Radboud University

Mass Composition and More: Results from the Auger Engineering Radio Array

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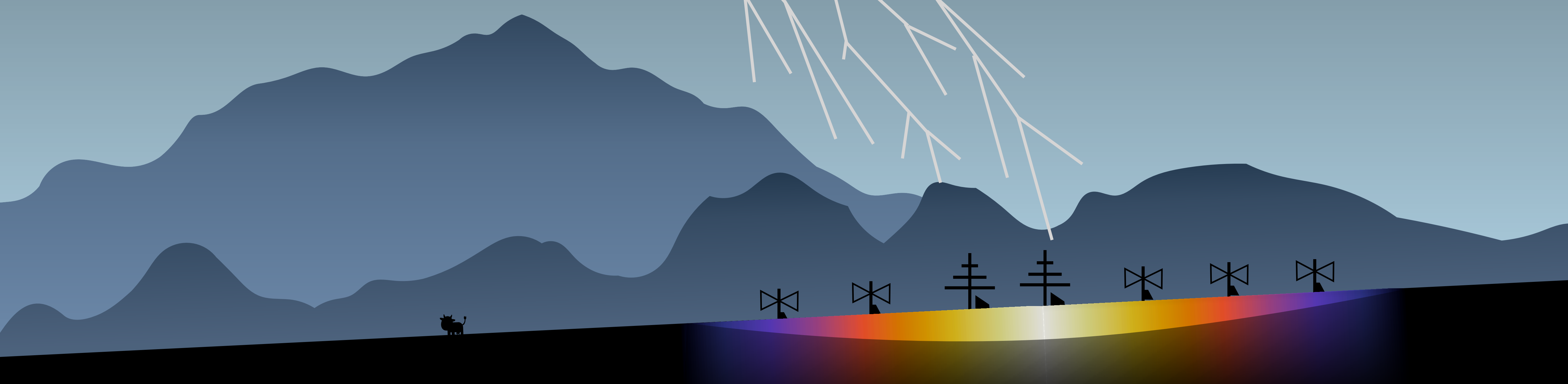
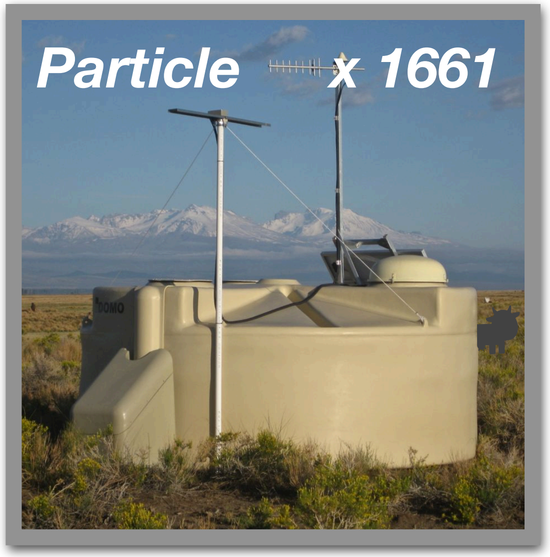
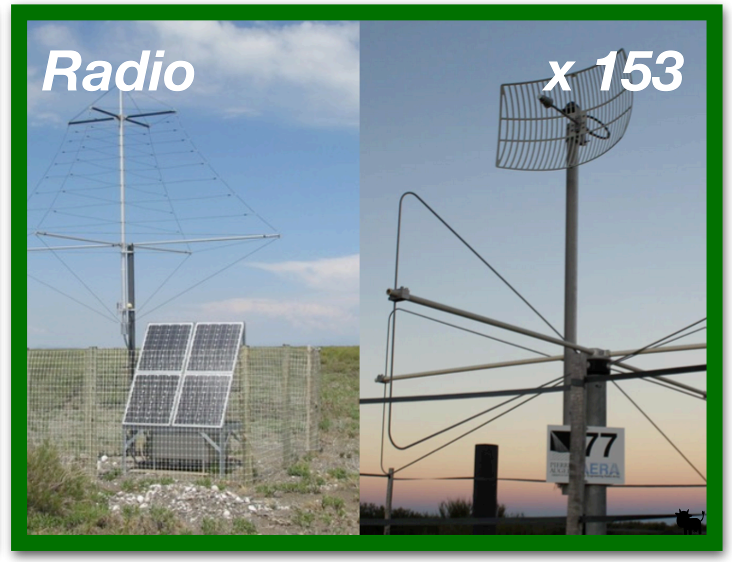


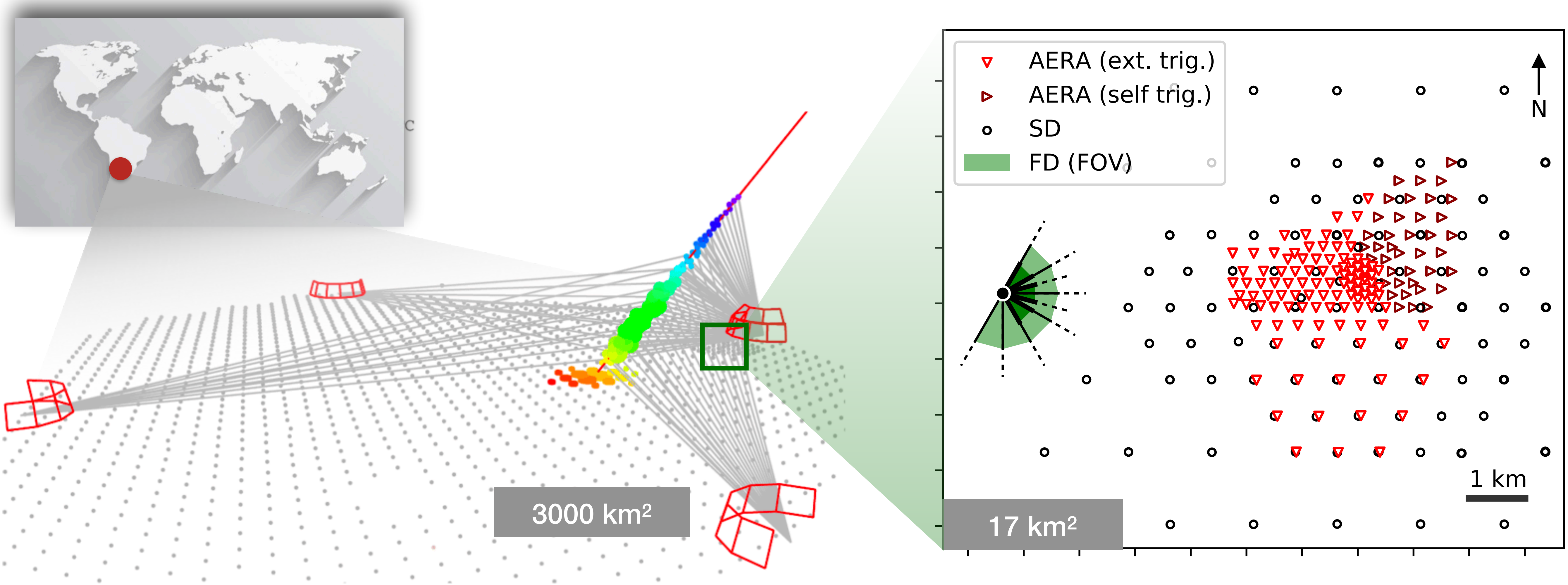
Introduction: AERA at the Pierre Auger Observatory





