PROCEEDINGS OF SCIENCE

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

Marvin Gottowik[a,*] **for the Pierre Auger Collaboration**[b]

[a] *Karlsruher Institut für Technologie, Institut für Astroteilchenphysik, Karlsruhe, Germany*
[b] *Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina*
Full author list: https://www.auger.org/archive/authors_2024_06.html

E-mail: spokespersons@auger.org

We present a novel approach for assessing the muon content of inclined air showers based on a combined analysis of the radio emission and particle footprint. We will use the radiation energy reconstructed by the Auger Engineering Radio Array (AERA) as an energy estimator and estimate the muon number independently with the water-Cherenkov detector array (WCD) of the Pierre Auger Observatory. We focus our analysis on air showers with primary energy above 4 EeV to ensure full efficiency of the WCD with a grid spacing of 1500 m. Over approximately six years of data, we identify a set of 31 high-quality events that are used in the analysis. The estimated muon content in data is compatible with the one for an iron primary as predicted by current-generation hadronic interaction models. This result can be interpreted as a deficit of muons in simulations as a lighter mass composition is expected from X_{max} measurements. Such a muon deficit was already observed in previous analyses of the Auger Collaboration and is now confirmed for the first time with radio data.

10th International Workshop on Acoustic and Radio EeV Neutrino Detection Activities (ARENA2024)
11-14 June 2024
The Kavli Institute for Cosmological Physics, Chicago, IL, USA

*Speaker

PoS(ARENA2024)033

1. Introduction

In this proceeding, we present a new method for measuring the muon content of inclined air showers with zenith angles above 60° at the Pierre Auger Observatory using a combination of radio and particle detections. For these inclined air showers, the water-Cherenkov detectors (WCDs) primarily measure muons, as other particles are mostly absorbed in the atmosphere before reaching the ground. However, the radio emission originating from the shower's electromagnetic component can still be detected at ground level as there is neither significant absorption nor scattering in the atmosphere. This hybrid detection approach enables independent estimations of both the muon number and the energy of the air shower.

For the particle reconstruction, we will use the well-established reconstruction method described in [2]. This method involves rescaling two-dimensional reference maps of the lateral muon density generated by proton showers simulated at an energy of 10^{19} eV using QGSjetII-03 as hadronic interaction model to match the measured signals of the WCD stations. The rescaling factor, N_{19}, serves as a relative measure of the muon content compared to the reference model.

The lateral distribution function (LDF) of the radio emission detected by the Auger Engineering Radio Array [3] is described using a model specifically made for inclined air showers [4]. By integrating the LDF over the entire footprint, we obtain the total radiation energy, S_{rad}, which is directly related to the energy of the electromagnetic particle cascade, E_{EM} [5]. This work presents data as a function of S_{rad}, while the highest energy events are selected according to the conversion described in [4].

The analysis is constrained by low statistics due to the small area of AERA of only 17 km^2 and the high energy threshold of 4 EeV required for the WCDs to operate at full efficiency. Hence, this study serves as a proof of concept, demonstrating the feasibility of the proposed measurement technique. Consequently, we focus on the estimators for muon content and energy without converting them into high-level physical quantities of the air showers. The analysis is already detailed in [6]. In the following, we will present an update of the analysis highlighting the recent changes. A journal publication of this analysis is currently being finalized.

2. Validation of the AERA inclined reconstruction

The model used to describe the lateral distribution of the radio emission was initially developed for the AugerPrime Radio Detector [7]. Its application to AERA requires validation, which is performed using a set of more than 1000 air showers simulated with CoREAS [9] using QGSjetII-04 as the hadronic interaction model and proton and iron nuclei as primary particles. The simulations cover the entire phase space of potential event detections with randomly sampled geometry and energy values. Showers were generated with energies between 2 EeV and 40 EeV and zenith angles between 58° and 82°. The core positions were randomized to ensure that a sufficient number of antennas were within a maximum of three Cherenkov radii from the shower core.[1] The simulations are reconstructed including a realistic detector simulation and the addition of environmental noise measured at randomly selected timestamps.

[1]The radius of the Cherenkov ring in the shower plane increases from ~200 m at a zenith angle of 60° to more than 700 m at 80°.

