PROCEEDINGS OF SCIENCE

Measuring the muon content of inclined air showers using AERA and the particle detector of the Pierre Auger Observatory

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

[a] *Bergische Universität Wuppertal, Gaußstraße 20, 42119 Wuppertal, Germany*

[b] *Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina.*

E-mail: gottowik@uni-wuppertal.de, spokespersons@auger.org

A first measurement of the muon content of air showers using hybrid measurements combining radio and particle detection is presented. For inclined air showers with zenith angles above 60°, the water-Cherenkov detector (WCD) of the Pierre Auger Observatory performs an almost pure measurement of the muonic component, whereas the Auger Engineering Radio Array (AERA) allows reconstructing the electromagnetic energy independently using the radio emission of the air shower. The analysis of more than six years of AERA data shows a deficit of muons predicted by all current-generation hadronic interaction models for energies between 4 EeV and 20 EeV. This deficit, already observed in previous analyses of Auger, is now confirmed for the first time with radio data. This analysis is limited by low statistics of only 59 high-quality events due to the small area of AERA of 17 km^2 and the high energy threshold of 4 EeV originating from the WCD reconstruction. 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.

9th International Workshop on Acoustic and Radio EeV Neutrino Detection Activities - ARENA2022
7-10 June 2022
Santiago de Compostela, Spain

[*] Speaker
[†] Full author list at http://www.auger.org/archive/authors_2022_06.html.

PoS(ARENA2022)049

1. Introduction

Ultra-high energy cosmic rays can only be observed indirectly through air showers initiated in the Earth's atmosphere. The mass composition can be inferred from certain shower observables such as the depth of the shower maximum and the muon number. The number of muons in an air shower at ground-level increases nearly linearly with the cosmic-ray energy and weakly with the mass of the cosmic ray. The interpretation of the measured muon number in data relies on the comparison with predictions made by full Monte-Carlo air-shower simulations based on hadronic interaction models. Previous studies performed by the Pierre Auger Observatory, but also other experiments have shown a deficit of muons predicted by all current-generation hadronic interaction models [1].

The potential of a combined measurement of the radio emission and the muons was already shown for simulations [2]. In this proceeding, a new method to measure the muon content of inclined air showers with zenith angles above 60° using hybrid radio and particle detections at the Pierre Auger Observatory is presented. The feasibility of detecting and reconstructing such air showers with AERA has already been demonstrated [3, 4]. For inclined air showers, the water-Cherenkov detector (WCD) performs an almost pure measurement of the muons, other particles are mostly absorbed in the atmosphere and do not reach the ground. However, the radio emission of the air shower can still be detected on the ground as there is neither significant absorption nor scattering in the atmosphere. The radio emission originates from the electromagnetic component of the air shower and allows the reconstruction of its energy. Hence, the electromagnetic energy and the muon content can be reconstructed independently.

2. AERA and the water-Cherenkov detector of the Pierre Auger Observatory

The Pierre Auger Observatory is a multi-hybrid detector for the measurement of ultra-high-energy cosmic rays located in Mendoza, Argentina [5]. Its baseline detectors comprise the world's largest Surface Detector array of 1660 water Cherenkov particle detectors covering an area of $3000\,\text{km}^2$, and a Fluorescence Detector (FD) overlooking the array from 4 sites with 27 telescopes. The Auger Engineering Radio Array (AERA) [6] is located in the northwestern part of the WCD array. AERA is currently the largest radio detector for cosmic rays consisting of 153 radio stations distributed over an area of $17\,\text{km}^2$.

The total muon number is reconstructed by rescaling two-dimensional reference maps of the lateral muon density to the measured signals of the WCD stations. The rescaling factor can be interpreted as a relative muon number, R_μ, with respect to the reference model, a proton shower simulated at an energy of 10^{19} eV using QGSjetII-03 as hadronic interaction model [7]. To obtain the energy, the lateral distribution of the radio signal is fitted with a lateral distribution function (LDF). Integrating the LDF over the whole footprint yields the total radiation energy which can be used as an estimator of the electromagnetic energy of the air shower, E_{EM}, i.e. the energy in the electromagnetic particle cascade [8, 9]. In this work, an LDF is used that was made especially for inclined air showers [10].

