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Update on the Combined Analysis of Muon Measurements from Nine Air Shower Experiments

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Over the last two decades, various experiments have measured muon densities in extensive air showers over several orders of magnitude in primary energy. While some experiments observed differences in the muon densities between simulated and experimentally measured air showers, others reported no discrepancies.

We will present an update of the meta-analysis of muon measurements from nine air shower experiments, covering shower energies between a few PeV and tens of EeV and muon threshold energies from a few 100 MeV to about 10 GeV. In order to compare measurements from different experiments, their energy scale was cross-calibrated and the experimental data has been compared using a universal reference scale based on air shower simulations. Above 10 PeV, we find a muon excess with respect to simulations for all hadronic interaction models, which is increasing with shower energy. For EPOS-LHC and QGSJet-II.04 the significance of the slope of the increase is analyzed in detail under different assumptions of the individual experimental uncertainties.

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1. Introduction

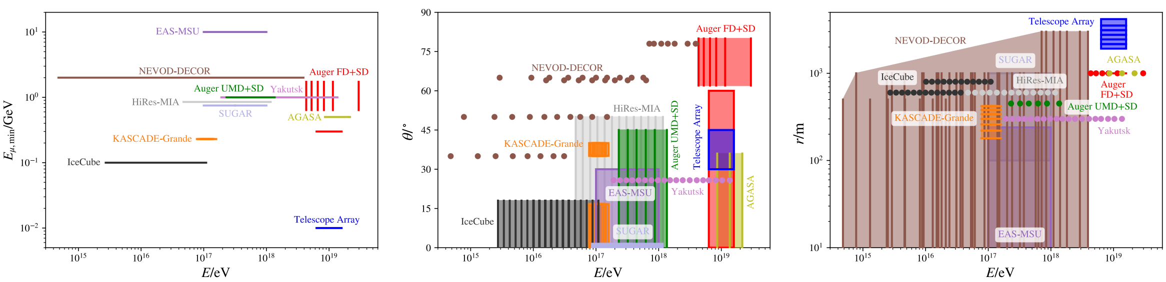
Cosmic rays enter the Earth's atmosphere where they produce *Extensive Air Showers* (EAS) which can be measured at the ground. Although the energy spectrum of cosmic rays has been measured with high precision over many orders of magnitude, the sources of cosmic rays are still unknown, their acceleration mechanism and mass composition are uncertain, and several features observed in the energy spectrum are not well understood [1, 2].

The main challenge lies in the measurements of the muon content in air showers, which have been performed by many experiments over the last 20 years. Various experiments reported discrepancies in the number of muons in simulated and observed air showers, such as the HiRes-MIA [3] and NEVOD-DECOR [4, 5] collaborations, as well as the Pierre Auger Observatory [6, 7] (Auger), Telescope Array [8] (TA), and SUGAR [9]. In contrast, no discrepancies in the average muon densities were observed by EAS-MSU [10], the Yakutsk EAS array [11], and KASCADE-Grande [12]. KASCADE-Grande, however, reported differences in the muon number evolution with the zenith angle with respect to model predictions.

In this article, we present an update of the meta-analysis of global measurements of the lateral muon density by multiple EAS experiments which was previously reported in Refs. [13, 14]. This update includes new data from Auger [15] and its Underground Muon Detectors [16] (UMD), and from the IceCube Neutrino Observatory [17] (IceCube). In addition, data from the AGASA experiment [18] is included for the first time and systematic studies of the energy-dependent trend of the muon discrepancies are discussed in detail. An overview of further measurements of the muon content in EAS is beyond the scope of this work and can be found in Refs. [13, 19].

