Measuring the muon content of inclined air showers using AERA and the water-Cherenkov detector of the Pierre Auger Observatory

Marvin Gottowik
for the *Pierre Auger Collaboration,*
Karlsruhe Institute of Technology (KIT)

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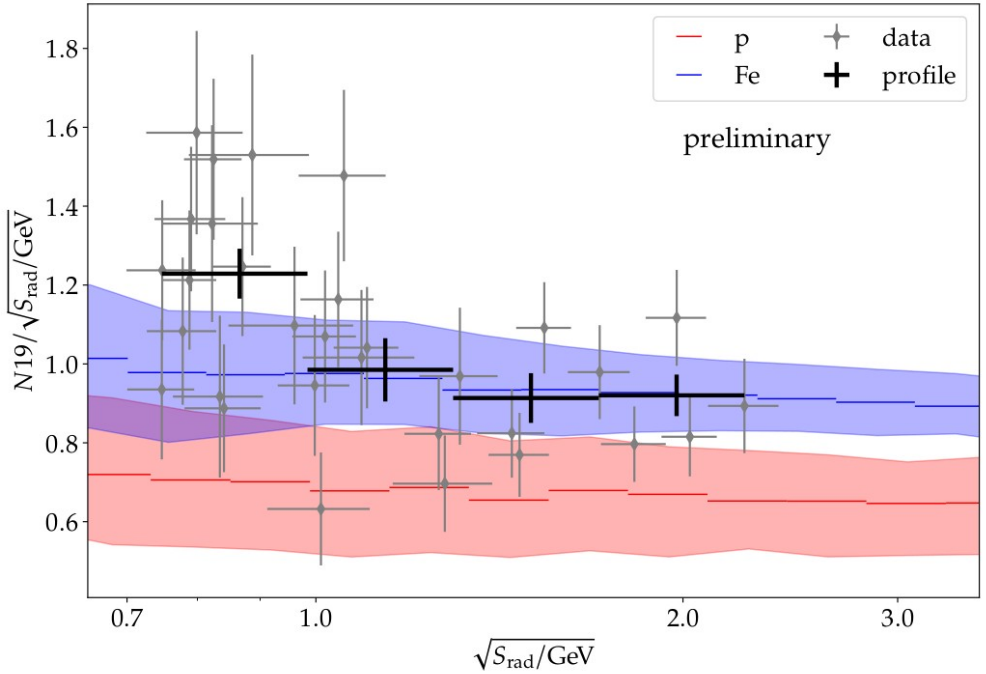
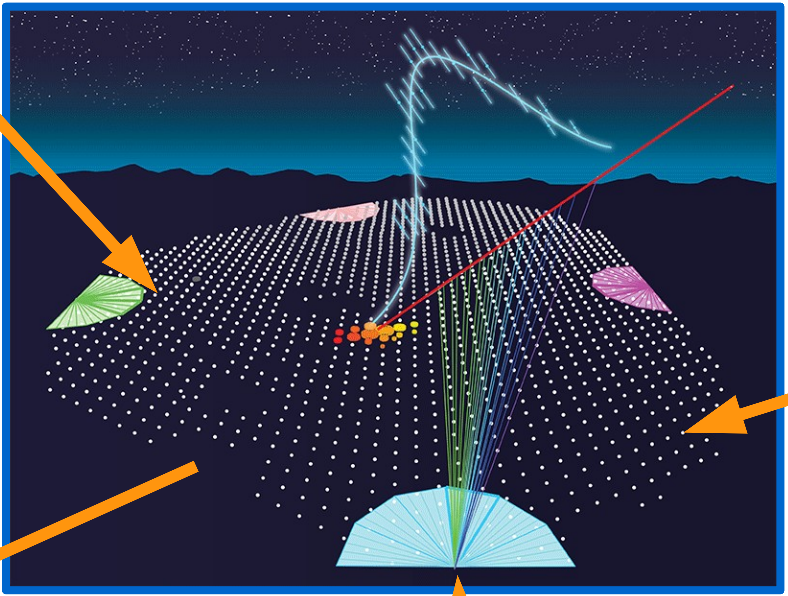


Karlsruher Institut für Technologie

The Pierre Auger Observatory

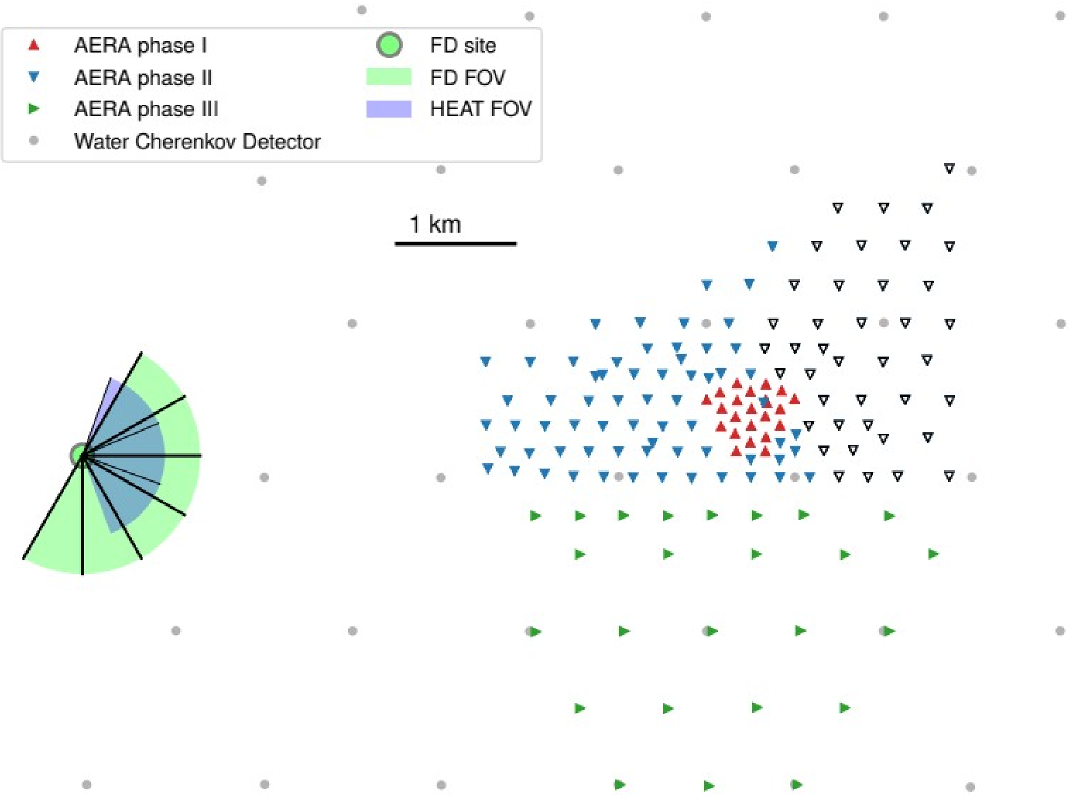
AERA
153 autonomous radio stations, total area: 17 km²