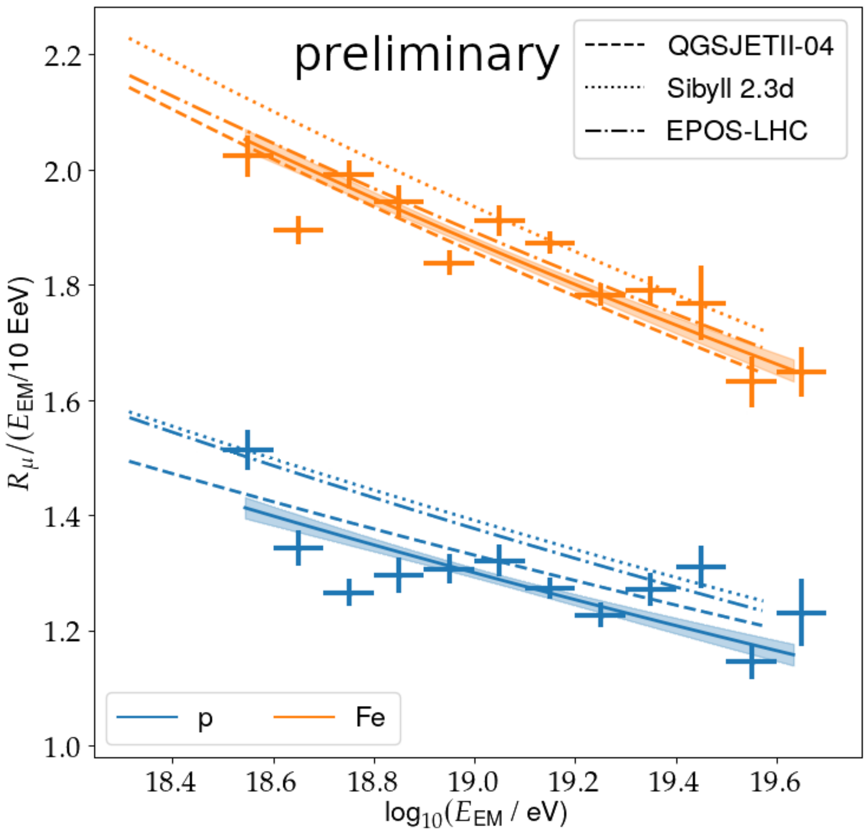

Figure 1: Predicted muon content of proton and iron induced air showers simulated using three different hadronic interaction models. The different primaries are denoted by color, the models by the linestyle. The profile indicates the reconstructed average muon content of the CoREAS simulations for discrete energy bins, the y-uncertainty is given by the uncertainty of the mean. The solid line shows a fit of the average muon content, the shaded area the fit uncertainty. See text for details.

3. Predicted muon content in simulations

The scaling of the muon content as a function of electromagnetic energy as predicted in simulations is derived by simulating more than 100.000 inclined air showers with CORSIKA [11] using QGSjetII-04 [12], EPOS-LHC [13], and Sibyll 2.3d [14] as hadronic interaction models. The simulations are made using protons and iron as primaries with energies between $10^{18.4}$ eV and $10^{19.6}$ eV. For each simulated air shower the total number of muons is counted and divided by a reference muon number. This reference is obtained from a zenith-angle dependent parametrization of the total muon number based on QGSjetII-03 simulations. Furthermore, the electromagnetic energy of the air shower is given by the sum of the energy deposited by all electromagnetic particles. Fitting a power law results in the dashed and dash-dotted lines in Fig. 1 for each primary and hadronic interaction model.

To test for a reconstruction bias a set of more than 1.000 air showers is simulated with CoREAS [16] using QGSjetII-04 as hadronic interaction model and protons and iron as primary

Table 1: Comparison of the scaling of the muon content as a function of electromagnetic energy (cf. Eq. (1)) predicted by CORSIKA simulations made with QGSjetII-04 and the reconstruction of CoREAS simulations using the same hadronic interaction model.

		model prediction	reconstruction
proton	a	1.33	1.300 ± 0.008
	b	0.92	0.921 ± 0.010
iron	a	1.86	1.874 ± 0.008
	b	0.91	0.913 ± 0.007

particles. The simulations are reconstructed including a realistic detector simulation and the addition of measured environmental noise. A high-quality event selection is applied which especially limits the zenith-angle range from 60° to 80° [7]. The radio event needs to have a successful LDF fit and a signal from a station inside of the Cherenkov ring[1] to ensure a high quality of the fit result. The reconstructed electromagnetic energy needs to be above 3.4 EeV which roughly corresponds to 4 EeV primary energy in case of an iron primary, i.e. the full efficiency threshold of the WCD. Events that have an opening angle between the shower direction reconstructed with the WCD and AERA larger than 2.08°[2] are removed from the analysis [17].

The energy scaling of the average muon content is estimated by an orthogonal-distance regression fit of a power law

$$R_\mu = a \cdot (E_{\mathrm{EM}}/10\,\mathrm{EeV})^b \tag{1}$$

to the profile of the data. The results are also shown in Fig. 1, the uncertainty of each fit is indicated by the shaded area. The final fit result is summarized and compared to the MC prediction of QGSjetII-04 in Tab. 1. A good agreement between the predicted muon content for QGSjetII-04 and the realistic reconstruction is obtained. Only for proton primaries, the absolute scale (parameter a) is slightly below the model prediction.