Auger Engineering Radio Array

- 153 autonomous radio antennas
- Energy range: 10^{17}-10^{19} eV
- Frequency range: 30-80 MHz



PIERRE AUGER OBSERVATORY

In this talk

Radboud University

Recent results from AERA:

paper in prep

- Measurements of the muon content of inclined air showers
- Long-term stability of the air-shower radio signal over time

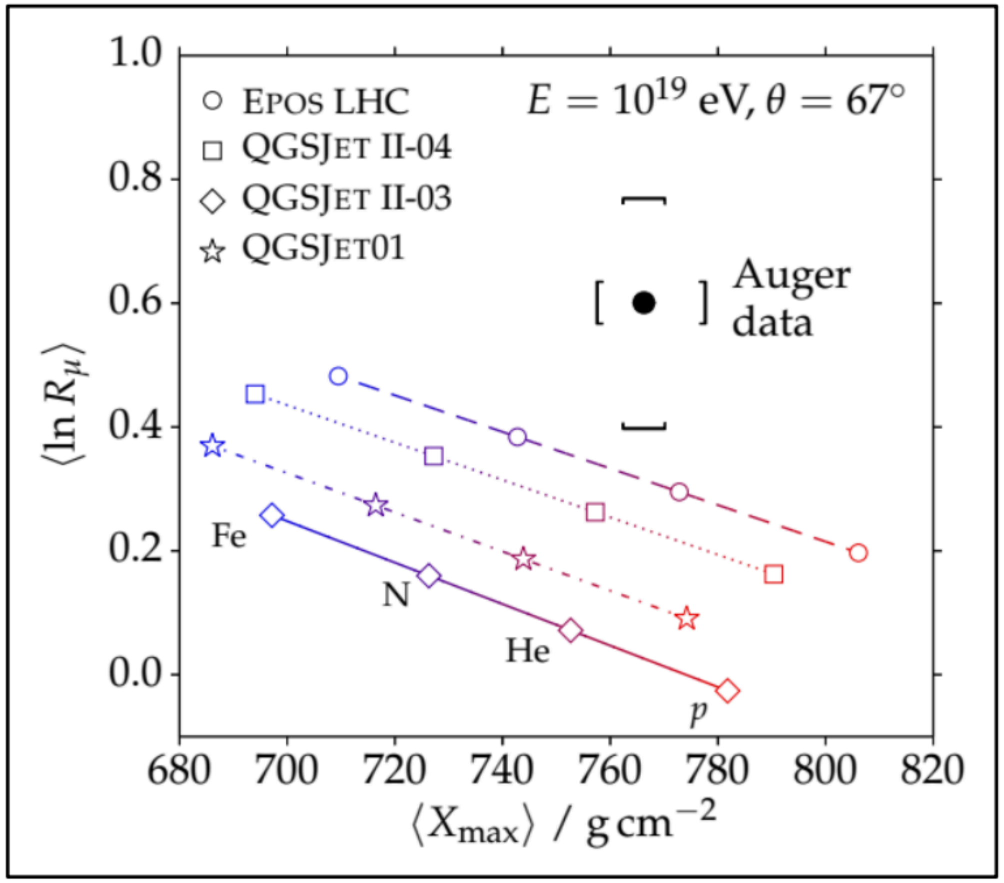
paper in prep

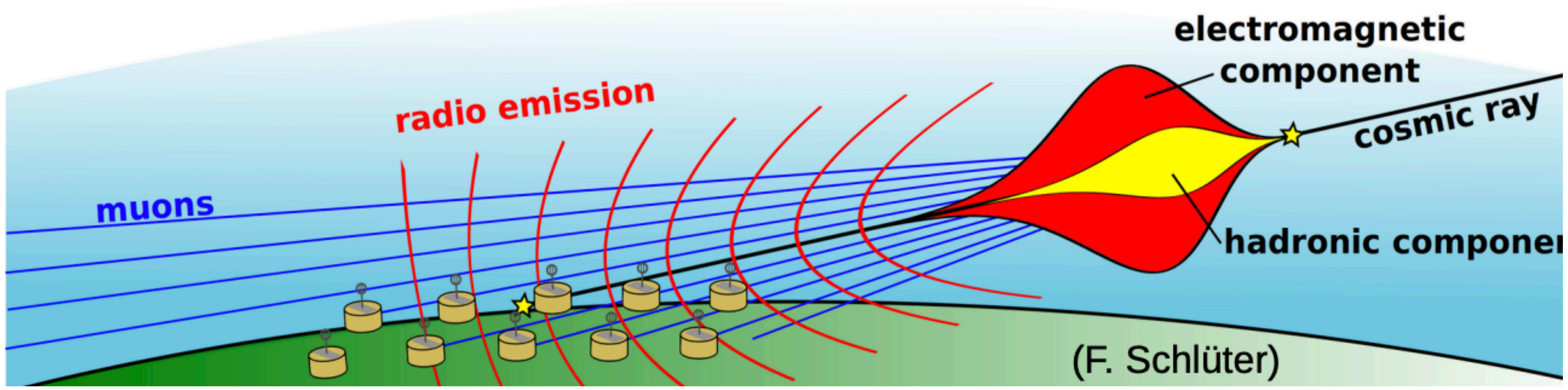
- Mass composition
  - Measurements of *the depth of shower maxima* (X_{max}) with AERA
  - Compatibility with fluorescence measurements
  - X_{max} resolution as a function of energy

Muon deficit in air-shower simulations

Work by M. Gottowik

- Number of muons N_μ underpredicted by all current-generation hadronic interaction models
- For inclined WCD-AERA hybrid events separation of electromagnetic and muonic component in the atmosphere
  - WCD: muon estimator
  - AERA: electromagnetic energy
- Independent analyses at Auger
  - **WCD–FD hybrids (cf. Phys. Rev. D91.3, 032003 (2015))**
  - MD-WCD hybrids (cf. Eur. Phys. J. C 80 (2020) 751)