2. Measurements of the Muon Lateral Density

The lateral density of muons measured at the ground depends on various parameters: cosmic-ray energy, E, zenith angle, θ, shower age (vertical depth, X, and zenith angle), lateral distance, r, from the shower axis, and energy threshold, $E_{\mu,\mathrm{min}}$, of the muon detectors. The parameter space covered by the experiments considered in this meta-analysis is shown in Fig. 1. Due to different experimental conditions and analysis techniques, a direct comparison of the muon measurements is not possible. Instead, to compare different results in a meaningful way, the measurements of each



(a) (b) (c)

Figure 1: Phase space of EAS experiments which have reported measurements of the muon density. Points and lines indicate a measurement in a narrow bin of the parameter, while boxes indicate integration over a parameter range. Figure (a) shows the muon energy thresholds, $E_{\mu,\mathrm{min}}$, (b) the zenith angle range, θ, and (c) the lateral distances, r, of the muon density measurements, as a function of the EAS energy, E.

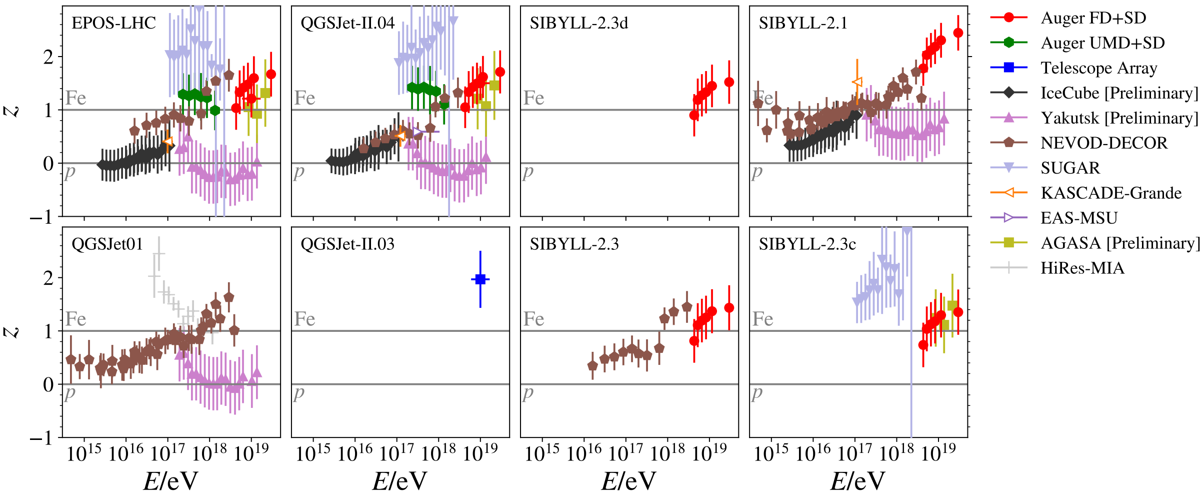


Figure 2: Muon density measurements converted to the z-scale, as defined in Eq. (1), for different hadronic interaction models. When corresponding simulations are missing for an experiment, no points can be shown. Error bars show statistical and systematic uncertainties added in quadrature.

experiment have to be compared to EAS simulations in the same observation conditions in terms of a data/MC ratio. Therefore, the measurements of the muon density from different experiments are converted to the *z-scale*,

$$z = \frac{\ln\langle N_\mu^{\mathrm{det}}\rangle - \ln\langle N_{\mu,\mathrm{p}}^{\mathrm{det}}\rangle}{\ln\langle N_{\mu,\mathrm{Fe}}^{\mathrm{det}}\rangle - \ln\langle N_{\mu,\mathrm{p}}^{\mathrm{det}}\rangle}, \tag{1}$$

where $\langle N_\mu^{\mathrm{det}}\rangle$ is the average muon density estimate as seen in the detector, while $\langle N_{\mu,\mathrm{p}}^{\mathrm{det}}\rangle$ and $\langle N_{\mu,\mathrm{Fe}}^{\mathrm{det}}\rangle$ are the simulated average muon densities for proton and iron showers after a full detector simulation. The z-scale is constructed such that an observation of the muon density of $z = 0$ is consistent with a simulated proton shower and $z = 1$ for a simulated iron shower. A dedicated discussion on the properties and calculation of the z-scale and its uncertainties can be found in Ref. [18].

