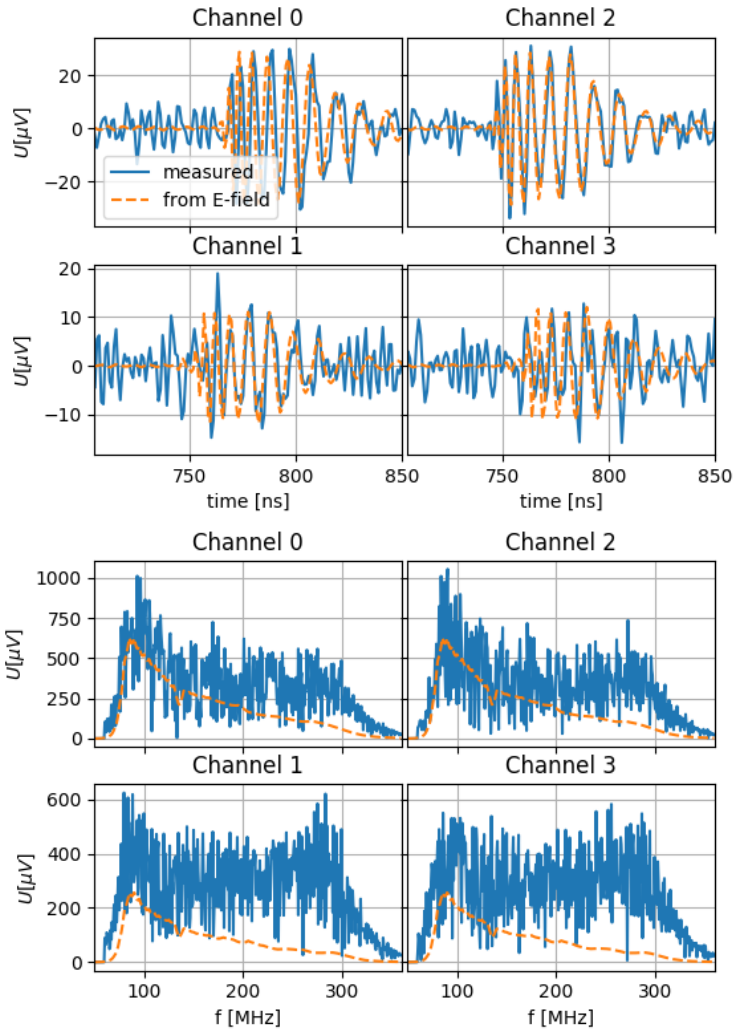
- Signal **polarization** to confirm origin as cosmic-ray signal
- Polarization is needed for neutrino reconstruction to determine the arrival direction of the signal (arrival direction of signal is not close to the shower axis)

### Dealing with noise

- If signal is small (in one antenna) noise will bias the signal, especially at high frequencies
- Needs better signal reconstruction than unfolding of hardware response

# Signal reconstruction

## Forward-folding method with CoREAS sims and an ARIANNA station layout




We assume that a CR pulse can be described by two amplitudes (e_phi, e_theta), a phase and one frequency slope.

The rest stems from the hardware response and noise.

Signal reconstruction is a fit of four parameters to all measurement.