Water Cherenkov Detector (WCD)
1660 stations with 1.5 km spacing
total area: 3000 km²

Muon Detector (MD)
Fluorescence Detector (FD)

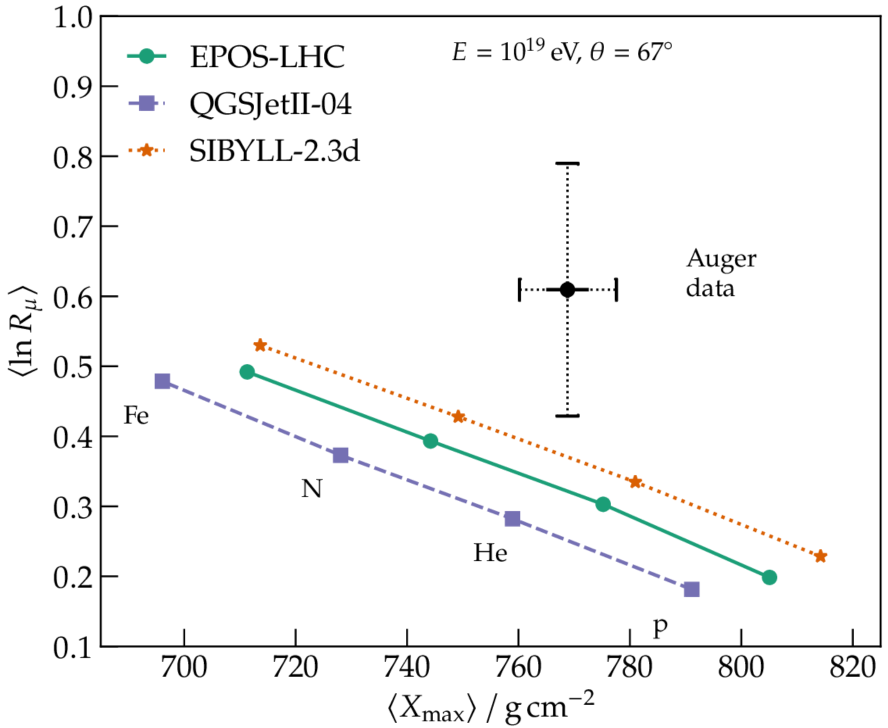
Auger Engineering Radio Array (AERA)



- Energy range: 10^{17} – 10^{19} eV
- Started data taking in 2011
- Largest radio detector for cosmic rays until 2023
- Precursor of the AugerPrime Radio Detector

Muon content in air showers

- Muon number N_μ contains complementary composition information to Xmax.
- N_μ underpredicted by all current-generation hadronic interaction models.
- At Auger: independent reconstructions of N_μ and primary energy
  - WCD–FD hybrids (cf. Phys. Rev. Lett. 126 (2021))
  - MD-WCD hybrids (cf. Eur. Phys. J. C 80 (2020) 751)
  - **Here: 1500 m WCD + AERA, proof of principle study**

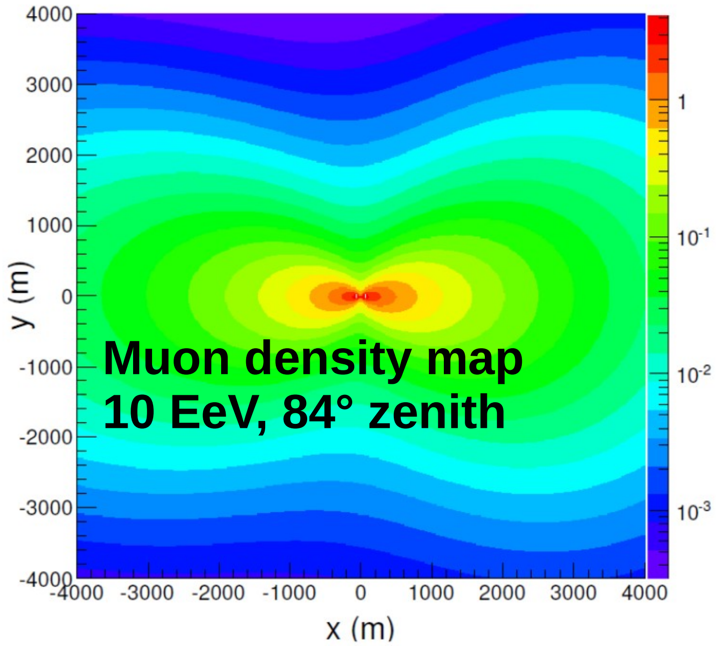


WCD inclined reconstruction

- Established reconstruction method for inclined showers with 62° < θ < 80°. Full efficiency of the 1500 m WCD array above 4 EeV primary energy.
  (cf. JCAP 08 (2014) 019)
- Rescale simulated muon density pattern on ground using 10^{19} eV proton shower to measurements:

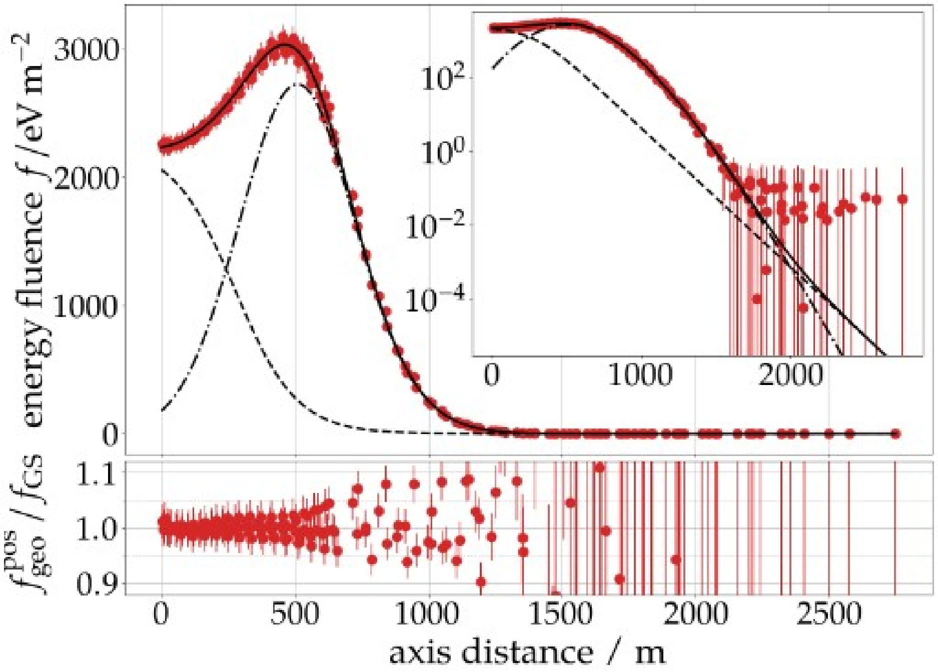
$$\rho_\mu(\vec{r};\theta,\phi,E) = N_{19} \cdot \rho_{\mu,19}(\vec{r};\theta,\phi)$$

- N19: relative muon number wrt ref map
- Refrain from calibrating N19 to absolute muon number for simplicity in this proof of principle study.