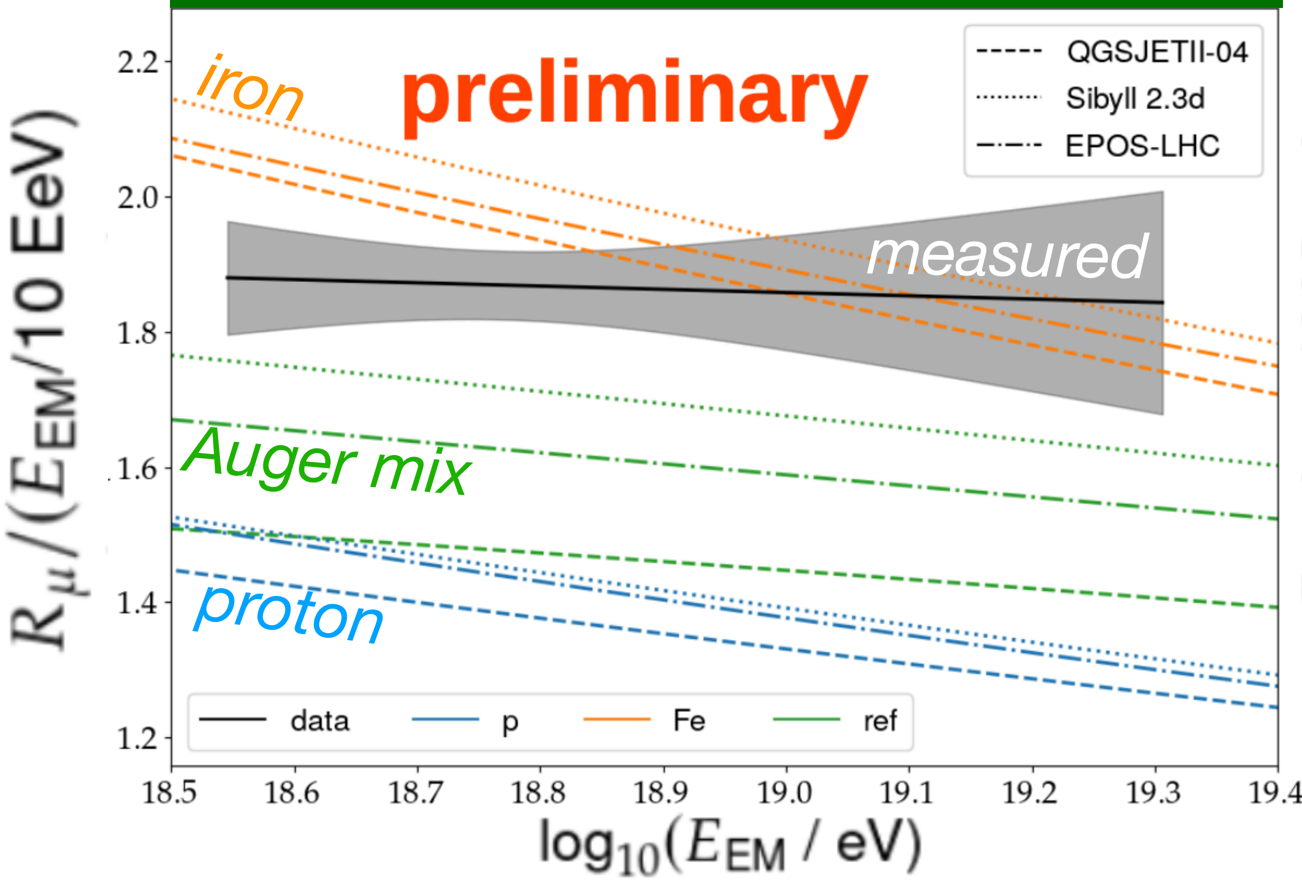




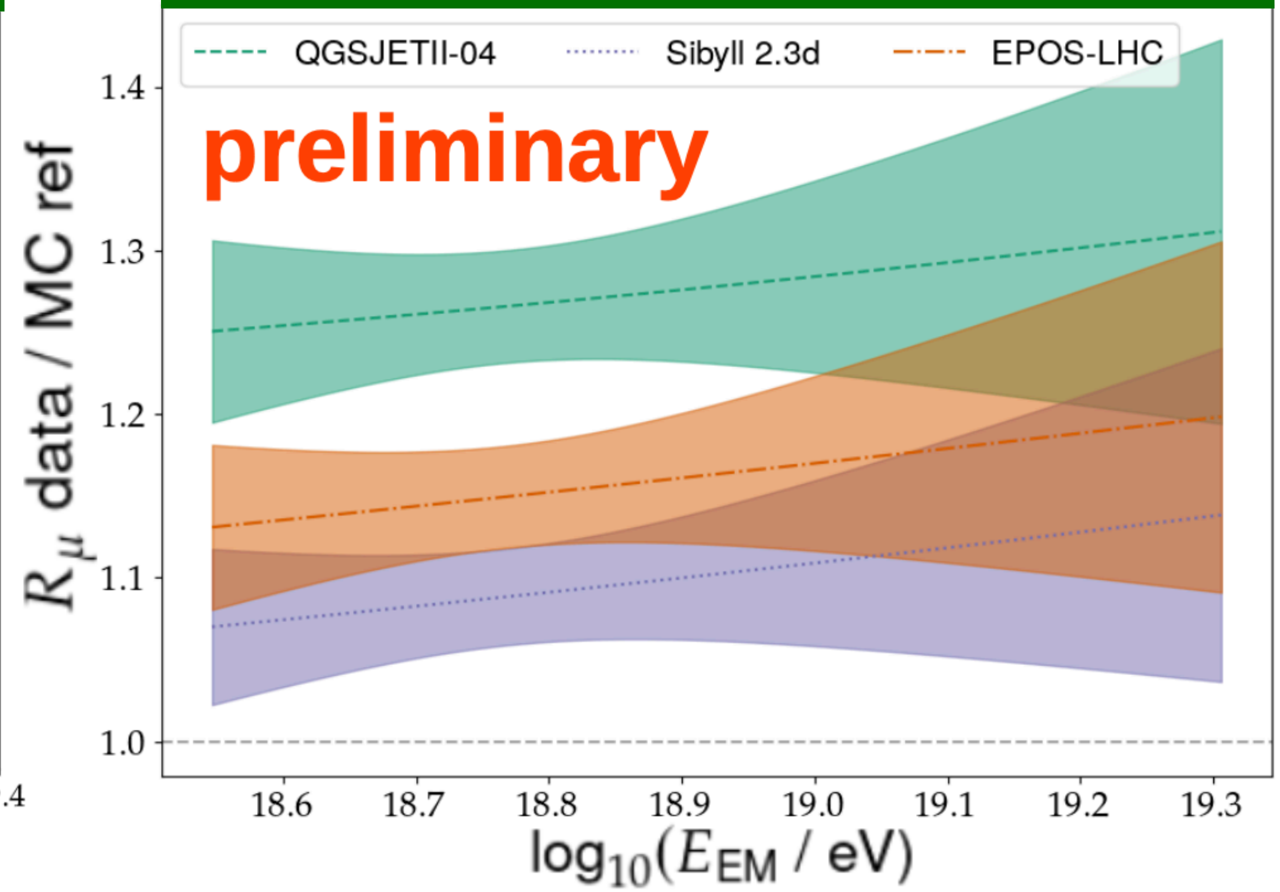
Muon content in measured air showers

Work by M. Gottowik

Measured muon content



—> muon deficit in simulations

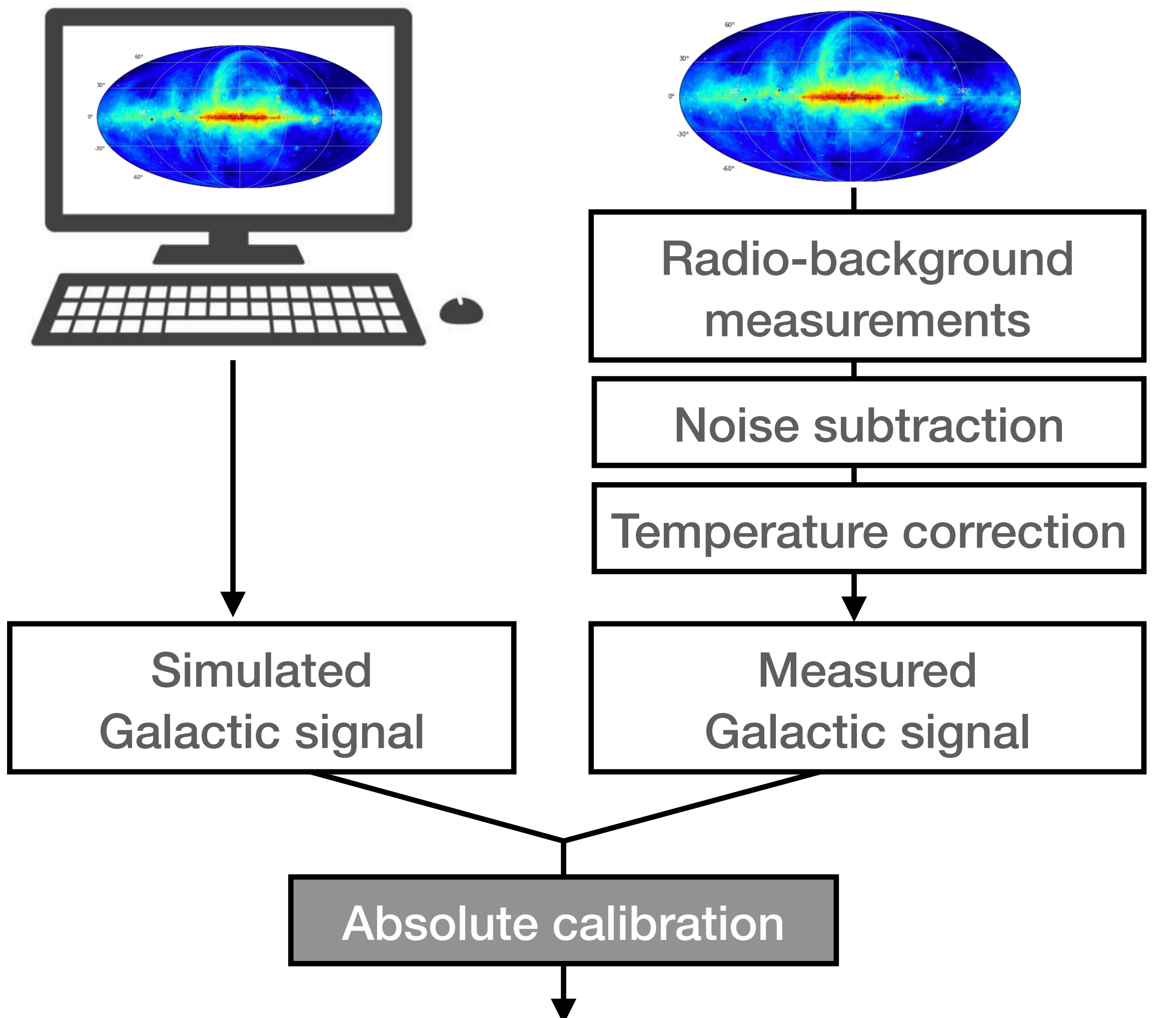


- First measurement of the muon deficit with AERA-WCD hybrid events
  - WCD: muon estimator
  - AERA: electromagnetic energy
- Analysis of 59 events in ~6 years of data shows fewer muons in simulations than in measured data
- Major science case for the **AugerPrime Radio Detector**
  → larger statistics at highest energies (order of magnitude more than hybrid FD-WCD event)

—> See talk by J. Hörandel: today 17:00, parallel 1