The z-values obtained by nine air shower experiments [4–12, 15–18] are shown in Fig. 2. Depending on the experiment, the distributions are given for the *post-LHC* hadronic interaction models EPOS-LHC [20], QGSJet-II.04 [21], and Sibyll 2.3(c/d) [22, 23], and for the *pre-LHC* models QGSJet01 and QGSJet-II.03 [24], and Sibyll 2.1 [25]. For all models the data lies between the expectations for proton and iron showers up to energies of about 10^{17} eV. However, at higher energies all data except Yakutsk suggest an unphysical mass composition heavier than iron.

2.1 Energy Scale Offsets and Cross-Calibration

According to the *Matthews-Heitler model* [26] the number of muons in EAS, N_μ, depends on the energy, E, and mass, A, of the initial cosmic ray as

$$N_\mu = A^{1-\beta} \cdot (E/\xi_C)^\beta, \tag{2}$$

with power-law index $\beta \simeq 0.9$ and energy constant, ξ_C. This causes two experiments with an energy-scale offset of 20%, for example, to have an 18% offset in the data/MC ratios because measurements are compared to EAS simulated at different apparent energies. To compare muon measurements between experiments, energy-scale offsets therefore need to be taken into account.

Assuming that the cosmic ray flux is a universal reference and that all deviations in measured fluxes between different experiments arise from energy scale offsets, a relative scale $E_{\mathrm{data}}/E_{\mathrm{ref}}$ can be determined for each experiment such that the all-particle fluxes match [27]. The relative energy-scale shift between Auger and TA has been found to be 10.4% [28] and the reference energy scale, E_{ref}, used in this work is placed between the two experiments, as shown in Fig. 3. The scaling factors for the other experiments are obtained from the Global Spline Fit (GSF) flux model [27] which also uses cross-calibration internally, with a reference energy scale $E_{\mathrm{ref,GSF}}/E_{\mathrm{ref}} = 0.948/0.880 \simeq 1.08$. Using the adjustment factors from Fig. 3, the z-values are energy cross-calibrated as described in detail in Ref. [13] and the individual uncertainties of each experiment are adjusted by removing the contribution from the energy-scale. However, the reference energy-scale, after cross-calibration, has a remaining uncertainty of at least 10%, causing potential shifts of the z-values by about ±0.25. No cross-calibration factor can be given for KASCADE-Grande because the cosmic ray flux is computed using a different energy estimator to which this method can not be applied [13]. For EAS-MSU, no all-particle flux is available for cross-calibration.

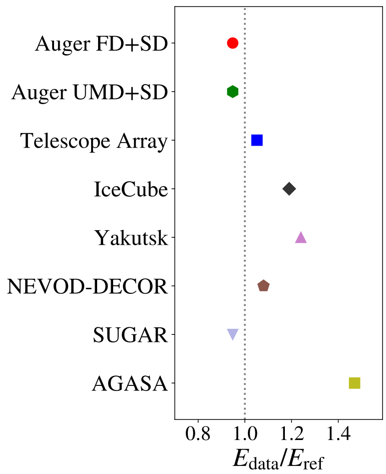


Figure 3: Energy-scale adjustment factors obtained from the cross-calibration described in Ref. [27].

The resulting z-values, after applying the energy-scale cross-calibration, are shown in Fig. 4, where a remarkably consistent picture is obtained. The measurements are in agreement with simulations based on the post-LHC hadronic interaction models, EPOS-LHC and QGSJetII.04, up to about a few 10^{16} eV, within the expectation from measurements of the maximum shower depth, X_{max}, and uncertainties. However, at higher energies, an increasing muon excess with respect to simulations is observed for all models, suggesting a mass composition heavier than iron.