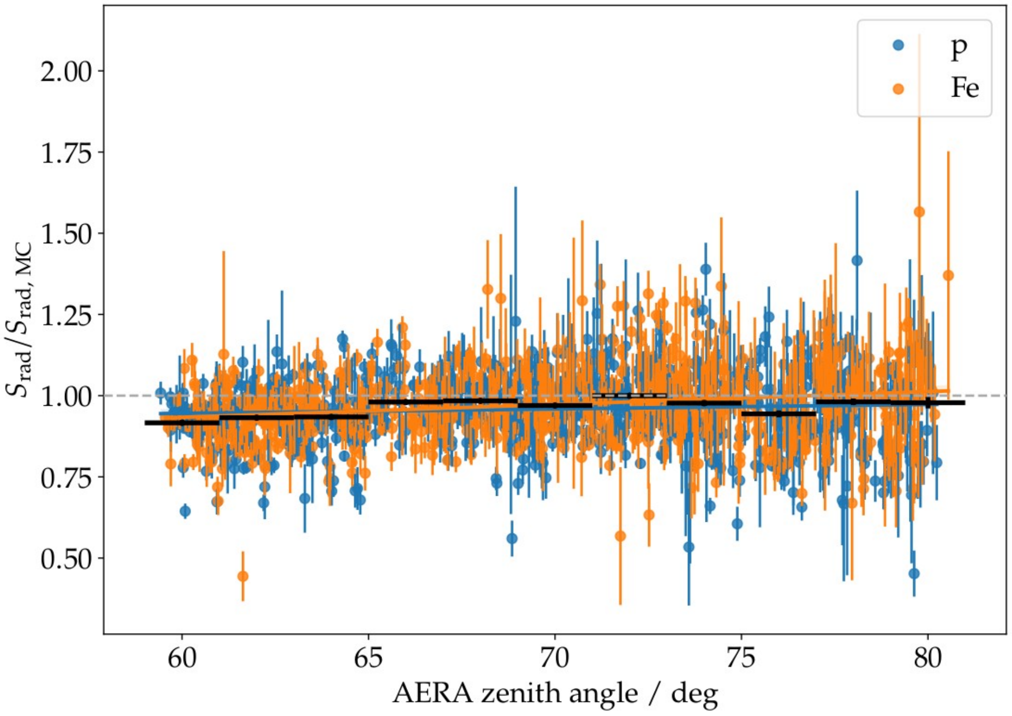


AERA inclined reconstruction

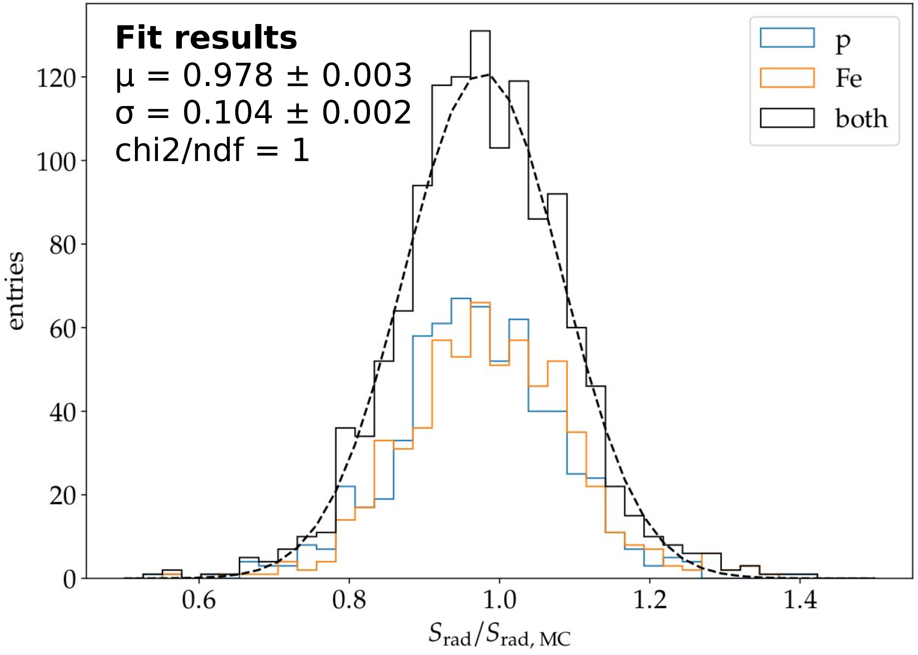
- Dedicated LDF model for inclined showers developed for the RD
  (cf. JCAP01(2023)008)
- Extraction of geomagnetic radio emission and 1D rotationally symmetric LDF (Gaussian + sigmoid)
- Corrected radiation energy S_{rad}: integral of LDF + Xmax correction
- Refrain from calibrating √Srad to shower energy until radio energy scale is established.
  (cf. next talk by Max Büsken)
  but use E_{EM}(Srad) for event selection



LDF validation for AERA

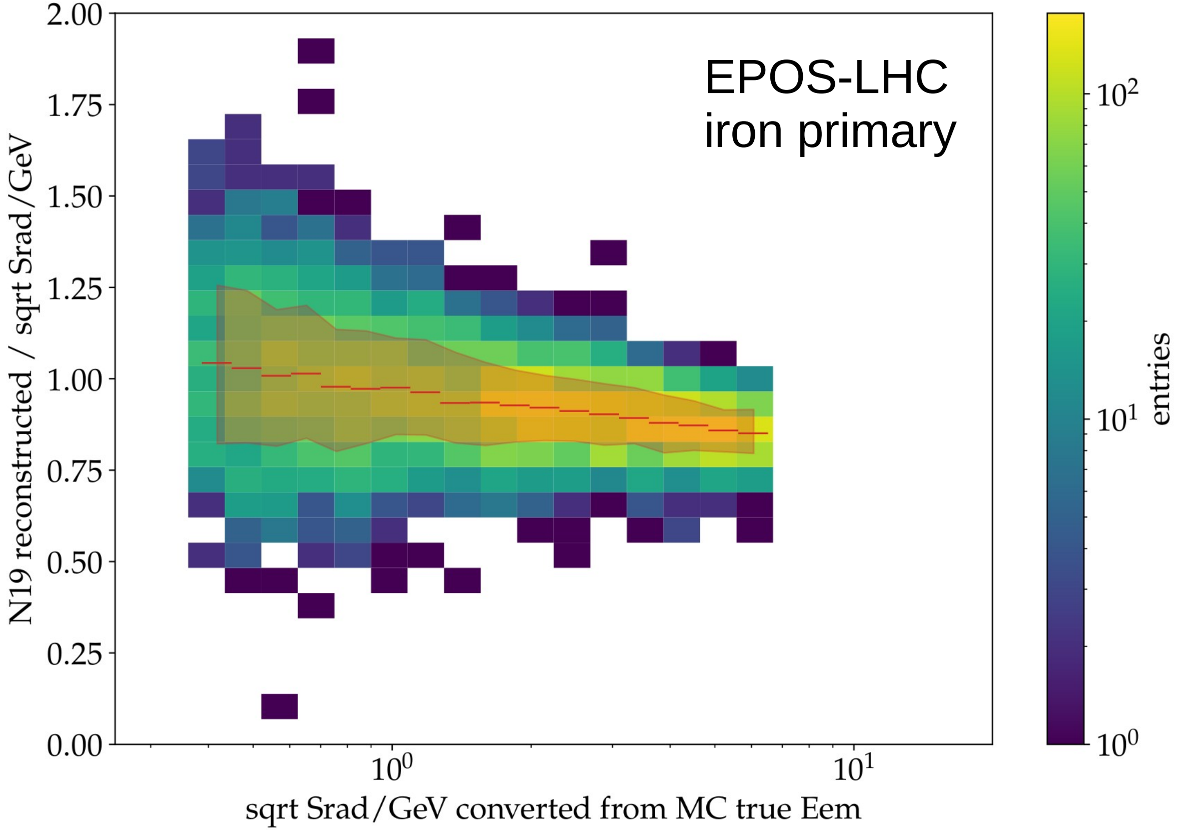


- Reconstruction performs worse for lower zenith angles (expected)
- Restrict analyis to 65° < θ < 80°
- Remaining bias maybe related to signal processing, eg. RFI removel



- S_{rad} uncertainties underestimated (cf. talk by Sara Martinelli), increase uncertainty by additional 10%

Hadronic model prediction



- Hybrid events allow measuring N19($\sqrt{S_{rad}}$) and compare result for data and simulations.
- Derive expectation from more than 100.000 corsika showers (no radio information).
- Reconstruct N19 and MC true S_{rad} calculated from energy of the electromagnetic component.
- Show central 68% of the distribution. Bands mostly similar for all hadronic models.

