# Update on the Offline Analysis Framework for AugerPrime and integration of the AugerPrime Radio Detector reconstruction

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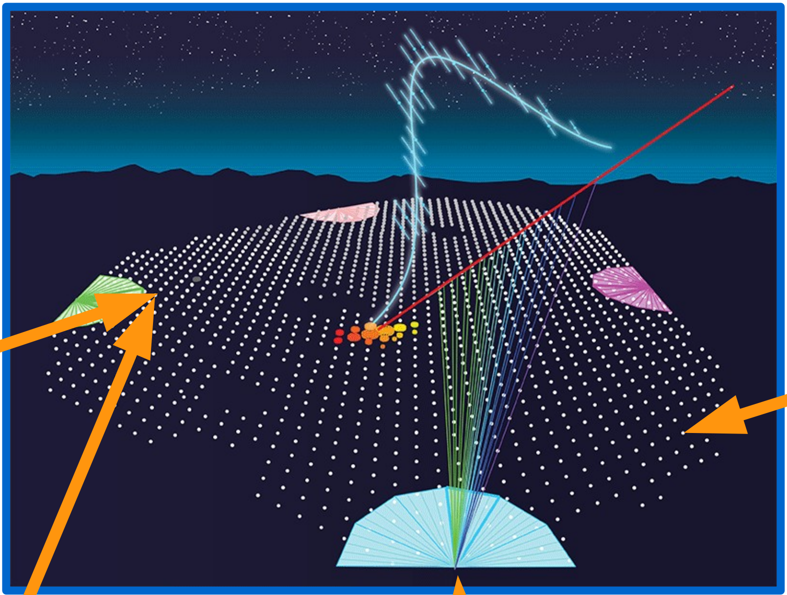
Auger Offline Framework v3r99p99-
Reference: Nucl. Instrum. Meth. A 580 (2007) 1485

# The Pierre Auger Observatory

**Auger Engineering Radio Array (AERA)**



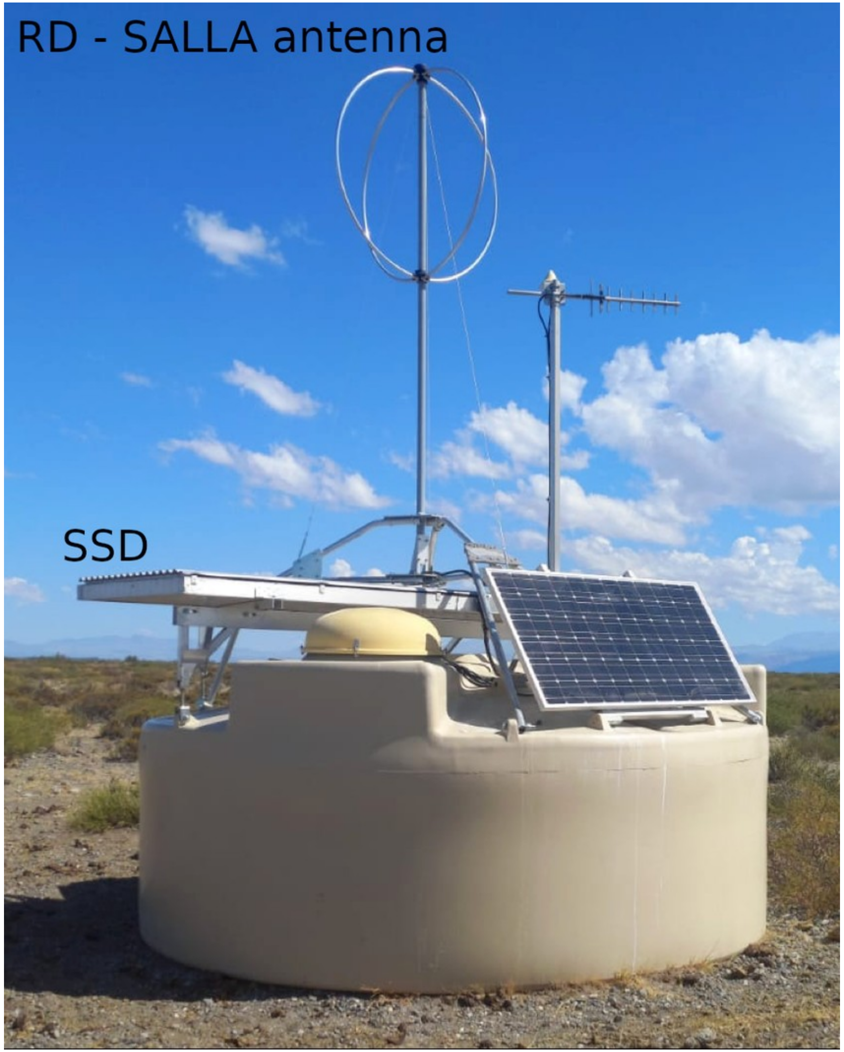
**Water Cherenkov Detector (WCD)**

**Fluorescence Detector (FD)**

**Underground Muon Detector (UMD)**

# AugerPrime

- Enhanced sensitivity to the mass of cosmic rays
- New detector types (small PMT, SSD, RD) and new station electronics
- Requires changes to the Auger Analysis Framework