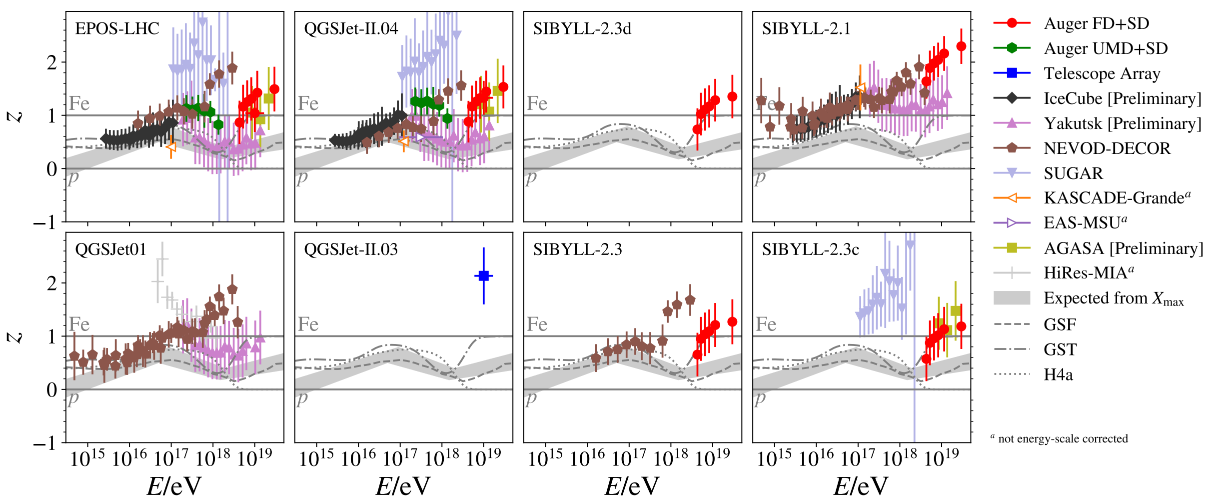


Figure 4: Combined data from Fig. 2 after applying energy-scale cross-calibration, as described in the text. The data of KASCADE-Grande and EAS-MSU cannot be cross-calibrated and are only included for comparison. Shown for comparison are z-values expected for a mixed composition from optical measurements (X_{max}), based on an update of Ref. [1], and from the flux models GSF [27], GST [29], and H4a [30].

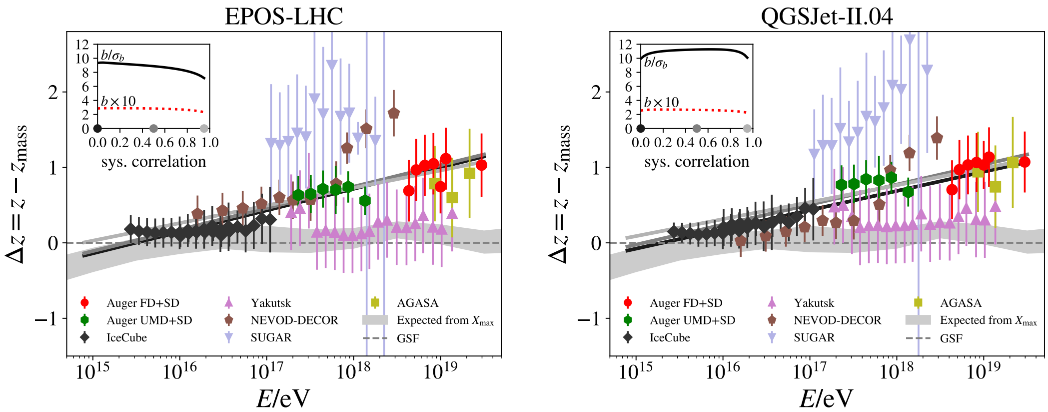


Figure 5: Linear fits to the $\Delta z = z - z_{\mathrm{mass}}$ distributions, as described in Eq. (3). Shown in the inset are the slope, b, and its deviation from zero in standard deviations for an assumed correlation of the point-wise uncertainties within each experiment. Examples of the fits are shown for a correlation of 0.0, 0.5, and 0.95.