Stability of the radio signal over time

Work by D. dos Santos & R. de Almeida



Radio as a calibrator for hybrid detectors

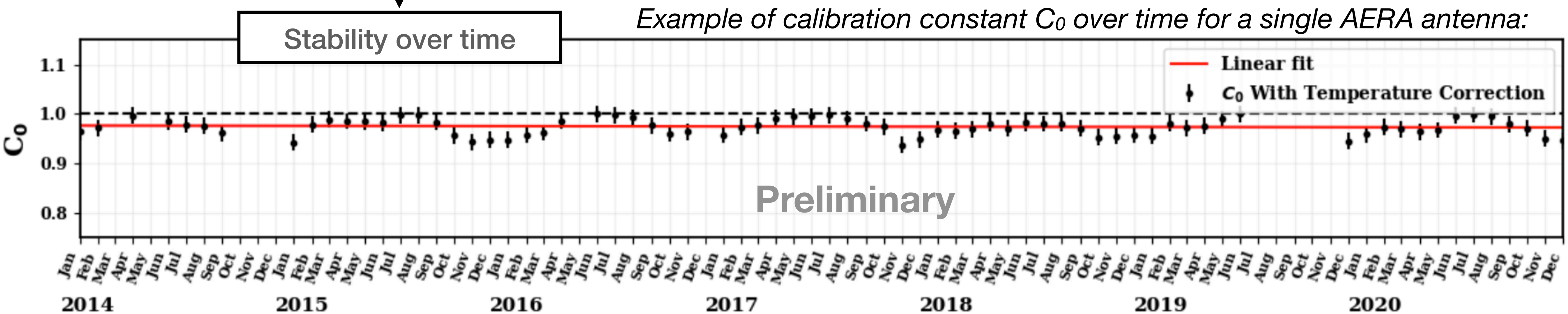
- ‘Ageing’ effects known for e.g. PMTs / dust on mirrors.
  —> Adds uncertainties on energy estimators
- Radio was hypothesized/assumed to be stable.

7yr of data: amplitude radio signal very stable:

Constrained to ±1% per decade

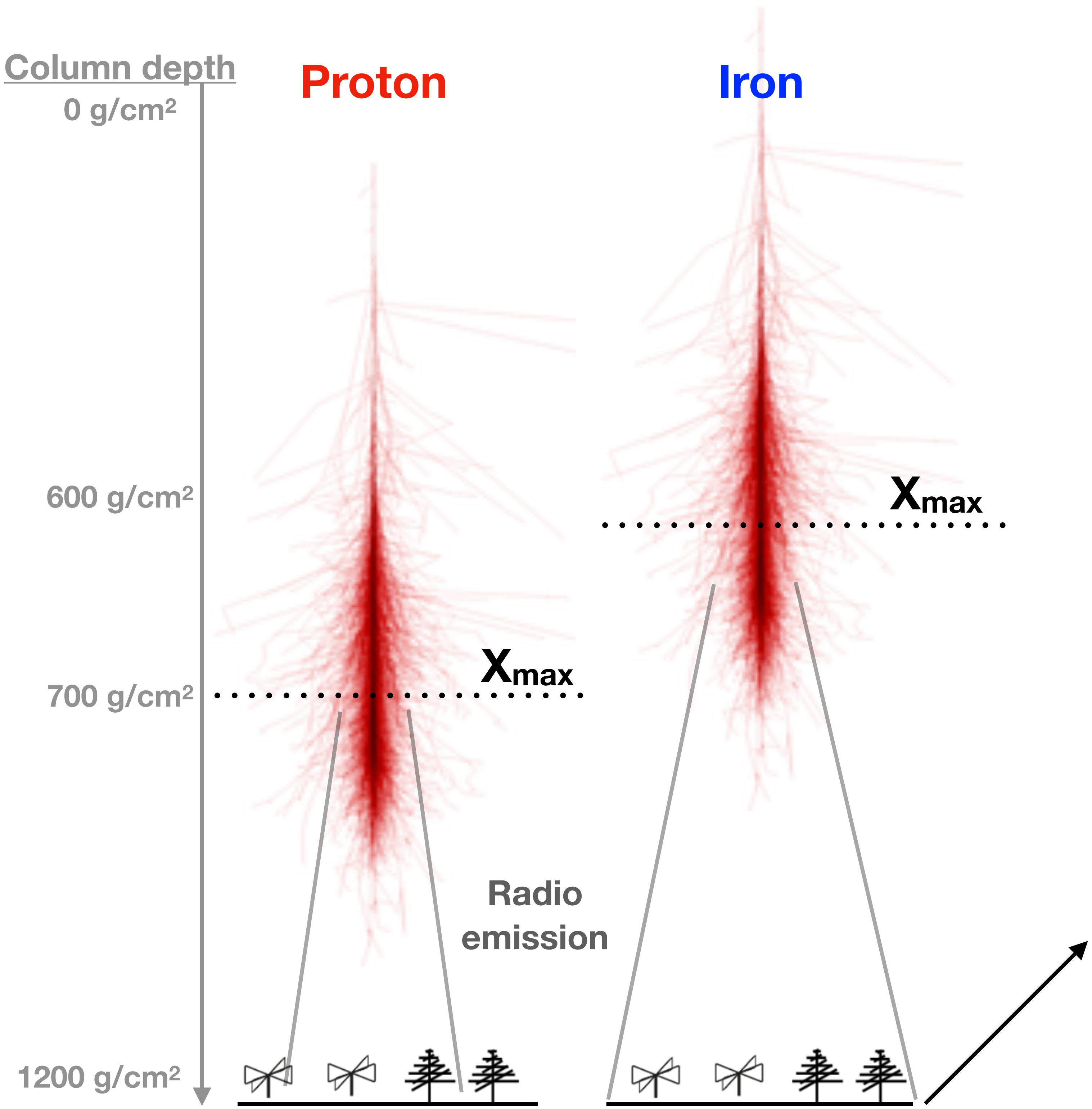
- Some residual (seasonal) variation remains
  —> Investigation ongoing to restrict stability further
- Shows potential for stable calibration source in hybrid detector setups such as the Pierre Auger Observatory