# Auger Offline framework

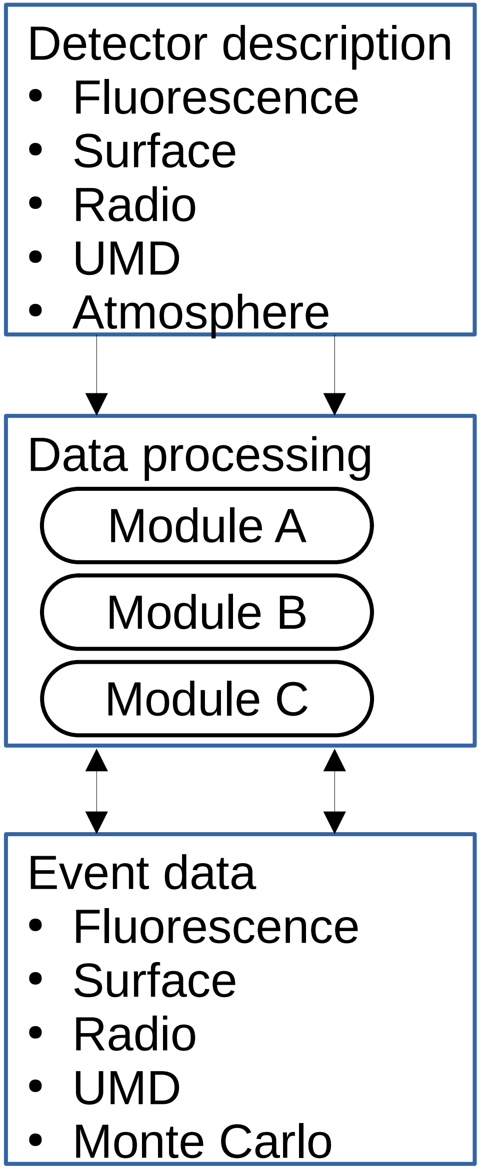
- Standard framework for:
  - Detector simulations
  - Calibration
  - Reconstruction
  - Data preparation
  - (some) analysis
- Flexible and extensible
- The Offline Framework stood the test of time. Could be extended to handle various extensions and a major upgrade

- Started over 20 years ago,
  first commit: 31st of January, 2003
  - CVS → SVN → git(lab)
  - C++98 → C++ 11/14 (→ C++ 17/20)
- Input:
  - Air shower simulation
  - Auger data
  - Offline format
- Output
  - Offline format
  - Auger Data Summary Trees (ADST)
    can be used stand-alone for further analysis