2.2 Energy-Dependent Trend

In order to systematically quantify the energy-dependent trend observed in the muon measurements shown in Fig. 4, the mass composition dependence expected from Eq. (2) needs to be taken into account. If the measured z-values follow z_{mass} as expectated from X_{max} measurements, the model describes the muon density at the ground consistently. Subtracting z_{mass} is thus expected to remove the effect of the changing mass composition. The resulting $\Delta z = z - z_{\mathrm{mass}}$ distributions are shown in Fig. 5 for EPOS-LHC and QGSJet-II.04 with z_{mass} determined from the GSF flux model [27]. A simple linear function of the form

$$\Delta z_{\mathrm{fit}} = a + b \cdot \log_{10}(E/10^{16}\mathrm{eV}) \tag{3}$$

is fit to the data, where a and b are free parameters. To account for (the unknown) correlated uncertainties in the experimental data, the least-squares method described in Ref. [13] is used. It assumes a correlation factor, α, between data points belonging to the same data set. The fit is repeated for values of α between 0 and 0.95. To adjust for over/under-estimated uncertainties, the raw result, σ_b^{raw}, is re-scaled with the χ^2 value and the degrees of freedom, n_{dof}, of the fit as $\sigma_b = \sigma_b^{\mathrm{raw}} \cdot \sqrt{\chi^2/n_{\mathrm{dof}}}$, as described in Ref. [13]. For EPOS-LHC, the resulting slope ranges from

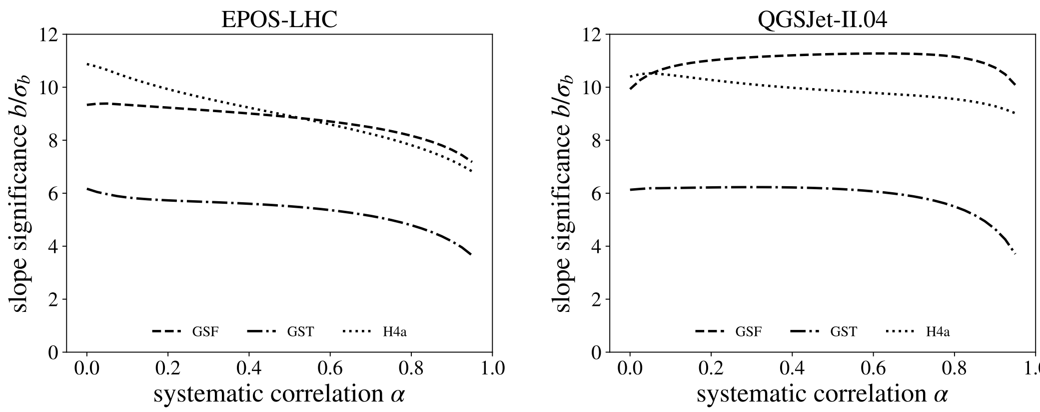


Figure 6: Significance of the deviation of the slope, b, in Eq. (3) from zero as a function of an assumed correlation, α, of the uncertainties within each experiment. The significances are shown for Δz with z_{mass} determined from the GSF, GST, and H4a models.