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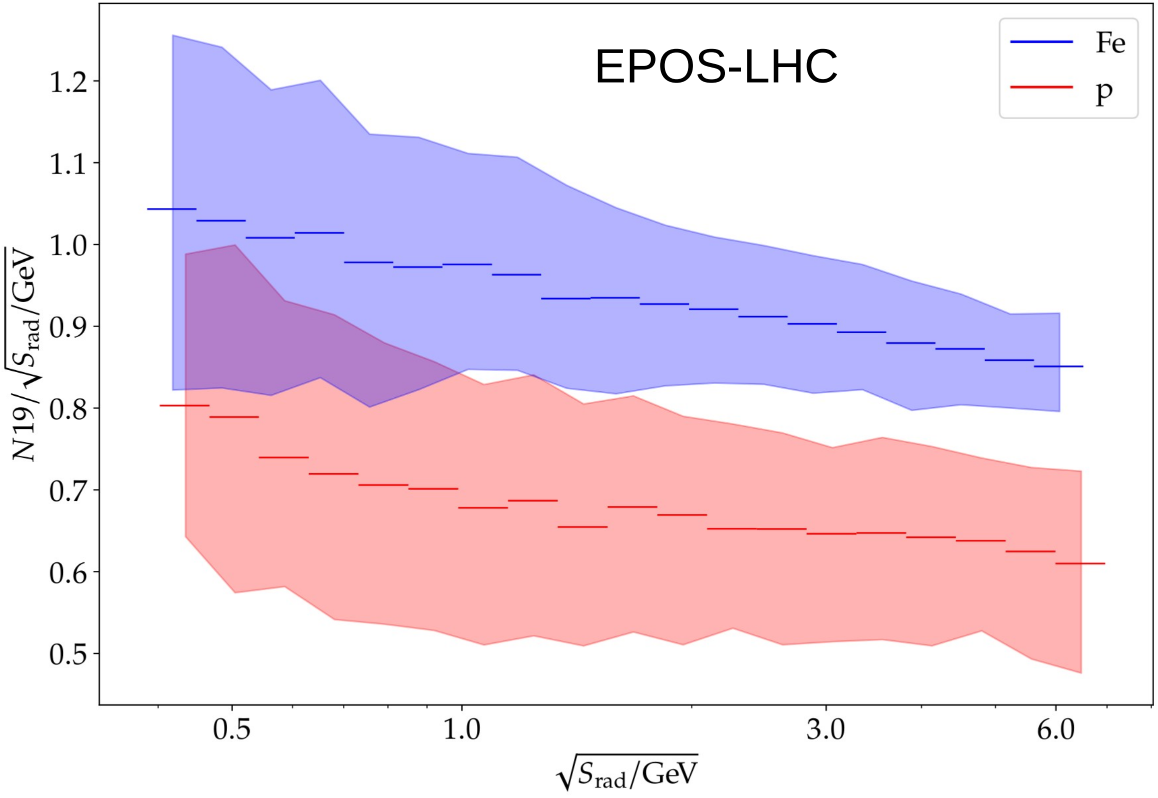

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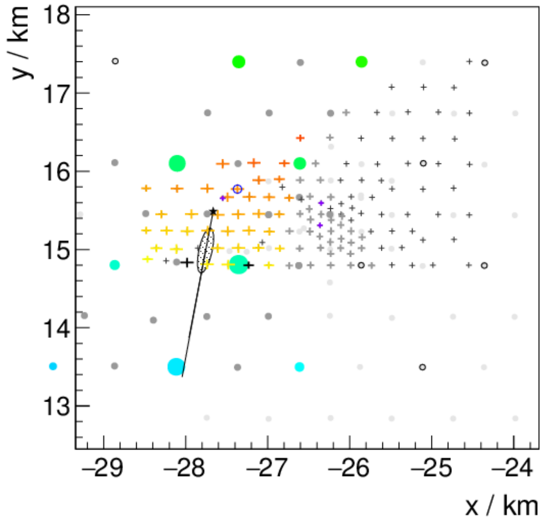
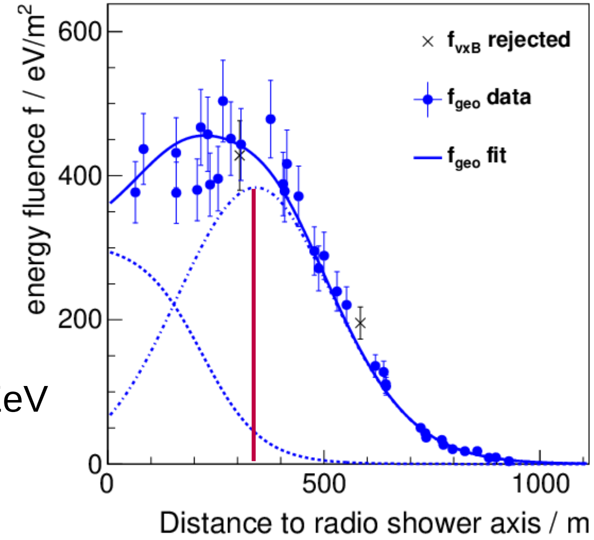
Data selection

- Independent WCD and AERA reconstruction
- AERA data from 26.06.2013 to 01.05.2019
  → 31 events after cuts (~4 to 12 EeV WCD energy)
- Extended bad period DB needed for newer data, work in progress.
- Strongest cut: high energy threshold of 4 EeV