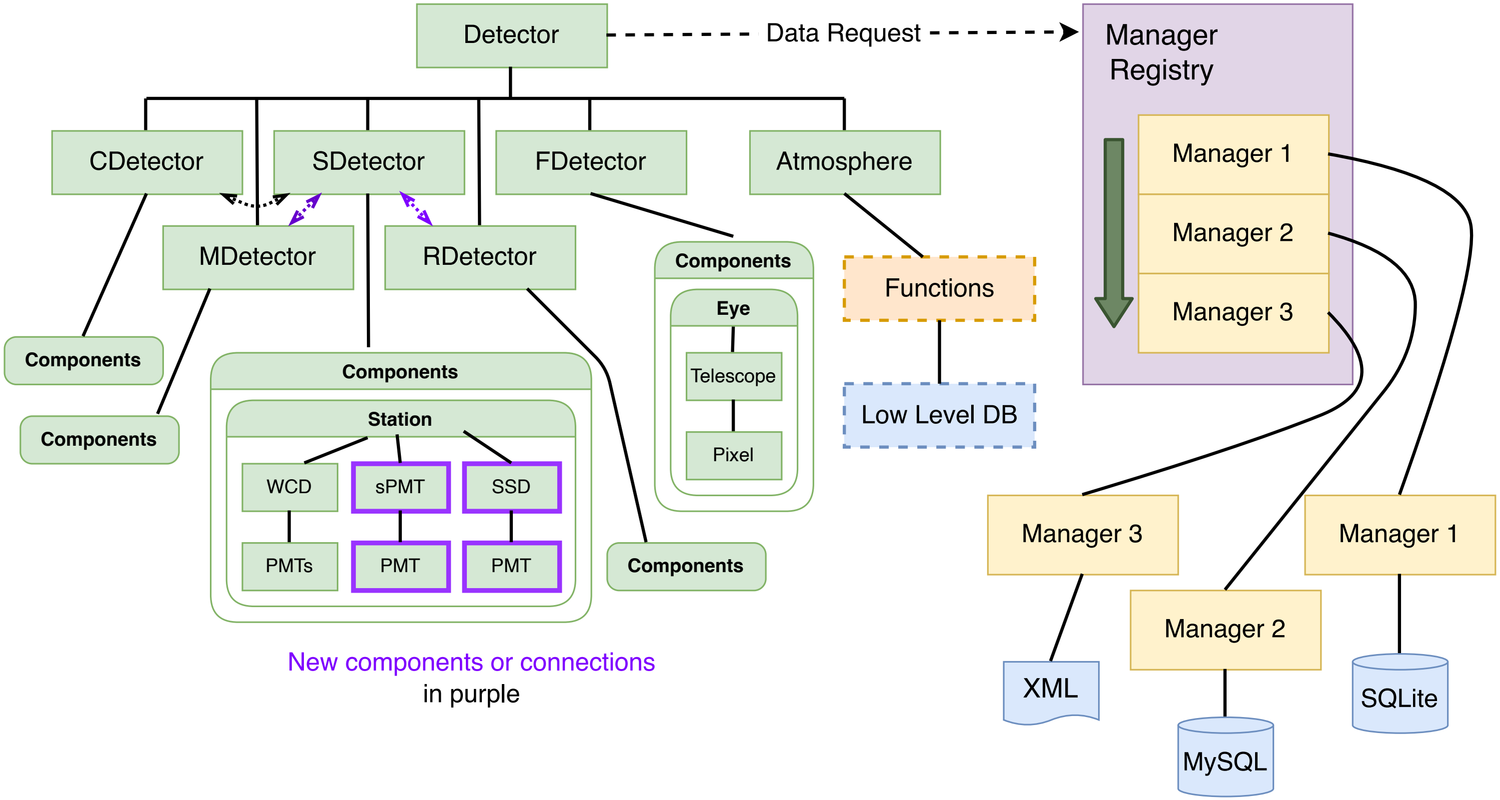
# Framework hierarchy

- Software components structured in non-cyclic hierarchy
  - access only to components lower in hierarcy
  - clean dependencies for parallel building

- Separate data holders from algorithms
- Framework: Detector, Event, RunControl
- Modules: simulation and reconstruction algorithms
- Utilities: used by modules
- Tools
- Validation tests
- ….