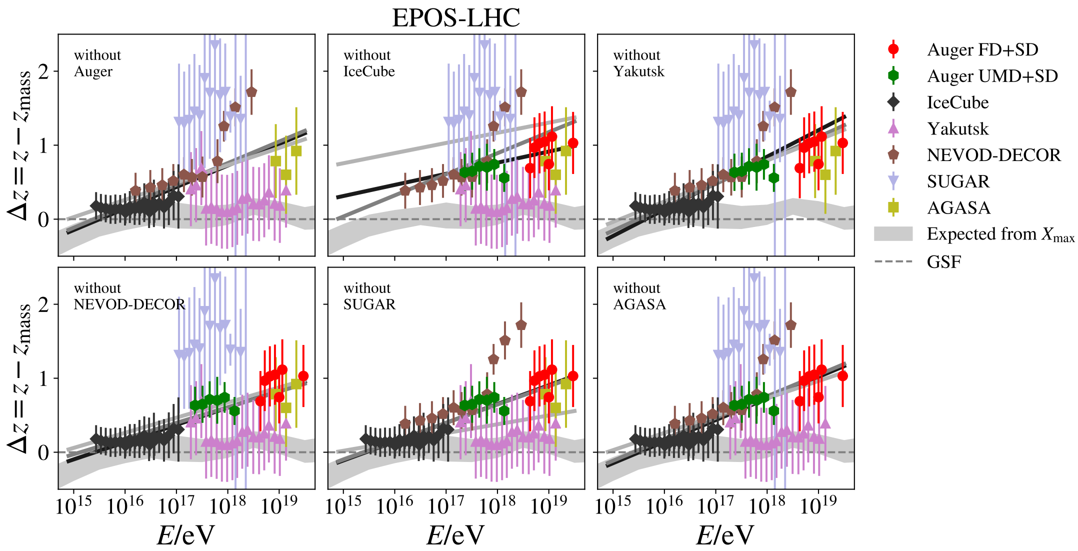


Figure 7: Linear fits to the data points as described in Eq. (3) with individual experiments excluded from the data. Examples of the fits are shown for systematic correlations of 0.0, 0.5, and 0.95.

$b = 0.23 \pm 0.03$ up to $b = 0.29 \pm 0.03$ for $\alpha = 0.95$ and $\alpha = 0.0$, respectively. For QGSJet-II.04, it ranges from $b = 0.22 \pm 0.02$ up to $b = 0.25 \pm 0.03$ for $\alpha = 0.95$ and $\alpha = 0.0$. The significances of the deviations from $b = 0.0$ are around 8σ for EPOS-LHC and above 10σ for QGSJet-II.04.

To study the influence of the underlying mass assumption, the fits in $\Delta z = z - z_{\text{mass}}$ are repeated with z_{mass} obtained from the GST [29] and H4a [30] flux models which are also based on fits to experimental data. The resulting significances for correlations between 0.0 and 0.95 are shown in Fig. 6. While the significances based on the H4a model increase, the GST model always yields smaller significances. However, as shown in Fig. 4, the GST model predicts a heavier cosmic ray mass composition which is in strong tension with measurements of X_{max} over the vast majority of the energy range considered here. This confirms the choice of the GSF model which shows the best overall agreement with optical measurements of the mass composition. In addition, the effect of the choice of the reference energy scale, E_{ref} in Fig. 3, was also studied and found to be negligible.

2.3 N-1 Tests

To study the contribution from each individual experiment to the significances of the fit slopes to the combined data, systematic $N - 1$ tests are performed where data from one experiment at a time is excluded from the fit. The resulting fits for EPOS-LHC are shown in Fig. 7 and the corresponding significances for the models EPOS-LHC and QGSJet-II.04 are depicted in Fig. 8 for systematic correlations α between 0.0 and 0.95. The significances of the fit slopes remain above 5σ when excluding most experiments. However, lower significances can be observed for EPOS-LHC, for extreme correlations, when removing data from IceCube, and to some extent when removing data from SUGAR. In contrast, excluding the measurements by Yakutsk causes an increase of the significances, in particular towards very small correlations. This indicates that measurements from Yakutsk, which are in strong tension with other data in the same energy region, have a stronger influence on the fit result if data from IceCube is removed. These effects are more pronounced for EPOS-LHC compared to QGSJet-II.04. This is due to a smaller scatter of the data for QGSJet-II.04, which causes smaller uncertainties in the slope, b, of the fit through the χ^2/n_{dof} re-scaling.