Example of calibration constant C_0 over time for a single AERA antenna:

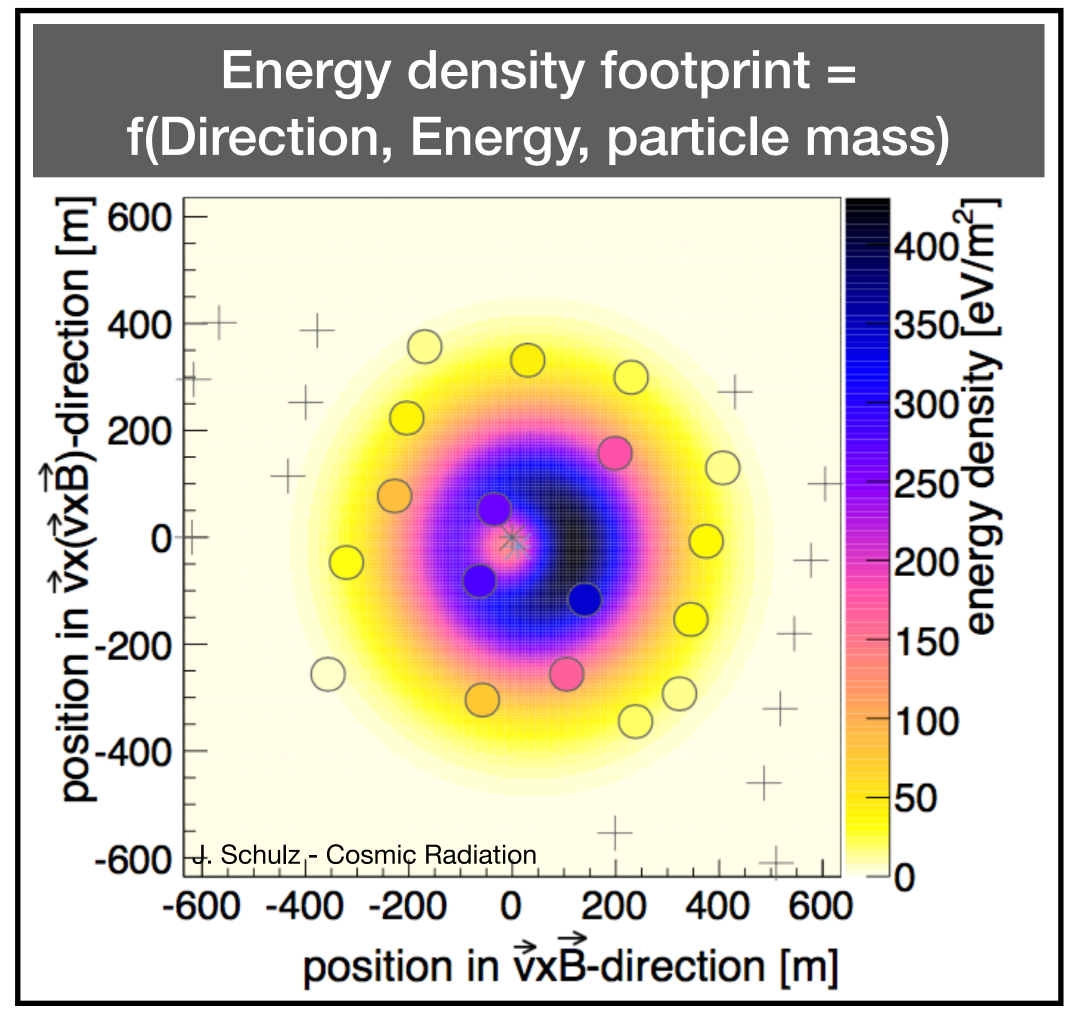


Introduction: Radio footprint is sensitive to Mass

Work by B. Pont



- X_{max} [g/cm²]: *column depth* where *Extensive Air Shower* is maximally developed.
  —> X_{max} depends on mass (particle type)
- Shape of radio footprint changes with X_{max}
  —> Radio footprint is probe for X_{max}.



Method: Reconstructing X_{max} from the radio footprint

Build upon simulation-template fitting method [Buitink+2016]

- From 7yr of data:
  - ~600 high-quality showers after anti-bias and reconstruction cuts ($E=10^{17.5}$ to $10^{18.8}$ eV)
  - 53 hybrid showers with independent FD and AERA reconstructions
- 15 proton +12 iron Corsika/CoREAS simulation for each air shower

—> likelihood analysis: template fitting to find X_{max} for each shower *[details]*

Using the ~600*(15+12) set of simulations

- Correct for reconstruction bias on an event-by-event basis
- Determine reconstruction uncertainty on an event-by-event basis
- Determine detection acceptance
- Determine reconstruction bias

Investigation of systematic uncertainties. Accounting for:

- **Basic effects** : *hadronic model in CORSIKA, GDAS atmosphere, Auger SD energy scale*
- **Method specific effects** : *data selection (acceptance), X_{max} reconstruction pipeline*
- **low-number statistics** : effects of *possible outlier values and reconstruction quality cuts*
- **Residual bias checks** : investigation of *shower zenith/azimuth/core/… vs $\langle X_{max}\rangle(E)$*