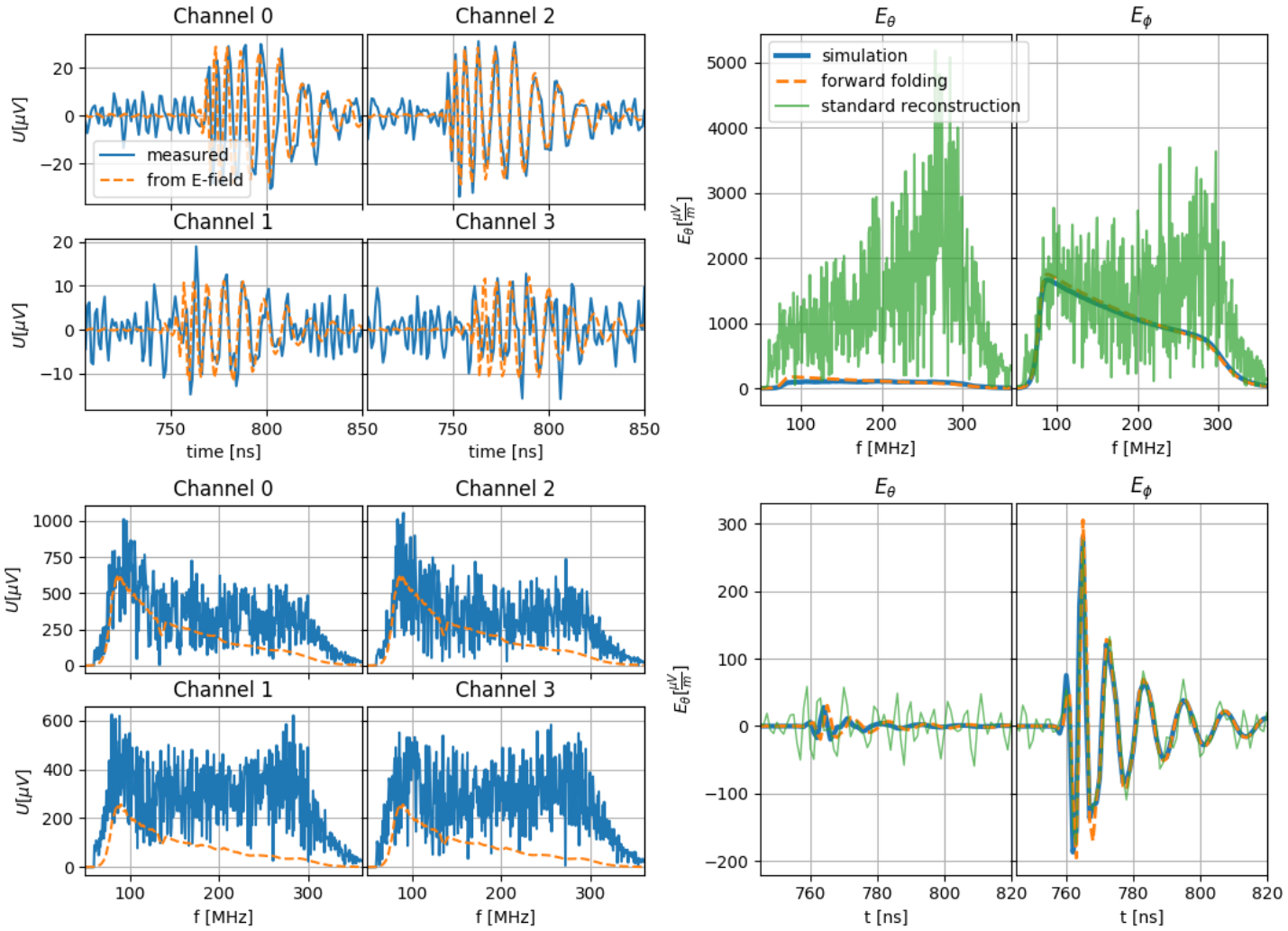
**See also poster C. Glaser PS3-110**



C.Glaser et al. Eur. Phys. J. C (2019) 79: 464

# Signal reconstruction

## Forward-folding method with CoREAS sims and an ARIANNA station layout

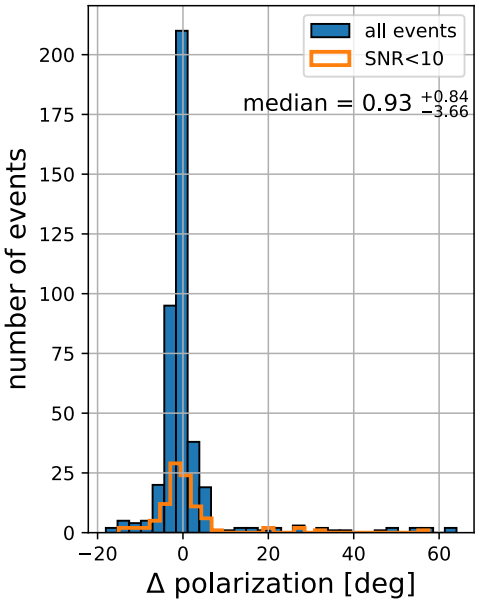


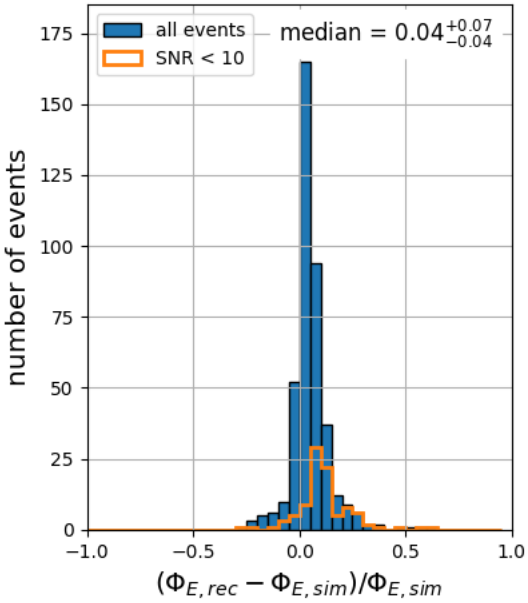


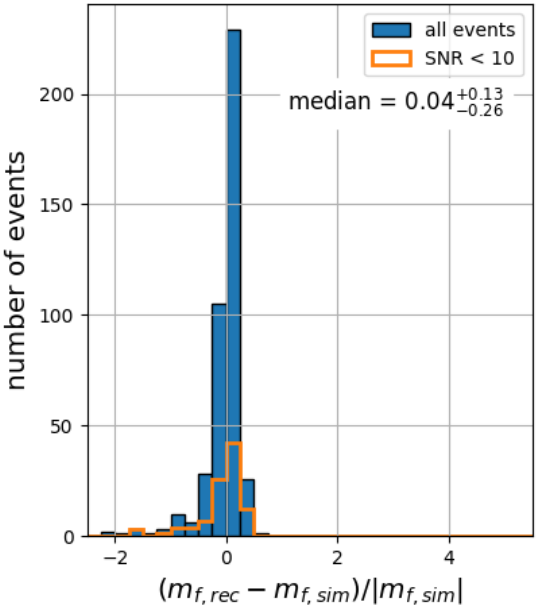