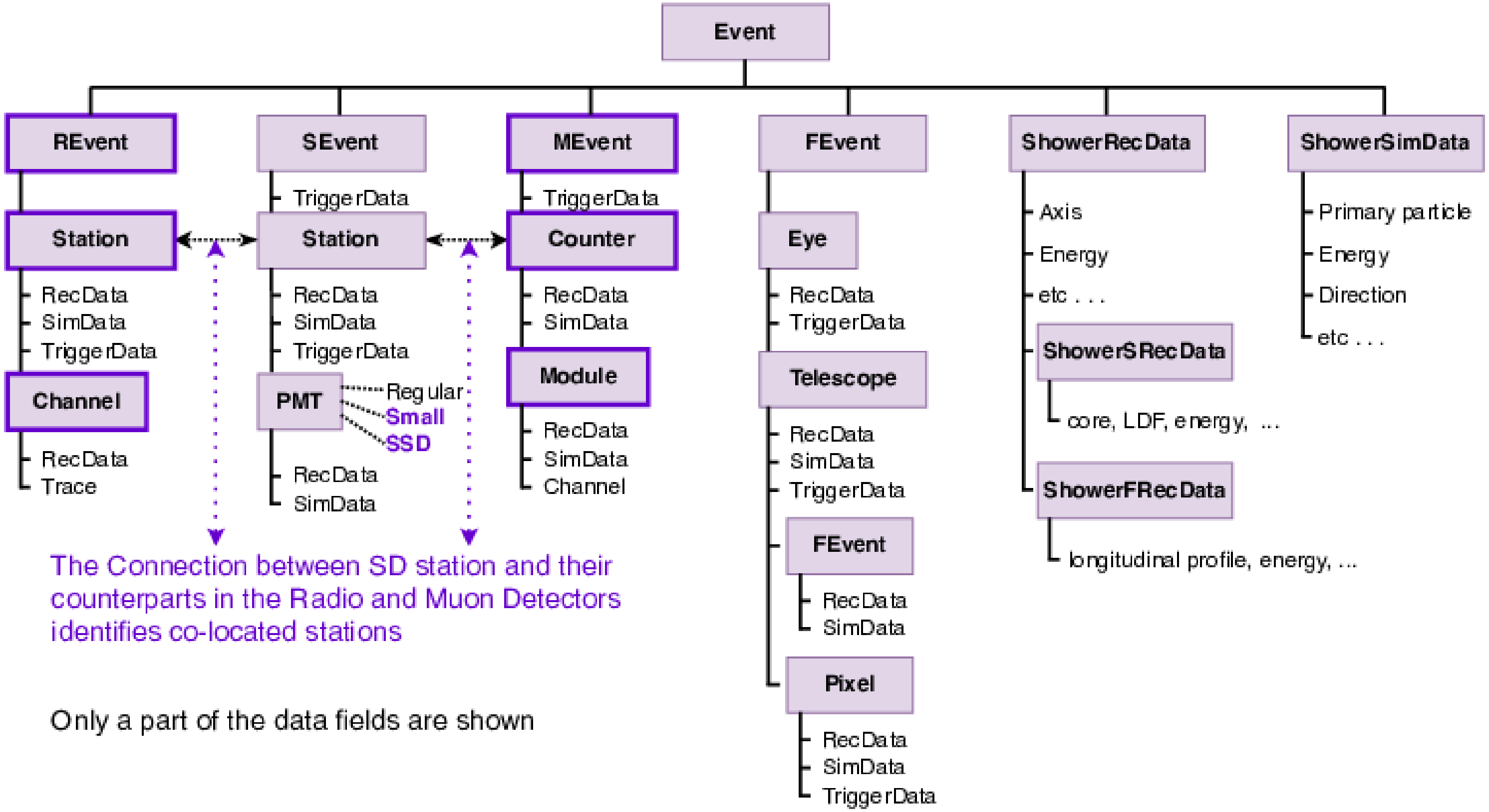


# The Detector




- Structure follows detector hierachy
- Atmosphere is part of the detector
- Managers as abstraction for data access

# The event

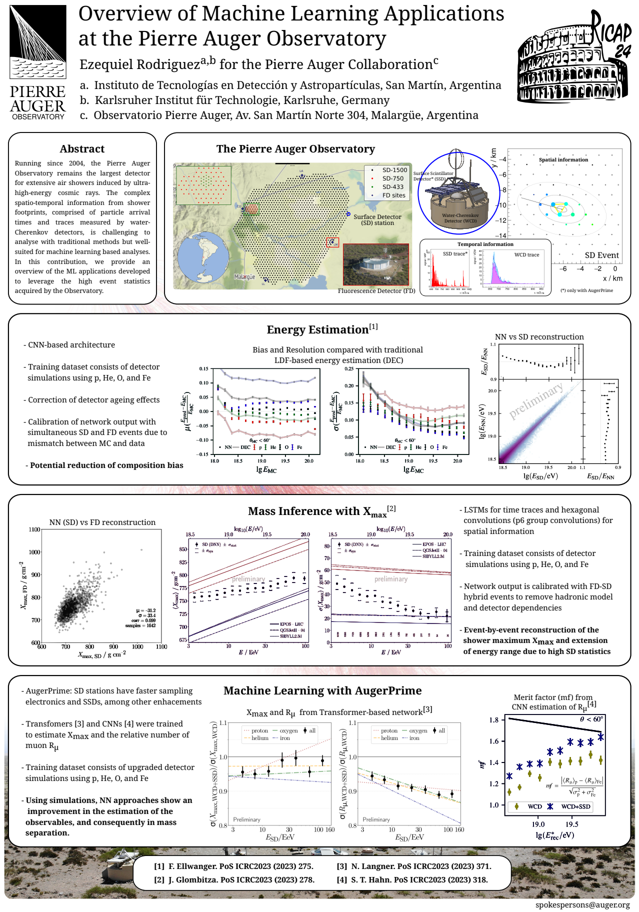



- Structure parallel to detector
- Contains raw, MC, and reconstructed data

# Some changes we had to do

- Upgraded electronics: different digitizer frequency (was hard-coded)
- Additional channels, PMTs (was hard-coded)
- Time delays:
  - PMT characteristics and change of FPGA
  - Have to match for comparison of Phase I and II

- In progress: Machine Learning support
  - Need to be able to use inference in regular modules
  - Evaluating Open Neural Network Exchange (ONNX)