4. Measurement of the muon content in data

In the following, the AERA data recorded between 26 June 2013 and 16 November 2019 are analyzed. Only radio stations that can provide data on an external trigger are used in the reconstruction. This amounts to 76 stations before 02 March 2015. Afterwards, 29 additional radio stations have been deployed. The same event selection as in Sec. 3 is applied. Furthermore, events that fall into thunderstorm periods [17] are excluded. This selection yields 59 high-quality hybrid events.

As neither a pure proton nor a pure iron composition is expected in data, a mixed composition is assumed as a reference that matches the mean atomic mass number, $\langle \ln A \rangle$, as measured by the FD [15]. The measured data should follow these reference lines if data is correctly described by the hadronic interaction models. The reconstructed electromagnetic energy and muon estimator of

[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°.

[2]Mean value plus three standard deviations of a Gumble fit to the opening angle distribution.

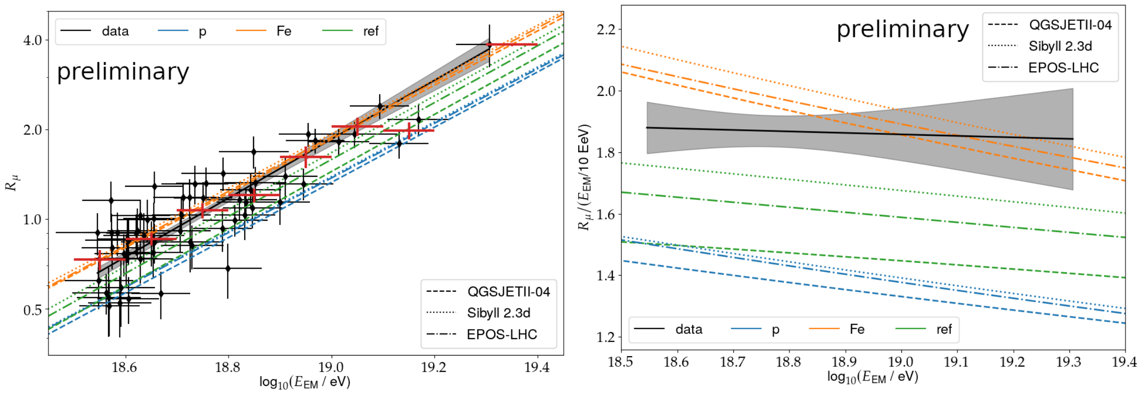

Figure 2: Muon content as a function of electromagnetic energy (left). Muon content divided by electromagnetic energy (right) to remove the power-law scaling. In both figures, the model predictions are identical to Fig. 1. Measured data are shown in black, a profile of the data is given in red (left). The shaded area denotes the fit uncertainty.

Table 2: Fit results for the measured muon content in this analysis and comparison with the results obtained in hybrid WCD-FD events [18].

	WCD-AERA analysis $R_\mu = a_{EM} \cdot (E_{EM}/10\ \mathrm{EeV})^b$	WCD-FD analysis $R_\mu = a_{CR} \cdot (E_{CR}/10\ \mathrm{EeV})^b$
a_{EM}	1.86 ± 0.09	
a_{CR}	1.63 ± 0.10 (converted)	$1.841 \pm 0.029 \pm 0.324$
b	0.99 ± 0.07	$1.029 \pm 0.024 \pm 0.030$

each event is shown in Fig. 2 together with a profile of the data. The data are fitted with a power law and the fit results are stated in Tab. 2. To compare the fit results with a previous analysis [18] using hybrid FD-WCD events one has to convert between electromagnetic and primary energy[3]. We find fewer muons than in [18] but the converted parameters a_{CR} and b agree within the systematic uncertainty to the previous result.

We observe significantly more muons in data than predicted by all hadronic interaction models. Calculating the ratio of the data fit and the model prediction we can quantify the muon deficit in simulations as shown in Fig. 3. For an electromagnetic energy of 10 EeV ∼10 % more mouns are found in data than predicted by Sibyll-2.3d, ∼15 % more than in EPOS-LHC, and ∼25 % more than in QGSjetII-04.

5. Conclusion

We showed a first estimate of the muon content of inclined air showers using hybrid measurements combining radio and particle detection. The measured muon content is compatible within the systematic uncertainty with a previous analysis using hybrid measurements combining fluorescence

[3]Note that the converted primary energy is based on the radio energy scale, which may not necessarily align with the conventional FD energy scale employed by Auger.