C.Glaser et al. Eur. Phys. J. C (2019) 79: 464

# Obtained signal quantities

## Polarization, fluence, spectrum




## Reconstruction quality

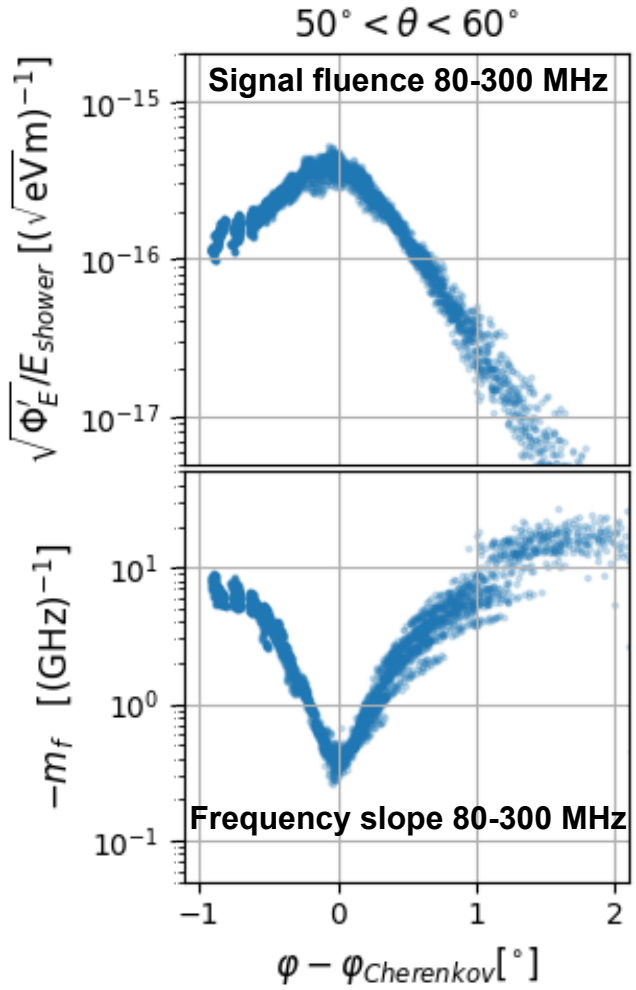
- Hardly a bias in the reconstruction, also true for low SNR signals
- Individual signals can now be used to determine shower parameters