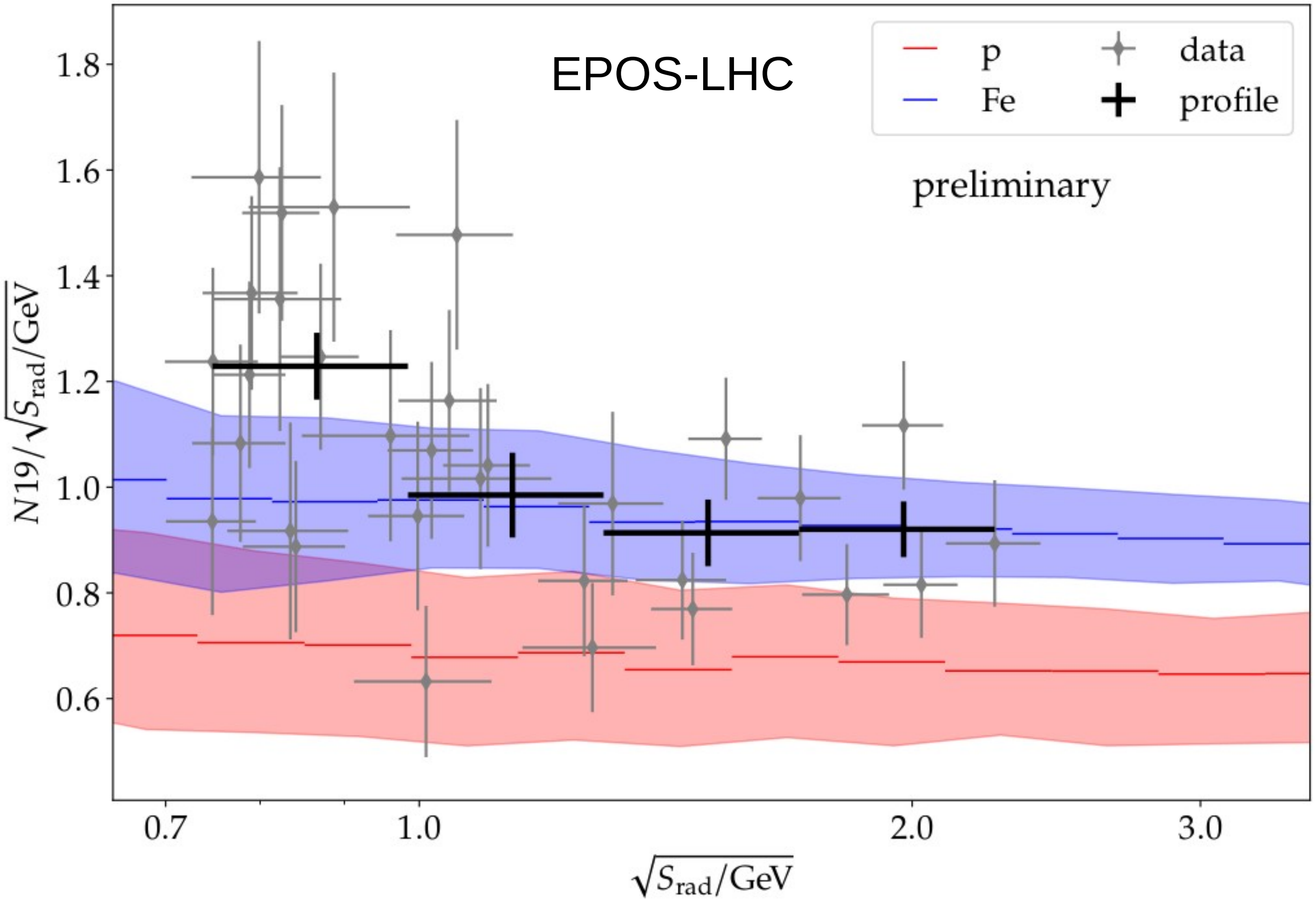


cut	number of events after cut
$65^\circ \leq \theta_{\mathrm{SD}} \leq 80^\circ$	1521
number of candidate stations ≥ 5	922
Full hexagon of stations	791
no thunderstorm conditions	707
SD-RD opening angle $< 2.08^\circ$	655
$E_{\mathrm{EM}} > 4\,\mathrm{EeV}$	91
station inside Cherenkov radius	45
reduced χ^2 of LDF fit < 5	38
number of stations > 5	34
relative E_{EM} uncertainty < 0.2	31

WCD reco
$\theta = (70.2 \pm 0.2)^\circ$
$\varphi = (10.0 \pm 0.2)^\circ$ west of south
$E = (5.25 \pm 0.75)$ EeV
12 WCD stations
37 AERA stations