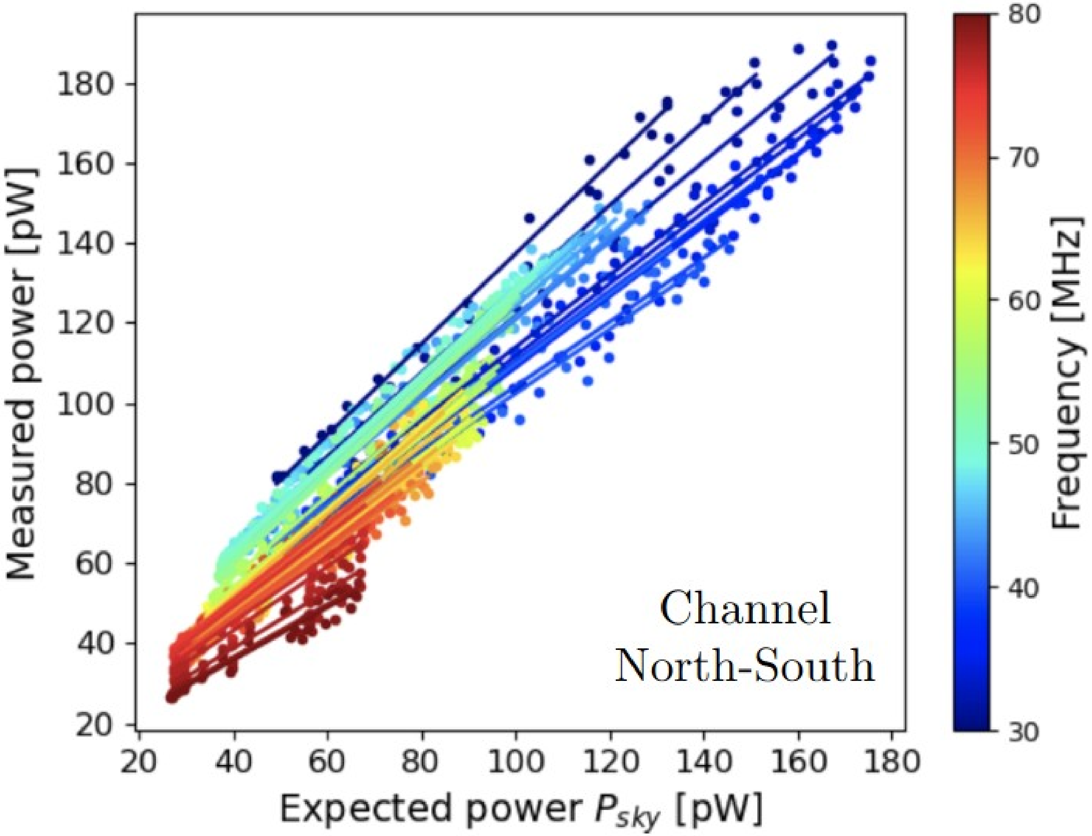


# RD reconstruction

# Calibration

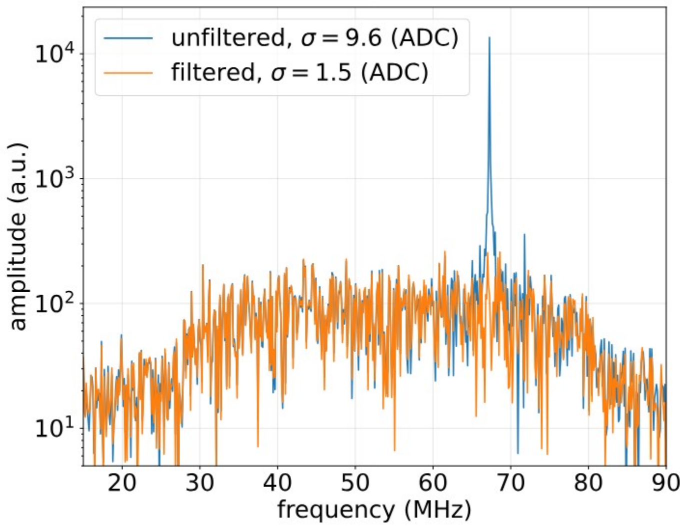
Relative directional calibration with reference antenna mounted on a drone
cf. PoS(ARENA2024)029

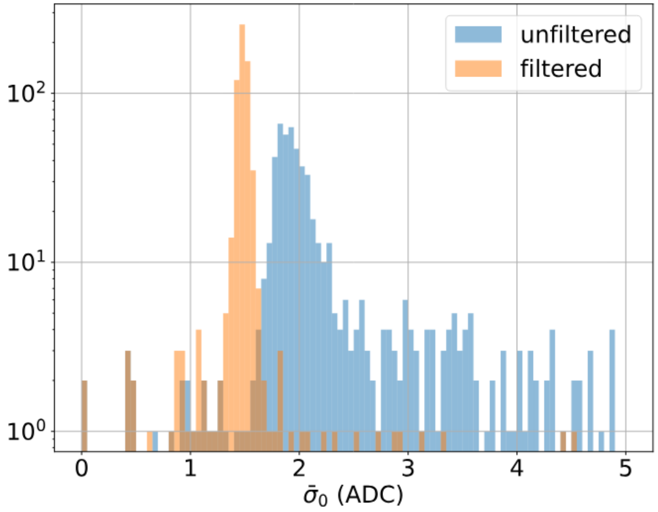
Absolute calibration using sky models of the galactic radio emission
cf. PoS(ARENA2024)030