Results: Resolution of AERA X_{max} method

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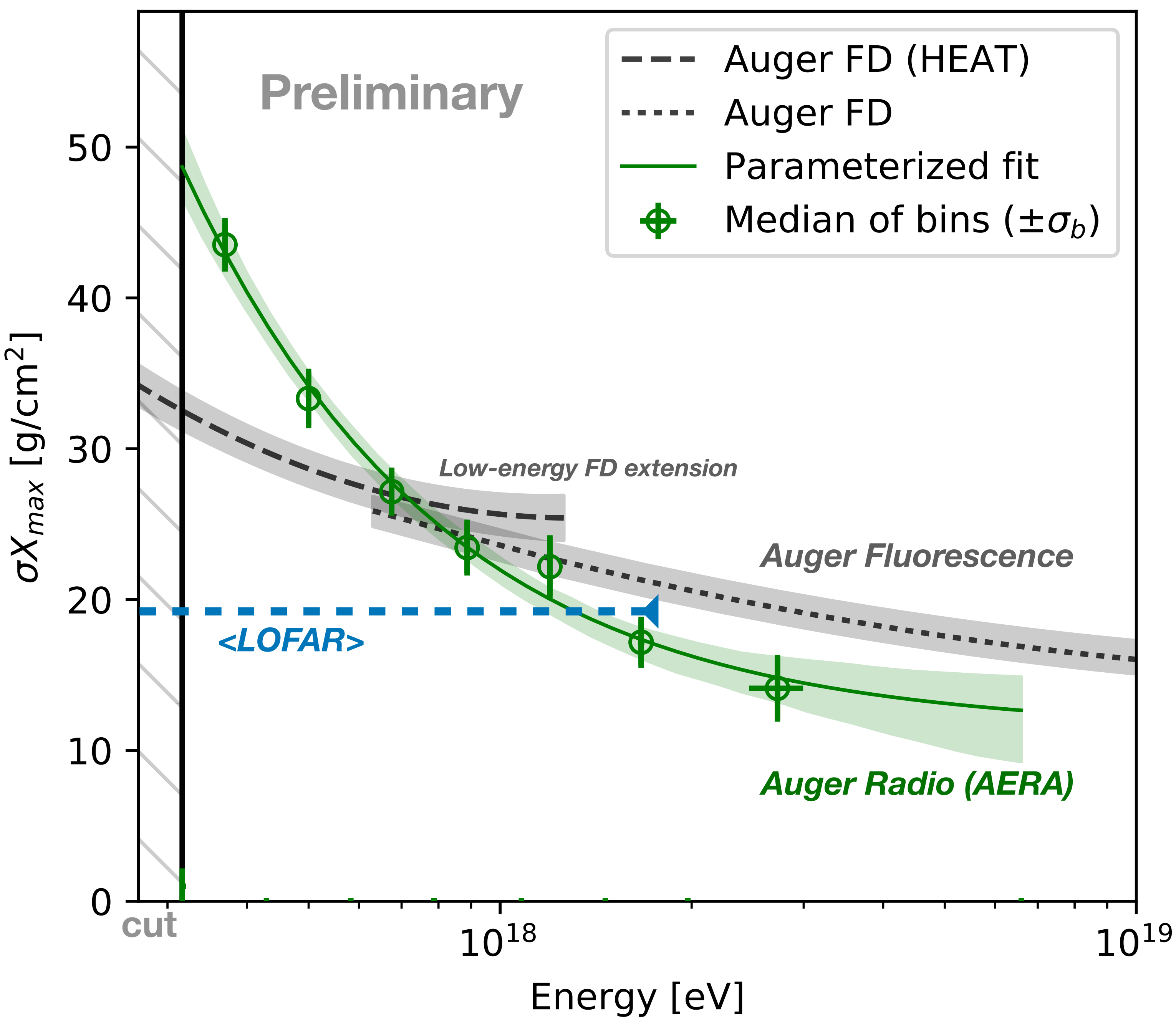
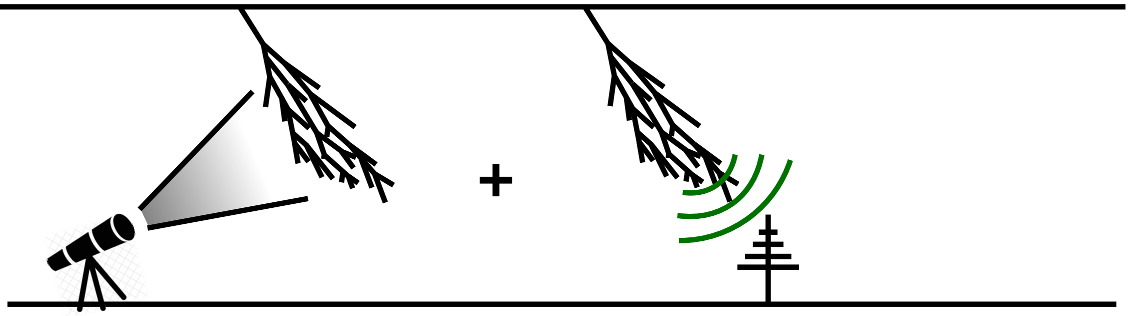
Radio X_{max} resolution





Resolution improves with energy.

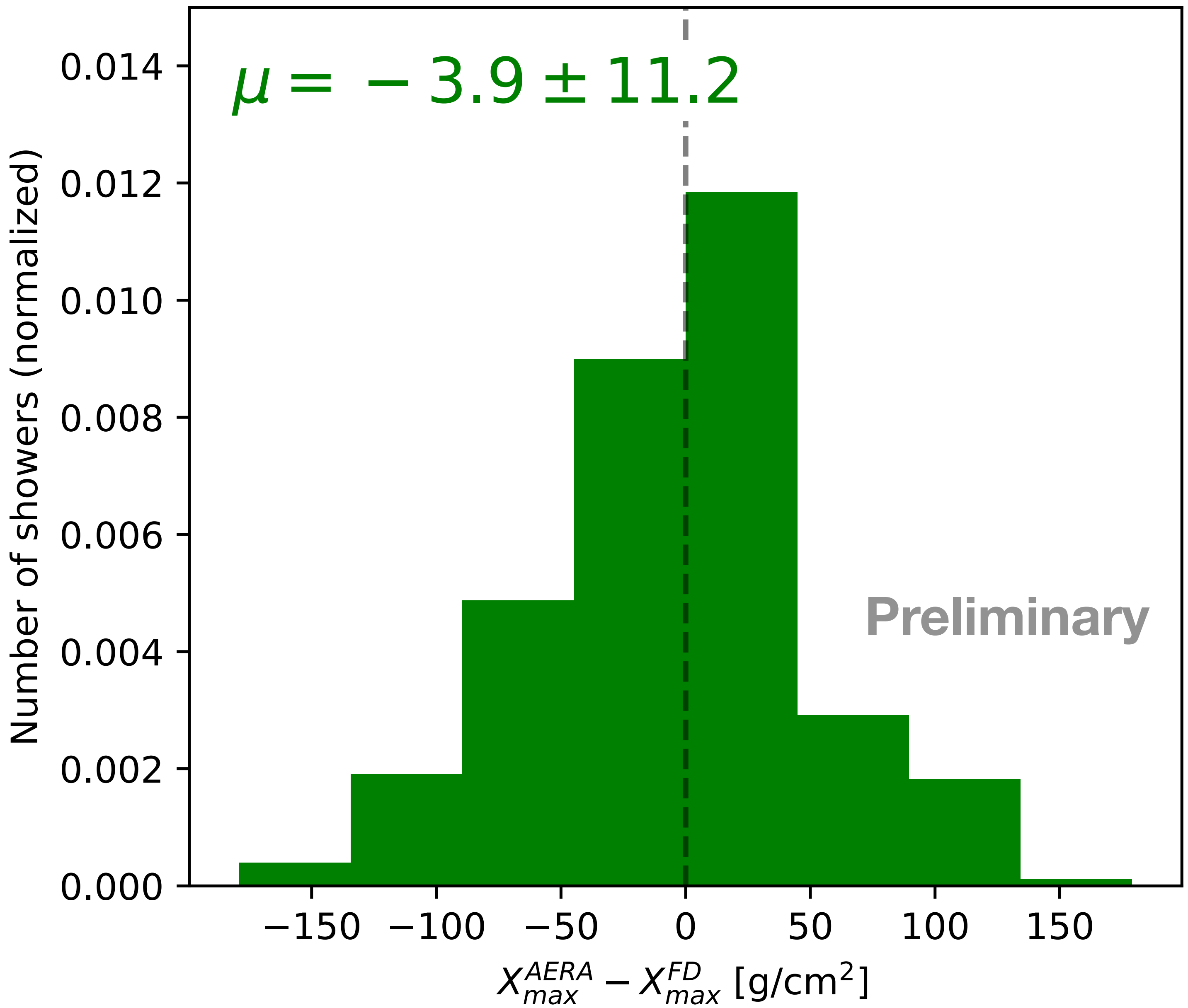
- Up to 'better than 15 g/cm^2'
- Trend driven by low SNR at low energy.