C.Glaser et al. Eur. Phys. J. C (2019) 79: 464

# Energy reconstruction

## Derived from a single station




**Per zenith bin, here on example**

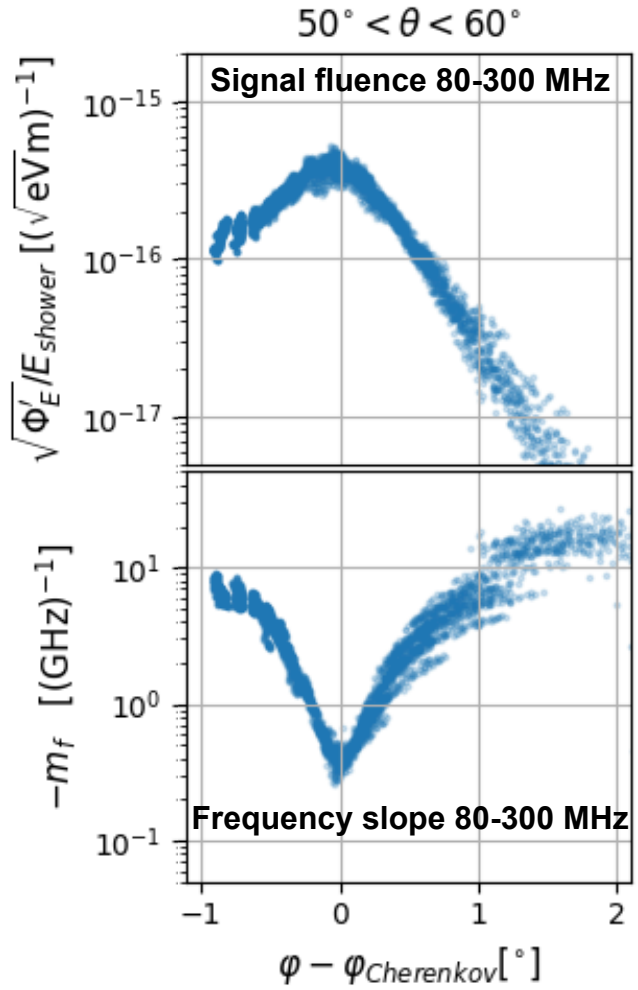
- Large set of CoREAS simulations
- One to make the parameterization
- One to test it
- Parameterizations tested for Moore's Bay, South Pole and Auger Site