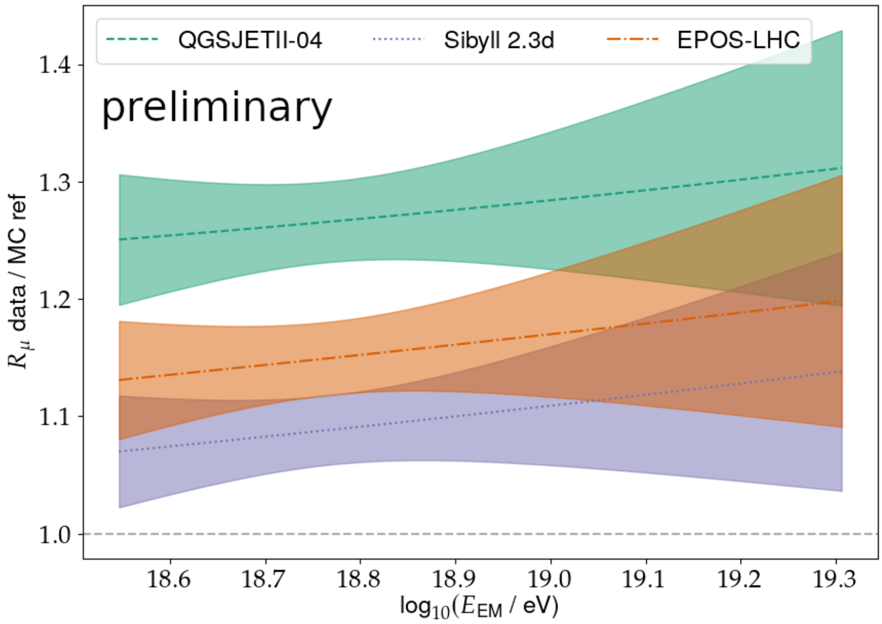

Figure 3: Ratio of measured muon content and the prediction of hadronic interaction models for a mixed composition matching the mean atomic mass number as measured by the FD as a function of electromagnetic energy. The shaded area denotes the fit uncertainty.

light and particle detection. We observe significantly more muons in data than predicted by hadronic interaction models and confirm the already known muon deficit in simulations. For an electromagnetic energy of 10 EeV ~10 % more mouns are found in data than predicted by Sibyll-2.3d, ~15 % more than in EPOS-LHC, and ~25 % more than in QGSjetII-04.

The analysis is still being refined and additional effects such as an increase of the radiation energy in simulations when reducing the STEPFC parameter in CORSIKA will be taken into account [19]. This will result in an updated calibration of radiation energy and E_{EM} increasing the energy of the data events by 5.5 % and thus improving the agreement of this analysis and [18].

Currently, the analysis is limited by the low statistics of 59 events which originate 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. This energy threshold can potentially be reduced using the 750 m WCD array in future analyses including three more years of data. With the AugerPrime Radio Detector [20] 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.

References

[1] D. Soldin et al. PoS(ICRC2021)349
[2] E.M. Holt et al. Eur. Phys. J. C 79, (2019)
[3] A. Aab et al. [Pierre Auger Collaboration], JCAP 1810.10 (2018)
[4] M. Gottowik for the Pierre Auger Collaboration, PoS(ICRC2019)274
[5] A.Aab et al. [Pierre Auger Collaboration], Nucl. Instrum. Meth. A 798(2015)172

[6] E. M. Holt for the Pierre Auger Collaboration, PoS(ICRC2017)492.
[7] A. Aab et al. [Pierre Auger Collaboration], JCAP 1408 (2014)
[8] A. Aab et al.[Pierre Auger Collaboration], Phys. Rev. Lett. 116.24 (2016)
[9] C. Glaser et al. JCAP09(2016)024
[10] F. Schlüter and T. Huege, JCAP01(2023)008
[11] D. Heck et al. FZKA Tech. Umw. Wis. B 6019, (1998)
[12] S. Ostapchenko. Phys. Rev. D 83, (2011)
[13] T. Pierog et al. Phys. Rev. C 92 (2015)
[14] F. Riehn et al. Phys. Rev. D 102, (2020)
[15] A. Yushkov for the Pierre Auger Collaboration, PoS(ICRC2019)482
[16] T. Huege et al. AIP Conf. Proc. 1535 128 (2013)
[17] M. Gottowik. PhD thesis. http://elpub.bib.uni-wuppertal.de/edocs/dokumente/fbc/physik/diss2021/gottowik
[18] A. Aab et al. [Pierre Auger Collaboration], Phys. Rev. D91.3, (2015)
[19] M. Gottowik et al. Astropart. Phys. 103 (2018)
[20] B. Pont for the Pierre Auger Collaboration, PoS (ICRC2019) 395

PoS(ARENA2022)049