# Improved RFI removal

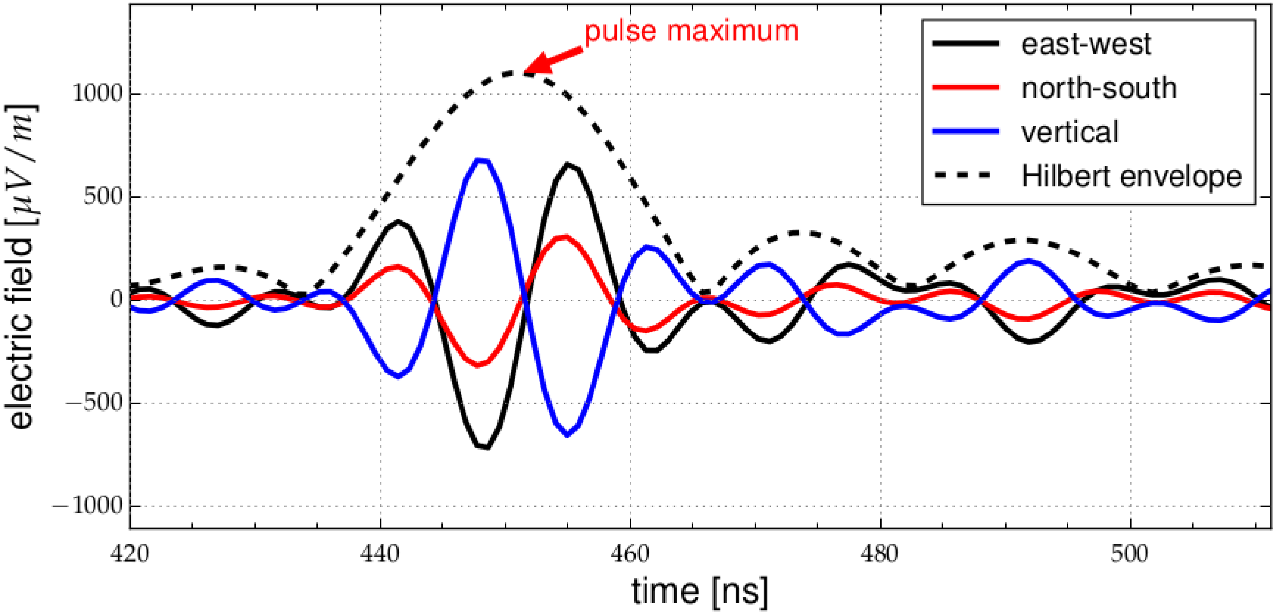
- Removing of strong narrowband RFI in the measurement challenging
  - Find frequency and phase of largest amplitude
  - Substract corresponding sin wave in time domain
  - Continue as long as significant reduction of std or max number of removed frequencies
- Improved reconstruction of low-signal stations and increased number of low-energy events