C.Welling et al, submitted to JCAP, arXiv:1905.11185

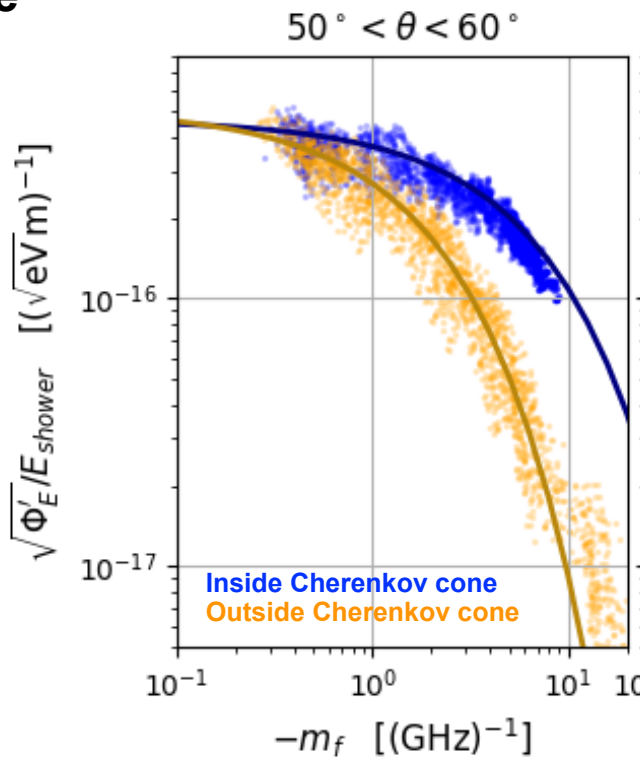
# Energy reconstruction

## Derived from a single station




**Per zenith bin, here on example**

- Large set of CoREAS simulations
- One to make the parameterization
- One to test it
- Parameterizations tested for Moore's Bay, South Pole and Auger Site