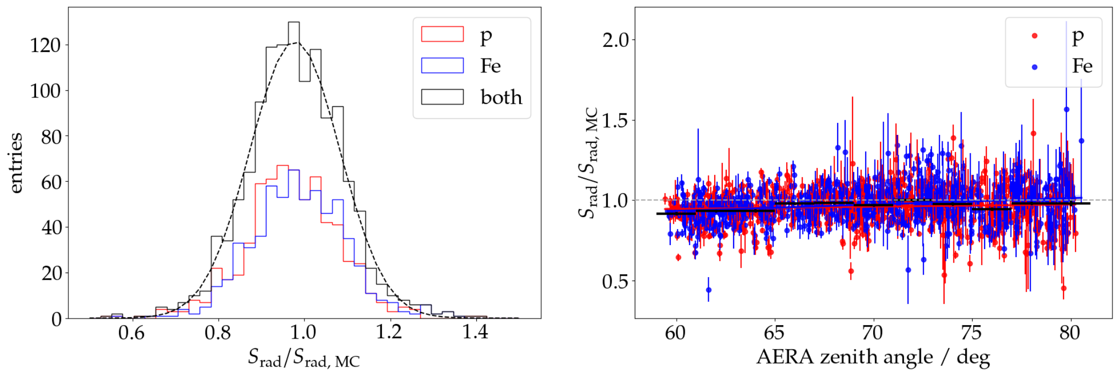

Figure 1: Validation of the reconstructed radiation energy for the high-quality set of simulated air showers. Left: reconstruction bias as a function of zenith angle. Right: histogram for the subset of events above 65° zenith angle.

To ensure high-quality fits, we applied several selection criteria. We required a signal from at least one station within the Cherenkov ring, more than five signal stations in total, and a reduced χ^2 value below 5. As we only have direct access to the electromagnetic energy, not the primary energy, we require that E_{EM} is above 4 EeV. This threshold guarantees that the primary energy exceeds the full efficiency threshold for WCD reconstruction. Events with an opening angle between the shower directions reconstructed by WCD and AERA greater than 2.08° were excluded from the analysis. This threshold corresponds to the mean value plus three standard deviations from a Gumbel fit to the full opening angle distribution [8].

We observed that the uncertainty of the reconstructed S_{rad} is generally underestimated. This is a known challenge and is already the case for the signal uncertainties on the station level used as input in the LDF fit. An improved station signal estimation in the presence of noise is currently being developed [10], improving also the estimation of signal uncertainties for all stations. The impact of this new method on the reconstruction of S_{rad} still needs to be evaluated. For the current analysis, we increased the uncertainty of the reconstructed S_{rad} by 10 % in quadrature so that the pull distribution, i.e., the number of standard deviations by which the observed values deviate from the expected values, more closely resembles a normal distribution. Occasionally, the reconstruction also exhibits very large uncertainties. We only select events with a relative uncertainty on the reconstructed E_{EM} below 20 %.

The resulting reconstruction performance is illustrated in Fig. 1. The figure on the left shows the reconstruction bias as a function of the zenith angle, ranging from 60° to 80°, which is the typical range used for inclined particle reconstruction. For zenith angles above 65°, we observe a constant small bias, while for zenith angles below 65°, the performance deteriorates, and the bias increases. Therefore, only events with zenith angles between 65° and 80° are used in the following. The figure on the right shows a histogram of the reconstruction accuracy. We find an underestimation of (0.978 ± 0.003) % and a spread of (0.104 ± 0.002) %. The remaining bias likely originates from the signal processing, such as the removal of radio frequency interference, and is not further investigated. Thus, we conclude that the LDF model is suitable for use with AERA.