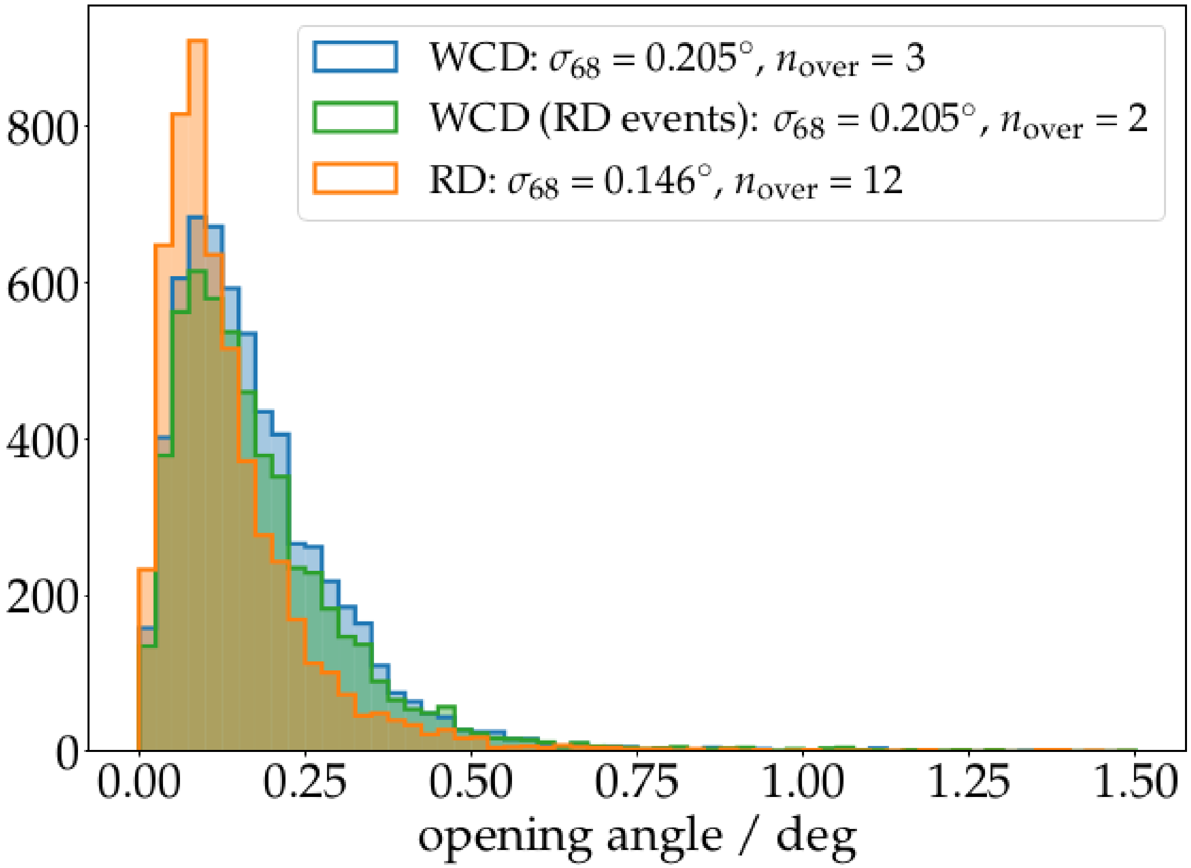
# Station signal reconstruction

- 3D electric field reconstruction from 2 channel traces
- Signal arrival time given by maximum of the hilbert envelope
- Energy fluence estimated by the time integral in a signal window substracting a noise contribution
- Working on an improved signal estimation in the presence of noise based on a robust and rigorous statistical background cf. arXiv:2407.18654
  - reduced bias and correctly estimated uncertainty
  - even at low SNR, no/lower SNR cut needed
  - lowering energy threshold for CR detection



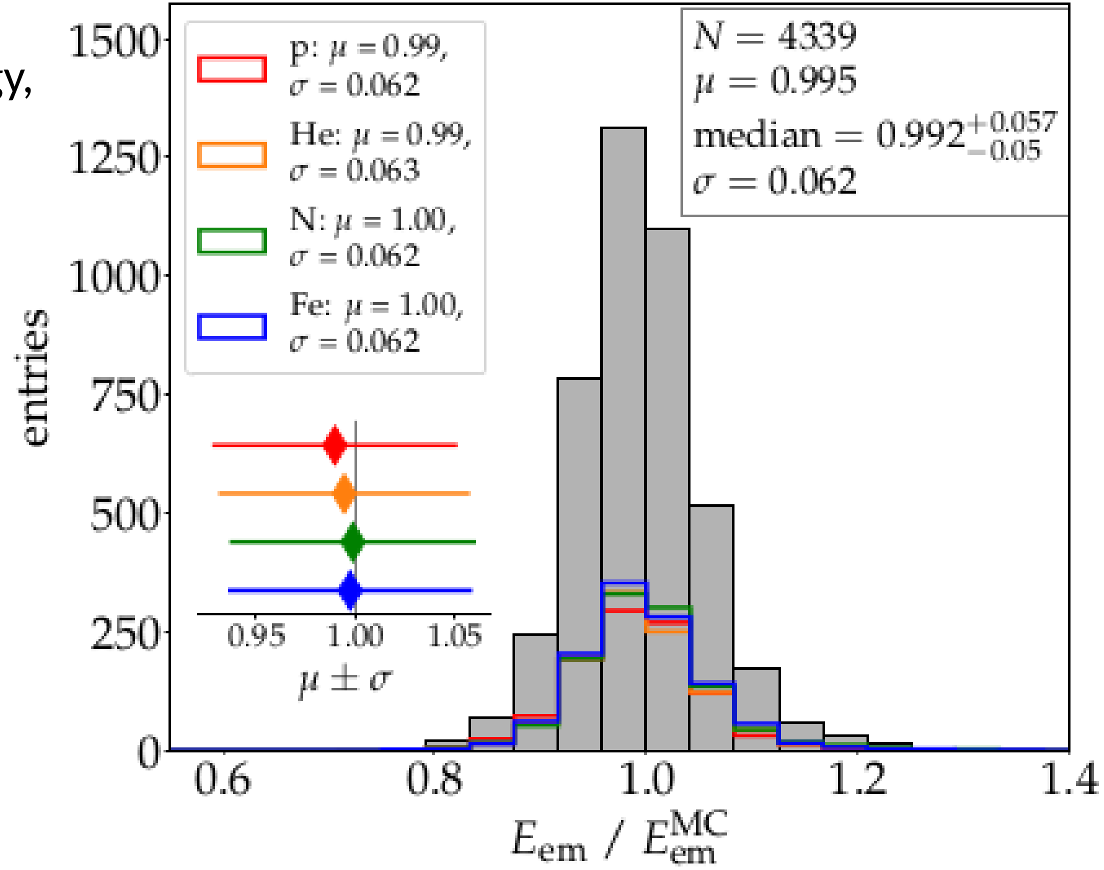
# Directional reconstruction

- Source of the radio emission close to Xmax, far away from detector for inclined showers → spherical wavefront model
- Needs at least 4 signal stations, i.e. zenith > ~68°
- RD angular resolution of 0.15°, better than WCD resolution