C.Welling et al, submitted to JCAP, arXiv:1905.11185

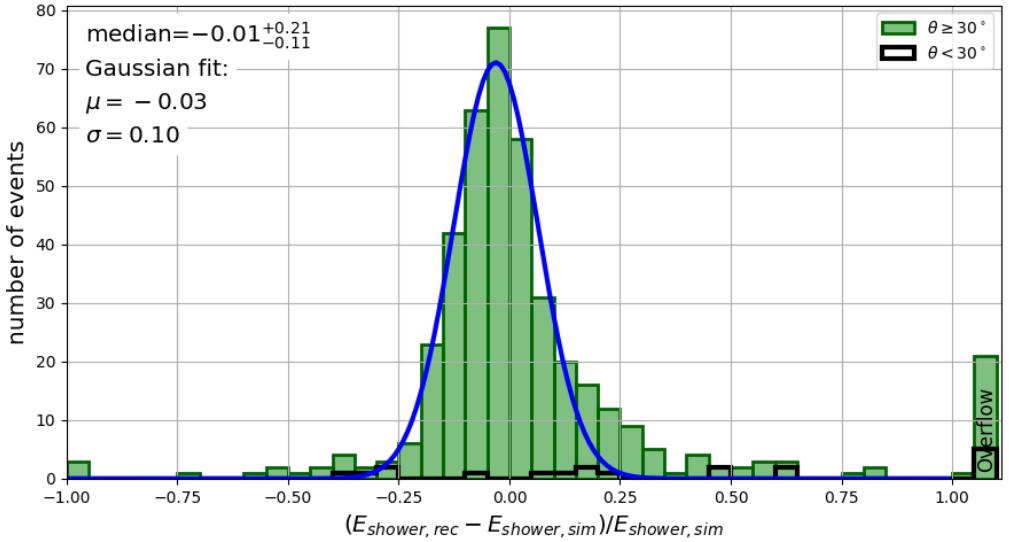
# Energy reconstruction

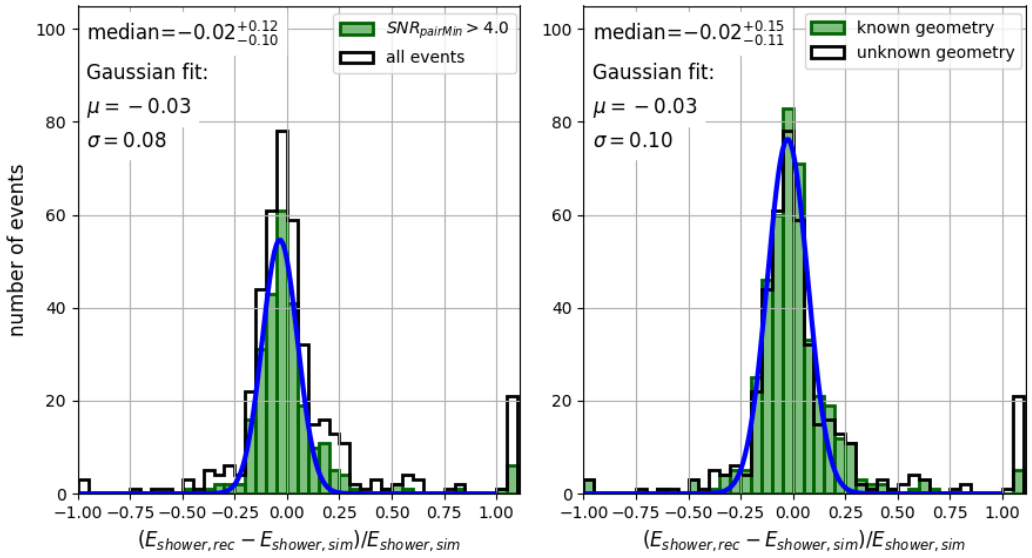
## Derived from a single station

C.Welling et al, submitted to JCAP, arXiv:1905.11185

### Obtainable resolution

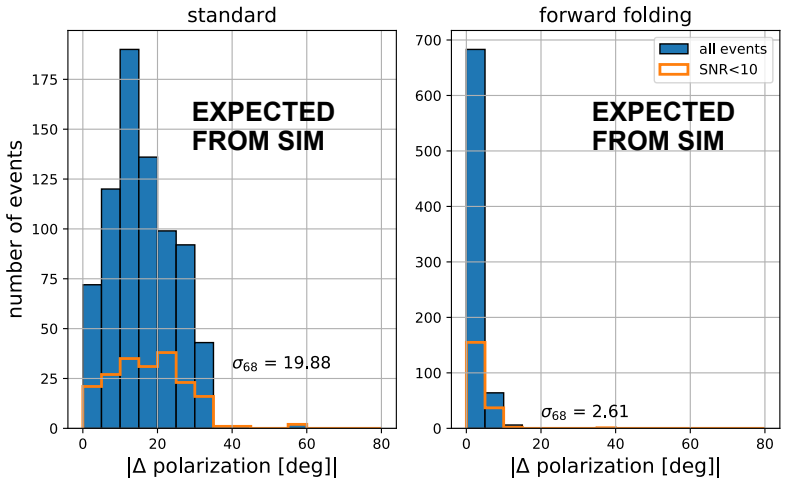
- For a perfect detector understanding < 15% resolution on energy
- But: in polar regions, vertical shower problematic, due to vertical magnetic field
- Detector uncertainties (amplifiers, antennas, cables) linearly add systematic uncertainties
- Calibration of highest importance for resolution