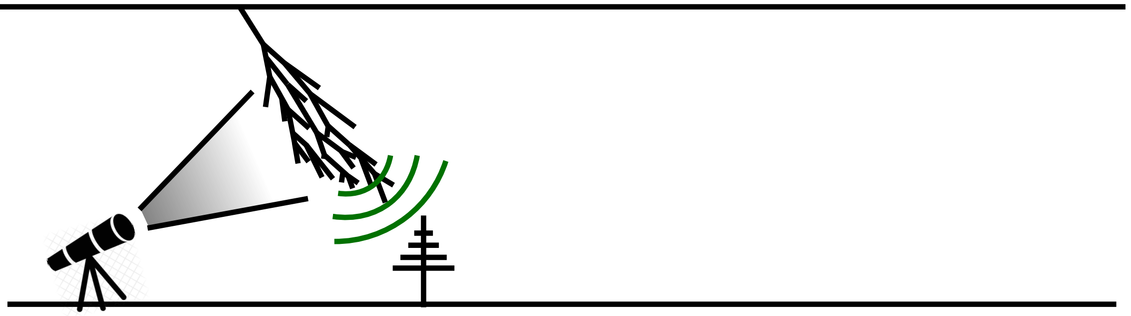
Resolution competitive with e.g.:

- Auger fluorescence [arXiv:1409.4809]
- LOFAR radio (E=$10^{16.8\ldots18.3}$eV) [arXiv:2103.12549v2]