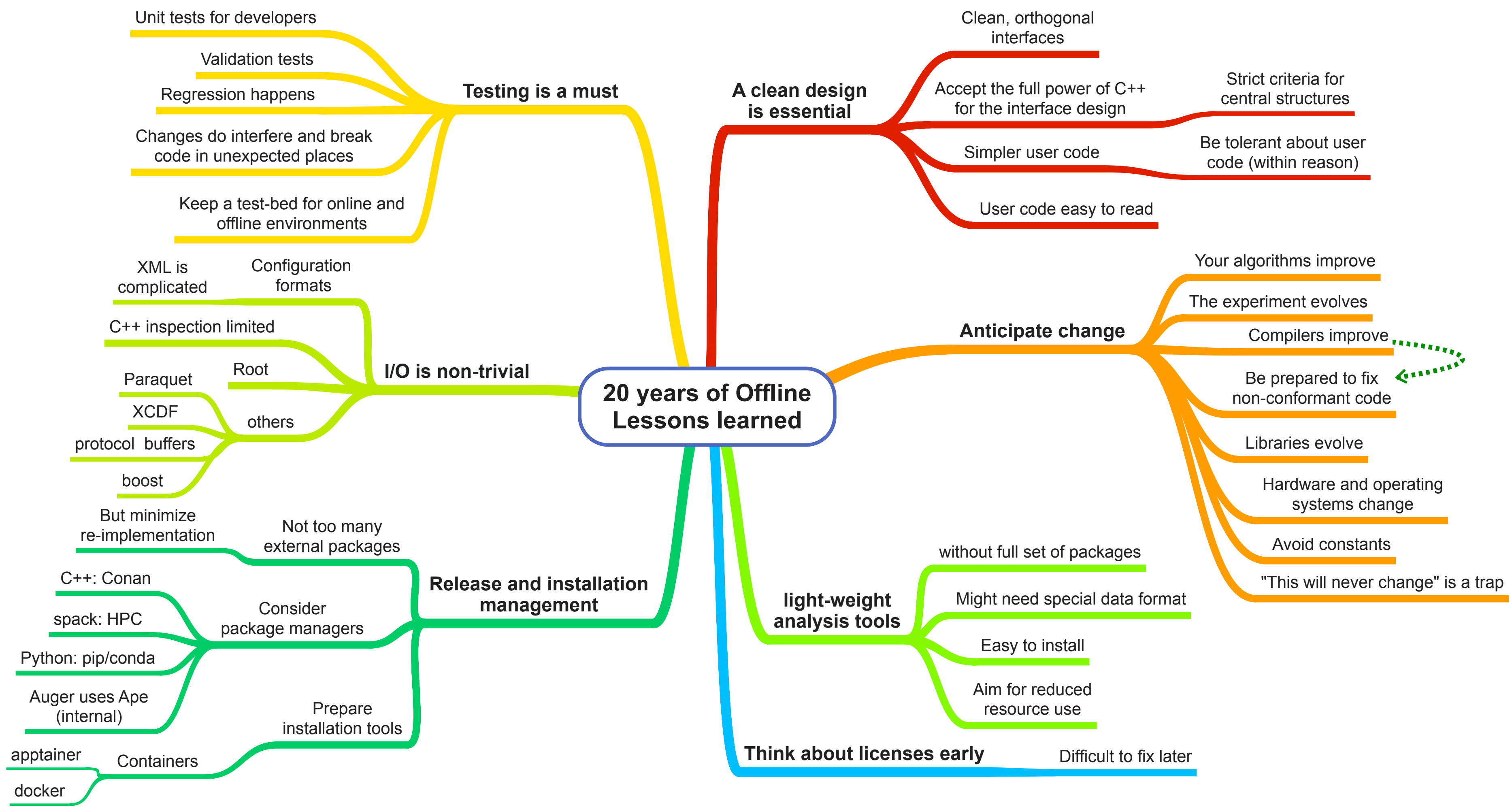


# Lateral signal distribution

- Dedicated model for the lateral signal distribution on ground for inclined showers:
  cf. F. Schlüter JCAP01(2023)008
- Reconstruction of electromagnetic energy, distance to $X_{max}$, and core
- 5 station needed for independent RD core estimation
- Bias-free reconstruction of $E_{EM}$, resolution of 6.2%



# Lessons learned



# Control Flow

- Application
  - sequence of steps, encapsulated as modules
- RunController
  - Configures sequence
  - Schedules execution
- CentralConfig configures
  - Detector
  - Modules
  - RunController

- Detector is read-only
- Event transports information between modules