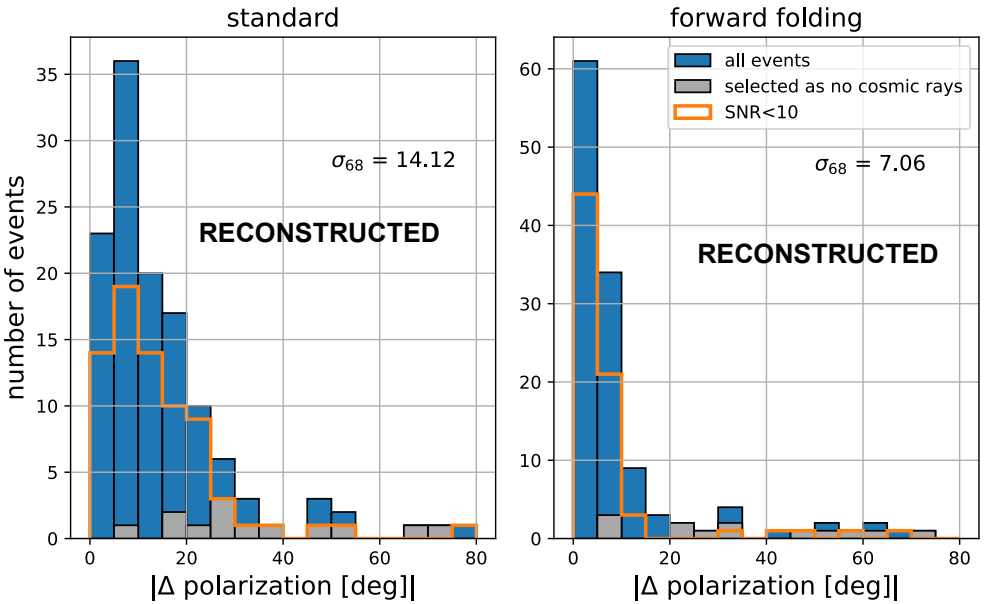



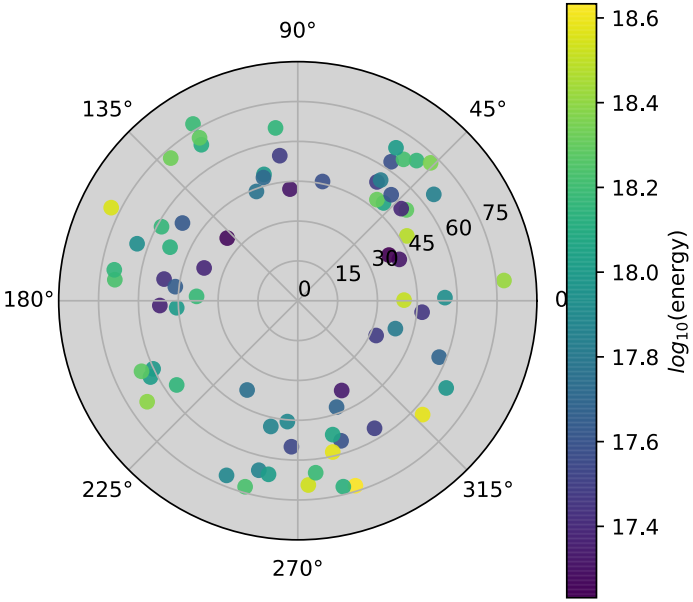
# Cross-check on cosmic ray data

## Work in progress from ARIANNA




- Use one year of ARIANNA cosmic rays with dedicated station
- Polarization reconstruction good, but some open questions regarding systematics
- Energy as expected dominated by threshold

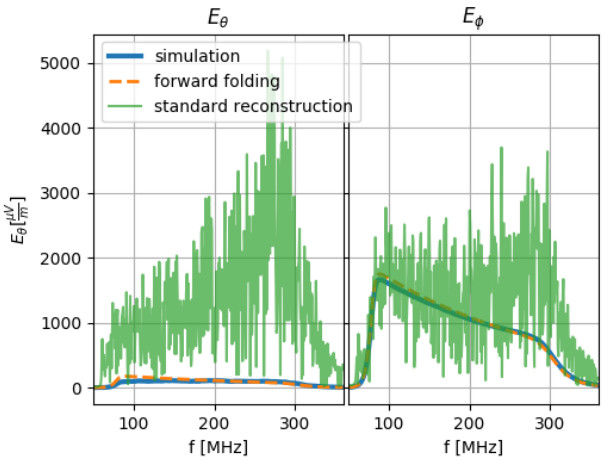


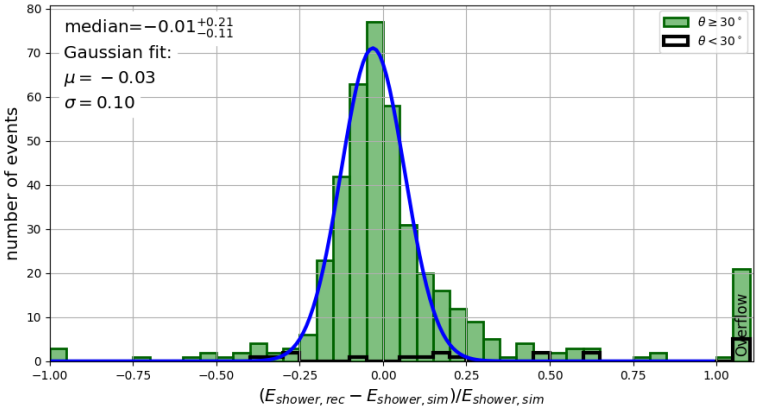



# Conclusion

## What could other experiments learn from this?

- **Forward-folding** developed to reconstruct signal from noise
- Better performance than “standard” unfolding
- Can be used to **combine spatially separated antennas**
- **Available at** github.com/nu-radio/NuRadioReco




- Used **frequency slope and signal fluence of single station to obtain energy**
- Parameterization for all showers
- Modulo detector uncertainties, < 15% energy resolution
- Large bandwidth needed for neutrinos, but helpful for cosmic rays