Measured muon content



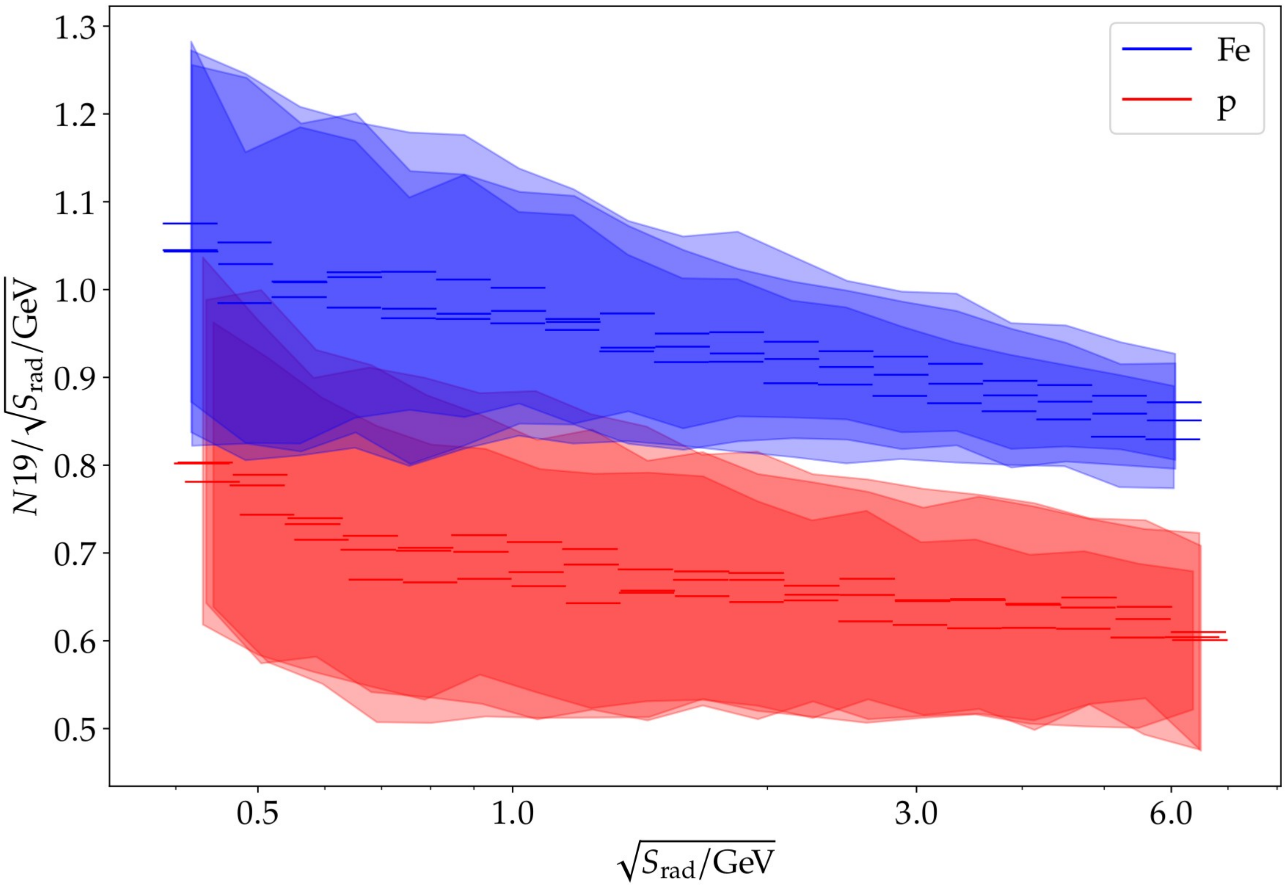
- Muon content in data consistent with model prediction for iron primaries
- Lighter composition expected from Xmax → *muon puzzle*
- Results are consistent with independent Auger analyses in different energy ranges

Summary & Outlook

- First measurement of the muon deficit with radio-hybrid events.
- Reconstruction of CoREAS simulations agrees with MC prediction.
- Analysis of 31 events in ~6 years of data shows fewer muons in simulations than in measured data.
  - Low statistics due to small area of AERA & high energy threshold of 1500 m WCD.
  - Results qualitatively consistent with independent Auger analyses.
- Finalizing publication including data after 01.05.2019.

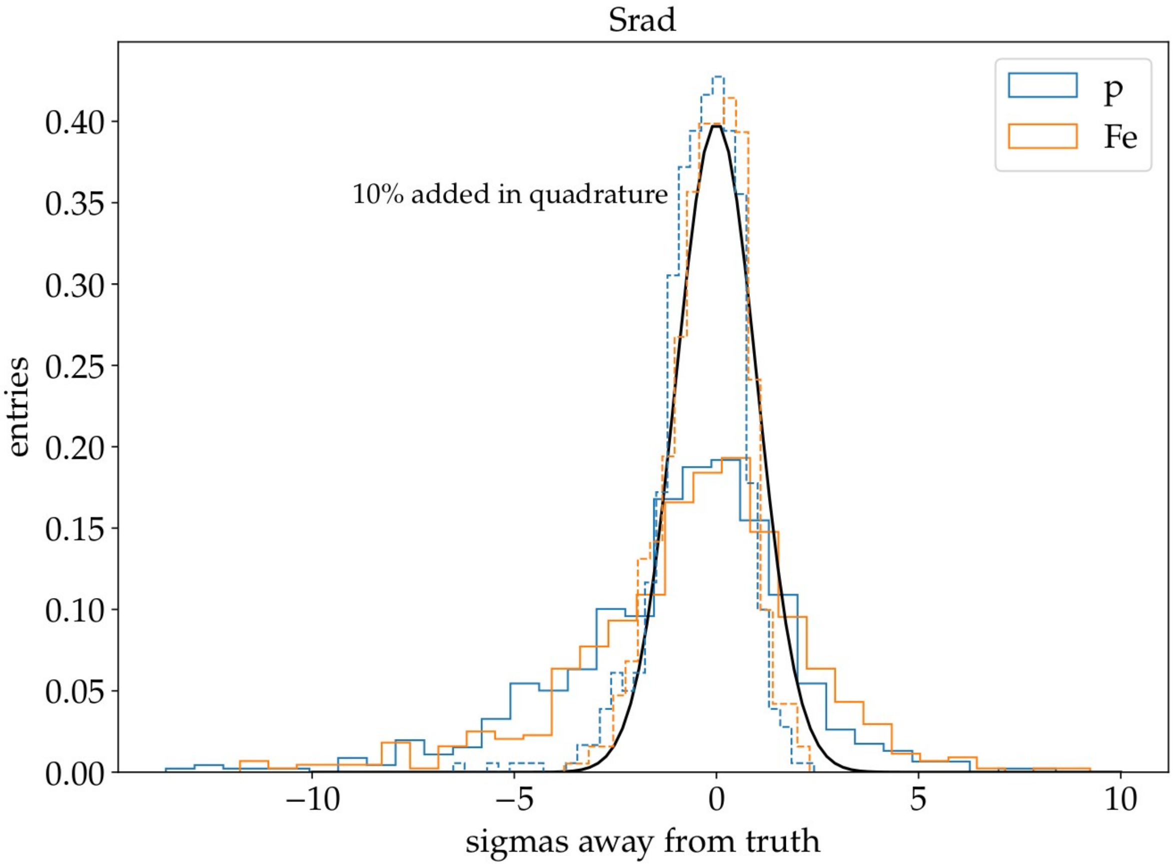
- High statistics measurements in the future with
  - AERA and 750 m WCD at lower energies and
  - RD and 1500 m WCD at highest energies.