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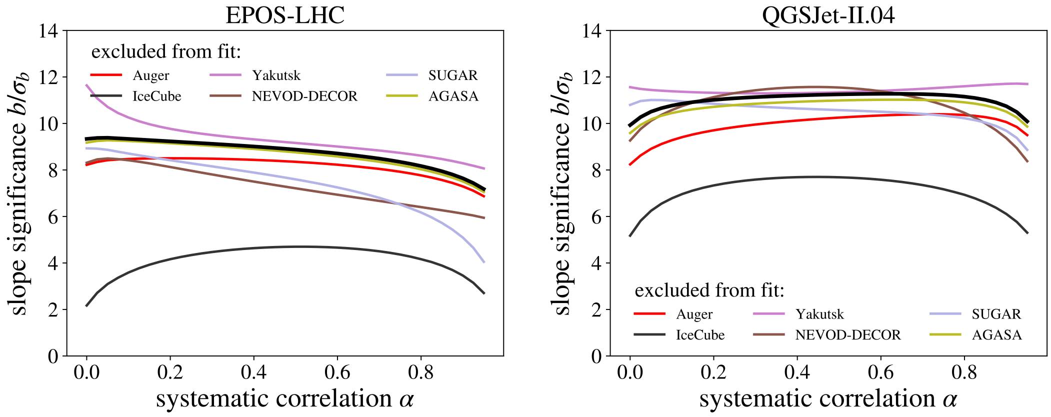

Figure 8: Significance of the deviation of the slope, b, in Eq. (3) from zero as a function of an assumed systematic correlation of the uncertainties within each experiment, α. Black lines show the result from Fig. 5 and colored lines the results where individual experiments are excluded from the fit (see text for details).

3. Conclusions

An update of the meta-analysis of muon measurements in EAS with energies from PeV up to tens of EeV was presented and a remarkably consistent picture is obtained after cross-calibrating the energy scales of the different experiments. The measurements agree with simulations based on the models EPOS-LHC and QGSJet-II.04, within uncertainties, up to energies of a few 10^{16} eV, assuming the GSF flux model. At higher energies, an increasing excess with respect to model predictions is observed. The slope of this increase is between $b = 0.23$ and $b = 0.29$ for EPOS-LHC and between $b = 0.22$ and $b = 0.25$ for QGSJet-II.04, with a significance of the deviations from $b = 0.0$ of around 8σ and 10σ, respectively. A small change of the fits compared to the previous meta-analysis [13, 14] is observed which arises mainly from the updates of the experimental data. Studies of other dependencies, for example the minimum energy of muons at production for each experiment, as described in Ref. [14], have yet been inconclusive due to the limited experimental data. It has been shown that the mass composition model is important for the mass subtraction in $\Delta z = z - z_{\text{mass}}$ and should be derived from optical measurements with the least amount of assumptions. The GSF model satisfies this requirement at a certain level, however, the possibility to use data from X_{max} measurements directly is currently under investigation.

When removing individual data from this meta-analysis, for extreme assumptions of the correlation of uncertainties, the significances for a non-zero slope can decrease to approximately 3σ for EPOS-LHC and around 5σ for QGSJet-II.04. This decrease is mainly due to the data from Yakutsk, which becomes more important when data from IceCube (or to some extent SUGAR) are removed and is in strong tension with other muon measurements. To understand these tensions, further studies of the treatment of systematic uncertainties and relative biases of the individual experiments are necessary. Moreover, additional measurements with high precision are needed, in particular at energies above 10^{17} eV. Ongoing EAS detector upgrades and improved analysis methods are expected to reduce the uncertainties of the experimental results and increase the parameter space. This will improve the data accuracy and help to investigate other dependencies of the deviations between simulations and data in future extensions of this meta-analysis.