Results: Event-by-event FD vs AERA X_{max}

Histogram of AERA-FD difference

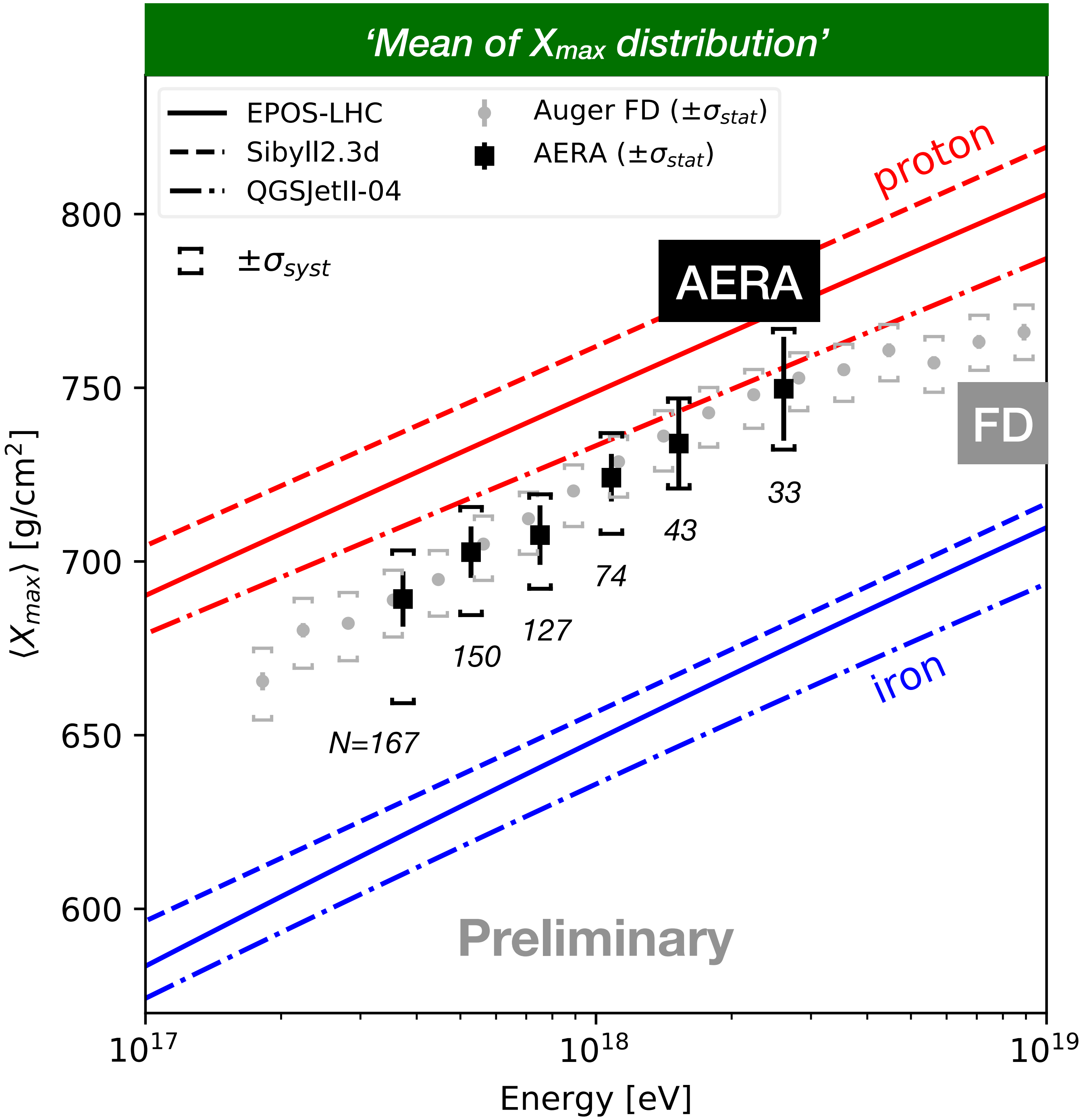


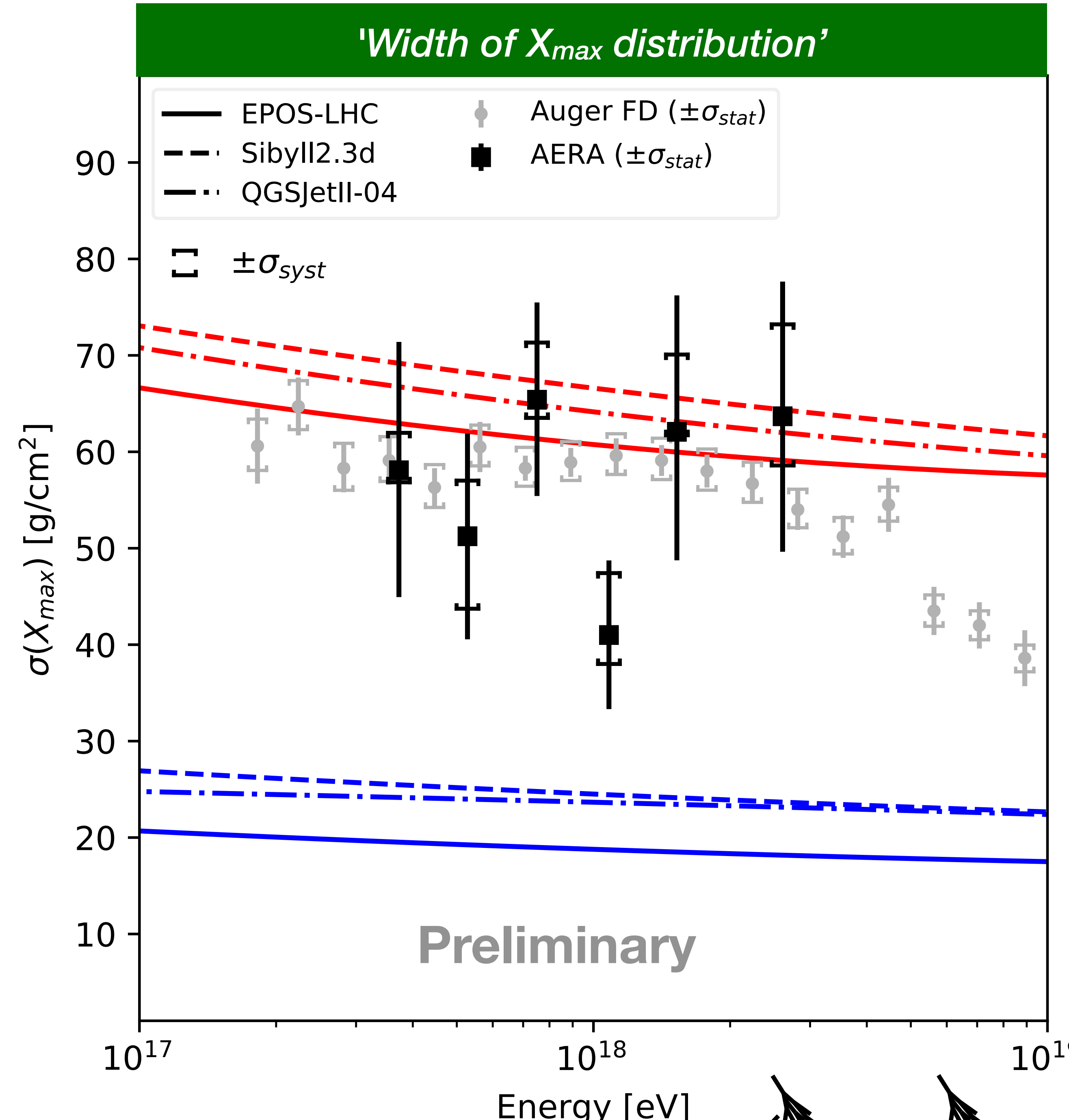


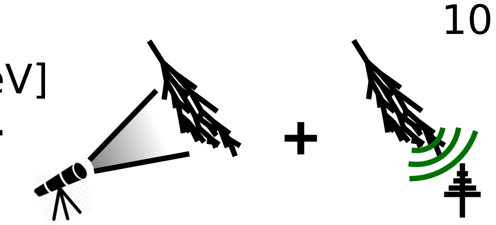
Auger has unique Radio-Fluorescence setup:

- X_{max} of **53** hybrid-showers with AERA and FD; (Are independent observations!)
- No significant bias radio X_{max} w.r.t. fluorescence X_{max}.
- Provides independent checks on:
  - X_{max} reconstruction methods
  - shower physics (probe different aspects)

Results: Measured AERA X_{max} distribution







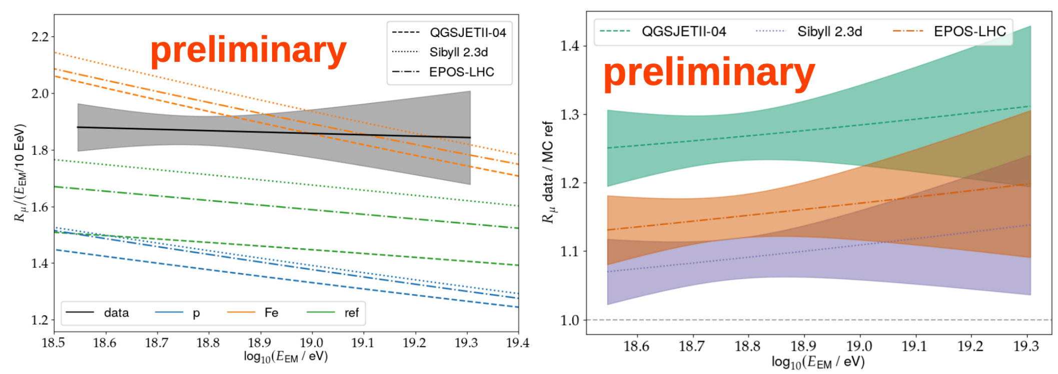
- ~600 showers after quality and anti-bias cuts.
- In agreement with Auger FD in mean and width.
- Light composition (p-He) at $E=10^{17.5}$ eV, seemingly becoming lighter towards $E=10^{18.5}$ eV.

Take home messages

Work on AERA is ongoing: Physics & survey-studies for upcoming AugerPrime Radio

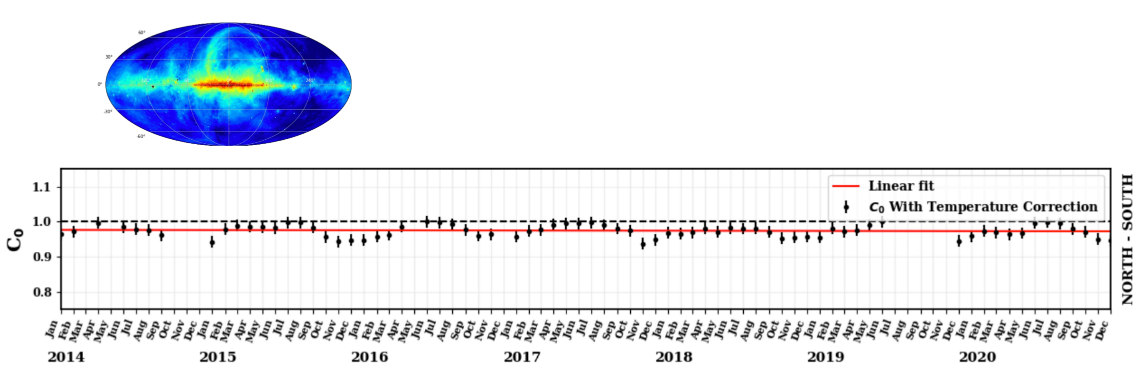
First muon deficit measurements with AERA-WCD

Very promising for the upcoming AugerPrime Radio Detector

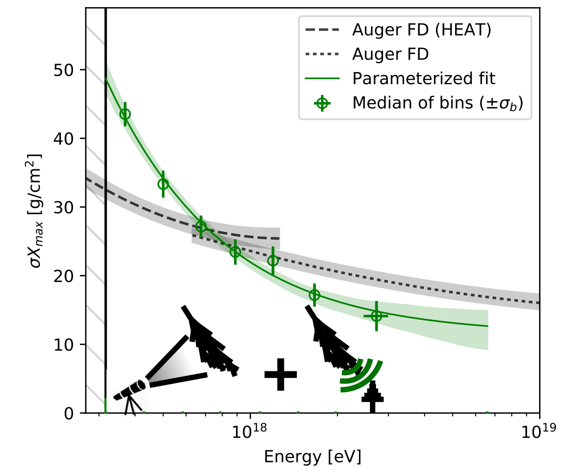


Radio signal is very stable over time

Potential for calibration source for hybrid detectors



Competitive radio X_{max} resolution



AERA X_{max} compatible with Auger Fluorescence

Independent support to our understanding of shower physics.