Hadronic model predictions



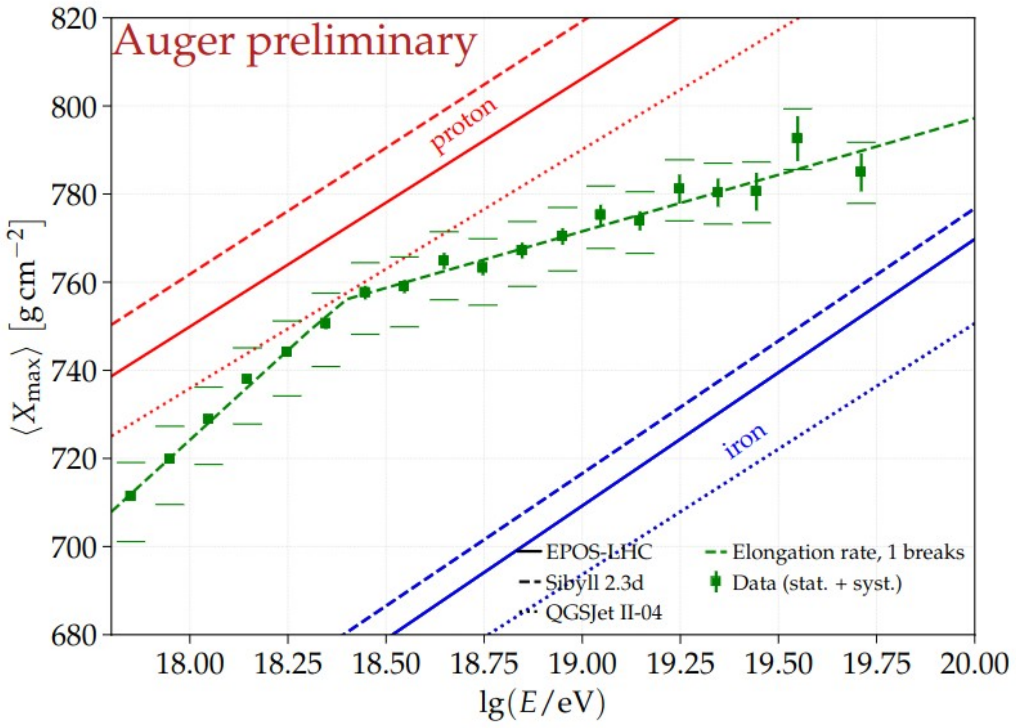
- Very similar predictions for QGSJET-II.04, Sibyll-2.3d and EPOS LHC

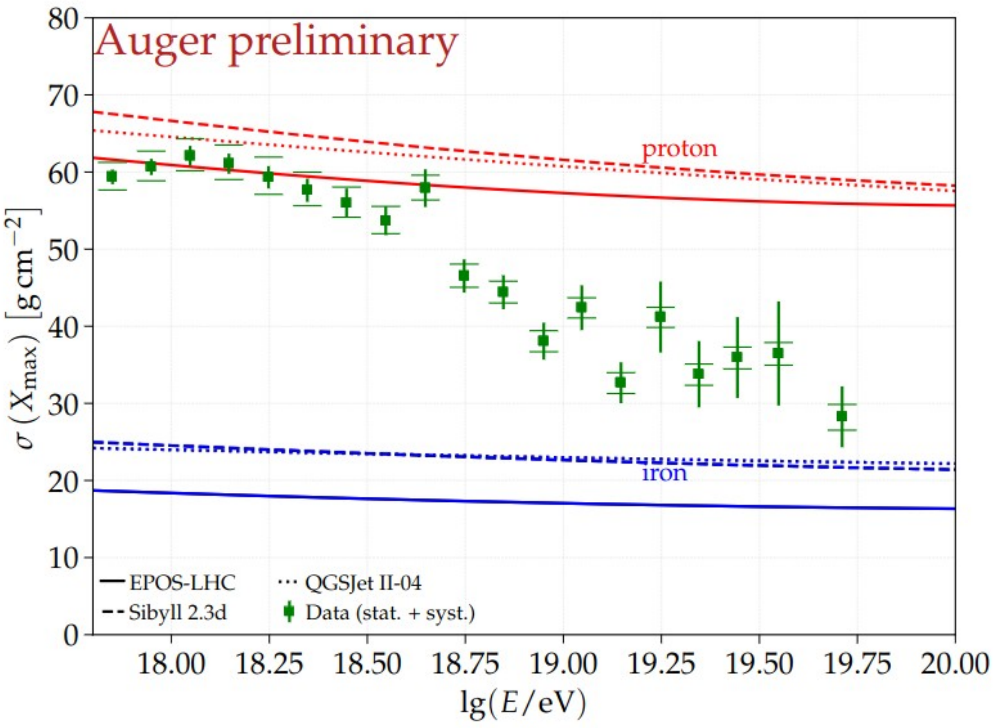
Srad uncertainty rescaling



- Original uncertainty from propagating station signal uncertainty through the LDF fit.
- Station signal uncertainty too small, cf. S. Martinelli. Hopefully improves with new signal model implementation.
- One-time thing, keep it simple → one global factor
- Adding 10% in quadrature yields pull distributions looking like a normal.

FD composition





cf. PoS(ICRC2023)319

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