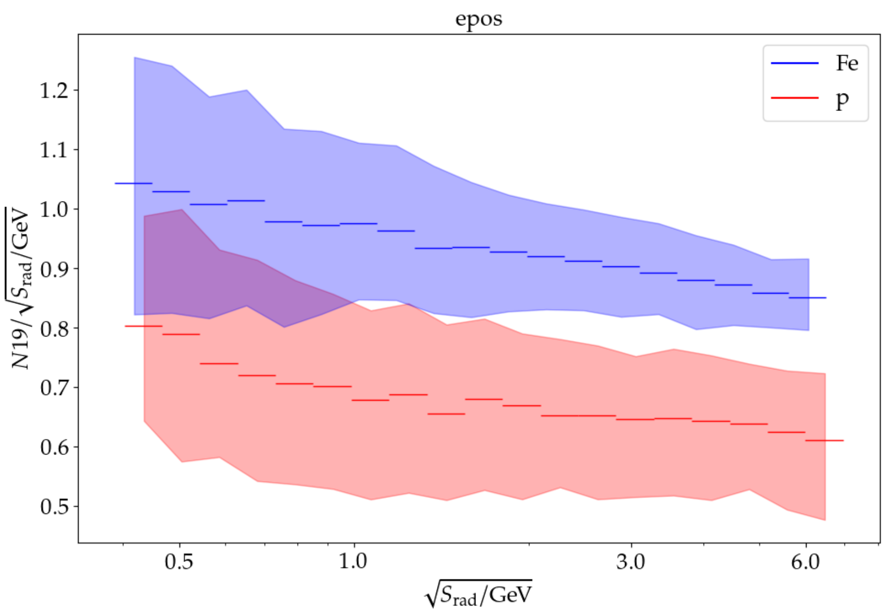

Figure 2: Predicted muon content estimator, N_{19}, as a function of the energy estimator, $\sqrt{S_{\text{rad}}}$. The N_{19} values are normalized by $\sqrt{S_{\text{rad}}}$ to remove the expected power-law dependence. For each bin in $\sqrt{S_{\text{rad}}}$, the median value is denoted by the horizontal line. The central 68 % quantile of the distribution is encoded by the colored bands. The different primary particles are denoted by color.

3. Predicted muon content in simulations

Using hybrid events that include both radio and particle reconstructions, we can compare the measured data with predictions from simulations. For this purpose, we utilized over 100 000 inclined air showers simulated with CORSIKA [11] using QGSjetII-04 [12], EPOS-LHC [13], and Sibyll 2.3d [14] as hadronic interaction models. The simulations use protons and iron nuclei as primaries with energies between $10^{18.4}$ eV and $10^{19.6}$ eV. The electromagnetic energy of each air shower was calculated as the sum of the energy deposited by all electromagnetic particles, which was then converted to the corresponding S_{rad} based on [4].

Each simulated air shower was reconstructed using the standard Auger analysis framework [15] to obtain N_{19}. Due to the reconstruction resolution, we obtain a large spread of N_{19} for the same S_{rad} values as shown in Fig. 2 for simulations made with EPOS-LHC. We find very similar bands with the other hadronic interaction models. Given the limited statistics available in this proof-of-concept study, we focus on presenting the predictions from the EPOS-LHC model, as differentiating between the models will be impossible.

4. Measurement of the muon content

In this analysis, we examine the AERA data recorded between June 26, 2013 (start of AERA phase II) and May 1, 2019 (the last date with identified bad periods). The same event selection as in the previous section is applied. Furthermore, events that fall into thunderstorm periods [8] are

Table 1: Number of events after each cut starting with 2663 reconstructed events. The first set of cuts is related to the WCD reconstruction, the second one to the AERA reconstruction.

cut	number of events after cut
$65° \leq \theta_{\text{SD}} \leq 80°$	1521
number of candidate stations ≥ 5	922
Full hexagon of stations	791
no thunderstorm conditions	707
SD-RD opening angle < 2.08°	655
$E_{\text{EM}} > 4$ 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

excluded. This selection yields 31 high-quality hybrid events. The number of events remaining after each cut is detailed in Tab. 1. The most restrictive cut is the minimum energy threshold of 4 EeV. The measured muon content in data is presented in Fig. 3 as a function of $\sqrt{S_{\text{rad}}}$. The average muon content shown in black is consistent with the predictions of hadronic interaction models for iron nuclei. A thorough estimation of the systematic uncertainties will be done in a future publication.

The expected mass composition can be inferred from X_{max} measurements of the Auger fluorescence detector. In the energy range of this analysis, the mean atomic mass number is likely to be between proton and nitrogen [16]. Hence, one can conclude that there is a deficit of muons in simulations. This deficit was already found by other Auger analyses for primary energies above 4 EeV [17] as well as for primary energies between 2×10^{17} eV and 2×10^{18} eV [18].

5. Conclusion

We have presented a first estimate of the muon content in inclined air showers using hybrid measurements that combine radio and particle detection. This work serves as a proof of concept for future analyses involving radio and particle events. Our findings indicate that the measured muon content in the data is consistent with predictions from hadronic interaction models for iron-induced air showers, despite the expected composition being between proton and nitrogen. This result demonstrates, for the first time, that hybrid detection of radio emission and particles can be used effectively to investigate the already known muon puzzle.

Currently, the analysis is limited by the low statistics of 31 high-quality events originating from the small area of AERA of 17 km^2 and the high energy threshold of 4 EeV needed for the reconstruction with the 1500 m WCD array. The event statistics can be increased moderately by including additional years of data, and this expanded data period will be presented in a future journal publication.