References

[1] K.-H. Kampert and M. Unger *Astropart. Phys.* **35** (2012) 660–678.

[2] J. Becker Tjus and L. Merten *Phys. Rept.* **872** (2020) 1–98.

[3] **HiRes-MIA** Collaboration, T. Abu-Zayyad *et al.* *Phys. Rev. Lett.* **84** (2000) 4276–4279.

[4] **NEVOD-DECOR** Collaboration, A. G. Bogdanov *et al.* *Phys. Atom. Nucl.* **73** (2010) .

[5] **NEVOD-DECOR** Collaboration, A. G. Bogdanov *et al.* *Astropart. Phys.* **98** (2018) 13–20.

[6] **Pierre Auger** Collaboration, A. Aab *et al.* *Phys. Rev. D* **91** no. 3, (2015) 032003.

[7] **Pierre Auger** Collaboration, A. Aab *et al.* *Phys. Rev. Lett.* **117** no. 19, (2016) 192001.

[8] **Telescope Array** Collaboration, R. U. Abbasi *et al.* *Phys. Rev. D* **98** no. 2, (2018) 022002.

[9] **SUGAR** Collaboration, J. A. Bellido *et al.* *Phys. Rev. D* **98** no. 2, (2018) 023014.

[10] **EAS-MSU** Collaboration, Y. A. Fomin *et al.* *Astropart. Phys.* **92** (2017) 1–6.

[11] **Yakutsk** Collaboration, A. Glushkov, M. Pravdin, and A. Sabourov *Priv. Comm.* (2018) .

[12] **KASCADE-Grande** Collaboration, W. D. Apel *et al.* *Astropart. Phys.* **95** (2017) 25–43.

[13] **EAS-MSU, IceCube, KASCADE Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array, Yakutsk EAS Array** Collaboration, H. P. Dembinski *et al.* *EPJ Web Conf.* **210** (2019) 02004.

[14] **EAS-MSU, IceCube, KASCADE Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array, Yakutsk EAS Array** Collaboration, L. Cazon *PoS* **ICRC2019** (2020) 214.

[15] **Pierre Auger** Collaboration, A. Aab *et al.* *Phys. Rev. Lett.* **126** no. 15, (2021) 152002.

[16] **Pierre Auger** Collaboration, A. Aab *et al.* *Eur. Phys. J. C* **80** no. 8, (2020) 751.

[17] **IceCube** Collaboration, D. Soldin *PoS* **ICRC2021** (2021) 342.

[18] F. Gesualdi *et al.* *PoS* **ICRC2021** (2021) 473.

[19] J. Albrecht *et al.* *submitted to Astrophysics and Space Science* (2021) .

[20] T. Pierog *et al.* *Phys. Rev. C* **92** no. 3, (2015) 034906.

[21] S. Ostapchenko *EPJ Web Conf.* **52** (2013) 02001.

[22] F. Riehn *et al.* *PoS* **ICRC2017** (2018) 301.

[23] F. Riehn *et al.* *Phys. Rev. D* **102** no. 6, (2020) 063002.

[24] N. Kalmykov and S. Ostapchenko *Phys. Atom. Nucl.* **56** no. 346, (1993) .

[25] E.-J. Ahn *et al.* *Phys. Rev. D* **80** (2009) 094003.

[26] J. Matthews *Astropart. Phys.* **22** (2005) 387–397.

[27] H. P. Dembinski *et al.* *PoS* **ICRC2017** (2018) 533.

[28] **Pierre Auger, Telescope Array** Collaboration, O. Deligny *PoS* **ICRC2019** (2020) 234.

[29] T. K. Gaisser, T. Stanev, and S. Tilav *Front. Phys.(Beijing)* **8** (2013) 748–758.

[30] T. K. Gaisser *Astropart. Phys.* **35** (2012) 801–806.

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