PoS(ARENA2024)033

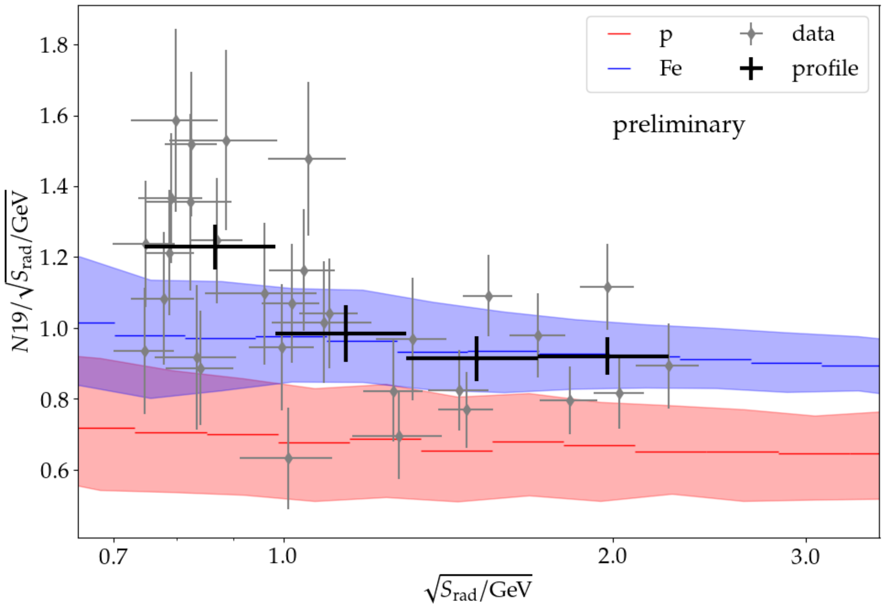

Figure 3: Predicted muon content estimator, N_{19}, as a function of the energy estimator, $\sqrt{S_{\mathrm{rad}}}$. For each measured event, the reconstructed estimators and their uncertainties are shown by the gray data points. The black profile denotes the average for each energy bin, the y-uncertainty is given by the uncertainty of the mean. The colored bands visualize the prediction for simulations made with EPOS-LHC as already shown in Fig. 2.

An adaption of the inclined reconstruction technique used for the 1500 m WCD array is currently being developed for the 750 m array which will allow reducing the energy threshold considerably and, therefore, collect more statistics at energies below 4 EeV. With the AugerPrime Radio Detector currently being deployed, this analysis can be extended to the highest energies to allow for in-depth tests of hadronic interaction models with large statistics [19].

References

[1] A.Aab *et al.* [Pierre Auger coll.], Nucl. Instrum. Meth. A **798** (2015) 172
[2] A. Aab *et al.* [Pierre Auger coll.], JCAP **08** (2014) 19
[3] E. M. Holt for the Pierre Auger Collaboration, PoS(ICRC2017)492
[4] F. Schlüter and T. Huege, JCAP **01** (2023) 008
[5] C. Glaser *et al.* JCAP **9** (2016) 24
[6] M. Gottowik for the Pierre Auger Collaboration, PoS(ICRC2023)345
[7] J. Pawlowsky for the Pierre Auger Collaboration, PoS(ICRC2023)344
[8] M. Gottowik. PhD thesis. (2021) `http://elpub.bib.uni-wuppertal.de/edocs/dokumente/fbc/physik/diss2021/gottowik`
[9] T. Huege *et al.* AIP Conf. Proc. **1535** (2013) 128
[10] S. Martinelli *et al*, arxiv: 2407.18654, submitted to astroparticle physics
[11] D. Heck *et al.* FZKA Tech. Umw. Wis. B 6019, (1998)
[12] S. Ostapchenko. Phys. Rev. D **83** (2011) 14018
[13] T. Pierog *et al.* Phys. Rev. C **92** (2015) 34906
[14] F. Riehn *et al.* Phys. Rev. D **102** (2020) 063002

[15] S. Argiro *et al.* [Pierre Auger coll.] Nucl. Instrum. Meth. A **580** (2007) 1485
[16] A. Yushkov for the Pierre Auger Collaboration, PoS(ICRC2019)482
[17] A. Aab *et al.* [Pierre Auger coll.], Phys. Rev. Lett. **126** (2021) 152002
[18] A. Aab *et al.* [Pierre Auger coll.], Eur. Phys. J. C **80** (2020) 751
[19] T. Huege for the Pierre Auger Collaboration, EPJ Web Conf. **283** (2023) 6002